Review of current research of nonlinear processes of radiation in vacuum electronic devices

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Motivation

Let us consider some physical phenomena and devices based on nonlinear processes of radiation of charged particles in various types of electronic vacuum devices. Such devices are functioning in the wide spectrum range from microwave to X-ray.

The purpose is to demonstrate the variety of such devices with their obvious generality in used physical principles, as well as the complex nonlinear dynamics of their functioning.

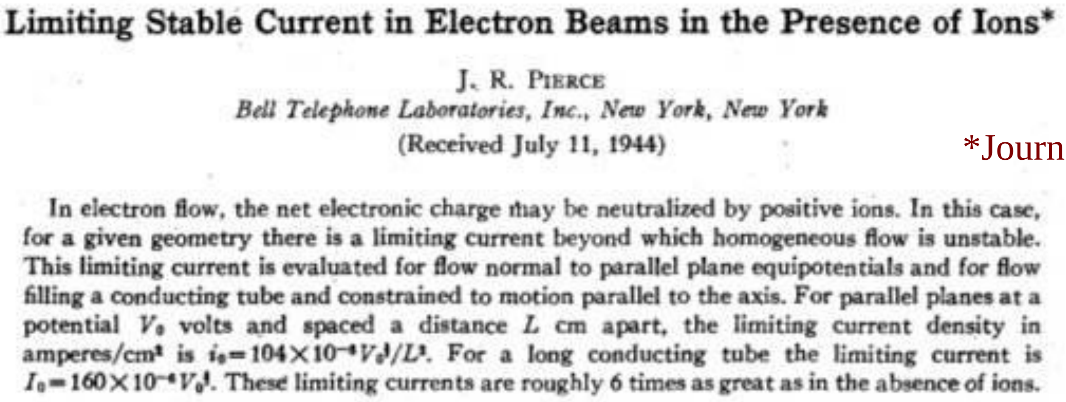
Theoretical and experimental research of each new type of such devices is of great importance for science and practice.

The performance and reliability of electronic vacuum devices are based on complex electromagnetic structures, new materials and advanced technologies. The widespread use of such devices in military and commercial applications requires them to operate reliably with high power, high efficiency, and low cost.

Outline

- Vacuum electronic devices (VED):
  - Travelling wave tubes (TWT)
  - Backward-wave tubes (BWT)
  - Multi-wave Cherenkov generators (MWCG)
  - Free electron lasers (FEL)
  - Free electron masers (FEM)
  - Volume free electron lasers (VFEL)
- VED as dynamical systems
- Conclusions

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.

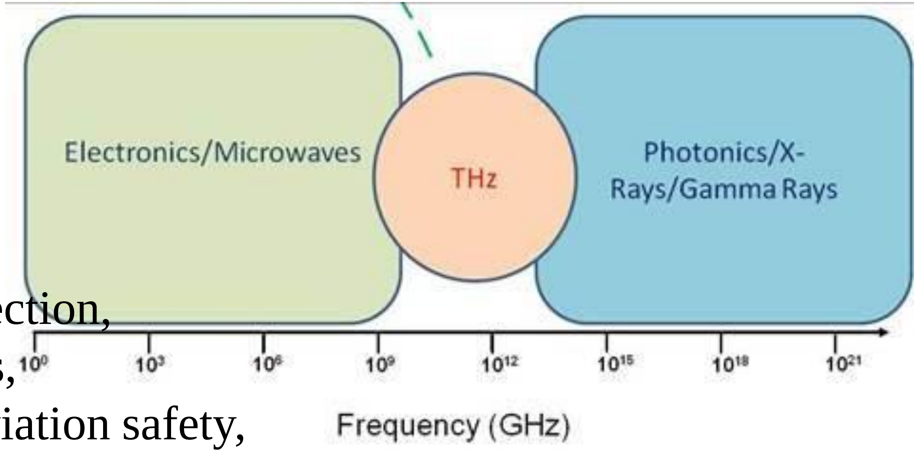
*Journal of Applied Physics 15, 721 (1944)

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.

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.

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 including various microwave heating devices for industrial and domestic use

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

https://sites.google.com/view/mmwave/research/%C2%B5-wave-vacuum-electronics

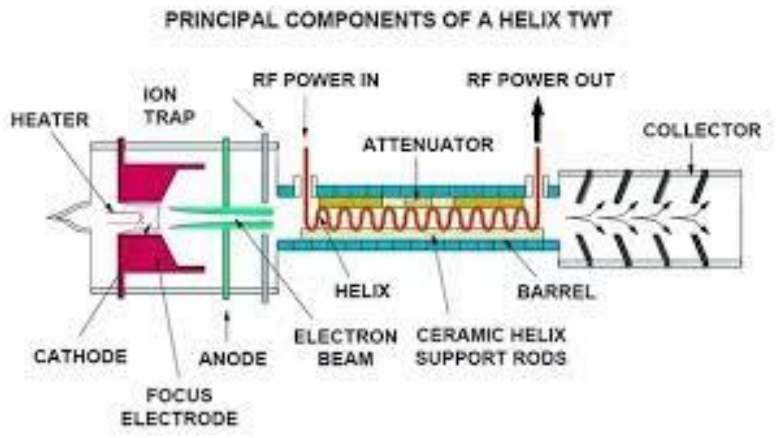
Vacuum electronic devices

Scientific important applications*

- high-energy particle accelerators,
- plasma heating for controlled thermonuclear fusion,
- in medical systems as compact accelerators for nuclear magnetic resonance

*J. Benford, J.A.Swegle, E. Schamiloglu. High Power Microwave. CRC Press, 2016.
T.C. Marshall, Free Electron Laser. McMillan, New York, 1985.
H. P. Freund, T. M. Antonsen, Jr. Principles of Free Electron Lasers. Springer, 2018.
V.G. Baryshevsky. High-energy nuclear optics of polarized particles. World Scientific Publishing Company, 2012.
V.G. Baryshevsky, I.D. Feranchuk, A. P. Ulyanenkov. Parametric X-ray Radiation in Crystals. Theory, Experiments and Applications. Springer, 2005.
B. Steinar. The physics of HPM sources. FFI-rapport 2008/00014, 2008-01-04.
L.A. Weinstein, V.A. Solntsev. Lectures on microwave electronics. Sov. Radio, 1973 (In Russian).
D.I. Trubetskov, A.E. Hramov. Lectures on microwave electronics for physicists: in 2 vol. FIZMATLIT, 2003, 2004 (In Russian).

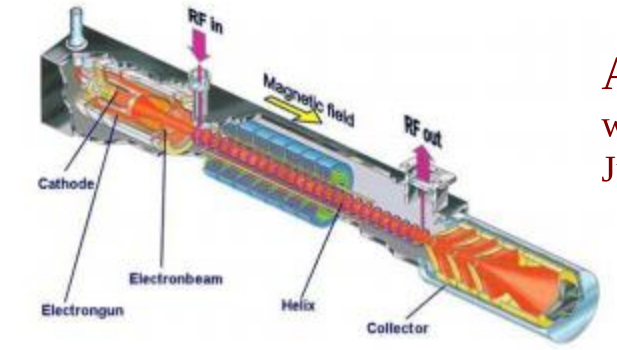
Vacuum electronic devices - TWT



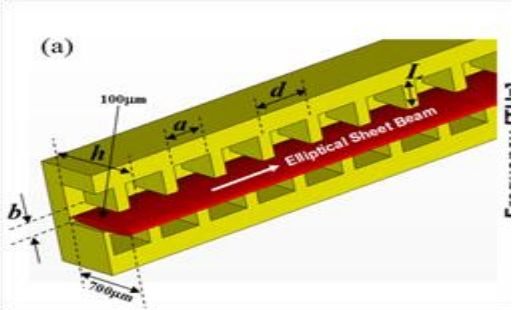
A major advantage of the TWT over some other microwave tubes is its operation at large bandwidth. Operating frequencies range from 300 MHz to 50 GHz.The output power ranges from a few watts to MWt. TWTs account for over 50% of the sales volume of all microwave vacuum tubes.

R. Kompfner. The traveling wave tube. Wireless World LII. 1946. P. 369–372.
Kompfner, R. Travelling-wave tubes / R. Kompfner. The traveling wave tube. Reports on Progress in Physics. 1952. Vol. 15. P. 275–327.
J. R. Pierce, Traveling Wave Tubes. Bell Technical Journal. Vol. 29, Iss.3. 1950. P. 390-460.
D. Shiffler, J. A. Nation, G. S. Kerslick. TWT Amplifier. IEEE Transactions on Plasma Science. 1990. Vol. 18, №3. P. 546–552.
G. S. Nusinovich, B. Levush, D. K. Abe. Review of the Development of Multiple-Beam Klystrons and TWTs. Naval Research Laboratory; NRL/MR/6840-03-8673.

Vacuum electronic devices - TWT



A. Aïssi, F. André, F. Doveil. New model of a travelling-wave tube. Proc. 35th EPS Conf. on Plasma Physics, 9–13 June, 2008. P. 5.090.



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

Young-Min, S., et al., *Modeling Investigation of an Ultrawideband Terahertz Sheet Beam Traveling-Wave Tube Amplifier Circuit.* Electron Devices, IEEE Transactions on, 2011. 58(9): p. 3213-3218.

Vacuum electronic devices - TWT

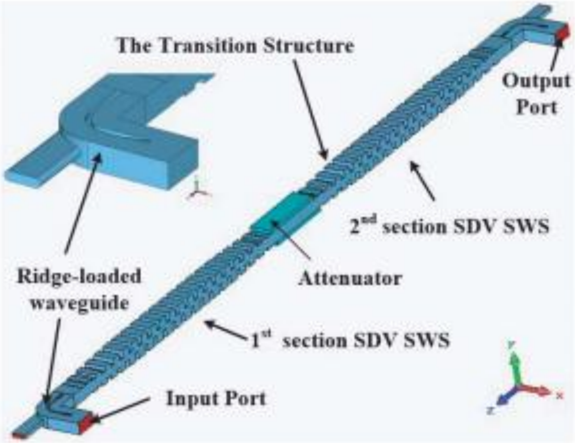


Figure 1. Typical SDV TWT with ridge-loaded input/output coupler.

