High Power Microwave sources on the basis of Volume Free Electron Laser:

BASIC RESEARCH and TECHNOLOGY

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BSU

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- Lasers: conventional and FELs
- What is Volume Free Electron Laser (VFEL)?
- VFEL history
- Recent results
- Nearest plans
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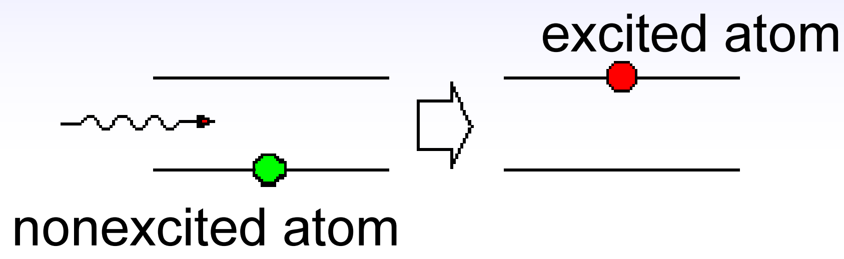
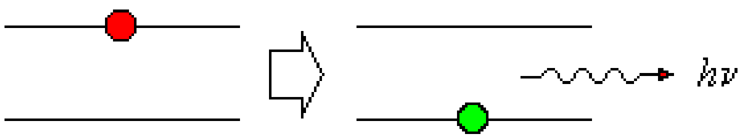
Lasers: principles of operation

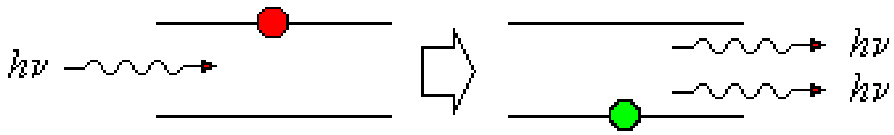
Energy is absorbed by media, which stores it as the energy of exited atoms and molecules



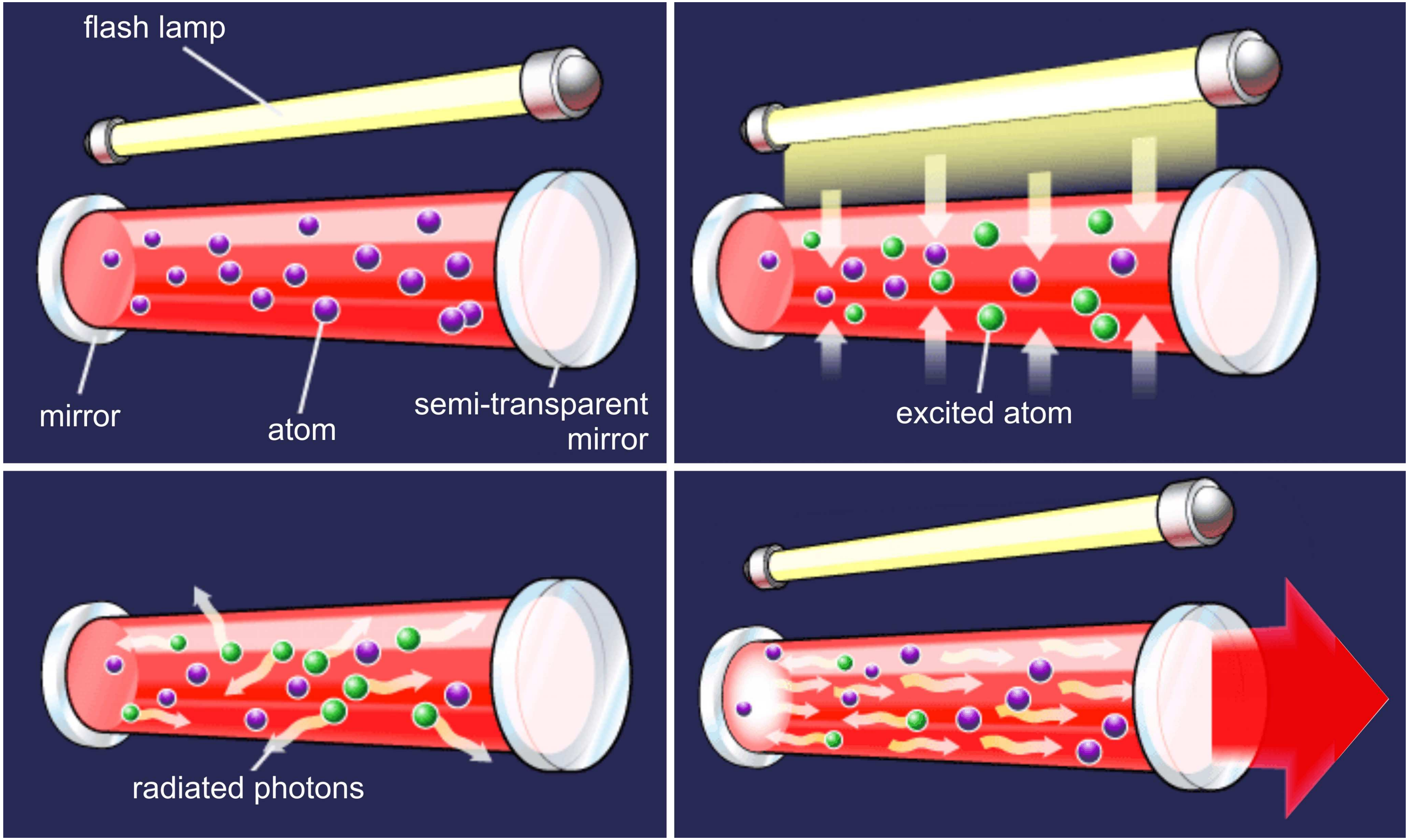


Transition of molecule, atom or ion from the exited sate to lower state can be spontaneous

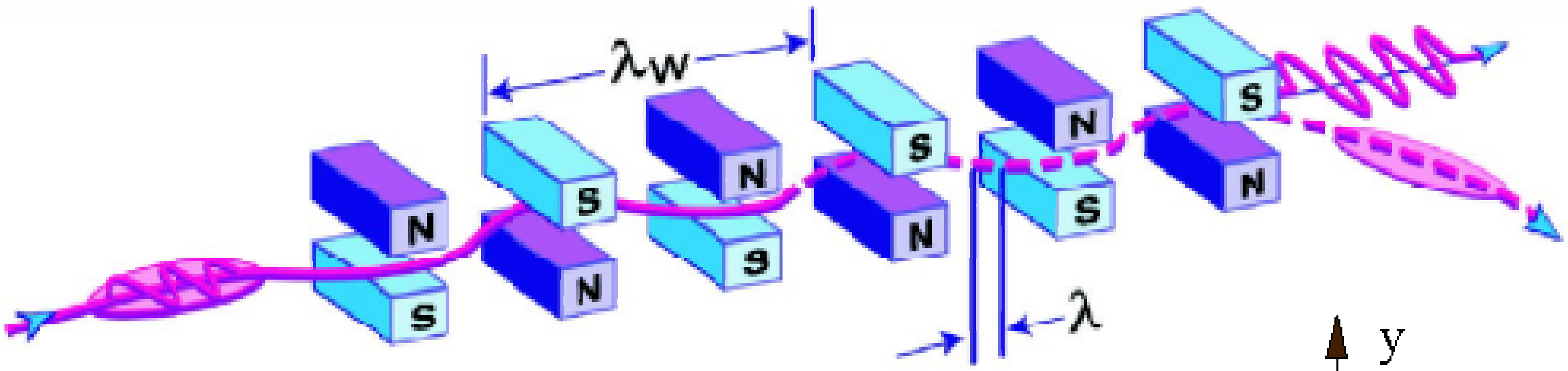
or stimulated by external electro-magnetic radiation with the frequency of spontaneously radiated quantum



