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Ginzburg's invention of undulators and their role in modern synchrotron radiation sources and free electron lasers

G N Kulipanov

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Abstract. **Undulators — periodic magnetic structures that were originally introduced by Vitalii Ginzburg in 1947 for electromagnetic radiation generation using relativistic electrons — are among the key elements of modern synchrotron radiation sources and free electron lasers (FELs). In this talk, the history of three generations of storage ring-based synchrotron X-ray sources using wigglers and undulators is briefly traced. Prospects for two types of next-generation space-coherent X-ray sources are discussed, which use long undulators and energy recovery accelerators or, alternatively, employ linear accelerator-based FELs. The recently developed Novosibirsk terahertz FEL facility, currently the world's most powerful terahertz source, is described. It was the generation of electromagnetic radiation in this range that Ginzburg discussed in his 1947 work.**

1. Introduction

Several years ago, upon having read Vitalii Ginzburg's book *Autobiography*, which had just been published, I addressed him after one of the meetings of the Editorial Board of the journal *Phys.-Usp.* noticing that in many of his books he reveals a sort of tenderness in describing the transition radiation he discovered [1], while he seems never to even mention his work [2] in which the radiation of relativistic electrons in periodic structures was dealt with for the first time (at present, such structures are usually termed undulator structures, and the radiation is known as undulator radiation). Transition radiation caused by an electron moving uniformly along a straight line is, naturally, beautiful on its own, but during the past 25 years undulators serve as the basis for developing modern sources of synchrotron radiation (SR) and free electron lasers (FELs). Such facilities, in turn, are part of the infrastructure of a broad class of scientific studies: involved are solid state physics, surface physics, high-temperature superconductivity, biology, and very much of what, for instance, was indicated in the famous Ginzburg list of the "most important and interesting problems". Ginzburg listened to me, thought for a moment and then said: "Well, why don't you write about it?" So, my talk is actually a response to his request.

2. Some history

I shall start my presentation by showing an image of the Crab Nebula (Fig. 1a). On the one hand, investigation of the Crab Nebula was very important for the development of astrophysics, and for this reason Ginzburg very often addresses this object in many articles and books. On the other hand, the birth of the Crab Nebula is related to a supernova outburst in 1054, a fact documented in chronicles by Japanese and Chinese monks (Fig. 1b) who observed the appearance of a new bright 'guest star' that for three weeks could be seen in daylight and during a whole year remained the brightest star in the night sky. In the middle of the last century, i.e., after nine hundred years, the hypothesis was put forward, and subsequently confirmed experimentally, that the radiation from the Crab Nebula is actually the synchrotron radiation of ultrarelativistic electrons in interstellar magnetic fields.

Figure 1b shows a photograph of artificial synchrotron radiation, first observed in 1947 at one of the first electron accelerators — a synchrotron made by the General Electric company in the USA. Several years later synchrotron radiation was observed at the Physical Institute of the USSR Academy of Sciences in the first Soviet synchrotrons.

G N Kulipanov G I Budker Institute of Nuclear Physics, Siberian Branch of the Russian Academy of Sciences,
prosp. akademika Lavrent'eva 11, 630090 Novosibirsk,
Russian Federation
Tel. (7-383) 339 44 98, 330 60 30
E-mail: G.N.Kulipanov@inp.nsk.su

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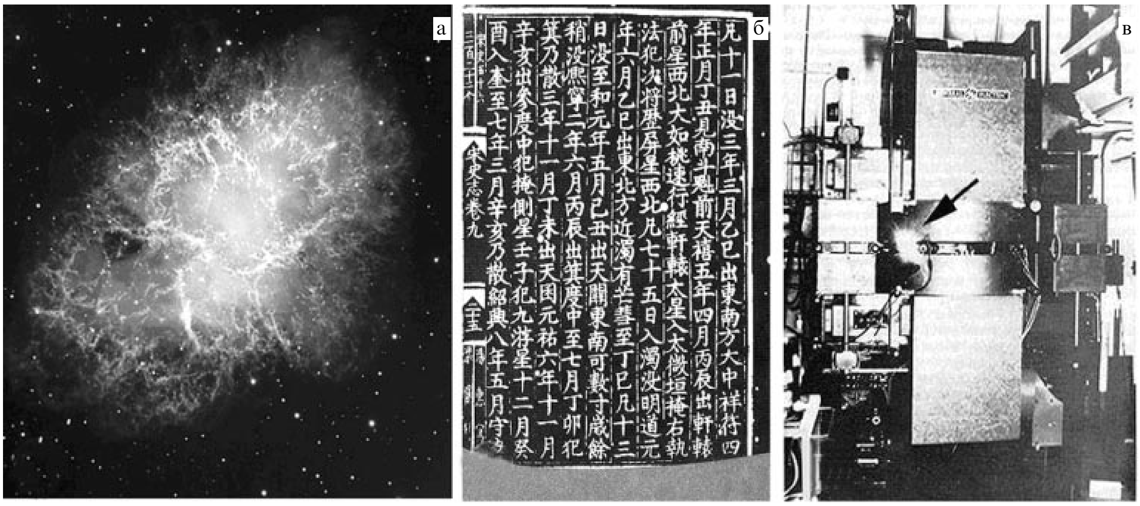

凡十一日沒三年三月乙巳出東南方大中祥符四年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅前星西北大如桃速行經軒轅大星入太微垣掩右執法犯次將歷屛星西北凡七十五日入濁沒明道元年六月乙巳出東北方近濁有芒彗至丁巳凡十三日沒至和元年五月己丑出天關東南可數寸歲餘稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯箕乃散三年十一月丁未出天囷元祐六年十一月辛亥出參度中犯掩側星壬子犯九游星十二月癸酉入奎至七年三月辛亥乃散紹興八年五月守婁

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Figure 1. (a) Photograph of the Crab Nebula — a cosmic source of synchrotron radiation. (b) Documented record made by Chinese monks, concerning the supernova explosion in 1054, at the site of which the formation of the Crab Nebula took place. (c) Photograph of the first artificial SR obtained at the electron synchrotron of the General Electric company (1947).

The events illustrated by Figs 1a and 1b were separated by nine hundred years. Such was the period of time necessary for humankind to comprehend that the glow of the Crab Nebula is produced by synchrotron radiation, on the one hand, and, on the other, to devise modern physics, to elaborate the theory of synchrotron radiation [3–6], to establish principles and develop methods for accelerating charged particles [7, 8], and, then, to create charged particle storage rings [9, 10] and special generators of synchrotron radiation — undulators and wigglers [2, 11–13].

