Compact SRF Linac for a High Brilliance Inverse Compton Scattering Light Source

Kirsten E. Deitrick

Center for Accelerator Science
Old Dominion University

deitrick@jlab.org
kdeit001@odu.edu

Outline

- Background
  - X-ray Uses and Sources
  - Compton Light Source (CLS)
  - Concept Goals and Constraints
- Machine Layout
- Beam Dynamics and Critical Factors
- X-Ray Performance
- Next Steps to a Full Design
- Conclusion
- Acknowledgments
- References

Focus of talk is on Ph.D. dissertation [1] at Old Dominion University, which was subsequently published [2]

X-ray Uses: A Partial List

Techniques:

- Phase contrast imaging (PCI)
- K-edge subtraction imaging
- Absorption radiography
- Radiotherapy
- Diffraction
- Spectroscopy

Fields:

- Medicine
- Cultural heritage
- Material science
- Security
- Basic science research (biology, chemistry, physics)

This is not a complete list – other techniques and fields use x-rays

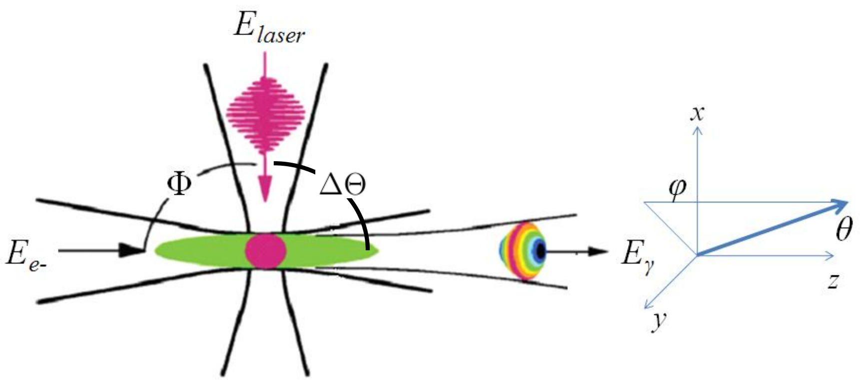
Existing X-ray Sources: A Partial List

- Rotating Anode Tube
- Compton X-ray Source
- Synchrotrons
  - Undulators
- Free Electron Lasers

Increasing:
Size
Cost
Quality

Decreasing:
Access

Compton Light Source (CLS)



Altered Fig. 1 from [2]

- Energy:

$$E_\gamma(\Phi,\theta,\phi) = \frac{E_{laser}(1-\beta\cos\Phi)}{1-\beta\cos\theta + E_{laser}(1-\cos\Delta\Theta)/E_{e^-}}$$

- Thomson limit:

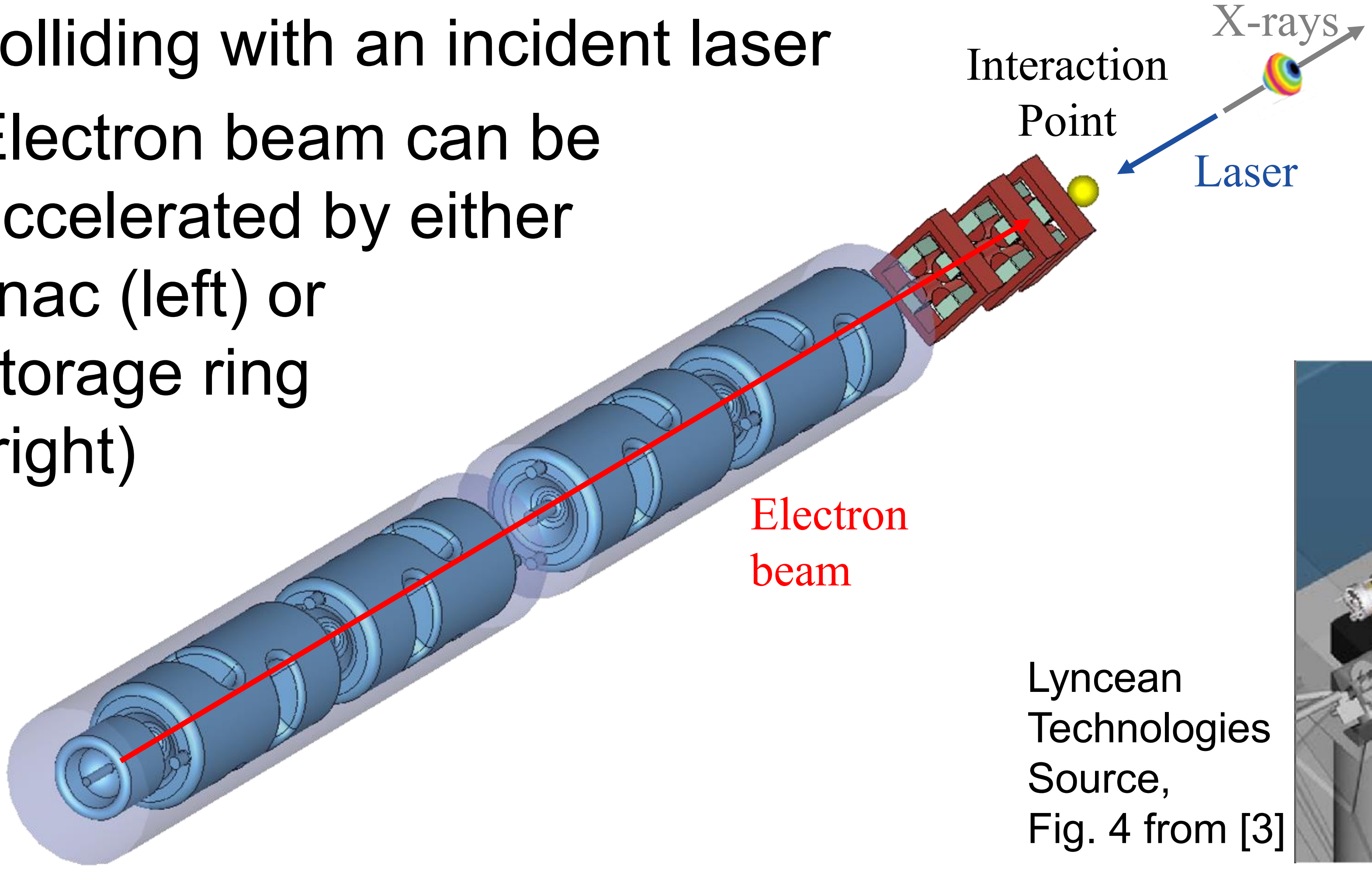
$$\gamma(1+\beta)E_{laser} \ll mc^2 \qquad E_\gamma(\Phi,\theta) \approx E_{laser}\frac{1-\beta\cos\Phi}{1-\beta\cos\theta}$$

- Head-on collision:

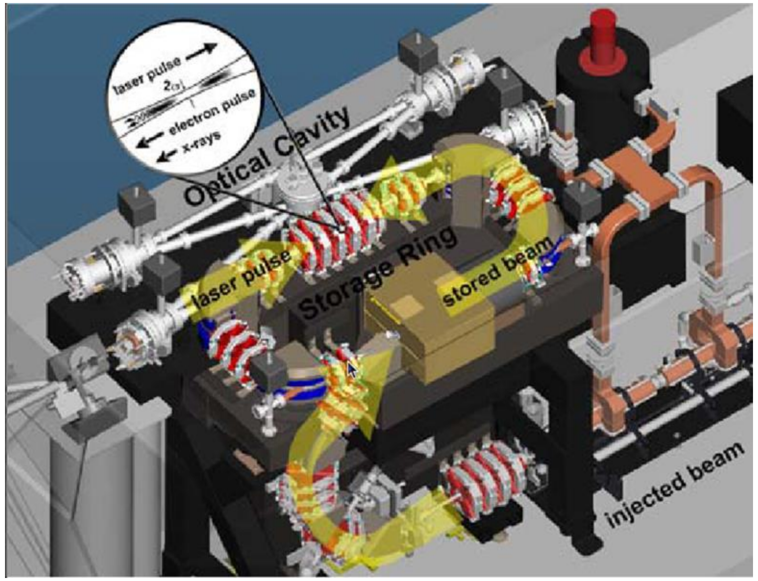
$$E_\gamma(\pi,0) = 4\gamma^2 E_{\text{laser}}$$

Compton Light Source (CLS)

- An electron beam is accelerated before colliding with an incident laser
- Electron beam can be accelerated by either linac (left) or storage ring (right)

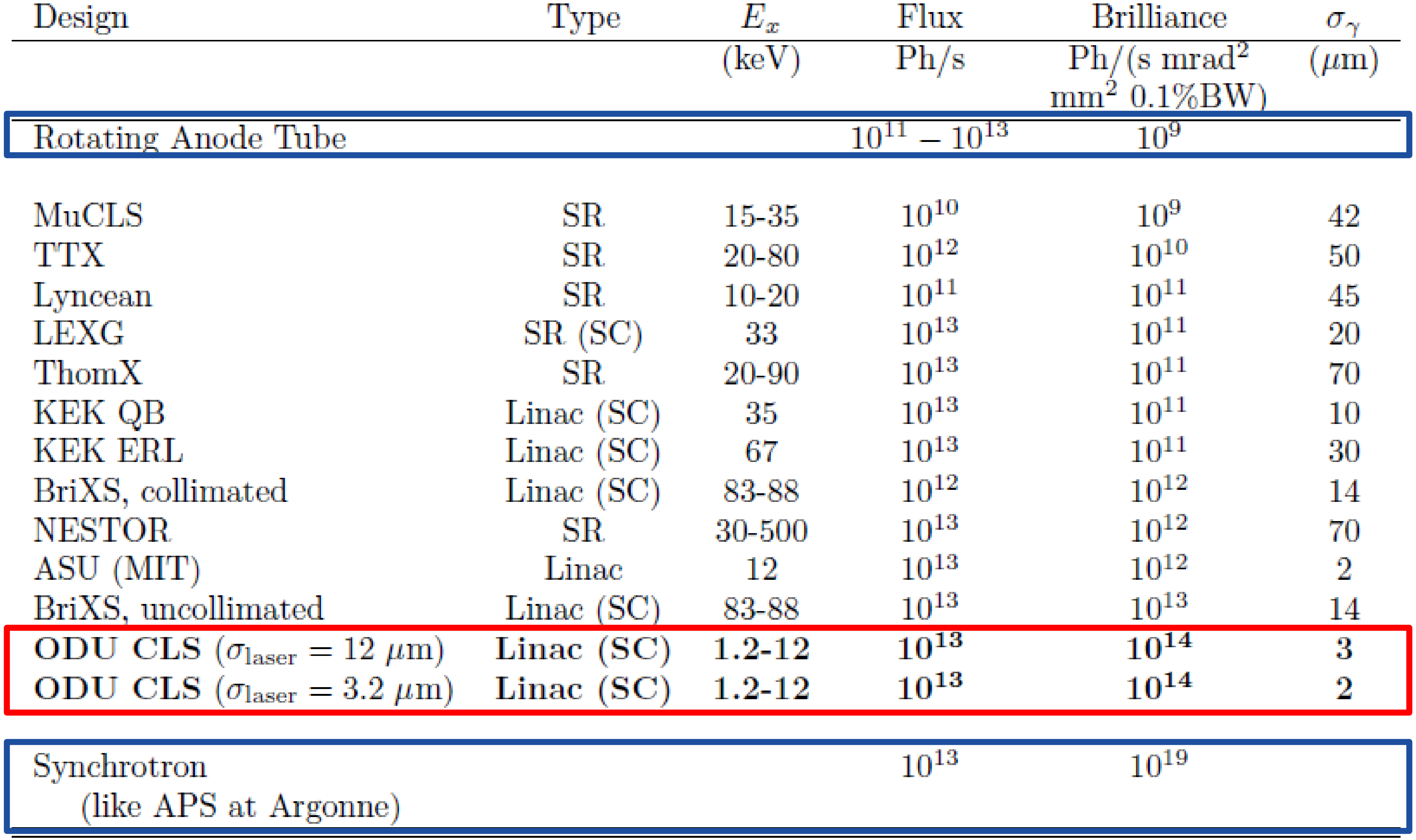


ODU CLS concept [2]



Lyncean Technologies Source, Fig. 4 from [3]

Compton Light Source (CLS)



Design	Type	E_x (keV)	Flux Ph/s	Brilliance Ph/(s mrad^2 mm^2 0.1%BW)	σ_γ (μm)
Rotating Anode Tube			$10^{11} - 10^{13}$	10^9	
MuCLS	SR	15-35	10^{10}	10^9	42
TTX	SR	20-80	10^{12}	10^{10}	50
Lyncean	SR	10-20	10^{11}	10^{11}	45
LEXG	SR (SC)	33	10^{13}	10^{11}	20
ThomX	SR	20-90	10^{13}	10^{11}	70
KEK QB	Linac (SC)	35	10^{13}	10^{11}	10
KEK ERL	Linac (SC)	67	10^{13}	10^{11}	30
BriXS, collimated	Linac (SC)	83-88	10^{12}	10^{12}	14
NESTOR	SR	30-500	10^{13}	10^{12}	70
ASU (MIT)	Linac	12	10^{13}	10^{12}	2
BriXS, uncollimated	Linac (SC)	83-88	10^{13}	10^{13}	14
ODU CLS ($\sigma_{\text{laser}} = 12$ μm)	**Linac (SC)**	**1.2-12**	$\mathbf{10^{13}}$	$\mathbf{10^{14}}$	**3**
ODU CLS ($\sigma_{\text{laser}} = 3.2$ μm)	**Linac (SC)**	**1.2-12**	$\mathbf{10^{13}}$	$\mathbf{10^{14}}$	**2**
Synchrotron (like APS at Argonne)			10^{13}	10^{19}	

Selected data from Table IV of [2]

Table compares X-ray parameters of different compact CLS designs, a typical rotating anode tube, and a synchrotron (APS).

