Smith-Purcell Free Electron Laser: A Compact Terhertz Source

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Indore

March 15, 2019

Symposium on coherence in particle and photon beams: Past, Present and Future

Argonne National Laboratory

In this talk, rather than making a review of Smith-Purcell free-electron lasers, I am going to share some of the things I learnt while working with Kwang-Je during 2003-05, and which continued ....

Outline of the talk

I. **Motivation for Smith-Purcell (SP) FELs**

II. **Surface Mode in SP-FEL**

III. **Beam-wave interaction in SP-FEL**

IV. **Example cases of SP-FEL as terahertz source**

V. **Conclusions**

Motivation for Smith-Purcell FELs

Coherent terahertz radiation can be produced using undulator based FELs.

But, we need high energy electron accelerator (~5-10 MeV), with radiation shielding.

Can we use low energy electron beam for terahertz generation?

Undulator based FEL with low energy?

$$\lambda_R = \frac{\lambda_u}{2\gamma^2}(1 + \frac{K^2}{2}) \qquad K = \frac{eB_u\lambda_u}{2\pi mc}$$

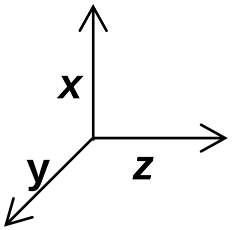
Need to use microundulators. Very low K. Gain will be low. FELs typically require high peak current, so bunched beam is needed.

Slow wave FEL with low energy?

Can we use slow wave structures, such as grating or dielectric based structures for this purpose?

If yes, why has it not been done so far. What are the challenges.

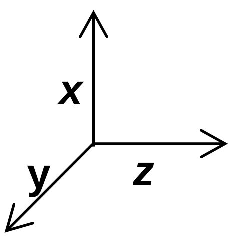
Fast and slow Waves



$$E_x = E_0 e^{(ik_z z - \omega t)}$$
$$H_y = H_0 e^{(ik_z z - \omega t)}$$

$$v_{phase} = \frac{\omega}{k_z} = c$$

Allowed in free space (fast wave)



$$E_x = E_0 e^{(ik_z z - \omega t)} e^{\pm \Gamma x}$$
$$H_y = H_0 e^{(ik_z z - \omega t)} e^{\pm \Gamma x}$$
$$\boldsymbol{E_z = E_1 e^{(ik_z z - \omega t)} e^{\pm \Gamma x}}$$

$$v_{phase} = \frac{\omega}{k_z} < c$$

$$k_z^2 - \Gamma^2 = \frac{\omega^2}{c^2} \rightarrow \Gamma = \frac{2\pi}{\beta\gamma\lambda}$$

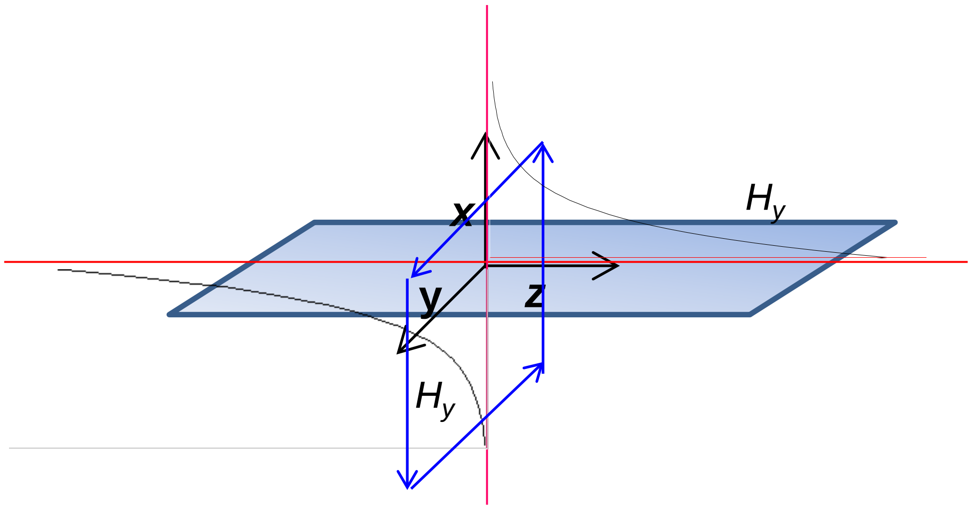
Energy propagated in z-direction only, not in x-direction

Allowed in free space, but needs some material to be present at the boundary to satisfy boundary conditions. (slow wave)

Slow waves generated by a modulated sheet electron beam

A modulated sheet electron beam moving with constant speed produces slow waves, decaying away in the transverse direction*

$$J_z = \delta(x) K_0(\omega) \exp[\, i(\alpha_0 z - \omega t)]$$



$$H_y^I = \frac{1}{2}\varepsilon(x) K_0(\omega) \exp[i\alpha_0 z - \varepsilon(x)\Gamma_0 x]$$

$$E_x^I = \frac{\alpha_0}{2\omega\varepsilon_0}\varepsilon(x) K_0(\omega) \exp[i\alpha_0 z - \varepsilon(x)\Gamma_0 x]$$

$$E_z^I = \frac{-i\Gamma_0}{2\omega\varepsilon_0} K_0(\omega) \exp[i\alpha_0 z - \varepsilon(x)\Gamma_0 x]$$

$$E_y^I = H_x^I = H_z^I = 0$$

$\varepsilon(x)$ = -1 for $x < 0$

+1 for $x > 0$

$$\Gamma_0 = \sqrt{\alpha_0^2 - \omega^2 / c^2}$$
$$= \omega / c\beta\gamma = 2\pi / \beta\gamma\lambda$$

These are slow plane waves, propagating along *z*-axis with speed *v*, but decaying along *x*-axis with length scale of **$\beta\gamma\lambda/2\pi$** . These are non-radiating, zeroth order evanescent wave.

* **K.-J. Kim** and S. -B. Song, NIMA 475 (2001) 158.

Evanescent waves generated by uniformly moving charge and its reflection

IL NUOVO CIMENTO VOL. XVI, N. 1 1° Aprile 1960

1916-2011

On the Theory of some Čerenkovian Effects (*).

G. TORALDO DI FRANCIA

Istituto di Fisica della Radiazione - Università di Firenze

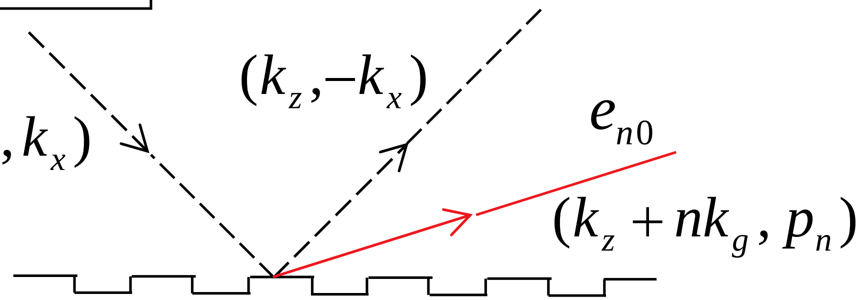
(ricevuto il 21 Dicembre 1959)

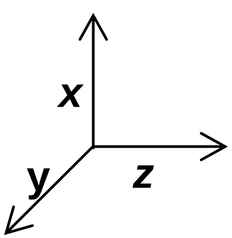
Summary. - The field generated by a charged article in uniform straight motion is expanded into a set of evanescent waves. The expansion is valid in any half-space with no points in common with the path of the particle. The evanescent waves may impinge on the surface of an optical diffraction grating and be diffracted. Some of the diffracted waves turn out to be ordinary plane waves, which carry energy away from the grating. It is possible in this way to explain the Smith and Purcell effect and to derive some quantitative conclusions.