In connection with the above it must be noted that, in spite of the international character of science, Russian scientists have practically always happened to be among the first to resolve the aforementioned problems. Figure 2 presents the photographs of outstanding Russian scientists who laid the physical foundations for the creation of SR sources: I Ya Pomeranchuk, L A Artsimovich, V I Veksler, G I Budker, and V L Ginzburg.

Although an early work by G A Schott [3], carried out in connection with studies of various models of the atom, did stimulate the development of the theory of synchrotron radiation, magnetic bremsstrahlung (synchrotron) radiation of relativistic electrons was actually first considered in 1938 by Pomeranchuk in Ref. [4]. Pomeranchuk was interested in magnetic bremsstrahlung radiation of electrons as a possible reason for the limitation of energy of electrons and positrons arriving on Earth from outer space, which could be due to their losing energy via magnetic bremsstrahlung radiation in passing through the magnetosphere. The paper [4] indicated the beginning of studies of the astrophysical aspect of magnetic bremsstrahlung radiation. In subsequent works by Pomeranchuk and coauthors [5, 6], devoted to the influence of magnetic bremsstrahlung radiation on the operation of a cyclic accelerator, the betatron, it was shown that this radiation results in the establishment of an energy limit for electrons accelerated in the betatron. Moreover, in a joint work by Pomeranchuk and Artsimovich [6] the angular and spectral distributions of magnetic bremsstrahlung radiation were studied, and for the first time the main formulae for the radiation of relativistic electrons were obtained in a simple form.

Figure 2. Outstanding Russian scientists (from left to right): I Ya Pomeranchuk, L A Artsimovich, V I Veksler, G I Budker, and V L Ginzburg.

The creation of electron accelerators of very high energies became possible after Veksler [7] and, independently, E McMillan [8] formulated the principle of phase stability, which made it possible to apply high-frequency acceleration of charged particles moving along a circle of constant radius in accelerators which were termed synchrotrons. Since the radiation of relativistic electrons in a magnetic field was first observed in a synchrotron, it was called synchrotron radiation, although in *The Classical Theory of Fields* by L D Landau and E M Lifshitz the relevant section in Chapter 9 is titled, maybe more correctly from a physical point of view, "Magnetic bremsstrahlung radiation".

Subsequent progress in the creation of SR sources was related to the proposal of creating elementary particle storage rings [9], so as to arrange experiments on colliding beams. One of the founders of this line of research was Budker [10], who was the first to propose using radiative damping for accumulating particles and obtaining long-lived electron and positron beams of small dimensions and high intensity.

Among the main elements of modern SR sources are undulators and wigglers — periodic magnetic structures, the use of which was first proposed in the work by Ginzburg [2]; several years later, the first undulator was created and tested in the beam of a linear accelerator by Motz et al. [11].

3. What are undulators and wigglers?

Using straight segments of electron storage rings for housing wigglers and undulators (also called 'snakes'), which give rise to a periodic magnetic field of alternating signs and of period λ_0 along a segment of length $L = N\lambda_0$ (where N is the number of periods) is a very effective method for enhancing the synchrotron radiation intensity. In the simplest case, the field in such structures has the form

$$B_y(z) = B_0 \sin \frac{2\pi z}{\lambda_0} \, .$$

The total energy losses of electrons passing through such a periodic structure of length L are independent of the peculiarities of its construction:

$$\Delta W \sim r_{\mathrm{e}}^2 \bar{B}_y^2 \gamma^2 L \, ,$$

where $r_{\mathrm{e}} = e^2/(mc^2)$ is the classical electron radius, and γ is the ratio of the electron energy to its rest energy mc^2.

However, the spectral and angular distributions of radiation from the snake depend significantly on how the condition for interference of the radiation is provided for and, correspondingly, on the geometric overlapping of electron radiation from all the poles of the undulator. This is why the operation mode of the snake is determined by the relation between the maximum turning angle of the electron in the magnetic field of the snake, $\alpha_0 = \lambda_0/(2\pi R) = \lambda_0 e B_0/(2\pi\gamma mc)$, and by the characteristic angle of radiation divergence from each point of the electron's trajectory, $\psi_{x,z} \sim 1/\gamma$. The ratio of these quantities, $K = \alpha_0\gamma = \lambda_0 e B_0/(2\pi mc)$, is conventionally known as the undulatory parameter.

3.1 Undulator mode ($K \ll 1$)

For relativistic electrons in the case of small fields, $K \ll 1$, the transverse motion of electrons in the snake is nonrelativistic, and the longitudinal velocity modulation for an electron moving in the snake can be neglected. The electromagnetic wave emitted by an electron passing through the snake a single time (Fig. 3) arrives at the observation point on the axis of the snake in the form of a 'zug' of bursts of the electric and magnetic fields with a period

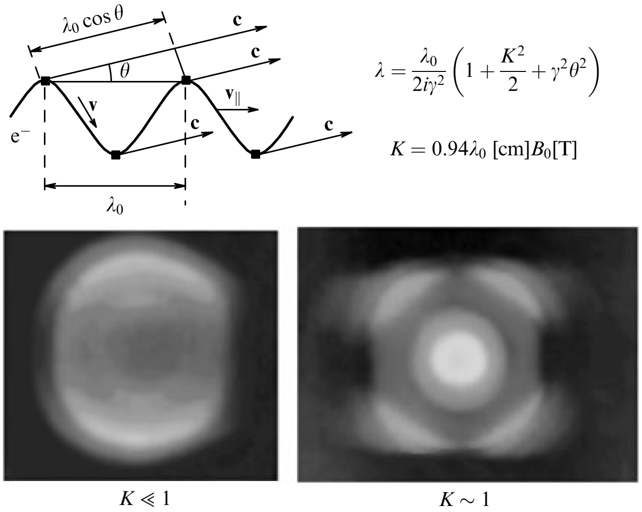
$$T_1 = \frac{\lambda_0}{v_{\|}} \approx \frac{\lambda_0}{c} \, ,$$

where $v_{\|}$ is the electron velocity along the axis of the snake. Owing to the trajectory inside the snake being curved, the average longitudinal velocity of the electrons along the z-axis is given by

$$v_{\|} = v\left(1 - \frac{\alpha_0^2}{4}\right) ,$$

whence follows

$$T_1 = \frac{\lambda_0}{v\,(1 - \alpha_0^2/4)} - \frac{\lambda_0}{c} = \frac{\lambda_0}{2\gamma^2 c}\left(1 + \frac{\alpha_0^2\gamma^2}{2}\right) .$$



$K \ll 1$ $K \sim 1$

Figure 3. Photographs of the beams of undulator radiation for different values of the undulatory parameter *K*.

