A USPAS school project:

Compact ring-based X-ray source with on-orbit and on-energy laser-plasma injection

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Studies performed during the USPAS class 'Unifying Physics of Accelerators, Lasers and Plasma.' of Prof. Andrei Seryi
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Outline

-Introduction to the USPAS class

-Goal of the Project

-Magnet Choices

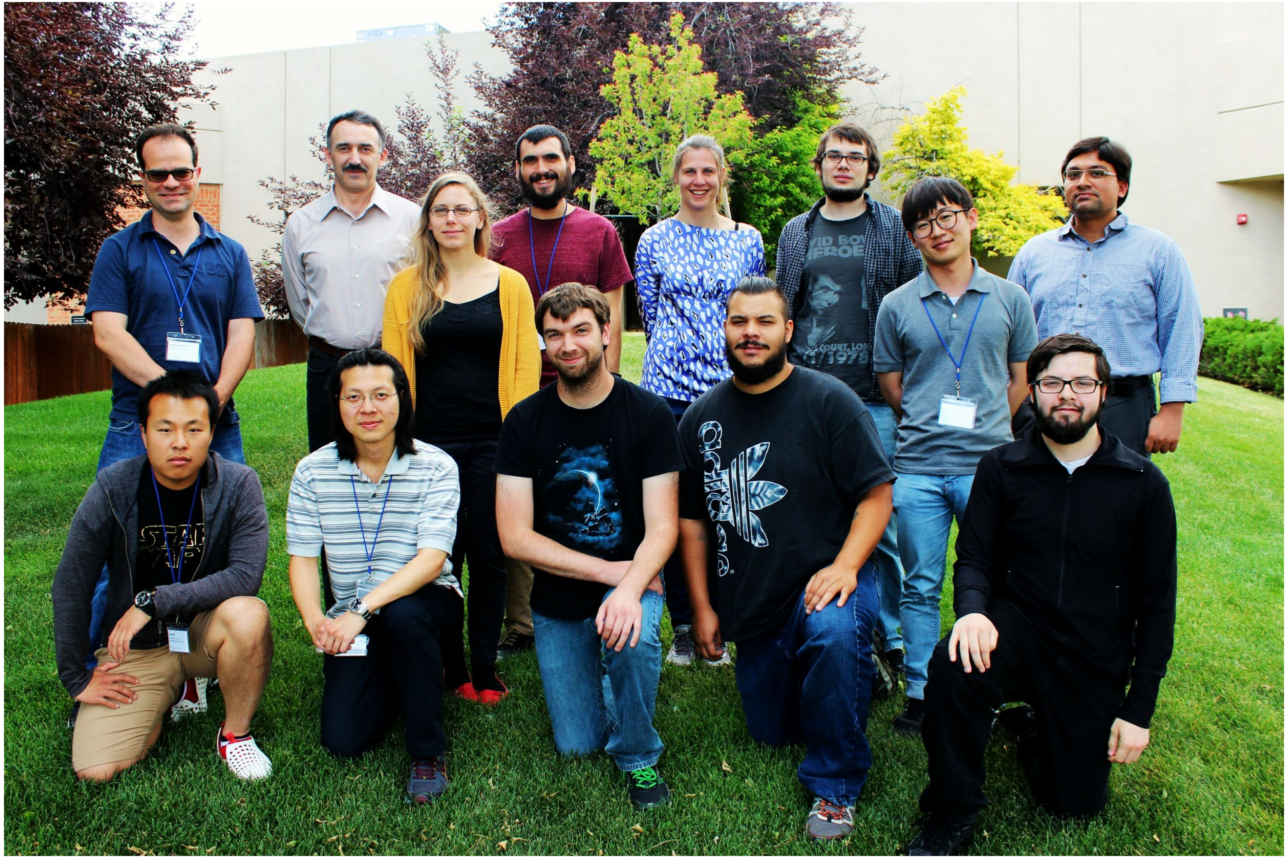
-Plasma Injector

-Wiggler and Radiation Parameters

-Discussion and Further Work

-Summary

The 2016 “Unifying Physics...” Class



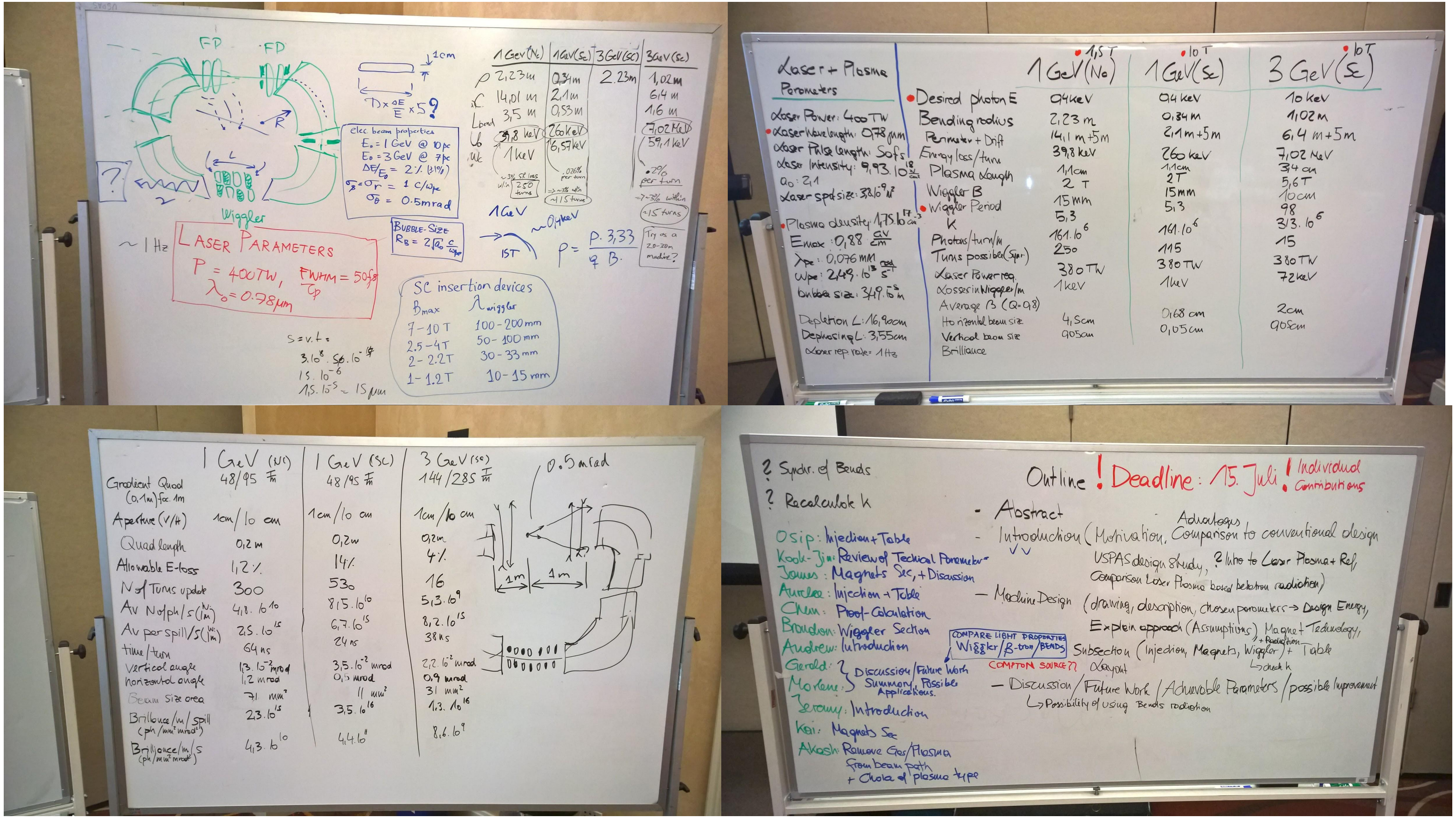
The 1 week long “**Unifying Physics of Accelerators, Lasers and Plasma**” class was held in June 2016 in Fort Collins, Colorado to earn credit from Colorado State University.