Reflection of evanescent wave by a metallic reflection grating

$$H_y = A_0^I \exp(i\alpha_0 z + \Gamma_0 x - i\omega t) + \sum_{n=-\infty}^{+\infty} A_n^R \exp(i\alpha_n z + ip_n x - i\omega t)$$

$$k_x = -i\Gamma_0,\ k_z = \alpha_0$$





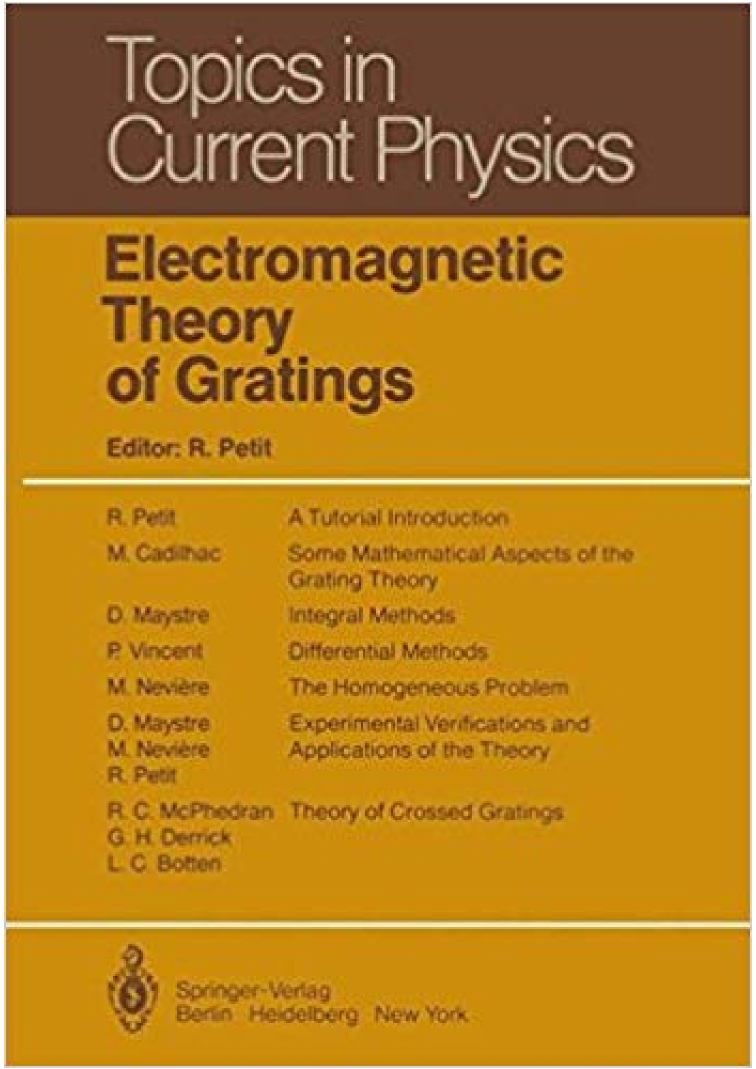
$$p_n = \sqrt{\frac{\omega^2}{c^2} - (k_z + nk_g)^2}$$

real $\rightarrow$ propagating, radiative

imaginary $\rightarrow$ evanescent, non-radiative

For some values of n (<0), k_x and k_z are real, those are SP radiation orders.

Diffraction at the grating surface



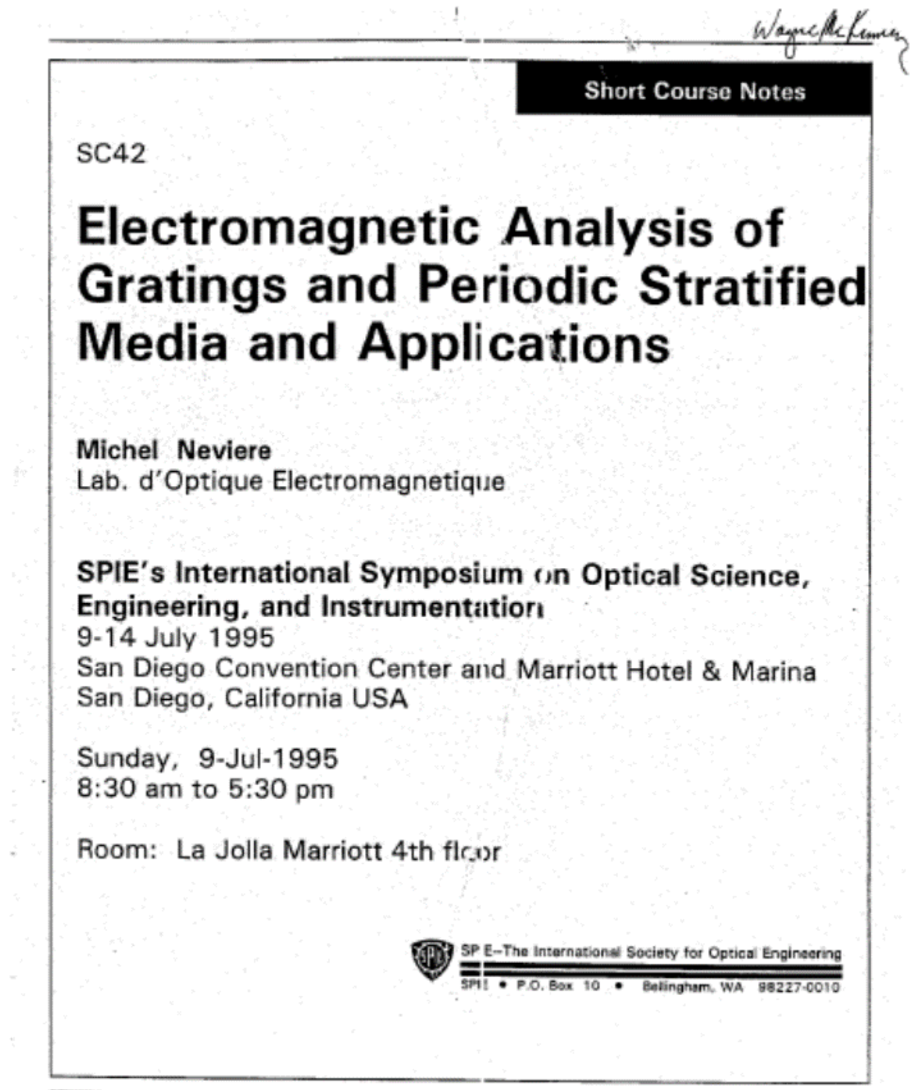
Topics in Current Physics

Electromagnetic Theory of Gratings

Editor: R. Petit

R. Petit	A Tutorial Introduction
M. Cadilhac	Some Mathematical Aspects of the Grating Theory
D. Maystre	Integral Methods
P. Vincent	Differential Methods
M. Nevière	The Homogeneous Problem
D. Maystre M. Nevière R. Petit	Experimental Verifications and Applications of the Theory
R. C. McPhedran G. H. Derrick L. C. Botten	Theory of Crossed Gratings

Springer-Verlag
Berlin Heidelberg New York



Short Course Notes

SC42

Electromagnetic Analysis of Gratings and Periodic Stratified Media and Applications

Michel Neviere
Lab. d'Optique Electromagnetique

SPIE's International Symposium on Optical Science, Engineering, and Instrumentation
9-14 July 1995
San Diego Convention Center and Marriott Hotel & Marina
San Diego, California USA

Sunday, 9-Jul-1995
8:30 am to 5:30 pm

Room: La Jolla Marriott 4th floor

SPIE–The International Society for Optical Engineering
SPIE • P.O. Box 10 • Bellingham, WA 98227-0010

Phys. Rev. paper by Smith-Purcell

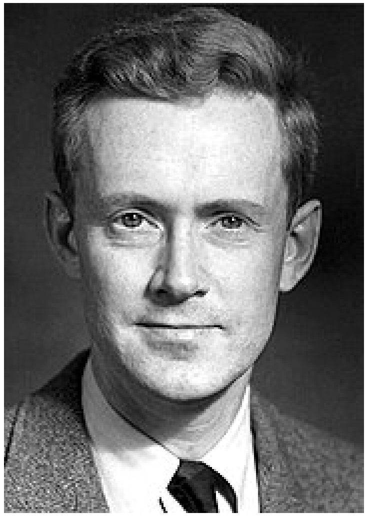
Visible Light from Localized Surface Charges Moving across a Grating

S. J. SMITH* AND E. M. PURCELL

Lyman Laboratory, Harvard University, Cambridge, Massachusetts

(Received September 25, 1953)

IT occurred to one of the authors (EMP) that if an electron passes close to the surface of a metal diffraction grating, moving at right angles to the rulings, the periodic motion of the charge induced on the surface of the grating should give rise to radiation. A simple Huygens construction shows the fundamental wavelength to be $d(\beta^{-1}-\cos\theta)$, in which d is the distance between rulings, β stands for v/c as usual, and θ is the angle between the direction of motion of the electron and the light ray. If $d=1.67$ microns, as in a typical optical grating, and if electrons of energy around 300 kev are used, the light emitted forward should lie in the visible spectrum. As for intensity, if we assume that the surface charge traversing the hills and dales is equivalent to a point charge e oscillating with an amplitude $d/10$, we find that in the forward



