Generation of Medical X-ray and Terahertz Radiation Using Table-Top Accelerators

Baryshevsky V., Gurinovich A., Gurnevich E., Lobko A.

Research Institute for Nuclear Problems
Minsk Belarus

INP

MOTIVATION

In the Executive Summary of the first International Workshop “Physics for Health in Europe” held in February 2010 at CERN is stressed that dose reduction during diagnostic radiology and tomographic examinations is the hot research topic worldwide

[http://cdsweb.cern.ch/record/1269323/files/PHEE-10_EN.pdf].

Among the most important parts of this activity is the development of new intensive (quasi)-monochromatic tunable x-ray sources.

What do we need for high-quality *in vivo* medical imaging?

Current understanding shows, that we need approximately

~10^{12} photons/s

with tunable x-ray energy in **10-70 keV** spectral range.

Monochromaticity could be of **~10^{-2}** and less for a patient's dose reduction.

Radiation background should be low.

Monochromatic x-rays

The main problem in development of monochromatic x-ray sources is the gap between achievable photon generation efficiency (photons per electron) and existing electron beam current in the table-top accelerators.

We showed

Baryshevsky V., Feranchuk I., Gambaccini M., Lobko A., Taibi A., Abstracts of Intl. Workshop “Physics for Health in Europe” (CERN Geneva Switzerland, 2-4 February 2010), Book of Abstracts, p. 48

that x-ray source with required properties can be developed using parametric x-rays (PXR) and table-top accelerators like compact storage ring or pulsed race-track microtron.

Yuri M. Tsipenyuk, Microtron: Development and Applications. – CRC Press, 2001, 368 p.

Diffracted Radiation of Relativistic Oscillator (DRO)

DRO is the coherent process of x-ray photon emission by the relativistic oscillator (e.g. electron channeling in a crystal) and its diffraction within the single crystal target. It is sometimes called **diffracted channeling radiation** – **DCR**. DRO formation was firstly considered in

Baryshevsky V.G., Dubovskaya I.Ya., Doklady Akad. Nauk SSSR, 231 (1976) 1336, (in Russian)

detailed review and references can be found in

Baryshevsky V.G., Dubovskaya I.Ya., Diffraction phenomena in spontaneous and stimulated radiation by relativistic particles in crystals, Lawrence Berkeley Laboratory, LBL-31695 (1991) 122

For example, for *Si* target DCR to PXR ratio for electrons of 34 MeV energy channeled between (100) planes and radiation diffracted by (220) planes is estimated as **R~5**.

$$R = \frac{I_{DCR}}{I_{PXR}}$$

Terahertz radiation (T-rays)

T-rays are also very prospective for biomedicine applications: because of the photon low energy they cannot ionize biological media but this energy corresponds to vibrational levels of important bio molecules including DNA and RNA. This allows make directed efforts for stimulation of viruses, cells, and their components and provides control of bio-chemical reactions. Thus T-rays may be applied in therapy, surgery, imaging, and tomography. Terahertz radiation is extremely important for the bio-medical applications and its wider usage depends on the progress in development of THz sources

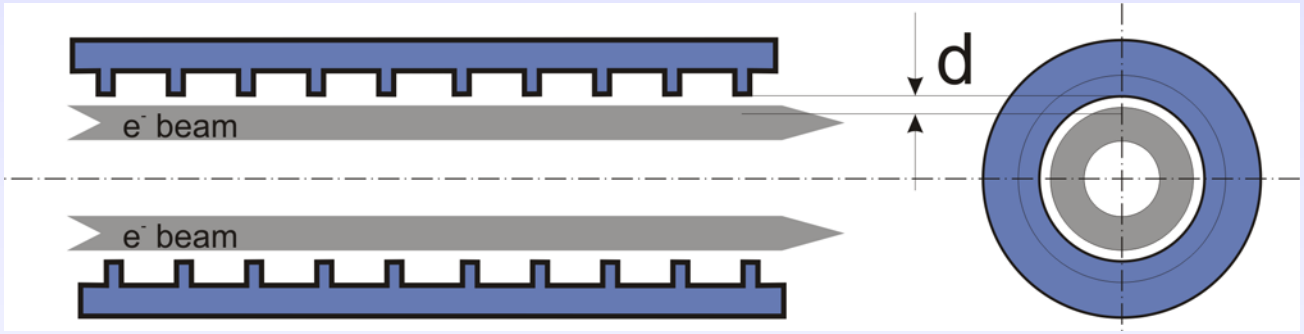
Kazarinov K.D., Electronnaya Technika, ser. 1, v. 4(503) (2009) 48 (in Russian)

