LASER TECHNOLOGY FOR ACCELERATOR

1. Introduction

One of the most significant inventions of the last century is the invention of the laser, which is now used in almost all aspects of sciens and daily life. The word LASER is formed from the abbreviation of the English phrase "light amplification by stimulated emission of radiation".

Back in 1916, Albert Einstein [1] predicted the possibility of transition of atoms from a higher energy state to a lower one under external influence. During this transition, a certain amount of energy is released, and such radiation is called stimulated. Stimulated radiation is the basis for the operation of lasers.

The principle of laser operation [2, 3] is based on the stimulated emission of light photons when exposed to an external electromagnetic field. As it is known from the high school physics, the structure of the atom has a planetary model according to which negatively charged electrons revolve around a positively charged nucleus in certain energy orbits. Each orbit corresponds to a certain value of the electron energy. In an unexcited state, electrons are located at low energy levels, which are due to the minimum energy consumption, can only absorb the radiation that falls on them. When an atom is exposed to radiation, it receives an additional portion of energy, which provokes the transition of electrons (one or more) to higher energy levels of the atom, that is, the electron goes into an excited state. Energy is absorbed in strictly defined portions - quanta. The excited atom strives to return to the relaxed state again, and gives up excess energy, emitting it in strictly defined portions as well. In this case, the electrons return to their original energy levels. The resulting quanta or photons of light have energy equal to the difference between the energies of the two involved levels. Thus, stimulated emission occurs.

An atom in an excited state can emit energy itself, or it can emit when exposed to external radiation, Fig. 1. It is characteristic that the quantum that is emitted and the quantum that caused the emission are similar to each other. This characteristic determines that the wavelength of the induced radiation is equal to the wave that caused this radiation. In total, the induced radiation will increase with an increase in the number of electrons that have jumped to the upper energy levels.

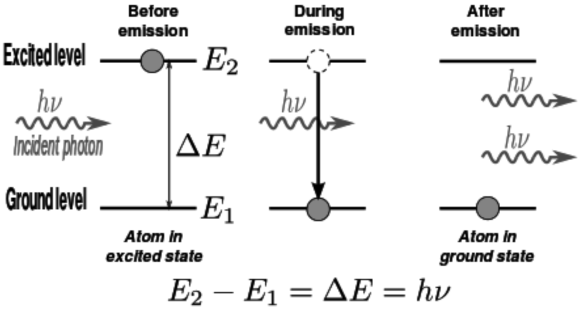

Fig. 1 Principle of lasers

In addition, there are inverse systems of atoms in which electrons are concentrated at higher energy levels. In such systems, the process of quanta emission dominates over the process of absorption. Inverse systems are used to design optical quantum generators (lasers). The active substance (medium) is placed in an optical resonator consisting of two parallel high-quality mirrors, which are placed on both sides of the active media. The emitted quanta, getting inside and repeatedly reflecting from the mirrors, cross the active media many times, thereby cause the appearance of similar quanta through the emission of atoms, where electrons are in distant orbits. The active medium can be of different materials, any aggregation state, and its choice determined by what characteristics are required from the laser. The main characteristics of lasers - power and spectral range - depend on the active medium. Please refer to Fig. 2. The laser effect (lasing) can occur only when the number of atoms in an excited state exceeds the number of atoms in a rest state.

A medium with such characteristics can be prepared by pumping it with additional energy from a certain external source. This operation called pumping. Pumping can be carried out under the influence of electromagnetic radiation, electric current, electric discharge, beam of relativistic electrons, as well as chemical reaction. The kind of energy used depends on active medium.

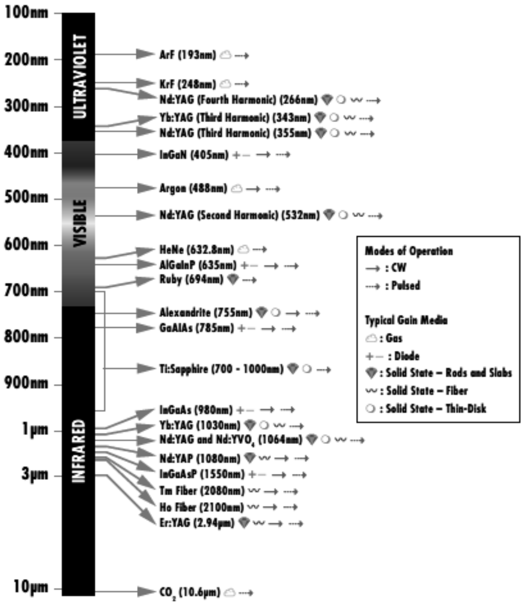

Fig. 2 Elements emission bands

Based on everything written above, it is possible to determine three main parts of the structure that any laser has in its composition:

1) Active media environment
2) Power source or pumping system
3) A device for amplifying the emitted light - a system of mirrors (optical resonator)

2. The main types of lasers

Gas lasers

The use of gas in a laser as an active medium has a very important quality - high optical uniformity, that is, the light beam in the gas is scattered and distorted to the least extent. The gas laser is characterized by high directivity and monochromaticity of radiation, and can also operate in a continuous mode. The power of a gas laser can be significantly increased by using different methods of excitation and by increasing the gas pressure. Therefore, these lasers are most often used where a very high directivity and monochromaticity of the beam is required. The very first gas laser was created in 1960 based on a mixture of helium and neon, which remains the most common to this day, Fig. 3. After that, many different gas lasers were created, and still in the process of creation, where quantum transitions of neutral ions, atoms and molecules are used in various ranges of the spectrum of a light beam (from ultraviolet to infrared, and even X-rays). Such lasers are widely used in accelerator laboratories as the devices for beamline and accelerator components alignment.