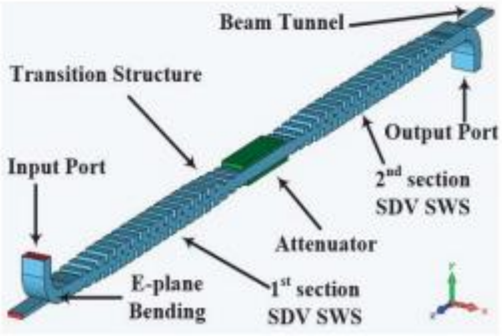
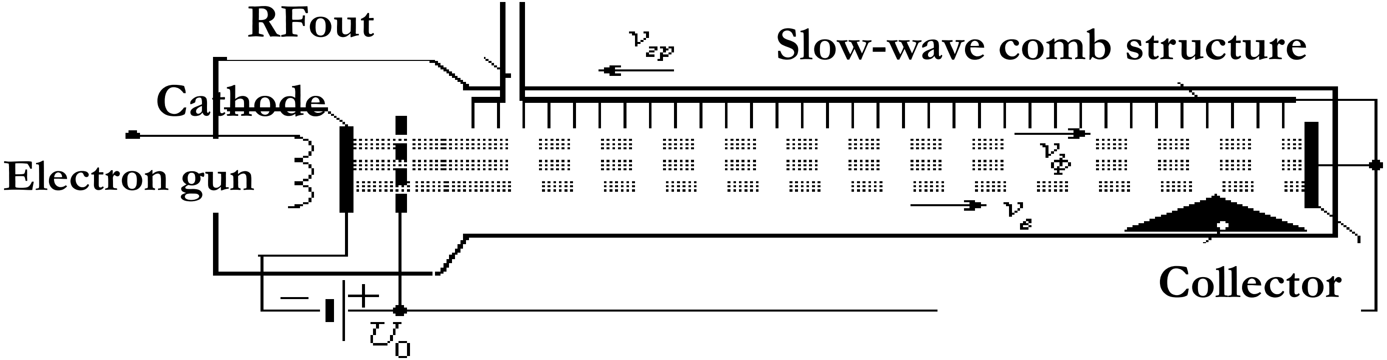


Figure 2. SDV TWT with *E*-plane bending input/output coupler.

Double-vane half period staggered 0.22 THz Sheet Seam TWT*

*X. Shi et al. High Efficiency and High Power Staggered Double Vane TWT Amplifier Enhanced by Velocity-Taper Design. Progress In Electromagnetics Research C. 2016. Vol. 66. P. 39–46.

Vacuum electronic devices - BWT



B. Epsztein. Backward flow travelling wave devices: Patent FR1035379 (A), France. Publ. date 1959-03-31.

N.S. Ginzburg, S. P. Kuznetsov, T. N. Fedoseeva. The theory of transient processes in a relativistic BWT. Izvestiya vuzov. Radiophysics. 1978. Vol. 21. P. 1037–1052.(In Russian)

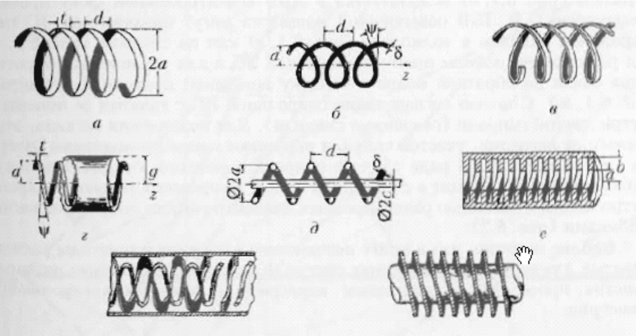
J. A. Swegle, J. W. Poukey, G. T. Leifeste. Backward wave oscillators with rippled wall resonators: Analytic theory and numerical simulation. Phyics Fluids. 1985. Vol. 28. P. 2882–2894.

N.I. Zaitsev et al. Relativistic carcinotron with a wavelength of 3 centimeters and a pulse duration of 0.4 microseconds. Technical Physics Letters. 1981. Vol. P. 879–882.

V.A. Solntsev.Karsinotrod: Patent for invention USSR №2121194RU2121194C1.B.I. No. 30. Publ. 10/27/1998

D. K. Abe et al. Experimental studies of overmoded relativistic backward-wave oscillators. IEEE Trans. Plasma Sci. 1998. Vol. 26. P. 591–604.

Resonators, spatially–periodic systems* for microwave range



Spirals

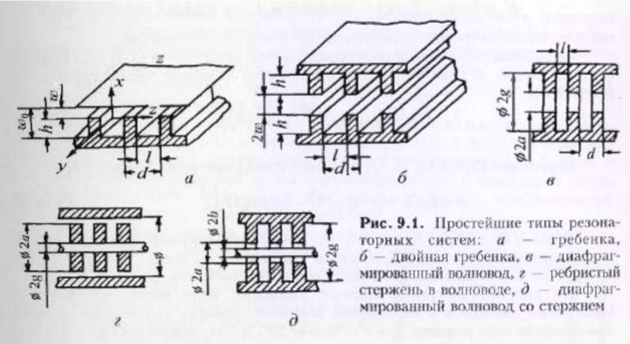
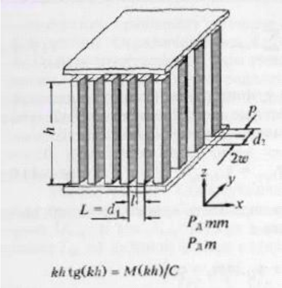
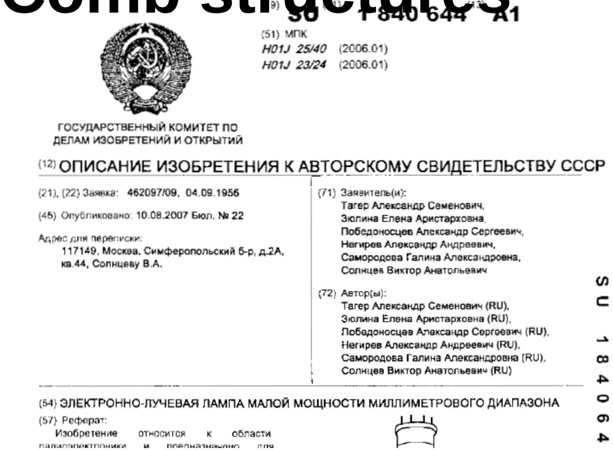


Рис. 9.1. Простейшие типы резонаторных систем: *а* — гребенка, *б* — двойная гребенка, *в* — диафрагмированный волновод, *г* — ребристый стержень в волноводе, *д* — диафрагмированный волновод со стержнем

Comb structures



Pin-type and slotted systems



SU 1 840 644 A1

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H01J 23/24 (2006.01)

ГОСУДАРСТВЕННЫЙ КОМИТЕТ ПО
ДЕЛАМ ИЗОБРЕТЕНИЙ И ОТКРЫТИЙ

(12) ОПИСАНИЕ ИЗОБРЕТЕНИЯ К АВТОРСКОМУ СВИДЕТЕЛЬСТВУ СССР

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(45) Опубликовано: 10.08.2007 Бюл. № 22

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SU 184064

(54) ЭЛЕКТРОННО-ЛУЧЕВАЯ ЛАМПА МАЛОЙ МОЩНОСТИ МИЛЛИМЕТРОВОГО ДИАПАЗОНА

(57) Реферат:
Изобретение относится к области

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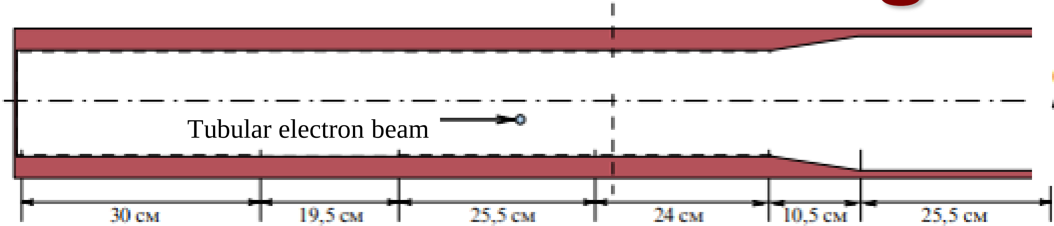
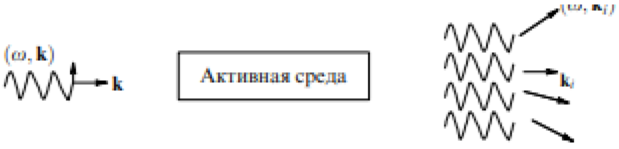
* R.A.Silin. Periodical waveguides. 2002.

Invention SU 1 840 644 A1 dated 04.09.1956, published 10.08.2007

Multiwave Cherenkov generators





Forward and backward waves near the border of the transparency band are coupled and form oscillations with a finite diffraction Q-factor, due to which it is possible to excite several modes at once.

Diode voltage - 1.5 -2MVolt. Current - 10 - 20 kA. Leading magnetic field strength – 15-30 kOe. Output power - 15 GWt , 3 cm wavelenght. Electronic efficiency – till 50 %.

S.P. Bugaev et al. Relativistic multiwave Cherenkov generator. Tech. Phys. Lett. 1983. Vol.9. P. 1385–1389.
S.P. Bugaev et al. Relativistic multi-wave microwave generators. Novosibirsk: Science. 1991 (In Russian).
V. A. Cherepenin. Relativistic multiwave oscillators and their possible applications. UFN, 176:10 (2006), 1124–1130; Phys. Usp., 49:10 (2006), 1097–1102.
S. Ting, Y. Liu. Particle simulation of a millimeter wave multiwave Cherenkov generator producing GigaWatt power levels. Int. J. Infrared and Millimeter Waves. 1998. Vol. 19. P. 385–397.

Cherenkov generators

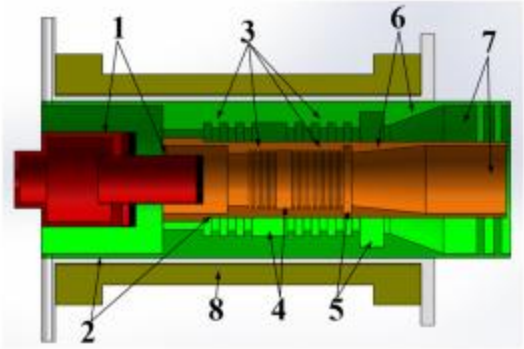
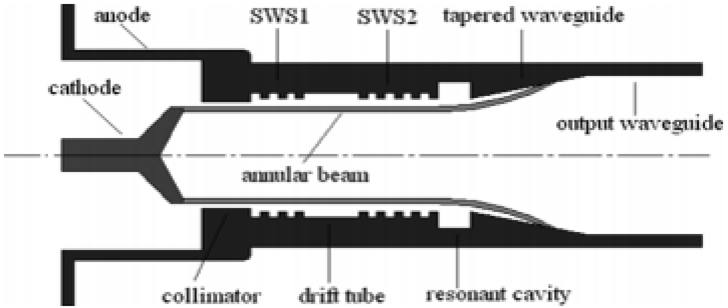


FIG. 1. Schematic diagram: 1-coaxial doubt-annular cathode, 2-anode, 3-SWSs, 4-drift cavity, 5-resonant cavity, 6-taper, 7-output waveguide, 8-guiding magnetic field

Zhang, P., Ge, X., Dang, F., Huang, C., Zhao, C., Cheng, X., … Ling, J. (2019). *Investigation of a cross-band relativistic Cherenkov oscillator based on the cathode adjustment. AIP Advances, 9(3), 035110.* doi:10.1063/1.5086190

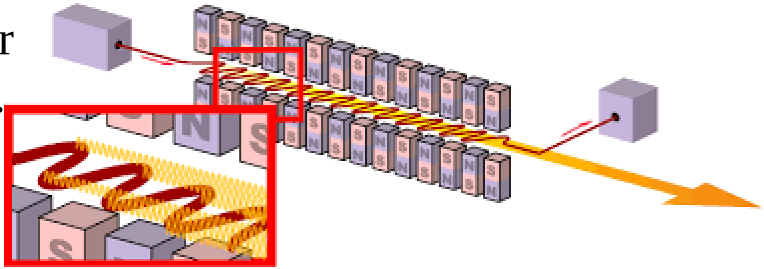


J. Zhang, H.-H. Zhong, L. Luo. A Novel Overmoded Slow-Wave High-Power Microwave (HPM) Generator. IEEE Transactions on Plasma Science. 2004. Vol. 32. P. 2236–2242.