The class was taught by **Prof. Andrei Seryi** following his book “Unifying Physics of Accelerators, Lasers and Plasma.” [1]

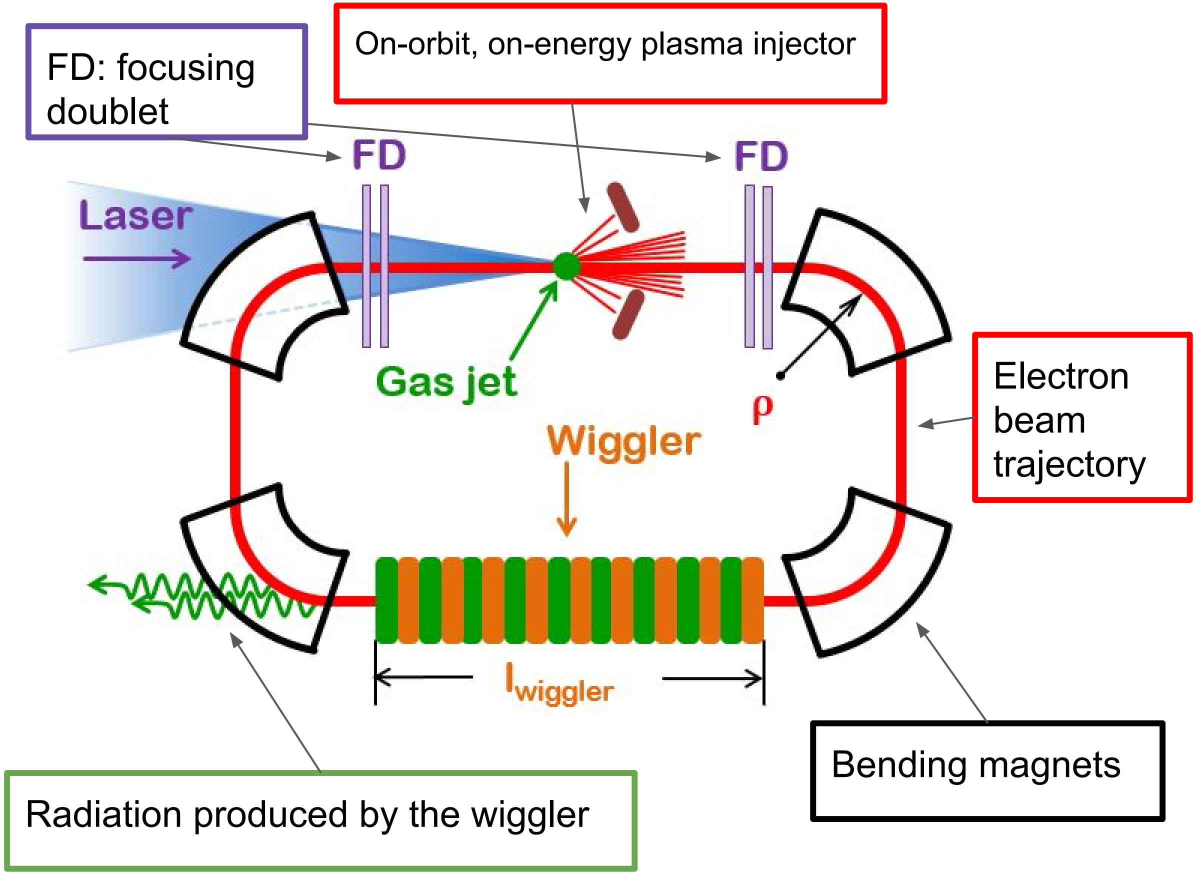
During the group projects, we worked on the design of the compact light source using the art of inventiveness **TRIZ**.

[1] A. Seryi, Unifying Physics of Accelerators, Lasers and Plasma, CRC Press, 2015.

