



A USPAS school project:

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

**Marlene Turner**, Auralee Edelen, Andrei Seryi, Jeremy Cheatham  
Osip Lishilin, Aakash Ajit Sahai, Brandon Zerbe,  
Andrew Lajoie, Chun Yan Jonathan Wong, Kai Shih, James Gerity,  
Gerard Lawler, Kookjin Moon.

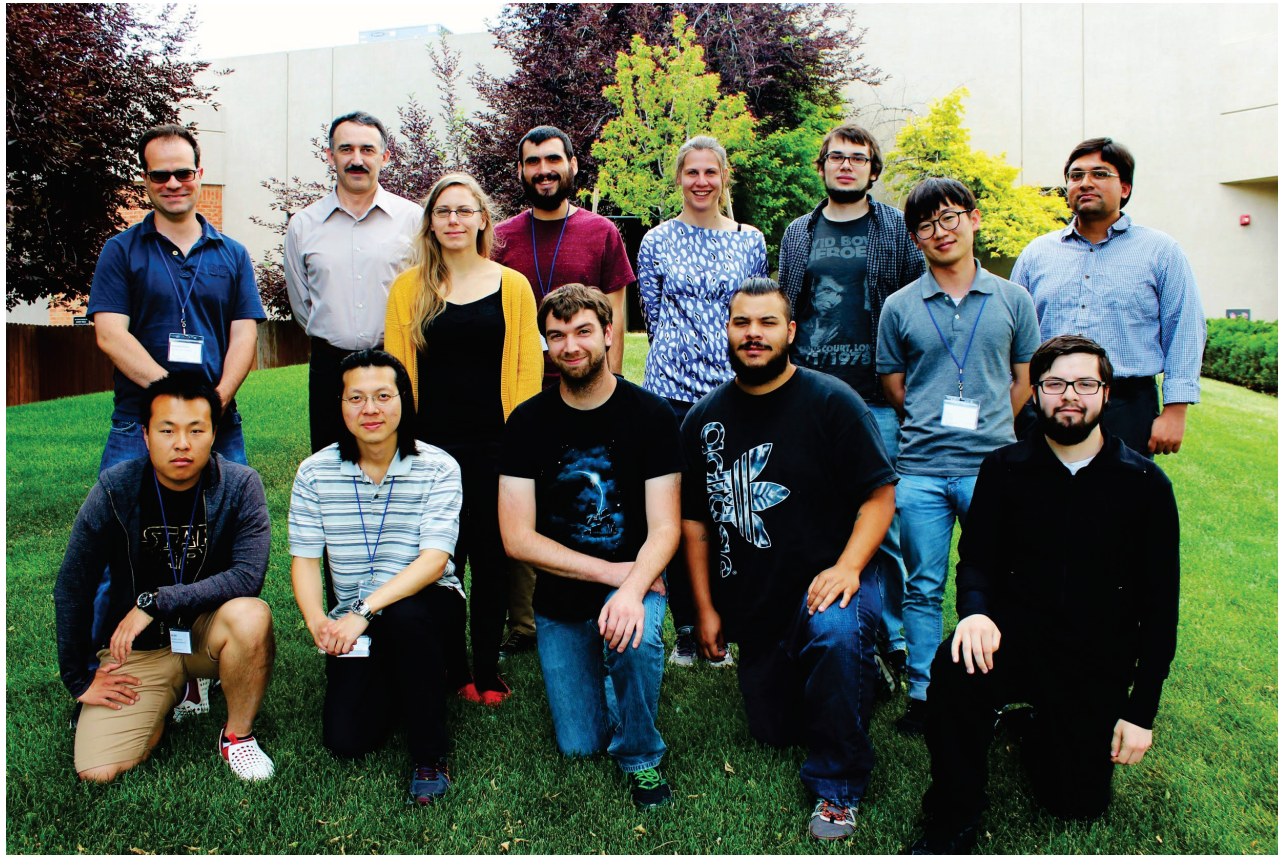
Studies performed during the USPAS class 'Unifying Physics of Accelerators, Lasers and Plasma.' of Prof. Andrei Seryi  
Teaching assistant: Aakash Sahai

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

**SC insertion devices**

$B_{\text{max}}$	$\lambda_{\text{wiggler}}$
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

Other parameters:  $E_1 = 1 \text{ GeV}$ ,  $E_2 = 3 \text{ GeV}$ ,  $\sigma_x = 2 \mu\text{m}$ ,  $\sigma_y = 1 \text{ nm}$ ,  $\sigma_z = 0.5 \text{ mm}$

**Laser + Plasma Parameters**

	1 GeV (No)	1 GeV (Se)	3 GeV (Se)
Desired photon E	04 keV	04 keV	10 keV
Bending radius	2.23 m	0.84 m	1.02 m
Bendmat + Drift	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 density	11 cm	1.1 cm	34 cm
Wiggler B	2 T	2 T	5.6 T
Wiggler Period	15 mm	15 mm	10 cm
K	5.3	5.3	98
Photons/turn/Hz	$16.1 \cdot 10^6$	$16.1 \cdot 10^6$	$3.3 \cdot 10^6$
Turns possible (Spr)	250	115	15
Laser Power req	380 TW	380 TW	380 TW
Average B (Gauss)	1 keV	1 keV	72 keV
Horizontal beam size	4.5 cm	0.68 cm	2 cm
Vertical beam size	0.05 cm	0.05 cm	0.05 cm
Brilliance			