Correspondingly, radiation with a wavelength

$$\lambda_{\mathrm{u}} = T_1 c = \frac{\lambda_0}{2\gamma^2}\left(1 + \frac{\alpha_0^2\gamma^2}{2}\right) = \frac{\lambda_0}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) .$$

will be registered at the observation point on the z-axis

The source of radiation approaches an observation point on a ray situated at a certain angle θ to the axis of the snake with a velocity $v_{\|}\cos\theta$ (see Fig. 3). At this point, the radiation is registered with the wavelength

$$\lambda_{\mathrm{u}} = \frac{\lambda_0}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right) .$$

The monochromaticity of undulator radiation at the zero angle is determined by the length of the 'zug' and, correspondingly, by the number of emitters (periods of the undulator):

$$\frac{\Delta\lambda}{\lambda_{\mathrm{u}}} \sim \frac{1}{N_{\mathrm{u}}} \, .$$

The angular divergence of the undulator radiation by order of magnitude amounts to

$$\Delta\psi_{0z} \approx \Delta\psi_{0x} \approx \sqrt{\frac{\lambda_{\mathrm{u}}}{L_{\mathrm{u}}}} \approx \frac{\sqrt{1 + K^2/2}}{\gamma\sqrt{2N_{\mathrm{u}}}} \, .$$

The 'effective' lateral dimension of the source, corresponding to this angular divergence, is equal to

$$\varDelta_{1z} \sim \varDelta_{1x} \sim \frac{1}{4\pi}\,\sqrt{\lambda_{\mathrm{u}} L_{\mathrm{u}}} \, .$$

The total number of quanta emitted by a single electron passing through the undulator is evaluated as

$$N_{1\mathrm{u}} = \frac{\Delta W_{\mathrm{sn}}\lambda_{\mathrm{u}}}{2\pi\hbar c} \approx \frac{1}{137}\,N\,(\alpha_0 K^2\gamma)^2 \, .$$

The radiation from an undulator with a transverse magnetic field is linearly polarized, while the radiation from an undulator with a helical magnetic field, in which $B_y = B_0 \sin(2\pi z/\lambda_0)$, and $B_x = B_0 \cos(2\pi z/\lambda_0)$, is circularly polarized.

At present, the term 'undulator' is used for a snake with a large number of poles, a weak magnetic field, and a small period, which deflects the trajectory of an electron by an angle $\alpha_0 \leqslant 1/\gamma$. The main requirement for the operation of a snake in the undulator mode, which consists in providing conditions for constructive interference of the electron beam radiation from all the poles of the undulator, imposes severe restrictions on the angular divergence inside the electron beam. Thus, for example, modern projects of X-ray sources ($\lambda_{\text{u}} \sim 1$ Å) foresee the use of undulators ~ 100 m long, for which, according to the simple interference condition

$$\frac{1}{2} L_{\text{u}} \Theta_{x,z}^2 < \frac{\lambda_{\text{u}}}{2\pi} \, ,$$

electron beams are required that exhibit angular divergences $\Theta_{x,z} < 10^{-6}$.

3.2 Generation of undulator radiation harmonics ($K \gtrsim 1$)

When the magnetic field in the snake strengthens, the quantity K increases, the transverse motion of the electrons becomes relativistic, and modulation of the longitudinal electron velocity along the axis of the snake becomes significant. In this case, harmonics of the undulator radiation ($i = 1, 2, \ldots$) arise in the radiation spectrum:

$$\lambda_{\text{u}} = \frac{\lambda_0}{2i\gamma^2} \left(1 + \frac{K^2}{2} + \gamma^2 \theta^2 \right) .$$

The parameter K determines the ratio of two characteristic times peculiar to radiation from the snake in the case of a strong magnetic field. The first time corresponds to the duration of the burst of electric and magnetic, fields from the sole magnet, registered by the observer:

$$\Delta T_{\text{SR}} \sim \frac{m}{\gamma^2 e B} \, .$$

The second time is determined by the interval between the bursts of electric and magnetic fields, emitted from adjacent periods:

$$\Delta T_{\text{u}} = \frac{\lambda_0}{2\gamma^2 c} \left(1 + \frac{K^2}{2} + \gamma^2 \theta^2 \right) .$$

It is the ratio $\Delta T_{\text{u}}/\Delta T_{\text{СИ}} \sim K(1 + K^2/2)$ that determines the number of harmonics contributing significantly to the total radiation power of the snake,

Figure 3 presents two photographs of radiation from an undulator: in one of the photos only generation of the first harmonic ($i = 1$) is seen for $K \ll 1$, while in the other generation is seen of two harmonics ($i = 1, 2$) for $K \sim 1$. We note that visual observation of undulator radiation, i.e., of a colored rainbow wrapped up in a cone, is always a pleasure.

3.3 Operation in the wiggler mode ($K \gg 1$)

In the case of a high magnetic field ($K \gg 1$), many harmonics appear in the radiation spectrum, which exhibit maximum intensity in the region of the synchrotron radiation wavelength determined by the local curvature of the trajectory in a single magnet ($\lambda \sim R/\gamma^3$). Characteristics of the SR flux at the observation point are obtained by adding up the contributions from different segments of the trajectory. Integrating the intensity over a finite solid angle and averaging it over the parameters of electrons in the beam result in the higher harmonics (for $K \gg 1$) broadening and overlapping in the spectrum. The radiation angle in the long-wave region of the spectrum exceeds $\psi_{x,z} \sim 1/\gamma$, since $\psi_\lambda \sim (1/\gamma)(\lambda/\lambda_c)^{1/3}$, therefore interference in the long-wave part of the spectrum is also observed for $K \gg 1$.

Today, the word 'wiggler' is used in describing a snake with a strong magnetic field and long period, which deflects electron trajectories at large angles $\alpha \gg 1/\gamma$, and is intended for generating radiation with a spectrum typical of SR. The use of wigglers permits:

(1) obtaining radiation with photons exhibiting higher energies, owing to the strong magnetic fields of a wiggler;

(2) enhancing the photon flux by a factor of $2N_{\text{u}}$ (N_{u} is the number of periods) as compared to the radiation from bending magnets, owing to the radiation from all the poles of the wiggler being added up;

(3) varying the spectrum independently at different experimental stations that make use of the radiation from different wigglers.

