Research Institute for Nuclear Problems,
Belarus State University,
Minsk, Belarus

Volume Free Electron Lasers

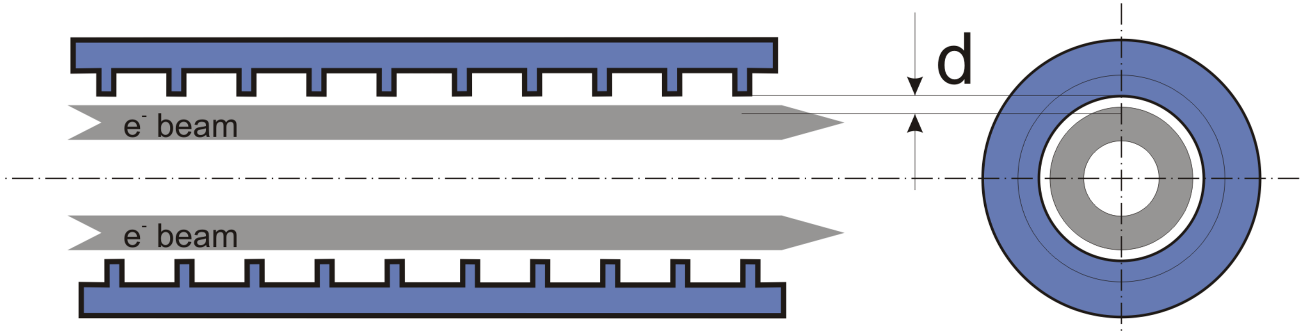
V.G. Baryshevsky

51st Workshop: "Channeling 2008" Charged and Neutral Particles Channeling Phenomena, Erice (Trapani) Italy, 25 October - 1 November 2008

High Power Microwave Systems: 1st class

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

Travelling Wave Tubes (TWT),
Backward Wave Oscillator (BWO),
Magnetically Insulated Line Oscillator (MILO)



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

When radiation wavelength decreases, **d** declines

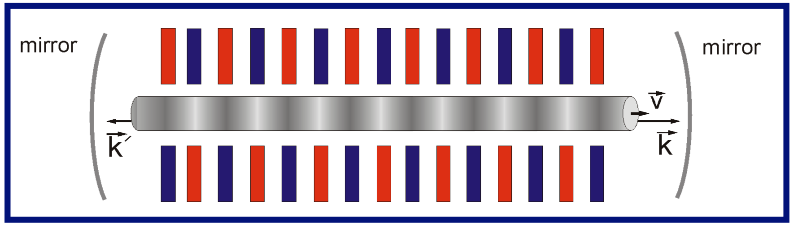
When an electron passes near the surface of the diffraction grating at the distance less then **d** it effectively excites an electromagnetic wave.

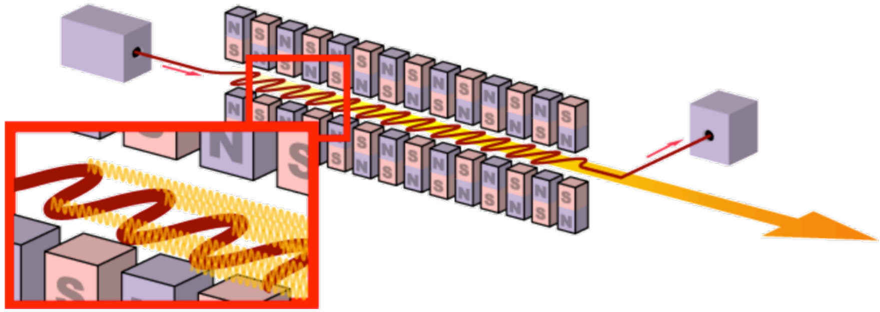
for 500 keV electrons (γ=1.98, β=0.86) and λ=3 mm (ν=100 GHz) **d**=0.4 mm	for 500 keV electrons (γ=1.98, β=0.86) and λ=0.3 mm (ν=1THz) **d**=0.04 mm

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

High Power Microwave Systems: 2nd class

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 an electromagnetic radiation field.

For a cold electron beam in Compton regime increment of electron beam instability is proportional to $\sqrt[3]{\rho}$, 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) ~ $\sqrt[3]{\rho}$

The higher electron beam energy and shorter radiation wavelength => the higher threshold current

Use of resonators with transverse dimension, which are much larger than the radiation wavelength, results in excitation of many modes

High Power Microwave Systems :3rd class (history)

Volume Free Electron Laser (VFEL): how it started …….

Доклады Академии наук БССР

1971. Том XV, № 4

УДК 537.531.85

В. Г. БАРЫШЕВСКИЙ

О РАССЕЯНИИ СВЕТА ПОТОКОМ ЭЛЕКТРОНОВ, ПРОХОДЯЩИХ ЧЕРЕЗ КРИСТАЛЛ

(Представлено академиком АН БССР М. А. Ельяшевичем)

Пусть поток электронов движется через кристалл, в котором распространяется электромагнитная лазерная волна $E \sim \exp\ \{i(\mathbf{k}_0\mathbf{r}-\omega_0 t)\}$. Частота рассеянных фотонов может быть найдена при помощи формул, описывающих эффект Допплера в преломляющей среде и имеющих вид ([1], [2])

$$\omega=\omega_0\frac{1-\beta n_0\cos\vartheta_0}{1-\beta n(\omega)\cos\vartheta}, \qquad (1)$$

где n_0 — показатель преломления падающей волны; $n(\omega)$ — то же для рассеянного фотона частоты ω; ϑ_0 — угол между направлением скорости электронов $\mathbf{v}$ и потоком света; ϑ — то же для электронов и рассеянного света; $\beta=\frac{v}{c}$.

Как отмечено в ([1]), выражение (1) описывает не только нормальный и аномальный эффект Допплера, но и индуцированный эффект Вавилова—Черенкова. Следует заметить, что соотношение (1) выведено фактически в предположении, что стационарными состояниями электромагнитного поля в среде являются плоские волны. В этой связи необходимо обратить внимание на то обстоятельство, что для рассеянных фотонов с длиной волны, сравнимой с межатомными расстояниями, стационарными состояниями в кристалле являются волны Блоха. Как известно (см., например, ([3], [4])), указанное обстоятельство приводит к возникновению дифракции. При этом оказывается, что в условиях дифракции (т. е. при выполнении условий Брегга) кристаллу нельзя приписать некоторый один определенный показатель преломлений ([3]).

