

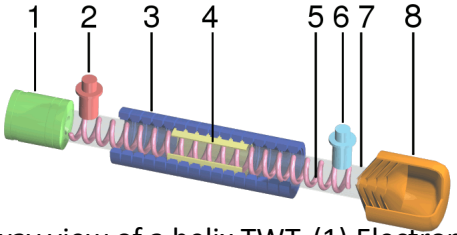
Review of Volume Free Electron Lasers

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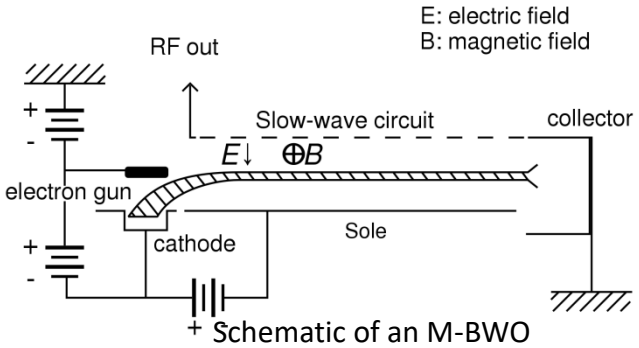
sytova@inp.bsu.by

Vacuum electronic devices

- There is a variety of such devices with their obvious generality in used physical principles, as well as the complex nonlinear dynamics of their functioning.
- Their performance and reliability are based on complex electromagnetic structures, new materials and advanced technologies.
- The widespread use of such devices in military and commercial applications requires them to operate reliably with high power, high efficiency, and low cost.
- The basis of the operation is the emission of electrons, grouped in bunches and interacting in a cavity (slow-wave spatially periodic medium) with slow electromagnetic waves. The generated electromagnetic wave power has its group velocity directed along or oppositely to the direction of motion of the electrons.



Cutaway view of a helix TWT. (1) Electron gun; (2) RF input; (3) Magnets; (4) Attenuator; (5) Helix coil; (6) RF output; (7) Vacuum tube; (8) Collector

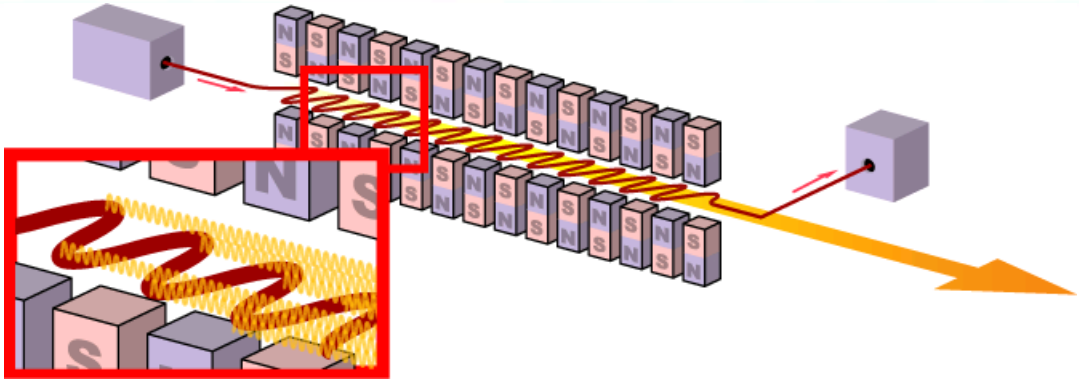


Schematic of an M-BWO

R. Kompfner. The traveling wave tube. Wireless World LII (1946), 369

R. Kompfner, N. T. Williams. Backward-wave tubes. Proc. IRE 41 (1953), 1602

Free electron lasers (FEL)



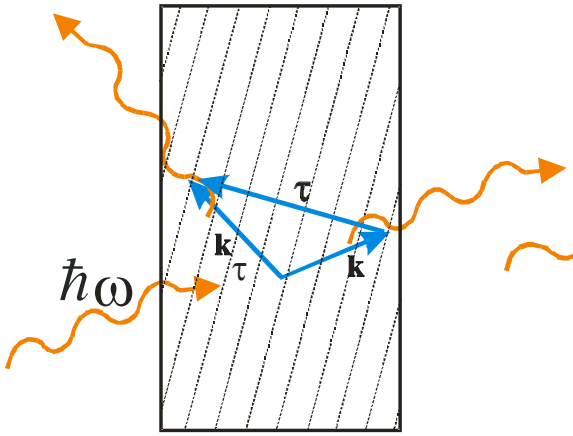
A Free Electron Laser* differs from conventional lasers in using a relativistic electron beam as its lasing medium, as opposed to bound atomic or molecular states, hence the term free-electron. FELs generate tunable, coherent, high power radiation in wavelengths from millimeter till ultraviolet and X-ray.