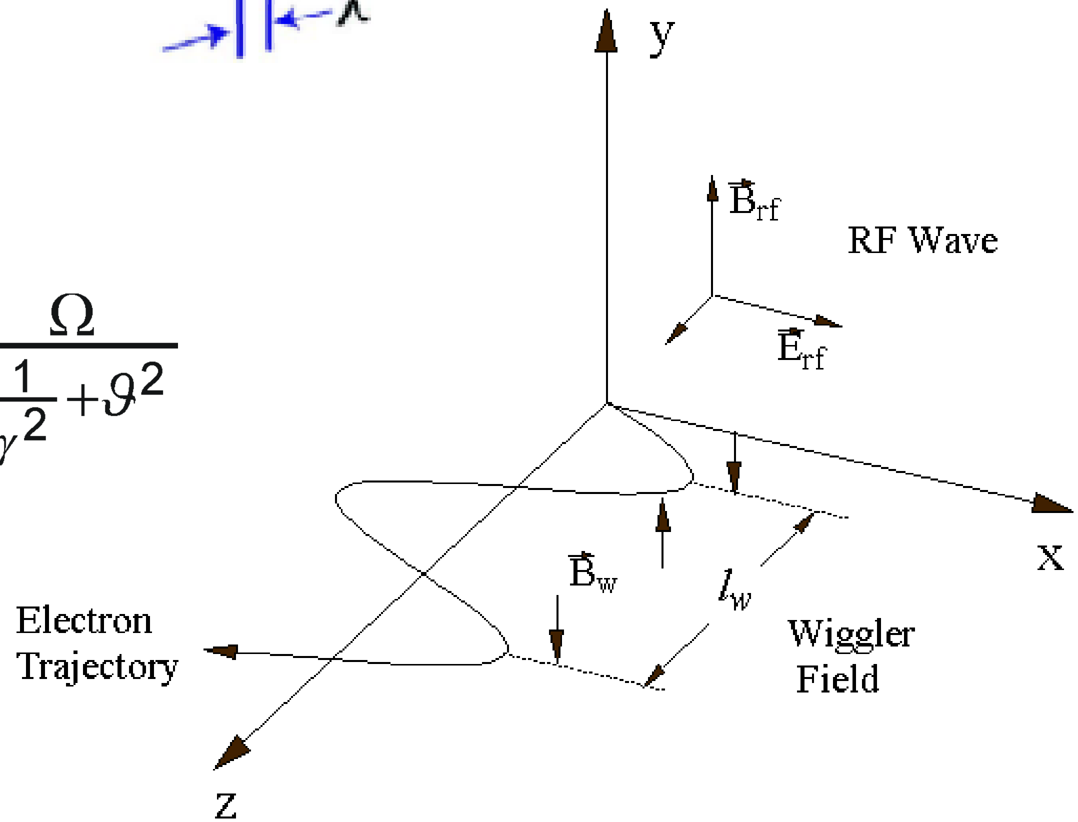
Ruby laser


flash lamp
mirror
atom
semi-transparent mirror
excited atom
radiated photons

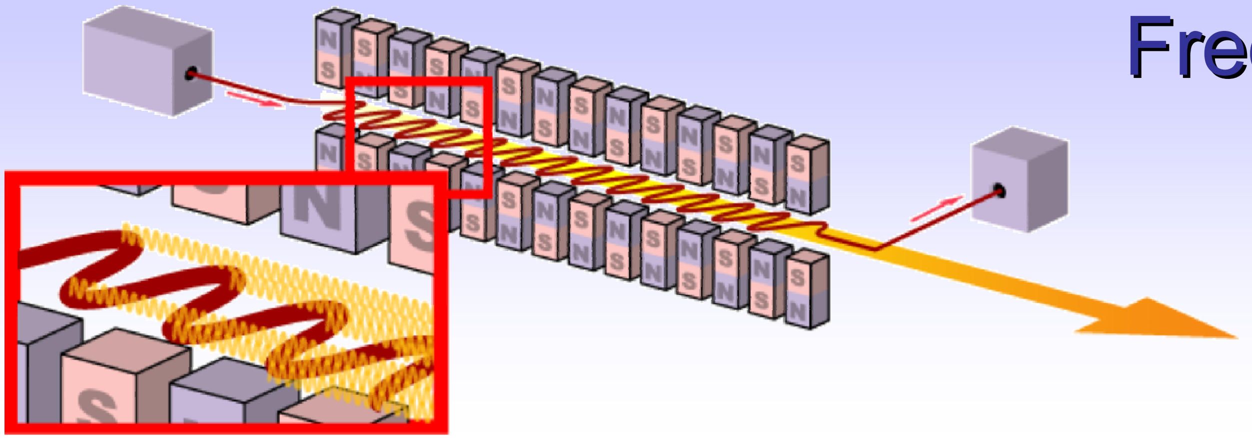
Electron in magnetic field as a light moving atom



$$\omega = \frac{\Omega}{1-\beta\cos\vartheta} \approx \frac{\Omega}{\frac{1}{\gamma^2}+\vartheta^2}$$

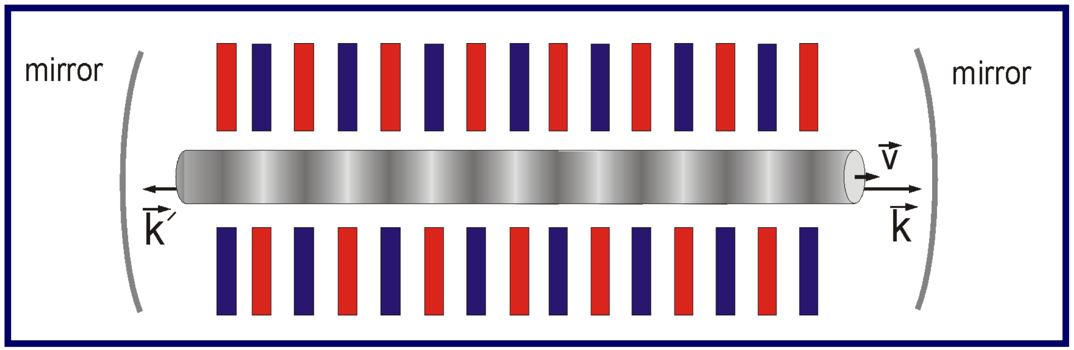


Free Electron Laser

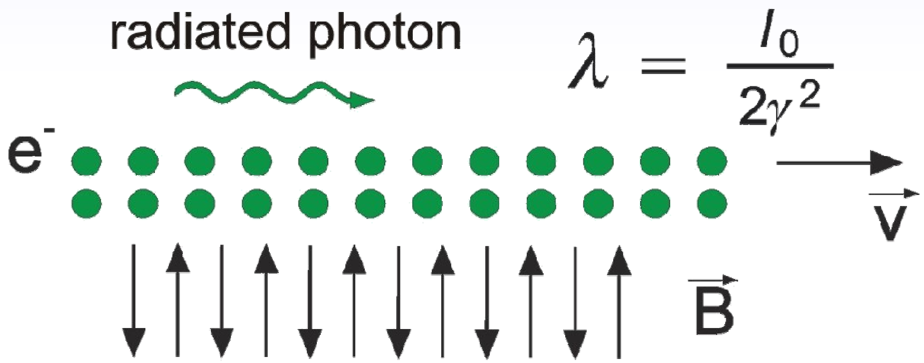


FEL lasing is aroused by different types of spontaneous radiation: magnetic bremsstrahlung in undulator, Smith-Purcell or Cherenkov radiation and so on. But regardless of type of spontaneous radiation applied for certain FEL lasing, all FEL-like devices use feedback, which is formed either by two parallel mirrors placed on the both sides of working area or by one-dimensional diffraction grating, in which incident and diffracted (reflected) waves move along electron beam (one-dimensional distributed feedback).

Feedback is provided by mirrors that capture the released photons to generate resonant gain



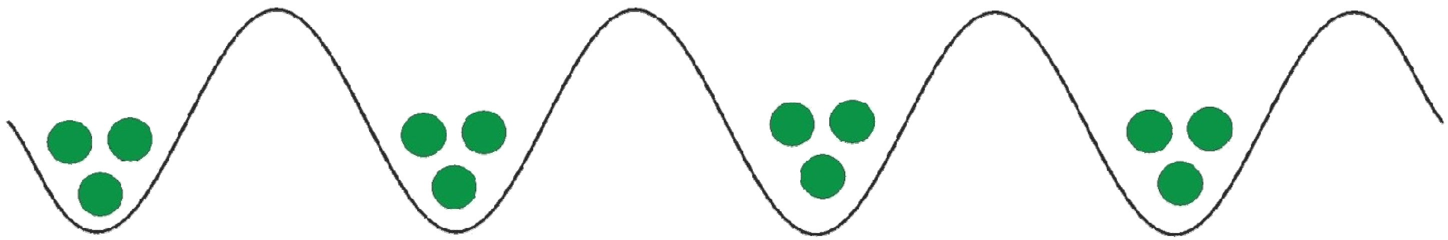
FEL operation principles



$$\lambda = \frac{l_0}{2\gamma^2}$$

$$\omega = \frac{\Omega}{1 - \beta\cos\vartheta} \approx \frac{\Omega}{\frac{1}{\gamma^2} + \vartheta^2}$$

for undulator period l_0=3 cm and γ~10^4 radiation wavelenght λ~10^{-8} cm

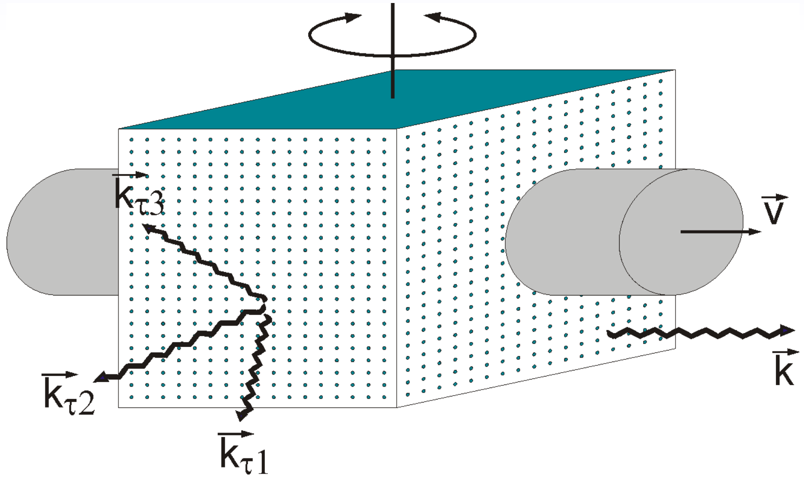


$$I \sim \left|\sum_i e^{i\vec{k}\vec{r}_i}\right|^2 = N + \sum_{i \neq j} e^{i\vec{k}(\vec{r}_i - \vec{r}_j)}$$

$$I_{сп} \sim N\,,$$

$$I_{вын} \sim N \cdot I_{сп} \sim N^2$$

Spontaneous parametric radiation



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

V.G. Baryshevsky: Doklady Akademy of Science Belarus 15, 306 (1971)
V.G.Baryshevsky, I.D.Feranchuk: Zh. Exper. Teor. Fiz. 61, 944 (1971) [Sov.Phys. JETP 34, 502 (1972)]

Parametric X-ray radiation was observed for electron and proton beams in crystals

Y.N. Adishchev, V.G. Baryshevsky, S.A. Vorobiev et al.: Sov.Phys.JETP.Lett. 41 (1985) 361
V.P. Afanasenko, V.G. Baryshevsky, S.V. Gatsicha, et.al.: Sov. JETP Lett. 51 (1990) 213

Detailed analysis of induced PXR demonstrated unique possibilities provided by the volume distributed feedback

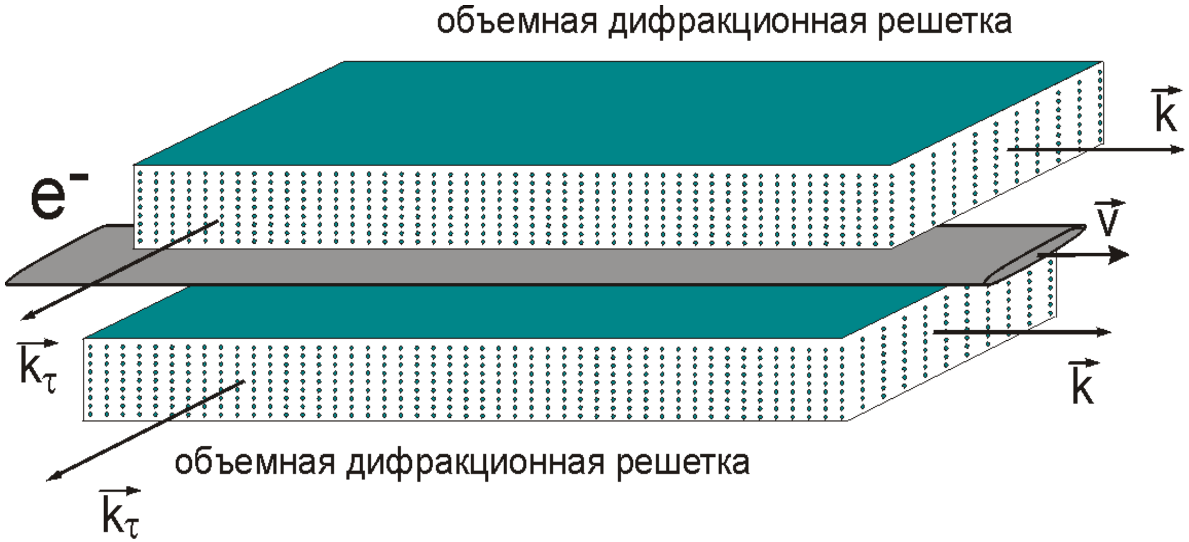
V.Baryshevsky, I.Feranchuk Phys. Lett. 102 A, 141 (1984)