Рассмотрим возникающую ситуацию подробнее. Наличие световой

Prediction of spontaneous and induced parametric and diffraction transition X-ray radiation from charged particles in crystals

V.G. Baryshevsky: *“About light scattering by an electron beam, passing through a crystal”* Doklady Akademy of Science Belarus 15, 306 (1971)

V.G.Baryshevsky, I.D.Feranchuk: ***“****About transition radiation of γ-quanta in a crystal****”*** JETP v.61 (1971) (Sov.Phys. JETP 34, 502 (1972))

High Power Microwave Systems :3rd class (history)

Volume Free Electron Laser (VFEL): how it started …….

Experimental observation of parametric X-ray radiation from electron and proton beams in crystals

Y.N. Adishchev, V.G. Baryshevsky, S.A. Vorobiev et al.: Sov.Phys.JETP.Lett. 41 (1985) 361

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V.P. Afanasenko, V.G. Baryshevsky, S.V. Gatsicha, et.al.: Sov. JETP Lett. 51 (1990) 213

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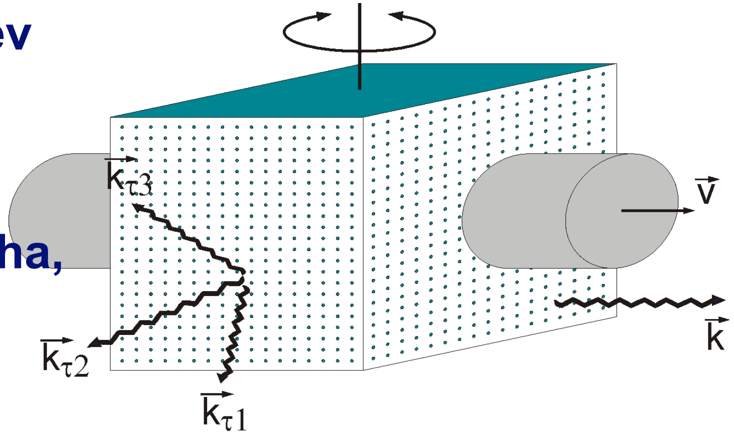


Recent review of PXR theory, experiment and applications

V.Baryshevsky, I.Feranchuk, A.Ulyanenkov "Parametric X-Ray Radiation in Crystals. Theory, Experiment and Applications" Series: Springer Tracts in Modern Physics , Vol. 213 (2005)

High Power Microwave Systems :3rd class (history)

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 Bragg diffraction there are several refraction indices. When these refraction indices coincide, a new law of radiation instability originates. For example, in case of two wave diffraction the increment of electron beam instability is proportional to $\sqrt[4]{\rho}$ in contrast to $\sqrt[3]{\rho}$.

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

The law was demonstrated to be valid not only for parametric radiation but for any type of spontaneous radiation (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, Doklady Akademy of Science USSR 299 (1988) 6

High Power Microwave Systems: 3^{rd} class

VFEL 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

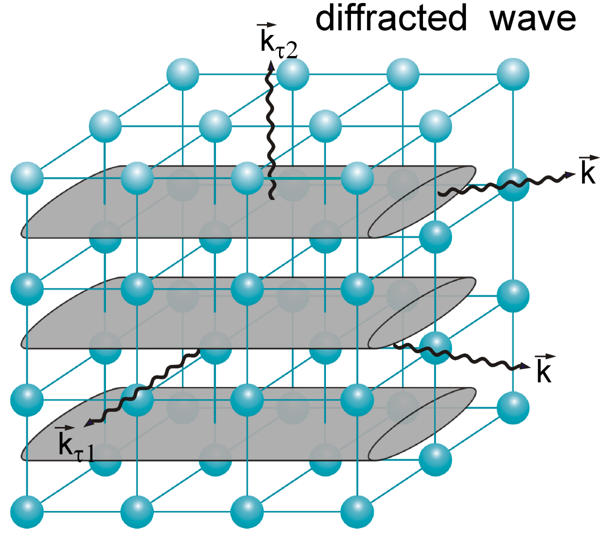
dynamical Bragg diffraction in a periodic medium (crystal) evokes the peculiar conditions, that result in a new law of electron beam instability:

$\sqrt[3+s]{\rho}$ (compare with $\sqrt[3]{\rho}$ for conventional systems)

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).

Within these 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 $j_{thr} \sim L^{-3}$)

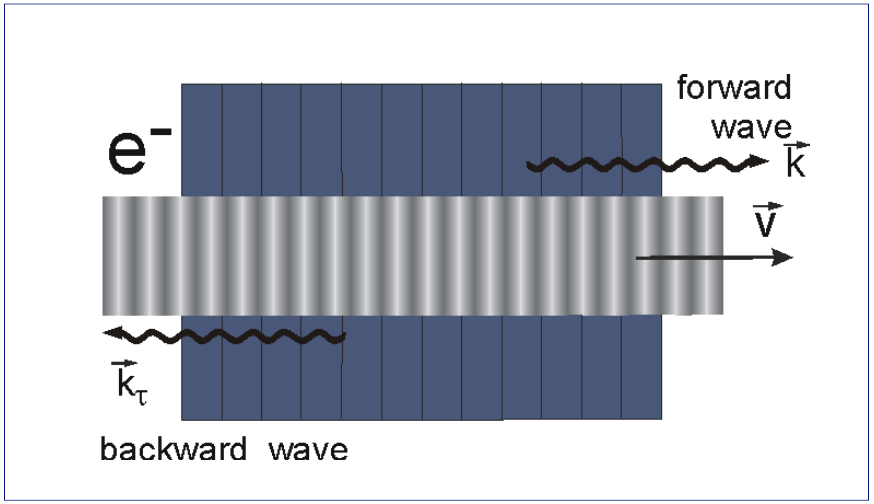


V.G.Baryshevsky, I.D.Feranchuk, Phys. Lett. 102 A, 141 (1984)
V.G.Baryshevsky, Doklady Akademy of Science USSR 299 (1988) 6
V.G.Baryshevsky, NIM 445A (2000), II-281

What is volume distributed feedback ?

