



A USPAS school project:

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

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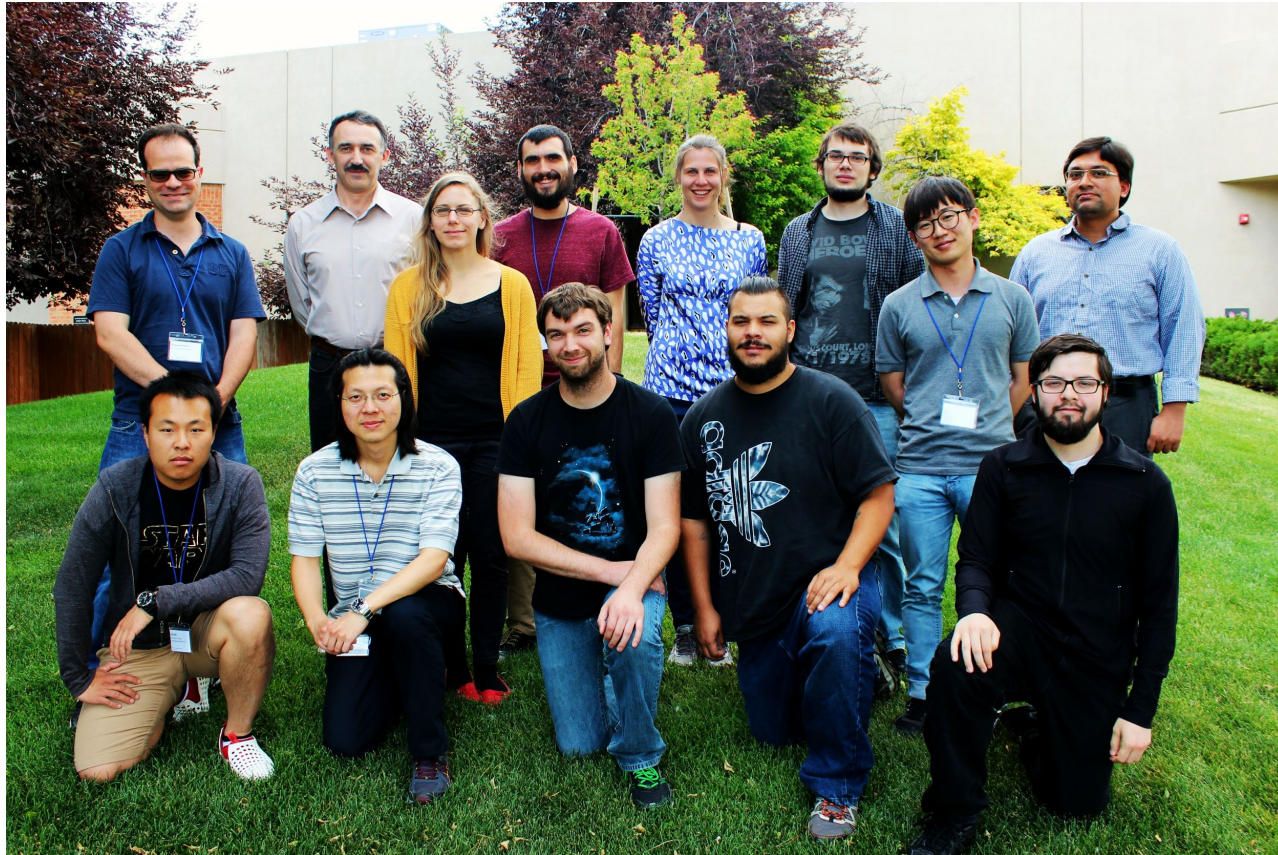
Studies performed during the USPAS class 'Unifying Physics of Accelerators, Lasers and Plasma.' of Prof. Andrei Seryi  
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# Outline



- 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



**LASER PARAMETERS**  
 $P = 400 \text{ TW}$ ,  $F_{\text{WDM}} = 50 \text{ fs}$   
 $\lambda_0 = 0.98 \mu\text{m}$

**Electron Beam Parameters**  
 $E = 1 \text{ GeV}$  @  $0 \text{ pA}$   
 $E = 3 \text{ GeV}$  @  $7 \text{ pA}$   
 $\Delta E/E = 2\%$   
 $\sigma_x = 1 \text{ cm}$   
 $\sigma_y = 0.5 \text{ mmrad}$