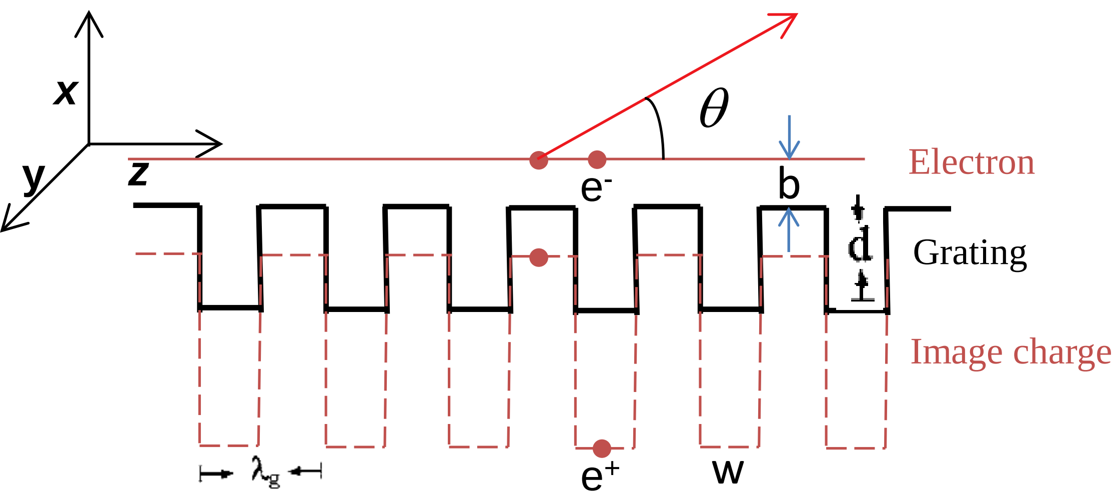
1912-1997

Smith-Purcell radiation

An electron beam traveling close and parallel to a metallic reflection grating, with grating rulings perpendicular to the electron motion gives off polarized electromagnetic radiation, known as SP radiation[*].

Dartmouth parameters[**]

λ_g = 173 μm, β = 0.35 (35 keV)
d = 100 μm, w = 62 μm,
b = 10 μm, L = 12.7 mm



(Assume translational symmetry in y-direction)

$$\lambda = \frac{\lambda_g}{\beta}(1-\beta\cos\theta)$$

θ	λ
0	321 μm
$\pi/2$	494 μm
π	667 μm

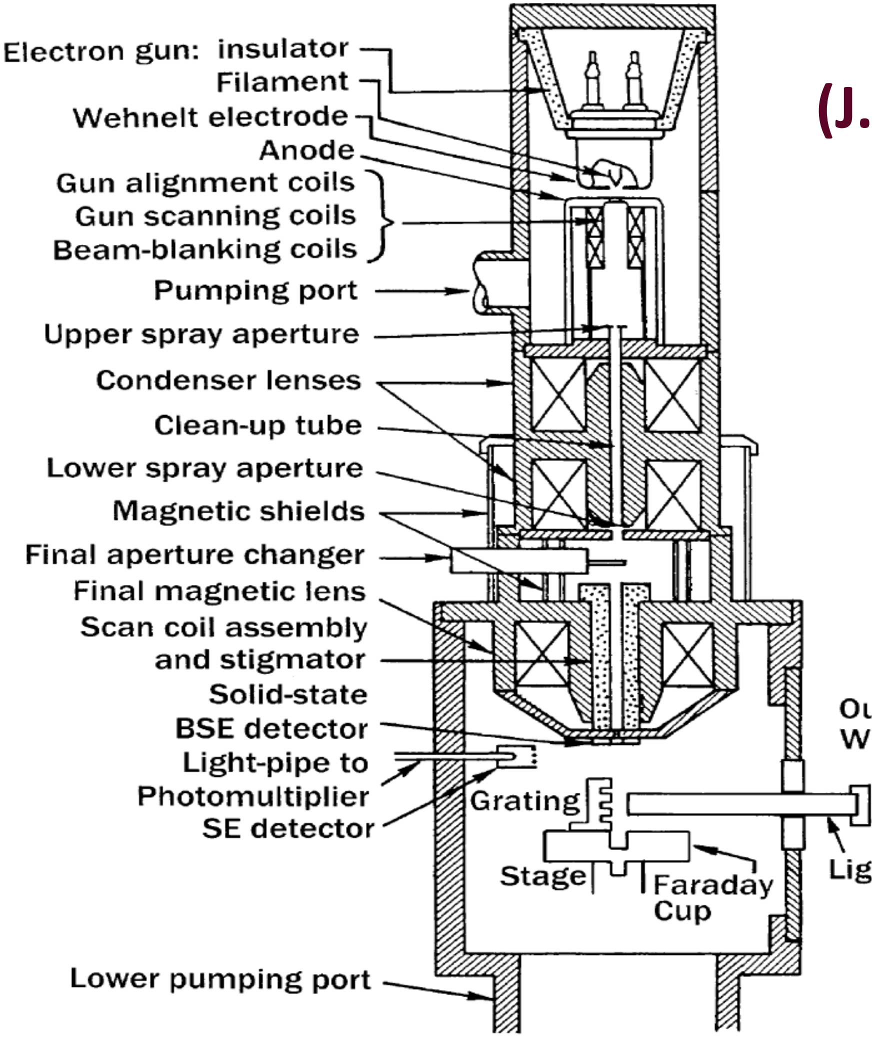
$\lambda_{SP} < 667\ \mu$m

[**] J. Urata et al., Phys. Rev. Lett., 80, 516 (1998)

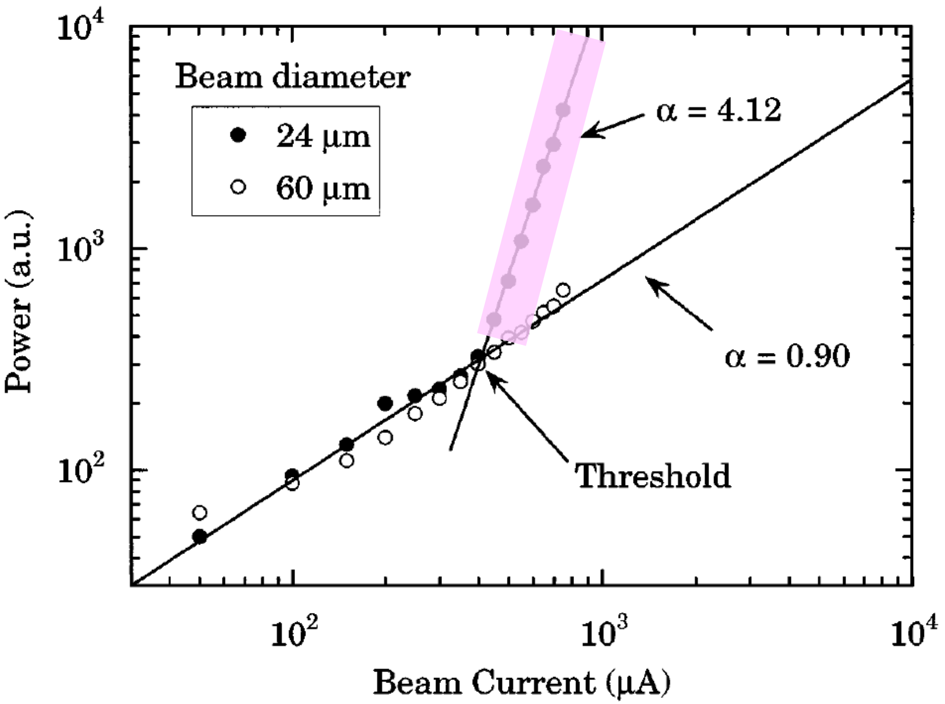
[*] S. J. Smith and E. M. Purcell, Phys. Rev. 92, 1069 (1953)

Phys. Rev. Lett. paper by Urata and Walsh

SEM-based Smith-Purcell FEL?