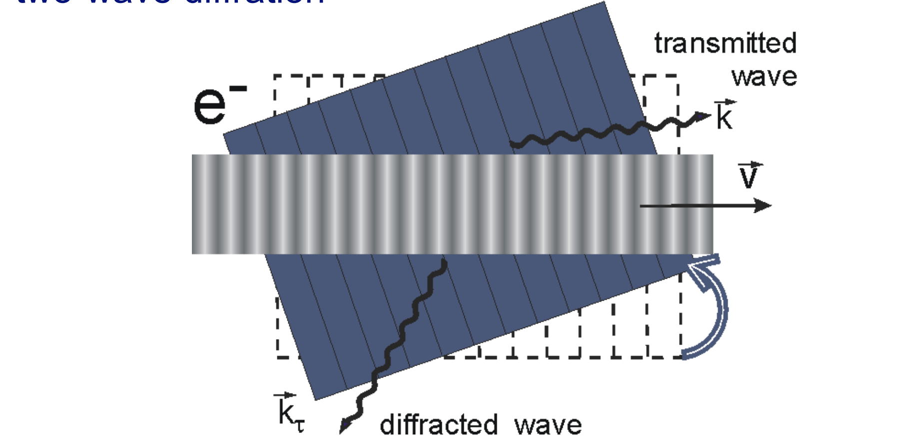
Volume (non-one-dimensional) multi-wave distributed feedback is the distinctive feature of Volume Free Electron Laser (VFEL)

one-dimensional distributed feedback

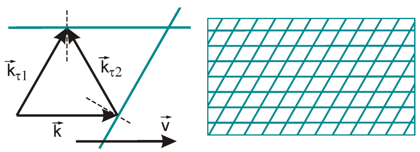


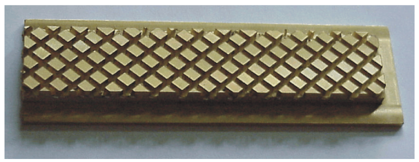
two-dimensional distributed feedback

two-wave diffration

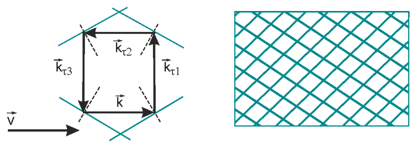


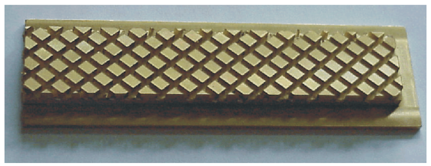
three-wave diffration



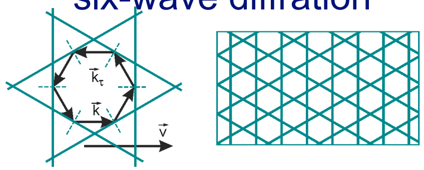


four-wave diffration





six-wave diffration



eight-wave diffration

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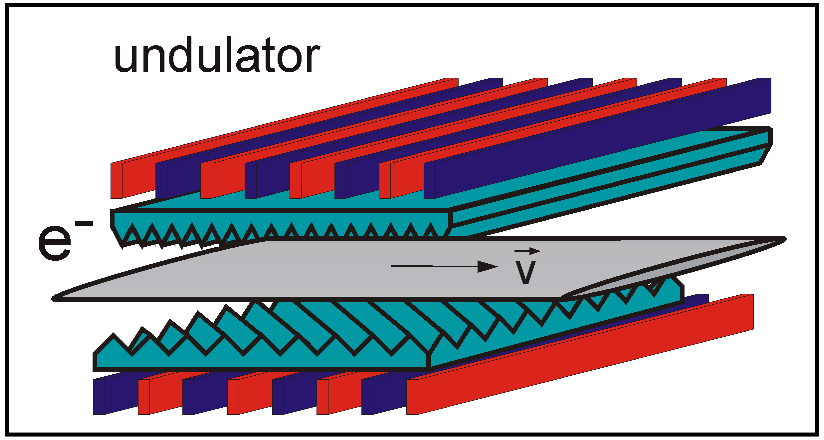
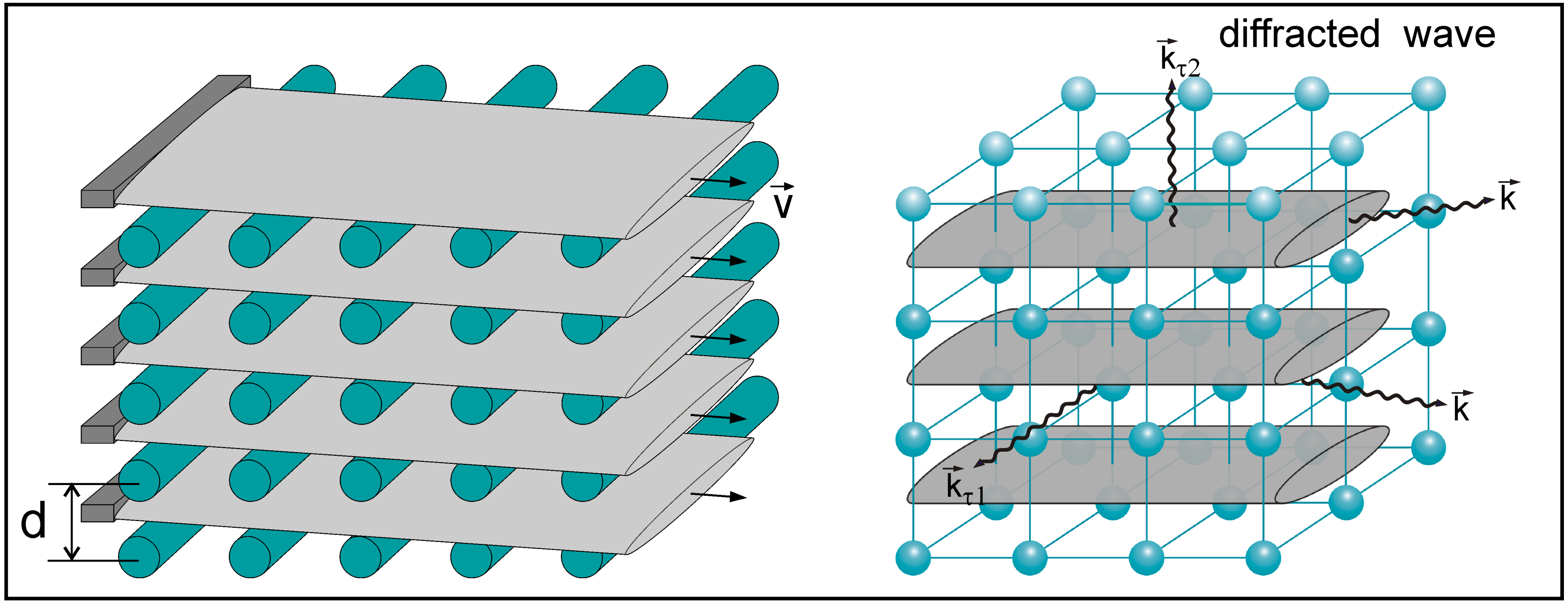
What is Volume Free Electron Laser ? *

VFEL can use any spontaneous radiation mechanism (magnetic bremsstrahlung in undulator, radiation in laser wave, Smith-Purcell, diffraction or Cherenkov radiation and so on).





