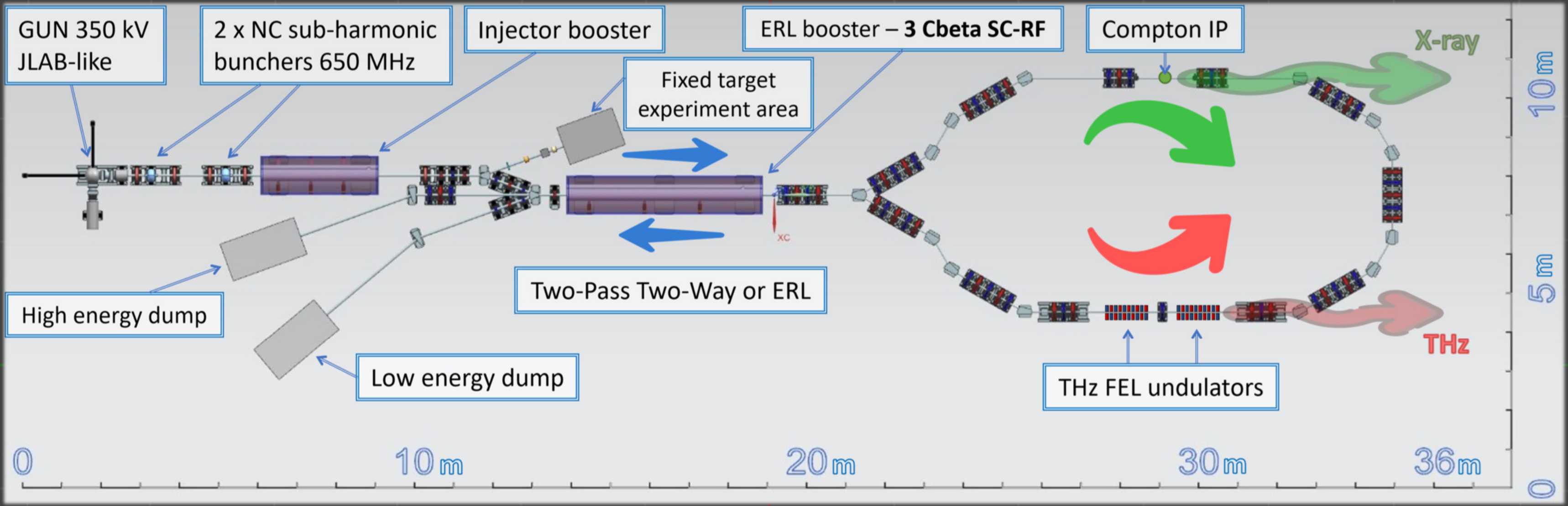
High-Flux Dual X-Ray and THz Radiation Source Based on Energy Recovery Linacs

BriXSinO

BriXSinO

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



BRIXSINO HIGH-FLUX DUAL X-RAY AND THZ RADIATION SOURCE BASED ON ENERGY RECOVERY LINACS

Two main working mode:
As ERL for light source at electrons energy ~45 MeV
And double acceleration up to 80 MeV

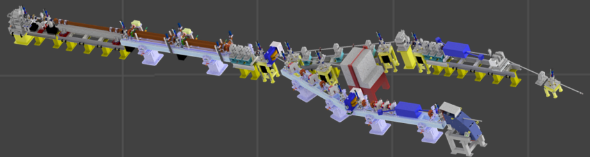
Light sources installed in the arc : X rays based on Compton Scattering
And FEL Oscillator for THz radiation

Why ERL?

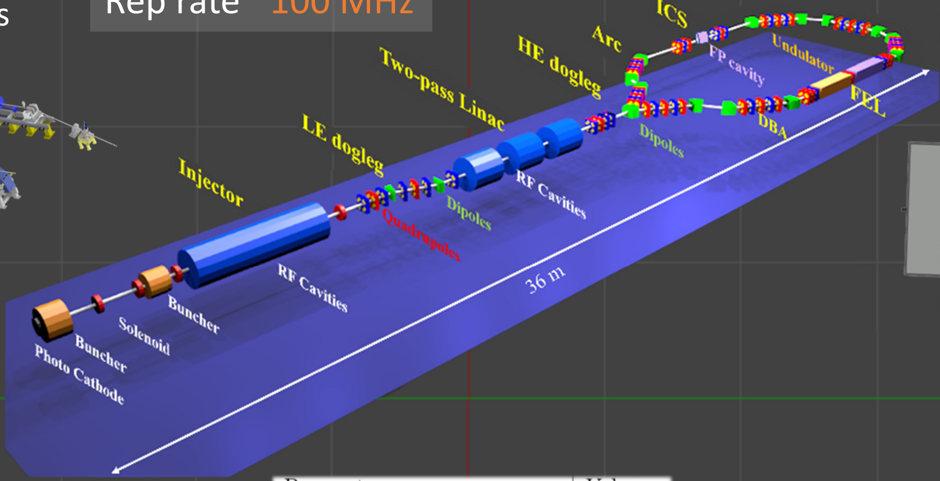
$$N \sim \frac{\sigma_c f N_e N_L}{\sigma^2}$$

Rep rate ~100 MHz

Based on linear accelerators



Projects:
STAR2
SMART*LIGHT



Based on storage rings

Projects:
MuCLS
ThomX
NESTOR

Parameter	Value
Energy (MeV)	20-45
Bunch charge (pC)	50 - 200
Repetition rate (MHz)	100
Average Current (mA)	<5
Beam power @ dump (W)	400
$\epsilon_{n,x,y}$ (mm mrad)	1.0
energy spread (%)	< 0.2
Bunch separation (μs)	> 1
Beam energy fluctuation (%)	< 0.2
Pointing jitter (μm)	50.

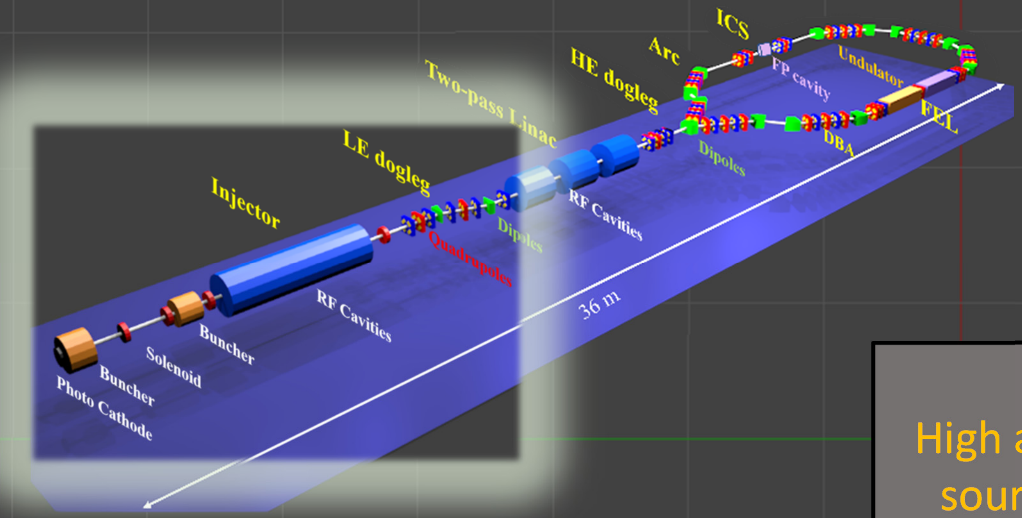
Advantage:
- Small emittance 2-3 mmrad
- Possibility to focus beam at 5-10 μm
- Hight flexibility in tuning

Disadvantage
- Low repetition rate 100 Hz

Advantage:
- Hight repetition rate 17.8 MHz

Disadvantage
- Bigger emittance 60 mmrad
- Bigger transvers size at IP ~70 μm

The BriXSinO's injector



An ERL injector (or merger) has typically 3 major objectives:

(1)
High brightness → i.e. A high beam qualities for experiments

(2)
High average beam current → e.g. high flux light sources (FEL, ICS) or Luminosity in colliders, …

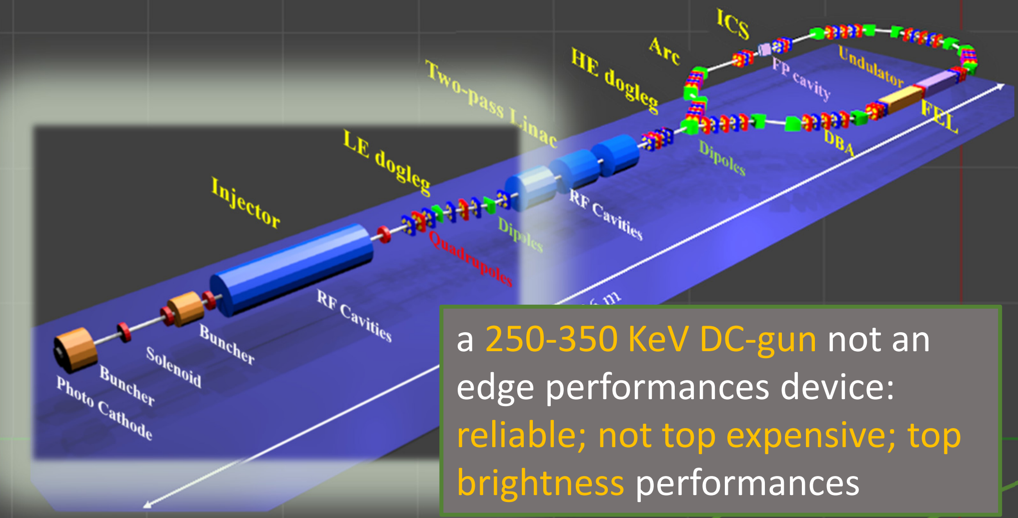
(3)
Low injection energy
→ It is the energy that will be never be recovered
→ It the energy going into the dumper.

Keeping in mind this concepts we developed the following high performing beam-line

Courtesy A. Bacci

BriXSinO's injector devices

An innovative injector in more aspects:



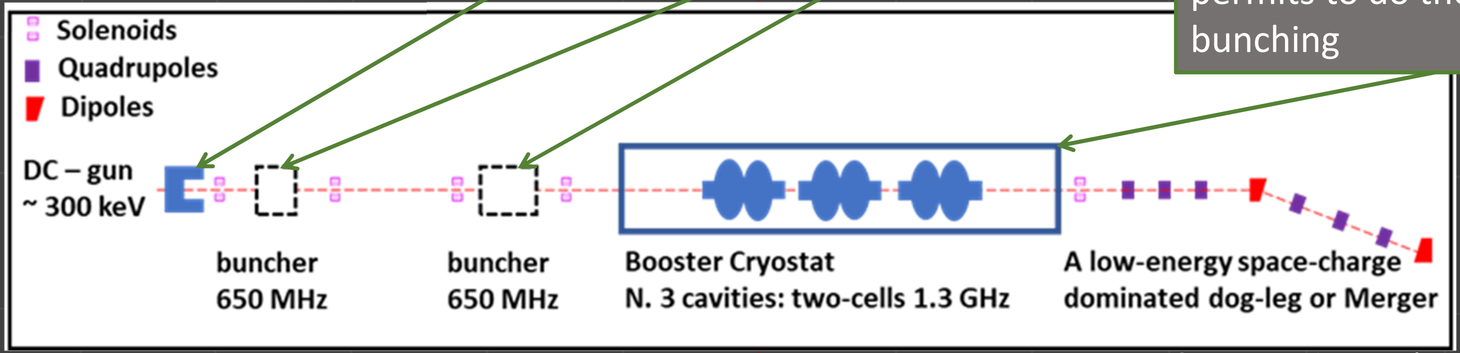
Two 650 MHz bunchers guarantee both acceleration & compression:
- outstanding σE/E compensation
- a longer λ (than 1.3 GHz) for

Longer bunches @ cathode i.e. sigar-like distrib. → low emittances

a 250-350 KeV DC-gun not an edge performances device: reliable; not top expensive; top brightness performances

3 two-cells SC cryostat:

boost @ 4.5MeV low energy . Different RF injection phases permits to do the Velocity bunching