How to build the effective THz source without huge FEL facilities ?!

For medical practice the table-top THz source is required!!!

Generators using diffraction radiation

Travelling Wave Tubes (TWT),
Backward Wave Oscillator (BWO),



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

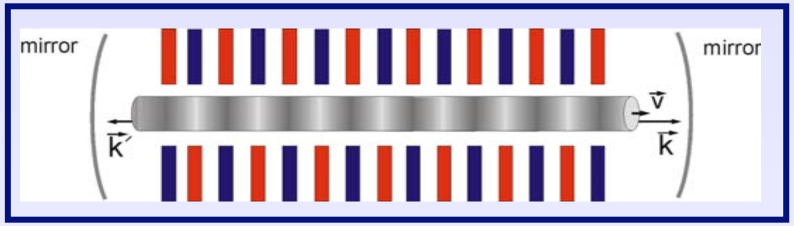
When radiation wavelength decreases, **d** declines

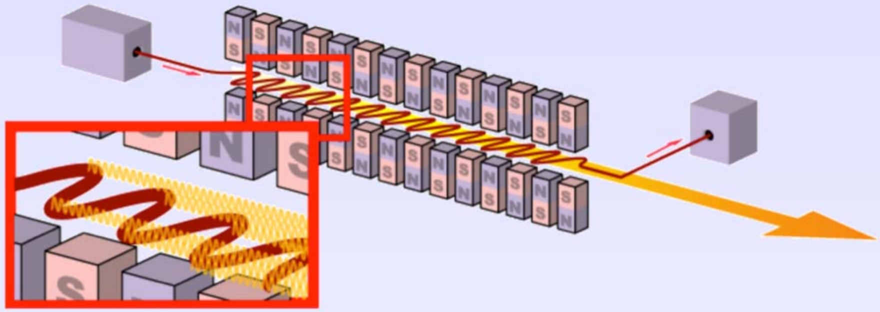
When an electron passes near the surface of the diffraction grating at the distance less then **d** it effectively excites an electromagnetic wave.

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

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 the larger dimensions

Volume Free Electron Laser can solve the problem

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 $\sqrt[3]{\rho}$. The possibility of creation of X-ray laser using induced PXR or DCR is proved.

V.Baryshevsky, I.Feranchuk, Phys. Lett. 102 A, 141 (1984)
V.G.Baryshevsky, I.Ya. Dubovskaya, Lawrence Berkeley Laboratory, LBL-31695 (1991) 122
V.Baryshevsky, K.Batrakov, I.Dubovskaya, J.Phys.D 24 (1991) 1250
V.Baryshevsky, K.Batrakov, I.Dubovskaya, NIM 375A (1996) 292

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 (natural or photonic crystal) or close to its surface.