High Performance CLS

- Increasing bunch charge, repetition rate, laser power
  Decreasing spot size (electron and laser beams)
  → Higher average flux

- Increasing electron energy
  Decreasing normalized transverse emittance
  → Higher average brilliance

- Small electron energy spread
  → Monochromatic (narrow bandwidth) x-rays

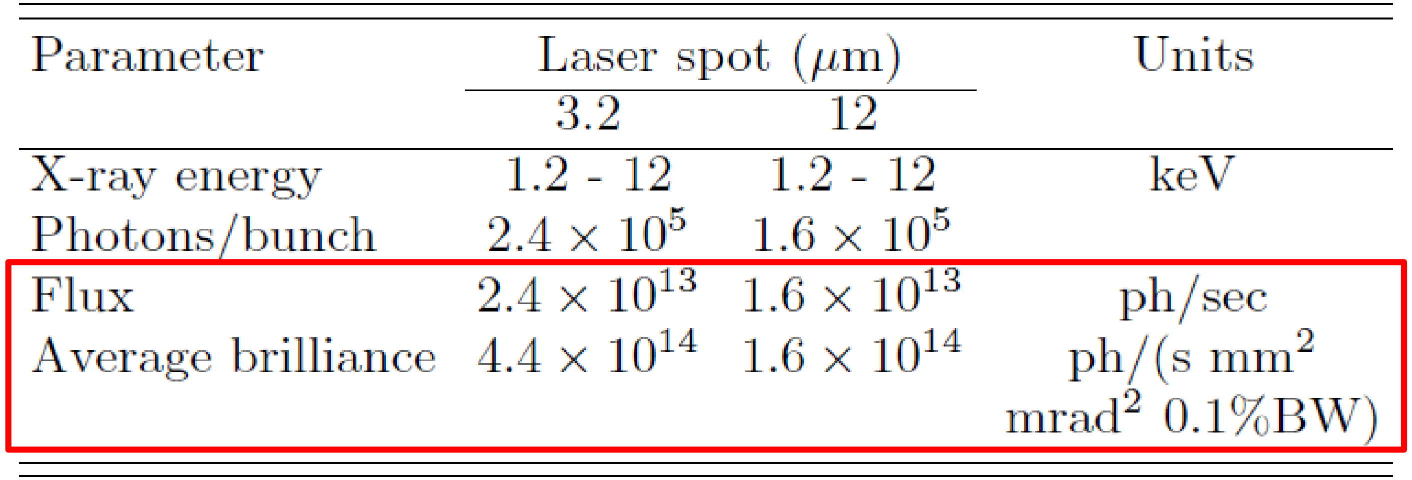
Concept Goals and Constraints

- Compact, reasonable cost to build and operate
  - 25 MeV electron beam → 12 keV x-rays

- High average flux
  - High repetition rate → Continuous wave (cw)
  - SRF at 4 K (lower capital cost and easier operation)
    - Low frequency (500 MHz)
    - Spoke cavities instead of TM_{010} (elliptical)

- High average brilliance
  - Low emittance → Linac, low bunch charge

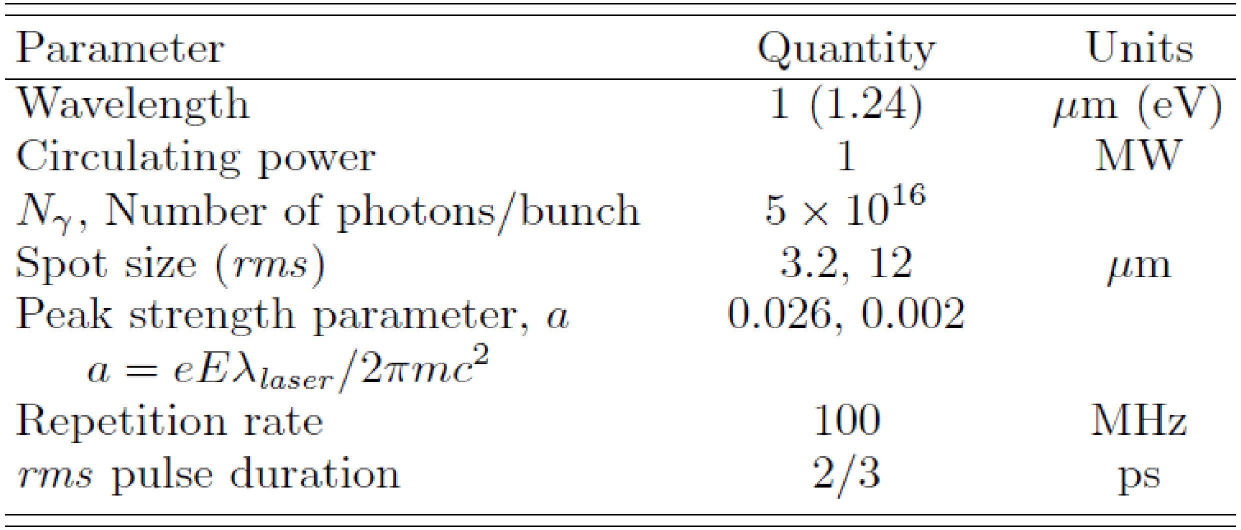
Design Goals for ODU CLS



Parameter	Laser spot (μm)		Units
	3.2	12	
X-ray energy	1.2 - 12	1.2 - 12	keV
Photons/bunch	2.4×10^5	1.6×10^5	
Flux	2.4×10^{13}	1.6×10^{13}	ph/sec
Average brilliance	4.4×10^{14}	1.6×10^{14}	ph/(s mm^2 mrad^2 0.1%BW)

