ELECTRON INJECTION INTO A CYCLIC ACCELERATOR USING LASER WAKEFIELD ACCELERATION

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Abstract

We consider a technique for electron injection into a cyclic accelerator using the laser wakefield acceleration (LWFA) technique. Accelerators with this type of injector can be used for different purposes due to lower size, cost and low radiation hazard. To use the LWFA technique it is necessary to create a small gas cloud inside the accelerator vacuum chamber. But it leads to the increase of particle losses due to scattering on residual gas atoms. Therefore we propose to use magnesium as evaporated gas because of its high absorbability – its atoms stick to walls at the first contact. We presented estimations of the LWFA-based injection system parameters, including maximum stored current. The proposed technique looks very prospective for compact accelerators and storage rings.

INTRODUCTION

Electron synchrotrons use rather complicated injection system. It typically consists of fast kicker, septum magnet, transport beamline and injector, which accelerates electrons to the injection energy. This system may be replaced by the laser wakefield accelerator (LWFA), installed inside the vacuum chamber of the cyclic accelerator.

The principle of compact electron accelerator using LWFA was proposed many years ago [1]. It became feasible due to appearance of lasers with hundred-terawatt peak power. High density plasma ($n = 10^{18} - 10^{19} cm^{-3}$) under the influence of high power laser light pulse can generate high accelerating gradient, which several orders exceeds fields in metallic cavities of ordinary linear accelerators [2].

Acceleration of electrons to injection energy occurs inside the vacuum chamber of the cyclic accelerator. This technique eliminates separate injector from the accelerator facility. Moreover, there is no need in complicated and expensive septum magnet and injection beamline from injector to the cyclic accelerator. Also, the radiation hazard is reduced significantly, as high-energy electrons appear inside accelerator magnetic system, and their average current can not be high. It makes possible to use such accelerators in non-shielded halls with local shielding only.

THE INJECTION SCHEME

The simplest realization of the technique proposed is shown in Fig. 1.

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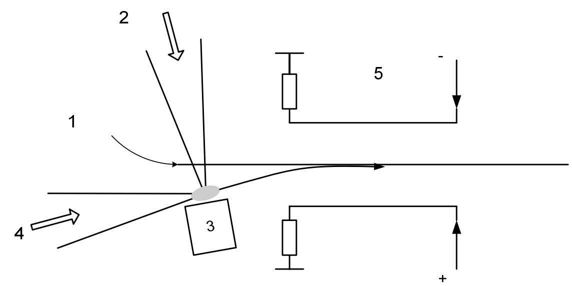

Figure 1: Layout of injection in a cyclic accelerator using LWFA. 1 – closed orbit, 2 – evaporating light, 3 – Mg target, 4 – accelerating light, 5 – fast kicker.

A gas source (for example, solid state evaporator 3) is situated near the strait part of the closed orbit. Immediately prior to injection, pulse of laser radiation 2 evaporates magnesium atoms from the magnesium target. After that main laser light pulse 4 passes through the magnesium cloud. Due to the LWFA phenomenon high energy electrons, moving near the closed orbit, are produced in the gas. The fast kicker 5 put these electrons exactly to the closed orbit. When electrons return to the kicker after the first turn, the kicker field must be zero. Then the electrons keep circulation. The transverse phase space diagram for this injection scheme is shown in Fig. 2.

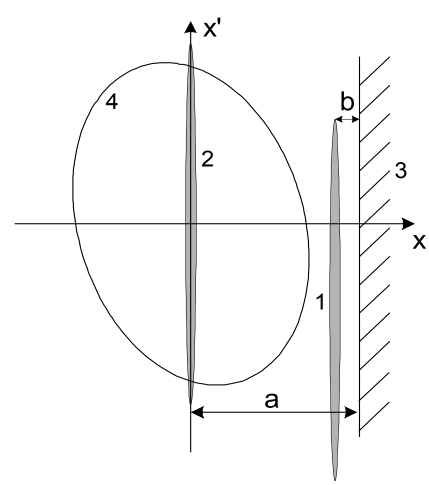

Figure 2: Scheme of injection in the phase plane. 1 - injected beam, 2 - injected beam after the kick, 3 - the wall, 4 – the acceptance ellipse.

As it is seen from Fig. 2, the maximum captured angle spread $\Delta\theta = \Theta_x = \sqrt{A/\beta}$ depends on acceptance A and beta function β at the injection azimuth. For A = 0.1 mm and β = 1 m, $\Delta\theta$ = 0.01, which is not much less, than angle spreads, obtained in LWFA experiments [2, 3]. It means that the injection efficiency may be high enough.