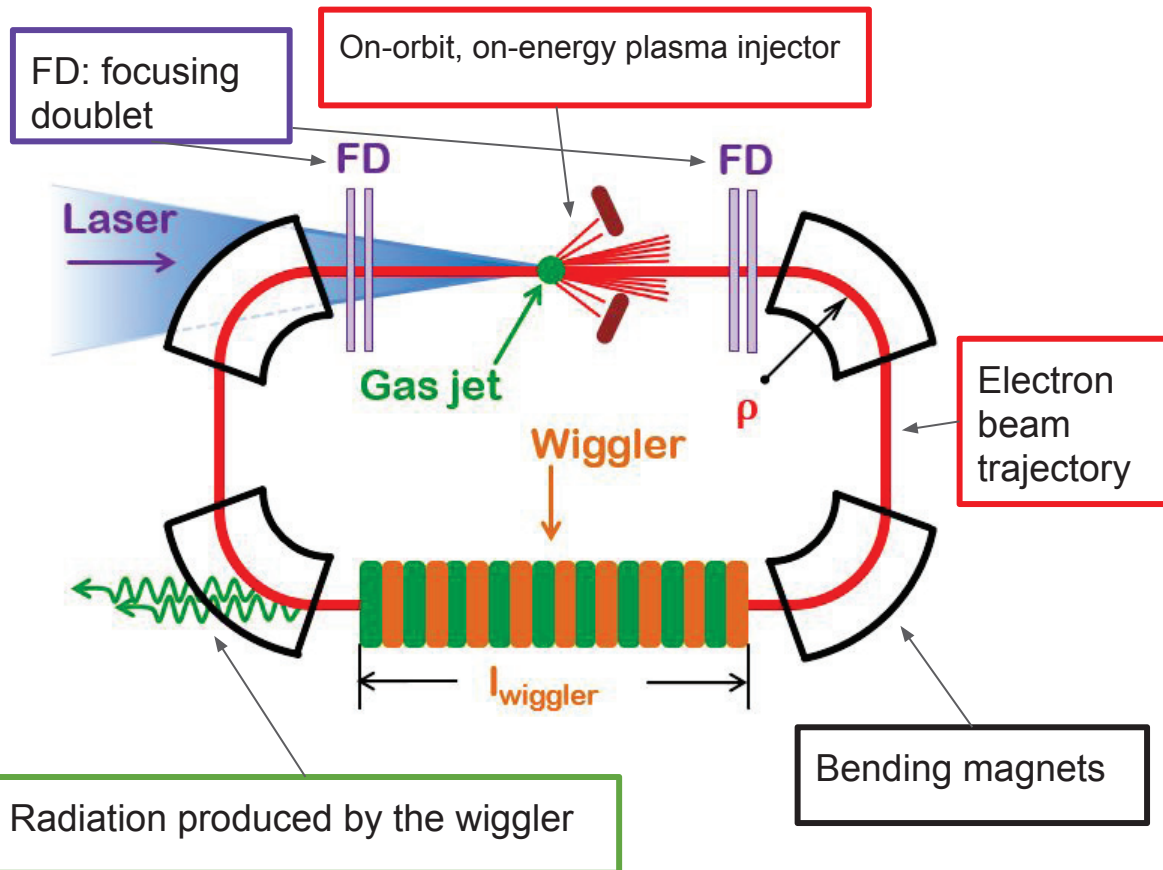
	1 GeV (US)	1 GeV (Se)	3 GeV (Se)
Circular Quad ( $\text{cm/m}$ ) for 4m	48/95 $\frac{\text{cm}}{\text{m}}$	48/95 $\frac{\text{cm}}{\text{m}}$	144/285 $\frac{\text{cm}}{\text{m}}$
Aperture (V/A)	1cm/10 cm	1cm/10 cm	1cm/10 cm
Quad length	0.2 m	0.2 m	0.2 m
Allowable E-loss	1/2 %	1/4 %	4 %
N of Turns updat	300	530	16
AV Nofph/s (1/m)	$4.1 \cdot 10^{10}$	$8.15 \cdot 10^{10}$	$5.3 \cdot 10^9$
AV per spill/s (1/m)	$2.5 \cdot 10^{15}$	$6.7 \cdot 10^{15}$	$8.2 \cdot 10^{15}$
Time/turn	84 ns	24 ns	38 ns
Vertical angle	$1.3 \cdot 10^{-3} \text{ mrad}$	$3.5 \cdot 10^{-2} \text{ mrad}$	$2.2 \cdot 10^{-2} \text{ mrad}$
Horizontal angle	1.2 mrad	0.5 mrad	0.9 mrad
Beam size area	71 $\mu\text{m}^2$	11 $\mu\text{m}^2$	31 $\mu\text{m}^2$
Brilliance (1/s/100 $\mu\text{m}^2$ )	$2.3 \cdot 10^{15}$	$3.5 \cdot 10^{16}$	$1.3 \cdot 10^{16}$
Brilliance (1/s/100 $\mu\text{m}^2$ )	$4.3 \cdot 10^{10}$	$4.4 \cdot 10^8$	$8.6 \cdot 10^7$