1 GeV (N)	1 GeV (S)	3 GeV (S)	3 GeV (e)
2.23 m	0.31 m	2.23 m	1.02 m
14.01 m	2.1 m	1.02 m	6.4 m
3.5 m	0.55 m	7.02 MeV	16 m
		59.1 keV	

**SC insertion devices**  
 $B_{\text{max}}$   
 7-10 T 100-200 mm  
 2.5-4 T 50-100 mm  
 2-2.2 T 30-33 mm  
 1-1.2 T 10-15 mm

**Laser + Plasma Parameters**

	1 GeV (No)	1 GeV (S)	3 GeV (S)
Desired photon E	0.4 keV	0.4 keV	10 keV
Bending radius	2.23 m	0.34 m	1.02 m
Penumbra + Diff	14.1 m + 5 m	2.1 m + 5 m	6.4 m + 5 m
Energy loss/turn	39.8 keV	260 keV	7.02 MeV
Plasma length	1.1 cm	3.4 cm	3.4 cm
Wiggle B	2 T	15 mm	10 cm
Wiggle Period	15 mm	5.3	98
Plasma density	$1.75 \times 10^{21} \text{ cm}^{-3}$	$1.1 \times 10^{16}$	$3.3 \times 10^6$
Photon flux	$1.6 \times 10^6$	250	15
Turns possible (Sp)	380 TW	380 TW	380 TW
Average B (G-Q)	1 keV	1 keV	1 keV
Horizontal beam size	4.5 cm	0.68 cm	2 cm
Vertical beam size	0.05 cm	0.05 cm	0.05 cm

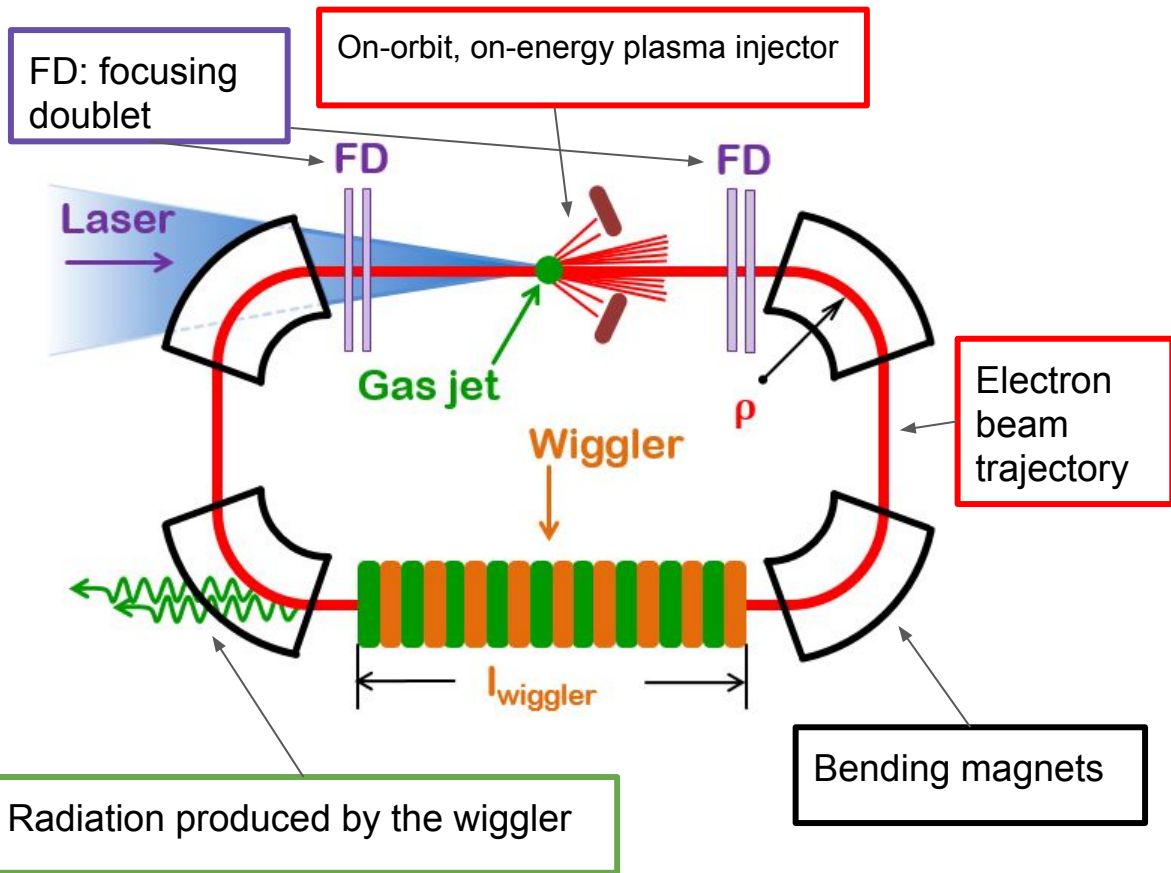
	1 GeV (US)	1 GeV (SC)	3 GeV (SC)
Gradient Quad (G/m) for 4m	48/95 #	48/95 #	144/285 #
Aperture (cm)	1cm/10 cm	1cm/10 cm	1cm/10 cm
Quad length	0.2 m	0.2 m	0.2 m
Attainable E-loss	1.2%	1.4%	4%
N of Turns updat	300	530	16
Av Nofph/s (m)	$4.1 \times 10^{10}$	$8.15 \times 10^{10}$	$5.3 \times 10^9$
Av per spill/s (m)	$2.5 \times 10^{16}$	$6.7 \times 10^{15}$	$8.2 \times 10^{15}$
Time/turn	64 ns	24 ns	38 ns
Vertical angle	$1.3 \times 10^{-2} \text{ mrad}$	$3.5 \times 10^{-2} \text{ mrad}$	$2.7 \times 10^{-2} \text{ mrad}$
Horizontal angle	12 mrad	0.9 mrad	0.9 mrad
Beam size area	71 mm <sup>2</sup>	11 mm <sup>2</sup>	31 mm <sup>2</sup>
Brilliance/m/spill (cpm/mm/mrad)	$2.3 \times 10^{15}$	$3.5 \times 10^{16}$	$1.3 \times 10^{16}$
Brilliance/m/s (cpm/mm/mrad)	$4.3 \times 10^{10}$	$4.4 \times 10^{10}$	$8.6 \times 10^9$