4. Undulators and the development of X-ray synchrotron radiation sources

An analysis of the requirements to synchrotron radiation sources for various types of experiments [14] reveals that the main 'consumer' characteristic consists in the spectral brightness $B_\lambda = \dot{N}_{\text{ph}}/(S\Omega)$ determined by the number of photons emitted per unit time within a given spectral band $(\Delta\lambda/\lambda)$ from a unit area ($S \sim \varDelta_x \varDelta_z$) to a unit solid angle ($\Omega \sim \varDelta_{x'} \varDelta_{z'}$).

In estimating the radiation brightness of undulators it is necessary to take into account the size of the source. So, the effective lateral dimensions of the radiation source are

$$\varDelta_{x,z} = \sqrt{\sigma_{x,z}^2 + \frac{\lambda_{\text{u}} L_{\text{u}}}{(4\pi)^2} + \Theta_{x,z}^2 L_{\text{u}}^2} \, ,$$

while the effective angular divergence of the radiation is

$$\varDelta_{x',z'} = \sqrt{\frac{\lambda}{L_{\text{u}}} + \Theta_{x,z}^2} \, ,$$

where $\sigma_{x,z}$ is the electron beam cross section, and $\Theta_{x,z}$ is the angular divergence of the electron beam. Since

$$\sigma_{x,z} \Theta_{x,z} = \varepsilon_{x,z} \, , \quad \sigma_{x,z} = \sqrt{\varepsilon_{x,z} \beta_{x,z}} \, , \quad \Theta_{x,z} = \sqrt{\frac{\varepsilon_{x,z}}{\beta_{x,z}}} \, ,$$

where $\varepsilon_{x,z}$ is the emittance (phase volume) of the electron beam, $\beta_{x,z}$ is the local effective focal distance of the magnetic system ($\beta_{x,z} \sim L$, when the undulator has been placed in an optimal manner), the most important condition for enhancement of the brightness consists in the reduction of the emittance of the electron beam together with a simultaneous increase in its energy, which permits applying long undulators for generating short-wave radiation (Fig. 4).

The diagram in Fig. 5 outlines the history, the present-day state of affairs, and the plans for enhancing the brightness of X-ray sources. Everything, naturally, started with the discovery by W C Roentgen in 1895 of the rays that bear his name, after which the first X-ray tubes were created with a brightness $B_\lambda \sim 10^6$ photons per 1 s per mm^2 mrad^2 (0.1% $\Delta\lambda/\lambda$). After about 60 years, their brightness was increased

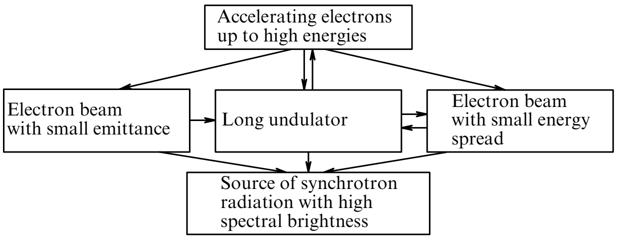


Figure 4. Paths to be followed in creating sources of synchrotron radiation with high spectral brightness.

Table 1. Change in the parameters of accelerator-sources of synchrotron radiation: history and predictions.

Year	Emittance ε, nm rad	Energy spread in electron beam, σ_E/E	Number of undulator periods N_{u}	Type of SR source
1980	300	10^{-3}	10	Electron storage ring
1990	30	10^{-3}	10^2	Electron storage ring
2000	3	10^{-3}	10^3	Electron storage ring
2015	10^{-2}	10^{-4}	10^4	Accelerator-recuperator (MARS)

via evolutionary development approximately by two orders of magnitude owing to enhancement of the electron beam power due to the use of a rotating anode and of microfocus X-ray tubes which allowed reducing the dimension of the electron beam at the anode.

The use of electron synchrotrons, and subsequently of electron storage rings, as sources of X-ray synchrotron radiation permitted the accelerator community, starting from the 1980s, to perform purposeful work (see Table 1) aimed at achieving a revolutionary increase in the brightness of X-ray sources. Passage from synchrotrons to storage rings in the 1970s resulted in an increase in the brightness approximately by a factor of 10^2-10^3 owing to the average current in storage rings being higher and the emittance and, subsequently, the electron beam lateral dimensions being smaller ($\varepsilon_x \sim 300$ nm rad) due to radiative damping.

Further enhancement of the brightness (approximately by a factor of 10–100) was implemented by making use of multipole wigglers. The creation in the 1980s of specialized storage devices — SR sources of the second generation — permitted reducing the emittance of electron beams to $\varepsilon_x \sim 30$ nm rad and, thus, decreasing the area of the radiation source and enhancing the brightness by approximately one more order of magnitude. The SR sources of the third generation, created in the 1990s and having even smaller emittances ($\varepsilon_x \sim 3$ nm rad) and higher energies ($E \sim 6-8$ GeV), make use of long undulators with $N_{\mathrm{u}} \sim 10^2-10^3$ as X-ray sources. This enabled increasing the flux of quanta as compared to the case of beam-bending magnets by a factor of N_{u} and, also, owing to interference of the radiation from all poles of the undulator, additionally decreasing the solid angle by N_{u} times, as a result of which the brightness of the undulator increased by a factor of N_{u} ($\sim 10^4-10^6$)!

It is seen from Fig. 5 that owing to the purposeful work of accelerator physicists the brightness of new sources of X-ray synchrotron radiation increased by three orders of magnitude

