Milestones in development of vacuum electronic devices

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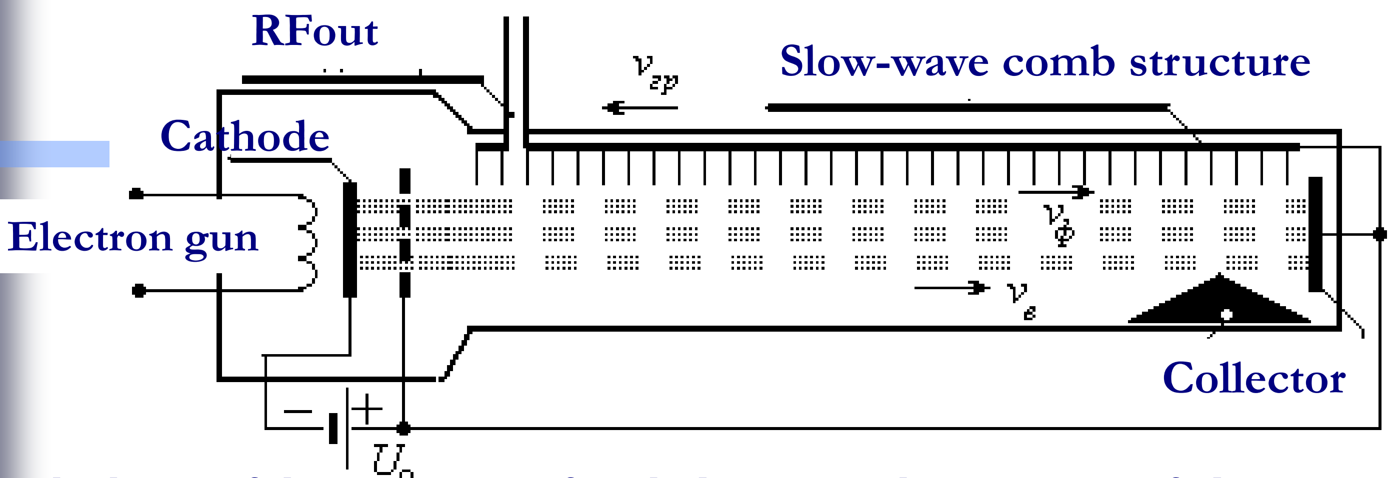
Outline

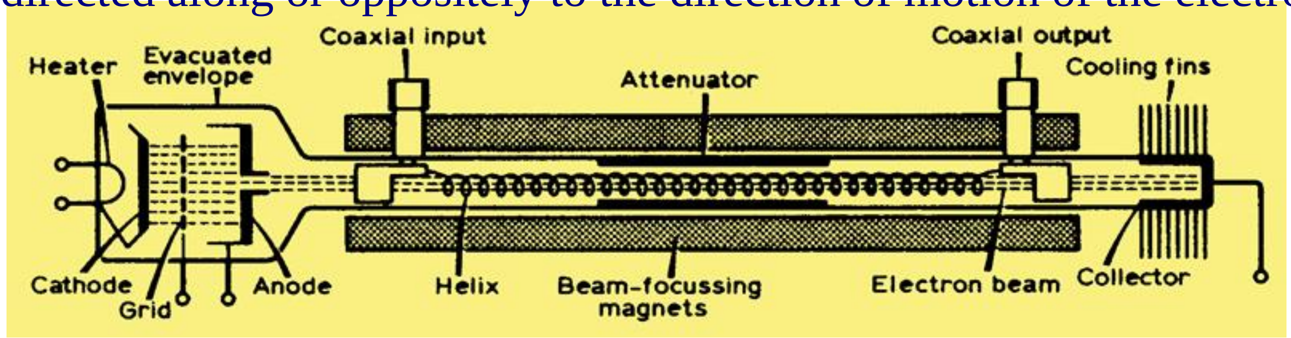
- Vacuum electronic devices (VED)
- Free electron lasers (FEL)
- Overview of simulation programs
- Dynamical systems
- Dynamical diffraction and parametric (quasi-Cherenkov) radiation
- History and review of the theory of volume free electron lasers (VFEL)
- VFEL model for simulation and its simulation
- Conclusions

Vacuum electronic devices



BWT* (1951)(BWO, carcinotron)

The basis of the operation of such devices is the emission of electrons, grouped in bunches and interacting in a cavity (slow-wave spatially periodic medium) with slow electromagnetic waves. The generated electromagnetic wave power has its group velocity directed along or oppositely to the direction of motion of the electrons.



TWT** (1942)

*Patent FR1035379 (A) : Bernard Epsztein, "Backward flow travelling wave devices", published 1959-03-31

** R Kompfner. Wireless World 52(1946), 369; Proc. IRE 35(1947), 124; Travelling-wave tubes. Reports on Progres in Physics,15 (1952),275

Pierce J R Traveling-Wave Tubes. In the Bell System Technical Journal (New York: Van Nostrand). Jan 1950. Vol. XXIX, N1, p.1-59; April 1950, p.189-250. Traveling-Wave Tubes. Published by D. Van Nostrand Co., 1950. 260 p.

Vacuum electronic devices

Limiting Stable Current in Electron Beams in the Presence of Ions*

J. R. Pierce
Bell Telephone Laboratories, Inc., New York, New York
(Received July 11, 1944)

In electron flow, the net electronic charge may be neutralized by positive ions. In this case, for a given geometry there is a limiting current beyond which homogeneous flow is unstable. This limiting current is evaluated for flow normal to parallel plane equipotentials and for flow filling a conducting tube and constrained to motion parallel to the axis. For parallel planes at a potential V_0 volts and spaced a distance L cm apart, the limiting current density in amperes/cm^2 is $i_0=104\times10^{-6}V_0^{3/2}/L^2$. For a long conducting tube the limiting current is $I_0=160\times10^{-6}V_0^{3/2}$. These limiting currents are roughly 6 times as great as in the absence of ions.

Journal of Applied Physics 15, 721 (1944)

АО «НИИ «Полюс» им. М.Ф.Стельмаха» (Моск

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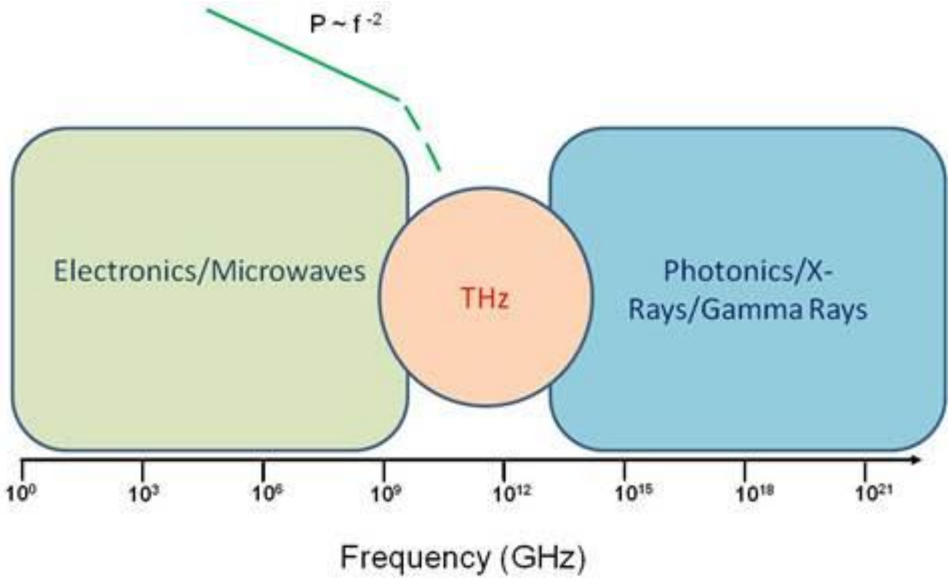
Vacuum electronic devices

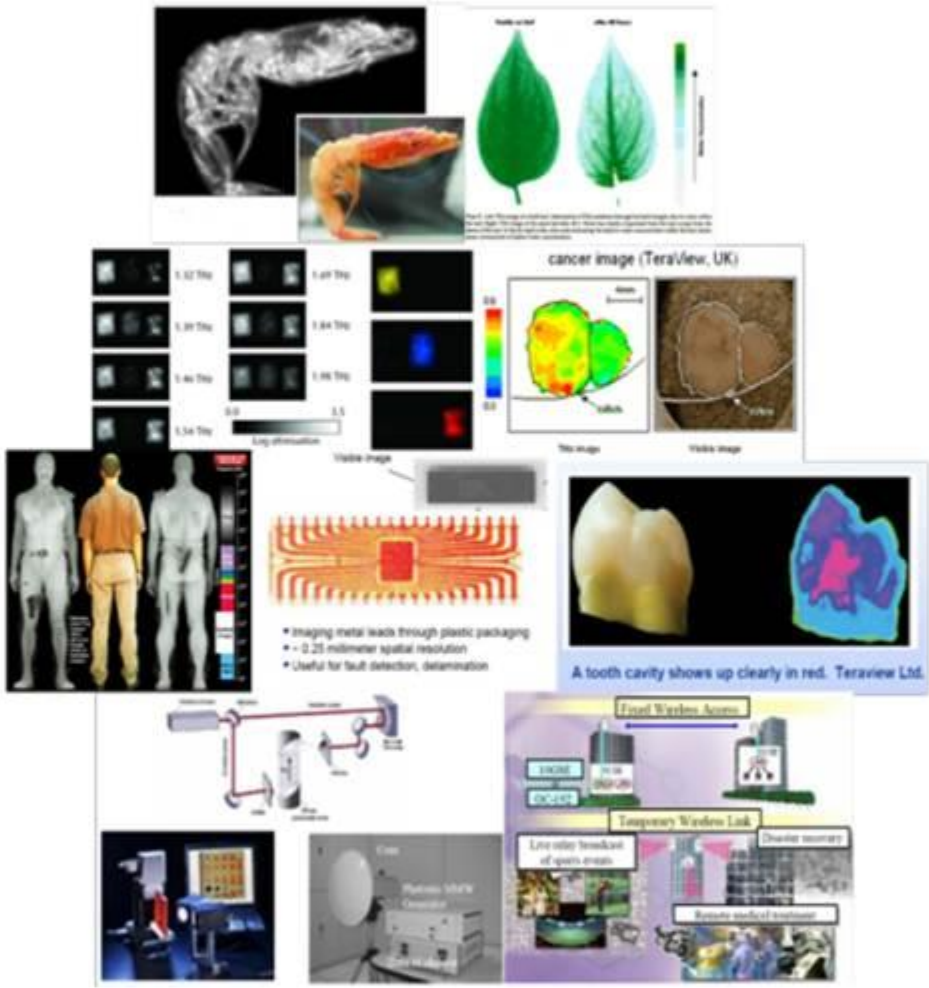


The THz regime 100 GHz – 1 THz and beyond lies in between the electronics and photonics area of research. The green line emphasizes the sharp drop in output power ($P \sim f^{-2}$ scaling no longer holds) observed for both solid state and vacuum based compact microwave devices in the THz region*.

*Williams, G.P. Rep. Prog. Phys., 2006. 69: p. 301-326; Siegel, P.H. IEEE Trans.Microwave Theory and Techniques, 2002. 50(3).

Vacuum electronic devices

Millimeter Wave to THz important applications*

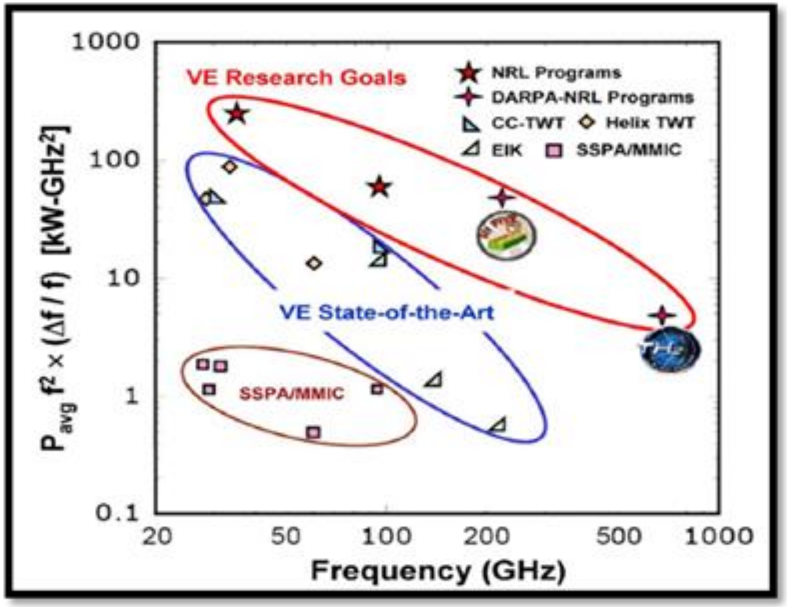


- industrial quality control,
- non-intrusive contra-band item detection,
- medical imaging/cancer diagnostics,
- all weather visibility systems for aviation safety,
- advanced telecommunication systems,
- radar with high wireless data transfer rates for LPI (low probability of interception),
- commercial applications

* Appleby R. H.B. Wallace. IEEE Trans. Antennas and Propagation, 2007. 55(11): p. 2944; Davies A.G. et al. Materials Today, 2008. 11(3): p. 18-26; Tonouchi M. Nat Photon, 2007. 1(2): p. 97-105; Yujiri L., M. Shoucri, P. Moffa. IEEE Microwave Magazine, 2003: p. 39 - 50.