* Eurasian Patent no. 004665

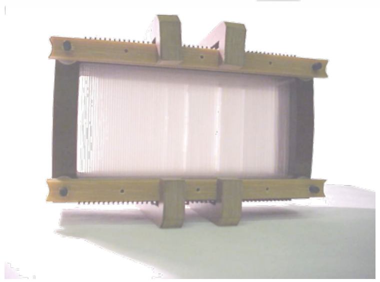
Use of volume distributed feedback makes available:

- ✓more effective interaction of electron beam and electromagnetic wave, which leads to significant reduction of threshold current of electron beam and, as a result, miniaturization of generator
- ✓reduction of limits for available output power by the use of wide electron beams and diffraction gratings of large volumes
- ✓resonator dimensions can be much larger then radiation wavelength

VFEL experimental history

1996

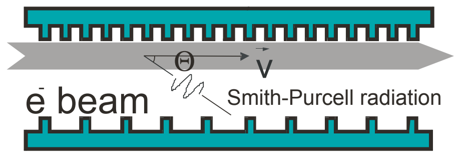
Experimental modeling of electrodynamic processes in the volume diffraction grating (photonic crystal) made from dielectric threads (Q-factor ~ 10^5)



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

2001

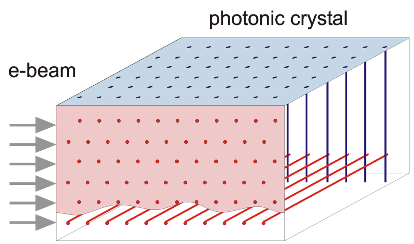
First lasing of volume free electron laser in mm-wavelength range. Demonstration of validity of VFEL principles and possibility for frequency tuning at constant electron energy



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

2004

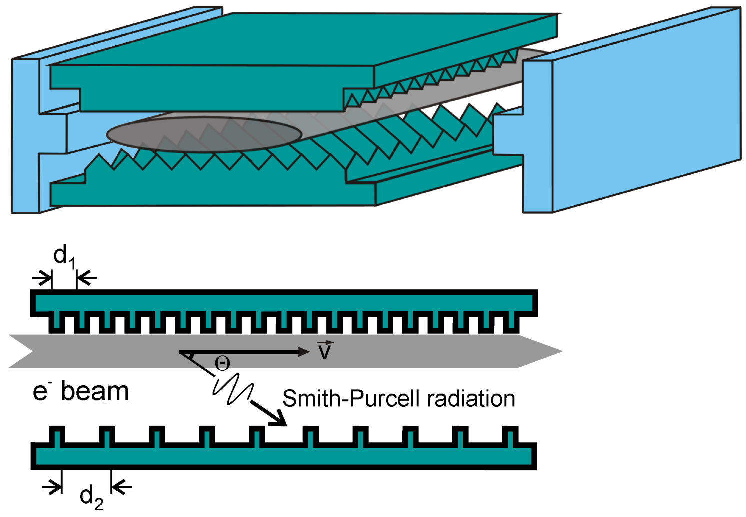
VFEL prototype with volume photonic crystal made from metallic threads

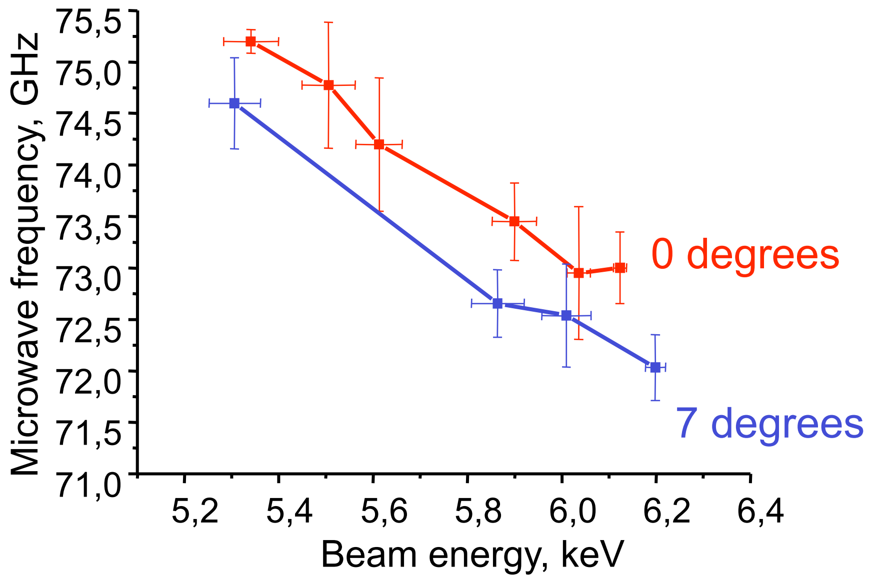


V.G.Baryshevsky, A.A.Gurinovich, *NIM 252B (2006) 91*
V.G.Baryshevsky, *Proc. of the 28th Intern. Free Electron Laser Conference FEL2006 (2006) 331*

First Volume FEL

- Rectangular resonator
- Two diffraction gratings with different periods
- Sheet electron beam (energy 10 keV)
- Operation range about 4 mm





