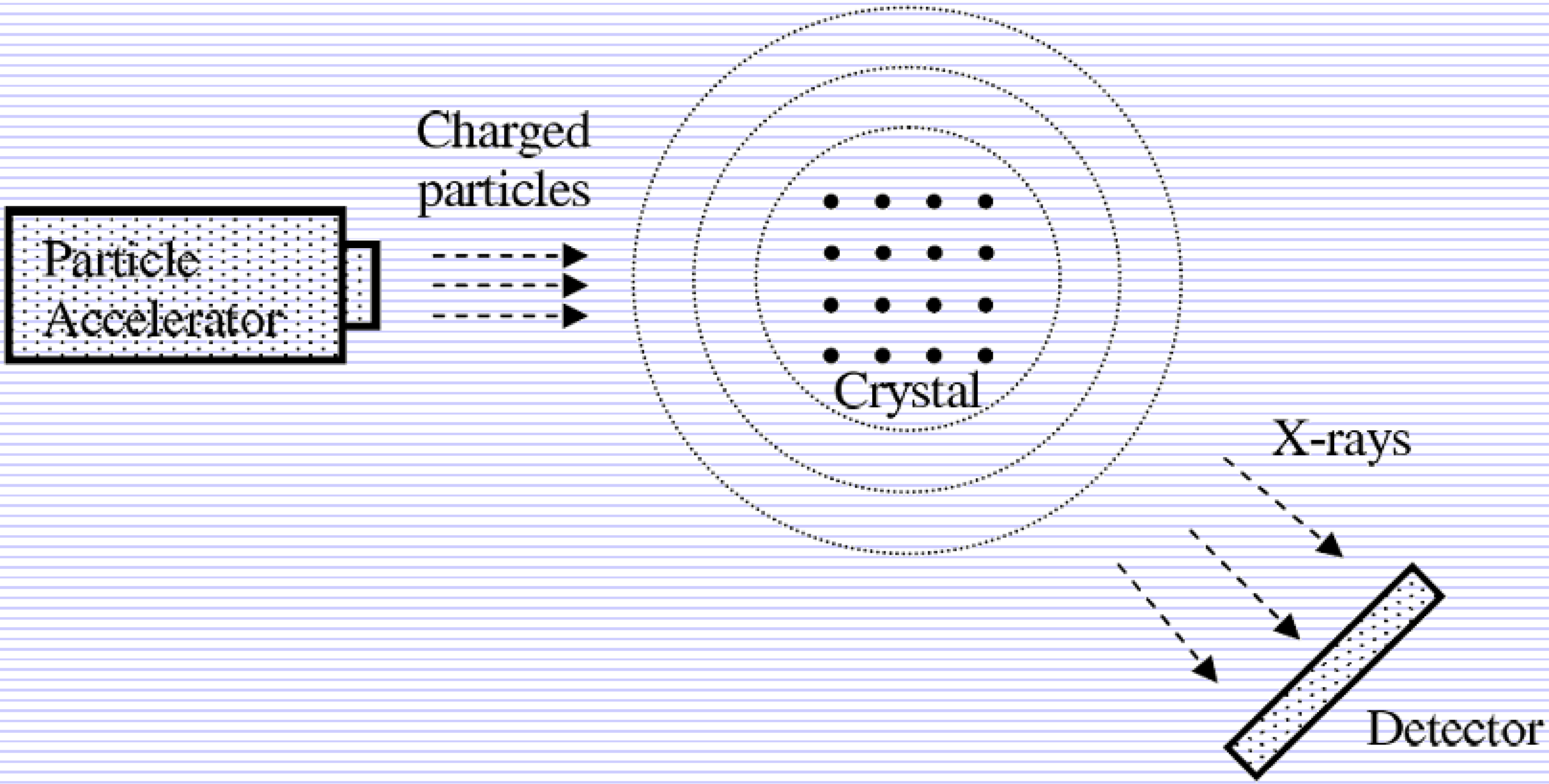
Spontaneous and Induced Radiation of Relativistic Electrons/Positrons in Natural and Photonic Crystals. Volume Free Electron Laser: from Microwave and Optical to X-Ray Range

Vladimir Baryshevsky

X-ray radiation from charged particles in crystals



Spontaneous Radiation of Relativistic Electrons/Positrons in Natural and Photonic Crystals

Parametric quasi-Cherenkov X-rays

Prediction of spontaneous and induced X-ray Cherenkov (parametric) ,diffraction transition X-ray radiation and diffracted radiation from relativistic oscillator in crystals.

V.G. Baryshevsky, About light scattering by an electron beam, passing through a crystal, Dokl. Akad. Nauk BSSR 15 (1971) 306.

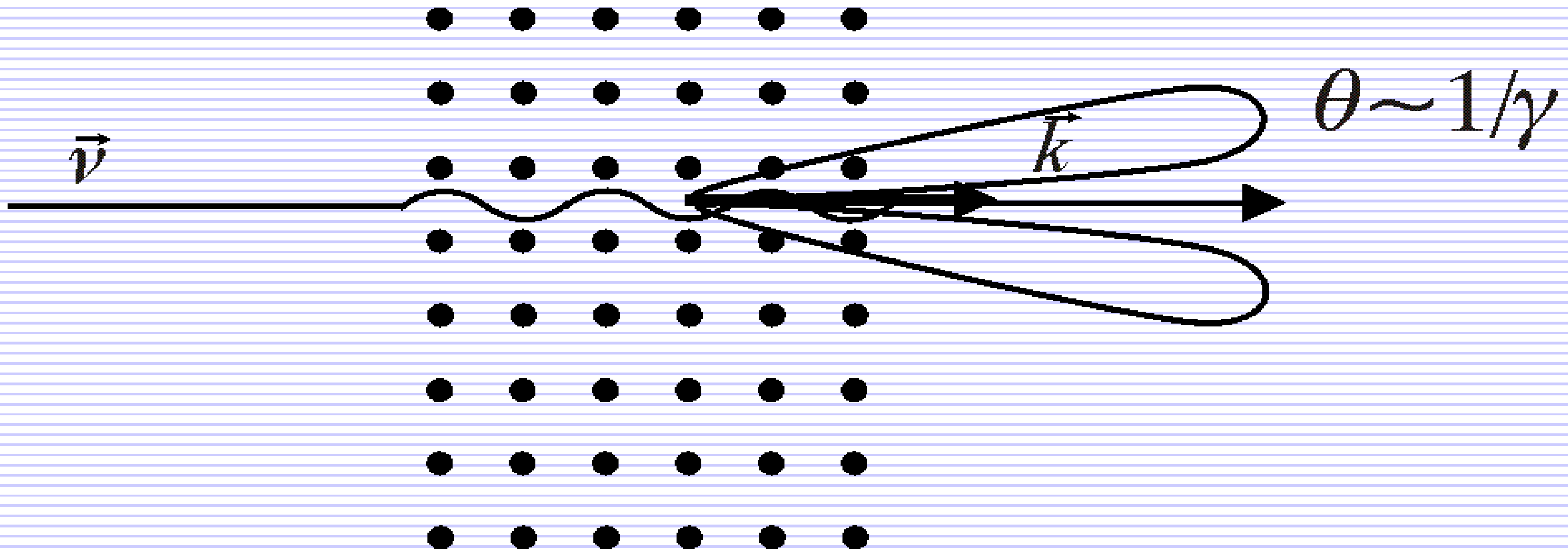
The refractive index for X-ray is $n(\omega) = 1 - \frac{\omega_p^2}{2\omega^2} < 1$

Due to diffraction, the refractive index in crystals can be greater than unity!

$n > 1,$ $\quad 1 - vn\left(\vec{k}, \omega\right)\cos\theta = 0$

V.G. Baryshevsky, I.D. Feranchuk, About transition radiation of γ-quanta in a crystal, JETP v.61 (1971) (Sov. Phys. JETP 34 (1972) 502.
V. G. Baryshevsky, I.D. Feranchuk, A.P. Ulyanenkov, Parametric X-Ray Radiation in Crystals. Theory, Experiment and Applications, Series: Springer Tracts in Modern Physics , Vol. 213 (2005).
V. G. Baryshevsky, High-Energy Nuclear Optics of Polarized Media, World Scientific Publishing, Singapore, 2012.

Channeling radiation

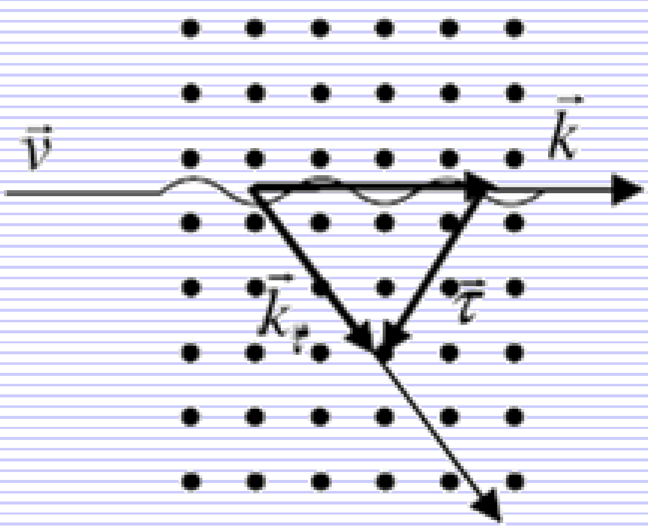


V.G. Baryshevsky, I.Ya. Dubovskaya, Complex and anomalous Doppler effect for channelized positrons (electrons), Dokl. Akad. Nauk SSSR 231 (1976) 1335;

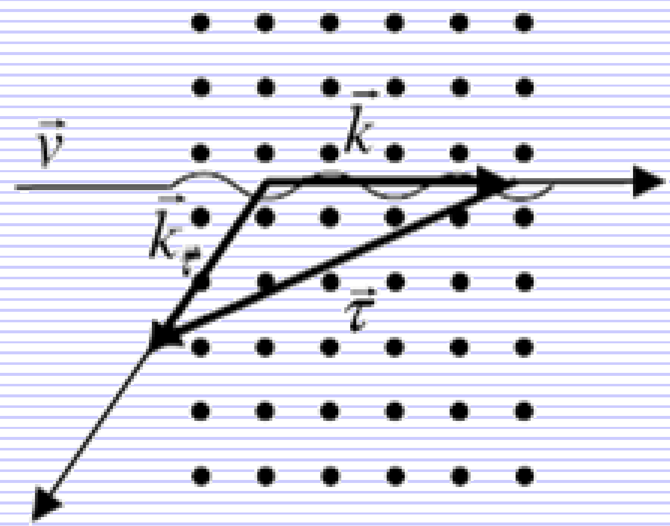
M.A. Kumakhov, On the theory of electromagnetic radiation of charged particles in a crystal, Phys. Lett. A 57, 1 (1976) 17;
X. Artru and P. Dhez, Novel Radiation Sources Using Relativistic Electrons: from Infrared to x-Rays, World Scientific Publishing, Singapore, 1998;

V. G. Baryshevsky, High-Energy Nuclear Optics of Polarized Media, World Scientific Publishing, Singapore, 2012.

Diffracted channeling radiation and diffracted radiation from a relativistic oscillator



The Laue case



The Bragg case

V.G. Baryshevsky, About light scattering by an electron beam, passing through a crystal, Dokl. Akad. Nauk BSSR 15 (1971) 306.

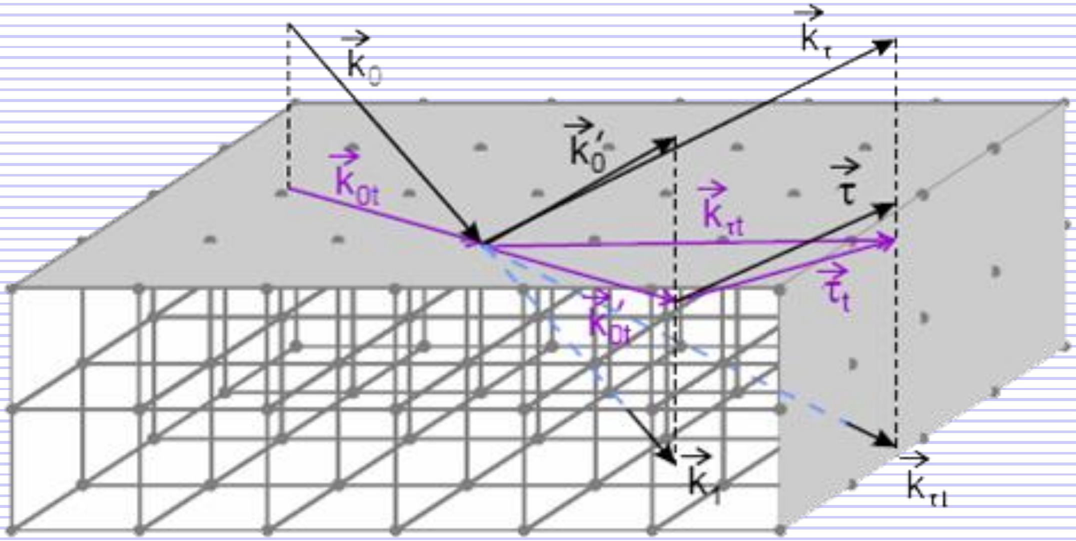
V.G. Baryshevsky, I.Ya. Dubovskaya, Complex and anomalous Doppler effect for channelized positrons (electrons), Dokl. Akad. Nauk SSSR 231 (1976) 1335;

V.G. Baryshevsky, I.Ya. Dubovskaya, Angular distribution of photons from channeled particles, J. Phys. C16 (1983) 3663;

K.B. Korotchenko, Yu.L. Pivovarov, T.A. Tukhfatullin, Angular distributions of diffracted X-ray radiation from channeled electrons in Si and LiF crystals: Influence of energy levels bandstructure, Nucl. Instrum. Methods B 266, 17 (2008) 3753.

