Comparative Analysis of Some Types of Free Electron Lasers

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* Strophotron

Intensive Standing Wave

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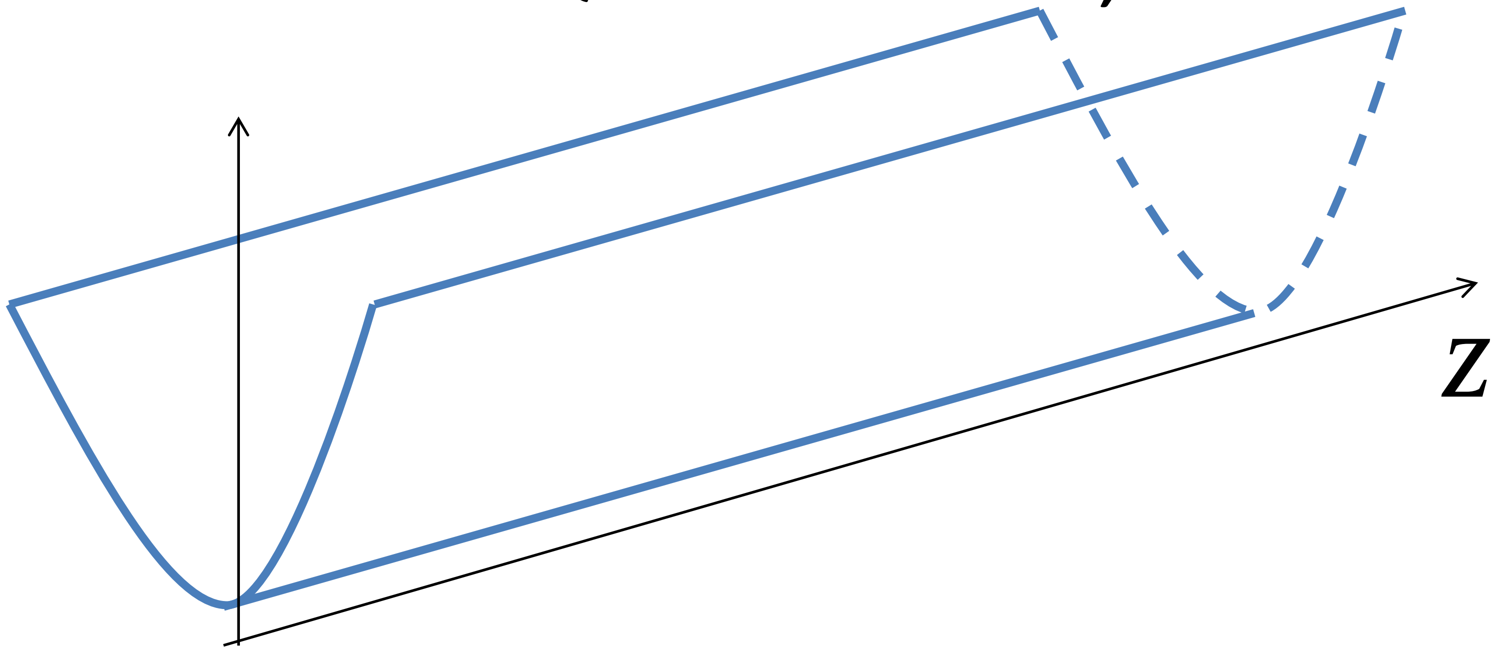
* Smith-Purcell Radiation

Strophotron

M.V. Fedorov and K.B. Oganesyan
IEEE J.of Quant. Electr., 1988



$$\frac{d\mathbf{p}}{dt} = e[\mathbf{vH}] \qquad \boxed{x(\mathrm{t}) = a_0 \cos\left(\Omega t + \theta_0\right),} \qquad a_0 = \sqrt{x_0^{\,2} + \frac{\alpha^2}{\Omega^2}},$$

$$\boxed{z(\mathrm{t}) = \mathrm{t} + \left\{-\left(\frac{1}{2\gamma^2} + \frac{a_0^{\,2}\Omega^2}{4}\right)t + \frac{a_0^{\,2}\Omega}{8}\left[\sin(2\Omega\,\mathrm{t} + \varphi_0) - \sin\varphi_0\right]\right\}}$$

$$\sin\theta_0 = -\frac{\alpha/\Omega}{a_0}. \qquad \cos\theta_0 = \frac{x_0}{a_0},$$

$$\boxed{\frac{d\varepsilon}{d\omega do} = \frac{e^2\omega^2}{4\pi^2}\left|\int_o^T dt\dot{x}e^{i\omega(\mathrm{t}-\mathrm{z})}\right|^2}$$

$$\frac{d\varepsilon}{d\omega do} = \frac{T^2e^2\omega^2 a_0^{\,2}\Omega^2}{16\pi^2}\sum_{s=0}^{\infty}\frac{\sin^2 u_s}{u_s^{\,2}}\left[\mathrm{J}_s(\mathrm{Z}) - \mathrm{J}_{s+1}(\mathrm{Z})\right]^2$$

$$u_s = \frac{T}{4\gamma^2}\left[\omega\left(1 + \frac{\gamma^2 a_0^{\,2}\Omega^2}{2}\right) - 2\gamma\Omega(2\,\mathrm{s}+1)\right] \qquad \omega_{res} = \frac{2\gamma^2\Omega}{1 + \dfrac{\gamma^2 a_0^{\,2}\Omega^2}{2}}$$

$$Z = \frac{\omega a_0^{\,2}\Omega^2}{8\Omega}$$

$$A_x = -\frac{E_0}{\omega}\sin\omega(\mathrm{t}-\mathrm{z})$$

$$\frac{d\varepsilon}{dt} = e\boldsymbol{vE} = eE_0 v_x \cos\omega(\mathrm{t}-\mathrm{z}).$$

$$\frac{d\varepsilon}{dt} = eE_0 v_x^{(1)} \cos\omega\left(t - z^{(0)}\right) + eE_0 \omega v_x^{(0)} z^{(1)} \sin\omega\left(t - z^{(0)}\right)$$

$$\left(\Delta\varepsilon = \int_0^T \frac{d\varepsilon}{dt} dt\right) \qquad G = \frac{4\pi N_e}{E_0^{\ 2}}\Delta\varepsilon,$$

$$\Delta\varepsilon = \frac{e^2 \mathrm{E}_0^{\ 2} T^3 \omega a_0^{\ 2}\Omega^2}{64\varepsilon_0}\left(\frac{1}{2\gamma^2} + \frac{a_0^{\ 2}\Omega^2}{4}\right)\sum_{n,m,k}^{\infty}\left[J_n(\mathrm{Z}) - J_{n+1}(\mathrm{Z})\right]^2 \frac{d}{du}\left(\frac{\sin u}{u}\right)^2,$$

$$G = 7.6\times10^{-3}\frac{N_e r_0 L^{5/2}}{\sqrt{d_e}\gamma^{7/2}} = 2\times10^6 \frac{\mathrm{I(A)\,r_0}\, L^{5/2}}{d_e^{\ 5/2}\gamma^{7/2}} \qquad \omega = 5.3\times10^7 \gamma^2 d_e g$$

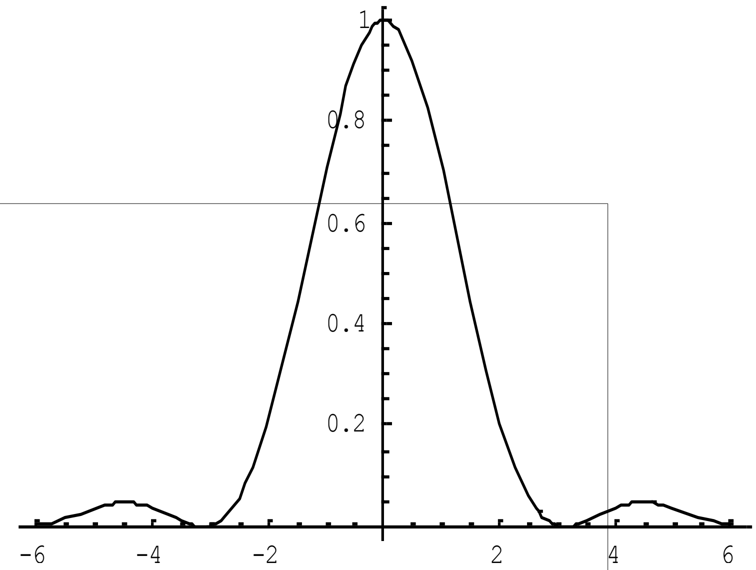
$$r_\mathrm{e} = \frac{e^2}{m_\mathrm{e}c^2} = 2.8179403267(27)\times10^{-13}\ \mathrm{cm}$$

$$d_e = 1cm, \ldots I = 10A, \ldots \gamma = 10, \ldots g = 10 Oe/cm, \ldots L = 3m$$

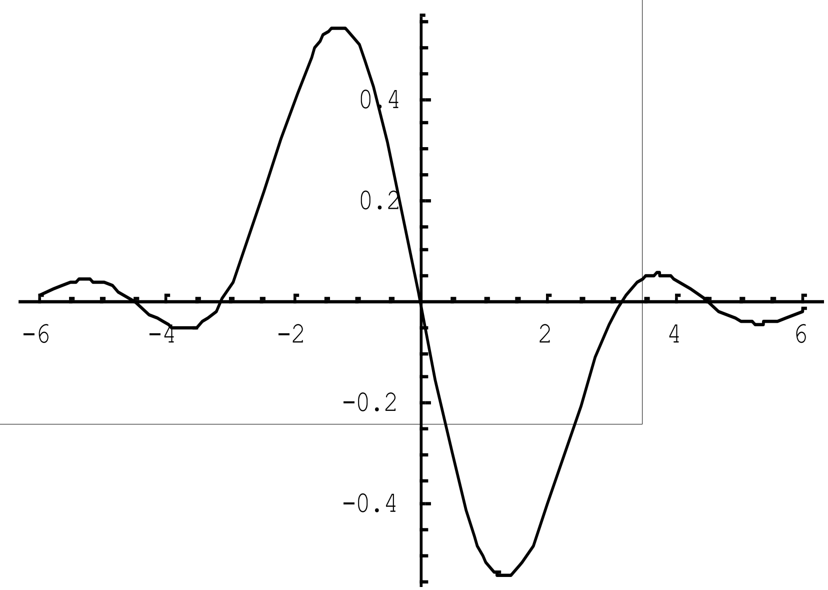
$$G \approx 0.3\%, \ldots\ldots. \omega = 5.3\times10^{13} s^{-1} (\lambda = 36\mu m)$$

Madey theorem

$$\frac{Sin^2 x}{x^2}$$



$$\partial_x \left(\frac{Sin^2 x}{x^2} \right)$$



Intensive Standing Wave

$$\overrightarrow{A^{(0)}} \parallel Oy$$

$$A^{(0)} = \frac{1}{\omega_0}\left[E_1 \cos \omega_0 (t - x) - E_2 \cos \omega_0 (t + x)\right]$$

$$H = \left[P_z{}^2 + P_x{}^2 + \left(P_y - eA^{(0)}\right)^2 + m^2\right]^{1/2} \approx p_z + \frac{1}{p_z}\left[p_x{}^2 + \left(P_y - eA^{(0)}\right)^2 + m^2\right]$$

It is assumed, that the electron momentum along the p_z axis is much greater than the other components of the momentum p_x and p_y . ***Py = 0***

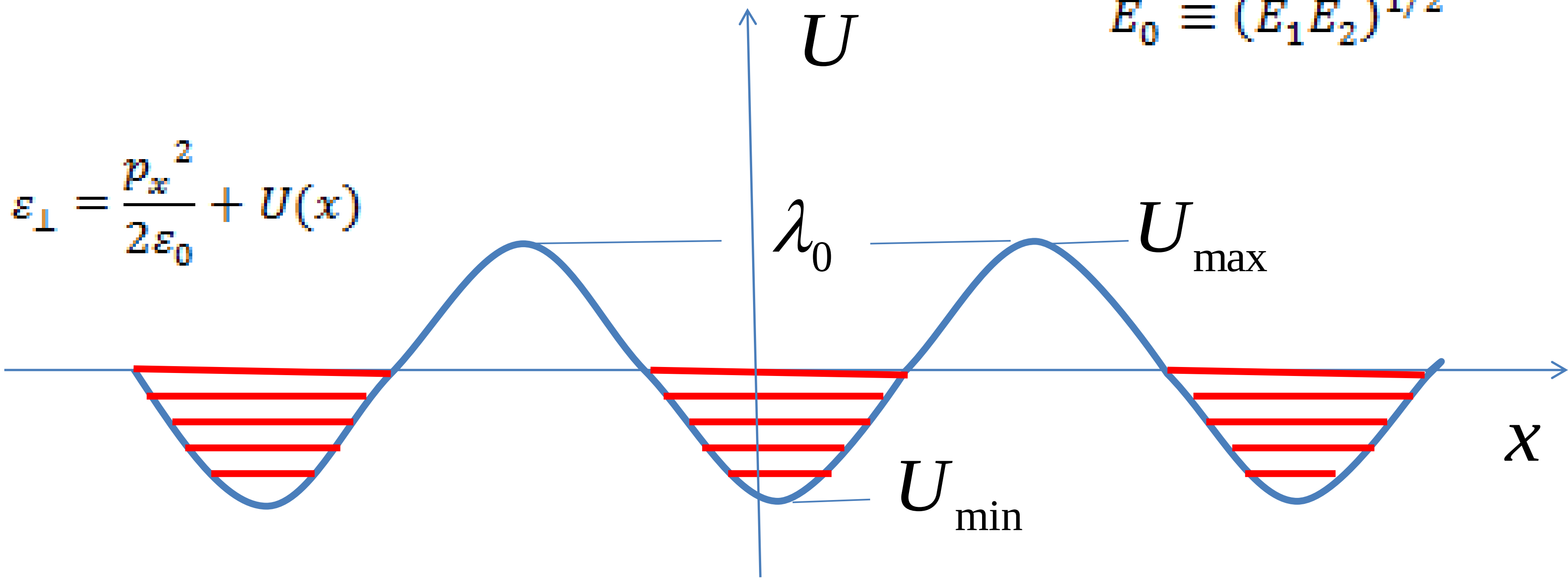
$$H_x \approx \frac{1}{2\varepsilon_0}\left[p_x{}^2 + e^2 A^{(0)2} m^2\right] \qquad p_z \approx \varepsilon \approx \varepsilon_0 \qquad 2\pi/\omega_0$$

$$\overline{H_x} = \frac{p_x{}^2}{2\varepsilon_0} - \frac{e^2 E_1 E_2 \cos 2\omega_0 x}{2\omega_0{}^2 \varepsilon_0} + const \approx \frac{p_x{}^2}{2\varepsilon_0} + \frac{e^2 E_1 E_2 x^2}{\varepsilon_0} + const$$

$$U(x) = -\frac{e^2 E_1 E_2}{2\varepsilon_0 \omega_0{}^2} \cos 2\omega_0 x \qquad \Omega = \frac{e(2E_1E_2)^{1/2}}{\varepsilon_0} \equiv \frac{eE_0 2^{1/2}}{\varepsilon_0}$$

$$E_0 \equiv (E_1 E_2)^{1/2}$$

$$\varepsilon_\perp = \frac{p_x{}^2}{2\varepsilon_0} + U(x)$$



$$g_{eff} = \frac{2eE_1E_2}{\varepsilon_0}.$$

$$\Omega < \omega_0$$

$$U_{max} - U_{min} = \frac{1}{2}\varepsilon_0(\Omega/\omega_0)^2 \ll \varepsilon_0 \qquad A = \frac{E}{\omega}cos\omega(t-z)$$

$$\frac{d\varepsilon}{dt} = -e\boldsymbol{v}\boldsymbol{E}_{tot} = -ev_x E\sin\omega(t-z) - ev_y[E_1\sin\omega_0(t-z) - E_2\sin\omega_0(t+z)$$

$$\Delta\varepsilon = -\frac{e^2 E_0{}^2 t^3 \Omega^2 a^2 \omega}{32\varepsilon_0}\left(1 - v_{z0} + \frac{a^2\Omega^2}{2}\right)\sum_{s=0}^{\infty}\frac{d}{du_s}\left(\frac{\sin u_s}{u_s}\right)^2 [J_s(Z) - J_{s+1}(Z)]^2$$

$$u_s = \frac{t}{2}\left[\omega\left(1 - v_{z0} + \frac{a^2\Omega^2}{4}\right) - \Omega(2s+1)\right] \qquad \gamma\Omega a \ll 1 \quad Z \ll 1 \quad s = 0$$

$$G = \frac{\pi^3 r_0 N_e l^3 \Omega^3}{16\gamma\omega_0{}^2 v_{z0}{}^3}\frac{d}{du}\left(\frac{\sin u}{u}\right)^2, \quad u = \frac{t}{2}[\omega(1 - v_{z0}) - \Omega]$$

$$\omega \approx \Omega(1 - v_{z0})^{-1}$$

$$\Omega_0 = 3.27 \times 10^{11} \frac{W^{1/2}}{\gamma d (c\tau)^{1/2}}, \quad \omega = \frac{\Omega_0}{1 - v_0} \qquad G = 4.5 \times 10^{-12} \frac{N_e d_0{}^2 \gamma}{\gamma^2 - 1} \left(\frac{\Omega_0}{\omega_0}\right)^2$$

$$\lambda_0 = 9.6 \times 10^{-4} cm \qquad \omega_0 = 1.96 \times 10^{14} sec^{-1} \qquad \Omega_0/\omega_0 = 1/3$$

$$\frac{1}{\gamma d}\left(\frac{W}{c\tau}\right)^{1/2} = 2\times 10^2$$

$$v_0 = 0.44c,,,,,,\gamma = 1.116$$

$$\varepsilon_{0,kin} = (\gamma - 1)\,\mathrm{mc}^2 = 65keV \qquad W = 1J \qquad \tau = 1.6ps$$

$$d_0 = 2\times 10^{-2} cm \qquad N_e = 10^{13} cm^{-3} \qquad j = 50kA/cm^2$$

$$G \approx 1\% \qquad \omega \approx 1.18\times 10^{14} s^{-1} \qquad \lambda \approx 16\times 10^{-4} cm$$

M.V. Fedorov, K.B. Oganesyan and A.M. Prokhorov
Appl. Phys. Lett., JETP; 1988

The research direction suggested in this papers was studied recently with the aim of creating high-power lasers. Here are some of the institutions, where the studies were done:

Univ. Bordeaux, CELIA (Centre Lasers Intenses et Applications, France),

Eindhoven University of Technology (Netherlands),

INFN-Frascati (Italy).

www.lasphys.com

25 th International Laser Physics Workshop

Yerevan, Armenia

2016 July 11 - 15

LPHYS'16 will be dedicated to paying tribute to two major events:
Next year the scientific world will celebrate

100th anniversary of Alexander M Prokhorov,
the Nobel Prize winner in physics of 1964 (for lasers) and

100th anniversary of the Optical Society (OSA) of America.