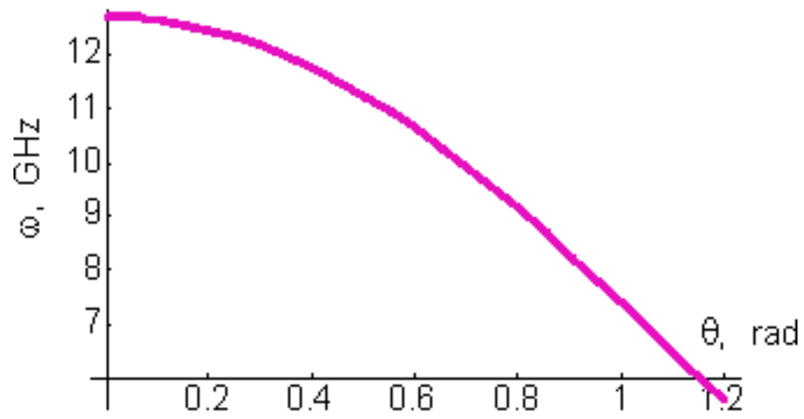
- ✓ Lasing was observed
- ✓ Radiation frequency change at rotation of diffraction grating was studied

Frequency tuning by grating rotation

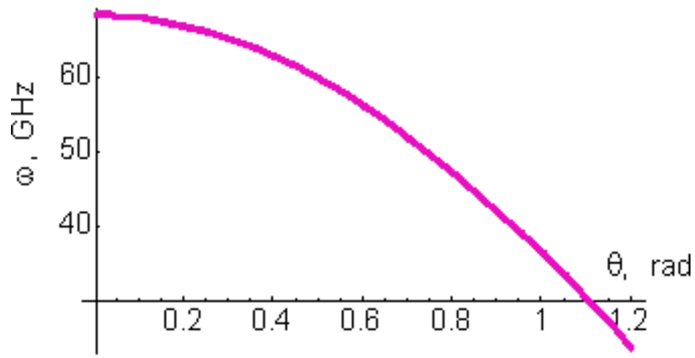
simultaneous rotation of two diffraction gratings placed inside a rectangular resonator changes both radiation and diffraction conditions

radiation frequency depends on the angle of gratings rotation θ:

$$\omega_{mn}(\theta)=\frac{\tau_z(\theta)\mathrm{v}}{1-\beta^2}\left(1\pm\beta\sqrt{1-\frac{\kappa_{mn}^2}{\tau_z^2(\theta)}\frac{1-\beta^2}{\beta^2}}\right)$$



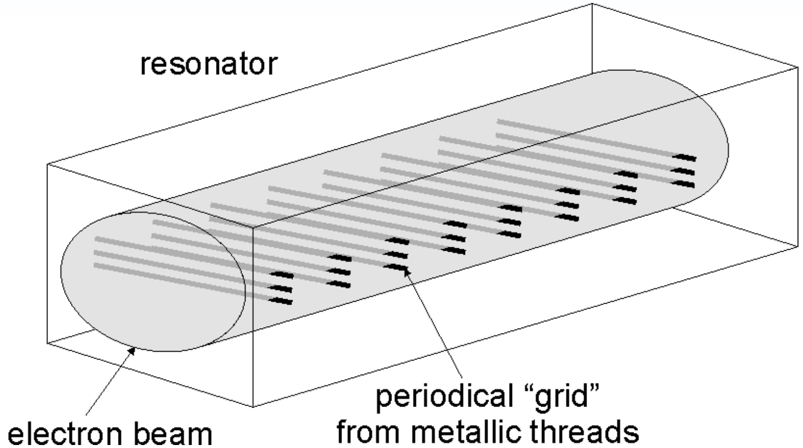
θ is the angle of gratings rotation, β=v/c, v is the electron beam velocity, κ_{mn} describes the eigenfrequencies of resonator (m=n=1) and τ_z is the projection of reciprocal lattice vector on the electron beam velocity direction



two radiation frequencies - frequency splitting similar to complex Doppler effect

Electrodynamical properties of a "grid" photonic crystal *

Theoretical analysis* showed that periodic metal grid does not absorb electromagnetic radiation and the "grid" photonic crystal, made of metal threads, is almost transparent for the electro-magnetic waves in the frequency range from GHz to THz.



* **Baryshevsky V.G., Gurinovich A.A.** Spontaneous and induced parametric and Smith–Purcell radiation from electrons moving in a photonic crystal built from the metallic threads // Nucl. Instr. Meth. B. Vol.252. (2006) P. 92-101, physics/0409107

Refraction index

Analysis based on the multi-wave diffraction theory in periodical structures allowed us to find refraction indices for a “grid” photonic crystal built from metallic threads and to demonstrate that in contrast to a solid metal an electromagnetic wave falling on the described "grid" volume structure is not absorbed on the skin depth, but passes through the "grid" damping in accordance its polarization

$$n_{||} \neq n_{\perp}$$

the system own optical anysotropy (it possesses birefringence and dichroism)

Baryshevsky V.G., Gurinovich A.A. Spontaneous and induced parametric and Smith–Purcell radiation from electrons moving in a photonic crystal built from the metallic threads // Nucl. Instr. Meth. B. Vol.252. (2006) P. 92-101, physics/0409107

V.G.Baryshevsky, A.A. Gurinovich. THz and MMW Sources using "Grid" Photonic Crystals. // IRMMW-THz2007 Conference digest (Cardiff, UK, 3-7 September 2007). – 2007. – P. MonP5-54.

Theory of VFEL lasing

To describe VFEL lasing Maxwell equations, motion equations for a particle in an electromagnetic field and method of diffraction theory are used

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

here $\vec{E}$ and $\vec{H}$ are the electric and magnetic fields, $\vec{j}$ and ρ are the current and charge densities, the electromagnetic induction $D_i(\vec{r},t') = \int \varepsilon_{il}(\vec{r},t-t')E_l(\vec{r},t')dt'$ and, therefore, $D_i(\vec{r},\omega) = \varepsilon_{il}(\vec{r},\omega)E_l(\vec{r},\omega)$, the indices $i,l = 1,2,3$ correspond to the axes x,y,z, respectively. The current and charge densities are respectively defined as:

