n. maisuraZe, m. cirekiZe, m. Sengelia

leqciebis kursi zogad fizikaSi

II nawili

2017 w.

winamdebare saxelmZRvanelo warmoadgens leqciebis kursis eleqtronul versias zogad fizikaSi. igi Sedgenilia amJamad moqmedi zogadi fizikis silabusis mixedviT.

wigni gamiznulia informatikisa da marTvis sistemebis fakultetis studentebisaTvis. aseve am wigniT SeuZlia isargeblon energetikis, samSeneblo, samTo - geologiis, satransporto da manqanaTmSeneblobis fakultetis studentebma.

avtorTa mizania swori warmodgena Seuqmnas studentebs gamocdebze moTxovnaTa donis Sesaxeb da daexmaros maT fizikis gamocdebisaTvis momzadebaSi.

am leqciebis kursiT SeuZliaT isargeblon fizikis leqtorebmac da aseve sxva pirebmac, romlebic daintersdeba fizikis saswavlo kursiT saq. teqnikur universitetSi.

amJamad warmodgenilia II semestris 15 saleqcio kviris masala, romelic dayofilia programiT gaTvaliswinebuli TiToeuli kviris leqciebis mixedviT.

avtorebi mwuxarebas gamoTqvamen, rom maT rigebs gamoaklda niWieri mecnieri da Tavisi profesiis Rrma mcodne profesori nodar maisuraZe, romelsac didi wvlili aqvs Setanili winamdebare fizikis leqciebis kursis SedgenaSi.

sarCevi

I leqcia

daeleqtroba xaxuniT. eleqtruli muxti. elementaruli muxti. eleqtruli muxtis mudmivobis kanoni. kulonis kanoni. dieleqtrikuli SeRwevadoba. eleqtruli veli. eleqtruli velis

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$1. daeleqtroba xaxuniT. eleqtruli muxti. elementaruli muxti. eleqtruli muxtis mudmivobis kanoni.

jer jidev Zvel saberZneTSi mecnierebma daadgines, rom qarvisgan damzadebuli sxeuli Salis naWerze xaxunis Sedegad iZenda sxva msubuqi sxeulebis mizidvis unars. qarvas berZnulad eleqtroni ewodeba da termini eleqtroba swored aqedan aris warmoqmnili. am movlenas eleqtrizacia ewodeba, xolo sxeuls, romelic iZens msubuqi sagnebis mizidvis unars – daeleqtroebuli, anda damuxtuli. aseTive mizidvis unars iCenen sxva sxeulebic, mag. mina abreSumis qsovilis naWerze xaxunisas. AaRmoCnda rom bunebaSi arsebobs ori tipis muxti. pirobiTad erT-erTs uwodes dadebiTi (minis eleqtroba) da meores (qarvis eleqtroba) uaryofiTi. cdebidan dadginda, rom erTi niSniT damuxtuli sxeulebi erTmaneTs ganizidavs, xolo sxvadasxva saxeliani ki erTmaneTs miizidavs.

damuxtuli sxeulebis urTierTqmedebas eleqtromagnituri urTierTqmedeba ewodeba. eleqtruli muxti aris fizikuri sidide, romelic gansazRvravs eleqtromagnituri urTierTqmedebis intensivobas, iseve rogorc masa

gansazRvravs gravitaciuli urTierTqmedebis intensivobas. magram gravitaciuli urTierTqmedebis Zala ∼100-jer naklebia el. magn. urTierTqmedebis Zalaze.

xaxuniT sxeulTa daeleqtroba axsnili iqna nivTierebis agebulebis eleqtronuli Teoriis safuZvelze. am Teoriis Tanaxmad yoveli atomi Sedgeba ori tipis damuxtuli nawilakebisagan – eleqtronebisa da protonebisagan. umciresi sididis eleqtrul muxts elementaruli muxti ewodeba. uaryofiTi elementaruli muxti aqvs eleqtrons, dadebiTi protons. sididiT maTi muxtebi erTmaneTis tolia (elementaruli muxtis sidide $e = 1{,}6 \cdot 10^{-19}$ k). atomSi isini toli raodenobiTaa da maTi maTi erTmaneTis kompensirebis gamo, atomi neitraluria. xaxunis dros eleqtronebi gadadian erTi sxeulidan meoreSi da iq sadac eleqtronebis siWarbea, is sxeuli imuxteba uaryofiTad, xolo romelsac aklia eleqtronebi – dadebiTad.

eleqtronebs SeuZliaT gadaadgileba sxeulis SigniT, xolo protonebi arian atomis birTvSi (asruleben rxeviT moZraobas). xaxunis Sedegad im sxeulidan, romelSic eleqtronebis sxeulTan kavSiri SedarebiT mcirea, gadadian meore sxeulSi. amis Sedegad erT sxeulSi eleqtronebis siWarbea, meoreSi ki nakleboba da rodesac maT ganvacalkevebT erTi aRmoCndeba uaryofiTad damuxtuli, meore ki dadebiTad. e.i. xaxuniT daeleqtrobis dros orive sxeuli imuxteba toli raodenobis sxvadaxva niSnis muxtiT, radgan ramdeniTac Semcirdeba erTi sxeulis uaryofiTi muxti eleqtronebis dakargvis gamo, imdeniTve gaizrdeba meore sxeulis uaryofiTi muxti eleqtronebis SeZenis gamo. es movlena gamoxatavs muxtis Senaxvis kanons: eleqtruli muxti ar warmoiqmneba da arc qreba, igi gadadis erTi sxeulidan meoreSi, an gadaadgildeba sxeulis SigniT. SeiZleba moxdes elementarul nawilakTa urTierTgardaqmna, magram yvela Sem-Si damuxtuli nawilakebi warmoiqmneba wyvilad sididiT toli da sapirispiro niSnis muxtebiT, an ori sapirispiro niSnis muxti iqceva neitralur nawilakad., ise rom jamuri muxti ar icvleba. e.i. **Caketil sistemaSi muxtebis algebruli jami mudmivia** (Caketilia is sistema, romelSic ar Sedian da ar gamodian damuxtuli nawilakebi)**.**

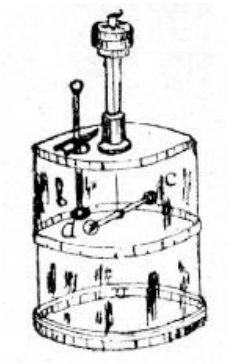
garda orniSnianobisa da mudmivobisa eleqtruli muxtebisaTvis damaxasiaTebeli aseve diskretuloba, anu wyvetiloba. misi arsi isaa, rom arsebobs elementaruli (umciresi) muxti daA nebismieri damuxtuli sxeulis muxti am muxtis jeradia. e.i. sxeulis muxtis gazrda an Semcireba SeiZleba am elementaruli muxtis an misi jeradiT.

el. Tvisebebis mixedviT sxeulebi iyofian sam jgufad: gamtarebad, dieleqtrikebad da naxevargamtarebad. gamtarebSi muxtebs SeuZliaT Tavisuflad gadaadgileba (liTonebi, mJavas, tuteebis, marilebis wyalxsnarebi). dieleqtrikebSi maT Tavisuflad gadaadgileba ar SeuZliaT (mina, eboniti, kauCuki da sxva). naxevargamtarebs ukaviaT maT Soris Sualeduri mdg-ba.

$2. kulonis kanoni. dieleqtrikuli SeRwevadoba.

uZravi muxtebis urTierTqmedebas Seiswavlis eleqtrostatika. misi ZiriTadi kanonia kulonis kanoni, romelic ganixilavs wertilovan muxtebs Soris urTierTqmedebis Zalebs.

damuxtul sxeulebs, romelTa geometriuli zomebi gacilebiT naklebia maT Soris manZilze, wertilovani muxtebi ewodeba. wertilovani muxtebis urTierTqmedebis Zala gansazRvra kulonma grexiTi sasworis gamoyenebiT, romlis sqema mocemuli nax.1.1-ze. vercxlis Zafze dakidebulia minis wvrili Rero. Reros erT boloze damagrebulia mooqruli anwlis a burTula, xolo meoreze c sapirwone burTula. amis gamo Rero horizontaluradaa. mTeli es sistema moTavsebuli iyo minis cilindrul WurWelSi haeris moZraobis gavlenis

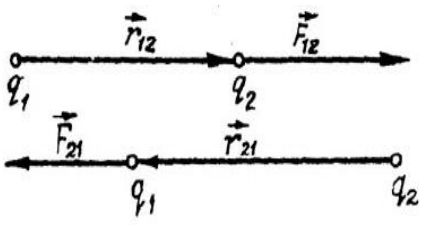


nax. 1.1

dasacavad. a burTulas exebian uZrav RerZze damagrebuli iseTive zomis b damuxtuli burTulaTi. muxti am dros Tanabrad nawildeba a da b burTulebs Soris. radgan burTulebze erTnairi niSnis muxtebia, amitom isini ganizidebian raRac ZaliT, ris gamoc a burTula gadaixreba. es iwvevda Zafis dagrexvas. gadaxra maSin wydeboda, rodesac ZafSi aRZruli drekadobis Zalis momenti awonasworebda eleqtruli ganzidvis Zalis moments. grexis kuTxis mixedviT sazRvravdnen mabrunebeli Zalis moments da Sesabamisad muxtebs Soris urTierTqmedebis Zalasac. cda Catarda birTvebis muxtebisa da maT Soris manZilis sxvadasxva mniSvnelobebisTvis. am cdebis safuZvelze kulonma daadgina, rom uZrav wertilovan muxtebs Soris urTierTqmedebis Zala sididiT proporciulia muxtebis sididis namravlisa da ukuproporciulia maT Soris manZilis kvadratisa da mimarTulia muxtebis SemaerTebeli wrfis gaswvriv , e.i. kulonis Zala centraluri Zalaa. is gamoisaxeba formuliT**:**

$$F = k\frac{q_1 q_2}{r^2} \qquad (1.1),$$

sadac q_1 da q_2 wertilovani muxtebia, $r-$ maT Soris manZili, $k-$proporciulobis koeficientia, romelic ricxobrivad tolia erTeulovani muxtebis urTierTqmedebis Zalisa, roca muxtebs Soris manZili sigrZis erTeulis tolia. rogorc avRniSneT Zala mimarTulia muxtebis SemaerTebeli wrfis gaswvriv. Tu muxtebi erTniSnaa, maSin $q_1 \cdot q_2 > 0$, amitom $F > 0$. sxvadasxva niSnis Sem-Si $q_1 \cdot q_2 < 0$ da $F < 0$. veqtoruli saxiT, Zala romliTac q_1 muxti moqmedebs q_2-ze, tolia: $\vec{F}_{12} = k\frac{q_1 q_2}{r^3}\vec{r}_{12}$, sadac $\vec{r}_{12}$ mimarTulia q_1-dan q_2-sken.



analogiurad $\vec{F}_{21} = k\frac{q_1 q_2}{r^3}\vec{r}_{21}$ aris Zala romliTac q_2 muxti moqmedebs q_1-

ze, xolo $\vec{r}_{21}$ mimarTulia q_2-dan q_1-sken. $\vec{r}_{12} = -\vec{r}_{21}$ (nax. 1.2). erTeulTa saerTaSoriso ***SI*** sistemaSi muxtis erTeulia kuloni (k), romelic ganisazRvreba denis Zalis formulidan $I = \frac{q}{t}$ da $q = It$. denis Zalis erTeuli aris amperi, amitom 1 kuloni aris iseTi muxtis raodenoba, romelic gadaitaneba gamtaris ganivkveTSi 1 wamSi, rodesac masSi gadis

nax. 1.2 1 amperi deni. dadginda, rom proporciulobis koeficientis ricxviTi mni-ba ***SI*** sistemaSi tolia $k = 9 \cdot 10^9$ n·m^2/k^2 , anu 1 metriT daSorebuli TiTo kulonis sididis muxtebi urTierTqmedeben. $9 \cdot 10^9$ niutoni ZaliT.

xSirad praqtikaSi gamoiyeneba iseTi formulebi, romelTa mniSvneli Seicavs 4π-s. amitom kulonis kanons gardaqmnian da viRebT mis **"racionalizebul"** formulas (sistemas sadac aseTi racionalizebuli formaa Caweris – **racionalizebuli sistema** ewodeba). ***SI*** sistema aseTi sistemaa. maSin gveqneba

$$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2} \quad (1.2).$$

aq $\frac{1}{4\pi}$ – racionalizaciis koeficientia, xolo ε_0 – eletruli mudmiva da is tolia

$$\varepsilon_0 = \frac{1}{4\pi k} = 8{,}85 \cdot 10^{12} \text{ k}^2/\text{n}\cdot\text{m}^2.$$

(1.2) formula samarTliania vakuumisTvis. dieleqtrikSi (TxevadSi an airadSi) ki kulonis kanoni ase Caiwereba:

$$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{\varepsilon r^2} \quad (1.3),$$

sadac ε dieleqtrikis dieleqtrikuli SeRwevadobaa. e.i. dieleqtrikSi muxtebs Soris urTierTqmedebis Zala ε-jer mcirdeba.

$3. eleqtruli veli. eleqtruli velis daZabuloba. velebis superpoziciis principi.

imis da mixedviT, Tu rogor xdeba muxtebis urTierTqmedeba, arsebobda ori Teoria: Sorsqmedebis da axloqmedebis.

pirveli Teoriis Tanaxmad erTi muxtis moqmedeba meoreze gadaecema manZilze, ise rom maT Soris moTavsebuli garemo araviTar rols ar TamaSobs am moqmedebis gadacemaSi. am moqmedebis gadacema am TeoriiT xdeba myisierad (saWiro dro $t = 0$).

meore Teoriis Tanaxmad piriqiT – erTi muxtis moqmedeba meores gadaecema TandaTan, sasruli siCqariT, romelic tolia sinaTlis gavrcelebis siCqarisa vakuumSi ($c = 3 \cdot 10^8$ m/wm). moqmedebis gadamcemi obieqti ki materiis gansakuTrebuli formaa, romelic faradeis Tanaxmad eleqtruli velia. misi Teoriis Tanaxmad uZravi muxtebi Tavis garSemo qmnian Zalur vels, romlis meSveobiTac isini erTmaneTze moqmedeben. is materiis erT-erTi formaa. xasiaTdeba energiiT da inerciiT. maSasadame eleqtruli veli aris materiis gansakuTrebuli forma, romelic aRiZvreba yoveli damuxtuli sxeulis irgvliv da romlis arseboba vlindeba imiT, rom am velSi Setanil yovel damuxtul sxeulze moqmedebs Zala. am Teoriam sabolood gaimarjva mas Semdeg, rac maqsvelma Teoriulad daasabuTa el. magn. velis arseboba da gamoTvala misi siCqare.

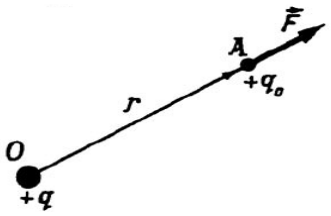
uZravi muxtis el. vels eleqtrostatikuri veli ewodeba. mis Sesaswavlad mis yovel wertilSi SeaqvT e.w. sasinji q_0 muxti (mcire zomis sxeulze moTavsebuli mcire muxti, romelic ar iwvevs Sesaswavli velis damaxinjebas). velis mocemul wertilSi Setanil sxvadasxva sididis sasinj muxtebze moqmedebs sxvadasxva sididis Zalebi, amitom Zala velis dasaxasiaTeblad ar gamodgeba. magram kulonis kanonidan gamodis, rom Zalis fardoba muxtTan ar aris damokidebuli muxtis sidideze da am fardobiT axasiaTeben velis mocemul wertils. am fardobas uwodeben daZabulobas. mas aRniSnaven E asoTi. e.i. $E = \frac{F}{q_0}$. veqtorulad

$$\vec{E} = \frac{\vec{F}}{q_0} \qquad (1.4).$$

e.i. daZabuloba velis Zaluri maxasiaTebelia, romelic veqtoruli sididea da tolia velSi Setanil e.w. sacdel (wertilovan) muxtze moqmedi Zalis fardobisa am muxtis sididesTan.. ricxobrivad is dadebiT erTeulovan muxtze moqmedi Zalis tolia. erTeulia 1 n/k (niutoni kulonze). mimarTulebiT is emTxveva dadebiT muxtze moqmedi Zalis mimarTulebas. aqedan muxtze moqmedi Zala $\vec{F} = q_0 \vec{E}$.

$4. wertilovani muxtis daZabuloba. velebis superpoziciis principi.

vTqvaT veli Seqmnilia raime wertilovani $q > 0$ muxtiT. maSin daZabuloba am muxtidan r manZiliT daSorebul raime nebismier A wertilSi (sadac moTavsebulia sasinji q_0 muxti) tolia (nax. 1.3): $E = \frac{F}{q_0}$. kulonis kanonidan



$$F = \frac{1}{4\pi\varepsilon_0}\frac{q \cdot q_0}{r^2} \text{ da } E = \frac{F}{q_0} = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}. \quad (1.5)$$

e.i wertilovani muxtis daZabuloba proporciulia velis aRmZvreli muxtisa da

nax. 1.3 ukuproporciulia misgan manZilis kvadratisa. veqtorulad gveqneba: $\vec{E} = \frac{q}{4\pi\varepsilon_0 r^3}\cdot\vec{r}$. daZabulobis mimarTulebas mocemul A wertilSi, Tu velis Semqneli muxti dadebiTia, aqvs am A wertilidan q da sasinji q_0 muxtebis SemaerTebel wrfeze q muxtidan iqiT mimarTuleba. Tu q uaryofiTia, maSin daZabulobis veqtori mimarTulia mocemuli A wertilidan muxtebis SemaerTebel wrfeze muxtisaken.

Tu veli Seqmnilia ramdenime $q_1, q_2, q_3 ..... q_n$ wertilovani muxtebiT, maSin velis daZabuloba nebismier wertilSi

$$\vec{E} = \frac{\vec{F}}{q_0}, \qquad (1..6)$$

sadac $\vec{F} = \sum_{i=1}^{n}\vec{F}_i$ aris am wertilSi moTavsebul q_0 muxtze yvela wertilovani muxtis mxridan moqmedi Zalebis jami da Sesabamisad

$$\mathbf{E}\,\vec{E} = \frac{\sum_{i=1}^{n}\vec{F}_{iq}}{q_0} = \sum_{i=1}^{n}\frac{\vec{F}_i}{q_0}. \qquad (1.7)$$

aq $\vec{F}_i$ aris is Zala romliTac q_i muxtis veli moqmedebs q_0 muxtze, e.i. $\frac{\vec{F}_i}{q_0} = \vec{E}_i$ da

$$\vec{E} = \sum_{i=1}^{n}\vec{E}_i = \vec{E}_1 + \vec{E}_2 + \vec{E}_3 + ... + \vec{E}_n \qquad (1.8),$$

anu **ramdenime muxtiT Seqmnili saerTo velis daZabuloba tolia calkeuli muxtebis velis daZabulobaTa veqtoruli jamisa.** es debuleba cnobilia velebis superpoziciis principiT (rom velebis zeddebisas isini erTmaneTze gavlenas ar axdenen da TviToeuli muxtis daZabuloba am Sem-Si iseTivea, rogoric iqneboda gancalkevebuli muxtis Sem-Si).

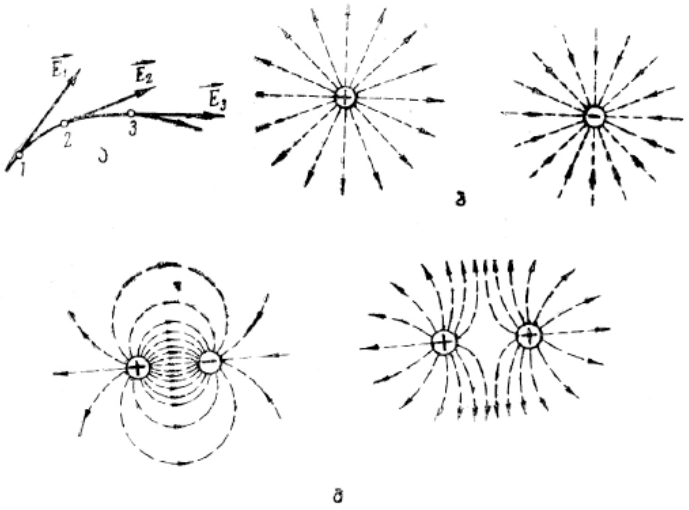
II leqcia

eleqtruli velis Zalwirebi. erTgvarovani eleqtruli veli. Zalwirebis nakadi. gaus-ostrogradskis Teorema (gamoyvanis gareSe). muxtis zedapiruli simkvrive. Tanabrad damuxtuli usasrulo sibrtyis, sxvadasxva niSniT damuxtuli ori paraleluri usasrulo sibrtyis, Tanabrad damuxtuli sferuli zedapiris velis daZabuloba.

$1. eleqtruli velis Zalwirebi. erTgvarovani eleqtruli veli.

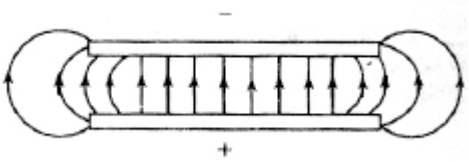
rom davinaxoT, Tu rogor aris el. veli sivrceSi ganawilebuli, amisTvis SemoRebulia daZabulobis wiris (Zalwiris) cneba. **Zalwiri ewodeba wirs, romlis yovel wertilSi gavlebuli mxebis mimarTuleba emTxveva am wertilSi $\vec{E}$ daZabulobis veqtoris mimarTulebas** (nax. 2.1 a). Zalwirs aqvs garkveuli mimarTuleba. radgan daZabulobis mimarTuleba dadebiT muxtxe moqmedi Zalis mimarTulebas emTxveva, amitom Zalwiri iwyeba dadebiTi muxtidan da mTavrdeba uaryofiT muxtze, an grZeldeba usasrulobaSi. Zalwirebi ar gadaikveTebian, radgan $\vec{E}$ daZabulobis veqtors ar SeiZleba erT wertilSi ori mimarTuleba hqondes. nax. 2.1

b-ze naCvenebia wertilovani muxtis velis Zalwirebi, romelic mimarTulia arian radialurad gareT, rodesac $q > 0$ muxti dadebiTia da radialurad SigniT Tu $q < 0$. aqve 2.1 g-ze mocemulia ori wertilovani muxtis Zalwirebi.



nax. 2.1

Zalwiri ar SeiZleba gavaigivoT muxtis traeqtoriaTan, radgan traeqtoriis yovel wertilSi gavlebuli mxebi gamoxatavs siCqaris mimarTulebas, xolo Zalwiris mxebi ki gamoxatavs muxtze moqmedi Zalis (Sesabamisad aCqarebis) mimarTulebas.



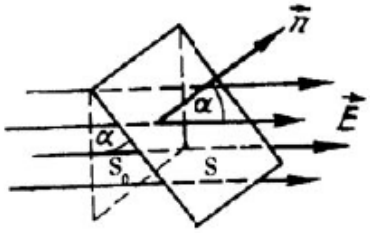
vels, romlis yvela wertilSi daZabulobis veqtoris sidide da mimarTuleba erTnairia , erTgvarovani veli ewodeba. aseTi velis Zalwirebi erTmaneTis paraleluri da Tanabrad daSorebuli wrfeebia. aseTi veli miiReba sxvadasxva niSniT damuxtul or paralelur firfitas Soris (nax. 2.2@). Zalwirebs avleben ise, rom maTi saSualebiT gaigon ara marto mimarTuleba, aramed sididec. sadac daZabuloba didia iq Zalwirebs avleben meti sixSiriT, kerZod iseTi sixSiriT, rom , rom Zalwirebisadmi marTobul farTobis erTeulSi gamavali Zalwirebis raodenoba

nax. 2.2 toli iyos daZabulobis mniSvnelobisa am wertilSi.

$2. Zalwirebis nakadi. gaus-ostrogradskis Teorema (gamoyvanis gareSe).

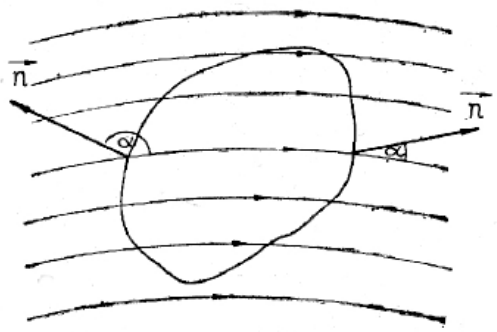
raime daZabulobis velSi mocemuli farTobis gamWol Zalwirebis ricxvs Zalwirebis nakadi ewodeba. e.i. Tu $\vec{E}$ daZabulobis velSi mis marTobulad moTavsebulia raime brtyeli S_0 farTobi, maSin imis gamo rom velis marTobul erTeulovan farTobSi SesaZlebelia E raodenobis Zalwiris gavleba, amitom S_0 farTobSi gamavali Zalwirebis raodenoba anu nakadi tolia $N = ES_0$. Tu S farTobi daxrilia Zalwirebisadmi raime α kuTxiT (kuTxe sibrtyis normalsa da daZabulobis veqtors Soris) (cxadia aseTive kuTxe iqneba S da S_0 sibrtyeebs Soris) (nax. 2.3), maSin $S_n = S\cos\alpha$ da S farTobisaTvis nakadi $N = ES\cos\alpha$. $E_n = E\cos\alpha$ aris $\vec{E}$ -s gegmili S sibrtyis normalis mimarTulebaze da amitom

$$N = E_n S \qquad (2.1)$$



nax. 2.3

N – igive daZabulobis nakadia. is SeiZleba iyos, rogorc dadebiTi, ise uaryofiTi. misi niSani damokidebulia kuTxeze Zalwirebsa da normalis im mimarTulebas Soris, romelic dadebiTadaa (nax. 2.4). Sekruli konturis Sem-Si miRebuli normali, amitom zedapiridan gamo-dadebiTad iTvleba gare ($\alpha < \frac{\pi}{2}$, $\cos\alpha > 0$) dadebiTia, xolo suli nakadi



masSi Sesuli ki

nax. 2.4 uaryofiTi ($\alpha > \frac{\pi}{2}$, $\cos\alpha < 0$).

Tu veli araerTvarovania da zedapiri ar aris brtyeli, maSin S -s yofen usasrulod mcire dS elementebad (rom CaiTvalos brtyelad), veli mis farglebSi iyos erTgvarovani, maSin elementaruli nakadi am elementSi $dN = E_n dS$, sadac $E_n = E\cos\alpha$ da mTel S -s zedapirSi daZabulobis nakadi iqneba am elementaruli nakadebis jami, anu elementaruli nakadis integrali $N = \int E_n dS$, sadac integrali vrceldeba mTel S zedapirze.

Tu zedapiri Caketilia, maSin nakadi aseTi Caketili zedapiris SigniT

$$N = \oint_S E_n dS \qquad (2.2).$$

Tu veli erTgvarovania, maSin $E = const$ da $\int_S dS = S$ da $N = E_n dS$.

gaus-ostrogradskis TeoremiT gamoiTvleba daZabulobis nakadi nebismieri formis Caketil zedapirSi da ase Camoyalibdeba: **Caketili zedapiris gamWoli Zalwirebis nakadi tolia $\frac{1}{\varepsilon_0}$ (ε_0 – eleqtruli mudmivaa) ricxvis namravlisa am zedapiris SigniT moTavsebuli muxtebis algebruli jamze.**

$$N = \frac{1}{\varepsilon_0}\sum_{i=1}^{n} q_i \qquad (2.3),$$

sadac E aris saerTo velis daZabuloba Caketili zedapiris SigniT mocemul wertilSi, xolo $\sum_{i=1}^{n} q_i$ – am zedapiris SigniT moTavsebul muxtTa algebruli jami.

es formula gamoviyvanoT r – radiusiani sferuli formis Caketili zedapirisTvis, rodesac zedapiris SigniT moTavsebulia erTaderTi q muxti:

$$N = \oint_S E_n dS = \frac{1}{4\pi\varepsilon_0}\cdot\frac{q}{r^2}\cdot 4\pi r^2 = \frac{q}{\varepsilon_0} \qquad (2.4).$$

formula (2.4) marTebulia nebismieri Caketili zedapirisTvis.

Tu $q > 0$, maSin muxtidan gamodis N Zalwiri da Tu $q < 0$, maSin Sedis. amitom Tu zedapiris SigniT moTavsebulia q_1, q_2, ...q_n muxti, zedapiris gamWoli sruli nakadi toli iqneba:

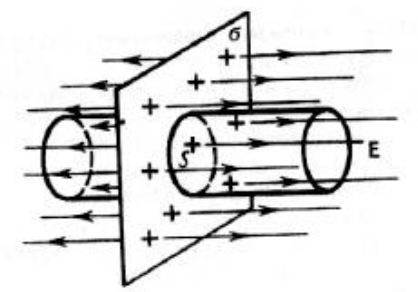
$$N = \frac{q_1}{\varepsilon_0} + \frac{q_2}{\varepsilon_0} + ... + \frac{q_n}{\varepsilon_0} = \frac{1}{\varepsilon_0}\sum_{i=1}^{n} q_i \ . \qquad (2.5).$$

Tu Caketili zedapiris SigniT dadebiTi da uaryofiTi muxtebis raodenoba tolia, maSin maTi algebruli jami nulia ($\sum q_i = 0$) da nakadic nuli iqneba. am dros zedapiridan gamosuli Zalwirebis ricxvi udris masSi Sesuli Zalwirebis raodenobas. aseve Tu Caketili zedapiris SigniT muxtebi araa, maSin am drosac nakadi nulia. Tu Zalwirebi kveTen zedapirs, ise rom mis SigniT arc iwyebian da arc bolovdebian (muxtebi gareTaa), maSin imis gamo, rom zedapirSi Semavali da gamomavali Zalwirebis raodenoba erTnairia, nakadi aseve nulia.