Inhomogeneous Magnetic Field

K.B. Oganesyan, JMO, **61**, Issue 9, **61**, Issue 17, 2014 JCP, **50**, 2, 2015)

$$\mathbf{A}_w = -\frac{H_0}{q_0}\cosh q_0 x \sin q_0 z \mathbf{j}$$

E. Jerby. NIM, **A27**, 457 (1988).

we consider paraxial approximation when $q_0 x < 1,$ $\quad \frac{d\mathbf{p}}{dt} = e[\mathbf{vH}]$

$$x = a_0 \cos\left(\Omega t + \theta_0\right), \quad \Omega = \frac{eH_0}{\sqrt{2}\varepsilon}, \quad a_0 = \sqrt{x_0^{\ 2} + \frac{\alpha^2}{\Omega^2}}, \quad \sin\theta_0 = -\frac{\alpha/\Omega}{a_0}. \quad \cos\theta_0 = \frac{x_0}{a_0},$$

$$z = t\left(1 - \frac{1}{2\gamma^2} - \frac{\Omega^2}{2q_0^{\ 2}}\right) + \frac{\Omega^2}{4q_0^{\ 3}}\sin 2q_0 t + \frac{a_0^{\ 2}\Omega^2}{16q_0}\sin\left\{2\left(q_0 + \Omega\right)t + 2\theta_0\right\} + \frac{a_0^{\ 2}\Omega^2}{16q_0}\sin\left\{2\left(q_0 - \Omega\right)t - 2\theta_0\right\}.$$

$$1 - v = \frac{1}{2\gamma^2} \quad \gamma = \frac{\varepsilon}{mc^2} \quad e^{-iA\sin x} = \sum_{n=-\infty}^{\infty} J_n(\mathrm{A}) e^{-inx} \quad a_0 q_0 < 1, \quad \frac{\Omega}{q_0} < 1, \quad a_0\Omega < 1.$$

$$\frac{d\varepsilon}{d\omega do}=\frac{e^2\omega^2\Omega^2T^2}{8\pi^2 q_0^{\;2}}\sum_{n,m,k=-\infty}^{\infty}\left(I_{n+1,k,m}-I_{n,k,m}\right)^2\left(\frac{\sin u}{u}\right)^2,$$

$$\left[\begin{array}{l} u=\dfrac{T}{2}\left[\omega\left(\dfrac{1}{2\gamma^2}+\dfrac{\Omega^2}{2q_0^{\;2}}\right)-(2\mathrm{n}+1)q_0-2m\Omega\right], \\ I_{n,k,m}=J_{n-k}\left(Z_1\right)J_{\frac{k+m}{2}}\left(Z_2\right)J_{\frac{k-m}{2}}\left(Z_2\right), \\ Z_1=\dfrac{\omega\Omega^2}{4q_0^{\;3}},Z_2=\dfrac{\omega a_0^{\;2}\Omega^2}{4q_0}. \end{array}\right.$$

$$\omega_{\mathrm{res,und}}=\frac{2\gamma^2 q_0}{1+\gamma^2\dfrac{\Omega^2}{q_0^{\;2}}},\qquad \omega_{\mathrm{res,str}}=\frac{2\gamma^2\Omega}{1+\gamma^2\dfrac{\Omega^2}{q_0^{\;2}}}.$$

$$\mathbf{A}_w=-\frac{E_0}{\omega}\sin\omega(t-z)\mathbf{i}\qquad \frac{d\varepsilon}{dt}=e\boldsymbol{vE}=eE_0 v_x\cos\omega(\mathrm{t}-\mathrm{z}).$$

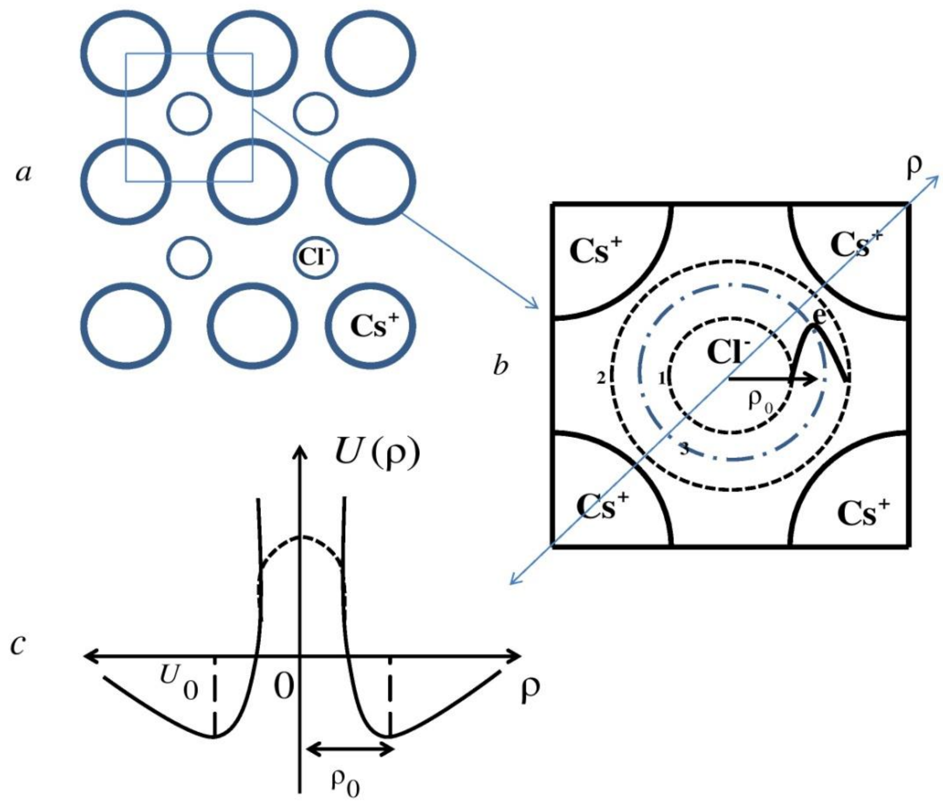
$$\frac{d\varepsilon}{dt}=eE_0 v_x^{(1)}\cos\omega\left(t-z^{(0)}\right)+eE_0\omega v_x^{(0)}z^{(1)}\sin\omega\left(t-z^{(0)}\right)$$

$$\left\{\begin{array}{l} \dfrac{dp_x^{(1)}}{dt}=-\varepsilon_0\Omega^2 x^{(1)}+eE_0\left(1-v_z^{(0)}\right)\cos\omega\left(t-z^{(0)}\right), \\ \dfrac{dp_z^{(1)}}{dt}=eE_0 v_x^{(0)}\cos\omega\left(t-z^{(0)}\right). \end{array}\right.$$

$$\left(\Delta\varepsilon=\int_0^T\frac{d\varepsilon}{dt}dt\right)\qquad G=\frac{4\pi N_e}{E_0^{\;2}}\Delta\varepsilon,$$

$$G=\frac{e^2\omega^2\Omega^2N_eT^3}{4\pi q_0^{\;2}\gamma^2}\left(1+\gamma^2\frac{\Omega^2}{q_0^{\;2}}\right)\sum_{n,m,k}^{\infty}\left(I_{n+1,m,k}-I_{n,m,k}\right)^2\frac{d}{du}\left(\frac{\sin u}{u}\right)^2,$$

Positron Channeling in Ionic Crystals



The annihilation processes of positrons with medium electrons are investigated in detail. The lifetime of a positron in the regime of channeling is estimated; the existence of a long relaxation lifetime has been shown.

10^{-6}sec

JMO_2009,2015; LPL_2015, JCP_2016

Channeling and quasi-characteristic radiation of charged particles in charged axes of CsCl-type ionic crystals

N.V. Maksyuta, V.I. Vysotskii, S.V. Efimenko

Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms
Volume 355, 15 July 2015, Pages 90–93
Proceedings of the 6th International Conference “Channeling 2014: Charged & Neutral Particles Channeling Phenomena” October 5-10, 2014, Capri, Italy

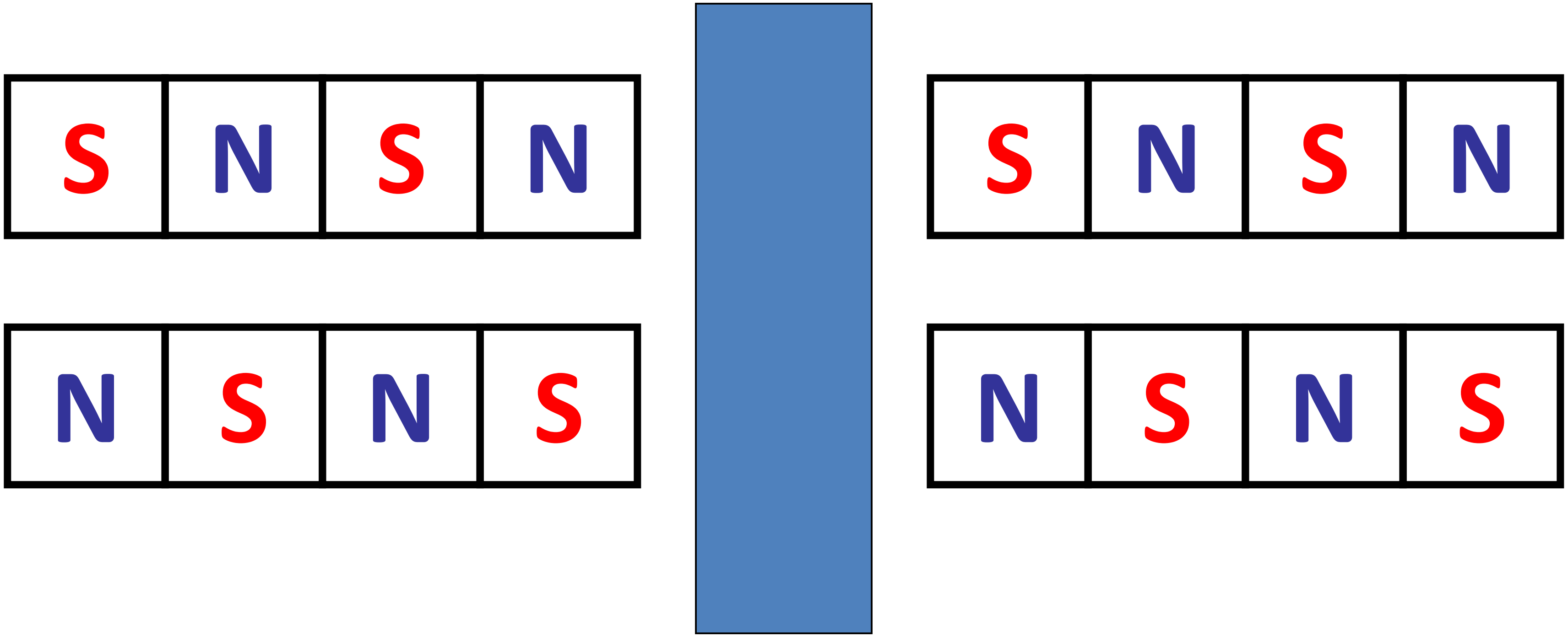
A.W. Hunt a,b,*, D.B. Cassidy a,b, F.A. Selim c, R. Haakenaasen d, T.E. Cowan b, R.H. Howell b, K.G. Lynn e, J.A. Golevchenko a

The recently constructed 3 MeV monoenergetic positron beamline Pelletron at Lawrence Livermore National Laboratory has sufficient flux (10^5 ps/s) to demonstrate the dramatic new annihilation effects expected from channeled positron experiments.

Free Electron Laser Without Inversion

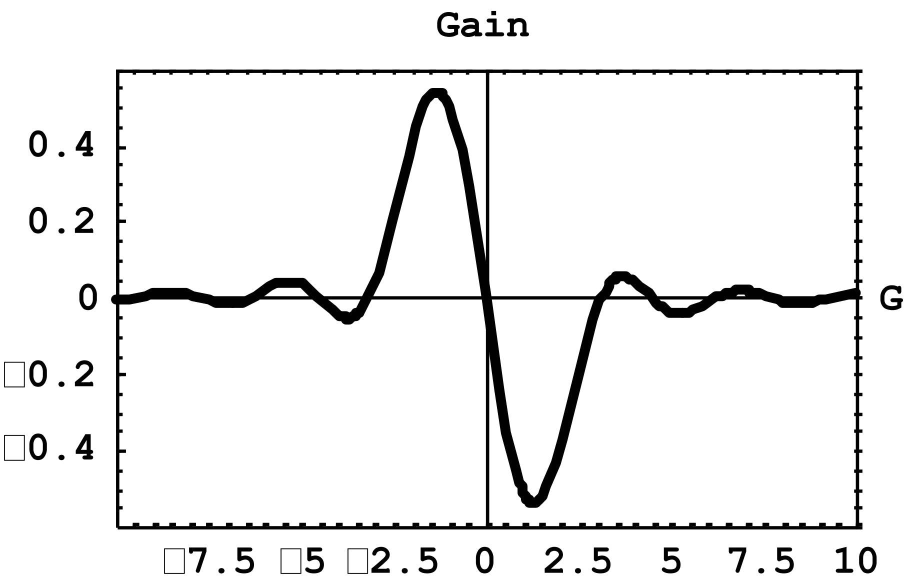
LP_2007; PS_2010, LPL_2014, JCP_2016, JMO_2015

More specifically, the idea of FELWI is based on a two-wiggler scheme with a specially organized dispersion region between the wigglers.

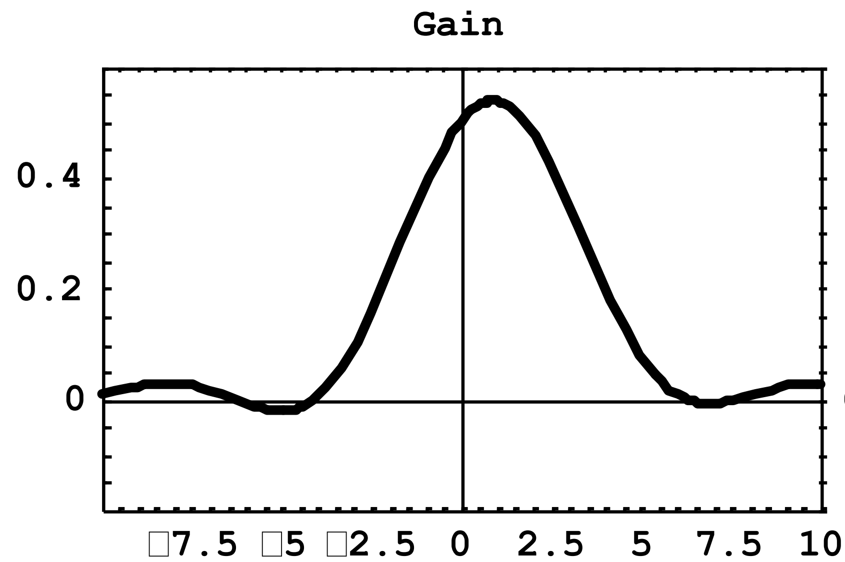


$$\lambda = \frac{\lambda_0}{2\gamma^2}\left(1 + K^2\right)$$

$$K = \frac{eH_0\lambda_0}{2\pi mc^2}$$



FEL



FELWI

$$\int G(\Omega)d\Omega = 0$$

$$\int G(\Omega)d\Omega > 0$$

$$\omega_{res} = 2\gamma^2 c k_w$$

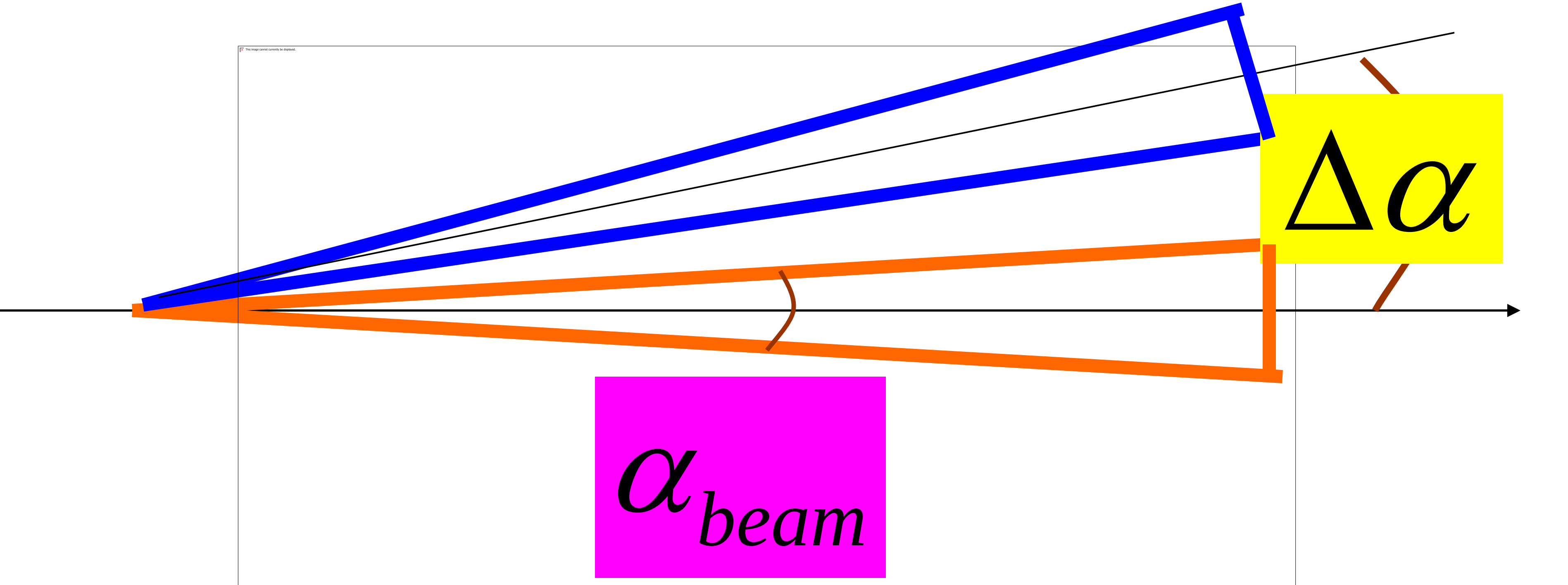
where $\gamma = E/mc^2 ? \; 1$ $\quad k_w = 2\pi/\lambda_0$