Top: Desired X-ray source parameters, reported for top energy

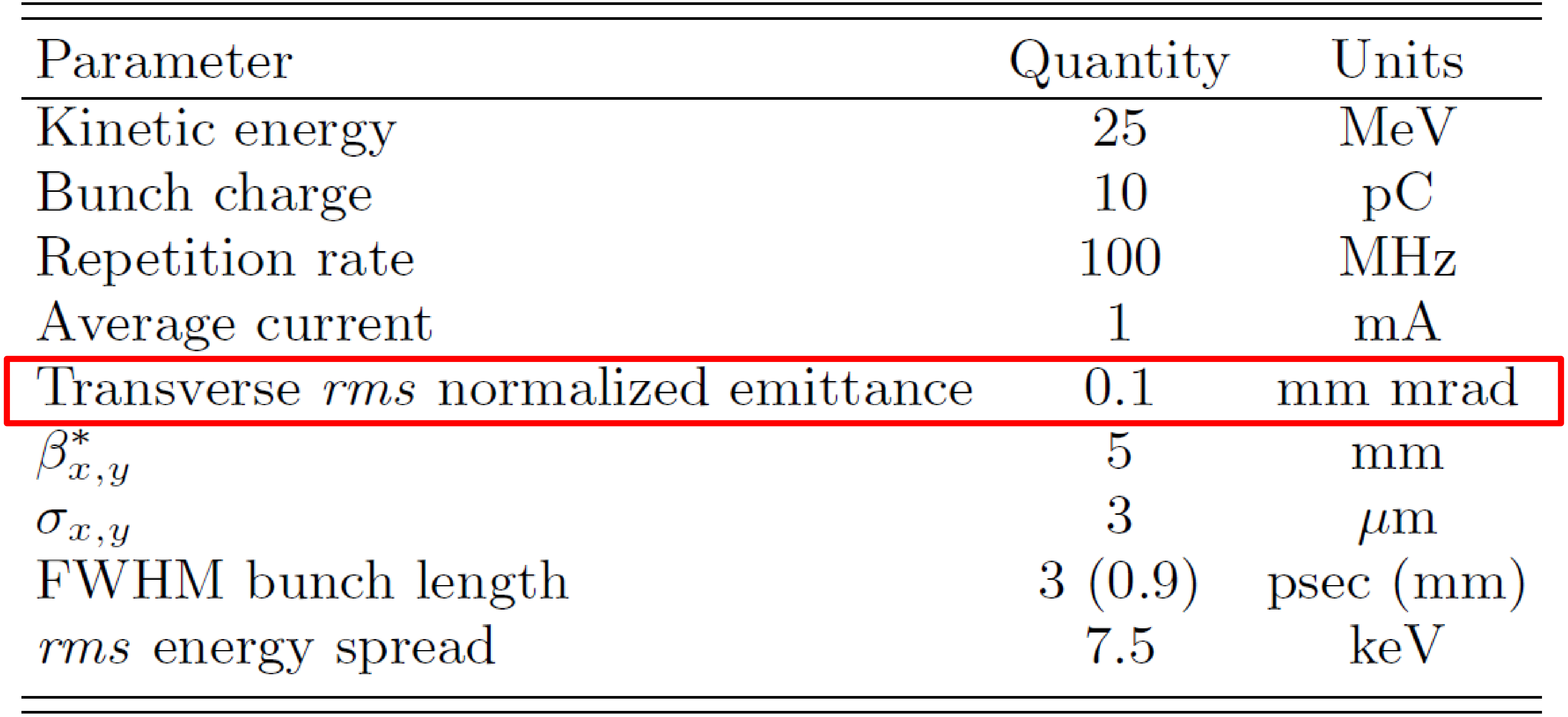
Bottom: Desired scattering laser parameters at interaction point



Parameter	Quantity	Units
Wavelength	1 (1.24)	μm (eV)
Circulating power	1	MW
N_γ, Number of photons/bunch	5×10^{16}	
Spot size (rms)	3.2, 12	μm
Peak strength parameter, a $a = eE\lambda_{laser}/2\pi mc^2$	0.026, 0.002	
Repetition rate	100	MHz
rms pulse duration	2/3	ps

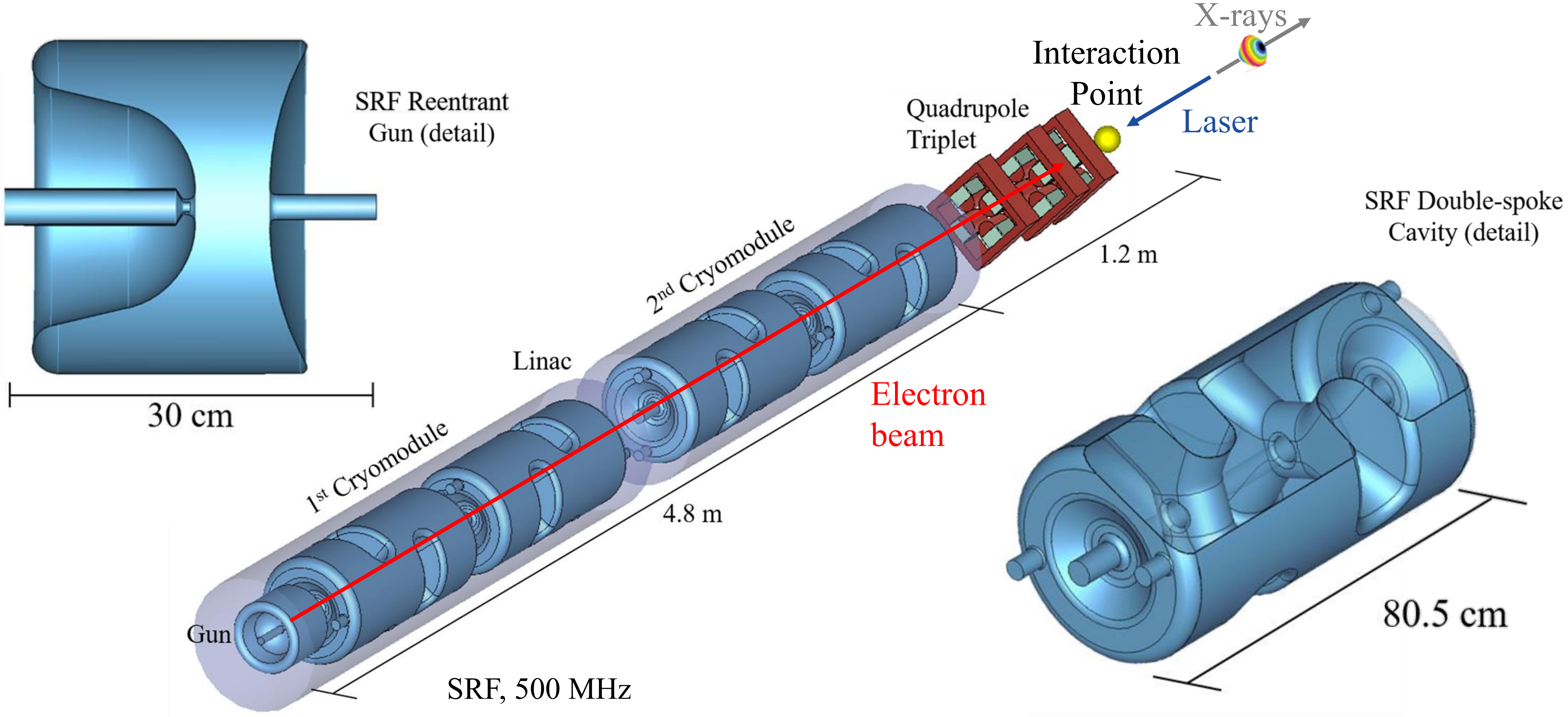
Design Goals for ODU CLS

Desired electron beam parameters at interaction point (IP)



Parameter	Quantity	Units
Kinetic energy	25	MeV
Bunch charge	10	pC
Repetition rate	100	MHz
Average current	1	mA
Transverse *rms* normalized emittance	0.1	mm mrad
$\beta^*_{x,y}$	5	mm
$\sigma_{x,y}$	3	μm
FWHM bunch length	3 (0.9)	psec (mm)
rms energy spread	7.5	keV