J. M. J. Madey. J. Appl. Physics, 42(1971), 1906
W. B. Colson. Phys. Let., 59A (1976), 187
D. A. Deacon et al. Phys. Rev. Let. 38 (1977), 892
M. Billardon et al. Phys. Rev. Let. 51 (1983),1652
J. Madey, M. O. Scully, P. Sprangle. Physica Scripta, 91 (2016), 063003

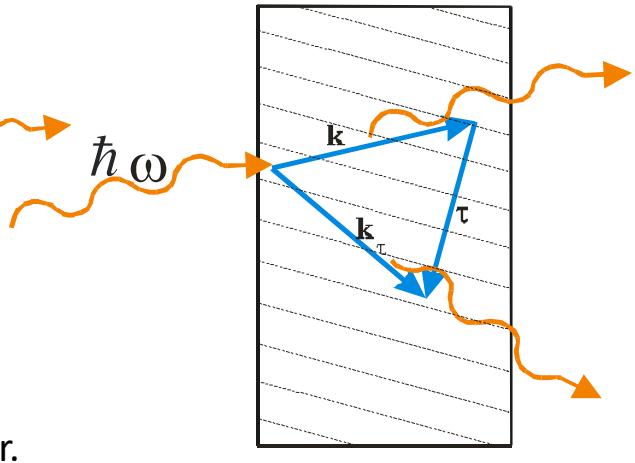
Dynamical diffraction*

**Bragg, W.H.; Bragg, W.L. Proc. R. Soc. Lond. A. 88 (1913), 428*

Bragg geometry



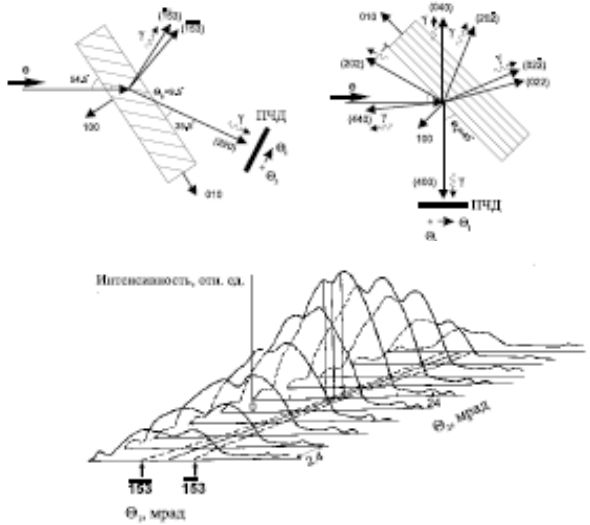
Laue geometry



τ is a reciprocal lattice vector.
Principles of diffraction are valid from X-ray to THz range.

Scheme of multi-wave experiments**

4-wave 8-wave



***V.Afanasenko, V.Baryshevsky et al. Tech.Phys. Let. 15 (1989) 33*
V.Afanasenko, V.Baryshevsky et al. Phys. Lett. A141 (1989) 311
V.Afanasenko, V.Baryshevsky et al. JETP Let. 51 (1990) 213

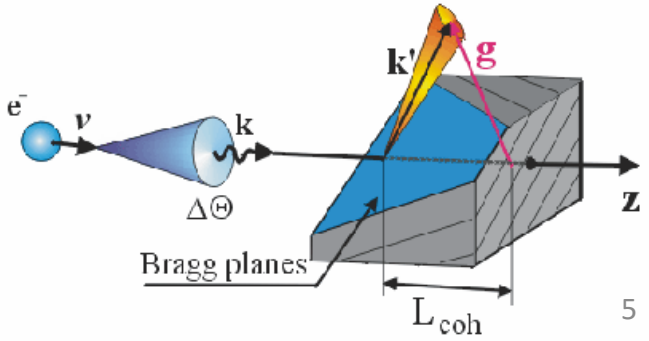
Parametric (quasi-Cherenkov) radiation

Cherenkov radiation* is electromagnetic radiation emitted when a charged particle passes through a dielectric medium at a speed greater than the phase velocity of light in that medium. According to Landau (vol.VIII), the dielectric permittivity $\varepsilon < 1$ (the refractive index $n = \sqrt{\varepsilon} < 1$) and Cherenkov radiation in the X-ray region should be absent. However, in 1971** it was showed that, nevertheless, when a large-energy particle moves through a crystal due to the diffraction of emitted photons in a crystal, it is possible that X-ray induced radiation (and, as a consequence, spontaneous) Cherenkov radiation.

A new type of radiation was called **Parametric X-ray radiation** (**PXR**).

Its origin is due to the fact that in a periodic medium, which is a crystal, photons have several refractive indices, among which there are refractive indices of $n > 1$ in the X-ray (and γ-) range. PXR generation in a crystal is accompanied by excitation in the X-ray range of waves with $n > 1$ (slow waves) and waves with $n < 1$ (fast waves).

PXR was experimentally discovered in 1985***.



Cherenkov P. A. Doklady Akademii Nauk SSSR, 2(1934), 451

**Baryshevsky V.G., Feranchuk I.D.Sov. J. Exp. Tech. Phys, 61, N 3(9) (1971), 944; Sov. J. Exp. Tech. Phys, 64 (1973),760*

Baryshevsky V. G., Feranchuk I.D. Doklady Akad. Sci. BSSR, 18, N 6 (1974), 499

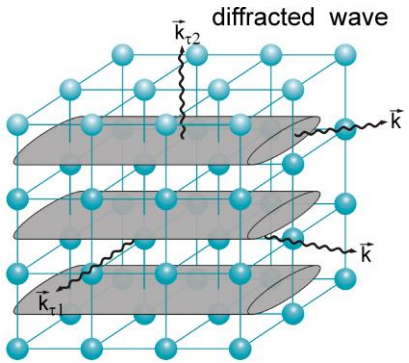
*** Adischev Yu.N., Baryshevsky V.G. et al. // Sov. JETP. Lett. 41 (1985) 295*

VFEL new law of instability

New law of instability* for an electron beam passing through a spatially-periodic medium, valid for all wavelength range and any type of spontaneous radiation (PXR, Smith-Purcell, diffraction or Cherenkov radiation, radiation in laser wave etc.)