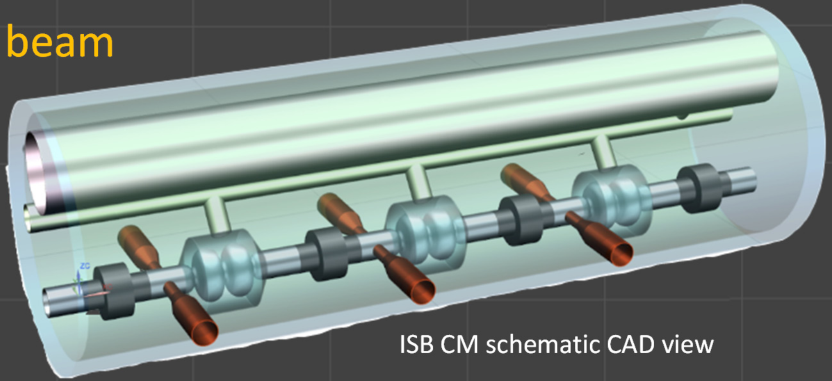


Courtesy A. Bacci

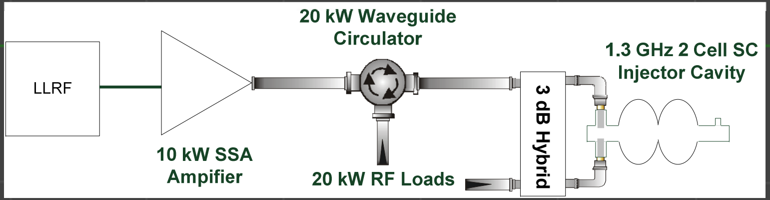
The Injector Superconducting Booster - ISB

ISB is a **full beam-loading** cryomodule that boosts beam energy up to 5 MeV for the injection in the ERL section

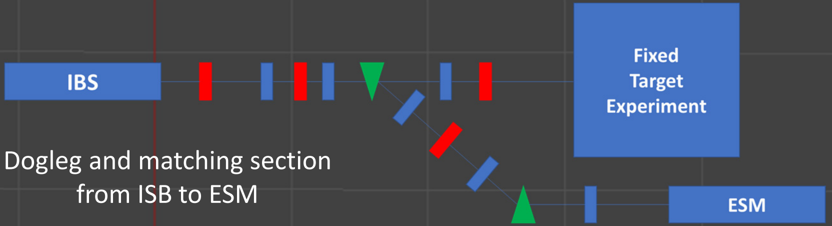
- Three 2-cell SC cavities, 1.3 GHz
  - Acc. gradient up to 7.5 MV/m CW
  - Quality factor at 2e10, 2.0 K
  - Coaxial Blade fast tuner
- **Double, symmetrical power coupler** to minimize transversal kicks to the beam
  - 10 kW SSA, one each cavity
- **Coaxial HOM adsorbers** between cavities
  - Silicon Carbide ring, actively cooled



ISB CM schematic CAD view



ISB cavities RF power chain scheme

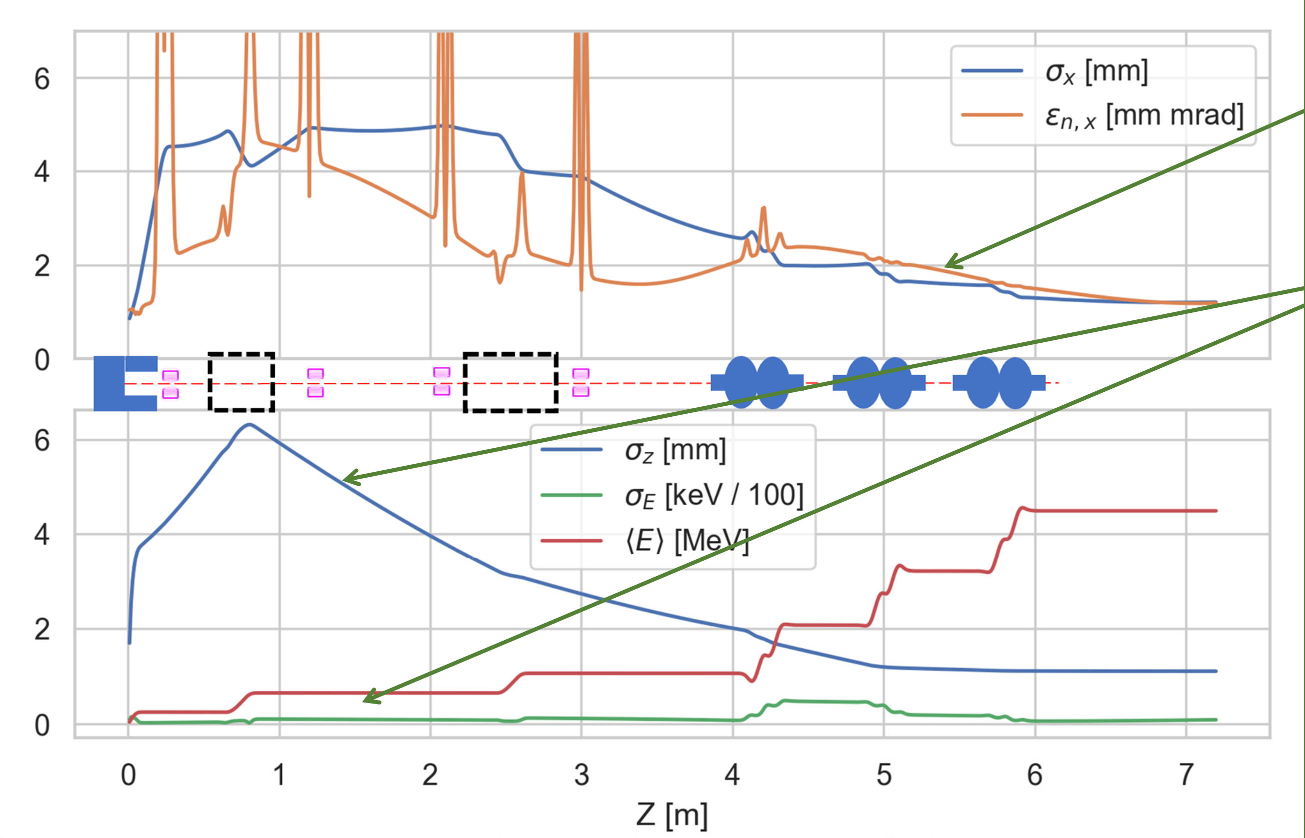


Dogleg and matching section from ISB to ESM

Courtesy D. Sertore, R. Paparella

BriXSinO's injector the BD

An innovative injector in more aspects:



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

The two bunchers perform both compression & acc.

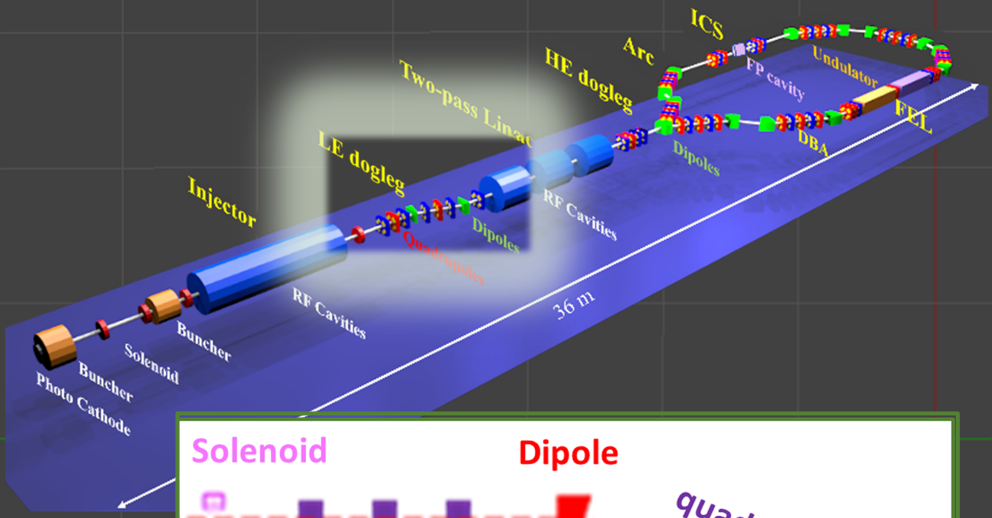
BD @ injector exit:

- 1mm envelope size
- 1mm sig_z size
- 1um xy norm. emit
- A very low energy spread

→ Very good to enter into the disp. path

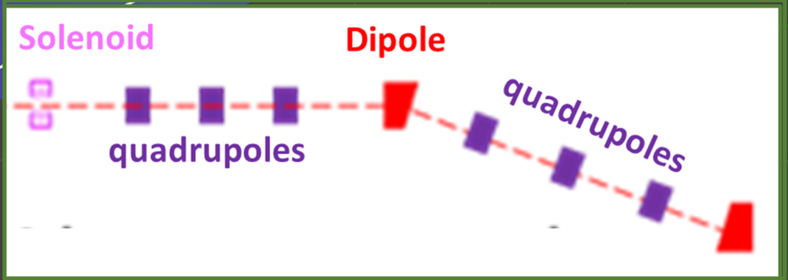
Courtesy A. Bacci

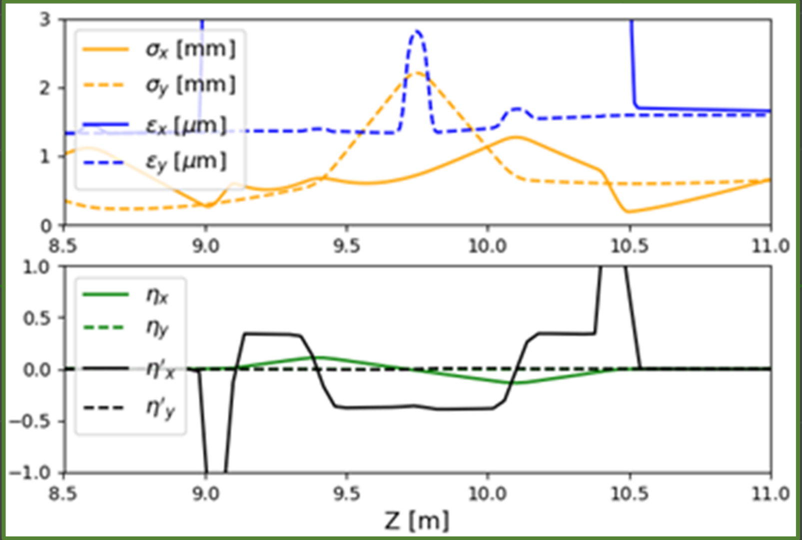
The BriXSinO's injector the dispersive path



BD @ the dispersive path exit:

- The emittance are conserved
- eta & eta' are reset to zero

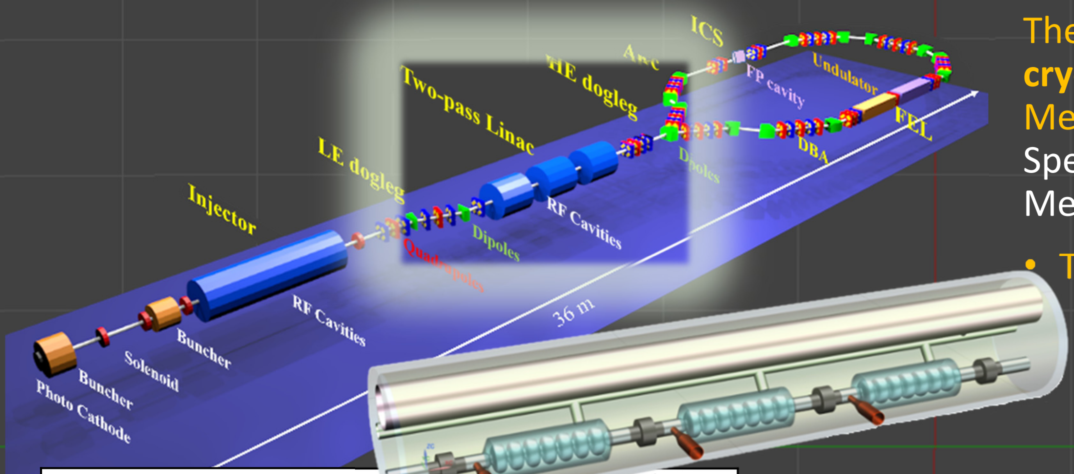




It is a standard dogleg but the BD is complex by the space charge. It is used the Genetic Algorithm GIOTTO [IPAC 2016 WEPOY039] to solve the BD.

Courtesy A. Bacci

The ERL Superconducting Module - ESM



Parameter	Value
Type Of Accelerating Structure	Standing Wave
Accelerating Mode	TM_{010} p-mode
Fundamental Frequency [MHz]	1300
Design Gradient [MV/m]	16.5
Intrinsic Quality Factor Q_0	$2\cdot10^{10}$
Loaded Quality Factor Q_{EXT}	$3.25\cdot10^{7}$
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
Cavity Bandwidth $df=f/(2\cdot Q_{EXT})$ [Hz] HWHM	20
Total longitudinal loss factor $k_{||}$ [V/pC], s = 0.6 mm	14.7
Longitudinal loss factor, [V/pC], non fundamental, s = 0.6 mm	13.1
Transverse loss factor [V/pC], s = 0.6 mm	13.7

The **ESM is a two-way, energy recovery cryomodule** boosting 5 mA beam energy to 45 MeV.