V. G. Baryshevsky, High-Energy Nuclear Optics of Polarized Media, World Scientific Publishing, Singapore, 2012.

Surface parametric quasi-Cherenkov radiation and diffracted radiation from a relativistic oscillator



Natural or artificial (photonic) crystal

V.G. Baryshevsky, Surface parametric radiation of relativistic particles, Dokl. Akad. Nauk SSSR 299, 6 (1988) 1363.

Induced Radiation of RelativisticElectrons/Positrons in Natural and Photonic Crystals

Induced radiation and Volume Free Electron Laser (VFEL): how it started …

Detailed analysis of induced PXR showed that for a photon radiated by an electron in a crystal in conditions of the photon Bragg diffraction, there appears a **new law of radiation instability** compared with usual FELs and microwave devices. This new law provides for noticeable reduction of electron beam current density necessary for running up to the generation threshold and even makes it possible to reach the generation threshold for the induced parametric and diffracted channeling X-ray radiation in crystals i.e. to create X-ray laser.

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

The law was demonstrated to be valid for any type of spontaneous radiation in different wave range (magnetic bremsstrahlung in undulator, radiation in laser wave, Smith-Purcell, diffraction or Cherenkov radiation, and so on) from a charged particle moving either in a periodic medium or close to its surface.

V.G.Baryshevsky, Dokl. Akad. Nauk SSSR 299 (1988) 1363.

Dispersion equation

From Maxwell's equations and the equations of particle motion we can derive the dispersion equation, i.e. the relation between the frequency ω and the wave vector k

For two coupled waves:

$$\left(\omega-\vec{k}_{\parallel}\vec{u}\right)^2\left[\left(k_{\parallel}^2c^2-\omega^2\varepsilon_0\right)\left(\left(\vec{k}_{\parallel}+\vec{\tau}\right)c^2-\omega^2\varepsilon_0\right)-\omega^4\chi_{\tau}^{nn}\chi_{-\tau}^{nn}\right]=$$

$$=-\frac{\omega_L^2}{\gamma}A_{nn}\left(\left(\vec{k}_{\parallel}+\vec{\tau}\right)^2c^2-\omega^2\varepsilon_0\right)$$

Analysis of the dispersion equation reveals the necessary conditions for absolute and convective instabilities, and so serves to find the gain and the threshold of generation.

Instability Increment

In the absence of the lattice $\chi_\tau^{nn} = 0$

$$\left(\omega - \vec{k}_{\parallel}\vec{u}\right)^2\left(k_{\parallel}^2 c^2 - \omega^2 \varepsilon_0\right) = -\frac{\omega_L^2}{\gamma} A_{nn}$$

This equation describes the Cherenkov beam instability in a medium.

If the Cherenkov condition is fulfilled, then $1 - \omega/c\sqrt{\varepsilon_0}\, cos\vartheta = 0$

$$Imk_{\parallel} = \frac{\sqrt{\varepsilon_0}}{2c}\sqrt[3]{\frac{\omega_L^2|A_{nn}|}{2\omega\varepsilon_0\gamma}}$$

$\omega_L^2 = 4\pi e^2 \rho_0 / m$- Langmuir frequency

that is, **the electron-beam instability increment under the condition of wave synchronism is proportional to $\rho_0^{1/3}$,** where ρ_0 is the beam's density.

Dispersion curve

Assume that we have a diffraction grating $(\chi_{\tau}^{nn} \neq 0)$. **In the absence of the beam-grating interaction**, the dispersion equation splits into two:

$$\left(k_{\parallel}^{2}c^{2}-\omega^{2}\varepsilon_{0}\right)\left(\left(\vec{k}_{\parallel}+\vec{\tau}\right)^{2}c^{2}-\omega^{2}\varepsilon_{0}\right)-\omega^{4}\chi_{\tau}^{nn}\chi_{-\tau}^{nn}=D\left(\vec{k}_{\parallel},\omega\right)=0 \quad (a)$$

$$\left(\omega-\vec{k}\vec{u}\right)^{2}=0 \quad (b)$$

Equation (a) describes the spectrum of the electromagnetic wave propagating in a waveguide with diffraction grating.

Equation (b) describes fluctuations in the charge density of the electron beam.

Increment of instability

Inclusion of the beam-grating electromagnetic interaction at the root coincidence point of equations (a) and (b) leads to the following expression for $Im k_{\|}$

$$Im\,k_{\|} = \left(\frac{\omega_0 \,|\, Q \,||\, \chi_\tau \,|\, \tau}{u^2 c^2 \sqrt{2\tau_z^2 - \tau^2}} \right)^{1/4} = \left(\frac{\omega_L^2 A_{nn} \,|\, \chi_\tau \,|\, \tau}{2\gamma u^2 c^2 \sqrt{2\tau_z^2 - \tau^2}} \right)^{1/4} \sim \rho_0^{1/4}$$

The electron-beam instability increment is proportional to $\rho_0^{1/4}$

In the general case, the electron-beam instability increment appears to be proportional to $\rho_0^{1/(3+s)}$ instead of $\rho_0^{1/3}$. Here *s* is the number of emitted electromagnetic waves that are produced through Bragg diffraction in the grating, (e.g., s=1 for two-wave diffraction and s=2 for three-wave diffraction and so on) .

This dependence leads to an increase in the instability increment (gain), e.g.,

$$\frac{Im k_{\|}^{(s=1)}}{Im k_{\|}^{(s=0)}} \approx \left(\frac{\omega_L^2 |A_{nn}|}{\omega^4 \chi_\tau^3 \gamma} \right)^{-\frac{1}{12}} \gg 1$$

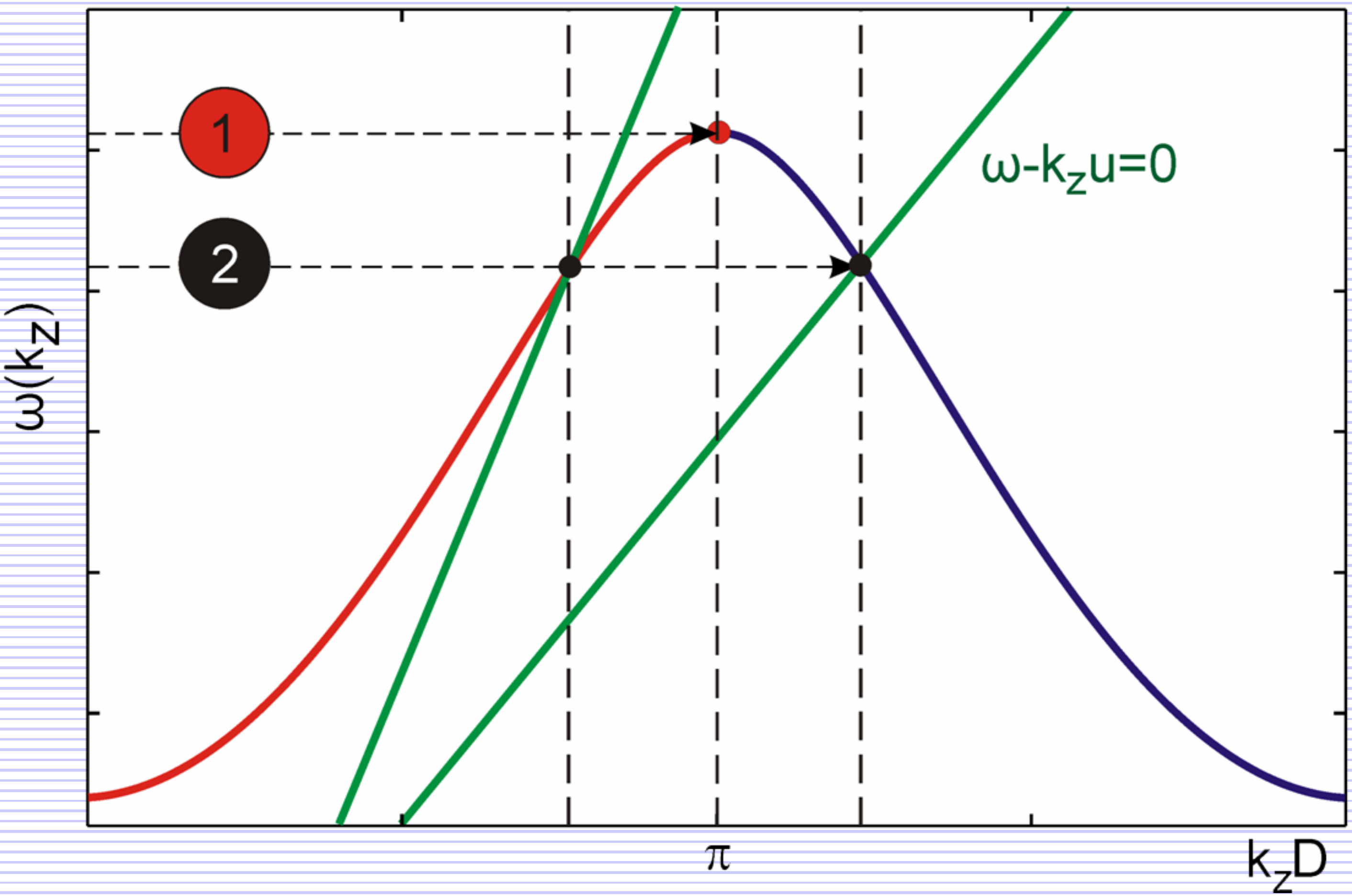
V.G.Baryshevsky, I.D.Feranchuk, Parametric beam instability of relativistic charged particles in a crystal, Phys. Lett. 102 A (1984) 141.

V. G. Baryshevsky, K. G. Batrakov, I.Ya. Dubovskaya, Parametric (quasi-Cherenkov) X-ray free-electron lasers, J. Phys. D: Appl. Phys., 24 (1991) 1250;

V.G.Baryshevsky, High Power Microwave and Optical Volume Free Electron Lasers (VFELs), arXiv:1211.4769 [physics.optics] .