The increment of instability in degeneration points:

$$G \sim \sqrt[3+s]{\rho}$$



instead of $\sim \sqrt[3]{\rho}$ for other systems (TWT, BWT, FEL etc.)

Threshold current in degeneration points:

$$j_{start} \sim 1/(kL)^{3+2s}$$

instead of $\sim (kL)^{-3}$ for other systems.

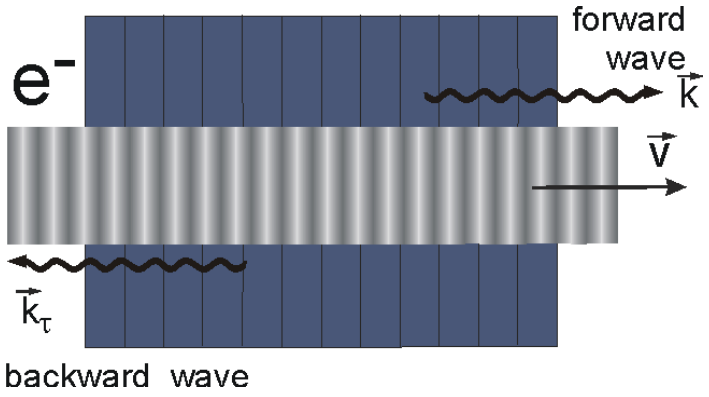
s is the number of surplus waves appearing due to diffraction.

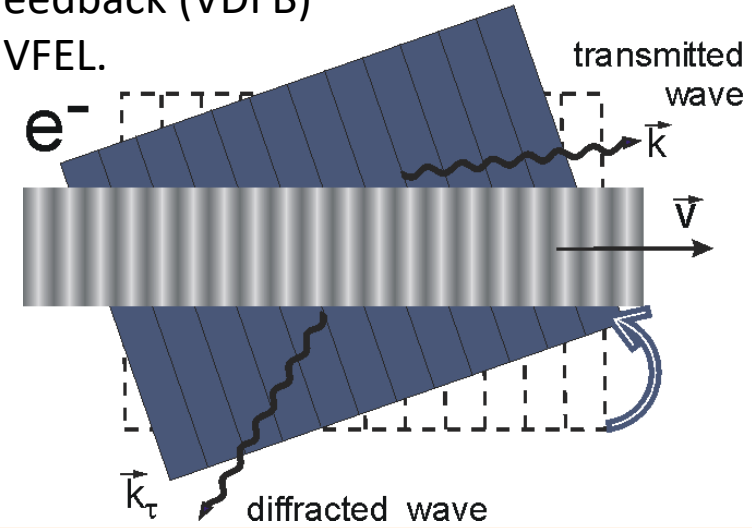
V.G.Baryshevsky, I.D.Feranchuk, Phys.Lett. 102A (1984) 141,

V.G.Baryshevsky, Proc. of the USSR Nat. Ac. Sci., 299(1988), 1363

Volume free electron lasers (VFEL)

Volume (non-one-dimensional) multi-wave distributed feedback (VDFB) under diffraction conditions is the distinctive feature of VFEL.





Diffraction condition

$$2\mathbf{k\tau} + \boldsymbol{\tau}^2 \approx 0$$

Synchronism condition

$$\left|\omega - \mathbf{ku}\right| = \delta\omega \approx 0$$

Interacting of the electron beam with electromagnetic field in VFEL is much more efficient than in one-dimensional situation because the group velocity of electromagnetic waves decreases sharply due to continuous reflections of them at periodic planes of resonator. VFEL is an oversized system where electron beams of broad cross-section can be used. Due to this and VDFB electron beam radiates more effectively.

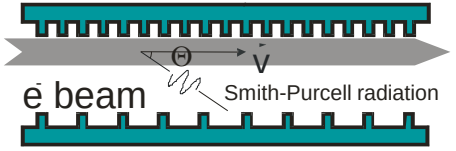
VFEL experiments at INP



1996 Experimental modeling of electrodynamic processes in volume diffraction grating made from dielectric threads

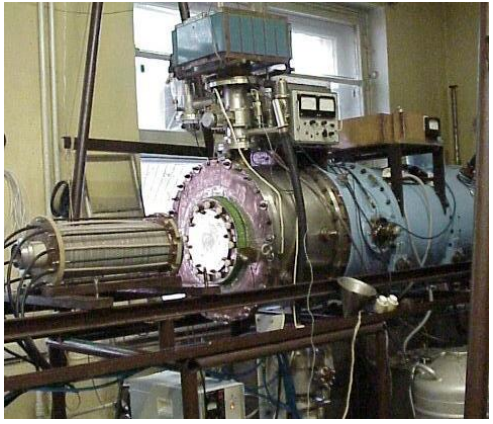
V.G.Baryshevsky et al., NIM 393A (1997) 71