Alternatively, at a given frequency ω , this relation determines a resonance value of the electron relativistic factor γ

$$\gamma_{res} = \left(\omega / c k_w\right)^{1/2} \qquad E_{res} = mc^2 \left(\omega / c k_w\right)^{1/2}$$

FELWI mechanism can work only if the interaction-induced deviation of electrons(with characteristic angle $\Delta\alpha$) is larger than the angular width of electron beam α_{beam}

$$\Delta\alpha > \alpha_{beam}$$



$$\Delta\alpha > \alpha_{beam}$$

A transverse velocity v_x and the energy ΔE acuired by an electron after a passage through the undulator are directly proportional to each other

$$v_x = c\theta \frac{\Delta E}{E_0}$$

D.E. Nikonov, M.O. Scully, G.Kurizki, Phys.Rev. E 54, 6780 (1996)

A.I. Artemiev, M.V. Fedorov, Yu.V. Rostovtsev, G.Kurizki, M.O. Scully, Phys.Rev.Lett. 85, 4510 (2000)

Which gives in the first order the following estimate of the electron deviation angle

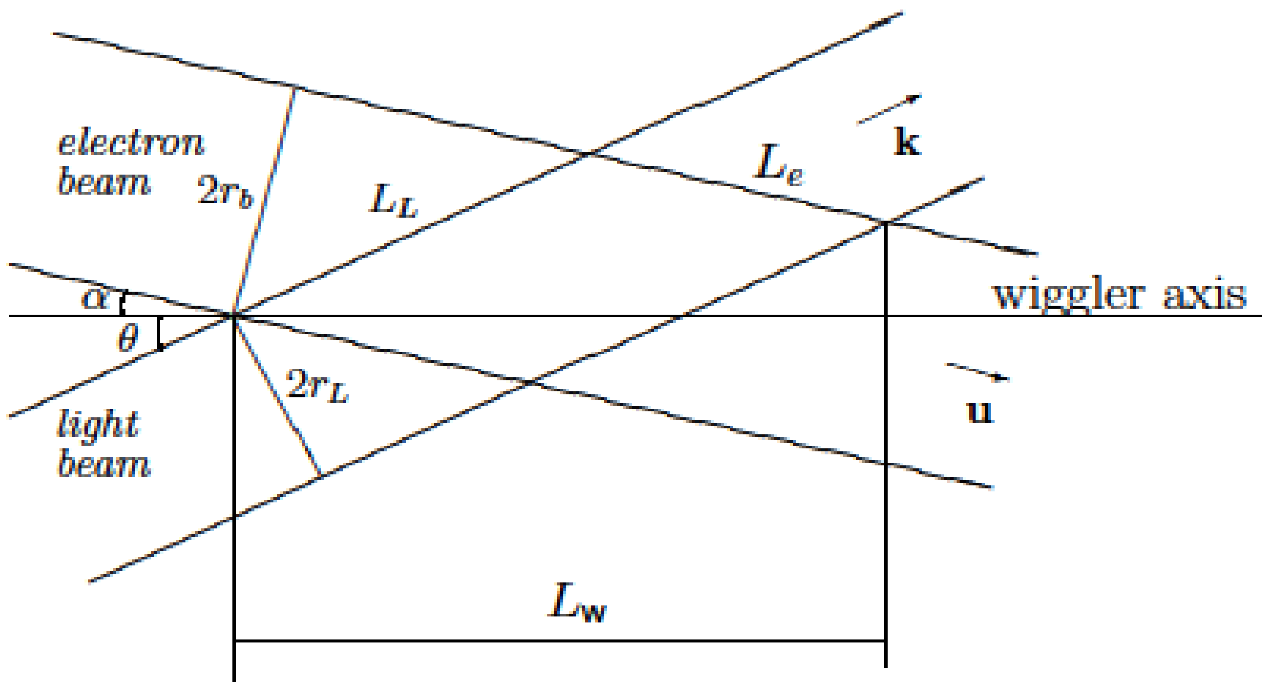
$$\Delta\alpha \approx \frac{v_x^{(1)}}{v_0} \approx \frac{v_x^{(1)}}{c} = \theta \frac{\Delta E^{(1)}}{E_0} : \quad \theta\mu^2 \frac{\lambda_0}{4\pi L} : \quad \mu^2 \frac{d\lambda_0}{4\pi L^2}$$

$$\Delta E^{(1)} = \frac{E_0}{2cq} \varphi\&^{(1)} : \quad \frac{E_0}{2cq} \frac{\mu^2 c}{L} = \mu^2 E_0 \frac{\lambda_0}{4\pi L}$$

For these reasons let us take for estimates maximal value of the saturation parameter μ compatible with the weak field approximation $\mu \sim 1$

Let $\lambda_0 = 3cm, d = 0.3cm,$ $L = 300cm$

$$\Delta\alpha \sim \mu^2 \frac{d\lambda_0}{4\pi L^2} \sim 10^{-6}$$



electron beam
$2r_b$
L_L
L_e
$\mathbf{k}$
wiggler axis
α
θ
$2r_L$
$\mathbf{u}$
light beam
L_w

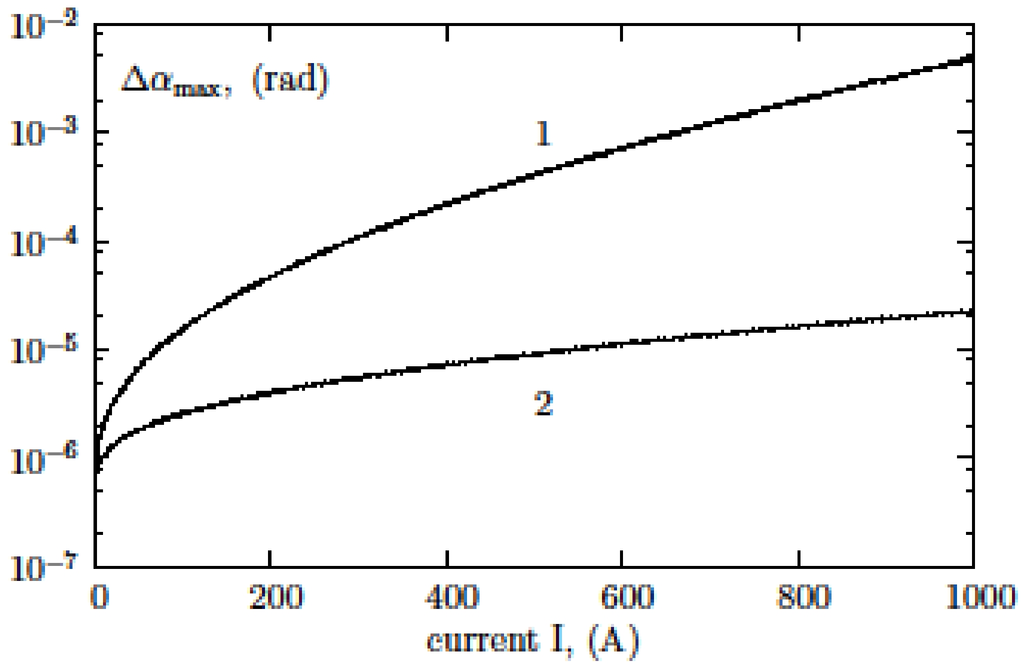
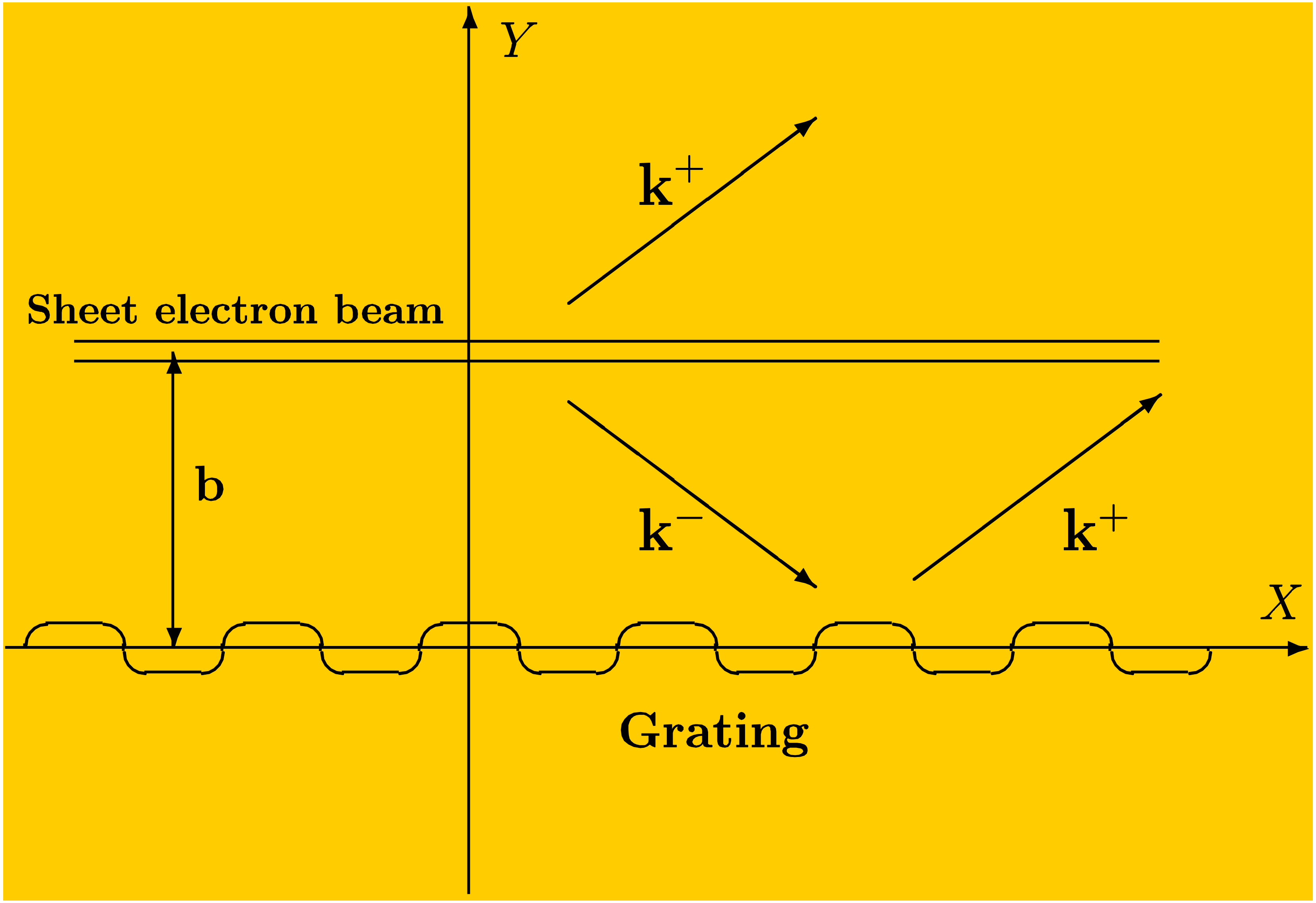


Figure 3. The deviated angle *$\Delta\alpha max$ as a function of a beam current*
I for two values of the angle between laser and electron beams: line 1 corresponds to *$\alpha + \vartheta = 0.05$ rad and line 2 corresponds to $\alpha + \vartheta = 0.13$ rad. Other parameters are: electron energy $\gamma = 15$,* electron beam radius *$rb = 0.02$ cm, laser wavelength $\lambda L = 359\ \mu m$,* period of the wiggler magnets *$\lambda W = 2.73$ cm, normalized wiggler* field *$K = 0.635$, $rL = 1.0$ cm*

Smith-Purcell Radiation

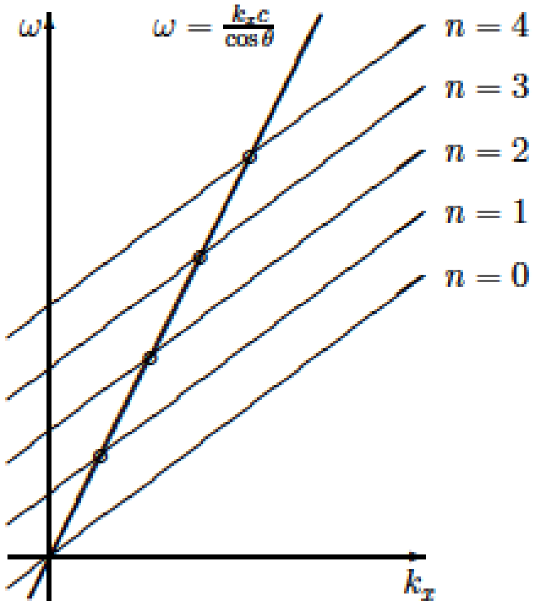
PS_2010; JMO_2009; JCSP,_2009;
JMO_2015; LPL_2015



Y
$\mathbf{k}^{+}$
Sheet electron beam
b
$\mathbf{k}^{-}$
$\mathbf{k}^{+}$
X
Grating

I.M. Frank,
Izv. Akad. Nauk SSSR, Ser. Fiz. 6, 3 (1942).

S.J. Smith and E.M. Purcell,
Phys. Rev. 92, 1069 (1953).



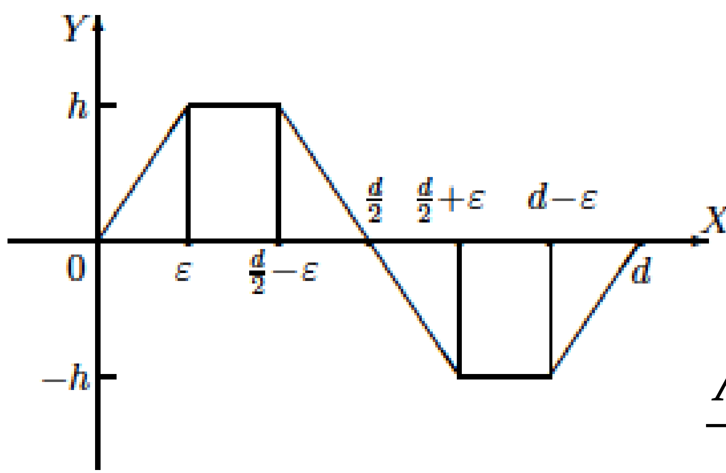
$$\omega_n = \left(k_x + n\frac{2\pi}{d}\right)u$$

$$\omega = k_x c / \cos\theta$$

The dispersion relations for the electromagnetic wave and the beam waves are shown. The intersection points determine the spectrum of frequency of Eq. (39).

$$\omega_n = \frac{2\pi n u}{d\left(1-\beta\cos\theta\right)}$$

$$\lambda = \frac{d}{n}\left(\frac{1}{\beta} - \cos\theta\right)$$



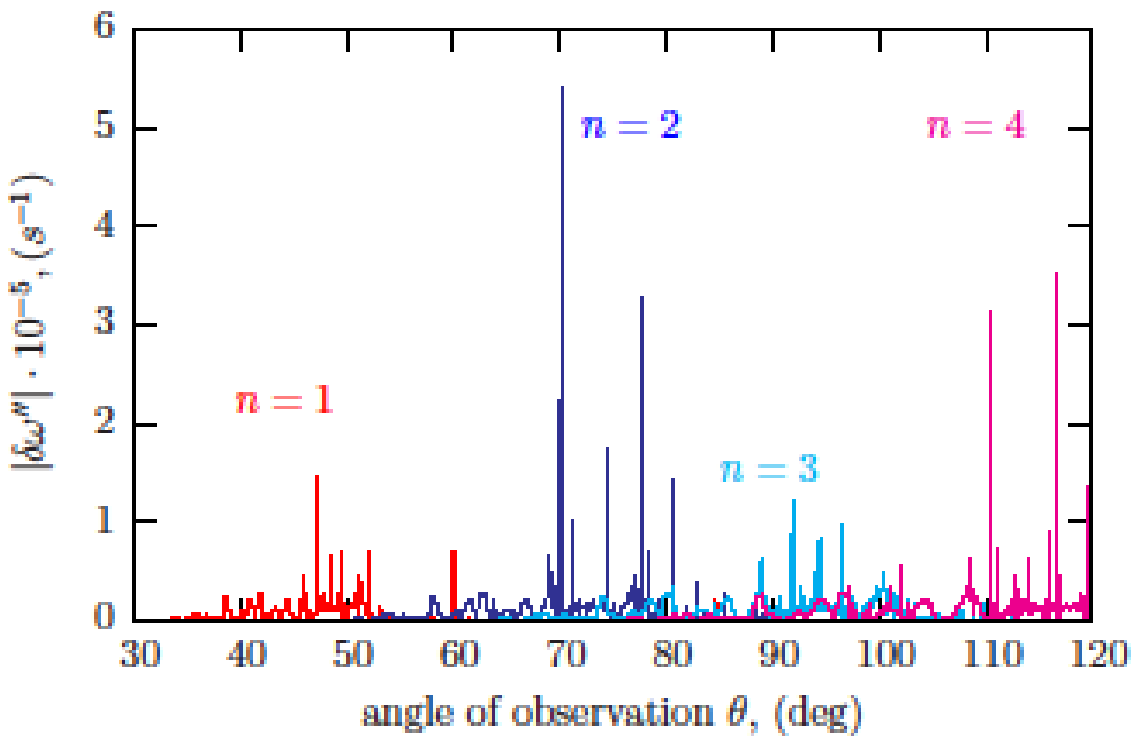
$$\frac{A_{out}}{A_{in}} = \exp\left(2\pi\delta\omega''\frac{L}{c}\right)$$

We have used the framework of the dispersion equation to study coherent Smith-Purcell (SP) radiation induced by a relativistic magnetized electron beam in the absence of a resonator.