V.G. Baryshevsky, I.D. Feranchuk, A.P. Ulyanenkov “Parametric X-Ray Radiation in Crystals: Theory, Experiment and Applications”, Springer Tracts in Modern Physics (2006)

Vacuum parametric radiation

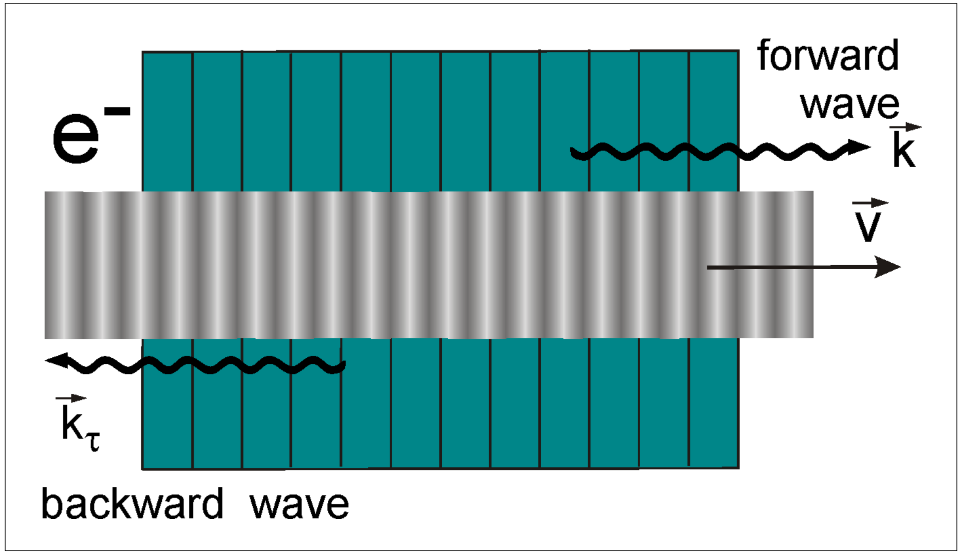
The next important step – all the conclusions are valid for a beam moving in vacuum close to the periodic medium

V.G. Baryshevsky: Doklady Akademy of Science USSR 299 (1988) 6

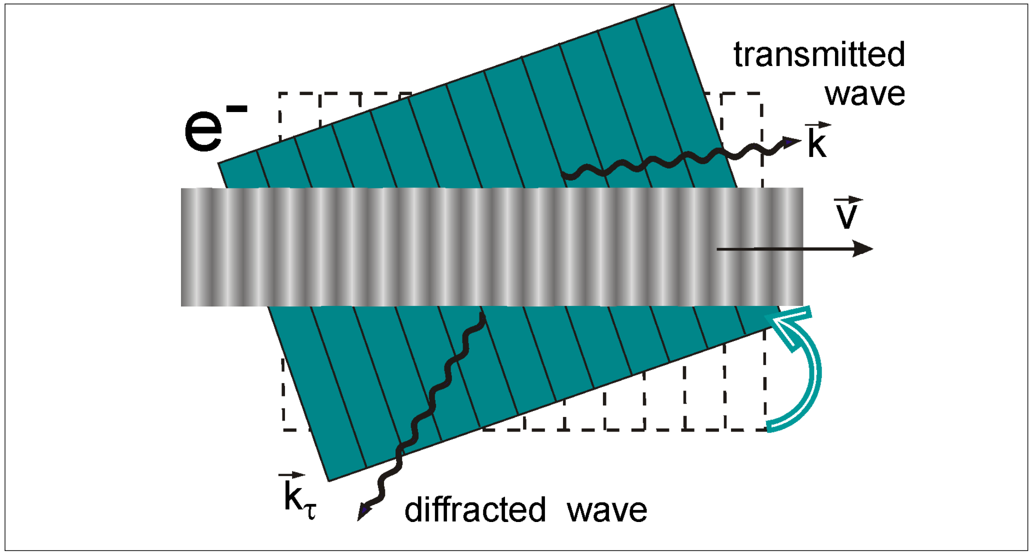


What is volume distributed feedback ?

one-dimensional distributed feedback



two-dimensional distributed feedback



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

Benefits provided by volume distributed feedback

The new law of instability for an electron beam passing through a spatially-periodic medium provides the increment of instability in degeneration points proportional to $\rho^{1/(3+s)}$, here **s** is the number of surplus waves appearing due to diffraction. This increment differs from the conventional increment for single-wave system (TWTA and FEL), which is proportional to $\rho^{1/3}$.

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

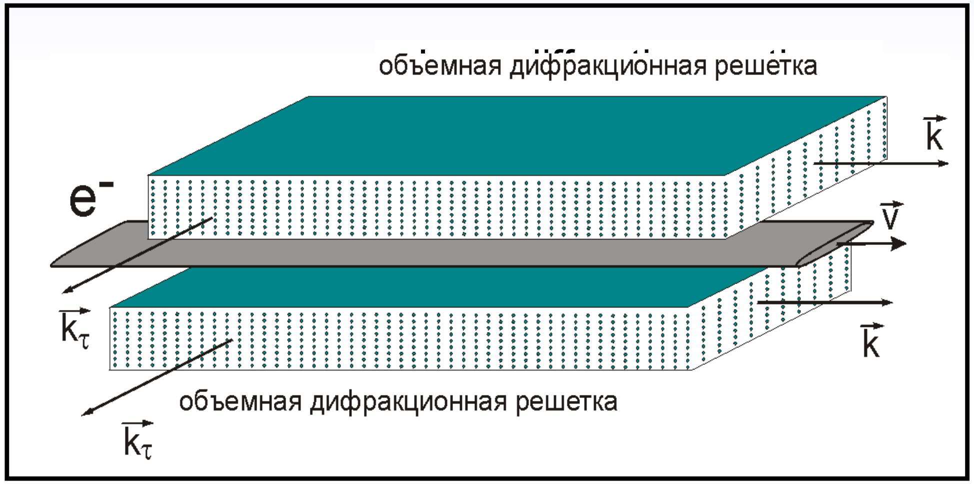
This new law provides for noticeable reduction of electron beam current density (10^8 A/cm^2 for LiH crystal against 10^{13} A/cm^2 required in G.Kurizki, M.Strauss, I.Oreg, N.Rostoker, Phys.Rev. A35 (1987) 3427) necessary for running up to the generation threshold and even makes possible to reach generation threshold for the induced parametric X-ray radiation in crystals i.e. to create X-ray laser

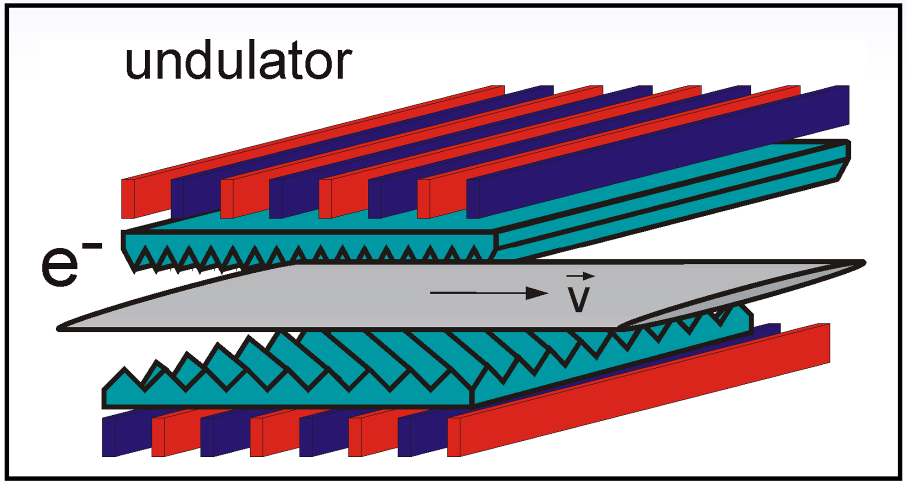
$$j_{start} \sim 1 \Big/ \left[(kL)^3 (k\chi_\tau L)^{2s} \right]$$

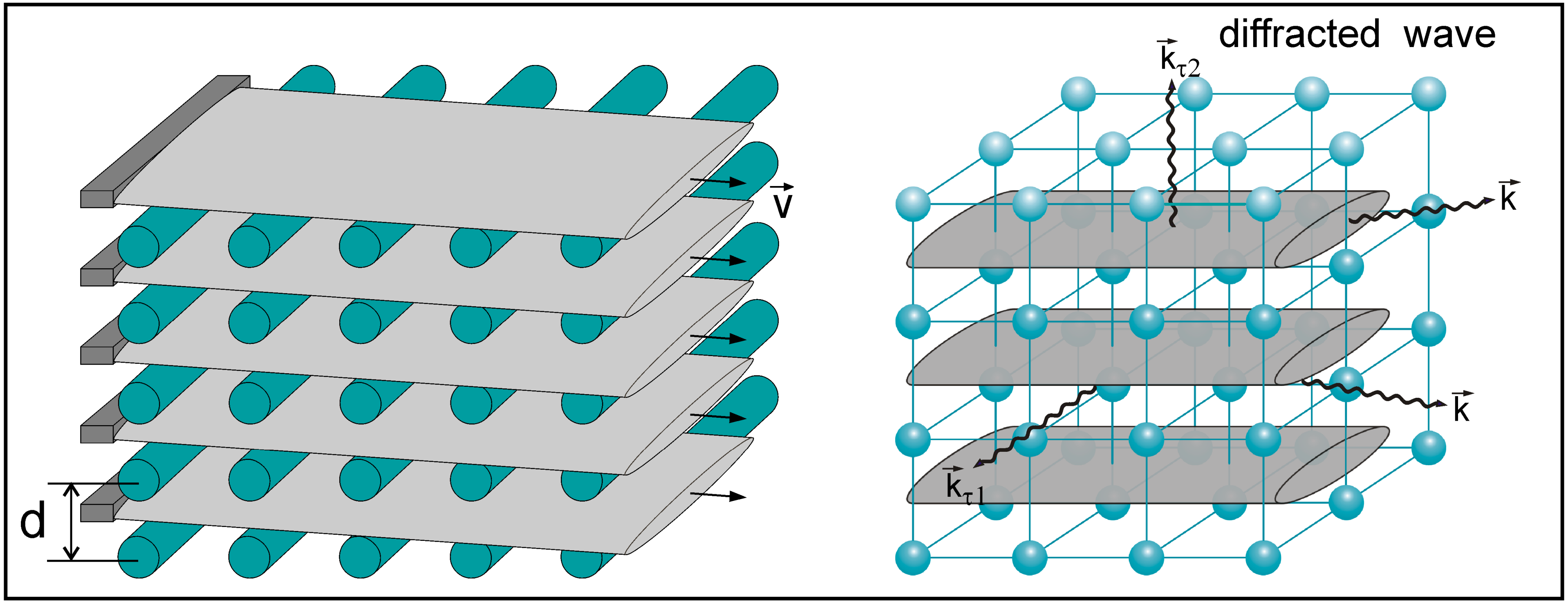
V.G.Baryshevsky, K.G.Batrakov, I.Ya. Dubovskaya, *Journ.Phys D24 (1991) 1250*