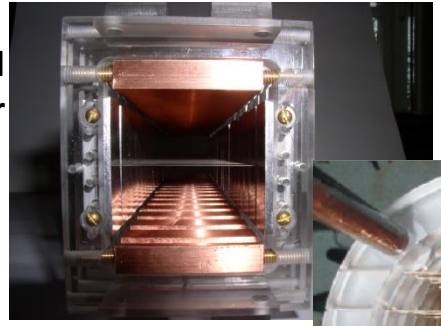
2001 The first VFEL generation in the millimeter range. Experimental verification of VFEL principles. Demonstration of frequency tuning for a fixed electron energy

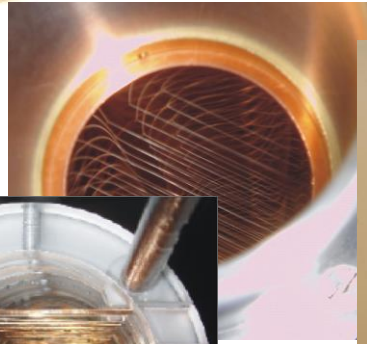
V.G.Baryshevsky et al., NIM 483 A (2002) 21

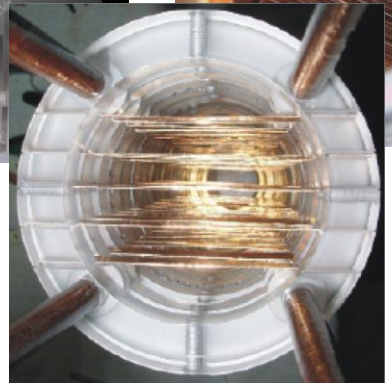


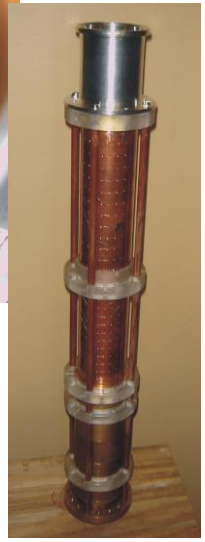
2004 VFEL with grid rectanglular resonator

V.G. Baryshevsky et al., NIM. B 252 (2006) 86







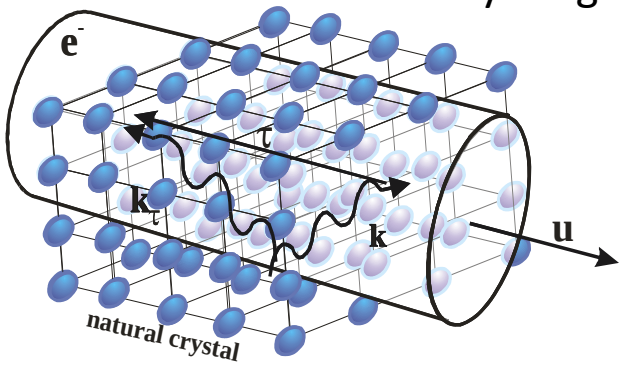


2007 VFEL with grid and foil resonators (photonic crystals)

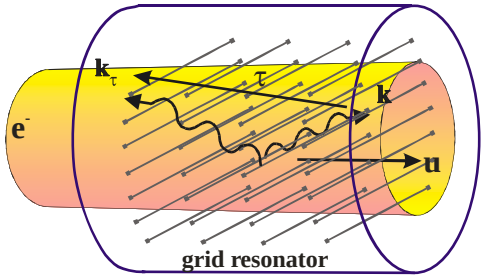
V. G. Baryshevsky et al. Proc FEL2007, 496; Proc. IRMMW-THz 2010; Proc. FEL2010. Nuovo Cimento 34 (2011), 199

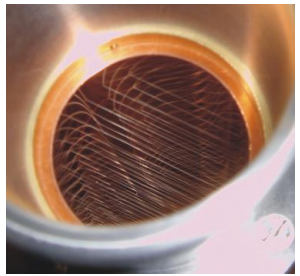
VFEL in different wavelenght range

X-ray range

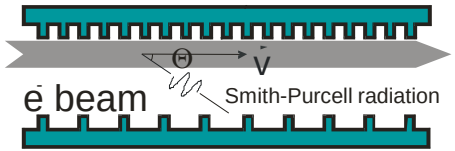


Microwave range (2007)

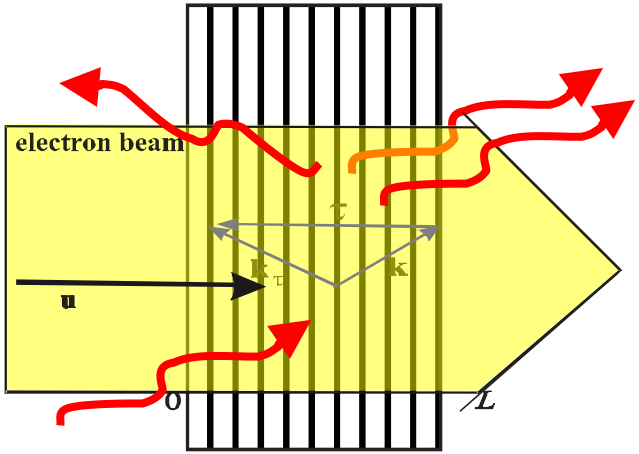








VFEL with ribbon electron beam (2001)



