COMPACT RING-BASED X-RAY SOURCE WITH ON-ORBIT AND ON-ENERGY LASER-PLASMA INJECTION

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Abstract

We report here the results of a one week long investigation into the conceptual design of an X-ray source based on a compact ring with on-orbit and on-energy laser-plasma acceleration injection (mini-project 10.4 from [1]) performed during the June 2016 USPAS class "Physics of Accelerators, Lasers, and Plasma…". We describe three versions of the light source with the constraints of the electron beam with energy 1 GeV or 3 GeV and a lattice bending magnetics being normal (only for the 1 GeV beam) or superconducting (for either beam). We describe the design choices, present relevant parameters, and describe insights into such machines.

INTRODUCTION

Due to the high accelerating gradients that can be achieved using plasma, combining the field of Laser wakefield acceleration (LWFA) with synchrotron light production offers the possibility of creating compact accelerators and light sources. We sought to outline a design for a compact synchrotron light source that produces 0.4 keV (water-window) or 10 keV photons using such acceleration technology. We estimate the design parameters of the compact light source, the achievable brilliance, and we discuss the feasibility and challenges of the design.

We assume the presence of state of the art technology including a laser plasma gas-jet accelerator, a quadrupole doublet to focus and confine the beam, four 90 degree dipole bending magnets (super-conducting or normal conducting) to keep the beam on a periodic lattice, and a 2 m long wiggler magnet to produce the desired radiation. A schematic of the design is in Fig. 1, and investigated designs criteria are detailed below:

- 0.4 keV photons produced by a 1 GeV electron beam and normal-conducting magnets.
- 0.4 keV photons produced by a 1 GeV electron beam and super-conducting magnets.
- 10 keV photons produced by a 3 GeV electron beam and super-conducting magnets.

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DESIGN OF THE MACHINE

Plasma based electron injector

The laser wakefield acceleration and injection stage provides the electron beam for the compact ring. An intense laser pulse from a Ti:Sapphire laser is injected through a window in one of the bending dipoles, impinges on a gas jet, ionizes the plasma, and creates strong plasma wakefields inject electrons from the background plasma and accelerate them. The chosen laser and plasma parameters are summarized in Tables 1 and 2. Based on existing systems, we choose laser parameters achievable in the near future. A Ti:Sapphire laser system with a laser wavelength of $\lambda_l = 780$ nm, a pulse duration of 50 fs, a maximum laser power of 400 TW, 20 J of energy per pulse, and a laser spot size of 3.8 nm^2 [2]. The laser intensity I is then approximately $9.9 \cdot 10^{18}$ W/cm^2 which corresponds to an a_0 of about 2.1 for a Gaussian radial laser distribution.

$$a_0 \approx \left(\frac{I[\mathrm{W/cm^2}]}{1.37e18}\right)^{\frac{1}{2}} \cdot \lambda_l[\mu\mathrm{m}] \tag{1}$$

The chosen plasma density of the gas-jet is n $=1.75 \times 10^{17}\,\mathrm{cm^{-3}}$ and optimizes the achievable maximum electron energy. The laser frequency was confirmed to be greater than the critical plasma frequency ω_c [reference]

$$\omega_c = \frac{n^2}{4\pi c^2 r_e} \tag{2}$$

where c is the speed of light and r_e is the classical electron radius.

The depletion L_{dpl} and dephasing length L_{dph} for this injector system are estimated with:

$$L_{dpl} = \frac{1}{2a_0}\frac{\lambda_p^3}{\lambda_l^2}, L_{dph} = \frac{1}{2}\frac{\lambda_p^3}{\lambda_l^2} \quad (3)$$

to be $L_{dpl} \approx 17$ cm and $L_{dph} \approx 35$ cm, thus 17 cm is the upper bound on our total possible acceleration length. The maximum accelerating gradient E_{max} is estimated with

$$eE_{max} = 1\frac{\text{eV}}{\text{cm}} \cdot n^{1/2}[\text{cm}^{-3}] \quad (4)$$

to be 420 MeV/cm. This means that our target energies of 1 GeV and 3 GeV can be reached with an acceleration length of 2.4 cm and 7.2 cm. This acceleration length is longer than gas jets in use presently and may require a novel gas jet setup [references?], particularly for the 3 GeV beam.