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

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

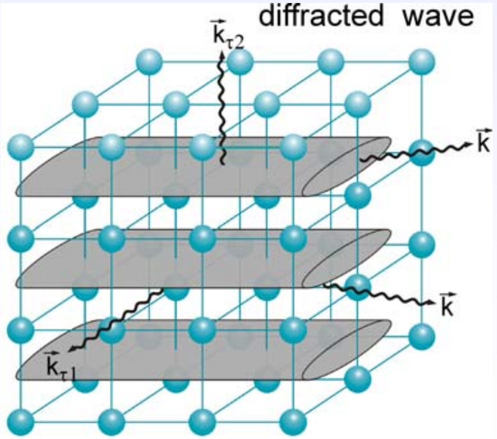
dynamical Bragg diffraction in a periodic medium (crystal) evokes the peculiar conditions, that result in a new law of electron beam instability:

$\sqrt[3+s]{\rho}$ (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}~$L^{-(3+2s)}$ (for conventional systems j_{thr}~L^{-3})

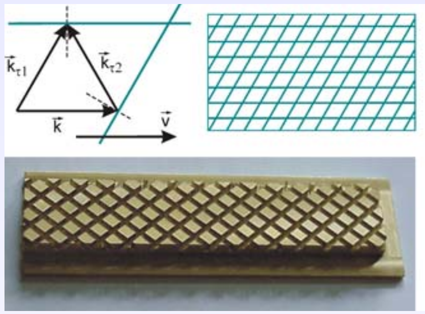


V.G.Baryshevsky, I.D.Feranchuk, Phys. Lett. 102 A, 141 (1984)
V.G.Baryshevsky, Doklady Akademy of Science USSR 299 (1988) 6
V.G.Baryshevsky, NIM 445A (2000), II-281

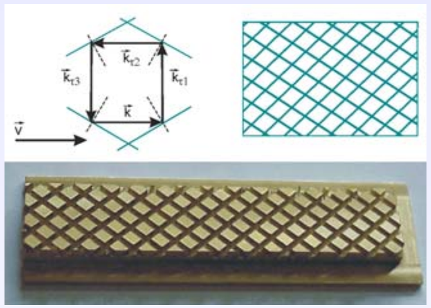
What is volume distributed feedback ?

Volume (non-one-dimensional) multi-wave distributed feedback is the distinctive feature of Volume Free Electron Laser (VFEL). VFEL can use any spontaneous radiation mechanism (magnetic bremsstrahlung in undulator, radiation in laser wave, Smith-Purcell, diffraction or Cherenkov radiation and so on).

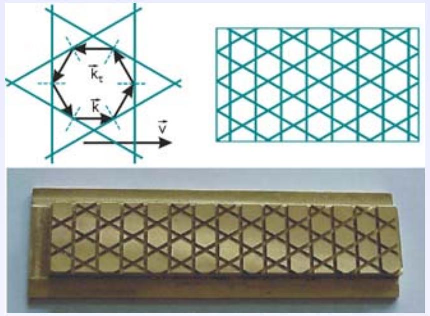
three-wave diffration



four-wave diffration

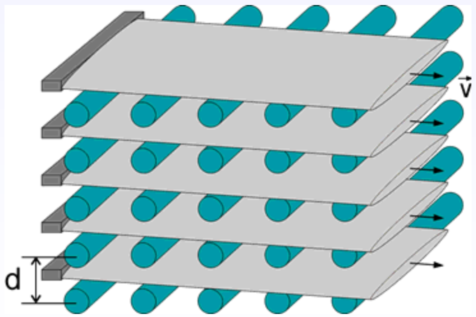


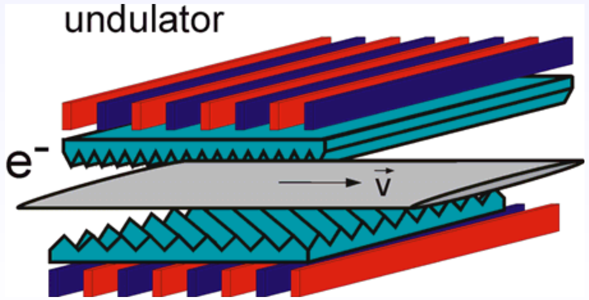
six-wave diffration



eight-wave diffration

Afanasenko V., Baryshevsky V... JETP Letters, v.51 (1990), n.4, p.213



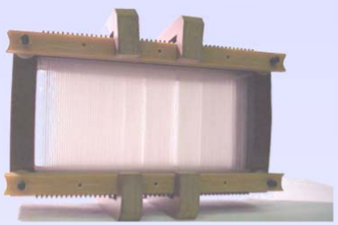


Use of volume distributed feedback makes available:

- ✓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**
- ✓resonator dimensions can be much larger then radiation wavelength

VFEL experimental history

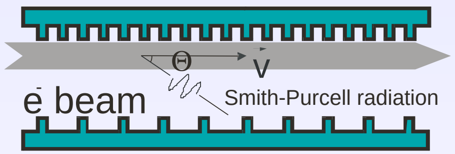
1996



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*

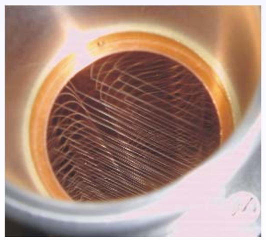
2001



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 - 2010



VFEL prototypes with photonic crystals made from metallic threads, foils …..

V.G.Baryshevsky, A.A.Gurinovich, *NIM 252B (2006) 91*
V.G.Baryshevsky et al., *FEL2006, FEL2009, FEL2010*

VFEL with a photonic crystal: state-of-the-art

Theory of Volume FELs with a photonic crystal is developed and reported. Volume Free Electron Laser is shown to be promising for development of radiation sources in centimeter, millimeter and sub-millimeter wavelength ranges.

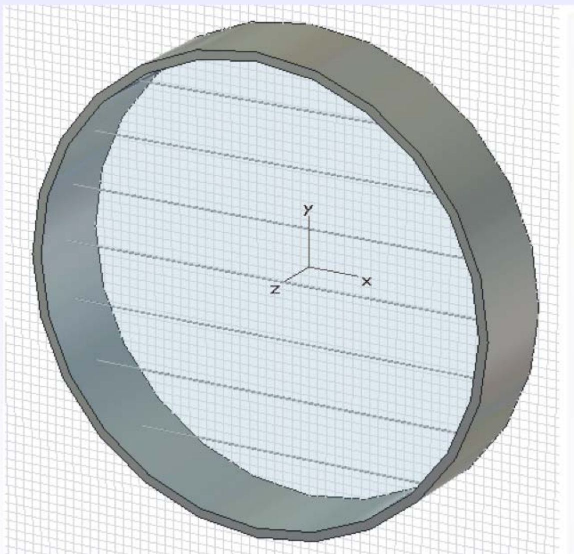
V.G. Baryshevsky, A.A. Gurinovich “Spontaneous and induced parametric and Smith–Purcell radiation from electrons moving in a photonic crystal built from the metallic threads” Nucl. Instr. Meth. B. Vol. 252. (2006) P. 92-101, physics/0409107

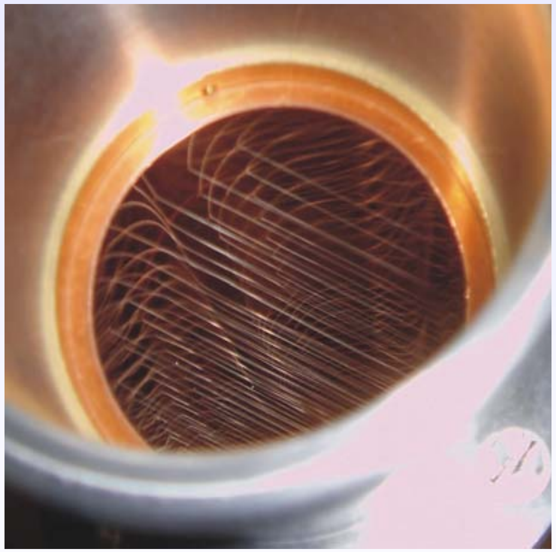
V.G. Baryshevsky, A.A. Gurinovich "Electrodynamical properties of a Volume Free Electron Laser with a "grid" volume resonator" FEL'06, Berlin, August 2006, TUPPH013, p.335, http://www.JACoW.org

Review of recent experiments.
The experiments are still preliminary for complete realization of VFEL idea, which implies volume distributed feedback with several diffracted waves.