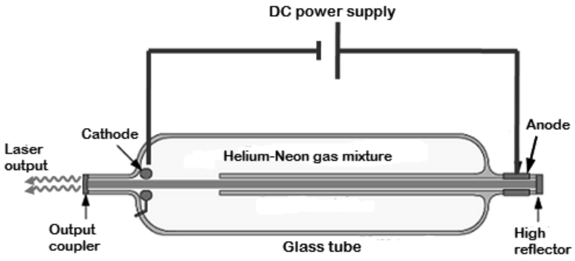

Fig. 3 Principle of He-Ne laser

Semiconductor lasers

Semiconductor lasers operate in the visible and infrared ranges. They have a number of unique characteristics that make them especially valuable in practice. Semiconductor lasers are characterized by a high, almost 100% efficiency of conversion of electrical energy into coherent (stimulated) radiation; low degree of inertia; can work in continuous mode; have a fairly simple design; have the ability to tune the radiation wavelength, as well as availability of a large number of semiconductor materials that can continuously overlap wavelengths in the range 0.32 - 32 μm, Fig. 4. Unfortunately, semiconductor lasers also have their disadvantages - weak directivity of radiation, which is associated with their small size; difficulties in obtaining high monochromaticity of radiation, which is due to the large width of the spontaneous emission spectrum. Semiconductor lasers are used when the coherence and directivity of wave processes are not particularly important, but small dimensions and high laser efficiency are required. Typically, such lasers are used as a pump lasers within large laser systems.

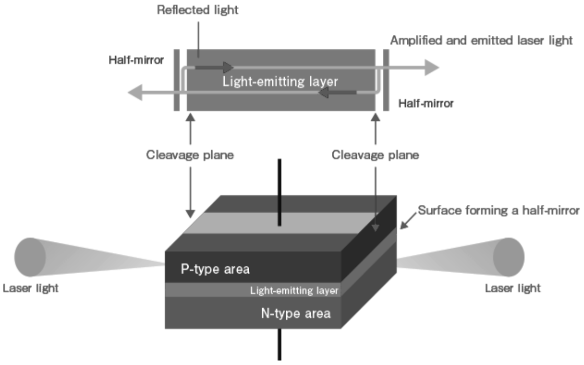

Fig. 4 Principle of semiconductor laser

Liquid dye lasers

In liquid dye lasers, the active medium is a liquid. An important characteristic of this laser is the possibility of obtaining high energy and radiation power in pulsed and continuous modes of operation, using the circulation of the active liquid for cooling. They are not used in practice now due to their low emitted energy and insufficient chemical resistance.

Solid state lasers

A solid-state laser active medium is activated dielectric crystals, glasses, or dielectric crystals with their own point defects. As activators of crystals and glasses, ions of rare earth elements or ions of the iron group are usually used. Intrinsic point defects in crystals arise under the influence of ionizing radiation or by additive coloring. The energy levels of activators or intrinsic defects are used to create an inverted population. These lasers are widely based on a ruby crystal - aluminum oxide (Al2O3), in which about 0.05% of aluminum atoms are replaced by chromium ions Cr3 +, on yttrium aluminum garnet (Y3Al5O12), on glasses doped with neodymium (Nd3 +), terbium (Tb3 +) ions , ytterbium (Yb3 +), etc. Stimulated radiation of various frequencies is produced by more than 250 crystals and about 20 glasses.

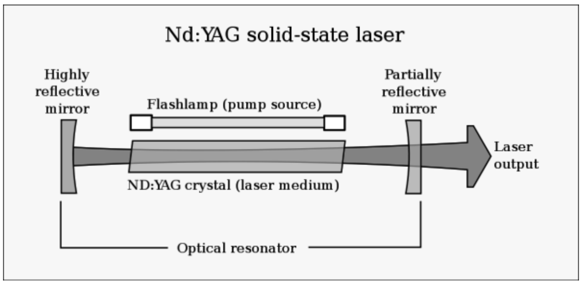

Fig. 5 Principle of Nd:YAG solid-state laser

The generation wavelength range of solid-state lasers extends from the UV to the mid-IR region. They operate in pulsed, CW and quasi-CW modes and are the main devices for diagnosing of charged particle beams.

Solid-state lasers are constructed utilizing a three- or four-level scheme. The active element of these lasers is usually in the form of a circular cylinder or a rectangular bar. The active element of more complex configurations is sometimes also used. The most widespread design contains a cylindrical active element together with a gas-discharge pump lamp that is placed in an illuminator chamber, which concentrates the radiation of the pump lamp into the active element, Fig. 5. Due to the multiple reflection of the pump radiation from the inner surface of the illuminator chamber, its more complete absorption into the active element is achieved. Schemes with one pumping lamp for several active elements or one active element pumping by several or more lamps is used.