Vacuum electronic devices

State of the art and prospective devices in terms of $P_{avg}f^2\Delta f/f$ figure of merit*



At all frequencies VED supersedes in producing higher power than a solid state power amplifier (SSPA) device.

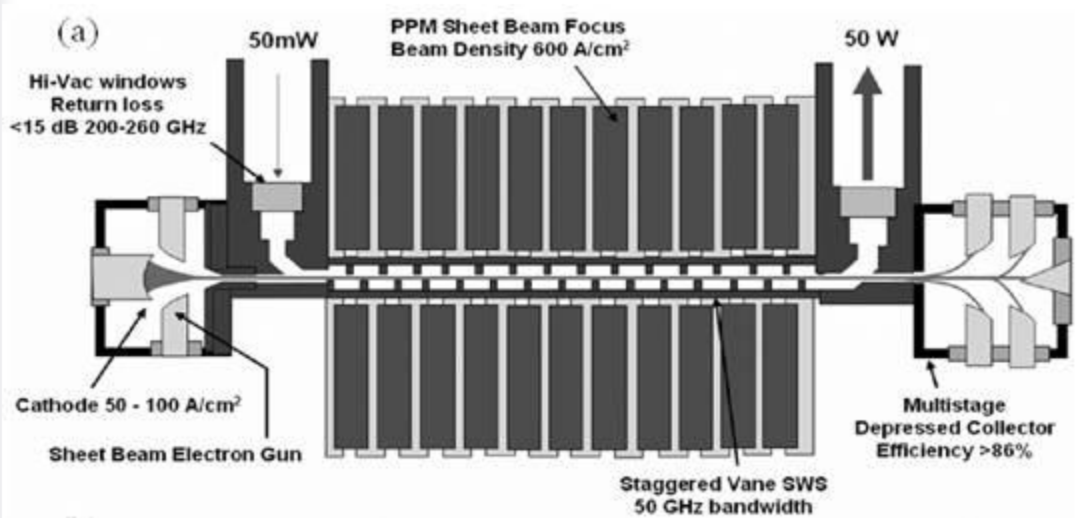
Fundamental differences:

In VED the electron beam flow in vacuum is collisionless.

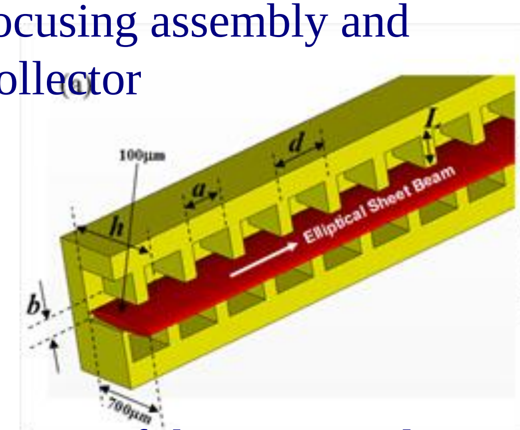
In SSPA the collision-dominated stream diffuses through a semi-conducting solid.

* Borsuk, G.M., B. Levush. In Vacuum Electronics Conference (IVEC), 2010 IEEE Int.

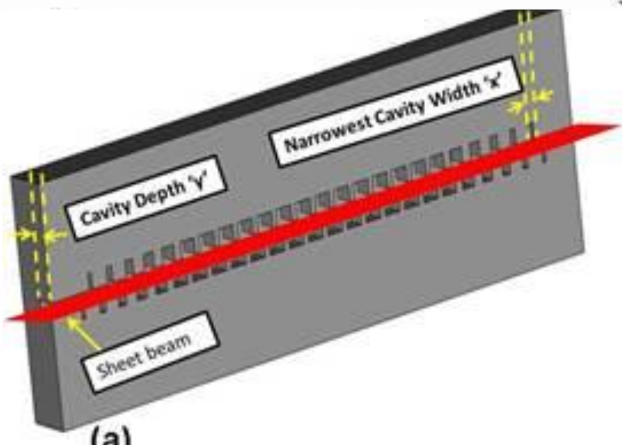
Vacuum electronic devices*



Conceptual Drawing of 220 GHz TWTA including electron gun section, input/output couplers, PPM focusing assembly and collector



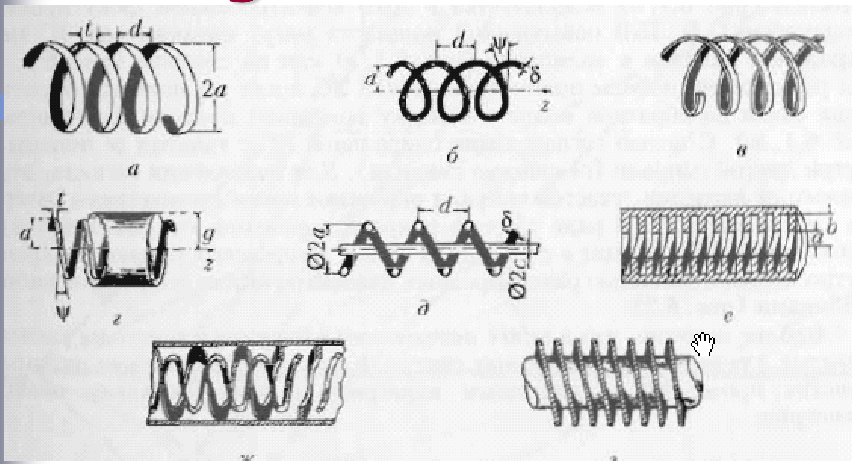
Conceptual 3D drawing of the staggered double vane THz sheet beam TWT circuit with the elliptical sheet beam



Double-vane half period staggered 0.22 THz Sheet Seam TWT

* http://tempest.das.ucdavis.edu/vacuum/

Resonators, spatially–periodic systems* for microwave range



Spirals

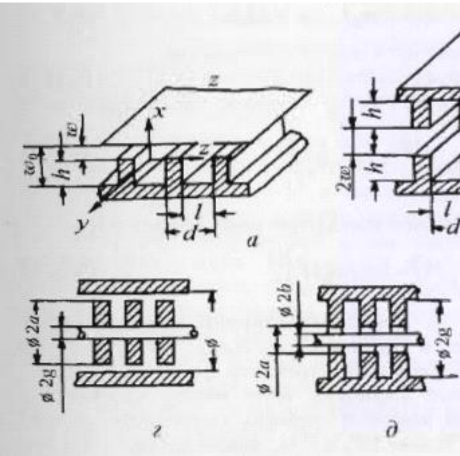
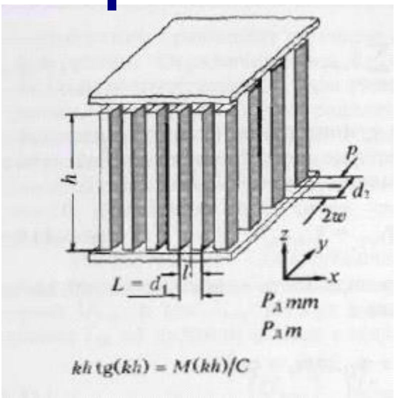


Рис. 9.1. Простейшие типы резонаторных систем: *а* — гребенка, *б* — двойная гребенка, *в* — диафрагмированный волновод, *г* — ребристый стержень в волноводе, *д* — диафрагмированный волновод со стержнем

Comb structures



(19) **SU** (11) **1 840 644** (13) **A1**

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H01J 23/24 (2006.01)

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(54) ЭЛЕКТРОННО-ЛУЧЕВАЯ ЛАМПА МАЛОЙ МОЩНОСТИ МИЛЛИМЕТРОВОГО ДИАПАЗОНА

(57) Реферат:
Изобретение относится к области радиоэлектроники и предназначено для

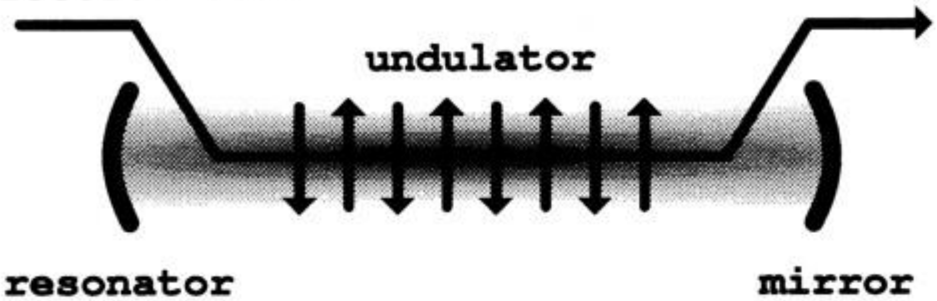
Pin-type and slotted systems

* R.A.Silin. Periodical waveguides. 2002

Invention SU 1 840 644 A1 dated 04.09.1956, published 10.08.2007

Free Electron Lasers (FEL)

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

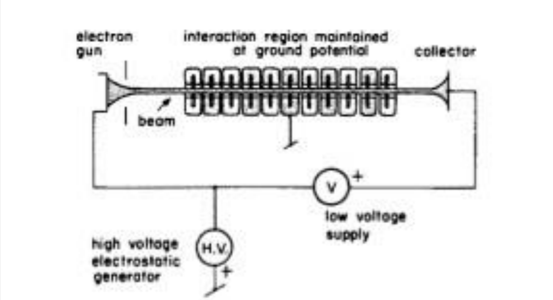


JOURNAL OF APPLIED PHYSICS VOLUME 42, NUMBER 5 APRIL 1971

Stimulated Emission of Bremsstrahlung in a Periodic Magnetic Field

JOHN M. J. MADEY
Physics Department, Stanford University, Stanford, California 94305
(Received 20 February 1970; in final form 21 August 1970)

The Weizsäcker–Williams method is used to calculate the gain due to the induced emission of radiation into a single electromagnetic mode parallel to the motion of a relativistic electron through a periodic transverse dc magnetic field. Finite gain is available from the far-infrared through the visible region raising the possibility of continuously tunable amplifiers and oscillators at these frequencies with the further possibility of partially coherent radiation sources in the ultraviolet and x-ray regions to beyond 10 keV. Several numerical examples are considered.



*J. Madey, J. Appl. Phys. **42** (1971), 1906

Free Electron Lasers (FEL)

VOLUME 38, NUMBER 16 PHYSICAL REVIEW LETTERS 18 APRIL 1977

First Operation of a Free-Electron Laser*

D. A. G. Deacon,† L. R. Elias, J. M. J. Madey, G. J. Ramian, H. A. Schwettman, and T. I. Smith
High Energy Physics Laboratory, Stanford University, Stanford, California 94305
(Received 17 February 1977)

A free-electron laser oscillator has been operated above threshold at a wavelength of 3.4 μm.

Ever since the first maser experiment in 1954, physicists have sought to develop a broadly tunable source of coherent radiation. Several ingenious techniques have been developed, of which the best example is the dye laser. Most of these devices have relied upon an atomic or a molecular active medium, and the wavelength and tuning range has therefore been limited by the details of atomic structure.

Several authors have realized that the constraints associated with atomic structure would not apply to a laser based on stimulated radiation by free electrons.[1-5] Our research has focused on the interaction between radiation and an electron beam in a spatially periodic transverse magnetic field. Of the schemes which have been proposed, this approach appears the best suited to the generation of coherent radiation in the infrared, the visible, and the ultraviolet, and also has the potential for yielding very high average power. We have previously described the results of a measurement of the gain at 10.6 μm.[6] In this Letter we report the first operation of a free-electron laser oscillator.

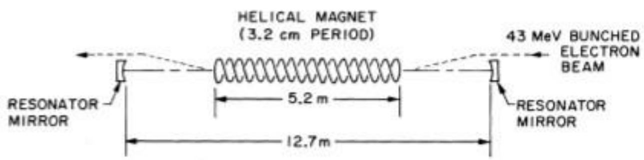


FIG. 1. Schematic diagram of the free-electron laser oscillator. (For more details see Ref. 6.)

VOLUME 51, NUMBER 18 PHYSICAL REVIEW LETTERS 31 OCTOBER 1983

First Operation of a Storage-Ring Free-Electron Laser

M. Billardon,[a] P. Elleaume,[b] J. M. Ortega,[a] C. Bazin, M. Bergher, M. Velghe,[c] and Y. Petroff
Laboratoire pour l'Utilisation du Rayonnement Electromagnétique, Université de Paris-Sud, F-91405 Orsay, France

and

D. A. G. Deacon,[d] K. E. Robinson, and J. M. J. Madey
High Energy Physics Laboratory, Stanford University, Stanford, California 94305
(Received 1 August 1983)

A storage-ring free-electron laser oscillator has been operated above threshold at a visible wavelength λ≈6500 Å.

PACS numbers: 42.60.-v

Free Electron Lasers

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Phys. Scr. **91** (2016) 083003 (10pp) doi:10.1088/0031-8949/91/8/083003

Invited Comment

The free electron laser: conceptual history

John Madey[1], Marlan O Scully[2,3] and Phillip Sprangle[4,5]

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Abstract

The free electron laser (FEL) has lived up to its promise as given in (Madey 1971 *J. Appl. Phys.* **42** 1906) to wit: 'As shall be seen, finite gain is available …from the far-infrared through the visible region …with the further possibility of partially coherent radiation sources in the x-ray region'. In the present paper we review the history of the FEL drawing liberally (and where possible literally) from the original sources. Coauthors, Madey, Scully and Sprangle were involved in the early days of the subject and give a first hand account of the subject with an eye to the future.

FELs in the world *

Only operating FEL oscillators with wavelength < 10 mm are included.

User facility" means a dedicated scientific research facility open to outside researchers.