The originated law is universal and valid for all wavelength ranges regardless the spontaneous radiation mechanism

What is Volume Free Electron Laser ? *







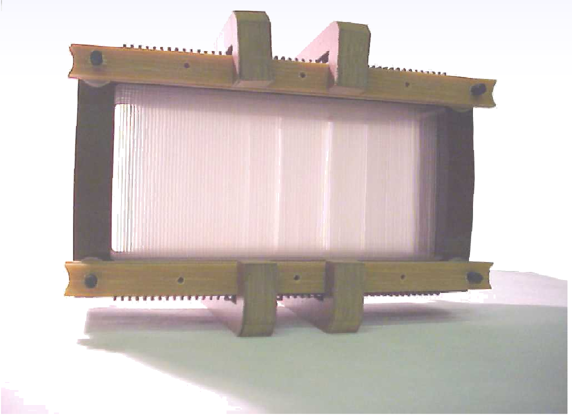
* Eurasian Patent no. 004665

Use of volume distributed feedback makes available:

- ✓ frequency tuning at fixed energy of electron beam in significantly wider range than conventional systems can provide
- ✓ 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
- ✓ simultaneous generation at several frequencies

VFEL experimental history

1996



Experimental modeling of electrodynamic processes in the volume diffraction grating (photonic crystal) made from dielectric threads

V.G.Baryshevsky, K.G.Batrakov, I.Ya. Dubovskaya, V.A.Karpovich, V.M.Rodionova, *NIM 393A (1997) 71*

2001

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

V.G.Baryshevsky, K.G.Batrakov,A.A.Gurinovich, I.I.Ilienko, A.S.Lobko, V.I.Moroz, P.F.Sofronov, V.I.Stolyarsky, *NIM 483 A (2002) 21*

2004

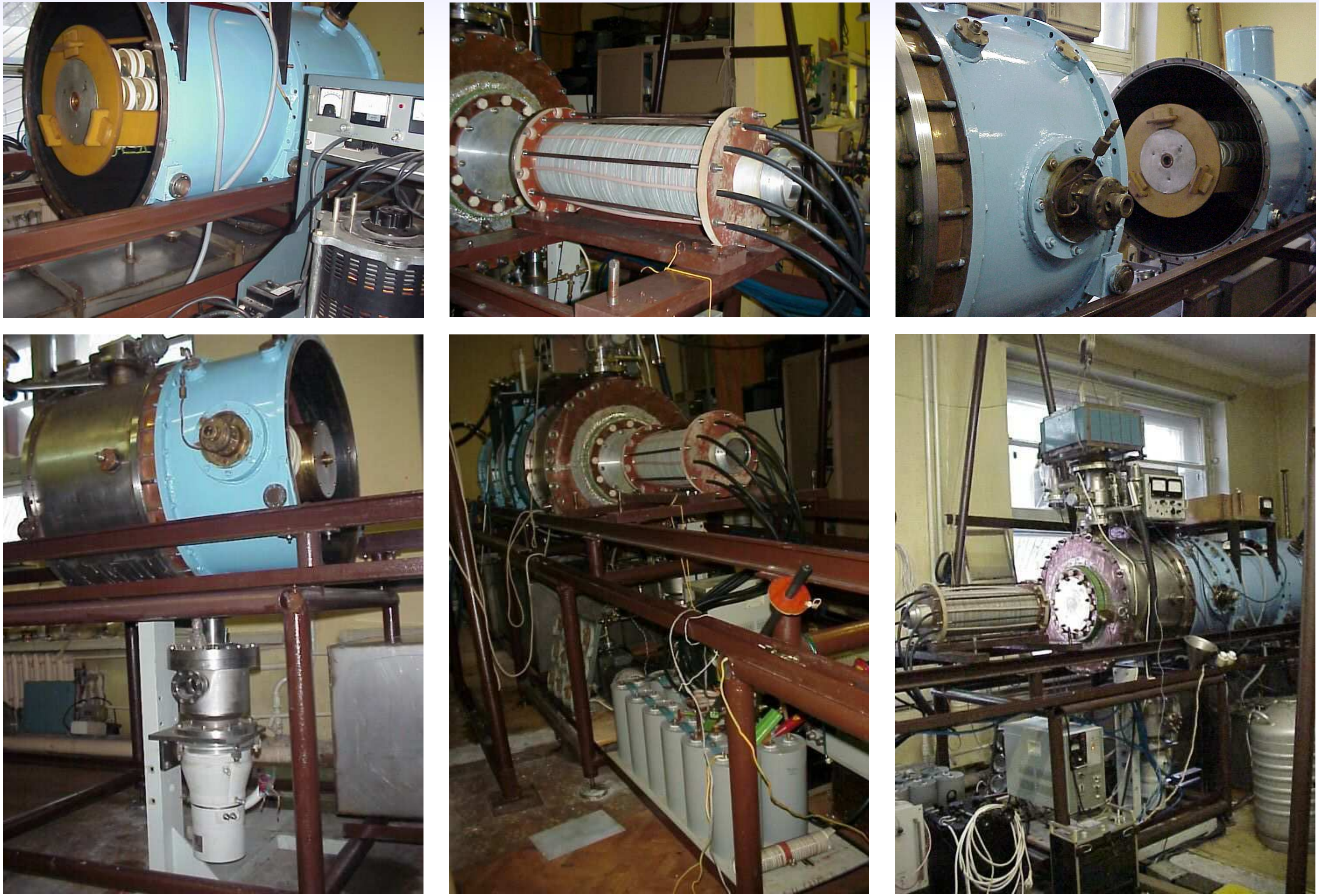
New VFEL prototype with volume photonic crystal as resonator

VFEL generator at Research Institute for Nuclear Problems

Main features:

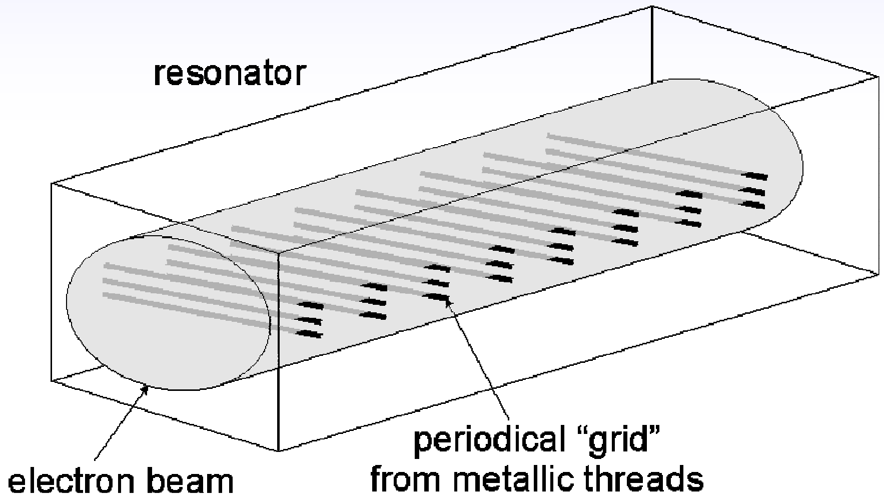
- “grid” photonic crystal as resonator
- electron beam of large cross-section
- electron beam energy 180-250 keV

Volume Free Electron Laser at Research Institute for Nuclear Problems



Electrodynamical properties of a "grid" photonic crystal *

Electrodynamical properties of a volume resonator that is formed by a perodic structure built from the metallic threads inside a rectangular waveguide are considered.



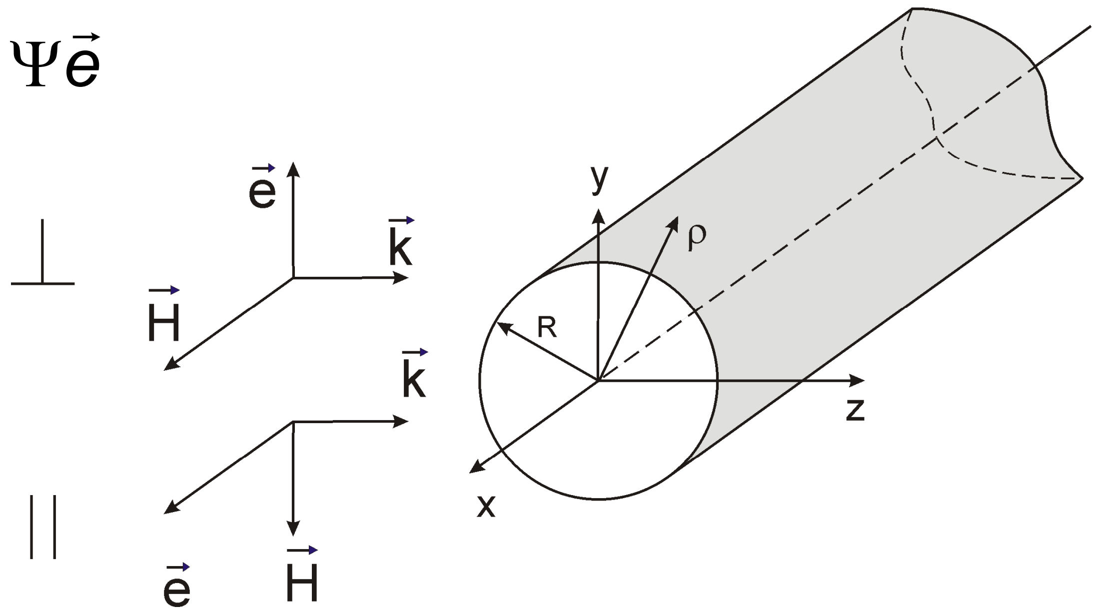
Peculiarities of passing of electromagnetic waves with different polarizations through such volume resonator are discussed. If in the periodic structure built from the metallic threads diffraction conditions are available, then in this system the effect of anomalous transmission for electromagnetic waves could appear similarly to the Bormann effect well-known in the dynamical diffraction theory of X-rays.