As electrons are born inside the vacuum chamber, some of them may be captured even without kicker. Then the injected beam stays in position 1 at Fig. 2. If the Mg target is inserted deep enough, so that evaporating surface coordinate a is inside the accelerator acceptance $\sqrt{A\beta} > a$, the reduced acceptance is a^2/β. In this case the maximum captured angle spread is $\Delta\theta \approx \sqrt{2ab}/\beta$, where b is the initial distance of the LWFA-generated beam from the evaporating surface. In spite of lower efficiency, the kicker-free injection may be interesting for very compact storage rings [4].

The typical bunch charge in the LWFA is of the order of 1 nC. Therefore, to achieve significant beam current, multiple injections are necessary. Several options are well-developed for existing synchrotrons and storage rings [5]. We will mention only few of them. Using very fast (few ns) kicker pulses one can fill independently several RF buckets (see, e. g., [6, 7]). With the kicker pulse amplitudes, lower, than optimal, one can accumulate particles in the same bucket, using radiation damping. The limiting case of this option is the above-mentioned kicker-free injection.

To obtain LWFA it is necessary to create the gas cloud with proper parameters. For pulse duration τ = 30 fs (f.w.h.m.) the maximum plasma frequency π/τ is about $2\cdot10^{13}$ Hz, which corresponds to the electron density n_e = $4\cdot10^{18}$. Then the characteristic accelerating gradient $\sqrt{4\pi n_e mc^2}$ is about 0.6 GeV/cm. Therefore hundred-MeV energies may be used for injection.

ESTIMATION OF THE BEAM LOSS

Motion of the magnesium atoms in the accelerator vacuum chamber may be estimated as adiabatic expansion of the small gas sphere in vacuum. Hence, according to [8], the sphere boundary is expanded with velocity $u = 2c_0/(\Gamma-1)$, where $\Gamma = 5/3$, $c_0 = \sqrt{\Gamma kT/M}$ is the velocity of sound, k is the Boltzmann's constant, M is the mass of a Mg atom, T is the temperature of evaporated atoms.

Mg particle density distribution is given by

$$n(r) = \frac{A}{R_0^{\,3}}\left(1-\frac{r^2}{R_0^{\,2}}\right) \tag{1}$$

where $R_0 = ut = 3c_0t$ is the radius of the gas sphere. Constant $A = 15N/(8\pi)$ may be expressed through the number of extracted atoms $N = \int_0^{R_0} n(r)4\pi r^2 dr$, and hence

$$n(r) = \frac{15}{8\pi}\frac{N}{R_0^{\,3}}\left(1-\frac{r^2}{R_0^{\,2}}\right) \tag{2}$$

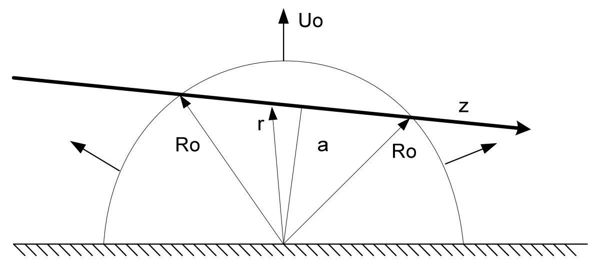

Figure 3: Scheme of the electron bunch motion through Mg gas cloud

Assuming sizes of the stored beam to be small, one can estimate the loss due to the elastic scattering per one injection. The elastic scattering phenomenon is described by the Rutherford scattering cross-section. Total cross-section of scattering with particle loss can be calculated by integration over angles. For rectangular aperture with limit angles $\Theta_x = \sqrt{A/\beta}$ and Θ_y it is [9]

$$\sigma \approx \frac{Z^2 r_e^2}{4\gamma^2} F(\Theta_x, \Theta_y) \tag{3}$$

where Z is the atomic number, γ is the Lorentz factor, r_e is the classical radius of electron, and

$$F(\Theta_x,\Theta_y) = \frac{8}{\Theta_y^{\,2}}\left(\pi + \left(\left(\frac{\Theta_y}{\Theta_x}\right)^2 + 1\right)\sin(2arctg(\frac{\Theta_y}{\Theta_x})) + 2\left(\left(\frac{\Theta_y}{\Theta_x}\right)^2 - 1\right)arctg(\frac{\Theta_y}{\Theta_x})\right) \tag{4}$$