For existing solid-state lasers, the output power in the continuous mode can reach 1-3 kW with a specific energy output of ~ 10 W per 1 cm^3 of the active medium with an efficiency of ~ 3%. The average power of 10^3 W at a pulse repetition rate of up to 100 Hz is realized in pulse-periodic solid-state lasers in the free-running mode with a pulse duration of 0.1 – 1 ms. Solid state lasers occupy a unique place in the development of lasers. They are easy-to-maintain devices capable of generating high power energy. For pumping solid-state lasers, LEDs, lamps, and other lasers can be used.

3. Fiber lasers

The term "fiber laser" generally refers to a laser with an optical fiber as gain medium, although some semiconductor gain medium and fiber cavity lasers are also called fiber lasers.

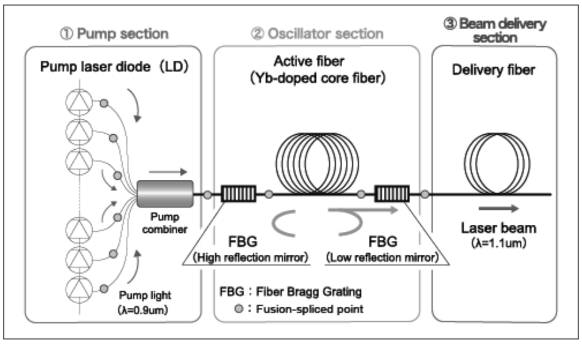

Fig. 6 Principle of fiber laser

In most cases, the gain medium for fiber lasers is fiber doped with rare earth ions such as erbium ($Er3^+$), neodymium ($Nd3^+$), ytterbium ($Yb3^+$), thulium ($Tm3^+$), or praseodymium ($Pr3^+$). One or more laser diodes are used for pumping, Fig.6.

Fiber Laser Resonator

To create a linear cavity of a fiber laser, it is necessary to use some kind of reflector (mirror), or create a ring cavity (ring fiber laser). Various types of mirrors are used in linear resonators of an optical fiber laser:

- In simple laboratory setups, conventional dielectric mirrors can be attached to the perpendicularly cleaved ends of the fiber, as shown in Fig. 7. This approach, however, is not very practical for mass production and is also not very reliable.

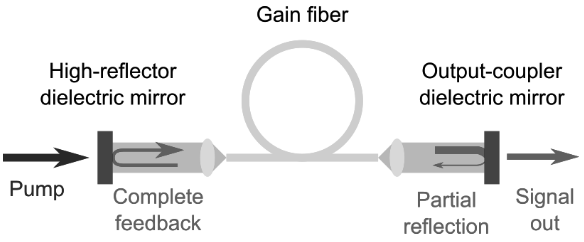

Fig. 7 Principle of fiber laser resonator

- Fresnel reflection from the fiber end face is often sufficient for use as an output mirror of a fiber laser cavity.
- It is also possible to deposit dielectric coatings directly on the ends of the fiber, usually by sputtering. Such coatings can be used for a wide range of reflections.
- Many fiber lasers use fiber Bragg gratings formed directly in a doped fiber, or in an undoped fiber soldered to an active layer.

The best power characteristics can be obtained by using a collimator at the exit of light from the fiber and reflecting it back using a dielectric mirror (Fig. 7). The intensity at the mirror is significantly reduced due to the much larger beam area. However, a small offset can lead to significant reflection loss, polarization dependent loss, etc.

Another option is to use a fiber loop mirror, based on a fiber sleeve (e.g. 50:50 split ratio) and a piece of passive fiber, Fig. 8.

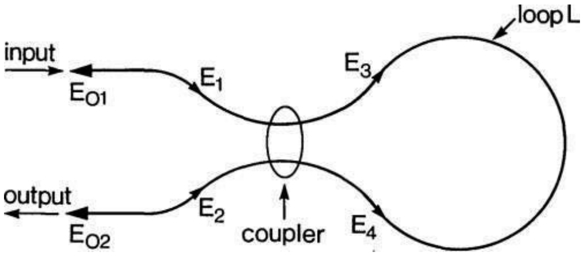

Fig. 8 Principle of fiber loop mirror

Most fiber lasers are pumped with one or more fiber-output diode lasers (laser diode radiation is injected into the fiber). Light can be pumped directly into the core or into the inner cladding of the fiber in high-power lasers.

Laser resonator modes

While laser light is perhaps the purest form of light, it still depends on more than just frequency or wavelength. All lasers emit light over some natural bandwidth or frequency range. The bandwidth of a laser is determined primarily by the active medium included in the design of the laser, as well as the frequency range in which the laser can operate (better known as the bandwidth). For example, a typical helium-neon (He-Ne) gas laser has a lasing bandwidth of about 1.5 GHz (wavelength range of about 0.002 nm at a center wavelength of 633 nm), while a titanium-sapphire (Ti: Sapphire) solid-state laser has a bandwidth of about 128 THz (300 nm wavelength range centered around 800 nm).