LOCATION	NAME	WAVELENGTHS	TYPE	STATUS
RIKEN (Japan)	SACLA FEL	0.63 - 3 Å	Linac	operating user facility
SLAC-SSRL (USA)	LCLS FEL	1.2 - 15 Å	Linac	operating user facility
DESY (Germany)	FLASH FEL	4.1 - 45 nm	SC Linac	operating user facility
ELETTRA Trieste, Italy	FERMI	4 - 100 nm	Linac	operating user facility
SDL(NSLS) Brookhaven (USA)	HGHG FEL	193 nm	Linac	operating experiment
Duke Univ. NC (USA)	OK-4	193 - 400 nm	storage ring	operating user facility
iFEL (Japan)	3 2 1 4 5	230 nm - 1.2 μm 1 - 6 μm 5 - 22 μm 20 - 60 μm 50 - 100 μm	linac	operating user facility
Univ. of Hawaii (USA)	MK-V	1.7 - 9.1 μm	linac	operating experiment
FOM (Netherlands)	FELIX1 FELIX2	3.1 - 35 μm 25 - 250 μm	linac	operating user facility
LURE - Orsay (France)	CLIO	3 - 150 μm	linac	operating user facility
Jefferson Lab VA (USA)		3.2 - 4.8 μm 363 - 438 nm	SC-linac	operating user facility
Science Univ. of Tokyo (Japan)	FEL-SUT	5 - 16 μm	linac	operating user facility
FZ Rossendorf (Germany)	FELBE	4-22 μm 18-250 μm	SC-linac	operating user facility
UCSB CA (USA)	FIR-FEL MM-FEL 30 μ-FEL	63 - 340 μm 340 μm - 2.5 mm 30 - 63 μm	electrostatic	operating user facility

* http://sbfel3.ucsb.edu/www/fel_table.html

FELs in the world *

ENEA – Frascati (Italy)		3.6 - 2.1mm	microtron	operating user facility
ETL – Tsukuba (Japan)	NIJI-IV	228 nm	storage ring	operating experiment
IMS – Okazaki (Japan)	UVSOR	239 nm	storage ring	operating experiment
Dortmund, Univ. (Germany)	Felicita 1	470 nm	storage ring	operating experiment
LANL NM (USA)	AFEL RAFEL	4 - 8 μm 16 μm	linac	operating experiment
Darmstadt Univ. (Germany)	IR-FEL	6.6 - 7.8 μm	SC-linac	operating experiment
IHEP (China)	Beijing FEL	5 - 25 μm	linac	operating experiment
CEA – Bruyeres (France)	ELSA	18-24 μm	linac	operating experiment
ISIR – Osaka (Japan)		21-126 μm	linac	operating experiment
JAERI (Japan)		22 μm 6 mm	SC-linac induction linac	operating experiment
Univ. of Tokyo (Japan)	UT-FEL	43 μm	linac	operating experiment
ILE – Osaka (Japan)		47 μm	linac	operating experiment
LASTI (Japan)	LEENA	65 - 75 μm	linac	operating experiment
KAERI (Korea)		80 - 170 μm 10 mm	Microtron electrostatic	operating experiment
Budker Inst. Novosibirsk, Russia		110 - 240 μm	linac	operating experiment
Univ. of Twente (Netherlands)	TEU-FEL	200-500 μm	linac	operating experiment
Tel Aviv Univ. (Israel)		3 mm	electrostatic	operating experiment

FELs Under Development

- FELiChEM (China)
- European X-ray FEL (Germany)
- TARLA FEL, Turkish Accelerator and Radiation Laboratory at Ankara (Turkey)
- SwissFEL, Paul Scherrer Institute (Switzerland)
- Institute for Plasma Research (India)
- LEUTL APS, Argonne National Lab (US)
- Center for Advanced Technology (India)
- University of Hawaii (US)
- UCLA Particle Beam Physics Lab
- Osaka University - ISIR (Japan)
- Photonic FEL (Netherlands)

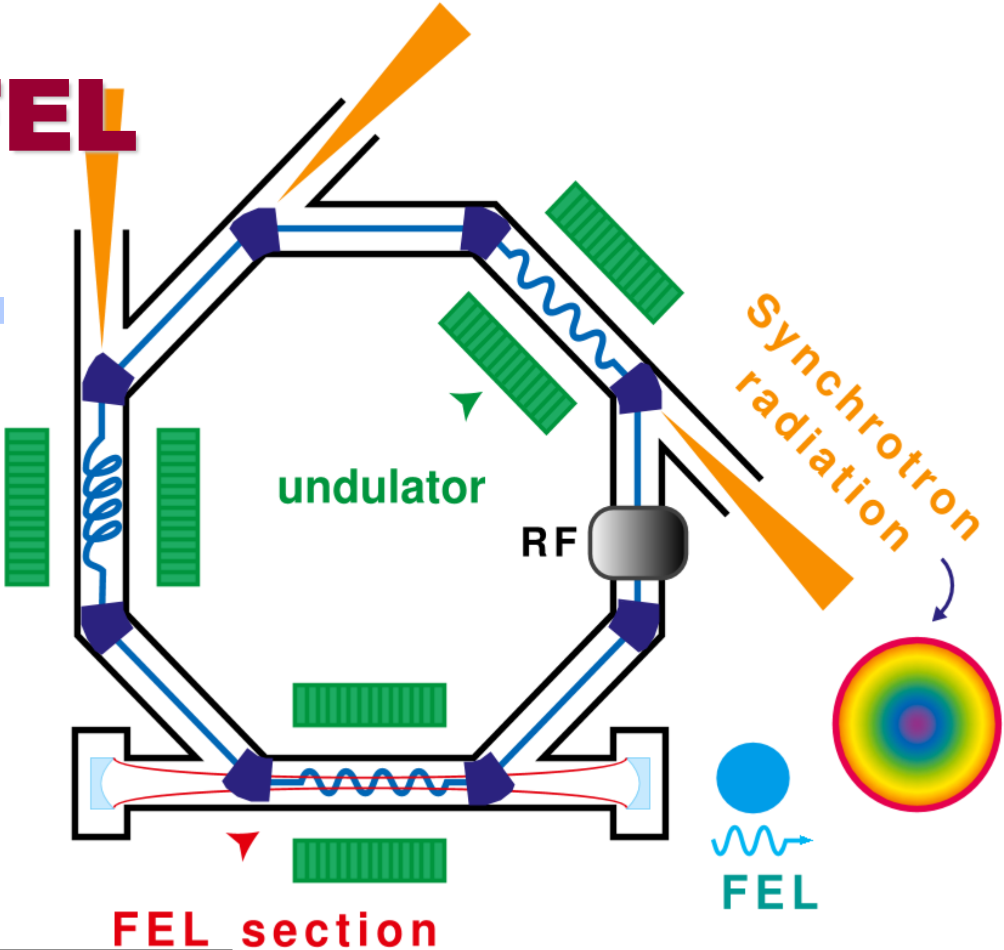
Proposed FELS

- WIFEL - University of Wisconsin, Madison (US)
- NGLS - Lawrence Berkeley Lab (US)
- SPARC Project - INFN (Italy)
- Daresbury 4GLS (UK)

Super-ACO FEL

Super-ACO (Orsay, France) is a 800 MeV storage ring dedicated for applications of synchrotron radiation that has been operated in Orsay since March 1987 till 2003.

The Super-ACO FEL (SRFEL) source has been the first storage ring FEL to provide coherent radiation for users in the UV, since 1993



The Super-ACO FEL	
Beam energy (MeV)	800
Laser-off bunch length $\sigma_{\tau,0}$ (rms, ps)	85
Laser-off beam energy spread σ_0 (rms)	$5.4 \cdot 10^{-4}$
Synchrotron damping time τ_s (ms)	8.5
Laser width at perfect tuning (rms, ps)	20
Laser width at the maximum detuning (rms, ps)	40
Laser wavelength (nm)	350
Pulse period (two bunches operation) ΔT (ns)	120
Laser-off peak gain g_i (%)	~ 2.5
Cavity losses P (%)	~ 0.5

An application of laser–plasma acceleration: towards a FEL amplification

Plasma Phys. Control. Fusion **58** (2016) 034020 M E Couprie *et al*

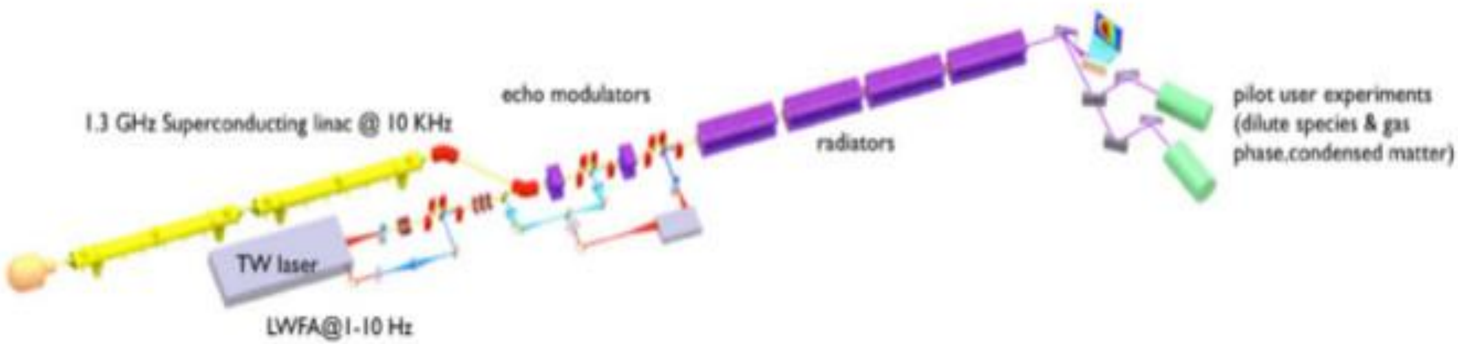
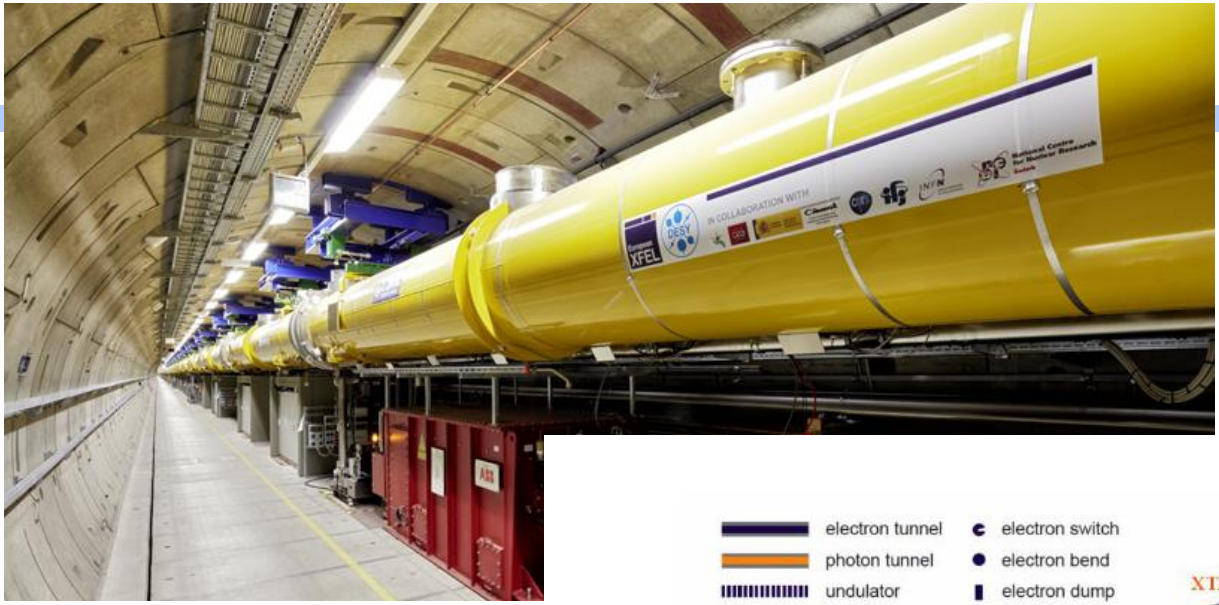


Figure 1. Sketch of the LUNEX5 (free-electron laser using a new accelerator for the exploitation of x-ray radiation of 5th generation) demonstrator of advanced and compact FEL in the 4–40 nm spectral range with 20 fs FEL pulses. LUNEX5 comprises two accelerators: a superconducting one for high repletion rate operation and multi-user operation, and a laser plasma accelerator to be qualified by the FEL application. The single FEL line will be composed of the most advanced seeding configurations: seeding with HHG (high order harmonics generated in gas), EEHG (echo-enable harmonic generation) and will be terminated by pilot-user experiments to characterize and evaluate the performance of these sources from a user perspective.