$3. muxtis zedapiruli simkvrive. Tanabrad damuxtuli usasrulo sibrtyis, sxvadasxva niSniT damuxtuli ori paraleluri usasrulo sibrtyis, Tanabrad damuxtuli sferuli zedapiris velis daZabuloba.

am TeoremiT SeiZleba ganvsazRvroT sxvadasxva formis damuxtuli sxeulebis el. velis daZabulobebi.

1. Tanabrad damuxtuli usasrulo sibrtyis veli.



mag. ganvixiloT $+\sigma$ muxtis zedapiruli simkvriviT ($\sigma = \frac{q}{S}$ anu zedapiris erTeul farTobze moTavsebuli muxti) Tanabrad damuxtuli usasrulo sibrtye. Zalwirebi gamodian sibrtyis orive mxridan zedapirisadmi marTobulad (nax. 2.5). Caketil zedapirad gamovyoT cili-

nax. 2.5

ndri, romlis fuZeebi paraleluria sibrtyis, xolo RerZi ki mis marTobulia. nakadi gverdiT zedapirSi iqneba nulis toli, radgan $\alpha = 90^0$ da $cos\alpha = 0$. maSin sruli nakadi am cilindris gaswvriv tolia nakadebis jamisa mis fuZeebSi, romelTa farTobebi tolia da $\vec{E}_n$ emTxveva $\vec{E}$ – s. maSin

$$N = N_1 + N_2 = \oint_S E_n dS = E \cdot S + E \cdot S = 2E \cdot S \qquad (2.6).$$

meore mxriv gaus-ostrogradskis Teoremis Tanaxmad igive nakadi

$$N = \frac{1}{\varepsilon_0} \cdot q = \frac{1}{\varepsilon_0} \sigma \cdot S \qquad (2.7).$$

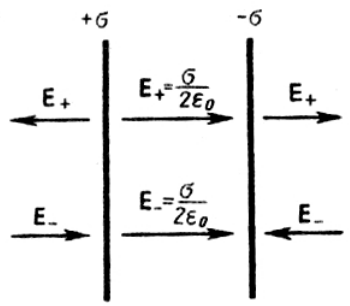
(2.6) da (2.7)-is gatolebis Semdeg gveqneba:

$$E = \frac{\sigma}{2\varepsilon_0} \qquad (2.8).$$

am formulidan Cans, rom usasrulo sibrtyis mier Seqmnili velis daZabuloba ar aris damokidebuli manZilze. is sivrceSi yvelgan erTnairia da proporciulia muxtis zedapiruli simkvrivis.

2. sxvadasxva niSniT damuxtuli ori paraleluri usasrulo sibrtyis veli.

vTqvaT ori paraleluri usasrulo sibrtye damuxtulia Tanabrad $+\sigma$ da $-\sigma$ muxtis zedapiruli simkvriviT (nax. 2.6). ganvsazRvroT velis daZabuloba sibrteebs SigniT da mis gareT. rogorc cnobilia dadebiTi muxtidan Zalwirebi gamodian, uaryofiTSi ki Sedian. sibrtyeebs gareT Zalwirebs aqvT urTierTsawinaaRmdego mimarTuleba. sibrtyeebs SigniT ki erTnairi. amitom daZabuloba sibrtyeebs



gareT nulis tolia , $E = E_+ - E_- = 0$, xolo sibrtyeebs Soris ki $E = E_+ + E_- = 2E_+$ (radgan sididiT $E_+ = E_-$).

nax. 2.6 (2.8) formulis Tanaxmad gveqneba:

$$E = 2\frac{\sigma}{2\varepsilon_0} = \frac{\sigma}{\varepsilon_0} \qquad (2.9).$$

e.i. 2-jer metia, vidre erTi sibrtyis Sem-Si. maSasadame am Sem-Si veli Tavmoyrilia sibrtyeebs Soris da am areSi is erTgvarovania.

3. Tanabrad damuxtuli R radiusiani Caketili sferuli zedapiri, romelzec q muxti Tanabradaa ganawilebuli. am dros Zalwirebi radialuri wrfeebia. sferuli zedapiris normalsac radiusis mimarTuleba aqvs, amitom $E_n = E$ da is am zedapiris yvela wertilSi simetriis gamo erTnairia ($E = const$).

erTi mxriv Zalwirebis nakadi tolia:

$$N = \oint_S E dS = E \oint_S dS = E \cdot S = E \cdot 4\pi r^2 , \quad (2.10)$$

sadac $r \geq R$ – raRac manZilia sferos centridan

meore mxriv gaus-ostrogradskis Teoremidan

$$N = \frac{1}{\varepsilon_0} q \qquad (2.11)$$

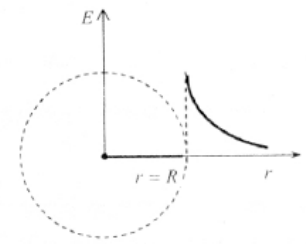
da maTi gatolebis Semdeg sferos zedapirze da mis gareT gveqneba

$$E = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{r^2} \qquad (2.10).$$

es formula emTxveva wertilovani muxtis daZabulobis formulas. e.i. sferuli zedapiris zedapirze da gareT daZabuloba iseTia, TiTqos zedapiris mTeli q muxti moTavsebulia mis centrSi. is manZilis zrdasTan erTad misi kvadratis ukuproporciulad mcirdeba.

Tu sferos centridan SemovxazavT $r' < R$ radiusian zedapirs, maSin aseTi Caketili zedapiri ar Seicavs muxts, amitom aseTi Tanabrad damuxtuli sferuli zedapiris signiT e. statikuri veli ar gvaqvs, anu $E = 0$.

maSasadame Tanabrad damuxtuli zedapiris SigniT daZabuloba nulis tolia, sferos gareT ki nulisgan gansxvavebulia. grafikulad daZabulobis manZilze damokidebuleba ase gamoisaxeba (nax. 2.6).



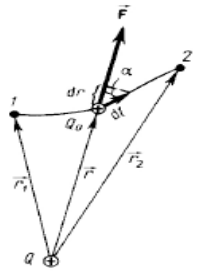
nax. 2.6

III leqcia

eleqtrostatikur velSi muxtis gadadgilebaze Sesrulebuli muSaoba. potenciuri veli. daZabulobis veqtoris cirkulacia Caketili wiris gaswvriv. potenciali. potencialTa sxvaoba. wertilovani muxtis velis potenciali. kavSiri daZabulobasa da potencials Soris.

$1. eleqtrostatikur velSi muxtis gadadgilebaze Sesrulebuli muSaoba. potenciuri veli. daZabulobis veqtoris cirkulacia Caketili wiris gaswvriv.

el. statikur velSi Setanil muxtze moqmedebs el. Zala, amitom is gadaadgildeba, e.i. sruldeba muSaoba. gamovTvaloT is. davuSvaT $q > 0$ wertilovani muxtis mier Seqmnil velSi 1 wertilSi movaTavseT sasinji



nax. 3.1

$q_0 > 0$ wertilovani muxti. veli imoqmedebs masze $\vec{F}$ el. ZaliT da gadaadgilebs raime 2 wertilSi (nax. 3.1). maSin sruldeba muSaoba. Mmis sapovnelad gza davyoT imdenad mcire dl ubnebad, rom TiToeulis farglebSi Zala CaiTvalos mudmivad da muSaoba TiToeul am ubanze $dA = (\vec{F} \cdot \vec{dl}) = F dl \cos\alpha = F \cdot dr$, sadac $\alpha -$ kuTxea $\vec{F}$ Zalasa da $\vec{dl}$ gadaadgilebas Soris, xolo dr aris r manZilis cvlileba q_0 muxtis dl ubanze gadaadgilebisas. an

$$dA = \frac{qq_0}{4\pi\varepsilon_0}\frac{1}{r^2}dr .$$

sruli muSaoba iqneba am elementaruli muSaobebis jami, anu $A_{12} = \int_{r_1}^{r_2} dA =$ $\int_{r_1}^{r_2} \frac{1}{4\pi\varepsilon_0}\frac{qq_0}{r^2}dr =$ $\frac{1}{4\pi\varepsilon_0} qq_0 (\frac{1}{r_1} - \frac{1}{r_2})$ $(\int \frac{1}{r^2}dr = -\frac{1}{r})$. Aanu $A_{12} = q_0(\frac{q}{4\pi\varepsilon_0 r_1} - \frac{q}{4\pi\varepsilon_0 r_2})$ (3.1).

aqedan Cans, rom es muSaoba, iseve rogorc simZimis Zalis muSaoba araa damokidebuli gzis formaze. igi damokidebulia q_0 muxtis sawyis da saboloo mdg-ze da velis aRmZvreli q muxtis sidideze. Ee.i. Caketil konturSi ($r_1 = r_2$) is nulis tolia. es velic potenciuri velia, radgan masSi Sesrulebuli muSaoba gzis formaze damokidebuli ar aris. aseT velSi rogorc cnobilia moqmedeben potenciuri (konservatuli) Zalebi. e.i. el. statikuri veli gravitaciulis msgavsad potenciuria, xolo el. statikuri Zala ki potenciuri Zala.

muSaoba dadebiTia, Tu mas asruleben velis Zalebi (am dros muxtebis urTierTqmedebis potenciuri energia mcirdeba) da uaryofiTia Tu mas asruleben gare Zalebi (potenciuri energia izrdeba). maSasadame elstatikuri Zalebi-konservatuli Zalebia.

Tu $r_1 = r_2$ anu muxti gadaadgildeba Caketil konturze, maSin muSaoba nulia. A gamovsaxoT velis potenciuroba maTematikurad. radgan q_0 muxtze moqmedi Zala $F = q_0 E$, amitom elementaruli muSaoba $dA = F dl \cos\alpha = q_0 E_l dl$. sadac $E_l = E\cos\alpha$ aris $\vec{E}$-s gegmili $\vec{dl}$ mimarTulebaze. Tu muxti erTeulovania ($q_0 = 1$), maSin $dA = E_l dl$ da sruli muSaoba $A_{12} = \int E_l dl$, xolo Caketil konturze ($r_1 = r_2$): $A_{12} = \oint E_l dl = 0$. (3.2)

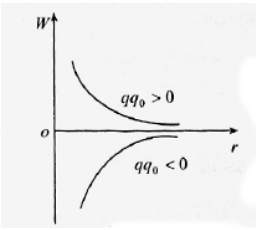
sidides $\oint(\vec{E} \cdot \vec{dl}) = \oint E_l dl$ ewodeba $\vec{E}$ veqtoris cirkulacia l Caketili wiris gaswvriv. E $\oint E_l dl = 0$. e.i. velis potencialuroba maTematikurad niSnavs, rom el.statikuri velis daZabulobis cirkulacia nulis tolia. is aseve gviCvenebs, rom daZabulobis wirebi ar SeiZleba iyvnen Caketili (maT aqvT dasawyisi-dadebiT da dasasruli-uaryofiT muxtebze).

$2. potenciali. potencialTa sxvaoba.

radgan el. statikuri veli potenciuria, amitom maTSi moTavsebul muxtebs unda gaaCndeT potenciuri energia. el. velis mier muSaobis Sesrulebis dros potenciuri energia mcirdeba, anu muSaoba tolia muxtis potenciuri energiis cvlilebisa Sebrunebuli niSniT $dA = -dW$. elementaruli muSaoba dr manZilze q_0 muxtis gadaadgilebisas wina paragrafidan tolia $dA = \frac{1}{4\pi\varepsilon_0}\frac{qq_0}{r^2}dr$ da $dW = -\frac{1}{4\pi\varepsilon_0}\frac{qq_0}{r^2}dr$. aqedan

$$W = \int dW = k\frac{qq_0}{r} \quad (\int \frac{dx}{x^2} = -\frac{1}{x}), \quad (3.3)$$

anu es aris q_0 Mmuxtis potenciuri energiaa $r-$ manZilze q muxtis velSi. Tu q da q_0 muxtebi erTi niSnisaa, maSin maTi ganzidvis potenciuri energia dadebiTia da muxtebis daaxloebisas izrdeba. Tu sxvadasxva niSnisaa, maSin maTi mizidvis potenciuri energia uaryofiTia da izrdeba nulamde erT-erTi muxtis usasrulobaSi gadatanisas . ori wertilovani muxtis potenciuri energiis damokidebuleba maT Soris manZilze mocemulia nax. 3.2-ze.



muxtis sasrul manZilze 1 wertilidan saboloo 2-Si gadaadgilebisas potenciuri energiis cvlileba toli iqneba:

nax. 3.2 $A_{12} = -(W_2 - W_1)$, an $W_2 - W_1 = \frac{1}{4\pi\varepsilon_0}\frac{qq_0}{r_2} - \frac{qq_0}{r_1}$ (3.4).

zogadad Tu CavTvliT, rom q_0 muxtis potenciuri energia nulis tolia maSin, roca is imyofeba q muxtidan usasrulod Sors ($r \to \infty$, $W = 0$), miviRebT rom misi potenciuri energia r manZiliT daSorebul wertilSi tolia:

$W = \frac{1}{4\pi\varepsilon_0}\frac{qq_0}{r}$ (3.5). (3.5) formulidan Cans, rom q muxtis velis mocemul wertilSi q_0 muxtis potenciuri energia proporciulia q_0 muxtis. Aamitom fardoba $\frac{W}{q_0}$ velis erTsa da imave wertilSi erTi da igivea (q_0 – .is 2-jer gazrdisas W – c 2-jer izrdeba da a.S. ise, rom fardoba $\frac{W}{q_0}$ yovelTvis mudmivia da ar icvleba). Sesabamisad velis mocemul wertilSi muxtis pitenciuri energiis Sefardebas muxtis sididesTan ewodeba velis potenciali am wertilSi $\varphi = \frac{W}{q_0}$. (3.6)

is skaluri sididea. Tu $q_0 = 1$, maSin $\varphi = W$. e.i. velis potenciali mocemul wertilSi ricxobrivad tolia am wertilSi moTavsebuli erTeulovani dadebiTi muxtis potenciuri energiis. is velis energetikuli maxasiaTebelia, gansxvavebiT daZabulobisagan, romelic velis Zaluri maxasiaTebelia. Tu $q > 0$, maSin potenciali $\varphi > 0$ da piriqiT.

(3.5) da (3.6) formulebidan miviRebT q wertilovani muxtis potencials misgan r manziliT daSorebul wertilSi Semdegi formuliT: $\varphi = \frac{1}{4\pi\varepsilon_0}\frac{q}{r}$ (3.7).

aqedan Cans, rom potenciali usasrulobaSi ($r = \infty$) nulis tolia.

Tu mocemulia ramdenime q_1, q_2,.....q_n wertilovani muxtis veli, maSin velis potenciali romelime wertilSi tolia muxtebis velebis potencialTa algebruli jamisa: (superpoziciis principi)

$\varphi = \varphi_1 + \varphi_2 + ...\varphi_n = \sum_{i=1}^{n}\varphi_i$ (3.8).

radgan muSaobis formula radgan $A = W_1 - W_2$, xolo $W = q_0\varphi$, amitom

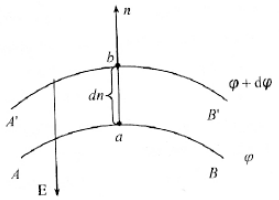
$$A_{12} = q_0(\varphi_1 - \varphi_2) \qquad (3.9).$$

maSasadame elstatikur velSi muxtis gadaadgilebaze Sesrulebuli muSaoba tolia muxtis namravlisa sawyis da saboloo wertilebis potencialTa sxvaobaze.Aaqedan $\varphi_1 - \varphi_2 = \frac{A_{12}}{q_0}$. Ee.i. potencialTa sxvaoba velis or wertils Soris tolia velis Zalebis mier q_0 muxtis gadaadgilebaze Sesrulebuli muSaobis fardobasa am muxtis sididesTan. (3.9) formulidan ganvmartoT potencialis fizikuri azri. vTqvaT muxti gadaadgilda 1 wertilidan usasrulobaSi ($r_2 = \infty$). maSin $\varphi_2 = 0$ da $A_{12} = q_0\varphi_1$, saidanac $\varphi_1 = \frac{A_{12}}{q_0}$. Tu $q_0 = 1$, maSin $\varphi_1 = A_{12}$. e.i.

velis mocemuli wertilis potenciali ricxobrivad im muSaobis tolia, romelsac asrulebs el. Zala am wertilidan usasrulobaSi dadebiTi muxtis gadaadgilebisas.

potencialTa sxvaobas aseve Zabvas uwodeben: $\boldsymbol{U = \varphi_1 - \varphi_2}$ da $\boldsymbol{U = \frac{A_{12}}{q_0}}$ (3.10) Aaqedan misi erTeulia volti. 1v=1j/k. volti aris iseTi ori wertilis potencialTa sxvaobaa, romelTa Soris erTi kuloni muxtis gadaadgilebaze sruldeba erTi jouli muSaoba.

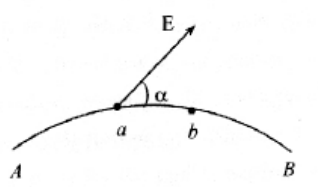
zogadad radgan muSaoba ganisazRvreba potencialTa sxvaobis saSualebiT, amitom praqtikuli mniSvneloba aqvs swored potencialTa sxvaobas da ara potencials. potencialis mniS-ba damokidebulia nulovani donis arCevaze. nulad miCneulia usasrulobaSi mdebare wertilis potenciali. magram miRebulia, rom nulis toli iyos dedamiwis potenciali.



$3. wertilovani muxtis velis potenciali. kavSiri daZabulobasa da potencials Soris.

maSasadame el. statikur vels axasiaTeben veqtoruli – daZabulobiT da skalaruli sididiT – potencialiT. amitom maT Soris arsebobs raRac kavSiri, romelic gamoviyvanoT. muSaoba SeiZleba gamoisaxos am oris sididis saSualebiT calk-calke.

SemovitanoT ekvipotencialuri zedapiris cneba. ekvipotencialuri (izopotencialuri) zedapiri iseTi zedapiria, romlis yovel wertilSi potenciali erTi da igivea – $\varphi = const$. wertilovani muxtis velis ekvipotencialuri zedapirebi koncentruli sferuli zedapirebia, romelTa centri muxtis moTavsebis wertilSia. daZabuloba, (anu velis Zalwiri) yovelTvis marTobia ekvipotencialuri zedapiris. vTqvaT AB ekvipotencialur zedapirze a wertilidan b wertilSi gaadgilda q_0 muxti (nax. 3.3). kuTxe daZabulobasa da gadaadgilebas Soris iyos α. maSin Sesrulebuli muSaoba toli iqneba $A = F \cdot ab \cdot \cos\alpha$. meore mxriv $A = q_0(\varphi_a - \varphi_b) = 0$, $(\varphi_a = \varphi_b)$. e.i. $F \cdot ab \cdot \cos\alpha = 0$. magram $F \cdot ab \neq 0$,



nax. 3.3

e.i. $\cos\alpha = 0$ da $\alpha = \frac{\pi}{2}$. radgan el. veli gamoisaxeba ZalwirebiT, amitom is gamovsaxoT ekvipotencialuri zedapirebis saSualebiTac. am zedapirebis normali gviCvenebs daZabulobis mimarTulebas, xolo maTi gavlebis sixSire ki daZabulobis sidides, radgan erTi zedapiridan meoreze q_0 muxtis gadaadgilebisas sruldeba erTi da igive muSaoba $A = F \cdot d = q_0 E \cdot d$, sadac d – zedapirebs Soris umoklesi manZilia. iq sadac E didia, d mcirea da piriqiT.

aviRoT ori uasarulod axlos mdebare ekvipotencialuri zedapirebi – AB da $A'B'$ (nax. 3.4). am zedapirebis potencialebi iyos φ da $\varphi + d\varphi$. amasTan $d\varphi > 0$.

radgan es zedapirebi axlos arian erTmaneTTan, amitom normali $\vec{n}$ maTTvis saerToa. damuSvaT q_0 muxti gadaadgilda a wertilidan b wertilSi normalis gaswvriv. radgan daZabuloba (anu muxtze moqmedi Zala) marTobia ekvipotencialuri zedapiris, amitom Sesrulebuli muSaoba toli iqneba:

nax. 3.4

$$dA = F \cdot ab = q_0 E \cdot dn \qquad (3.11).$$

meore mxriv muSaoba tolia

$$dA = q_0[\varphi - (\varphi + d\varphi)] = -q_0 d\varphi \qquad (3.12).$$

am formulebis gatolebidan miviRebT, rom

$$E = -\frac{d\varphi}{dn}, \qquad (3.13)$$

sadac $\frac{d\varphi}{dn}$ aris potencialis cvlileba (warmoebuli) im mimarTulebis gaswvriv, romelzedac am cvlilebis siCqare maqsimaluria. mas potencialis gradienti ewodeba. anu daZabuloba aris potencialis gradienti Sebrunebuli niSniT:

$$E = -grad\varphi \qquad (3.14).$$

potencialis gradienti veqtoruli sididea da mimarTulia potencialis zrdis mimarTulebiT. (3.13)-Si niSani "–" imas miuTiTebs, rom daZabulobis $\vec{E}$ veqtori mimarTulia potencialis gradientis sapirispirod anu potencialis Semcirebis mimarTulebiT. gradientis mdgenelebi koordinatTa RerZebze aris $\frac{\partial\varphi}{\partial x}$, $\frac{\partial\varphi}{\partial y}$, $\frac{\partial\varphi}{\partial z}$. Sesabamisad Tu daZabulobis veqtoris mdgenelebi iqneba E_x, E_y, E_z, maSin

$$E_x = -\frac{\partial\varphi}{\partial x}, \quad E_y = -\frac{\partial\varphi}{\partial y}, \quad E_z = -\frac{\partial\varphi}{\partial z} \qquad (3.15),$$

xolo daZabulobis veqtoris sidide $E = \sqrt{E_x^2 + E_y^2 + E_z^2} = \sqrt{(\frac{\partial\varphi}{\partial x})^2 + (\frac{\partial\varphi}{\partial y})^2 + (\frac{\partial\varphi}{\partial z})^2}$.

Tu veli erTgvarovania, $d\varphi = \varphi_2 - \varphi_1$, xolo $dn = d$, maSin damokidebuleba daZabulobasa da potencialTa sxvaobas Soris gamoisaxeba formuliT: $E = \frac{\varphi_1 - \varphi_2}{d}$, (3.16)

sadac potencialTa sxvaoba $\varphi_1 - \varphi_2$ aRebulia Zalwirebis mimarTulebiT, xolo d manZilia am wertilebs Soris. (3.15) formulidan Cans, rom daZabuloba ricxobrivad tolia potencialis cvlilebisa sigrZis erTeulze Zalwiris mimarTulebiT.

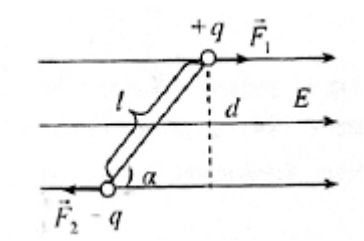
(3.15) formulidan aseve SeiZleba davadginoT daZabulobis kidev sxva (n/k – niutoni kulonTan) erTeuli SI sistemaSi. es erTeulia v/m (volti metrze). es aris iseTi velis daZabuloba, romlis potenciali mcirdeba erTi voltiT Zalwiris gaswvriv erTi metriT gadanacvlebisas. n/k da v/m erTmaneTs emTxveva ($E = \frac{U}{d} = \frac{A}{q_0 d} = \frac{F \cdot d}{q_0 d} = \frac{F}{q_0}$).

IV leqcia

dipoli gare eleqtrul velSi. dieleqtrikebis polarizacia. polaruli da arapolaruli molekulebi. polarizaciis veqtori. kavSiri polarizaciis veqtorsa da eleqtruli velis daZabulobas Soris. dieleqtrikuli amTvisebloba. dieleqtrikuli SeRwevadoba.

$1. dipoli gare eleqtrul velSi. dieleqtrikebis polarizacia. polaruli da arapolaruli molekulebi.

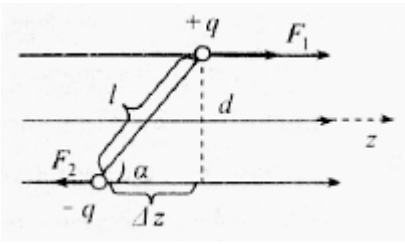
vTqvaT $\vec{E}$ daZabulobis erTgvarovan ($\boldsymbol{E = const}$) velSi moTavsebulia dipoli, romlis muxtia $\boldsymbol{q}$, xolo mxari $\boldsymbol{l}$. kuTxe romelsac dipolis RerZi daZabulobasTan adgens iyos $\boldsymbol{\alpha}$ (nax. 4.1). dipolis dadebiT da uaryofiT muxtebze imoqmedeben velis gaswvriv da mis sapirispirod mimarTuli $\vec{F}_1 = q\vec{E}$ da $\vec{F}_2 = q\vec{E}$ Zalebi, romlebic sididiT tolia da mimarTulebiT sawinaaRmdego.



nax. 4.1

isini gamoiwveven dipolis mobrunebas. maTi, rogorc wyvilZalis mabrunebeli momenti tolia erT-erTi Zalis namravlisa wyvilZalis $\boldsymbol{d}$ mxarze $\boldsymbol{M = Fd = qEd = qEl \sin\alpha}$. radgan dipolis momenti $\boldsymbol{p = ql}$, amitom $\boldsymbol{M = pE \sin\alpha}$, an veqtorulad $\vec{M} = [\vec{p}\vec{E}]$. momentis gavleniT dipoli iqamde mobrundeba, sanam misi $\vec{p}$ momentis mimarTuleba ar daemTxveva velis $\vec{E}$ daZabulobis mimarTulebas. am dros $\boldsymbol{M = 0}$, radgan $\boldsymbol{\alpha = 0}$ da dipoli aRmoCndeba wonasworobaSi, radgan masze imoqmedebs toli da sapirispirod mimarTuli ori Zala.

Tu veli araerTgvarovania ($\boldsymbol{E \neq const}$), maSin aseTi velis Zalwirebi erTmaneTis paraleluri ar arian, magram dipolis mxris simciris gamo SeiZleba CavTvaloT paralelurad. magram am dros $\boldsymbol{+q}$ da $\boldsymbol{-q}$ muxtebze moqmedi Zalebi $\vec{F}_1 = q\vec{E}_1$ da $\vec{F}_2 = q\vec{E}_2$ toli ar arian (nax. 4.2). maSin dipolze garda mabrunebeli momentisa, imoqmedebs $\vec{F}_1$ da $\vec{F}_2$ Zalebis tolqmedi, romelic sididiT udris $\boldsymbol{F = F_1 - F_2 = q(E_1 - E_2)}$. Tu $\boldsymbol{z}$ RerZi Zalwirebis gaswvrivaa, maSin $\boldsymbol{E_1 - E_2 = \frac{dE}{dz} \cdot \Delta z = \frac{dE}{dz} \cdot l \cos\alpha}$. aq $\boldsymbol{\frac{dE}{dz}}$ - daZabulobis gradientia sigrZis erTeulze. radgan $\boldsymbol{p = ql}$, amitom



nax. 4.2

$$\boldsymbol{F = p\frac{dE}{dz}\cos\alpha} \quad (4.1).$$

Tu $\boldsymbol{\alpha < 90^0}$, maSin es mimarTulia meti daZabulobis mxares da is maqsimaluria, rodesac $\boldsymbol{\alpha = 0^0}$, anu rodesac dipoli daZabulobis paraleluria.

am ZaliT ixsneba damuxtuli sxeulebis mier msubuqi sxeulebis mizidva. mag. minis Reros tyavze xaxunisas (imuxteba dadebiTad) masze axlos myofi qaRaldis naWris mopirdapire mxareebze polarazaciis Sedegad aRiZvreba toli da niSniT sawinaaRmdego niSnis bmuli muxtebi. amis gamo es naWeri iqceva dipolad da igi imoZravebs velis zrdis (minis joxisken) mxares.

dieleqtriki Sedgeba neitraluri atomebis da molekulebisagan. liTonebisgan gansxvavebiT masSi ar aris Tavisufali muxtebi. dieleqtrikis muxtebi dakavSirebulia mis atomebTan da molekulebTan da el. velis moqmedebiT isini wainacvleben mxolod mikroskopiul manZilebze.

am movlenas-velis moqmedebiT dieleqtrikSi el. muxtebis wanacvlebas dieleqtrikis polarizacia ewodeba.

dieleqtrikebi iyofa or ZiriTad jgujad:

a) polaruli-iseTi dieleqtrikia, romelic Sedgeba polaruli molekulebisgan. es aris arasimetriuli molekulebi, sadac dadebiTi muxtebis simZimis centri ar emTxveva uaryofiTi muxtebis simZimis centrs. faqtiurad isini eleqtruli dipolebia, Tavis dipoluri momentiT $p = ql$, (is veqtoria, mimarTulebiT uaryofiTi muxtidan dadebiTisken $\vec{p} = q\vec{l}$), sadac $l -$manZils dipolis RerZis gaswvriv dadebiT da uaryofiT muxtebs Soris dipolis mxari ewodeba (zogadad dipoli es aris ori urTierTsawinaaRmdego niSnis muxtebis erToblioba, romelTa Soris manZili gacilebiT mcirea im manZilTan, romelzec ganixileba misi moqmedeba). aseTi dieleqtriki Tu ar aris moTavsebuli e. velSi, imis gamo rom molekulebis dipoluri momentebi qaosuradaa orientirebuli, raime ΔV moculobaSi maTi veqtoruli jami nulis tolia $\sum \vec{p}_i = 0$. dieleqtrikis Setanisas el. velSi TviToel dipolze imoqmedebs mabrunebeli momenti da gamoiwvevs maT met-naklen orientacias velis gaswvriv.. sruli orientacia ar xdeba siTburi moZraobis gamo. dipolebis Semobrunebisas dadebiTi muxtebi wainacleben velis gaswvriv, uaryofiTebi velis sapirispirod. es aris orientaciuli polarizacia da Sesabamisad gveqneba polarizebuli dieleqtriki. am dros ukve dieleqtrikis nebismier moculobaSi dipoluri momentebis jami nulisagan gansxvavebulia $\sum \vec{p}_i \neq 0$ da miT metia, rac metia velis daZabuloba da naklebia temperatura. polaruli dieleqtrikebia H_2O, HCl, HBr, CO da aseve myari sxeulebi.

b) arapolaruli–iseTi dieleqtrikia, romelic Sedgeba arapolaruli molekulebisgan. es aris simetriuli molekulebi, sadac dadebiTi muxtebis simZimis centri emTxveva uaryofiTi muxtebis simZimis centrs. rodesac veli ar gvaqvs, maT dipoluri momenti ar gaaCniaT ($\vec{p} = 0$, radgan $l = 0$). eleqtrul velSi xdeba aseTi molekulebis deformacia: dadebiTebi wainacleben velis gaswvriv, uaryofiTebi velis sapirispirod. e.i. isini gardaiqmnebian dipolebad, romlebic orientirebuli iqnebian velis gaswvriv da maTi jami $\sum \vec{p}_i \neq 0$. es aris eleqtronuli polarizacia.

aseTi tipis dieleqtrikebia H_2, N_2 da a.S. aseve jgufi dieleqtrikebisa ($NaCl$, KCl, KBr), romelTac aqvT ionuri aRnagoba, anu warmoadgenen iseT kristalebs, romelTa sivrculi meseri Sedgeba sxvadasxva niSnis ionebisagan. gare velis moqmedebiT xdeba mesris deformacia (dadebiT muxtebi velis mimarTulebiT da piriqiT), rac iwvevs dipoluri momentebis gaCenas (ionuri polarizacia).