Calculations were performed during school



Schematics of the compact ring



We studied the parameters of the compact ring for three different cases:

1) Producing **0.4 keV** photons with **1 GeV** electrons and **normal conducting** magnets

2) Producing **0.4 keV** photons with **1 GeV** electrons and **super conducting** magnets

3) Producing **10 keV** photons with **3 GeV** electrons and **super conducting** magents

Magnet Choice (1/2)

Magnetic lattice of the compact ring:

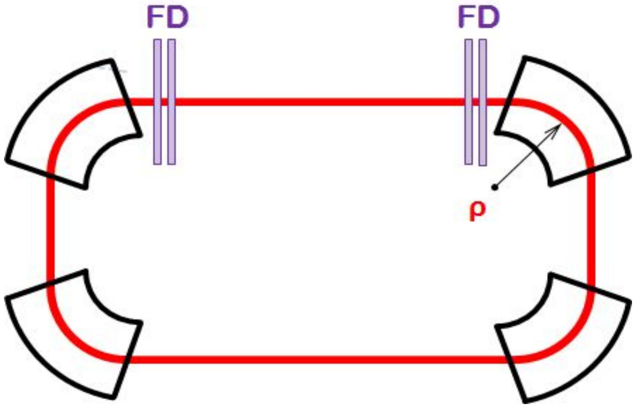


Table 3: Optics- and dipole magnet parameters.

Parameter	1 GeV n.c.	1 GeV s.c.	3 GeV s.c.	
Ben. field	1.5 T	10 T	10 T	
Ben. radius ρ	2.23 m	0.33 m	1.02 m	(1)
C	19.1 m	7.1 m	9.4 m	
$\overline{\beta}$	10.1 m	3.8 m	5 m	(2)
$\Delta x/\Delta y$	4.5/0.05 cm	0.68/0.05 cm	2/0.05 cm	
E_{sr}/turn	40 keV	260 keV	7 MeV	(4)
N_{turns}	62	490	13	(5)
$\overline{D}$	2.23 m	0.33 m	1.02 m	(3)

The bending radius ρ was calculated from the magnet field strength B of the dipole magnets:

eq. 2.13 from [1]

$$\rho = \frac{p}{q \cdot B} \qquad (1)$$

The circumference C then follows from the length of a 360° bending plus 5 m drift spaces. Assuming the betatron tune Q = 0.3, we calculated the average β- function:

eq. 2.53 from [1]

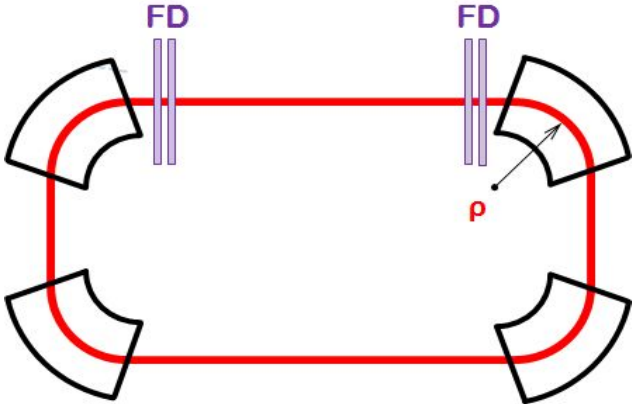
$$2\pi Q = \oint \frac{ds}{\beta(s)} = \frac{C}{\overline{\beta}} \qquad (2)$$

We estimated the average dispersion function with:

$$\overline{D} \approx \rho \qquad (3)$$

Magnet Choice (2/2)

Magnetic lattice of the compact ring:



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We estimated the horizontal Δx and vertical Δy beam sizes based on the bending radius ρ and the circumference C. The main contribution of the energy loss per turn comes from the radiation emitted by the bending magnets E_{sr}:

$$E_{sr} = \frac{4\pi}{3}\frac{r_e\gamma^4}{\rho}mc^2N_{elec} \quad (4)$$

derived from eq. 3.8 from [1]