* **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

Electrodynamical properties of a thread

a plane electromagnetic wave $\vec{E} = \Psi \vec{e}$

suppose this wave
falls onto the cylinder placed
into the origin of coordinates
and the cylinder axis
coincides with the axis x



Two polarization states should be considered, for clarity suppose $\vec{e} \parallel 0x$

The scattered wave

$$\Psi = e^{ikz} + a_0 H_0^{(1)}(k\rho)$$

$\rho=(y,z)$, $H_0^{(1)}$ is the Hankel function

Scattering by a set of threads

a set of threads with $\rho_n=(y_n,z_n)$

$$\Psi = e^{ikz} + a_0 \Sigma_n H_0^{(1)}(k\,|\overrightarrow{\rho} - \overrightarrow{\rho}_n|) e^{ikz_n} = e^{ikz} + A_0 \Sigma_n \int\limits_{-\infty}^{\infty} \frac{e^{ik\sqrt{|\overrightarrow{\rho} - \overrightarrow{\rho}_n|^2 - x^2}}}{\sqrt{|\overrightarrow{\rho} - \overrightarrow{\rho}_n|^2 - x^2}} dx e^{ikz_n}$$

$$A_0 = -\frac{ia_0}{\pi},\ |\overrightarrow{\rho} - \overrightarrow{\rho}_n|^2 = (y - y_n)^2 + (z - z_n)^2$$

Threads are distributed in the plane x0y on the distance d_y - summation over the coordinates y_n provides for Ψ:

$$\Psi = e^{ikz} + \frac{2\pi i A_0}{kd_y} e^{ikz}$$

after passing m planes standing out of each other in the distance d_z - summation over the coordinates z_n

$$\Psi = \left(\sqrt{\left(1 - \frac{2\pi\ ImA_0}{k\ d_y}\right)^2 + \left(\frac{2\pi\ ReA_0}{k\ d_y}\right)^2}\right)^m e^{ikz} e^{i\varphi m},\ \varphi = arctg\left(\frac{\frac{2\pi\ ReA_0}{k\ d_y}}{1 - \frac{2\pi\ ImA_0}{k\ d_y}}\right)$$

The amplitudes

Radiation frequencies of our interest is $\nu \geq 10$ GHz. In this frequency range the skin depth δ is about 1 micron for the most of metals (for example, δ_{Cu}=0.66 μm, δ_{Al}=0.8 μm, δ_{W}=1.16 μm). Thus, in this frequency range the metallic thread can be considered as perfect conducting. From the analysis [*Nikolsky V.V., Electrodynamics and propagation of radio-wave (Nauka, 1978)*] the amplitudes A_0 for the perfect conducting cylinder:

for polarization of the electromagnetic wave parallel to the cylinder axis

$$A_{0(\|)} = \frac{1}{\pi}\frac{J_0(kR)\,N_0(kR)}{J_0^2(kR)+N_0^2(kR)} + i\frac{1}{\pi}\frac{J_0^2(kR)}{J_0^2(kR)+N_0^2(kR)}$$

for polarization of the electromagnetic wave perpendicular to the cylinder axis

$$A_{0(\perp)} = \frac{1}{\pi}\frac{J_0'(kR)\,N_0'(kR)}{J_0'^2(kR)+N_0'^2(kR)} + i\frac{1}{\pi}\frac{J_0'^2(kR)}{J_0'^2(kR)+N_0'^2(kR)}$$

R is the thread radius, J_0, N_0, J_0', N_0' are the Bessel and Neumann functions and their derivatives

radiation frequency ν=10 GHz the thread radius R=0.1 mm

$A_{0(\|)}=-0.1087 + i \cdot 0.0429$; $A_{0(\perp)}=-0.00011 + i \cdot 3.78 \cdot 10^{-8}$

The refraction index for a set of threads

Wavefunction can be expressed as $\Psi = e^{iknz}$, n is the refraction index

$$n = \left(1 + \frac{\lambda}{2\pi d_z} Arctg\left(\frac{\frac{\lambda}{d_y} ReA_0}{1 - \frac{\lambda}{d_y} ImA_0}\right)\right) - i\frac{\lambda}{2\pi d_z}\ln\left(\sqrt{\left(\frac{\lambda}{d_y} ReA_0\right)^2 + \left(1 - \frac{\lambda}{d_y} ImA_0\right)^2}\right)$$

If ReA_0, ImA_0 <<1

$$n = 1 + \frac{2\pi}{d_y d_z k^2} A_0$$

radiation frequency ν=10 GHz

the thread radius R=0.1 mm

$n_{||}$=0.8984 + i · 0.043

$n_{\perp}$=0.9998 - i · 3.37 · 10^{-8}

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)

Rescattering of the wave by different threads

the above consideration provides only summation of scattering events, but does not include rescattering: taking it to the account provides for amend in the refraction index

The values $ReA_{0(||)}$ and $ImA_{0(||)}$ are quite large and for polarization parallel to the thread axis the exact expressions for n should be used. Moreover, in all calculations we should carefully check whether the condition $|n-1| \ll 1$ is fullfilled. If no, then we should use more strict description of volume structure and consider rescattering of the wave by different threads.

$$\Psi(\rho) = e^{ikz} + \Sigma_m F_m H_0^{(1)}(k|\overrightarrow{\rho} - \overrightarrow{\rho}_m|),$$

$$F_m = a_0 e^{ikz_m} + a_0 \Sigma_{n\neq m} F_n H_0^{(1)}(k|\overrightarrow{\rho} - \overrightarrow{\rho}_n|)$$

where F_m is the effective scattering amplitude

The long-wave case kd << 1

$$F_m(\rho) = a_0 \left\{ e^{ikz} + \frac{1}{\Omega_2} \int\limits_V F_m(\rho') H_0^{(1)}(k \left| \overrightarrow{\rho} - \overrightarrow{\rho}' \right|) d^2\rho' \right\}$$

$$(\Delta + k^2)\Psi(\rho) = \frac{4iB}{\Omega_2}\Psi(\rho) \quad \Rightarrow \quad q^2 = k^2 + \frac{4\pi A_0 b_0}{\Omega_2}$$

$$b_0 = \frac{1}{1+\frac{a_0}{\Omega_2}\int_{\Delta V} H_0^{(1)}(k\left|\overrightarrow{\rho} - \overrightarrow{\rho}'\right|)d^2\rho'} = \frac{1}{1+a_0(1+i\frac{2}{\pi}C)+i\frac{2}{\pi}\ln\frac{kR}{2}}$$

here C=0.5772 is the Eiler constant, $a_0 = i\pi A_0$

the refraction index $n^2 = 1 + \frac{4\pi A_0}{\Omega_2 k^2} \frac{1}{1 + i\pi A_0 - 2CA_0 - 2A_0 \ln\frac{kR}{2}}$

Regular set of threads (photonic crystal)

$$\Psi(\rho) = e^{ikz} + a_0 H_0^{(1)}(k\left|\overrightarrow{\rho} - \overrightarrow{\rho}'\right|)e^{ikz_n}$$ scattering by a thread

The solution in a volume grid $\Psi(\vec{\rho}) = \chi(\vec{\rho})e^{i\vec{k}'\vec{\rho}},\ \vec{\rho} = (y, z)$, $\chi(\vec{\rho}) = \sum_{\tau} c_{\tau} e^{i\vec{\tau}\vec{\rho}},$

The equation for the wavefunction $(\Delta + k^2)\Psi(\vec{\rho}) = 4iF\sum_{m} e^{i\vec{k}'\vec{\rho}}\delta(\overrightarrow{\rho} - \overrightarrow{\rho}_m)$

the refraction index

$$n^2 = 1 + \frac{4\pi A_0}{\Omega_2 k^2}\ \frac{1}{1 + i\pi A_0 - 2CA_0}$$

Evaluation

$n_{\|\|}=0.77923 + i \cdot 0.0$ **$n_{\perp}=0.9998 + i \cdot 0.0$**	Wave rescattering is taken into account

compare

$n_{\|\|}=0.8984 + i \cdot 0.043$ $n_{\perp}=0.9998 - i \cdot 3.37 \cdot 10^{-8}$	Wave rescattering is not taken into account

Rescattering effects significantly change the index of refraction and its imaginary part appears equal to zero.

VFEL lasing in photonic crystal

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

Applying the method of slow-varying amplitudes the solution for this system can be expressed as

$$\vec{E}(\vec{r},t) = \vec{e}_1 A_1(\vec{r},t) e^{i(\vec{k}_1\vec{r}-\omega t)} + \vec{e}_2 A_2(\vec{r},t) e^{i(\vec{k}_2\vec{r}-\omega t)}, \ \vec{k}_2 = \vec{k}_1 + \vec{\tau}.$$

Substituting this expression to the exact system of equations and collecting the quick-oscillating terms we obtain the system

$$\begin{aligned}
&2i\vec{k}_1\vec{\nabla}A_1(\vec{r},t) - k_1^2 A_1(\vec{r},t) + \tfrac{\omega^2}{c^2}\varepsilon^0(\omega)A_1(\vec{r},t) + \boxed{i\tfrac{1}{c^2}\tfrac{\partial\omega^2\varepsilon^0(\omega)}{\partial\omega}\tfrac{\partial A_1(\vec{r},t)}{\partial t}} + \\
&+\tfrac{\omega^2}{c^2}\varepsilon^{-\tau}(\omega)A_2(\vec{r},t) + \boxed{i\tfrac{1}{c^2}\tfrac{\partial\omega^2\varepsilon^{-\tau}(\omega)}{\partial\omega}\tfrac{\partial A_2(\vec{r},t)}{\partial t}} = J_1, \\
&2i\vec{k}_2\vec{\nabla}A_2(\vec{r},t) - k_2^2 A_2(\vec{r},t) + \tfrac{\omega^2}{c^2}\varepsilon^0(\omega)A_2(\vec{r},t) + \boxed{i\tfrac{1}{c^2}\tfrac{\partial\omega^2\varepsilon^0(\omega)}{\partial\omega}\tfrac{\partial A_2(\vec{r},t)}{\partial t}} + \\
&+\tfrac{\omega^2}{c^2}\varepsilon^{\tau}(\omega)A_1(\vec{r},t) + \boxed{i\tfrac{1}{c^2}\tfrac{\partial\omega^2\varepsilon^{\tau}(\omega)}{\partial\omega}\tfrac{\partial A_1(\vec{r},t)}{\partial t}} = J_2,
\end{aligned}$$

J_1, J_2 are the currents, their explicit expressions can be found in [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)]

This system includes terms describing wave dispersion, if omit these terms we get the system analyzed in the foregoing paper

Photonic crystal inside a waveguide

$$\vec{E}(\vec{r}_\perp, z, t) = \sum_{\lambda mn} C_{\lambda mn}(z,t)\vec{Y}_{\lambda mn}(\vec{r}_\perp)$$

$\vec{Y}_{\lambda mn}(\vec{r}_\perp)$ are the waveguide eigenfunctions $\Delta_\perp \vec{Y}_{\lambda mn} + (\varkappa_{mn}^{\lambda})^2 \vec{Y}_{\lambda mn} = 0$

considering the waveguide with the diffraction grating in vacuum

$$D_i(\vec{r},\omega) = (\delta_{il} + \chi_{il}(\vec{r},\omega))E_l(\vec{r},\omega) = E_i(\vec{r},\omega) + \chi_{il}(\vec{r},\omega)E_l(\vec{r},\omega)$$