Photonic crystal (resonator)

VFEL main equations*

$$\frac{\partial E}{\partial t}+\gamma_0 c\frac{\partial E}{\partial z}+0.5i\,l\,E-0.5i\omega\chi_\tau E_\tau=I,$$

$$\frac{\partial E_\tau}{\partial t}+\gamma_1 c\frac{\partial E_\tau}{\partial z}-0.5i\omega\chi_{-\tau}E+0.5i\omega l_1 E_\tau=0,$$

$$I=2\pi\, j\Phi\int_0^{2\pi}\frac{2\pi-p}{8\pi^2}\left(e^{-i\theta(t,z,p)}+e^{-i\theta(t,z,-p)}\right)dp,$$

$$E(t,0)=E_0,\quad E_\tau(t,L)=E_{\tau 0}$$

$$\frac{d^2\theta(t,z,p)}{dz^2}=\frac{e\Phi}{m\gamma^3\omega^2}\left(k-\frac{d\theta(t,z,p)}{dz}\right)^3\mathrm{Re}\left(E(t-z/u,z)\exp(i\theta(t,z,p))\right),$$

$$\frac{d\theta(t,0,p)}{dz}=k-\omega/u,\quad \theta(t,0,p)=p,$$

$$t>0,\quad z\in[0,L],\quad p\in[-2\pi,2\pi]$$

Two-wave VFEL in Bragg geometry

$\gamma_{0,1}$ are direction cosines, δ is departure from synchronism conditions.

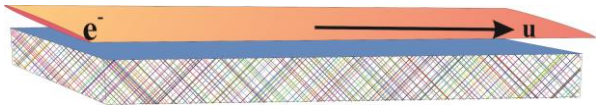
$\chi_{0,\pm\tau}$ are Fourier components of the dielectric susceptibility of the target.

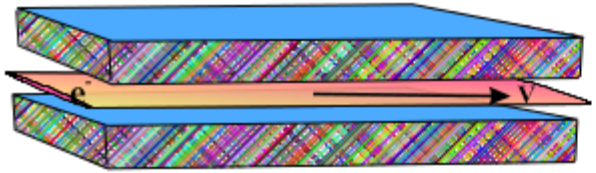
$\theta(t, z, p)$ is an electron phase in a wave.

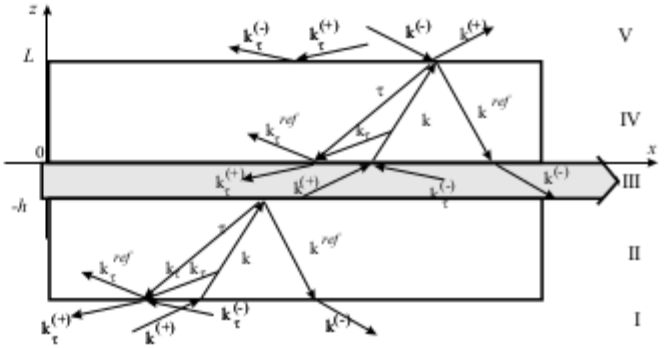
We use the method of averaging over initial phases of electron entrance in the resonator that takes into account as initial phase of an electron not only the moment of time t_0 but also transverse spatial coordinate of an electron entrance in the resonator at $z = 0$.

Batrakov K., Sytova S. Comp. Math. Math. Phys. 45 (2005), 666

Surface VFEL with diffraction gratings







$$\frac{\partial E^{(\pm)}}{\partial t} \pm \frac{k_z^0 c^2}{\omega}\frac{\partial E^{(\pm)}}{\partial z} + \frac{k_x c^2}{\omega}\frac{\partial E^{(\pm)}}{\partial x} = \frac{2\pi i}{\omega}\frac{\partial j^{(\pm)}}{\partial z} - 2\pi\frac{\partial j^{(\pm)}}{\partial z} \qquad \text{(III)}$$

$$\frac{\partial E}{\partial t} + \frac{k_z c^2}{\omega\varepsilon_0}\frac{\partial E}{\partial z} + \frac{k_x c^2}{\omega\varepsilon_0}\frac{\partial E}{\partial x} + \frac{i(\mathbf{k}^2 - \omega^2/c^2\varepsilon_0)}{2\omega\varepsilon_0}E + \frac{i\omega\chi_\tau}{2\varepsilon_0}E_\tau = 0,$$