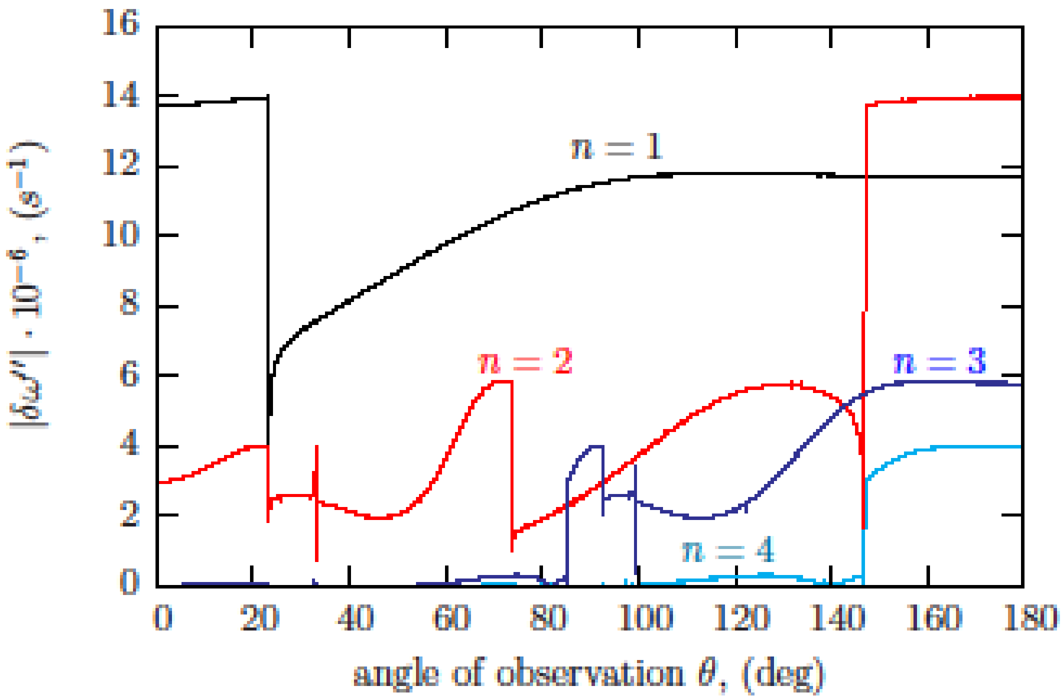
We have found that the dispersion equation describing the induced SP instability is a quadratic equation for frequency; and the zero-order approximation for solution of the equation, which gives the SP spectrum of frequency, corresponds to the mirror boundary case, when the electron beam propagates above plane metal surface (mirror).

It was found that the conditions for both the Thompson and the Raman regimes of excitation do not depend on beam current and depend on the height of the beam above grating surface. The growth rate of the instability in both cases is proportional to the square root of the electron beam current.

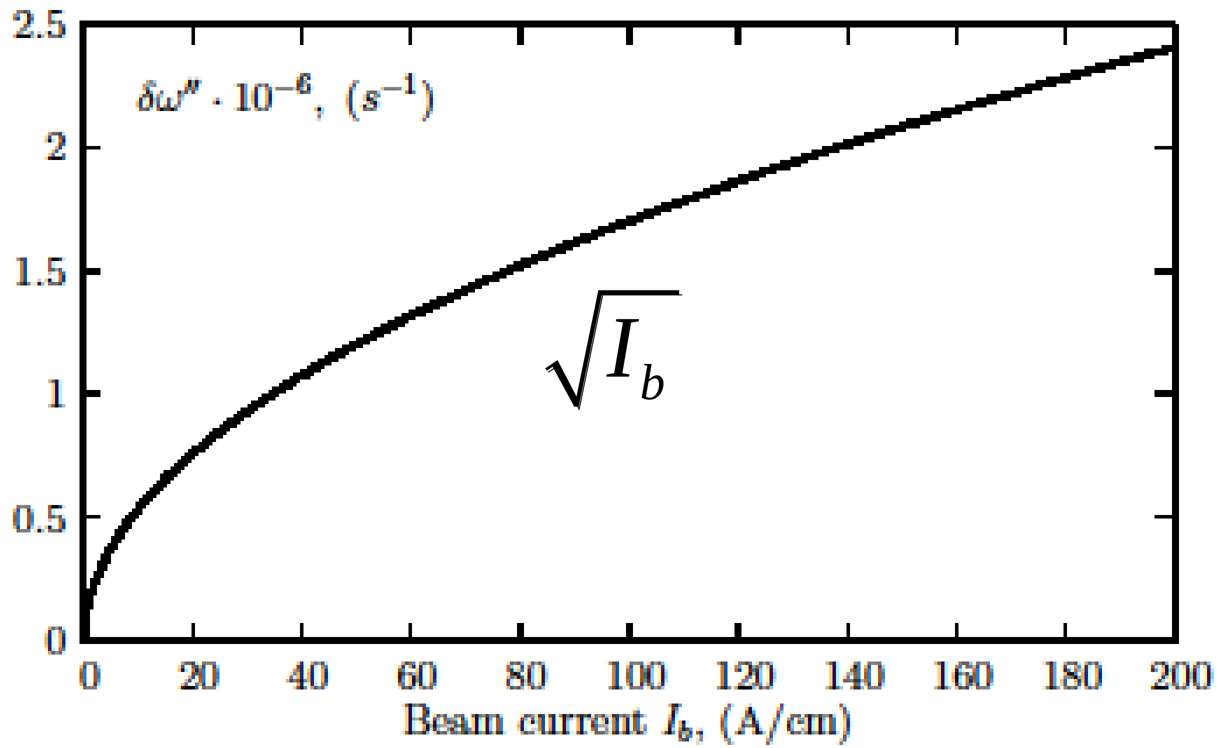
As an important example of the application of the results obtained, the growth rate of SP FEL in the case of a rectangular grating was calculated and the calculated results are consistent with experimental data obtained by Urata, et al. [Phys. Rev. Lett. 80, 516 (1998)].



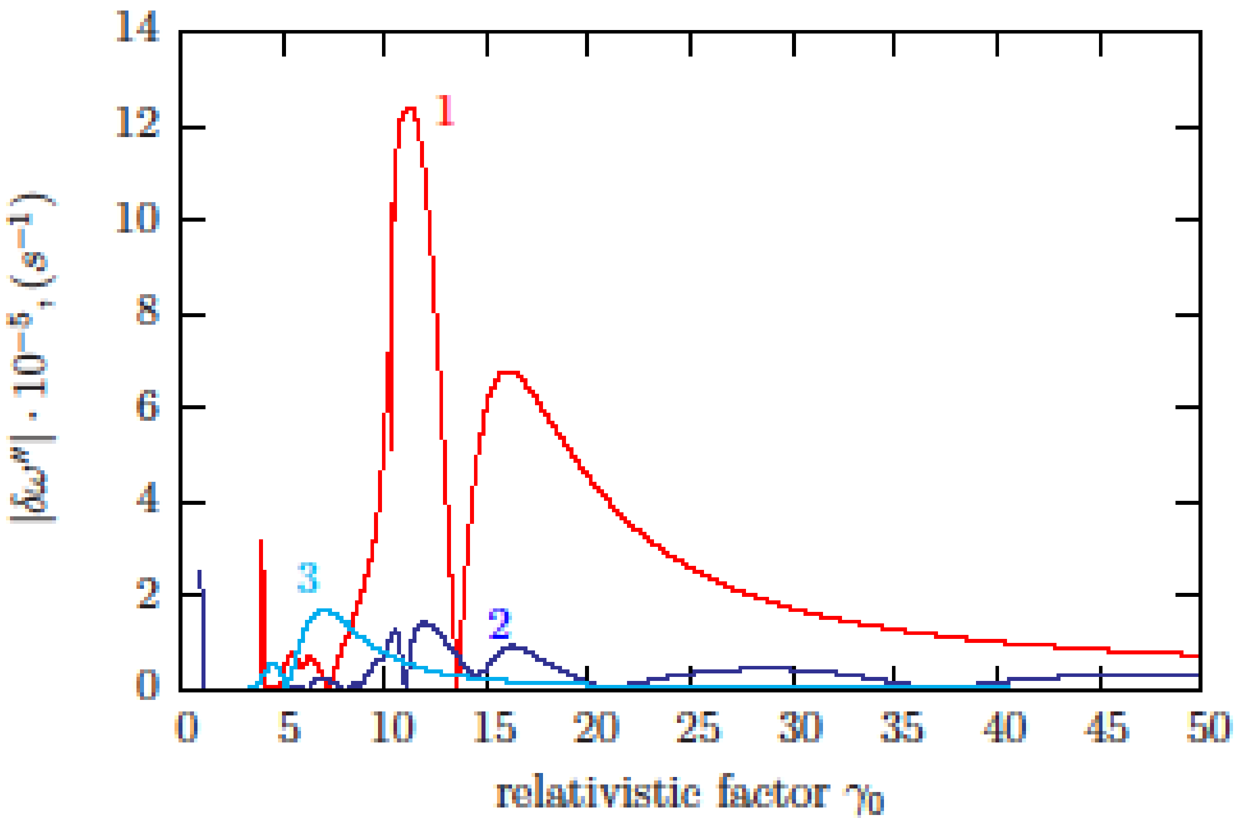
The growth rate as a function on the observation angle µ for different modes n of SP-radiation. The parameters of calculation are relativistic factor = 4, beam current = 10 A, period of grating d = 1 cm, amplitude of the grating h = 1 cm, height of the beam b = 1 cm.



The growth rate as a function on the observation angle µ for different modes n of SP-radiation for parameters which are closed for parameters of Dartmouth experiment [7]. The parameters of calculation are relativistic factor = 1.068493 (corresponding electron energy is E = 35 keV), beam current = 10 A, period of grating d = 173 mkm, amplitude of the grating h = 50 mkm, height of the beam b = 70 mkm (corresponding gap between beam and top of grating is y0 = 20 mkm). Our calculation marks good agreement with results of the Dartmouth experiment, where only first mode was observed [7].



The growth rate as a function on the beam current for mode n = 1 of SP-radiation and observation angle = 38.75 deg. The parameters of calculation are relativistic factor = 10, period of grating d = 1 cm, amplitude of the grating h = 1 cm, height of the beam b = 1 cm. One can see that within wide range of current values the growth rate places under the law sqrt from beam current.



The growth rate as a function on the relativistic factor . (1) for mode n = 1 of SP-radiation and observation angle μ = 38.75 deg, (2) for mode n = 1 of SP-radiation and observation angle μ = 32.83 deg, (3) for mode n = 3 of SP-radiation and observation angle μ = 80.21 deg. The parameters of calculation are the beam current = 10 A/cm, period of grating d = 1 cm, amplitude of the grating h = 1 cm, height of the beam b = 1 cm.

Спасибо

Thanks

Shie Shie

Jakuem

Շնորհակալություն

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Спасибо

Thanks

Shie Shie

Շնորհակալություն

One can select two theoretical target settings for SP radiation. The first of them is the problem of generating SP radiation. In this case, the waves incoming from infinity are absent. The SP system generates outgoing waves. Another problem is the amplification or attenuation of incoming waves by the SP system. One can expect that these different

problems have different solutions.

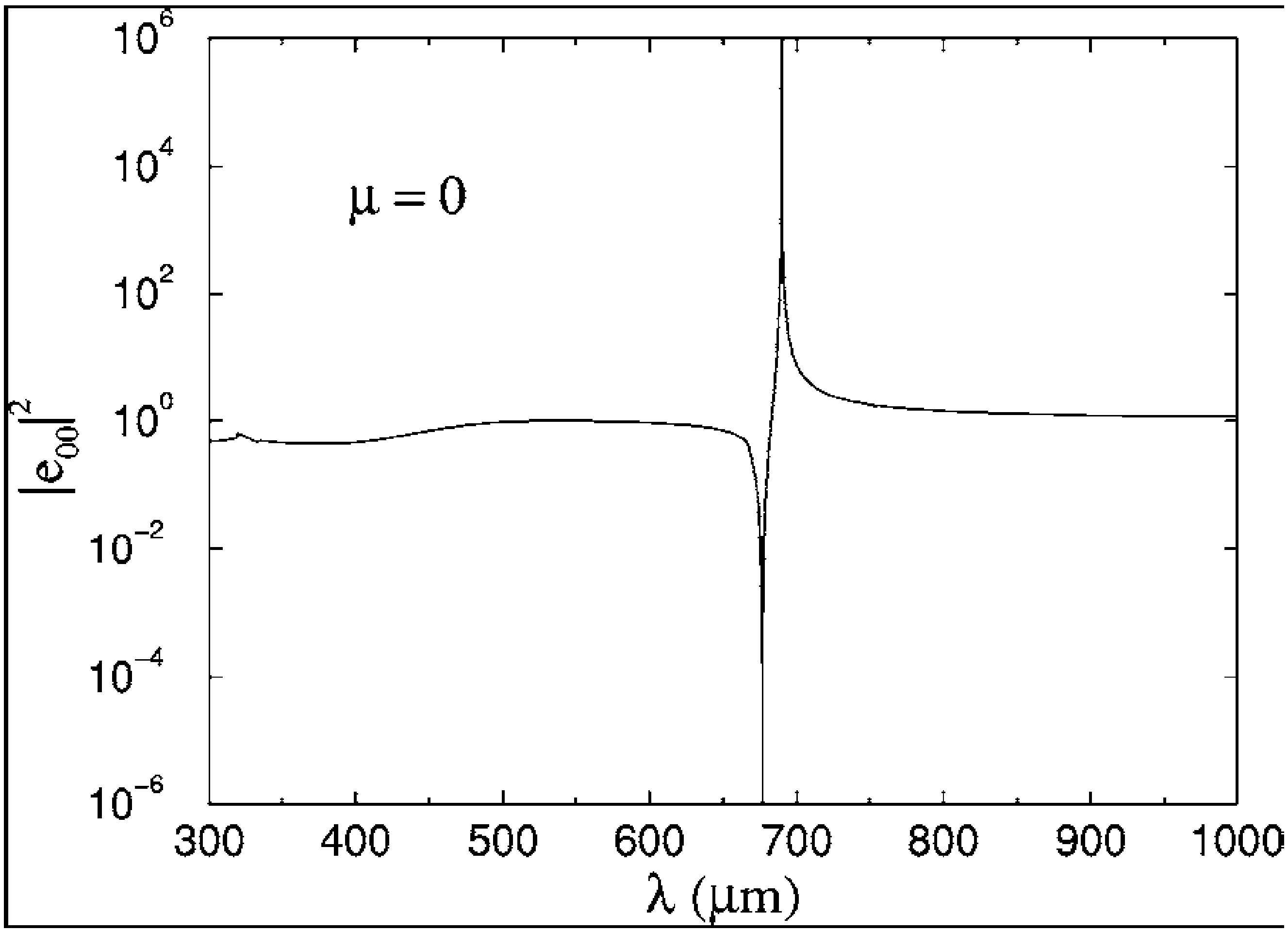
we consider only the problem of generating
waves by the SP system when the incoming waves are absent

$$\omega_p = \sqrt{\frac{4\pi n_e e^2}{m}}$$

We have a closed agreement with results obtained in Ref. [8], for the Thompson regime $\mu_p ? \; 1$

We have found that zero-order approximation for solution of dispersion equation of SP-generation corresponds to the mirror case, when the electron beam propagates above plane metal surface (mirror).

Vinit Kumar and Kwange-Je Kim, Phys. Rev. E 73, 026501 (2006) the coefficient *e*00 of reflecting matrix was calculated



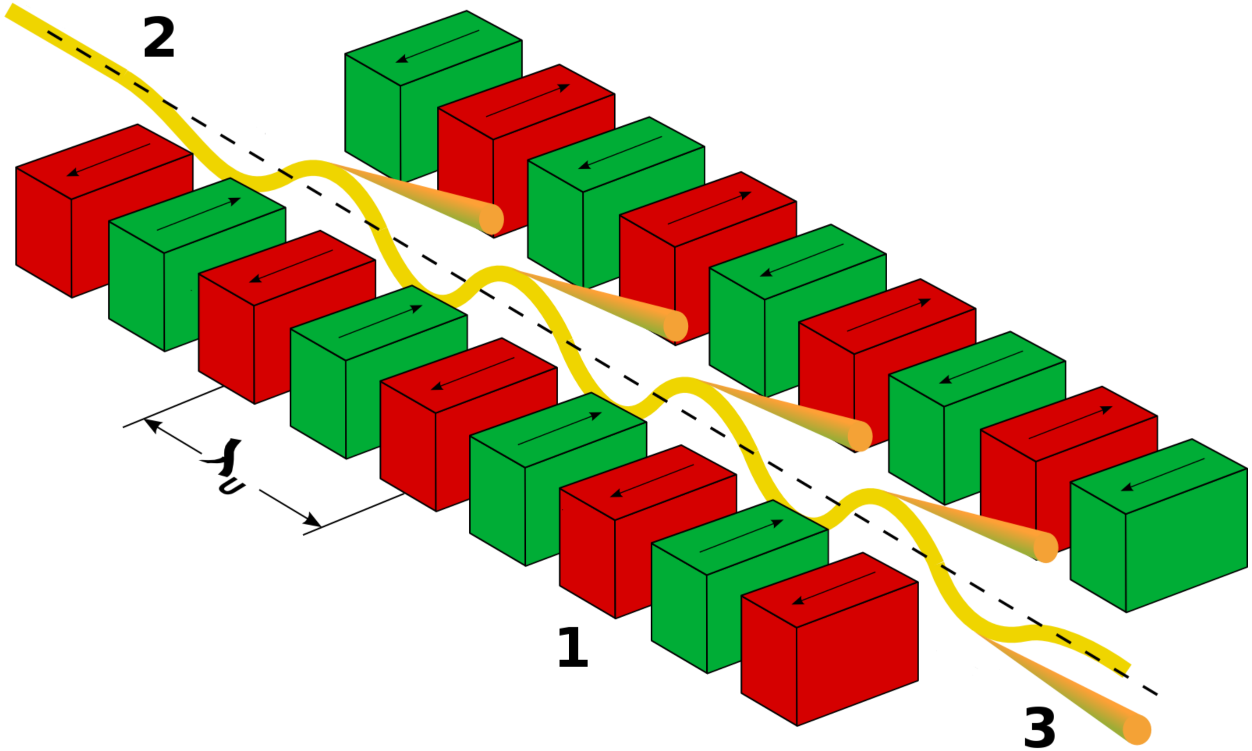
In paper Vinit Kumar and Kwange-Je Kim, Phys. Rev. E 73, 026501 (2006) the coefficient *e*00 of reflecting matrix was calculated for the case of rectangular grating for the following parameters: grating period *d* = 1 $w = 62\,\mu m$ ove $d = 173\,\mu m$ 2 ¹, groove depth = 100 ¹*m*, electron ene $h = 100\,\mu m$ /, beam height from $35 KeV$ top surface *b* = 10 ¹*m*.