Spent, **counter-propagating beam** is dimmed to 5 MeV for the low-energy dump

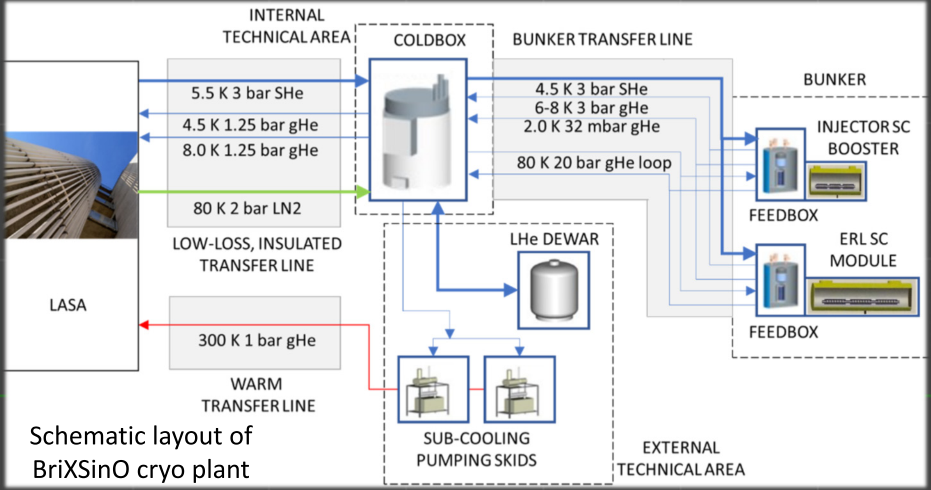
- Three 7-cells SC cavities
  - **Zero nominal beam loading**
  - **High Q** to minimize cryogenic load
  - RF chain design driven by 20 Hz_{rms} residual microphonics
- Several **common technical solutions** shared by ESM and
  ISB vessels
  - Cryogenic piping and structures layout
  - Inter-cavity HOM adsorbers
- **Re-acceleration** at lower current by phase matching
  - Beam-to-RF phase tuning section in the loop

Courtesy D. Sertore, R. Paparella

Cryogenics

The **cryogenic plant** of the BriXSinO complex will integrate the central LASA plant and provide support to:

- **Controlled cool-down and warm-up** of cold masses
- Stable **stand-by cryogenic configurations** for long stops at a safe intermediate temperature between beam runs
- Safe **cold operations** at peak cavity performances



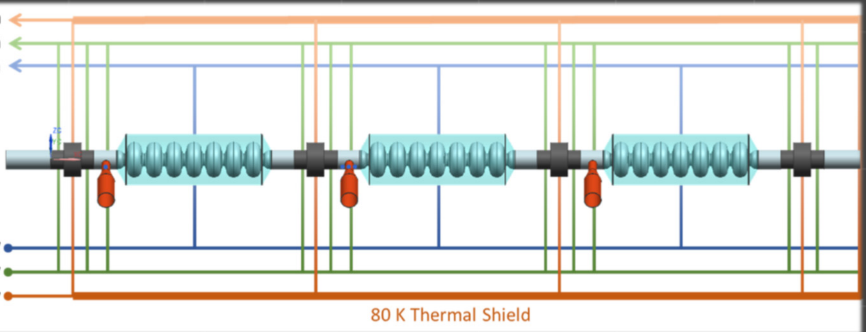
Schematic layout of BriXSinO cryo plant

HOM thermal power is exchanged **to liquid nitrogen coolant** via pressurized helium gas stream

- Larger heat load dynamic range

Intercepts	ISB Static	ISB Dyn.	ESM Static	ESM Dyn.	Total Static	Total
	W	W	W	W	W	**W**
2.0 K	5	4	5	36	10	**50**
4.5 K	48	12	43	6	91	**109**
80 K	136	240	128	210	264	**714**

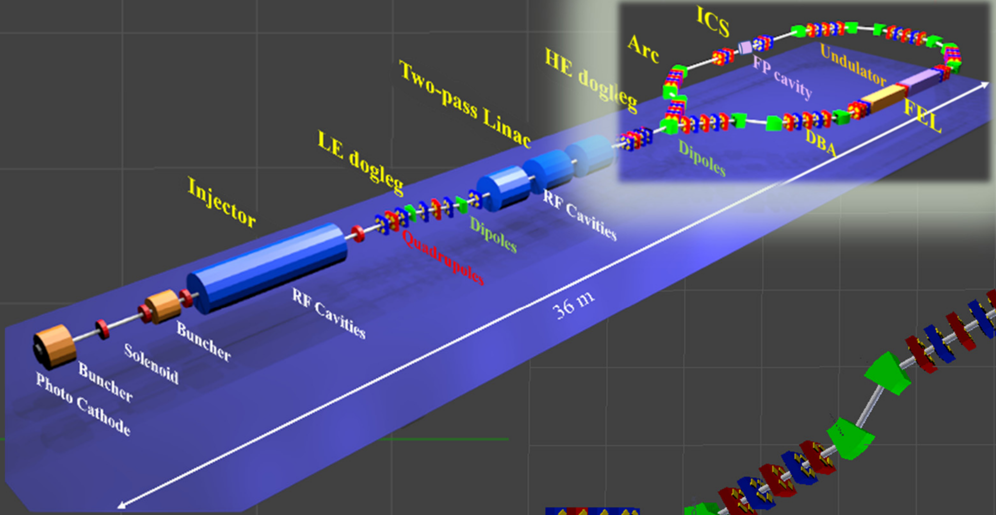
Expected cryogenic BriXSinO heat loads



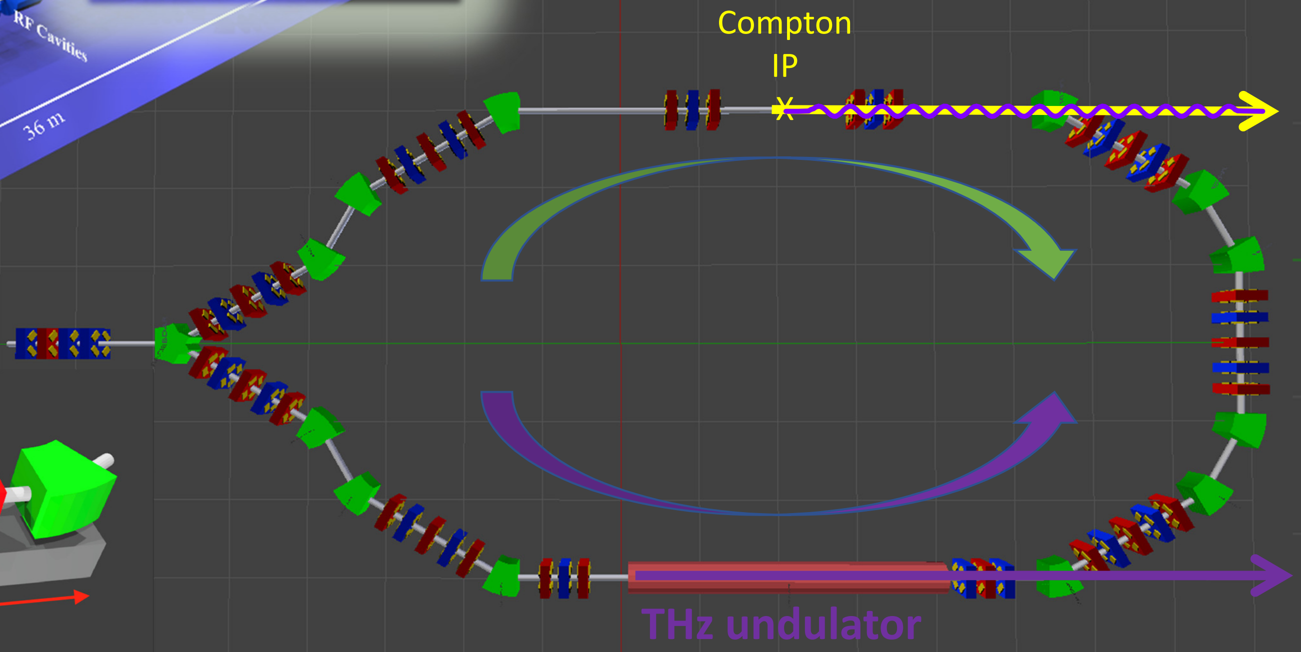
Schematic cryogenic circuitry for ESM

Courtesy D. Sertore, R. Paparella

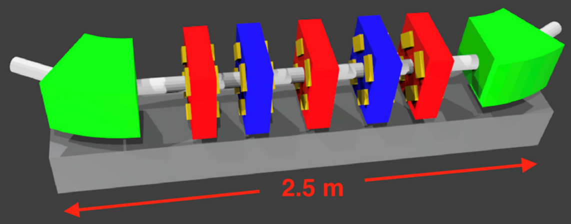
ARC



ICS
Arc
HE dogleg
Two-pass Linac
LE dogleg
Injector
FP cavity
Undulator
FEL
DBA
Dipoles
RF Cavities
Quadrupoles
36 m
Buncher
Solenoid
Photo Cathode