News, 04 May 2017*



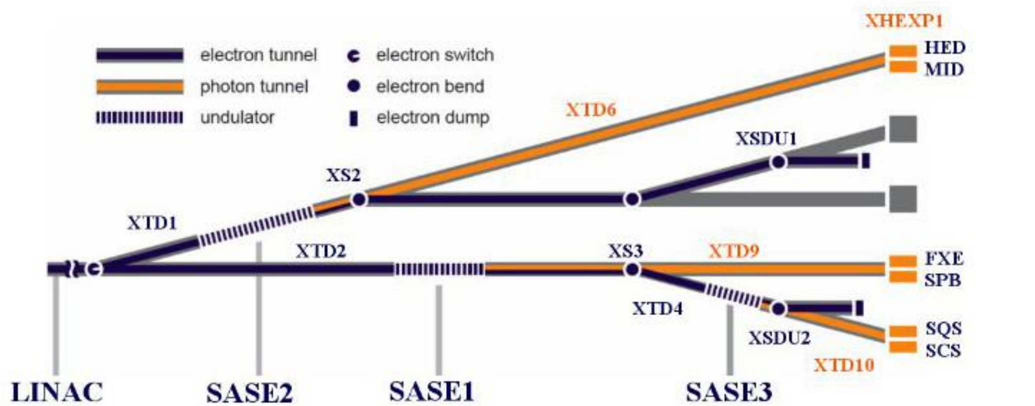


Figure 1: Schematic layout of the European XFEL facility showing the SASE undulators and corresponding experimental end stations.

Biggest X-ray laser in the world generates its first laser light. With its first lasing, the European XFEL reaches the last big milestone before the official opening

* http://www.xfel.eu/

FEL properties*

- **Tunability.** Because the FEL uses a single gain medium, the relativistic electron beam, and because the resonant condition can be easily tuned by changing either the electron beam energy or the magnetic field strength, FELs are broadly and easily tuned. A factor-of-10 tunable frequency range has already been demonstrated with the same accelerator and undulator.

- **High peak power.** Because waste energy is carried away at nearly the speed of light and because the lasing medium cannot be damaged by high optical fields, FELs can produce very high peak powers.

- **Flexible pulse structure.** Because the pulse structure of the radiation follows the pulse structure of the electron beam, the mature RF technology of linear accelerators can be used to manipulate and control the FEL pulse structure. Picosecond pulses with sub-picosecond jitter can be produced, the interval between pulses can be varied, and there is the possibility of producing complicated pulse structures.

*Free Electron Lasers and Other Advanced Sources of Light: Scientific Research Opportunities. The National Academies Press (1994) doi: 10.17226/9182

FEL properties*

- **Good laser characteristics.** FELs easily achieve desirable properties associated with conventional lasers, such as a single transverse mode, high spatial and temporal coherence, and flexible polarization properties.

- **Broad wavelength coverage.** Because the gain medium is transparent at all wavelengths, FELs in principle can produce radiation at any wavelength. In practice, electron-beam energy, current, emittance, and energy spread requirements become more stringent as the wavelength decreases, and the cost, size, and complexity of the FEL are therefore higher at shorter wavelengths.

- **Size and cost.** Because it requires an electron accelerator with its associated shielding, the FEL has not been a device that can be placed in an individual investigator's laboratory an FELs have been used principally in central facilities, where their utilization in scientific research involves associated costs of maintaining and operating the facility in addition to the cost of the device itself.

*Free Electron Lasers and Other Advanced Sources of Light: Scientific Research Opportunities. The National Academies Press (1994) doi: 10.17226/9182

Simulation programs*

Code	Description	Platform	Parallel	Source
Parmela (UCLA)	Particle Tracking	Linux, Mac	no	yes
Homdyn	Particle Tracking	Linux, Mac	no	no
Tredi	Particle Tracking	Linux	yes	yes
QUINDI	Particle Tracking and Lienard-Weichert	Linux	yes	yes
Genesis 1.3	Particle Tracking	Linux, Mac	no	yes
Elegant	Particle Tracking	Linux, Mac, Win	no	no
Spur	Lienard-Weichert	Linux, Mac	yes	yes
fieldEye	Lienard-Weichert	Linux	yes	yes
Ampere	Maxwell Solver	Win	no	no
Poisson/Superfish	Maxwell Solver	Linux	no	yes
Gdfidl	Maxwell Solver	Linux	no	yes
Radia	Maxwell Solver	Mac, Win	no	no
HFSS	Maxwell Solver	Win	no	no
Magic	Plasma Dynamics	Win	no	no
OopicPro	Plasma Dynamics	Linux	yes	yes

*http://pbpl.physics.ucla.edu/Computing/Code_Overview/

System of equations for FEL simulation

REVIEWS OF MODERN PHYSICS, VOLUME 88, JANUARY–MARCH 2016

The physics of x-ray free-electron lasers

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(published 9 March 2016)

X-ray free-electron lasers (x-ray FELs) give us for the first time the possibility to explore structures and dynamical processes of atomic and molecular systems at the angstrom-femtosecond space and time scales. They generate coherent photon pulses with time duration of a few to 100 fs, peak power of 10 to 100 GW, over a wavelength range extending from about 100 nm to less than 1 Å. Using these novel and unique capabilities new scientific results are being obtained in atomic and molecular sciences, in areas of physics, chemistry, and biology. This paper reviews the physical principles, the theoretical models, and the numerical codes on which x-ray FELs are based, starting from a single electron spontaneous undulator radiation to the FEL collective instability of a high density electron beam, strongly enhancing the electromagnetic radiation field intensity and its coherence properties. A short review is presented of the main experimental properties of x-ray FELs, and the results are discussed of the most recent research to improve their longitudinal coherence properties, increase the peak power, and generate multicolor spectra.

DOI: 10.1103/RevModPhys.88.015006

System of equations for FEL simulation*

We now use the vectors $\vec{x}_B$ and $\vec{p}_B$ with components (ξ, ς) and $(\beta_B d\xi/cdt, \beta_B d\varsigma/cdt)$ and Eqs. (2.33) and (2.34) to write the betatron oscillation equations. Using also Eqs. (3.11), (3.18), and (3.34) we have the complete set of FEL equations

$$\frac{d}{cdt}\vec{x}_{B,n} = \frac{\vec{p}_{B,n}}{\beta_{B,F}}, \tag{3.36}$$

$$\frac{d}{cdt}\vec{p}_{B,n} = -\frac{\vec{x}_{B,n}}{\beta_{B,F}}, \tag{3.37}$$

$$\frac{d\Phi_n}{cdt} = k_U \beta_{z0}\left[1 - \frac{\gamma_R^2}{\gamma_n^2} - \frac{k_r}{2k_U\beta_{B,F}}\left(\frac{\vec{x}_{B,n}^2}{\beta_{B,F}} + \beta_{B,F}\vec{p}_{B,n}^2\right)\right], \tag{3.38}$$

$$\frac{d\gamma_n}{cdt} = \frac{eK}{2mc^2\gamma_n}(\alpha e^{i\Phi_n} + \text{c.c.}), \tag{3.39}$$

$$\left(\frac{\partial}{\partial z} + \frac{1}{c}\frac{\partial}{\partial t}\right)\alpha - \nabla_T^2 \frac{i\alpha}{2k_r} = 2\pi e n_e(x, y, z - \beta_0 ct) \times \left[K\left\langle \frac{e^{-i\Phi}}{\gamma}\right\rangle - \frac{ie\alpha}{mc^2 k_r}\left\langle\frac{1}{\gamma}\right\rangle\right], \tag{3.40}$$

for $n = 1, \ldots, N_e$.

This is a system of $6N_e + 1$ nonlinear equations with no simple analytical solution. It includes radiation diffraction, longitudinal and transverse electron dynamics, betatron oscillations for equal and constant focusing in the horizontal and vertical planes, and electron beam distribution in its six-dimensional phase space. It does not include quantum effects nor the effect of the radiation field on the electron velocities. In

*Pellegrini C., Marinelli A., Reiche S. Rev. Mod. Phys., Vol. 88(2016), 015006

1D system of equations for BWT, TWT, FEL etc.*

$$\partial^2\theta/\partial\zeta^2 = -\mathrm{Re}\left[F\exp(i\theta)\right],\ \ \partial F/\partial\tau - \partial F/\partial\zeta = \tilde{I},\ \ \tilde{I} = -\frac{1}{\pi}\int_0^{2\pi} e^{-i\theta}\,d\theta_0,$$

$$\theta|_{\zeta=0} = \theta_0,\quad \partial\theta/\partial\zeta|_{\zeta=0} = 0,\quad F|_{\zeta=L} = 0,$$

System is versatile in the sense that they remain the same within some normalization for a wide range of electronic devices (FEL, BWT, TWT etc.).

$$\frac{\partial\Phi_n}{\partial\bar{z}} = \eta_n, \tag{5.1}$$

$$\frac{\partial\eta_n}{\partial\bar{z}} = \hat{a}e^{i\Phi_n} + \mathrm{c.c.}, \tag{5.2}$$

$$\left(\frac{\partial}{\partial\bar{z}} + \frac{\partial}{\partial\bar{z}_1}\right)\hat{a} = \langle e^{-i\Phi}\rangle. \tag{5.3}$$

*N.S.Ginzburg, S.P.Kuznetsov, T.N.Fedoseeva. Izvestija VUZov - Radiophysics, 21 (1978), 1037
**Pellegrini C., Marinelli A., Reiche S. Rev. Mod. Phys., Vol. 88(2016), 015006

Simulation of FEL

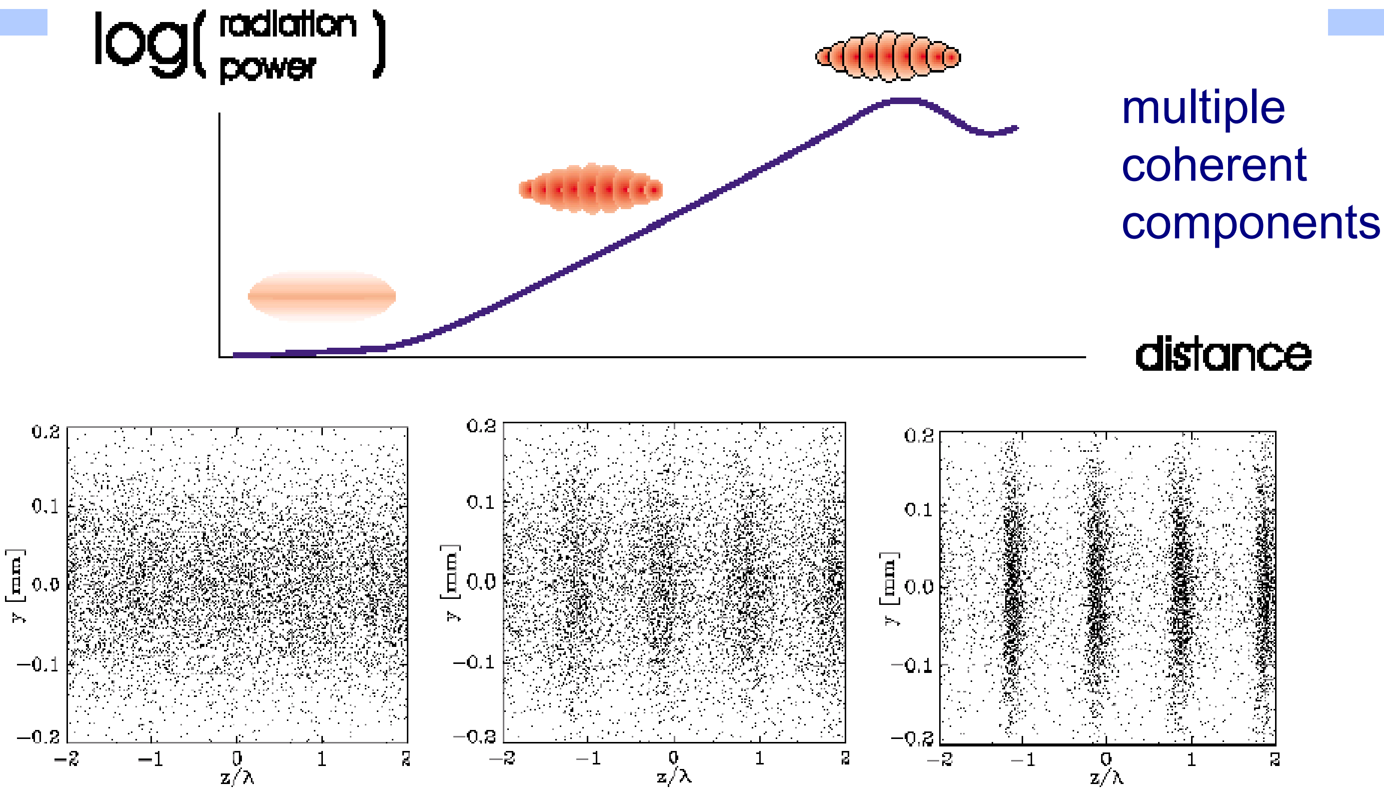


Figure 2.2.2.: *Example of the development of micro-bunching of the XFEL electron beam along*