$b = 10\,\mu m$

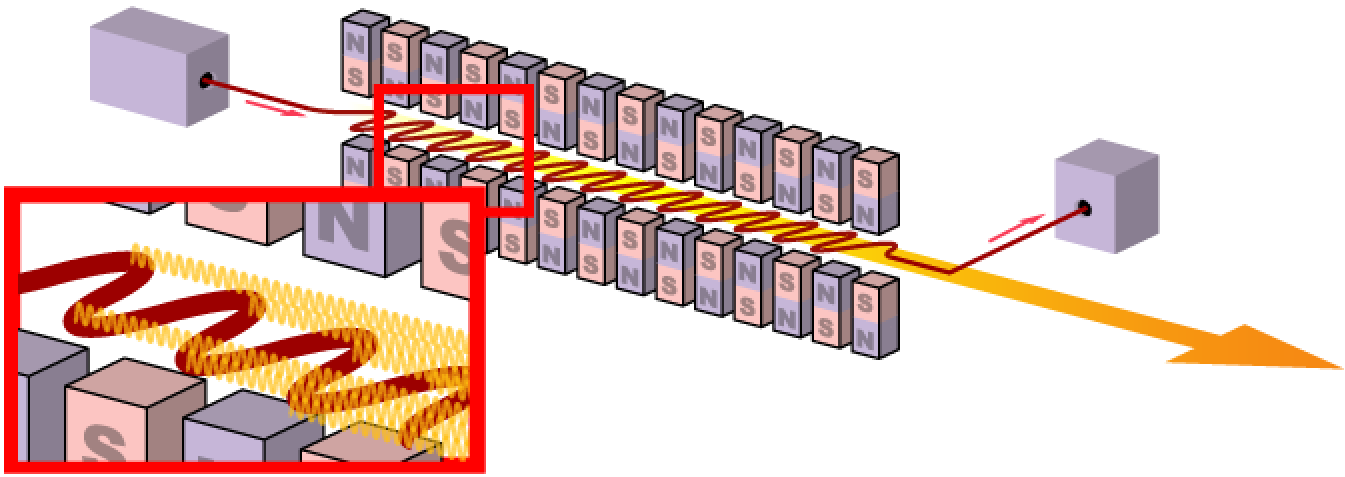
Plot of *e*00 as a function of free-space wavelength of the zeroth-order evanescent wave shown that there are two resonant peaks: peak-down at

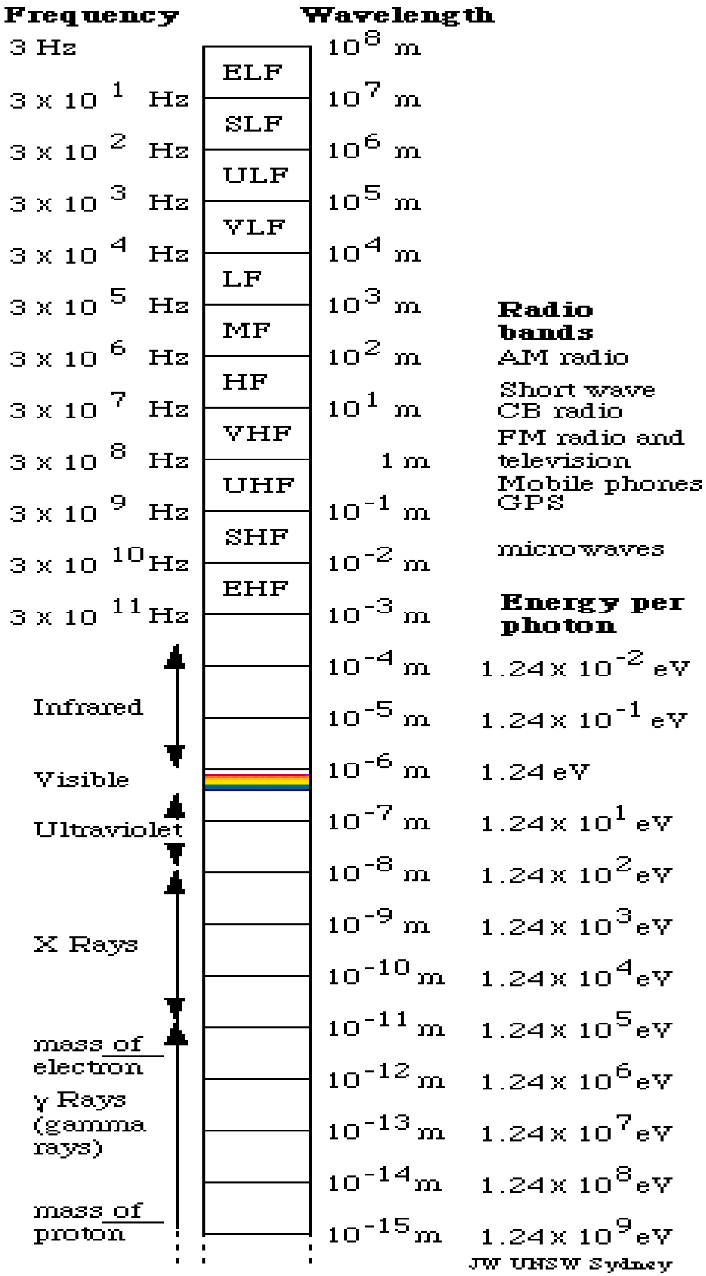
$675.2\,\mu m$ h 675:2 ¹*m*, when *e*00 has a zero, and peak-up at wavelength 69 $690\,\mu m$ en *e*00 has a singularity.

The growth rates for both Thompson and Raman types of waves excitation are proportional ω_b the Langmuir frequency *!b* or square root of beam current $I_b^{1/2}$. The conditions of excitations for both Thompson and Raman types do not depend on Langmuir beam frequency (or beam current), but depend on the beam height *b* above the grating.

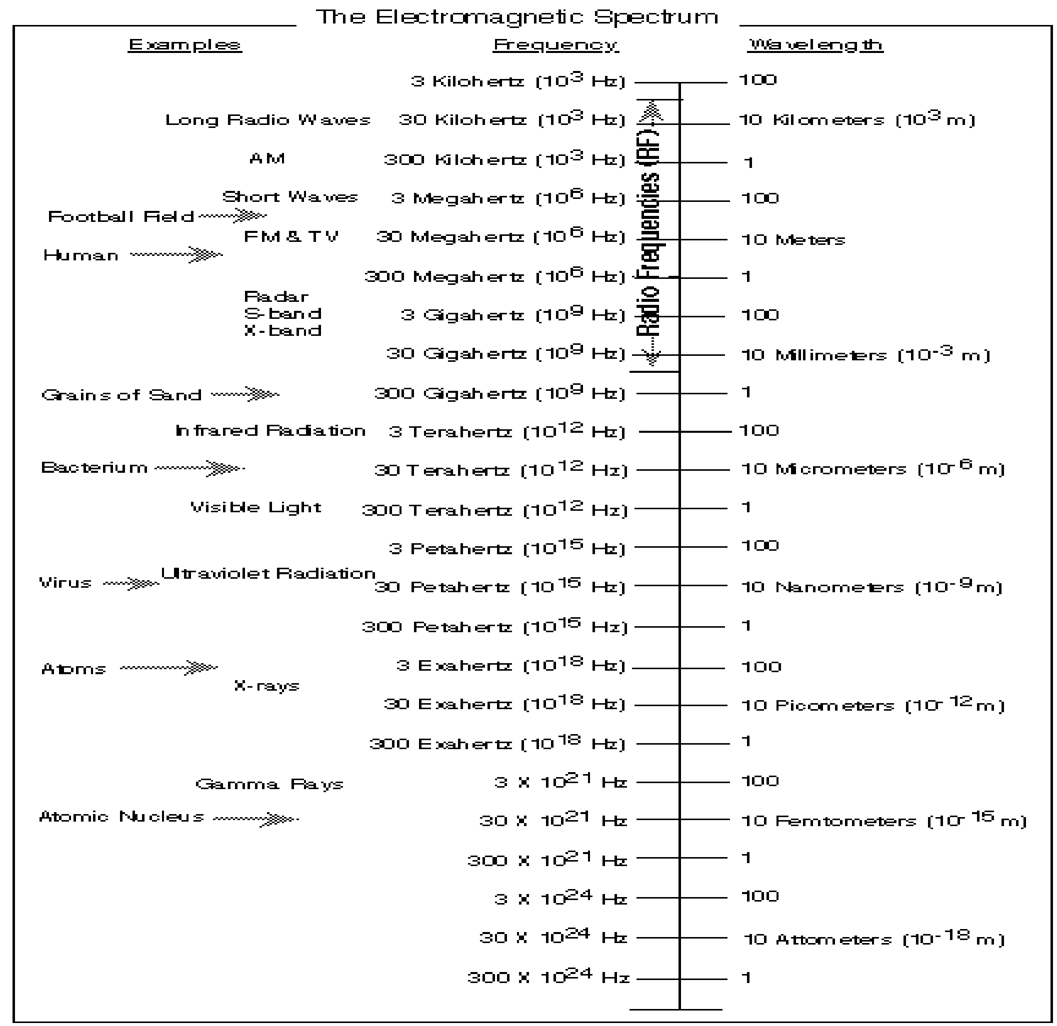


The first undulator was built by Hans Motz and his coworkers at Stanford[3][4] in 1952. It produced the first manmade coherent infrared radiation, having a total frequency range was from visible light down to millimeter waves. The Russian physicist Vitaly Ginzburg showed theoretically that undulators could be built in a 1947 paper



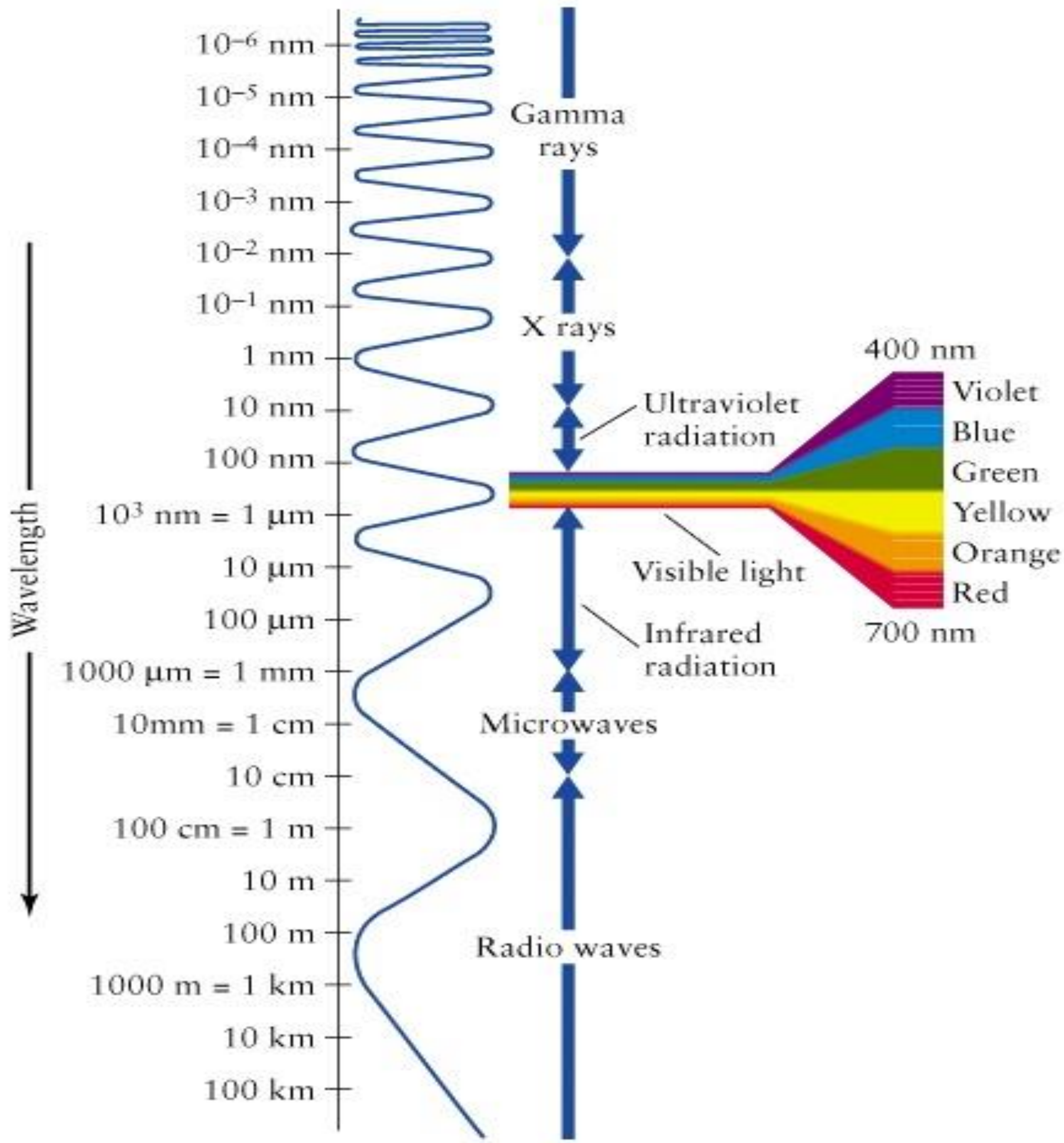


Frequency
Wavelength
3 Hz
ELF
SLF
ULF
VLF
LF
MF
HF
VHF
UHF
SHF
EHF
3×10^{1} Hz
3×10^{2} Hz
3×10^{3} Hz
3×10^{4} Hz
3×10^{5} Hz
3×10^{6} Hz
3×10^{7} Hz
3×10^{8} Hz
3×10^{9} Hz
3×10^{10} Hz
3×10^{11} Hz
10^{8} m
10^{7} m
10^{6} m
10^{5} m
10^{4} m
10^{3} m
10^{2} m
10^{1} m
1 m
10^{-1} m
10^{-2} m
10^{-3} m
10^{-4} m
10^{-5} m
10^{-6} m
10^{-7} m
10^{-8} m
10^{-9} m
10^{-10} m
10^{-11} m
10^{-12} m
10^{-13} m
10^{-14} m
10^{-15} m
Radio bands
AM radio
Short wave
CB radio
FM radio and television
Mobile phones
GPS
microwaves
Energy per photon
1.24×10^{-2} eV
1.24×10^{-1} eV
1.24 eV
1.24×10^{1} eV
1.24×10^{2} eV
1.24×10^{3} eV
1.24×10^{4} eV
1.24×10^{5} eV
1.24×10^{6} eV
1.24×10^{7} eV
1.24×10^{8} eV
1.24×10^{9} eV
Infrared
Visible
Ultraviolet
X Rays
mass of electron
γ Rays (gamma rays)
mass of proton
JW UNSW Sydney

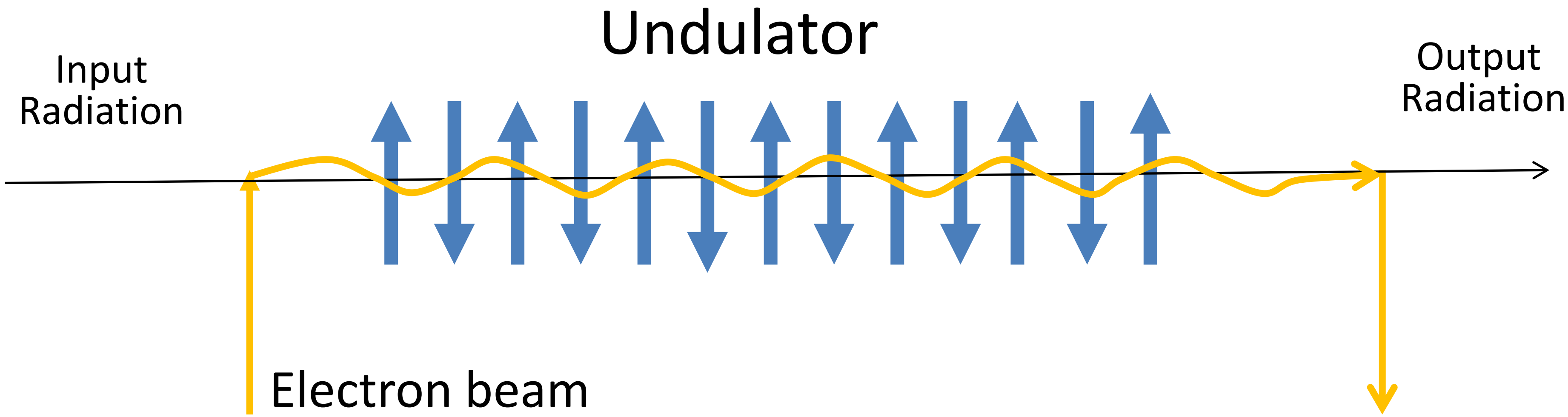


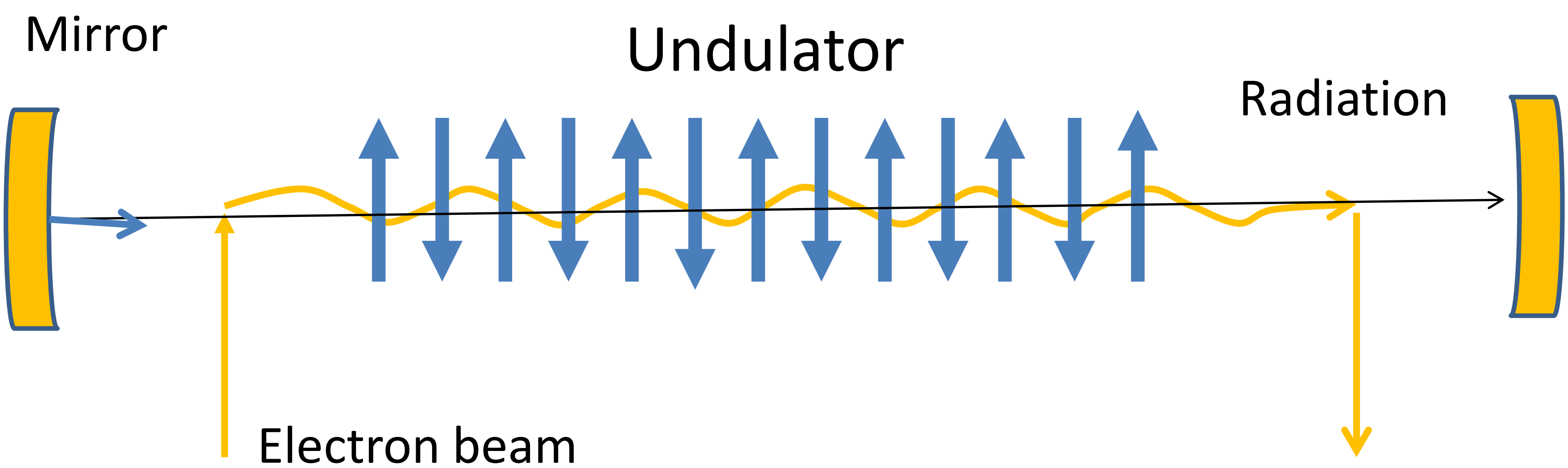
The Electromagnetic Spectrum
Examples
Frequency
Wavelength
3 Kilohertz (10^{3} Hz)
100
Long Radio Waves
30 Kilohertz (10^{3} Hz)
10 Kilometers (10^{3} m)
AM
300 Kilohertz (10^{3} Hz)
1
Short Waves
3 Megahertz (10^{6} Hz)
100
Football Field
FM & TV
30 Megahertz (10^{6} Hz)
10 Meters
Human
300 Megahertz (10^{6} Hz)
1
Radar
S-band
X-band
3 Gigahertz (10^{9} Hz)
100
30 Gigahertz (10^{9} Hz)
10 Millimeters (10^{-3} m)
Radio Frequencies (RF)
Grains of Sand
300 Gigahertz (10^{9} Hz)
1
Infrared Radiation
3 Terahertz (10^{12} Hz)
100
Bacterium
30 Terahertz (10^{12} Hz)
10 Micrometers (10^{-6} m)
Visible Light
300 Terahertz (10^{12} Hz)
1
3 Petahertz (10^{15} Hz)
100
Virus
Ultraviolet Radiation
30 Petahertz (10^{15} Hz)
10 Nanometers (10^{-9} m)
300 Petahertz (10^{15} Hz)
1
Atoms
3 Exahertz (10^{18} Hz)
100
X-rays
30 Exahertz (10^{18} Hz)
10 Picometers (10^{-12} m)
300 Exahertz (10^{18} Hz)
1
Gamma Rays
3×10^{21} Hz
100
Atomic Nucleus
30×10^{21} Hz
10 Femtometers (10^{-15} m)
300×10^{21} Hz
1
3×10^{24} Hz
100
30×10^{24} Hz
10 Attometers (10^{-18} m)
300×10^{24} Hz
1