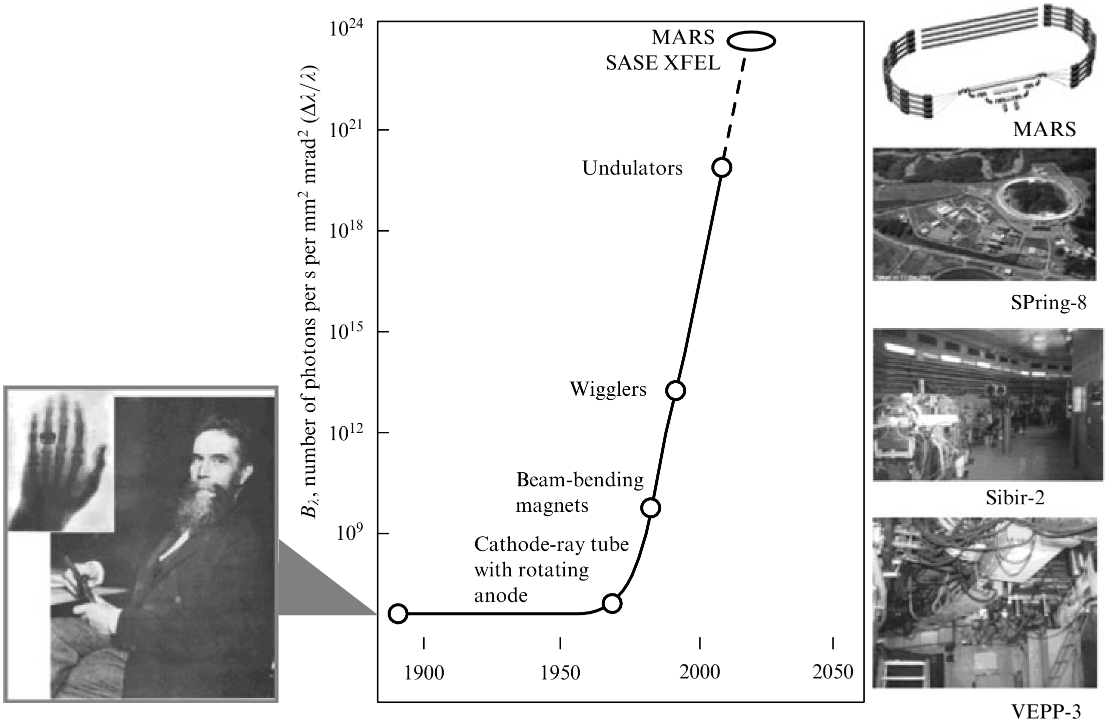


Figure 5. An increase with time of the spectral brightness of X-ray sources starting from the discovery of X-rays by W C Roentgen: history and prospects. MARS is an SR source of the fourth generation under development; SASE XFEL (Self Amplified Spontaneous Emission X-ray Free Electron Laser) is an X-ray FEL under development operating in the SASE mode; VEPP-3 (Novosibirsk), Sibir-2 (Moscow), and SPring-8 (Super Photon Ring) (Himeji, Japan) represent examples of three generations of SR sources now in operation.

every decade, which has permitted increasing the brightness of X-ray sources by a factor of 10^9 during the past thirty years.

The flux of spatially coherent quanta increased in proportion to the brightness enhancement, since according to Ref. [14] one has

$$\dot{N}_{\text{coh}} \sim B_\lambda \lambda^2 .$$

Nevertheless, in the most modern sources, APS (Advanced Photon Source) (USA) and SPring-8 (Super Photon ring) (Japan), the flux of coherent quanta only amounts to 10^{-3} of the total flux. Therefore, in spite of successful experiments on X-ray holography, this method has not become effective for structure studies of real objects (the structures of most of which are not crystalline). Even in studies of crystalline structures, the speckle spectroscopy, for which spatially coherent irradiation is also necessary, rather often happens to be very important.

The realization of a totally spatially coherent source will become possible if the phase volume of the optical source becomes smaller than the diffraction limit:

$$\varDelta_{x,z}\varDelta_{x',z'} \leqslant \frac{\lambda}{4\pi} .$$

To this end, the emittance of the electron beam must be sufficiently small, so that

$$\varepsilon_{x,z} = \sigma_{x,z}\,\varTheta_{x,z} < \frac{\lambda}{4\pi}$$

(which for X-ray radiation means $\varepsilon_{x,z} < 10^{-2}$ nm rad).

The emittance and energy spread of an electron beam in an electron storage ring depends on the equilibrium between radiative damping and diffusion, caused by quantum fluctuations in the synchrotron radiation and by scattering inside the beam in the case of high-density beams. Additional analysis (see, for example, Ref. [15]) has shown that in a storage ring it is impossible to obtain an emittance of the electron beam inferior to 10^{-1} nm rad and an energy spread less than 10^{-3}, therefore realization of a totally spatially coherent X-ray source is possible in the case of passage from electron storage rings to energy recovery linacs. This proposal, first put forward by our team in 1997 at the conference SRI-97 (6th International Conference on Synchrotron Radiation Instrumentation) [16] has now been adopted and is being actively developed at many world centers [17].

Energy recovery linacs (ERLs) combine the advantages of electron storage rings (high reactive power of the beam; small losses of high-energy particles per unit time, and, correspondingly, a low radiation background and the absence of induced radioactivity) and linear accelerators (the normalized emittance ε_n of the electron beam and energy spread can be kept during acceleration). Therefore, if a good injector with $\varepsilon_n < 100$ nm rad is available, then, owing to adiabatic damping during acceleration up to high energies ($E > 5$ GeV, $\gamma > 10^4$), it is possible to obtain an emittance $\varepsilon_{x,z} = \varepsilon_n/\gamma \sim 10^{-2}$ nm rad and an energy spread $\sigma_E/E \sim 10^{-4}$. In ERLs, the acceleration time ($\tau_{\text{acc}} \sim 1-10$ μs) is significantly shorter (by 3–4 orders of magnitude) than the characteristic time of radiative damping in storage rings ($\tau_{\text{rad}} \sim 10$ ms), therefore diffusion processes cannot have a negative influence on the emittance and the energy spread of the electron beam. Figure 6 presents the layout of the four-turn energy recovery linac MARS (Multi-turn Accelerator-Recuperator Source) [18], which is at present being developed by our team. In the ERL, the electrons obtained in the injector with an energy of ~ 5 MeV are then accelerated in an additional two-cascade injector, after which they pass through the main accelerating high-frequency structure four times, thus increasing their energy up to 6 GeV. After acceleration, the electrons again travel in the same direction through the same high-frequency structures, but in a deceleration phase, decrease their energy to 5 MeV, and then land in the dump. In the ERL, electrons undergoing acceleration and deceleration travel simultaneously along four tracks. The users of synchrotron radiation will perceive the radiation from the MARS undulators like radiation from a storage ring, with the only difference that each time new ('fresh') electrons are used with a small emittance $\varepsilon_{\min} \sim 10^{-2}$ nm rad and energy spread $\sigma_E/E \sim 10^{-4}$. In the MARS project, four undulators 150–200 m long ($N \sim 10^4$) are to be placed in the four tracks, as well as

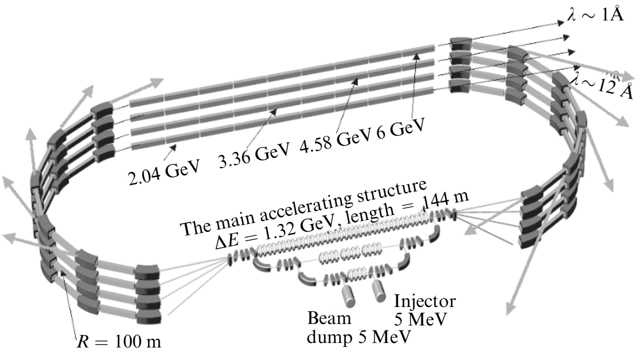


Figure 6. Conceptual layout of the fourth-generation synchrotron radiation source MARS.

