Gigawatt cm-to-mm Free-Proton Lasers

E.G.Bessonov
Lebedev Phys. Inst. of the Russian Academy of Sciences, Moscow, Russia

Abstract

Applications of accelerator developments in the field of cm-to-mm Free-Ion Lasers (FILs) are considered. The use of three-dimensional Radiative Ion Cooling (RIC) in arbitrary energy ion storage rings of FILs is discussed.

1 INTRODUCTION

Sources based on the energy transformation of particle beams to the coherent electromagnetic radiation can be named Free-Particle Lasers (FPLs). It is considered that electrons are the most suitable active medium for FPLs because the electron mass is much less than the mass of other particles, and hence electrons can be accelerated easily to a necessary relativistic factor $\gamma = \varepsilon/mc^2$, and they will emit more powerful electromagnetic radiation in given external fields. That is why only Free-Electron Lasers (FELs) were investigated to this day. However in some cases the Free-Ion Lasers (FILs) can become preferable [1]. Indeed, the wavelength of the radiation emitted by a particle is $\lambda = \lambda_u(1+p_\perp^2)/2\gamma^2$ where λ_u is the undulator period and $p_\perp$ is the deflecting parameter. The power of a particle beam is $P_b = mc^2\gamma i/e$, where m and e are the mass and the charge of the particle, and i is the current of the particle beam. At the conditions of optimal generation, $p_\perp \sim 1$, the power can be presented in the form $P_b = (mc^2 i/e)\sqrt{\lambda_u/\lambda}$. The power P_b increases with m, i and λ_u. Ion masses and ion beam currents are higher than electron ones. It is reasonable to adopt $\lambda_u \sim 1m$, $p_\perp = 1$ for high power sources both of electron and ion beams. At the condition of equal efficiencies, the limiting power of FILs can be three and more orders higher than limiting power of FELs. For example, the electron beam of the APS possesses two orders higher emittance and five orders less stored energy than the proton beams of the LHC (under construction) and SSC (project) [2]. The relativistic factors of the electrons and protons are nearly the same in these cases. The beam stored energy of the LHC storage ring will exceed the value 500 MJ.

By analogy with the synchrotron radiation, a cooling method of non-fully stripped ion beams in storage rings of arbitrary energy can be used at top energy of the rings which is based on the process of resonance Rayleigh scattering of a laser light by relativistic ions [1]. It will give a chance to store the ultimately achievable high current, and low-emittance ion beams using multiple injection of ions in the storage ring.

This article is attempting to adopt the developments in the high energy proton accelerator techniques to the case of the high power cm-to-mm FILs.

2 MAIN CONSEQUENCES FROM THE FPL AND ACCELERATOR THEORY

The minimum wavelengths λ_n of the electromagnetic radiation emitted by the relativistic charged particle in the undulator on the harmonic n in the free space and in the waveguide, accordingly, are defined by the undulator period λ_u, γ, the cutoff wavelength of the waveguide mode λ_c, and the deflecting parameter $p_\perp$

$$\lambda_n^{fs} = \frac{\lambda_u}{2n\gamma^2}(1+p_\perp^2),$$

$$\lambda_n^{wg} = \frac{\lambda_u\left(1 \pm \sqrt{1-(1+p_\perp^2)(1+\lambda_u^2/n^2\lambda_c^2)/\gamma^2}\right)}{n\,(1+\lambda_u^2/n^2\lambda_c^2)}, \quad (1)$$

where $\gamma = \varepsilon/mc^2$, $p_\perp = \left(\overline{|\vec{p}_\perp|^2}\right)^{1/2} = \left(\overline{|\vec{B}_\perp|^2}\right)^{1/2}/B_c$ is the root-mean-square relative transverse particle momentum, $\vec{p}_\perp = \gamma\vec{\beta}_\perp$, $\vec{\beta}_\perp = \vec{v}_\perp/c$, $\vec{v}_\perp$ is the transverse velocity of the particle, $\vec{B}_\perp$ is the transverse magnetic field strength of the undulator, $B_c = 2\pi mc^2/n^+e\lambda_u$, e

is the electron charge, m is the mass of the particle, n^+ is the number of the ion charge state [1], the coefficient $2\pi m_p c^2/e \simeq 19.7 MGs \cdot cm$, m_p is the proton mass.