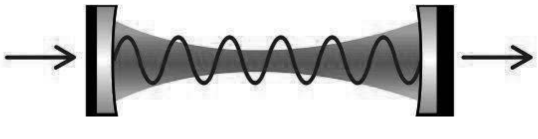

Fig. 9 Fabry-Perot resonator

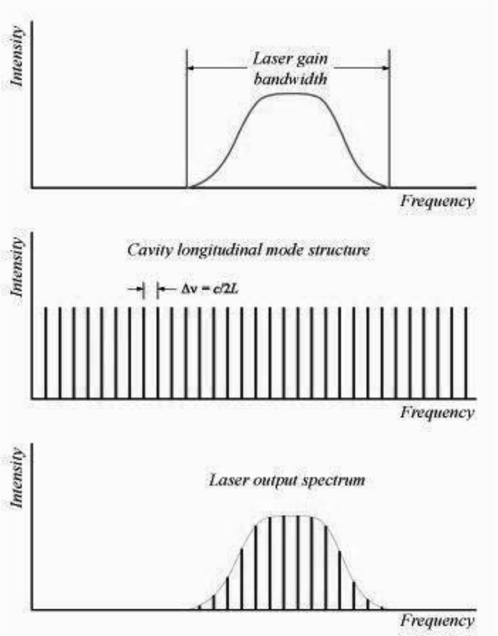

Fig. 10 Principle of laser resonator mode amplification

The second factor that determines the frequency of laser radiation is the optical resonator of the laser. In the simplest case, it consists of two flat mirrors set opposite to each other. The active medium of the laser is placed between them (this configuration is called a Fabry-Perot resonator, Fig. 9). Since light is a wave, when reflected between the mirrors of the resonator, the light will interfere with itself with amplification and attenuation, which leads to the formation of standing waves or modes between the mirrors.

These standing waves form a discrete set of frequencies known as longitudinal resonator modes. Only these modes possess such radiation frequencies that are capable of self-sustaining in the cavity of the resonator, and all other light frequencies are suppressed by destructive interference, Fig. 10. For a simple flat mirror resonators, the supported modes are those for which the distance L between the mirrors is a multiple of half the light wavelength λ: $L = q\lambda / 2$, where q is an integer known as the order of the mode.

In practice, the distance between the mirrors L is usually much greater than the wavelength of light λ, so the corresponding q values are large (about 10^5 to 10^6). Most interesting is the frequency spacing between any two adjacent modes q and q +1. This value is specified (for an empty linear resonator of length L) as Δv:

$$\Delta \nu = \frac{c}{2L}$$

, where c is the speed of light ($\approx 3 \times 10^8$ m/s). Using the above equations, a small laser with a mirror spacing of 30 cm has a longitudinal mode spacing of 0.5 GHz. Thus, for the two lasers discussed above, a helium-neon laser with a 30 cm resonator and a 1.5 GHz lasing bandwidth will support up to 3 longitudinal modes, while a titanium-sapphire laser with a bandwidth of 128 THz can support about 250,000 modes. When more than one longitudinal mode is excited, the laser is said to operate in a "multimode mode". When only one longitudinal mode is excited, the laser is said to operate in a "single mode".

Each longitudinal mode has a certain bandwidth within which this mode is amplified, but usually this bandwidth, determined by the Q factor of the resonator (see Fabry-Perot interferometer), is much smaller than the mode spacing.

Mode synchronization theory

In a simple laser, each of these modes will oscillate independently, without a fixed ratio between themselves and other modes, essentially like a set of independent lasers emitting light at slightly different frequencies. The individual phases of the light waves in each mode are not fixed and can change randomly due to factors such as thermal vibrations of the laser design. In lasers that support only a few oscillating modes, interference between modes can cause a beating effect at the laser output, resulting in random intensity fluctuations; in lasers with many thousands of modes, these interference effects are typically averaged out to a near constant output intensity, and this is called continuous wave operation, Fig. 11.

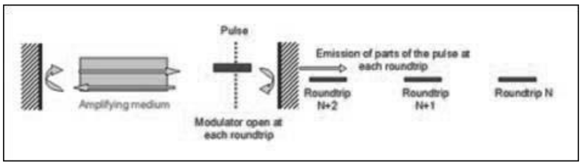

Fig. 11 Principle of mode-locking

If instead of independent oscillations, each mode oscillates with fixed relationships between its phase and the phases of other modes, the output power of the laser behaves quite differently. Instead of random or constant output intensity, the laser modes will intermittently interfere with each other, creating an intensity burst or pulse of light. Such a laser is called a mode-locked laser or a phase-locked laser. These pulses are separated in time by $\tau = 2L / s$, where τ is the time during which the light makes a complete round trip of the laser cavity. This time corresponds to the frequency interval between any two adjacent modes, $\Delta v = 1 / \tau$.