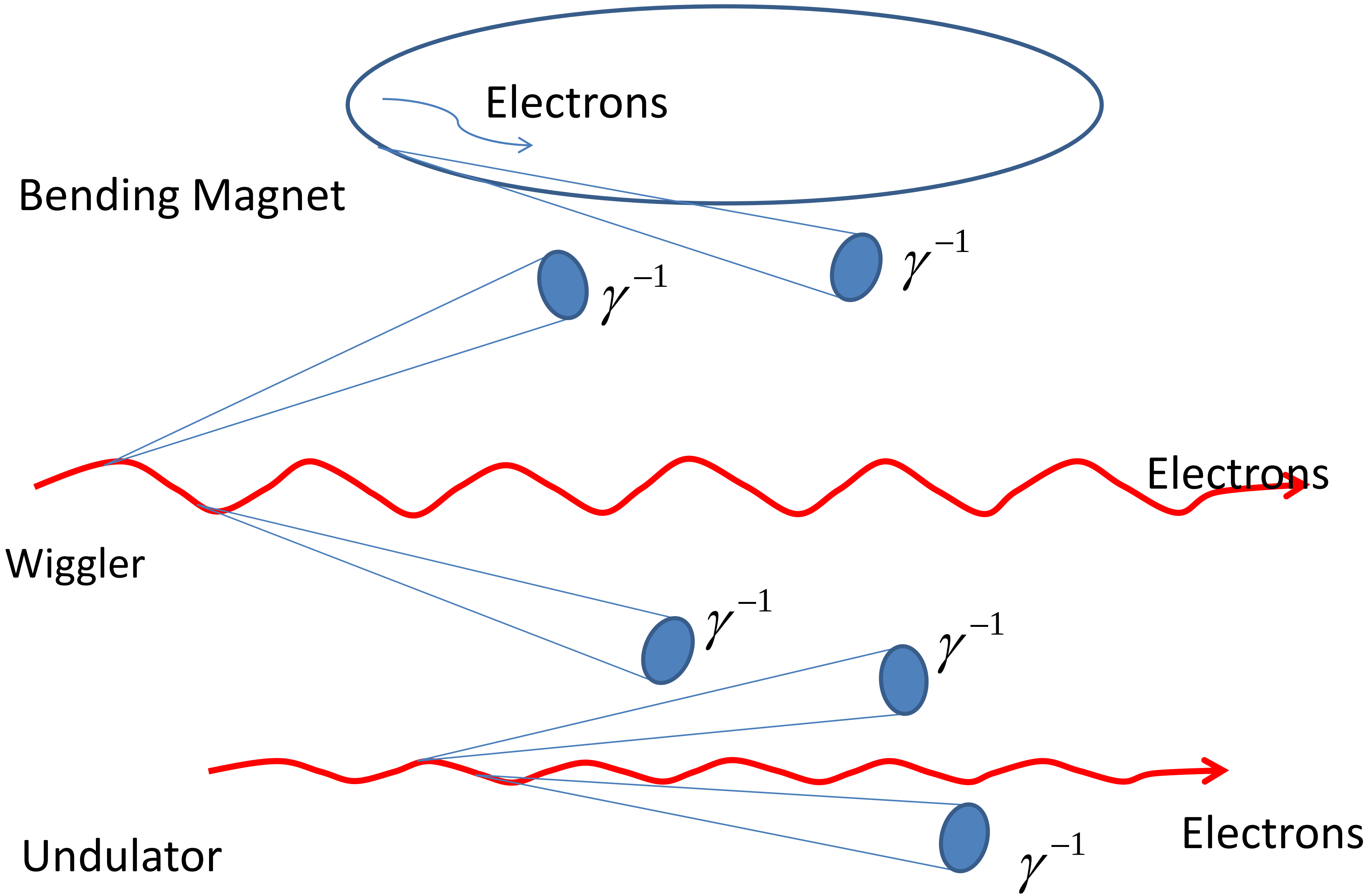
Espectro de Radiação Eletromagnética				
Região	**Comp. Onda (Angstroms)**	**Comp. Onda (centímetros)**	**Frequência (Hz)**	**Energia (eV)**
Rádio	$> 10^9$	> 10	$< 3 \times 10^9$	$< 10^{-5}$
Micro-ondas	$10^9 - 10^6$	$10 - 0.01$	$3 \times 10^9 - 3 \times 10^{12}$	$10^{-5} - 0.01$
Infra-vermelho	$10^6 - 7000$	$0.01 - 7 \times 10^{-5}$	$3 \times 10^{12} - 4.3 \times 10^{14}$	$0.01 - 2$
Visível	$7000 - 4000$	$7 \times 10^{-5} - 4 \times 10^{-5}$	$4.3 \times 10^{14} - 7.5 \times 10^{14}$	$2 - 3$
Ultravioleta	$4000 - 10$	$4 \times 10^{-5} - 10^{-7}$	$7.5 \times 10^{14} - 3 \times 10^{17}$	$3 - 10^3$
Raios-X	$10 - 0.1$	$10^{-7} - 10^{-9}$	$3 \times 10^{17} - 3 \times 10^{19}$	$10^3 - 10^5$
Raios Gama	< 0.1	$< 10^{-9}$	$> 3 \times 10^{19}$	$> 10^5$



Wavelength
10⁻⁶ nm
10⁻⁵ nm
10⁻⁴ nm
10⁻³ nm
10⁻² nm
10⁻¹ nm
1 nm
10 nm
100 nm
10³ nm = 1 μm
10 μm
100 μm
1000 μm = 1 mm
10mm = 1 cm
10 cm
100 cm = 1 m
10 m
100 m
1000 m = 1 km
10 km
100 km
Gamma rays
X rays
Ultraviolet radiation
Visible light
Infrared radiation
Microwaves
Radio waves
400 nm
Violet
Blue
Green
Yellow
Orange
Red
700 nm

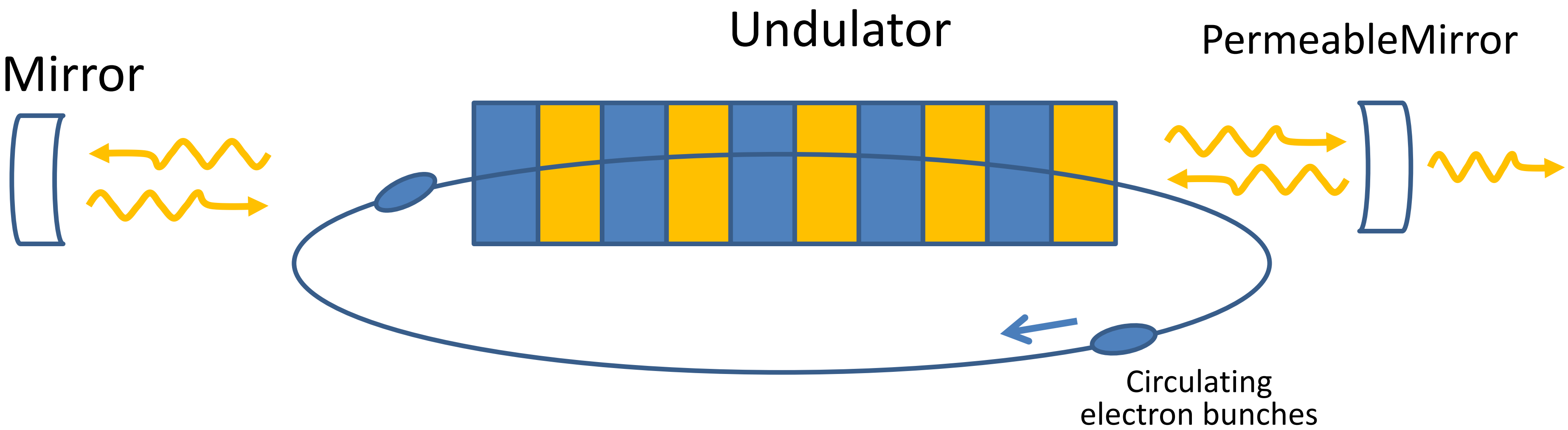

Undulator
Input Radiation
Output Radiation
Electron beam


Mirror
Undulator
Radiation
Electron beam

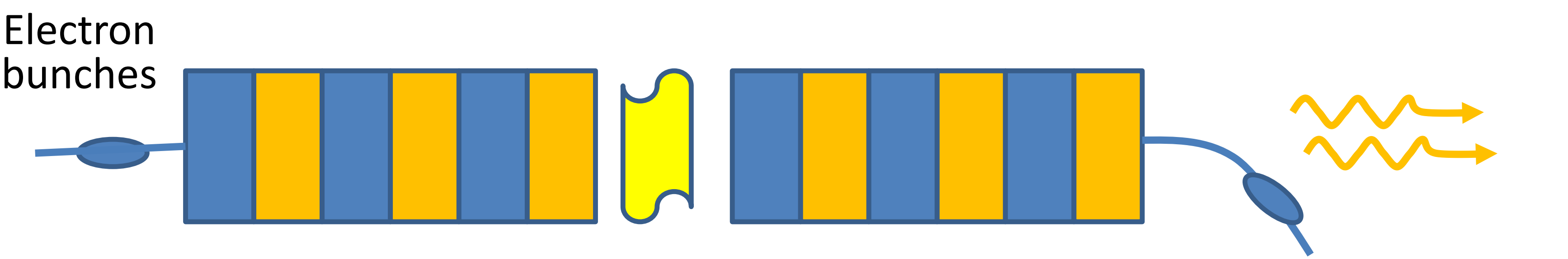


Electrons
Bending Magnet
γ^{-1}
γ^{-1}
Electrons
Wiggler
γ^{-1}
γ^{-1}
Undulator
γ^{-1}
Electrons

FEL

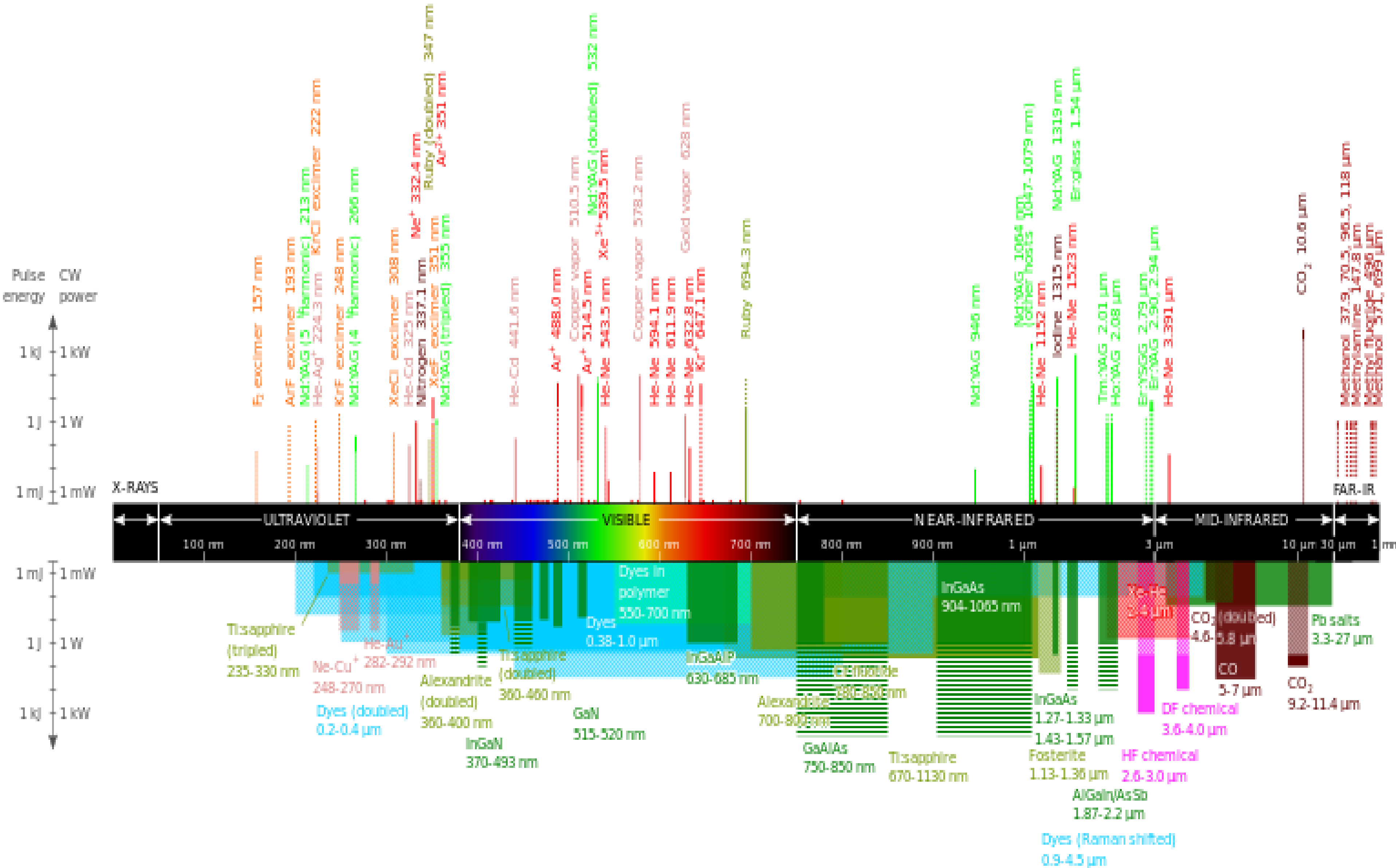

Undulator
PermeableMirror
Mirror
Circulating
electron bunches

SASE FEL


Electron
bunches

Principle of free-electron laser. For visible or infrared light an optical
resonator can be used. A increase in light intensity of a few % per passage of a short undulator magnet is sufficient to achieve laser saturation within many round trips.
In the ultraviolet and X-ray region one can apply the mechanism of Self-Amplified Spontaneous Emission where a large laser gain is achieved in a single passage of a
very long undulator

The principle of the Free-Electron Laser (FEL) was invented by John Madey in 1971 [1]. The first FEL, operating in the infrared at a wavelength of 12 μm, was built at Stanford University in the 1970s by Madey and coworkers [2, 3]. For many years FELs have played a marginal role in comparison with conventional lasers except at microwave and infrared wavelengths. Only in recent years it has become clear that these devices have the potential of becoming exceedingly powerful light sources in the X-ray regime [4, 5, 6]. The ultraviolet and soft X-ray free-electron laser facility FLASH in Hamburg has been playing a pioneering role in the development of X-ray FELs. The successful operation of FLASH as a user facility, providing radiation pulses of unprecedented brightness and shortness at wavelengths down to 6.5 nm, has paved the way for new FELs in the Ångström regime