TESLA Technical Design Report

Simulation of FEL

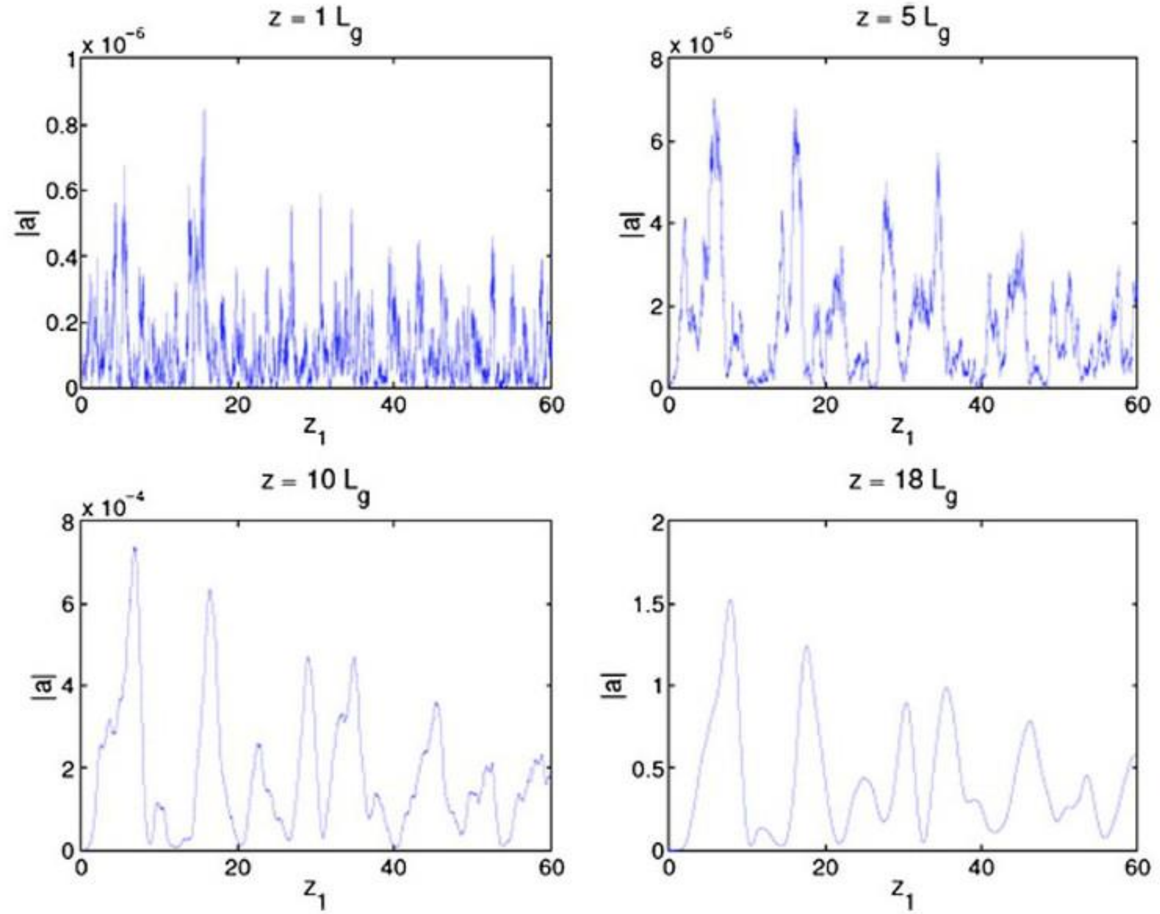


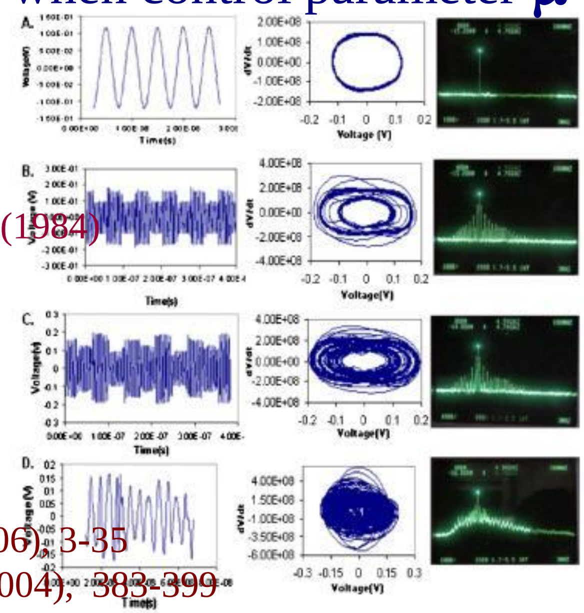
Figure 7. Evolution of the temporal profile of the radiation pulse of a SASE FEL. The coordinate z_1 gives the position along the electron bunch in units of the cooperation length and $|a|$ is proportional to the wave electric field amplitude. Reproduced with permission from [17].

Dynamical systems*

Chaotic dynamics means the tendency of wide range of systems to transition into states with deterministic behavior and unpredictable behavior.

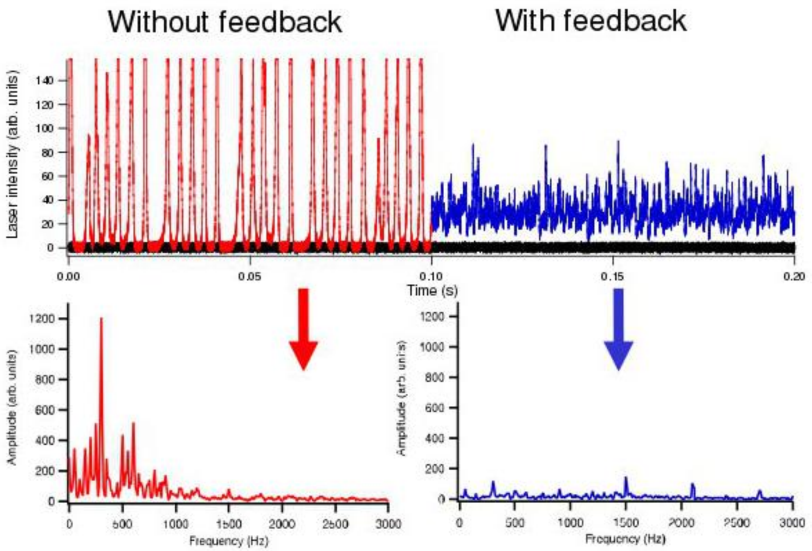
Nonlinearity is necessary but non-sufficient condition for chaos in the system. The main origin of chaos is the exponential divergence of initially close trajectories in the nonlinear systems. This is so-called the “Butterfly effect”** (the sensibility to initial conditions).

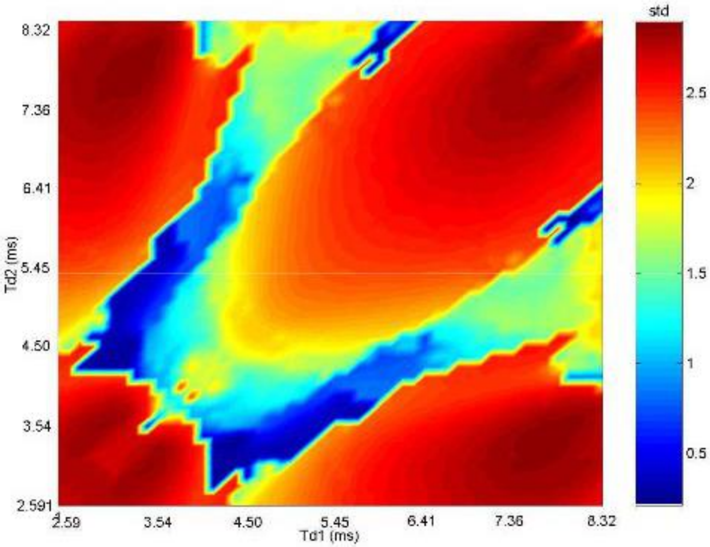
Bifurcation is any qualitative changes of the system when control parameter μ passes through the bifurcational value μ_0.



*H.-G. Schuster, "Deterministic Chaos" An Introduction, Physik Verlag, (1984)
** E.N. Lorenz, J. Atmos. Sci. 20 (1963), 130
Hur M. S. et al. Phys. Rev. E58 (1998), 936-941
Ninno G., Fanelli. D. Phys. Rev. Let. 92 (2004), 094801
Bruni C. et al. Nucl. Instr. Meth. A528 (2004), 273-277
Thomas C.A. et al. Eur. Phys. J. D32 (2005), 83-93
Marchewka C. et al. Phys. Plasma (2006),13, 013104
Kuznetsov S.P. Izvestija VUZov - Applied Nonlinear Dynamics, 14 (2006), 3-35
Kuznetsov S.P., Trubetskov D.I. Izvestija VUZov – Radiophysics, 47 (2004), 383-399

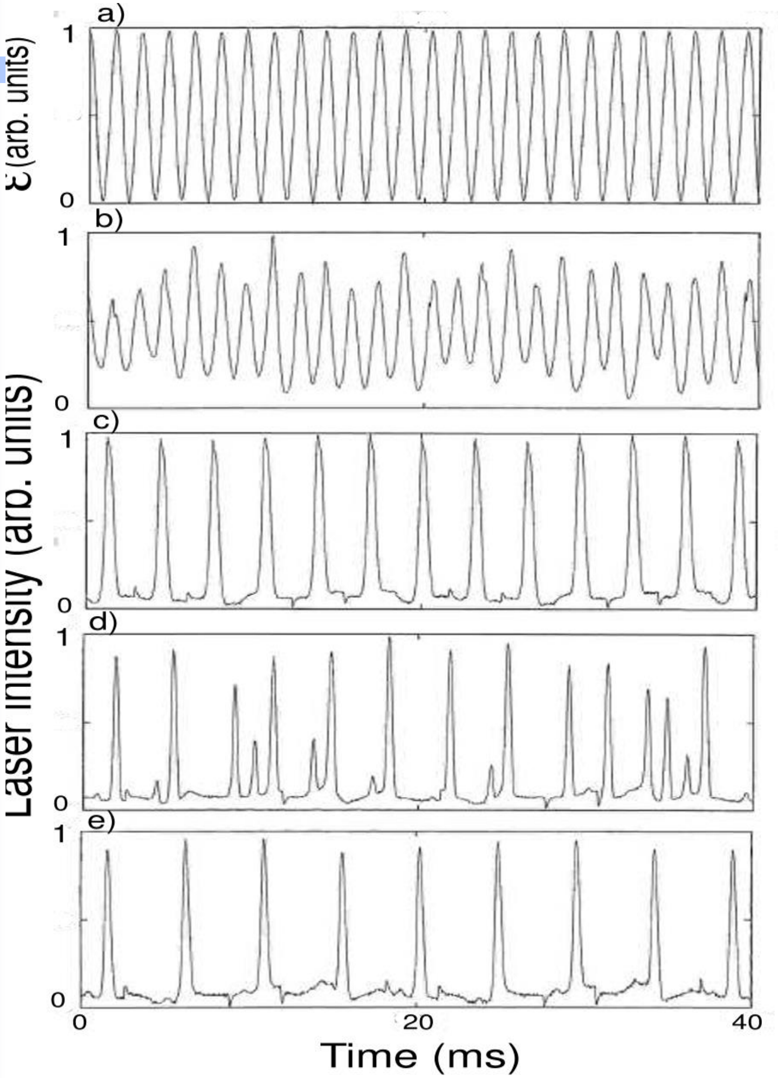
Chaos in FEL

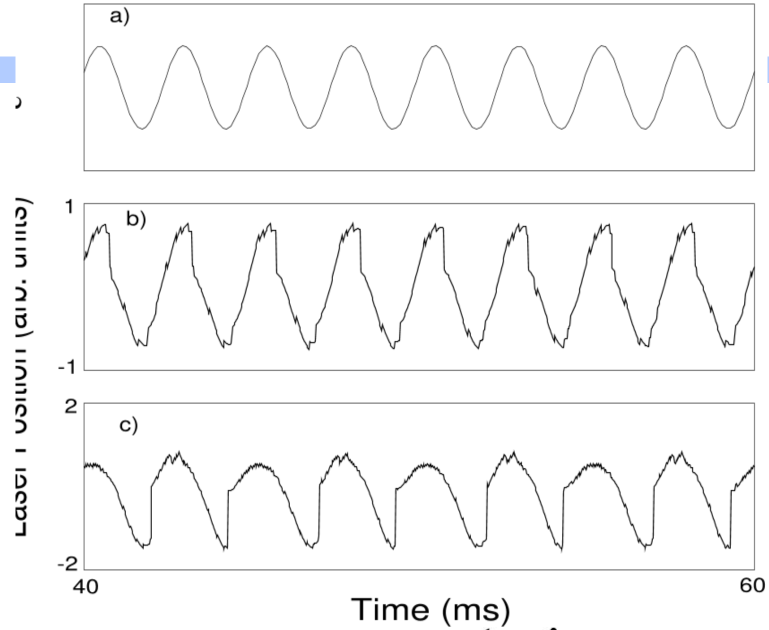


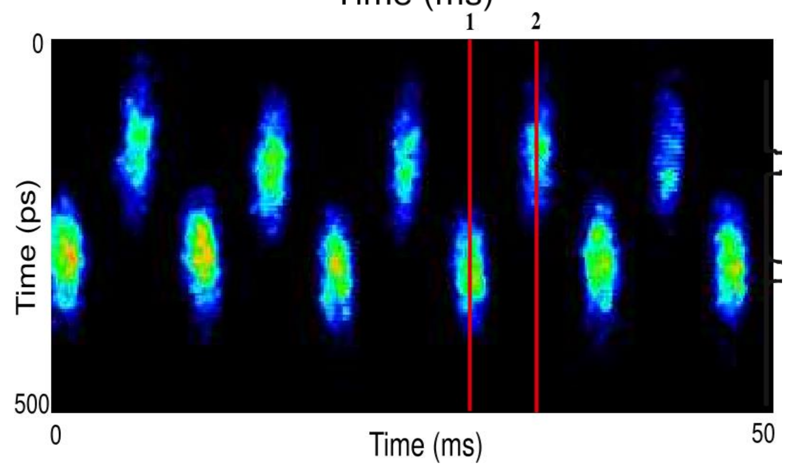


*M. Billardon. Storage ring free-electron laser and chaos Phys. Rev. Lett. 65 (1990), 713
S.J. Hahn, J.K. Lee. Bifurcations in a short-pulse free-electron laser oscillator. Physics Letters A 175 (1993) 339-343

Chaos in Super-ACO FEL*







*De Ninno, G., Fanelli, D., Bruni, C. et al.. Eur. Phys. J. D (2003) 22: 269.
C. Bruni et al. Eur. Phys. J. D 55, 669-677 (2009)

Dynamical diffraction*

In accordance with Landau** an expression for the dielectric permittivity of a crystal can be used to describe the diffraction of X-ray quanta in a crystal, which is independent of the polarization of the photon as a spatially periodic function:

$$\varepsilon(\mathbf{r},\omega) = \sum_{\tau} \varepsilon(\tau,\omega)\exp(-i\boldsymbol{\tau}\mathbf{r})$$

$$\boldsymbol{\tau} = \left(\frac{2\pi}{d_1}, \frac{2\pi}{d_2}, \frac{2\pi}{d_3}\right)$$

$$\varepsilon(0,\omega)=1+\chi_0 \ ,$$

$$\varepsilon(\pm\tau,\omega)=\chi_{\pm\tau}$$

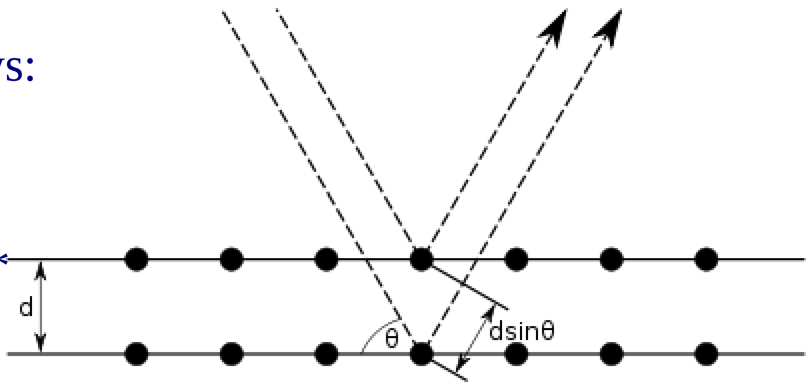
$\boldsymbol{\tau}$ is a reciprocal lattice vector.