The duration of each light pulse is determined by the number of modes that oscillate in one phase (in a real laser, it is not always true that all laser modes will be phase locked). If N modes are locked with the frequency interval Δv, then the total width of the locked modes is $N\Delta v$, and this value is the wider, the shorter the laser pulse duration. In practice, the actual pulse width is determined by the shape of each pulse, which in turn is determined by the exact relationship between the amplitude and phase of each longitudinal mode. For example, for a laser generating Gaussian pulses, the minimum possible pulse duration Δt is determined by the formula:

$$\Delta t = \frac{0.441}{N\Delta\nu}.$$

The value of 0.441 is known as the time-bandwidth product of the pulse, and varies with the shape of the pulse. For ultrashort pulse lasers, the pulse shape is often the square of hyperbolic secant (sech2), which corresponds to a pulse generation interval of 0.315. Using this equation, the minimum pulse width can be calculated according to the measured width of the laser spectrum. For a helium-neon laser with a spectral width of 1.5 GHz, the shortest Gaussian pulse with this spectral width will have pulse duration of about 300 ps. For a Ti:Sa laser with a bandwidth of 128 THz, this pulse duration is only 3.4 fs. These values correspond to the shortest possible Gaussian pulses according to the laser cavity length. In a real mode-locked laser, the actual pulse width depends on many other factors, such as the actual pulse shape and the overall dispersion of the medium.

Also, for generation of a short pulses the chirped pulse amplification scheme is in use. Readers are advised to follow references at the bottom of the article for further learning.

4. Laser application to accelerator

As applied to accelerators, the type and parameters of the laser system are usually selected based on the needs of the particular application.

Generation of charged particles

Electron beams are used in most modern accelerators as accelerated electron beam generators. The role of the electron gun is to create and form a flow of electrons in the desired [4] form for injection into accelerating fields. Although the electron gun usually makes up only a small part of the entire system, its characteristics have a decisive influence on the final parameters of the electron beam. Electron guns can operate in continuous or pulsed mode.

An electron gun is a device that produces a beam of electrons with a given kinetic energy and a given configuration. The operation of an electron gun is possible only in a deep vacuum, so that the electron beam is not scattered when colliding with molecules of atmospheric gases.

Electron guns used in accelerator technology can be divided according to the way they generate electrons:

1) Electron guns with thermionic emission.

With a long history of development and use, thermionic cathodes are the most practical sources for applications that require long life and low duty cycle.

2) Electron guns with photoemission.

Photoemission cathodes, Fig. 12 have long been used in electro-optical devices at low current densities. The advent of high-intensity pulsed lasers has prompted the development of photocathodes for high-energy and high-brightness electron beams. The principle of operation of the photocathode is as follows: pulses of high-power laser radiation pull

Fig. 13 Photograph of KEK-B photocathode

electrons from the cathode surface from a material with a low work function, Fig. 13. Photoemission electron guns have some advantages over thermionic ones. Among them, there is no heater, which simplifies the design of the gun; higher values of the maximum current density; higher beam brightness, since electrons have much lower average transverse momenta. Disadvantages of photocathodes: the presence of a complex laser system; high requirements for the vacuum in the gun; impossibility of working with high current densities at low duty cycle due to high average power of laser radiation.

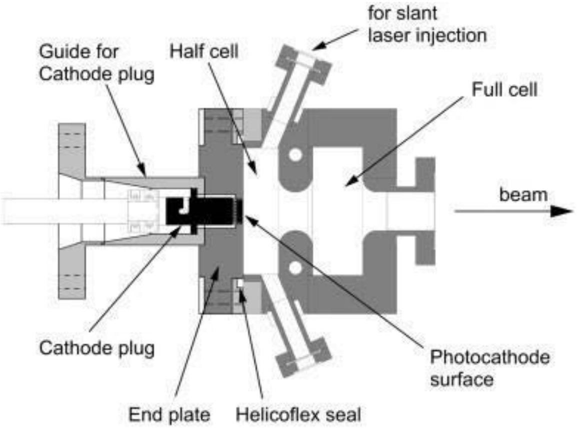

Fig. 12 Schematics of 1.6 cell room temperature, S-band RF gun

Laser acceleration

Laser acceleration of charged particles, based on the use of electric fields created by powerful pulses of laser radiation in a vacuum or matter. The use of laser acceleration for electrons was first proposed by the Japanese physicist K. Shimoda and the Russian physicists A.A. Kolomensky and A.N. Lebedev in the early 1960s, immediately after the creation of lasers. In 1979 the American scientists T. Tajima and J.M. Dawson put forward the idea of using lasers to accelerate electrons in plasma. This idea is close to the collective acceleration method developed under the leadership of Ya.B. Feinberg [5].

The laser pulse creates a high intensity of the accelerating electric field (up to 10^{14} V / m), which makes it possible to reduce the length of the accelerator by several orders of magnitude. The beginning of active experimental development of laser acceleration started in the mid-1980s by the laser pulses with duration of less than 1 pc and a power of several hundred TW. In 2000, the effect of ion acceleration was discovered [6, 7] when a thin foil was irradiated with high-intensity laser pulses. In this case, the laser pulse knocks out a cloud of electrons from the foil, the electric field of which accelerates the ions of the gas adsorbed on the foil surface.