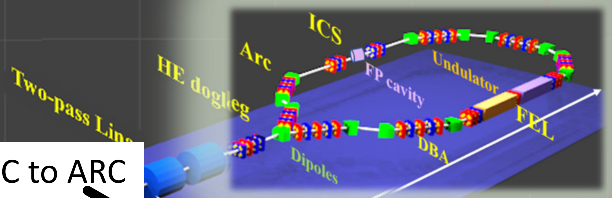


Compton
IP
THz undulator

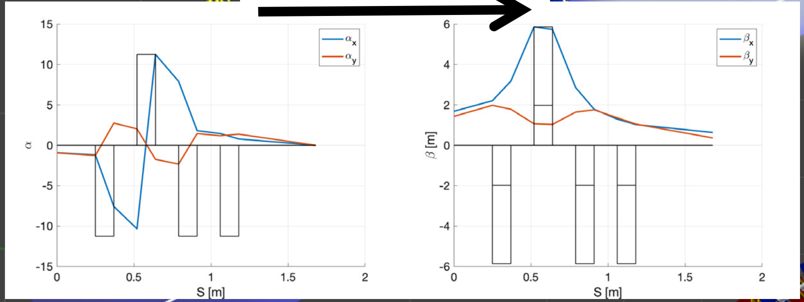


2.5 m

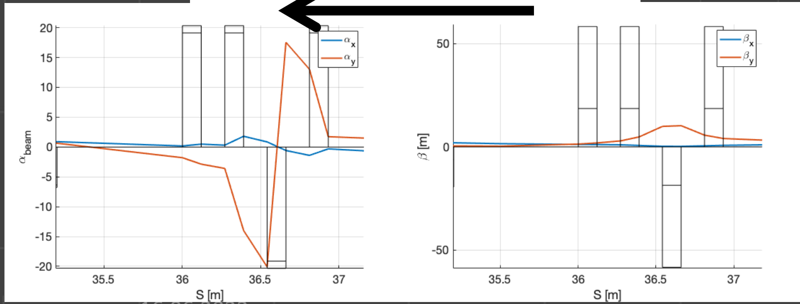
ARC

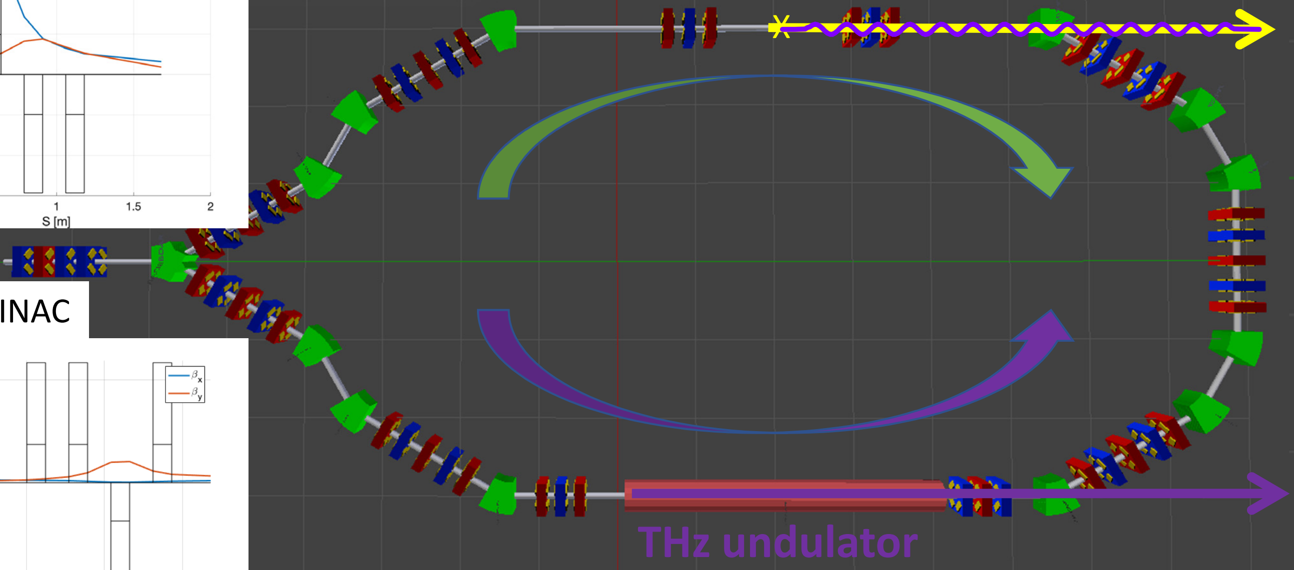


From LINAC to ARC

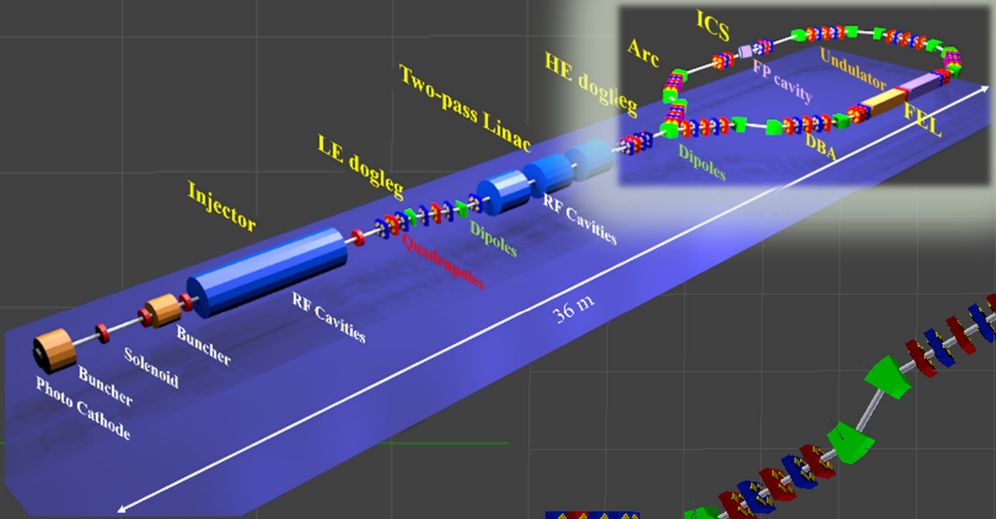


Returned from ARC to LINAC





ARC



ICS
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Injector
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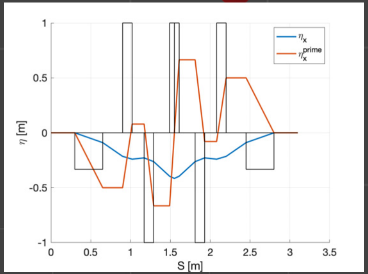
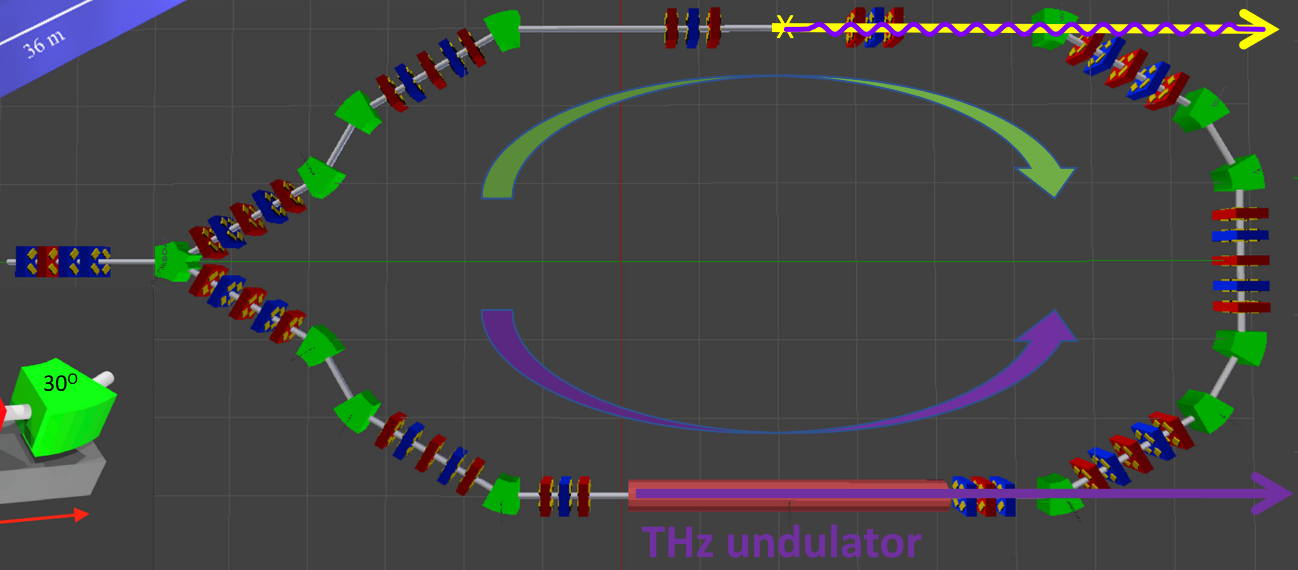
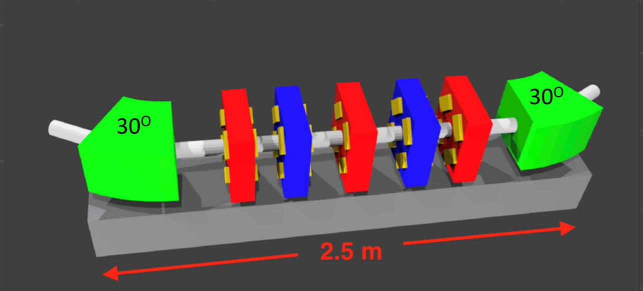
36 m
Buncher
Solenoid
Buncher
Photo Cathode



η [m]
S [m]

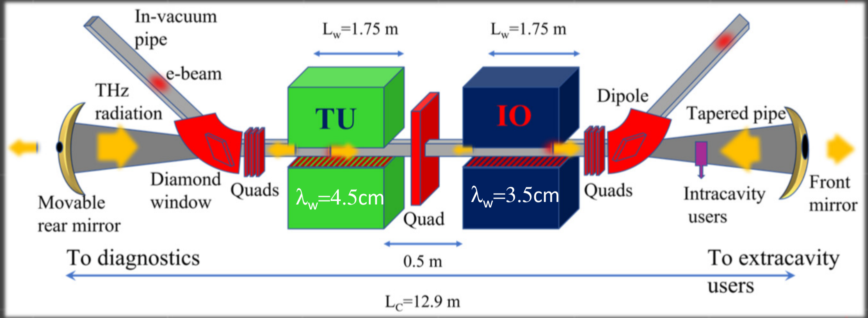


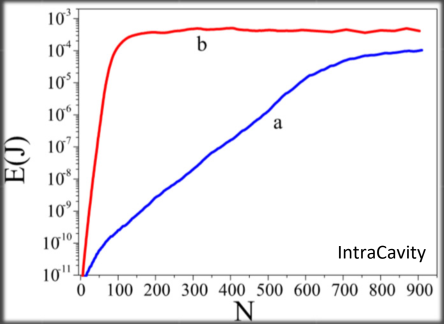
Compton
IP
THz undulator



30°
30°
2.5 m

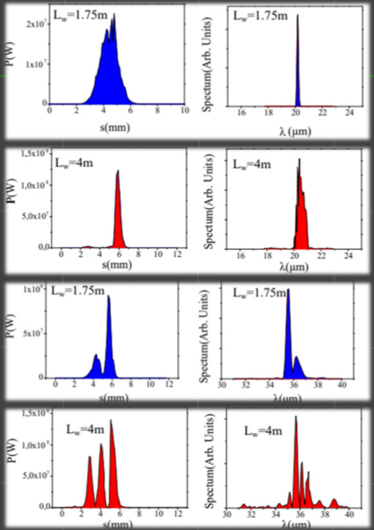
TerRa@BriXSino: FEL oscillator for TeraHertz production





Growth of the radiation vs number of round trips (a) L_w= 4m (only IO), (b) L_w=1.75 m (TU&IO)

Power Spectrum



IO tuned at λ=20 µm

TU and IO tuned at the same λ=20 µm

IO tuned at λ=35 µm

TU and IO tuned at the same λ=35 µm

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

Courtesy V.Petrillo

Submitted in NIM

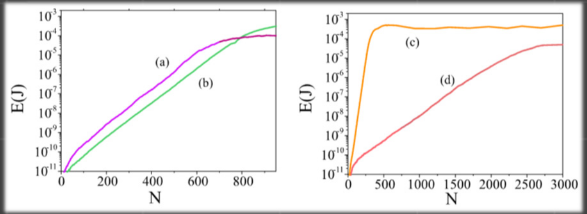
Production of two color terahertz radiation

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

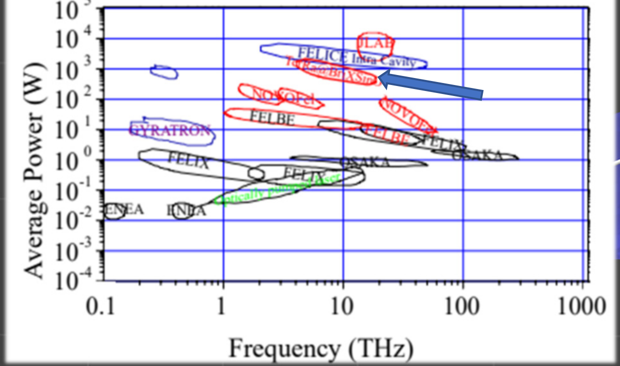
Undulator	IO	TU	IO	TU
Electron energy	40 MeV	40 MeV	20 MeV	20 MeV
Wavelength	20 μm	35 μm	40 μm	50 μm
Single shot IC energy	84 μJ	305 μJ	340 μJ	46 μJ
Single shot EC energy	3.36 μJ	12.2 μJ	13.6 μJ	1.84 μJ
Average power	0.156 kW	0.6 kW	0.63 kW	0.085 kW
Bandwidth	0.65%	0.7%	0.49%	0.46% 0.5%
Size	2 mm	2.5 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	1200μm
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

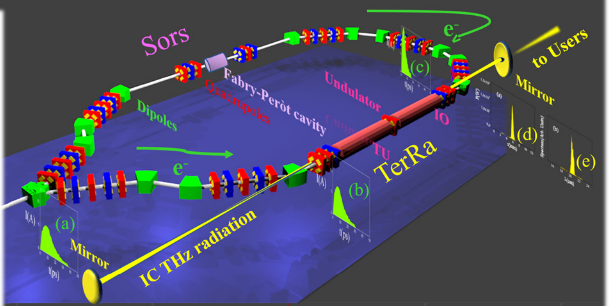
IO tuned at λ=20 μm and TU tuned at λ=35 μm for E_e=40 MeV
IO tuned at λ=40 μm and TU tuned at λ=50 μm for E_e=25 MeV

Growth of radiation vs number of round trips

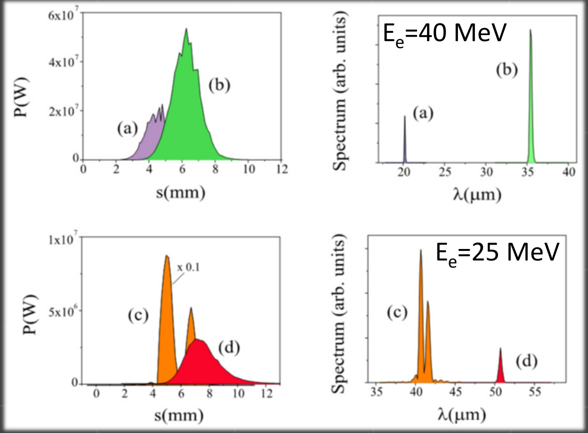


Performance of BriXSinO





Power Spectrum



Courtesy V.Petrillo
Submitted in NIM

LASER system for ISC

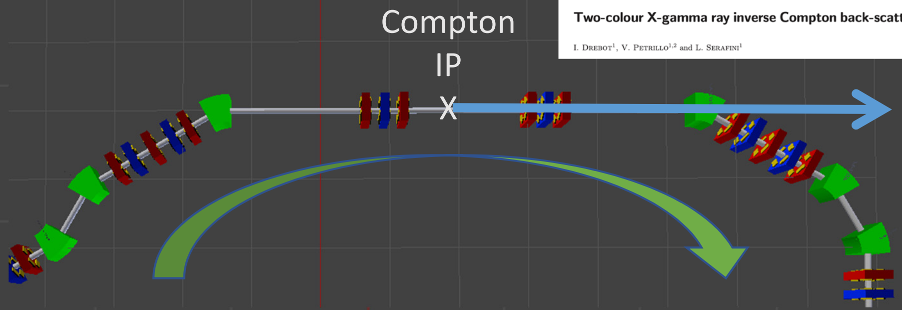
$$\varepsilon_{\gamma m} = \frac{4\gamma^2 \varepsilon_L \cos^2\frac{\alpha_0}{2}}{4\gamma\frac{\varepsilon_L}{mc^2}\cos^2\frac{\alpha_0}{2}+1} \approx 4\gamma^2\varepsilon_L cos^2\frac{\alpha_0}{2}$$

