Istituto Nazionale di Fisica Nucleare
Sezione di Milano

NELSON MANDELA UNIVERSITY

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George, South Africa.

X-Ray and Terahertz Source Based on Energy Recovery Linac.

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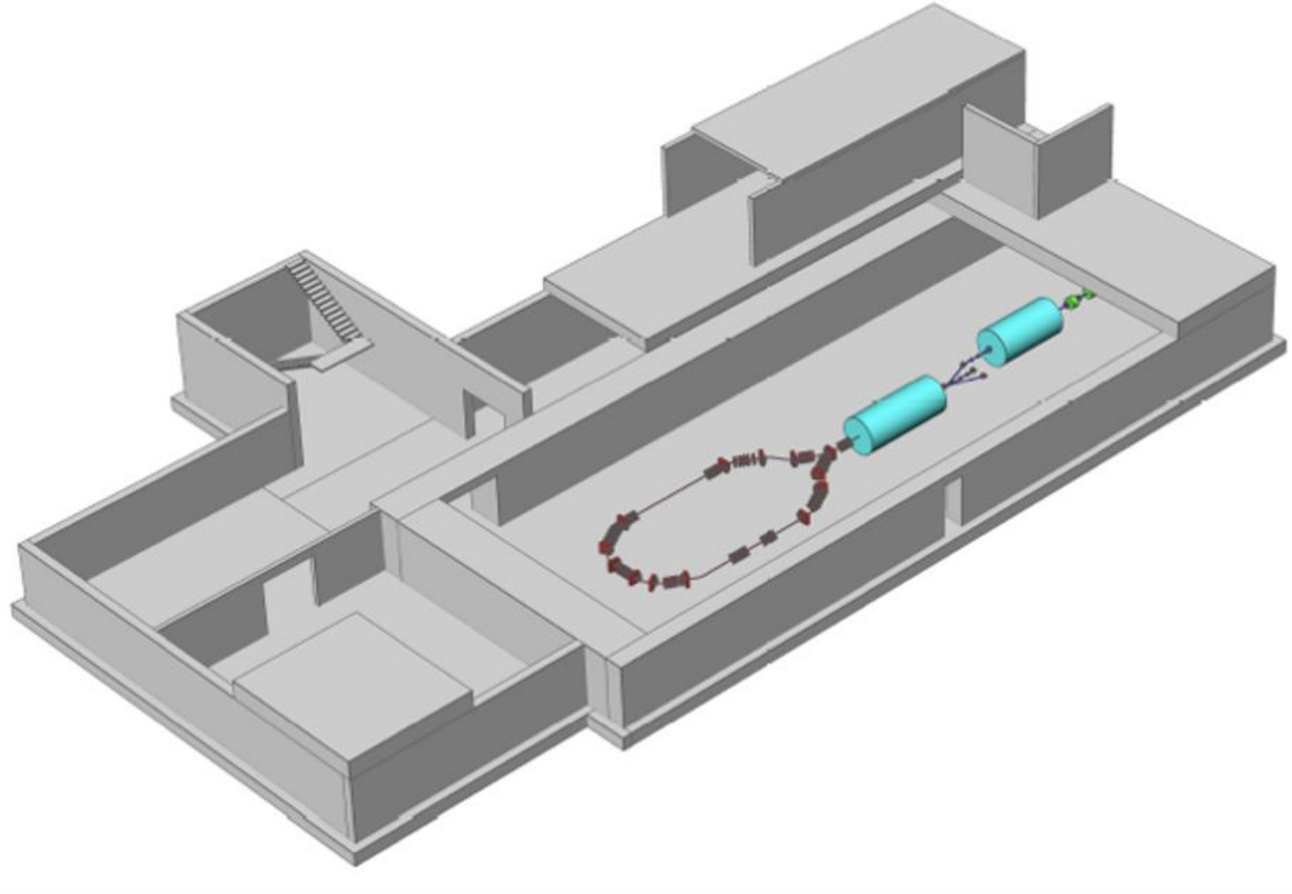
INFN-Milan/LASA

BriXSinO

BriXSinO

***Bri**lliant source of **X**-rays based on **S**ustainable and **in**n**O**vative accelerators*



LASA aerial view and rendering of the building

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UNIVERSITÀ DEGLI STUDI DI MILANO

BriXSinO

BriXSinO

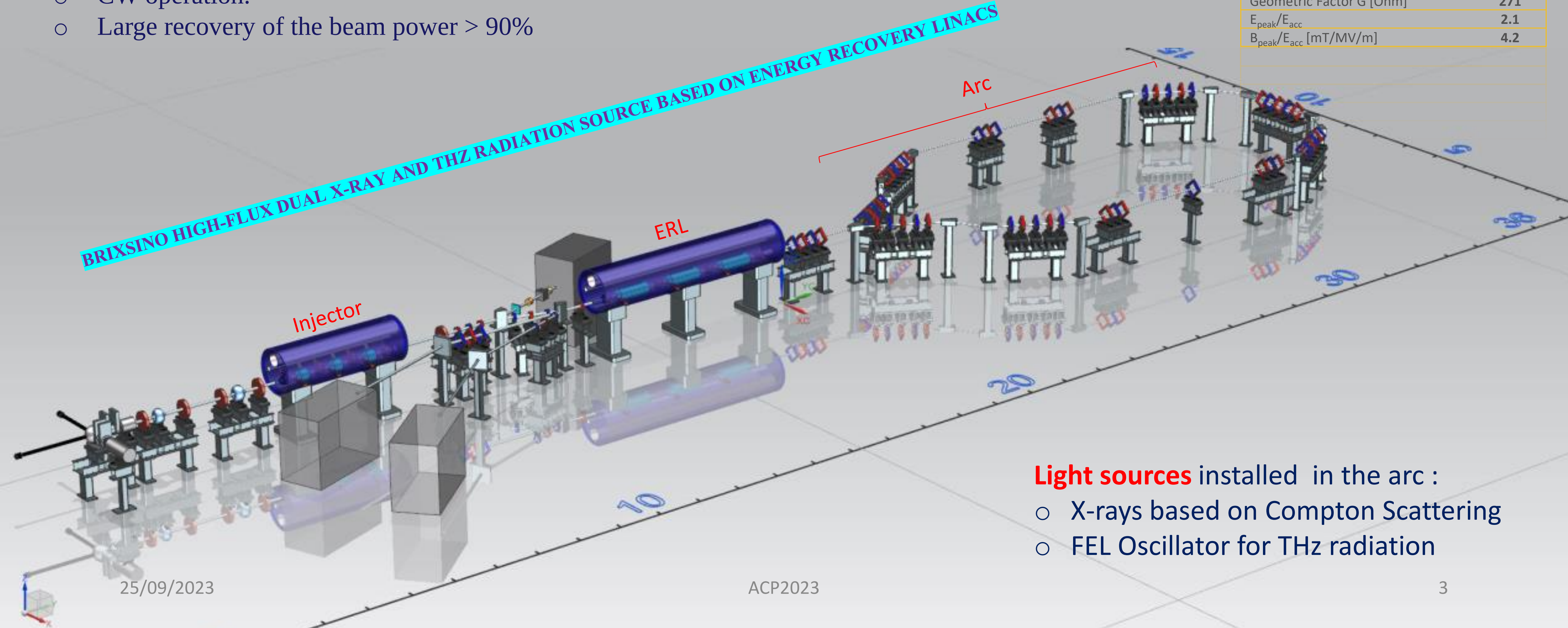
Brilliant source of X-rays based on Sustainable and innOvative accelerators

Un acceleratore di elettroni innovativo verso la frontiera dell'alta intensità sostenibile, per i futuri acceleratori di particelle di larga scala, e per applicazioni avanzate con raggi X mono-cromatici e radiazione THz coerente

BriXSinO

Parameter	Value
Type Of Accelerating Structure	SW
Accelerating Mode	TM_{010} π-mode
Fundamental Frequency [MHz]	1300
Design Gradient [MV/m]	16.5
Intrinsic Quality Factor Q_0	$2X10^{10}$
Loaded Quality Factor Q_{EXT}	$3.25X10^{7}$
Active Length [m]	0.81
Cell to cell coupling [%]	2.2
R/Q [Ohm]	774
Geometric Factor G [Ohm]	271
E_{peak}/E_{acc}	2.1
B_{peak}/E_{acc} [mT/MV/m]	4.2

- 5 mA of average current.
- 100 MHz repetition rate.
- CW operation.
- Large recovery of the beam power > 90%

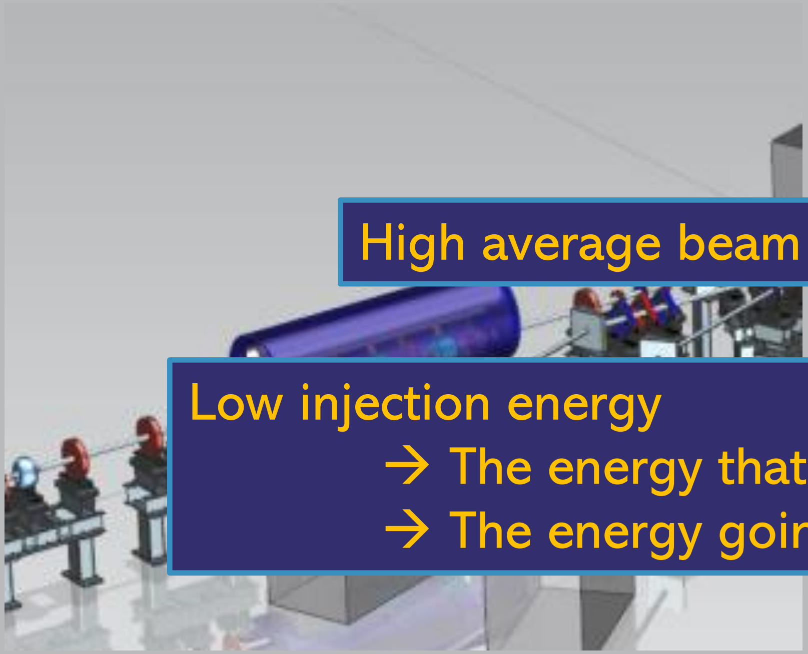


Light sources installed in the arc :

- X-rays based on Compton Scattering
- FEL Oscillator for THz radiation

The Injector Superconducting Booster - ISB

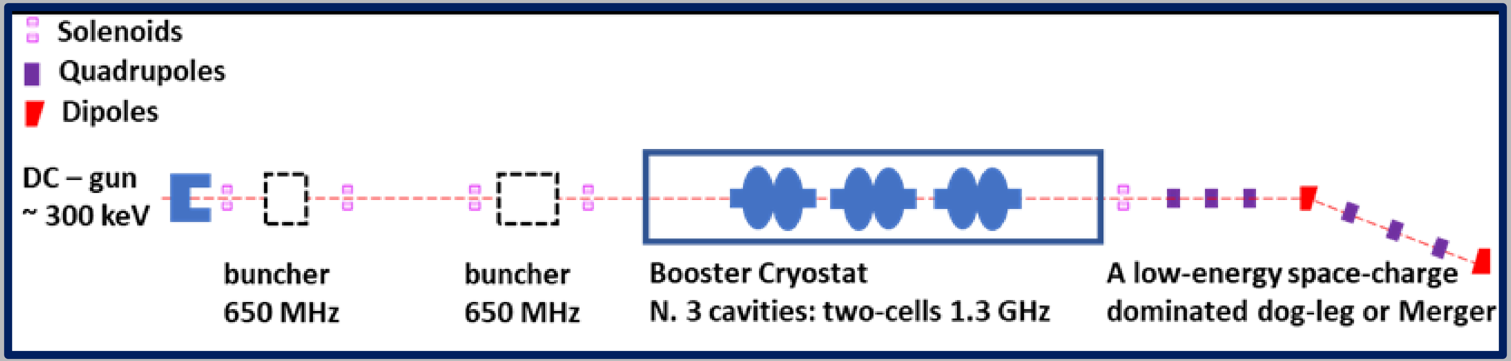
An ERL injector (merger) has 3 major objectives:



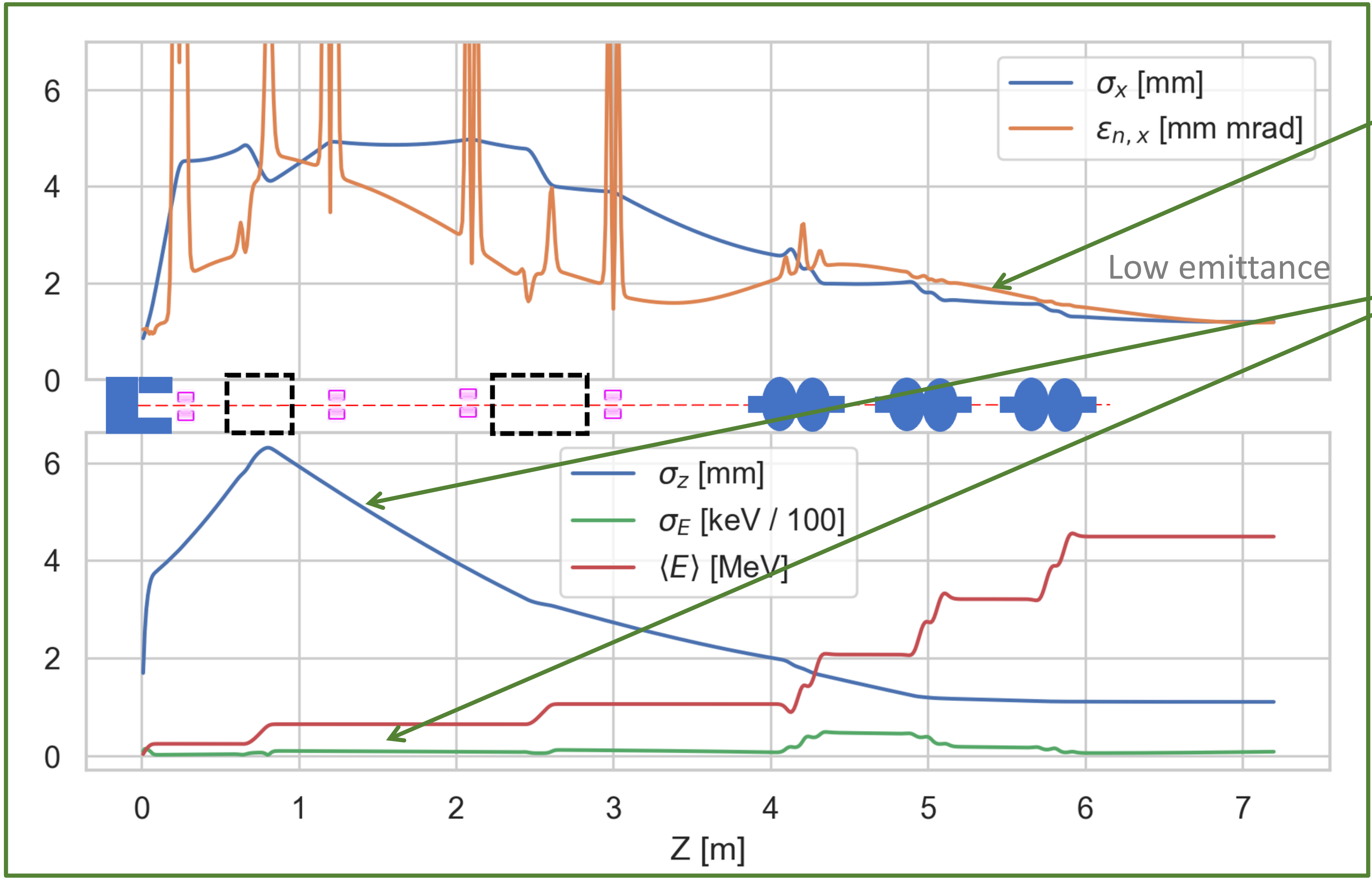
High brightness

High average beam current

Low injection energy
→ The energy that will never be recovered
→ The energy going into the dumper



BD of the Injector



Space-charge regime : emit-oscillation tuned for a good compensation

The two bunchers perform both compression & acc.

