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LIGHT SOURCE TOP-UP THROUGH DIRECT GENERATION OF ELECTRON BEAM BASED ON LPA TECHNOLOGY

Masamitsu Aiba and Micha Dehler
Paul Scherrer Institut, Villigen, Switzerland
Alexander Molodozhentsev
Extreme Light Infrastructure, Prague, Czech Republic

Abstract

Laser plasma acceleration (LPA) technology is advancing day by day, getting ready for user facility applications. LPA might be applicable to the generation of electron beams directly within a light-source storage-ring vacuum chamber. A typical injector of a light source facility consists of a linac and a synchrotron booster (or simply a full energy linac). It can be replaced by a laser plasma cell and a driving laser system that can generate multi-GeV electron beams through so-called self injection. The electron beam out of the plasma cell typically has a large energy spread. In this application, however, we do not require small energy spread since the storage ring can accept off-energy electrons in a range of ± 5 % or so. It can also have a transverse angular acceptance of a few hundred micro radian. Therefore, a large fraction of the generated electrons can eventually be accepted by the storage ring. An LPA system, which replaces the conventional injector, may contribute to significant energy saving.

INTRODUCTION

Modern light souce facilities operate in the so-called top-up mode, where electrons are injected periodically, compensating for the inevitable, continuous beam loss arising from Touschek scatterings and other effects. The beam current in the storage ring is kept approximately constant, and the top-up mode is essential to maximize the photon beam performance in terms of flux and stability.

A typical injector of a light source facility consists of a linac and a synchrotron booster (or simply a full energy linac). We study whether the laser plasma acceleration (LPA) technology [1] can be applied, replacing the injector by a plasma cell and a driving laser system.

Similar study was performed at DESY [2]: the electron beam generated through a laser plasma accelerator is manipulated with a chicane and an X-band cavity such that the energy jitter and spread of the beam are significantly suppressed. The beam is then sent to the injection septum, as is done for the beam prepared through the conventional injector. Our study explores a direct generation of injection beams, i.e., the plasma cell is installed into the storage ring vacuum chamber. The energy accepance of the storage ring can be up to ±5 % or so. It can also have a transverse angular acceptance of several hundred microradians. Hence a significant fraction of the generated electrons can eventually be captured by the storage ring. The injection septum is not needed anymore while the injection kicker is still useful. We discuss also a scheme that requres neither injection septum nor injection kicker.

DIRECT GENERATION

Figure 1 illustrates a concept of direct generation within a straight section of the storge ring.

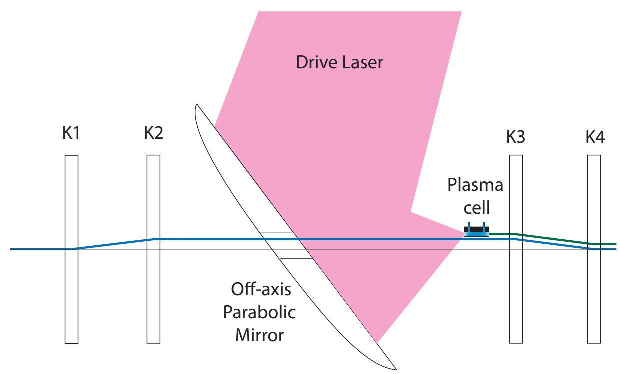

Figure 1: Schematic layout of direct generation within a straight section of the storage ring. The boxes labeled K1–K4 are injection kickers that make a closed orbit bump at the time when the drive laser arrives: the stored beam, passing along the blue line is brought to the vicinity of the plasma cell. The green line represents the generated electron beam.

In Fig. 1, four injection kickers are installed into the straight section, as in typical conventional top-up injection, to excite a pulsed closed-orbit bump. The injection septum, which is installed between the second and third kickers, is replaced by a plasma cell, where electron beams are generated through the so-called self-injection mode. Concerning the injection kicker, other types can be applicable such as multipole/nonlinear kicker [3, 4], or short pulse kicker [5]. These kickers can be installed into a downstream location and may facilitate the implementation of LPA.

The drive laser is coupled in with an off-axis parabolic mirror that focuses the laser into the plasma cell. In order to generate multi-GeV beams, we need a high power laser. The diameter of the mirror, therefore, needs to be sufficiently large such that the drive laser size can be enlarged and hence the energy density does not exceed a threshold, above where the mirror can be damaged. A short focal length, 2 m or so, is assumed to fit the space between the second and third kicker. When the size of the drive laser is much larger than the aperture required for the electron beam stored in the ring, we can make a hole through the mirror to let the stored

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beam pass, without spoiling the laser plasma acceleration, as illustrated in Fig. 1. The angle of the bumped orbit at the location of the plasma cell can be adjusted to facilitate the drive laser injection. It is also an interesting option to apply a curved plasma cell [6] since it may allow us to install the final focusing mirror completely away from the stored beam orbit.