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

- 2. Synchr. of Bands
- 2. Recalculate h
- Abstract
- Introduction (Motivation, Comparison to conventional design)
  - USPAS design study, 2. Intro to Laser Plasma + Ref
  - Comparison Laser Plasma based betatron radiation
- Machine Design (drawing, description, chosen parameters  $\rightarrow$  Design Energy, Expen approach (Assumptions))
  - Magne + Technology
  - Wiggler/Beam/Bands Subsection (Injection, Magnets, Wiggler + Table)
  - Output
- COMPARE LIGHT PROPERTIES Wiggler/B-Tube/BANDS
- CONCEPT SOURCE??
- Discussion/Future Work Summary/Possible Applications
  - Discussion/Future Work/Adjustable Parameters/possible improvement
  - Probability of using Bands radiation
- Key: Magnets Se
- ALASIN: Remove Gap/Plasma from beam path + Choice 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:

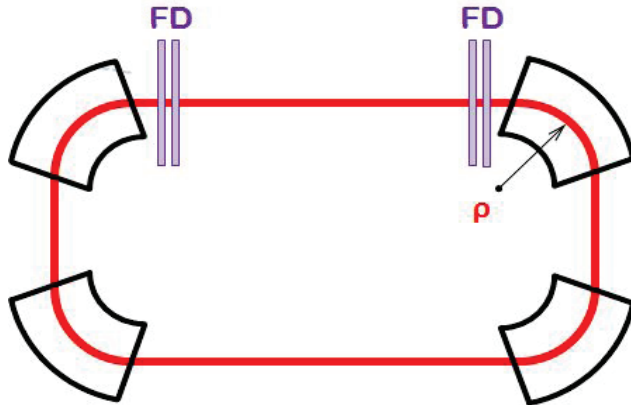


Table 3: Optics- and dipole magnet parameters.

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:

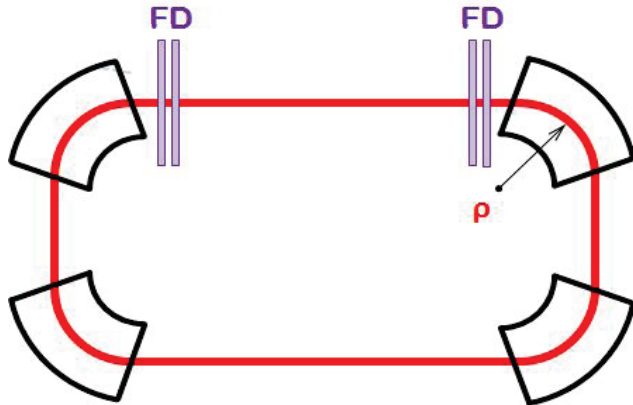


Table 3: Optics- and dipole magnet parameters.

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:

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

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

## 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	

Further values for the electron beam, we used typical values: Electron beam size  $\sigma_r \approx \sigma_z \sim c/\omega_p \sim 12\mu\text{m}$ , 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:

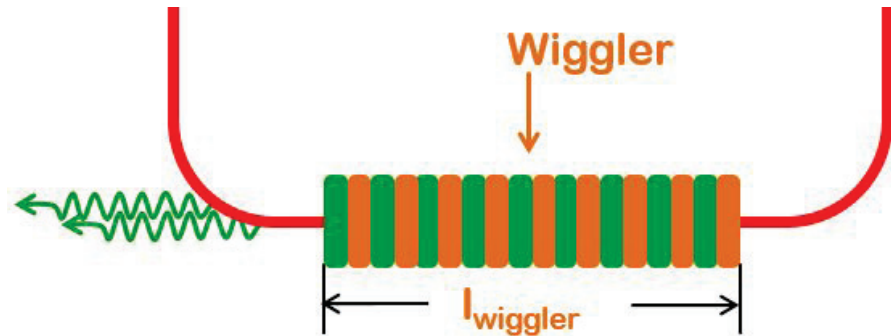
$$a_0 \approx \left( \frac{I[\text{W}/\text{cm}^2]}{1.37 \times 10^{18}} \right)^{\frac{1}{2}} \cdot \lambda_l[\mu\text{m}] \quad (11)$$

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:

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

## 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
$B_{\text{e-life}}$ ( $\frac{\text{photons}}{\text{mm}^2 \text{mrad}^2 \text{s}}$ )	$2 \times 10^{10}$	$9 \times 10^{10}$	$1 \times 10^{10}$ (13)
$B_{\text{spill}}$ ( $\frac{\text{photons}}{\text{mm}^2 \text{mrad}^2 \text{s}}$ )	$5 \times 10^{15}$	$8 \times 10^{15}$	$3 \times 10^{15}$ (12)
train durat. ( $\mu\text{s}$ )	3.9	12	0.47

And the Brilliance per electron lifetime with:

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



# 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.