

# 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 (superconducting or normal conducting) (see figure 1). 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 interaction of the electron beam with the residual gas from the gas-jet, and mention further possibilities of creating X-rays with this design.

## 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 one of the bending dipoles.

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, 20 J of energy per pulse, and a laser spot size of 3.8 nm (see Table 1)[reference?]. The laser intensity  $I$  is then approximately  $9.9 \cdot 10^{18}$  W/cm<sup>2</sup> which corresponds to an  $a_0$

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

of about 2.1 for a Gaussian radial laser distribution. The chosen plasma density of the gas-jet is  $n = 1.75 \times 10^{17}$  cm<sup>-3</sup> (see Table 2) and optimizes the achievable maximum electron energy. We also made sure that the laser frequency is above the critical plasma frequency  $\omega_c$

$$\omega_c = \frac{n^2}{4\pi c^2 r_e} \quad (2)$$

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

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The depletion  $L_{dpt}$  and dephasing length  $L_{dph}$  for this injector system are calculated with

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

to be  $L_{dpt} \approx 17$  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

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

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  $\sigma_r \approx 1 \frac{c}{\omega_p} \approx 12 \mu\text{m}$ , the electron energy spread  $\frac{\Delta E}{E_0} = 2\%$  and the electron beam divergence  $\sigma_\theta = 0.5$  mrad. The bunch charge for the 1 GeV and 3 GeV electron beam was set to be 10 pC and 7 pC.

Table 1: Laser parameters of the plasma injector

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

Table 2: Plasma parameters

Plasma density	$1.75 \times 10^{17} \text{ cm}^{-3}$
Plasma wavelength	76 $\mu\text{m}$
Plasma frequency	$3.97 \times 10^{12} \text{ Hz}$
Plasma angular frequency	$2.49 \times 10^{13} \text{ s}^{-1}$
Accelerating gradient	0.42 GeV/cm
Bubble size	38 $\mu\text{m}$
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 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  $\sim 50 \text{ T/m}$ ,  $100 \text{ T/m}$ ) used to

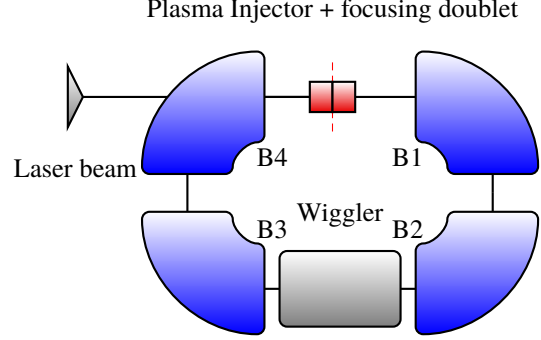


Figure 1: Schematics of the compact ring design. The laser beam enters through a window in the B4 dipole bending magnet, ionizes the gas jet and creates strong plasma wakefields to self-inject and accelerate electrons. Furthermore the produced electron beam gets focused with a quadrupole doublet (red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

begin transport of the diverging electron beam born from the laser wakefield injector. The focusing strength of the quadrupole magnets was calculated to parallelize an electron beam with a radial size  $\sigma_r = 12 \mu\text{m}$  and a divergence of 0.5 mrad. Dipole magnets provide weak focusing. 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. 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 ( $\sigma_r$ ) including energy spread and calculating how much energy can be lost before the beam touches the aperture.

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
$E_{sr}/\text{turn}$	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 (10 T) 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 the circulating electron beam. The gas flow velocity from typical gas jets is  $M = 20$  km/s [2]. One electron beam turn in a 10 m circumference ring takes  $\sim 30$  ns, and the gas flow advances by  $\sim 600$   $\mu\text{m}$ . Taking  $10^{14}$  W/cm<sup>2</sup> as ionization threshold of the plasma and assuming a radial laser size of 35  $\mu\text{m}$  gives a plasma channel radius of 143  $\mu\text{m}$ . 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  $\sigma_r = 5$   $\mu\text{m}$  and  $\sigma_z = 10$   $\mu\text{m}$  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 [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 the section 'Production of Radiation' and reaches up to  $7.8 \times 10^{16}$  photons/(mm<sup>2</sup> mrad<sup>2</sup>). Even though modern light sources routinely create a peak brilliance in the order of  $10^{25}$  photons/(mm<sup>2</sup> mrad<sup>2</sup> 0.1% BW) [4], this design can be considered attractive due to its compactness and small footprint.

Future work should include plasma simulations to verify our chosen 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 precise description of the magnet design.

## REFERENCES

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

$E_{\text{electron}}$ (GeV)	1.0	1.0	3.0
$B_{\text{turn}}$ (T)	1.5	10.0	10.0
$E_{\text{photon}}$ (keV)	0.4	0.4	10.0
$\lambda_{\text{wiggler}}$ (mm)	15	15	100
$B_{\text{wiggler}}$ (T)	2.0	2.0	5.6
K	0.84	0.84	16
$E_{\text{radiated}}$ (keV)	2.1	2.1	140
Brilliance per electron lifetime $\left(\frac{\text{photons}}{\text{mm}^2 \text{mrad}^2 \text{sec}}\right)$	$3.3 \times 10^{10}$	$8.7 \times 10^{10}$	$5.9 \times 10^{10}$
Brilliance per spill $\left(\frac{\text{photons}}{\text{mm}^2 \text{mrad}^2 \text{sec}}\right)$	$4.7 \times 10^{15}$	$78 \times 10^{15}$	$27 \times 10^{15}$
x-ray train duration ( $\mu\text{sec}$ )	60	1.1	2.2