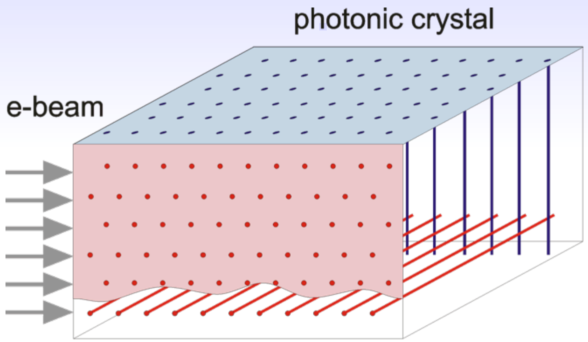
$$\vec{j}(\vec{r},t) = e\sum_{\alpha}\vec{v}_{\alpha}(t)\delta(\vec{r}-\vec{r}_{\alpha}(t)), \ \rho(\vec{r},t) = e\sum_{\alpha}\delta(\vec{r}-\vec{r}_{\alpha}(t)),$$

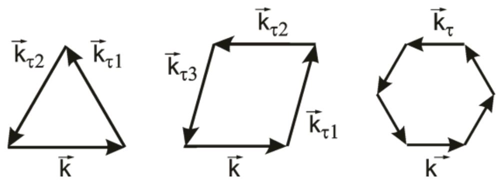
where e is the electron charge, $\vec{v}_{\alpha}$ is the velocity of the particle α (α numerates the beam particles),

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

here $\gamma_{\alpha} = (1-\frac{v_{\alpha}^2}{c^2})^{-\frac{1}{2}}$ is the Lorentz-factor, $\vec{E}(\vec{r}_{\alpha},t)$ and $\vec{H}(\vec{r}_{\alpha},t)$ are the electric and magnetic field in the point of location $\vec{r}_{\alpha} = \vec{r}_{\alpha}(t)$ of the particle α.

The method





Applying the method of slow-varying amplitudes the solution of Maxwell equations, which describe diffraction of **s** electromagnetic waves by a diffraction grating in 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 to the exact system of equations and collecting the quick-oscillating terms we obtain the system of (s+1) equations for waves A_m

Two-wave diffraction

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

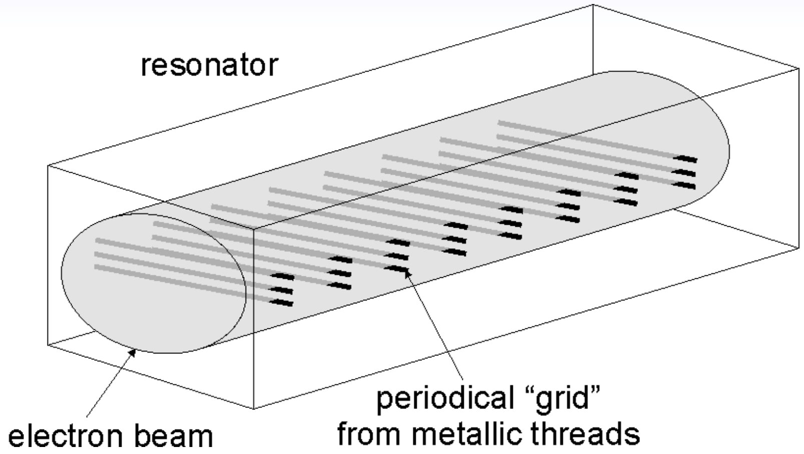
J_1, J_2 are the currents, $A_1 \equiv A_{\tau=0},\ A_2 \equiv A_\tau,\ \vec{k}_1 = \vec{k}_{\tau=0},\ \vec{k}_2 = \vec{k}_1 + \vec{\tau}.$

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 resonator

Detailed numerical analysis of these equations in linear and nonlinear regimes was made by Batrakov and Sytova [*K.G. Batrakov, S.N. Sytova. Nonlinear analysis of quasi-Cherenkov electron beam instability in VFEL (Volume Free Electron Laser). Nonlinear Phenomena in Complex Systems, 42-48 (2005)*]

Thread heating evaluation

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



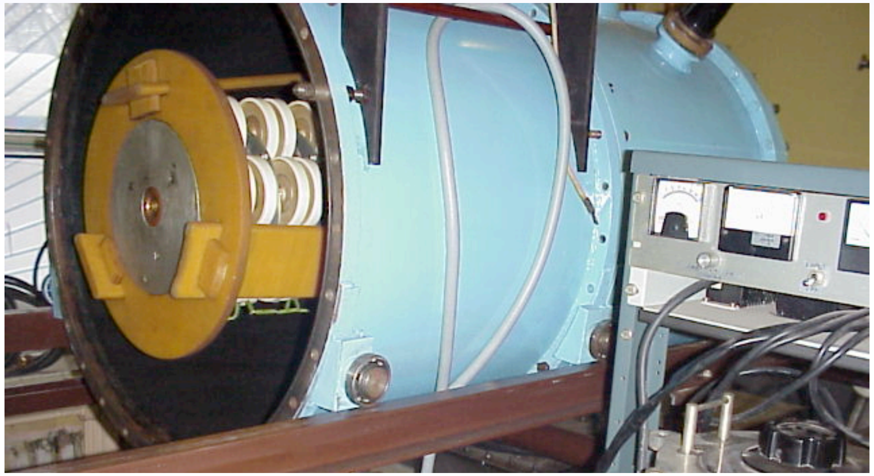
- $6 \cdot 10^{14}$ electrons in the beam
- $2 \cdot 10^{12}$ electrons passes through a thread
- 0.08 Joule transferred to the thread

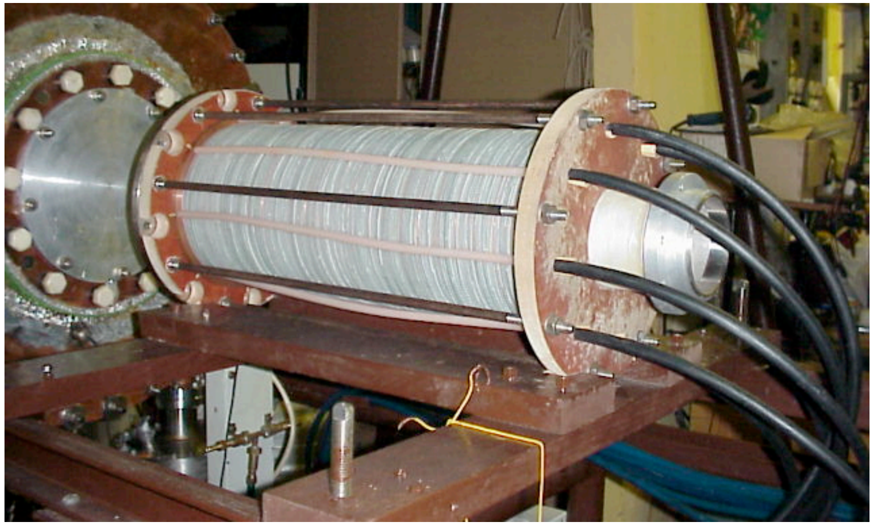
if suppose that all electrons passing through the thread lose the whole energy for thread heating