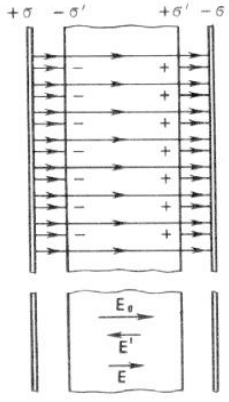
$2. polarizaciis veqtori. kavSiri polarizaciis veqtorsa da eleqtruli velis daZabulobas Soris. dieleqtrikuli amTvisebloba. dieleqtrikuli SeRwevadoba.

rogorc avRSniSneT dieleqtrikis gare velSi moTavsebisas is polarizdeba, anu iZens nulisgan gansxvavebul dipolur moments.

polarizaciis xarisxs axasiaTeben polarizaciis veqtoriT, romelic ewodeba dieleqtrikis erTeul moculobaSi dipoluri momentebis veqtorul jams. e.i.

$$\vec{P} = \frac{\sum_{i=1}^{n} \vec{p}_i}{\Delta V} \qquad (4.2).$$

$\vec{p}_V = \sum_{i=1}^{n} \vec{p}_i$ – yvelas jamia. $\vec{P}$ – s ganzomilebaa k·m/m^3=k/m^2 (kuloni/metrkvadratze) emTxveva $\varepsilon_0 E$ – s ganzomilebas, radgan wertilovani muxtisTvis $E = \frac{q}{4\pi\varepsilon_0 r^2}$. amitom $\vec{P}$ da $\vec{E}$ veqtorebs Soris proporciuli damokidebulebaa $\vec{P} = \chi\varepsilon_0\vec{E}$. χ – s nivTierebis dieleqtrikuli amTvisebloba ewodeba (ganyenebuli ricxvia). $\chi > 0$ yovelTvis da ZiriTadad tolia ramdenime erTeulis. magram zogierTvis is didia (spirtisTvis 25, wylisTvis 80).



imis dasadgenad Tu rogor icleba eleqtruli veli masSi dieleqtrikis Setanisas, CavataroT cda: SevitanoT dieleqtriki gare el.statikur velSi (romelic iqmneba ori usasrulo paraleluri sxvadasxva niSniT damuxtuli firfitebiT, romelTa muxtebis zedapiruli simkvriveebia $\pm\sigma$), ise rom dieleqtriki mTlianad avsebdes firfitebs Soris sivrces (nax.

4.3). firfitebs Soris daZabuloba $E_0 = \frac{\sigma}{\varepsilon_0}$. velis gavleniT dieleqtriki polarizdeba, anu xdeba muxtebis wanacleba-dadebiTebi velis gaswvriv da piriqiT. amitom dieleqtrikis marjvena

nax. 4.3 mxares gveqneba dadebiTi muxtebis siWarbe $+\sigma'$ simkvriviT, marcxena mxares ki uaryofiTebi $-\sigma'-$Ti. es gaukompensirebuli muxtebi bmuli muxtebia, romlebic dieleqtrikSi qmnian el. vels $\vec{E}_0 -$daZabulobis sapirispiro $\vec{E}'-$daZabulobiT da is asustebs mas. jamuri veli dieleqtrikSi toli gaxdeba $E = E_0 - E'$, sadac cxadia $E' = \frac{\sigma'}{\varepsilon_0}$. vipovoT σ'.

viciT $p_V = P\Delta V = PSd$, sadac $S -$firfitis farTobia, $d -$sisqe. magram $p = ql$ dipolis momentis formulidan aseTi $q' = \sigma' S$ bmuli muxtebis mTliani dipoluri momenti toli iqneba:

$$p_V = \sigma' Sd, \text{ an } PSd = \sigma' Sd \text{ da } \sigma' = P. \quad (4.3)$$

e.i. bmuli muxtebis zedapiruli simkvrive tolia polarizaciis veqtoris mniSvnelobis. maSin $E = E_0 - E' = E_0 - \frac{P}{\varepsilon_0}$ da $E = E_0 - \frac{\chi\varepsilon_0 E}{\varepsilon_0} = E_0 - \chi E$. an $E = E_0 /(1+\chi)$. avRniSnoT $1+\chi = \varepsilon$. gveqneba

$$E = \frac{E_0}{\varepsilon} \quad (4.4)$$

$\varepsilon -$s ewodeba nivTierebis fardobiTi dieleqtrikuli SeRwevadoba da gviCvenebs Tu ramdenjer metia Tavisufali muxtebis mier Seqmnili velis daZabuloba vakuumSi dieleqtrikTan SedarebiT ($\varepsilon = \frac{E_0}{E}$). (4.4) formula samarTliania erTgvarovani velisTvisac.

radgan daZabuloba dieleqtrikSi $\varepsilon -$jer mcirdeba, amitom aseT dieleqtrikSi muxtebis urTierTqmedebis Zalac ($F = qE$) imdenjerve Semcirdeba da kulonis kanoni ase Caiwereba: $F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{\varepsilon r^2}$.

(4.5)

sidides $\varepsilon' = \varepsilon_0\varepsilon$ ewodeba absoluturi dieleqtrikuli SeRwevadoba. aseve $\varepsilon_0 -$s xSirad vakuumis dieleqtrikul SeRwevadobasac uwodeben.

vakuumSi $\varepsilon = 1$. haerisTvis ki is tolia 1,0006 da faqtiurad ar gansxvavdeba erTisagan, amitom haerSi velis daZabuloba, potenciali da kulonis Zala faqtiurad igivea, rac vakuumSi. misi mniSvneloba sxvadasxva nivTierebebisTvis sxvadasxvaa, arapolarulebisTvis 2,5-8, polarulebisTvis 10-81 da a.S. mag. wylis 81.

V leqcia

gamtaris eleqtrotevadoba. kondensatori. brtyeli kondensatoris tevadoba. damuxtuli kondensatoris energia. eleqtrostatikuri velis energia. energiis simkvrive.

$1. gamtaris eleqtrotevadoba

sxvadasxva gamtarebs gansxvavebuli el. Tvisebebi aqvT. mag. toli sididis muxtebis gadacemisas isini sxvadasxva potencialamde imuxtebian. amitom gamtaris am Tvisebis dasaxasiTeblad SemoaqvT eleqtrotevadobis cneba.

gamtars, romelic daSorebulia sxva sxeulebisgan iseTi manZiliT, rom maT Soris eleqtrul urTierTqmedebas adgili ar aqvs, ganmxoloebuli gamtari ewo–deba. aseT daumuxtav gamtars (romlis potenciali nulia) gadavceT garkveuli sididis muxti, romelic garkveuli wesiT ganawildeba mis zedapirze. ganawilebis xasiaTi (muxtis zedapiruli simkvrive σ) damokidebulia ara mxolod gadacemuli muxtis sidideze, aramed gamtaris zedapiris formazec. damuxtuli gamtari gare sivrceSi Seqmnis eleqtrul vels, romlis yovel wertilSi potencials eqneba raRac mniSvnelobaba, xolo gamtaris yvela wertils ki eqneba erTnairi potenciali.

Tu gamtars muxtis axal raodenobas gadavcemT, igi wina muxtis msgavsad ganawildeba zedapirze, gaizrdeba calkeul wertilebSi muxtis zedapiruli simkvrive σ da gaizrdeba TviToeuli wertilis potencialic. e.i. ganmxoloebuli gamtaris potenciali φ pirdapirproporciulia masze moTavsebuli q muxtisa:

$$\varphi = \frac{1}{C} q \text{ an } q = C\varphi \quad (5.1).$$

proporciulobis C koeficients ganmxoloebuli gamtaris eleqtrotevadoba ewodeba. is damokidebulia gamtaris zomaze, formaze, garemomcveli garemos dieleqtrikul Tvisebebze da sxva gamtarebis siaxloveze. gamtaris gvarobaze da siRrueze is damokidebuli ar aris. mocemuli gamtarisTvis C mudmivia da udris muxtis Sefardebas gamtaris potencialTan:

$$C = \frac{q}{\varphi} \qquad (5.2).$$

e.i. rac nakleb potencials iZens gamtari q muxtis gadacemisas, miT metia misi tevadoba. (5.2)-dan Cans tevadobis fizikuri Sinaarsi: Tu $\varphi = 1$, maSin $C = q$ da maSasadame gancalkevebuli gamtaris eleqtrotevadoba ricxobrivad im muxtis tolia, romelic gamtaris potencials erTi erTeuliT cvlis. misi erTeulia faradi. 1 faradi iseTi gamtaris tevadobaa, romlis potencials 1 kuloni muxti 1 voltiT cvlis. 1 f=1 k/v. farada Zalian didi tevadobaa. mag. is gaaCnia sferos vakuumSi, romlis radiusi 1400-jer metia dedamiwis radiusze. dedamiwis tevadoba 0,7 milifaradaa. gamoiyeneba aseve mikrofarada 1 mkf=10^{-6}f da pikofarada 1 pkf=10^{-12}f.

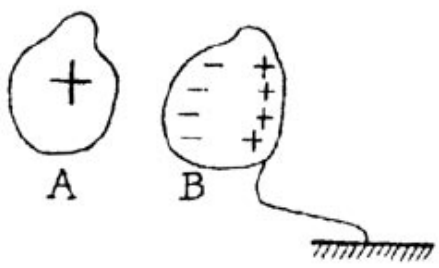
aviRoT r radiusiani sfero, romelic moTavsebulia ε dieleqtrikuli SeRwevadobis erTgvarovan dieleqtrikSi. gadavceT mas q muxti. is zedapirze Tanabrad ganawildeba. Tanabrad damuxtuli sferos el. veli ki iseTia, rogorsac Seqmnida mis centrSi moTavsebuli muxti. amitom sferuli zedapiris potenciali

$$\varphi = \frac{1}{4\pi\varepsilon_0}\frac{q}{\varepsilon r} \qquad (5.3)$$

sadac $\varepsilon -$ fardobiTi dieleqtrikuli SeRwevadobaa. damuxtuli sferos SigniT daZabuloba nulis tolia, amitom is izopotenciur moculobas warmoadgens da amitom sferos nebismier wertilSi potenciali yvelgan erTnairia.

radgan $C = \frac{q}{\varphi}$, amitom $C = 4\pi\varepsilon_0\varepsilon r$. vakuumisTvis $\varepsilon = 1$ da $C = 4\pi\varepsilon_0 r$. e.i. is proporciulia sferos r radiusis da garemos ε dieleqtrikuli SeRwevadobis.

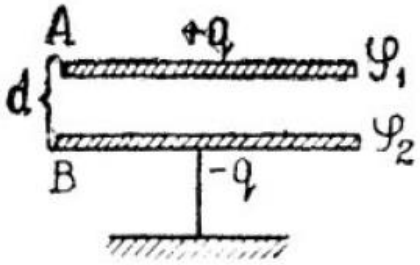
$2. kondensatori da misi eleqtrotevadoba. brtyeli kondensatoris tevadoba.



gamtaris tevadoba damokidebulia masTan sxva gamtaris siaxloveze. vTqvaT A damuxtul gamtars, romlis tevadoba $C = \frac{q}{\varphi}$, mivuaxlovoT B daumuxtavi gamtari (nax. 5.1). maSin A gamtaris potencials gansazRvravs ara mxolod masze moTavsebuli muxti, aramed

nax. 5.1 mezobeli gamtaris muxtic. im drosac ki rodesac mezobeli gamtari damuxtuli ar aris, A gamtaris potenciali mainc icvleba, radgan A gamtaris el. velis moqmedebiT B gamtarSi adgili aqvs muxtebis gadanawilebas., ise rom $A-$sTan uaxloes zedapirze induqciiT ganlagdeba sapirispiro niSnis, romlis potenciali iqneba φ', xolo daSorebul zedapirze igive niSnis muxti $-\varphi''$ potencialiT. $\varphi'-$aseve iqneba A gamtarze B gamtaris uaryofiTi muxtiT Seqmnili potenciali, xolo $\varphi''-$ki B gamtaris dadebiTi muxtiT Seqmnili. maSin $A-$s saerTo potenciali gaxdeba $\varphi_A=\varphi-\varphi'+\varphi''$. radgan A-sTan siaxlovis gamo $\varphi'>\varphi''$, amitom es gamoiwvevs damuxtuli gamtaris potencialis Semcirebas $\varphi_A<\varphi$ (sadac φ aris $A-$s potenciali, rodesac is gancalkevebulia) da Sesabamisad misi tevadobis gazrdas $C_A=\frac{q}{\varphi_A}>\frac{q}{\varphi}=C$. Tu B-s davamiwebT, maSin gamtaris potenciali kidev ufro Semcirdeba (radgan dadebiTi muxti ukve gadava didi zomis dedamiwis Soreul nawilSi) da gamtaris potenciali gaxdeba $\varphi_A=\varphi-\varphi'$ da tevadoba kidev ufro gaizrdeba. A-s sawyis potencialamdis dasamuxtad saWiroa masze meti muxtis gadideba. e.i. meore gamtaris miaxloeba saSualebas gvaZlevs davagrovoT pirvel gamtarze imaze meti muxti, vidre gancalkevebuli gamtaris Sem-Si da misi tevadoba izrdeba. es movlena gamoyenebulia didi tevadobis xelsawyoebis (kondensatorebis) dasamzadeblad.

kondensatori ewodeba dieleqtrikiT gancalkevebul ori gamtaris erTobliobas. arsebobs brtyeli, sferuli, cilindruli da sxva konstruqciis kondensatorebi. kondensatoris tevadobaze gavlena rom ar moaxdinos garemomcvelma sxeulebma, Semonafenebs aZleven iseT formas, rom masze dagrovili muxtebis mier Seqmnili veli Tavmoyrili iyos maT Soris. amas akmayofilebs ori paraleluri firfita – brtyeli kondensatori (nax. 5.2), romelic warmoadgens or brtyel paralelur gamtars, romelTa Soris dieleqtrikia (parafiniT gaJRenTili qaRaldi, qarsis fena da a.S.). am firfitebs kondensatoris Semonafenebi ewodeba. maT muxtaven toli da sapirispiro niSnis muxtiT. mis tevadoba tolia erT-erTi Semonafenis q muxtis fardobisa Semonafenebs Soris potencialTa sxvaobaze



nax. 5.2

$$C=\frac{q}{\varphi_1-\varphi_2}. \quad (5.4)$$

aq unda gaviTvaliwinoT, rom TviToeul gamtaris potenciali ganisazRvreba orive gamtarze ganawilebuli muxtiT. misi tevadoba ricxobrivad tolia im muxtis sididisa, romelic unda gadavitanoT erTi gamtaridan meoreze, rom potencialTa sxvaoba maT Soris Seicvalos erTi erTeuliT.

gamoTvlebiT miRebulia brtyeli kondensatoris tevadoba: $C=\frac{\varepsilon_0\varepsilon S}{d}$ (viciT $E=\frac{\sigma}{\varepsilon_0\varepsilon}$, xolo $\sigma=\frac{q}{S}$, $E=\frac{q}{\varepsilon_0\varepsilon S}$. aseve daZabulobasa da potencialTa sxvaobas Soris kavSiridan gvaqvs $E=\frac{\varphi_1-\varphi_2}{d}$ da $\frac{q}{\varepsilon_0\varepsilon S}=\frac{\varphi_1-\varphi_2}{d}$,. aqedan $q=\frac{(\varphi_1-\varphi_2)\varepsilon_0\varepsilon S}{d}$ da $C=\frac{q}{\varphi_1-\varphi_2}=\frac{\varepsilon_0\varepsilon S}{d}$). am formulidan gamodis, rom

forfitebs Soris d – manZilis SemcirebiT SeiZleba didi tevadobis konde\nsatori miviRoT, magram ucvleli potencialTa sxvaobis dros izrdeba E – daZabuloba da SeiZleba moxdes dieleqtrikis garRveva, amitom ar SeiZleba misi usasrulod Semcireba. igi proporciulia Semonafenis farTobis (S) da ukuproporciulia firfitebs Soris manZilis (d). ε_0 eleqtruli mudmivaa, ε fardobiTi dieleqtrikuli SeRwevadoba.

$3. damuxtuli kondensatoris energia. eleqtrostatikuri velis energia. energiis simkvrive.

damuxtuli kondensatoris ganmuxtvisas gamoiyofa siTbo, e.i. kondensators gaaCnia energia. es energia ase gamoiTvleba: kondensatoris energia, Tu φ – s nacvlad aviRebT potencialTa sxvaobas (Zabvas- U) da visargeblebT kondensatoris tevadobis formuliT toli iqneba:

$$W_P = \frac{CU^2}{2} \qquad (5.5)$$

radgan $C = \frac{q}{U}$, amitom kondensatoris energiisaTvis miviRebT aseve

$$W_P = \frac{qU}{2} = \frac{q^2}{2C} \qquad (5.6)$$

(ganmuxtvisas Semonafenebs Soris dq – muxtis gadatanaze el. statikuri velis muSaoba $dA = dqU$. radgan $q = CU$, amitom $dq = CdU$ da $A = W = C\int_0^U UdU = \frac{CU^2}{2} = \frac{q^2}{2C} = \frac{qU}{2}$).

rogorc vnaxeT kondensatoris energiis gamosaTvleli erT-erTi formula aseTia

$$W = W_P = \frac{qU}{2} = \frac{1}{2}q(\varphi_1 - \varphi_2) \qquad (5.7)$$

(gamoisaxeba muxtisa da potencialebis saSualebiT). gamovsaxoT is velis maxasiaTebeli sidideebiT. Semonafenebs Soris velis daZabuloba cnobilia $E = \frac{\sigma}{\varepsilon_0\varepsilon} = \frac{q}{\varepsilon_0\varepsilon S}$. aqedan $q = \varepsilon_0\varepsilon ES$. meore mxriv

erTgvarovani velis SemTxvevaSi $E = \frac{\varphi_1 - \varphi_2}{d}$ da $\varphi_1 - \varphi_2 = Ed$. am sidideebis SetaniT $W = \frac{1}{2} q(\varphi_1 - \varphi_2)$ formulaSi, miviRebT

$$W = \frac{1}{2} \varepsilon_0 \varepsilon E^2 Sd = \frac{1}{2} \varepsilon_0 \varepsilon E^2 \tau \qquad (5.8),$$

sadac $\tau = Sd$ aris Semonafenebs Soris sivrcis moculoba (maT gareT $E = 0$).

(5.8) formula gamosaxavs kondensatoris energias Semonafenebs Soris arsebuli velis daZabulobis saSualebiT. e.i. kondensatoris Semonafenebs Soris arsebul el. statikur vels aqvs energia da es aris **eleqtro-statikuri velis energia.**

energias, romelic modis moculobis erTeulze, ewodeba eleqtrostatikuri velis simkvrive. maSasadame energiis simkvrive toli iqneba:

$$\omega = \frac{W}{\tau} = \frac{1}{2} \varepsilon_0 \varepsilon E^2 \qquad (5.9)$$

(5.9) formula miRebuli iqna erTgvarovani velisTvis, magram igi samarTliani araerTgvarovani velebisTvisac. erTgvarovani velis Sem-Si ω sivrcis yvela wertilSi erTnairia, xolo araerTgvarovanis dros is icvleba wertilidan wertilamde.

vakuumisTvis $\varepsilon = 1$ da $\omega = \frac{1}{2} \varepsilon_0 E^2$, anu velis energiis simkvrive velis E daZabulobis erTi da igive mniSvnelobis dros dieleqtrikSi metia, vidre vakuumSi. es imitom, rom vakuumSi kondensatoris damuxtvisas muSaoba ixarjeba mxolod el. velis Seqmnaze, xolo dieleqtrikis Sem-Si rogorc velis Seqmnaze, ise mis polarizaciaze. muSoba ki gansazRvravs energiis marags.

VI leqcia

eleqtruli deni. eleqtruli denis arsebobis pirobebi. denis Zala. denis simkvrive. denis wyaroebi. eleqtromamoZravebeli Zala da Zabva. omis kanoni wredis erTgvarovani ubnisaTvis da misi diferencialuri saxe. gamtaris winaRobis gamosaTvleli formula.

$1. eleqtruli deni. eleqtruli denis arsebobis pirobebi. denis Zala. denis simkvrive.

eleqtrobis im nawils, romelSic ganixileba eleqtruli muxtebis mimarTul moZraobasTan dakavSirebuli movlenebi, eleqtrodinamika ewodeba.

gamtarSi eleqtruli velis gavleniT muxtebis mowesrigebul (mimarTul) moZraobas eleqtruli deni ewodeba. nivTierebas, romelSic SesaZlebelia aseTi moZraoba eleqtrobis gamtari ewodeba, xolo aRZrul dens, gamtareblobis deni. denis mimarTulebad miRebulia dadebiTi muxtebis moZraobis mimarTuleba. Tu deni Seqmnilia mxolod uaryofiTi muxtebiT (mag. liTonebSi eleqtronebiT), maSin denis mimarTuleba eleqtronebis moZraobis sapirispiro mimarTulebaa.

denis arsebobisTvis saWiroa Semdegi pirobis Sesruleba:

a) sxeulSi unda არსებობდეს Tavisufali damuxtuli nawilakebi, romlebsac SeuZliaT gadaadgileba gamtaris mTel moculobaSi. liTonebSi Tavisufal muxtebs warmoadgenen atomebidan moSorebuli eleqtronebi, xolo eleqtrolitebSi ki dadebiTi da uaryofiTi ionebi.

b) gamtarSi unda arsebobdes eleqtruli veli, romlis energiis xarjzec gadaadgildeba muxtebi. es niSnavs, Tavisufal damuxtul nawilakebze imoqmedos $\boldsymbol{F = qE}$ eleqtrulma Zalam, ris gamoc muxtebi qaosur moZraobasTan erTad Seasruleben mimarTul moZraobas. radgan velis daZabuloba ZabvasTan (potencialTa sxvaoba) aseT kavSirSia $\boldsymbol{E = \frac{\varphi_1 - \varphi_2}{d}}$, gamodis rom gamtaris bolebze unda arsebobdes potencialTa sxvaoba, anu masze modebuli iyos Zabva.

denis sididis dasaxasiaTeblad SemoaqvT denis Zalis cneba. denis Zala ewodeba sidides, romelic izomeba gamtaris ganivkveTSi drois erTeulSi gavlili muxtis raodenobiT**.** Tu gamtaris ganivkveTSi $\boldsymbol{t}$ droSi gadis $\boldsymbol{q}$ muxti, maSin denis Zala

$$\boldsymbol{I = \frac{q}{t}} \qquad (6.1).$$

Tu gamtaris ganivkeTSi drois raRac SualedSi gadis erTi da igive ∂uxti, maSin gvaqvs mudmivi deni.

denis Zalis erTeuli SI sistemaSi aris amperi (a). **amperi iseTi denis Zalaa, romelic gadis vakuumSi 1 metriT daSorebul or usasrulod grZel da wvril paralelur gamtarebSi da sigrZis yovel metrze iwvevs $2\cdot10^{-7}$ niutonis tol urTierTqmedebis Zalas.**

(6.1) formulidan gamodis, rom amperi tolia iseTi mudmivi denis Zalisa, romlis drosac gamtaris ganivkveTsi 1 wamSi gadis 1 kuloni muxti.

Tu deni ar aris mudmivi, maSin misi saSualo mniSvneloba drois Δt SualedSi tolia $\bar{I}=\frac{\Delta q}{\Delta t}$, xolo mocemul momentSi denis sidide (myisi mniS-ba) toli iqneba:

$$I=\lim_{\Delta t\to 0}\frac{\Delta q}{\Delta t}=\frac{dq}{dt} \qquad (6.2),$$

anu muxtis warmoebulia droiT.

denis Zala skalaruli sididea. is ganekuTvneba gamtaris mTel ganivkveTs. ganivkveTis farTobis erTeulze mocul denis Zalis (an farTobis erTeulSi erT wamSi gavlili eleqtrobis raodenoba) sidides **denis simkvrive ewodeba.** mudmivi denisTvis is tolia $i=\frac{I}{S}=\frac{q}{St}$ (6.3).

aramudmivi denis Sem-Si (anu gamtaris farTobSi denis araTanabari ganawileba) gveqneba denis simkvrivis saSualo $\bar{i}=\frac{\Delta I}{\Delta S}$ da myisi, anu simkvrive mocemul wertilSi

$$i=\lim_{\Delta t\to 0}\frac{\Delta I}{\Delta S}=\frac{dI}{dS}=\frac{dq}{dS\cdot dt} \qquad (6.4),$$

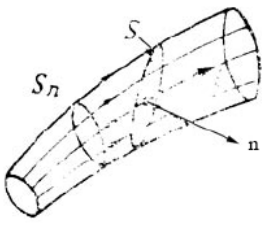
anu simkvrive denis warmoebulia droiT.

denis simkvrivis erTeulia a/m^2 (amperi metrkvadratTan). is veqtoruli sididea da misi mimarTuleba emTxveva dadebiTi muxtebis moZraobis mimarTulebas.

Tu farTobi ar aris denis mimarTulebis marTobuli, maSin $i=\frac{\Delta I}{\Delta S_n}$ da

$$i=\frac{dI}{dS_n}=\frac{dI}{dS\cos\alpha} \qquad (6.5)$$

sadac α aris kuTxe denis simkvrivis veqtorsa $(\vec{i})$ da S farTis normals Soris (nax. 6.1). Sesabamisad (6.5)-dan gveqneba $dI=i\cdot dS\cos\alpha$ da $I=\int dI=\int_S i dS_n=\int_S i_n dS$ $(i_n=i\cos\alpha)$ (6.6).



nax. 6.1

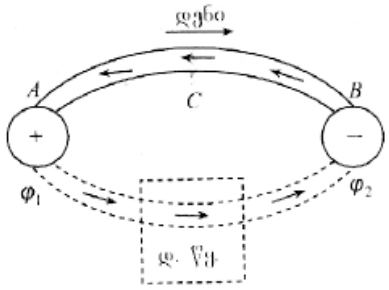
aq i_n arisdenis simkvrivis veqtoris gegmili dS farTobis normalze. (6.6)-dan Cans, rom denis Zala denis simkvrivis veqtoris nakadia S farTobSi.

$2. denis wyaroebi. eleqtromamoZravebeli Zala da Zabva.

denis gavlisas gamtarSi xdeba muxtebis iseTi gadanawileba, rom el. veli ispoba (e.i. potenciali yvela wertilSi Tanabrdeba) da deni wydeba. maSasadame deni rom SevinarCunoT saWiroa xeli SevuSaloT velis mospobas gamtaris SigniT, unda Sesruldes muSaoba elstatikuri Zalebis winaaRmdeg arael. statikuri bunebis ZalebiT, romlebic uzrunvelyofen el. velis mier muxtebis gadaadgilebaze daxarjuli energiis ganuwyvetliv Sevsebas. es unda sruldebodes energiis raime wyaros (denis wyaro) xarjze. aseTi wyaroebia meqanikuri,

siTburi, qimiuri da sxva. denis wyaroSi moqmedi Zalebi (gare Zalebi) iwveven sxvadasxva niSnis muxtebis gancalkevebas da qmnian masSi el. vels.