Usually VED uses thin ribbon or tubular electron beams and only surface part of such beam interacts with resonator.

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.



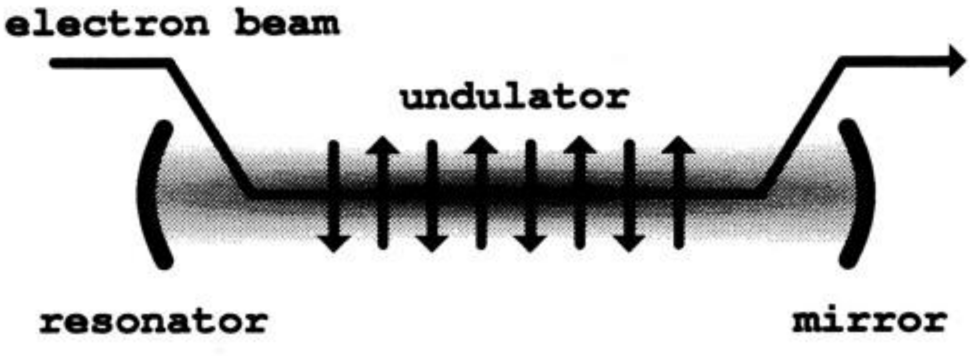
Laser is a light amplification by stimulated emission of radiation.

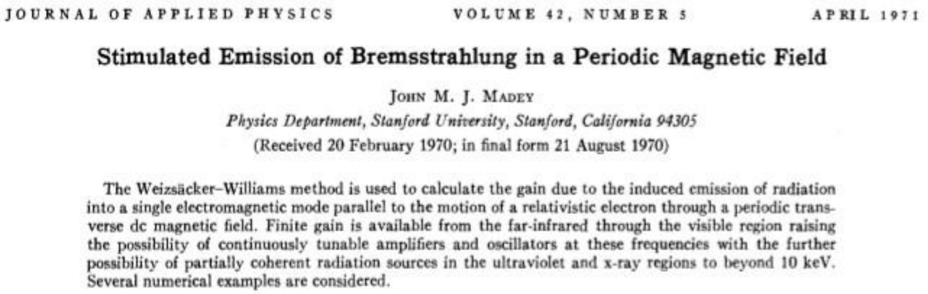
FEL properties*:

- Tunability.
- High peak power.
- Flexible pulse structure.
- Good laser characteristics.
- Broad wavelength coverage.
- Size and cost.

*National Research Council. 1994. Free Electron Lasers and Other Advanced Sources of Light: Scientific Research Opportunities. Washington, DC: The National Academies Press. https://doi.org/10.17226/9182.

Free Electron Lasers (FEL)




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. M. J. Madey. Stimulated Emission of Bremsstrahlung in a Periodic Magnetic Field. J. Appl. Physics. 1971. Vol. 42. P. 1906–1913

Free Electron Lasers (FEL)

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.

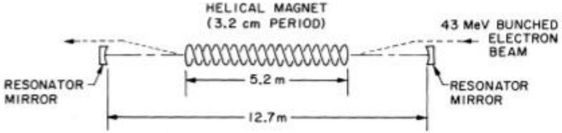
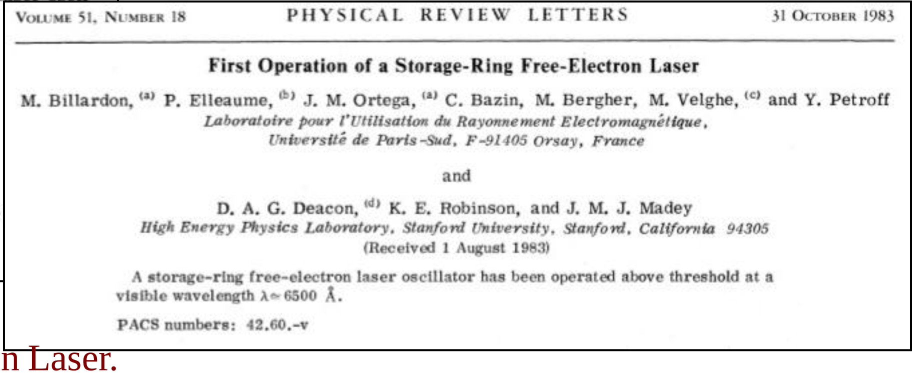


FIG. 1. Schematic diagram of the free-electron laser oscillator. (For more details see Ref.

892



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.

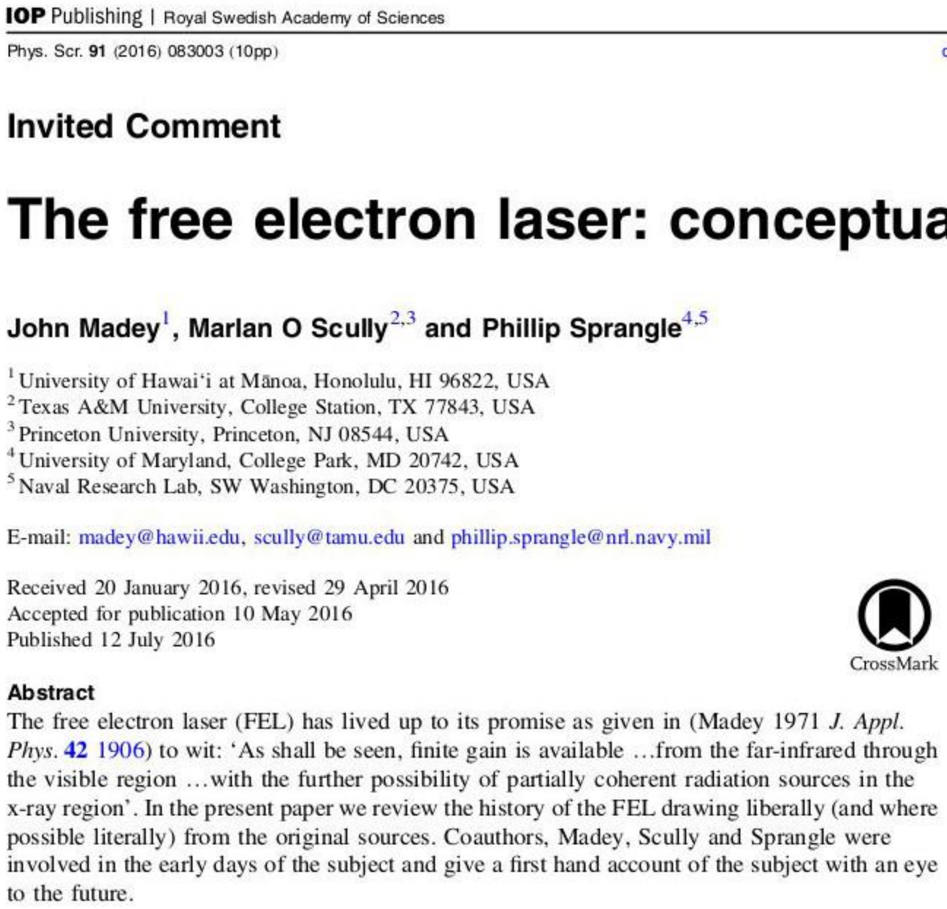
PACS numbers: 42.60.-v

D. A. Deacon et al. First operation of a Free-Electron Laser. Phys. Rev. Let. 1977. Vol. 38, No.16 P. 892–894.
M. Billardon et al. First Operation of a Storage-Ring Free-Electron Laser. Phys. Rev. Let. 1983. Vol. 51, N 18. P. 1652–1655.

Free Electron Lasers

W. B. Colson. Theory of a Free Electron Laser. Phys. Let. 1976. Vol. 59A. P. 187–190.
W. B. Colson. The Nonlinear Wave Equation for Higher Harmonics in Free Electron Lasers. IEEE J. Quantum Electron. 1981. Vol. QE-17. P. 1417–1427.
J. Andruszkow et al. First Observation of Self-Amplified Spontaneous Emission in a Free-Electron Laser at 109 nm Wavelength. Phys. Rev. Let. 2000. Vol. 85, N 18. P. 3825–3829.
P. Emma et al. First lasing and operation of an Angstrom-wavelength free-electron laser. Nature Photonics. 2010. Vol. 4. P. 641–647.
E. Prat, S. Reiche. Simple Method to Generate Terawatt-Attosecond X-Ray Free-Electron-Laser Pulses. Phys. Rev. Let. 2015. Vol. 114. P. 244801.
C. Emma et al. High efficiency, multiterawatt x-ray free electron lasers. Phys. Rev. ST Accelerators and Beams. 2016. Vol. 19. P. 020705.
P. J. Neyman et al. Free Electron Lasers in 2017. Proc. FEL2017. P. 204–209.