Machine Layout



Beam Dynamics

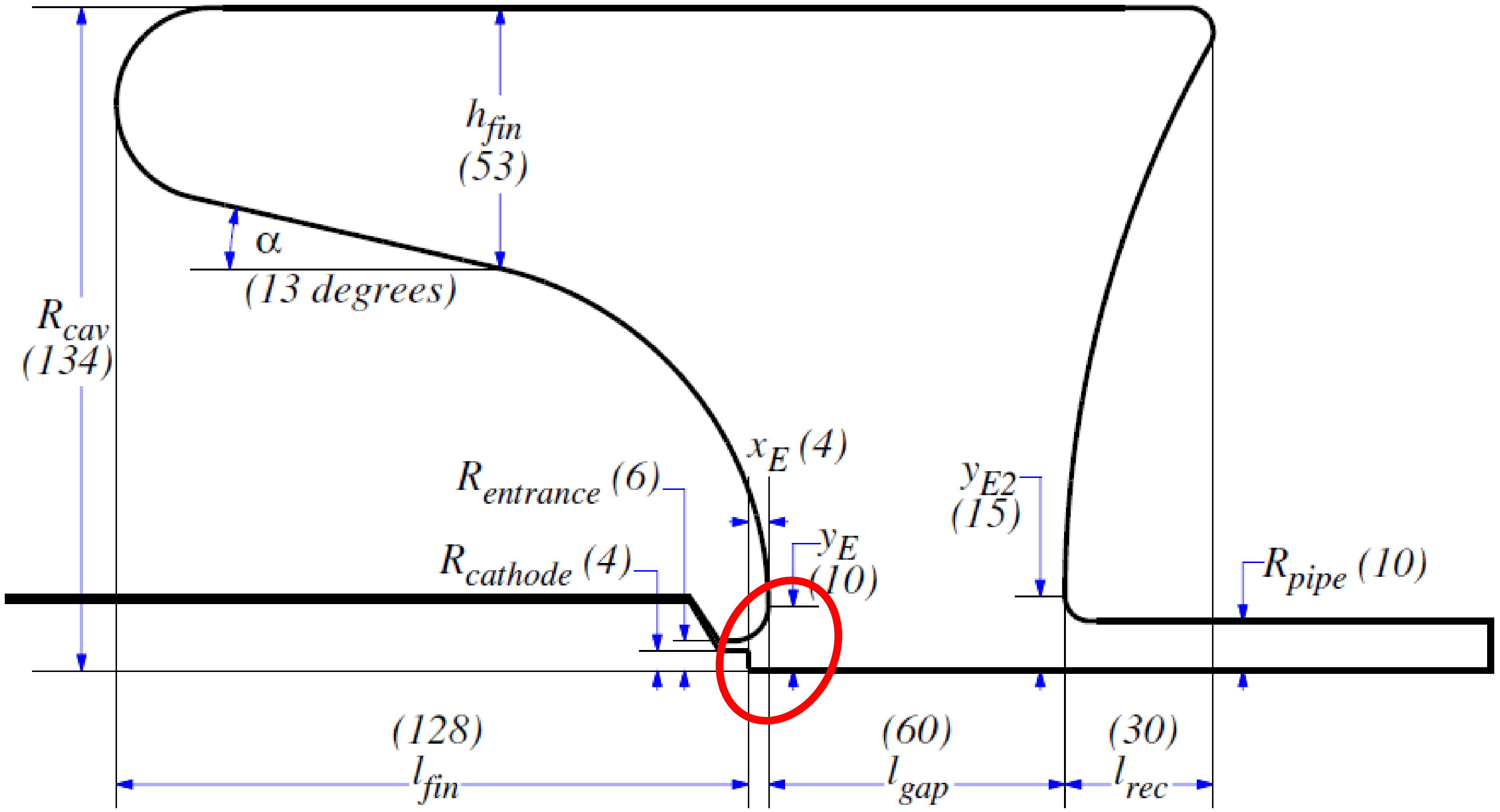
- Emittance compensation is the manipulation of a beam’s transverse phase space, typically by a solenoid, to decrease the projected *rms* transverse emittance

- In our concept, emittance compensation is achieved by providing rf focusing – altering the geometry of the reentrant gun to produce the necessary fields

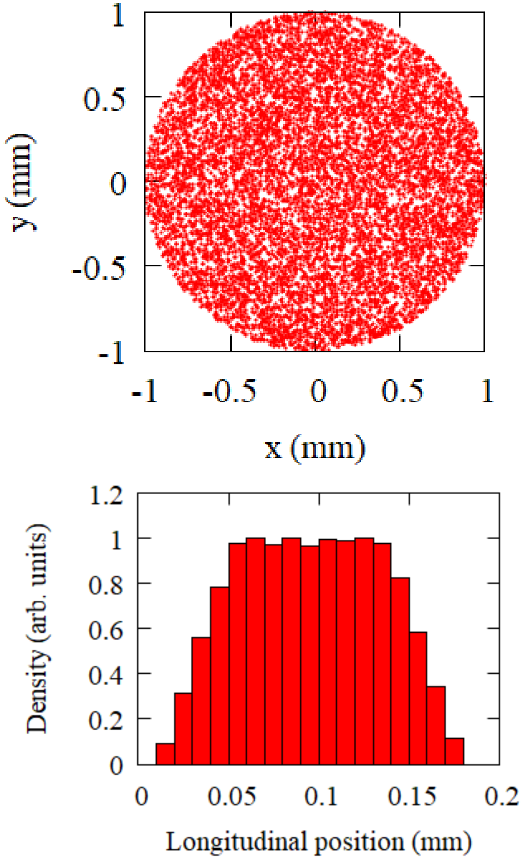
- Emittance compensation is achieved without a solenoid, unlike most systems