**Outline ! Deadline: 15. Juli ! Individual Contributions**

- Abstract
- Introduction (Motivation, Comparison to conventional design)
  - USPAS design study, 2 liter to Laser Plasma + Ref
  - Comparison Laser Plasma based betatron radiation
- Machine Design (drawing, description, chosen parameters → Design Energy, Explan approach (Assumptions), Machine + Technology, Subsection (Injection, Magnets, Wiggle + Table)
  - COMPARE LIGHT PROPERTIES: Wiggler/B-bend/BENDS
  - COMMON SOURCE??
- Discussion / Future Work / Achievable Parameters / possible improvement
  - possibility of using Bends radiation

**Key:** Magnets Sec  
 Avash Remove Gas/Plasma from beam path + Close of plasma type

# 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** magnets

# Magnet Choice (1/2)



## Magnetic lattice of the compact ring:

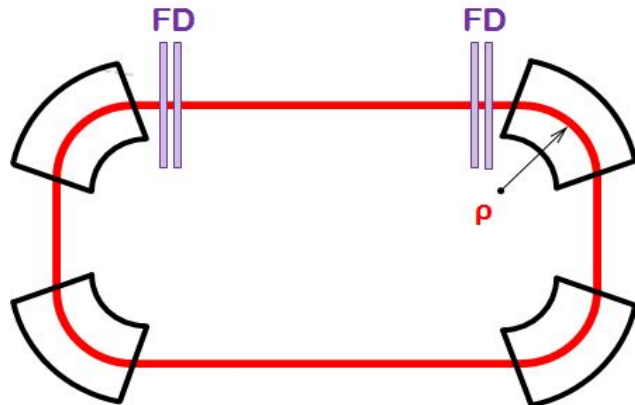


Table 3: Optics- and dipole magnet parameters.

Parameter	1 GeV n.c.	1 GeV s.c.	3 GeV s.c.	
Ben. field	1.5 T	10 T	10 T	
Ben. radius $\rho$	2.23 m	0.33 m	1.02 m	(1)
$C$	19.1 m	7.1 m	9.4 m	
$\bar{\beta}$	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	
$E_{sr}/\text{turn}$	40 keV	260 keV	7 MeV	(4)
$N_{\text{turns}}$	62	490	13	(5)
$\bar{D}$	2.23 m	0.33 m	1.02 m	(3)

The bending radius  $\rho$  was calculated from the magnet field strength  $B$  of the dipole magnets:

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

eq. 2.13  
from [1]

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

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

eq. 2.53  
from [1]

We estimated the average dispersion function with:

$$\bar{D} \approx \rho \quad (3)$$

# Magnet Choice (2/2)



## Magnetic lattice of the compact ring:

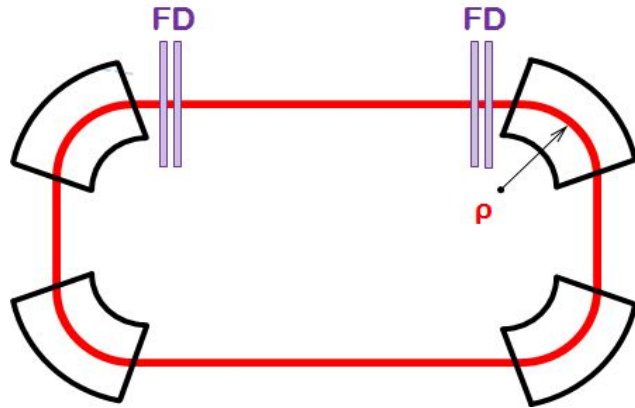


Table 3: Optics- and dipole magnet parameters.

Parameter	1 GeV n.c.	1 GeV s.c.	3 GeV s.c.	
Ben. field	1.5 T	10 T	10 T	
Ben. radius $\rho$	2.23 m	0.33 m	1.02 m	(1)
$C$	19.1 m	7.1 m	9.4 m	
$\bar{\beta}$	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	
$E_{sr}/\text{turn}$	40 keV	260 keV	7 MeV	(4)
$N_{\text{turns}}$	62	490	13	(5)
$\bar{D}$	2.23 m	0.33 m	1.02 m	(3)

We estimated the horizontal  $\Delta x$  and vertical  $\Delta y$  beam sizes based on the bending radius  $\rho$  and the circumference  $C$ . The main contribution of the energy loss per turn comes from the radiation emitted by the bending magnets  $E_{sr}$ :

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

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:

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

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



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

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

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

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

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

and the bubble radius with:

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

## Plasma and gas jet parameters:

Plasma density	$1.75 \times 10^{17} \text{ cm}^{-3}$	(6)
Accelerating gradient	0.4 GeV/cm	(9)
Bubble radius	37 $\mu\text{m}$	(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	

**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  $\sigma_r \simeq \sigma_z \sim c/\omega_p \sim 12\mu\text{m}$ , electron energy spread  $\Delta E/E \sim 2\%$ , beam divergence  $\sigma_\theta = 0.5 \text{ mrad}$  and the bunch charge is 10 pC (1GeV) and 7 pC (3 GeV).



# Laser system of the plasma gas-jet injector



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  $f_{\text{rep}}$  to be 1 Hz.

The laser strength parameter  $a_0$  was calculated with:

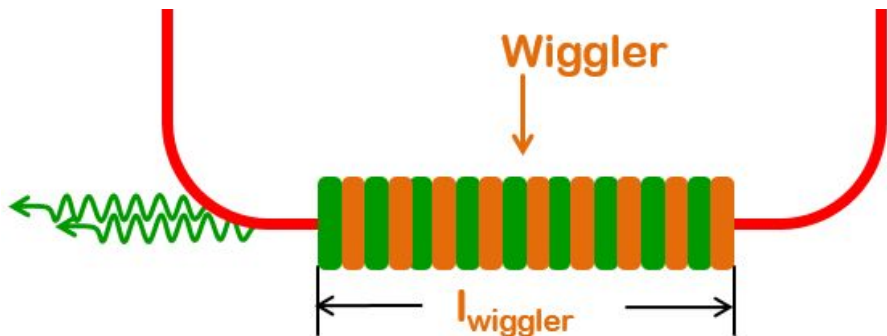
$$a_0 \approx \left( \frac{I[\text{W}/\text{cm}^2]}{1.37 \times 10^{18}} \right)^{\frac{1}{2}} \cdot \lambda_l[\mu\text{m}] \quad (11)$$

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

## Ti:Sapphire laser parameters:

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

# Radiation production



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:

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

## Parameters of the produced radiation:

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

And the Brilliance per electron lifetime with:

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

# 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  $\mu\text{m}$  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  $\mu\text{rads}$ .

## 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:  $1.75 \times 10^{17}$  electrons/cm<sup>-3</sup>. 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<sup>2</sup>mrad<sup>2</sup>s.