Tu sxvadasxva niSniT damuxtul or A da B gamtar sferoebs SevaerTebT C mavTuliT (nax. 6.2), maSin maRali potencialis mqone gamtaridan meoreSi gadava dadebiTi muxtebi (eleqtronebi BCA mimarTulebiT) da warmoiSoba deni. aseTi gadasvla rogorc avRSniSneT amcirebs potencialTa sxvaobas. potenciali yvela wertilSi Tanabrdeba da mcire droSi deni moispoba. denis SenarCunebisTvis ki aucilebelia muxtebi A-dan isev B-Si gadavitanoT kulonuri Zalebis sawinaaRmdegod, anu unda ganxorcieldes denis mier A sferoze gadmotanili eleqtronebis isev B sfe-



nax. 6.2

roze gadatana (naxazze punqtiri), rac xorcieldeba denis wyaroSi arsebuli gare (araeleqtrostatikuri) Zalebis meSveobiT. denis wyaroSi xdeba dadebiTi da uaryofiTi muxtebis gancalkeveba, rac kulonur Zalebs ar SeuZliaT.

wyaroSi gare Zalebi muxtebs gadaadgilebs el. Zalebis moqmedebis sawinaaRmdegod mimarTulebiT. gare wredSi ki muxtebi gadaadgildebian el. Zalebis moqmedebiT, rac uzrunvelyofs wredis Caketvas.

gare Zalebis mier muxtis gadatanaze Sesrulebul muSaobas axasiaTeben sididiT, romelsac eleqtromamoZravebeli Zala (emZ) ewodeba. emZ ricxobrivad tolia gare ZalTa mier wredis gaswvriv erTeuli dadebiTi muxtis gadatanaze Sesrulebuli muSaobisa da tolia:

$$\varepsilon = \frac{A}{q} \qquad (6.9)$$

formulidan Cans, rom is izomeba voltebiT (rogorc Zabva) da is skalaruli sididea. deni mudmivia, Tu gamtaris ganivkveTSi drois tol SualedSi toli sididis muxtebi gadaitaneba. aseTi denis SesanarCuneblad wredi aucileblad Caketili unda iyos.

q muxtze moqmedi gare Zala tolia: $\vec{F}_g = q\vec{E}_g$ (6.10).

$\vec{E}_g$ aris gare ZalTa velis daZabuloba da am Zalebis mier q muxtis wredis 1-2 ubanze gadasatanad Sesrulebuli muSaoba tolia: $A_{12} = \int_1^2 (\vec{F}_g \cdot d\vec{l}) = q\int_1^2 (\vec{E}_g \cdot d\vec{l})$ (6.11).

am muSaobis gayofa q muxtze mogvcems mocemul ubanze moqmed emZ-s, anu

$$\varepsilon_{12} = \int_1^2 (\vec{E}_g \cdot d\vec{l}) \qquad (6.12).$$

Caketili wredisaTvis aseTi integrali mogvcems am wredSi moqmed emZ-s:

$$\varepsilon = \oint (\vec{E}_g \cdot d\vec{l}) \qquad (6.13).$$

e.i. Caketil wredSi moqmedi emZ ganisazRvreba rogorc gare ZalTa daZabulobis veqtoris cirkulacia.

muxtze aseve Caketil wredSi moqmedebs el. statikuri velis Zala $F_E = qE$ da jamuri Zala muxtze wredis yovel wertilSi tolia

$$\vec{F} = \vec{F}_E + \vec{F}_g = q(\vec{E} + \vec{E}_g) \qquad (6.14).$$

maSin muSaoba romelsac es jamuri Zala asrulebs q muxtis wredis 1-2 ubanze gadasaadgileblad tolia:

$$A_{12} = q\int_1^2 (\vec{E} \cdot d\vec{l}) + q\int_1^2 (\vec{E}_g \cdot d\vec{l}) = q(\varphi_1 - \varphi_2) + q\varepsilon_{12} \quad (6.15).$$

sidides, romelic ricxobrivad tolia eleqtrostatikuri da gare Zalebis mier erTeulovani muxtis gadatanaze Sesrulebuli muSaobis, ewodeba mocemul ubanze **Zabva** (U). e.i. Zabva 1-2 ubanze toli gamodis $U_{12} = \varphi_1 - \varphi_2 + \varepsilon_{12}$.

wredis iseT ubans, sadac ar moqmedebs gare Zalebi, ergvarovani ewodeba da Tu ubanze denis matareblebze moqmedebs gare Zalebi, maSin aseT ubans araerTgvarovani ewodeba. Tu ubani erTgvarovania, $\varepsilon_{12} = 0$, maSin $U_{12} = \varphi_1 - \varphi_2$ (6.16)
da Zabva Tanxvdeba ubnis boloebze potencialTa sxvaobas.

$3. omis kanoni wredis erTgvarovani ubnisaTvis da misi diferencialuri saxe. gamtaris winaRobis gamosaTvleli formula.

gamtarSi gamavali denis Zala damokidebulia gasmtaris boloebze arsebul potencialTa sxvaobaze anu Zabvaze: $I = f(\varphi_1 - \varphi_2) = f(U)$ (6.17).
denis Zalasa da Zabvas Soris funqcionalur damokidebulebas volt-amperuli maxasiaTebeli ewodeba da es damokidebuleba eqsperimentalurad daadgina omma (germaneli), romlis Tanaxmad liTonur gamtarSi gamavali denis Zala gamtaris bolebze arsebuli Zabvis pirdapirproporciulia: $I = kU$ (6.18).
$k -$ proporciulobis koeficients eleqtrogamtaroba ewodeba. Tu $T = const$, maSin $k = const$. rac metia k, miT meti deni gadis gamtarSi mocemuli Zabvis dros.

$R = \frac{1}{k}$ sidides, romelic gamtarobis Sebrunebulia, gamtaris winaRoba ewodeba. maSin

$I = \frac{U}{R}$ (6.19).

es formula gamosaxavs omis kanons erTgvarovani wredis ubnisaTvis da ase Camoyalibdeba: **gamtarSi gamavali denis Zala pirdapirproporciulia gamtaris boloebze**
arsebuli Zabvis da ukuproporciulia gamtaris winaRobis.

rac metia winaRoba, miT naklebia deni, anu winaRoba gamtaris is Tvisebaa, rom winaaRmdgeboba gauwios denis gavlas. e.i. ukuqmedebaa el. denis mimarT.

sidides $U = IR$ ewodeba Zabvis varna mocemul ubanze da is tolia ubnis winaRobis namravlisa masSi gamaval denze. Tu wredi gawyvetilia, maSin gvaqvs wredis or wertils Soris mxolod Zabva (potencialTa sxvaoba) da ara Zabvis vardna.

formulidan $R = \frac{U}{I}$ dgindeba winaRobis erTeuli SI sistemaSi: volti/amperi=omi, anu omis aris iseTi gamtaris winaRoba, romlis boloebze 1 volti Zabvis dros masSi gadis 1 amperi deni.

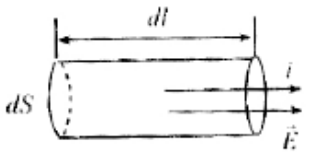
gamtaris winaRoba damokidebulia gamtaris masalaze (ρ) da mis geometriul zomebze (l – sigrZe da S – ganivkveTis farTi) da is gamoiTvleba formuliT:

$$R = \rho \frac{l}{S} \qquad (6.20).$$

aq ρ aris nivTierebis gvarobaze damokidebuli da mas kuTri winaRoba ewodeba. Tu $l = 1$ da $S = 1$, maSin $\rho = R$, anu kuTri winaRoba erTeulovani sigrZis da erTeulovani ganivkveTis farTis mqone gamtaris winaRobaa. SI sistemaSi misi erTeulia omi·m (omi metrze). teqnikaSi gamoiyeneba aseve erTeuli omi·mm^2/m. mcire kuTri winaRoba aqvT Zvirfas liTonebs (mag. vercxlisTvis 1,6·10^8 omi·m) da spilenZs (1,7·10^8 omi·m). kuTri winaRobis Sebrunebuli sididea kuTri eleqtrogamtaroba: $\gamma = \frac{1}{R}$ (6.21).

omis kanonidan vigebT denis Zalas, romelzec damokidebulia denis siTburi, qimiuri da magnituri moqmedebani. $I = \frac{U}{R}$ aseTi saxiT Caweril omis kanons integralur saxes uwodeben. integralurs imitom, rom gamtaris mocemul ganivkveTSi denis Zalis gasagebad saWiroa integraluri sidideebis (gamtaris winaRoba da Zabva) codna. magram rig SemTxvevebSi GAMgamtaris erTi wertilisTvis saWiroa vicodeT denis Zalasa da velis maxasiaTebel sidides Soris. aseT kavSirs gamoxatavs omis diferenecialuri kanoni.

gamtarSi azrobrivad gamovyoT dl sigrZis da dS ganivkveTis farTis elementaruli cilindri, romlis msaxvelebi velis $\vec{E}$ daZabulobis da e.i. denis simkvrivis veqtorebis paraleluria (nax. 6.3). cilindris ganivkveTSi denis Zala $I = idS$. masze modebuli Zabva $U = Edl$, sadac $\vec{E}$ velis daZabulobaa mocemul adgilas. cilindris



nax. 6.3 winaRoba $R = \rho \frac{dl}{dS}$. yvela am sididis $I = \frac{U}{R}$ formulaSi Setana gvaZlevs $idS = \frac{dS}{\rho dl} Edl$, an $i = \frac{1}{\rho} E = \gamma E$. e.i. denis simkvrive daZabulobis proporciulia. radgan $\vec{i}$ – is mimarTuleba emTxveva $\vec{E}$ – s mimarTulebas, amitom bolo formula veqtorulad ase Caiwereba: $\vec{i} = \gamma \vec{E}$ (6.22).

aseTi saxiT gamosaxul omis kanons diferencialuri saxe ewodeba. diferencialuri imitom ewodeba, rom igi gvaZlevs denis simkvrivis mniSvnelobas gamtaris mocemul wertilSi, Tu cnobilia velis daZabuloba am wertilSi, anu kavSirs i – sa da E – s Soris mocemulia gamtaris erTi da igive wertilisaTvis. am ori veqtoris paralelobidan gamomdinareobs, rom denis wirebi emTxveva eleqtrul Zalwirebs da denis simkvrivis veqtori marTobulia ekvipotencialuri zedapirebis.

VII leqcia

denis muSaoba da simZlavre. joul-lencis kanoni da misi diferencialuri saxe. omis kanoni Caketili wredisaTvis. kirhofis kanonebi.

$1. denis muSaoba da simZlavre: joul-lencis kanoni da misi diferencialuri saxe.

gamtarSi denis gavlis dros eleqtruli veli asrulebs garkveul muSaobas, romelsac denis muSaoba ewodeba. wredis romelime ubanze el. velSi q muxtis gadaadgilebaze Sesrulebuli muSaoba

$$A = q(\varphi_1 - \varphi_2) = qU = IUt \qquad (7.1),$$

radgan $q = It$. e.i. wredis ubanze denis muSaoba tolia denis Zalis, Zabvis da denis dinebis drois namravlisa. Tu visargeblebT omis kanoniT ($I = \frac{U}{R}$ da $U = IR$, maSin gveqneba sami ekvivalenturi formula muSaobisTvis:

$$A = IUt = I^2Rt = \frac{U^2}{R}t \qquad (7.2).$$

$A = I^2Rt$ Fformula mosaxerxebelia gamtarTa mimdevrobiTi SeerTebis dros, radgan am dros denis Zala yvela gamtarSi erTi da igivea. $A = \frac{U^2}{R}t$ – ki paraleluri SeerTebis dros, radgan am dros yvela gamtarze erTi da igive Zabvaa modebuli.

radgan simZlavre es aris drois erTeulSi Sesrulebuli muSaoba, amitom denis simZlavre tolia:

$$P = \frac{A}{t} = IU = I^2R = \frac{U^2}{R} \qquad (7.3)$$

denis muSaobis erTeuli SI sistemaSi aris jouli , maSin simZlavris erTeuli iqneba vati (vt) da 1vt=1j/1wm=1a·1v. aseve sistemgareSe erTeulia kilovati (kvt).

1kvt=1000vt. eleqtroteqnikaSi muSaobis erTeulad aseve miRebulia kilovatsaaTi.

$1kvtsT=10^3vt\cdot 3600wm=3,6\cdot 10^6j.$

rodesac wredis gamtarebi uZravia da masSi gadis deni, gare Zalebis mier muxtis gadaadgilebaze Serulebuli muSaoba mTlianad gardaiqmneba gamtaris Sinagan energiad, rac iwvevs gamtaris gaTbobas. energiis mudmivobis kanonis Tanaxmad, gamoyofili siTbos raodenoba Sesrulebuli muSaobis tolia, e.i.

$$Q = A = I^2Rt = \frac{U^2}{R}t \qquad (7.4).$$

formula $Q = I^2Rt$ atarebs joul-lencis kanonis saxels: **denis mier gamtarSi gamoyofili siTbos raodenoba proporciulia denis Zalis kvadratis, winaRobis da gamtarSi denis dinebis drois.**

miviRoT am kanonis diferencialuri saxe. amisTvis gamovyoT gamtarSi elementaruli cilindri dl simaRliT da dS fuZis farTobiT. maSin misi moculoba toli iqneba $dV = dldS$. cilindris winaRoba $R = \rho \frac{dl}{dS}$. joul-lencis kanonis Tanaxmad mcire dV moculobaSi dt droSi gamoiyofa siTbos raodenoba

$$dQ = I^2 Rdt = (idS)^2 \cdot \rho \frac{dl}{dS} \cdot dt = \rho i^2 dldSdt = \rho i^2 dVdt \qquad (7.5)$$

SemovitanoT siTburi simZlavris simkvrivis (kuTri siTburi simZlavre), cneba, romelic tolia erTeul moculobaSi erTeul droSi gamoyofili siTbos raodenobis. Tu usasrulod mcire dV moculobaSi dt droSi gamoiyo dQ siTbo, maSin kuTri siTburi simZlavre toli iqneba $w = \frac{dQ}{dVdt} = \rho i^2$. Tu gamoviyenebT omis kanonis diferencialur formas $i = \gamma E$ da viciT aseve kuTri ρ winaRoba kuTri γ winaRobis Sebrunebuli sididea $\rho = \frac{1}{\gamma}$, gveqneba

$$w = \rho i^2 = \frac{1}{\gamma} \gamma^2 E^2 = \gamma E^2 \qquad (7.6)$$

es formula gamosaxavs joul-lencis kanons diferencialuri formiT: **gamtaris mocemul wertilSi denis kuTri siTburi simZlavre proporciulia amave wertilSi velis daZabulobis kvadratis.** formula marTebulia nebismieri gamtarisTvis mudmivi da cvladi denisTvis.

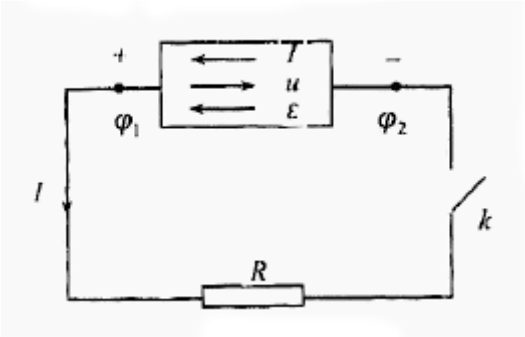
denis siTburi moqmedeba farTod gamoiyeneba varvarebis naTurebSi. aseve gamaxurebel xelsawoebSi, rodesac gvaqvs mimdevrobiT SeerTebuli wredi. am dros $I = const$, amitom yvelaze didi siTbo gamoiyofa im ubanze, sadac winaRoba didia, mag. gamxureblis spirali, an naTuris Zafi, xolo am dros radgan SemaerTebel sadenebs mcire winaRoba aqvT, iq naklebi siTbo gamoiyofa. spiralebad gamoyenebuli niqromi, romlis kuTri winaRoba $\rho = 110 \cdot 10^{-8}$ omi·m, xolo spilenZis (rogorc miyvani sadenebi) $\rho = 2{,}7 \cdot 10^{-8}$ omi·m.

$2. omis kanoni Caketili wredisaTvis.

vTqvaT gvaqvs Caketili wredi, romelic Sedgeba denis wyarosa da raime momxmareblisagan. denis wyaros emZ iyos ε, xolo mis Siga winaRoba r. momxmareblis winaRoba (gare winaRoba) avRniSnoT $R-$iT, xolo mimyvani sadenebis winaRoba ugulebelvyoT (nax. 7.1). I denis wredSi gavlisas denis wyaros mier dt droSi Sesrulebuli muSaoba toli iqneba:

$$dA = I\varepsilon dt \qquad (7.7)$$

(radgan raime q muxtis gaadgilebisa Caketil wredSi tolia sami muSaobis jamisa:



nax. 7.1

$A = A_1 + A_2 + A_3 = q\varepsilon = I\varepsilon dt$, sadac $A_1 = q(\varphi_1 - \varphi_2)$ aris gare wredSi eleqtruli Zalebis mier dadebiTi polusidan uaryofiTisken muxtis gadaadgilebaze Sesrulebuli muSaoba, $A_2 = -q(\varphi_1 - \varphi_2)$ – aris eleqtruli Zalebis, romlebic ewinaaRmdegebian muxtis gadaadgilebas denis wyaros SigniT, Sesrulebuli uaryofiTi muSaoba da $A_3 = q\varepsilon$ aris denis wyaros SigniT gare Zalebis, romlebsac muxti gadaaqvT uaryofiTi polusidan dadebiTze, mier Sesrulebuli muSaoba da amitom $A = I\varepsilon dt$). energiis mudmivobis kanonis Tanaxmad am muSaobis xarjze xdeba joul-lencis kanonis Tanaxmad siTbos gamoyofa wredis gare da Siga ubnebze:

$$dA = dQ = I^2 Rdt + I^2 rdt = I\varepsilon dt, \quad (7.8)$$

saidanac $\varepsilon = Ir + Ir$, rac niSnavs rom Caketil wredSi moqmedi emZ tolia wredis gare da Siga ubnebze Zabvis vardnaTa jamisa. radgan $U = IR$ (U – wyaros momWerebze Zabvaa), amitom

$$\varepsilon = U + Ir. \quad (7.9)$$

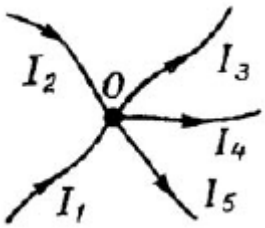
e.i. denis wyaros em Zala metia wyaros polusebs Soris Zabvaze Ir sididiT, romelic Zabvis vardnaa Siga wredSi. bolo formulidan

$$I = \frac{\varepsilon}{R + r}, \quad (7.10)$$

romelic gamosacavs omis kanons Caketili wredisaTvis: **denis Zala proporciulia wredis em Zalisa da ukuproporciulia gare da Siga winaRobaTa jamisa**.

Tu wredi ganrTulia, maSin $I = 0$ da formulidan $\varepsilon = U$, anu em Zala ricxobrivad ganrTuli wredis boloebze arsebuli Zabvis tolia. aseve wyaros ucvleli ε da r – isTvis deni damokidebulia gare R winaRobaze. deni udidesia, rodesac $R = 0$, $I_0 = \frac{\varepsilon}{r}$ (mokle CarTvis deni). R – is gadidebiT deni mcirdeba da rodesac $R \to \infty$, maSin $I = 0$, rac ganrTul wreds Seesabameba.

$3. kirhofis kanonebi.



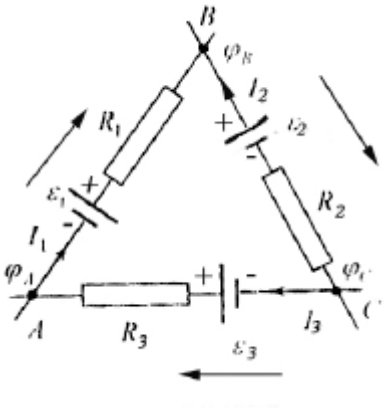
kirxofis I kanoni exeba kvanZs (iseTi wertilia, sadac Tavs iyris aranakleb sami deniani gamtari). O kvanZSi (nax. 7.2) Sedis I_1 da I_2, xolo gamodis I_3, I_4, I_5 denebi. MmaSin $I_1+I_2=I_3+I_4+I_5$. Tu davuSvebT, rom $I_1+I_2>I_3+I_4+I_5$, maSin kvanZSi muxtebi grovdeba, rac denis stacionarobas nax. 7.2 ewinaaRmdegeba. piriqiT Tu $I_1+I_2<I_3+I_4+I_5$, maSin kvanZSi unda iyos moTavsebuli denis wyaro. maSasadame kirxofis I kanoni ase Camoyalibdeba: **kvanZSi Sesuli denebis jami udris kvanZidan gamosuli denebis jams**. Tu CavTvliT, rom Sesuli denebi dadebiTia, xolo gamosuli uaryofiTi,

maSin $$I_1+I_2+(-I_3)+(-I_4)+(-I_5)=0. \quad (7.11)$$

e.i. kvanZSi Tavmoyrili denebis algebruli jami nulis tolis. zogadad

$$\sum_{i=1}^{n} I_i = 0 \qquad (7.12).$$

kirxofis II kanoni ki exeba rTuli wredidan gamoyofil raime konturs, romlis calkeul ubnebSi CarTulia denis wyaroebi. mag. ***ABCA*** konturi (nax. 7.3). Semovlis mimarTulebad avirCioT saaTis isris moZraobis mimarTuleba. denebi, romelTa mimarTulebebic emTxveva Semovlis mimarTulebas iTvleba dadebiTad (I_1, I_3), xolo romlebic Semovlis mimarTulebis sapirispiroa – uaryofiTad (I_2). emZ-bi dadebiTia, Tu isini qmnian dens, romelTa mimarTuleba emTxveva Semovlis mimarTulebas, anu Semovlis mimarTulebiT gadavdivarT uaryofiTi polusidan dadebiTisken.



nax. 7.3

TiToeuli araerTgvarovani ubnisaTvis omis kanonidan gveqneba

$$I_1R_1 = \varphi_A - \varphi_B + \varepsilon_1$$
$$-I_2R_2 = \varphi_B - \varphi_C - \varepsilon_2 \qquad (7.13)$$
$$I_3R_3 = \varphi_c - \varphi_A + \varepsilon_3$$

SevkriboT es tolobebi:

$$I_1R_1 - I_2R_2 + I_3R_3 = \varepsilon_1 - \varepsilon_2 + \varepsilon_3,$$

an zogadad

$$\sum_{i=1}^{n} I_iR_i = \sum_{i=1}^{n} \varepsilon_i \qquad (7.14).$$

(7.14) formula gamosaxavs kirxofis II kanons: **Caketili konturis calkeul ubnebSi Zabvis vardnaTa algebruli jami udris konturSi moqmed em ZalaTa algebrul jams.**

rTuli ganStoebuli wredebisTvis vadgenT imden gantolebas, ramdeni ucnobi sididecaa saZiebeli.

VIII leqcia

magnituri veli. magnituri induqciis veqtori. magnituri momenti. magnituri induqciis nakadi. magnituri velis grigaluri xasiaTi.

$1. magnituri veli. magnituri induqciis veqtori. magnituri momenti.

bunebaSi arsebobs rkinis madani (magnituri rkinaqva Fe_3O_4), romelic izidavs rkinasa da zogierT sxva liTons. mas bunebrivi magniti ewodeba. misi mizidvis unari maqsimaluria magnitis boloebSi, centraluri nawilisken mcirdeba da SuaSi nulis tolia. magnitis boloebs magnitis polusebi ewodeba, xolo Sua adgils neitraluri zona. aRniSnaven N (CrdiloeTi) da S-iT (samxreTi) polusebi. polusebis aseTi aRniSvna dakavSirebulia imasTan, rom Tavisuflad moZravi magnituri isari ise orientirdeba dedamiwis magnitur velSi, rom misi erTi bolo mimarTulia dedamiwis CrdiloeT polusisiken, xolo meore samxreTisken. im sivrces romelic gars akravs magnits da mJRavndeba misi mizidvis unari, magnituri veli ewodeba. is el. velis msgavsad materialuria, gaaCnia energia. am velis maorientirebeli moqmedeba magnitur isarze saSualebas gvaZlevs magn. vels mivceT mimarTuleba. es mimarTuleba magn. isris CrdiloeT polusze moqmedi Zalis mimarTulebaa. e.i. magn. isarze magn. velSi, ise rogorc dipolze ($+\boldsymbol{q}$ da $-\boldsymbol{q}$ muxtebisagan Semdgari sistema, romlebic erTmaneTTan xistad arian dakavSirebuli raRac $\boldsymbol{l}$ manZiliT – mxariT) el. velSi, moqmedebs mabrunebeli momenti da is Semobrundeba. arsebiTi gansxvaveba dipolsa da mudmiv magnits Soris is aris, Tu dipols “gavWriT” SuaSi, mis erT nawilze aRmoCndeba dadebiTi , xolo meore mxares uaryofiTi muxti. magnitis gaWrisas ki miiReba ori magniti Tavis polusebiT. e.i. bunebaSi “magnituri muxtebi “ ar arsebobs.

1820 wels erstedma aRmoaCina, rom magn. vels qmnis aseve gamtarSi gamavali denic (zogadad moZravi muxtebi). dens, romelic ganpirobebulia gamtarSi Tavisufali muxtebis mimarTuli moZraobiT

(gamtarobis deni), vuwodoT makroskopiuli deni (makrodeni), xolo atomSi an molekulaSi eleqtronebis wriuli moZraobiT ganpirobebul dens – mikroskopiuli deni (mikrodeni). aseT moZrav muxtebs gaaCniaT sxva (magnituri) urTierTqmedebebi (deniani gamtarebis urTierTqmedeba, el. denis moqmedeba magn. isarze da sxva), romelic ar daiyvaneba eleqtrul urTierTqmedebamde.

magnituri velis ZiriTadi maxasiaTebelia magnituri induqciis $\vec{B}$ veqtori, romelic Seqmnilia yvela makro da mikrodenebis mier. mocemuli makrodenis Sem-Si misi mniS-ba damokidebulia garemos Tvisebebze.

makroskopiuli deniT Seqmnil magnitur vels axasiaTeben damxmare $\vec{H}$ magn. velis daZulobis veqtoriT, romelic ar aris damokidebuli garemos Tvisebebze. e. magn. velis dasaxasiaTeblad gamoyenebuli ori veqtoridan $\vec{B}$ –s analogiuria el. velis $\vec{E}$ daZabulobis veqtori da ara $\vec{H}$. aseve sxeulis magnituri Tvisebebis dasaxasiaTeblad, rogorc dieleqtrikis Sem_Si $\vec{P}$ polarizaciis veqtori axasiaTebs dieleqtrikis eleqtrul Tvisebebs, aqac SemoRebulia damagnitebis $\vec{P}$ veqtori da is ganimarteba rogorc elementaruli magnituri momentebis jami moculobis erTeulSi. damagnitebis $\vec{P}$ veqtori axasiaTebs sxeulSi arsebuli mikrodenebis mier Seqmnil magnitur vels.

SI sistemaSi $\vec{B}$ –s erTeulia tesla (tl) – 1 tl=v·wm/m^2, xolo $\vec{H}$ -s amperi metrze (a/m).

vakuumSi $\vec{B}_{vak} = \mu_0 \vec{H}$, sadac proporciulobis μ_0 koeficients vakuumis magnitur Sewevadobas an magnitur mudmivas uwodeben. μ_0 -s sidides adgenen deniani gamtarebis urTierTqmedebis safuZvelze da tolia

$\mu_0 = 4\pi \cdot 10^{-7} \cdot \frac{v \cdot wm}{a \cdot m} = \frac{hn}{m}$, sadac

1 henri=1v·wm/a iduqciurobis erTeulia.

damagnitebis $\vec{P}$ veqtors ***SI*** sistemaSi aqvs $\vec{H}$ -is ganzomileba, amitom veqtori $\vec{B}$, romelic axasiaTebs yvela makro ($\vec{H}$) da mikro ($\vec{P}$) denebis mier Seqmnil jamur vels, ganisazRvreba tolobiT:

$$\vec{B} = \mu_0 (\vec{H} + \vec{P}) \qquad (8.1).$$

e.i. makro da mikrodenebis mier Seqmnili veli calk-calke velebis veqtoruli jamis tolia.