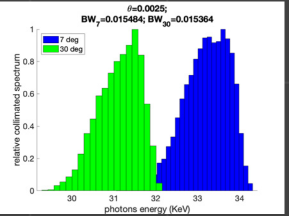
epl A Letters Journal Exploring the Frontiers of Physics
October 2017
EPL, 120 (2017) 14002 www.epljournal.org
doi: 10.1209/0295-5075/120/14002

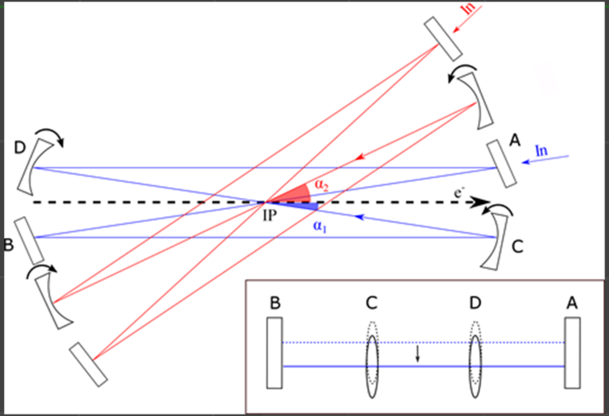
Two-colour X-gamma ray inverse Compton back-scattering source

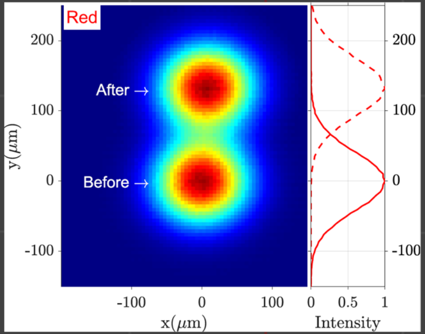
I. Drebot[1], V. Petrillo[1,2] and L. Serafini[1]

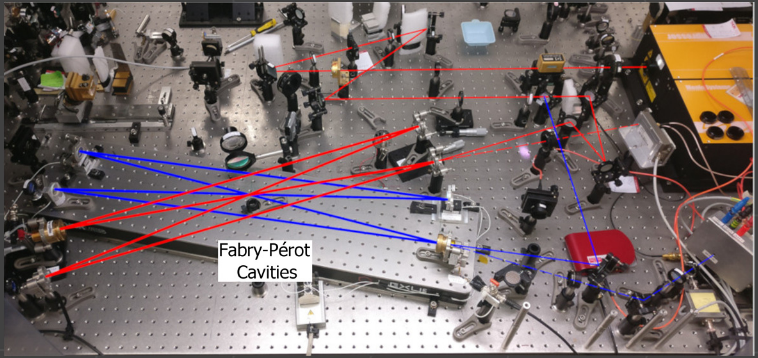
Laser Parameter	Value
Pulse energy (mJ)	2.7
Wavelength(nm)	1030
Pulse length (ps)	1.5
Repetition rate (MHz)	1300./ 14
Focal spot size (x,rms,μm)	90
Focal spot size (x,rms,μm)	80
Laser parameter a_0	$3.3\ 10^{-3}$
Collision angle ()	7
Collision angle for two colors ()	30











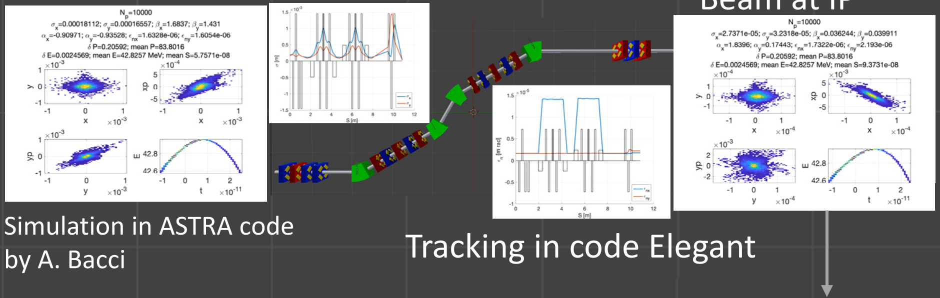
 Published in NIM doi: 10.1016/j.nima.2021.165852

BriXSinO

Start to end simulation

Beam from linac

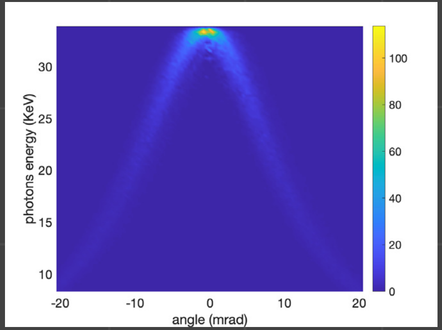
Beam at IP



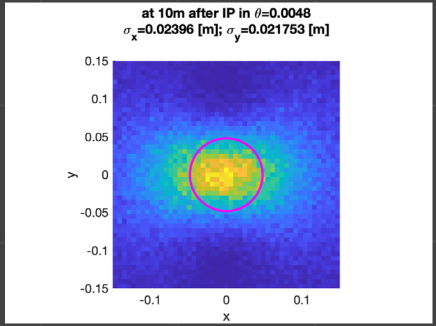
Simulation in ASTRA code by A. Bacci

Tracking in code Elegant

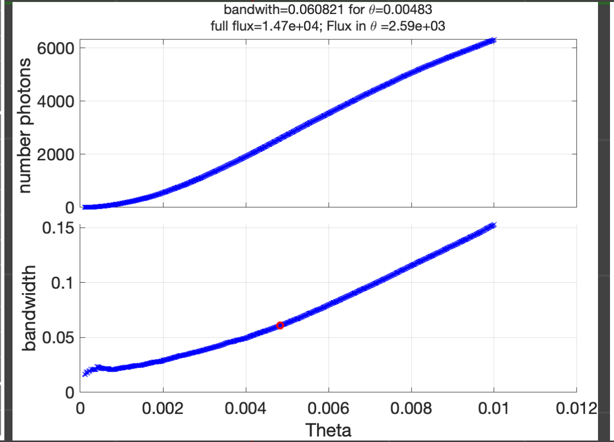
deceleration

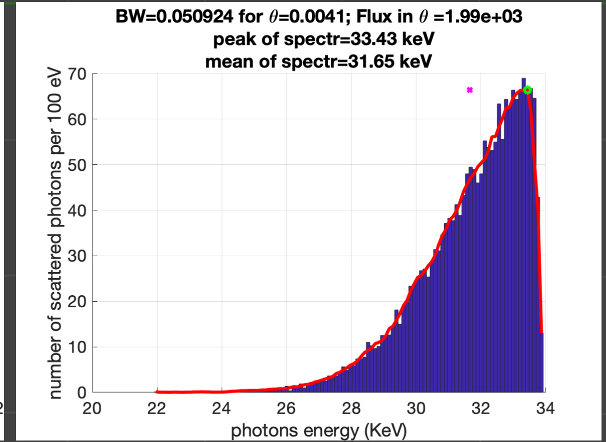


X-ray at 10 m



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

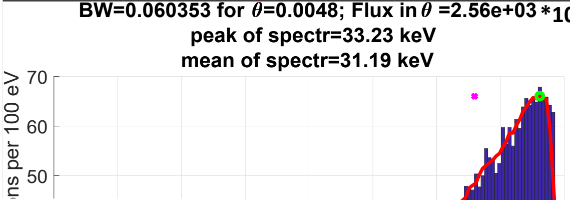


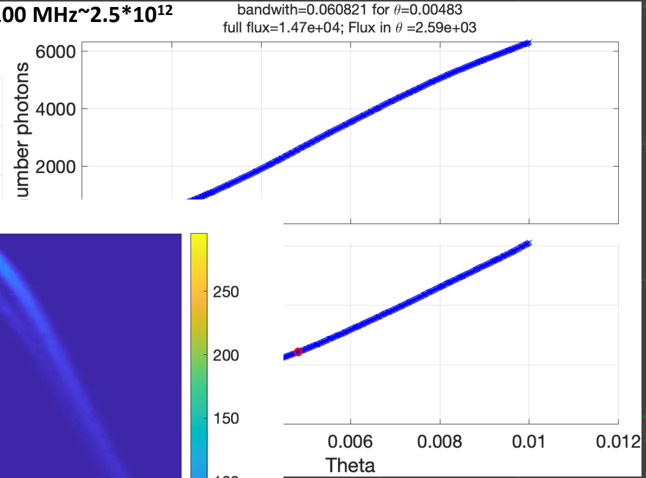


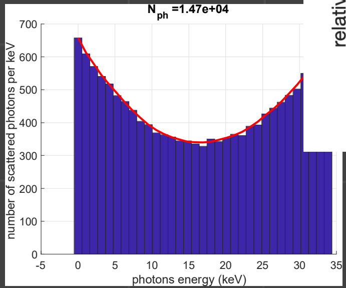
BriXSinO

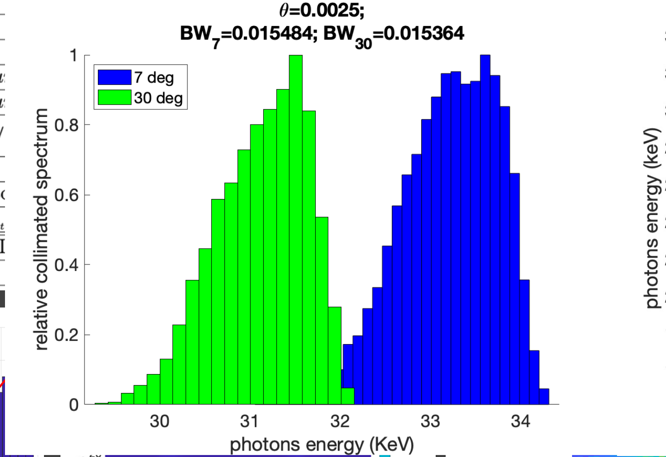
Start to end simulation

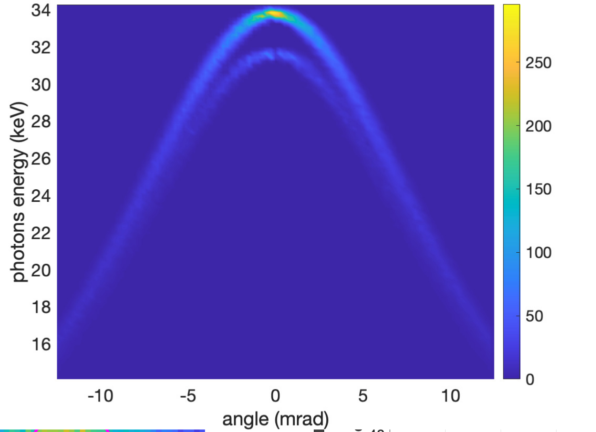
Electron beam Parameters	
Electrons mean energy $[MeV]$	4.28257e+01
Bunch charge $[C]$	1.00000e-10
Bunch length rms, FWHM $[\mu m]$	2.29571e+03, 5.11277e+00
Nominal normalized ϵ_{nx}, ϵ_{ny} $[mm.mrad]$	1.73224e+00, 2.19305e+00
Nominal relative energy spread σ_e %	2.45647e-01
Focal spot size σ_x, σ_y μm	2.73712e+01, 3.23179e+01
Laser Parameters	
Laser pulse energy (J)	
Laser wavelength (nm)	
Laser pulse length $[psec]$	
Laser focal spot size w0x RMS $[\mu$	
Laser focal spot size w0y RMS $[\mu$	
Laser papameter $\alpha_0 = 6.8 * (\lambda_{las}/$	
Collision angle [deg]	
γ-ray Phot	
Nominal # photons per shot N_{ph_t}	
Source rms size $\sigma_{\gamma x}$, $\sigma_{\gamma y}$ $[\mu m]$ at I	
Rad. pulse length $\sigma_{\gamma z}$ $[psec]$	