Applying the method of slow-varying amplitudes we can obtain the system of equations describing the excited waves

$$C_{\lambda mn}(z,t) = A_{\lambda mn}(z,t)e^{i(\varkappa_{mn}^{\lambda} z - \omega t)}$$

$\varkappa_{mn}^{\lambda}$ and ω corresponds to the waveguide without a diffraction grating

Photonic crystal inside a waveguide

$$\frac{\partial^2 C_{\lambda mn}(z,t)}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 C_{\lambda mn}(z,t)}{\partial t^2} - (\varkappa_{mn}^{\lambda})^2 C_{\lambda mn}(z,t) -$$

$$-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\int \vec{Y}^*_{\lambda mn}(\vec{r}_\perp)\vec{\chi}(t-t')\sum_{\lambda' m' n'} C_{\lambda' m' n'}(z,t')\vec{Y}_{\lambda' m' n'}(\vec{r}_\perp) d^2 r_\perp +$$

$$+\vec{Y}^*_{\lambda mn}(\vec{r}_\perp)\vec{\nabla}(div\vec{\chi}\sum_{\lambda' m' n'} C_{\lambda' m' n'}(z,t'))\vec{Y}_{\lambda' m' n'}(\vec{r}_\perp) d^2 r_\perp =$$

$$= \frac{4\pi}{c^2}\frac{\partial}{\partial t}\int \vec{Y}^*_{\lambda mn}(\vec{r}_\perp)\vec{j}_{\lambda mn} d^2(r_\perp) + 4\pi\int \vec{Y}^*_{\lambda mn}(\vec{r}_\perp)\vec{\nabla}\rho d^2(r_\perp)$$

In general case different modes are separated, but grating rotation could mixes different modes (similar waves mixing in the vicinity of Bragg condition). To describe this process the equations for the mixing modes should be solved conjointly.

Thread heating evaluation

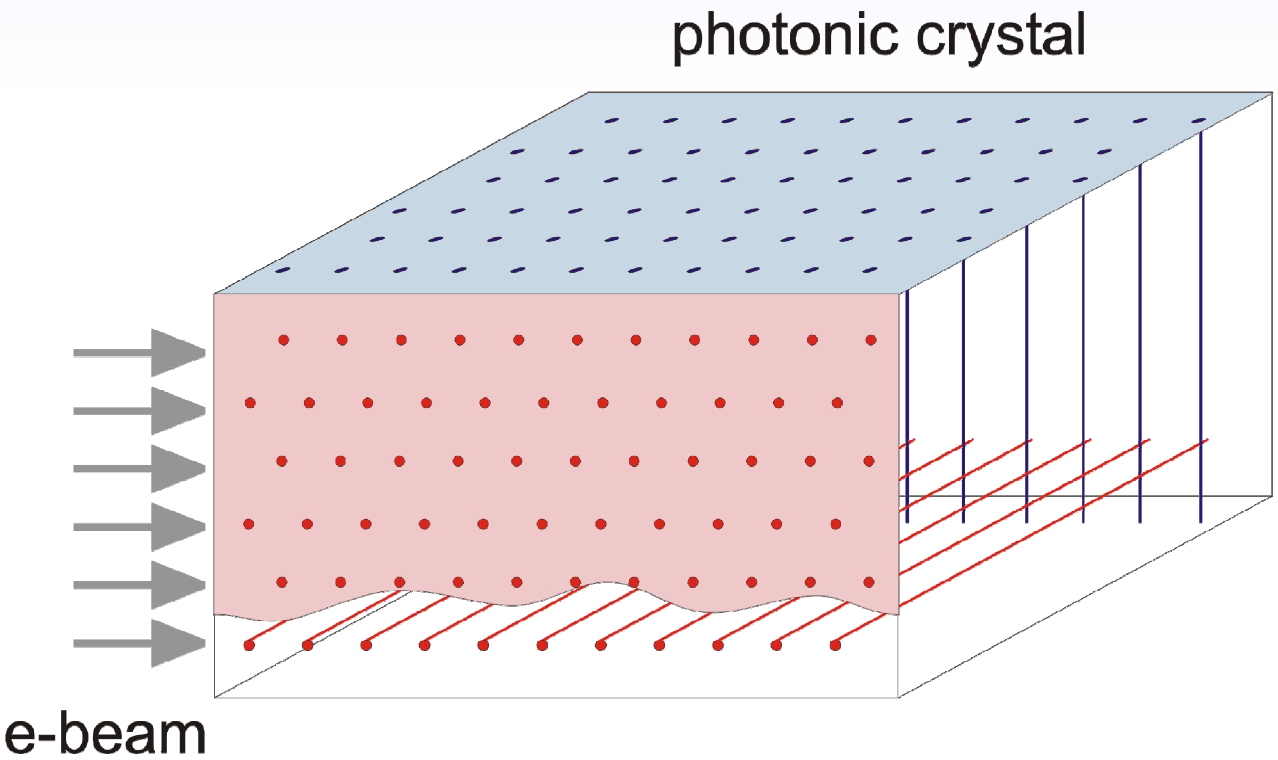
- tungsten threads of 100μm diameter
- electron beam energy 250 keV
- electron beam current 1 kA
- pulse duration 100 nsec
- electron beam diameter 32 mm

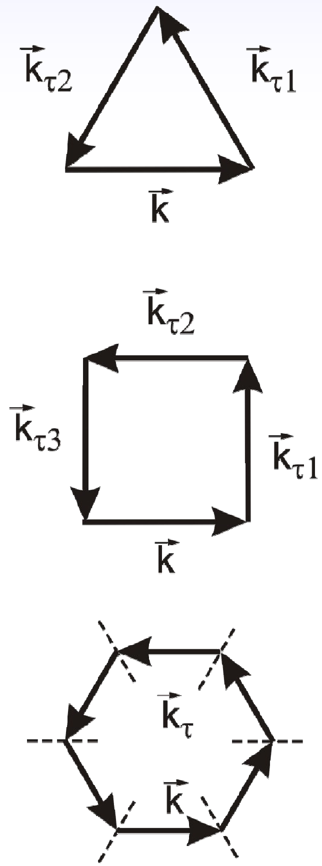
- $6 \cdot 10^{14}$ electrons in the beam
- $2 \cdot 10^{12}$ electrons passes through a thread
- 0.08 Joule transferred to the thread

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

$$\Delta T < 125°$$

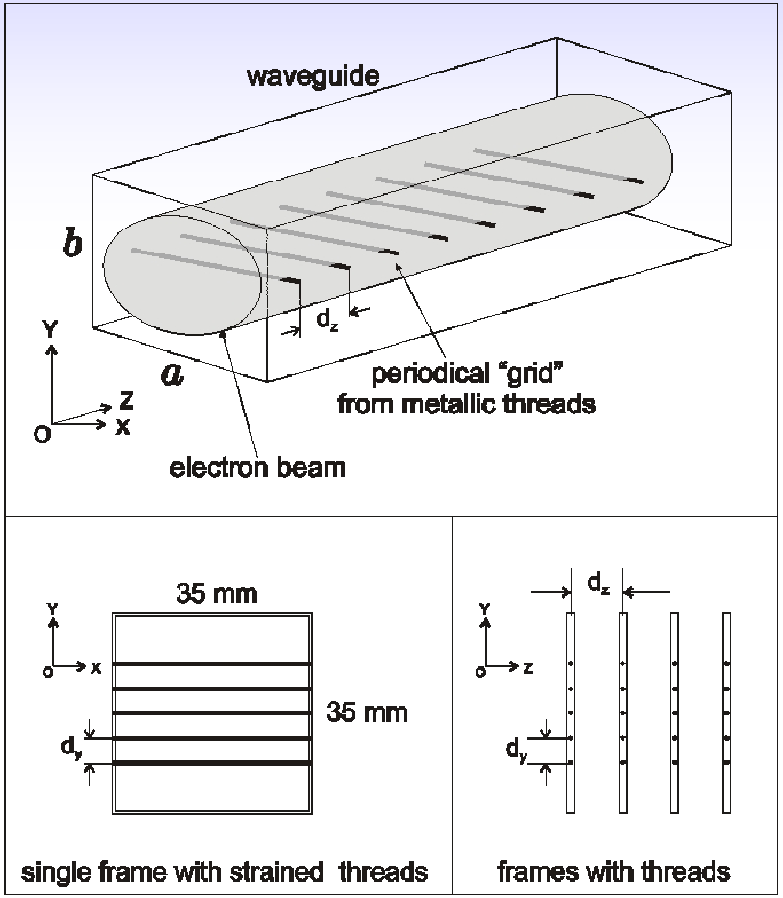
Photonic crystal providing multi-wave distributed feedback





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 photonic crystal

VFEL – recent experiments



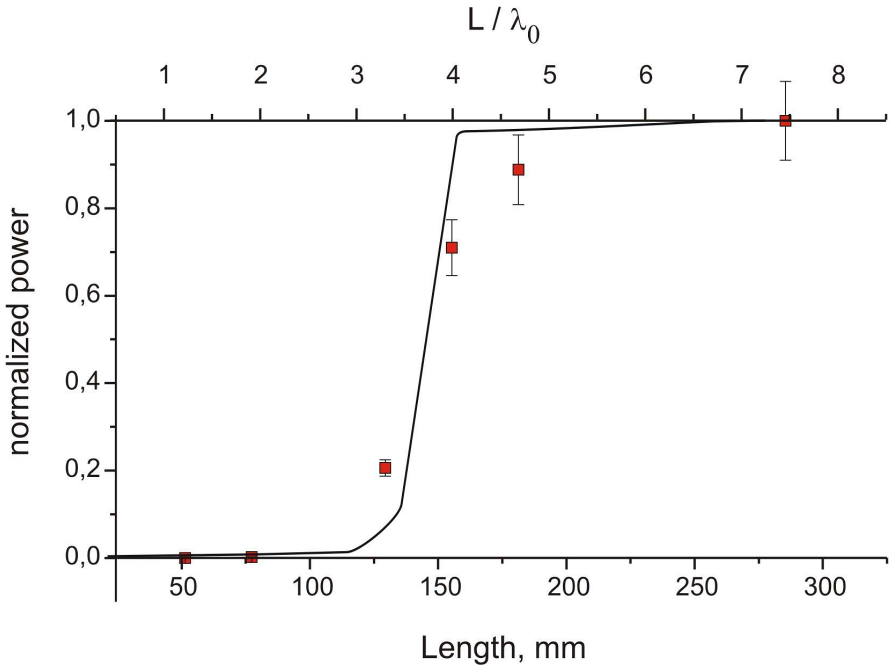
electron beam energy about 200 keV

electron beam current 2kA

pencil-like electron beam with the diameter 32 mm

magnetic field guiding the electron beam is 1.55 - 1.6 tesla.

Parameters of resonator are chosen to provide radiation with frequency about 10 GHz.