Table 2. Comparison of the parameters of the synchrotron radiation source MARS ($I_e = 2.5$mA) and of SPring-8 ($I_e = 100$ mA); N_u is the number of periods of the undulator.

SR source		Number of undulators	Spectral brightness B_λ, number of photons per s per mm^2 mrad^2 ($\Delta\lambda/\lambda = 10^{-3}$)	Flux F, number of photons per s ($\Delta\lambda/\lambda = 10^{-3}$)
MARS	Undulator, $N_u \sim 10^2$	32	10^{22}	4.6×10^{13}
	Undulator, $N_u \sim 10^3$	12	10^{23}	4.6×10^{14}
	Undulator, $N_u \sim 10^4$	4	10^{24}	4.6×10^{15}
SPring-8	Bending magnet	—	10^{16}	10^{13}
	Undulator, $N_u = 130$	34	3×10^{20}	2×10^{15}
	Undulator, $N_u = 780$	4	10^{21}	1.2×10^{16}

several dozen undulators 5 – 20 m long ($N = 10^2 - 10^3$) (see Table 2).

5. Undulators and the development of free electron lasers

In the work by Ginzburg [2], in which the radiation of relativistic electrons in periodic magnetic structures was first considered, estimation was also made of the conditions for coherent radiation from a single short electron bunch in an undulator, and, in addition, the issue was raised of making use to this end of microbunches distributed at distances equal to the wavelength of the radiation generated. And although in Ref. [2] no discussion was presented of possible methods for creating such a sequence of microbunches, it is interesting to note its relationship to modern works on the creation of FELs [19], in which the undulator is a key element. It permits, on the one hand, synchronizing the motions of the electrons and of the wave, and, on the other hand, obtaining longitudinal modulation of the electron beam density with the radiation wavelength.

The FEL operation principle is demonstrated in Fig. 7. An electron bunch with energy $E = \gamma mc^2$ flies through the undulator, thus generating undulator radiation with the wavelength

$$\lambda = \frac{\lambda_0}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

at zero angle, where $K = eB\lambda_0/(2\pi mc)$ is the undulatory parameter. As the electron bunch moves along the undulator, at the initial segment the intensity of undulator radiation increases in proportion to the number of particles in the bunch and to the distance covered in the undulator. If the current of the electron bunch is sufficiently high and the undulator long, then the influence of the radiation on the electrons becomes essential. In spite of it being a plane electromagnetic wave that propagates along the undulator (the vector **E** is perpendicular to the axis of the undulator), owing to the sinusoidal trajectory of the electrons moving through the undulator the interaction results in modulation of the electron energy along longitudinal coordinate. Owing also to the propagation of the wave being synchronized with the motion of electrons in the undulator (at each period of the undulator, the electron bunch lags behind the electromagnetic wave by exactly one radiation wavelength), the energy modulation becomes sufficiently enough to lead to electron density modulation along the bunch either due to the dependence of the velocity of electrons on their energy in the simplest case [19] or due to utilization of the 'optical clystron' invented by N A Vinokurov and A N Skrinsky [20]. The resulting electron bunch turns out to be 'sliced up' into microbunches situated at a radiation wavelength from each other. If there are $N_e \sim 10^9 - 10^{10}$ electrons in a bunch of length l_b, then each microbunch will contain $N_{mb} = N_e\lambda/l_b \sim 10^4 - 10^6$ electrons. All the microbunches emit radiation coherently, so that the intensity of radiation from an FEL increases, as compared to the ordinary noncoherent radiation from a undulator, by a factor of $10^4 - 10^6$.

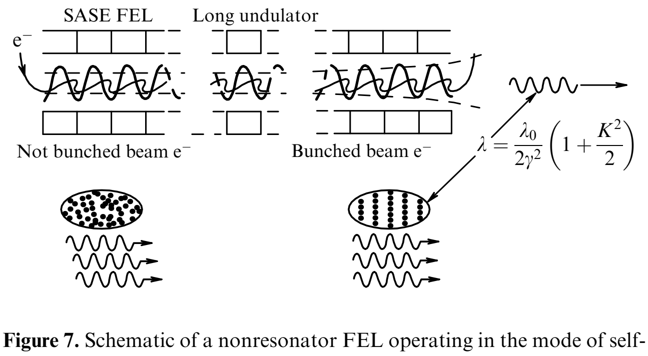


Figure 7. Schematic of a nonresonator FEL operating in the mode of self-amplified spontaneous emission (SASE)

The advantages of FELs compared to other types of lasers consist in the following:

(1) radiation can be generated with any desired wavelength between 1 mm and 1 Å (the range between 1 mm and 130 Å has already been realized [21]);

(2) operative smooth tuning of the monochromatic radiation wavelength can be performed through variation of the magnetic field in the undulators or of the electron energy from the accelerator;

(3) the 'working medium' in an FEL is a relativistic electron beam that is capable of generating radiation of high mean power up to 10^6 W (a power of 10^4 W has already been realized [22]).

The main disadvantages of FELs are their large dimensions and high cost. Therefore, the fields suitable for FEL application are those which are not accessible to conventional lasers.

One such interesting field is the creation of X-ray FELs ($\lambda = 1 - 20$ Å) exhibiting a high mean brightness $[B_\lambda \sim 10^{23} - 10^{24}$ photons per s per m^2 mrad^2 $(10^{-3}\,\Delta\lambda/\lambda)]$ with a short rigidly synchronized pulse (10 – 100 fs) and a fantastic peak power (10 – 100 GW) [21, 23, 24]. X-ray FELs are created on the basis of linear accelerators designed to provide an energy $E = 5 - 20$ GeV, with a high current pulse ($I_{peak} \sim 3 - 10$ kA), $N_e \sim 10^{10}$, $l_b \sim 100$ μm. It must be noted that the idea of a nonresonator FEL (see Fig. 7) operating in the SASE (Self-Amplified Spontaneous Emission) mode was first put forward at the beginning of the 1980s in the former USSR by A M Kondratenko and E L Saldin [25], and then implementation of this idea started with the active participation of one of the authors of the mentioned work [25] at DESY (Germany) [21]. Moreover, similar devices are being created at the Stanford Linear Accelerator Center (SLAC) (USA) [23] and SPring-8 (Japan) [24]. X-ray FELs are expected to be put into operation in 2010 – 2012. The cost of these FELs amounts to 0.5 – 1.0 billion dollars.