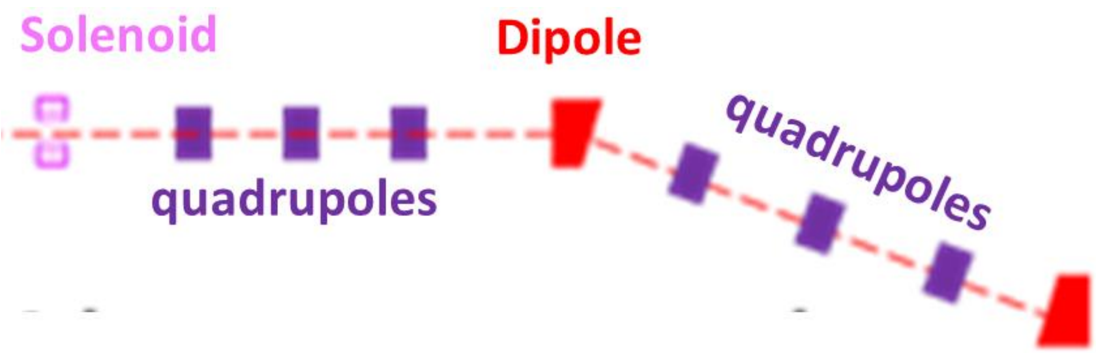
BD @ injector exit:

- 1 mm envelope size
- 1 mm σ_z size
- 1 µm x, y norm. emit
- A very low energy spread

→ Ready to go into the disp. path

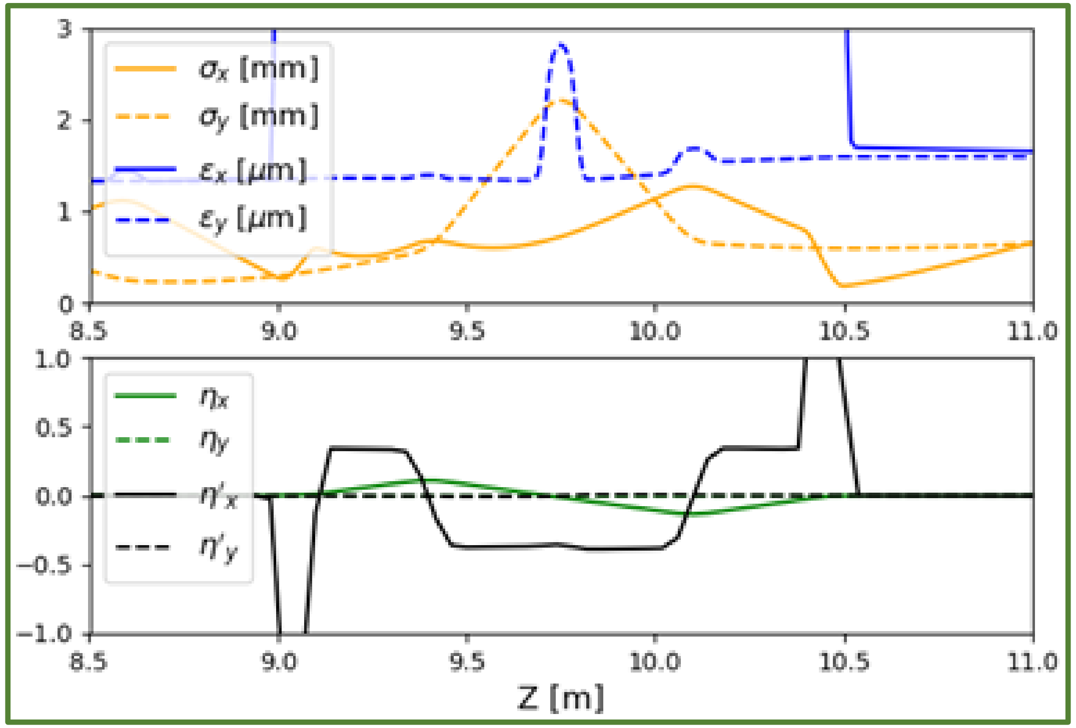
Courtesy to A. Bacci

Low Energy Dogleg of the Injector



BD @ the dispersive path exit:

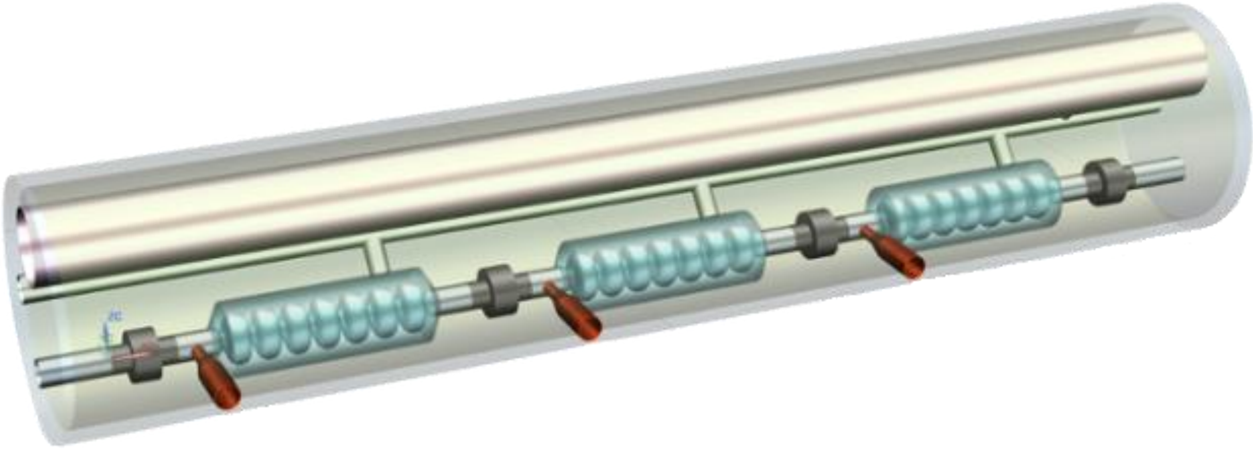
- The emittance is conserved
- η & η' are reset to zero



Closing dispersion

It is a standard dogleg but the BD is complex due to the space charge. Extensive use of the Genetic Algorithm GIOTTO [IPAC 2016 WEPOY039] was required to solve the BD.

The ERL Superconducting Module



3 coupled SC accelerator cavities

Two main working modes:

As ERL for light source at electrons energy ~ 50 MeV
And double acceleration ~ 100 MeV

- Three 7-cells SC cavities
    - **Zero nominal beam loading**
    - **High Q** to minimize cryogenic load

ERL: BD Simulation

The theory of HOMEN model

***H**igh **O**rder **M**ode **E**volution based on **En**ergy badget*

Based on the concept of Energy Budget

The Stored Energy variation:

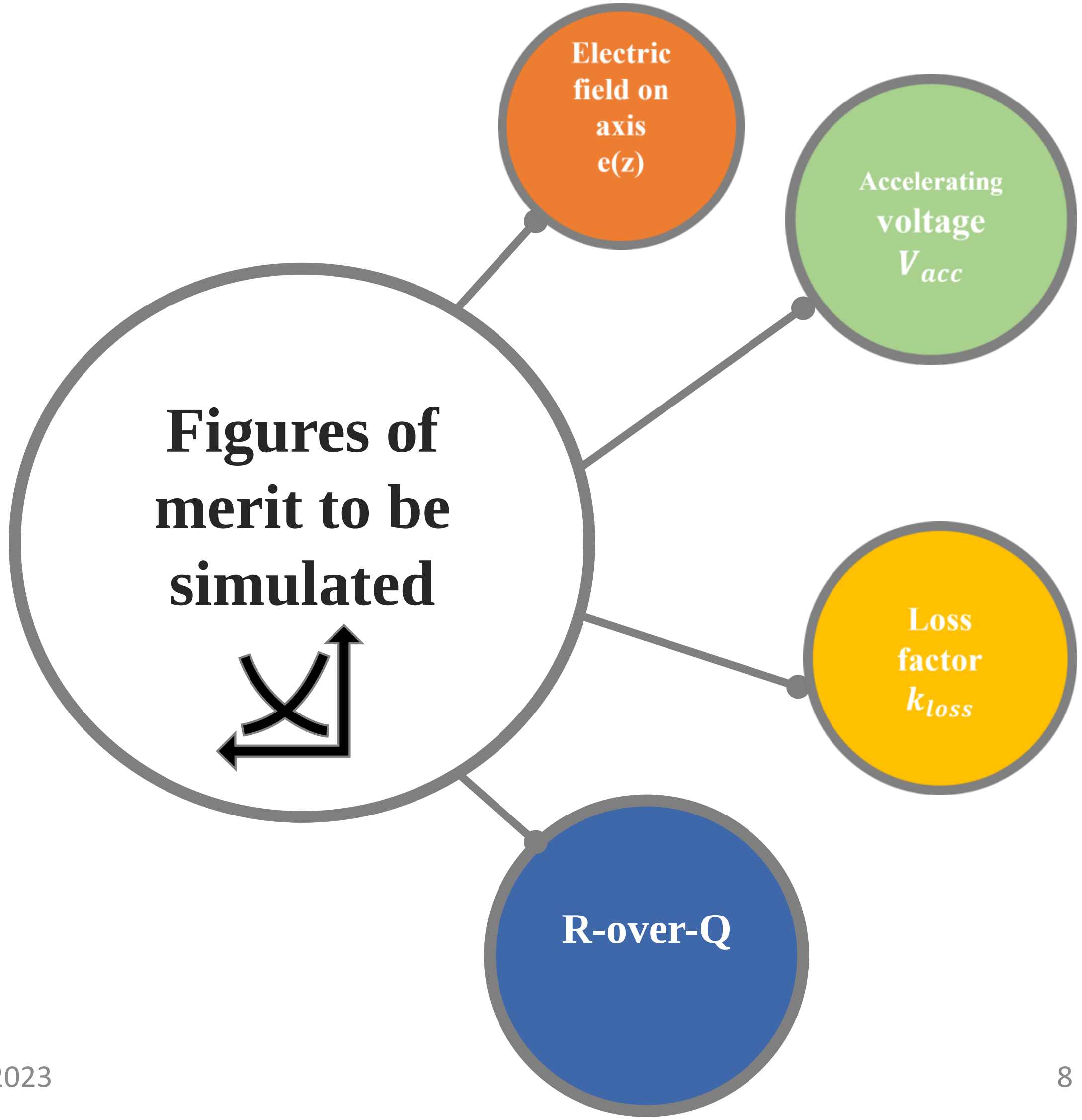
$$\frac{dU_n}{dt} = -\frac{\omega_n U_n}{Q_{L,n}} + \delta_{1,n}\left|P_{\mathrm{kly}}\right| \pm \frac{q_i V_{acc_{n,i}}}{\tau_{cav}} + \frac{q_i^2 k_{loss,n}}{\tau_{cav}}$$

Mode Oscillation amplitude based on SVEA approximation:

$$\frac{dA_n}{dt} = \frac{A_n}{2U_n}\frac{dU_n}{dt}$$

Energy gain of the bunch:

$$\frac{d\gamma_n}{dt} = \frac{e}{m_0 c^2 \tau_{cav}} \sum_{n=1}^{N_{RF}} V_{acc_{n,i}}$$



Accelerating Mode TM010 in 7–cell SW SC cavity

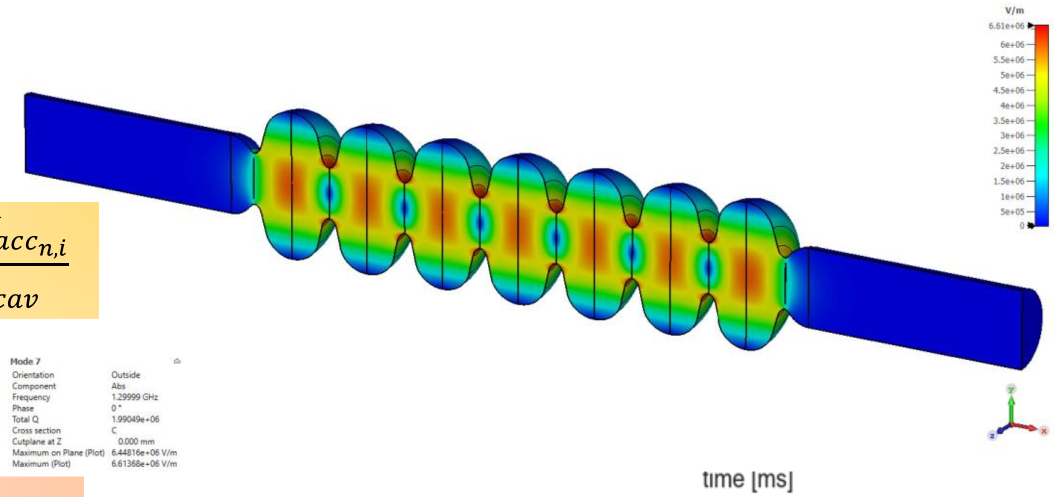
- Only acceleration direction have been considered