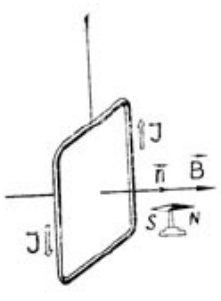
magnituri velis Zaluri maxasiaTeblis gansazRvra SeiZleba sami xerxiT:

a) denian gamtarze moqmedi Zalis saSualebiT (amperis Zala),

b) moZrav muxtze moqmedi Zalis saSualebiT (lorencis Zala)

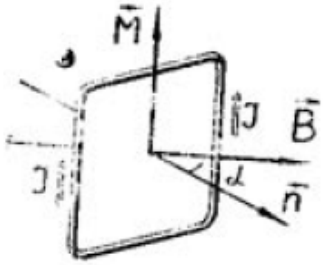
g) denian brtyel konturze (denian CarCoze) moqmedi Zalis momentis saSualebiT (maorientirebeli moqmedebis saSualebiT).

g)–s dros gamoiyeneba metad mcire zomis deniani CarCo, romelSic gamavali deni aseve mcirea. magnituri veli CarCoze maorentirebel moqmedebas da is Semobrundeba (nax. 8.1). am dros magnituri induqciis $\vec{B}$ veqtoris mimarTuleba emTxveva CarCos dadebiTi normalis mimarTulebas, romelic ganisazRvreba marjvena burRis wesiT: Tu burRis



taris brunvis mimarTuleba emTxveva CarCoSi gamavali denis mimarTulebas, maSin burRis gadataniTi moZ-raobis

nax. 8.1 mimarTuleba emTxveva dadebiTi normalis mimarTulebas. magn. isaric daikavebs nax-ze naCveneb mdg-s. e.i. magn. velis mimarTuleba Tanxvdeba magn. isris CrdiloeT polusze moqmedi Zalis mimarTulebas. maSasadame denian CarCoze magn. velSi moqmedebs mabrunebeli momenti $\boldsymbol{M}$. cdebidan dgindeba, rom $\boldsymbol{M}$-is sidide damokidebulia CarCos orientaciaze (kuTxe α CarCos normalsa da magn. induqciis veqtors Soris), masSi gamaval denze da mis FfarTobze (da ara mis formaze). velis mocemul wertilSi sxvadasxva sididis CarCoebze moqmedebs sxvadasxva sididis mabrunebeli momenti, magram fardoba $\frac{\boldsymbol{M}}{\boldsymbol{ISsi\alpha}}$ magn. velis mocemuli wertilisTvis mudmivia da is miCneulia magn. velis induqciad: $\boldsymbol{B=\frac{M}{ISsi\alpha}}$. am formuliT ganisazRvreba $\boldsymbol{B}$-s sidide. aqedan $\boldsymbol{M=IBS}\sin\alpha$.



dadgenilia, rom $\vec{\boldsymbol{M}}$ yovelTvis marTobulia $\vec{\boldsymbol{n}}$ da $\vec{\boldsymbol{B}}$ veqtorebze gamavali sibrtyis da mimarTulia im burRis gadaadgilebis gaswvriv, romlis tarsac vabrunebT $\vec{\boldsymbol{n}}-$dan $\vec{\boldsymbol{B}}$-sken (nax. 8.2). veqtorulad $\vec{\boldsymbol{M}}=\boldsymbol{IS}[\vec{\boldsymbol{n}}_0\vec{\boldsymbol{B}}]=[\boldsymbol{IS}\vec{\boldsymbol{n}}_0\vec{\boldsymbol{B}}]$, sadac $\vec{\boldsymbol{n}}_0$- normalis erTeulovani veqtoria. veqtors $\vec{\boldsymbol{P}}_m=\boldsymbol{IS}\vec{\boldsymbol{n}}_0$, romlis moduli to-

nax. 8.2 lia CarCoSi gamavali denis da CarCos farTobis namravlisa da romelic mimarTulia CarCos dadebiTi normalis gaswvriv, CarCos magnituri momenti ewodeba. e.i. $\vec{\boldsymbol{M}}=[\vec{\boldsymbol{P}}_m\vec{\boldsymbol{B}}]$. maqsimaluri momenti maSin aris Tu $\boldsymbol{\alpha=\frac{\pi}{2}}$ da maSin $\boldsymbol{M_{maks}=IBS}$ da $\boldsymbol{B=\frac{M_{maks}}{IS}}$ (8.2).

aqedan dgindeba $\boldsymbol{SI}$ sistemaSi magn. induqciis erTeuli _ tesla. **tesla (tl) iseTi magn. velis induqciaa, rodesac CarCoze, romlis farTobia 1 m^2 da romelSic gadis 1 a deni, moqmedebs $\boldsymbol{M_{maks}=1}$ n·m mabrunebeli momenti.**

$$1\text{tl}=1\frac{\text{n}\cdot\text{m}}{\text{a}\cdot\text{m}^2}=\mathbf{1}\frac{\text{j}}{\text{a}\cdot\text{m}^2}=\mathbf{1}\frac{\text{v}\cdot\text{wm}}{\text{m}^2}.$$

1 tesla sakmaod didi induqciaa. mag. mZlavri eleqtromagnitebis induqcia 10 teslas rigisaa. dedamiwis magn. velis induqcia magn. polusze aris $0{,}65\cdot10^{-4}$ tesla.

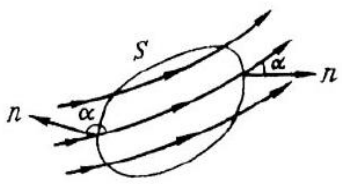
magn. velisTvis, ise rogorc el. velisTvis marTebulia superpoziis (zeddebis) principi: ramodenime denis mier Seqmnili magnituri veli ($\vec{\boldsymbol{B}}$) calkeuli denebis mier Seqmnili magnituri velebis ($\vec{\boldsymbol{B}}_i$) veqtoruli jamis tolia:

$$\vec{\boldsymbol{B}}=\vec{\boldsymbol{B}}_1+\vec{\boldsymbol{B}}_2+.....\vec{\boldsymbol{B}}_n=\sum_{i=1}^{n}\vec{\boldsymbol{B}}_i \quad (8.3)$$

$2. magnituri induqciis nakadi. magnituri velis grigaluri xasiaTi.

magnituri veli iseve rogorc el. veli Zaluri velia da grafikulad gamoisaxeba magnituri Zalwiris (iseTi wiri, romlis yovel wertilSi gavlebul mxebs aqvs am wertilSi arsebuli magn. induqciis veqtoris mimarTuleba) saSualebiT. wirebs avleben iseTi sixSiriT, rom wirebisadmi marTobul farTobis erTeulSi gamavali wirebis raodenoba toli iyos magn. induqciis veqtoris mniSvnelobisa am wertilSi.

raime farTobis gamWol magn. induqciis wirebis raodenobas, magnituri induqciis nakadi ewodeba. radgan wirebisadmi marTobul erTeulovan farTobs ganWolavs $\boldsymbol{B}$ – raodenoba, maSin raime elementarul $\boldsymbol{dS_0}$ farTobSi magn. induqciis nakadi iqneba $d\boldsymbol{\Phi_0 = BdS_0}$. Tu zedapiri ar aris marTobuli, maSin nakadi $d\Phi = \boldsymbol{BdS}\cos\boldsymbol{\alpha}$, sadac $\boldsymbol{\alpha}$ kuTxea



$\vec{B}$ – sa dS zedapiris $\vec{n}$ normals Soris. radgan $B\cos\alpha = B_n$ (es aris $\vec{B}$ – s gegmili $\vec{n}$ normalis mimarTulebaze), amitom $d\Phi = B_n dS$ da sruli nakadi sasrul S farTobSi toli iqneba: $\Phi = \int_S d\Phi = \int_S B_n dS = \int_S (\vec{B}\cdot d\vec{S})$. Tu veli erTgvarovania, maSin $B_n = const$ da $\Phi = B_n S$.

magn. induqciis nakadis erTeuli SI sistemaSi aris veberi (vb). 1 veberi iseTi magn. nakadia, romelic ganWolavs 1 m^2 farTobis marTobul zedapirs 1 tesla magnituri velis induqciis dros. Tu S zedapiri Caketilia, maSin nakadi nulis tolia. marTlac zedapiridan gamosuli nakadi yovelTvis dadebiTia ($\alpha < \frac{\pi}{2}$, $\cos\alpha > 0$), xolo zedapirSi Sesuli ki uaryofiTi ($\alpha > \frac{\pi}{2}$, $\cos\alpha < 0$. magnituri induqciis wirebis Caketilobis gamo es nakadebi sididiT erTmaneTis tolia, amitom maTi jami, anu sruli nakadi nulis tolia:

$$\oint_S B_n dS = \oint_S (\vec{B}d\vec{S}) = 0 \qquad (8.4).$$

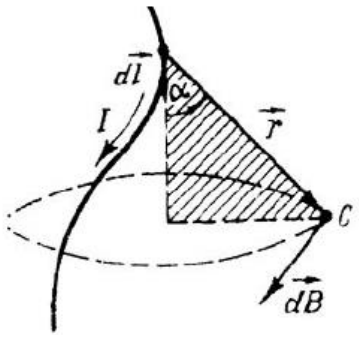
es toloba gamosaxavs gaus-ostrogradskis Teoremas magn. induqciis nakadisTvis da gamoxatavs im faqts, rom magn. veli grigaluri velia, anu bunebaSi ar arsebobs magn. muxtebi, romelzedac daiwyeboda an damTavrdeboda magn. induqciis wirebi. magnituri veli gansxvavebiT eleqtruli velisagan, romlis Zalwirebi ar arian Caketili (aqvT dasawyisi da dasasruli – potencialuri velia), grigaluri (arapotenciuri) velia, riTac is gansxvavdeba el. velisgan, romlis daZabulobis veqtoris cirkulacia nebismieri Caketili wiris gaswvriv nulis tolia $\oint_l E_l dl = 0$, xolo magnituri velisa ki $Z = \oint_l (\vec{B}\cdot d\vec{l}) = \mu_0 \sum_{i=1}^{n} I_i$. es formula gamoxatavs sruli denis kanons magnituri velisTvis vakuumSi: magn. velis induqciis veqtoris cirkulacia Caketili konturis gaswvriv tolia magnituri mudmivas namravlisa im denebis algebrul jamze, romelsac es konturi moicavs.

IX leqcia

bio-savar-laplasis kanoni. sasruli, usasrulo sigrZis wrfivi deni, wriuli denis da solenoidis magnituri velis induqcia.

$1. bio-savar-laplasis kanoni.

kanonis arsi imaSia, rom vipovoT raime deniani gamtaris mier Seqmnili magnituri velis induqcia misgan raime manZilze. amisTvis saWiroa deniani gamtari davyoT denis usasrulo mcire elementebad, vipovoT TviToeli elementis mier mocemul wertilSi Seqmnili magn. velis induqcia da Sedegebi Semdeg veqtorulad SevkriboT. es kanoni mdg-s SemdegSi: elementaruli dB induqcia magn. velisa, romelsac qmnis I denis dl elementi (Idl-s denis elementi ewodeba, veqtoria da aqvs denis mimarTuleba) misgan r manZilze gamoiTvleba formuliT (nax. 9.1):



$$dB = k\frac{Idl\sin\alpha}{r^2} \qquad (9.1)$$

sadac α kuTxea Idl elementsa da $\vec{r}$ radius veqtors Soris, k proporciulobis koeficientia. $d\vec{B}$ –yovelTvis marTobia $Id\vec{l}$ da $\vec{r}$ veqtorebze gamavali sibrtyis da mimarTulia burRis gaswvriv Tu burRis tars vabrunebT $Id\vec{l}$ -dan $\vec{r}$ -sken.

nax. 9.1

veqtorulad (9.1) formulas aseTi saxe eqneba

$$d\vec{B} = k\frac{\left[Id\vec{l}\cdot\vec{r}\right]}{r^3} \qquad (9.2).$$

superpoziciis principis Tanaxmad mTeli deniani gamtaris mier Seqmnili magn. velis induqcia velis mocemul wertilSi tolia calkeuli $d\vec{B}$ veqtorebis geometriuli jamisa anu

$$\vec{B} = \sum_{i=1}^{n} d\vec{B}_i \qquad (9.3).$$

Tu yvela $d\vec{B}$ erTnairadaa mimarTuli, maSin jami icvleba integraliT $l-$is gaswvriv

$$B = \int_l dB = kI \int_l \frac{\sin\alpha dl}{r^2} \qquad (9.4).$$

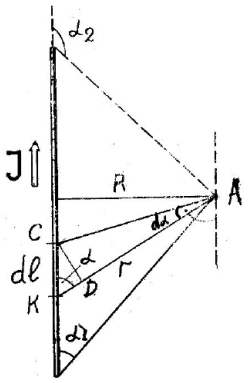
SI sistemaSi $k = \frac{\mu_0}{4\pi}$, sadac $\mu_0 = 4\pi \cdot 10^{-7}$ hn/m aris magnituri mudmiva da gveqneba

$$dB = \frac{\mu_0}{4\pi} \frac{Idl \sin\alpha}{r^2} \quad \text{da} \quad B = \frac{\mu_0 I}{4\pi} \int_l \frac{\sin\alpha dl}{r^2} \qquad (9.5).$$

$2. sasruli, usasrulo sigrZis wrfivi denis, wriuli denis da solenoidis magnituri velis induqcia.

(9.5) formulis gamoyenebiT SegviZlia gamovTvaloT induqciebi:

1) **sasruli sigrZis wrfivi deniani gamtarisTvis** misgan raime R manZilze. vTqvaT am gamtarSi gadis I deni. davyoT gamtari mcire dl elementebad da vipovoT TviToelis mier Seqmnili induqcia A wertilSi da miRebuli Sedegebi SevkriboT. am dros yvela $d\vec{B}$ veqtori mimarTulia erTnairad – naxazis sibrtyis marTobulad Cvengan, amitom SeiZleba maTi algebruli Sekreba. (nax. 9..2). viciT $B = \frac{\mu_0 I}{4\pi} \int_l \frac{\sin\alpha dl}{r^2}$. davideT erT cvladze. dl monakveTis bolo C wertilidan davuSvaT CD marTobi $\vec{r}$ radius-veqtorze. naxazidan $CD = rd\alpha = dl \sin\alpha$ ($dl-$is simciris gami, SeiZleba CavTvaloT, rom $CA \approx r$). aqedan $\frac{dl}{r^2} = \frac{d\alpha}{r \sin\alpha}$. radgan $r \sin\alpha = R$, amitom



nax. 9.2

$$\frac{dl}{r^2} = \frac{d\alpha}{R}$$ da sigrZiT integreba SevcvaloT kuTxis integrebiT,

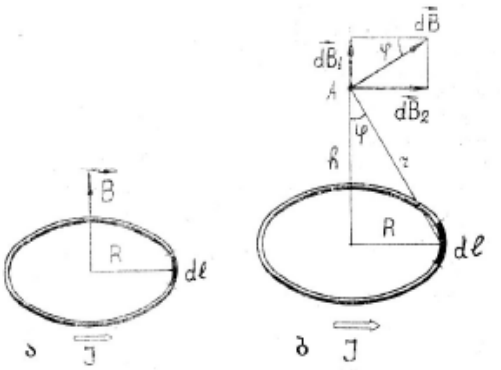
$$B = \frac{\mu_0 I}{4\pi} \int_{\alpha_1}^{\alpha_2} \frac{\sin\alpha d\alpha}{R} = \frac{\mu_0 I}{4\pi R} \int_{\alpha_1}^{\alpha_2} \sin\alpha d\alpha = -\frac{\mu_0 I}{4\pi R}(\cos\alpha_2 - \cos\alpha_1) = \frac{\mu_0 I}{4\pi R}(\cos\alpha_1 - \cos\alpha_2). \qquad (9.6)$$

am formulidan SeiZleba mag. kvadratis formis gamtarisTvis mis centrSi induqciis gansazRvra da is tolia $B = \frac{\mu_0 I}{\pi a} 2\sqrt{2}$, sadac a kvadratis gverdia.

2) usasrulo sigrZis deniani gamtarisTvis (9.6) formulaSi $\alpha_1 = 0, \alpha_2 = 180^0$, $\cos\alpha_1 - \cos\alpha_2 = [1-(-1)] = 2$ da $B = \frac{\mu_0 I}{2\pi R}$. es formula gamosadegia sakmaod grZeli wrfivi denis magn. induqciis gamosaTvlelad, Tu gamtaris l sigrZe gacilebiT metia R manZilze.

3) R radiusiani wriuli deniani gamtarisTvis :

a) wriuli denis centrSi (nax. 9.3 a). am dros yvela $d\vec{B}$ mimarTulia wriuli denis sibrtyis marTobulad qvevidan



zeviT-erT mxares. amitom $B = \frac{\mu_0 I}{4\pi}\int_l \frac{\sin\alpha}{r^2}dl$ (9.7)

amasTan yvela dl elementisTvis $r = R$, $\sin\alpha = 1$ $r = R$, $\sin\alpha = 1$ da formulidan gamodis

$$B = \frac{\mu_0 I}{4\pi R^2}\int_l dl = \frac{\mu_0 I}{4\pi R^2}\cdot 2\pi R = \frac{\mu_0 I}{2R} \qquad (9.8).$$

nax. 9.3

aqac induqcia pirdapirproporciulia gamtarSi gamavali denisa da ukuproporciulia am gamtaridan manZilisa.

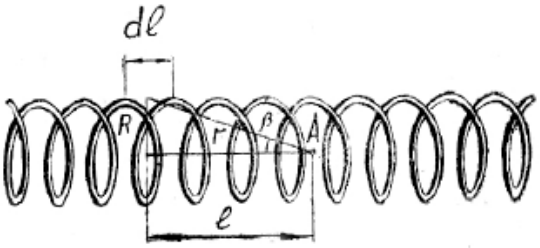
b) wriuli denis RerZze centridan h manZiliT daSorebul A wertilSi (nax. 9.3 b) gamoTvlebiT miRebulia rom,

$$B = \frac{\mu_0 R^2 I}{2(R^2 + h^2)^{3/2}} \qquad (9.9).$$

$\vec{B}$ mimarTulia wriuli denis RerZis gaswvriv. centrisTvis $h = 0$ da (9.8) formula gadadis (9.8)-Si.

4) solenoidisTvis.

solenoidi aris wrfivi RerZis mqone wriuli denebis erToblioba, amitom induqcia mis RerZze toli iqneba calkeuli wriuli denebis induqciaTa jamisa. gamoviyvanoT induqciis gamosaTvleli formula grZeli solenoidis RerZze. amisTvis gamovyoT solenoidis mcire dl elementi (nax. 9.4). igi Seicavs ndl xvias, sadac n xviaTa ricxvia solenoidis sigrZis erTeulze. solenoidis TiToeul xviaSi gadis I deni da TiToeuli elementi SeiZleba ganvixiloT rogorc wriuli gamtari, romelSic gadis $Indl$ deni. maSin (9.9) –s Tanaxmad am wriuli denis mier



nax. 9.4

Seqmnili magnituri velis induqcia l manZiliT daSorebul A wertilSi toli iqneba $dB = \frac{\mu_0 R^2 Indl}{2(R^2 + l^2)^{3/2}}$ (9.10)

yvela elementis mier Seqmnili magnituri velis induqcia A wertilSi erTnairadaa mimarTuli (RerZis gaswvriv) da amitom jamuri induqcia miiReba (9.9)-s integrebiT:

$$B = \int_l dB = \frac{\mu_0 R^2 In}{2}\int_l \frac{dl}{(R^2 + l^2)^{3/2}}. \qquad (9.11)$$

dl da $R^2 + l^2$ cvladebi gamovsaxoT erTi damoukidebli cvladiT. A wertilidan mocemul elementamde gavavloT $\vec{r}$ radius veqtori. kuTxe $\vec{r}$-sa da solenoidis RerZs Soris iyos β. naxazidan $l = Rctg\beta$ da aqedan $dl = \frac{Rd\beta}{\sin^2\beta}$. aseve $R^2 + l^2 = R^2(1 + ctg^2\beta) = \frac{R^2}{\sin^2\beta}$. SevitanoT dl da $R^2 + l^2$ (9.9-Si) da sigrZiT integreba SevcvaloT kuTxiT integrebiT. maSin

$$B = \frac{\mu_0 R^2 nl}{2}\int_{\beta_1}^{\beta_2}\frac{\frac{R}{\sin^2\beta}}{(\frac{R^2}{\sin^2\beta})^{3/2}}d\beta = \frac{\mu_0 nl}{2}\int_{\beta_1}^{\beta_2}\sin\beta d\beta = \frac{1}{2}\mu_0 nI(\cos\beta_1 - \cos\beta_2). \quad (9.12)$$

aq β_1 da β_2 solenoidis kidura elementebis Sesabamisi kuTxeebia, aTvlili RerZis imave mimarTulebiT. Tu solenoidi grZelia, maSin $\beta_1 = 0$ da $\beta_2 = \pi$ da

$$B = \mu_0 nI . \quad (9.13)$$

solenoidi MmaSin iTvleba usasrulod grZelad, rodesac solenoidis L sigrZe gacilebiT metia xviis R radiusze.

gamoTvlebiT miRebulia, rom sasruli sigrZis solenoidisTvis induqcia naklebia, vidre usasrulo sigrZis da am dros maqsimaluri induqcia solenoidis Sua wertilisTvis $B = \mu_0 nL\sqrt{4R^2 + L^2}$ (9.13)

radgan $B_0 = \mu_0 H$, maSin gveqneba:

bio-savar-laplasis kanoni:

$$dH = \frac{1}{4\pi}\frac{Idl\sin\alpha}{r^2} \quad (9.14)$$

usasrulo wrfivi denis magnituri veli;

$$H = \frac{I}{2\pi R} \quad (9.15)$$

wriuli denis magnituri veli centrSi:

$$H = \frac{I}{2R}.$$

e.i. magnituri velis daZabulobis ganzomileba tolia denis ganzomilebis gayofisa sigrZis ganzomilebaze, anu **amperi metrze (a/m).** Tu $I = 1$a da $R = \frac{1}{2\pi}$, maSin $H =$a/m, anu amperi metrze aris iseTi magnituri velis daZabuloba, romelsac qmnis usasrulo wrfivi gamtari, romelSic gadis 1 a deni misgan $\frac{1}{2\pi}$ manZilze.

X leqcia

magnituri velis moqmedeba denian gamtarze. amperis formula. denebis urTierTqmedeba. magnituri velis moqmedeba moZrav muxtze. lorencis Zala.

$1. magnituri velis moqmedeba denian gamtarze. amperis formula. denebis urTierTqmedeba.

amperma eqsperimentulad daadgina, rom F Zala, romliTac erTgvarovani magnituri veli moqmedebs wrfiv denian gamtarze, damokidebulia magn. velis induqciaze (B), gamtaris sigrZeze (l), masSi gamaval denze (I) da gamtaris orientaciaze magnitur velSi velSi. es damokidebuleba mocemulia amperis formuliT: $F = kIBl\sin\alpha$, sadac α aris kuTxe $\vec{B}$-sa da denis mimarTulebas Soris. SI sistemaSi proporciulobis koeficienti $k = 1$ da

$$F = IBl\sin\alpha \qquad (10.1)$$

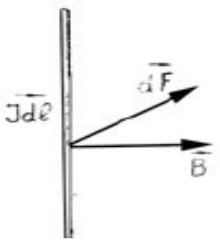
Tu $\alpha = \frac{\pi}{2}$ (deniani gamtari moTavsebulia $\vec{B}-$s marTobulad) , maSin Zala maqsimaluria da $F = F_{maks} = IBl$. Tu $\alpha = 0$ (moTavsemulia $\vec{B}-$s paralelurad), maSin $F = 0$.

Tu veli araerTgvarovania, xolo gamtari nebismieri formisaa, maSin gamtari iyofa mcire dl elementebad (SeiZleba CavTvaloT wrfivad da veli mis maxloblobaSi erTgvarovnad) da masze moqmedi Zala

$$dF = IdlB\sin\alpha \qquad (10.2)$$

sadac α kuTxea $Id\vec{l}$ denis elementsa da $\vec{B}-$s Soris.

amperis Zalis mimarTuleba ganisazRvreba a) **marcxena xelis wesiT**: Tu marcxena xels gavSliT ise, rom magnituri induqciis wirebi Sediodes xelis gulSi, xolo oTxi gaSlili TiTi emTxveodes denis mimarTulebas, maSin marTi kuTxiT gaSlili ceri emTxveva denze moqmedi Zalis mimarTulebas. b) **universaluri** – burRis wesi: Tu burRis saxelurs vabrunebT $Id\vec{l}$ eqtoridan $\vec{B}$ Bveqtorisken, maSin burRis gadataniTi moZraoba gviCvenebs $d\vec{F}-$is mimarTulebas (nax. 10.1).



nax. 10.1

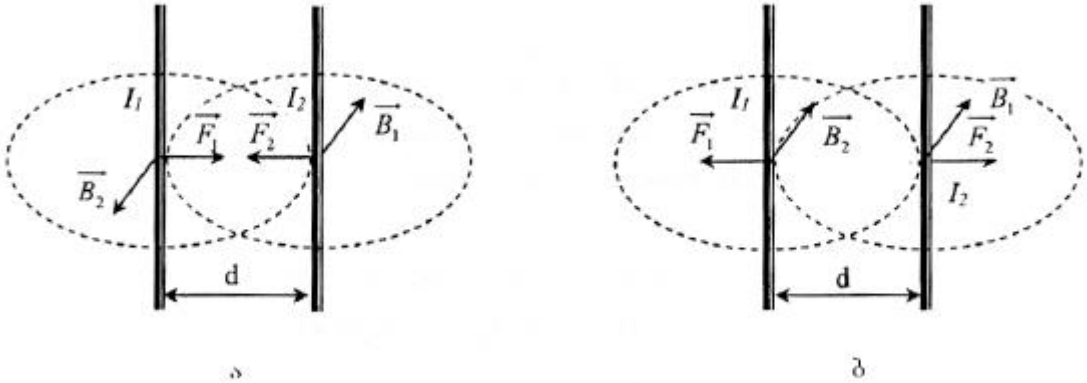
veqtorulad (10.2) formula ase Caiwereba:

$$d\vec{F} = \left[Id\vec{l}\cdot\vec{B}\right] \qquad (10.3)$$

magnituri velis es moqmedeba denian gamtarze gamoiyeneba mag. EleqtroZravebSi, aseve is safuZvlad udevs eleqtrosazomi xelsawyoebis mowyobilobas.

deniani gamtarebi erTmaneTze moqmedeben. es gamowveulia TviToeli denis magnituri velis moqmedebiT meoreze. nax. 10.2 –ze (a b) naCvenebia is SemT-va,

rodesac sakmaod grZeli deniani gamtarebi (gadis I_1 da I_2 denebi) erTmaneTis paraleluri da antiparaleluria. TviToeli gamtaris sigrZe iyos l, xolo d maT Soris manZili.



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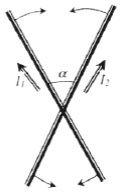


nax. 10.2

rodesac denebi paraleluria (a) am dros burRis wesiT vadgenT, rom I_1 denis magnituri velis induqciis veqtori ($\vec{B}_1$) I_2 denis areSi mimarTulia suraTis sibrtyis marTobulad Cvengan da sididiT tolia $B_1 = \frac{\mu_0 I_1}{2\pi d}$. (sasruli sigrZis wrfivi denis magnituri velis induqcia bio-savar-laplasis kanonis Tanaxmad). amperis kanonis Tanaxmad B_1 induqciis magn. veli l sigrZis I_2 denian gamtarze imoqmedebs ZaliT:

$$(\alpha = \frac{\pi}{2}) \quad F_2 = I_2 B_1 l = \frac{\mu_0 I_1 I_2}{2\pi d} l. \qquad (10.4)$$

marcxena xelis wesis Tanaxmad am $\vec{F}_2$ Zalas aqvs suraTze naCvenebi mimarTuleba (pirveli gamtarisken). analogiuri msjelobiT Zala romliTac meore I_2 deniani gamtaris mier Seqmnili magnituri veli $B_2 = \frac{\mu_0 I_2}{2\pi d}$ imoqmedebs I_1-denian gamtarze F_1 ZaliT, romelic tolia: $F_1 = I_1 B_2 l = \frac{\mu_0 I_1 I_2}{2\pi d} l$. es Zala sididiT tolia F_2 Zalis da mimarTulia mis sapirispirod $\vec{F}_1 = -\vec{F}_2$. e.i. paraleluri denebi erTmaneTs miizidaven. analogiurad dgindeba, rom antiparaleluri denebi ganizidaven imave sididis ZaliT. e.i. mizidvis da ganzidvis Zalebis sidide erTnairia da tolia

$$F = \frac{\mu_0 I_1 I_2}{2\pi d}. \qquad (10.5).$$

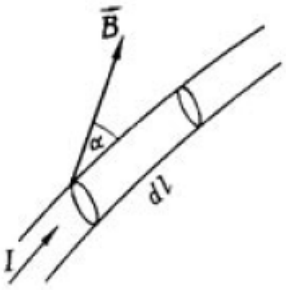
dadgenilia, rom Tu deniani gamtarebi erTmaneTs gadakveTen raRac α kuTxiT (nax. 10.3), maSin maT Soris aRiZvreba magnituri urTierTqmedebis Zalebi, romlebic cdiloben Semoabrunon gamtarebi da daayenon erTmaneTis paralelurad, ise rom orive gamtarSi erTi mimarTulebis deni gadiodes.

(10.5)-dan da denis Zalis SI sistemaSi amperis ganmartebidan gamodis, rom magnituri mudmivas ricxviT mn-ba tolia ($I_1 = I_2 =$1a), $l =$1 m, $d =$1 m, $F = 2 \cdot 10^{-7}$ n) $\mu_0 = \frac{F \cdot 2\pi d}{I_1 I_2 l} = 4\pi \cdot 10^{-7} \frac{\text{hn}}{\text{m}}$. (10.6)

nax. 10.3

$2. magnituri velis moqmedeba moZrav muxtze. lorencis Zala.

amperis kanonis Tanaxmad magnituri veli garkveuli ZaliT moqmedebs denian gamtarze, xolo deni es aris muxtebis mowesrigebuli moZraoba. e.i. magn. veli raRac ZaliT moqmedebs moZrav muxtze da am Zalas **lorencis** Zala ewodeba. cnobilia B induqciis magn. veli I denis dl elementze moqmedebs amperis ZaliT $dF = IdlB\sin\alpha$, sadac α kuTxea $Id\vec{l}$ denis elementsa da $\vec{B}-$s Soris (nax. 10.4). denis Zala $I = n_0 qSv$ ($n_0 -$.damuxtuli nawilakebis koncentraciaa, $q-$elementaruli nawilakis muxti, $S-$gamtaris



ganivkveTis farTobi da $v-$damuxtuli nawilakebis mimarTuli moZraobis siCqare). amitom $dF = n_0 qvSBdl\sin\alpha$. es aris I denis dl elementze, anu Sdl moculobaSi yvela muxtze, romelTa raodenoba $dN = n_0 Sdl$, moqmedi nax. 10.4 Zala. es muxtebi mowesrigebulad moZraoben erTaniri v siCqariT. amitom erT muxtze moqmedi Zala (lorencis Zala) toli iqneba:

$$F_L = \frac{dF}{dN} = \frac{n_0 qvSBdl\sin\alpha}{n_0 Sdl} = qvB\sin\alpha \quad (10.7)$$

aq ukve α kuTxea $\vec{v}$ da $\vec{B}-$s Soris. lorencis Zalis mimarTulebac ganisazRvreba marcxena xelis an burRis wesiT. veqtorulad $\vec{F}_L = q[\vec{v}\vec{B}]$. radgan denis mimarTuleba dadebiTi muxtebis moZraobis mimarTulebaa, amitom lorencis Zalis mimarTuleba emTxveva $[\vec{v}\vec{B}]-$s mimarTulebas (marcxena xelis wesiT) maSin, roca $q > 0$ da roca $q < 0$, maSin $[\vec{B}\vec{v}]-$s mimarTulebas.