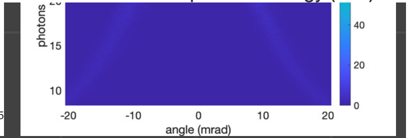


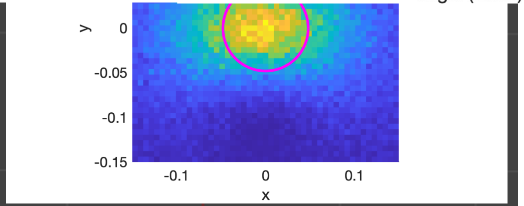


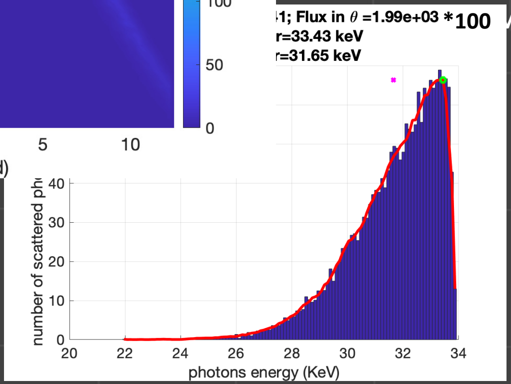




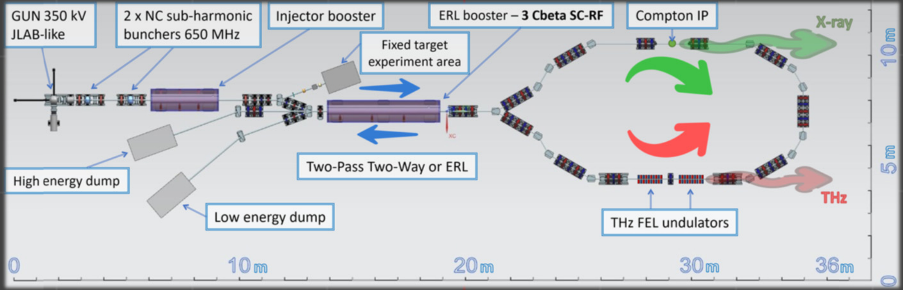




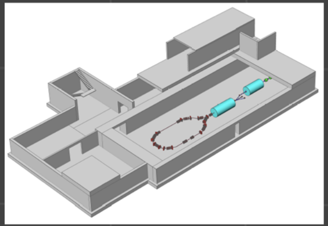




Conclusion



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



LASA aerial view and rendering of the building

Articles:

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)

Submitted:

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,* (2022)

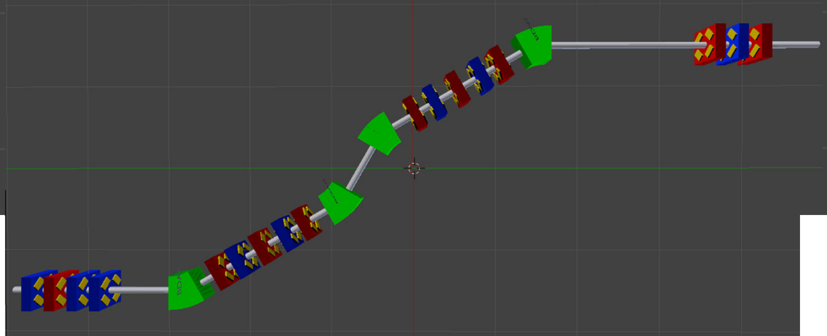
Also at IPAC '22 posters: **WEPOS042; MOPOTK016 and THPOPT025**

BriXSinO

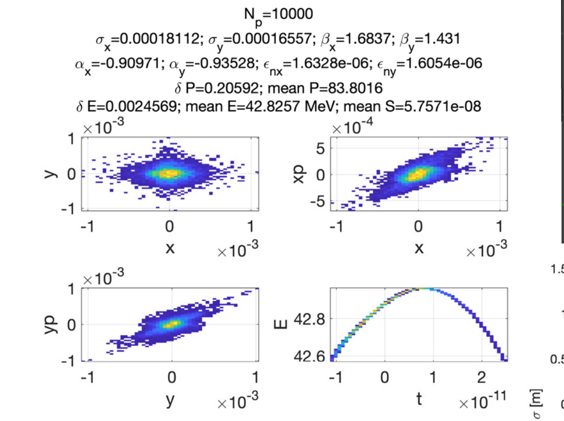
Star to end simulation

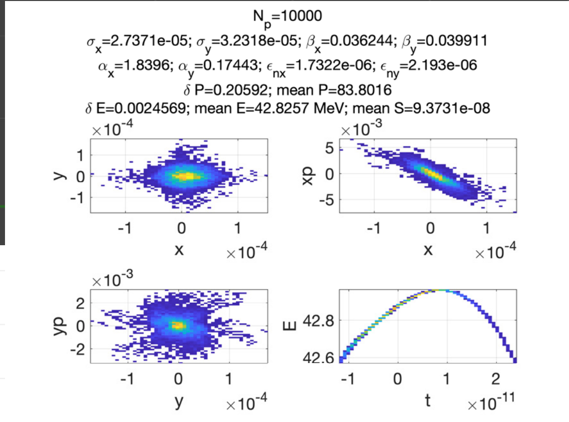
Beam from linac

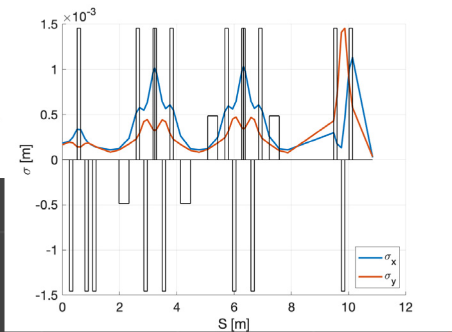
Beam at IP

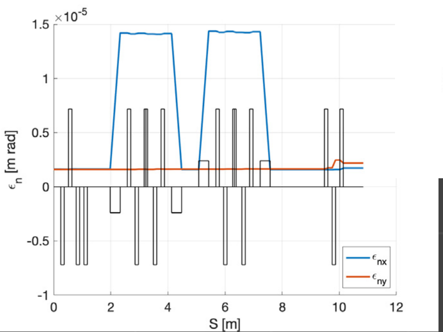


Tracking in code Elegant









Simulation in ASTRA code
by A. Bacci

BriXSinO

Start to end simulation

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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
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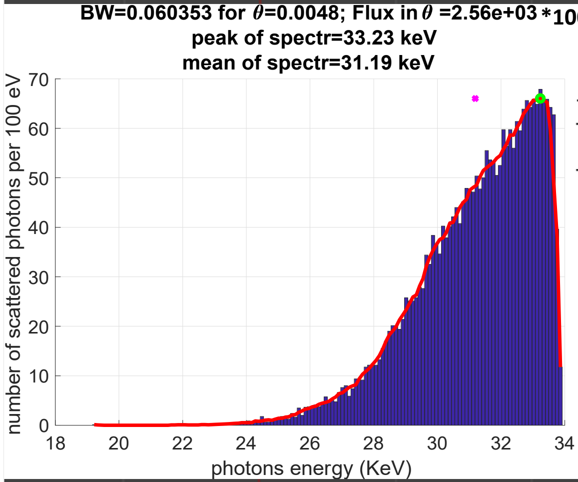
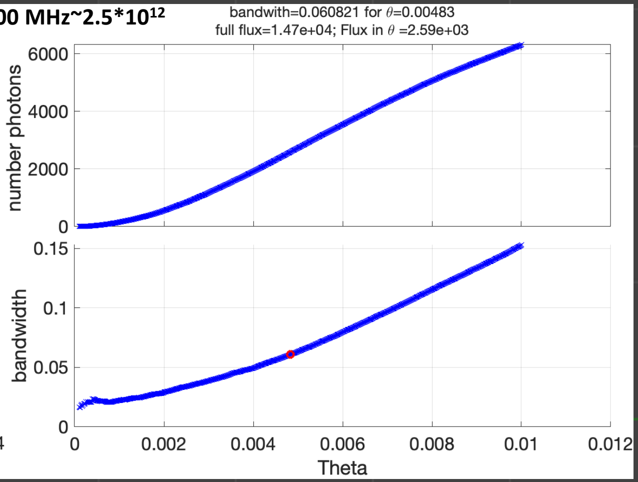
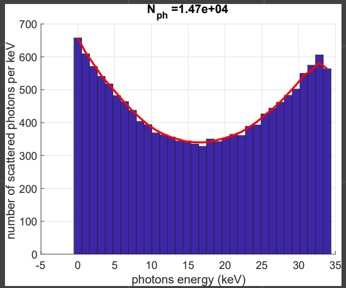
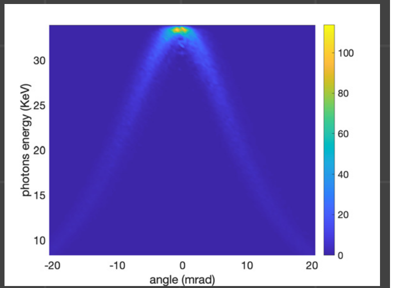
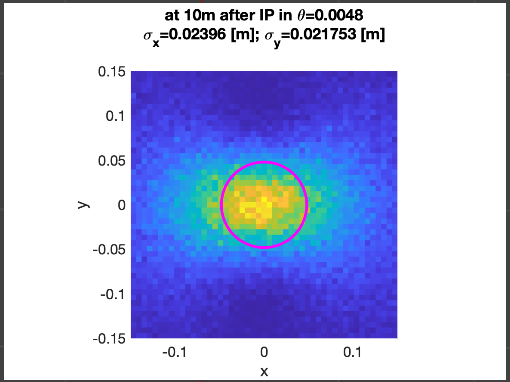
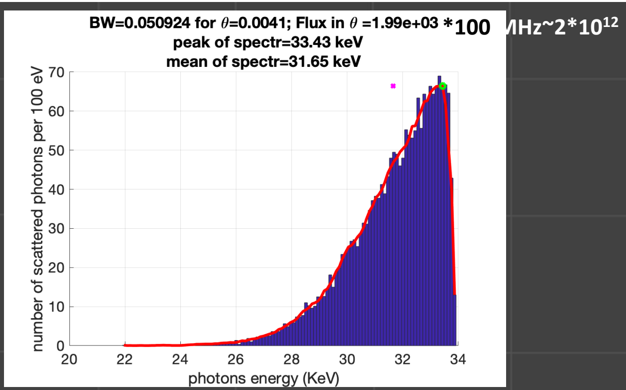












ARC

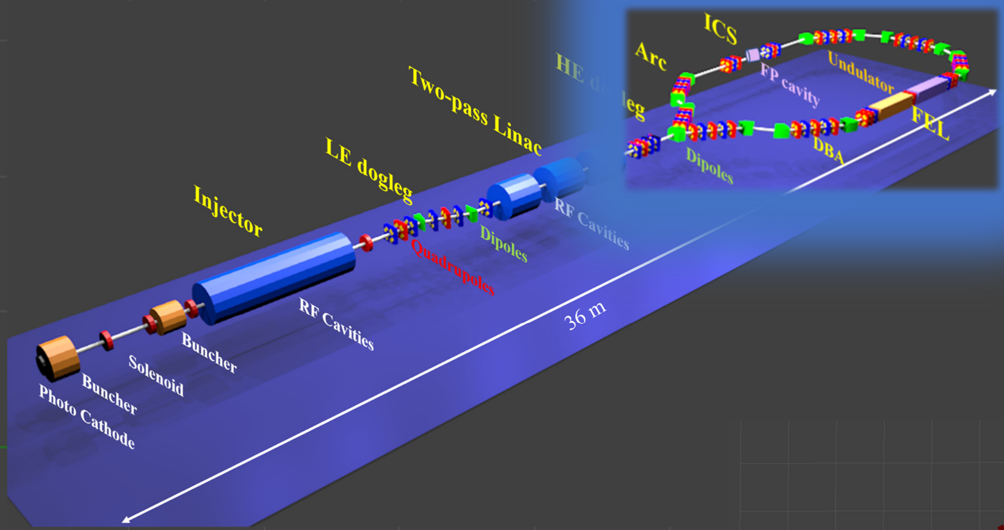
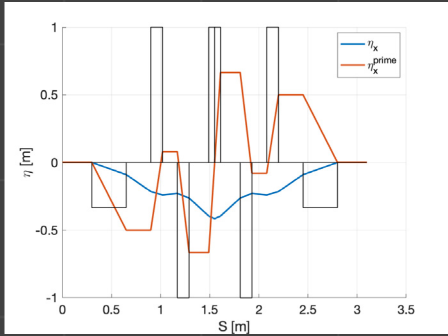
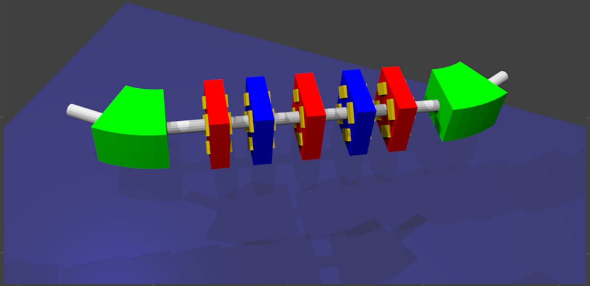
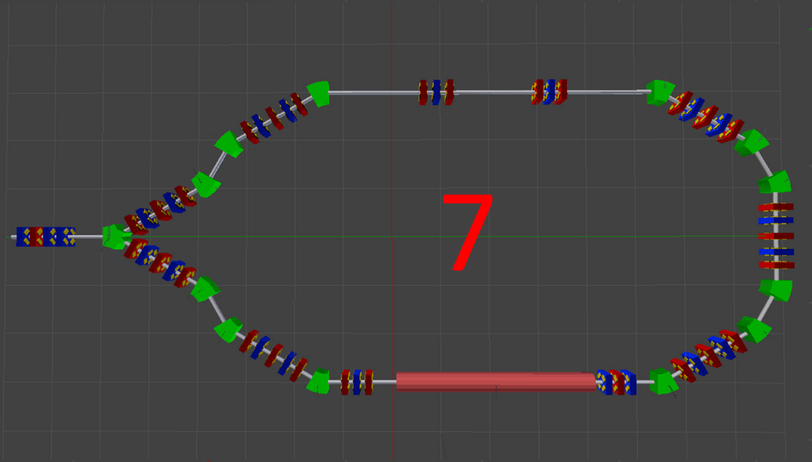