The "grid" structure is made of separate frames each containing the layer of 1, 3 or 5 parallel threads with the distance between the next threads d_y=6 mm). Frames are joined to get the "grid" structure with the distance d_z=12.5 mm between layers

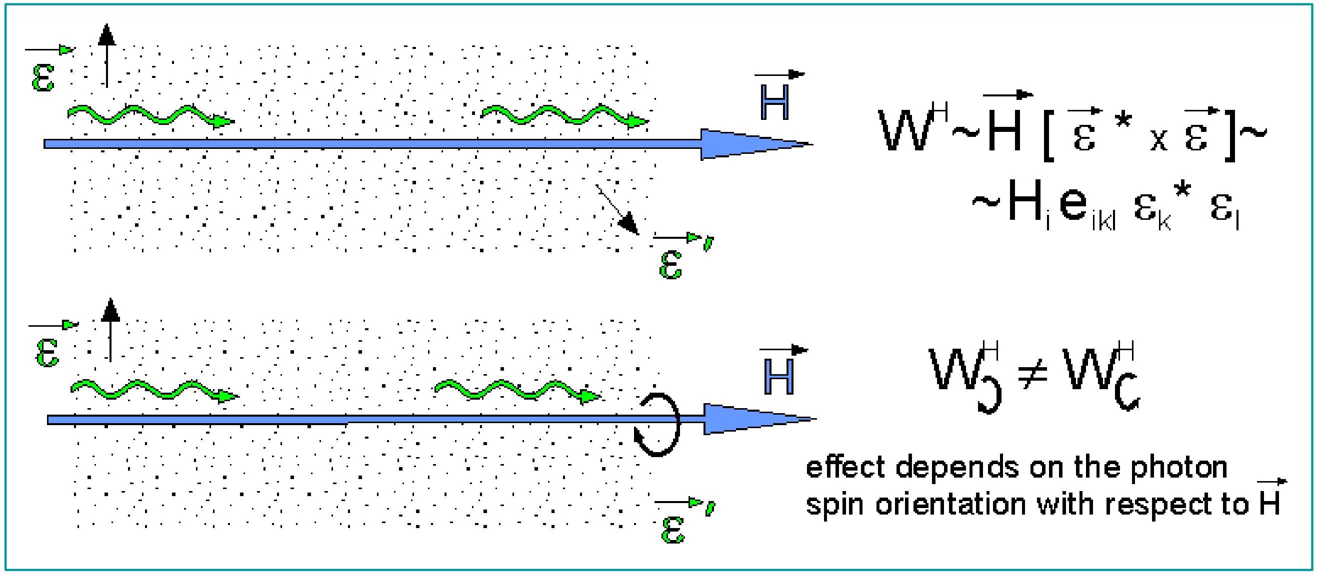
Applications

There are a lot of fields, where generators of electromagnetic radiation can be used:

- basic research
- resonance heating and current drive of thermonuclear fusion plasmas (for controlled fusion reactors);
- new-generation of powerful electron accelerators;
- radar and radio navigation systems with high spatial resolution, communications systems;
- industrial applications (microwave catalysis in plasma chemistry, material processing and atmospheric modification)
- anti-terror applications

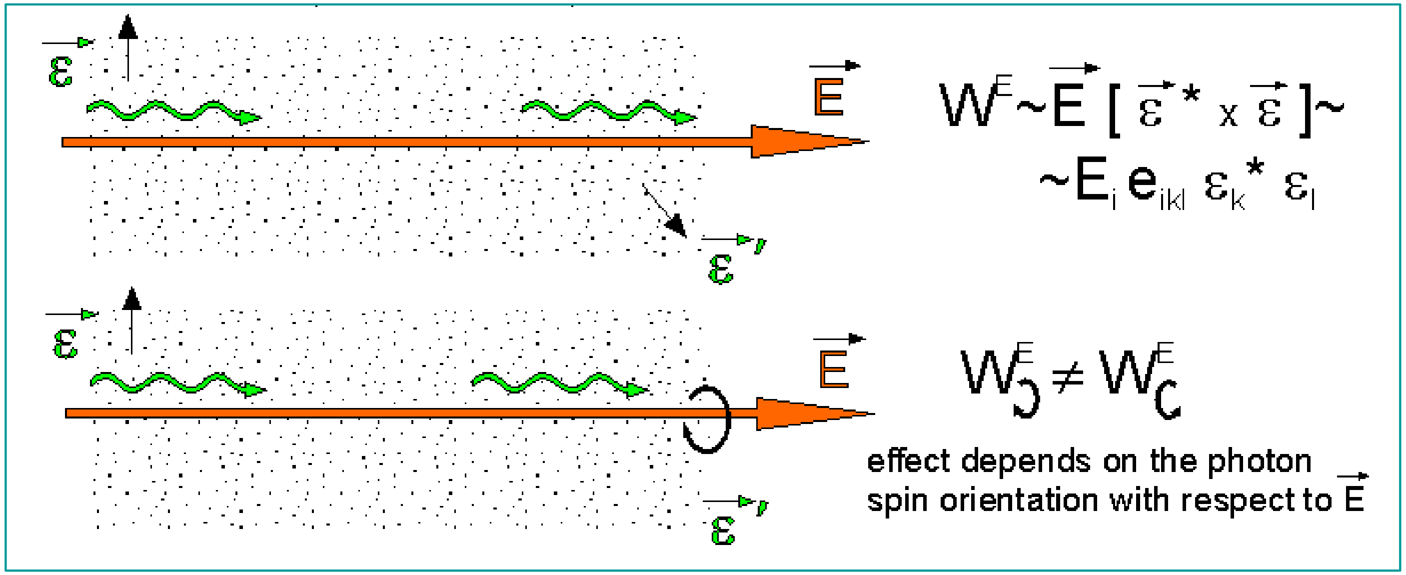
VFEL applications for basic research

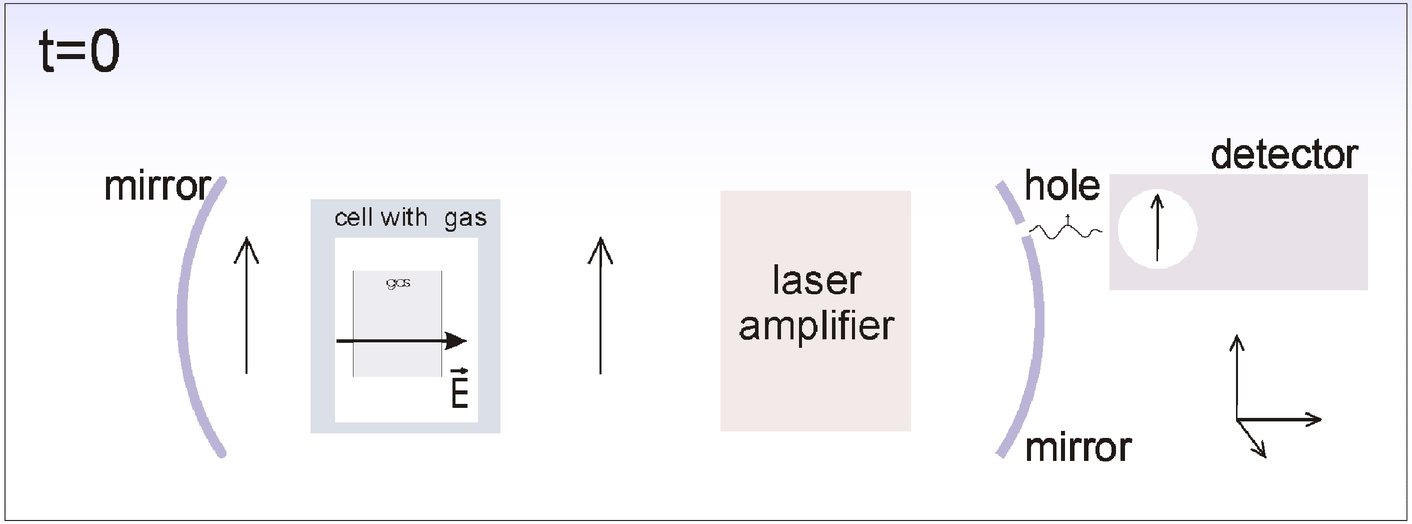
T-odd polarization plane rotation and circular dichroism for a photon in an electric field

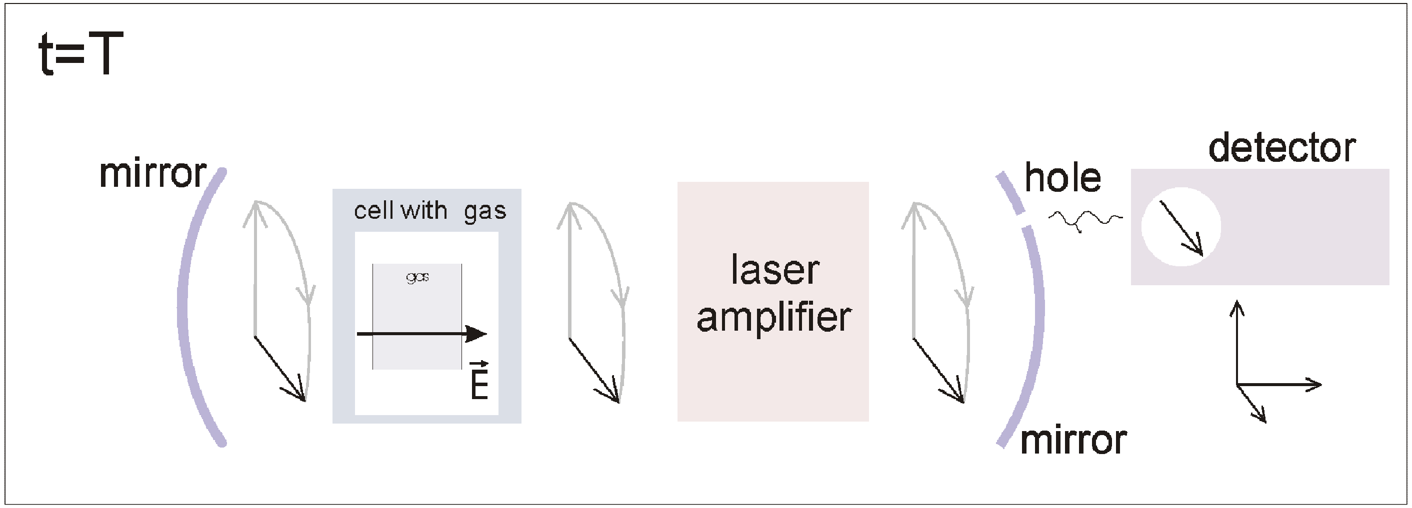


Faradey effect (T-invariant)