Tu $\alpha = 0$, anu nawilaki moZraobs velis ($\vec{B}$ – s) paralelurad, maSin $F_L = 0$. roca $\alpha = \frac{\pi}{2}$ anu nawilaki moZraobs velis marTobulad, maSin $F_L = F_{mals} = qvB$ – Zala maqsimaluria.

radgan lorencis Zala marTobulia nawilakis siCqaris, amitom misi muSaoba nulis tolia, ar cvlis mis siCqaris sidides da Sesabamisad mis energias. is cvlis mxolod siCqaris mimarTulebas, anu warmoadgens centriskenul Zalas $F = \frac{mv^2}{R}$,

sadac R –traeqtoriis simrudis radiusia. meore mxriv rodesac $\alpha = \frac{\pi}{2}$, $F_L = qvB$.

aqedan $qvB = \frac{mv^2}{R}$ da

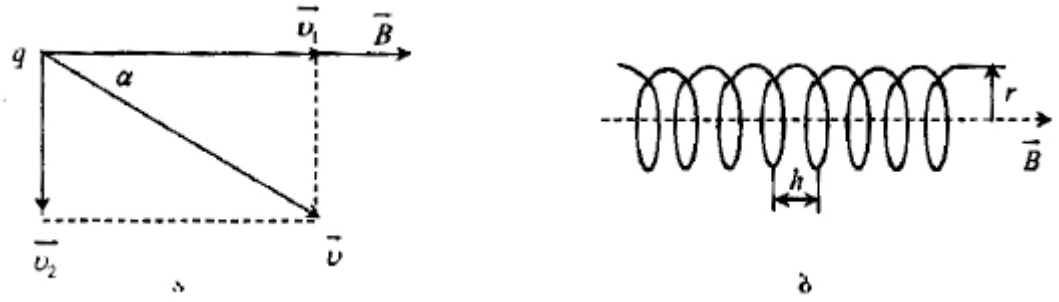
$$R = \frac{mv}{qB} \qquad (10.8).$$

e.i. am Zalis gavleniT nawilaki moZraobs wrewirze. Sesabamisad brunvis periodi, anu dro romlis ganmavlobaSic damuxtuli nawilaki Semowers R – radiusian wrewirs, tolia $T = \frac{2\pi R}{v} = \frac{2\pi m}{qB}$

(10.9)

e.i. is ar aris damokidebuli nawilakis siCqareze (wrewiris radiusze) da ganisazaRvreba mxolod magnituri velis B induqciiT. es safuZvlad udevs damuxtuli nawilakis cikluri amaCqareblis – ciklotronis muSaobas.

vTqvaT damuxtuli nawilaki moZraobs erTgvarovan magn. velSi, ise rom misi siCqaris veqtori adgendes magn. induqciis veqtorTan raime maxvil α kuTxes (nax. 10.5). siCqaris veqtori davSaloT or v_1 velis paralelur da v_2 velis marTobul



nax. 10.5

$v_1 = v\cos\alpha$; $v_2 = v\sin\alpha$ mdgelad. pirvel mdgenelze magnituri veli ar moqmedebs, xolo meores ucvlis mimarTulebas. am dros nawilaki moZraobs erTdroulad or moZraobaSi: igi Tanabrad brunavs v_2 siCqariT wrewirze, romlis radiusi

$$R = \frac{mv_2}{qB} = \frac{mv\sin\alpha}{qB} \qquad (10.9)$$

da gadaadgildeba magn. velis gaswvriv (brunvis sibrtyis marTobulad) Tanabrad v_1 siCqariT. Sedegad nawilaki imoZravebs xraxnul wirze, romlis RerZi Tanxvdeba magn. velis induqciis wirs (b). radiusi ganisazRvreba (10.8) formuliT, xolo xraxnis biji $$h = v_1 T = v \frac{2\pi m}{qB} \cos\alpha \quad (10.10).$$

Tu nawilakze erTdroulad moqmedebs eleqtruli $F = qE$ da magnituri Zala, maSin jamuri Zala tolia maTi veqtoruli jamis:

$$\vec{F} = q\vec{E} + q[\vec{v}\vec{B}] = q(\vec{E} + [\vec{v}\vec{B}]) \quad (10.11)$$HGGGFGF

A am Zalas lorencis ganzogadoebuli Zalsa ewodeba.MA

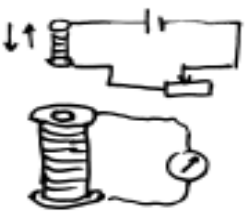
XI leqcia

eleqtromagnituri induqciis movlena. faradeis cdebi. lencis wesi. induqciis em Zala. faradeis kanoni. induqciis em Zalis aRZvris meqanizmi.

$1. eleqtromagnituri induqciis movlena. faradeis cdebi. lencis wesi. induqciis em Zala. faradeis kanoni.

elექტრული Ddeni Tavis garSemo qmnis magnitur vels. 1831 w. faradeim aRmoaCina sapirispiro (eleqtromagnituri induqciis) movlena, romelic SemdegSi mdg-s: **nebismier Sekrul (Caketil) konturSi konturis gamWoli magn. nakadis cvlilebisas, am konturSi aRiZvreba em Zala (induqciis), romelic iarsebebs manam, sanam es nakadi icvleba. Sesabamisad Caketil konturSi aRiZvreba induqciuri deni.** faradeim aCvena, rom garkveul pirobebSi magnituri velic qmnis eleqtrul dens. swored es aris eleqtromagnituri induqciis movlena.Ffaradeis klasikuri cdebi SemdegSia: 1) Tu Sekrul konturSi (solenoidi), sadac CarTulia galvanometri, SevitanT an gamovitanT mudmiv magnits (nax. 11.1), maSin Setanis an gamotanis momentSi konturSi aRiZvreba induqciuri deni, romlis mimarTuleba damokidebulia magnitis Setanis an gamotanis mimarTulebaze. es deni miT ufro metia, rac metia magnitis moZraobis siCqare. Tu magniti koWas mimarT uZravia, maSin isari ar ixreba, anu ucvleli

nax. 11.1 magnituri nakadi koWaSi induqciis em Zalas ar aRZravs. SeiZleba piriqiT magniti iyos uZravi, xolo solenoidi vamoZraoT. e.i. roca magniti Segvaqvs koWaSi gamWoli magn. nakadi izrdeba da piriqiT. Tu magniti gaCerebulia, maSin koWas magn. nakadi ar ganWolavs da deni ar aRiZvreba.

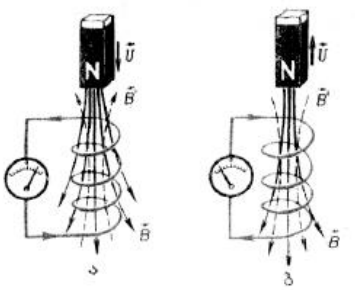


2) galvanometris isari gadaixreba maSinac, rodesac patara koWaSi irTveba an ganirTveba deni, an rodesac pataraSi icvleba deni (nax. 11.2). Aaqac denis mimarTuleba sxvadasxva Sem-Si sxvadasxvaa. Ee.i. induqciuri deni aRiZvreba yovelTvis, rodesac icvleba koWas gamWoli magnituri nakadi. Aam denis sidide ar aris damokidebuli

nax. 11.2 nakadis cvlilebis cvlilebis siCqareze. F

faradeim daadgina, rom induqciis em Zalis sidide konturiT SemosazRvrul farTobSi magnituri nakadis cvlilebis siCqaris tolia: $\varepsilon_i = \left|\frac{d\Phi}{dt}\right|$. amas faradeis kanoni ewodeba. davadginoT induqciuri denis

mimarTuleba. es daadgina lencma: **induqciur dens yovelTvis iseTi mimarTuleba aqvs, rom misi magn. veli ewinaaRmdegeba denis aRmZvreli magn. velis cvlilebas. M**marTlac rodesac magniti Crdilo polusiT Segvaqvs xviaSi (e.i. vzrdiT xviis gamWol nakads

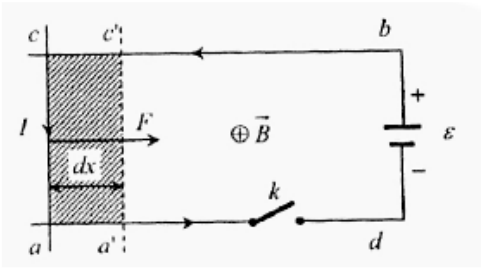


nax. 11.3

($\frac{d\Phi}{dt}>0$) (nax.. 11.3 a), maSin xviaSi aRiZvreba iseTi mimarTulebis deni, rom magnitisadmi xviis uaxloes boloze gaCndeba CrdiloeT polusi, romelic ewinaaRmdegegeba magnitis Semdgom miaxloebas. marjvena burRis wesis Tanaxmad denis mier aRZruli magn. velis induqciis veqtori $\vec{B}'$ mimarTuli iqneba $\vec{B}$ -s sapirispirod, xolo dens eqneba saaTis isris sawinaaRmdego mimarTuleba ($\varepsilon_i < 0$) da is Seamcirebs $\vec{B}$ -s. piriqiT Tu magniti gamogvaqvs, anu vamcirebT gamWol nakads ($\frac{d\Phi}{dt}<0$) **(**nax. 11. 3b**)**, dens eqneba **saaTis isris mimarTuleba ($\varepsilon_i > 0$) da** $\vec{B}'$ gaaZlierebs $\vec{B}$ -s. anu $\frac{d\Phi}{dt}$ -s da ε_i -s aqvT sawinaaRmdego niSnebi. saboolod gveqneba

$$\varepsilon_i = -\frac{d\Phi}{dt} \qquad (11.1).$$

es formula aerTianebs faradeis da lencis kanonebs da warmoadgens eleqtromagnituri induqciis ZiriTad kanons: **induqciis em Zala Caketil konturSi sididiT tolia da niSniT sapirispiro magnituri nakadis cvlilebis siCqarisa konturiT SemosazRvrul farTobSi. A**am formulidan dgindeba magn. induqciis nakadis erTeuli veberi (vb). **1 veberi iseTi magnituri nakadia, rodesac misi cvlilebisas konturSi 1 wm-Si aRiZvreba 1 volti induqciis em Zala.**



nax. 11.4

$\varepsilon_i = -\frac{d\Phi}{dt}$ formula miiRo helholcma (germaneli) energiis mudmivobis kanonis safuZvelze. vTqvaT mocemulia ***abcd*** Caketili konturi, romlis erTi ***ac*** gverdi moZravia (nax. 11.4). rodesac konturi ar aris magnitur velSi, maSin masSi denis gavlisas denis wyaros muSaoba $dA = Ia\Phi dt$ ***dt*** droSi xmardeba gamtaris gaTbobas–joul-lencis siTbos gamoyofas $dQ = I^2 Rdt$ da energiis mudmivobidan $dA = dQ$. anu $Ia\Phi dt = I^2 Rdt$ da $I = \frac{\varepsilon}{R}$, sadac $R-$ sruli winaRobaa (omis kanoni Caketili wredisaTvis). rodesac konturi moTavsebulia mag. velSi ($\vec{B}-$ mimarTulia konturis sibrtyis marTobulad Cvengan), maSin konturis ***ac*** moZrav gverdze imoqmedebs amperis Zala da is gadaadgildeba marjvniv ***dx*** manZilze da daikavebs $a'c'$ mdg-s. am dros mis gadaadgilebaze Sesrulebuli muSaoba $dA' = Fdx = BIacdx = BIdS = Id\phi\ (\alpha = 90^0)$, radgan $dS = ac \cdot dx$ aris gamtaris gadaadgilebisas mis mier Semowerili farTobi, xolo $d\Phi = BdS$ am farTobis gamWoli magnituri nakadi. e.i. am dros wyaros mier Sesrulebuli muSaobis nawili xmardeba gamtarebis

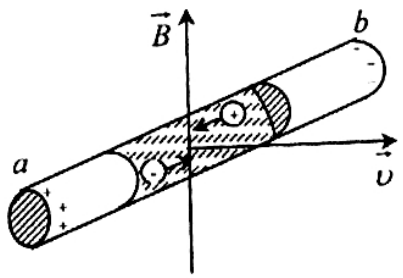
gaTbobas, xolo nawili gamtaris gadaadgilebaze dA' muSaobas, anu $dA = dQ + dA'$, an $Id\phi = I^2Rdt + Id\phi$

da $I = \frac{\varepsilon - \frac{d\phi}{dt}}{R}$ - Caketili wredis omis kanoni. aq aris axali wevri "$-\frac{d\phi}{dt}$" da swored es aris induqciis emZ $\varepsilon_i = -\frac{d\phi}{dt}$.

(11.1) formulaSi niSani "–" lencis wess gamoxatavs. rogorc avRniSneT rodesac $\frac{d\Phi}{dt}$ – nakadi izrdeba, aRZruli induqciis em Zala uaryofiTia ($\varepsilon_i < 0$) da konturSi iseTi deni gaivlis, romlis magnituri veli Sesasustebs (akompensirebs) am nakadis zrdas da piriqiT.

$2. induqciis em Zalis aRZvris meqanizmi.

misi aRZvra xdeba or Sem-Si



1. **rodesac gamtari moZraobs Zalwirebis marTobul mudmiv magnitur. velSi.** vTqvaT l sigrZis liTonis ab Rero moZraobs ox RerZis gaswvriv v siCqariT oz RerZis gaswvriv mimarTul mudmiv

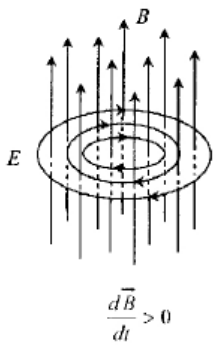
$\vec{B}$ induqciis magn. velSi (nax. 11.5). gamtarSi bmul dadebiT ionebze (romlebic moTavsemuli arian mesris kvanZebSi da uZravni arian) da Tavisufal qaosurad moZrav eleqtronebze, romlebic gamtarTan erTad

nax. 11. 5 moZraoben $\boldsymbol{v}$ siCqariT imoqmedebs lorencis Zala (mxolod eleqtronebze) $\vec{F}_L = q\left[\vec{v}\vec{B}\right]$, amis gamo eleqtronebi amoZravdebian $\boldsymbol{a}-$dan $\boldsymbol{b}-$sken, anu $\boldsymbol{b}$ boloze iqneba maTi siWarbe, xolo $\boldsymbol{a}-$ze maTi nakleboba, anu dadebiTi muxtebis siWarbe. es ki iwvevs gamtaris boloebs Soris potencialTa sxvaobis warmoqmnas (induqciis em Zala). mas ase gamovTvliT: muxtebis gancalkeveba gamtarSi qmnis $\boldsymbol{a}-$dan $\boldsymbol{b}-$sken mimarTul el. vels, romlis daZabuloba $\boldsymbol{E = \frac{\varphi_a - \varphi_b}{l}}$. amitom TiToeul eleqtronze imoqmedebs lorencis Zalis sapirispiro $\vec{F} = q\vec{E}$ el. Zala da rodesac es Zalebi erTmaneTs gautoldebian, myardeba wonasworoba, anu $q\vec{E} = q\left[\vec{v}\vec{B}\right]$ da $\vec{E} = \left[\vec{v}\vec{B}\right]$, an sididiT $E = vB$ $(\alpha = 90^0)$. am dros, radgan lorencis Zala muxtebs amoZravebs el. Zalis sawinaaRmdegod, aris gare Zala, romlis muSaoba $\boldsymbol{ab}$ ubanze erTeuli dadebiTi muxtis gadaadgilebisas em Zala anu induqciis em Zalaa da $\varepsilon_i = \varphi_b - \varphi_a = -El = -vBl$.

radgan gamtaris siCqare $\boldsymbol{v = \frac{dx}{dt}}$, amitom $\boldsymbol{\varepsilon_i = -B\frac{dx}{dt}\cdot l = -B\frac{dS}{dt}}$, sadac $\boldsymbol{dS = ldx}$ gamtaris mier $\boldsymbol{dt}$ droSi Semowerili farTobia, xolo $\boldsymbol{BdS = d\phi}$ – induqciis nakadi am farTobSi da induqciis em Zala toli iqneba $\boldsymbol{\varepsilon_i = -\frac{d\phi}{dt}}$ (el.magn. induqciis kanoni). Tu konturi Sekruli iqneba, maSin am Sem-Si masSi gaivlis induqciuri deni.

2. **rodesac uZravi gamtari moTavsebulia cvlad magn. velSi.** am dros ukve uZrav muxtebze lorencis Zala aRar imoqmedebs. imis gamo, rom uZrav muxtebze moqmedebs el. veli, unda vivaraudoT, rom es veli warmoSobilia cvladi magn. velis mier da is moqmedebs uZrav muxtebze da ganapirobebs induqciur dens. swored es daskvna gaakeTa maqsvelma, rom **droSi cvlilebisas magn. veli warmoqmnis el. vels,** romelic imiT gansxvavdeba el. statikuri velisagan, rom is iseve magn. veli grigaluri velia (romlis Zalwirebs arc dasawyisi aqvT, arc dasasruli). grigalur el. velSi (arael.statikuri – gare ZalTa veli) ki Caketil konturSi muxtebis gadaadgilebaze Sesrulebuli muSaoba nulis toli ar aris. Tu am velis daZabulobas Tu $\vec{E}_B -$Ti avRniSnavT, maSin misi cirkulacia gansxvavebiT el. statikuri velis cirkulaciisagan Caketil wredSi ar aris nulis toli da swored is aris induqciis em Zala $\boldsymbol{\varepsilon_i = \oint_l (\vec{E}_B d\vec{l}) = -\frac{\partial \Phi}{\partial t}}$. aq kerZo warmoebuli $\boldsymbol{\frac{\partial \Phi}{\partial t}}$ imas miuTiTebs, rom magn. induqciis nakadi damokidebulia mxolod droze.

e.i. cvladi magn. veli qmnis cvlad grigalur (arastatikur) el. vels, romlis Zalwirebis mimarTuleba (romelic moicavs magn. induqciis wirebs nax. 11.6) ganisazRvreba lencis wesiT. Tu magnturi induqcia izrdeba ($\boldsymbol{\frac{dB}{dt} > 0}$) el. velis Zalwirebi $\vec{B}-$s mimarTulebasTan qmnian marcxena xraxns (kavSirSi arian marcxena burRis wesiT).



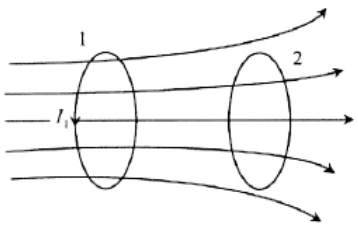
nax. 11.6

XII leqcia

urTierTinduqcia. TviTinduqcia. TviTinduqciis em Zala. induqciuroba. denis magnituri velis energia.

$1. urTierTinduqcia.

urTierTinduqcia el. magnituri. induqciis kerZo saxea da ewodeba **mocemul konturSi denis cvlilebis Sedegad sxva (mezobel) konturebSi induqciuri denis aRZvras.** vTqvaT mocemuli gvaqvs ori erTmaneTTan axlos mdebare ori Caketili konturi, sadac pirvel konturSi gadis I_1 deni (nax. 12.1). es deni



qmnis B_1 magn. vels, romlis meore konturiT SemosazRvrul farTobSi gamWoli magn. nakadia Φ_{21}. es nakadi dam-bia denze, konturis formaze, zomaze, urTierTganla

nax. 12.1 gebaze da garemos magn. Tvisebebze (μ). am I_1 denis cvlilebisas icvleba Φ_{21} nakadic da el. magn. induqciis kanonis Tanaxmad meore konturSi aRiZvreba urTierTinduqciis em Zala $$\varepsilon_{21} = -\frac{d\Phi_{21}}{dt} \quad (12.1)$$

nakadis ganmartebidan $\Phi_{21} \sim B_1$, xolo bio-savar-laplasidan $B_1 \sim I_1$, anu $\Phi_{21} = L_{21} \cdot I_1$.

L_{21} – s pirveli da meore konturebis urTierTinduqciis koeficienti an urTierTinduqciuroba ewodeba. is damokidebulia konturis formaze, zomaze, urTierTganlagebaze da garemos magn. Tvisebebze (μ). maSin

$$\varepsilon_{21} = -\frac{d}{dt}(L_{21}I_1) = -L_{21}\frac{dI_1}{dt} \quad (12.2),$$

radgan $L_{21} = const$. analogiurad gveqneba yvelaferi, rodesac deni gadis mxolod meore gamtarSi (I_2). aq gveqneba L_{12}, ε_{12}. mtkicdeba, rom $L_{21} = L_{12}$.

Tu (12.2)-Si $\frac{dI_1}{dt} = 1\frac{a}{wm}$, miviRebT $\varepsilon_{21} = -L_{21}$, anu ori konturis urTierTinduqciis koeficienti ricxobrivad im em Zalis tolia, romrlic aRiZvreba erTerT konturSi, rodesac meoreSi deni Zala icvleba 1 amperiT wamSi. misi erTeuli SI sistemaSi aris henri. rodesac $\frac{dI_1}{dt} = 1\frac{a}{wm}$ da $\varepsilon_{21} = 1$ v, maSin $L_{21} = 1\frac{v \cdot wm}{a} = 1$ henri (hn). e.i. **henri iseTi ori konturis urTierTinduqciis koeficientia, romelTagan erT-erTSi denis Secvla $1\frac{a}{wm}$**–iT meoreSi aRZravs 1 volt urTierTinduqcviis em Zalas.

es movlena safuZvlad udevs transformatoris moqmedebis princips.

$2. TviTinduqciis em Zala. induqciuroba

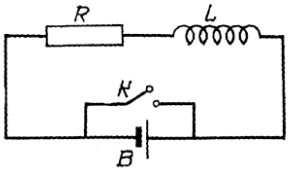
el. Ddeni, romelic gadis Caketil konturSi, Tavis garSemo qmnis magn. vels, romelic bio-savar-laplasis kanonis Tanaxmad proporciulia denis. amis gamo konturis gamWoli nakadi proporciuli iqneba konturSi I denisa e.i. $\Phi \sim I$. Tu konturis formaze, sidideze da garemoze damokidebul koeficients L-iT avRniSnavT, miviRebT $\Phi = LI$. $L-$s konturis induqciuroba ewodeba. Tu $I = 1$, maSin $L = \Phi$, anu induqciuroba ricxobrivad im magnituri nakadis tolia, romelsac mocemul konturSi erTeuli deni warmoqmnis. misi erTeulia henri. es iseTi konturis induqciurobaa, romelSic rodesac gadis 1 amperi deni gamWoli magnituri nakadi iqneba 1 veberi. zogadad induqciuroba damokidebulia konturis geometriul formaze, mis zomebze d aim garemos magnitur SeRwevadobaze, sadac is imyofeba. Tu konturSi icvleba deni, maSin Seicvleba misi gamWoli magnituri nakadic da masSi aRiZvreba induqciis em Zala. Aam movlenas – induqciis em Zalis aRZvras gamtar konturSi masSi denis cvlilebisas ewodeba TviTinduqcia. TviTinduqciis em Zala

$$\varepsilon_{is} = -\frac{d\Phi}{dt} = -\frac{d}{dt}(LI) = -(L\frac{dI}{dt} + I\frac{dL}{dt}). \quad (12.3)$$

Tu konturi ar ganicdis deformacias da magn. SeRwevadobac ar icleba, maSin $L = const$ da meore wevri nulis tolia , e.i. $\varepsilon_{is} = -L\frac{dI}{dt}$. niSani "–“ lencis wesis Tanaxmad gviCvenebs, rom Tu konturs aqvs induqciuroba, maSin is iwvevs denis Senelebul cvlilebas. marTlac Tu $\frac{dI}{dt} > 0$ e.i. izrdeba drois mixedviT, maSin $\varepsilon_{is} < 0$ anu mimarTulia denis sawinaaRmdegod da amuxruWebs mis zrdas, romelic gare wyaroTia ganpirobebuli. Tu deni mcirdeba $\frac{dI}{dt} < 0$, maSin $\varepsilon_{is} > 0$ da TviTinduqciis em Zala mimarTulia denis mxares da xels uSlis mis Semcirebas. Faqtiurad konturi iZens Tavisebur eleqtrul inerciulobas. maSasadame L aris

denis cvlilebis mimarT konturis inerciulobis zoma. aqedan aseve dgindeba induqciurobis erTeuli–henri. 1hn=1 v·1wm/1a e.i. **henri aris iseTi konturis induqciuroba, romelSic aRiZvreba 1v-is toli TviTinduqciis em Zala, Tu masSi deni 1 wm-Si 1 amperiT icvleba.**

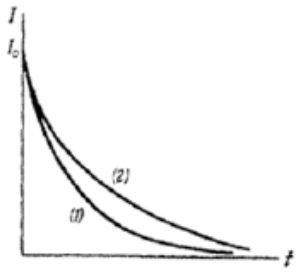
L lencis kanonis Tanaxmad TviTinduqciis gamo gamtarSi aRZruli damatebiTi deni isea mimarTuli, rom xels uSlis wredSi denis cvlilebas. Aamis gamo wredis CarTvisas denis zrda da gamorTvisas denis Semcireba xdeba ara myisierad, aramed TandaTanobiT. ganvixiloT denis Zalis cvlileba wredis gamorTvisas (nax. 12.2), romelic Sedgeba ε em



nax. 12.2 Zalis denis wyaros, L induqciurobis koWas da R omuri winaRobisagan. gamorTvisas denis Zala wredSi mcirdeba, misi magnituri velic mcirdeba, e.i. aRiZvreba TviTinduqciis em Zala $\varepsilon_i = -L\frac{dI}{dt}$ da e.w. gamorTvis eqstradeni $I = \frac{\varepsilon_i}{R} = -\frac{L}{R}\frac{dI}{dt}$, anu $IR = -L\frac{dI}{dt}$ (omis kanoni) romelsac ZiriTadi denis Tan-xvdenili mimarTuleba aqvs. Ggant-dan gvaqvs $\frac{dI}{dI} = -\frac{R}{L}dt$. integrebidan $\ln I = -\frac{R}{L}t + \ln C$. C integrebis mudmivaa. Aaqedan $I = Ce^{=\frac{R}{L}t}$. roca $t = 0$, maSin $C = I_0$ da

$$I = I_0 e^{-\frac{R}{L}t} \quad (12.4).$$

maSasadame wredis ganrTvisas deni mcirdeba eqsponencialurad I_0 – dan 0-mde (nax. 12.3). (12.4) formulidan Cans, rom denis Semcireba gamorTvisas miT ufro nela xdeba rac mcirea R da didia L (2) da piriqiT (1) ($\frac{R_2}{L_2} < \frac{R_1}{L_1}$). wredis CarTvis momentSi deni ucbad ar aRwevs mudmiv $\frac{\varepsilon}{R}$ mniS-s, aramed izrdeba TandaTanobiT. Aamave

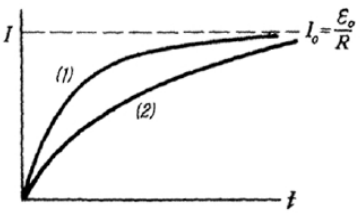


nax. 12.3 dros izrdeba magn. nakadic da aRiZvreba TviTinduqciis em Zala da TviTinduqciis e.w. CarTvis eqstradeni. Omisi kanoni axla ase Caiwereba: $IR = \varepsilon - \varepsilon_i$, an $IR = \varepsilon - L\frac{dI}{dt}$. Aaqedan

$$\frac{dI}{dt} + \frac{R}{L}I = \frac{\varepsilon}{R}.$$

sabolood Sesabamisi maTematikuri gardaqmnebiT miviRebT:

$$I = I_0(1 - e^{-\frac{R}{L}t}), \quad (12.5)$$



nax. 12.4

sadac $I_0=\frac{\varepsilon}{R}$ denis udidesi mniSvnelobaa. Aaqac denis zrda miT ufro nela mimdinareobs, rac metia L da naklebia R (1) da piriqiT (2) ($\frac{R_2}{L_2}<\frac{R_1}{L_1}$) (nax. 12.4).