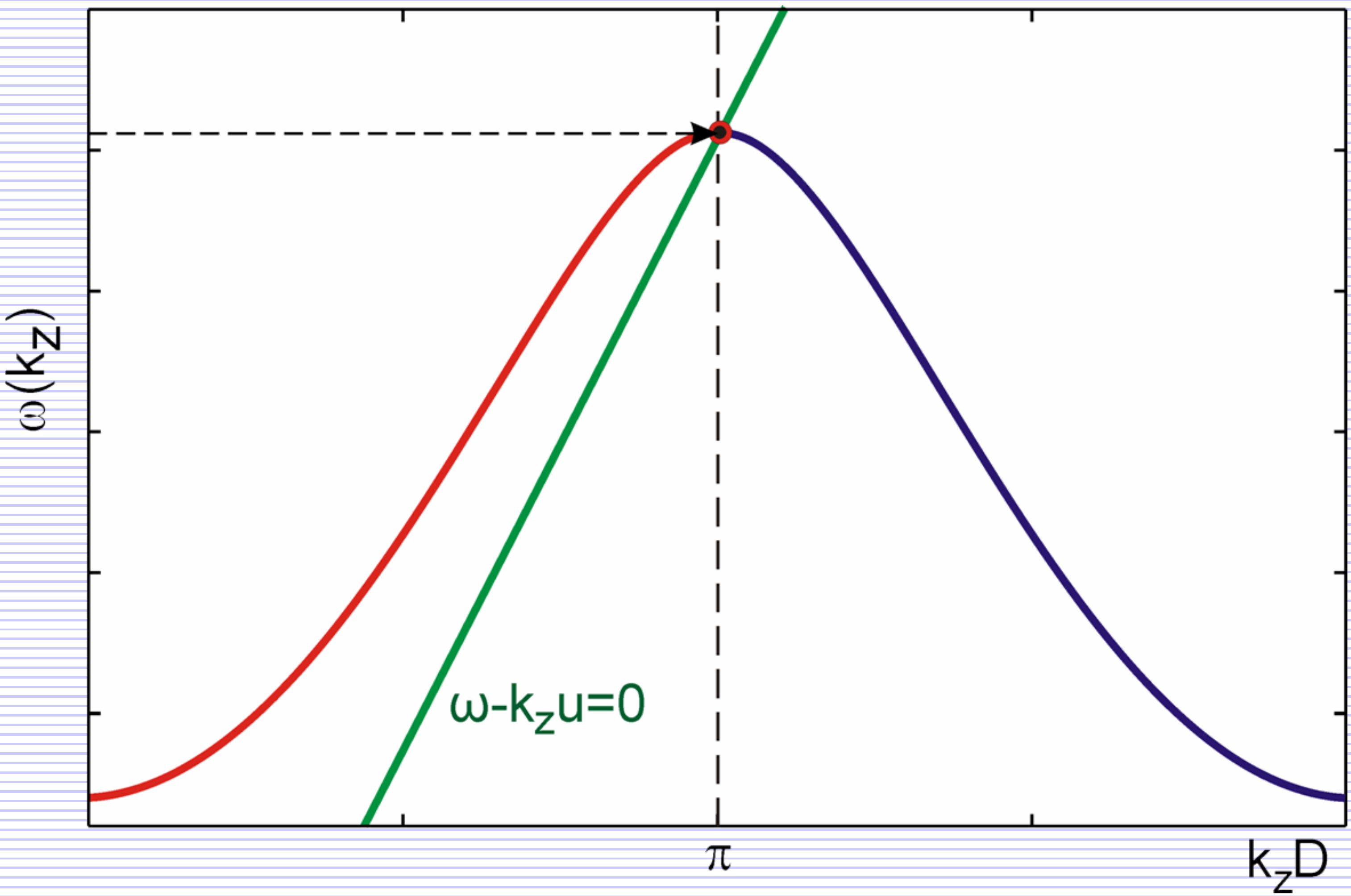
Dispersion curve

1. Point, where dispersion curve roots intercept
2. Cherenkov synchronism point



Dispersion curve

Intercept point of the dispersion curve roots and Cherenkov synchronism point coincide



Multiwave diffraction in a VFEL

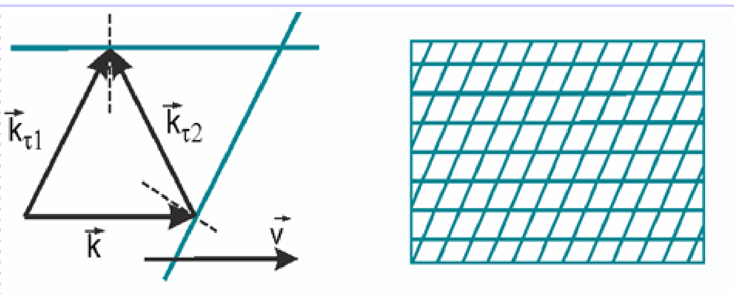
Multiwave diffraction affords a decrease in the generation threshold and a reduction of the resonator’s length.

The start current j relates to the interaction length L as

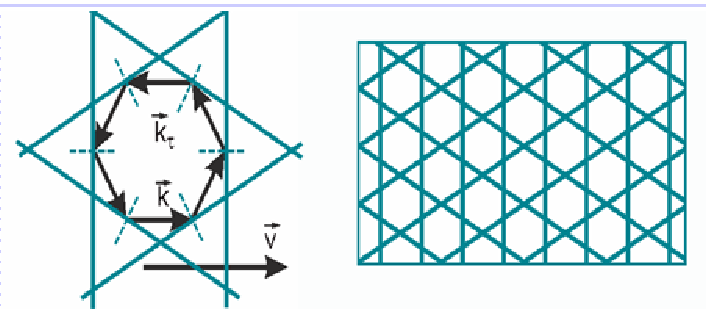
$$j_{start} \sim 1 \Big/ \left[(kL)^3 (k\chi_\tau L)^{2s} \right]$$

where **s** is the number of extra waves produced through diffraction.

3-wave diffraction (s=2)



6- wave diffraction (s=5)



Reduction of current density

This new law provides for noticeable reduction of the electron beam current density necessary for running up to the generation threshold and even makes it possible to reach the generation threshold for the induced parametric and diffracted channeling X-ray radiation in crystals, i.e., to create the X-ray laser.

Compare:

$j=10^{13}$ A/cm^2 ,

as required according to conventional law in [G.Kurizki, M.Strauss, I.Oreg, N.Rostoker, Phys. Rev. A35 (1987) 3427]

and

$j=10^{8}$ A/cm^2 for LiH crystal

according to new law [V. G. Baryshevsky, I. D. Feranchuk, Parametric beam instability of relativistic charged particles in a crystal, Phys. Lett. A 102, 3, (1984) 141; V. G. Baryshevsky, K. G. Batrakov, I.Ya. Dubovskaya, Parametric (quasi-Cherenkov) X-ray free-electron lasers, J. Phys. D: Appl. Phys., 24 (1991) 1250;

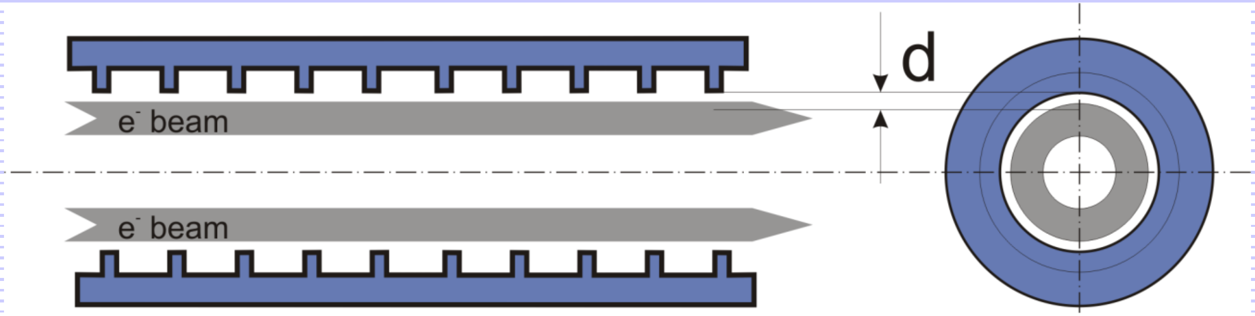
Volume Free Electron Laser (Maser) (VFEL, VFEM)

The law was demonstrated to be valid not only for X-ray radiation, but for any type of spontaneous optical and microwave radiation from a charged particle moving either in a periodic medium or close to its surface.
As a result, the new type of relativistic microwave and optical generators has been founded.

V.G.Baryshevsky, Dokl. Akad. Nauk SSSR 299 (1988) 1363.
V.G.Baryshevsky, Volume Free Electron Lasers, NIM 445A (2000), II-281
V.G. Baryshevsky, LANL e-print arXiv: 1101.0783. [physics.acc-ph], Spontaneous and Induced Radiation by Relativistic Particles in Natural and Photonic Crystals. Crystal X-ray Lasers and Volume Free Electron Lasers (VFEL)
V.G. Baryshevsky, LANL e-print arXiv: 1211.4769 [physics.optics], High Power Microwave and Optical Volume Free Electron Lasers (VFELs)

Generators using diffraction radiation (Cherenkov, transition radiation….)

Traveling Wave Tube (TWT),
Backward Wave Oscillator (BWO),
Magnetically Insulated Line Oscillator (MILO)



$$d \leq \frac{\lambda\beta\gamma}{4\pi}$$

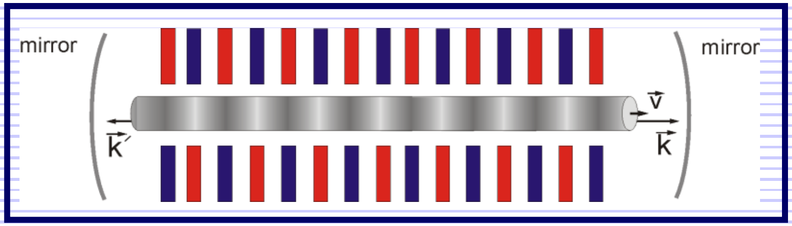
When the radiation wavelength decreases, **d** declines

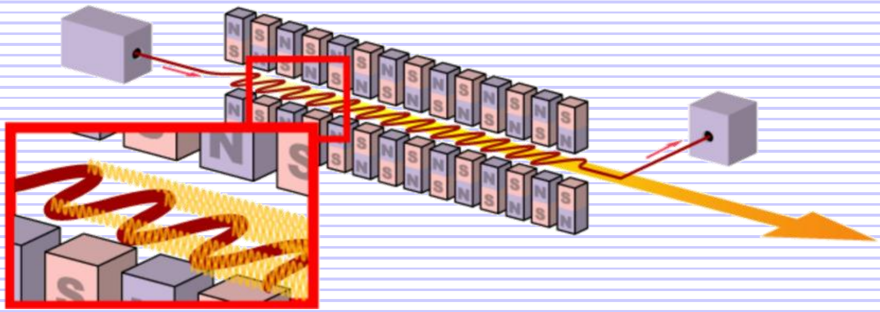
When an electron passes near the surface of the diffraction grating at the distance less then **d,** it effectively excites an electromagnetic wave.

for 500 keV electrons (γ=1.98, β=0.86) and λ=3 mm (ν=100 GHz) **d**=0.4 mm	for 500 keV electrons (γ=1.98, β=0.86) and λ=0.3 mm (ν=1THz) **d**=0.04 mm

Microwave instability of an electron beam ~ $\sqrt[3]{\rho}$, threshold current ~ **L**$^{-3}$, here ρ is the electron beam density, L is the length of the interaction zone.

Ubitron, Free Electron Laser (FEL)





In an FEL, a beam of relativistic electrons produced by an electron accelerator passes through a transverse, periodic magnetic field produced by a magnet called an undulator and exchanges energy with the electromagnetic radiation field.

For a cold electron beam in Compton regime, the increment of electron beam instability is proportional to $\sqrt[3]{\rho}$, the threshold current ~ L^{-3}, here ρ is the electron beam density, L is the length of the interaction zone

Specific features of the above systems

Threshold current $j_{thr} \sim L^{-3}$

Increment of electron beam instability (gain) ~ $\sqrt[3]{\rho}$

Use of resonators with transverse dimensions that are much larger than the radiation wavelength results in the excitation of many modes.

High Power Microwave and OPTICAL Systems: 3rd class

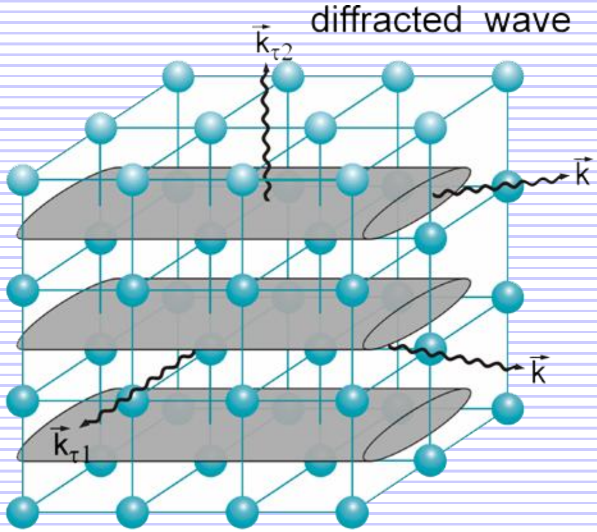
VFEL(VFEM) principles are applicable for

any type of crystals: either natural or artificial (photonic crystal)

any wavelength range (from microwave to optical and even X-ray)

any type of spontaneous radiation

Within peculiar conditions, the electron beam interacts with the electromagnetic wave more effectively yielding to drastic reduction of generation threshold:
$j_{thr} \sim L^{-(3+2s)}$ (for conventional systems $j_{thr} \sim L^{-3}$)
here s is the number of surplus waves appearing due to diffraction (for example, in case of two-wave diffraction s=1, for three-wave diffraction s=2, etc).