In this design, we are relying on analytic estimates rather than the results of 3D simulations of the setup. Consequently, for the remainder of the ring calculations we used electron beam parameters that are typically achievable with similar laser wakefield acceleration stages [reference]. The chosen electron beam size is $\sigma_r \approx 1\frac{c}{\omega_p} \approx 12\mu$m, the electron energy spread is $\frac{\Delta E}{E_0} = 2\%$, and the electron beam divergence is $\sigma_\theta = 0.5$ mrad. Reasonable bunch charge for the 1 GeV and 3 GeV electron beams are 10 pC and 7 pC.

Table 1: Laser parameters of the plasma injector

Laser wavelength	780 nm
Laser power	379 TW
Spot size	3.8×10^{-9} m^2
Intensity	9.9×10^{18} W/cm^2
a_0	2.1
Laser pulse length (FWHM)	50 fs
Reprate	~1 Hz
Pulse Energy	20 J

Table 2: Plasma parameters

Plasma density	1.75×10^{17} cm¯3
Plasma wavelength	76 µm
Plasma frequency	3.97×10^{12} Hz
Plasma angular frequency	2.49×10^{13} s¯1
Accelerating gradient	0.42 GeV/cm
Bubble size	38 µm
Depletion length	16.9 cm
Dephasing length	33.5 cm
Acceleration length for 1 GeV	2.4 cm
Acceleration length for 3 GeV	7.2 cm

Magnet Design

The design of the compact ring (see Figure 1) is laid out as four 90 –degree sector dipoles, either 10 T super-conducting (s.c.) or 1.5 T normal conducting (n.c.). Parameters for the bending magnets are shown in Table 3. The laser-plasma injection system is located in the middle of a 2 m drift, enclosed by a pair of focusing quadrupole doublets (strengths ~ 50 T/m, 100 T/m) used to begin transport of the diverging electron beam born from the laser wakefield injector. The focusing strengths of the quadrupole magnets were calculated to parallelize an electron beam with a radial size $\sigma_r = 12\,\mu$m and a divergence of 0.5 mrad. Dipole magnets provide weak focusing, which is employed to compensate for space-charge effects. The wiggler is located in the drift space opposing the injector, and the remaining two drift spaces are each 0.5 m leaving enough space for limited diagnostics and collimators. The electron energy loss per turn is dominated by the synchrotron radiation loss E_{sr} in the bending magnets. There is no accelerating section in our compact ring design. This means that the number of turns N_{turns} is limited by the energy loss and the 10 cm horizontal apertures of the bending magnets. The number of turns was calculated by taking the radial electron beam size (σ_r), including energy spread and an covservative engineering fudge factor of 2, and calculating how much energy can be lost before the beam touches the aperture.

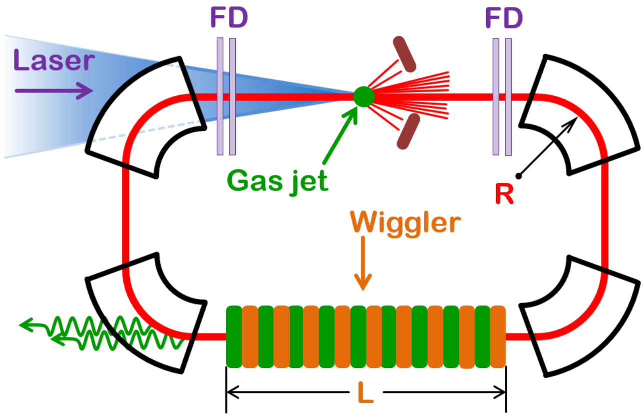

Figure 1: Schematics of the compact ring design. The laser beam enters through a window in the B4 dipole bending magnet, ionizes the gas jet and creates strong plasma wakefields to self-inject and accelerate electrons. Furthermore the produced electron beam gets focused with a quadrupole doublet. The electron beam is held on a circular trajectory by four 90-degree bending magnets (B1-B4). Opposite to the plasma injector, a Wiggler magnet produces the desired radiation.

Table 3: Dipole bending magnet parameters

Parameter	**1 GeV n.c.**	**1 GeV s.c.**	**1 GeV s.c.**
Bend. strength	1.5 T	10 T m	10 T
Bend. radius	2.23 m	0.84 m	1.02 m
Circumf.	19.1 m	7.1 m	9.4 m
E_{sr}/turn	40 keV	260 keV	7 MeV
N_{turns}	62	490	13

Table 4: Chosen (first box) and derived (second box) parameters detailing X-ray source.