$3. denis magnituri velis energia

deniani gamtaris garSemo arsebobs magnituri veli, e.i. denis energiis nawili midis magnituri velis Seqmnaze, romelic asve energiis matarebelia. Aamitom magnituri velis energia im muSaobis tolia, romelsac xarjavs deni am veils Seqmnaze. viciT konturSi $\Phi=LI$ .. Tu deni deni Seicvala $dI-$iT, maSin $d\Phi=LdI$. Mmagram magnituri nakadi rom SevcvaloT $d\Phi-$Ti amisTvis unda SevasruloT muSaoba $dA=Id\Phi=ILdI$ **(marTlac l sigrZis denian gamtarze, romelic moTavsebulia erTgvarovan naxazis sibrtyis marTobul B induqciis magn. velSi amperis Zalis moqmedebis Sedegad mag. velis mier Sesrulebuli muSaoba gamtaris gadaadgilebaze ase gamoiTvleba: vTqvaT am gamtars Tavisuflad SeuZlia gadaadgileba. maSin amperis Zala [$F=BIL$ $(\sin\alpha=1)$], romlis mimarTuleba marcxena xelis wesis Tanaxmad naCvenebia naxazze Tavis Tavis paralelurad dx manZilze Sesarulebs muSaobas** $dA=F\cdot dx=BIldx=BIdS=Id\Phi$ $(BdS=d\Phi)$ da mTeli muSaoba nakadis Seqmnaze toli iqneba $A=\int_0^I LIdI=\frac{LI^2}{2}$. Sesabamisad es muSaoba aris denis magn. velis energiis zoma

$$W_m=\frac{LI^2}{2}. \qquad (12.6)$$

Tu am formulas SevadarebT kinetikuri energiis formulas ($W=\frac{mv^2}{2}$), vaskvniT, rom L induqciuroba eleqtromagnitur movlenebSi iseTive rols asrulebs rogorc m masa meqanikur movlenebSi, anu rogorc avRniSneT induqciuroba eleqtruli wredis (denis magnituri velis) inertulobis zomaa. marTlac, rogorc masa ewinaaRmdegeba siCqaris cvlilebas, ise induqciuroba ewinaaRmdegeba denis cvlilebas.

an meorenairad: CavweroT omis kanoni Caketili wredisaTvis. wredis CarTvis momentidan, vidre denis Zala ar miaRwevs mudmiv I mniS-s, masSi garda denis wayros ε em Zalisa moqmedebs TviTinduqciis em Zala $\varepsilon_{is}=-L\frac{dI}{dt}$ da denis Zala wredSi iqneba $I=\frac{\varepsilon+\varepsilon_{is}}{R}=\frac{\varepsilon-L\frac{dI}{dt}}{R}$. (12.7)

gavamravloT $IRdt-$ze, gveqneba $I^2Rdt=Iεdt-LIdI$, an $Iεdt=I^2Rdt+LIdI$. es aris faqtiurad energiis mudmivobis kanoni. bolo formulidan Cans, rom drois ($0-dt$) SualedSi wyaros mier Sesrulebuli

$Iεdt$ muSaobis nawili xmardeba joulis I^2Rdt siTbos gamoyofas, nawili ki xmardeba denis Zalis gazrdas dI sididiT da es muSaoba tolia $dA = LIdI$. aqedan sruli muSaoba denis gasazrdelad nulidan maqsimalur I mniS-mde tolia $A = \int dA = \int_0^I LIdI = \frac{LI^2}{2}$ (12.8).

vinaidan denis gazrdisas izrdeba misi magnituri veli, amitom CavTvaloT, rom es muSaoba warmoadgens denis magn. velis Seqmnaze Sesrulebul dadebiT muSaobas, anu denis magn. velis energiis zomas

$$W_m = A = \frac{LI^2}{2} \qquad (12.9).$$

wredis ganrTvisas deni ispoba da denis momaragebuli energia ama Tu im saxiT mJRavndeba sakmaod Zlier naperwkalSi, romelic warmoiqneba didi induqciurobis wredSi.

XIII leqcia

magnetikebi: paramagnituri, diamagnituri da feromagnituri sxeulebi. damagnitebis veqtori. nivTierebis magnituri SeRwevadoba. eleqtronebis da atomebis magnituri momenti. paramagnetizmis, diamagnetizmis da feromagnetizmis buneba.

$1. magnetikebi: paramagnituri, diamagnituri da feromagnituri sxeulebi. damagnitebis veqtori. nivTierebis magnituri SeRwevadoba.

bunebaSi arsebuli yvela sxeuli gareSe magn. velSi Setanisas magnitdeba da iwvevs mis cvlilebas. magn. aqtiur sxeulebs magnetikebs uwodeben. arseboben sustmagnituri – paramagnetikebi da diamagnetikebi) da Zliermagnituri (feritebi, romlebsac naxevargamtaruli Tvisebebic aqvT da feromagnituri) sxeulebi.

rogorc cnobilia dieleqtriki el. statikur velSi Setanisas polarizdeboda – mis zedapirze warmoiqmneboda bmuli muxtebi, romlebic qmnidnen Tavis el. statikur vels da jamuri daZabuloba dieleqtrikis SigniT toli iyo $\vec{E} = \vec{E}_0 + \vec{E}'$, sadac $\vec{E}_0$ Tavisufali muxtebis (gare velis) mier Seqmnili velis daZabulobaa, xolo $\vec{E}'$ dieleqtrikis bmuli muxtebis mier Seqmnili.

analogiurad magnetikis gareSe magnitur velSi Setanisas is magnitdeba da is aRZravs sakuTar magn. vels, romelic ikribeba gareSe magn. velTan da cvlis mas. jamuri velis induqcia sxeulis SigniT superpoziciis principis Tanaxmad toli iqneba $\vec{B} = \vec{B}_0 + \vec{B}'$, sadac $\vec{B}_0$ gareSe magn. velis induqciaa, $\vec{B}'$-magnetikis mier Seqmnili. vinaidan $\vec{B}_0 = \mu_0 \vec{H}$ ($\vec{H}$ – magn. velis daZabulobaa), amitom $\vec{B} = \mu_0 \vec{H} + \vec{B}'$. $\vec{B}'$-s SeiZleba hqondes $\vec{B}_0$-is gare magn. velis rogorc sawinaaRmdego (asusteben gare magn. vels – diamagnetikebi), ise Tanxvdenili (aZliereben – paramagnetikebi) mimarTuleba. magn. velis ararsebobis Sem-Si es sxeulebi magnitur Tvisebebs ar amJRavneben. aseve am sxeulebisTvis $\vec{B}'$ mcirea $\vec{B}_0$-Tan SedarebiT. paramagnetikebidan gamoiyofa mcirericxovani jgufi sxeulebisa – feromagnetikebi, romelTaTvisac $\vec{B}' >> \vec{B}_0$ (mag. rkinisTvis), rac am sxeulebis Setanisas magn. velSi iwvevs velis mkveTr zrdas.

sxeulis magnituri Tvisebebis dasaxasiaTeblad SemoRebulia damagnitebis veqtori. damagnitebis veqtori ewodeba magnetikis erTeul moculobaSi moTavsebul molekulaTa magnituri momentebis jams anu is axasiaTebs sxeulSi arsebuli mikrodenebis mier Seqmnil magnitur vels: $\vec{P} = \frac{\sum_{i=1}^{N} \vec{P}_{mi}}{\Delta V}$, (13.1)

sadac $\vec{P}_{mi}$ i – uri molekulis magn. momentia, xolo N molekulebis ricxvi ΔV moculobaSi. unda CavTvaloT, rom veli mudmivia da magnetiki erTgvarovani da izotropiulia, maSin yvela molekulis $\vec{P}_m$ magn. momenti erTnairia da

$\sum_{i=1}^{N} \vec{P}_{mi} = N\vec{P}_m$. aqedan $\vec{P} = \frac{N\vec{P}_m}{V} = n\vec{P}_m$ (13.2),

sadac $n = \frac{N}{V}$ molekulebis koncentraciaa.

damagnitebis veqtoris erTeuli SI sistemaSi aris a/m (amperi metrze).

vinaidan sxeulis damagniteba Sedegia mikrodenebze gareSe magn. velis ($\vec{H}$) moqmedebisa, amitom damagnitebis xarisxi ($\vec{P}$) damokidebuli iqneba am velis sidideze. sustmagnituri sxeulebisTvis am or sidides Soris wrfivi proporciuli damokidebulebaa: $\vec{P} = k_m \vec{H} = \frac{k_m}{\mu_0} \vec{B}_0$. k_m– proporciulobis koeficients nivTierebis **magnituri amTvisebloba an damagnitebis koeficienti** ewodeba. mas ganzomileba ar aqvs da damokideblia nivTierebis gvarobaze. paramagnetikebisTvis is dadebiTia ($k_m > 0$), diamagnetikebisTvis uaryofiTi ($k_m < 0$). amasTan arsebobs garkveuli kavSiri damagnitebis ($\vec{P}$) veqtorsa da damagnitebuli sxeulis (magnetikis) sakuTar (mikrodenebis) $\vec{B}'$ magn. vels Soris. am kavSiris misaRebad davuSvaT cilindruli formis magnetiki Segvaqvs grZeli solenoidSi, romlis SigniT veli erTgvarovania ($\vec{B}_0 = const$). am dros sxeulis msaxveli magn. velis paraleluria. solenoidis velis gavleniT magnetikis wriuli molekuluri denebis magnituri momentebi orientirebdian cilindris RerZis gaswvriv, wriuli denebi ki RerZis marTobulad. magnetikis raime kveTaSi yvela molekuri deni erTnairia, ris gamoc isini erTmaneTs abaTileben da gvrCeba mxolod kveTis gare konturze denebi. e.i. sxeulis sakuTari magn. veli Seqmnilia RerZis marTobuli cilindris gare zedapirze gamavali denebiT. Tu erT-erTi wriuli denis sidide aris I' , xolo cilindris erTeul sigrZeze maTi ricxvi n– ia, maSin solenoidis magn. velis induqciis solenoidis RerZze gamosaTvleli formulis ($B' = \mu_0 nI$, sadac n aris xviaTa ricxvi solenoidis sigrZis erTeulze, I – solenoidSi deni). analogiurad gveqneba $B' = \mu_0 nI'$. aseve radgan magnetikis mcire elementis moculoba $\Delta V = S\Delta l$ -is tolia, xolo wriul denTa raodenoba am mcire Δl elementze aris $n\Delta l$, amitom misi magn. mometi toli iqneba $\left|\sum_{i=1}^{N} \vec{P}_{mi}\right| = n\Delta l I' S$ da damagnitebis veqtoris sidide gamodis $P = \frac{\left|\sum_{i=1}^{N} \vec{P}_{mi}\right|}{\Delta V} = \frac{n\Delta l I' S}{S\Delta l} = nI'$ (13.3).

maSin $B' = \mu_0 nI$ da $P = nI'$ Sedarebidan gveqneba $B' = \mu_0 P$, an veqtorulad

$$\vec{B}' = \mu_0 \vec{P} . \qquad (13.4)$$

amis gaTvaliwinebiT gveqneba: $\vec{B}' = \mu_0 \vec{P} = \mu_0 \frac{k_m}{\mu_0} \vec{B}_0 = k_m \vec{B}_0$. maSin

$$\vec{B} = \vec{B}_0 + \vec{B}' = \vec{B}_0 (1 + k_m) = \mu \vec{B}_0 \qquad (13.5).$$

uganzomilebo sidides $\mu = 1 + k_m$ nivTierebis **fardobiTi magnituri SeRwevadoba** ewodeba. is gviCvenebs Tu ramdenjer metia (an naklebia) makrodenis mier Seqmnili magnituri velis induqcia mocemul nivTierebaSi ($\vec{B}$) vidre sicarieleSi ($\vec{B}_0$).

diamagnituri sxeulebisTvis $k_m < 0$ da $\mu < 1$. paramagnetikebisTvis $k_m > 0$ da $\mu > 1$. radgan $\vec{B}_0 = \mu_0 \vec{H}$, amitom $\vec{B} = \mu_0 \mu \vec{H}$ (13.6).

aqedan Cans, rom Tu gvecodineba makrodenebis magn. veli da garemos magn. SeRwevadoba, SeiZleba $\vec{B}$ – s ganszaRvra mikrodenebis velis codnis gareSe.

$2. eleqtronebis da atomebis magnituri momenti.

atomi Sedgeba dadebiTi atombirTvisa da mis irgvliv didi siCqariT mbrunavi eleqtronebisagan. eleqtronebis moZraoba tolfasia wriuli deniani konturisa, romelic qmnis orbitalur magnitur moments. marTlac Tu m masisa da e muxtis mqone eleqtronis brunvisas dadebiTi birTvis garSemo, ganapirobebs wriul dens, maSin mas aqvs orbitaluri magn. momenti $p_0 = IS$, sadac I denis Zalaa, S orbitis farTobi. Tavis mxriv $I = e\nu$, sadac $\nu = \frac{1}{T}$ brunTa ricxvia erT wamSi, xolo $S = \pi r^2$ (r – orbitis radiusia). eleqtronis wriuli siCqare $v = 2\pi r \nu \rightarrow \nu = \frac{v}{2\pi r}$ da $p_0 = e\frac{v}{2\pi r} \cdot \pi r^2 = \frac{evr}{2}$. aseve mas gaaCnia orbituli meqanikuri momenti ($L_0 = m[\vec{r} \cdot \vec{v}]$), romlis mimarTuleba magn. momentis sapirispiroa.

amas garda eleqtroni brunavs sakuTari RerZis irvliv da Tvlidnen, rom mas gaaCnia Sesabamisi spinuri magnituri $p_s = \frac{eh}{4\pi m}$ da meqanikuri L_S momenti). Semdeg aRmoCnda, rom spinis Sesaxeb warmodgena TiTqos is dakavSirebuli iyo eleqtronis brunvasTan sakuTari RerZis garSemo, arasworia da spini aris eleqtro-

nisTvis iseTive Tviseba, rogor masa da muxti. orbituli da spinuri magn. momentebis jams eleqtronis sruli magnituri momenti ewodeba. anu veqtorulad atomis an molekulis yvela eleqtronis magn. momentebis jams (birTvuli momentebi ugulebelyofilia), atomis an molekulis magnituri momenti ewodeba: $\vec{P}_a = \sum_{i=1}^{n} \vec{p}_{oi} + \sum_{i=1}^{n} \vec{p}_{si}$ (13.7).

$3. paramagnetizmis, diamagnetizmis da feromagnetizmis buneba.

zogadad imis da mixedviT Tu rogoria atomSi Semavali eleqtronebis magn. momentebis (rogorc orbitaluris, aseve spinuris) orientacia, atomis magnituri momenti iqneba nulisgan gansxvavebuli, an nulis toli. Sesabamisad nivTierebebi iyofa or jgufad:

a) atomebis (molekulebis) magnituri momentebi nulisgan gansvavebulia.

aseTi nivTierebebisTvis gareSe magn. velis ararsebobis Sem-Si es momentebi qaosurad orientirebuli arian da erTmaneTs abaTileben, amitom sxeuli magn. Tvisebebs ar amJRavneben. gareSe (makrodenis) magn. velSi isini ise orientirdebian, rom sxeuli iZens makro magn. moments – igi magnitdeba da qmnis saku-Tar magn. vels $\vec{B}'$, romelic mimarTulebiT emTxveva gareSe $\vec{B}_0$ induqciis mimarTulebas da aZlierebs mas. sxeuli **paramagnituria** (tute liTonebi, iSviaTmiwaTa liTonebi, Cr, Mn, Pt da a.S.). maTTvis $k_m > 0$ da $\mu > 1$.

b) atomebis (molekulebis) magnituri momentebi nulis tolia.

am dros calkeuli eleqtronebis magn. momentebi ise arian orientirebuli, rom erTmaneTs abaTileben. aseTi nivTierebis magn. velSi Setanisas TviToel eleqtronze moqmedebs lorencis Zala, rac tolfasia wriuli denis warmoqmnisa, romlis mimarTuleba lencis wesis Tanaxmad iseTia, rom misi Sesabamisi magnituri momenti yovelTvis gare magn. velis sawinaaRmdegodaa mimarTuli. am dros sxeulis sakuTari magn. velis induqcia $\vec{B}'$ gareSe $\vec{B}_0$ induqciis sapirispiroa da amcirebs mas. sxeuli diamagnituria (wyali, mina faifuri, tyvia, naSirbadi, germaniumi, spilenZi, vercxli, oqro, TuTua da sxva). maTTvis $k_m < 0$ da $\mu < 1$.

rogorc paramagnituri, aseve diamagnituri sxeulebi miekuTvnebia sust magn. nivTierebaTa klass. maTTvis $k_m \sim 10^{-4}$ da $|k_m| \sim 10^{-6}$ rigisaa da $\mu \sim 1$, anu $B \sim B_0$, anu am sxeulebSi magn. velis induqcia umniSvnelod gansxvavdeba vakuumSi induqciisagan.

saxelwodebebi "paramagnituri" da "diamagnituri" dakavSirebulia im cdiseul faqtTan, rom Zafze dakidebuli paramagnituri nivTierebisgan damzadebuli Rero magn. velSi dgeba velis gaswvriv ("para"– gaswvriv nax. 13.1 a), xolo diamagnituri mis marTobulad ("dia" – ganivad nax. 13.1 b).

nax. 13.1

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zogadad paramagnituria nivTierebebi, romlebic Seizidebian Zlier magn. velSi, xolo diamagnituri nivTierebebvi piriqiT gamoizidebian.

paramagnituri sxeulebidan gamoiyofa mcirericxovani jgufi sxeulebisa, romelTa mier Seqmnili magn. veli asjer da aTasjer SeiZleba sWarbobdes gareSe magn. vels. aseT sxeulebs feromagnetikebi ewodebaT (rkina, nikeli, kobalti, titani, mTeli rigi Senadnobebi da sxva). maTTvis k_m aRwevs $10^3 - 10^5$ sidides, xolo $\mu >> 1$ (mag. rkinisTvis $\mu \approx 5000$, permaloisTvis (78% Ni +22% Fe)) $\mu \approx 100000$).

saerTod feromagnetizmi Tavs iCens mxolod kristalur mdg-Si. maTTvis arsebobs gansakuTrebuli temperatura, e.w. **kiuris wertili** (mag. rkinisTvis $770^\circ C$), romlis zeviTac isini kargaven feromagnitur Tvisebebs da gadaiqcevian Cveulebriv paramagnetikad.

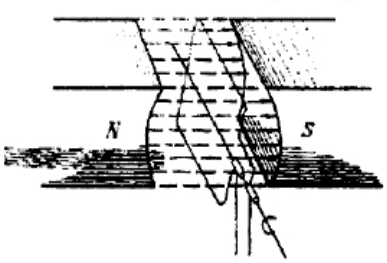
feromagnetizmis bunebis asaxsnelad frangma veisma wamoayena hipoTeza, romlis Tanaxmad yoveli feromagnetiki kiuris temperaturaze dabla iyofa mcire sididis areebad ($\approx 10^{-2}$ sm) (domenebad). rodesac gare magn. veli ara gvaqvs am calkeuli domenebis magn. momentebi orientirebuli arian qaosurad da erTmaneTs awonasworeben, anu jamuri momenti nulis tolia. gare magn. velSi orientirdebian ara calkeuli atomebis magn. momentebi (rogorc paramagnetikebSia), aramed spontanuri damagnitebis mTeli areebi da sxeuli xdeba erTi mTliani domeni (anu domenebs Soris xdeba sazRvrebis gadaadgileba da moculobis Secvla da sxeuli magnitdeba). magn. velis Semcirebisas nulamde feromagnetikebi inarCuneben narCen magnetizms, radgan siTburi moZraoba ar aZlevs saSualebas magn. domenebis swraf dezorientirebas. kiuris temperaturis zeviT domenebis struqtura irRveva. domenebis arseboba damtkicebul iqna eqsperimentalurad. aseve frenkelisa da haizenbergis mier damtkicebuli iqna, rom eleqtronebis mxolod spinuri da ara orbituli magn. momentebi ganapirobebs feromagnetizms.

XIV leqcia

cvladi deni. cvladi denis miReba. cvladi denis sruli wredi. simZlavre cvladi denis wredSi. denis Zalis, Zabvis, em Zalis efeqturi mniSvneloba.

$1. cvladi denis miReba, cvladi denis sruli wredi.

D dens, romlis sidide da mimarTuleba periodulad icvleba, cvladi deni ewodeba. mis miReba SeiZleba eleqtromagnituri induqciis movlenaze dayrdnobiT, raTa meqanikuri energia gardavqmnaT eleqtruli denis energiad.



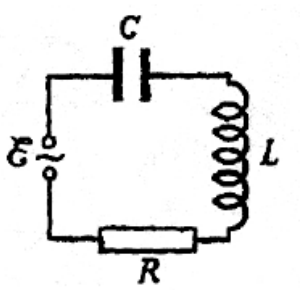
vTqvaT $\boldsymbol{B}$ induqciis mudmiv erTgvarovan magn. velSi velis marTobuli RerZis irgvliv mudmivi $\boldsymbol{\omega}$ kuTxuri siCqariT brunavs Tanabrad brunavs marTkuTxa gamtari CarCo, romelic SemosazRvravs $\boldsymbol{S}$ farTobs (nax. 14.1). brunvis dros ganuwyvetil icvleba CarCos farTobis gamWoli magn. induqciis nakadi, ris Sedegad am konturSi aRiZvreba

nax. 14.1 induqciis em Zala, romlis sidide da mimarTuleba sinusoidurad icvleba. Ees ki iwvevs induqciuri cvladi denis aRZvras. sawyis momentSi ($\boldsymbol{t=0}$) xviis sibrtye marTobulia magn. induqciis wirebis da kuTxe $\vec{\boldsymbol{B}}-$ sa da CarCos normals Soris $\boldsymbol{\alpha=0}$. am dros misi gamWoli nakadi maqsimaluria da tolia $\boldsymbol{\Phi_0 = BS}$. CarCos brunvisas $\boldsymbol{\omega}$ kuTxuri siCqariT, CarCo $\boldsymbol{t}$ droSi Semobrundeba $\boldsymbol{\alpha=\omega t}$ kuTxiT nakadi Seicvleba $\boldsymbol{\Phi = \Phi_0 \cos\alpha = BS\cos\alpha = BS\cos\omega t}$ (14.1)

kanoniT, amitom $\boldsymbol{\varepsilon = -\dfrac{d\phi}{dt} = \omega BS \sin\omega t = \varepsilon_0 \sin\omega t}$, (14.2)

sadac $\boldsymbol{\varepsilon_0 = BS\omega}$ induqciuri em Zalis amplitudaa, xolo $\boldsymbol{\varepsilon}$ myisi mniS-ba. Sesabamisad induqciuri myisi denis mniS-ba toli iqneba: $\boldsymbol{i = \dfrac{\varepsilon}{R} = \dfrac{\varepsilon_0}{R}\sin\omega t = I_0 \sin\omega t}$. (14.3)

aq $\boldsymbol{I_0 = \dfrac{\varepsilon_0}{R}}$ cvladi denis amplitudaa, xolo $\boldsymbol{R}$ CarCos winaRoba. rogorc vxedavT denis Zala icvleba sinusoidurad, harmoniuli kanoniT. $\boldsymbol{\omega}-$s cvladi denis wriuli anu cikluri sixSire ewodeba. $\boldsymbol{\omega = 2\pi\nu = \dfrac{2\pi}{T}}$, sadac $\boldsymbol{\nu}-$cvladi denis sixSirea ($\boldsymbol{\nu}=50$ hc teqn. denebisTvis, aSS-Si $\boldsymbol{\nu}=60$ hc), xolo $\boldsymbol{T}-$periodi.



omis da kirxhofis kanonebi aseve marTebulia cvladi denisa da ZabvisaTvis, Tu maTi cvlileba ar xdeba Zalian swrafad. cvladi denis sruli wredi Seicavs cvladi denis wyaros, $\boldsymbol{L}-$induqciurobis koWas, $\boldsymbol{C}-$tevadobis kondensators da $\boldsymbol{R}-$omur

(aqtiur) winaRobas (nax.). vTqvaT wyaros em Zala icvleba kanoniT $\varepsilon = \varepsilon_0 \sin \omega t$. kirxhofis II kanonis gamoyenebiT (viTvaliwinebT $U-$aris Zabva kondensatoris Semonafenebze, $IR-$Zabvis vardnaa omur winaRobaze, xolo koWaSi denis cvlilebisas aRiZvreba TviTinduqciis em Zala $\varepsilon_i = -L\frac{dI}{dt}$) miviRebT, rom

$$IR + U = \varepsilon_0 \sin t - L\frac{dI}{dt} \qquad (14.4),$$

romlis droiT gawarmoebis Semdeg ($U = \frac{q}{C}$, $I = \frac{dq}{dt}$) miviRebT meore rigis araerTgvarovan diferencialur gant-s: $L\frac{d^2I}{dt^2} + R\frac{dI}{dt} + \frac{1}{C}I = \varepsilon_0 \sin \omega t$, (14.5),

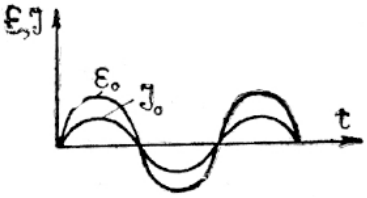
romlis kerZo amonaxsnia $i = I_0 \sin(\omega t - \varphi)$. (14.6)

aq denis Zalis amplituda $I_0 = \frac{\varepsilon_0}{\sqrt{R^2 + (L\omega - \frac{1}{C\omega})^2}}$, $tg\varphi = \frac{L\omega - \frac{1}{C\omega}}{R}$, (14.7)

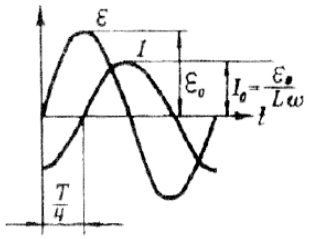
xolo fazaTa sxvaoba densa da em Zalas Soris tolia $\varphi = arctg\frac{L\omega - 1/C\omega}{R}$.

ganvixiloT kerZo SemT-vebi:

a) **omuri winaRoba cvladi denis wredSi** – $R \neq 0, L = 0, C = \infty$. ukanaskneli gamodis iqidan, rom Tu kondensators SevcvliT gamtariT, maSin Semonafenebi erTmaneTs exeba, maT Soris manZili $d \to 0$ da tevadoba $C = \frac{\varepsilon_0 \varepsilon S}{d} \to \infty$. maSin zemoTmoyvanili formulebidan gveqneba $\varphi = 0$ da $i = \frac{\varepsilon}{R} = \frac{\varepsilon_0 \sin \omega t}{R} = I_0 \sin \omega t$, sadac $I_0 = \frac{\varepsilon_0}{R}$ cvladi denis amplitudaa. aqedan Cans, rom deni da em Zala erTnair fazaSi icvlebian-erTdroulad iReben rogorc maqsimalur, ise minimalur mniS-bebs. omis kanoni iseTive saxisaa, rogorc mudmivi denis dros, mxolod aq winaRobas ukve aqtiuri winaRoba ewodeba. aqtiuri imitom rom, masze xdeba Zabvis varna da joulis siTbos gamoyofa (moixmars energias).



b) **induqciuroba cvladi denis wredSi** – $R = 0, L \neq 0, C = \infty$. (14.7)-dan gveqneba $I_0 = \frac{\varepsilon_0}{L\omega}$ da $tg\varphi = \frac{L\omega}{R} = \infty$ da $\varphi = \frac{\pi}{2}$. e.i. aq denis cvlileba em Zalis cvlilebas CamorCeba $\frac{\pi}{2}$ faziT, anu droSi $\frac{T}{4}-$iT



$$i = I_0 \sin(\omega t - \frac{\pi}{2}), \quad (14.8)$$

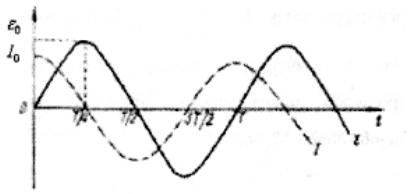
rac aixsneba koWaSi cvladi denis gavlisas TviTinduqciis em Zalis aRZvriT, romelic lencis kanonis Tanaxmad ewinaaRmdegeba wredSi denis cvlilebas. winaRobis rols aq asrulebs $R_L = L\omega$ sidide, romelsac induqciuri

(reaqtiuli) winaRoba ewodeba. am winaRobaSi joulis siTbo ar gamoiyofa, gansxvavebiT aqtiuri winaRobisgan. mudmivi denisTvis $\omega = 0$ da $R_L = 0$.

g) **tevadoba cvladi denis wredSi**, e.i. $R = 0, L = 0, C \neq \infty$. aqac (14.7)-dan gveqneba $I_0 = \frac{\varepsilon_0}{\frac{1}{C\omega}}, tg\varphi = -\frac{\frac{1}{C\omega}}{R} = -\infty$ da $\varphi = -\frac{\pi}{2}$. aq em Zala (Zabvac) CamorCeba dens $\frac{\pi}{2}$ faziT anu droSi $\frac{T}{4}$ – iT,

$$i = I_0 \sin(\omega t + \frac{\pi}{2}). \qquad (14.9)$$

CamorCenis mizezi isaa, rom denis cvlileba aq ufro swrafad xdeba da is aswrebs muxtisa da Zabvis

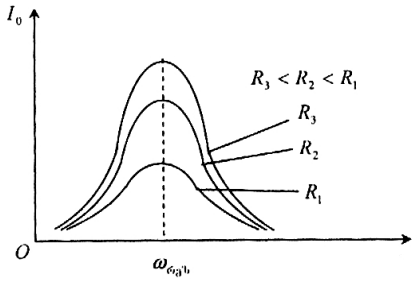


cvlilebas. roca deni $I = I_{max}$, maSin $\varepsilon = 0$ da $\frac{T}{4}$ drois Semdeg piriqiT $I = 0$, $\varepsilon = \varepsilon_{max}$. winaRobis rols aq asrulebs $R_C = \frac{1}{C\omega}$ – reaqtiuli tevaduri winaRoba. mudmivi denisTvis $\omega = 0$ da $R_C = \frac{1}{C\omega} = \infty$, anu is mudmiv dens ar atarebs. am winaRobis arseboba dakavSirebulia kondensatoris damuxtvas, ganmuxtvas da gadamuxtvasTan.

induqciuri da tevaduri winaRobebi analogiuria omuri (aqtiuri) winaRobebisa, mxolod denis Zalis amplitudaze moqmedebis TvalsazrisiT. gansxvaveba ki SemdegSia:

1. induqciuri da tevaduri winaRobebi warmoqmnian fazaTa sxvaobas denis Zalasa da em Zalas Soris da aseve damokidebuli arian sixSireze.
2. omur winaRobaze gamoiyofa energia joulis siTbos saxiT, xolo induqciur da tevadur winaRobaze energia ar gamoiyofa. amitom omuri winaRoba aqtiuria, xolo induqciuri da tevaduri – reaqtiuli.

zogadad rodesac gvaqvs samive saxis winaRoba, maSin sruli winaRoba, anu impedansi tolia $Z = \sqrt{R^2 + (R_L - R_C} $ da $tg\varphi = \frac{R_L - R_C}{R}$ da rodesac $R_L > R_C$, maSin $tg\varphi > 0, \varphi > 0$ $(0 < \varphi < \frac{\pi}{2})$ deni CamorCeba em Zalas (Zabvasac) da piriqiT, rodesac $R_L < R_C$, maSin $tg\varphi < 0, \varphi < 0$ $(-\frac{\pi}{2} < \varphi < 0)$, maSin aswrebs. e.i. denis Zala an CamorCeba an win uswrebs em Zalas, imis da mixedviT Tu romeli winaRobaa meti – induqciuri, Tu tevaduri. rodesac $R_L = R_C$, maSin sruli winaRoba umciresia ($Z = Z_{min} = R$), radgan sruli reaqtiuli winaRoba $R_L - R_C = 0$ da denis amplituda udidesia $I_0 = \frac{\varepsilon}{R}$, xolo $tg\varphi = 0$, $\varphi = 0$, anu fazaTa sxvaoba denis Zalasa da em Zalas Soris ara marto maSin aris nuli, rodesac wredSi CarTulia mxolod omuri winaRoba, aramed maSinac rodesac $R_L = R_C$. maSinac ki roca wredi Seicavs yvela elements da sruldeba piroba $R_L = R_C$, denis Zalis amplituda mkveTrad izrdeba da am movlenas **eleqtruli rezonansi ewodeba.** Sesabamisad gveqneba rezonansuli sixSire – ω_{rez} , romelsac ase gamoviTvliT: $L\omega = \frac{1}{C\omega}$, saidanac $\omega_{rez.}$



$= \frac{1}{\sqrt{LC}}$. aseve denis amplitudis rezonansuli mniS-ba $I_{rez.} = \frac{\varepsilon_0}{R}$, anu rac naklebia aqtiuri winaRoba, miT metia rezonansuli amplituda, an miT mkveTria rezonansi (nax.).