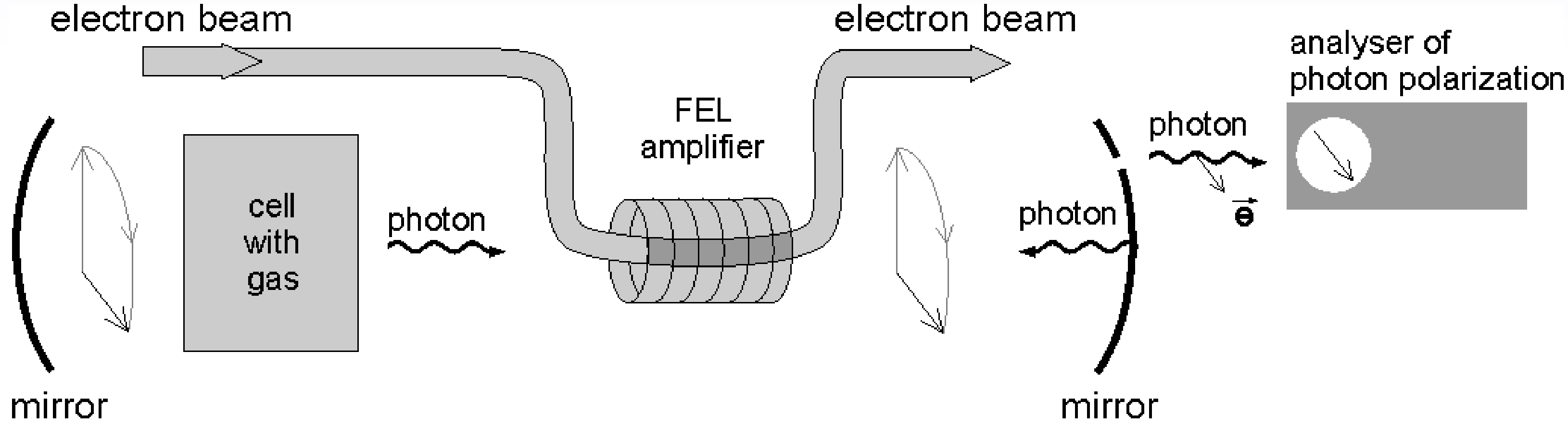
New effect (T-noninvariant)







Conventional laser amplifier is difficult to be used due to optical anysotropy

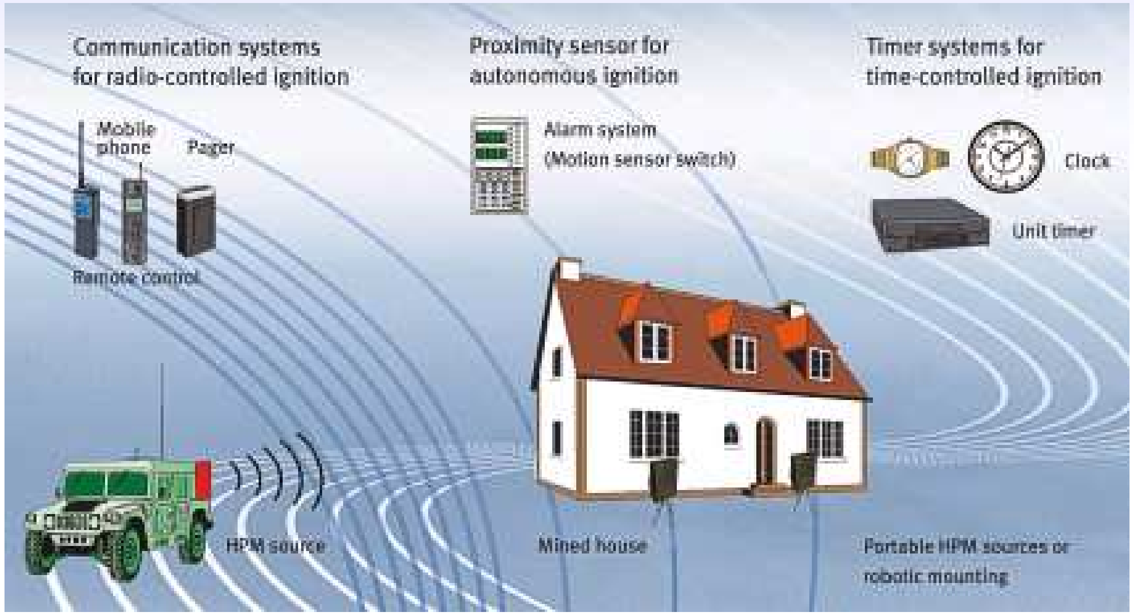


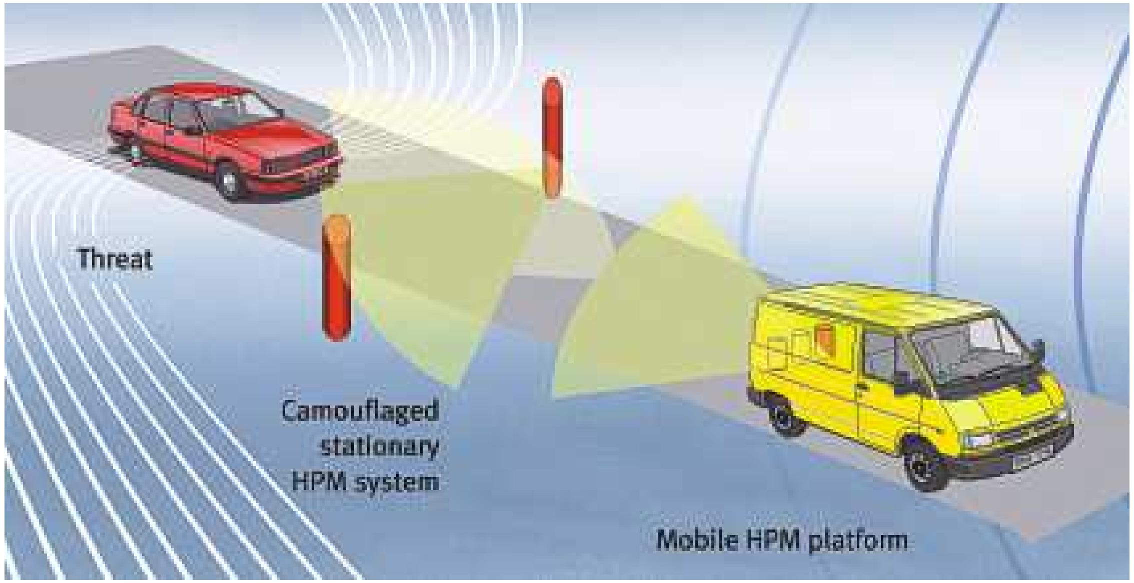
Two types of amplifiers:

1. Cherenkov: $d=\frac{\lambda}{4\pi}\gamma$ for $\lambda=1\,\mu m$, $\gamma \sim 10^5$

2. undulator: $\omega_{rad}=2\omega_{und}\gamma^2$ for $\lambda=1\,\mu m$, $\gamma>20$

Anti-terror applications





- Quick immobilization of vehicles
- Deactivation of the electronic devices inside vehicles and buildings
- No physical harm for the targeting person

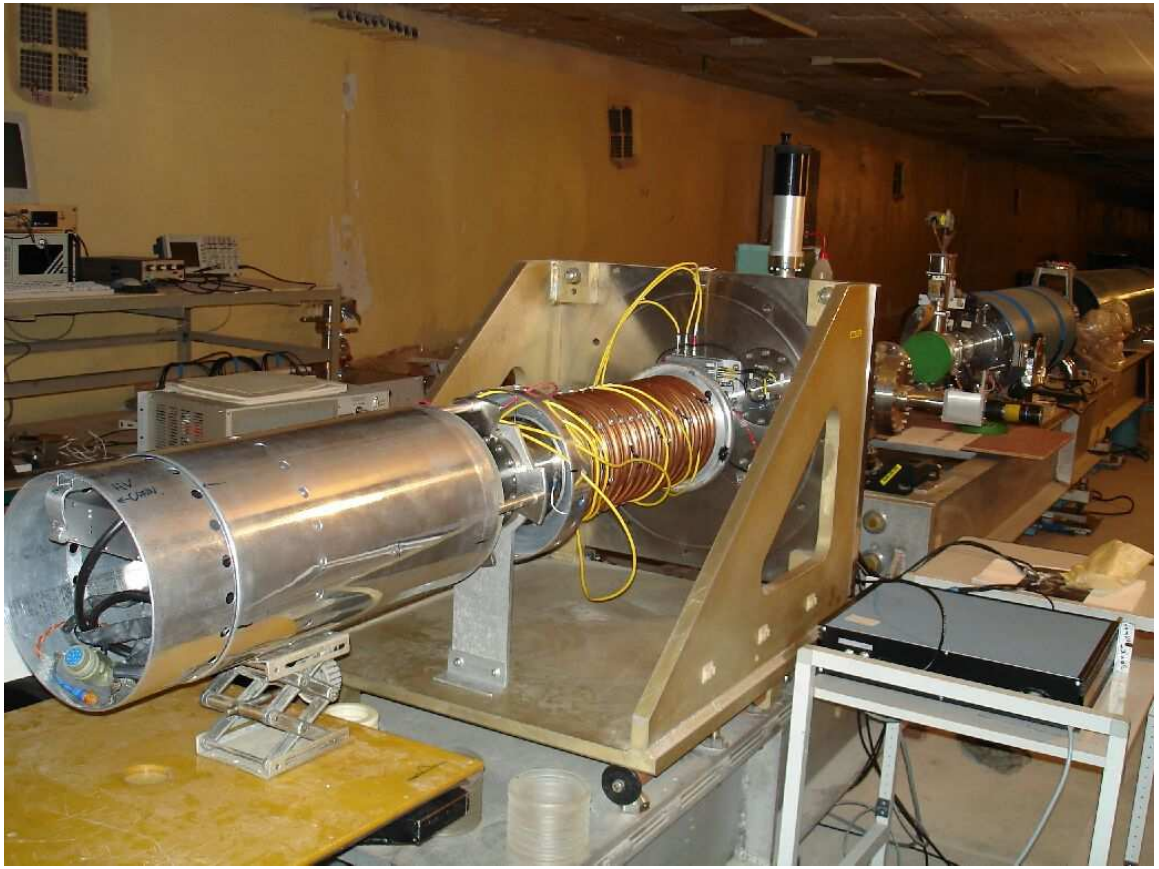
Planned experiment with 80 keV electrons

high voltage power supply

- voltage 30-80 kV
- current 1 A
- power <80kWt

Planned experiment with 6 and 20 MeV electrons at JINR, Dubna

Joint experiment is being prepared now by INP and Joint Institute for Nuclear Research (JINR, Dubna) at LINAC-800



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6MeV electrons will be used for generation of radiation with λ= 2 mm and λ= 0.3 mm (150 GHz and 1 THz,respectively) in grid photonic crystal

possibility to use 20 Mev electrons is under consideration