Coupling-out of the drive laser can be achieved by putting another mirror downstream. Alternatively, the laser can be dumped internally: a detailed simulation to estimate the maximum energy density along the beam chamber surface is required in order to validate the feasibility of such a design.

As the drive laser pulse is quite short, it is not necessary to fully synchronize it with the stored electron bunch: the timing is adjusted such that the laser arrives slightly earlier or later. The drive laser and the stored beam are not overlapping then. The electron beam out of the plasma cell is separated from the stored beam and totally mismatched to the storage ring optics. It is, however, merged to the stored beam and matched to the ring optics after several radiation damping times.

CHALLENGES AND DIFFICULTIES

The scheme illustrated in Fig. 1 neccesitates a quality electron beam out of the plasma cell. The smaller electron beam energy spread and divergence, the higher injection efficiency will be. It is also important to increase the stability of the drive laser, especially for the self-injection mode. We identify that a further development and improvement of the LPA technology to achieve a reasonable injection efficiency would be the primary challenge in this application. In case the injection efficiency is not very high, a collimation system may be required.

The wall of the plasma cell facing to the stored beam closed orbit is equivalent to the septum blade of the conventional injection. Therefore, a thinner wall achieves a better injection efficiency. The plasma cell, i.e., capillary, is normally made of sapphire, and it is an engineering challenge how thin the wall can be, keeping an adequate robustness and durability.

The plasma cell is filled with gas, and it has an inlet and an outlet. The gas, however, leaks out from the plasma cell. Differential pumping technique has to be applied to keep the vacuum pressure outside the plasma cell sufficiently low, such that the circulating beam loss due to gas scattering is mitigated. The pressure outside the plasma cell can be significantly improved if the plasma cell is filled only for a short time at every top-up injection. Such a gating or a pulsing of gas flow is possible but it has not been applied to the plasma cell to our knowledge.

The leaking gas is ionized by the stored beam and could be trapped by the stored beam, leading to (fast) ion instabilities. Although hydrogen and helium ion orbits are already instable over single bunch spacings (2 ns) [7], we may need further investigation for our specific case, where the pressure becomes very high for a short period.

The bunch length of the electron beam out of the plasma cell is quite short. The coherent synchrotron radiation beam impedance can potentially be a source of partial beam loss, lowering the injection efficiency. In some synchrotron light sources, the so-called femto slicing technique has been introduced. Several “femto-second bunches” are formed within a stored electron bunch. There no noticeable beam loss arising from the short internal bunches was observed. Further investigation may, however, be necessary, though it is difficult to properly simulate such a very short bunch interacting with the beam impedance. Space charge effects may also influence the injected beam, although the injected beam bunch length is prolonged in a few turns due to the large energy spread, and the longitudinal emittace dilution follows.

INJECTOR OF THE SLS UPGRADE

An upgrade of the Swiss Light Source (SLS) is ongoing: the storage ring is replaced by a new ring with seven-bend achromat lattice, reaching a natural emittance of 158 pm (130 pm with all insertion devices) [8]. The injector, a chain of a linac and a booster synchrotron, is to be reused with some (or minimal) hardware refurbishment. Given the aging of the present injector, we may need to renew a number of injector components in the next decades. We therefore investigate direct generation as a possible replacement of the present injector.

We assume the injection beam parameters summarized in Table 1 in the follwing investigation.

Table 1: Injection Beam Parameters Out of the Plasma Cell

Parameters	Values
Beam energy	2.7 GeV
Charge per pulse	200 pC
Energy spread	1 %, rms
Trans. divergence	100 μrad, rms
Pulse repetition	10 Hz

We performed a tracking simiulation to demonstrate direct generation. A beam was generated based on the parameters of Table. 1 and was injected at a distance of 2.5 mm from the stored beam (the orbit bump is not included in the simulation for simplicity). The optical functions at the injection point were optimized for the conventional injection: the horizontal beta function was about 23 m. Nevertheless, more than 99 % of the electrons were captured by the storage ring acceptance whereas the rest is intersepted by the aperture included in the tracking (horizontal aperture ± 6.5 mm at the injection point). More beam divergence can be accepted, and the injection efficiency could reach up to 100 %, if the optical functions are optimized.