Electrical induction is represented as follows:

$$\mathbf{D}(\mathbf{r},t) \approx \varepsilon(\mathbf{r},\omega)\mathbf{E}(\mathbf{r},t)$$

The well-known Bragg equation determines the Bragg diffraction angle*,***

$$2k\sin\Theta = \tau$$



The scattering amplitudes increase sharply when

$$\mathbf{k}_{\tau} = \mathbf{k} + \boldsymbol{\tau}$$

*Bragg, W.H.; Bragg, W.L.(1913) "The Reflexion of X-rays by Crystals". *Proc R. Soc. Lond. A.* **88** (605): 428–38.

** Landau & E.M. Lifshitz Electrodynamics of Continuous Media (Vol. VIII).

***Выведено в 1913 независимо У. Л. Брэггом и Г. В. Вульфом (Википедия).

Dynamical diffraction*

The Reflection of X-rays by Crystals.

By W. H. Bragg, M.A., F.R.S., Cavendish Professor of Physics in the University of Leeds; and W. L. Bragg, B.A., Trinity College, Cambridge.

(Received April 7,—Read April 17, 1913.)

In a discussion of the Laue photographs it has been shown* that they may conveniently be interpreted as due to the reflection of X-rays in such planes within the crystal as are rich in atoms. This leads at once to the ... gives a reflected pencil from its cleavage plane strong enough to make a ... has also been observed that the reflected pencil can be detected by the ionisation method.†

For the purpose of examining more closely the reflection of X-rays in ... an ionisation chamber taking the place of the telescope. The collimator is replaced by a lead block pierced by a hole which can be stopped down to ... crystal. The ionisation chamber is tubular, 15 cm. long and 5 cm. in diameter. It can be rotated about the axis of the instrument, to which its own axis is perpendicular. It is filled with sulphur dioxide in order to increase the ionisation current: both air and methyl iodide have also been used occasionally to make sure that no special characteristics of the gas in

* W. L. Bragg, 'Proc. Camb. Phil. Soc.,' vol. 17, Part I, p. 43.
† W. H. Bragg, 'Nature,' Jan. 23, 1913.

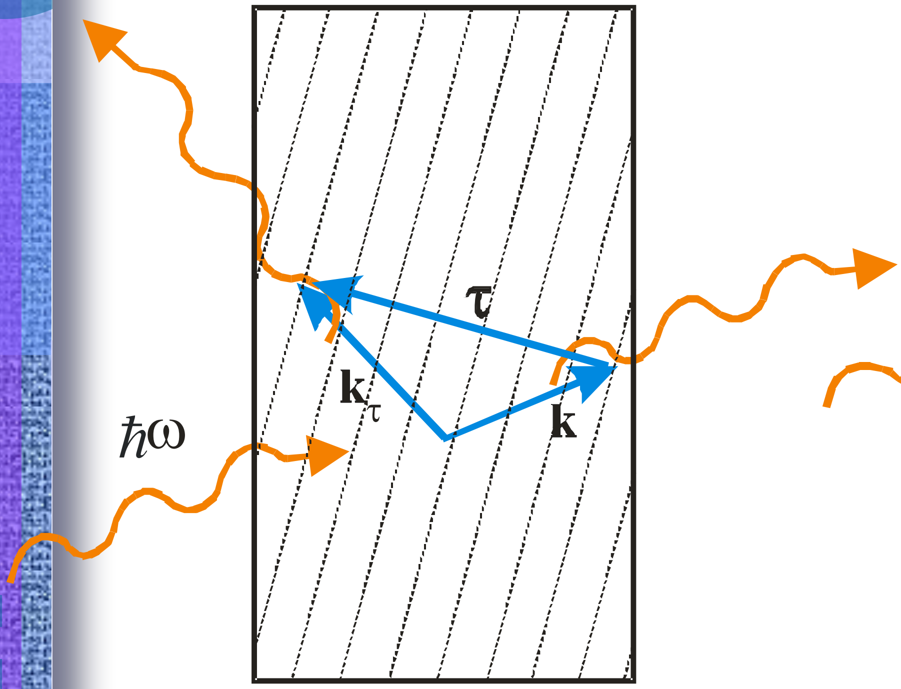
Nobel Prize 1914: Max von Laue - "For his discovery of the diffraction of X-rays by crystals",an important step in the development of X-ray spectroscopy.

Nobel Prize 1915: William Henry Bragg and William Lawrence Bragg - "For their services in the analysis of crystal structure by means of X-rays",an important step in the development of X-ray crystallography

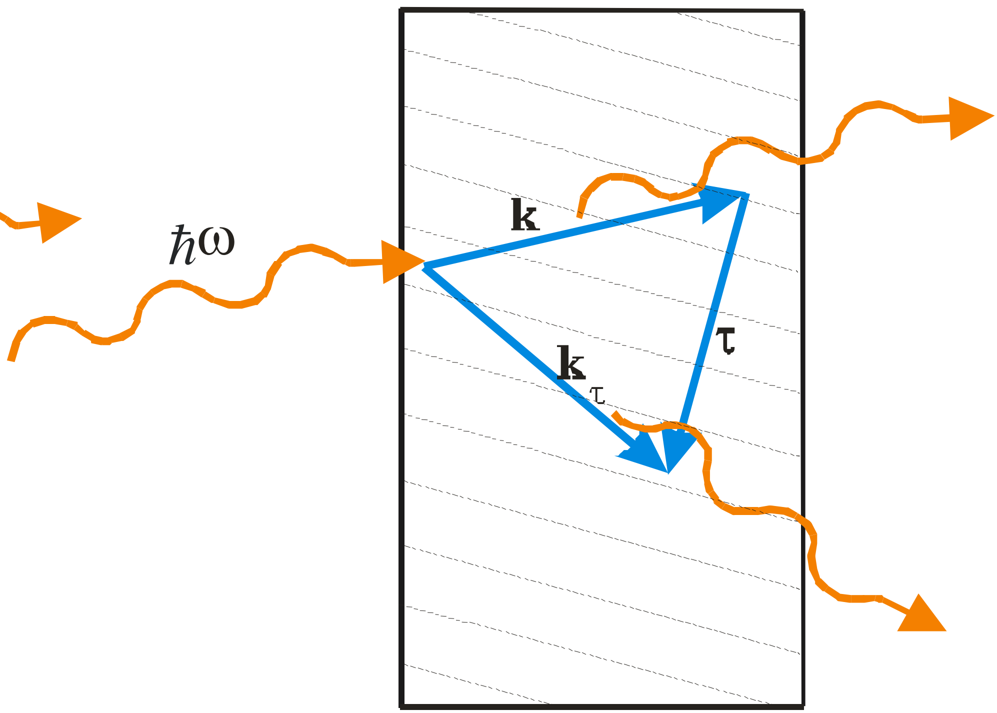
*****Bragg, W.H.; Bragg, W.L. (1913). *Proc R. Soc. Lond. A.* **88** (605): 428–38.

Different diffraction geometries

Bragg geometry



Laue geometry



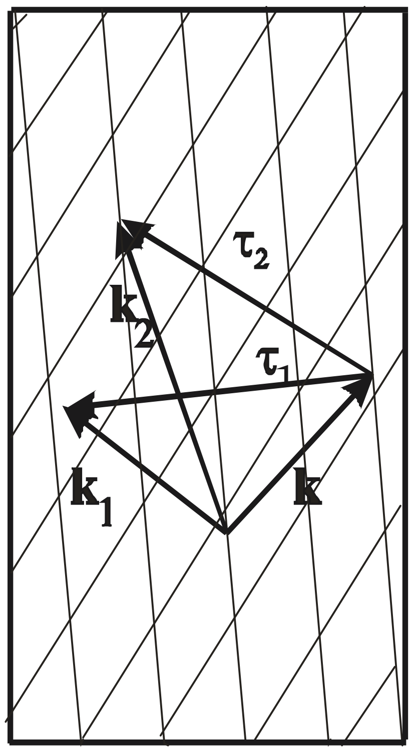
τ is a reciprocal lattice vector.

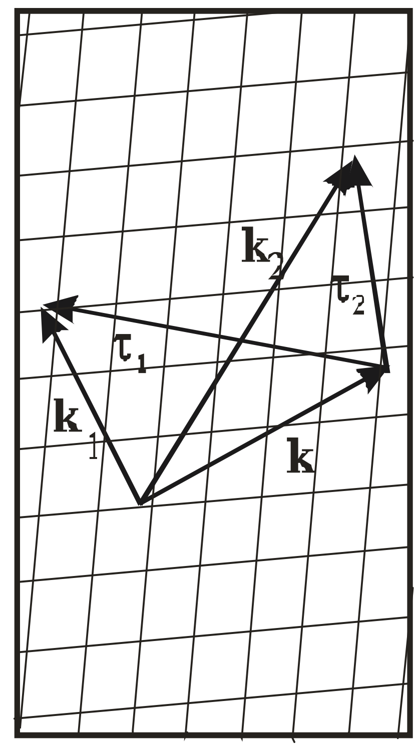
Principles of diffraction are valid from X-ray to THz range.

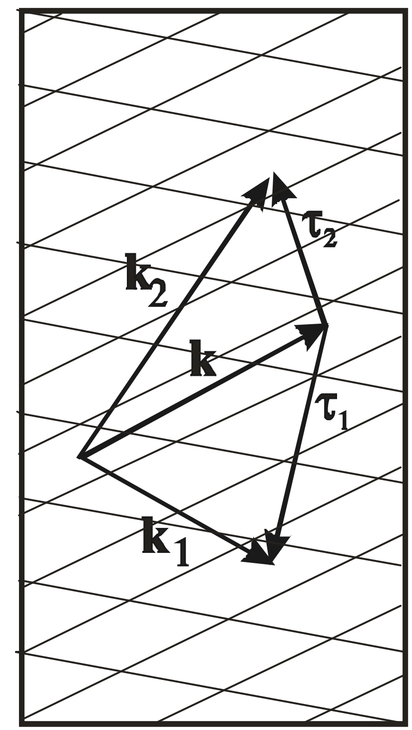
Different diffraction geometries

Bragg-Bragg geometry

Laue-Laue geometry

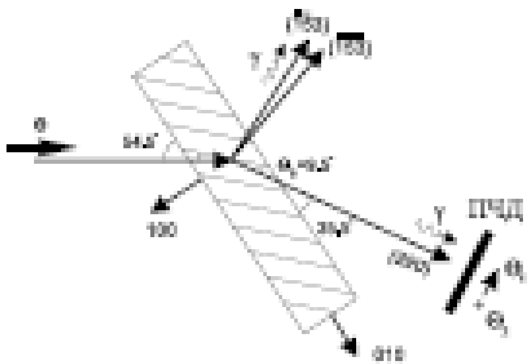


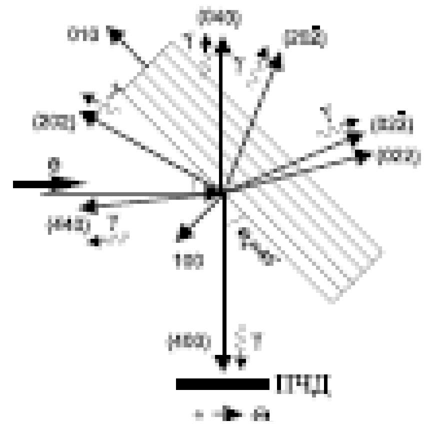




Bragg-Laue geometry

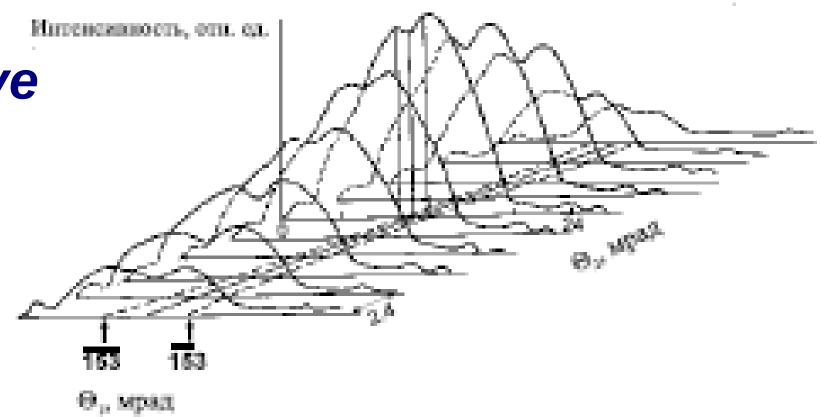
Experiments on multiwave X-ray dynamical diffraction*