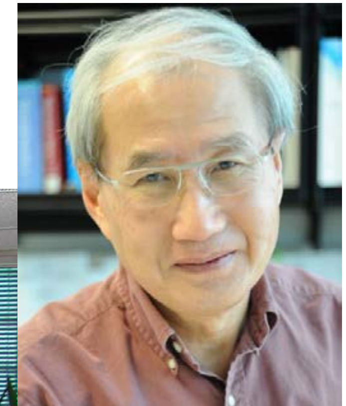


(J. Urata et al., PRL 80 (1998) 516-519)



Is it an FEL?

"Smith-Purcell FEL Lab" at the Univ. of Chicago following the Dartmouth set-up (O. Kapp, A. Crewe, Y.E. Sun, V. Kumar, KJK)



β= 0.35 (35 keV)
I = 1 mA
λg = 173 μm,
d = 100 mm,
w = 62 μm,
b = 10 μm,
L = 12.7 mm

Can the reflectivity be greater than unity, …infinity?

IL NUOVO CIMENTO Vol. XVI, N. 1 1° Aprile 1960

On the Theory of some Čerenkovian Effects (*).

G. Toraldo di Francia

Istituto di Fisica della Radiazione - Università di Firenze

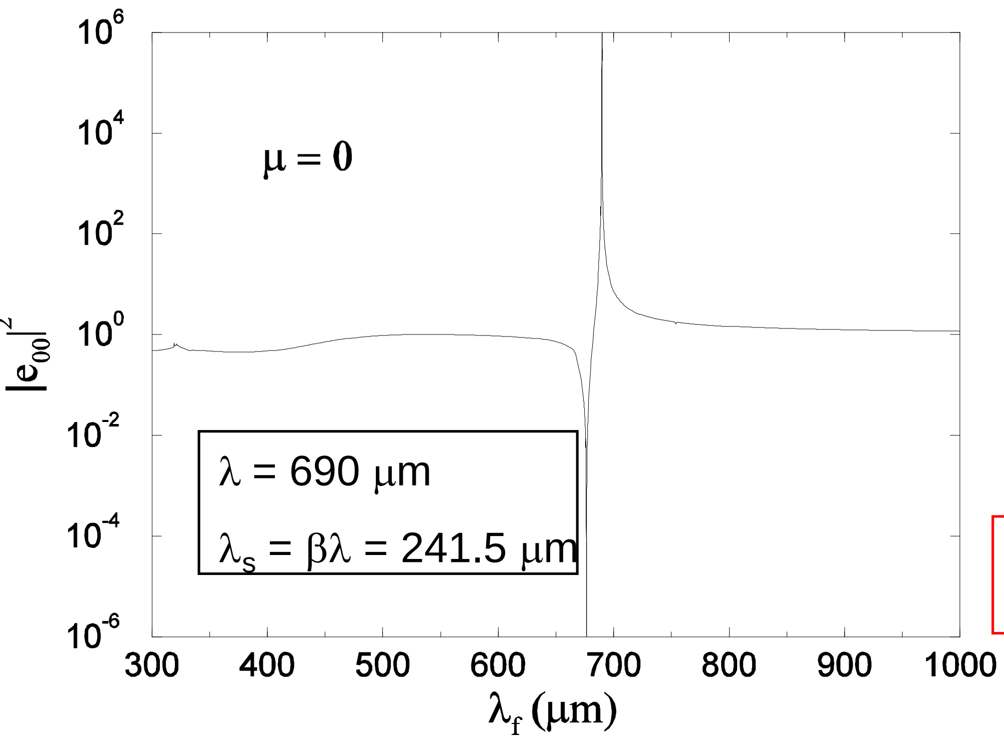
(ricevuto il 21 Dicembre 1959)

Summary. - The field generated by a charged article in uniform straight motion is expanded into a set of evanescent waves. The expansion is valid in any half-space with no points in common with the path of the particle. The evanescent waves may impinge on the surface of an optical diffraction grating and be diffracted. Some of the diffracted waves turn out to be ordinary plane waves, which carry energy away from the grating. It is possible in this way to explain the Smith and Purcell effect and to derive some quantitative conclusions.

For instance, if we want to estract from the particle as much energy as possible, we are interested in having a great value for δ_m. It is interesting to note that when both the incident and reflected waves are evanescent, the grating can show a sort of resonance (21) giving $\delta_m \gg 1$. It will be worthwhile to investigate whether a similar condition can be obtained when the incident wave is evanescent and the diffracted wave is an ordinary travelling wave.

Singularity in reflectivity and surface mode in SP-FEL

*V. Kumar and K.-J. Kim, PAC05 proceedings, Phys Rev. E 73, 026501(2006)



Dartmouth parameters**

λ_g = 173 μm, β = 0.35 (35 keV)

groove depth (d) = 100 μm,

groove width (w) = 62 μm,

$$H_y^{SM} = \sum C_n \exp(i\alpha_n z - \Gamma_n x - i\omega_s t)$$

•e_{00} blows up at λ = 690 μm which means that the zeroth order outgoing wave is supported there even in the absence of incoming wave.

•In fact, zeroth order wave and all higher order outgoing components add up with specific amplitude ratio to satisfy the boundary condition. This is the surface mode supported self-consistently by the grating

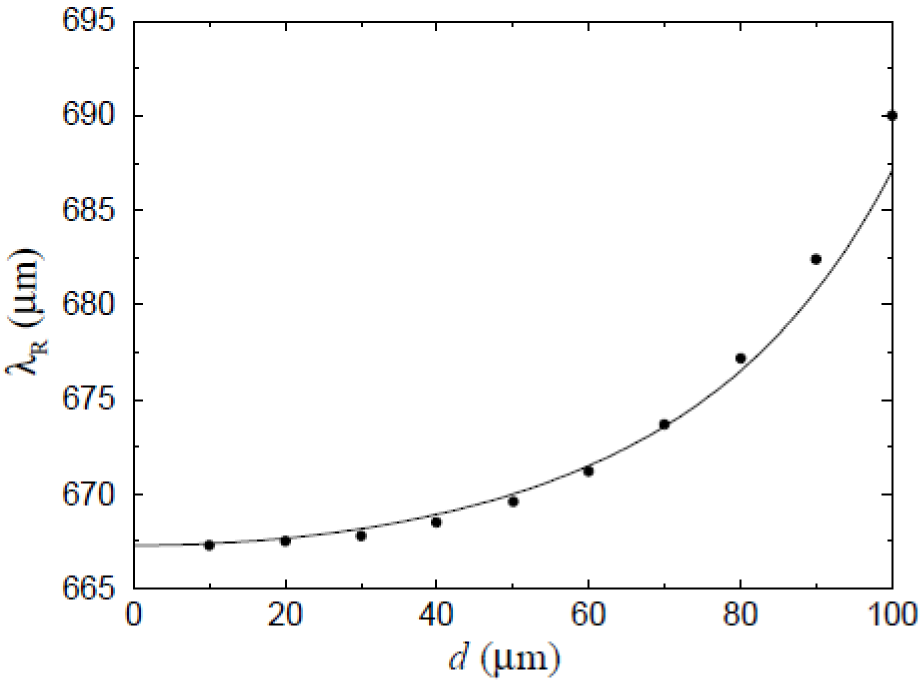
Approximate formula for resonant wavelength in SP-FEL

$$\lambda_R = \lambda_R^0 + \Delta\lambda$$

$$\lambda_R^0 = \lambda_g \frac{1+\beta}{\beta}$$

$$\Delta\lambda = \frac{\lambda_g}{2}\left(\frac{\delta}{k_R^0}\right)^2$$

$$\delta = \frac{2\tan(k_R^0 d)}{k_R^0 w \lambda_g}\{1-\cos(w k_R^0)\}$$

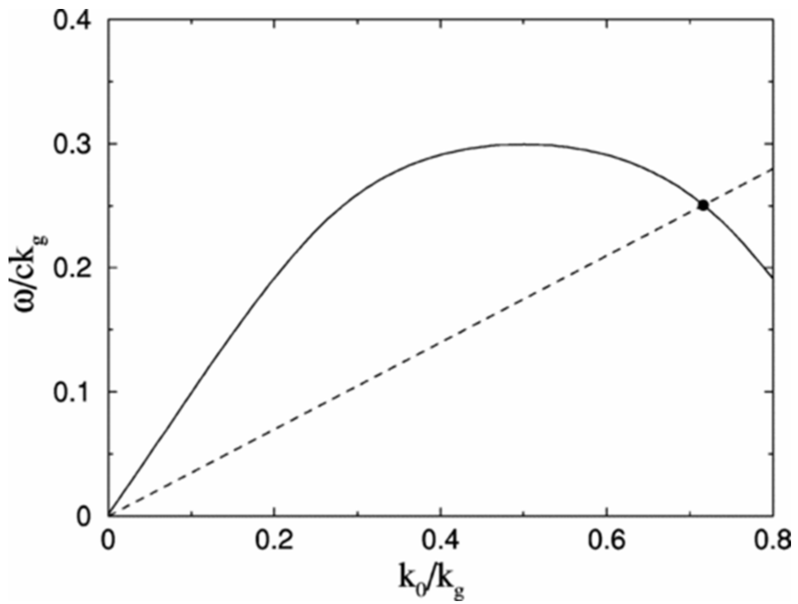


Notice the difference: U-FEL: $\lambda = \lambda_u \frac{1-\beta}{\beta}$, SP-FEL: $\lambda \cong \lambda_g \frac{1+\beta}{\beta}$

* V. Kumar and K.-J. Kim, PAC05.