Photo Cathode
Buncher
Solenoid
Buncher
RF Cavities
Injector
Quadrupoles
LE dogleg
Dipoles
Two-pass Linac
RF Cavities
36 m
Arc
ICS
FP cavity
Undulator
FEL
DBA
Dipoles

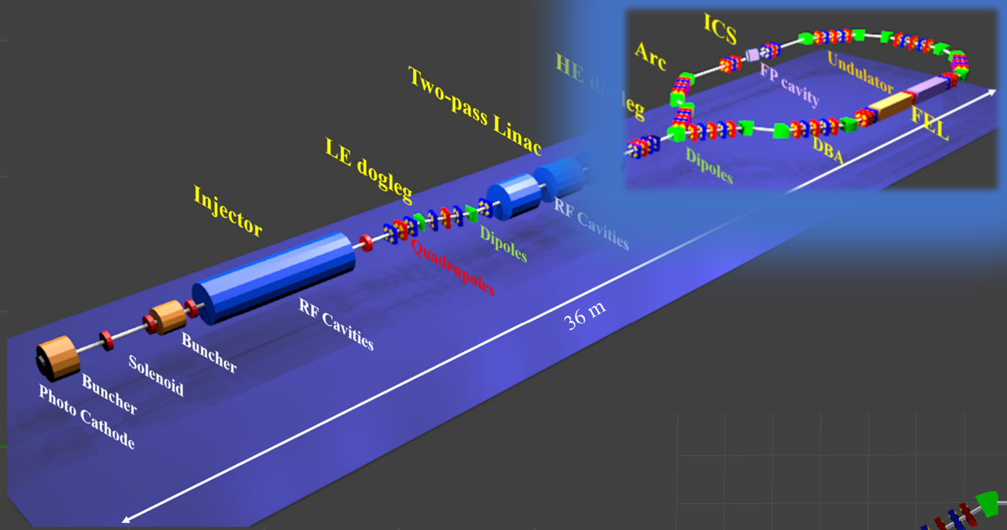

η_x
η_x^{prime}
η [m]
S [m]
1
0.5
0
-0.5
-1
0
0.5
1
1.5
2
2.5
3
3.5

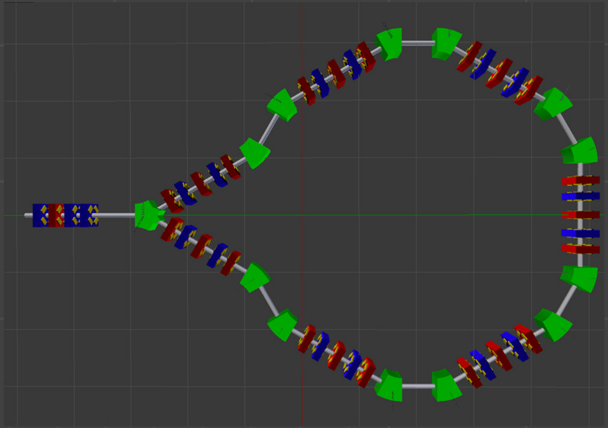


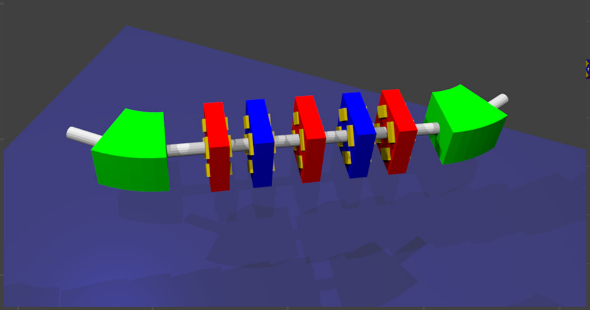

7

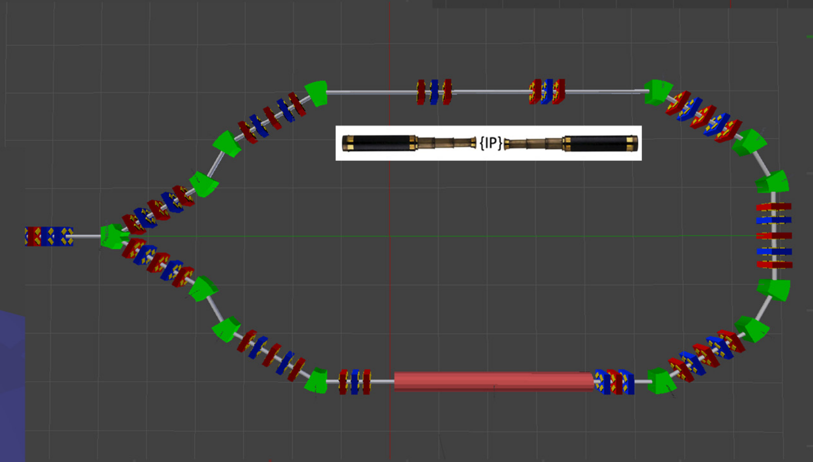
INFN MILANO BriXSinO IPAC22

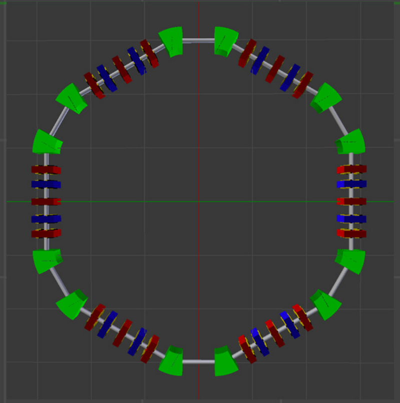
ARC



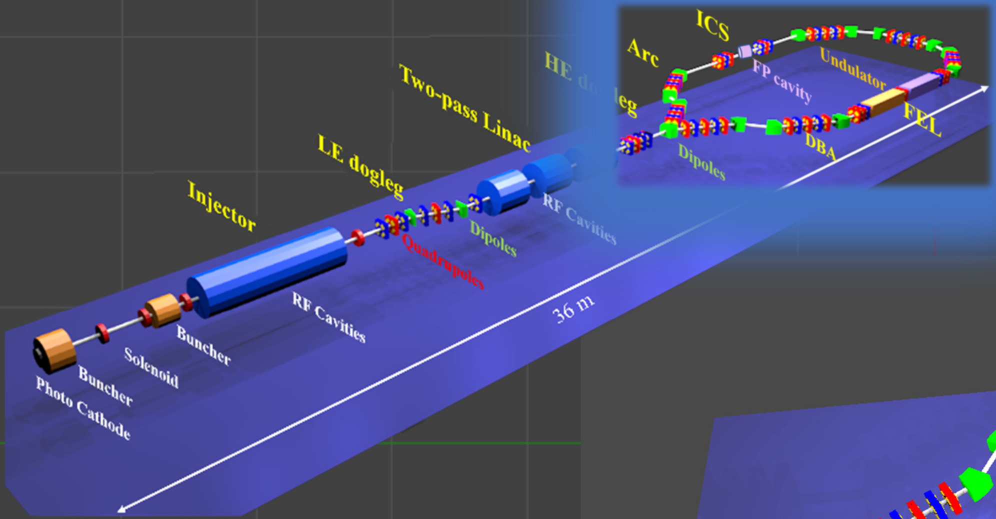