Beam Dynamics

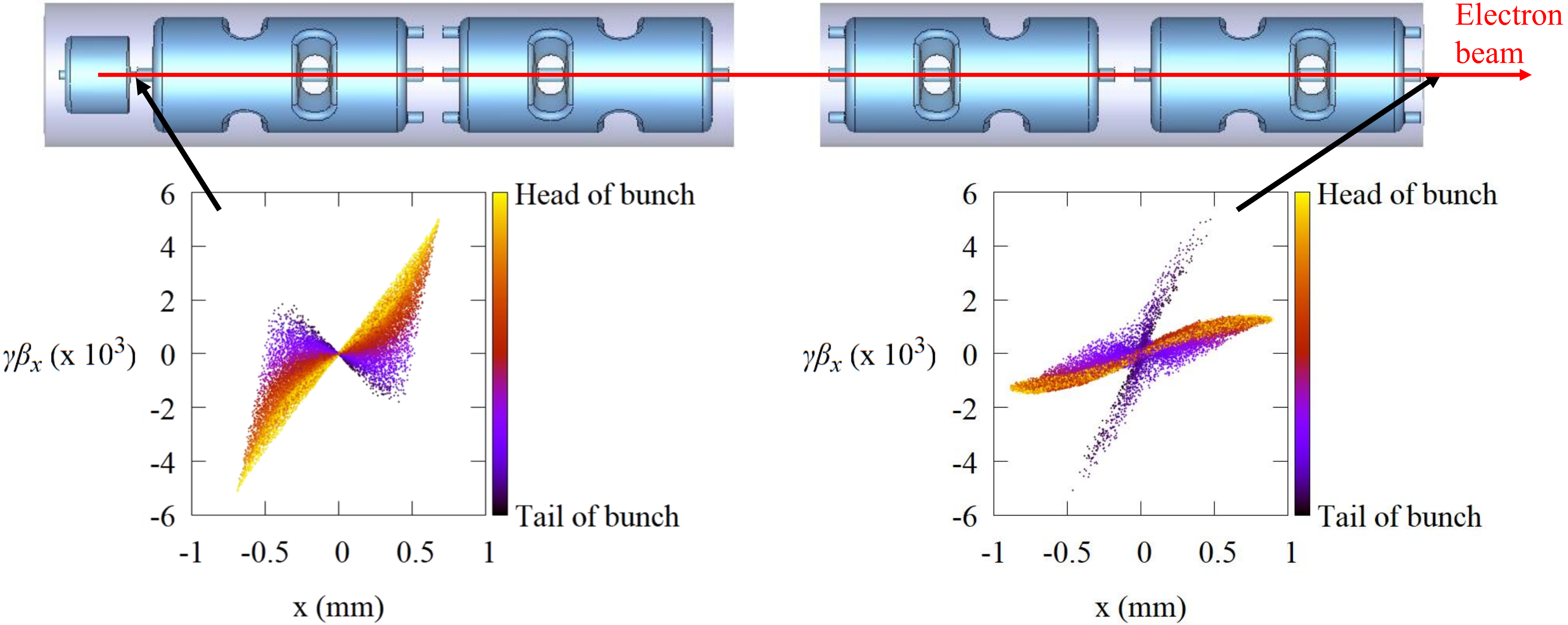
- Parameters used to generate geometry and optimize beam dynamics



Initial Distribution



Beam Dynamics



Normalized transverse phase spaces exiting the gun (left) and the linac (right), with the longitudinal position of the macroparticle within the bunch indicated by color. The emittance slices along the bunch length rotate to align better, for a decrease in projected normalized emittance.

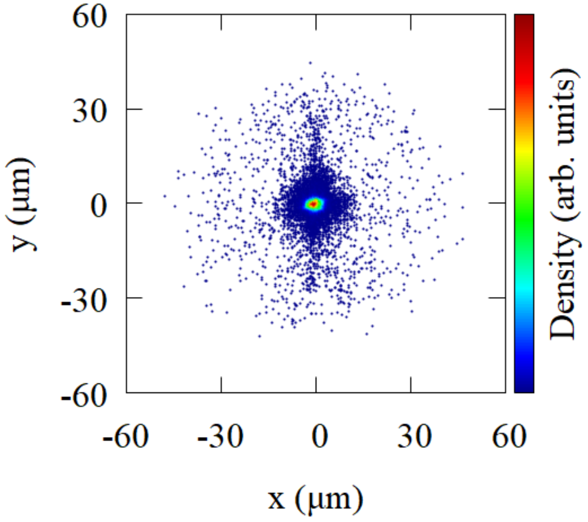
Critical Factors to Performance

- Extremely low emittance
  - Minimize separation between gun and first linac cavity
  - Must be in same cryomodule

- Low energy spread, correct bunch length
  - Choose correct bunch length from the cathode
  - Change initial spot size and rf focusing to achieve extremely low emittance

- Relatively round beam at linac exit
  - Change orientation of center two spoke cavities to compensate for “quadrupole-like” focusing effect

Interaction Point Parameters



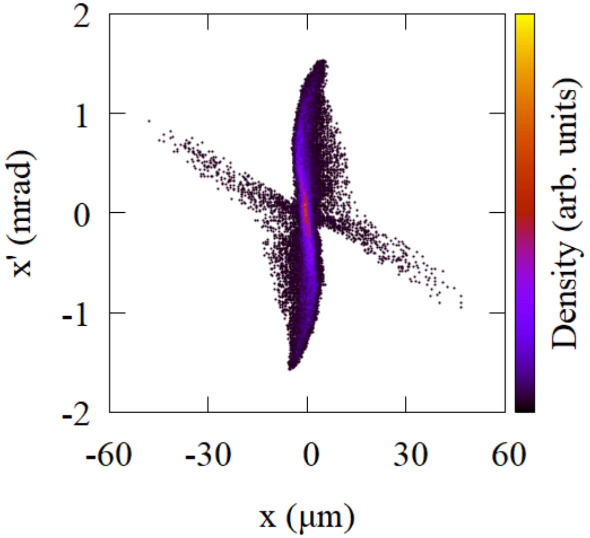
Top left: Beam spot at IP

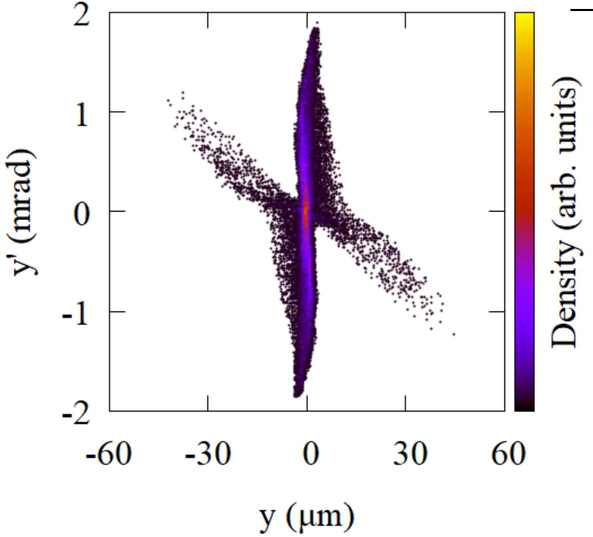
Bottom left: Horizontal phase space at IP