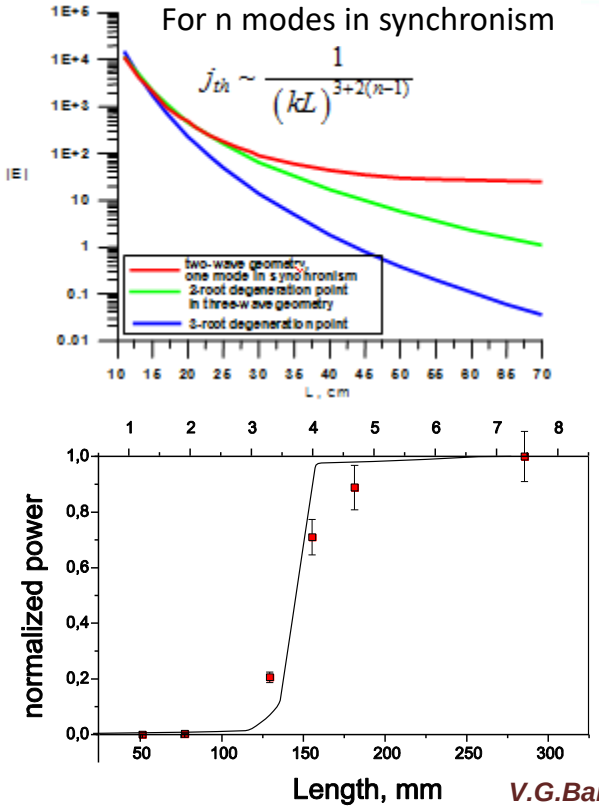
$$\frac{\partial E_\tau}{\partial t} + \frac{k_{\tau z} c^2}{\omega\varepsilon_0}\frac{\partial E_\tau}{\partial z} + \frac{k_{\tau x} c^2}{\omega\varepsilon_0}\frac{\partial E_\tau}{\partial x} + \frac{i\omega\chi_{-\tau}}{2\varepsilon_0}E + \frac{i(\mathbf{k}_\tau^2 - \omega^2/c^2\varepsilon_0)}{2\omega\varepsilon_0}E_\tau = 0. \qquad \text{(II), (IV)}$$

$$\frac{\partial E^{ref}_{\cdot,\tau}}{\partial t} \mp \frac{k_{z,\tau z} c^2}{\omega}\frac{\partial E^{ref}_{\cdot,\tau}}{\partial z} + \frac{k_x c^2}{\omega}\frac{\partial E^{ref}_{\cdot,\tau}}{\partial x} = 0$$

$$\mathbf{A}\frac{\partial \mathbf{E}}{\partial t} + \mathbf{B}\frac{\partial \mathbf{E}}{\partial z} + \mathbf{C}\frac{\partial \mathbf{E}}{\partial x}\mathbf{E} + \mathbf{D}\mathbf{E} = \mathbf{F}(\mathbf{E}^{(0)}, j^{(\pm)})$$

Baryshevsky et al. NIM (1994),A341,274, NIM (1995), A358, 508

VFEL main numerical results



It was obtained numerically all main VFEL physical laws.
It was demonstrated that there exists an optimal set of VFEL parameters for effective generation.
It was obtained generation thresholds for INP VFEL experimental setups
It was denoted the necessity of taking into account the dispersion of electromagnetic waves on photonic crystal for microwave VFEL
It was demonstrated numerically one of VFEL physical features of suppression of spurious modes inside the resonator.

VFEL was investigated as dynamical chaotic system
A gallery of different chaotic regimes for VFEL laser intensity with corresponding phase space portraits, bifurcation diagrams, attractors and Poincare maps was proposed.
It was obtained analytically solution for the stationary problem with electron beam and for non-stationary small-scale periodic regimes. It was demonstrated the origin of onset of oscillations.

V.G.Baryshevsky et al., Proc. FEL06, 331

Prospects for VFEL

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journal homepage: www.elsevier.com/locate/nimb

Radical increase of the parametric X-ray intensity under condition of extremely asymmetric diffraction

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[e] Faculty of Applied Sciences, Ton Duc Thang University, 19 Nguyen Huu Tho Str., Tan Phong Ward, District 7, Ho Chi Minh City, Viet
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Extremely asymmetric diffraction

ABSTRACT

Parametric X-ray radiation (PXR) from relativistic electrons movi
interface is considered. In this geometry the emission of photons
asymmetric diffraction (EAD). In the EAD case the whole crystal
X-ray radiation opposed to Laue and Bragg geometries, where t
X-ray absorption length. We demonstrate that this phenom
dynamical theory of diffraction and predict a radical increase o
realistic electron-beam parameters, an increase of two orders
be obtained in comparison with conventional experimental ges
in details the experimental feasibility of the detection of PXR-E

1. Introduction

Parametric X-ray radiation (PXR) occurs when a charged particle moves uniformly in a periodic medium [1,2] and possesses unique features such as high brightness, narrow spectral width and the possibility of tuning the X-ray frequency simply by rotating a crystal target. Moreover, PXR is emitted under a large angle with respect to the particle velocity and its brilliance is competitive with other X-ray sources, as already demonstrated experimentally [3]. Consequently, all these properties make it a suitable candidate for the development of novel-laboratory-compact X-ray sources with high brightness and tunable, quasi-monochromatic frequency.

angle to its surface, i.e., trar
according to kinematic model
is proportional to the smallest
tion L_{abs} lengths. In the X-ray
therefore in most cases $L_{abs} <$
of the electron trajectory cont

As was mentioned above,
with respect to the electron v
change the geometry of an e
entire crystal length will co
Accordingly, this will lead to
quanta in the PXR peak.