$$\Delta T < 125°$$

Volume Free Electron Laser at Research Institute for Nuclear Problems

electron beam energy 50-500 keV





Experiments with “grid” VFEL

electron beam with $\beta_{||}=v_{||}/c=0.5$ (energy ≈80 keV)

electron beam current participating in lasing process ≈ 10A

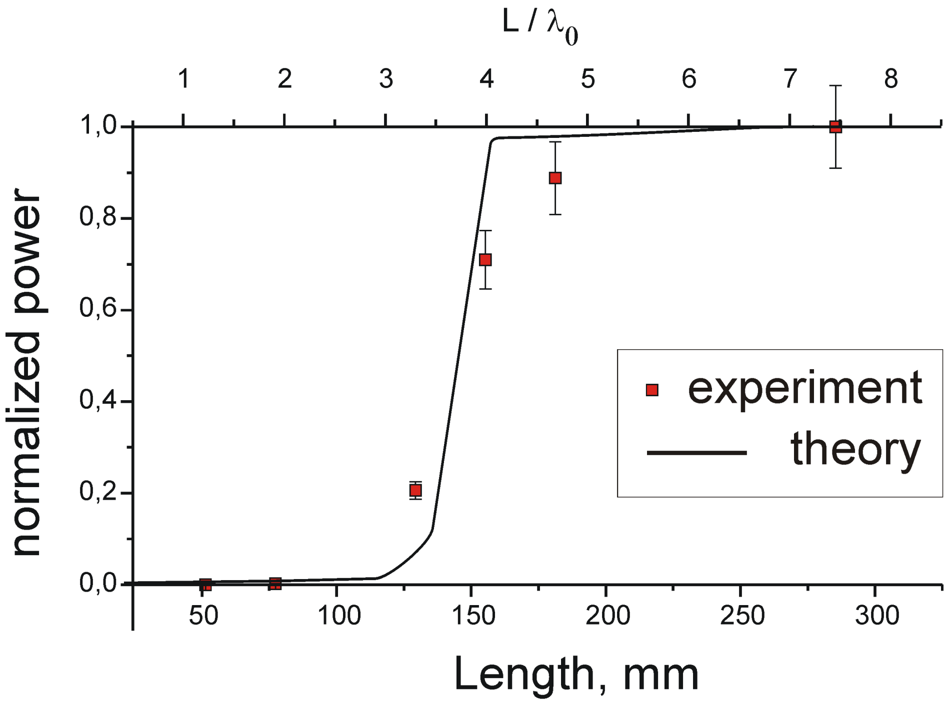
pencil-like electron beam with the diameter 32 mm

magnetic field guiding the electron beam ≈1.5 tesla.

radiation frequency ≈ 10 GHz.

BWO regime – detected power 10 kW

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). Frames are joined to get the "grid" structure.