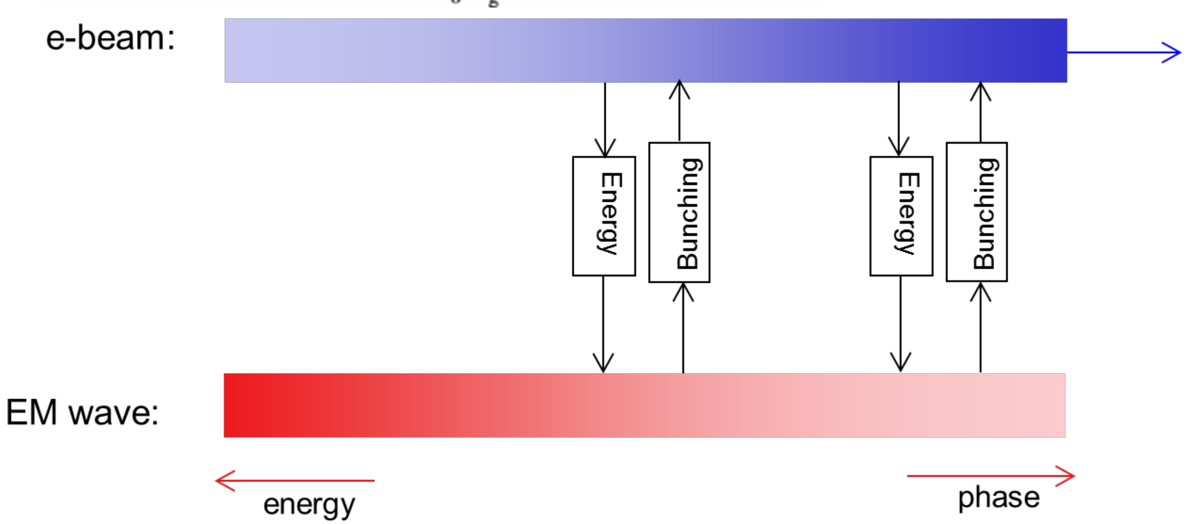
Beam-wave interaction

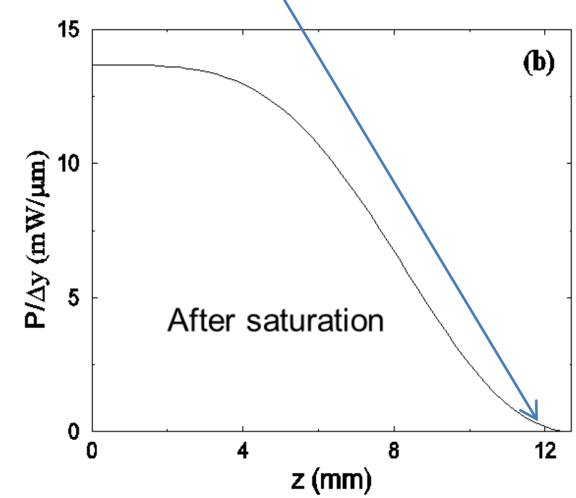
Interaction between slow wave and the co-propagating electron beam produces coherent radiation



Group velocity is typically -ve, works as a backward wave oscillator.

Boundary condition: Input field needs to be provided at the electron beam exit!





Singularity of reflection coefficient

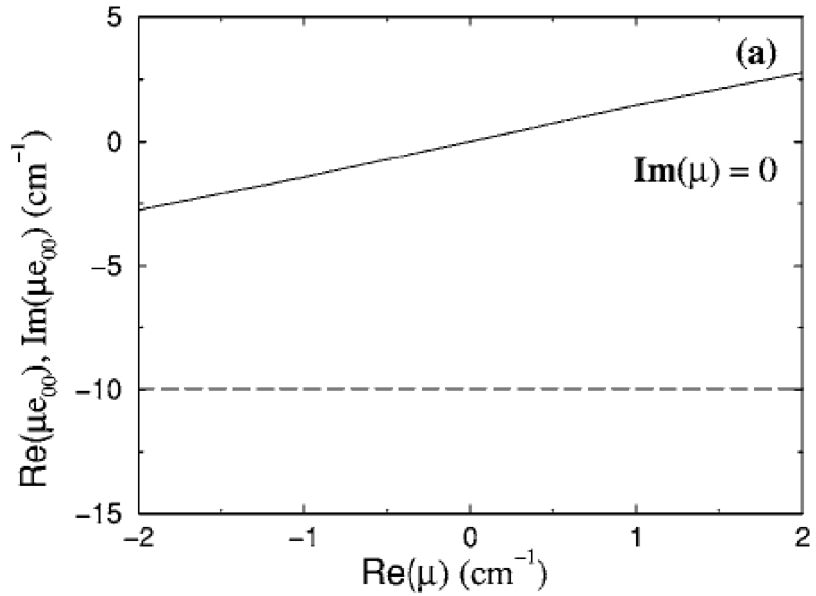
•We observe that the singularity in *R* is removed at non-zero growth rate (μ) of the incident wave.

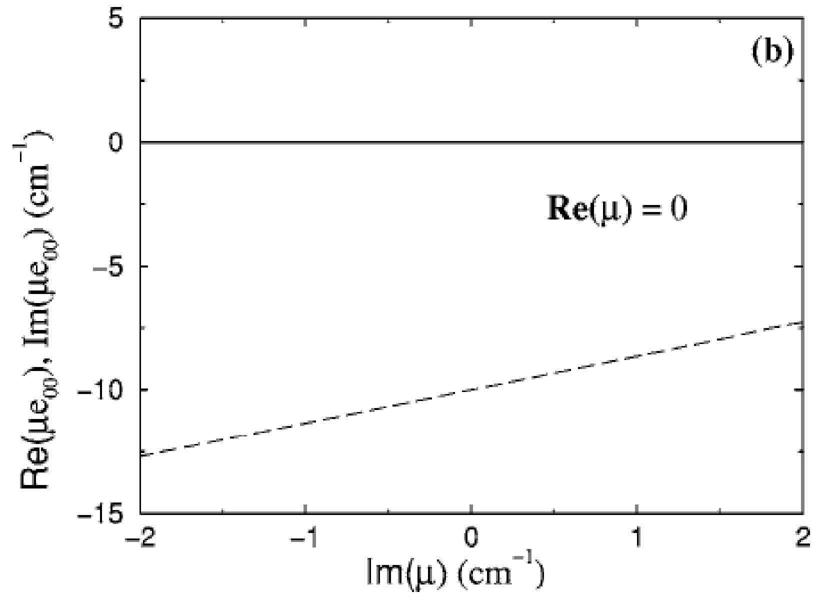
$$E_Z = E_0 e^{(ik_z z - \omega t)} e^{\Gamma x} e^{\mu z}$$