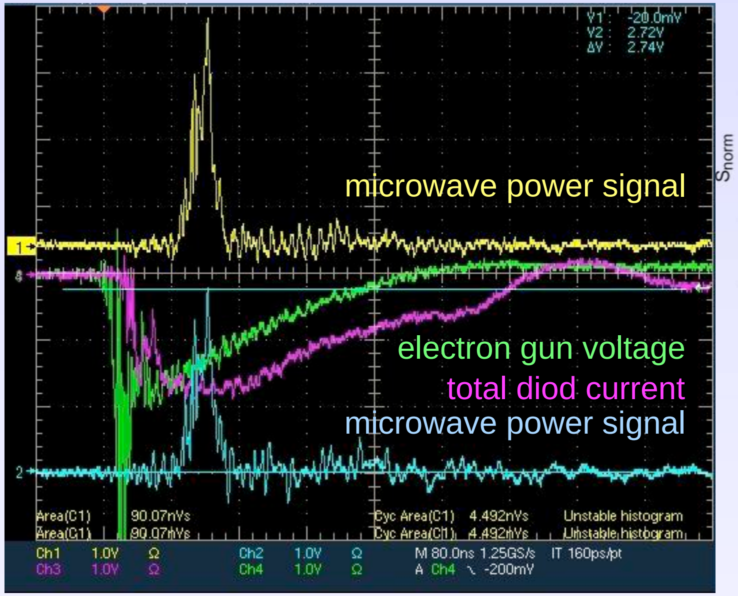
Photonic crystal made from tungsten threads

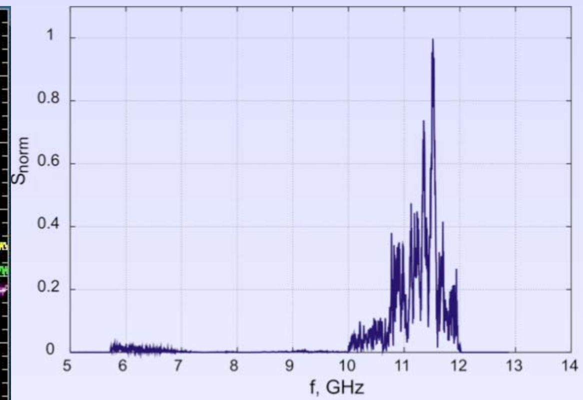
- a layer of 7 tungsten threads of 100 μm diameter distant 6.25mm
- two crystals with the periods d_1=12.5mm and d_2=10.5mm
- a circular waveguide with the internal diameter 50 mm
- up to 15 periods in the photonic crystal in different experiments