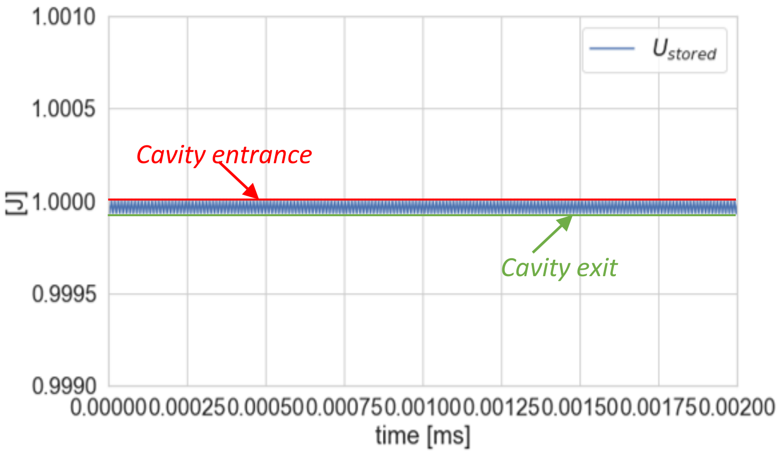
The Stored Energy variation:

$$\frac{dU_n}{dt} = -\frac{\omega_n U_n}{Q_0} + \delta_{1,n}\left|P_{\text{kly}}\right| \pm \frac{q_i V_{acc_{n,i}}}{\tau_{cav}}$$

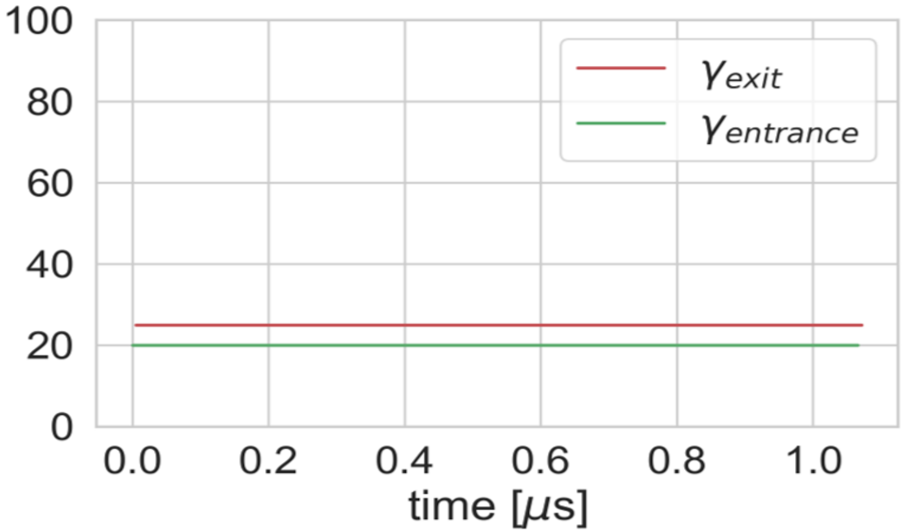
Energy gain of the bunch:

$$\frac{d\gamma_n}{dt} = \frac{e}{m_0 c^2 \tau_{cav}} \sum_{n=1}^{N_{RF}} V_{acc_{n,i}}$$



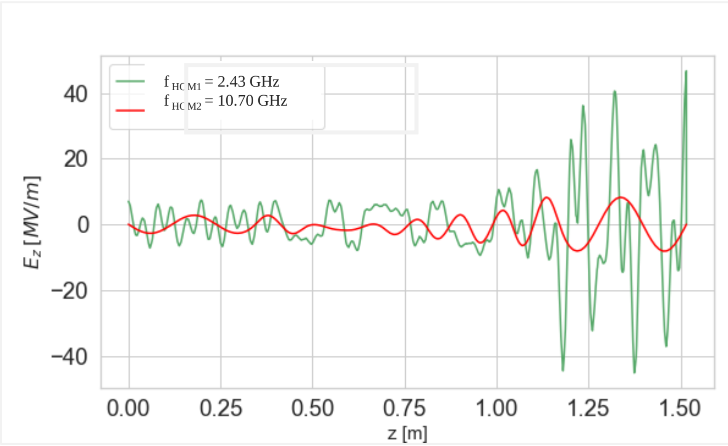


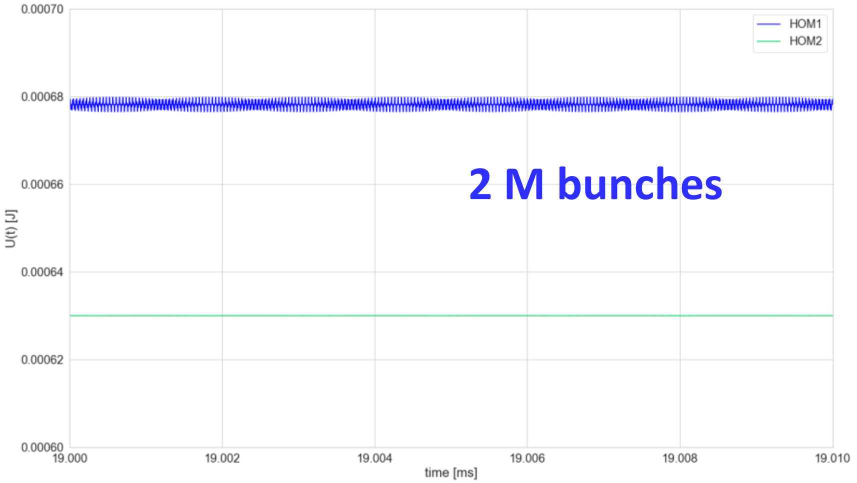
Parameters	Value
Quality factor Q_0	2.89×10^{10}
Injection energy E	10 MeV
RF frequency	1.3 GHz
Klystron Power	12.6 kW
Reptition rate	100 MHz

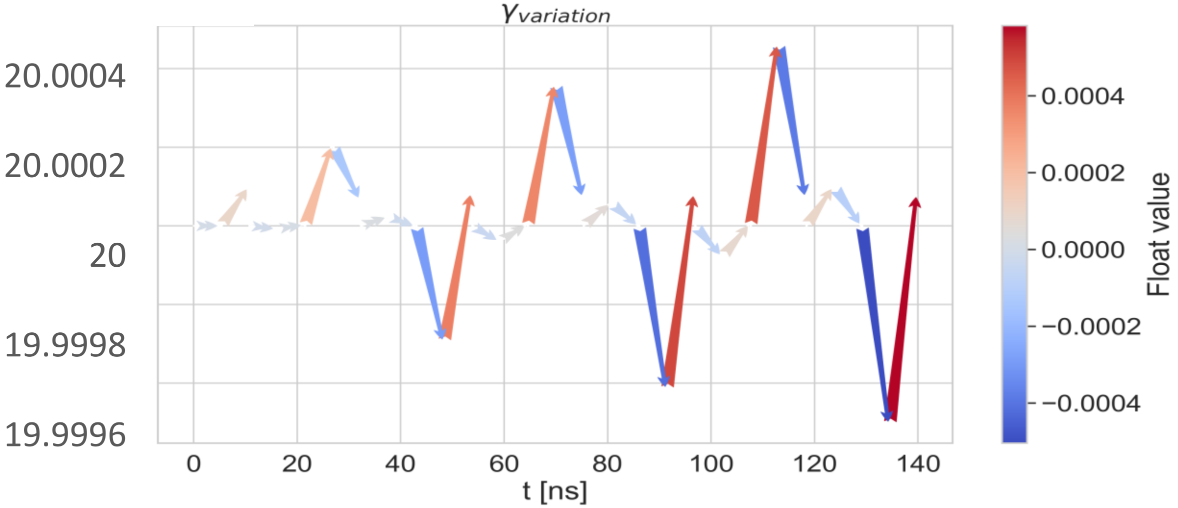


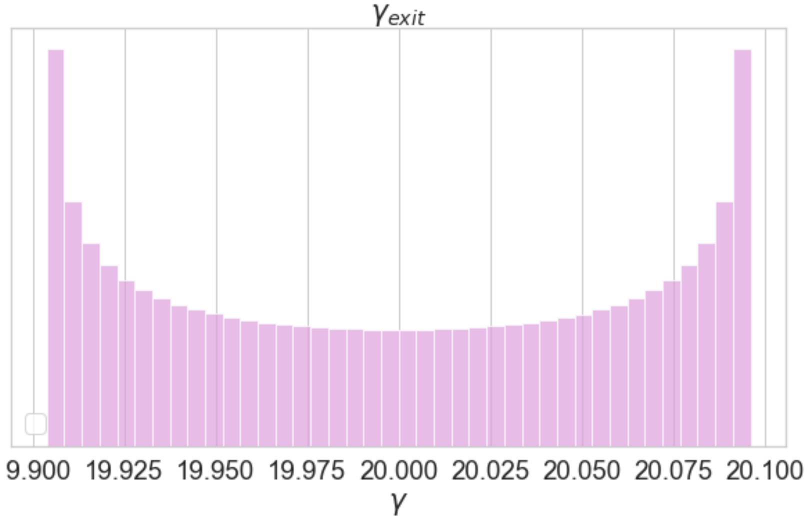
HOMs Analysis in the ERL

Parameters	Value
HOM1 frequency	2.43 GHz
HOM2 frequency	10.43 GHz
$k_{loss, HOM1}$	0.6 V/pC
$k_{loss, HOM2}$	0.2 V/pC
ERL: $P_{Kly,HOMs}$	0