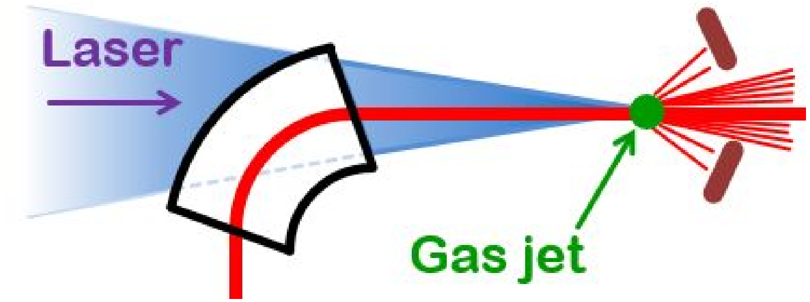
After we set the horizontal aperture to be x_{max}= 10 cm. The number of turns can be calculated with:

$$N_{\text{turns}} = \frac{x_{\max} - 2\Delta x}{\overline{D}}\frac{E}{E_{sr}/\text{turn}} \quad (5)$$

derived in class

The strength of the focusing doublets was calculated to focus and then parallelize the circulating electron beam. To achieve a focal length of 1m, the quadrupole gradients need to be in the range of 50-100 T/m.

Plasma gas-jet injector



Plasma and gas jet parameters:

Plasma density	1.75×10^{17} cm^{-3}	(6)
Accelerating gradient	0.4 GeV/cm	(9)
Bubble radius	37 μm	(10)
Depletion length	16.9 cm	(7)
Dephasing length	20 cm	(8)
Acceleration length for 1 GeV	2.4 cm	
Acceleration length for 3 GeV	7.2 cm	

We choose the plasma density (6) so that we can reach 3 GeV within the depletion (2) and dephasing length (3):

$$L_{dpl} = \frac{1}{2a_0}\frac{\lambda_p^3}{\lambda_l^2} \qquad (7)$$

$$L_{dph} = \frac{1}{4}\frac{\lambda_p^3}{\lambda_l^2} \qquad (8)$$

We estimated the accelerating gradient on the cold plasma wave-breaking limit:

$$E_{max} \sim \frac{mc\omega_p}{e} \qquad (9)$$

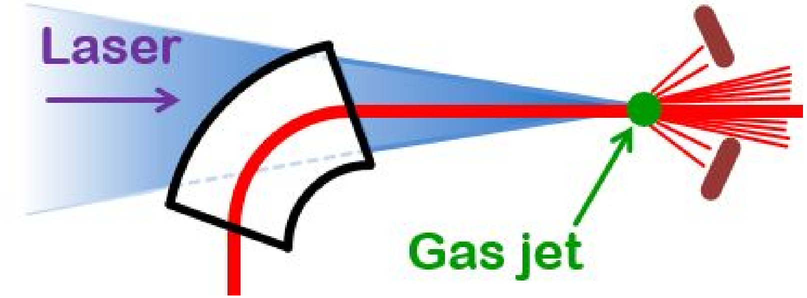
and the bubble radius with:

$$R_B \simeq 2\sqrt{a_0}\frac{c}{\omega_{pe}} \qquad (10)$$

Acceleration lengths of 2.4 and 7.2 cm require novel gas jet designs!

Further values for the electron beam, we used typical values: Electron beam size $\sigma_r \cong \sigma_z \sim c/\omega_p \sim 12\mu m$, electron energy spread ΔE/E ~ 2%, beam divergence σ_θ= 0.5 mrad and the bunch charge is 10 pC (1GeV) and 7 pC (3 GeV).

Laser system of the plasma gas-jet injector



Ti:Sapphire laser parameters:

Laser wavelength	780 nm	
Laser power	379 TW	
Spot size radius	37 μm	
Intensity	10^{19} W/cm^2	
a_0	2.1	(11)
Laser pulse length (FWHM)	45 fs	
Pulse reprate (f_{rep})	1 Hz	
Pulse Energy	30 J	

Based on existing systems, we choose laser parameters achievable in the near future.