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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[2] Texas A&M University, College Station, TX 77843, USA
[3] Princeton University, Princeton, NJ 08544, USA
[4] University of Maryland, College Park, MD 20742, USA
[5] Naval Research Lab, SW Washington, DC 20375, USA

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Published 12 July 2016

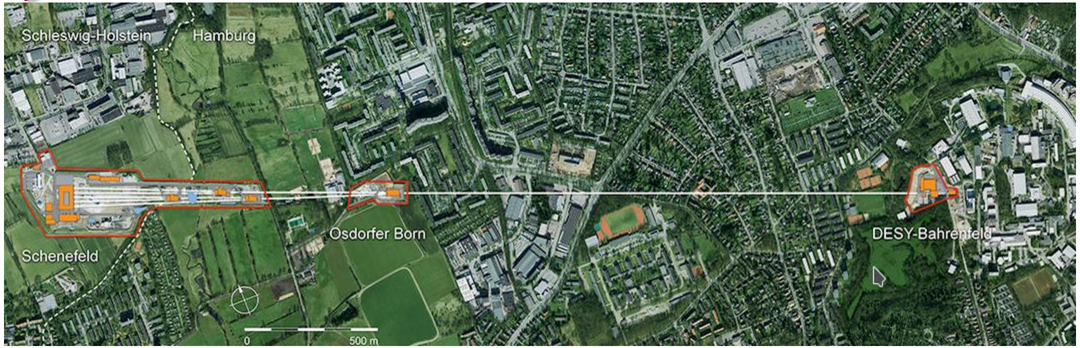
CrossMark

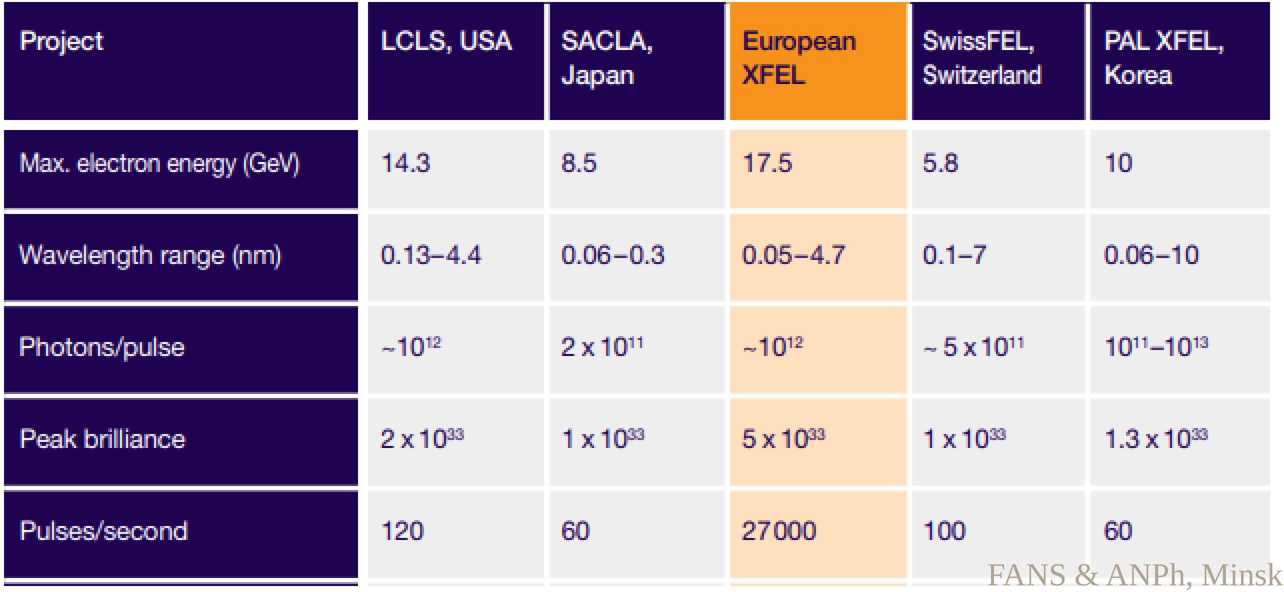
Abstract

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.

J. Madey, M. O. Scully, P. Sprangle. The free electron laser: conceptual history. Physica Scripta. 2016. Vol. 91. № art. 063003.

Some FEL projects





Project	LCLS, USA	SACLA, Japan	European XFEL	SwissFEL, Switzerland	PAL XFEL, Korea
Max. electron energy (GeV)	14.3	8.5	17.5	5.8	10
Wavelength range (nm)	0.13–4.4	0.06–0.3	0.05–4.7	0.1–7	0.06–10
Photons/pulse	$\sim 10^{12}$	2×10^{11}	$\sim 10^{12}$	$\sim 5 \times 10^{11}$	10^{11}–10^{13}
Peak brilliance	2×10^{33}	1×10^{33}	5×10^{33}	1×10^{33}	1.3×10^{33}
Pulses/second	120	60	27000	100	60

European XFEL

Biggest X-ray laser in the world generates its first laser light 04 May 2017.
The 3.4 km long European XFEL generates extremely intense X-ray flashes used by researchers from all over the world.
The flashes are produced in underground tunnels and allow scientists to map atomic details of viruses, film chemical reactions, and study processes in the interior of planets.
The European XFEL accelerator currently uses 768 cavities over a 1.7 km length and can currently energize electrons up to 17.5 GeV. The electrons are accelerated in pulses with 10 pulses per second. Each pulse can contains up to 2700 electron bunches so that in total up to 27000 X-ray flashes per second.

H. Weise, W. Decking. Commissioning and First Lasing of the European XFEL Proc. FEL2017. P. 9–13.

European XFEL

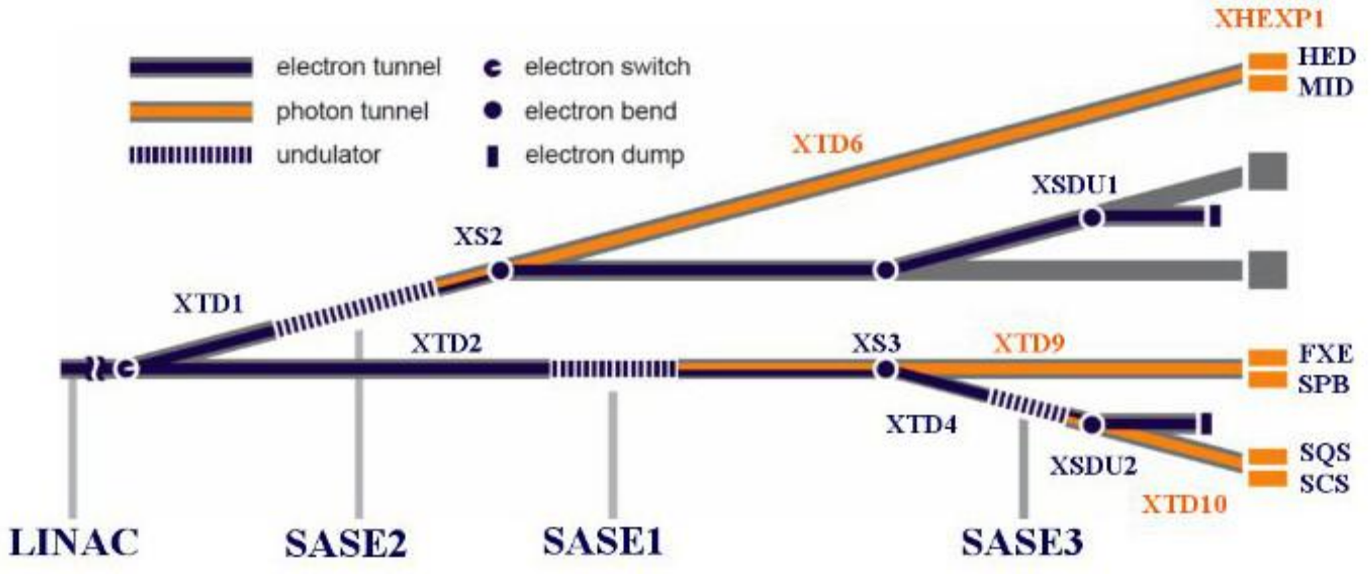


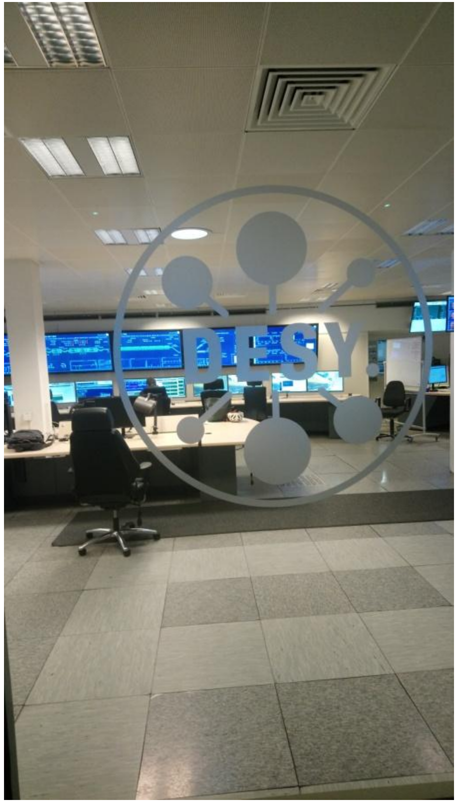
Figure 1: Schematic layout of the European XFEL facility showing the SASE undulators and corresponding experimental end stations.

http://www.xfel.eu/

European XFEL

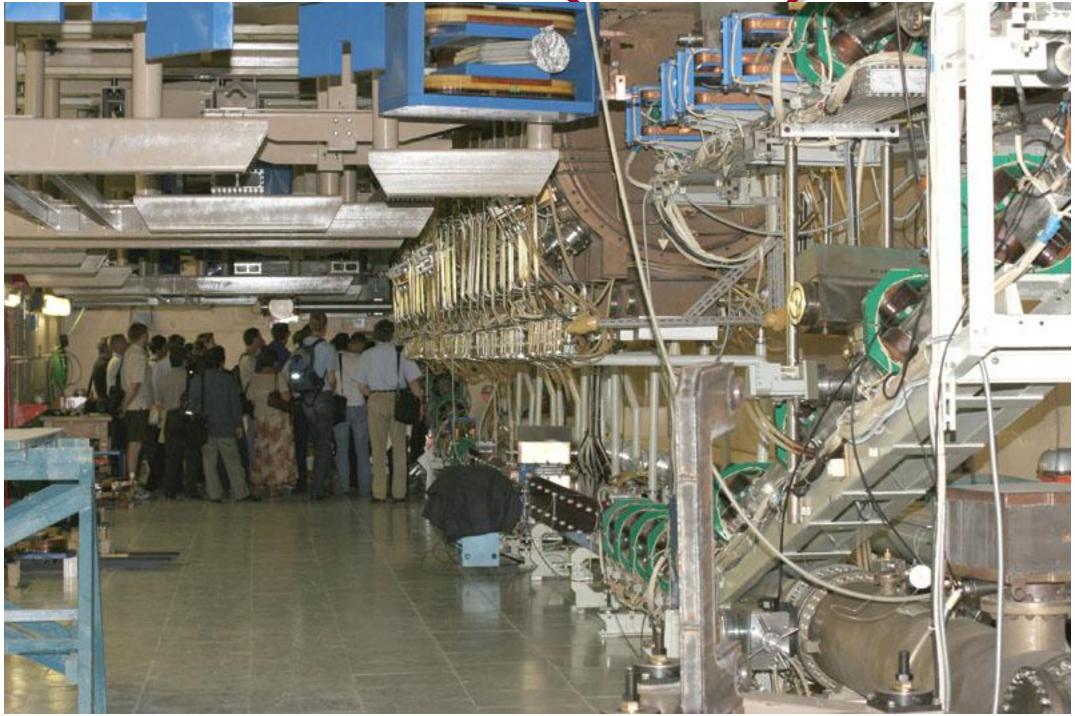

Booster

Linear accelerator+XFEL



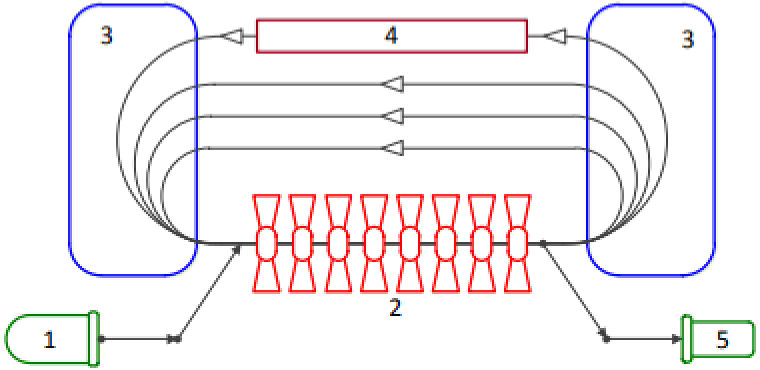
Control room

Novosibirsk FEL (2007)