Another field appropriate for FEL applications is the creation of powerful ($P = 10 - 100$ kW) infrared lasers for technological applications (photochemical technologies, separation of isotopes, nanotechnologies, biomedical technologies, etc.), exhibiting a good monochromaticity ($\Delta\lambda/\lambda < 10^{-4}$), and tunable within a wide range of wavelengths.

In the Budker Institute of Nuclear Physics of the RAS Siberian Branch, the creation of a powerful FEL based on a four-track ERL (being also the prototype of MARS!) with a maximum energy of 50 MeV is close to completion [26]. The planned range of wavelengths is between 240 and 5 μm, the expected radiation power varies from 1 kW in the long-wave range up to 50 kW in the short-wave range.

Three years ago, the first phase — a terahertz FEL based on a one-track ERL, the layout of which is shown in Fig. 8 — was put into operation. The 2-MeV electron beam from the injector accumulates energy up to 12 MeV in the main

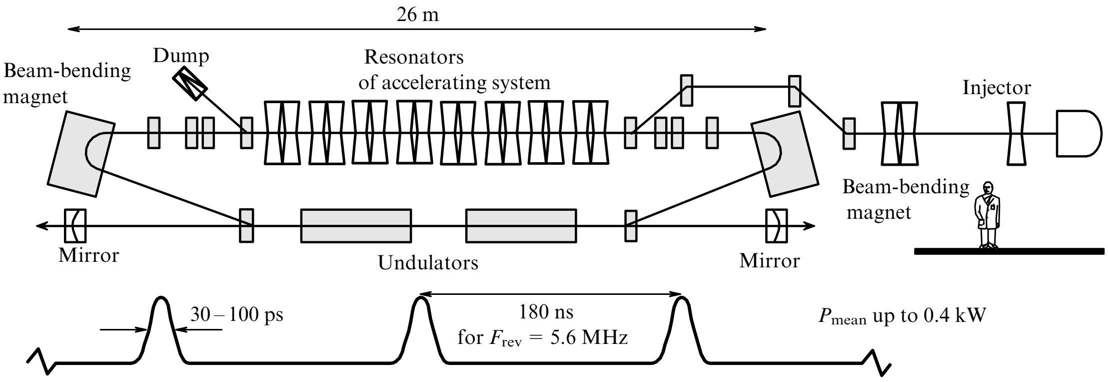


Figure 8. Layout of the Novosibirsk free electron laser operating in the terahertz range.

accelerating structure and then arrives at the undulator, where it loses part of its energy to radiation. After this, the electron beam returns to the main accelerating structure in the deceleration phase, slows down, and loses energy which practically drops to the injection energy value. Then the beam gets into the dump. In our terahertz FEL, as in nearly all existing FELs (with the exception of the aforementioned SASE XFEL), an optical resonator is used, inside of which the undulator is situated. The distance between the mirrors is chosen to be such that the light beam accumulated in the optical resonator propagates synchronously with the electron bunches. This permitted us to achieve generation in the terahertz region with relatively small peak currents ($I_{\text{peak}} \sim 10$ A) and the undulators of total length equal to 8 m. Radiation from the optical resonator is extracted through a hole 8 mm in diameter in one of the mirrors and further through a diamond window, separating the ultrahigh vacuum in the FEL from the beam extraction line filled with dry nitrogen at atmospheric pressure, is sent to experimental stations in a special hall, where Novosibirsk biologists, chemists, and physicists carry out their research [27].

Application of the Novosibirsk FEL as a terahertz radiation source permits obtaining the following:

— a smoothly tunable wavelength in the range between 110 and 240 μm with monochromaticity exceeding 0.3%;

— a mean power up to 400 W for the main harmonic and at a level of 10 W for the second and third harmonics (Fig. 9);

— a degree of linear polarization not less than 98%;

— short pulses of radiation (shorter than 100 ps);

— a high peak power (0.5 – 1 MW);

— a totally spatially coherent source with a longitudinal coherence length ~ 2 cm (without using a monochromator).

The interest in terahertz radiation is due to its following properties:

— the nonionizing radiation (the photon energy ranges 0.04 — 0.004 eV);

— the radiation passes through opaque media and weakly dispersive materials relatively well owing to a strong suppression of Rayleigh scattering $(1/\lambda^4)$;

— the frequency range of the radiation includes the region of molecular rotational spectra, the vibrations of biologically important collective modes of DNA and proteins, and frequencies characteristic of intermolecular interactions;

— terahertz radiation corresponds to the energy region of hydrogen bonds and van der Waals forces of intermolecular interactions;

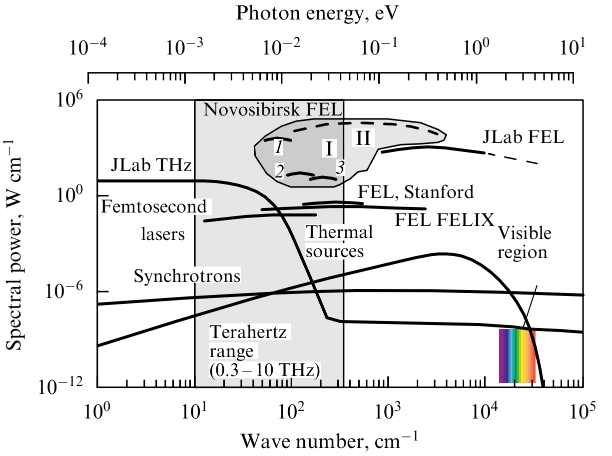


Figure 9. Comparison of the time-averaged spectral powers of various radiation sources: the Novosibirsk FEL (Russia): I — terahertz device in operation, where *1*, *2*, *3* are the numbers of radiation harmonics, II — infrared device to be constructed; JLab THz — coherent SR source utilizing beam-bending magnets; JLab FEL — FEL of the Jefferson Laboratory (USA); FELIX — infrared FEL of the Institute of Plasma Physics (Netherlands).