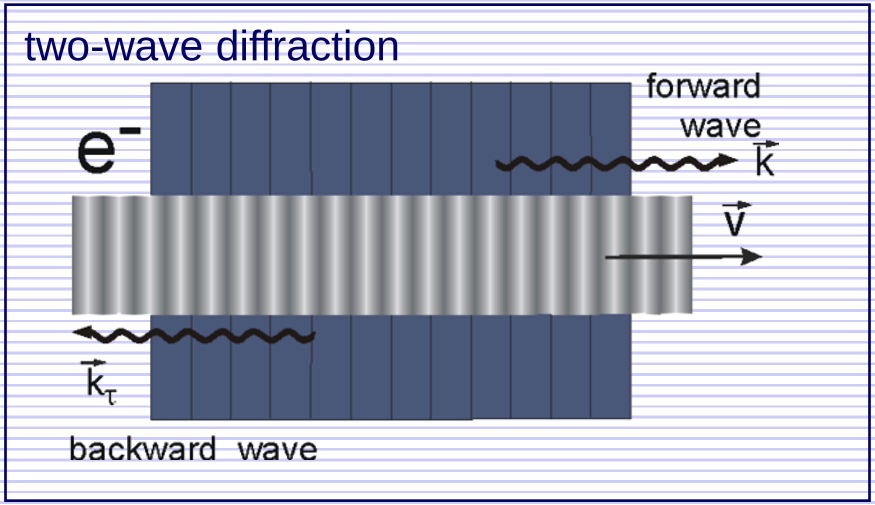
V.G. Baryshevsky, Surface parametric radiation of relativistic particles, Dokl. Akad. Nauk SSSR 299, 6 (1988) 1363.
V.G.Baryshevsky, Volume Free Electron Lasers, NIM 445A (2000), II-281
V.G. Baryshevsky, LANL e-print arXiv: 1101.0783. [physics.acc-ph], Spontaneous and Induced Radiation by Relativistic Particles in Natural and Photonic Crystals. Crystal X-ray Lasers and Volume Free Electron Lasers (VFEL)
V.G. Baryshevsky, LANL e-print arXiv: 1211.4769 [physics.optics], High Power Microwave and Optical Volume Free Electron Lasers (VFELs)

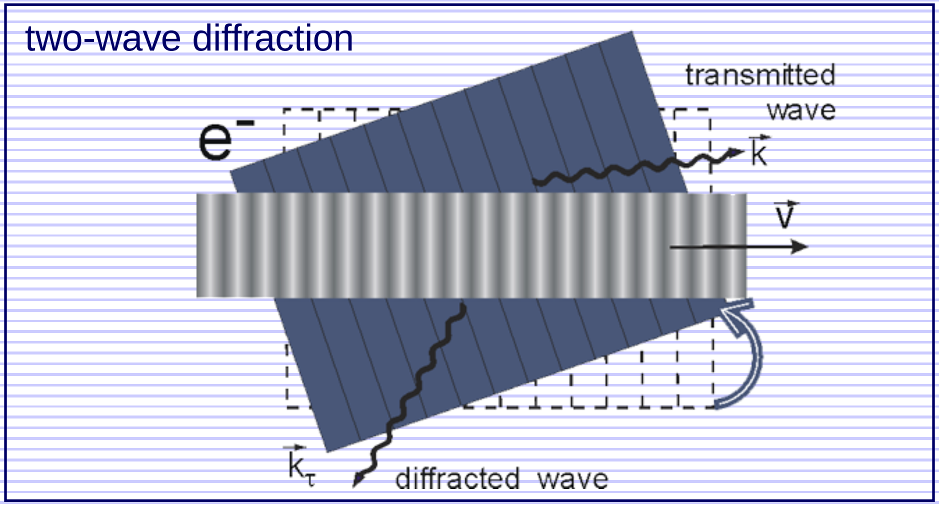
What is volume distributed feedback ?

Volume (non-one-dimensional) multiwave distributed feedback is the distinctive feature of Volume Free Electron Laser (VFEL)

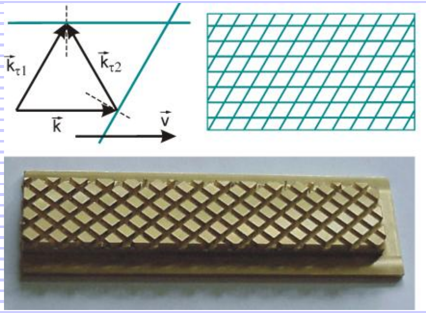
one-dimensional distributed feedback

two-dimensional distributed feedback

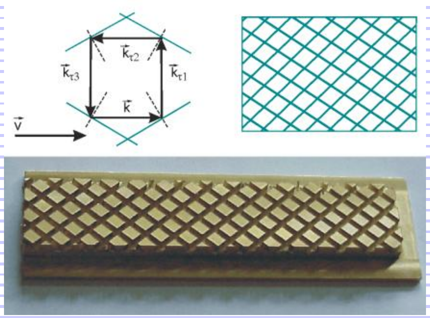




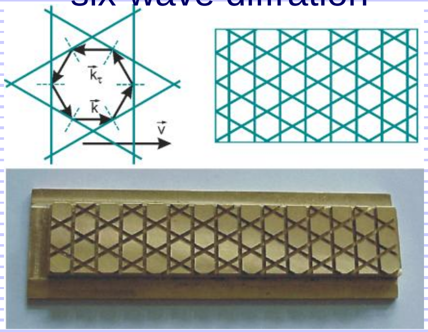
three-wave diffraction



four-wave diffraction



six-wave diffration



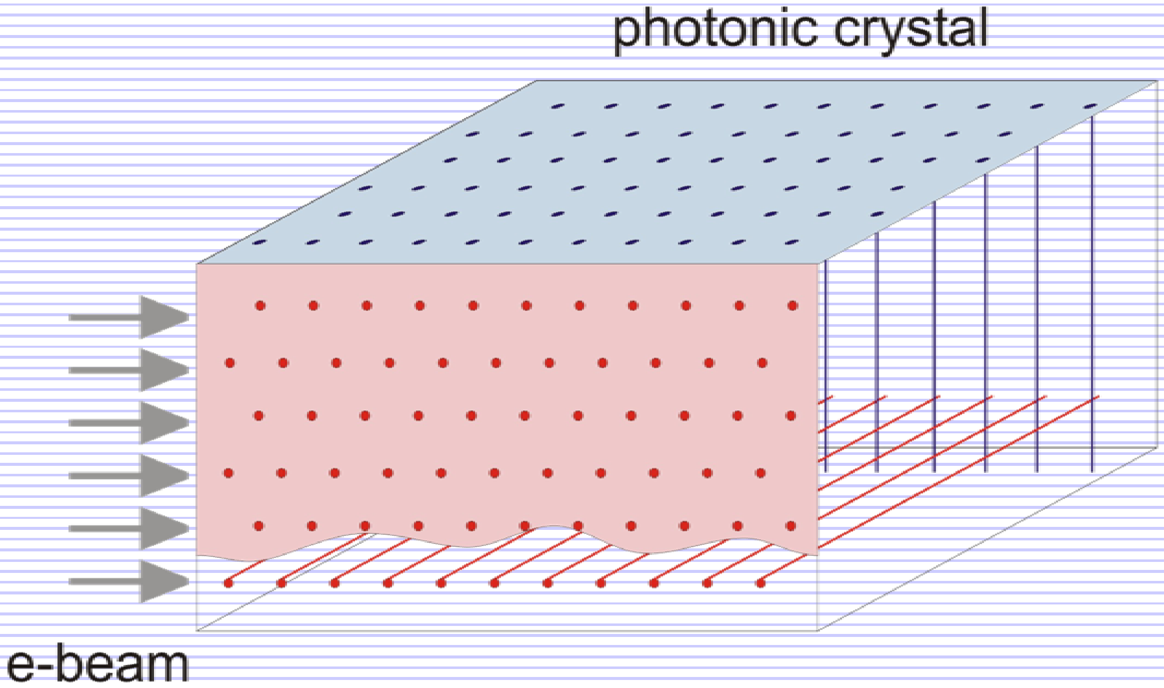
eight-wave diffraction

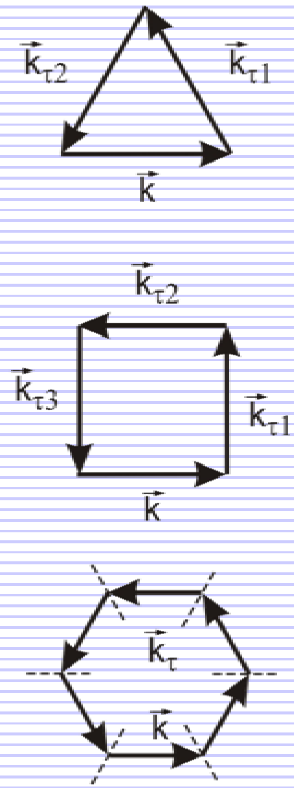
.

.

.

Photonic crystal providing multi-wave distributed feedback

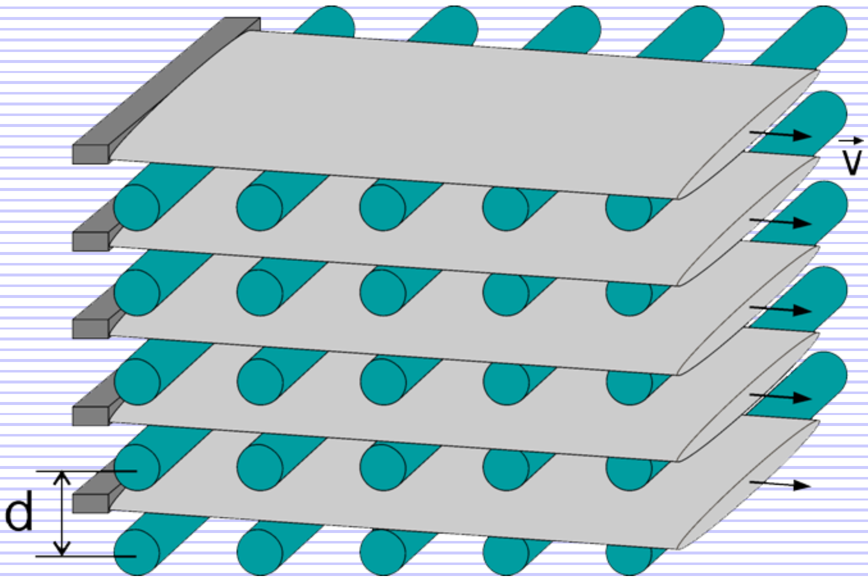


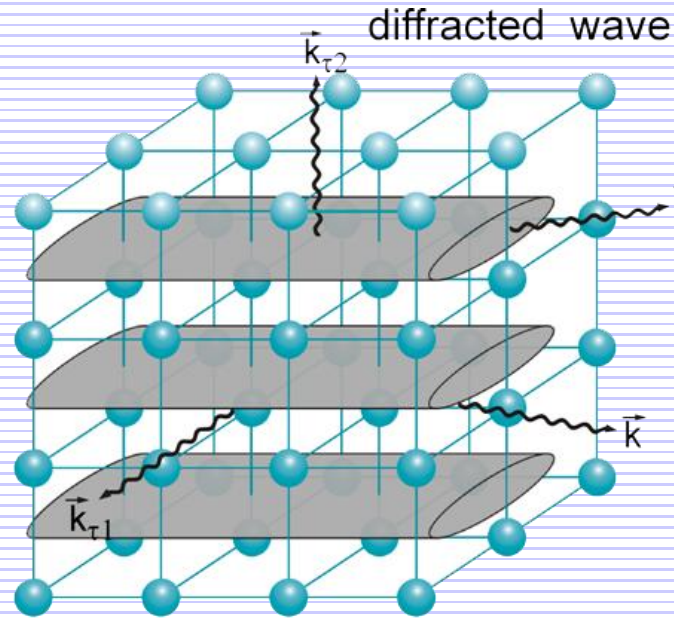


Threads are arranged to couple several waves (three, four, six...), which appear due to diffraction in such a structure, in both vertical and horizontal planes. The electron beam takes the whole volume of the photonic crystal.

Distributed interaction

Two- or three-dimensional diffraction gratings provide a means of distributing the interaction over a larger volume and relaxing the power limitations in the resonator.