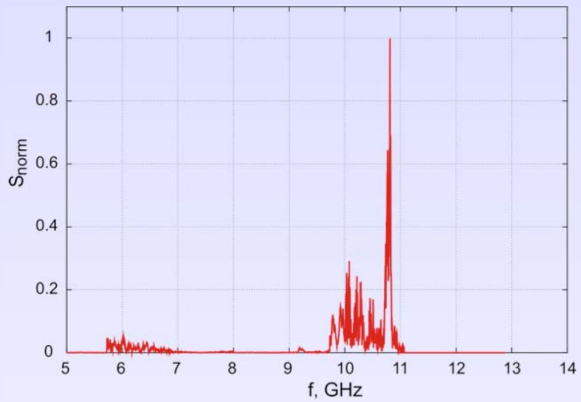




VFEL lasing: BWO regime





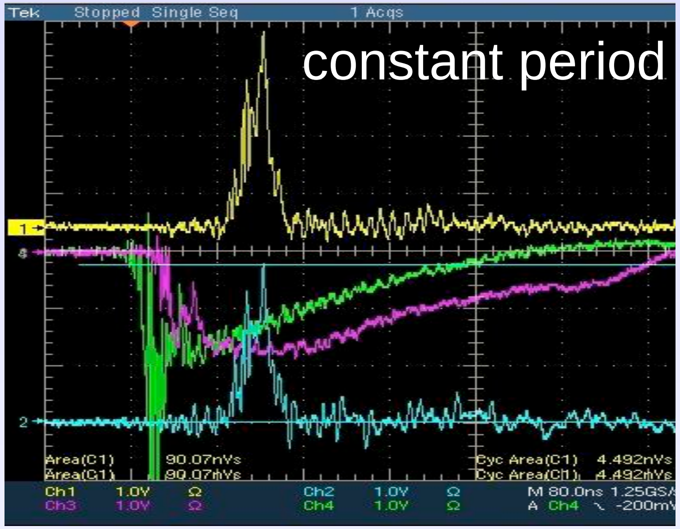


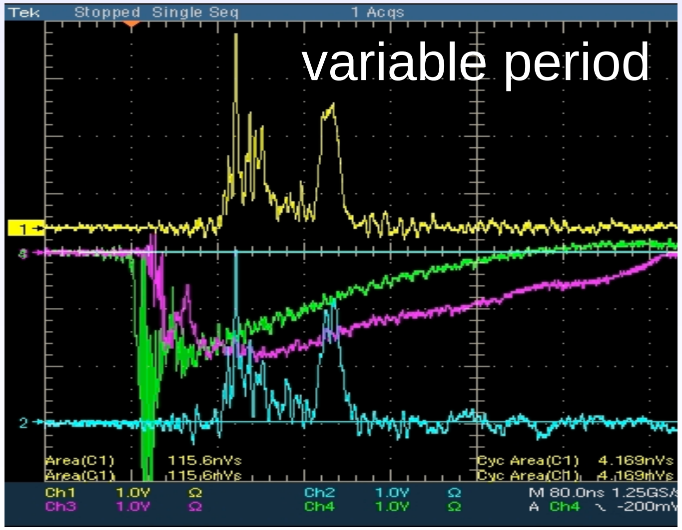
	150 keV	200 keV	250 keV
d_1=10.5 mm	11.5 GHz	12.1 GHz	12.6 GHz
d_2=12.5 mm	9.86 GHz	10.4 GHz	10.7 GHz

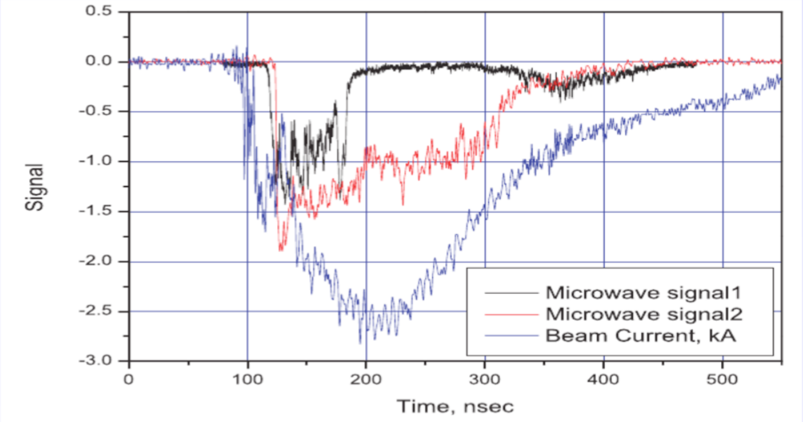
- a pencil-like electron beam, guiding magnetic field ~1.6 tesla
- electron energy up to 250 keV, total diode current is about 2 kA