The main disadvantage of laser acceleration is the greater energy and angular spread of particles as compared to traditional accelerators. A possible solution to this problem in the acceleration of electrons in plasma is associated with a new acceleration mode, discovered in 2004. This mode uses a laser pulse whose power is higher than the wake wave destruction threshold, and the length is

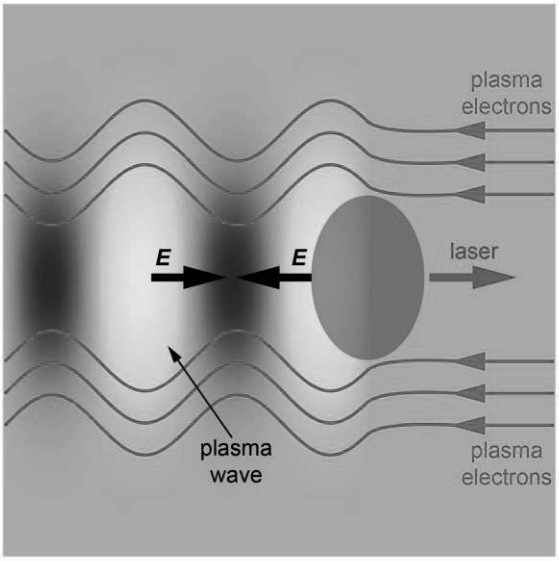

Fig. 14 Principle of laser plasma acceleration

comparable to the wavelength of plasma oscillations. Then a spherical region depleted of electrons (the so-called bubble) is formed behind the pulse, Fig. 14. Plasma electrons entering this region acquire approximately the same energy while accelerating. Ion beams of close energies are supposed to be obtained using foil targets, on the surface of which a layer (about 1 nm thick) is created.

By the beginning of the 21st century, the following prospects for the practical application of laser acceleration of charged particles are being considered:

- Use of plasma wakefield accelerators for the generation of synchrotron radiation
- Compact ion accelerators for proton radiography and radiation therapy.
- Plasma heating in the implementation of inertial thermonuclear fusion.

A constant developments of laser acceleration technologies are underway.

Laser beam profile monitors

A device concept based on the use of Compton scattering (laserwire technique) has been proposed to measure the transverse beam size in future linear colliders [8, 9]. Linear electron-positron colliders with beam energies of up to several TeV's and with a high luminosity will apparently be the first accelerators requiring non-destructive measurements of micron and submicron beam sizes in on-line mode. These measurements are necessary for continuous adjustment of the beams phase volume in order to increase the luminosity. Typical beam densities in linear colliders significantly exceed the values sufficient for melting and evaporating any material in a single beam pass, which makes it impossible to use traditional secondary emission sensors.

The use of a sharply focused beam of a high-power laser with a low diffraction divergence allows to develop a monitor for the transverse beam size measurements (laserwire). Functionally it is similar to a secondary emission sensor with a moving wire (wire scanner).

The main idea of the laserwire monitor is to replace the metal wire with a thin laser beam. The physical process used is the Compton effect, scattering of photons by a particle beam. A detailed theory of the relativistic Compton effect is presented, for example, in [10]. Following [11], we write down the main formulas concerning the use of the Compton effect for beam diagnostics. If the laser beam crosses the electron beam at a right angle and the laser power is evenly distributed along the path of interaction with the beam, the average number of Compton gamma quanta is described by the expression:

$$\langle N_\gamma \rangle = \sigma_c \langle n_0 \rangle N_e d = \frac{\sigma_c}{c\hbar\omega_0} \rho_L N_e d$$

,

where Ne is the number of particles in the beam; d interaction length; $\langle n_0 \rangle = \frac{\rho_L}{c\hbar\omega_0}$ average photon density; ρ_L is the power density and ω0 is the laser radiation frequency. The Compton scattering cross section σc is related to the Thomson scattering cross section $\sigma_e = \frac{8\pi}{3} r_e^2$ by the ratio:

$$\frac{\sigma_c}{\sigma_e} = \frac{3}{4}\left\{\frac{1+\epsilon}{\epsilon^3}\left[\frac{2\epsilon(1+\epsilon)}{1+2\epsilon} - \ln(1+2\epsilon)\right] + \frac{1}{2\epsilon}\ln(1+2\epsilon) - \frac{1+3\epsilon}{(1+2\epsilon)^2}\right\}$$

where $\epsilon = \frac{\gamma\hbar\omega_0}{m_e c^2}$ is the classical radius of an electron; $\gamma = \frac{E}{m_e c^2}$ is the relativistic factor, E is the energy of the electron beam. The spectrum of Compton gamma quanta is:

$$\frac{d\sigma}{dw} = \frac{3\sigma_e}{8\epsilon}\left\{\frac{1}{1-w} + 1 - w + \left[\frac{w}{\epsilon(1-w)}\right]^2 - \frac{2w}{\epsilon(1-w)}\right\}$$

where $w \equiv \hbar\omega_\gamma / E$ is the energy of gamma quanta, normalized to the energy of electrons. The maximum photon energy is

$$\hbar\omega_{\max} = \frac{2E\epsilon}{1+2\epsilon}$$

The flux of Compton gamma quanta is concentrated in a cone, the opening angle of which is on the order of the critical angle

$$\theta_c = \frac{\sqrt{1+2\epsilon}}{\gamma}$$

By measuring the count rate of scattered gamma quanta (or electrons) as a function of the position of the laser beam relative to the beam, it is possible to calculate the transverse distribution of particles in the beam for known parameters of the laser beam at the interaction point. With the help of Compton scattering, using various optical schemes, it is possible to measure both the transverse and longitudinal profile of a relativistic electron or positron beam