•*R* has a simple pole at μ = 0, and it can be expressed as

$$R(\mu) = \frac{-i\chi}{\mu} + \chi_1$$

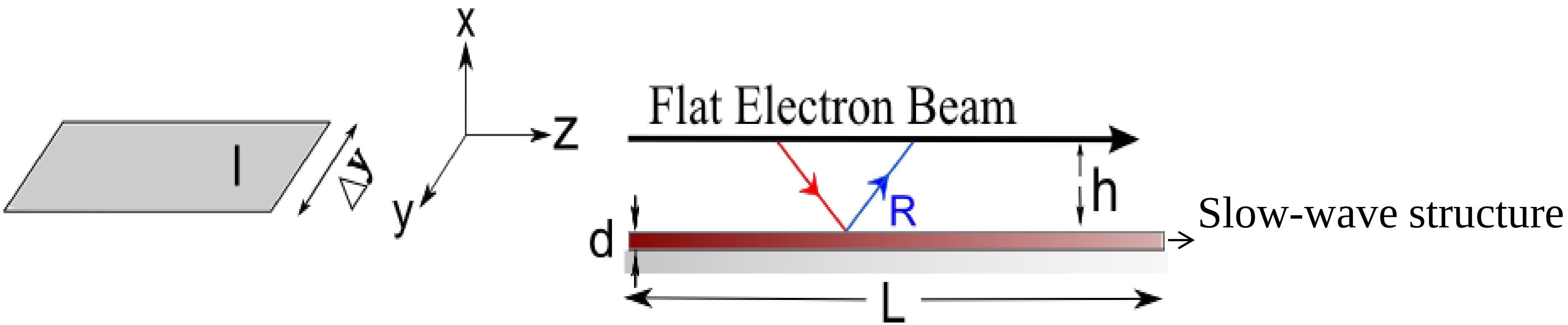
χ = 10 per cm, χ_1 = 1.37





*V. Kumar and K.-J. Kim, PRE 73 (2006)026501; Y. Kalkal and V.Kumar, PRSTAB 18 (2015)030707.

Maxwell-Lorentz equations - I



Surface current: $(I/\Delta y)\left\langle e^{-i\psi}\right\rangle e^{i(k_s z-\omega_s t)} + c.c.$

Axial electric field: $E_z(z,t)e^{i(k_s z-\omega_s t)} + c.c.$

$$E_z = \frac{iIZ_0}{2\beta\gamma\Delta y}\left(Re^{-2\Gamma_0 b} - 1\right)\left\langle e^{-i\psi}\right\rangle$$

$$E_z = \frac{iIZ_0}{2\beta\gamma\Delta y}\left(\frac{-i\chi}{\mu}e^{-2\Gamma_0 b} + \chi_1 e^{-2\Gamma_0 b} - 1\right)\left\langle e^{-i\psi}\right\rangle = E^{sur} + E^{sc}$$

A novel approach!

This approach of separating the total electromagnetic field into surface mode field and space charge field is similar to the approach described in Ref. [40], where it is stated that "*The total fields from an arbitrary, spatially periodic current are shown to consist of a pole term, which is identified as the structure field, and a remainder, which is identified as the space charge field*". Dynamics of the electron beam is governed by the surface mode field, as well as the

[40]. R. J. Pierce, *Traveling Wave Tubes* (D. Van Nostrand Company Inc; First edition, 1950)

Maxwell-Lorentz equations - II

$$\mu E^{sur} = \frac{IZ_0\chi}{2\beta\gamma\Delta y} e^{-2\Gamma_0 b}\left\langle e^{-i\psi}\right\rangle$$

Replacing μ with the operator *d/dz*, we get

$$\frac{dE^{sur}}{dz} = \frac{IZ_0\chi}{2\beta\gamma\Delta y} e^{-2\Gamma_0 b}\left\langle e^{-i\psi}\right\rangle$$

Time-dependent Maxwell equation:

$$\frac{\partial E}{\partial t} - v_g \frac{\partial E}{\partial z} = -\frac{IZ_0\chi v_g}{2\beta\gamma\Delta y} e^{-2\Gamma_0 b}\left\langle e^{-i\psi}\right\rangle$$

$$E^{sc} = \frac{-iIZ_0}{2\beta\gamma\Delta y}\left(1-\chi_1 e^{-2\Gamma_0 b}\right)\left\langle e^{-i\psi}\right\rangle$$

Lorentz equation:

$$\frac{\partial \gamma_i}{\partial t} + v\frac{\partial \gamma_i}{\partial z} = \frac{ev}{mc^2}\left(E + E^{sc}\right)e^{i\psi_i} \quad + c.c.$$

$$\frac{\partial \psi_i}{\partial t} + v\frac{\partial \psi_i}{\partial z} = \frac{\omega_s}{\beta^2\gamma^2}\frac{\left(\gamma_i - \gamma_p\right)}{\gamma_p}$$

No attenuation   No end reflection   No 3-D effects

Maxwell-Lorentz equations with attenuation and end reflections

Maxwell-Lorentz equations with attenuation and end reflections

Dimensionless variables:

$$\varsigma = z / L$$

$$\tau = \left(\tau - \frac{z}{v_p}\right)\left(\frac{1}{v_p} + \frac{1}{v_g}\right)^{-1} \frac{1}{L}$$

$$\eta_i = \frac{k_s L}{\beta_p^3 \gamma_p^3}\left(\gamma_i - \gamma_p\right)$$

$$\varepsilon = \frac{e}{mc^2} \frac{k_s L^2}{c\beta_p^3 \gamma_p^3} E$$

$$\varepsilon_s = \frac{e}{mc^2} \frac{k_s L^2}{c\beta_p^3 \gamma_p^3} E_s$$

$$J = 2\pi \frac{I}{I_A} \frac{\chi}{\Delta y} \frac{k_s L^3}{\beta_p^4 \gamma_p^4} e^{-2\Gamma_0 b}$$

Maxwell-Lorentz equations in dimensionless variables:

$$\frac{\partial \varepsilon_-}{\partial \tau} - \frac{\partial \varepsilon_-}{\partial \varsigma} = -J\left\langle e^{-i\psi}\right\rangle - \alpha L \varepsilon_-$$

$$\frac{\partial \varepsilon_+}{\partial \tau} + d_1 \frac{\partial \varepsilon_+}{\partial \varsigma} = -\alpha L \varepsilon_+$$

$$\frac{\partial \eta_i}{\partial \varsigma} = \left(\varepsilon_+ + \varepsilon^{sc}\right) e^{i\psi_i} + c.c.$$

$$\frac{\partial \psi_i}{\partial \varsigma} = \eta_i$$

$$\varepsilon^{sc} = i\frac{J}{\chi L}\left(\chi_1 - e^{2\Gamma_0 b}\right)\left\langle e^{-i\psi}\right\rangle$$

Boundary conditions:

$$\varepsilon_+(\varsigma = 1, \tau) = -\varepsilon_-(\varsigma = 1, \tau),$$

$$\varepsilon_-(\varsigma = 0, \tau) = Re^{-i2k_0 L}\varepsilon_+(\varsigma = 0, \tau)$$