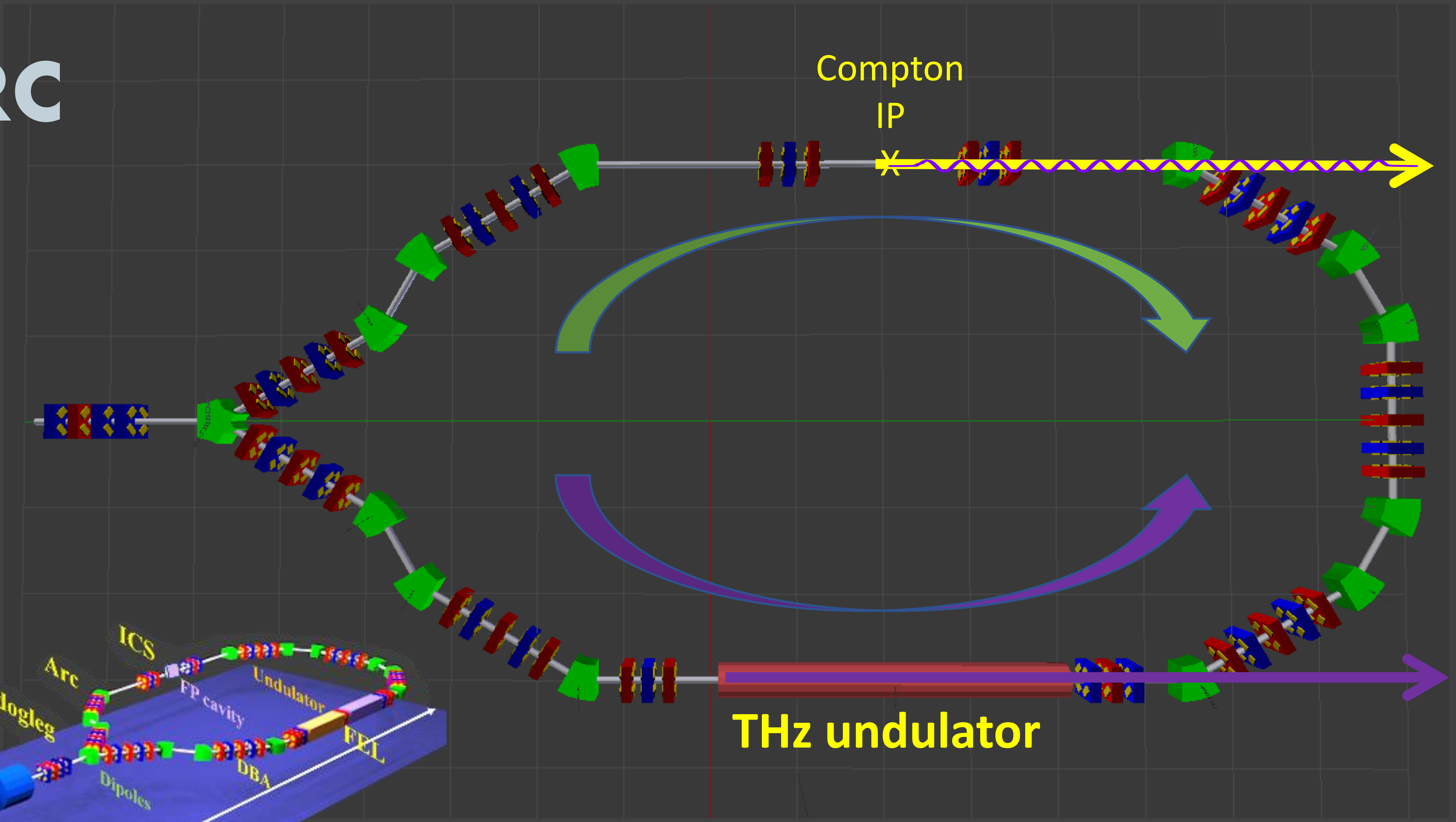


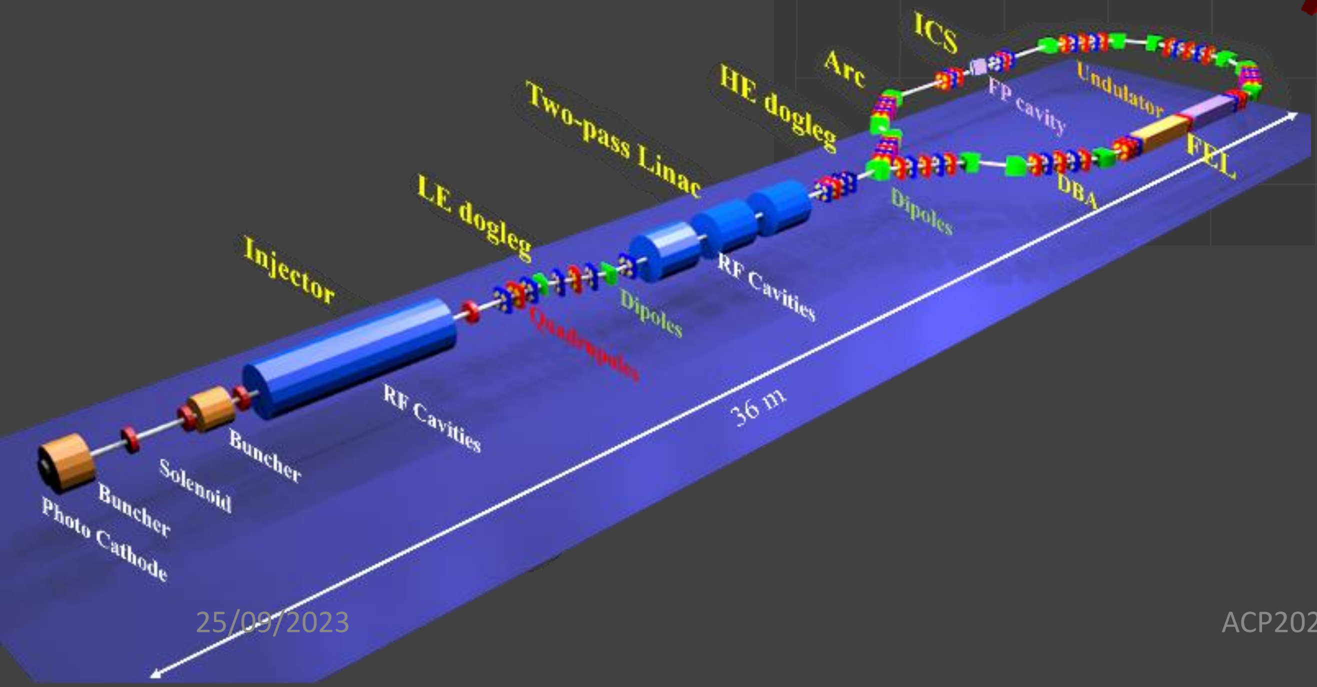




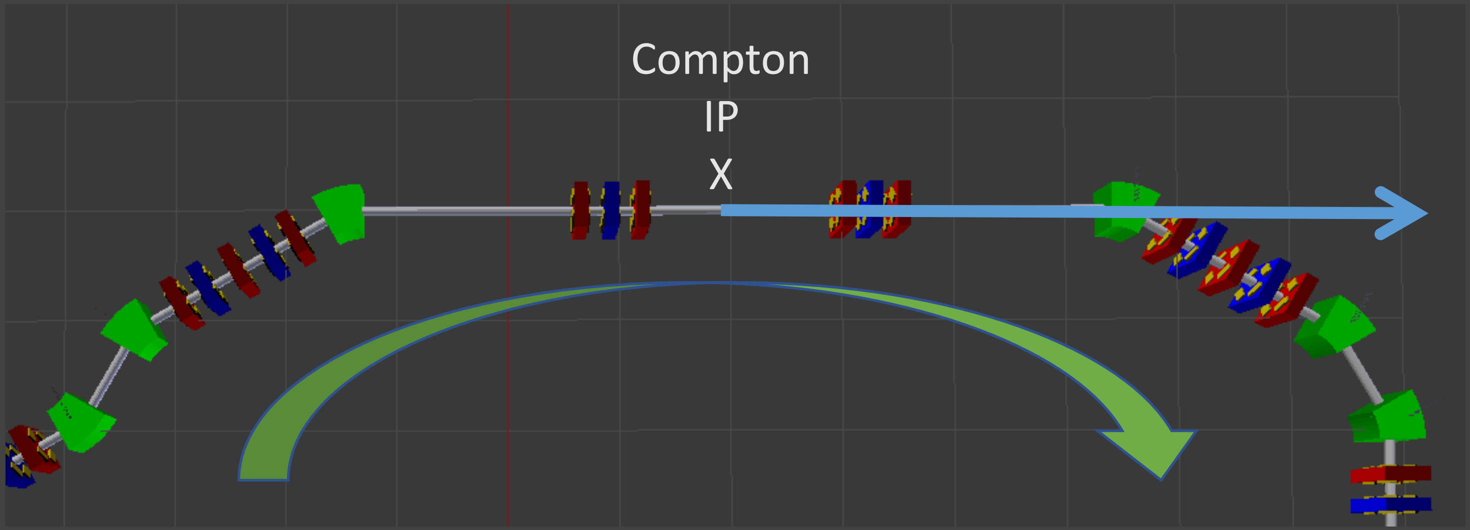
➢ Beam energy fluctuations about ± 5 ×10^{-3}

BriXSinO's ARC



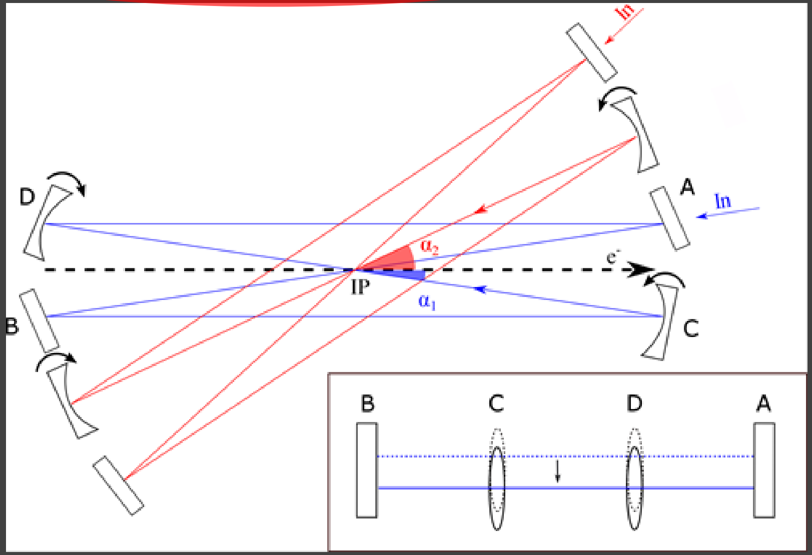


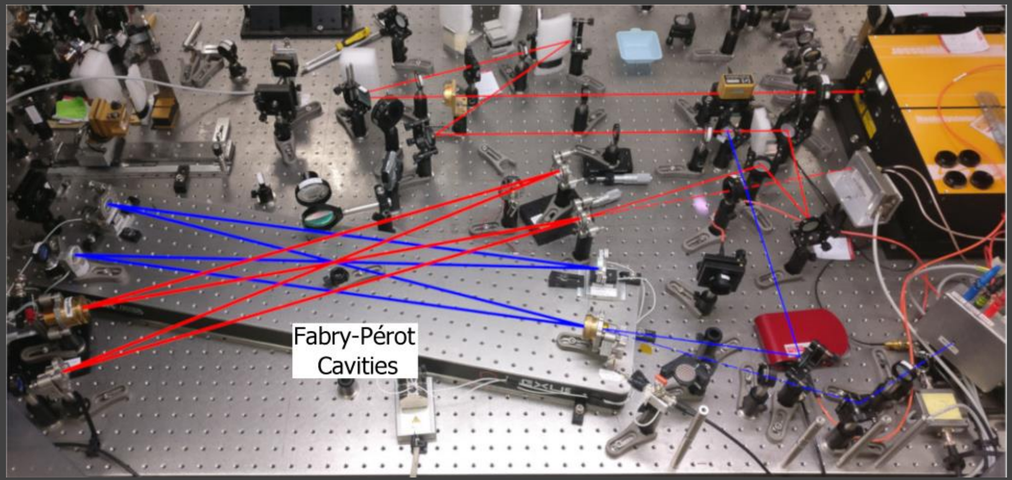
LASER system for ICS

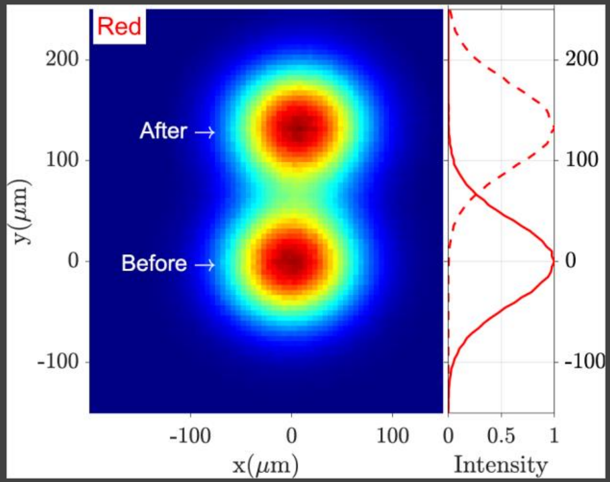


Laser Parameter	Value
Pulse energy (mJ)	2.7
Wavelength(nm)	1030
Pulse length (ps)	1.5
Repetition rate (MHz)	1300./ 14
Focal spot size (x,rms,μm)	90
Focal spot size (x,rms,μm)	80
Laser parameter a_0	3.3 10^{-3}
Collision angle ()	7
Collision angle for two colors ()	30

- Scattered photon E depends on the interaction angle between bunches and laser pulses.







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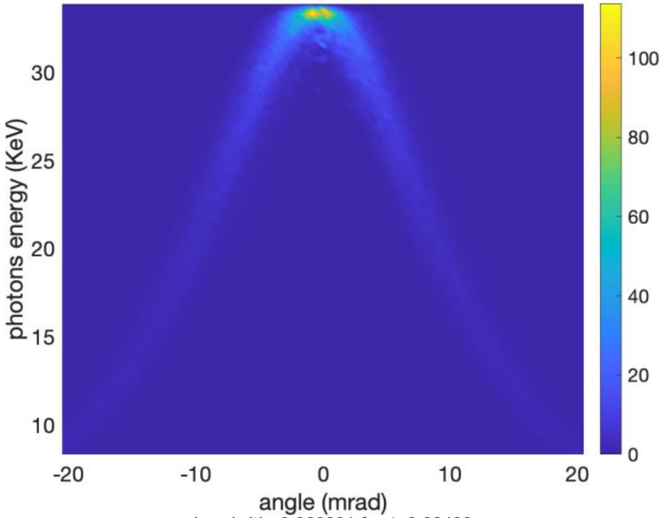
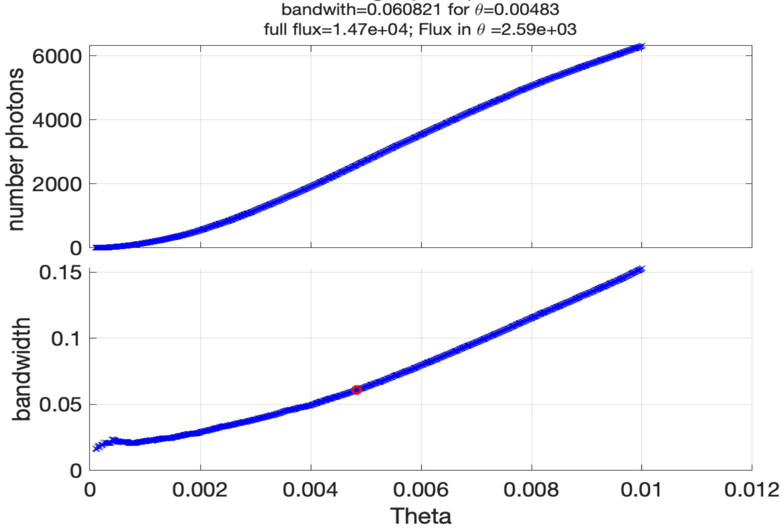
Ytterbium laser

ICS performances

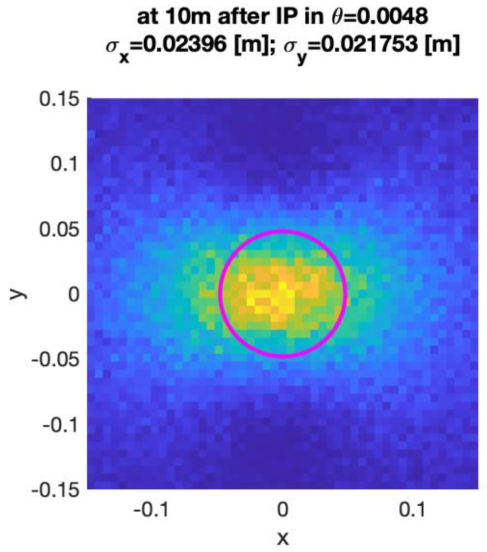
Electron beam Parameters	
Electrons mean energy $[MeV]$	4.28257e+01
Bunch charge $[C]$	1.00000e-10
Bunch length rms, FWHM $[\mu m]$	2.29571e+03, 5.11277e+00
Nominal normalized ϵ_{nx}, ϵ_{ny} $[mm.mrad]$	1.73224e+00, 2.19305e+00
Nominal relative energy spread σ_e %	2.45647e-01
Focal spot size σ_x, σ_y μm	2.73712e+01, 3.23179e+01
Laser Parameters	
Laser pulse energy (J)	2.7e-03
Laser wavelength (nm)	1030
Laser pulse length $[psec]$	2
Laser focal spot size w0x RMS $[\mu m]$	40
Laser focal spot size w0y RMS $[\mu m]$	80
Laser papameter $\alpha_0 = 6.8 * (\lambda_{las}/W0) * \sqrt{\frac{U_L(J)}{\sigma_t(ps)}}$	8.57811e-03
Collision angle [deg]	7
γ-ray Photon beam Parameters	
Nominal # photons per shot N_{phtot}	1.46860e+04
Source rms size $\sigma_{\gamma x}$, $\sigma_{\gamma y}$ $[\mu m]$ at IP	3.43587e+01, 2.54566e+01
Rad. pulse length $\sigma_{\gamma z}$ $[psec]$	3.17766e+00