With a charge per pulse of 200 pC, we need about 12 pulses every 3 minutes during the top-up operation mode so as to compensate for the slow beam loss (dominated by Touschek scattering) assuming a beam lifetime of 8 hours. The stored electrons scatter with the gas leaking out of the plasma

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cell, and hence the beam lifetime drops during injections. In the SLS upgrade, the gas-scattering beam lifetime is about 35 hours for a pressure of 10^{-9} mbar with carbon monoxide as residual gas. The vacuum pressure outside the plasma cell will be at the 10^{-2} mbar level, when the medium gas is continuously injected into the plasma cell. Starting with the above mentioned pressures, we consider three factors, 1) the effective length of the injection region, where the pressure is as high as 10^{-2} mbar level, 2) the effective period when the pressure is high, and 3) the cross section of gas scattering (Coulomb scattering). The efffective length may be about 50 cm while the circumference of the storage ring is 288 m. Thus, a factor of 0.5/288 would be applied. When the gas is injected only for a short period, synchronized with the drive laser arrival, the pressure outside can be minimized. With the present technology, a minimum duration of a gas-jet pulse can be shorter than 1 ms (see e.g. [9]). The fractional period of gas injection will be 6.6×10^{-5} assuming a total pulse length of 12 ms (12 pulses), every 3 minutes: 12 ms over 3 minutes and 1.2 second with a 10-Hz repetition. The repetition rate is an arbitrary choice to some extent and is not significant in this investigation. The cross section of the scatterings approximately proportional to the atomic number or the sum of the atomic numbers for molecules. When we use hydrogen or helium gas, the corresponding atomic number is two, while it is 22 for carbon monoxide. Collecting these three factors, the high pressure around the plasma cell is approximately equivalent to a carbon monoxide gas of 10^{-10} mbar along the storage ring, in terms of the Coulomb scattering rate averaged over time. Although the above estimation may not be very accurate and needs to be refined, the beam lifetime drop will not be significant; it will still be dominated by Touschek lifetime, which is about 16 hours with a bunch prolongation by the third harmonic cavity.

We now evaluate the LPA parameters, based on analytical equations and scaling laws, that can generate the assumed injection beam (Table. 1) applying the following guiding concept: The peak laser power exceeds the critical laser power such that self-focusing is enabled (no boundary condition is included). We keep the normalized vector potential close to one in order to avoid strong nonlinear regime.

Among several parameters, we first fix the laser wavelength to 820 nm, which is efficiently excited with Ti:sapphire laser. The numerical aperture is also fixed to 30 with a final focusing mirror of 2-m focal length and 100-mm diameter (laser size on the mirror), taking into account the implementation into the storage ring straight section and the power density on the mirror. The other parameters are optimized to achieve the target injection beam parameters. This includes the laser beam energy at focus, the laser pulse duration and the plasma density. A super-Gaussian transverse laser profile is employed. Finally, the following parameters are obtained (Table 2).

The obtained parameters are not very demanding, and even a commercially available laser can be sufficient. The repetition rate can be 10 Hz, which is not challenging, as in the vacuum estimation. The above investigation is for a single laser scheme. A multi-stage approach, i.e., two plasma cells, is also under consideration.

Table 2: LPA parameters to generage the injection beam of Table 1. The depletion length is shorter than the dephasing length, determining the beam energy.

Parameters	Values	Derivation
Laser wavelength	820 nm	Fixed
Numerical apeture	30	Fixed
Laser pulse duration	30 fs	Optimized
Laser pulse energy	3 J at focus	Optimized
Plasma density	0.35×10^{18} cm^{-3}	Optimized
Peak laser power	100 TW	Derived
Critical laser power	85 TW	Derived
Rayleigh length	4.7 mm	Derived
Norm. vector potential	1.35	Derived
Depletion length	41.4 mm	Derived
Dephasing length	63.8 mm	Derived
Beam energy	2.706 GeV	Derived
Beam charge	198.6 pC	Derived

Numerical simulation is required to predict the full property of the generated electron beam, including the energy spread and the transverse divergence. We are currently working on it. In case where the target divergence can not be achieved, we consider to apply an active plasma lens that focuses the beam in both transverse planes.

ULTIMATE SCHEME

The performance of LPA can be significantly improved when a capillary discharge waveguide is employed to expand the acceleration distance. If it is at all possible to generate a multi-GeV electron beam without a capillary, the injection beam can be generated in the vicinity of the stored beam: a gas-sheet is set up parallel to the stored beam with a minimum distance in between. In this scheme, we can remove not only the injection septum but also the injection kicker. The injection can be fully transparent, benefitting the beamlines, which are sensitive to the photon beam position jittering.

SUMMARY

It is proposed to generate the electron beam of the light-source storage ring directly within its vacuum chamber using the laser plasma acceleration technology. Our preliminary investigation established a conceptual design whereas several challenges and difficulties were identified. We plan further studies to explore the feasibility of the new LPA application.

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