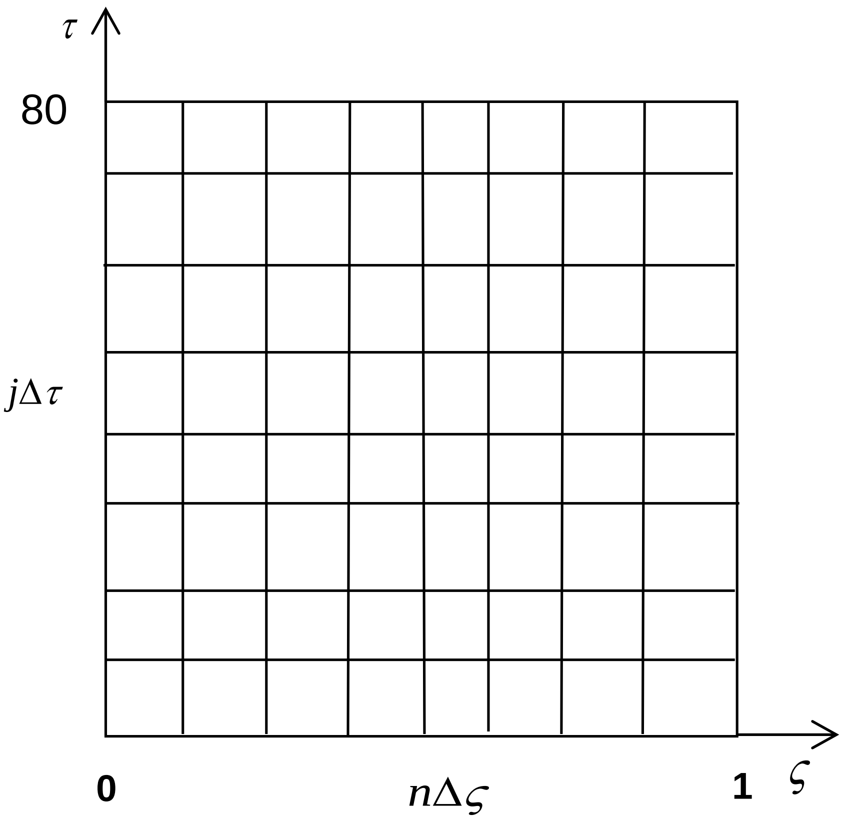
ε_+ : forward wave

ε_- : backward wave

$$d_1 = \frac{v_p + v_g}{v_p - v_g}$$

*V. Kumar and K.-J. Kim, Proceedings of FEL06

Numerical simulations



•Particles initialized as per Penman's algorithm to take care of shot noise

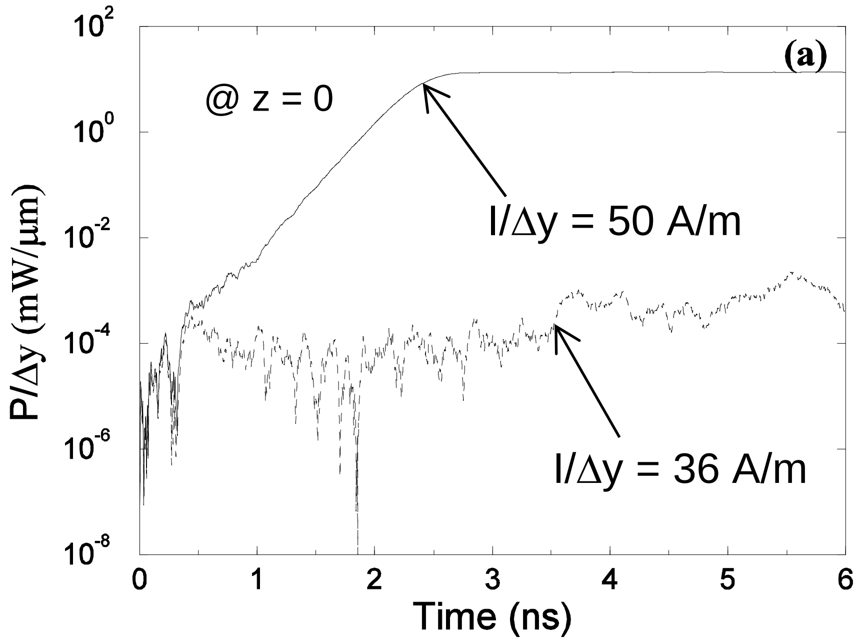
•Particle pushing for known field using predictor-corrector method.

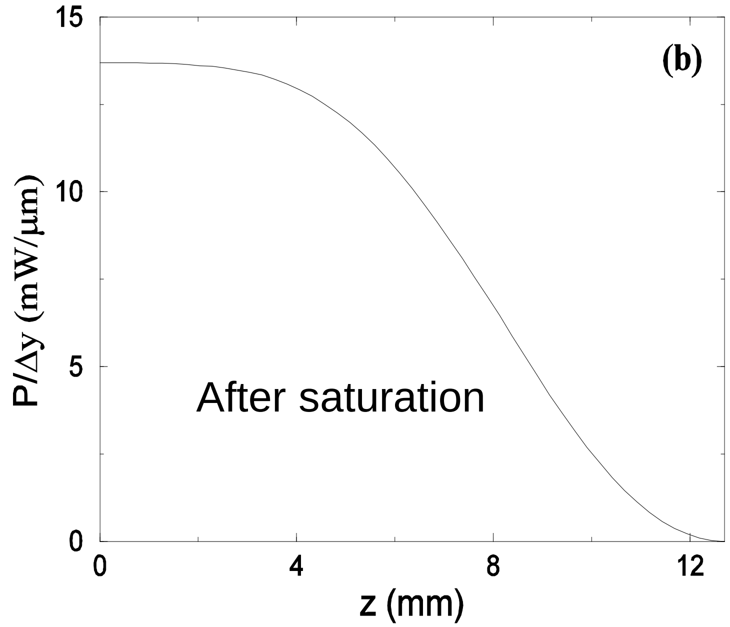
•Convert P. D. E for field to difference equation and updated the field using the difference equation

•Grid parameters:
$\Delta\tau = 0.01 \Rightarrow t = 2.02$ ps
$\Delta\zeta = 0.02$, $N_{part} = 1024$

*Our algorithm is similar to N. S. Ginzburg et al., Sov. Radiophys. Electron., 21, 728 (1979).

Simulation Results – I





For I/Δy = 50 A/m, at saturation, P/Δy = 13.7 mW/μm

Power e-folding time = 0.2 ns (simulation)

0.17 ns (analytic formula)

Lasing wavelength = 694.5 μm (simulation)

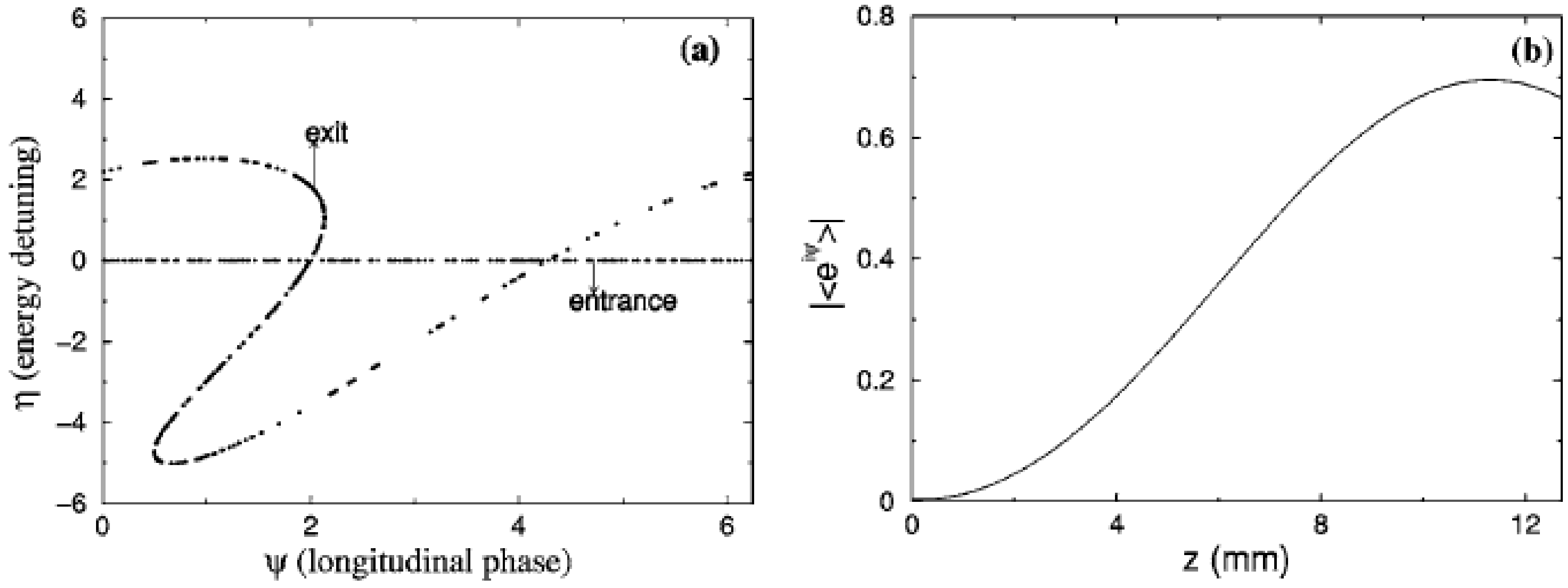
694 μm (analytic formula)

$$I_s = \mathcal{J}_s \frac{I_A \Delta y}{4\chi} \frac{\beta^4 \gamma^4}{k L^3} e^{2\Gamma_0 h}$$

$$\eta^{max} = \frac{\beta^3 \gamma^3}{(\gamma - 1)} \frac{\lambda}{L}$$

Energy conversion efficiency = 0.8%

Simulation Results – II



Bunching in Smith-Purcell FEL

Three Dimensional Effects

Three-dimensional surface mode can be constructed by combining the plane waves propagating at different angles with suitable weight factor[1].