The maximum rates of the energy loss per particle in the parametric FPLs using the helical undulator and the beam consisting of a series of short ($< \lambda_1$) particle microbunches situated in sequence on the distances of the emitted wavelength λ_1, or its subharmonic in free space, and in the circular waveguide (when $\lambda \sim r$, $\beta_{ph} \simeq \beta_g \simeq 1$), are

$$\left(\frac{d\varepsilon}{dy}\right)^{fs}_{max} = \frac{\pi^2 mc^2}{\lambda_u}\frac{p_\perp^2}{1+p_\perp^2}\frac{i}{i_A},$$
$$\left(\frac{d\varepsilon}{dy}\right)^{wg}_{max} = \frac{2mc^2 p_\perp^2 l^d}{k\gamma^2 r^2}\frac{i}{i_A}, \quad (2)$$

where $\pi^2 mc^2/i_A \simeq 0.3n^+$ MeV/kA, $2mc^2/i_A \simeq 0.061n^+$ MeV/kA, $i_A = mc^3/e$, l^d is the e-folding damping length of the electromagnetic wave field strength in the waveguide, r is the radius of the waveguide, coefficient k is determined by the waveguide mode, β_{ph} and β_g are the phase and group velocities [1]. The rates of the particle energy loss ($d\varepsilon/dy$) in free space when the wide beam of the radius, $\sigma_p \gg \lambda\gamma/\sqrt{1+p_\perp^2}$, is used, and in the waveguide, tend to (4) at the distances from the beginning of the undulator, $l_p = 2\pi\sigma_p^2/\lambda_1$ and l^d, accordingly.

There are some effective methods of particle beam cooling in storage rings that enable one to decrease the phase volumes (emittances) of particle beams. They are a method based on the radiative reaction force that appears when particles emit synchrotron radiation, an electron cooling method, and a stochastic cooling method. In Ref. [3] a three-dimensional cooling method of non-fully stripped ion beams in storage rings was investigated when the process of resonance Rayleigh scattering of laser light by relativistic ions was used. That method can be considered as a development of a laser cooling method of non-relativistic ions in storage rings [4,5].

The following scheme of radiative ion beam cooling will be considered. In a straight section of a storage ring, a laser photon beam is directed towards the ion beam and is scattered by the ions. The photon energy $\hbar\omega_l$ is of such a value that in the coordinate system connected with the average ion velocity it was close to the transition energy $\hbar\omega_0'$ between definite electron states in the ions. Since the scattered radiation is directed mainly along the direction of ion velocity, it will be decelerating and will lead to damping of vertical and horizontal betatron oscillations as well as phase oscillations of ions in the storage ring. The rate of damping can be tuned by adjusting the gradient of laser intensity in the radial direction.

The power of the scattered radiation can be represented in the form

$$P^s = \frac{2r_e f_{1,2}\gamma n_{int} P_l}{R(1+D)}\frac{\omega_l}{\Delta\omega_l}, \quad (3)$$

where $r_e = e^2/mc^2$ is the classical electron radius, R is the mean radius of the storage ring orbit, $f_{1,2}$ is the transition strength, $D = I/I_c$ is the saturation parameter, $I_c = (\pi c g_1 \hbar\omega_0'/\gamma^2 g_2 \lambda_0'^3)(\Delta\omega_l/\omega_l)$, n_{int} is the number of interaction regions, ω_l is the laser frequency, $\Delta\omega_l$ is the bandwidth of the laser beam spectrum, $\lambda_0' = 2\pi c/\omega_0'$. It was supposed, that the laser beam area $S = \lambda_l l_{eff}/2$, $\lambda_l = 2\pi c/\omega_l = \lambda_0'/2\gamma$, l_{eff} is the length of the straight section, $l_e \ll l_{eff}$, $l_e = \gamma c/\Gamma_{2,1}'$ is the length of the ion relaxation, $\Gamma_{2,1}' = 2r_e\omega_0'^2 f_{1,2} g_1/cg_2 \ll \omega_0'$ is the probability of the spontaneous photon emission of the excited ion or the natural linewidth, $g_{1,2}$ are the statistical weights of the states 1 and 2. The energy emitted by ion per one turn $eV = 2\pi RP^s/c$.