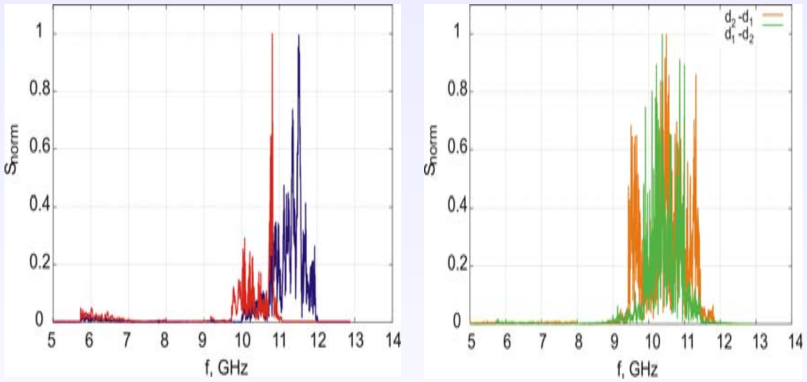
The electric field strength at the distance of 1.5 m from the output window is up to 10kV/m for 15 periods

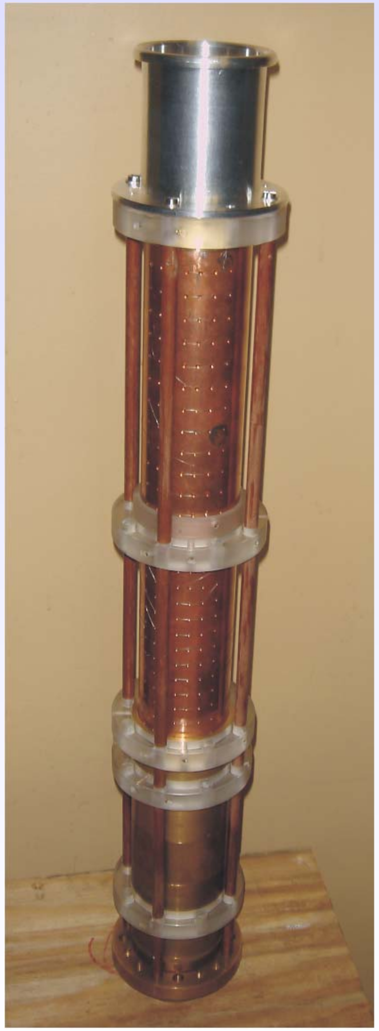
Photonic crystal with variable period





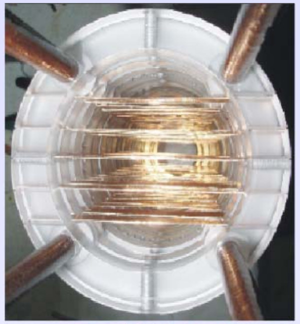


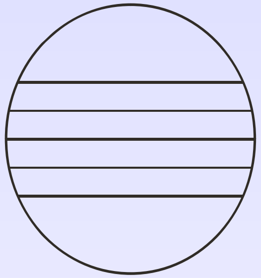


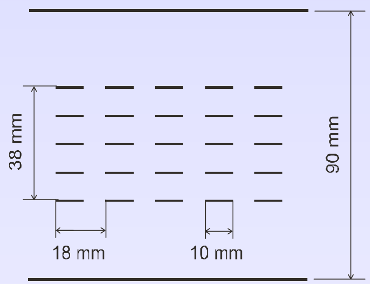


- increased pulse duration
- widened spectrum

A foil photonic crystal







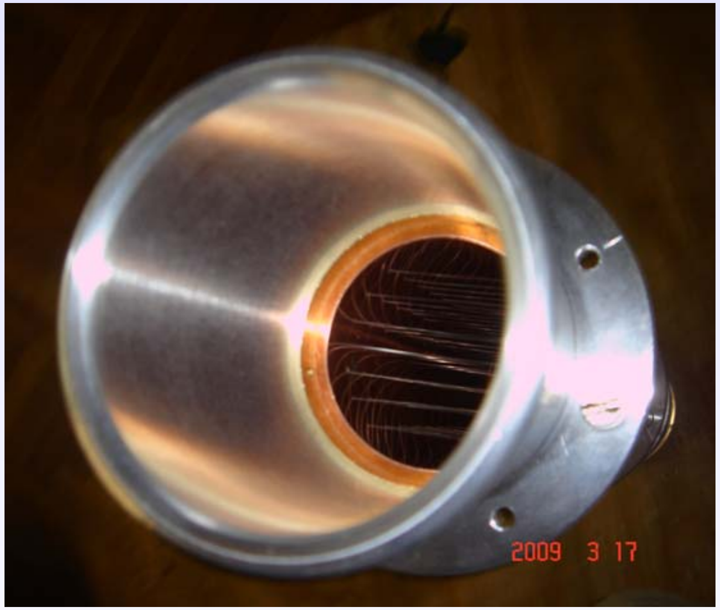
electron energy, keV	100	150	200	250
lasing frequency, GHz	1.68	1.68	1.68	1.68
	1.92	1.93	1.94	1.94
	4.99	5.00	5.00	5.03
	5.61	5.57	5.57	5.57
	6.70	7.24	7.60	7.83
	6.99	7.55	7.90	8.11

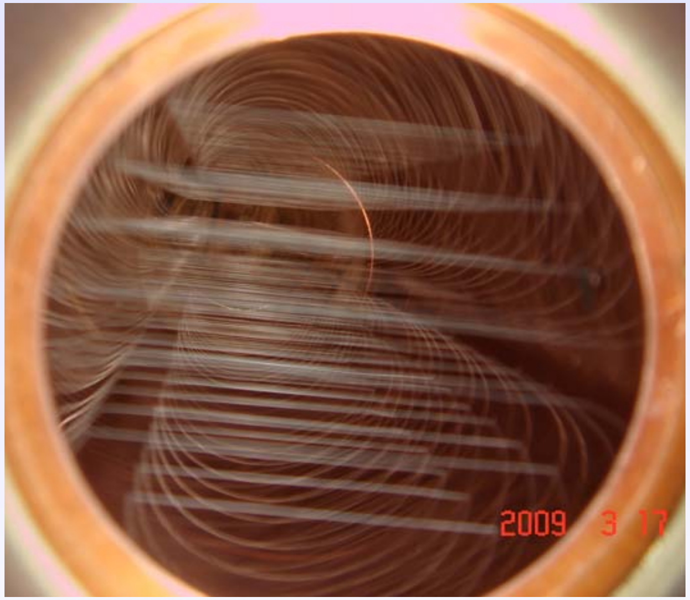
- brass foils of 100 μm thickness and 10 mm width
- 5-foils layers with 18 mm period inside the drift tunnel
- foil tapes are fixed in slots on plexiglas rings tightened by dielectric studs
- the pencil-like electron beam has diameter about 40 mm
- bent ends of foil tape ensure steady electric contact with the drift tube
- a combined resonance reflector

The electric field strength at the distance of 1.5 m from the output window is 10 kV/m for 10 periods and 15 kV/m for 15 periods of the photonic crystal. These values are 1.5 times higher than those for a crystal made of threads.

THz source with a photonic crystal

Wide e-beam (sheet or pencil-like) can excite the resonator as a whole





$d \leq \dfrac{\lambda\beta\gamma}{4\pi}$ for 50 MeV electrons (γ=100, β~1) and λ=0.3 mm (ν=1THz) **d**=3 mm

Conclusion

Theoretical and experimental studies of PXR and DCR combined with the experience of development of VFEL generators with photonic crystals give a promising basis for creation of X-ray and THz sources using the same table-top accelerator. Such a system could find a lot of application in medical practice and biomedical investigations.

THANK YOU FOR ATTENTION