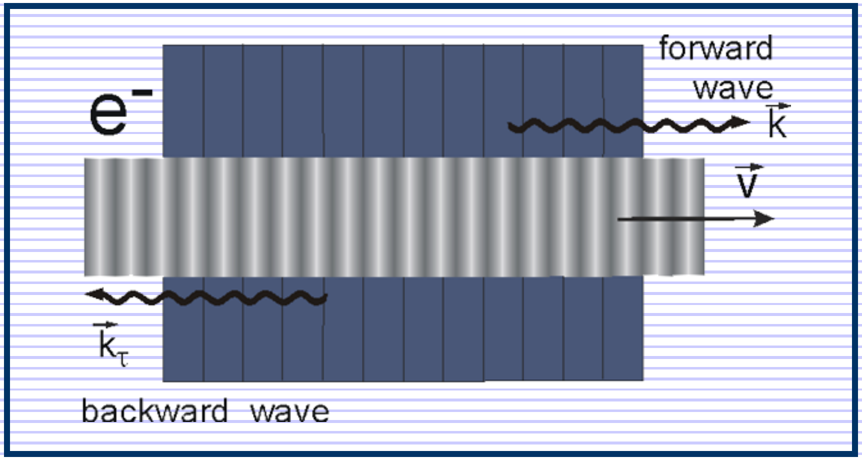


VFELs provide a more effective interaction of an electron beam with electromagnetic waves. Wide electron beams and diffraction gratings of large volumes can be used in VFELs. This enables one to obtain much higher radiation power without sparkovers and damage of resonator and output system. Life time of the system becomes longer.

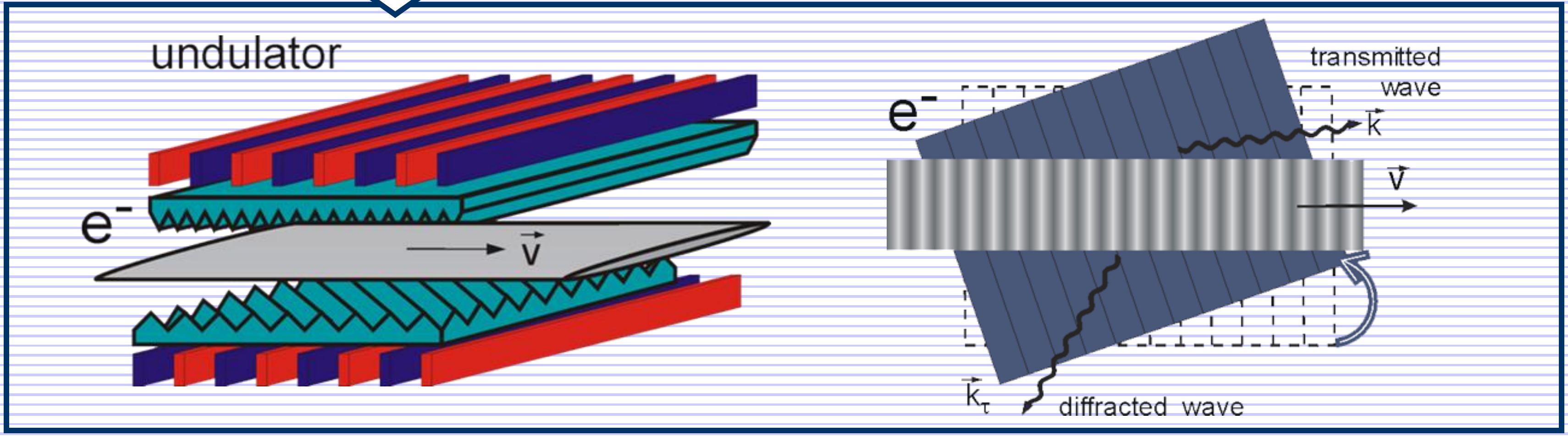
Frequency tuning in a VFEL

Rotation of the diffraction gratings allows VFEL lasing frequency to be tuned.

one-dimensional distributed feedback



two-dimensional distributed feedback



Sketch theory …

… of VFEL lasing using electron beam radiation in a volume "grid resonator"

Maxwell equations + equation of motion

$$rot\vec{H} = \frac{1}{c}\frac{\partial\vec{D}}{\partial t} + \frac{4\pi}{c}\vec{j}, \;\; \vec{D}(\vec{r},t) = \int_{-\infty}^{\infty}\varepsilon(\vec{r},t-t')\vec{E}(\vec{r},t')dt',$$

$$rot\vec{E} = -\frac{1}{c}\frac{\partial\vec{H}}{\partial t}, \;\; div\vec{D} = 4\pi\rho, \;\; \frac{\partial\rho}{\partial t} + div\vec{j} = 0,$$

$$rotrot\vec{E}(\vec{r},\omega) - \frac{\omega^2}{c^2}\varepsilon(\vec{r},\omega)\vec{E}(\vec{r},\omega = \frac{4\pi i\omega}{c^2}\vec{j}(\vec{r},\omega)$$

$$div\;\varepsilon(\vec{r},\omega)\vec{E}(\vec{r},\omega) = 4\pi\rho(\vec{r},\omega),$$

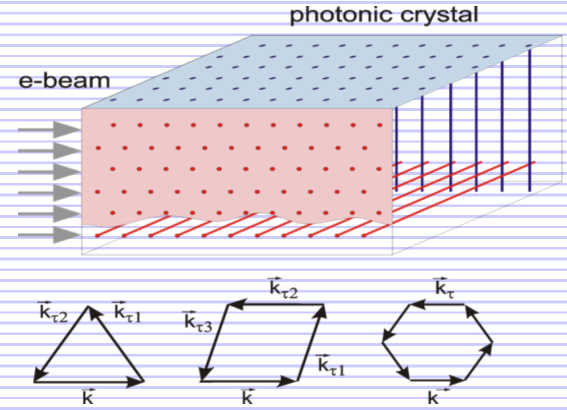
$$-i\omega\rho(\vec{r},\omega) + div\vec{j}(\vec{r},\omega) = 0,$$

$$\vec{j}(\vec{r},t) = e\sum_\alpha \vec{v}_\alpha(t)\delta(\vec{r}-\vec{r}_\alpha(t)), \;\; \rho(\vec{r},t) = e\sum_\alpha \delta(\vec{r}-\vec{r}_\alpha(t)),$$

$$\frac{d\vec{v}_\alpha}{dt} = \frac{e}{m\gamma}\left\{\vec{E}(\vec{r}_\alpha(t),t) + \frac{1}{c}[\vec{v}_\alpha(t)\times\vec{H}(\vec{r}_\alpha(t),t)] - \frac{\vec{v}_\alpha}{c^2}(\vec{v}_\alpha(t)\vec{E}(\vec{r}_\alpha(t),t))\right\}$$

The method

With the method of slow-varying amplitudes the solution of Maxwell equations, which describe diffraction of electromagnetic waves in the presence of an electron beam, can be expressed as follows:



$$E(\vec{r},t) = \mathrm{Re}\left\{\vec{A}_1 e^{i(\phi_1(\vec{r})-\omega t)} + \ldots + \vec{A}_m e^{i(\phi_m(\vec{r})-\omega t)} + ..\right\},$$

$$\phi_1(\vec{r}) = \int_0^{\vec{r}} \vec{k}_1(\vec{r}\,')d\vec{l},$$

$$\ldots$$

$$\phi_m(\vec{r}) = \int_0^{\vec{r}} \vec{k}_1(\vec{r}\,')d\vec{l} + \int_0^{\vec{r}} \vec{\tau}_m(\vec{r}\,')d\vec{l}, \qquad m = 1, .., s+1$$

Substituting this expression into the exact system of equations we obtain the system of (s+1) equations for waves A_m

Two-wave diffraction

$$2ik_{1z}(z)\frac{\partial A_1}{\partial z} + i\frac{\partial k_{1z}(z)}{\partial z}A_1 - (k_\perp^2 + k_{1z}^2(z))A_1 + \frac{\omega^2}{c^2}\varepsilon_0(\omega,z)A_1 + i\frac{1}{c^2}\frac{\partial\omega^2\varepsilon_0(\omega,z)}{\partial\omega}\frac{\partial A_1}{\partial t} +$$
$$+\frac{\omega^2}{c^2}\varepsilon_{-\tau}(\omega,z)A_2 + i\frac{1}{c^2}\frac{\partial\omega^2\varepsilon_{-\tau}(\omega,z)}{\partial\omega}\frac{\partial A_2}{\partial t} = i\frac{2\omega}{c^2}J_1(k_{1z}(z)),$$
$$2ik_{2z}(z)\frac{\partial A_2}{\partial z} + i\frac{\partial k_{2z}(z)}{\partial z}A_2 - (k_\perp^2 + k_{2z}^2(z))A_2 + \frac{\omega^2}{c^2}\varepsilon_0(\omega,z)A_2 + i\frac{1}{c^2}\frac{\partial\omega^2\varepsilon_0(\omega,z)}{\partial\omega}\frac{\partial A_2}{\partial t} +$$
$$+\frac{\omega^2}{c^2}\varepsilon_{\tau}(\omega,z)A_1 + i\frac{1}{c^2}\frac{\partial\omega^2\varepsilon_{\tau}(\omega,z)}{\partial\omega}\frac{\partial A_1}{\partial t} = i\frac{2\omega}{c^2}J_2(k_{2z}(z)),$$

J_1, J_2 are the currents, $A_1 \equiv A_{\tau=0},\ A_2 \equiv A_\tau,\ \vec{k}_1 = \vec{k}_{\tau=0},\ \vec{k}_2 = \vec{k}_1 + \vec{\tau}.$

These equations are obtained in [V.G.Baryshevsky, A.A.Gurinovich, in Proceedings of FEL 2006, pp.335-339 (2006); arXiv: physics/0608068] along with those for phase ϕ_m and change of Lorentz factor γ for an electron beam passing through the resonator.
They describes general case of generators with changing in space parameters of grating (photonic crystal)

Thread heating evaluation

- tungsten threads of 100μm diameter
- electron beam energy 250 keV
- electron beam current 1 kA
- pulse duration 100 ns
- electron beam diameter 32 mm

- $6 \cdot 10^{14}$ electrons in the beam
- $2 \cdot 10^{12}$ electrons pass through a thread
- 0.08 Joule transferred to the thread

if we suppose that all electrons passing through the thread lose the whole energy for thread heating

$$\Delta T < 125°$$

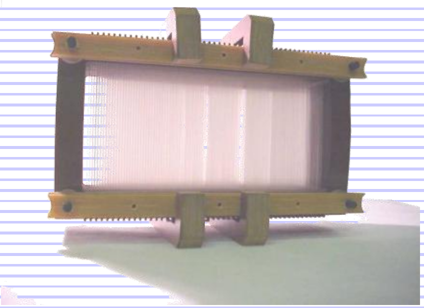
Use of volume distributed feedback makes available:

- ✓ more effective interaction of electron beam and electromagnetic wave, which leads to significant reduction of threshold current of electron beam
- ✓ high output power by the use of wide electron beams (several electron beams) and diffraction gratings of large volumes
- ✓ resonator dimensions can be much larger than the radiation wavelength

VFEL experimental history

1996

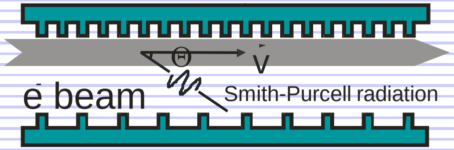
Experimental modeling of electrodynamic processes in the volume diffraction grating (photonic crystal) made from dielectric threads (Q-factor ~ 10^5)



V.G.Baryshevsky, K.G.Batrakov, I.Ya. Dubovskaya, V.A.Karpovich, V.M.Rodionova, NIM 393A (1997) II-75

2001

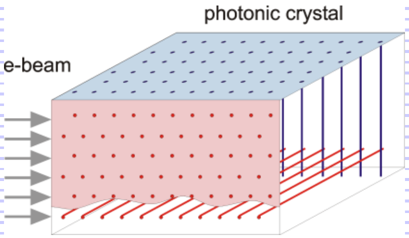
First lasing of volume free electron laser in mm-wavelength range. Demonstration of validity of VFEL principles and possibility for frequency tuning at constant electron energy