The damping times of vertical, radial betatron oscillations and phase oscillations are

$$\tau^z = \frac{R(1+D)}{cn_{int}f_{1,2}}\left(\frac{\Delta\omega_l}{\omega_l}\right)\left(\frac{P_A}{P_l}\right),$$
$$\tau_x = \tau_z, \quad \tau_s = \tau_z/2. \quad (4)$$

where $P_A = m_e m_i c^5/e^2$, m_i is the ion mass, m_e is the electron mass.

Quantum nature of the photon scattering will lead to an equilibrium radial dimension and energy spread of the ion beam

$$\sigma_x = \alpha R\sqrt{\frac{1.4\hbar\omega_0'}{m_i c^2}}, \quad \frac{\sigma_\gamma}{\gamma} = \sqrt{\frac{0.7\hbar\omega_0'}{m_i c^2}}, \quad (5)$$

where $\alpha \simeq \nu_x^{-2}$ and ν_x are the momentum compaction factor and radial betatron oscillation tune of the storage ring, accordingly. An equilibrium vertical dimension of the ion beam $\sigma_z \ll \sigma_x$. The equilibrium radial emittance of the ion beam in this case is

$$\epsilon_x = \frac{1.4\pi R}{\nu_x^3}\frac{\hbar\omega_0'}{m_i c^2}. \quad (6)$$

The Eqs. (4)-(6) are valid when the bandwidth of the laser spectral line exceeds the value $\Delta\omega_l/\omega_l > \theta_b^2/4 + \Delta\gamma_b/\gamma$, where $\Delta\gamma_b$ and θ_b are the energy and angular spreads of the ion beam. In the process of damping of the betatron and phase oscillations the bandwidth of the laser spectral line can be decreased.

In the Table the main ion beam parameters are presented for the case of $\lambda_l = 6 \cdot 10^{-5}$ cm, $l_{eff} = 150$ m (S=0.45 cm^2). In this case the damping time for

$^3_2He^{1+}$ is $\tau_z = 32.7$ sec, when $\Delta\lambda_l/\lambda_l = 10^{-3}$, n_{int}=10, $R = 400m$, $P_l = 1$ kW ($D \simeq 1.15$). Utilization of the laser resonator permits to decrease the laser power to the value $\sim 20W$. The damping time τ_s can be decreased by the factor $\gamma_b/\Delta\gamma_b \gg 1$ when high-degree monochromatic laser beam and sweeping of the laser frequency are used. In this case the laser power can be decreased in accordance with decreasing the laser bandwidth. After damping of the phase oscillations, the synchrotron-betatron resonance can be used to decrease the vertical and horizontal damping times.

Table

Ion	$^3_2He^{1+}$	$^{10}_5B^{4+}$	$^{238}_{92}U^{10+}$	$^{91}_{40}Zr^{39+}$
γ	9.87	61.7	299	3947
$m_ic^2\gamma[GeV]$	27.7	579	$6.7 \cdot 10^4$	$3.4 \cdot 10^5$
$\frac{\nu_x^3\epsilon_x}{1.4\pi R}10^8$	1.44	2.7	0.55	19
$\frac{\sigma_\gamma}{\gamma}10^4$	1.00	1.37	0.62	3.65

3 POSSIBLE PARAMETERS OF THE FILs

The following example illustrates possible parameters of the FILs in the centimeter wavelength region. The beam of $^{10}_5B^{4+}$ ions pass through the waveguide which has the form of a smooth pipe of the radius $r = 1.5$ cm and the e-folding length $l^d = 30$ m. The waveguide is installed into the helical undulator with the period $\lambda_u = 0.5$ m and magnetic field strength $B_\perp = 100$ k Gs. The H_{11} mode is excited ($\lambda_c = 3.41\ r$) and $k \simeq 0.5$. The energy of ions $\varepsilon_i \simeq 617$ GeV ($\gamma = 61.7$) and the current of the ion beam is $i = 5$ kA.