Beam sizes: $\Delta y = \sqrt{\lambda L/\pi\beta_g}$ $\Delta x = 1/2\Gamma_0$

(~ few tens mm) (~ few tens μm)

Unnormalized emittance: $\epsilon_y \leq \frac{\lambda}{4\pi\beta_g}$ $\epsilon_x \leq \frac{(\Delta x)^2}{4L}$

(~ few μm-rad) (~ few nm-rad)

Gaussian mode in free space:

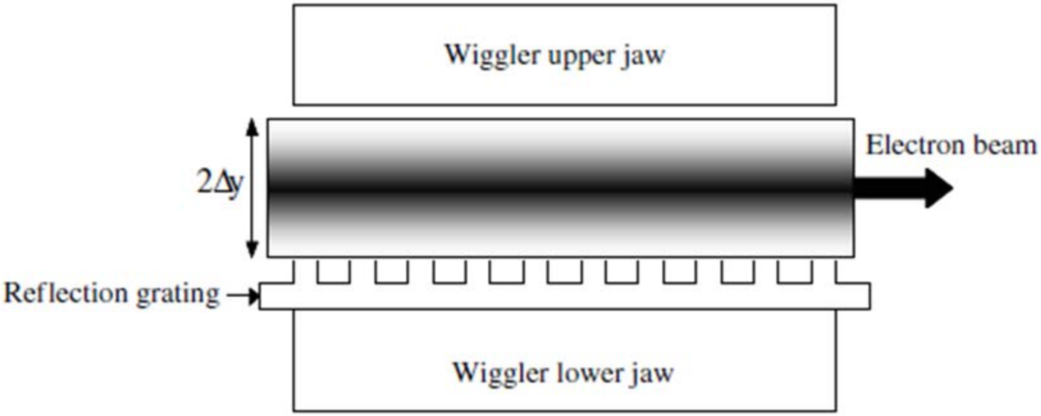
RMS beam size = $\sqrt{\frac{\lambda Z_R}{4\pi}}$

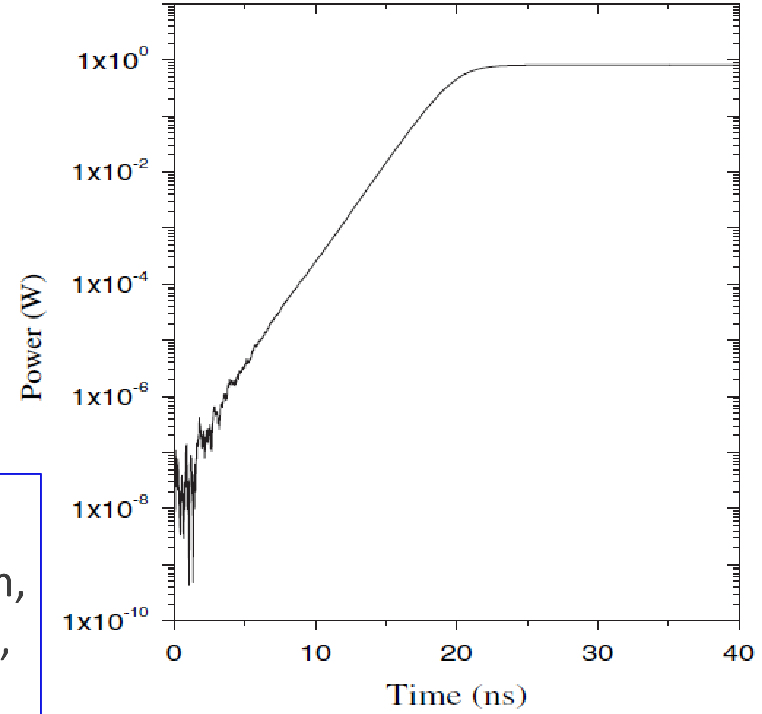
Need round to flat beam transformation to achieve this [2].

The stringent criterion on vert. emitt. can be somewhat relaxed with the help of external focusing[3].

1. **K.–J. Kim** and V. Kumar, PRSTAB **10**, 080702 (2007).
2. P. Piot, Y.-E. Sun, and **K.-J. Kim**, PRSTAB **09**, 031001 (2006).
3. V. Kumar and **K.–J. Kim**, PRSTAB **12**, 070703 (2009).

Relaxed beam parameters with external focusing[1]





Grating parameters:
λ_g = 173 μm,
d = 130 mm,
w = 110 μm,
L = 38.06 mm
λ_R = 761 mm

Beam parameters:
β= 0.35 (35 keV)
I = 30 mA
Δy = 45.6 μm
Δx = 7 mm
$\beta\gamma\varepsilon_x = 10^{-5}$ mrad
$\beta\gamma\varepsilon_y = 10^{-7}$mrad

Wiggler[2]:
λ_w = 2.7 mm,
gap = 1 mm,
B_{pk} = 4.7 kG

Similar performance can be achieved also by using a solenoid (instead of wiggler) having a field of 2.5 kG to focus the electron beam, the flat beam in that case should be generated using a line cathode. The line cathode followed by a reflection grating should be immersed together in the uniform field region of the solenoid.

1. V. Kumar and **K.–J. Kim**, PRSTAB **12**, 070703 (2009).

2. V. A. Papadichev V. E. Rybalchenko, NIMA **19**, 407 (1998).

Conclusions

- Smith-Purcell FELs seem to be interesting and useful alternative to undulator based FELs for compact sources of terahertz radiation.

- SP-FEL can be described by Maxwell-Lorentz equations of the form similar to that of undulator based FELs. **Effect of attenuation and diffraction are particulary important, and can not be ignored.**

- Main challenge in achieving successful lasing in SP-FEL is to meet the stringent critera on beam quality. Flat beam with low emittance in vertical direction is needed.

- If the challenge on beam quality is met in future, it appears that SP-FELs will be very useful as a compact source to generate average power of the order of Watt at terahertz wavelengths.


Thank You!

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Observation of THz evanescent waves in a Smith-Purcell free-electron laser

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We present experimental observations of evanescent waves in a Smith-Purcell free-electron laser (FEL). These waves, predicted by both theory and simulations, have wavelengths longer than the Smith-Purcell radiation, group velocity antiparallel to the electron beam, and for sufficiently high current, provide feedback to bunch the electron beam. This feedback is the basis of oscillator operation of the Smith-Purcell FEL. The wavelengths observed agree with theoretical predictions, and strong radiation from the upstream end of the grating confirms the negative group velocity. Radiation observed at the second harmonic may indicate electron bunching by the evanescent wave.

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EMITTANCE MEASUREMENT OF A DC GUN FOR SMITH-PURCELL BACKWARD WAVE OSCILLATOR FEL*

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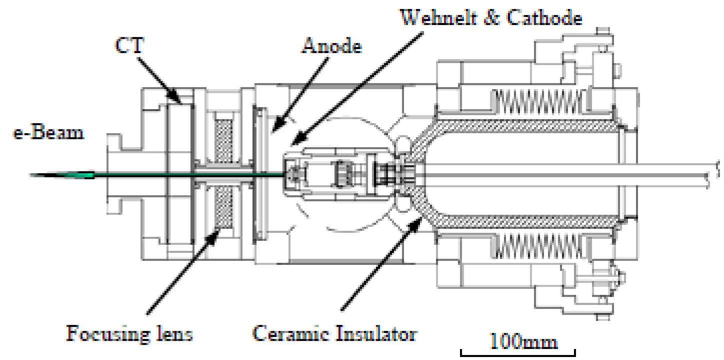
Abstract

A terahertz light source based on Smith-Purcell Backward Wave Oscillator FEL (S-P BWO-FEL) has been studied at Laboratory of Nuclear Science, Tohoku University. The DC gun employs a high voltage of 50 kV to extract electrons, which is suitable to drive S-P BWO-FEL [1]. Emittance measurement has been performed by means of a double slit technique. The deduced normalized rms emittance is about 2 π mm mrad. We present the results of emittance measurement and analysis.

INTRODUCTION

Currently, various sources of terahertz (THz) radiation are based on accelerator or laser and semiconductor technology. Especially, the accelerator based sources have the potential to serve the THz light with very high intensity. It is expected that such THz radiation will be

power supply and cathode heater power supply with the feedback system is required to generate a high stability beam. The accelerating voltage was measured by a high voltage probe. It was found the fraction of the accelerating voltage is less than about ±0.4 % during one measurement of charge intensity profile. In addition the cathode has been operated for 6000 hours without failure.



Design and test of low emittance electron beam for Smith-Purcell backward wave oscillator free electron laser

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