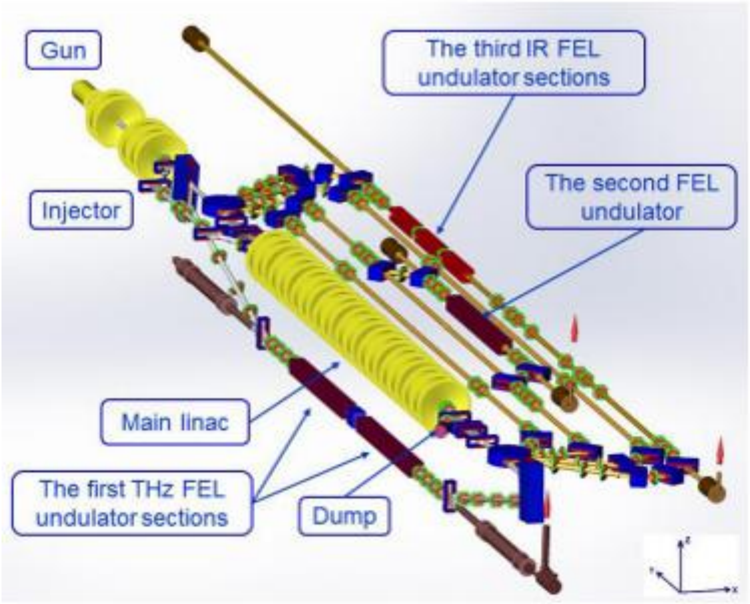


The first FEL has been in operation since 2003. It provides a narrow-band (less than 1%) terahertz radiation in the wavelength range of 80 240 µm at an average power of up to 0.5 kW and a peak power of up to 1 MW (100-ps pulses at a repetition rate of 5.6 MHz). About 30 user research projects in different fields of science were carried out at the facility in recent years.

Novosibirsk FEL



Simplest multi-turn ERL scheme: 1 – injector, 2 – linac, 3 – bending magnets, 4 – undulator, 5 – dump.



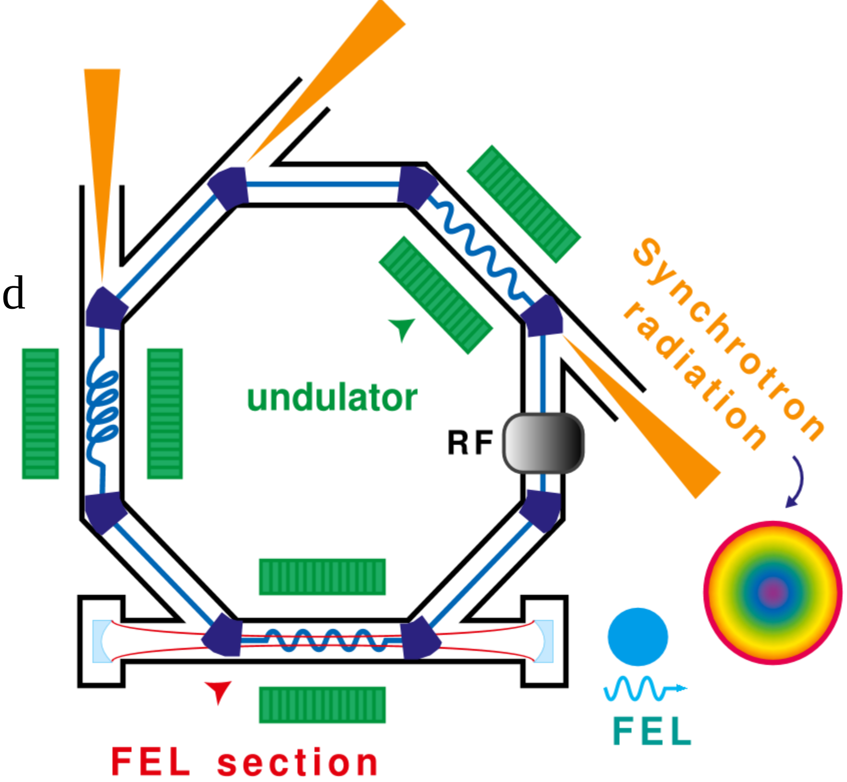
Kulipanov et al. Novosibirsk Free Electron Laser Facility Description and Recent Experiments IEEE Trans. on Therahertz Sience and Technology. 2015. Vol. 5, No. 5. P. 798–809.
N.A. Vinokurov et al. Novosibirsk Free Electron Laser: Terahertz and Infrared Coherent Radiation Source. Proc. RUPAC2016. DOI:10.18429/JACoW-RuPAC2016-TUXMH02

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



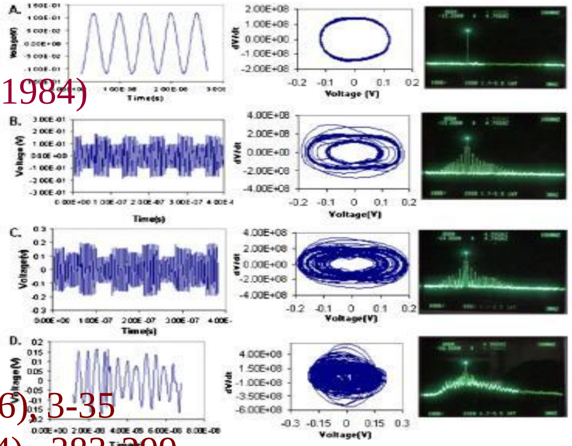
M. E. Couprie. Chaos studies on the super-ACO free electron laser. NIIM A. 2003. Vol. A507. P. 1–7.
C. Bruni et al. Chaotic nature of the super-ACO FEL. NIM. A. 2004. Vol. A528. P. 273–277.

Dynamical systems*

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

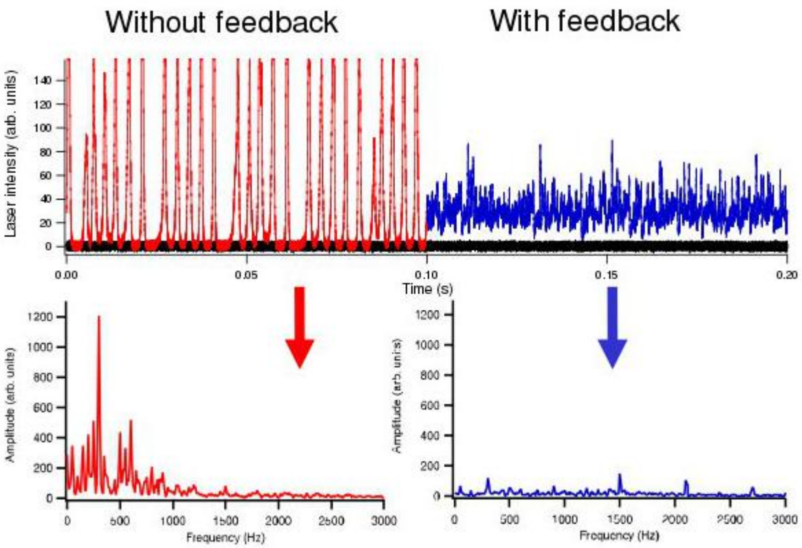
Nonlinearity is necessary but non-sufficient condition for chaos in the system. The main origin of chaos is the exponential divergence of initially close trajectories in the nonlinear systems. This is so-called the “Butterfly effect”** (the sensibility to initial conditions).

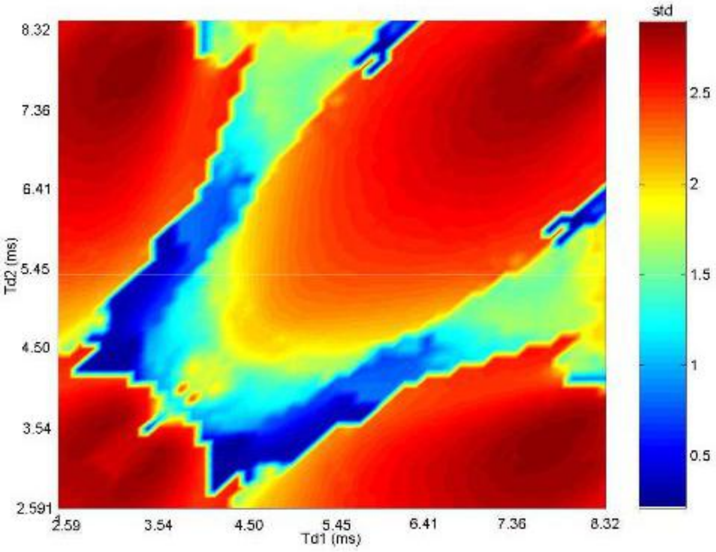
Chaos in electronic devices such as BWT, TWT, etc. is due to the delayed nature of distributed feedback.