Dependence of radiation power on resonator length

“Grid” VFEL with constant period

filtered microwave power signal

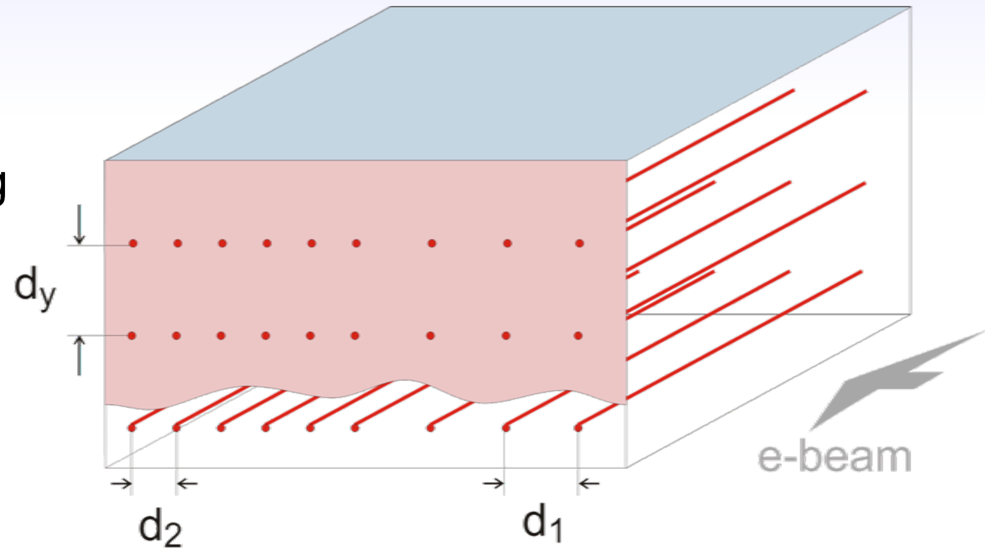
electron gun voltage

electron beam current

microwave power signal

“Grid” VFEL with variable period: set-up

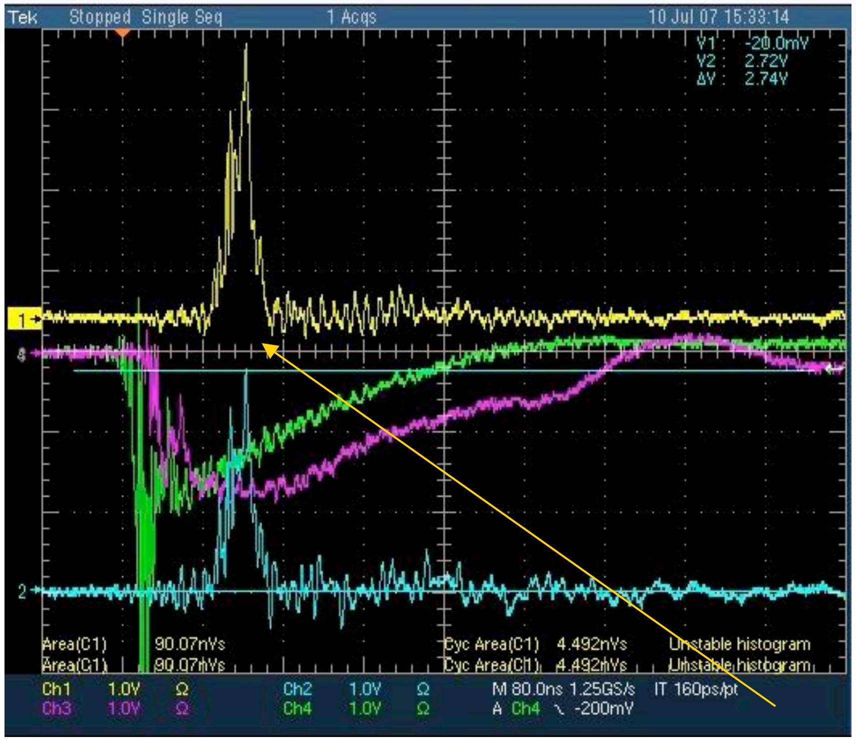
- electron beam with $\beta_{\|}=v_{\|}/c=0.5$ (energy ≈80 keV)
- pencil-like electron beam with the diameter 32 mm
- electron beam current participating in lasing process ≈ 10A
- radiation frequency ≈10 GHz.
- BWO regime
- resonator with two ‘’grid’’ photonic crystals



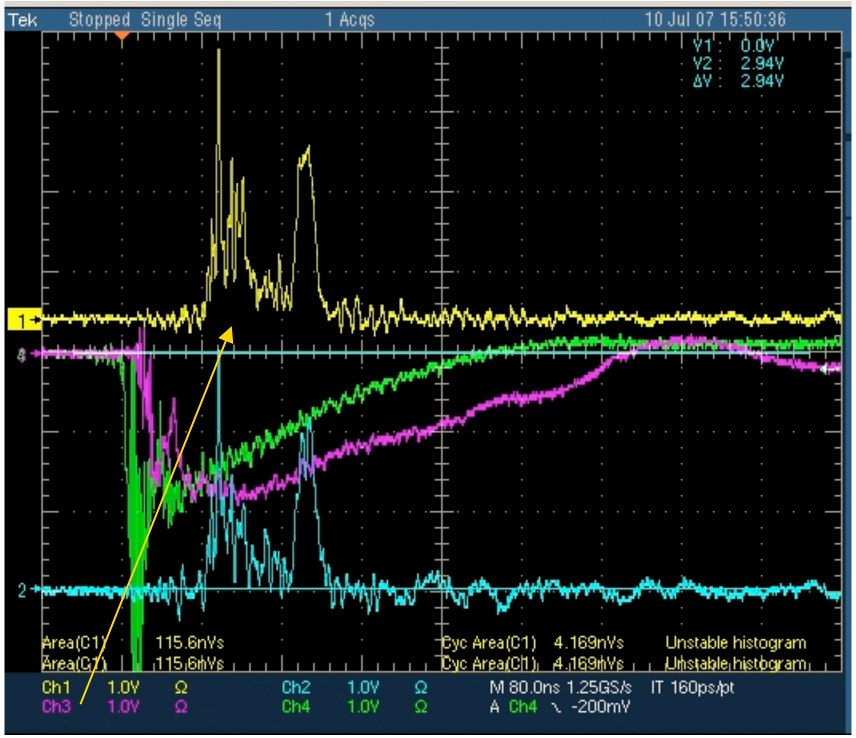
The "grid" structure is made of separate frames each containing the layer of 5 parallel threads with the distance between the next threads d_y=6 mm), 12 frames were joined to get the "grid“ photonic crystal with the period 12.5 mm and another 12 frames formed "grid“ photonic crystal with the period 10.5 mm .
Period of the second photonic crystal was chosen to provide for the electron beam, which have lost part of its energy for radiation in the first photonic crystal, the same radiation frequency.

“Grid” VFEL with variable period: experiment

resonator with one ‘’grid’’ photonic crystal



resonator with two ‘’grid’’ photonic crystals with different periods



filtered microwave power signal

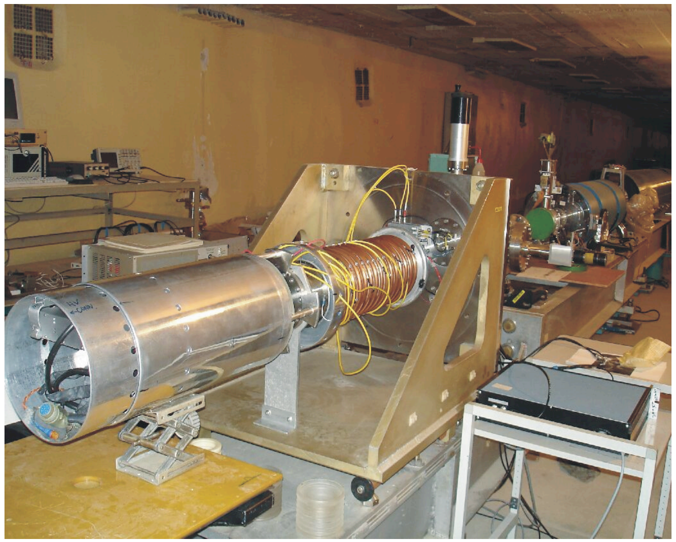
Experiment results confirmed conclusion that photonic crystal with variable period could increase radiation output.

Experiments under preparation

Several experiments with Volume Free Electron Laser with the “grid” photonic crystals in millimeter and sub-millimeter wavelength ranges are in preparation now.

At Research Institute for Nuclear Problems (INP) in the experiments with 50-200 keV elecron beam

• radiation in the range 4-5 mm is expected to be observed for the ”grid” photonic crystal, built from periodically strained tungsten threads in the waveguide.
• double-cascaded Volume FEL with variable parameters
• Volume FEL with dynamical wiggler with spatially varied period



Joint experiment is being prepared by INP and Joint Institute for Nuclear Research (JINR, Dubna) at LINAC-800 (electron beam energy 6 MeV)

In 2008 the grid photonic crystal will be used for generation of radiation with l= 2 mm (150 GHz) and l= 0.3 mm (1 THz)

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 Volume Free Electron Laser is very promising for development of radiation sources in centimeter, millimeter, sub-millimeter and optical wavelength ranges. Use of volume resonators of the described types provides to weaken requirements for the electron beam shape and guiding precision. 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 sources.