LIGHT SOURCES IN RUSSIA

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Abstract

Possible ways of development of Light Sources (LS) based on relativistic electron and ion beams in accelerators and storage rings in Russia are discussed.

INTRODUCTION

Progress in various fields of natural science, medicine, biology, chemistry and technology is closely connected with the development and use of LS based on relativistic electron and ion beams. One of the main motivations to build such sources is to have a very brilliant and bright source of monochromatic photon beams with smoothly varied frequency in a wide spectral region and varied kinds of polarization. This is achieved on one hand with the production of low emittance particle beams in accelerators and storage rings of differed energy, on the other hand with the use of a variety of undulators and on the third hand with the use of different kinds of the emitting particles (electrons, ions) which can be optimized to the special demands of a certain experiment.

By definition, the LS's are sources of powerful beams of IR to X-rays having high degree directionality, narrow bandwidth, tunability, variable photon energy and polarization. These sources are based on accelerators and storage rings and make possible basic and applied reseach in different fields that are not possible with more conventional equipment. They are UR sources, including Backward (or Inverse) Compton scattering (BCS) sources and possibly future Backward Rayleigh scattering (BRS) sources. These sources are both spontaneous incoherent UR sources, spontaneous coherent UR sources (prebunched fel's) and stimulated UR sources (fel's) [1]. Development of LS's go on in all these directions. 3 Generations of the LSs are developed. 4th Generation of LSs is in the process.

One of the main motivations to build new generation LS is to have more bright source of photons in a wide spectral region. Brightness and brilliance (*) are determined by the equations

$$B_{rn} = \frac{1}{\hbar\omega}\frac{\partial^2 W}{\partial\omega\partial o}\Delta\omega, \qquad B_{rl} = \frac{1}{\hbar\omega}\frac{\partial^2 W}{\partial\omega\partial o\partial s}\Delta\omega,$$

where adopted $\Delta\omega/\omega = 10^{-3}$, $\hbar$ is the Planck constant, ∂s is the effective source area [2].

If the emitted UR beam is focused onto the sample, then the figure of merit of the UR source is its brilliance. In this case the smaller the particle beam dimensions and divergence, the smaller the sport size and divergence of the photon beam at the sample. The figure of merit of the source for the unfocused UR beams is its brightness. The brilliance was chosen to be an absolute criterions for generations of LS's. But it can obscure essential distinctions between particular machines which determine if the machine is suited for a given application. Existing IR and optical FELs and future fully coherent monochromatic long duration x-ray FELs are not included in any generation of LSs. A full characterization of a LS involves specification of the brilliance, polarization, spectrum, coherence, and time structure of the emitted radiation. Third generation LSs based on storage rings can complement of forth generation LS's.

Third generation LSs based on storage rings are physically very large (~1000 meters in circumference) with a capability for 30 or more insertion-devices, and a comparable number of bend-magnets and beam lines. They are very expensive and occupy an area the size of a sports stadium. Can be such installation shrunk down to fit on the desk? Similar suggestions are discussed for a long time. Now the Compact LS (CLS) based on small storage ring (~20 – 100 MeV) and laser beam stored in high quality open resonator and propagated along a straight section of the storage ring with zero dispersion and low beta-function is developed. Radiative cooling of the electron beam in the storage ring by high intensity laser light permits to overcome the problem of intrabeam scattering and to maintain the low emittance of the stored beam and its cross section at the IP at the average beam current I > 10 mA which permits to produce brightness enough for many experiments. Experiments will show the limiting stored currents which are determined by the laser intensity at the interaction point.

BCS and BRS sources can be considered as UR sources. In this case electron trajectories both for free electrons and for electrons bounded by nuclei (in classical approach) are undulator ones. Electrons bounded by nuclei are a very high quality oscillators. The amplitude of oscillations of an electron bounded by nuclei at resonance is much higher then for electron in free space. That is why the cross-section of the Rayleigh scattering is much higher (~10-15 orders) then Compton one (†). Ion storage rings are much expensive then electron ones. At the same time BRS sources are fraught the ultimate in the capabilities both spontaneous and stimulatd radiation sources in X-ray and gamma-ray regions.