— the energy of photons of terahertz radiation lies in the region of the energy gap of superconductors.

The reason I have spoken about the Novosibirsk terahertz FEL in such detail is not the fact that it is one of the few Russian experimental installations of international standards created recently with parameters exceeding by several orders of magnitude the parameters of the best foreign installations in this spectral range (see Fig. 9). I have dwelt in such detail on the Novosibirsk FEL only because this was precisely the spectral range discussed by Ginzburg in his work [2] so long ago in 1947.

6. Conclusion

In recent years, a large family of undulators has been created throughout the world on the basis of various technologies: ordinary electromagnetic undulators; undulators making use of only constant magnets; hybrid undulators, in which a combination is used of constant magnets and soft magnetic materials, and superconducting undulators. Modern undulators permit not only generating radiation of any spectral composition between the terahertz and X-ray ranges with various polarizations (linear in any plane, left- or right-hand circular), but also spending relatively little time in changing its wavelength and polarization mode. In spite of severe requirements to the mechanical and magnetic parameters of undulators, there already exist undulators several dozen meters long with the number of periods amounting to several hundred. Undulators 150 – 200 m long are being designed. Taking into account the large number of SR sources (~ 60) and of FELs (~ 80) in the world, for which undulators are required, the construction of undulators has become a noticeable branch of the scientific instrument-making industry. And each time a new improved undulator is created, the 'door opens' for experimental physicists to new fields of research, which were not even discussed at the time when Ginzburg was proposing a new type of electromagnetic source in his work [2], which has now become famous.

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References

1. Ginzburg V L, Frank I M *Zh. Eksp. Teor. Fiz.* **16** 15 (1946); *J. Phys. USSR* **9** 353 (1945) (brief English version)
2. Ginzburg V L *Izv. Akad. Nauk SSSR, Ser. Fiz.* **11** (2) 165 (1947)
3. Schott G A *Electromagnetic Radiation and the Mechanical Reactions Arising from It* (Cambridge: Univ. Press, 1912)
4. Pomeranchuk I Ya *Zh. Eksp. Teor. Fiz.* **9** 915 (1939)
5. Ivanenko D D, Pomeranchuk I Ya *Dokl. Akad. Nauk SSSR* **44** 343 (1944)
6. Artsimovich L A, Pomeranchuk I Ya *Zh. Eksp. Teor. Fiz.* **16** 379 (1946)
7. Veksler V I *Dokl. Akad. Nauk SSSR* **43** 329 (1944)
8. McMillan E M *Phys. Rev.* **68** 144 (1945)
9. Kerst D W et al. *Phys. Rev.* **102** 590 (1956)
10. Budker G I *Usp. Fiz. Nauk* **89** 533 (1966) [*Sov. Phys. Usp.* **9** 534 (1967)]
11. Motz H, Thon W, Whitehurst R N *J. Appl. Phys.* **24** 826 (1953)
12. Baier V N, Katkov V M, Strakhovenko V M *Zh. Eksp. Teor. Fiz.* **63** 2121 (1972) [*Sov. Phys. JETP* **36** 1120 (1973)]
13. Alferov D F, Bashmakov Yu A, Bessonov E G *Zh. Tekh. Fiz.* **42** 1921 (1972) [*Sov. Phys. Tech. Phys.* **17** 1540 (1973)]
14. Kulipanov G N, Skrinskiĭ A N *Usp. Fiz. Nauk* **122** 369 (1977) [*Sov. Phys. Usp.* **20** 559 (1977)]
15. Kulipanov G N, Mezentsev N A, Skrinsky A N *Rev. Sci. Instrum.* **63** 289 (1992)
16. Kulipanov G N, Skrinsky A N, Vinokurov N A *J. Synchrotron Rad.* **5** 176 (1998); Preprint No. 97-103 (Novosibirsk: G I Budker Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Sciences, 1997)
17. Chattopadhyay S, Merminga L (Eds) *Energy Recovering Linacs 2005*: *Proc. of the 32nd Advanced ICFA Beam Dynamics Workshop on Energy Recovering Linacs, Newport News, USA, March 19 – 23, 2005* (Nucl. Instrum. Meth. A, Vol. 557, No. 1) (Amsterdam Elsevier, 2006)
18. Kulipanov G, Skrinsky A, Vinokurov N, in *Proc. of the 9th Intern. Conf. on Synchrotron Radiation Instrumentation, Daegu, Korea, 28 May – 2 June, 2006* (Abstract 10060003, B2-006) (CD-ROM); *AIP Conf. Proc.* **879** 234 (2007)
19. Elias L R et al. *Phys. Rev. Lett.* **36** 717 (1976)
20. Vinokurov N A Skrinsky A N, Preprint No. 77-59 (Novosibirsk: Institute of Nuclear Physics of the Siberian Branch of the USSR Academy of Sciences, 1977)
21. Brinkmann R, in *Proc. of the 28th Intern. Free Electron Laser Conf., FEL-06, Aug. 27 – Sept. 1, 2006, Berlin, Germany, MOBAU03,* p. 24; http://www.bessy.de/fel2006/proceedings/PAPERS/MOBAU03.pdf
22. Neil G R et al. *Nucl. Instrum. Meth. A* **557** 9 (2006)
23. "LCLS conceptual design report", SLAC-R-593 UC-414 (Stanford: Stanford Synchrotron Radiation Laboratory, 2002); http://www-ssrl.slac.stanford.edu/lcls/cdr/
24. Shintake T and SCSS Team, in *Proc. of the 28th Intern. Free Electron Laser Conf., FEL-06, Aug. 27 – Sept. 1, 2006, Berlin, Germany, MOBAU05*, p. 33; http://www.bessy.de/fel2006/proceedings/PAPERS/MOBAU05.pdf
25. Kondratenko A M, Saldin E L *Particle Accel.* **10** 207 (1980); Preprint No. 79-43 (Novosibirsk: Institute of Nuclear Physics of the Siberian Branch of the USSR Academy of Sciences, 1979)
26. Bolotin V P et al. *Nucl. Instrum. Meth. A* **543** 81 (2005)
27. *The Joint 31st Intern. Conf. on Infrared and Millimeter Waves and 14th Intern. Conf. on Terahertz Electronics*: *IRMMW – THz 2006, Sept. 18 – 22, 2006, Shanghai, China, Conf. Digest* (New York: IEEE) (in press)