*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

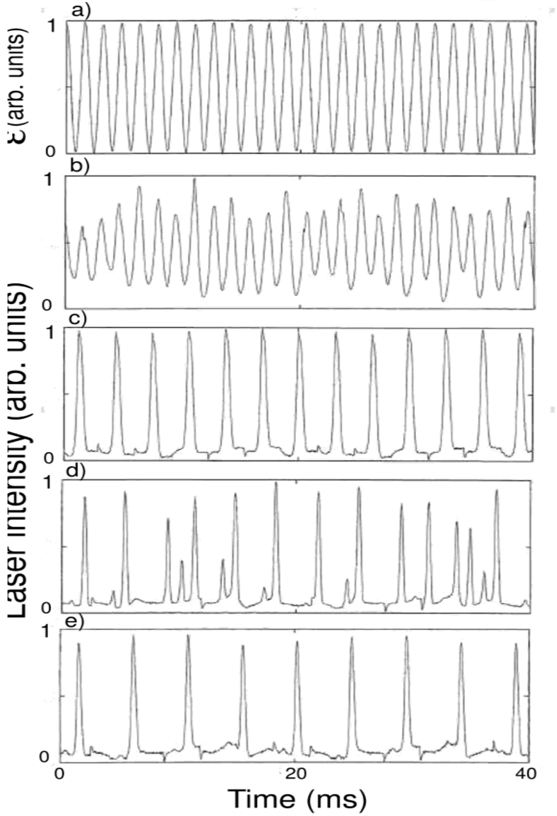
Chaos in FEL

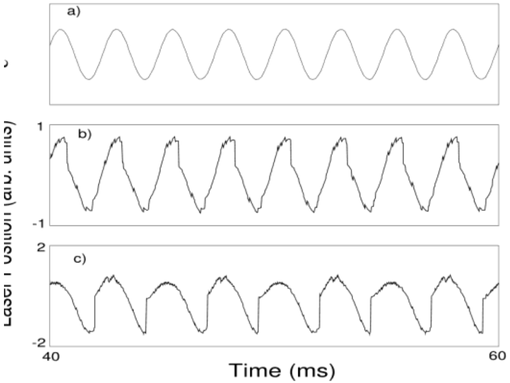


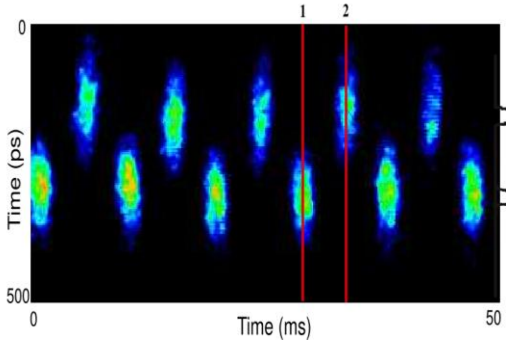


M. Billardon. Storage ring free-electron laser and chaos. Phys. Rev. Lett. 65 (1990), 713
S.J. Hahn, J.K. Lee. Bifurcations in a short-pulse free-electron laser oscillator. Phys. Let. A 175 (1993), 339-343

Chaos in Super-ACO FEL

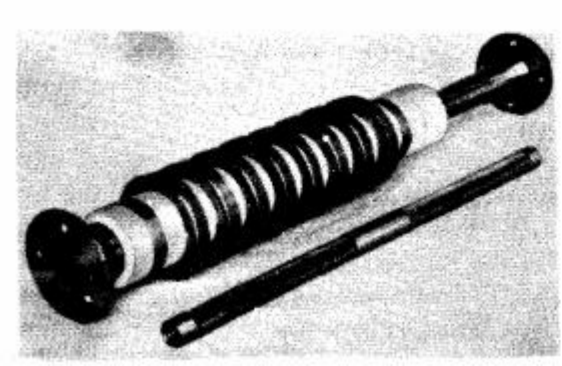


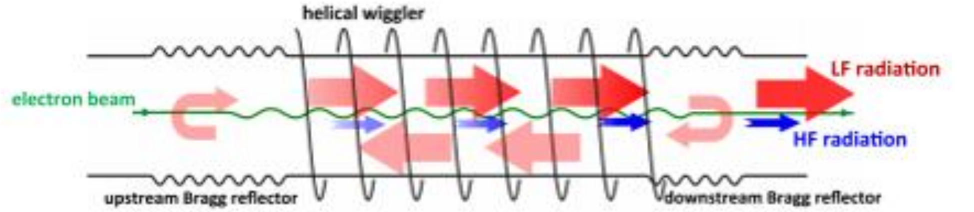




De Ninno, G., Fanelli, D., Bruni, C. et al.. Eur. Phys. J. D (2003) 22: 269.
C. Bruni et al. Eur. Phys. J. D 55, 669-677 (2009)

Free Electron Maser*





Scheme of the FEM multiplier with a helical wiggler and a two-mirror Bragg resonator.

Maser is a microwave amplification by stimulated emission of radiation.

*I. E. Botvinnik et. al. Free-electron maser. Pis'ma Zh. Éksp. Teor. Fiz. **35**, 418 (1982) [JETP Lett. **35**, 516 (1982)].

T. S. Chu et al. Single-Mode Operation of a Bragg Free-Electron Maser Oscillator. Phys. Rev. Let.1994. Vol. 72. P. 2391–2394.

N. S. Ginzburg et al. Theory of free-electron maser with two-dimensional distributed feedback driven by an annular electron beam. Journal of Applied Physics. 2002. Vol. 92. P. 1619

N. Yu. Peskov et al. High-power free-electron maser operated in a two-mode frequency-multiplying regime. Phys. Rev. Accel. Beams. 19, 060704 (2016)

M. Thumm. State-of-the-Art of High Power Gyro-Devices and Free Electron Maser. KIT Scientific Reports 7735. 2016.

Free Electron Maser*

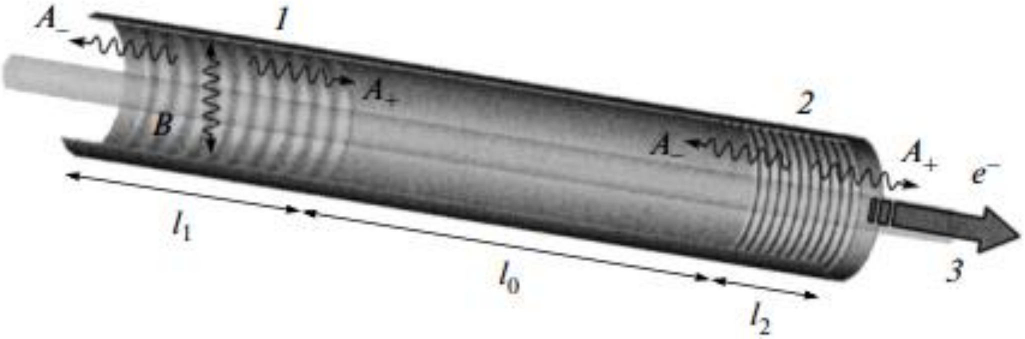
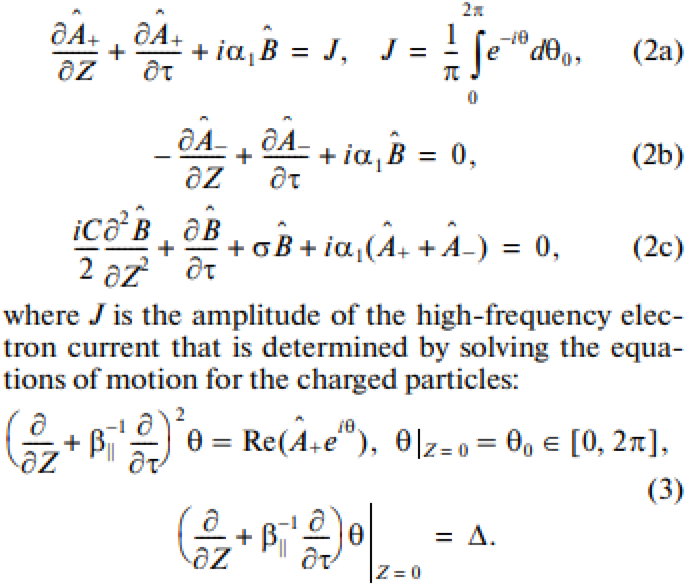


Fig. 1. Schematic diagram of a FEM with a combined double-mirror resonator: (*1*) modified Bragg reflector (*2*) traditional 1D Bragg reflector; (*3*) electron beam. Wavy lines show the directions of propagation of the electromagnetic flows $A_\pm$ and *B*. The corrugation period of the modified Bragg structure (*1*) is about twice that of the traditional structure (*2*).

FEM uses tubular electron beam.

*N. S. Ginzburg et al. Free Electron Maser with High Selectivity Bragg Resonator Using Coupled Propagating and Trapped Modes. Technical Physics Letters, 2010, Vol. 36. P. 952–956

Free Electron Maser*



$$\frac{\partial \hat{A}_+}{\partial Z} + \frac{\partial \hat{A}_+}{\partial \tau} + i\alpha_1 \hat{B} = J, \quad J = \frac{1}{\pi}\int_0^{2\pi} e^{-i\theta} d\theta_0, \qquad (2a)$$

$$-\frac{\partial \hat{A}_-}{\partial Z} + \frac{\partial \hat{A}_-}{\partial \tau} + i\alpha_1 \hat{B} = 0, \qquad (2b)$$

$$\frac{iC}{2}\frac{\partial^2 \hat{B}}{\partial Z^2} + \frac{\partial \hat{B}}{\partial \tau} + \sigma \hat{B} + i\alpha_1(\hat{A}_+ + \hat{A}_-) = 0, \qquad (2c)$$

where J is the amplitude of the high-frequency electron current that is determined by solving the equations of motion for the charged particles:

$$\left(\frac{\partial}{\partial Z} + \beta_{\|}^{-1}\frac{\partial}{\partial \tau}\right)^2 \theta = \mathrm{Re}(\hat{A}_+ e^{i\theta}), \quad \theta|_{Z=0} = \theta_0 \in [0, 2\pi],$$

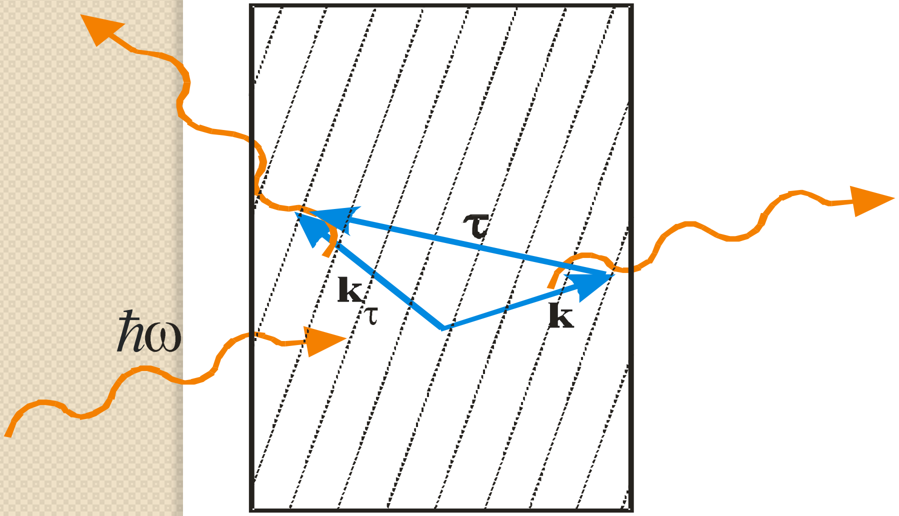
$$(3)$$

$$\left(\frac{\partial}{\partial Z} + \beta_{\|}^{-1}\frac{\partial}{\partial \tau}\right)\theta\Bigg|_{Z=0} = \Delta.$$