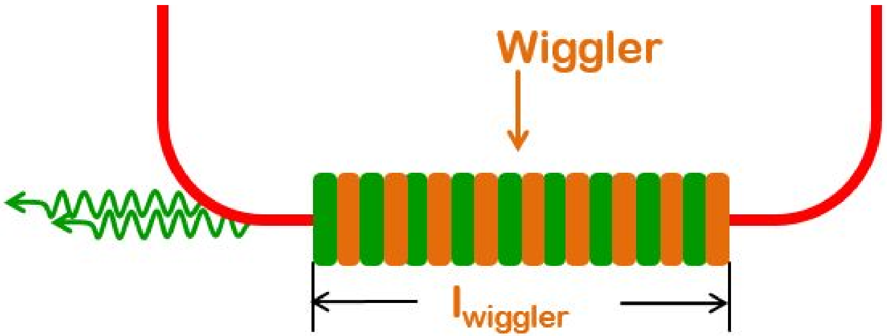
A Ti:Sapphire laser system with a laser wavelength of 780 nm. The spot size radius was chosen to be the plasma bubble radius (1), the laser pulse length to be 45 fs, and the repetition rate f_{rep} to be 1 Hz.

The laser strength parameter a_0 was calculated with:

$$a_0 \approx \left(\frac{I[\mathrm{W/cm^2}]}{1.37 \times 10^{18}} \right)^{\frac{1}{2}} \cdot \lambda_l[\mu\mathrm{m}] \qquad (11)$$

The required laser power, laser intensity, and pulse energy were estimated based on the plasma parameters.

Radiation production



Parameters of the produced radiation:

Parameter	1 GeV n.c.	1 GeV s.c.	3 GeV s.c.	
E_{ph} (keV)	0.4	0.4	10.0	
$\lambda_{wiggler}$ (mm)	15	15	100	
$B_{wiggler}$(T) [13]	0.60	0.60	1.7	
K	0.84	0.84	16	
E_{rad}(keV)	2.1	2.1	140	
$B_{e-life}\left(\frac{\text{photons}}{\text{mm}^2\text{mrad}^2\text{s}}\right)$	2×10^{10}	9×10^{10}	1×10^{10}	(13)
$B_{spill}\left(\frac{\text{photons}}{\text{mm}^2\text{mrad}^2\text{s}}\right)$	5×10^{15}	8×10^{15}	3×10^{15}	(12)
train durat.(μs)	3.9	12	0.47	

After choosing the size, strength and periodicity of the wiggler magnet we can estimate the brilliance of the radiation produced.

The Brilliance per spill was estimated with:

$$B_{spill} = \frac{N_{ph} l_{wiggler}}{\pi \Delta x \Delta y \theta_v \theta_h \Delta t} \cdot N_{elec} \qquad (12)$$

And the Brilliance per electron lifetime with:

$$B_{e-life} = \frac{N_{ph} l_{wiggler}}{\pi \Delta x \Delta y \theta_v \theta_h} \cdot N_{elec} \cdot f_{rep} \cdot N_{turns} \qquad (13)$$

Discussion

Do the electrons circulating in the ring interact with residual plasma?

Assuming a gas flow velocity of 20 km/s, the plasma propagated a few 100 μm during one electron turn. Hence we assume that the circulating electrons -after being focused by the upstream doublet- only scatter off the gas-atoms, which causes scattering angles in the order of μrads.

Further studies should include:

•Possibility of creating a compton light source by making the laser pulse collide with the electrons

•Study of the radiation produced by the betatron radiation of the electrons in the plasma bubble.

•Further studies on the radiation produced by the bending magnets.

•Study on how to achieve gas jet lengths in the order of 7 cm.

•Detailed plasma and optics simulations to confirm the estimates

Summary

- We presented our studies on the design of ‘Compact ring-based X-ray source’. The studies were performed as part of the USPAS 2016 'Unifying Physics …' class of Prof. Andrei Seryi.

- We inject the electrons with an on-orbit and on-energy laser plasma injector, with a plasma density of: 1.75×10^{17} electrons/cm^{-3}. A 400 TW laser system creates strong plasma wavefields to self-inject and accelerate electrons to 1 or 3 GeV.

- A wiggler magnet produces 0.4 and 10 keV photons with a brilliance per spill in the order of 10^{15} photons/mm^{2}mrad^{2}s.