Laser wire monitor

In the scheme of transverse beam profile laserwire monitor, the laser beam is focused into a small spot with a Gaussian power distribution. For a sharply focused laser beam with a diffractive divergence, the minimum attainable rms spot size σ_r is given by the formula:

$$\sigma_r = \frac{\lambda}{\pi\theta}$$

where λ is the laser wavelength; θ half of the laser beam divergence angle in the waist. The distance at which the laser beam diverges by $\sqrt{2}$ times the minimum size is called the Rayleigh length $x_R = 4\pi\sigma_r^2/\lambda$ and determines the boundaries of the used laser beam cross-section, Fig.15 . The minimum achievable light spot size is on the order of the wavelength λ. A yttrium-aluminum garnet (YAG) or neodymium-yttrium-lithium-fluoride (Nd: YLF) laser, operating at higher harmonics, allows precise scanning of electron beams with a transverse size down to 350 nm. The resolution of such a monitor system can be approximately doubled by generating a transverse dipole mode on a half-wave plate mounted in the path of the laser beam. A high-power laser beam is split into two directions using a system of mirrors to measure both horizontal and vertical beam intensity distributions.

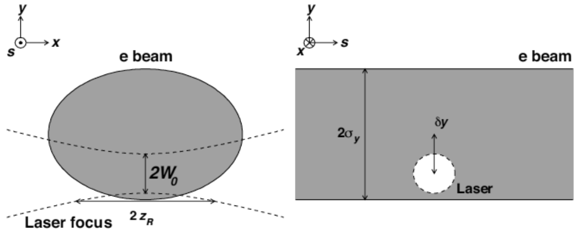

Fig. 15 Electron and laser beam interaction geometry

The scanning is performed by means of acousto-optical scanners or mirrors controlled by piezo drives, Fig. 16. The laser beam is focused before interacting with the electron beam. After the interaction, the electron beam moves along a curved trajectory in the field of the bending magnet, while Compton gamma quanta goes in a straight direction and hit the detector.

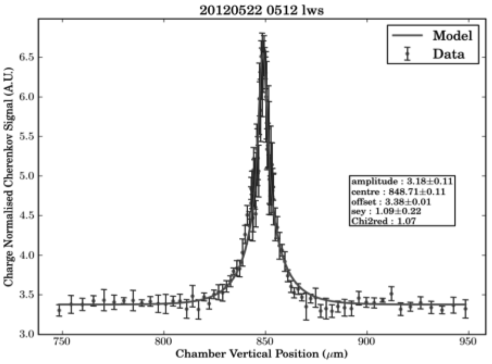

Fig. 16 Example of 1um 1.28GeV electron beam size measurement [12]

Assuming that the beam particles and the laser beam power have a Gaussian transverse distribution with the rms width σ_y and σ_r, respectively, we can estimate the average number of Compton gamma quanta depending on the displacement along the y axis:

$$\langle N_\gamma \rangle = \frac{P_L \sigma_c}{c\hbar\omega_0} \frac{1}{\sqrt{2\pi}\,\sigma_s} e^{-\frac{y^2}{2\sigma_s^2}} \frac{1}{\sqrt{2\pi}\,\sigma_r} \int_{-\infty}^{\infty} e^{-\frac{z^2}{2\sigma_r^2}} \mathrm{d}z$$

where P_L is the laser power; σs is the size of the interaction area; $\sigma_s^2 = \sigma_y^2 + \sigma_r^2$. The pulsed power of the laser beam must be on the order of several megawatts in order to obtain several thousand Compton gamma quanta in one scan [11].

Laser interferometer

The idea of using the interference pattern produced by two crossed laser beams to measure the size of electron beams in the nanometer range was first proposed and successfully tested in the FFTB (Final Focus Test Beam) experiment at the Stanford Linear Accelerator Center [13]. The step of the interference pattern, an example of which is shown in Fig. 17, depends on the laser wavelength and the angle of intersection of the beams.

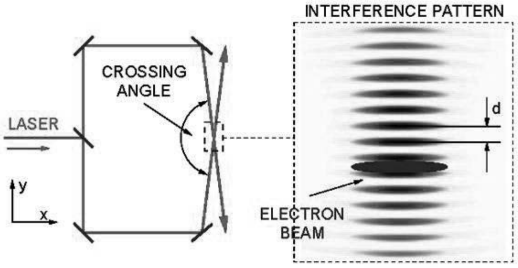

Fig. 17 Principle schematics of the laser interference monitor and fringe pattern

The motion of the electron beam across the fringes of the interference pattern leads to modulation of the intensity of the flux of Compton gamma quanta generated by high-energy electrons in the electromagnetic field of laser radiation. If the beam size is large compared to the period of the interference fringes, then the beam always crosses several maxima and minima of the interference pattern, and the number of Compton gamma quanta depends weakly on the position of the beam. If the beam size is much less than the period of the interference fringes, then the number of gamma quanta is proportional to the brightness of the interference pattern at a given point. The dependence of the number of Compton gamma quanta N on the transverse position of the beam y can be represented as:

$$N_\gamma = A + B\cos(2\pi k y + \mathrm{const})$$

where $k = 2\pi/\lambda$ is the wave number of laser radiation. The ratio B / A = 0 if the transverse size of the beam is much larger than the interaction region, and B / A = 1 for an infinitely thin beam. Thus, the beam size can be calculated from the measured B / A.