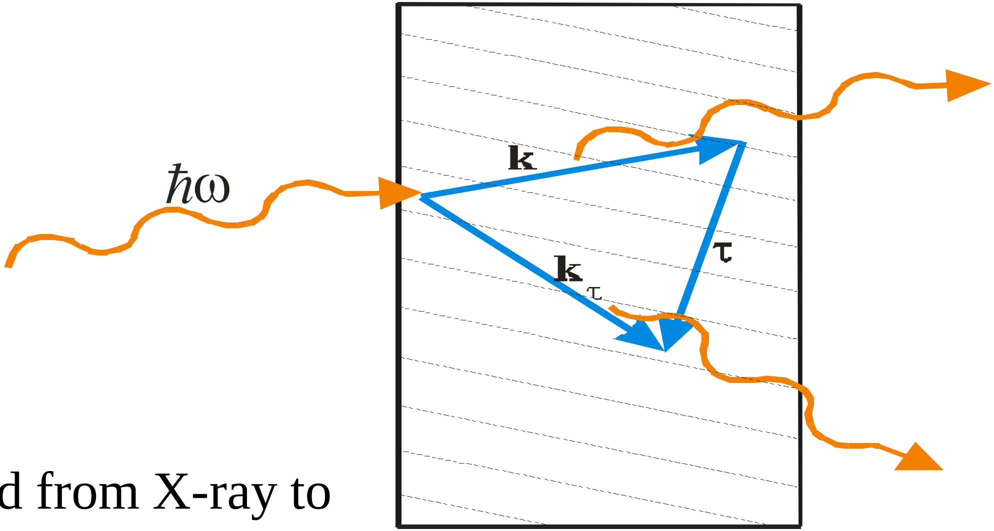
*N. S. Ginzburg et al. Free Electron Maser with High Selectivity Bragg Resonator Using Coupled Propagating and Trapped Modes. Technical Physics Letters, 2010, Vol. 36. P. 952–956

Dynamical diffraction*

Bragg geometry



Laue geometry



τ is a reciprocal lattice vector.

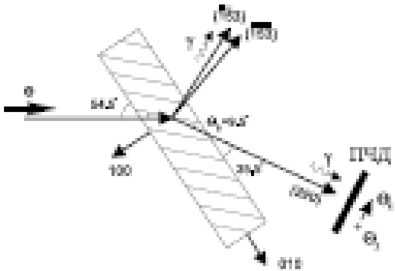
Principles of diffraction are valid from X-ray to THz range.

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

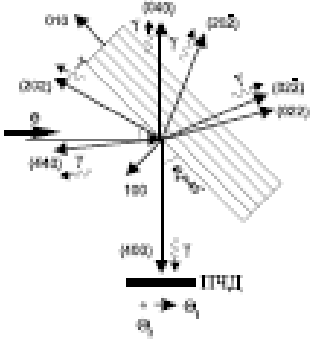
Experiments on multiwave X-ray dynamical diffraction*

Scheme of experiments

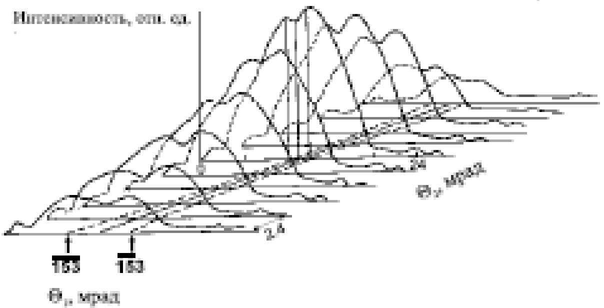
4-wave



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* 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. According to Landau (vol.VIII), the dielectric permittivity ε<1 (the refractive index $n = \sqrt{\varepsilon} < 1$) and Cerenkov radiation in the X-ray region should be absent. However, in 1971, V.G. 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) 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.

Main physical VFEL principles

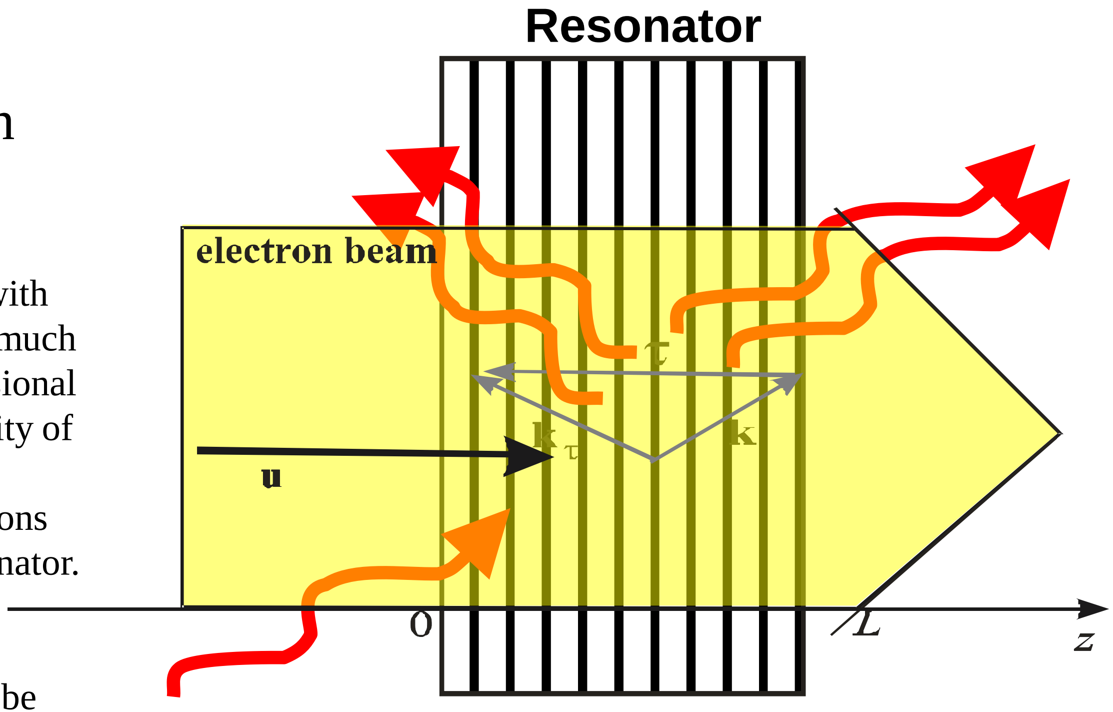
Diffraction condition

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

Synchronism condition

$$\left|\omega-\mathbf{k}\mathbf{u}\right|=\delta\omega\approx 0$$

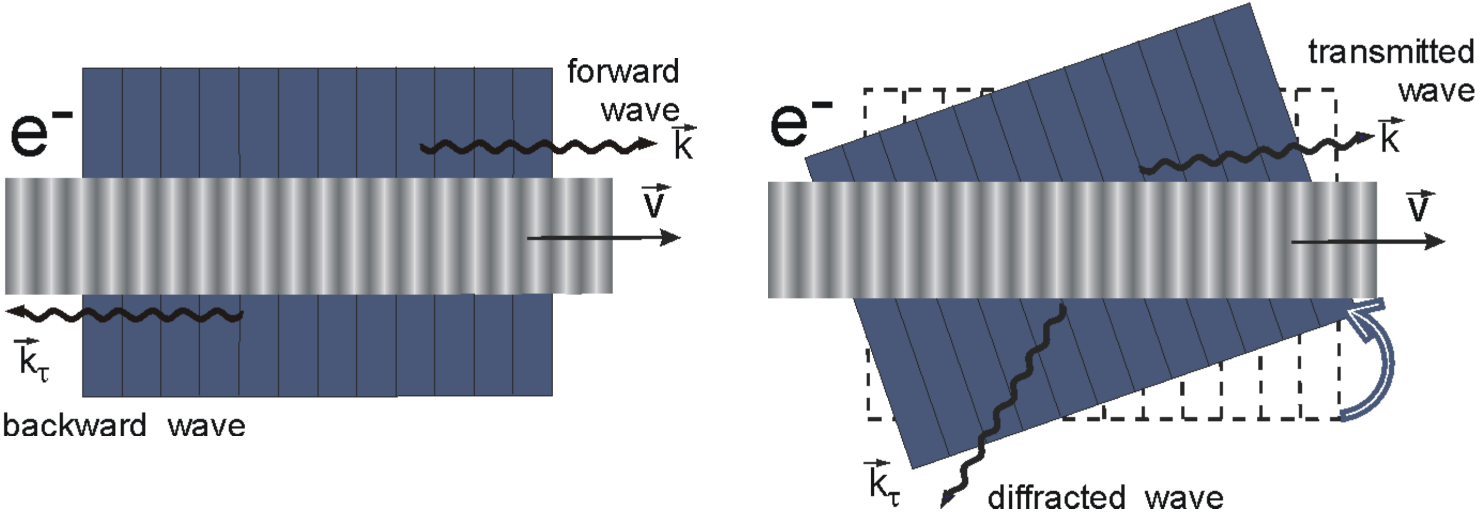
Interacting of the electron beam with electromagnetic field in VFEL is much more efficient than in one-dimensional situation because the group velocity of electromagnetic waves decreases sharply due to continuous reflections of them at periodic planes of resonator. Moreover VFEL is an oversized system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



Photonic crystal (resonator)

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 (TWT, FEL etc.)

Threshold current in degeneration points: $\boxed{j_{start} \sim 1/(kL)^{3+2s}}$

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

Expression for generation in FEL

In the one-dimensional case, from the implicit expressions* for the generation processes in FEL with distributed feedback and a corrugated waveguide, one can obtain the following expression** for the threshold current, which coincides with the threshold current for the case of an FEL:

$$-\frac{\pi^2 n^2}{4}(CL')^3 f(y) = \frac{2\pi^2 n^2}{(\sigma L')^2}$$

where $L' = \frac{\omega}{c} L$, $C \sim I^{1/3}$ is a generalized Pierce parameter.

* V.L. Bratman, N.S. Ginzburg, G.G. Denisov, Sov. Tech. Phys. Lett. **7**, 11 (1981) 565–567 (Pis'ma Zh. Tekh. Fiziki **7**, 21, (1981) 1320–1324).