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

2004

VFEL prototype with volume photonic crystal made from metallic threads



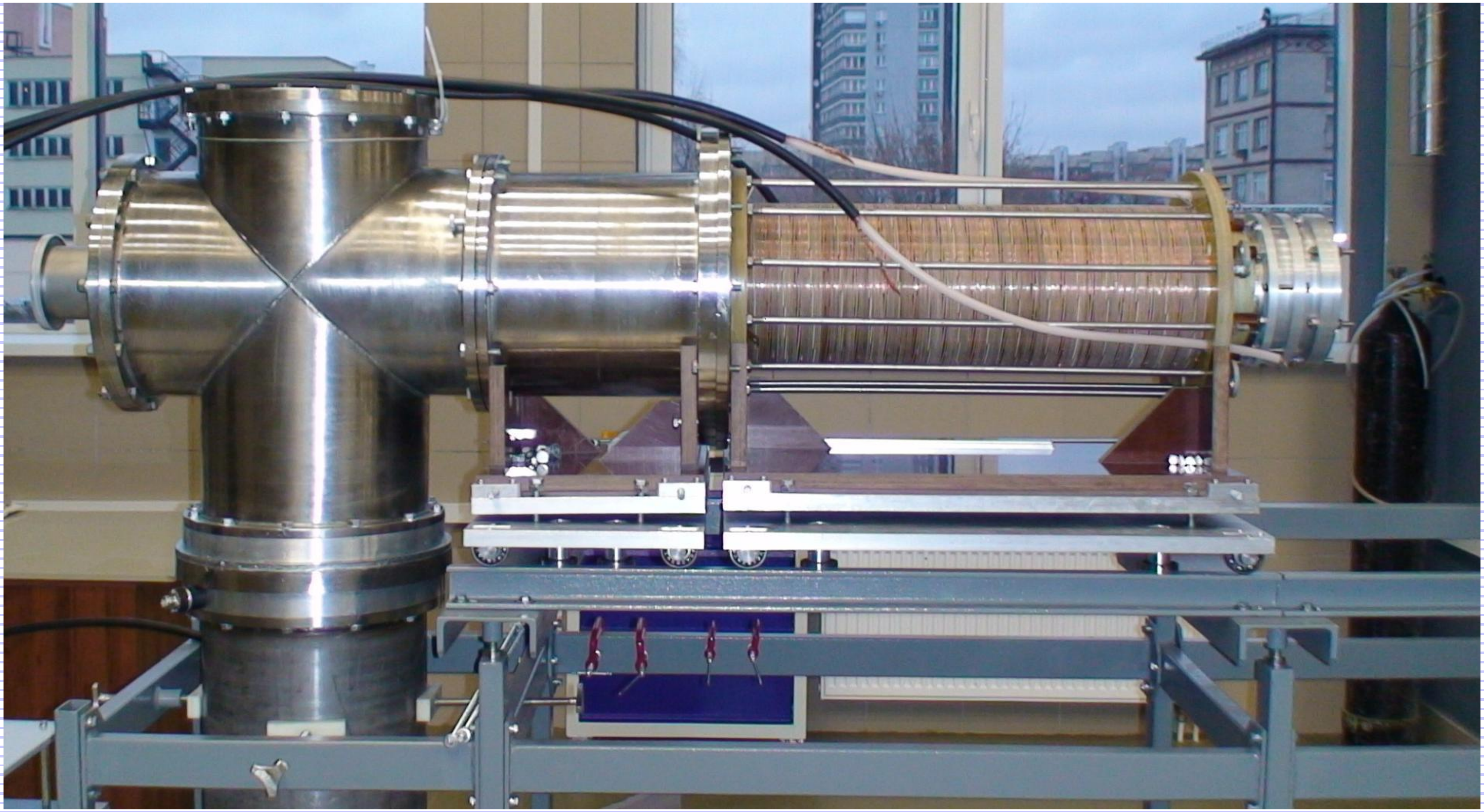
V.G.Baryshevsky, A.A.Gurinovich, NIM 252B (2006) 91
V.G.Baryshevsky, Proc. of the 28th Intern. Free Electron
Laser Conference FEL2006 (2006) 331

Recent experiments

- photonic crystal made of threads
- photonic crystal with variable period
- foil photonic crystal

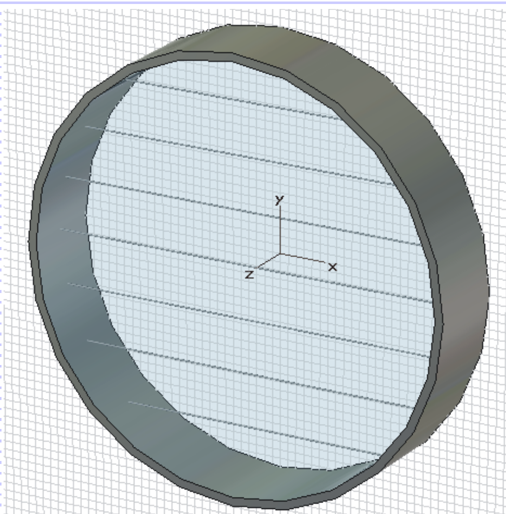
Volume Free Electron Laser

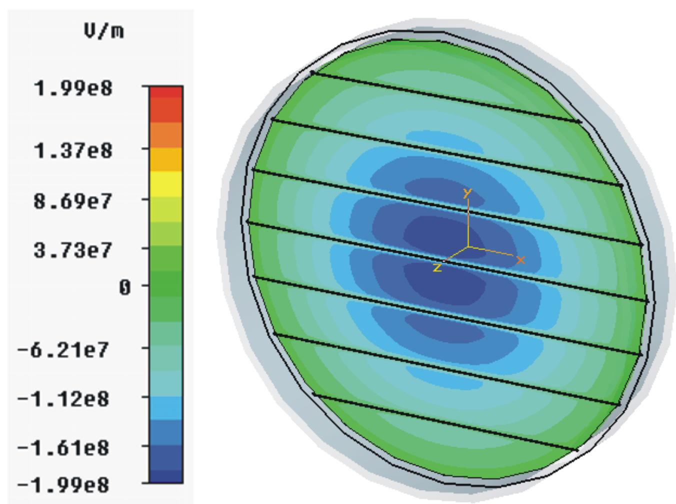
electron beam energy up to 500 keV

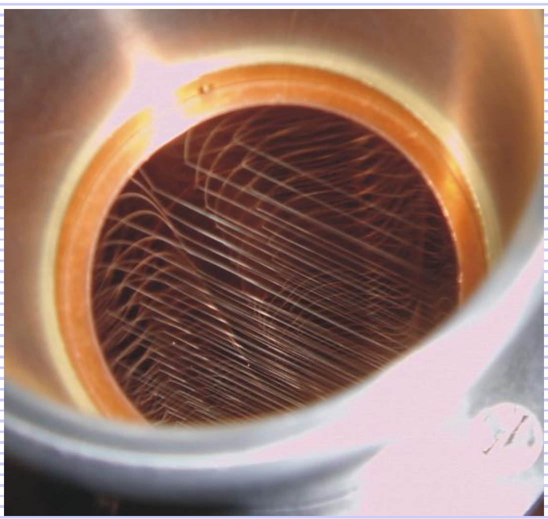


Photonic crystal made from tungsten threads

- a layer of 7 tungsten threads of 100 μm diameter distant 6.25mm
- two crystals with the periods d_1=12.5mm and d_2=10.5mm
- a circular waveguide with the inner diameter 50 mm
- up to 15 periods in the photonic crystal in different experiments

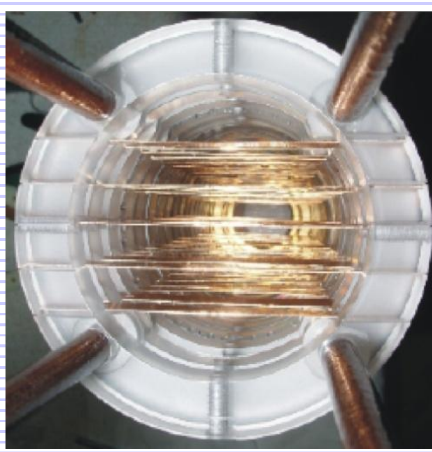


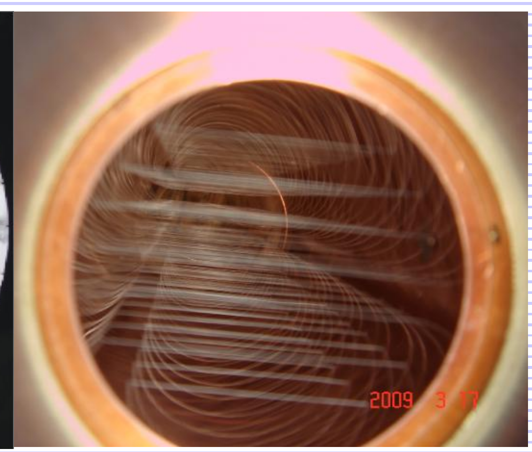


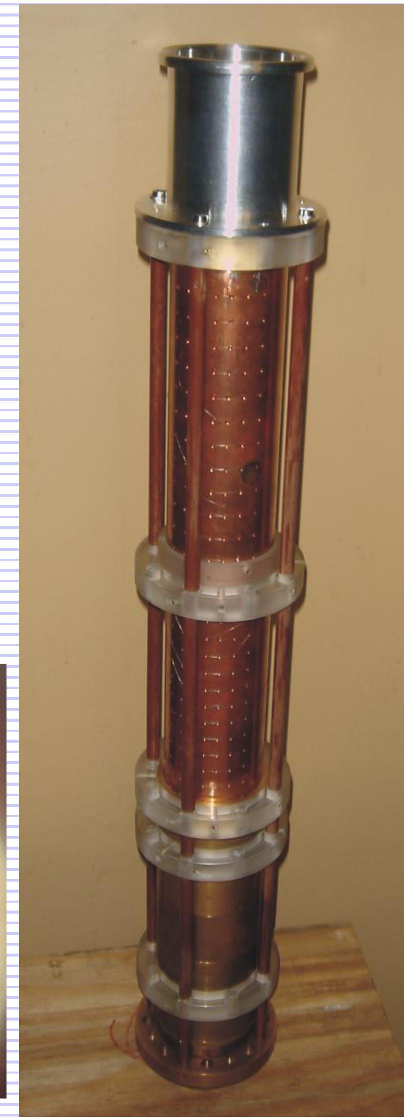


V. G. Baryshevsky et. al., Proceedings of 35th International Conference on Infrared, Milimeter and Terahertz waves (2010) IRMMW-THz2010

Photonic crystals for VFEL lasing



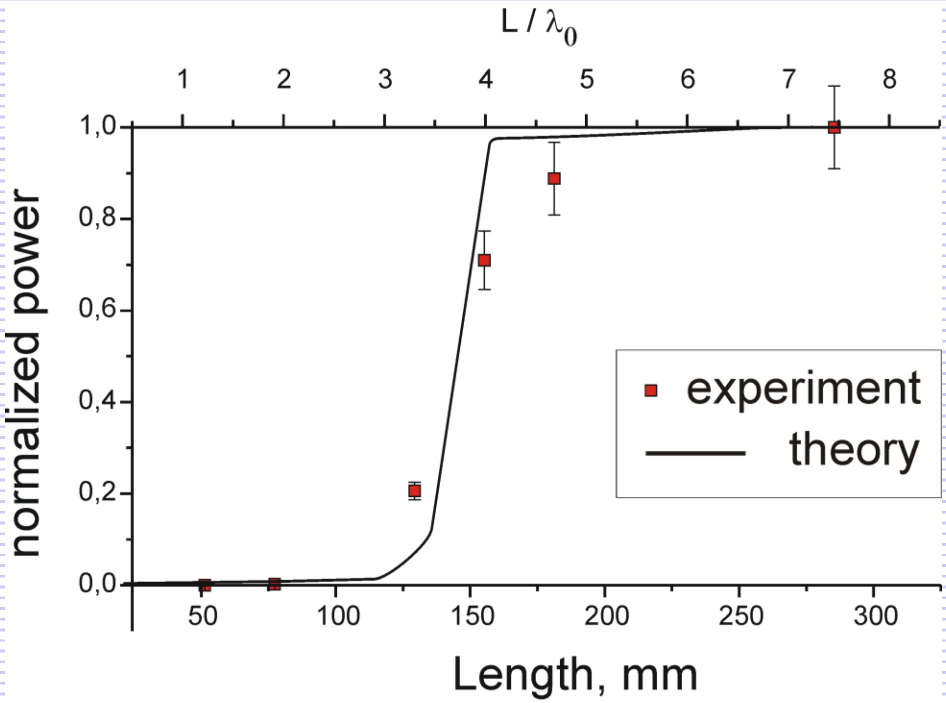




Experiments with “grid” VFEL

BWO regime

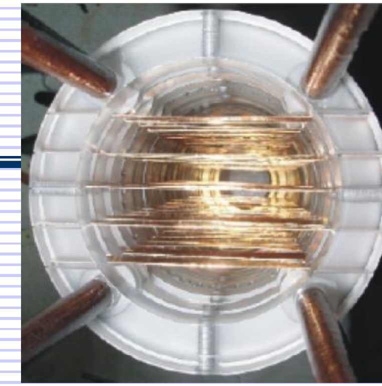
The "grid" structure is made of separate frames each containing the layer of 5 parallel metallic threads with the distance between the next threads d_y=6 mm. Frames are joined to get the "grid" structure.