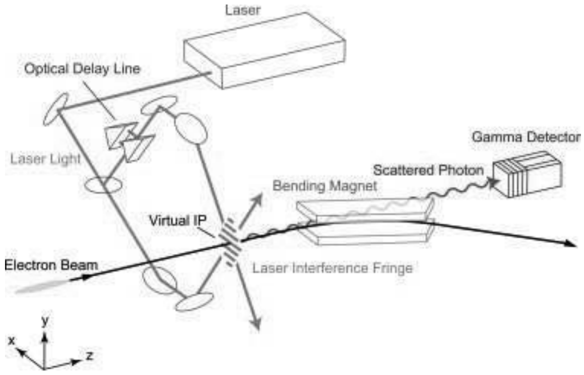

Fig. 18 Schematics of the laser interference monitor system

The schematic of the laser interferometer is shown in Fig. 18. The laser beam is divided into two half, which are directed in the x - y plane from different sides to the trajectory of the electron beam and are focused to one point on the trajectory. An interference pattern is formed around this point. An electron beam moving along the z-axis, interacting with the fields of laser beams, produces Compton gamma quanta, after which it is deflected from a straight path by a bending magnet. The intensity of the Compton photon flux is recorded by a detector. A corrector magnet located in front of the interaction region of the beam with the laser radiation provides scanning of the beam across the interference fringes.

Following [46], let us estimate the intensity of Compton radiation produced by the beam electrons in the electromagnetic field of laser beams in the interference region. For an electron beam with a Gaussian particle density distribution, the modulation of the Compton gamma-ray flux can be written as follows:

$$N_\gamma \propto \frac{1}{\sqrt{2\pi}\,\sigma_y} \int_{-\infty}^{\infty} \exp\left[-\frac{(y-y_0)^2}{2\sigma_y^2}\right] (1+\cos\theta\,\cos 2k_y y)\,\mathrm{d}y$$

where σy is the rms vertical size of the electron beam; y0 is the vertical position of the center of mass of the beam; $k_y = 2\pi \sin\varphi/\lambda$. Integrating above expression we obtain the dependence of the number of Compton gamma quanta on the beam position:

$$N_\gamma(y_0) = \frac{\langle N_\gamma \rangle}{2}\left[1+\cos 2k_y y_0\,\cos\theta\, e^{-2(k_y\sigma_y)^2}\right]$$

The modulation depth of the Compton gamma-ray flux, defined as

$$M = \frac{N_{\gamma\max} - N_{\gamma\min}}{N_{\gamma\max} + N_{\gamma\min}},$$

is described by the expression:

$$M = |\cos\theta|\, e^{-2(k_y\sigma_y)^2}.$$

Thus, we can calculate the beam size σy from the measured modulation depth M of the interference pattern:

$$\sigma_y = \frac{d}{2\pi}\sqrt{2\ln\frac{|\cos\theta|}{M}}.$$

In practical consideration, the following corrective factors should be considered. First, the laser radiation intensity is not uniform in the transverse profile, $I(r) = I_0 \exp(-r^2/2\sigma_z^2)$. Second, the power of the two intersecting laser beams is not the same, although fortunately the dependence of the interference pattern contrast on the power imbalance is weak. Third, the size of the electron beam changes along the z axis:

$$\sigma_y = \sigma_y^*\sqrt{1+(z/\beta_y^*)^2},$$

, where σ＊y and β＊y are the vertical size of the beam and the beta function at the center of the interaction region. Taking into account all the above factors, the modulation depth of the Compton gamma-ray flux has the form:

$$M = \frac{2\sqrt{P_2/P_1}}{1+P_2/P_1}\,\frac{1}{\sqrt{1+(2k_y\sigma_y^*)^2(\sigma_z/\beta_y^*)^2}}\,|\cos\theta|\, e^{-2(k_y\sigma_y)^2}$$

In the FFTB experiment [47] at β * y = 100 μm and σz = 50 μm, the correction was 6%. An Nd: YAG laser with a wavelength of 1064 nm (~ ω = 1.17 eV) was used. The duration of the laser pulse is 10 ns, the energy is 100 mJ, the power density of the laser beam at the focus is ρL = 1.3 × 10^{15} W/m2, and the photon density in one beam is 2.3 × 10^{19} cm^{-2}. The average number of gamma quanta generated by Compton scattering of electrons by photons of one laser beam, is N = 1000 at E = 50 GeV; Ne = 10^{10}.

In the Accelerator test facility at KEK, similar monitor is in operation. It demonstrated a record 1.28 Gev vertical electron beam size measurements of the level of 43.2 nm [14].

5. Conclusion

The given review is not intended to be complete and cover all the details of presented apparatus. Readers are advised to follow references for deeper understanding of the laser physics and techniques including Electro-optic methods for bunch length measurement [15].

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