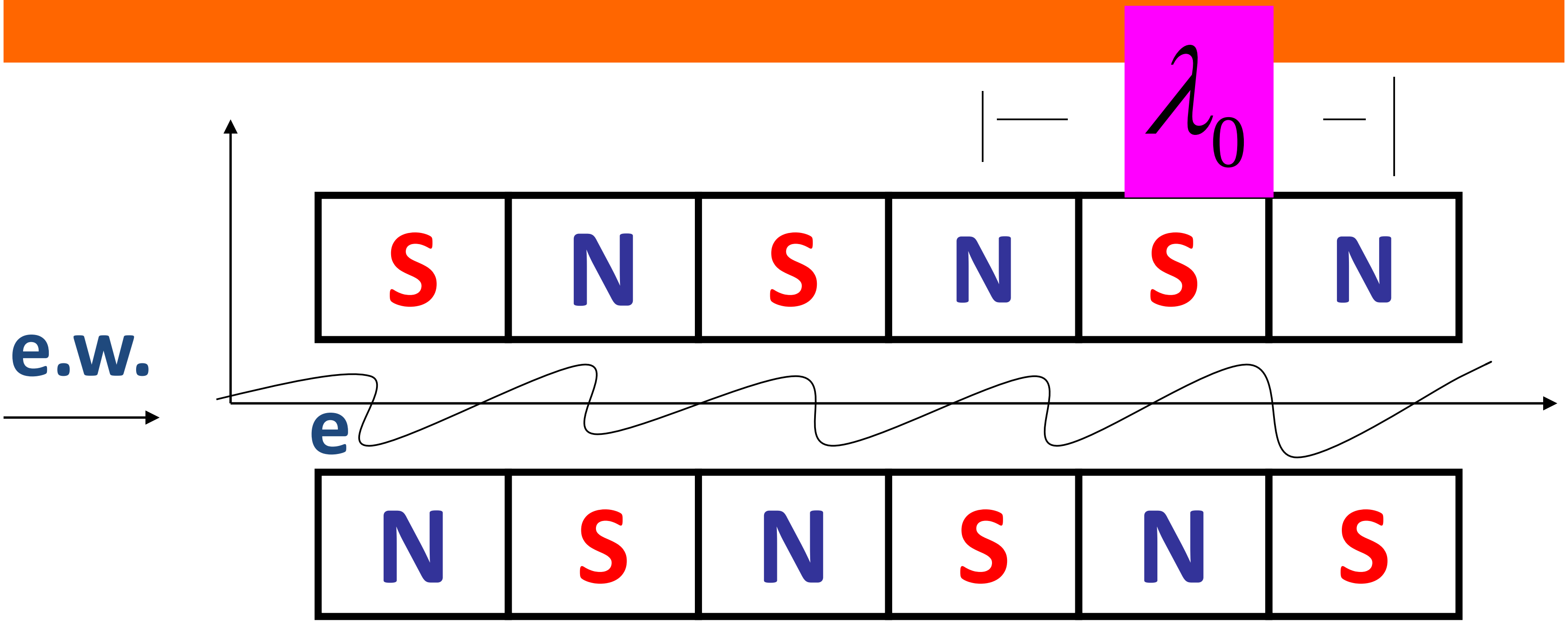


Pulse energy
CW power
1 kJ
1 kW
1 J
1 W
1 mJ
1 mW
X-RAYS
ULTRAVIOLET
VISIBLE
NEAR-INFRARED
MID-INFRARED
FAR-IR
100 nm
200 nm
300 nm
400 nm
500 nm
600 nm
700 nm
800 nm
900 nm
1 µm
3 µm
10 µm
30 µm
1 mm
F2 excimer 157 nm
ArF excimer 193 nm
Nd:YAG (5th harmonic) 213 nm
He-Ag+ 224.3 nm
KrCl excimer 222 nm
KrF excimer 248 nm
Nd:YAG (4th harmonic) 266 nm
XeCl excimer 308 nm
He-Cd 325 nm
Nitrogen 337.1 nm
Ne+ 332.4 nm
Ruby (doubled) 347 nm
XeF excimer 351 nm
Nd:YAG (tripled) 355 nm
Ar2+ 351 nm
He-Cd 441.6 nm
Ar+ 488.0 nm
Copper vapor 510.5 nm
Ar+ 514.5 nm
Nd:YAG (doubled) 532 nm
Xe2+ 539.5 nm
He-Ne 543.5 nm
Copper vapor 578.2 nm
He-Ne 594.1 nm
He-Ne 611.9 nm
He-Ne 632.8 nm
Kr+ 647.1 nm
Gold vapor 628 nm
Ruby 694.3 nm
Nd:YAG 946 nm
Nd:YAG 1064 nm (other hosts 1047-1079 nm)
He-Ne 1152 nm
Iodine 1315 nm
Nd:YAG 1319 nm
He-Ne 1523 nm
Er:glass 1.54 µm
Tm:YAG 2.01 µm
Ho:YAG 2.08 µm
Er:YSGG 2.79 µm
Er:YAG 2.90, 2.94 µm
He-Ne 3.391 µm
CO2 10.6 µm
Methanol 37.9, 70.5, 96.5, 118 µm
Methylamine 147.8 µm
Methyl fluoride 496 µm
Methanol 571, 699 µm
Ti:sapphire (tripled) 235-330 nm
Ne-Cu+ 248-270 nm
He-Ag+ 282-292 nm
Dyes (doubled) 0.2-0.4 µm
Alexandrite (doubled) 360-400 nm
Ti:sapphire (doubled) 360-460 nm
InGaN 370-493 nm
GaN 515-520 nm
Dyes 0.38-1.0 µm
Dyes in polymer 550-700 nm
InGaAlP 630-685 nm
Alexandrite 700-800 nm
GaAlAs 750-850 nm
Cr:LiSAF 780-850 nm
Ti:sapphire 670-1130 nm
InGaAs 904-1065 nm
InGaAs 1.27-1.33 µm 1.43-1.57 µm
Forsterite 1.13-1.36 µm
AlGaIn/AsSb 1.87-2.2 µm
Dyes (Raman shifted) 0.9-4.5 µm
Xe-He 2-4 µm
HF chemical 2.6-3.0 µm
DF chemical 3.6-4.0 µm
CO2 (doubled) 4.6-5.8 µm
CO 5-7 µm
CO2 9.2-11.4 µm
Pb salts 3.3-27 µm

	LCLS Stanford	LCLSII	Eu-XFEL	SACLA Spring-8 Japan	FLASH Hamburg, DESY
Shortest wavelength	1.5 A	1 A	0.5 A	1 A	40 A
Undulator type, hard X-ray	Fixed gap	Variable gap	Variable gap	In vacuum Var.gap	-----
Max electron energy	13.6 GeV	14 GeV	17.5 GeV	8 GeV	1.2 GeV
Approx. facility length	1.7 km	1.7 km	3.4 km	0.8 km	0.32 km
Start operation	2009	2017	2015	2011	2005

FLASII	FERMI	Swiss FEL	PAL XFEL Pohang, Korea	Shanghai XFEL	MaRIE
40 A	40 A	1 A	1 (0.6) A	1 A	0.3 A
---	------	In vacuum Var.gap	Variable gap	Var.gap	?
1.2 GeV	1.5 GeV	5.8 GeV	10.0 GeV	6.4 GeV	12 GeV
0.32 km	0.5 km	0.7 km	1.1 km	0.6 km	1.0 km
2013	2010	2016	2015	2019	?

In the free-electron laser (FEL) the accelerated motion of electrons in the ponderomotive potential, formed by the combined field of the wiggler and electromagnetic wave, produces coherent stimulated radiation.



$$\lambda = \frac{\lambda_0}{2\gamma^2}\left(1 + K^2 + \gamma^2\theta^2\right)$$

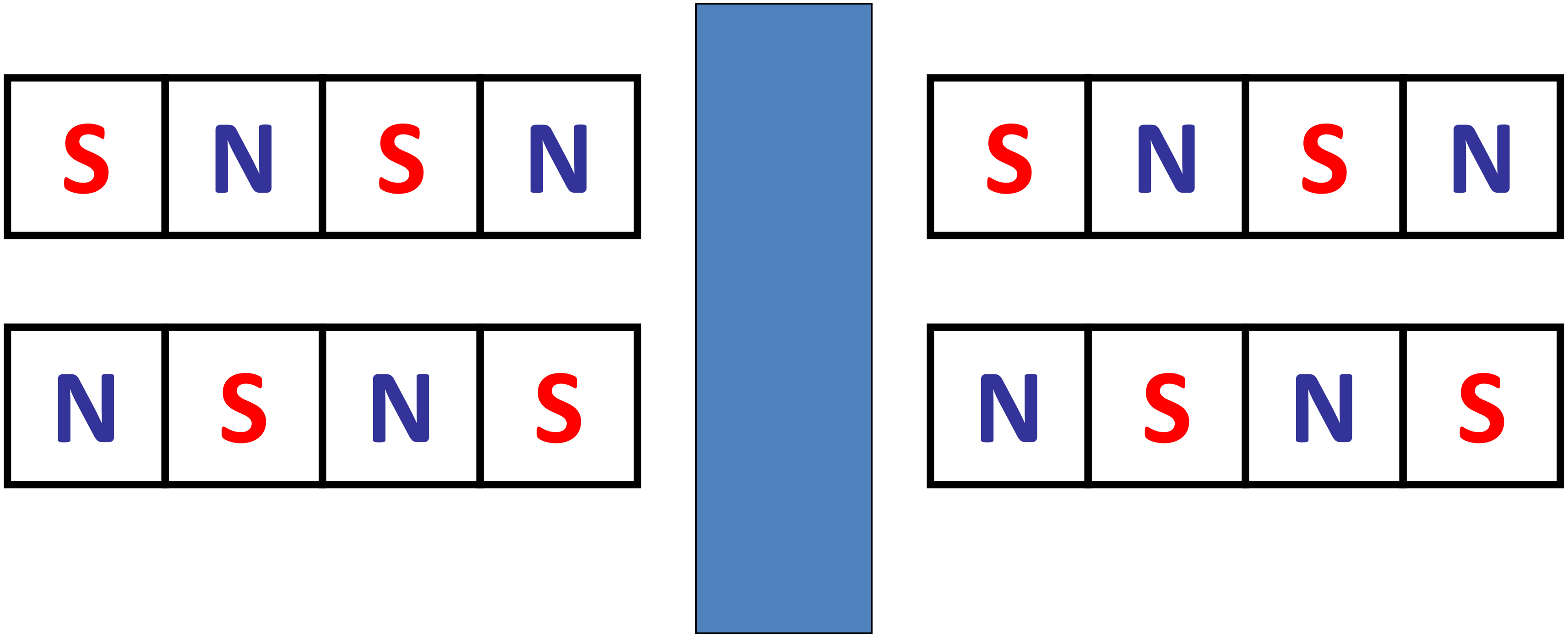
$$K = \frac{eH_0\lambda_0}{2\pi mc^2} = 0.0934 \times H_0\left(kGs\right) \times \lambda_0\left(cm\right)$$

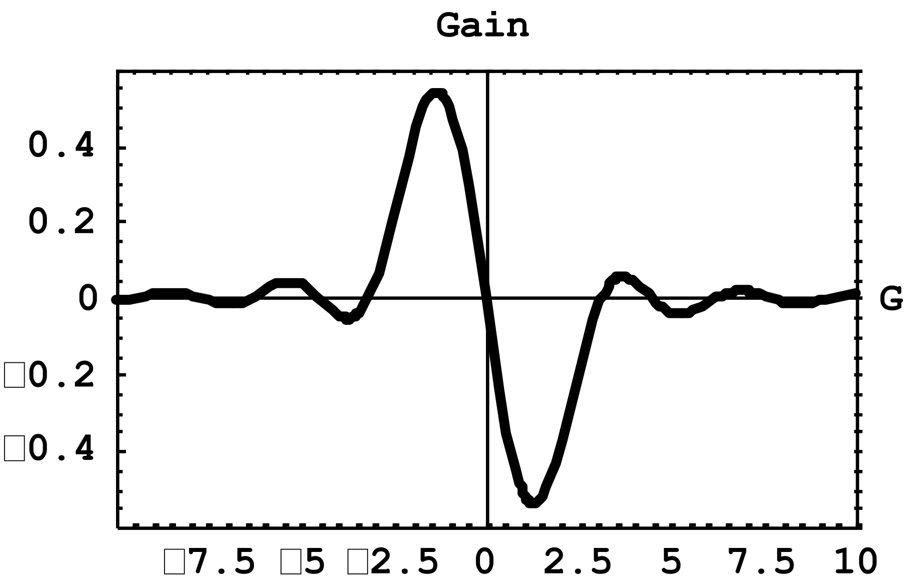
$$x(\mathrm{z}) = \frac{K}{\beta\gamma k_u}\sin k_u z \qquad k_u = \frac{2\pi}{\lambda_u}$$

$$\vartheta_{max} \approx \left[\frac{dx}{dz}\right]_{\max} = \frac{K}{\beta\gamma} \approx \frac{K}{\gamma}$$

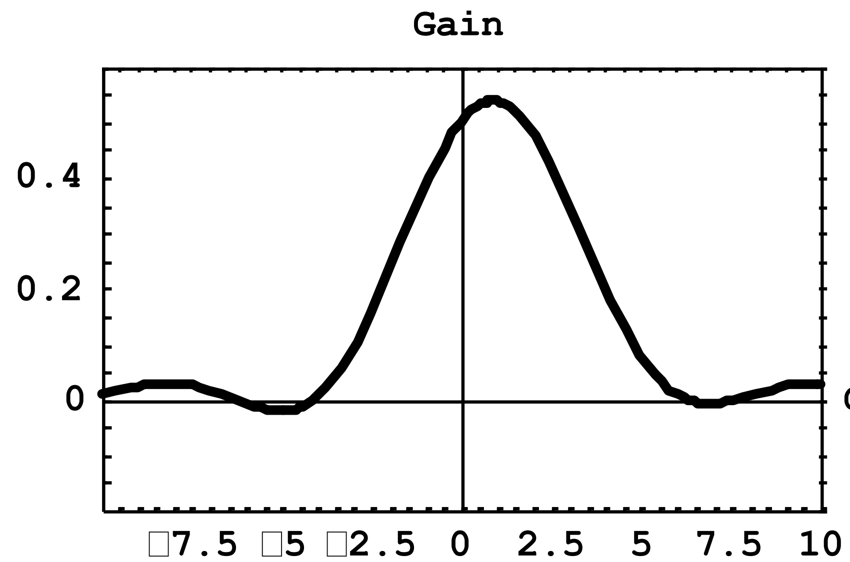
$$v_x(\mathrm{z}) = \frac{Kc}{\gamma}\cos \mathrm{k}_u z$$

More specifically, the idea of FELWI is based on a two-wiggler scheme with a specially organized dispersion region between the wigglers.





FEL



FELWI

$$\int G(\Omega)d\Omega = 0$$

$$\int G(\Omega)d\Omega > 0$$

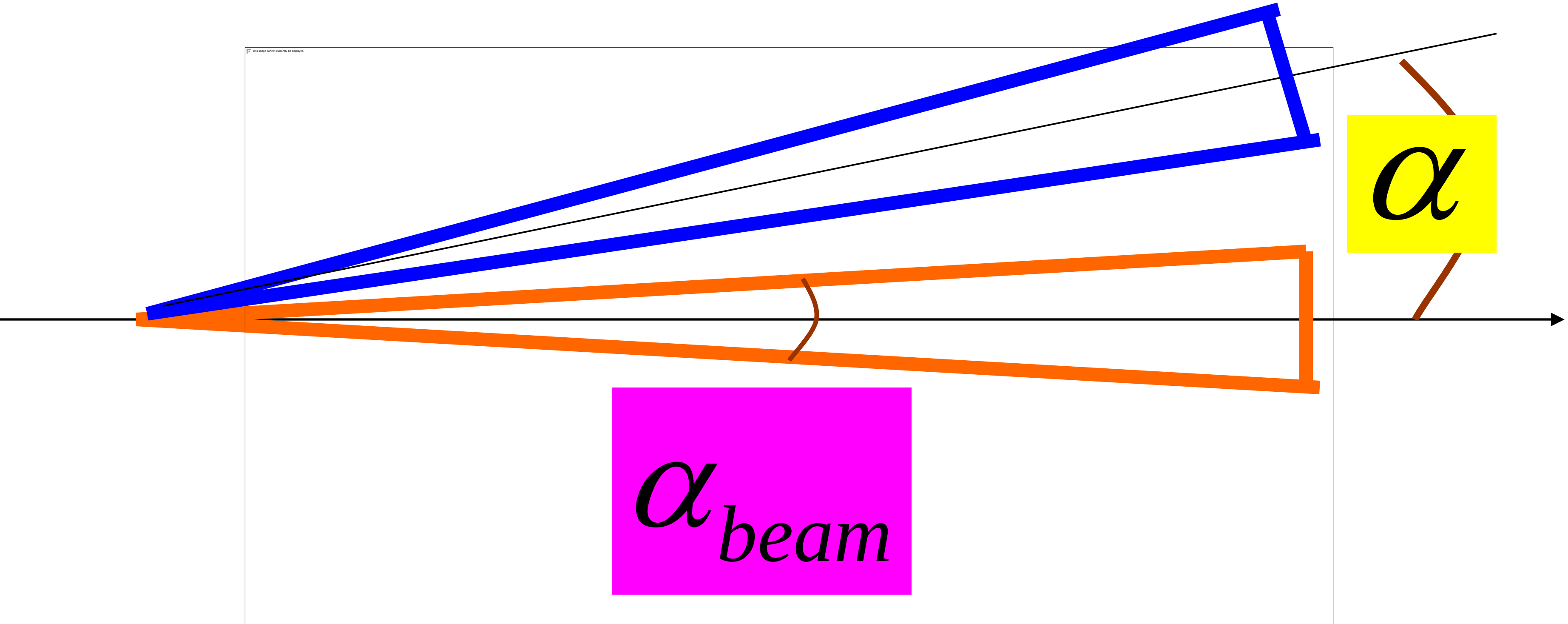
D.E. Nikonov, M.O. Scully, and G. Kurizki

Phys.Rev. E **54,** 6780 (1996)

FELWI realization is strongly related to a deviation of electrons from their original direction of motion owing to interaction with the fields of undulator and co-propagating light-wave

FELWI mechanism can work only if the interaction-induced deviation of electrons(with characteristic angle α) is larger than the angular width of electron beam α_{beam}

$$\alpha > \alpha_{beam}$$



$$\alpha > \alpha_{beam}$$

A transverse velocity v_x and the energy ΔE acuired by an electron after a passage through the undulator are directly proportional to each other

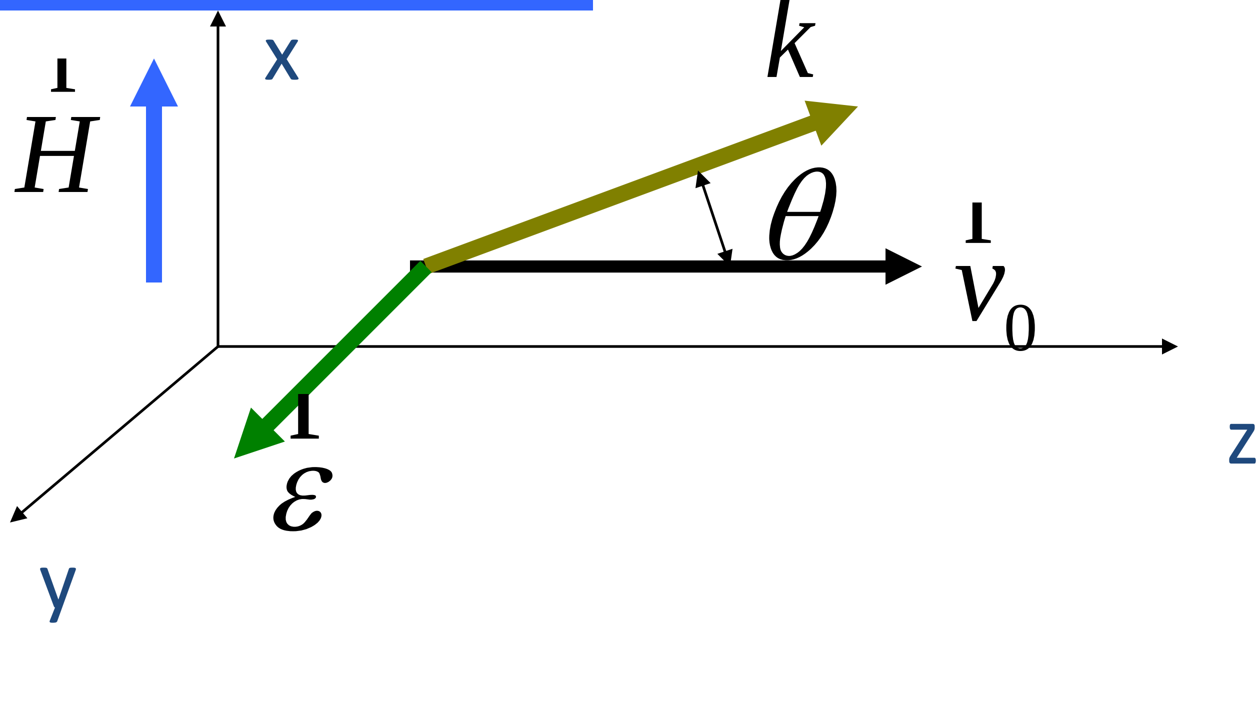
$$v_x = c\theta \frac{\Delta E}{E_0}$$

D.E. Nikonov, M.O. Scully, G.Kurizki, Phys.Rev. E 54, 6780 (1996)

A.I. Artemiev, M.V. Fedorov, Yu.V. Rostovtsev, G.Kurizki, M.O. Scully, Phys.Rev.Lett. 85, 4510 (2000)

$$A_{wave} = \frac{c\varepsilon_0}{\omega}\cos(\vec{k}\vec{r} - \omega t)$$

$$A_{und} = \frac{H_0}{q}\cos(qz)$$



In the non-collinear FEL the electron slow-motion phase is determined as

M.V. Fedorov, Atomic and free electrons in strong light field, World Scientific, Singapore, 1997

$$\varphi = qz + \vec{k}\vec{r} - \omega t$$

$$q = \frac{2\pi}{\lambda_0} \qquad \left|\vec{k}\right| = \omega / c$$

$$\vec{r} = \vec{r}(t)$$

$$z = z(t)$$

The slow motion phase obeys the usual pendulum equation

$$\ddot{\varphi} = -a^2 \sin\varphi$$

$$a = \frac{ce\sqrt{\varepsilon_0 H_0}}{E_0}$$

$$E_0 = \gamma mc^2$$

If L is the undulator length, the ratio L/c is the time it takes for an electron to pass through the undulator. The product of this time by the parameter a is known as the saturation parameter μ

$$\mu = \frac{aL}{c} = \frac{eL\sqrt{\varepsilon_0 H_0}}{E_0}$$

Amplification in FEL (with $H_0 = const$) is efficient one as long as $\mu \le 1$. At $\mu > 1$ the FEL gain falls. The condition $\mu = 1$ determines the saturation field $\varepsilon_{0,sat}$ and intensity I_{sat} .