Bottom right: Vertical phase space at IP

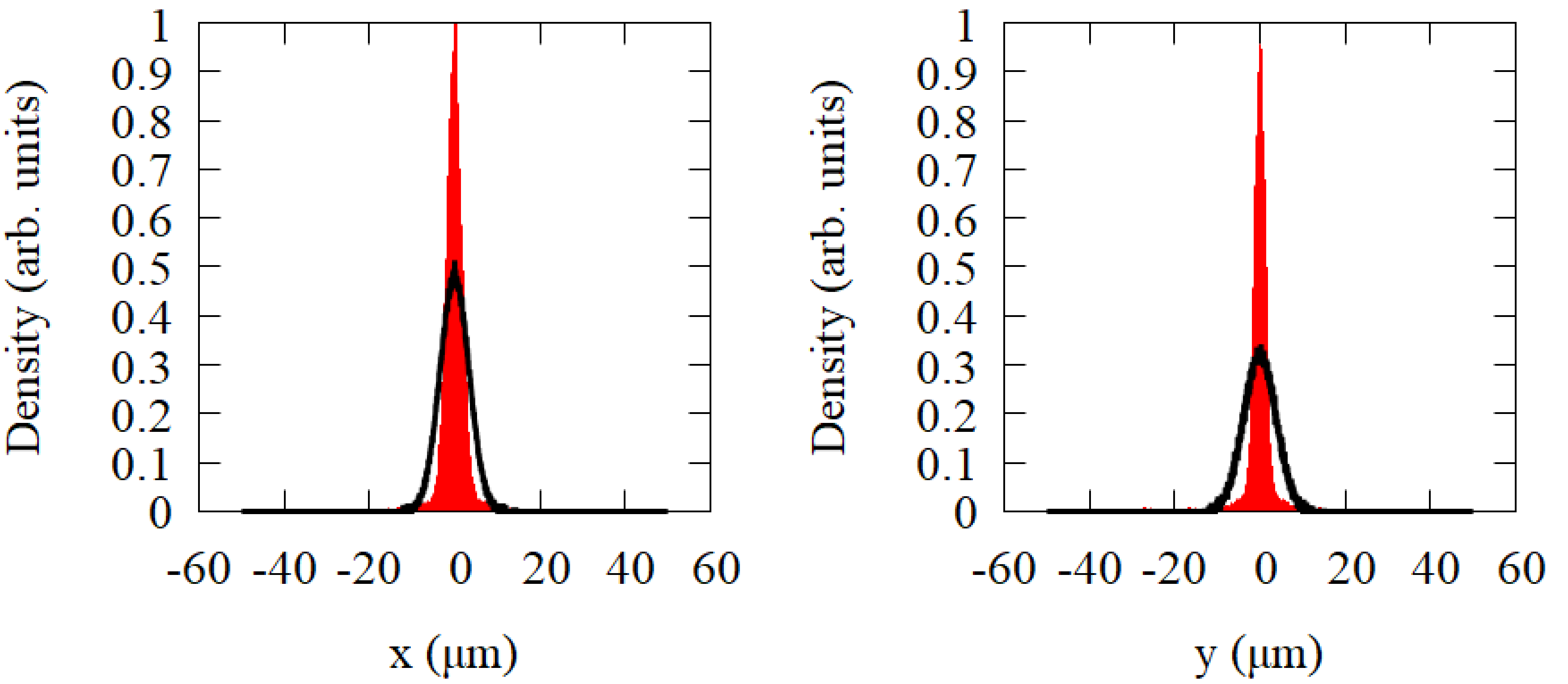
Parameter	Desired	Achieved	Units
β_x	5	5.4	mm
β_y	5	5.4	mm
$\epsilon^N_{rms,x}$	0.1	0.1	mm-mrad
$\epsilon^N_{rms,y}$	0.1	0.13	mm-mrad
σ_x	3.2	3.4	μm
σ_y	3.2	3.8	μm
$>$ 76% longitudinal distribution	3	3	ps
rms energy spread	7.5	3.4	keV

Beam parameters achieved at IP, compared to desired parameters



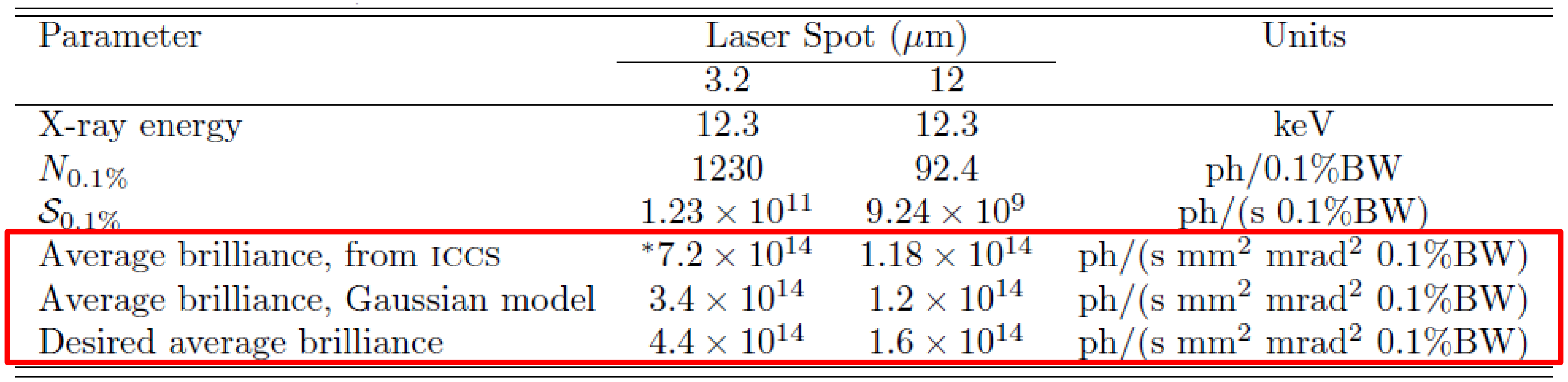


Interaction Point Parameters



The horizontal (left) and vertical (right) distribution of the simulated beam (red) at the IP and a Gaussian distribution with the same *rms* values

X-Ray Performance

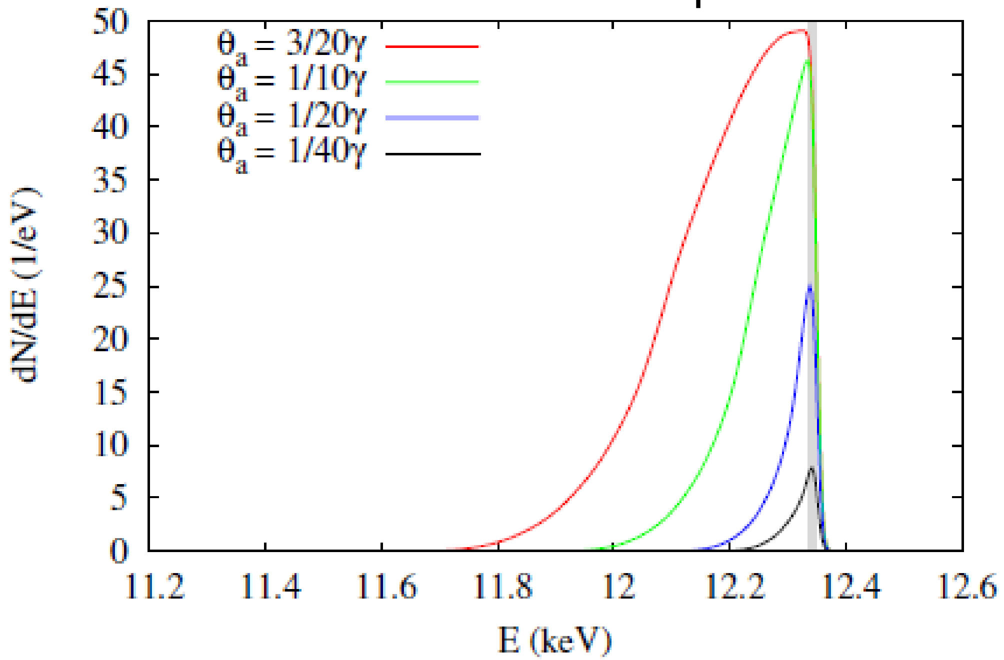


Parameter	Laser Spot (μm)		Units
	3.2	12	
X-ray energy	12.3	12.3	keV
$N_{0.1\%}$	1230	92.4	ph/0.1%BW
$\mathcal{S}_{0.1\%}$	1.23×10^{11}	9.24×10^{9}	ph/(s 0.1%BW)
Average brilliance, from ICCS	$^{*}7.2 \times 10^{14}$	1.18×10^{14}	ph/(s mm^2 mrad^2 0.1%BW)
Average brilliance, Gaussian model	3.4×10^{14}	1.2×10^{14}	ph/(s mm^2 mrad^2 0.1%BW)
Desired average brilliance	4.4×10^{14}	1.6×10^{14}	ph/(s mm^2 mrad^2 0.1%BW)