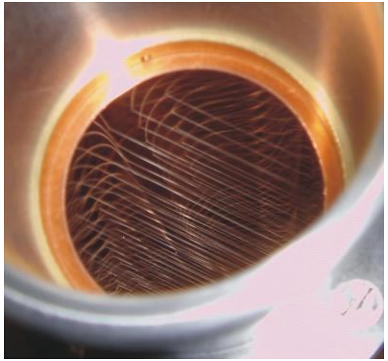
**V.G.Baryshevsky. High Power Microwave and Optical Volume Free Electron Lasers (VFELs), 2012, arXiv:1211.4769

VFEL references

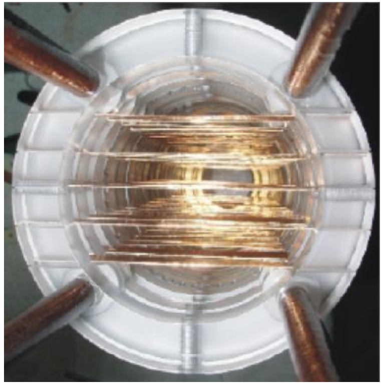
V. G. Baryshevsky, K. G. Batrakov, I. Ya. Dubovskaya. Parametric (quasi-Cerenkov) X-ray free electron lasers. J. Physics D: Appl. Physics. 1991. Vol. 24. P. 1250–1257.
V. G. Baryshevsky, K. G. Batrakov, I. Ya. Dubovskaya. Surface quasi-Cherenkov free-electron laser. NIM. 1994. Vol. A 341. P. 274–276.
V. G. Baryshevsky, K. G. Batrakov. Dependence of volume FEL (VFEL) threshold conditions on undulator parameters. NIM. 2002. Vol. A 483. P. 531–533.
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. NIM. 2006. Vol. B252. P. 92–101.
V. G. Baryshevsky, A. A. Gurinovich. Photonic crystal-based compact high-power vacuum electronic devices. Phys.l Rev. Acc. Beams. 2019. Vol. 2. № art. 044702.

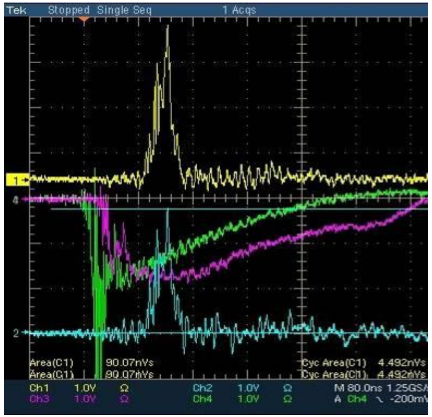
V. G. Baryshevsky et al. First lasing of a volume FEL (VFEL) at a length range λ~4-6 mm. NIM. 2002. Vol. A483. P. 21–24.
V. G. Baryshevsky et al. Experimental observation of radiation frequency tuning in "OLSE-10" prototype of volume free electron laser. NIM. 2006. Vol. B252. P. 86–91.
V. G. Baryshevsky et al. Experimental Study of Volume Free Electron Laser using a "grid" photonic crystal with variable period. Proc. FEL2007. P. 496–498.
V. G. Baryshevsky et al. Volume free electron laser with a ”grid” photonic crystal with variable period: theory and experiment. Proc. FEL2009. P. 134–137.

VFEL with grid and foil resonators*

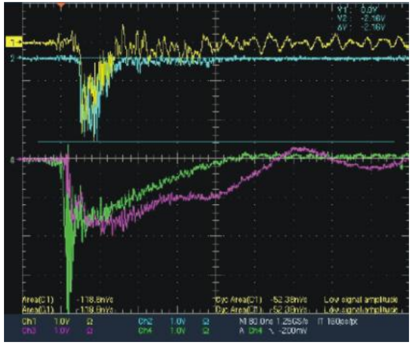


VFEL resonator is a circular metallic tube with a system of tungsten threads or foils with constant or variable period of the order of centimeter, providing dynamical diffraction, and electron beam of broad cross-section.





*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



Two-wave VFEL*

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

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

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

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

$$\Phi=\sqrt{l_0+\chi_0-1/(u/c\gamma)^2},$$

$$l_0=\frac{\mathbf{k}^2c^2-\omega^2\varepsilon_0}{\omega^2},$$

$$l_1=\frac{\mathbf{k}_\tau^2c^2-\omega^2\varepsilon_0}{\omega^2},$$

$$l=l_0+\delta,\qquad \mathbf{k}_\tau=\mathbf{k}+\boldsymbol{\tau}$$

$\gamma_{0,1}$ are direction cosines, δ is departure from synchronism conditions.

$\chi_{0,\ \tau}$ are Fourier components of the dielectric susceptibility of the target.

*K. Batrakov, S. Sytova. Modeling of volume free electron lasers. Computational Mathematics and Mathematical Physics. 2005. Vol. 45. P.666-676.

Equations for electron beam of broad cross-section*

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

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

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

$\theta(t, z, p)$ is an electron phase in a wave.

We use the method of averaging over initial phases of electron entrance in the resonator that takes into account as initial phase of an electron not only the moment of time t_0 but also transverse spatial coordinate of an electron entrance in the resonator at $z = 0$.

*K. Batrakov, S. Sytova. Computational Mathematics and Mathematical Physics. 2005. Vol. 45. P.666-676.

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

$$\partial^2\theta/\partial\zeta^2 = -\mathrm{Re}\left[F\exp(i\theta)\right], \ \ \partial F/\partial\tau - \partial F/\partial\zeta = \tilde{I}, \ \ \tilde{I} = -\frac{1}{\pi}\int\limits_0^{2\pi} e^{-i\theta}\,d\theta_0,$$

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

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

*N.S.Ginzburg, S.P.Kuznetsov, T.N.Fedoseeva. Izvestija VUZov - Radiophysics, 21 (1978), 1037
L.A. Weinstein, V.A. Solntsev. Lectures on microwave electronics. Sov. Radio, 1973 (In Russian).
D.I. Trubetskov, A.E. Hramov. Lectures on microwave electronics for physicists: in 2 vol. FIZMATLIT, 2003, 2004 (In Russian).
N. S. Ginzburg et al. Technical Physics Letters, 2010, Vol. 36. P. 952–956

VFEL numerical simulation

As a result of careful consideration of VDFB conditions and phases of electrons, the 1D computer code makes it possible to simulate the complex three-dimensional dynamics of electron beam and the propagation of electromagnetic waves in three-dimensional VFEL resonator.

- 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.
- The way of chaos control in VFEL for self-modulation elimination is changing of VDFB geometry.
- Changing the geometry of multidimensional diffraction leads to changes in the type of dynamic chaotic solutions and by the choice of geometry one can realized VFEL periodic dynamics rather chaotic one.

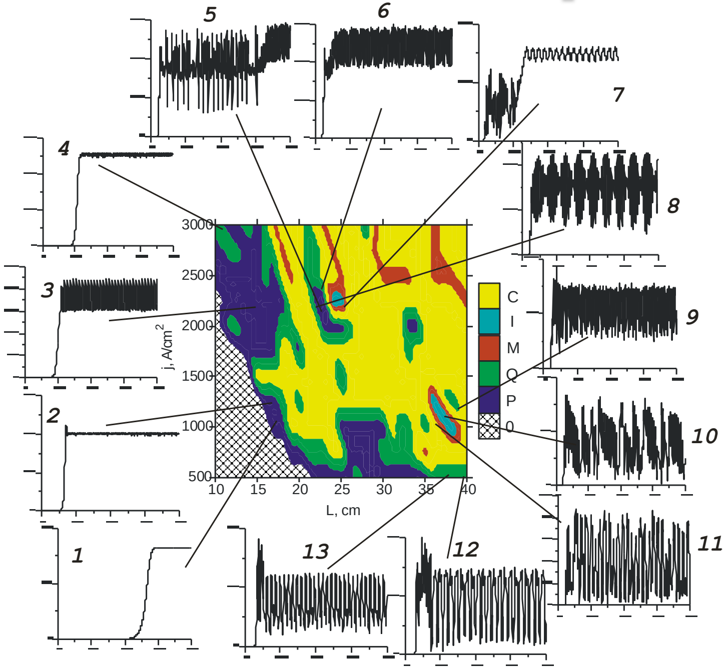
Origin of VFEL chaotic nature

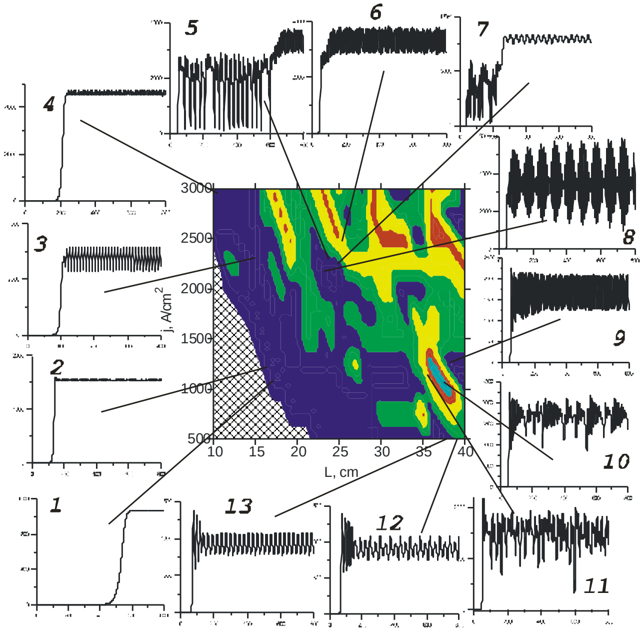
Chaos in VED is due to the delayed nature of distributed feedback.

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





0 depicts a domain under beam current threshold. P – periodic regimes, Q – quasiperiodicity, M – transient chaos, I – intermittency, C – chaos. On edges the most typical dependencies of amplitudes on time are presented.

VFEL effect of suppression of spurious modes becomes apparent as map for transmitted wave (left) is much more variegated than for diffracted one (right).

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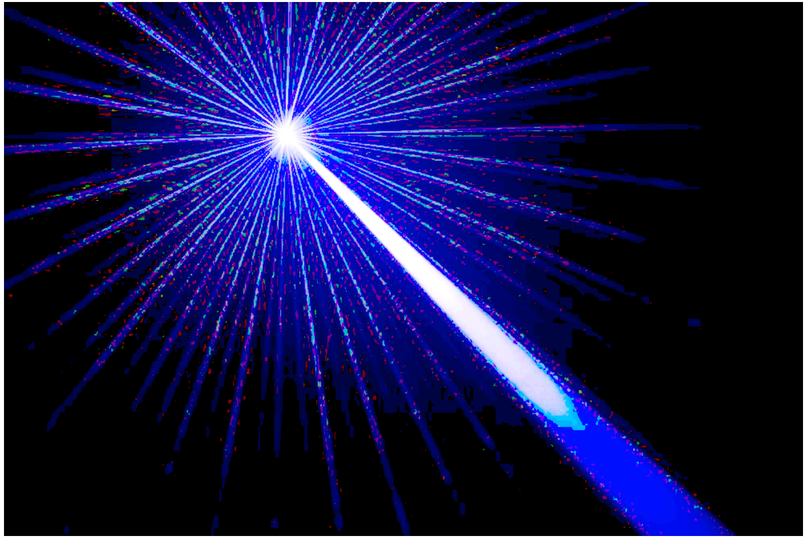
Conclusions

- Theoretical and experimental research of each type of considered devices is of great importance for science and practice.
- 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.

Thank you for attention!



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