For example, at

G

$L = 3m,$ $H_0 = 10^4 Oe,$ $\gamma = 10^2$

$$\varepsilon_{0,sat} : 1.2 \text{ x } 10^4 V / cm$$

$$I_{sat} : 2 \text{ x } 10^5 W / cm^2$$

The pendulum equation has a first integral of motion(kinetic+potential energy of a pendulum = const)

$$\frac{\dot{\varphi}^2(t)}{2} - a^2\cos[\varphi(t)] = const$$

Initial conditions are given by

$$\varphi(0)=\varphi_0 \qquad \dot{\varphi}(0)=\delta=\frac{\omega-\omega_{res}}{2\gamma^2}$$

Where φ_0 is an arbitrary initial phase, δ is the resonance detuning, and ω_{res} is the resonance frequency for noncolinear FEL given by

$$\omega_{res}=\frac{cq}{1-\frac{v_0}{c}\cos\theta}\approx\frac{2\gamma^2 cq}{1+\gamma^2\theta^2}$$

In the case of not too long undulators and sufficiently small energy width of electron beams a characteristic value of the detuning is evaluated as

$$|\delta| : \; 1/t : \; c/L$$

The rate of change of the electron energy is defined as the work produced by the light field per unit time, and this rate is connected directly with the second derivative of the slow-motion phase

$$\frac{dE}{dt} = \frac{E}{2cq}\ddot{\varphi} \approx \frac{E_0}{2cq}\ddot{\varphi}$$

$$E = E_0 \exp\left[\frac{\dot{\varphi}(t) - \dot{\varphi}(0)}{2cq}\right]$$

This approximate expression is written down in the approximation of a small change of the electron energy

$$\left|E - E_0\right| << E_0$$

In this approximation for the total gained of lost energy of a single electron after a passage through the undulator is given by

$$\Delta E = E\left(\frac{L}{c}\right) - E_0 \approx \frac{E_0}{2cq}\left[\dot{\varphi}\left(\frac{L}{c}\right) - \delta\right]$$

In the weak-field approximation($\mu << 1$) one can use the iteration method with the respect to the squared parameter a . The zero-order solution is evident and very simple

$$\dot{\varphi}^{(o)} = \delta$$

In the first order in a^2 one gets

$$\dot{\varphi}^{(1)} = \frac{a^2}{\delta}\left(\cos\left(\varphi_0 + \delta \cdot t\right) - \cos\varphi_0\right) : \quad \frac{a^2 L}{c} = \frac{\mu^2 c}{L}$$

The first-order change of the electron energy

$$\Delta E^{(1)} = \frac{E_0}{2cq}\varphi\&^{(1)} : \frac{E_0}{2cq}\frac{\mu^2 c}{L} = \mu^2 E_0 \frac{\lambda_0}{4\pi L}$$

A transverse velocity v_x and the energy ΔE acuired by an electron after a passage through the undulator are directly proportional to each other

$$v_x = c\theta \frac{\Delta E}{E_0}$$

D.E. Nikonov, M.O. Scully, G.Kurizki, Phys.Rev. E 54, 6780 (1996)

A.I. Artemiev, M.V. Fedorov, Yu.V. Rostovtsev, G.Kurizki, M.O. Scully, Phys.Rev.Lett. 85, 4510 (2000)

Which gives in the first order the following estimate of the electron deviation angle

$$\alpha \approx \frac{v_x^{(1)}}{v_0} \approx \frac{v_x^{(1)}}{c} = \theta \frac{\Delta E^{(1)}}{E_0} : \quad \theta \mu^2 \frac{\lambda_0}{4\pi L} : \quad \mu^2 \frac{d\lambda_0}{4\pi L^2}$$

where d is the electron beam diameter and we take

$$\theta = d / L$$

In the framework of a linear theory we can consider only such fields at which $\mu \leq 1$. Moreover, consideration of the case $\mu >> 1$ has no sense at all because the corresponding fields are too strong and because saturation makes the gain too small.

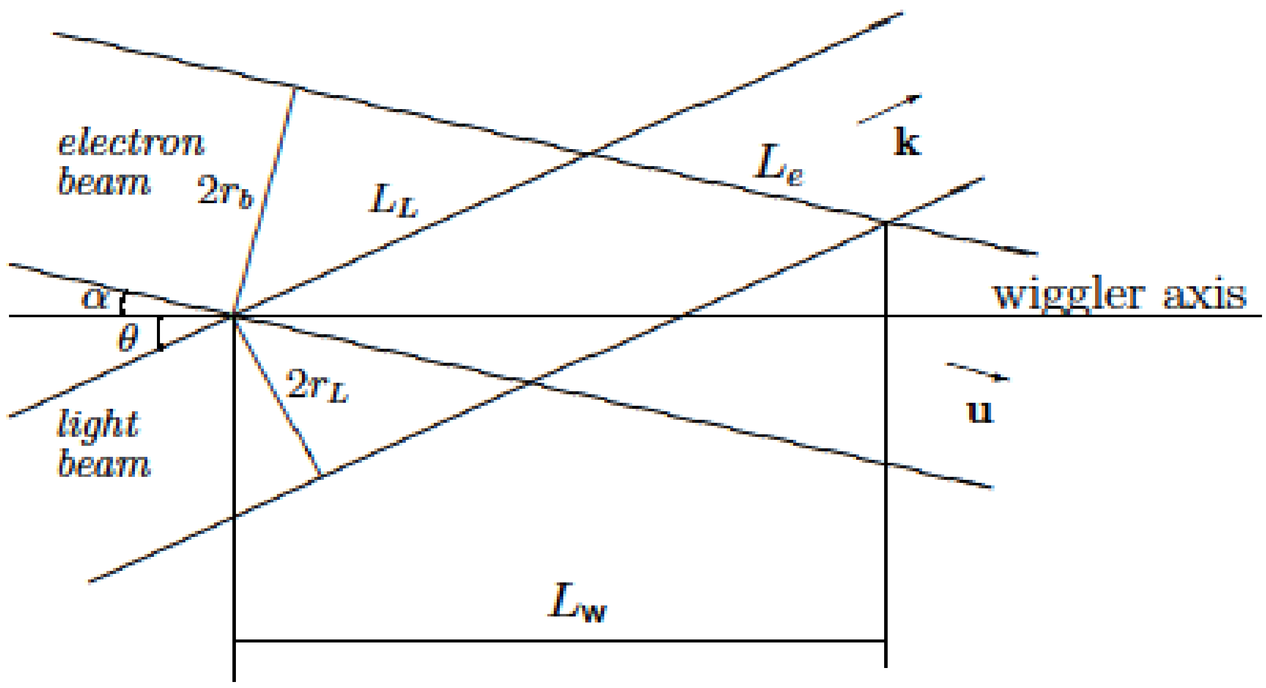
For these reasons let us take for estimates maximal value of the saturation parameter μ compatible with the weak field approximation $\mu : \ 1$

Let $\lambda_0 = 3cm, d = 0.3cm,$ $L = 300cm$

$$\alpha : \ \mu^2 \frac{d\lambda_0}{4\pi L^2} : \ 10^{-6}$$

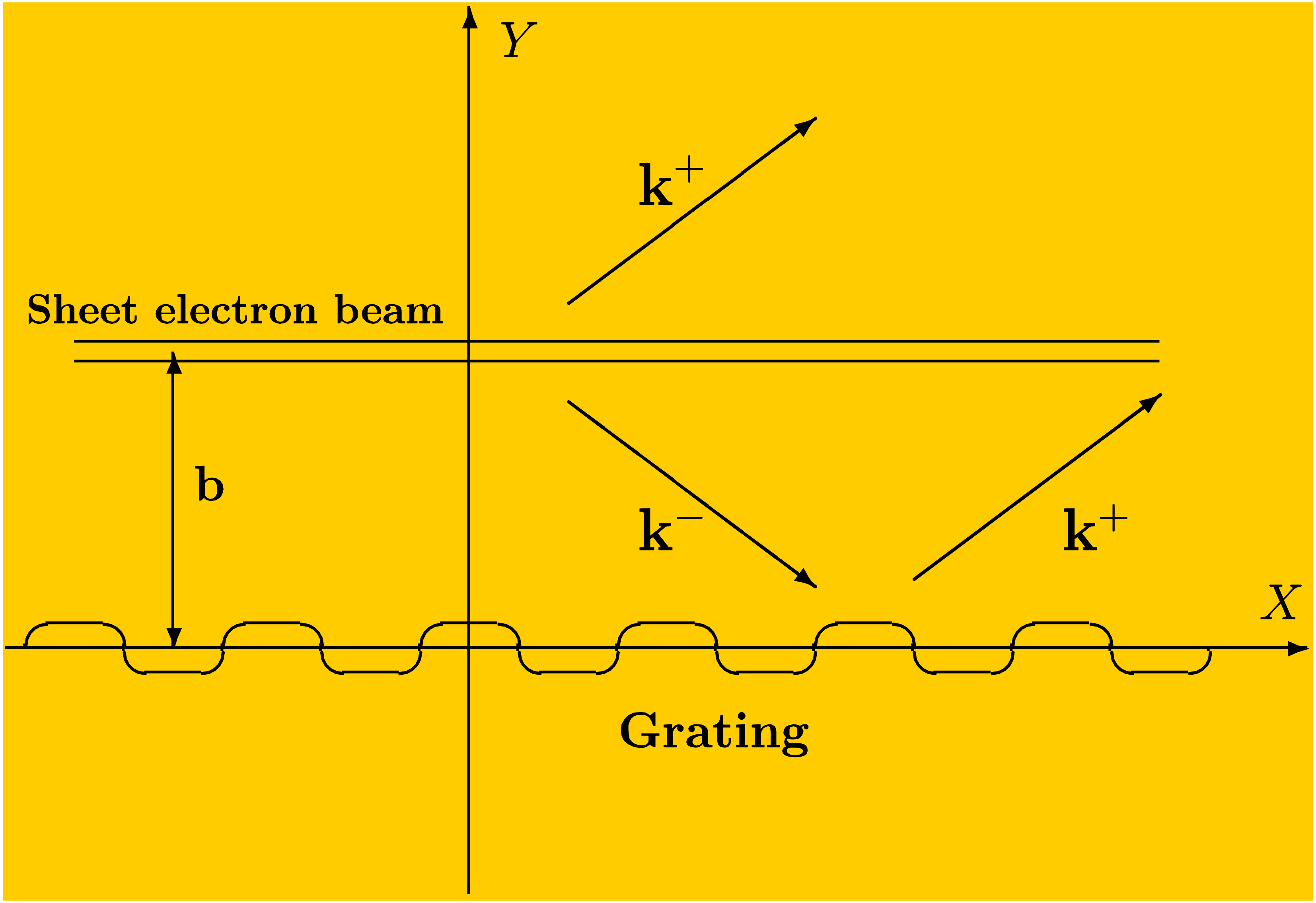
At weaker fields and smaller values of saturation parameter the deviation angle is even smaller than

$$\alpha : \ 10^{-6}$$



electron beam
$2r_b$
L_L
L_e
$\mathbf{k}$
wiggler axis
α
θ
$2r_L$
$\mathbf{u}$
light beam
$L_\mathbf{w}$

Smith-Purcell Radiation



Y
$\mathbf{k}^{+}$
Sheet electron beam
$\mathbf{b}$
$\mathbf{k}^{-}$
$\mathbf{k}^{+}$
X
Grating

One can select two theoretical target settings for SP radiation. The first of them is the problem of generating SP radiation. In this case, the waves incoming from infinity are absent. The SP system generates outgoing waves. Another problem is the amplification or attenuation of incoming waves by the SP system. One can expect that these different problems have different solutions.

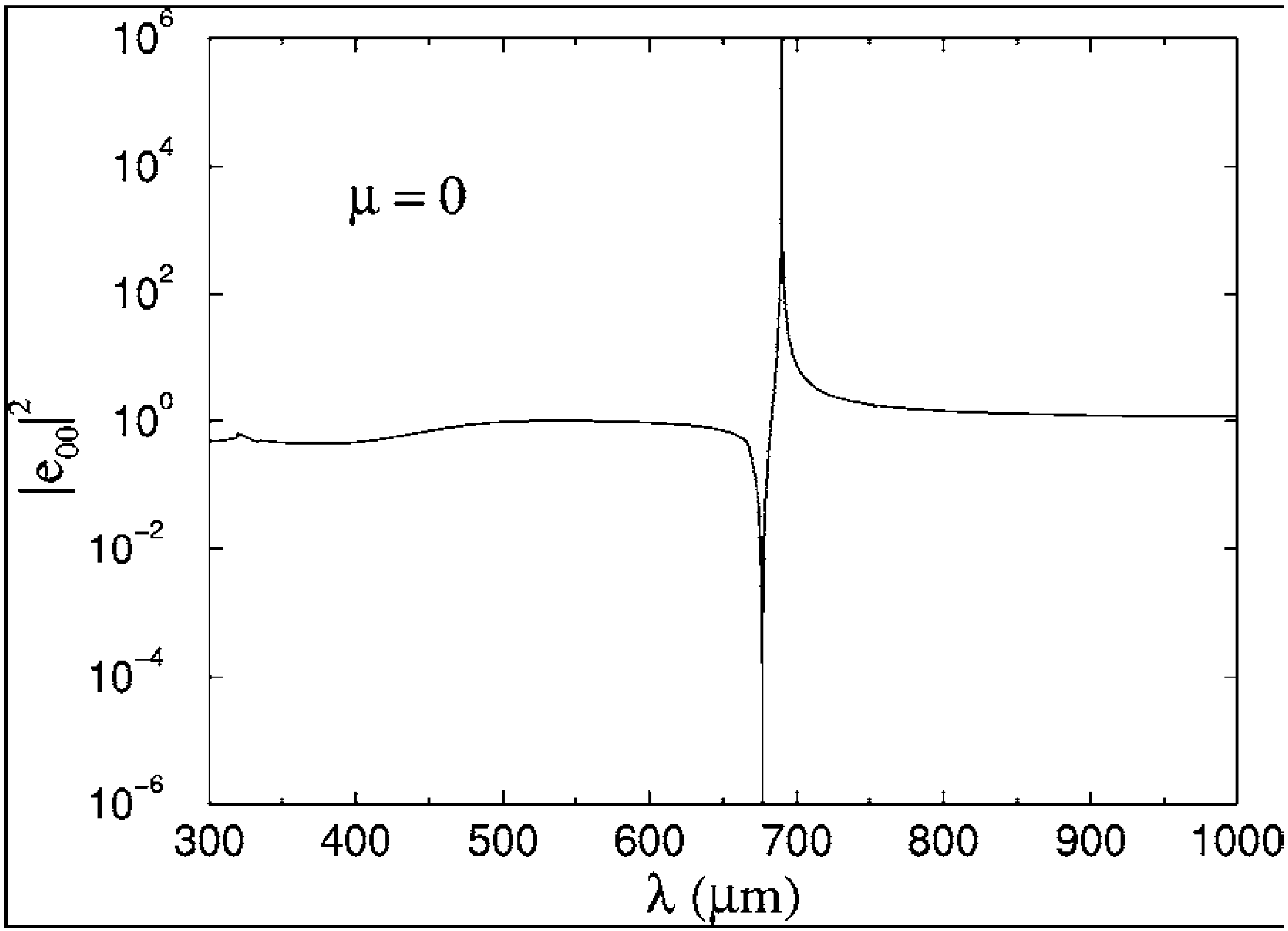
we consider only the problem of generating
waves by the SP system when the incoming waves are absent

$$\omega_p = \sqrt{\frac{4\pi n_e e^2}{m}}$$

We have a closed agreement with results obtained in Ref. [8], for the Thompson regime $\mu_p ? \ 1$

We have found that zero-order approximation for solution of dispersion equation of SP-generation corresponds to the mirror case, when the electron beam propagates above plane metal surface (mirror).

[Vinit Kumar and Kwange-Je Kim, Phys. Rev. E 73, 026501 (2006)] the coefficient *e*00 of reflecting matrix was calculated



In paper Vinit Kumar and Kwange-Je Kim, Phys. Rev. E 73, 026501 (2006) the coefficient *e*00 of reflecting matrix was calculated for the case of rectangular grating for the following parameters: grating period *d* =

1 $w = 62\mu m$ ove $d = 173\mu m$ 2 ¹, groove

depth = 100 ¹*m*, electron ene $h = 100\mu m$ /,

beam height from $35 KeV$ top surface *b* =

10 ¹*m*. $b = 10\mu m$

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Plot of *e*00 as a function of free-space wavelength of the zeroth-order evanescent wave shown that there are two resonant peaks: peak-down at

$675.2\,\mu m$ h 675*:*2 *¹m*, when *e*00 has a zero, and peak-up at wavelength

69 $690\,\mu m$ en *e*00 has a singularity.

The growth rates for both Thompson and Raman types of waves excitation are proportional ω_b the Langmuir frequency *!b* or square root of beam current $I_b^{1/2}$. The conditions of excitations for both Thompson and Raman types do not depend on Langmuir beam frequency (or beam current), but depend on the beam height *b* above the grating.