The energy of scattered photons is high. It can reach high value ~5 MeV at the electron energy ~ 500 MeV and the photon energy ~ 1 eV. In this case the electron will be lost at the walls of the storage ring after interaction with a laser photon. Cross section of Compton scattering is small. That is why the intensity and hardness of CLS is

(*) Flux refers to the number of photons/s/0.1percentBW, Brightness refers to: photons/s/unit solid angle/ 0.1percentBW and Brilliance refers to: photons/s/unit solid angle/0.1 percent BW/unit area. Forth generation LS will have average brilliance >10^{22} and peak one >10^{30} at photon energies > 1 KeV.

(†) Transition energies and equilibrium amplitudes (oscillator strengths) are calculated in the framework of the quantum theory.

limited. At the same time in case of ion beams the cross section of the Rayleigh scattering is 10 orders higher, the ion mass is much higher and equilibrium emittances in the processes of radiative ion cooling by broad band laser beams [3], [4] can be less then for electron beams, there is no loss of ions on the walls of the storage ring. The main disadvantage of the BRS source is its large dimensions at the relativistic energies and high cost. Now the relativistic ion storage rings are used in elementary particle physics and can be used later for production of BRS radiation. Dedicated BRS can be produced.

What will be 5th generation LSs? Fully coherent monochromatic (relative bandwidth < 10^{-8}) prebunched x-ray FELs or x-ray and gamma-ray sources based on backward Rayleigh scattering or quantum generators on moving ions?

HISTORY

In 1897, J.Larmor derived an expression for the instantaneous total power radiated by an accelerated charged particle. The following year, A.Liénard extended this result to the case of a relativistic particle undergoing acceleration in a circular trajectory. In 1907, G.Schott obtained expressions for the angular distribution of the radiation emitted by a relativistic electron in a homogeneous magnetic field as a function of the harmonic of the orbital frequency. The helical and sine-like trajectories were considered in general case as well. Nowadays they are named "undulator trajectories". His search in this field was presented in a book devoted to an attempt to explain the discrete nature of atomic spectra in 1912 [5]. In 1944 D.Ivanenko and I.Pomeranchuk showed that SR energy losses due to radiating electrons would set a limit on the energy obtainable in a betatron (~0.5 GeV). Later Schwinger in USA, I.Pomeranchuk, A.Sokolov and I.Ternov (USSR) had worked out in detail the theory of SR from accelerated relativistic electrons. For the first time the observation of SR was produced by H.Pollack in USA. In 1947, V.Ginzburg suggested the idea of spontaneous incoherent UR sources, prebunched FELs and a ring for multiple using electron beams (synchrotrons were absent that time) [6]. In 1951-1953, H.Motz produced first experiments on spontaneous incoherent UR sources and prebunched FELs based on Linear Accelerators (LA). He made an important contribution to the theory of UR sources. First experiments with UR produced in undulator installed in the straight section of a synchrotron were done at LPI RAS, Moscow (1977) [7], [8]. R.Twiss, H.Motz, M.Nakamura and other authors proved prebunched FELs and paid attention on bunching electron beams in fields of undulators and electromagnetic waves in conventional FELs by analogy with the traveling-wave tubes. First FEL based on LA was produced by R.M.Phyllips in 1960 in cm wavelengths [11], [12]. He named such devices "ubitron" (from undulator beam interaction) and suggested the idea of the undulator klystron (UK) consisting of a train of two undulators with a drift space between them for bunching. Bunching of electron beams and harmonic generation on frequencies multiple to the frequency of the amplified wave takes place in such system. Using dispersion section between undulators of the UK for lengthening of the distance between the wavelets of the UR emitted from these undulators and increasing the gain of the FEL was suggested by N.A.Vinokurov and A.N.Skrinsky in 1977 [13]. Such system was named optical klystron (OK). First experiments with FEL in IR region was produced in 1977 (USA) [14]. High quality optical resonators were used to increase the power of prebunched fel's in [15].