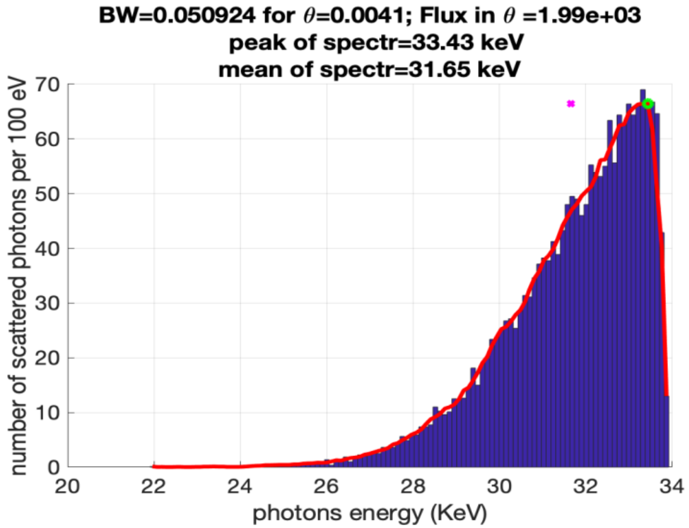
Compton edge





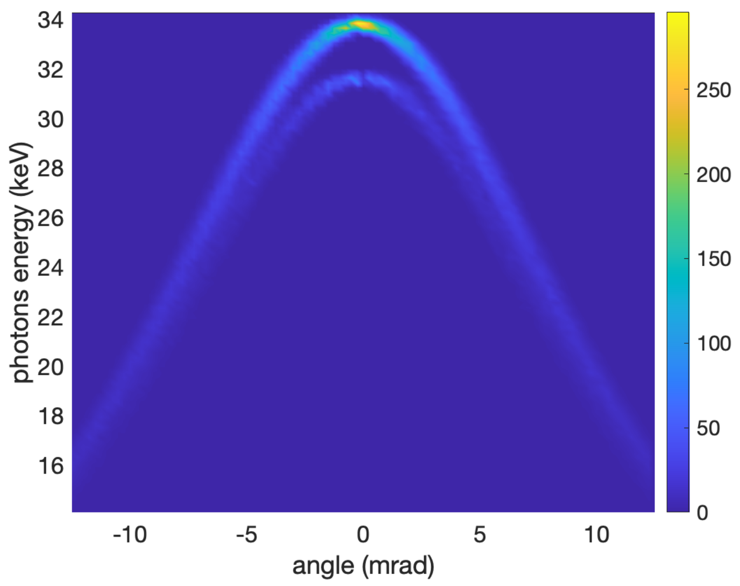
X-ray at 10 m

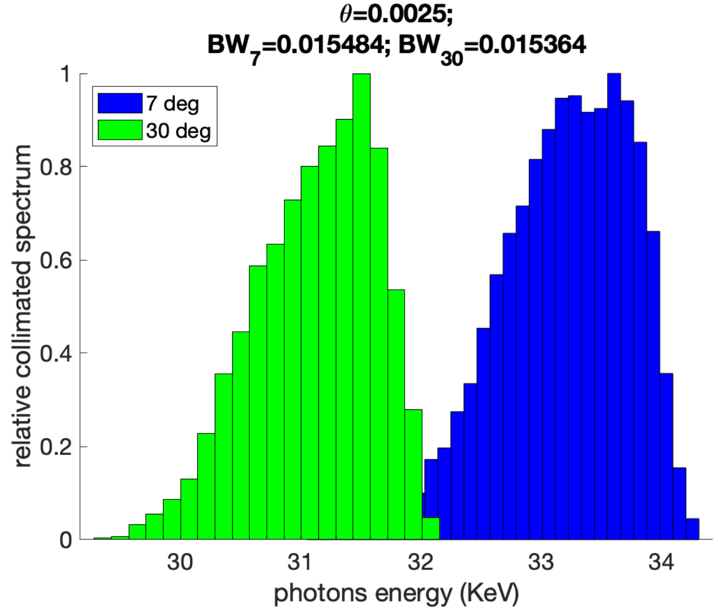




ICS performances: two colors

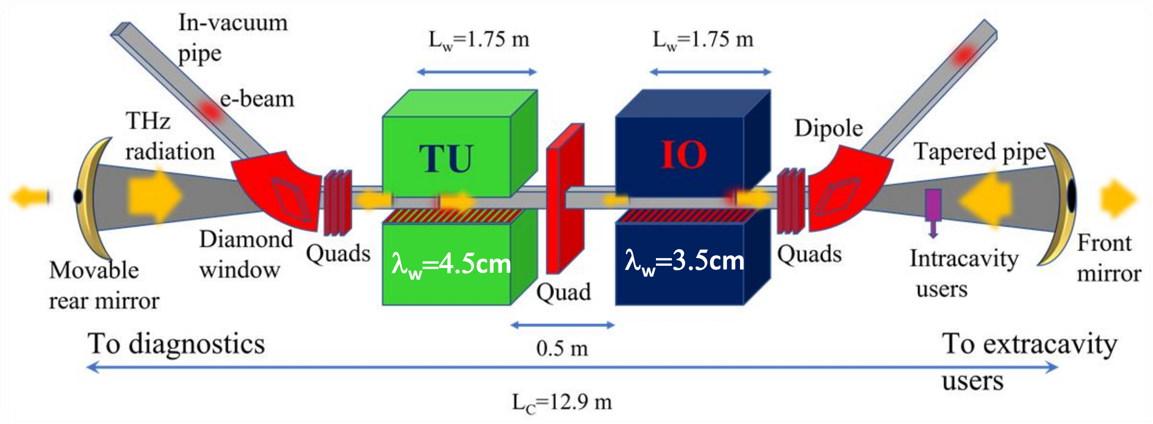
Electron beam Parameters	
Electrons mean energy $[MeV]$	4.28257e+01
Bunch charge $[C]$	1.00000e-10
Bunch length rms, FWHM $[\mu m]$	2.29571e+03, 5.11277e+00
Nominal normalized ϵ_{nx}, ϵ_{ny} $[mm.mrad]$	1.73224e+00, 2.19305e+00
Nominal relative energy spread σ_e %	2.45647e-01
Focal spot size σ_x, σ_y μm	2.73712e+01, 3.23179e+01
Laser Parameters	
Laser pulse energy (J)	2.7e-03
Laser wavelength (nm)	1030
Laser pulse length $[psec]$	2
Laser focal spot size w0x RMS $[\mu m]$	40
Laser focal spot size w0y RMS $[\mu m]$	80
Laser papameter $\alpha_0 = 6.8 * (\lambda_{las}/W0) * \sqrt{\frac{U_L(J)}{\sigma_t(ps)}}$	8.57811e-03
Collision angle [deg]	7
γ-ray Photon beam Parameters	
Nominal # photons per shot N_{ph_tot}	1.46860e+04
Source rms size $\sigma_{\gamma x}$, $\sigma_{\gamma y}$ $[\mu m]$ at IP	3.43587e+01, 2.54566e+01
Rad. pulse length $\sigma_{\gamma z}$ $[psec]$	3.17766e+00





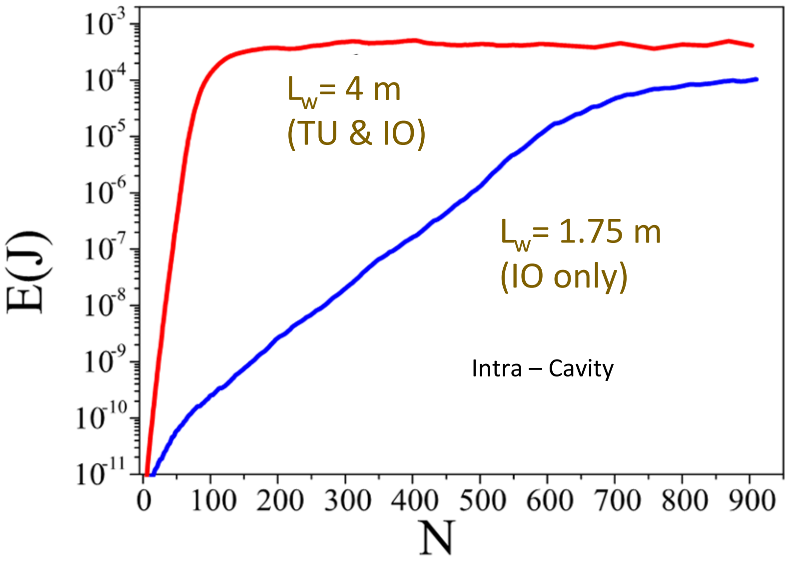
Energies centered above and bellow the iodine k-line

TerRa@BriXSino: FEL oscillator for THz production

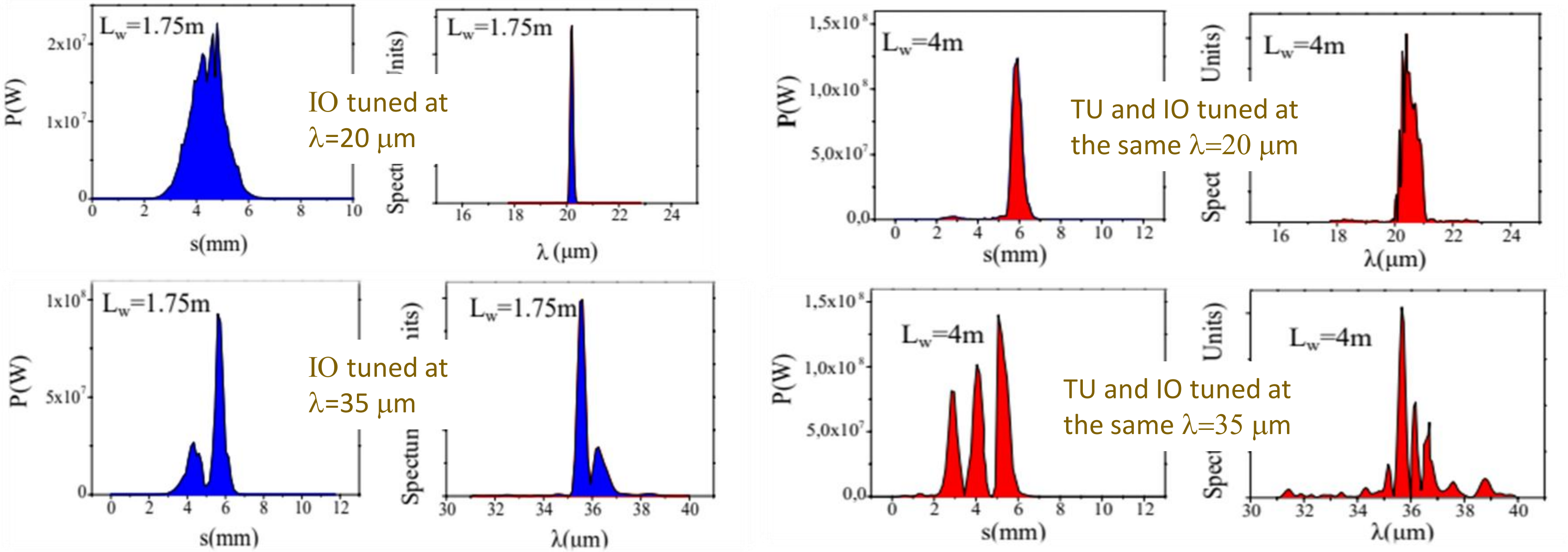


Wavelength	20 μm	20 μm	35 μm	35 μm
Undulator length	1.75 m (only IO)	4 m (TU&IO)	1.75 m (only IO)	4 m (TU&IO)
Single shot IC energy	84 μJ	420 μJ	250 μJ	420 μJ
Single shot EC energy	3.36 μJ	16.8 μJ	10 μJ	17 μJ
Average power	0.156 kW	0.78 kW	0.46 kW	0.8 kW
Bandwidth	0.65 %	2.5%	1.85%	4.2 %
Size	2 mm	2.6 mm	2.4 mm	2.8 mm
Divergence	2.8 mrad	4 mrad	4.2 mrad	5 mrad
Pulse rms length	635 μm	830 μm	749 μm	1000μm
Self coherence rms length	755 μm	1330 μm	800 μm	1300 μm
Mutual coherence rms length	700 μm	1000 μm	600 μm	1000 μm
Transverse coherence rms length	1.48 mm	2.98 mm	2.42 mm	4. mm

Characteristics of the radiation at λ = 20 μm and λ = 35 μm. IC: intra-cavity, EC: extra-cavity. Round trip losses=7%, extraction efficiency 4%. Repetition rate= 46.4 MHz



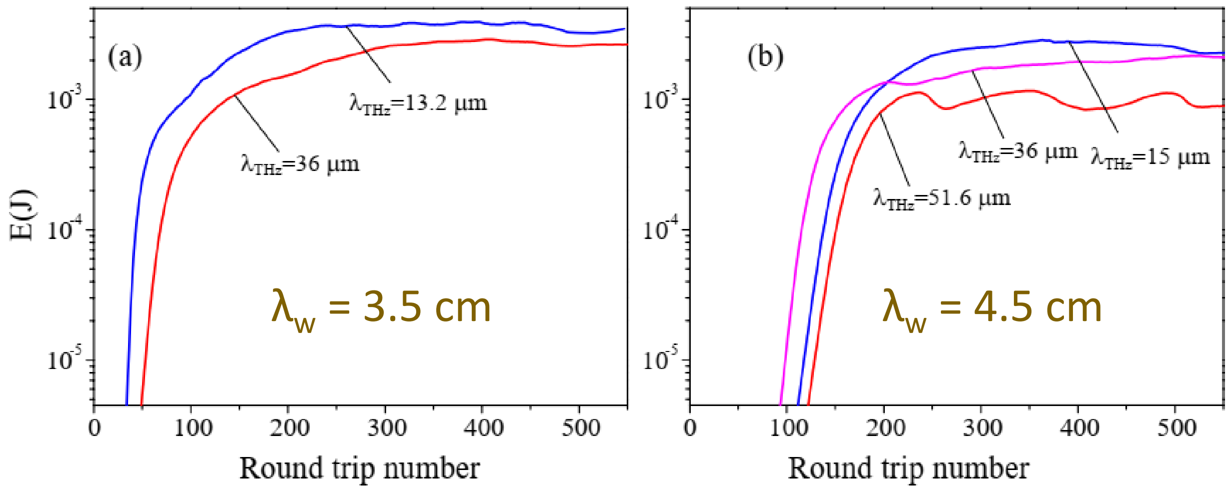
Radiation growth vs number of round

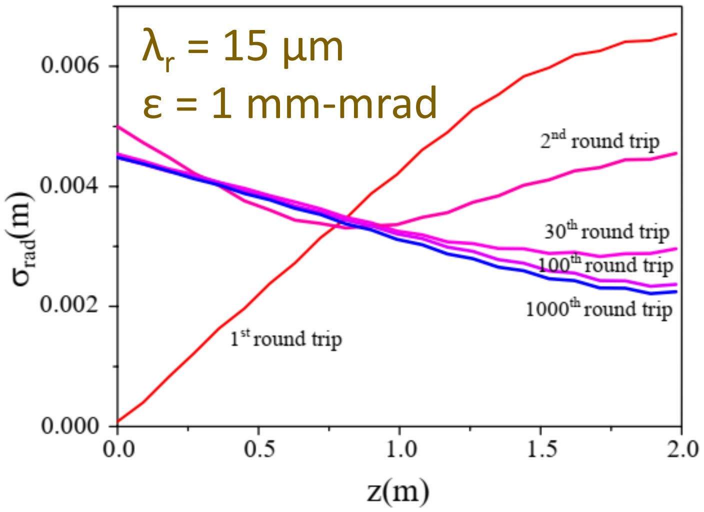


Radiation divergence and synchronization

Radaiation energy growth:

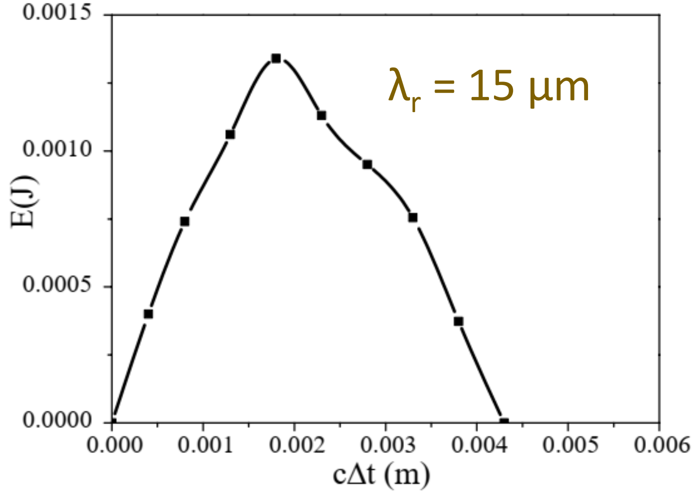
Intra – Cavity power





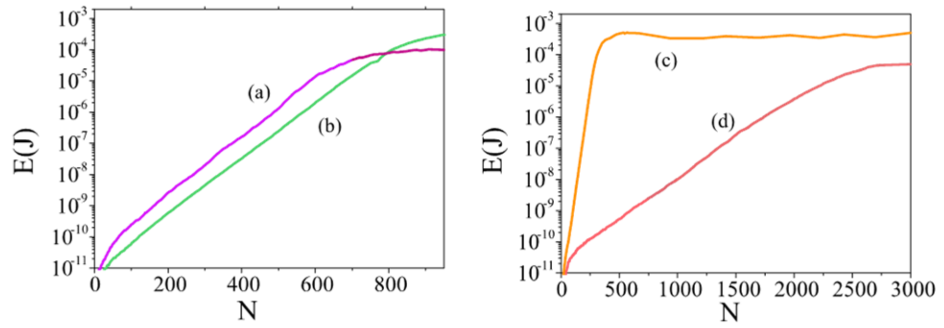
Size of the radiation during the growth.
Affects:

- Radiation growth
- Pipe size
- Mirrors size



Energy as function of synchronization

Two color THz radiation

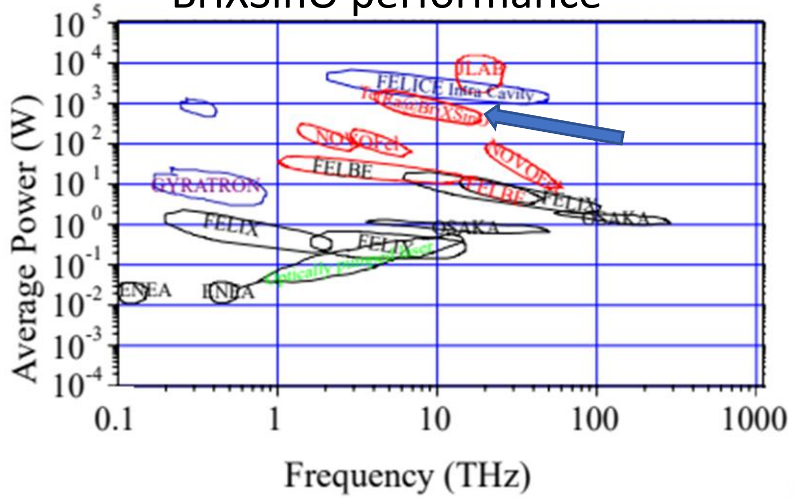


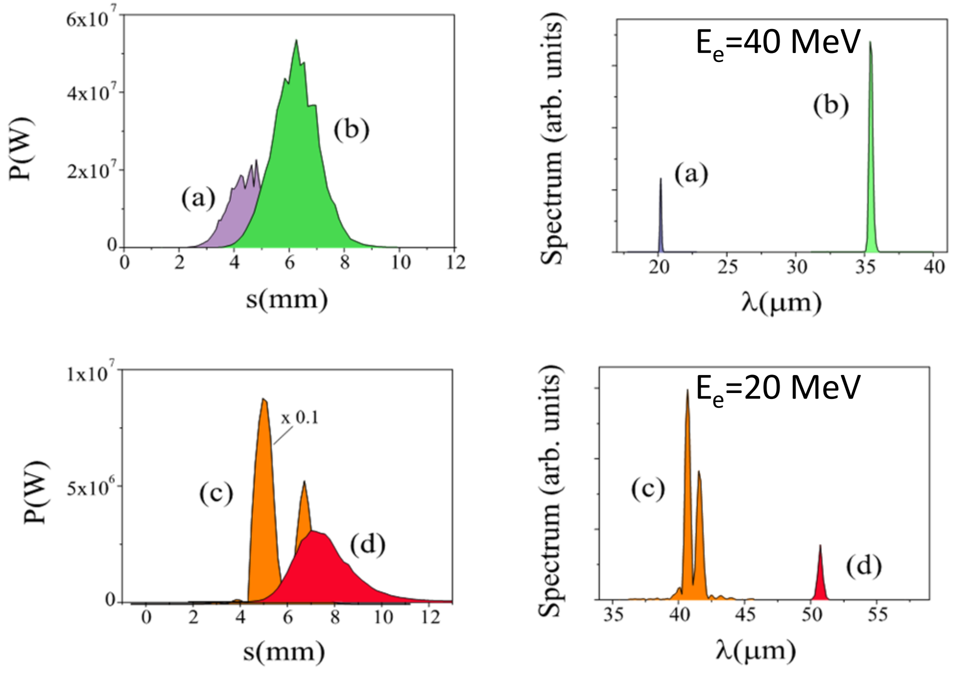
Growth of radiation power vs number of round trips

(a,b): IO tuned at λ=20 μm and TU tuned at λ=35 μm for E_e=40 MeV

(c,d): IO tuned at λ=40 μm and TU tuned at λ=50 μm for E_e=20 MeV

BriXSinO performance





Undulator	IO	TU	IO	TU
Electron energy	40 MeV	40 MeV	20 MeV	20 MeV
Wavelength	20 μm	35 μm	40 μm	50 μm
Single shot IC energy	84 μJ	305 μJ	340 μJ	46 μJ
Single shot EC energy	3.36 μJ	12.2 μJ	13.6 μJ	1.84 μJ
Average power	0.156 kW	0.6 kW	0.63 kW	0.085 kW
Bandwidth	0.65%	0.7%	0.49%	0.46% 0.5%
Size	2 mm	2.5 mm	2.5 mm	2.2 mm
Divergence	2.8 mrad	3.8 mrad	5 mrad	6.3 mrad
Pulse rms length	635 *μm*	830 *μm*	720 *μm*	1200*μm*
Self coherence rms length	755 μm	1000 μm	1300 μm	1500 μm
Mutual coherence rms length	700 μm	900 μm	1000 μm	1200 μm
Transverse coherence rms length	1.48 mm	2.63 mm	2.44 mm	2.9 mm

Characteristics of the two color radiation. IC: intra-cavity, EC: extra-cavity. Extraction efficiency 4%. Repetition rate = 46.4 MHz.

References

BriXSinO TDR: https://marix.mi.infn.it/brixsino-docs/

Multi-Pass Free Electron Laser Assisted Spectral and Imaging Applications in the Terahertz/Far-IR Range Using the Future Superconducting Electron Source BriXSinO
C. Koral, *et al*., *Front. Phys.,* Vol.10 (2022)
Two-Color TeraHertz Radiation by a Multi-Pass FEL Oscillator
M. Opromolla, *et al*., *Appl. Sci.,* Vol.11 (2021))
A new method for spatial mode shifting of stabilized optical cavities for the generation of dual-color X-rays
E. Suerra, *et al*., *Nucl. Instrum. Methods Phys. Res. A,* Vol.1019 (2021)
Synchronized THz radiation and soft X-rays produced in a FEL oscillator
V. Petrillo, *et al*., *Appl. Sci.,* Vol.12 (2022)
High brilliance Free-Electron Laser Oscillator operating at multi-MegaHertz repetition rate in the short-TeraHertz emission range
V. Petrillo, *et al*., *Nucl. Instrum. Methods Phys. Res. A,* Vol.1040 (2022)
IPAC’22 contributions: **WEPOS042; MOPOTK016 and THPOPT025**
IPAC’23 contribution: **TUPL162**

BriXSinO collaboration

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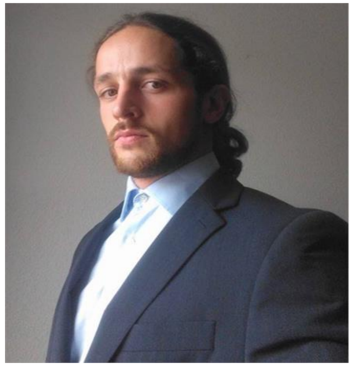

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Thank you


Scientific Program
Topics
Space Physics, Astrophysics & Cosmology
Nuclear and Particle Physics
Medical and Radiation Physics
Biophysics
Physics Education, Outreach, & Communication
Diversity Equity & Inclusion in Physics
Condensed and Material Physics
Photonics
Applied and Industrial Physics
Theoretical and Computational Physics
Physics for Sustainable Development
100 Years of Physics in Africa and the Future
100 years of Physics in Africa
Past, Present, And Future

Simulated Parameters

- $w(t) = \frac{\Delta U}{qq'}$
- $W(s) = \int_{-\infty}^{s} \lambda(s')w(s-s')ds'$
- $k_{loss} = \int_{-\infty}^{+\infty} \lambda(s)W(s)ds$

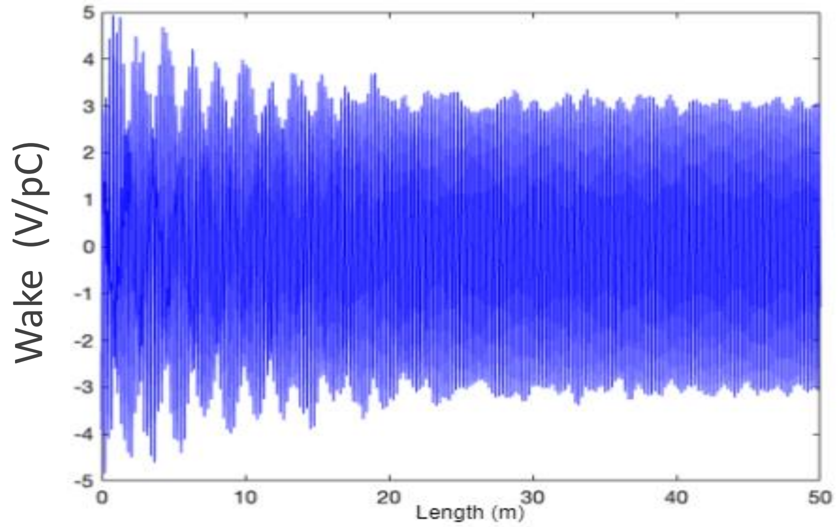
Longitudinal Impedance:

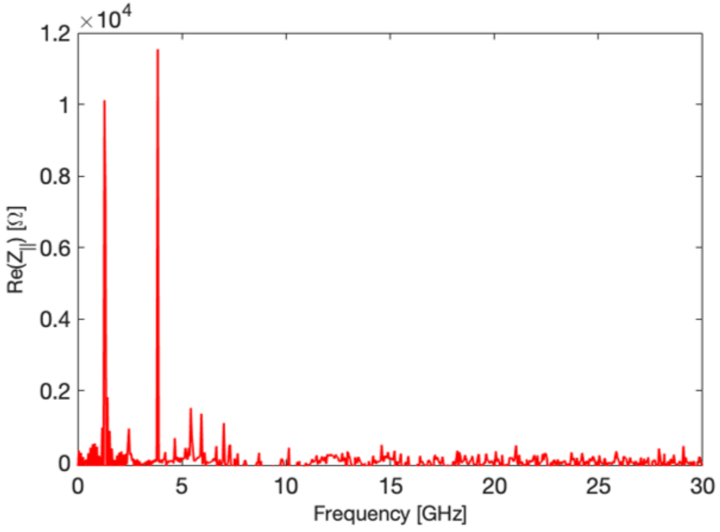
- bunch-length σ=2.2 mm
- Repetition rate ~ 100 MHz.

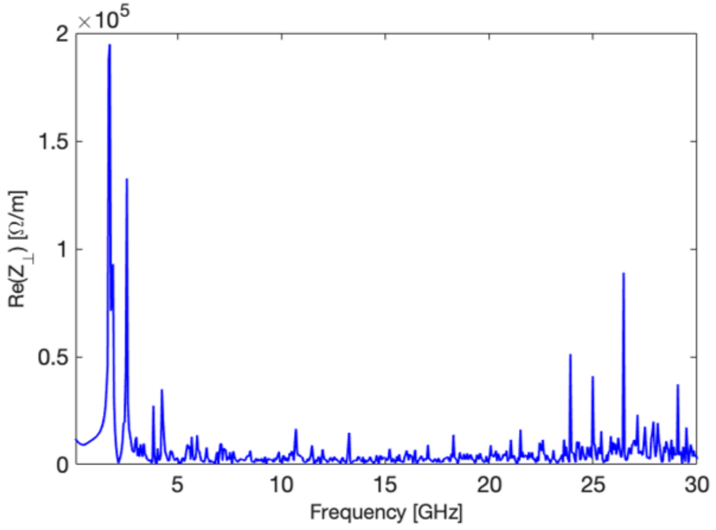
Main peaks relative to the impedance :

- ✓ 5 peaks: 1.3, 2.43, 3.84, 5.45 and 6.7 GHz.
- ✓ 7 peaks: 1.74, 2.56, 3.83, 4.25, 10.7, 13.26 and 18.27 GHz .

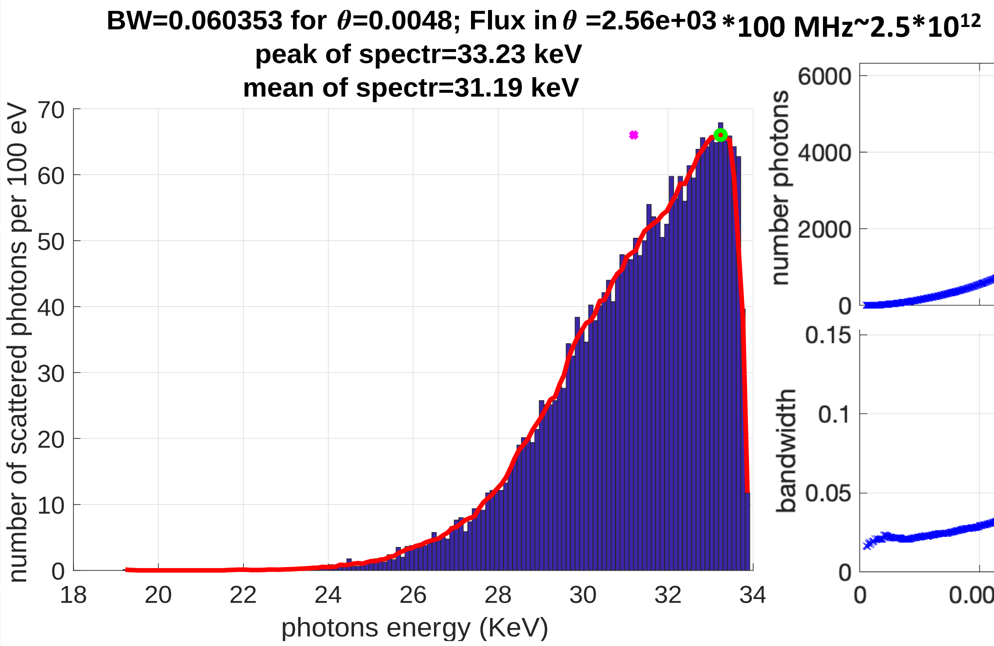
Credit: Maria Rosaria Masullo & Andrea Passarelli