The trajectory of electron motion of through the gas cloud is shown in Fig. 3. Then the density, integrated along the trajectory, is

$$n_{Mg} = \int_{-\infty}^{\infty} n\left(\sqrt{a^2+z^2}\right)dz = \frac{4A\left(R_0^{\,2}-a^2\right)^{3/2}}{3R_0^5} \tag{5}$$

The probability of electron loss per one turn is $P_1 = \sigma n_{Mg}$, where σ is the scattering cross-section. For many turns (T_0 is the revolution period) the integrated density of Mg cloud is given by

$$n_t \approx \int_{a/(3c_0)}^{\infty} \frac{4}{3}A\frac{\left((3c_0t)^2-a^2\right)^{3/2}}{(3c_0t)^5}\frac{dt}{T_0} = \frac{5}{32}\frac{N}{T_0c_0a} \tag{6}$$

The probability of a particle loss is the product of Eq. (3) and Eq. (6)

$$w = \frac{5}{128}\frac{NZ^2r_e^2}{\gamma^2T_0c_0a}F(\Theta_x,\Theta_y) \tag{7}$$

A good upper estimate is $F(\Theta_x, \Theta_y) < 8\pi\left(1/\Theta_x^2 + 1/\Theta_y^2\right)$. Then

$$w < \frac{NZ^2 r_e^2}{\gamma^2 T_0 c_0 a}\left(\frac{1}{\Theta_x^2} + \frac{1}{\Theta_y^2}\right) \qquad (8)$$

Eq. (8) gives an estimate of the stored current loss per one injection. The probability of loss for off-axis particles is more. Therefore the loss for just injected particles is several times more, than the value, given by Eq. (8). Unfortunately, the parameters of evaporated magnesium are not known well. Nevertheless, one can try to make numerical estimation by Eq. (8). For $\Theta_x = \Theta_y = 0.01$, $N = 10^{19}$, $Z = 12$, $\gamma = 400$, $T_0 = 100$ ns , $c_0 = 2{,}6$ km/s , $a = 2$ cm it gives $w = 2.8 \cdot 10^{-4}$, and for $\gamma = 2000$, $w = 1.1 \cdot 10^{-5}$.

Using Eq. (5) one can calculate turn-by–turn distribution of beam losses. Fig. 4 shows a scattering loss of the circulating electron beam with energy 200 MeV vs. time in number of turns. It is clear, that first turns after the gas cloud reaches the orbit make the main contribution to the total loss, given by Eq. (6). The reason is, that the gas cloud expands quickly. Integrated loss are shown in Fig. 5. The asymptotic value is in a good agreement with estimate, given by Eq. (8).

The upper limit of stored beam charge is the ratio of the charge, injected per one pulse (about 1 nC), to the integrated loss probability Eq. (8). According to the estimates above, this limit is several microcoulomb, which exceeds circulating charge of contemporary cyclic accelerators. Therefore one can conclude, that the scattering losses do not limit the stored current.

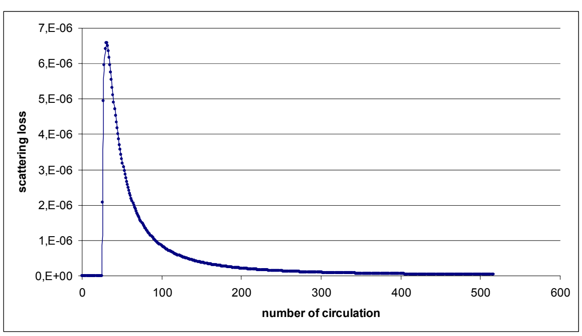

Figure 4: Beam losses vs. a turn number (E = 200MeV).

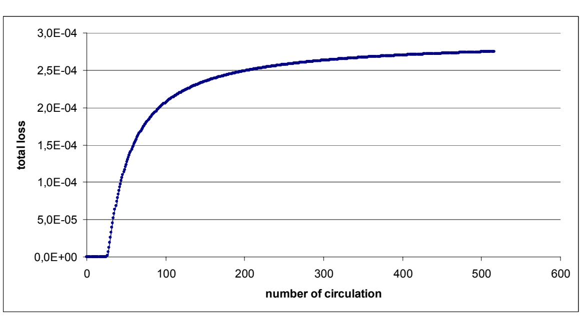

Figure 5: Integrated beam losses vs. a turn number (E = 200MeV).

CONCLUSION

In this paper we proposed the scheme of injection technique using LWFA. Advantages of this method are relatively small size and cost, and improved radiation safety. The problem of vacuum degradation is solved using material with good adsorption properties, such as magnesium. Calculations show that losses, caused by particle scattering on the cloud of the target gas, do not limit the stored current.

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