BCS, in which low energy photons are scattered off high energy electrons, was first discussed by E.Feinberg and H.Primakoff in 1948 with regard to the interaction of cosmic electrons with starlight. K.Landeker, M.Lampert considered sources based on reflection of electromagnetic waves from electron beams beginning from 1952. First papers devoted to backward scattering of light from moving mirrors appeared at the beginning of the 19th edge.

Generation hard radiation through BCS in accelerators was discussed by G.Arushanov et al. in 1962 [16]. First BCS gamma-rays were generated by O.Kulikov et al. in 1964 at 680 MeV synchrotron LPI RAS [17]. BRS sources were suggested by K.A.Ispirian, A.T.Margarian in 1973 [18]. In the paper [19] the use of very powerful BRS X-ray radiation for inertial confinement fusion was suggested by N.Basov et al., LPI RAS, 1985. Quantum generators based on relativistic ion beams were suggested L.Miller in 1979 [20].

One of main problems facing the researches is the production of low emittance beams in LA's and storage rings. Cooling of particle beams in storage rings can be used. Synchrotron radiation damping (cooling) of electron beams in storage rings leads to this goal. It is originated from bending magnets of the rings due to the radiative reaction force and is limited by quantum excitation of betatron and phase oscillations. The main task of researches to find optimal magnetic lattice for the rings in this case. Strong focusing lattice with low beta- and zero dispersion functions at straight sections of the rings are required at the undulator locations to obtain high brilliance sources. Additional cooling of the electron beams in compact electron and ion storage rings based on the radiative reaction force in the fields of laser beams can be used as well [3].

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LSs underlies scientific and technological progress in different regions of the human activity. Now they include about 100 operating facilities in different countries. Each of them produces IR, VUV, soft- and hard X-ray beams for different applications in science and technology and γ -ray beams for high-energy physics research. Different magnetic and laser undulators are used. Dozens of photon beam transport lines allow to propagate the radiation to optical systems and experimental stations.

Russia in 70th had one of leading positions in theoretical and experimental investigations of the properties of both spontaneous incoherent, spontaneous coherent and stimulated UR sources. Nowadays there are 3 centres where LSs are in operation. They are in INP RAS, Novosibirsk; IAE, Moscow; and LPI, Moscow. LSs based on storage rings are constructed in Zelenograd, Moscow region. Projects of LSs are developed in JINR, Dubna, Moscow region. The most significant results are in INP, where 2 storage rings (VEPP 3 and VEPP 4) and IR FEL are in operation. Unfortunately these storage rings are very old and used for high energy physics simultaneously (2d Generation LSs). Projects of 3d and 4th Generation LSs exist. The LS in IAE is the dedicated LS. Booster for the top-up injection is needed to work in the 3d Generation LS regime. There are 2 synchrotrons in LPI (C-60 on 680 MeV in Moscow and synchrotron "Pachra", 1.2 GeV in Moscow region). Synchrotron "Pachra" is used for elementary particle physics and sometimes is used as LS simultaneously. It can be used as a booster for intermediary (~1GeV) dedicated LS based on a storage ring (top up energy injection). Superconducting recirculator on the energy 1-2 GeV for the particle physics and as LS simultaneously is discussed as well.

CONCLUSION

Nowadays electromagnetic Light sources (ELS) based on emission of electromagnetic radiation by electron beams in periodic electromagnetic fields produced by undulators in vacuum stay to be highly promising. As a rule of thumb, the higher the generation of the LS, the higher the brilliance. This is not an absolute criterion and, in fact obscures essential distinctions between particular machines which determine if the machine is suited for a given application. A full characterization of a LS involves specification of the brilliance, brightness, polarization, spectrum, special-time coherence, and time structure of the emitted radiation.

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