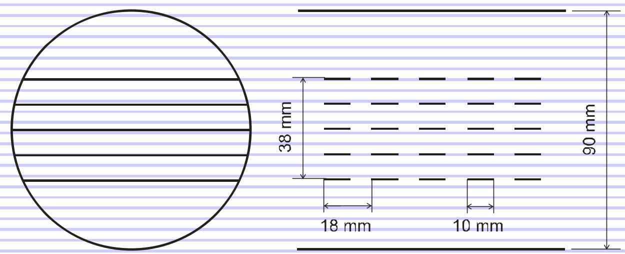


Dependence of radiation power on resonator length

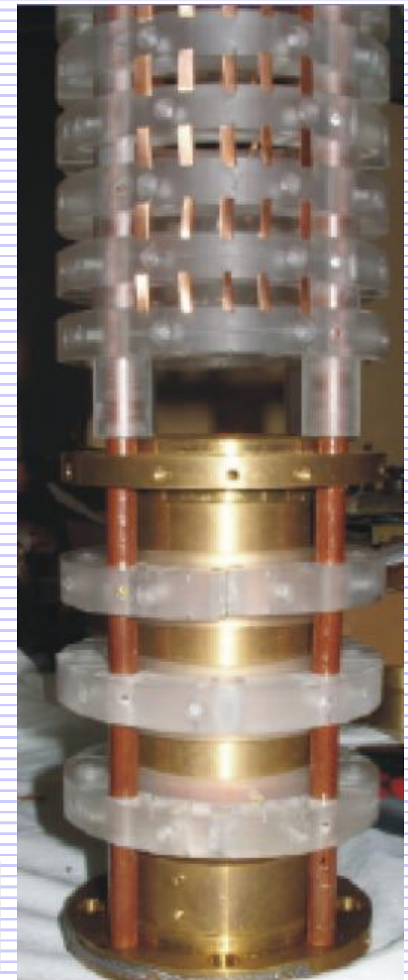
A foil photonic crystal

electron energy, keV	100	150	200	250
lasing frequency, GHz	1.68	1.68	1.68	1.68
	1.73	1.73	1.73	1.73
	1.92	1.93	1.94	1.94
	4.99	5.00	5.00	5.03
	5.13	5.13	5.13	5.13
	5.61	5.57	5.57	5.57
	6.12	6.66	7.03	7.29
	6.70	7.24	7.60	7.83
	6.99	7.55	7.90	8.11





- brass foils of 100 μm thickness and 10 mm width
- 5-foils layers with 18 mm period inside the drift tunnel

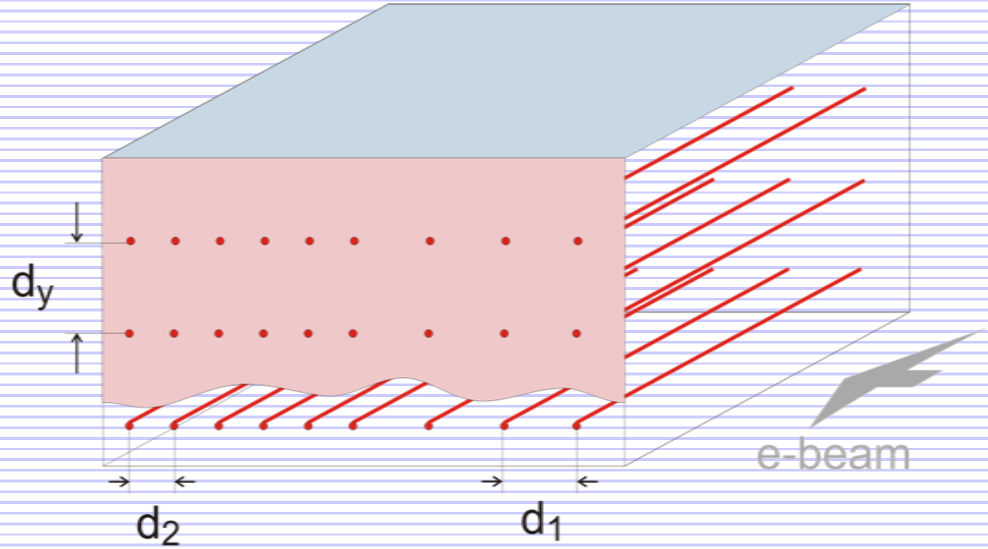


- foil tapes are fixed in slots on plexiglas rings tightened together by dielectric studs
- the pencil-like electron beam has diameter about 40 mm

V. G. Baryshevsky, et al. Proc. of the 32nd Intern. Free Electron Laser Conference FEL2010, THPB18.

“Grid” VFEL with variable period: set-up

- radiation frequency ≈10 GHz.
- BWO regime
- resonator with two ‘’grid’’ photonic crystals



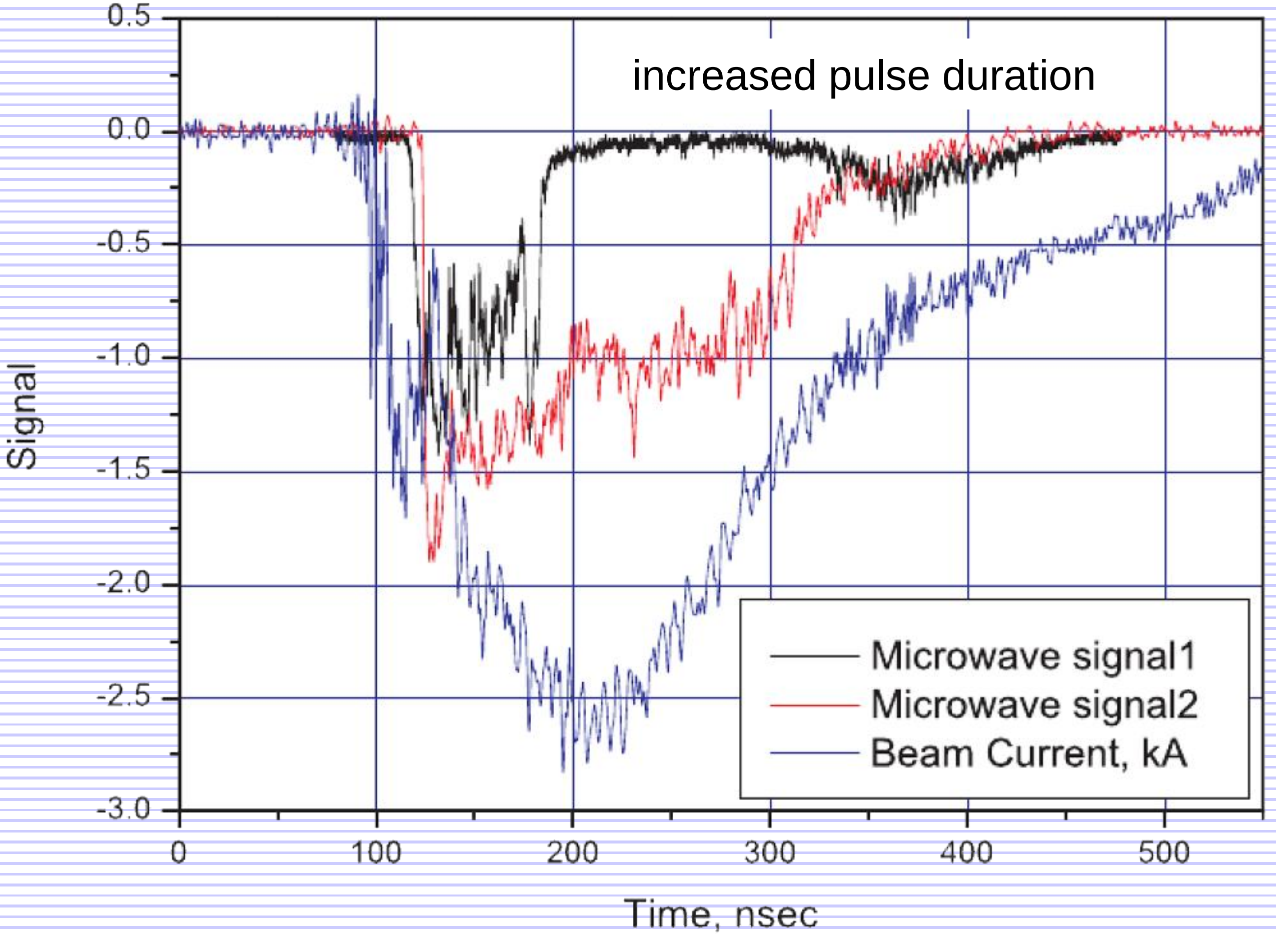
The "grid" structure is made of separate frames each containing the layer of 5 parallel threads with the distance between the next threads d_y=6 mm; 12 frames were joined to get the "grid“ photonic crystal with the period of 12.5 mm and another 12 frames formed a "grid“ photonic crystal with the period of 10.5 mm .

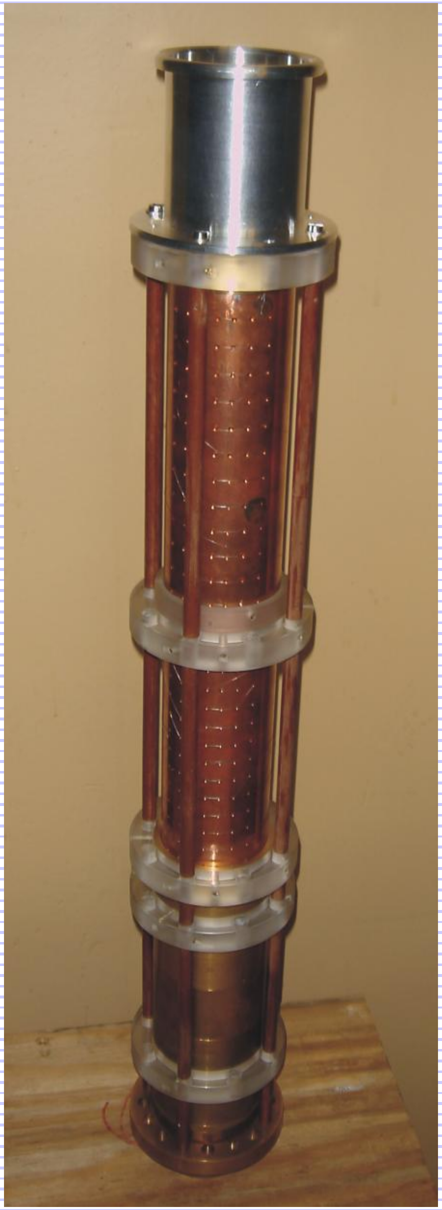
The period of the second photonic crystal is chosen such that the electron beam, which have lost part of its energy for radiation in the first photonic crystal, could provide the same radiation frequency as in the first crystal.

“Grid” VFEL with variable period: experiment

V. G. Baryshevsky et. al., Proc. of the 31st Intern. Free Electron Laser Conference FEL2009 (2009) MOPC49

V. G. Baryshevsky et. al., Proceedings of the 35th Intern. Conference on Infrared, Milimeter and Terahertz waves IRMMW-THz2010