$E_{electron}$(GeV)	1.0	1.0	3.0
B_{turn}(T)	1.5	10.0	10.0
E_{photon} (keV)	0.4	0.4	10.0
$\lambda_{wiggler}$ (mm)	15	15	100
$B_{wiggler}$(T)	0.60	0.60	1.7
K	0.84	0.84	16
$E_{radiated}$(keV)	2.1	2.1	140
Brilliance per electron lifetime $\left(\frac{\text{photons}}{\text{mm}^2\text{mrad}^2\text{sec}}\right)$	1.8×10^{10}	91×10^{10}	1.3×10^{10}
Brilliance per spill $\left(\frac{\text{photons}}{\text{mm}^2\text{mrad}^2\text{sec}}\right)$	4.7×10^{15}	78×10^{15}	27×10^{15}
x-ray train duration(μsec)	3.9	12	0.47

Production of Radiation

Table 4 details the radiation source parameters for all considered design versions. A standard length of 2 m was chosen for the undulating magnetic field region, where the electron bunch emits an approximately 6.7 ns-long X-ray pulse at each turn until it is scraped by the apertures. As can be seen in the table, X-ray energy was designed to either be within the water window (0.4 keV) or to be fairly hard (10 keV) depending on the energy of the injected electron pulse. The chosen parameters result in the source being near the wiggler/undulator transition or well within the wiggler regime, respectively, as can be seen by the parameter K. Of the chosen parameter sets, the 1 GeV electrons with the superconducting bending magnets (10 T) resulted in the largest brightness.

DISCUSSION

One worrying design issue is that the gas/plasma from the injector resides in the lattice longer than it takes the electron beam to make circle the lattice. The gas flow velocity from typical gas jets is $M = 20\,\text{km/s}$ [3], and one electron beam turn in a 10 m circumference ring takes ~ 30 ns. Thus the gas flow advances by ~600 μm and will therefore still be in the path of the beam for much of its residence time. Taking $10^{14}\,\text{W/cm}^2$ as ionization threshold of the plasma and assuming a radial laser size of 35 μm gives a plasma channel radius of 143 μm. This estimate suggest that the plasma column has already propagated far enough to eliminate the possibility of any further interaction with the beam. So, the electron beam is only likely to interact with the residual gas and not the laser-ionized plasma column. Thus, the interaction process of the beam is dominated by random scattering off the gas, which leads to a divergence growth of the order of micro-rad, as opposed to a coherent lensing of the order of milli-rad by the plasma [2]. It is unlikely that an electron beam with pC charge with a beam size of $\sigma_r = 5\mu$m and $\sigma_z = 10\,\mu$m ionizes gas.

Apart from using the radiation created by the wiggler, it would also be possible to use the radiation from the bending magnets or the X-rays produced by the betatron oscillations of the electron beam in the bubble. The latter has already been considered by [7] A Compton light source could be realized by making the electron bunch collide with a laser pulse.

CONCLUSIONS

In this report we propose different design solutions for a compact ring-based X-ray source with an on-orbit and on-energy laser-plasma injector. We consider four 90 degrees bending magnets to keep the particles on a circular orbit, the electrons are self-injected and accelerated by the plasma wakefield of a gas-jet excited by a 400 TW laser system, and the desired radiation is created by a wiggler magnet. The peak brilliance is calculated in the section 'Production of Radiation' and reaches up to $7.8e16\,\text{photons}/(\text{mm}^2\text{mrad}^2)$. Even though modern light sources routinely create a peak brilliance in the order of $10^{25}\,\text{photons}/(\text{mm}^2\text{mrad}^2 0.1\%\text{BW})$ [5], this design can be considered attractive due to its compactness and small footprint. This design would be suitable for use in, for example, a university setting. Future work should include plasma simulations to obtain better estimates for the electron beam parameters, optics simulations and particle tracking to obtain electron beam sizes, studies on the gas-jet design, further investigations on the electron scattering on the residual gas, and a more detailed description of the magnet design.

REFERENCES

[1] Unifying physics of accelerators, lasers and plasma, A. Seryi, CRC Press, 2015.

[2] Ultra-high intensity- 300-TW laser at 0.1 Hz repetition rate., Opt. Express 3, 2109–2114 (2008); doi: 10.1364/OE.16.002109

[3] High density gas jet nozzle design for laser target production, Review of Scientific Instruments 72, 2961 (2001); doi: 10.1063/1.1380393

[4] Beam interaction with Plasma-Vacuum interface, CLIC Experimental & Breakdown Studies Meeting, August 2013

[5] DESY Photon science

[6] Schlenvoigt, Hans-Peter. "Synchrotron radiation sources driven by laser-plasma accelerators." (2009).

[7] Rousse, Antoine, et al. "Production of a keV X-ray beam from synchrotron radiation in relativistic laser-plasma interaction." Physical review letters 93.13 (2004): 135005.