$2. simZlavre cvladi denis wredSi. denis Zalis, Zabvis, em Zalis efeqturi mniSvneloba.

rogorc aRniSnuli iyo zemoT mudmivi denis Caketil wredSi gamoyofili simZlavre denis Zalisa da em Zalis namravlis tolia: $P = I\varepsilon$. drois Zalian mcire intervalSi cvladi denic SeiZleba CaiTvalos mudmivad, amitom cvladi denis myisi simZlavre aseTive formuliT ganisazRvreba.

viciT cvladi denis wredSi denis Zalisa da em Zalis myisi mniS-bebi ase icvleba: $\varepsilon = \varepsilon_0 \sin\omega t$, $i = I_0 \sin(\omega t - \varphi)$. maSin cvladi denis myisi simZlavre

$$p = i\varepsilon = I_0\varepsilon_0 \sin\omega t \sin(\omega t - \varphi). \quad (14.10)$$

ufro mosaxerxebelia vicodeT simZlavris saSualo mniS-ba raime droSi mag. periodSi, radgan momdevno periodebSic simZlavre igivea, da Tu gamoviyeneT ori sinusis namravlis formulas: $\sin\alpha \cdot \sin\beta = \frac{1}{2}[\cos(\alpha - \beta) - \cos(\alpha + \beta)]$, Sesabamisi maTematikuri gardaqmnebiT miviRebT $p = \frac{1}{2} I_0\varepsilon_0 [\cos\varphi - \cos(2\omega t - \varphi)]$ ($\alpha = \omega t$, $\beta = (\omega t - \varphi)$. am tolobaSi droze meore wevria droze damokidebuli, romelic periodis ganmavlobaSi nulis tolia da saSualo simZlavrisTvis periodis ganmasvlobaSi gveqneba

$$\bar{P} = \frac{I_0 \varepsilon_0}{2} \cos\varphi = \frac{I_0}{\sqrt{2}} \frac{\varepsilon_0}{\sqrt{2}} \cos\varphi . \quad (14.11)$$

(14.11) formula SeiZleba asec CavweroT. cnobilia $\cos\varphi = \frac{1}{\sqrt{1+tg^2\varphi}}$, xolo $tg\varphi = \frac{R_L - R_C}{R}$, maSin

$\cos\varphi = \frac{R}{\sqrt{R^2 + (R_L - R_C)^2}}$ da aseve radgan $\sqrt{R^2 + (R_L - R_C)^2} = \frac{\varepsilon_0}{I_0}$, miviRebT $\bar{P} = \frac{1}{2} I_0^2 R$. SemoviRoT

aRniSvna $I_{ef} = \frac{I_0}{\sqrt{2}}$, maSin $\vec{P} = I_{ef}^2 R$. (14.12)

Tu deni wredSi ar asrulebs meqanikur muSaobas, maSin saSualo simZlavre gamoiyofa aqtiur winaRobaze siTbos saxiT. e.i. raime t droSi gamoyofili siTbo

$$Q = \vec{P}t = I_{ef}^2 Rt . \quad (14.13)$$

Tu (14.13) formulas SevadarebT mudmivi denis mier imave aqtiur R winaRobaze imave droSi gamoyofili joul-lencis siTbos – $Q' = I^2 Rt$, maSin $Q = Q'$ da $I_{ef} = I$.

I_{ef} –s ewodeba cvladi denis efeqturi (moqmedi) mniSvneloba. is iZleva igive energetikul efeqts, rasac misi toli mudmivi deni. amitom I_{ef}**-is mniS-ba iseTi mudmivi denis Zalis tolia, romelic imave winaRobaze, imave droSi gamohyofs iseTive siTbos raodenobas, rogorsac mocemuli cvladi deni.**

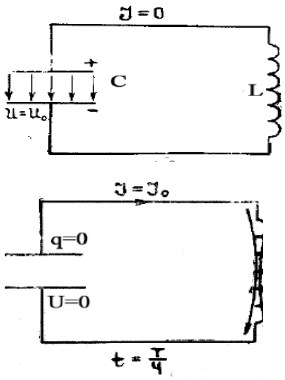
sidideebs $\varepsilon_{ef} = \frac{\varepsilon_0}{\sqrt{2}}$, $U_{ef} = \frac{U_0}{\sqrt{2}}$ – cvladi em Zalis da Zabvis efeqturi mniSvnelobebi ewodebaT. e. i. saSualo simZlavre $\bar{P} = I_{ef} \cdot \varepsilon_{ef} \cdot \cos\varphi$. (14.14)

Tu $\cos\varphi = 1$, $\varphi = 0$, maSin simZlavre maqsimaluria. es ki maSin xdeba, rodesac gvaqvs an rezonansi da am dros $\bar{P} = P_{maqs} = I_{ef.} \varepsilon_{ef.} = \frac{1}{2} I_0 \varepsilon_0$, an wredSi gvaqvs mxolod aqtiuri winaRoba. aqtiur winaRobaze $\bar{P} = I^2_{ef.} R$ da is maqsimaluria. Tu wredSi ara gvaqvs aqtiuri winaRoba $R = 0$, anu wredSi gvaqvs mxolod reaqtiuli winaRoba ($\cos\varphi = 0$, $\varphi = \frac{\pi}{2}$), maSin simZlavre nulis tolia. es niSnavs, rom energia, romelsac wayro awvdis wreds pirvel meoTxedSi (mag. kondensatoris damuxtvisas), ukanve ubrundeba wyaros periodis meore meoTxedSi (kondensatoris ganmuxtvisas).

XV leqcia

rxeviTi konturi. tomsonis formula. milevadi eleqtromagnituri rxevebi. wanacvlebis deni. maqsvelis gantolebebi da maTi fizikuri Sinaarsi. eleqtromagnituri veli. eleqtromagnituri talRa. eleqtromagnituri talRebis Tvisebebi.

$1. rxeviTi konturi. tomsonis formula.



el.magn. rxevebi ewodeba eleqtruli da magnituri sidideebis periodul cvlilebas. umartivesi sistema maT misaRebad rxeviTi konturia. es aris mimdevrobiT SeerTebuli $C-$ tevadobis kondensatori da $L-$ induqciurobis koWa (nax. 15.1). davmuxtoT kondensatori q_0 muxtiT. Semonafenebze gveqneba sxvadasxva niSniani muxtebi da maT Soris aRiZvreba maqsimaluri Zabva U_0. radgan konturis omuri winaRoba $R=0$, amitom energiis kargva ar xdeba. kondensators movaciloT denis wyaro da davakvirdeT mimdinare procesebs periodis meoTxedi $\frac{T}{4}$ toli drois Sualedis Semdeg. sawyis momentSi $(t=0)$ Zabva maqsimaluria, eleqtruli velis energia $W_e=\frac{CU_0^2}{2}=\frac{q_0^2}{2C}$ aseve maqsimaluria, xolo denilȣ Zala nulis tolia ($I=0$, Sesabamisad magn. velis energiac $W_m=\frac{LI^2}{2}$). am Zabvis gavleniT kondensatori daiwyebs ganmuxtvas, muxti da Zabva mcirdeba, xolo deni izrdeba. Sesabamisad el. energia mcirdeba, xolo magnituri izrdeba. deni TviTinduqciis gamo (warmoiqmneba TviTinduqciis deni, romelic ZiriTadi denis sapirispirodaa mimarTuli) nela izrdeba. periodis meoTxedis gavlis Semdeg deni iqneba maqsimaluri (aseve

magnituri velis energiac $W_m = \frac{LI_0^2}{2}$). muxti, Zabva da el. energia am dros nulis tolia. amis Semdeg Zabvis ararsebobis gamo deni mimarTulebis Seucvlelad iwyebs Semcirebas. magram aseve TviTinduqciis gamo (TviTinduqciis deni axla mimarTulebiT emTxveva ZiriTad dens) deni myisierad ar mcirdeba da nel-nela xdeba nuli (periodis naxevari). am dros xdeba kondensatoris gadamuxtva sawinaaRmdego mimarTulebiT (qveda firfita dadebiTad, zeda uaryofiTad). e.i. periodis naxevris Semdeg deni iqneba nuli (magn. energiac), xolo muxti da Zabva (el. energiac) maqsimaluri. Semdgom daiwyeba wina procesis msgavsi procesi (dens eqneba sawinaaRmdego mimarTuleba) da a.S. periodis gavlis Semdeg sistema daubrundeba sawyis mdgomareobas. es rxevebi analogiuri zambariani qanqaris rxevebis procesebis. $W_{pmaks} = \frac{kx_0^2}{2} \equiv W_{emaks} = \frac{CU_0^2}{2} = \frac{q_0^2}{2C}$ anu zambaris maqsimaluri potenciuri energia maqsimaluri gadaxrisas analogiuria maqsimaluri eleqtruli energiis. aseve maqsimaluri kinetikuri energia wonasworobis mdgomareobaSi (siCqare maqsimaluria) analogiuria maqsimaluri magnituri veils energiis $W_{kmaks} = \frac{mv_m^2}{2} \equiv W_{mmaks} = \frac{LI_0^2}{2}$. e.i. $L-$ induqciurobis rols asrulebs burTulas $m-$masa, xolo $\frac{1}{C}-$s rols $k-$sixistis koeficienti. Sesabamisad $x \equiv q$, $v \equiv I$. viciT zambariani qanqaras rxevis periodi $T = 2\pi\sqrt{\frac{m}{k}}$. analogiurad rxevis periodi elmagn. rxevebisaTvis (periodulad icvlebian muxti, Zabva da el. energia kondensatoris Semonafenebze, xolo deni da magn. energia koWaSi) am analogiidan $T = 2\pi\sqrt{LC}$**.** am formulas **tomsonis** formula ewodeba**.** maSasadame yvela am sididis rxevas elmagn. rxevebi ewodeba, romelTa rxevis periodi tomsonis formuliT gamoisaxeba.

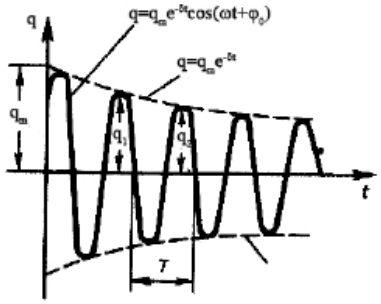
$2. milevadi eleqtromagnituri rxevebi.

rxeviT konturSi aRZruli rxevebi Tu CavTvliT, rom konturis aqtiuri winaRoba $R = 0$, harmoniulia. am dros energiis kargva (joulis siTbos saxiT) ar xdeba da konturis sruli energia (el. da magn. energiaTa jami) drois mixedviT ar icvleba, anu $\frac{1}{2}CU^2 + \frac{1}{2}LI^2 = const$. Sesabamisad rxevebi miulevadia (rxevis amplituda mudmivia – rxeva sinusoiduria). realur konturSi rogorc koWas gragnils, aseve SemaerTebel sadenebs gaaCniaT raRac $R \neq 0$ aqtiuri winaRoba. amitom konturis energiis maragi TandaTan ixarjeba am winaRobaSi joulis siTbos gamoyofaze, ris gamoc Tavisufali rxevebi miileva da yvela sidides: Zabvas, denis Zalas, muxts, el. da magn. velis daZabulobebs eqneba klebadi amplitudebi. vnaxoT am dros rogor icvleba es sidideebi.

zogadad kirxhofis II kanonis Tanaxmad konturSi, romelic Seicavs $L-$induqciurobis koWas, $C-$tevadobis kondensators da $R-$winaRobas gvaqvs

$$\frac{d^2q}{dt^2} + \frac{R}{L}\frac{dq}{dt} + \frac{1}{LC}q = 0 \quad (15.1).$$

realur konturSi gant-ba zemoTmoyvanili saxiT ZalaSi rCeba da misi amonaxsni ukve aseTi saxisaa $q = q_m e^{-\delta t}\cos(\omega t + \varphi_0)$, sadac $\delta = \frac{R}{2L}-$s rxevis milevis koeficienti ewodeba. cikluri sixSire $\omega = \sqrt{\omega_0^2 - \delta^2} = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$. e.i. kondensatoris muxtis rxevis amplituda ($q_M = q_m e^{-\delta t}$) mcirdeba eqsponencialuri kanoniT (nax.). aseTnairad mcirdeba aseve Zabva kondensatoris Semonafenebze da deni wredSi. rogorc zemoT moyvanilidan Cans $\omega = \sqrt{\omega_0^2 - \delta^2}$. e.i. rxevis milevas maSin aqvs adgili, rodesac $\omega_0^2 > \delta^2$. aqedan gamodis, rom $R-$winaRobis gazrdiT sixSire mcirdeba (periodi izrdeba $T = \frac{2\pi}{\omega} = \frac{2\pi}{\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}}$) da rxeva TandaTan miileva.



piriqiT $L-$is gazrda iwvevs sixSiris zrdas (periodi mcirdeba). e.i. winaRoba xels uSlis rxevis SenarCunebas, xolo induqciuroba xels uwyobs.

$3. wanacvlebis deni. maqsvelis gantolebebi.

aqamde eleqtrul denSi vgulisxmobdiT muxtebis mimarTul moZraobas. aseT dens gamtarobis deni ewodeba. aseve cnobilia, rom gamtarobis denis wirebi aucileblad Caketili unda iyos. mudmivi denis Sem-Si es yovelTvis sruldeba, magram aramudmivi denis Sem-Si gamtarobis denis wirebi SeiZleba Cauketavi aRmoCndes. mag. cvladi denis wredSi SeiZleba CarTuli iyos kondensatori. radganac mis Semonafenebs Soris muxtebis gadaadgileba ar xdeba, amitom gamodis, rom cvladi deni SeiZleba arsebobdes Cauketav konturSi. imisTvis rom, denis wirebis Caketiloba gaevrcelebina cvladi denis Sem-Sic, maqsvelma Semoitana wanacvlebis denis cneba.

cnobilia maqsvelis pirveli ZiriTadi debuleba: magnituri velis yovelgvari cvlilebisas droSi warmoiqmneba grigaluri eleqtruli veli. aseve am Teoriis meore ZiriTadi debulebaa Sebrunebuli movlena: el. velis yovelgvari cvlileba droSi iwvevs grigaluri magn. velis warmoqmnas. radgan magn. veli yovelTvis dakavSirebulia eleqtrul denTan, amitom maqsvelma cvlad el. vels uwoda wanacvlebis deni. amiT man es ganasxvava gamtarobis denisgan, romelic ganpirobebulia muxtebis mimarTuli moZraobiT.

wanacvlebis denis SemoRebis Semdeg Seicvala Cveni warmodgena cvladi denis wredis Cauketavobis Sesaxeb. mudmivi denis wredi yovelTvis Caketilia. rac Seexeba cvladi denis wreds is SeiZleba iyos Cauketavi. amas maSin aqvs adgili, roca cvladi denis wredi Seicavs kondensators (mudmivi deni kondensatorSi ar gadis). kondensatoris damuxtvisas da ganmuxtvis dros deni gadis Semonafenebis SemaerTebel gamtarSi da ar gadis Semonafenebs Soris dieleqtrikSi. maqsvelis mixedviT rogorc avRniSneT aseve piriqiT el. velis cvlilebisas unda aRiZras grigaluri magn. veli. maqsvelma am cvlad el. vels, romelic qmnis magn. vels daarqva wanacvlebis deni, romelic gansxvavdeba gamtarobis denisagan, romelic gamowveulia damuxtuli nawilakebis mowesrigebuli moZraobiT. maSasadame wanacvlebis denis aRZvrisaTvis maqsvelis Tanaxmad saWiroa cvladi el. velis arseboba. cnobilia, rom mudmivi denis wredi unda iyos Caketili. Tu wredSi gvaqvs kondensatori, maSin aseT wredSi mudmivi deni ar gadioda. maqsvelamde Tvlidnen, rom cvladi denis Sem-Si kondensatoris firfitebs Soris deni ar gadioda da deni gadis mxolod SemaerTebel sadenebSi kondensatoris damuxtvisa da ganmuxtvis dros. firfitebs Soris dieleqtrikSi deni ar gadioda, e.i. wredi araa Caketili. maqsvelma ki aCvena, rom nebismieri cvladi denis wredic Caketilia, anu gadis kondensatoris Semonafenebs Soris dieleqtrikSi da am dens ewodeba wanacvlebis deni. firfitebs Soris radgan gvaqvs wanacvlebis deni, gvaqvs cvladi el. veli da firfitebs Soris aRiZvreba magn. veli. vTqvaT firfitebs Soris dieleqtrikia da maT Soris erTgvarovani el. velia, romelic icvleba kondensatoris damuxtvisa da ganmuxtvis dros drois mixedviT. Tu firfitebs gamtariT SevaerTebT maqsvelis Tanaxmad es cvladi el. veli kondensatorSi nebismier dros qmnis iseT magn. vels, TiTqos firfitebs Soris gvaqvs iseTi deni, romlis Zala da simkvrive im denis tolia, romelic gadis SemaerTebel sadenebSi, e.i. sadenebSi rodesac gadis gamtarobis deni, misi wirebi ganicdian wyvetas dieleqtrikis zedapirze. dieleqtrikSi velis gavleniT dieleqtrikis atomebTan da molekulebTan dakavSirebuli muxtebi wainacvleba da swored am bmuli muxtebis wanacvlebas ewodeba wanacvlebis deni, gansxvavebiT im denisgan, romelic miiReba gamtarSi Tavisufali muxtebis gadaadgilebiT. maqsvelis Tanaxmad gamtarobis denis wirebi uwyvetad gadadian wanacvlebis denis wirebSi. **maSasadame bunebaSi arseboben mxolod Caketili denebi.** SeiZleba iTqvas, rom gamtarobis da wanacvlebis denis simkvriveebi

erTmaneTis tolia $j_{wan.} = J$. e.i. gare wredSi gamtarobis denis wirebi uwyvetad gadadian firfitebs Soris wanacvlebis denis wirebSi (gamtarobis deni ikvreba wanacvlebis deniT). maSasadame el. velis cvlilebisas (rogorc vakuumSi, aseve dieleqtrikSi) aRiZvreba wanacvlebis deni da masTan Sekruli magn. veli. vakuumSic ki el. velis yovelgvari cvlileba garemomcvel sivrceSi aRZravs magn. vels. es aris maqsvelis Teoriis ZiriTadi Sedegi – wanacvlebis deni aRiZvreba yovelTvis, roca sivrceSi icvleba el. veli. maSasadame gamtarSi gamavali cvladi deni gaivlis kondensatorSi wanacvlebis denis saxiT, anu kondensatori atarebs cvlad dens imis gamo, rom Semonafenebze icvleba muxti da masTan erTad el. veli, rac warmoqmnis wanacvlebis dens. e.i. **bunebaSi yvela el. denebi Sekrulia. es aris maqsvelis daskvna.**

wanacvlebis dens ar axasiaTebs gamtarobis denis arc erTi Tviseba (siTburi, qimiuri da sxva), garda erTisa – igi qmnis magnitur vels.

maqsvelma ganazogada cdiseuli kanonebi da Seqmna el.magn. velis Teoria, romelsac nebismieri muxtebi da denebi qmnian. am Teoriis Tanaxmad maqsvelma Camoayaliba ZiriTadi integraluri gantolebebi:

1. **maqsvelis pirveli gantoleba (eleqtromagn. induqciis kanoni).** eleqtromagnituri induqciis kanonidan $\varepsilon = -\frac{d\Phi}{dt}$. cnobilia $\varepsilon = \oint_l (\vec{E}d\vec{l})$ da $\Phi = \int_S (\vec{B}d\vec{S})$, amitom $\oint_l (\vec{E}d\vec{l}) = -\frac{\partial\Phi}{\partial t}$

es aris uZrav konturSi aRZruli induqciis em Zala, roca is moTavsebulia cvlad magn. velSi anu **el. velis daZabulobis cirkulacia nebismieri Caketili l konturis gaswvriv tolia am konturis momWimavi zedapiris gamWoli magn. nakadis cvlilebis siCqarisa Sebrunebuli niSniT.** radgan el. veli SeiZleba iyos rogorc potenciuri $\vec{E}_q$, aseve grigaluri $\vec{E}_B$. Aamitom mTliani daZabuloba $\vec{E} = \vec{E}_q + \vec{E}_B$. Mmagram $\vec{E}_q$-s cirkulacia nulis tolia da mTliani cirkulacia toli iqneba $\oint_l \vec{E}d\vec{l} = -\oint_S \frac{\partial B}{\partial t} d\vec{S}$. e.i. es gan-ba gviCvenebs, rom el. velis wyaro SeiZleba iyos ara marto el. muxtebi, aramed drois mixedviT cvladi magn. velebi, amasTan meore Sem-Si is grigaluri xasiaTisaa.

2. maqsvelis meore gantoleba (kanoni, romelic akavSirebs magnitur vels eleqtrul denTan). zogadi Teorema $\vec{H}-$is cirkulaciis Sesaxeb, anu sruli denis kanoni: Caketili konturis gaswvriv magn. velis daZabulobis cirkulacia udris am konturis SigniT gamavali denebis algebrul jams: $\oint_L \vec{H}d\vec{l} = \sum I$. aq gaTvalis-winebulia rogorc gamtarobis, aseve wanacvlebis denebi. e.i. $I = I_{g.} + I_{w.}$ I_g gamtarobis deni igivea, rac I_{makro} makrodenebis, amitom $\oint_l (\vec{H}d\vec{l}) = I_{makro} + I_w$. es gantoleba ase ikiTxeba: **magnituri velis daZabu-lobis cirkulacia nebismieri Caketili l konturis gaswvriv tolia im makro da wanacvlebis denebis algebruli jamisa, romelsac es konturi moicavs.** e.i magn. veli SeiZleba aRiZras an el. denebiT (moZravi muxtebiT), an cvladi el. velebiT.

3. **maqsvelis mesame gantoleba (gausis Teorema el.statikuri velisTvis dieleqtrikSi) –** el.statikuri induqciis veqtoris nakadi dieleqtrikSi nebismier Caketil konturSi tolia am zedapiris SigniT muxtebis algebruli jamisa

$\oint_S \vec{D}d\vec{S} = q$, sadac $\oint_S \vec{D}d\vec{S} = N$ aris el. induqciis nakadi S Caketili zedapiris mimarT, xolo $q = \sum q_i$ – zedapiris SigniT moTavsebuli Tavisufal muxtTa algebruli jami. **eleqtruli induqciis nakadi el.magn. velSi azrobrivad gavlebuli nebismieri Caketili zedapiris mimarT tolia am zedapiris SigniT moTavsebuli Tavisufal muxtTa algebruli jamisa.** e.i. eleqtruli veli iqmneba Tavisufali muxtebiT. rac Seexeba bmuli (polarizirebul) muxtebis vels, maTi gaTvaliswineba xdeba arapirdapiri gziT-dieleqtrikuli SeRwevadobis saSualebiT. aqdan Cans rom $\vec{D}$ – s wirebi SeiZleba iwyebodnen da mTavrdebodnen muxtze.

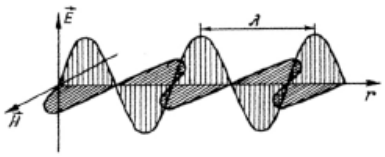
4. maqsvelis meoTxe gantoleba (gausis Teorema $\vec{B}$ magn. velisTvis) – magn. induqciis veqtoris nakadi nebismier Caketil konturSi nulis tolia $\oint_S (\vec{B}d\vec{S}) = 0$. **magnituri induqciis nakadi el.magn. velSi azrobrivad gavlebuli nebismieri Caketili zedapiris mimarT nulis tolia.** es gant-ba asaxavs $\vec{B}$ – s im Tvisebas, rom misi wirebi Caketilia. es gantoleba gviCvenebs, rom Tavisufali magnituri muxtebi ar arsebobs. am gant-bebidan gamomdinareobs, rom el. velis wyaroebia an el. muxtebi, an cvladi magn. velebi, xolo magn. velis: an moZravi muxtebi (el. denebi), an cvladi el. velebi.

$4. eleqtromagnituri veli. eleqtromagnituri talRa. eleqtromagnituri Tvisebebi.

sivrceSi eleqtruli velis cvlilebis Sedegad warmoiqmneba aseve cvladi magn. veli. am magn. velis daZabuloba proporciulia eleqtruli velis cvlilebis siCqarisa $H \sim |\frac{d\vec{D}}{dt}|$. Aaq $\vec{D}$-eleqtrostatikuri induqciis veqtoria, romelic $\vec{E}$ – el. velis daZabulobis veqtorTan aseT kavSirSia $\vec{D} = \varepsilon_0 \varepsilon \vec{E}$. Aaq ε_0 eleqtruli mudmivaa, xolo ε dieleqtrikuli SeRwevadoba. Aaseve aRmoCnda, rom magn. velis cvlilebis Sedegad warmoiSoba el. veli. magn. velis cvlilebis Sedegad warmoqmnili eleqtruli velis daZabuloba proporciulia magn. velis cvlilebis siCqaris $E \sim |\frac{d\vec{B}}{dt}|$. aRsaniSnavia, rom muxtis el.statikuri velisgan gansxvavebiT, romelic potencialur vels warmoadgens, magn. velis cvlilebis Sedegad warmoqmnili el. veli grigaluria, anu misi Zalwirebi Caketilia.

sabolood gvaqvs, rom cvlad el. velTan dakavSirebulia cvladi (grigaluri-romlis Zalwirebi yovelTvis Sekrulia) magn. veli da cvlad magn. velTan – cvladi (grigaluri) el. veli. Aam erTmaneTTan dakavSirebul cvladi eleqtruli da magnituri velebis erTobliobas **eleqtromagnituri veli ewodeba.**

maqsvelis Teoriidan gamomdinareobs, rom Tu raime saSualebiT sivrceSi warmoiqmna cvladi eleqtruli an magnituri veli, garemomcvel sivrceSi adgili eqneba cvladi eleqtruli da magnituri velebis urTierT-gardaqmnis process, romelic vrceldeba wertilidan wertilamde da periodulia rogorc droSi, ise sivrceSi e.i. warmoadgens talRur process – el.magn. talRas. es talRa xasiaTdeba periodulad cvladi ori veqtoriT: eleqtruli daZabulobis $\vec{E}$ da magnituri daZabulobis $\vec{H}$ veqtoriT. aseTi talRebi pirvelad miiRo da gamoikvlia hercma. am talRebs gaaCniaT Semdegi Tvisebebi: 1. elmagn. talRa ganivia, anu misi $\vec{E}$ da $\vec{H}$ veqtorebi irxevian talRebis gavrcelebis da urTierTmarTobulad. $\vec{E}$ da $\vec{H}$ periodulad cvladebi arian. 2. elmagn. talRa vakuumSi vrceldeba sinaTlis siCqariT $c = 3 \cdot 10^8$ m/wm, xolo raime garemoSi $v = \frac{c}{\sqrt{\varepsilon\mu}}$, sadac ε da μ garemos



dieleqtrikuli da magnituri SeRwevadobebia. 3. elmagn. talRis $\vec{E}$ da $\vec{H}$ veqtorebis modulebi erTmaneTTan dakavSirebuli arian tolobiT $\sqrt{\varepsilon_0 \varepsilon}\, E = \sqrt{\mu_0 \mu}\, H$. ε_0 da μ_0 eleqtruli da magnituri mudmivebia.