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Parametric X-ray radiation in the Smith-Purcell geometry for non-destructive beam diagnostics

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[c] Faculty of Applied Sciences, Ton Duc Thang University, 19 Nguyen Huu Tho Str., Tan Phong Ward, District 7, Ho Chi Minh City, Viet Nam
[d] Belarusian State University, 4 Nezavisimosty Ave., 220030 Minsk, Belarus
[e] Faculty of Physics, The University of Danang - University of Science and Education, B3 Building, 459 Ton Duc Thang, Lien Chieu, Da Nang, Viet Nam

ARTICLE INFO

Keywords:
Parametric X-ray radiation
Smith-Purcell effect
Dynamical diffraction
Extremely asymmetric diffraction

ABSTRACT

We investigate parametric X-ray radiation (PXR) under condition of the extremely asymmetric diffraction, when the ultra-relativistic electron bunch is moving in vacuum parallel to the crystal-vacuum interface, close to the crystal surface. This type of geometry coincides with the well known mechanism of generation of radiation, when the self-field of the particle beam interacts with the reflecting metal grating, namely the Smith-Purcell effect. We demonstrate that in this geometry the main contribution is given via a tail region of the beam distribution, which penetrates the crystal and X-rays are radiated along the normal to the crystal surface. We determine the electron beam characteristics, when this phenomenon can be observed. It is essential that in this geometry the majority of electrons does not undergo multiple scattering and consequently the characteristics of the particle beam are not changed, thus allowing the usage of the emitted X-rays for the purpose of non-destructive beam diagnostics, which can complement the traditional knife-edge method.

1. Introduction

Parametric X-ray radiation (PXR) is generated when a charged particle moves uniformly in a periodic medium [1,2]. The typical property of this type of radiation is that it is emitted under the large angle to the velocity of the charged particle. In addition, it is characterized by high brightness, narrow spectral interval and possibility to uniformly tune the frequency of the radiated photons. Moreover, the intensity of radiation is relatively weakly dependent on the particle energy. Furthermore, the large angle of the emitted photons allows one to employ non-conventional geometries, which can lead to the improvements of the various characteristics of the emitted radiation [3].

Recently, it was demonstrated [4] that the intensity of the radiation can be significantly increased if the grazing geometry under condition of the extremely asymmetric diffraction of the emitted photons (PXR-EAD) is employed. However, in that case the electrons were moving *inside* a crystal, parallel to the crystal vacuum interface. Consequently, in that situation the effective length of the electron trajectory, which electrons exhibits moving inside the crystal.

For this reason, it is essential to investigate the geometry, in which the whole crystal length contributes to the intensity, but the limiting factor of multiple electron scattering is removed. The most natural way is to consider that the electron beam is moving *outside* of a crystal in vacuum, at a small distance to it, but still parallel to the crystal-vacuum interface. This geometry corresponds to the Smith-Purcell effect [5,6], but in the X-ray frequency range due to the parametric radiation mechanism (PXR-SPG). In this case the electronic density of a crystal corresponds to the metal surface grating, interaction with which generates the radiation in optical or microwave ranges [7,8] and for X-rays [9,10]. For this reason, the radiation field is formed due to the diffraction of the electron beam self-field on the periodic electronic density of the crystal. Consequently, the determination of the characteristics of PXR-SPG, the discussion of its possible observation and applications for the beam diagnostics [11] are the main goals of the present work.

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PHYSICS OF SOLID STATE AND CONDENSED MATTER

FLAP Collaboration: Tasks and Perspectives. Study of Fundamentals and New Applications of Controllable Generation of Electromagnetic Radiation by Relativistic Electrons Using Functional Materials

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Abstract—We present the scope of research of a new collaboration FLAP (Fundamental & applied Linear Accelerator Physics collaboration) devoted to the study of the basics of electromagnetic interactions and new applications of controllable generation of electromagnetic radiation by relativistic electrons using functional materials.

Photonic and Nano FEL

Photonic Free-Electron Lasers

P. J. M. van der Slot, T. Denis, J. H. H. Lee, M. W. van Dijk, and K. J. Boller

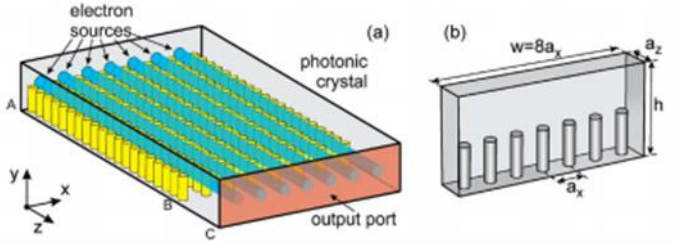
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Abstract: A photonic free-electron laser (pFEL) produces coherent Cerenkov radiation from a set of parallel electron beams streaming through a photonic crystal. The function of the crystal is to slow down the phase velocity of a copropagating electromagnetic wave, such that also mildly relativistic electrons (of about 10-keV energy) can emit coherent Cerenkov radiation. Starting from spontaneous emission, the feedback of the radiation on the electrons results in bunching of the electrons on the scale of the radiation wavelength, and consequently, coherent radiation can build up. The frequency of the coherent mode is set by the electron velocity and wave dispersion of the photonic crystal and can, *a priori*, be continuously varied by varying the electron energy. The scale invariance of Maxwell's equation allows operation from Gigahertz to Terahertz and possible infrared (IR) frequencies without the need to increase the electron beam energy. Therefore, the pFEL is a very



news & views

X-RAY OPTICS

Highly efficient nanoscale X-ray sources

Irradiating arrays of metal nanowires with intense femtosecond laser pulses produces high-brightness picosecond X-ray pulses. By specifically tailoring the plasma properties, up to 20% conversion efficiency of optical light into X-rays can be achieved.