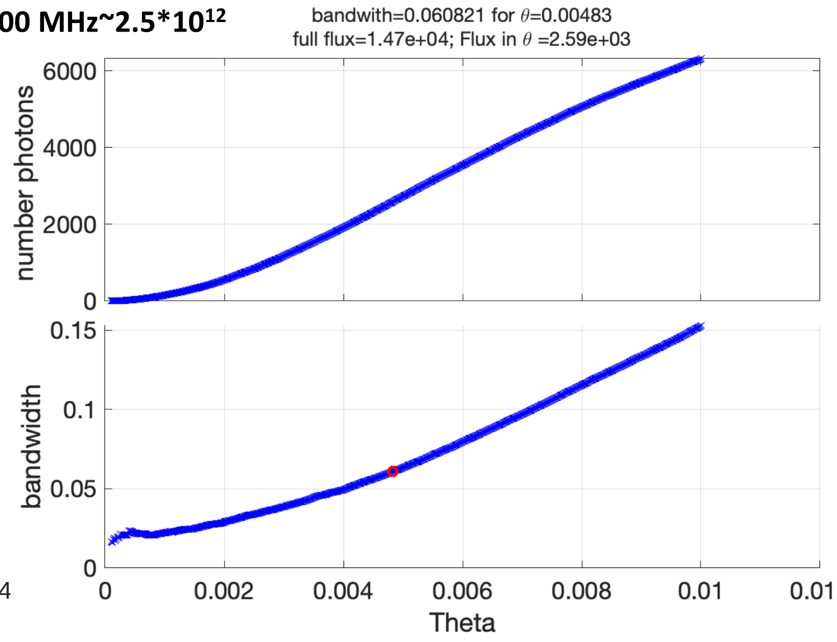


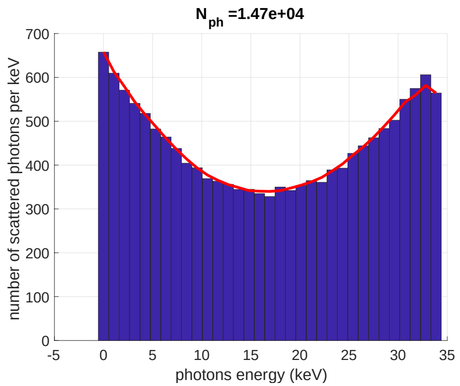


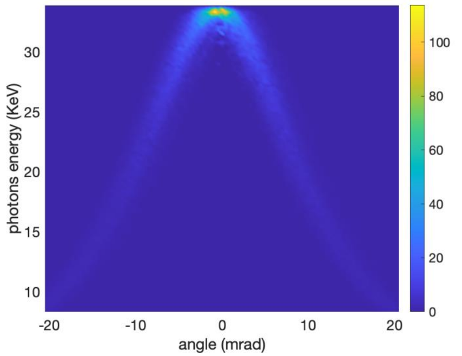


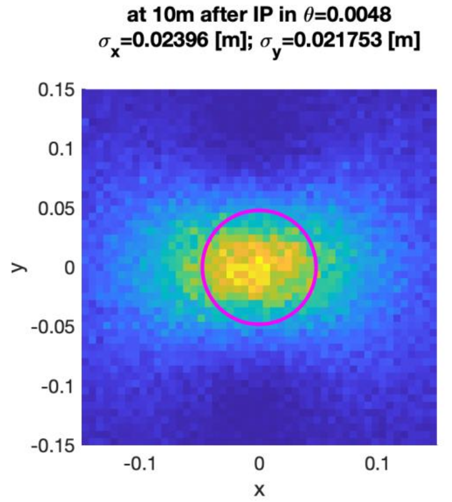
Electron beam Parameters	
Electrons mean energy $[MeV]$	4.28257e+01
Bunch charge $[C]$	1.00000e-10
Bunch length rms, FWHM $[\mu m]$	2.29571e+03, 5.11277e+00
Nominal normalized ϵ_{nx}, ϵ_{ny} $[mm.mrad]$	1.73224e+00, 2.19305e+00
Nominal relative energy spread σ_e %	2.45647e-01
Focal spot size σ_x, σ_y μm	2.73712e+01, 3.23179e+01
Laser Parameters	
Laser pulse energy (J)	2.7e-03
Laser wavelength (nm)	1030
Laser pulse length $[psec]$	2
Laser focal spot size w0x RMS $[\mu m]$	40
Laser focal spot size w0y RMS $[\mu m]$	80
Laser papameter $\alpha_0 = 6.8 * (\lambda_{las}/W0) * \sqrt{\frac{U_L(J)}{\sigma_t(ps)}}$	8.57811e-03
Collision angle [deg]	7
γ-ray Photon beam Parameters	
Nominal # photons per shot N_{phtot}	1.46860e+04
Source rms size $\sigma_{\gamma x}$, $\sigma_{\gamma y}$ $[\mu m]$ at IP	3.43587e+01, 2.54566e+01
Rad. pulse length $\sigma_{\gamma z}$ $[psec]$	3.17766e+00

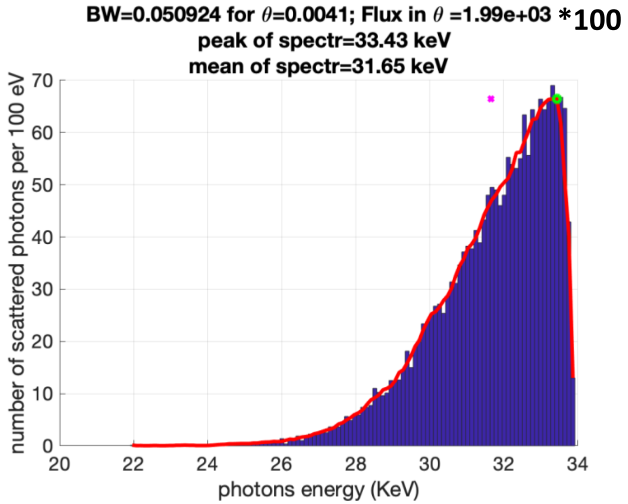




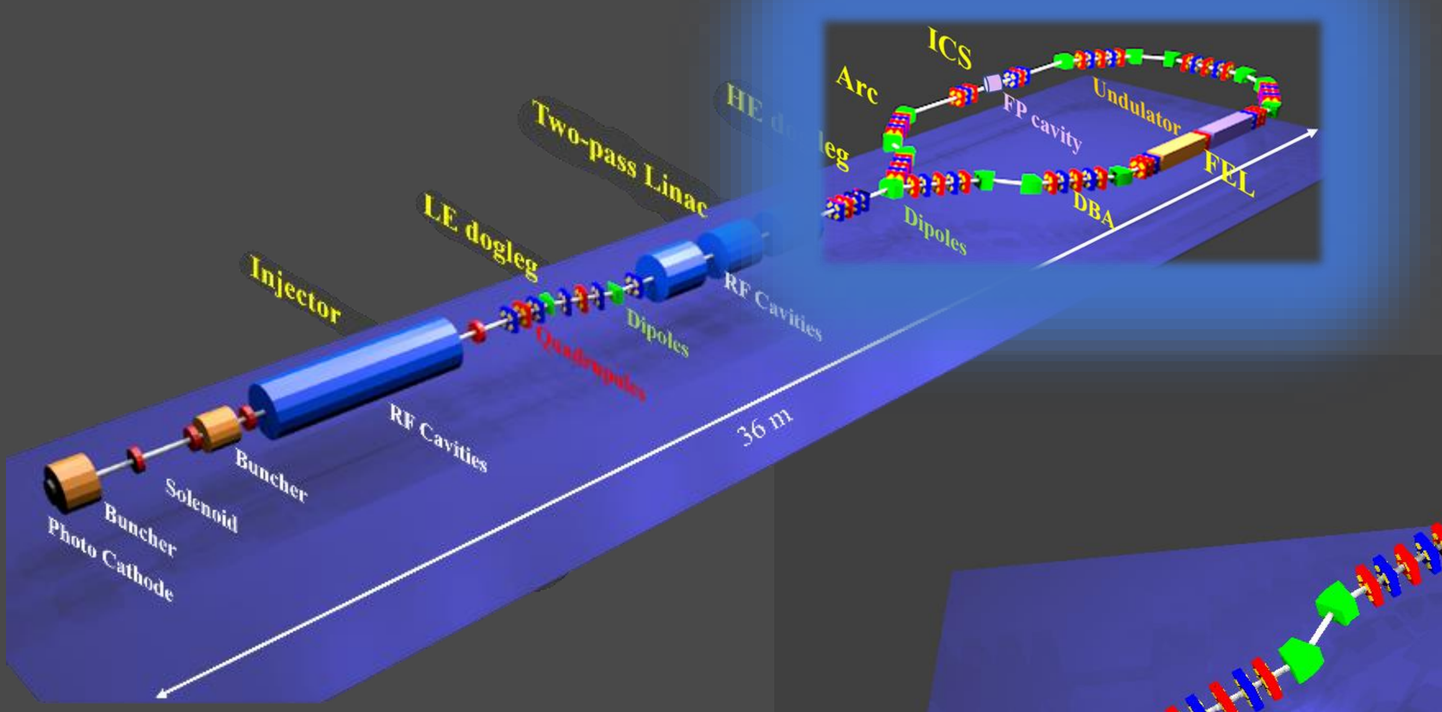




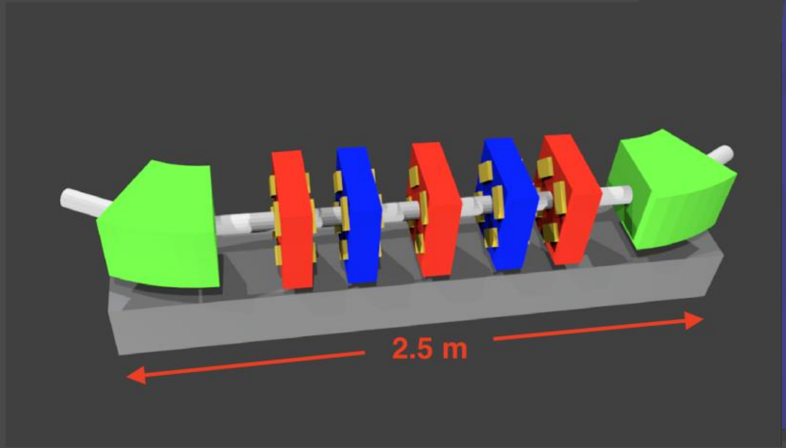


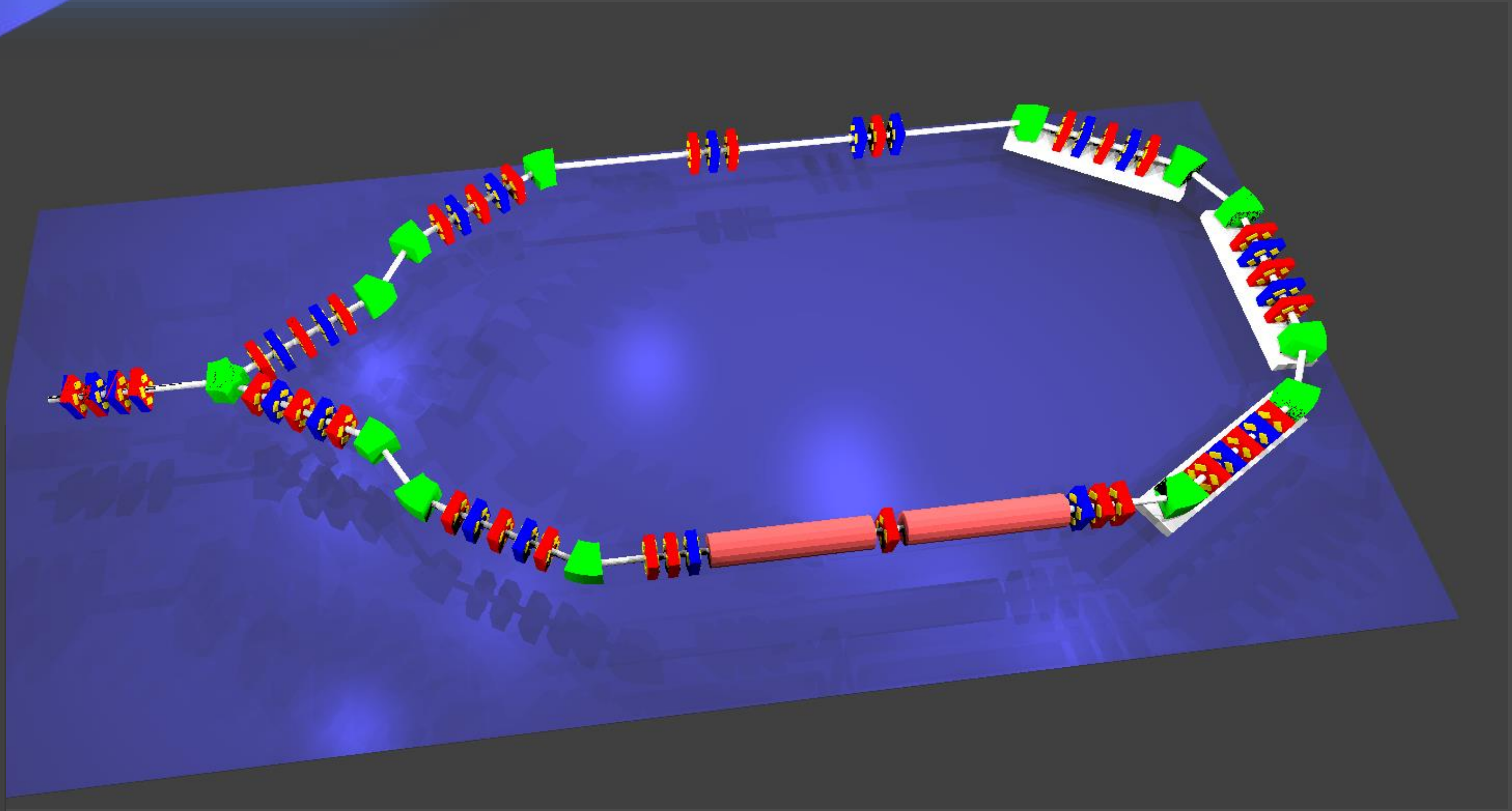


ARC



Phase matching





The ERL electron beam

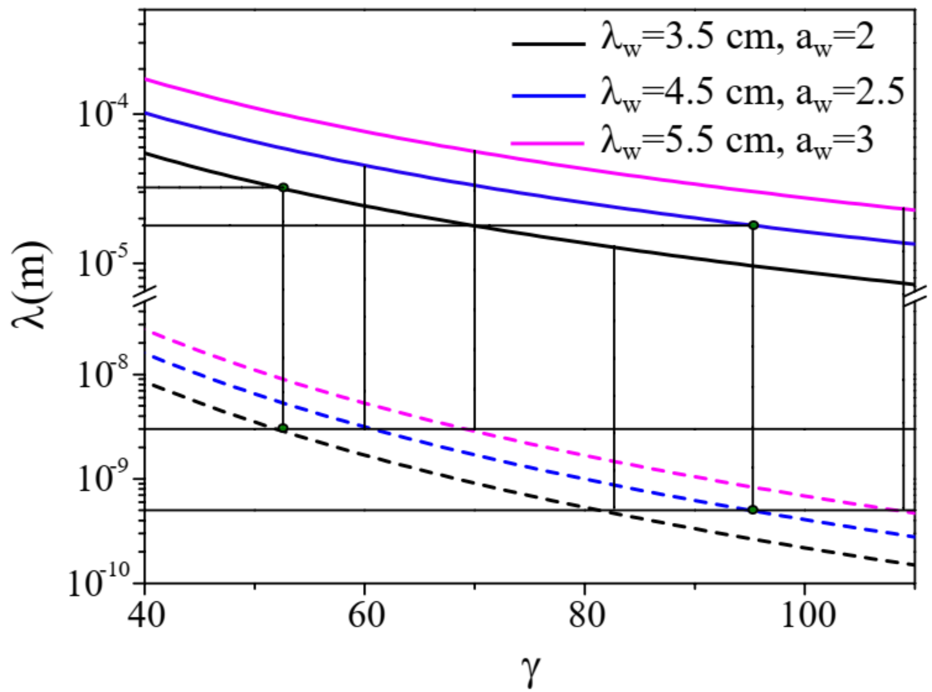
Quantity	Before the undulator
Energy	20-100
Charge	100-200 pC
Energy spread	0.1-1 %
Slice emittance	0.6-2 mm mrad
Transverse size σ_x	0.1-0.25 mm
Length σ_z	0.5-5 mm