In this case $B_c \simeq 10^6$ Gs, $p_\perp \simeq 0.1$, λ_c =5.115 cm, $n = 1$. According to (1) the wavelength of the coherent radiation $\lambda_1 \simeq 1$ cm, the rate of the energy loss per ion $d\varepsilon/dy \simeq 42n^+i$ keV/m kA$\simeq$ 850 keV/m and the power emitted by the ion beam per unit length $dP/dy = (i/n^+e)(d\varepsilon/dy) \simeq 42i^2MW/m\,kA = 1.05$ GW/m.

High quality and high current beam can be stored at the relativistic energy. For the case of $R = 400$ m, $\nu_x = 10$ the emittance of the beam $\epsilon_x = 1.42 \cdot 10^{-8}\pi$ m rad, the energy spread is $\sigma_\gamma/\gamma = 1.1 \cdot 10^{-4}$.

At energies above 90 MeV/u the life time of few-electron ions at pressures $\sim 10^{-10}$ mbar is rather high [6]. At high beam currents $\epsilon_{x,z}$ and σ_γ/γ are determined by the equilibrium between intra beam scattering and RIC. In this case there is strong limitation in the life time of ions through the ion charge exchange [7]. One can hope that the use of ions with high n^+ and low damping times will permit to get heavy ion beams of rather high current and excellent brilliance in the high energy storage rings.

4 CONCLUSION

The developments in high energy particle accelerators are making it much easier to generate high power cm wavelength electromagnetic radiation that can be used e.g. in linear colliders and other installations. The energy stored in the ISR beam has reached $5 \cdot 10^6$ J, in the form of a beam of 50 A at 31.5 Gev for duration of 3.3 mk sec. The peak currents in excess of 10^3 A have been focused to submillimetric spots without problems [7]. The high quality ion beam in this case can be extracted from the storage ring and directed into the long undulator with a waveguide that placed along the linear collider. The rejection of the electromagnetic power from the system is necessary in this case. High frequency warm synchrotrons-injectors for the storage rings must be applied. High harmonic number radio frequency grouper of the ion beam at the last stage of the beam manipulations in the storage ring must be used in order to group the beam in short bunches ($< \lambda$) with small (a few λ) period. External r.f. grouper can be used as well. Higher harmonics of continuous emission of more hard ($\sim 1mm$ radiation of the stored and bunched beams in the undulator installed in the storage ring can be generated for fusion and other applications.

References

[1] E.G.Bessonov, Nuclear Instruments and Methods, **A341** 355, (1994).

[2] Samir K. Dutt, *Proceedings of the Workshop on Fourth Generation Light Sources*, (SSRL/SLAC, February 24-27, 1992), 170.

[3] E.G.Bessonov, Preprint FIRAN No 6, Moscow, (1994); E.G.Bessonov, Physics Review Letters, (presented); E.G.Bessonov, Journal of Russian Laser Research, v.15, No 5, (1994).

[4] J.S.Hangst, K.Berg-Sorenson, P.S.Jessen *et al.*, *Proceedings of IEEE Particle Accelerator Conference "Accelerator Science and Technology"*, (San Francisco, May 6-9, 1991), **3**, 1764, (N.Y.), (1991).

[5] S.Schröder, R.Klein, N.Boos *et al.*, Physics Review Letters **64**, 2901, (1990).

[6] B. Franzke, K. Beckert, F. Bosch *et al.*, International Journal of Modern Physics A, *Proceedings of the 15th International Accelerator Conference* (Hamburg, DESY, July 20-24, 1992), supplements 2A, 2b, **1**, 60, (Hamburg, 1993).

[7] Carlo Rubbia, Nuclear Instruments and Methods, **A278**, 253, (1989).