Daniel Rolles

When it comes to intense and short-pulse X-ray sources, much of the attention in recent years has focused on X-ray free-electron lasers[1,2] and high-harmonic-generation sources[3,4]. Rightfully so, since their extreme intensities of up to 10^{20} W cm^{-2} and their ultrashort pulses down to a few tens of attoseconds have enabled studies of light–matter interactions in regimes that had previously been far beyond reach[5,6], and have spurred the development of ground-breaking techniques such as serial femtosecond nanocrystallography[7].

However, there are many time-resolved X-ray imaging and spectroscopy applications that do not require such mind-boggling intensities nor few-femtosecond or even attosecond pulses, but would benefit from a compact and high-brightness picosecond X-ray source. This is where the recent work of Reed Hollinger and co-workers, reported in *Optica*, can play out its full potential[8]. By irradiating an array of metal nanowires with high-power femtosecond laser pulses, the team is able to generate extraordinarily bright picosecond X-ray pulses, overcoming previous limitations in the conversion efficiency of optical laser light into X-rays by specifically tailoring the plasma properties to favour X-ray emission over competing cooling processes.

Although various methods for generating X-ray pulses from dense plasmas produced by irradiating solids with intense femtosecond laser pulses have been studied for several decades, most schemes suffer from a very low conversion efficiency of optical laser light into X-rays. Typically, less than 0.1% of the laser energy impinging on the target is converted into X-ray photons with a photon energy of 1 keV or above. Even the use of nanostructured surfaces, such as arrays of metal clusters or nanowires, which increase the fraction of the laser energy that is absorbed by the plasma, could not increase the conversion efficiency beyond 1% due to the rapid expansion of the plasma and the associated hydrodynamic cooling[9].

Guided by detailed numeric modelling of the plasma formation and evolution, Hollinger et al. have now managed to

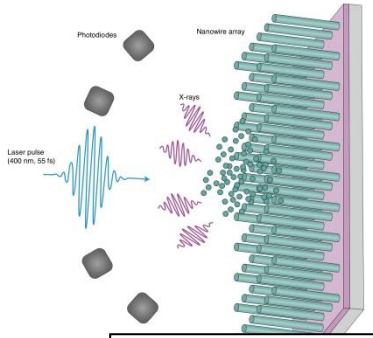


Fig. 1 | **Generation of picosecon**
irradiated by a 400-nm femtos
a short burst of X-rays that are
(not shown). Through an appro
of the laser pulse parameters, t
hydrodynamic cooling, thus inc
than one order of magnitude a

optimize the nanowire array
pulses to tailor the plasma p
such a way that they achieve
the conversion efficiency by
order of magnitude to about
experiment, an ultrahigh con
laser pulse with a pulse durat
a pulse energy up to 1 J was g
an array of free-standing, ver

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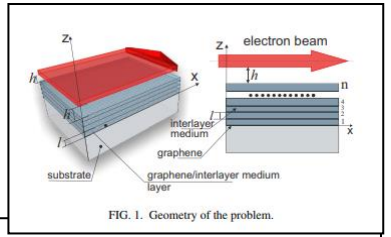


FIG. 1. Geometry of the problem.

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Toward the nano-FEL: Undulator and Cherenkov mechanisms of light emission in carbon nanotubes

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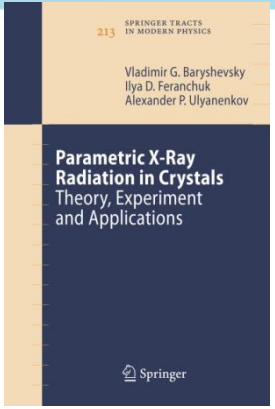
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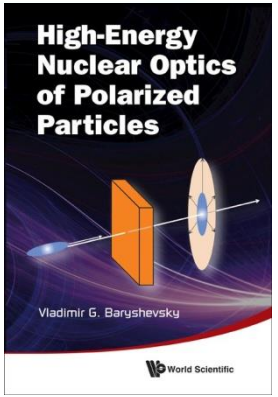
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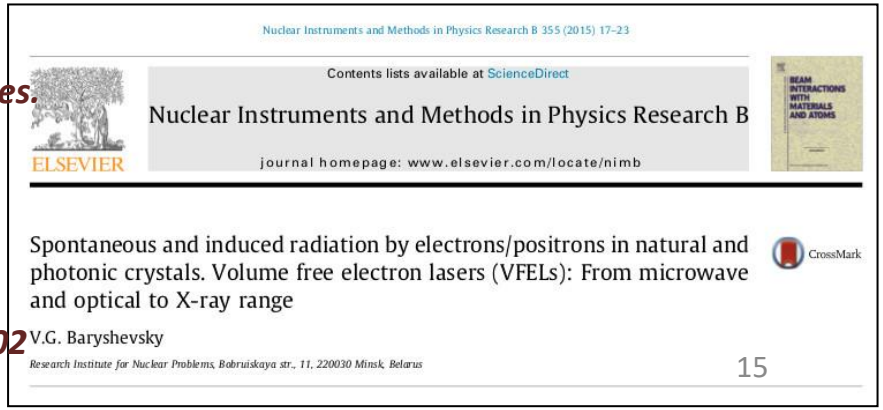
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Thank You for attention!



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