*The discrepancy originates from the assumption ICCS makes – that every electron sees the same scattering potential. While valid for laser spots much larger than the electron beam size, it loses validity and leads to overestimation as the sizes become comparable.

Top: X-ray parameters calculated by Improved Codes for Compton Simulation (ICCS) and formula from Gaussian beam model [3]

Bottom: Number spectra calculated for different apertures of 12 μm laser spot



Next Steps to a Full Design

- Reentrant Gun
  - Design for integrating cathode and SRF gun, re-optimize beam dynamics
- Linac
  - Integrate drive laser within first cryomodule to pass through first cavity
- SRF
  - Reduce surface resistance (~200 W for linac to ~100 W)
    - Recent developments and ongoing research may justify revisiting frequency choice and cavity geometry
- Final Focusing
  - Define necessary diagnostics for interaction point

Next Steps to a Full Design

- Drive Laser
  - Determine stability/sensitivity parameters
  - Investigate sensitivity of performance (emittance at IP) to photon distribution and potential compensation efforts
- Scattering Laser
  - Increase rep rate and power from 78 MHz, 287 W* or 70 Hz, 100 kW† to 100 MHz, 1 MW
  - Demonstrate 3 micron spot size
  - Develop non-diffracting beam (Airy, Bessel) with these properties

* K-H. Hong *et al.*, Generation of 287 W, 5.5 ps pulses at 78 MHz repetition rate from a cryogenically cooled Yb:YAG amplifier seeded by a fiber chirped-pulse amplification system, Optics Letters, Vol. 33, Issue 21, pp. 2473-2475 (2008).

† F. Della Valle *et al.*, Extremely long decay time optical cavity, Optics Express, Vol. 22, Issue 10, pp. 11570-11577 (2014).

Conclusion

- The concept presented is the highest average brilliance x-ray beam currently proposed by any compact Compton source
- While current parameters are for 12 keV x-rays, additional cryomodules in the linac can increase the x-ray energy, increasing the potential applications
- This performance is achieved through
  - A superconducting drive linac operating cw at 4 K
  - Low emittance and small spot size at the interaction point
    - Made possible by a small bunch charge and emittance compensation due to rf focusing by the gun (instead of a solenoid)

deitrick@jlab.org; kdeit001@odu.edu

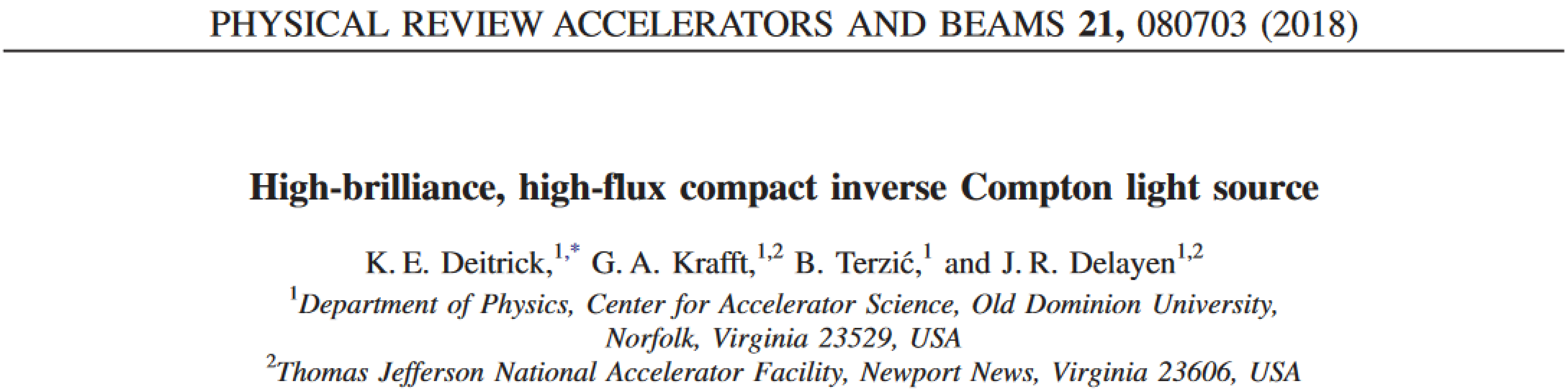
Acknowledgements

- Jean Delayen and Geoffrey Krafft
  - for serving as advisors for my Ph.D.
- Randika Gamage and Todd Satogata
  - for initial work on the magnetic bunch compressor
- Karim Hernández-Chahín and Rocio Olave
  - for initial work on the gun geometry
- Christopher Hopper
  - for designing the double-spoke cavities
- Erik Johnson, Nalin Ranjan, and Balša Terzić
  - for ICCS and its precursor
- LINAC’18 for conference support

References

- More details can be found in recently published Phys. Rev. Accel. & Beams article

https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.21.080703



PHYSICAL REVIEW ACCELERATORS AND BEAMS **21,** 080703 (2018)

High-brilliance, high-flux compact inverse Compton light source

K. E. Deitrick,[1,*] G. A. Krafft,[1,2] B. Terzić,[1] and J. R. Delayen[1,2]

[1]*Department of Physics, Center for Accelerator Science, Old Dominion University, Norfolk, Virginia 23529, USA*

[2]*Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA*

Thanks for your attention!

deitrick@jlab.org
kdeit001@odu.edu

References

1. K. Deitrick, Inverse Compton light source: A compact design proposal, Ph.D. thesis, Old Dominion University, 2017.
2. K. E. Deitrick, G. A. Krafft, B. Terzić, and J. R. Delayen, High-brilliance, high-flux compact inverse Compton light source, Phys. Rev. Accel. Beams **21**, 080703 (2018).
3. G. A. Krafft and G. Priebe, Compton sources of electromagnetic radiation, Reviews of Accelerator Science and Technology **03**, 147 (2010).
4. N. Ranjan, B. Terzić, G. A. Krafft, V. Petrillo, I. Drebot, and L. Serafini, Simulation of inverse Compton scattering and its implications on the scattered linewidth, Phys. Rev. Accel. Beams **21**, 030701 (2018).