Scheme of experiments

4-wave ***8-wave***



Experimental results

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

Parametric (quasi-Cherenkov) radiation

Cherenkov radiation*, also known as Vavilov–Cherenkov radiation is electromagnetic radiation emitted when a charged particle passes through a dielectric medium at a speed greater than the phase velocity of light in that medium. **Nobel Prize 1958 - P.A.Cherenkov, I.Frank, I.Tamm "for the discovery and the interpretation of the Cherenkov effect".**
According to Landau (vol.VIII), the dielectric permittivity ε<1 (the refractive index $n = \sqrt{\varepsilon} < 1$ and the Vavilov-Cerenkov radiation in the X-ray region should be absent. However, in 1971, Baryshevsky** showed that, nevertheless, when a large-energy particle moves through a crystal due to the diffraction of emitted photons in a crystal, it is possible that X-ray induced radiation (and, as a consequence, spontaneous) Vavilov-Cherenkov radiation.
A new type of radiation was called parametric X-ray radiation (PXR).
Its origin is due to the fact that in a periodic medium, which is a crystal, photons have several refractive indices, among which there are refractive indices of $n > 1$ in the X-ray (and γ-) range. PXR generation in a crystal is accompanied by excitation in the X-ray range of waves with $n > 1$ (slow waves) and waves with $n<1$ (fast waves).

*Cherenkov, P. A. Doklady Akademii Nauk SSSR. **2**(1934) 451.
Baryshevsky V.G. Dokl. Academy of Sciences of the BSSR, **15 (1971), 306.

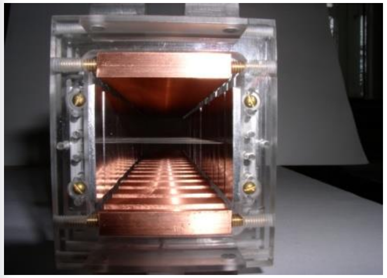
The history of VFEL (Volume Free Electron Laser) experiments

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

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

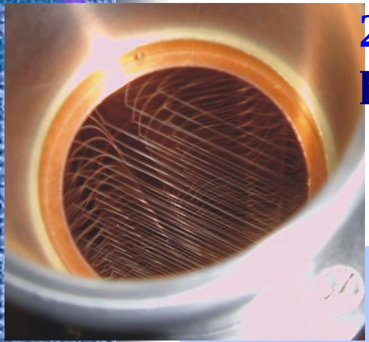
2001 The first VFEL generation in the millimeter range. Experimental verification of VFEL principles. Demonstration of frequency tuning for a fixed electron energy

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

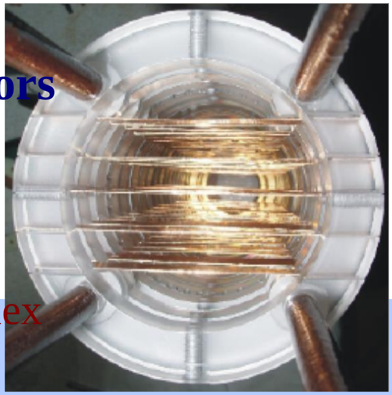


2004 VFEL with grid resonator

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

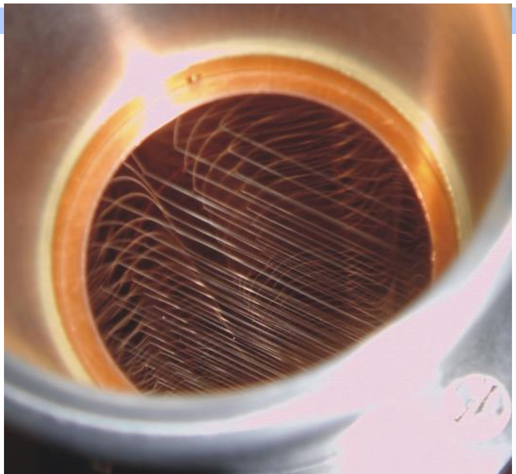


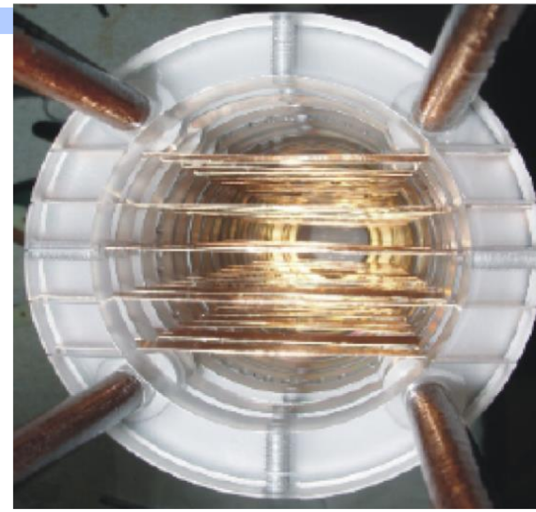
2009 VFEL with grid and foil resonators. Such resonators have all properties of photonic crystals.

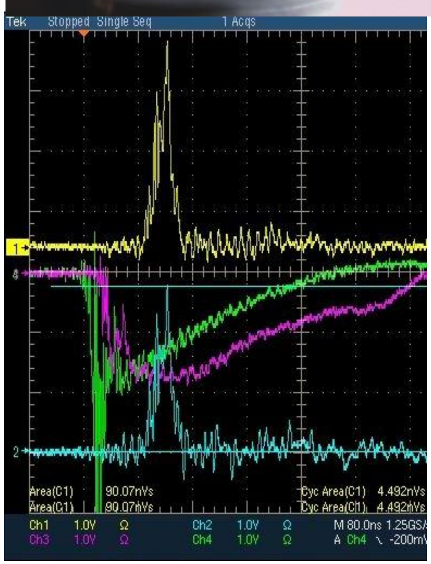


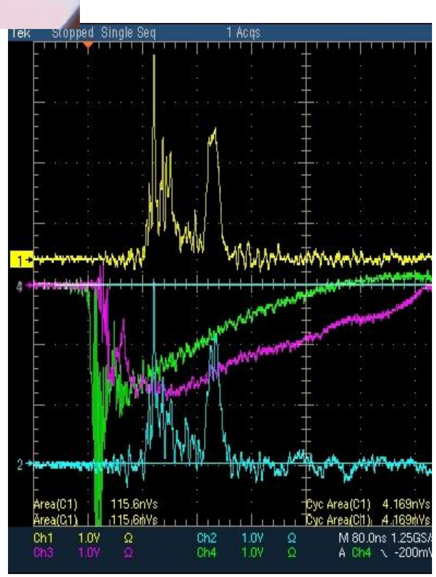
V. G. Baryshevsky et al. Proc. IRMMW-THz 2010; Proc. FEL2010. Nuovo Cimento 34 (2011), 199, Nonl. Phen. Complex Syst., vol. 16, no. 3 (2013), 209 - 216

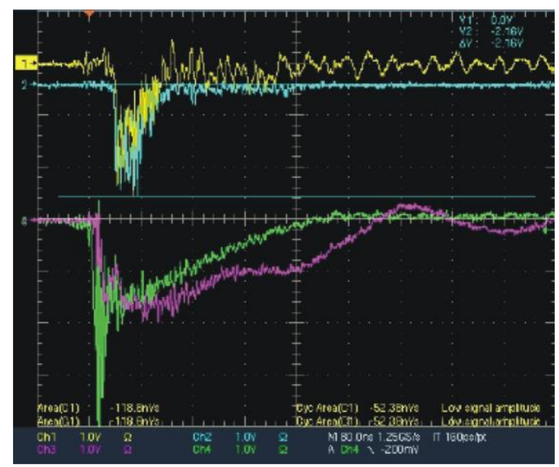
VFEL with grid and foil resonators*







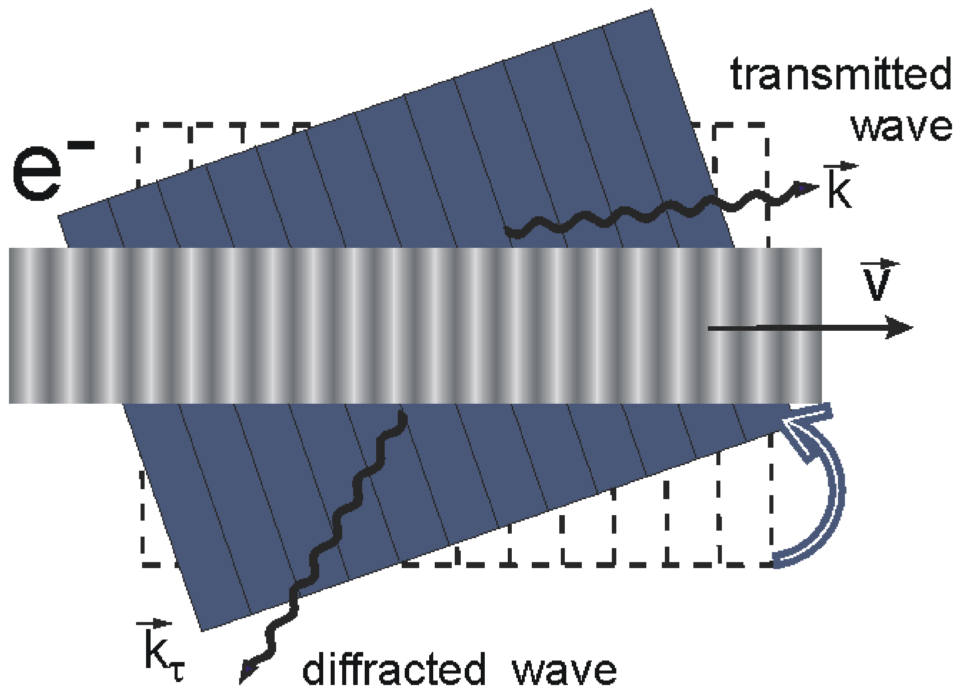




*V.G.Baryshevsky et al. Proc. IRMMW-THz 2010; Proc FEL2010

Distinctive VFEL feature

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



*V.G.Baryshevsky, I.D.Feranchuk, Phys.Lett. **102A** (1984) 141,
V.G.Baryshevsky. Dokl. Akad.Sci.USSR **229** (1988) 1363

New law of instability* for an electron beam passing through a spatially-periodic medium

The increment of instability in degeneration points:

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

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

Threshold current in degeneration points:

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

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

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

*V.G.Baryshevsky, I.D.Feranchuk, Phys.Lett. 102A (1984) 141,
V.G.Baryshevsky, Proc. of the USSR Nat. Ac. Sci., 299(1988), 1363-1366

Main physical VFEL principles

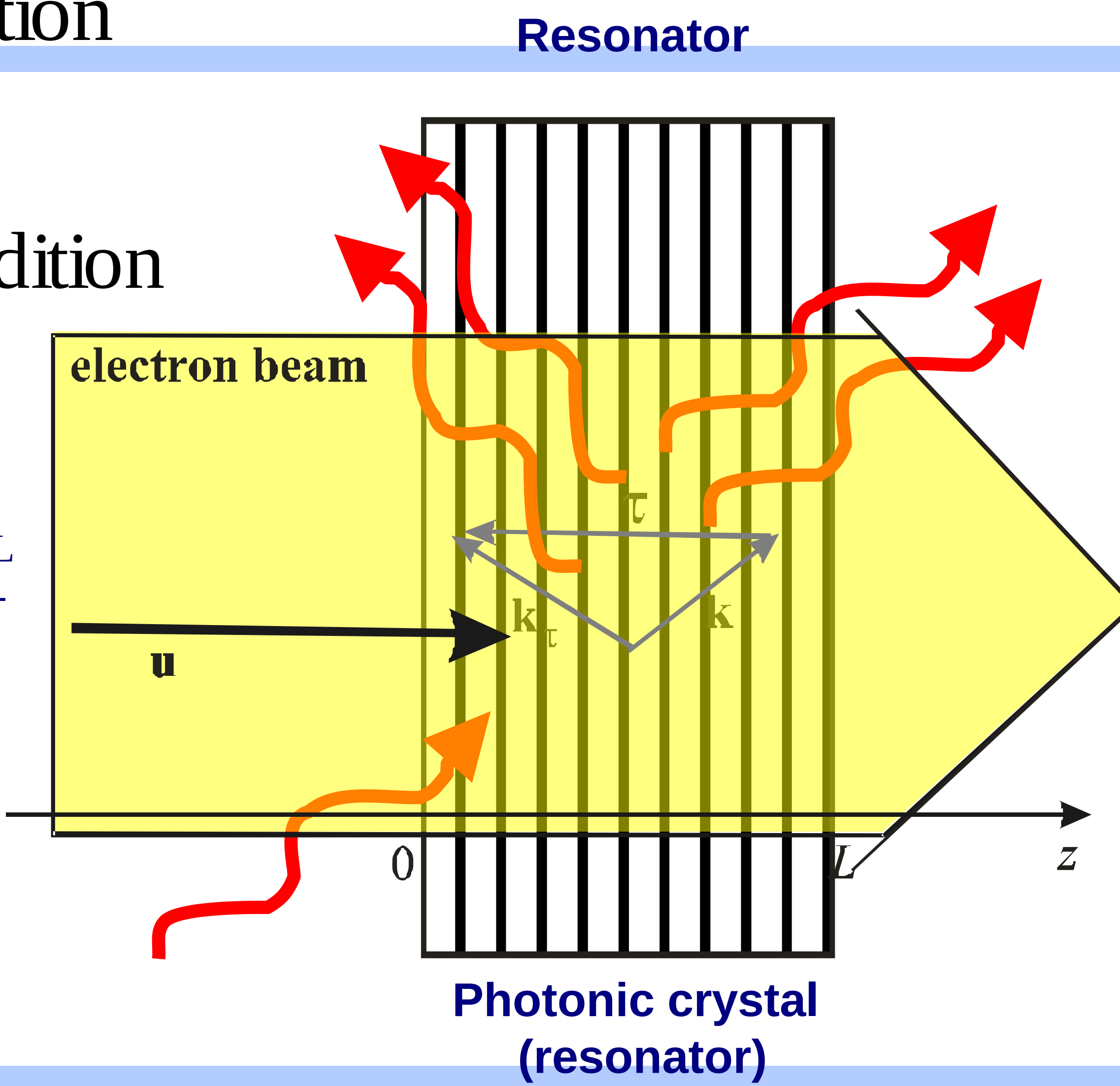
Diffractio n condition

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

Synchronis m condition

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

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



Maxwell equations:

$$\Delta\mathbf{E} - \nabla(\nabla\mathbf{E}) - \frac{1}{c^2}\frac{\partial^2\mathbf{D}}{\partial t^2} = \frac{\partial\mathbf{j}_\mathrm{b}}{\partial t},$$

n-wave approximation:

$$\mathbf{E} = \sum_{j=1}^{n}\mathbf{e}E_j e^{i(\mathbf{k}_j\mathbf{r}-\omega t)}, \qquad \dot{\mathbf{j}}_\mathrm{b} = \sum_{l=1}^{m}\mathbf{e}\dot{j}_l e^{i(\mathbf{k}_j\mathbf{r}-\omega t)},$$

$$\mathbf{D}(\mathbf{r},t) \approx \varepsilon(\mathbf{r},\omega)\mathbf{E}(\mathbf{r},t),$$

$$\varepsilon(\mathbf{r},\omega) = \sum_{\tau}\varepsilon(\tau,\omega)\exp(-i\tau\mathbf{r}),$$

$$\varepsilon(0,\omega) = 1 + \chi_0,\ \varepsilon(\tau,\omega) = \chi_\tau,\ \varepsilon(-\tau,\omega) = \chi_{-\tau}$$

Motion equation:

$$\frac{d\mathbf{p}}{dt} = e\left\{\mathbf{E} + \frac{1}{c}[\mathbf{v}\times\mathbf{H}]\right\}, \qquad \mathbf{p} = m\gamma\mathbf{v},$$

$$\frac{d^2z}{dt^2} = \frac{e}{m\gamma^3}(\mathbf{e}\mathbf{n})\mathrm{Re}\left[Ee^{i\theta(t,t_0,\mathbf{r}_\perp)}\right]$$

We use the method of averaging over initial phases of electron entrance in the resonator

$$\theta(t,t_0,\mathbf{r}_\perp) = k_z z + \mathbf{k}_\perp\mathbf{r}_\perp - \omega t(z,t_0)$$

electron phase in a wave

Two-wave VFEL*

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

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

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

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

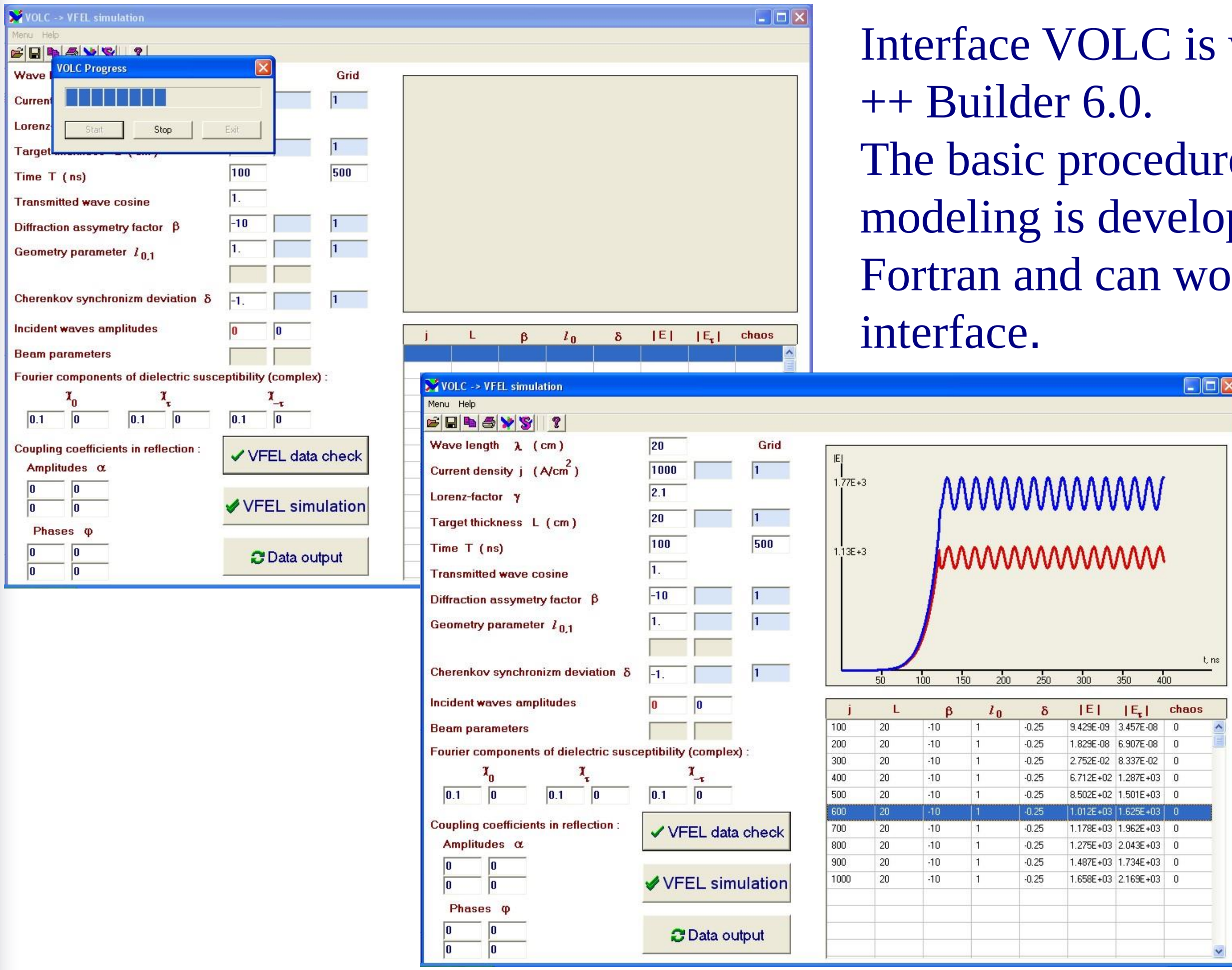
$$\frac{d^2\theta(t,z,p)}{dz^2} = \frac{e\Phi}{m\gamma^3\omega^2} \left(k - \frac{d\theta(t,z,p)}{dz} \right)^3 \mathrm{Re}\left(E(t - z/u, z) \exp(i\theta(t,z,p)) \right),$$

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

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

*Batrakov K., Sytova S. Comp. Math. Math. Phys. **45** (2005) 666–676

VOLC (“*VOLume Code*”)*



Interface VOLC is written on Borland C ++ Builder 6.0.
The basic procedure for the VFEL modeling is developed in Compaq Visual Fortran and can work without the VOLC interface.

*Sytova S. Proc. FEL2007 Aug 26–31 2007 Novosibirsk, Russia. P.14-17

Main numerical results

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

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

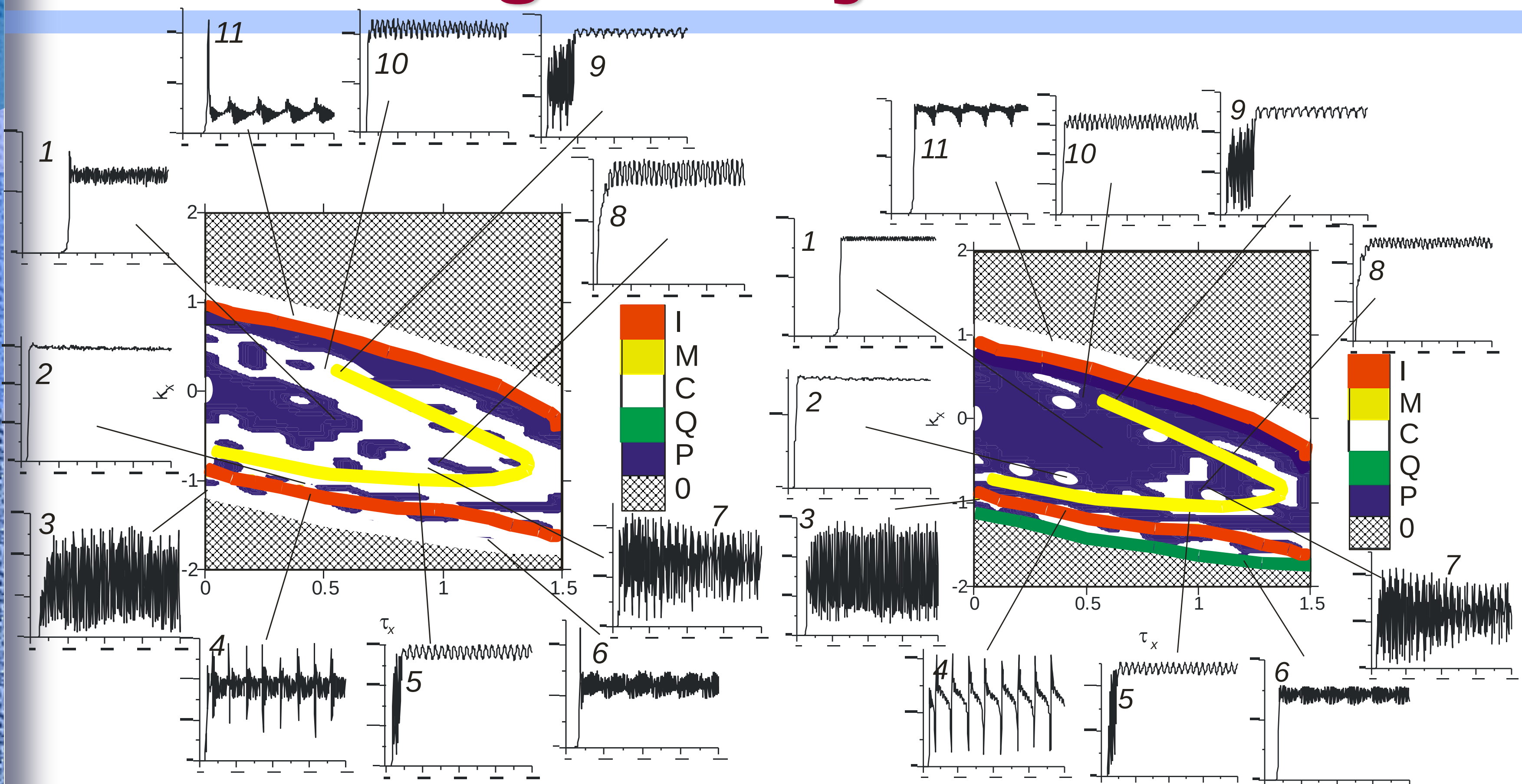
Origin of VFEL chaotic nature

Chaos in electronic devices such as BWT, TWT, etc. is due to the delayed nature of distributed feedback.

Source of the chaos in VFEL has more complicated nature because of the interaction of the electron beam with the electromagnetic field in a volume distributed feedback in resonator under the conditions of dynamical diffraction. This leads to a nonuniform distribution of electromagnetic field intensity and to significant perturbations in the motion of the electrons and thus to a variety of VFEL dynamics.

VFEL chaotic dynamics depends on dispersion of initial pulse in photonic crystal (periodic media) under Bragg diffraction (time delay and appearance of intricate temporal structure such as nonregular time beating and delayed response from the output grating interface, as well as simultaneous generating of some modes.

Parametric maps of the transition to chaos in dependence of the diffraction geometry



0 depicts a domain under generation threshold. P, Q, C correspond to periodic regimes, quasiperiodicity and chaos, respectively. M describes domains with transitions between large-scale and small-scale amplitudes. I stands for intermittency. On edges the most typical dependencies of amplitudes on going crystal on time are presented.

Conclusions

- As VFEL physical principles differ from ones of other vacuum electronic devices VFEL is a new object of investigation, that is the source of powerful electromagnetic radiation in different wavelength ranges.
- So, each step in investigation of VFEL nonlinear dynamics will profit some new results.

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Thank you for attention!

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