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 one week long investigation performed during June 2016 USPAS class "Unifying physics…" on 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]). We describe three versions of the light source, based on 1 GeV normal conducting and superconducting bending magnets, and 3 GeV superconducting. We describe the design choices, present the tables of parameters of the machines, and describe possible next steps of the design and optimization of the considered machines.

INTRODUCTION

Combining the field of Laser plasma acceleration (LWPA) with synchrotron light production, offers the possibility of creating compact accelerators and light sources, because of the high accelerating gradients that can be achieved using plasma.

In this paper we want to show the results of our design study of a compact synchrotron light source that produces 0.4 keV (water-window) or 10 keV photons. We estimate the design parameters of the compact light source, the achievable brilliance, and we discuss the feasibility and challenges of the design. Our design uses a laser plasma gas-jet accelerator to self-inject and accelerate electrons to either 1 GeV or 3 GeV [1]. Right after plasma, the electrons are focused using a quadrupole doublet and they are kept on circular trajectory using four 90 degree dipole bending magnets (super-conducting or normal conducting) (see figure **??**). The desired radiation is produced by a 2 m long wiggler magnet in one of the straight drift sections. We will discuss the following three options:

- 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.

Additionally we want to discuss the parameters of the radiation produced by the dipole bending magnets and the betatron motion of the electron beam in the plasma bubble.

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 impinges on a gas jet, ionizes the plasma, and creates strong plasma wakefields to accelerate and self inject electrons. The laser pulse is injected through a window in the bending dipole.

We choose to use a typical 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, and a laser spot size of 3.8 nm [reference?]. The laser intensity I is then approximately $9.9 \cdot 10^{18}$ W/cm^2 which corresponds to an a_0

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

of about 2.1 for a Gaussian radial laser distribution and 20 J of energy per pulse. The chosen plasma density of the gas-jet is n $=1.75 \times 10^{17}$ cm^{-}3 and optimizes the achievable maximum electron energy. We also made sure that the laser frequency is above the critical plasma frequency ω_c

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

with c the speed of light and r_e the classical electron radius.

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The depletion L_{dpl} and dephasing lengths L_{dph} for this injector system are calculated with

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

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

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

to be 420 MeV/cm. This means that our target energies of 1 GeV and 3 GeV can be reached in 2.4 cm and 7.2 cm. This acceleration length may require a novel gas jet setup, particularly for the 3 GeV case.

For further calculations, we assume typical achievable electron beam parameters [reference] from laser-plasma wakefield accelerators. The electron beam size is $\sigma_r \approx 1\frac{c}{\omega_p} \approx 12\mu$m, the electron energy spread $\frac{\Delta E}{E_0} = 2\%$ and the electron beam divergence $\sigma_\theta = 0.5$ mrad.

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 **??**) is laid out as four 90 −degree sector dipoles, either 10 T superconducting (s.c.) or 1.5 T normal conducting (n.c.) (Parameters see 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 strength of the quadrupole magnets was calculated such, to parallelize an electron beam with a radial size $\sigma_r = 12\ \mu m$ and a divergence of 0.5 mrad. The wiggler is located in the opposing drift space, and the alternate 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. The number of turns N_{turns} is limited by the energy loss and the 10 cm horizontal apertures of the bending magnets, because there is no accelerating section in our compact ring design. The number of turns was calculated taking the radial electron beam size (σ_r) including energy spread and calculating how much energy can be lost before the beam touches the aperture.

Plasma Injector + focusing doublet

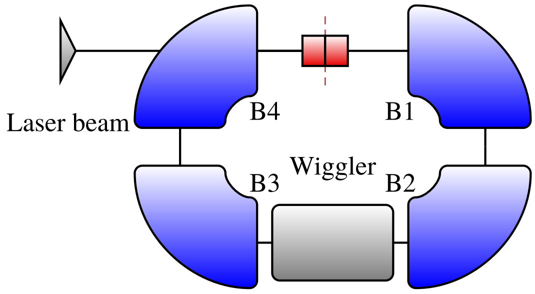

Figure 1: Schematics of the compact ring design. The laser beam enters through a window in the B4 dipole bending magnet, ionizes the gas jet and creates strong plasma wakefields to self-inject and accelerate electrons. Furthermore the produced electron beam gets focused with a quadrupole doublet (red box). 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 (grey box).

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}	300	530	16

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 resulting in the electron pulse emitting x-rays for approximately 6.7 ns pulses before the electron pulse 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 (10T) resulted in the largest brightness.

DISCUSSION

In this section we would first like to discuss the influence of the remaining gas/plasma from the injector onto to the circulating electron beam. The gas flow velocity from typical gas jets is $M = 20\,\mathrm{km/sec}$ [2]. One electron beam turn in a 10 m circumference ring takes ~ 30 ns, and the gas flow advances by ~600 μm. Taking $10^{14}\,\mathrm{W/cm}^2$ as ionization threshold of the plasma and assuming a radial laser size of 35 μm gives a plasma channel radius of 142.64 μm. This estimate suggest that the plasma column has already propagated far enough to eliminate the possibility of its 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 betatron oscillations of the electron beam in the bubble. The latter has already been considered by [6]. 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 use 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 section xx and reaches up to $7.8e16$ photons/(mm2 mrad2). Even though modern light sources routinely create a peak brilliance in the order of 10^{25} photons/(mm^{2}mrad^{2}0.1%BW) [4], this design can be considered attractive due to its compactness and small footprint.

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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)	2.0	2.0	5.6
K	0.84	0.84	16
$E_{radiated}$(keV)	2.1	2.1	140
Brilliance per electron lifetime $\left(\frac{\text{photons}}{\text{mm}^2\text{mrad}^2\text{sec}}\right)$	3.3×10^{10}	8.7×10^{10}	5.9×10^{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)	60	1.1	2.2