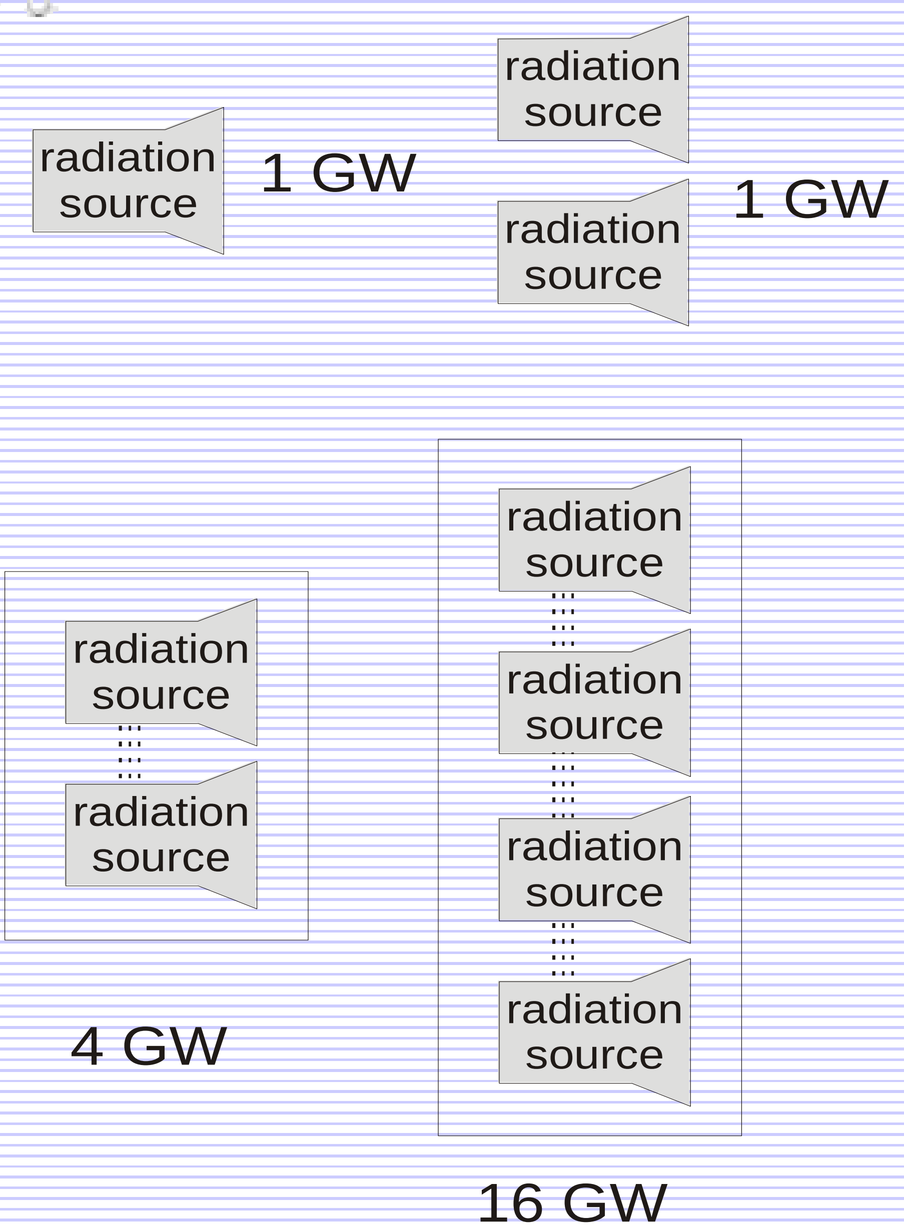


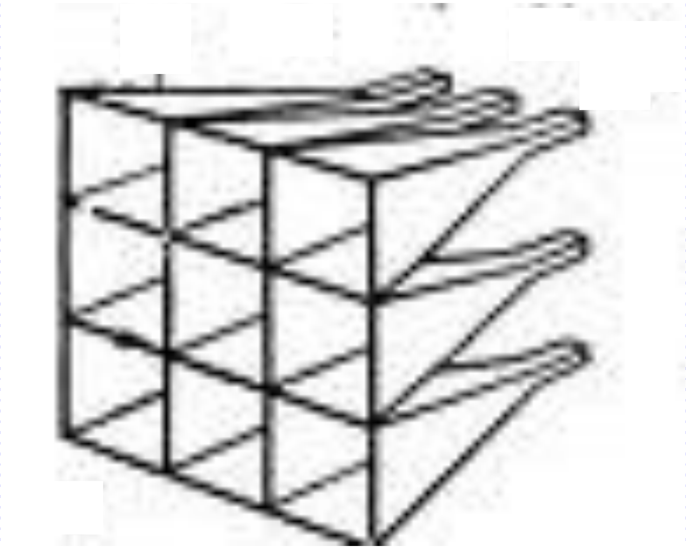


Perspectives

- Future experiments

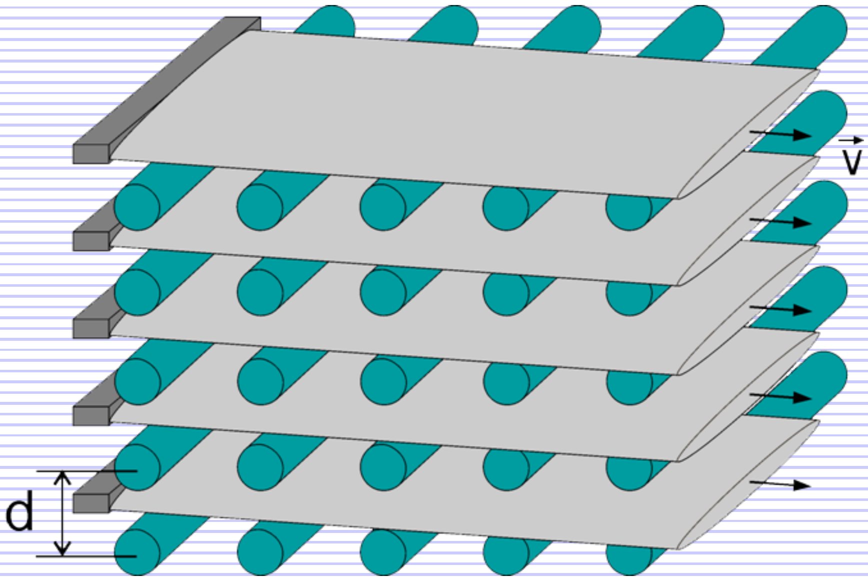
Phase-locking principle

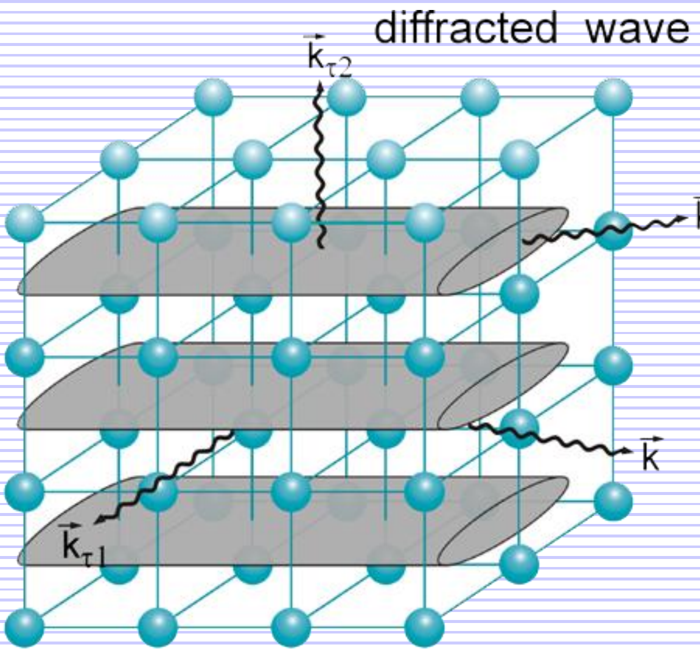




VFEL the self-phase-locking system

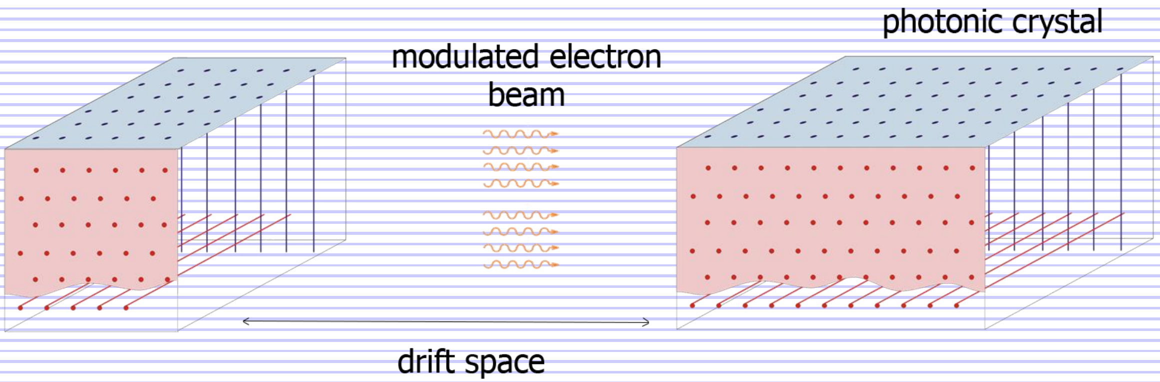
Volume (two- or three-dimensional) feedback formed in a VFEL resonator gives rise to the self-phase-locking process: as a result of radiated wave diffraction, the spatially separated points of the beam (or several beams) become linked and thus generate coherently.

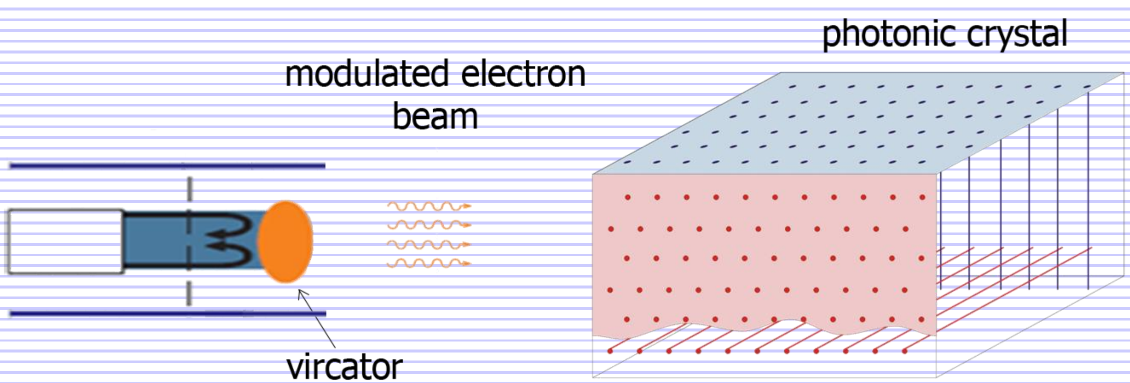




V.G. Baryshevsky and A.A Gurinovich, Volume Free Electron Laser - Self-Phase-Locking System, LANL e-print arXiv:1301.4330v1 [physics.acc-ph]

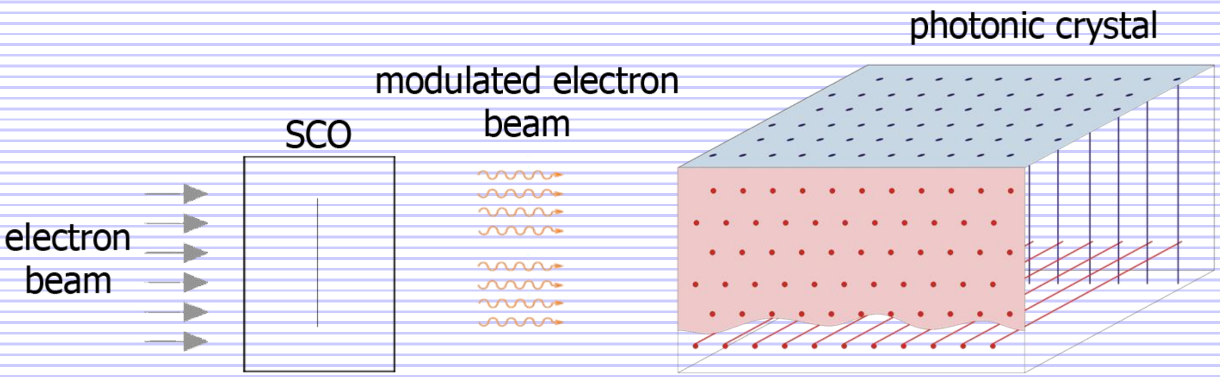
Hybrid systems. Klystron-like VFEL.





V.G. Baryshevsky, A.A. Gurinovich, Hybrid systems with virtual cathode for high power microvawes generation, arXiv: 0903.0300v1 [physics.acc-ph], 2009.

Hybrid systems. Klystron-like VFEL.



V.G. Baryshevsky, Relativistic Split-Cavity Oscillator, arXiv: 1402.3403 [physics.acc-ph], 2014.

High Power Microwave Sources

EAPPC 2012 / BEAMS 2012

4th Euro-Asian Pulsed Power Conference
19th International Conference on High-Power Particle Beams
September 30 - October 4, 2012, Karlsruhe, Germany

IET
The Institution of Engineering and Technology
20th Symposium on Pulsed Power
17-19 September, 2007; Rutherford Appleton Lab, Didcot, Oxon, UK

EUROPEAN MICROWAVE WEEK
NCC NUREMBERG, GERMANY
6-11 OCTOBER 2013
www.eumweek.com
MEET EXPERTS
MAKE FRIENDS

EA^2PPC 2008
2nd Euro-Asian Pulsed Power Conference

2
0
0
8

IRMMW
2010

fel 06
BERLIN

FEL
- MMX Sweden -
2010

Conclusion

All the principles and ideas, which are in the basis of VFEL operation, have been theoretically developed and experimentally confirmed. They give a good reason to conclude that the Volume Free Electron Laser is very promising for development of radiation sources in centimeter, millimeter, sub-millimeter and optical wavelength ranges.

Transverse dimensions of VFEL resonator could significantly exceed radiation wavelength. The electron beam and radiation power are distributed over the large volume that is beneficial for electrical endurance of the system and allow to create High Power Microwave and Optical sources.

Thanks and questions

Thank you for attention !!