FEL resonance

$$\lambda_{THz} = \frac{\lambda_w}{2\gamma^2}(1 + a_w^2)$$

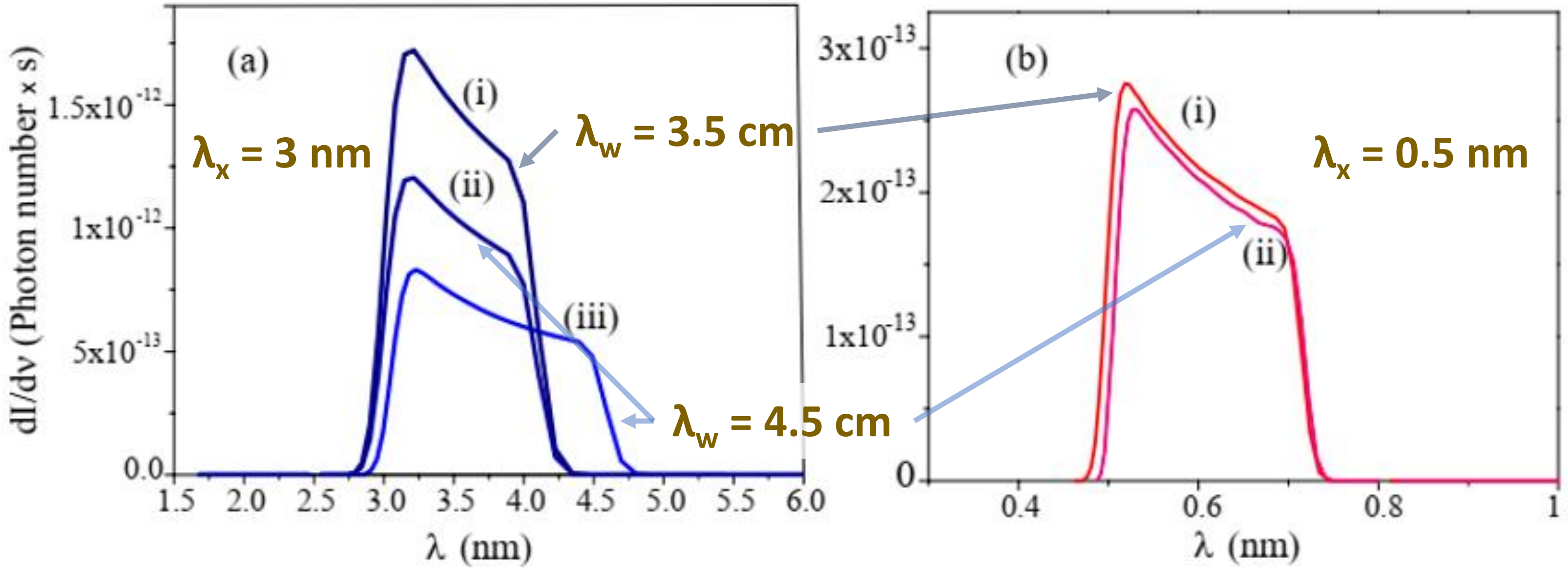
Compton edge

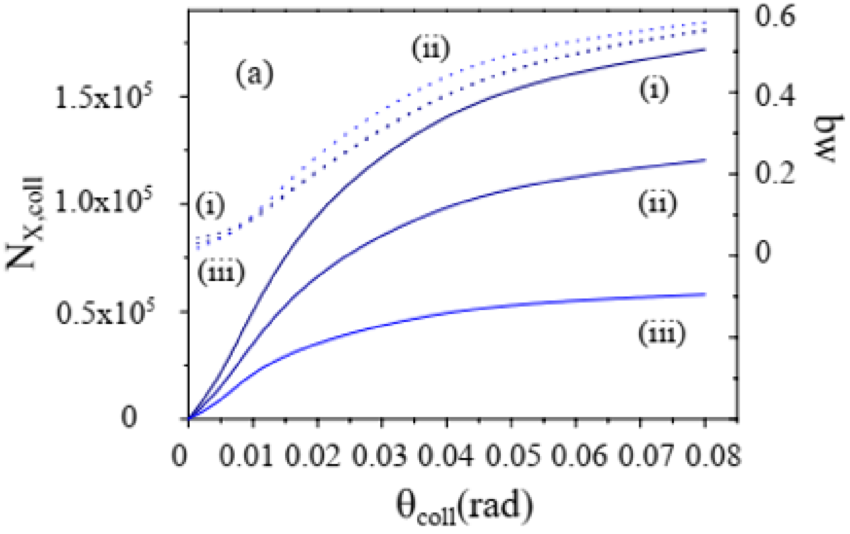
$$\lambda_X = \frac{\lambda_{THz}}{4\gamma^2} = \frac{\lambda_w}{8\gamma^4}(1 + a_w^2)$$

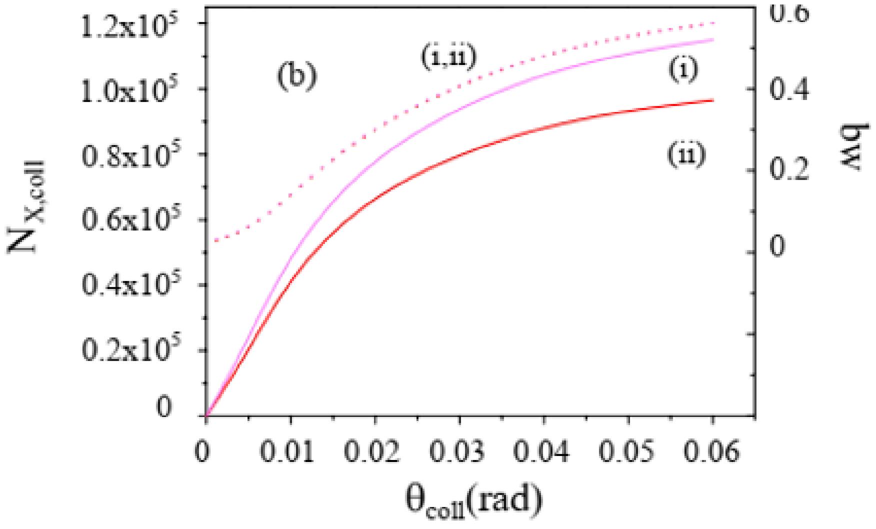


Number of X photons and spectrum

Spectrum of collimated X-ray @ 10% bandwidth





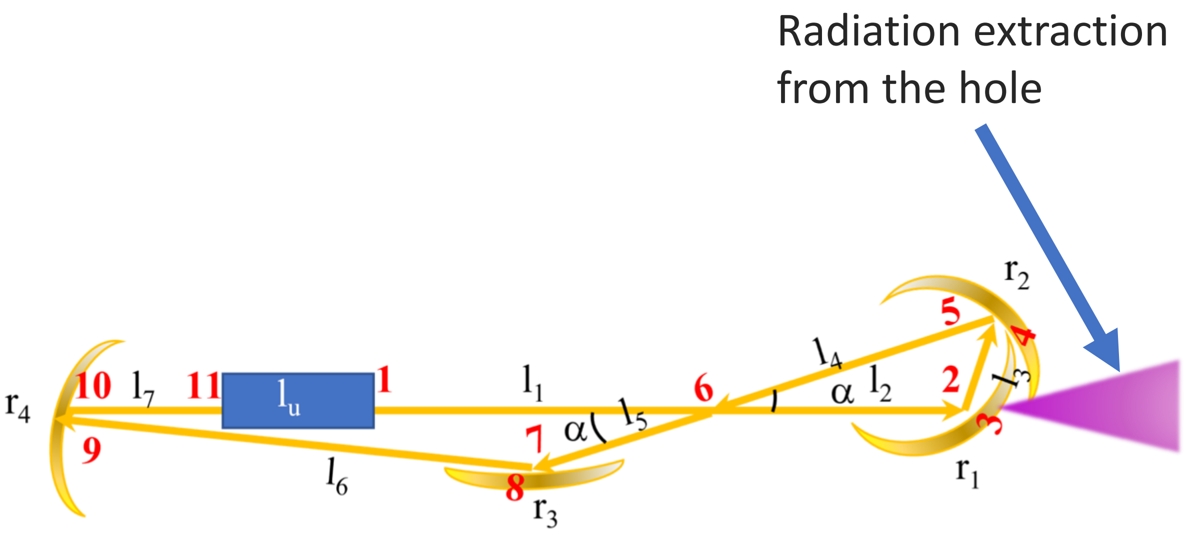


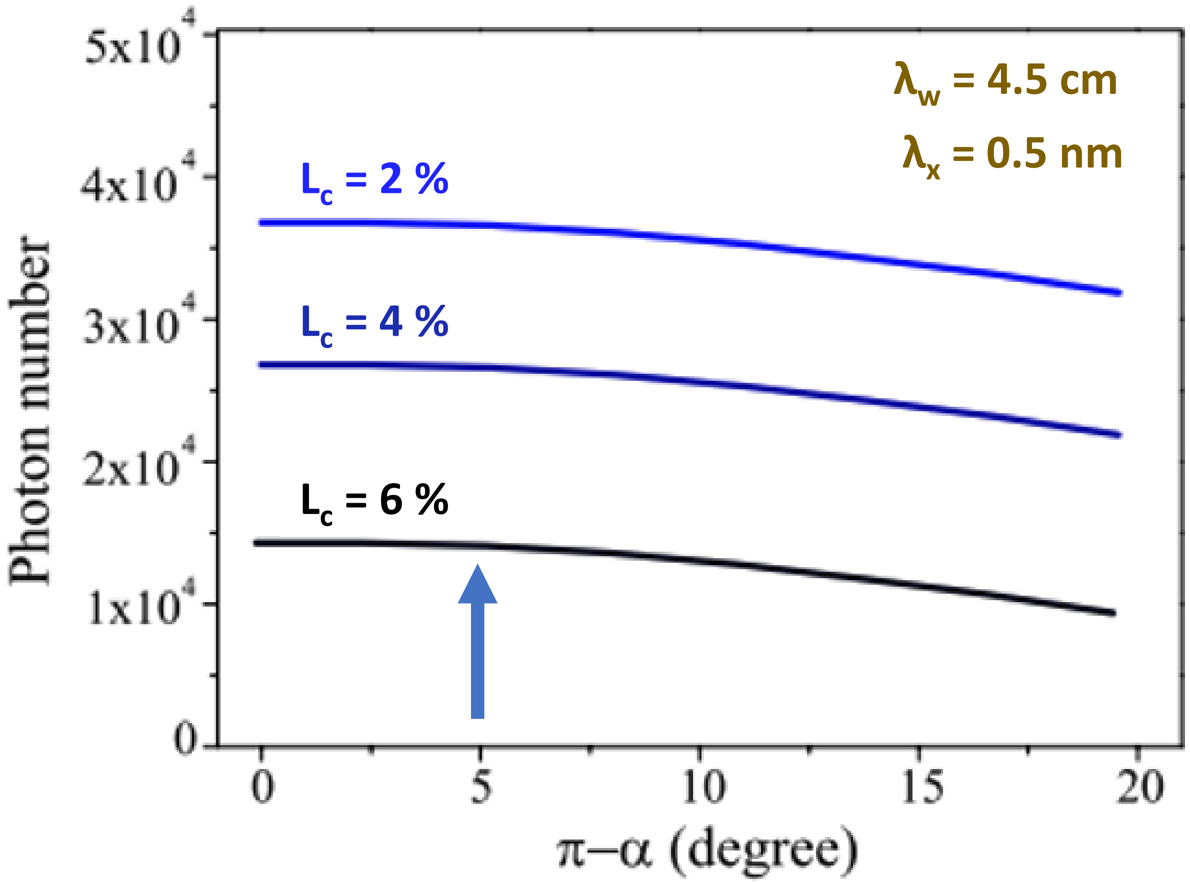
N_{ph} and bandwidth as a function of collimation angle:

- 10^4 - 10^5 photons per shot @ 10-20% bandwidth

Number of photons vs interaction angle

N_{ph} per shot as a function of collision angle and cavity losses L_c





ACP2023

Results

5 x 10^7 assumed repetition rate

IC: Intra – Cavity, EC: Extra – Cavity

γ	e-beam		55.5	81.5	65	55.5	86
λ_{THz}	THz	μm	36	13.2	51.6	36	15
E_{IC}	THz	mJ	3	3.38	1	2.1	2.8
N/shot	IC THz	$\times 10^{17}$	5.5	2.6	2.5	3.8	2.1
N/s	IC THz	$\times 10^{25}$	2.75	1.3	1.25	1.9	1.05
N/shot	EC THz	$\times 10^{15}$	11	5.2	5	7.6	4.2
N/s	EC THz	$\times 10^{23}$	5.5	2.6	2.5	3.8	2.1
size in IP	THz	μm	180	65	250	180	75
λ_X	X-ray	nm	3	0.5	3	3	0.5
N_X/shot	X-ray	$\times 10^5$	1.7	1.05	1.27	1.19	0.96
N_X/s	X-ray	$\times 10^{12}$	8.5	5.3	6.3	6	4.8
$N_{X,coll}$/shot	X-ray	$\times 10^5$	0.41	0.42	0.23	0.29	0.37
$N_{X,coll}$/s	X-ray	$\times 10^{12}$	2.2	2.25	1.15	1.45	1.85

10% bandwidth