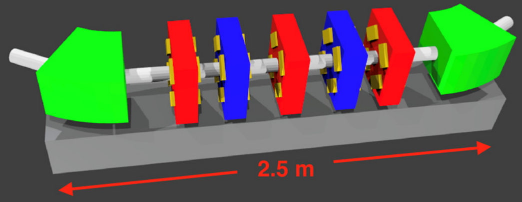


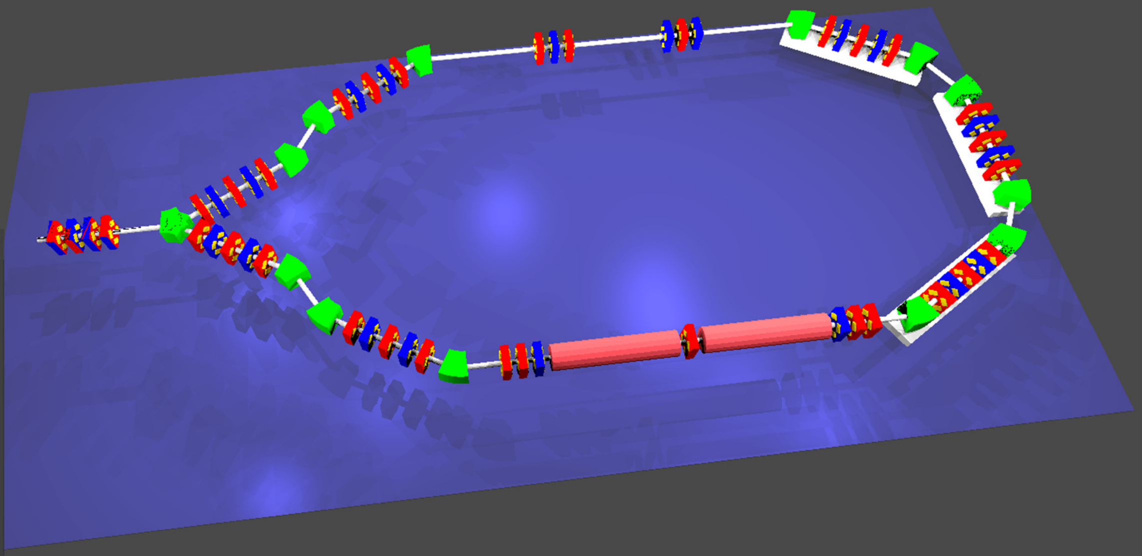


ARC



Phase matching

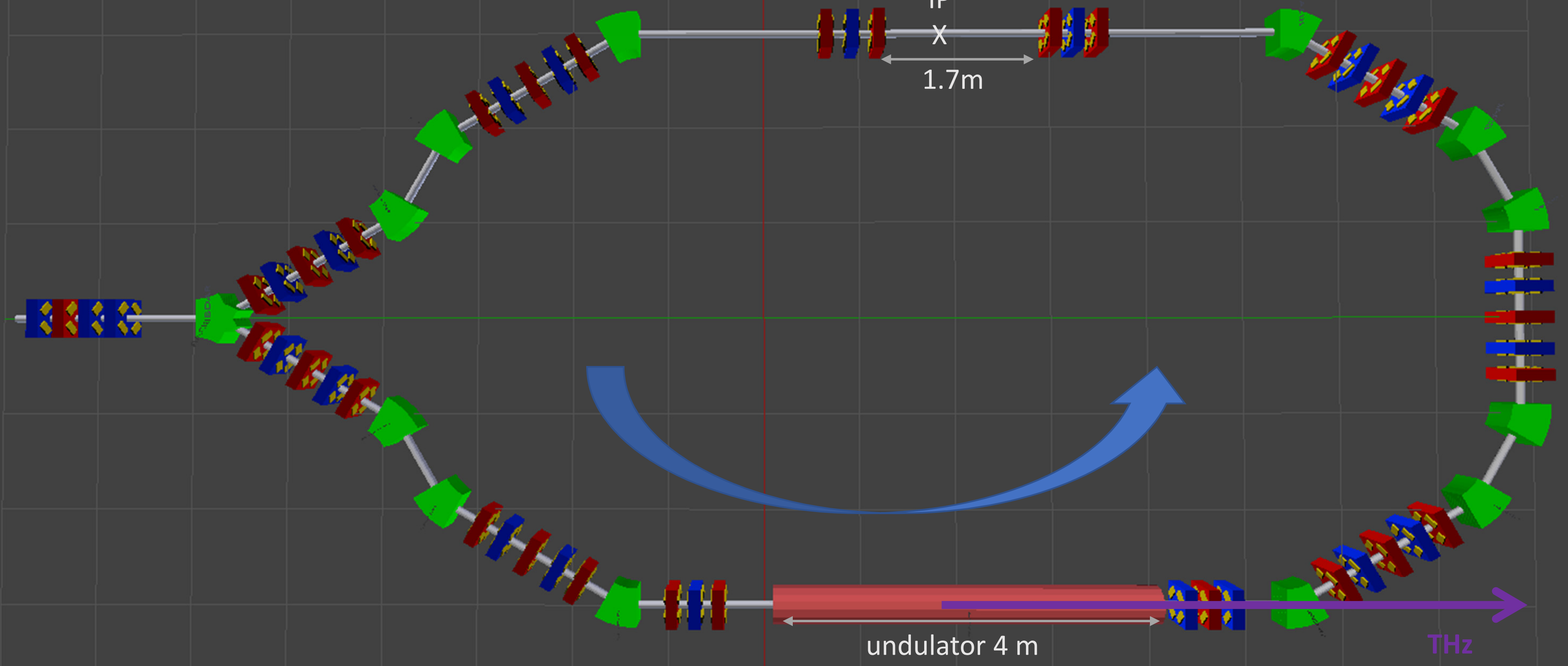




BriXSinO
ARC-DBA

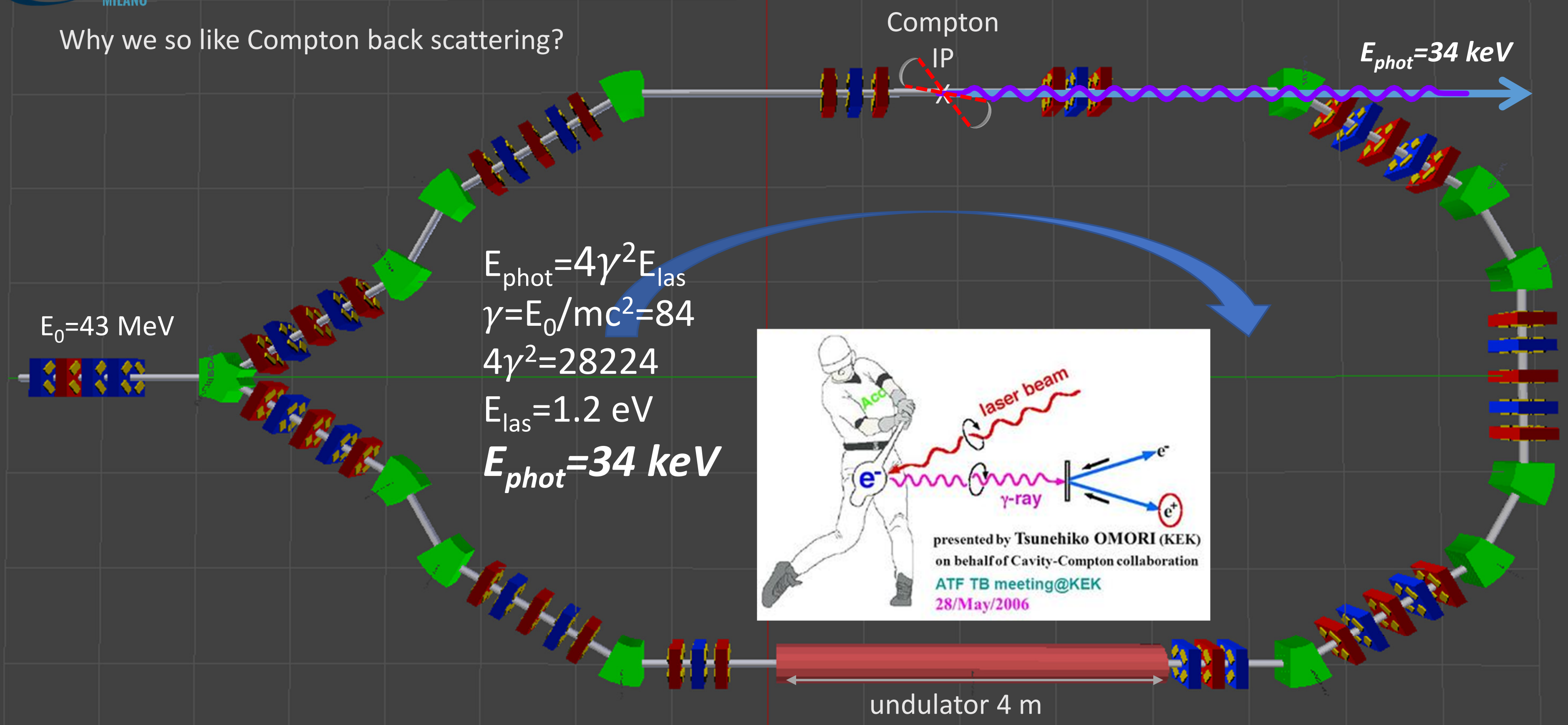
INFN MILANO

Arc footprint.   6x16 m



BriXSinO

Why we so like Compton back scattering?



$E_{phot}=4\gamma^2 E_{las}$

$\gamma=E_0/mc^2=84$

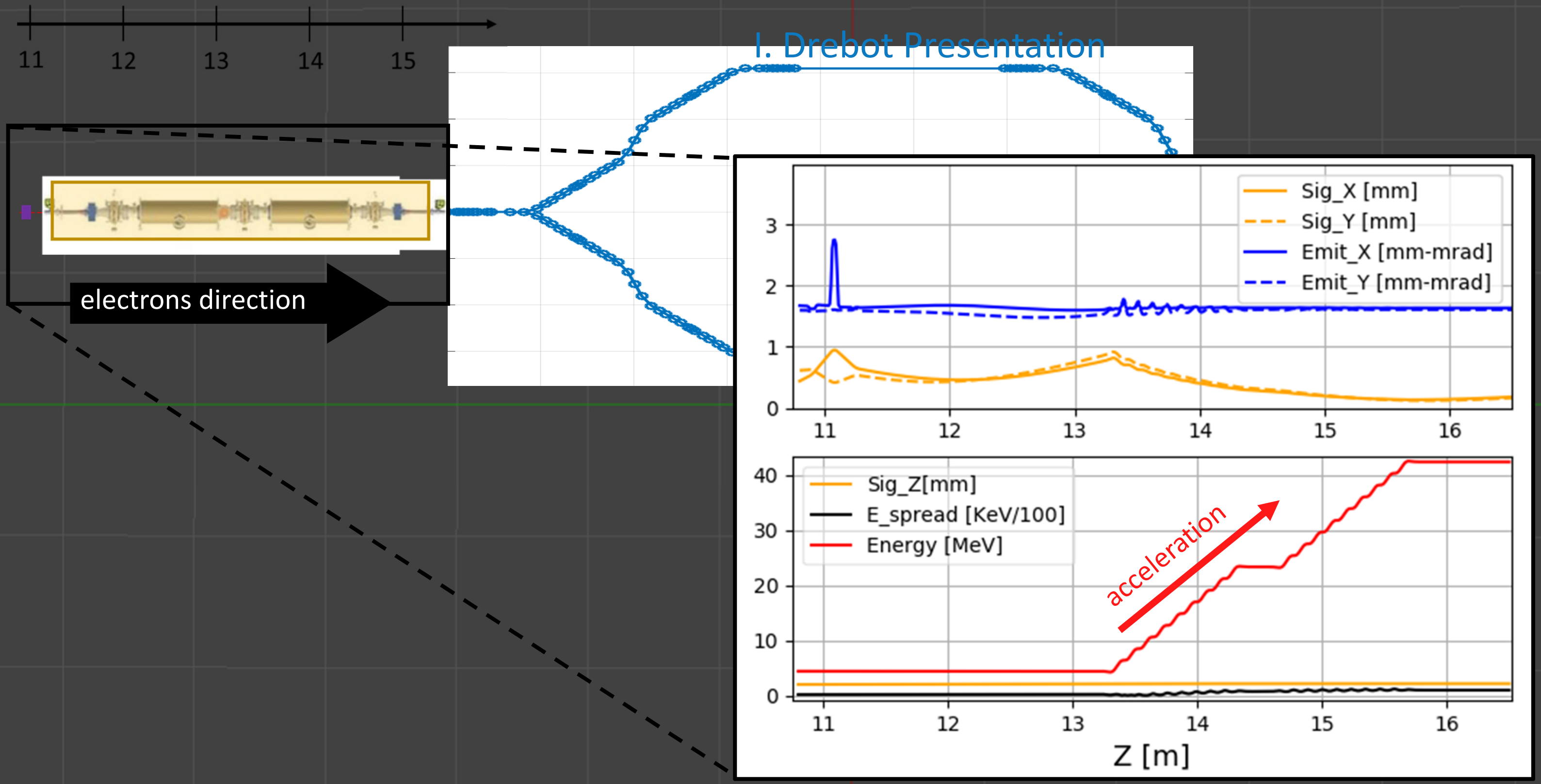
$4\gamma^2=28224$

$E_{las}=1.2$ eV

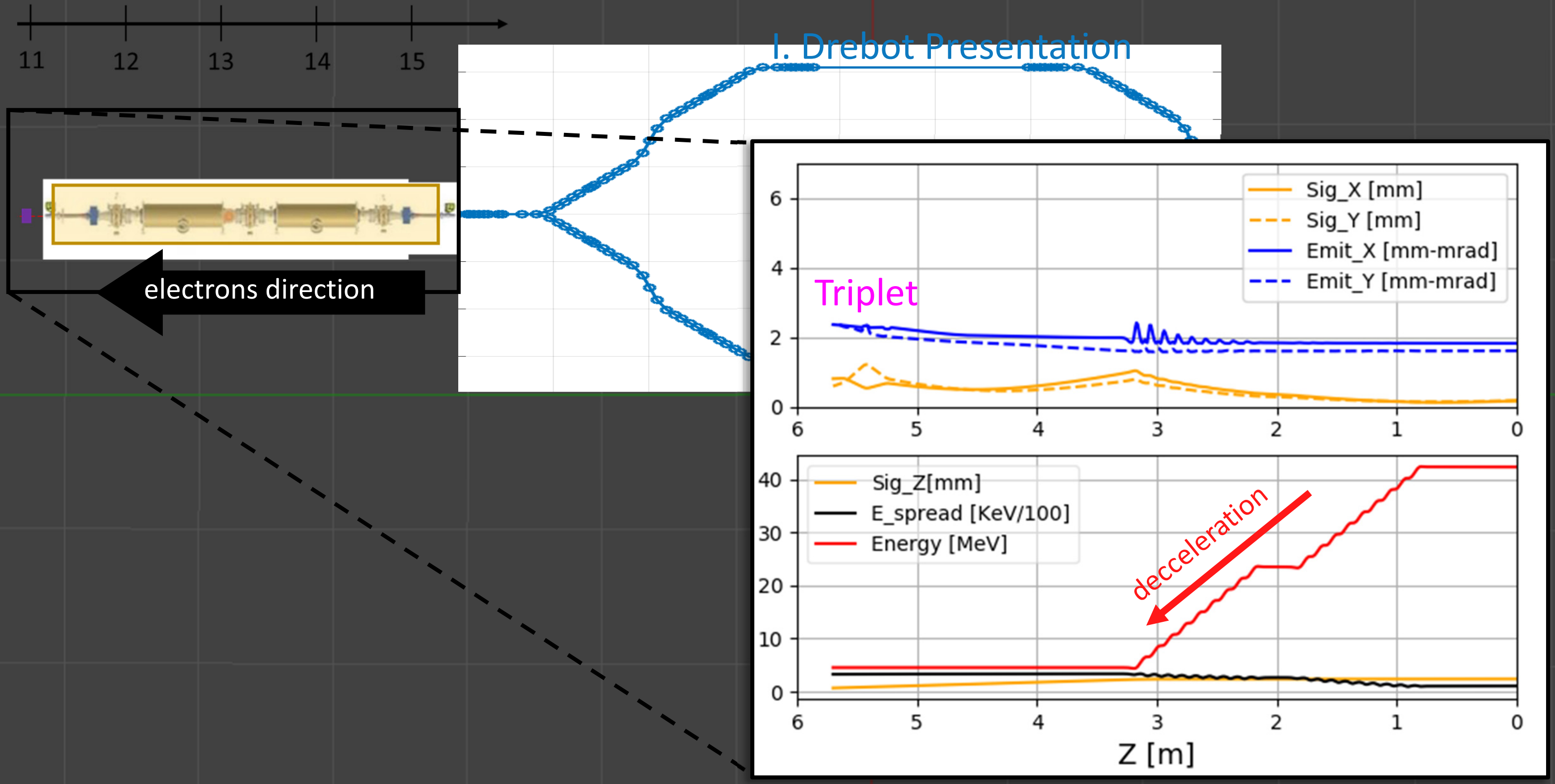
$E_{phot}=34$ keV

Forward direction

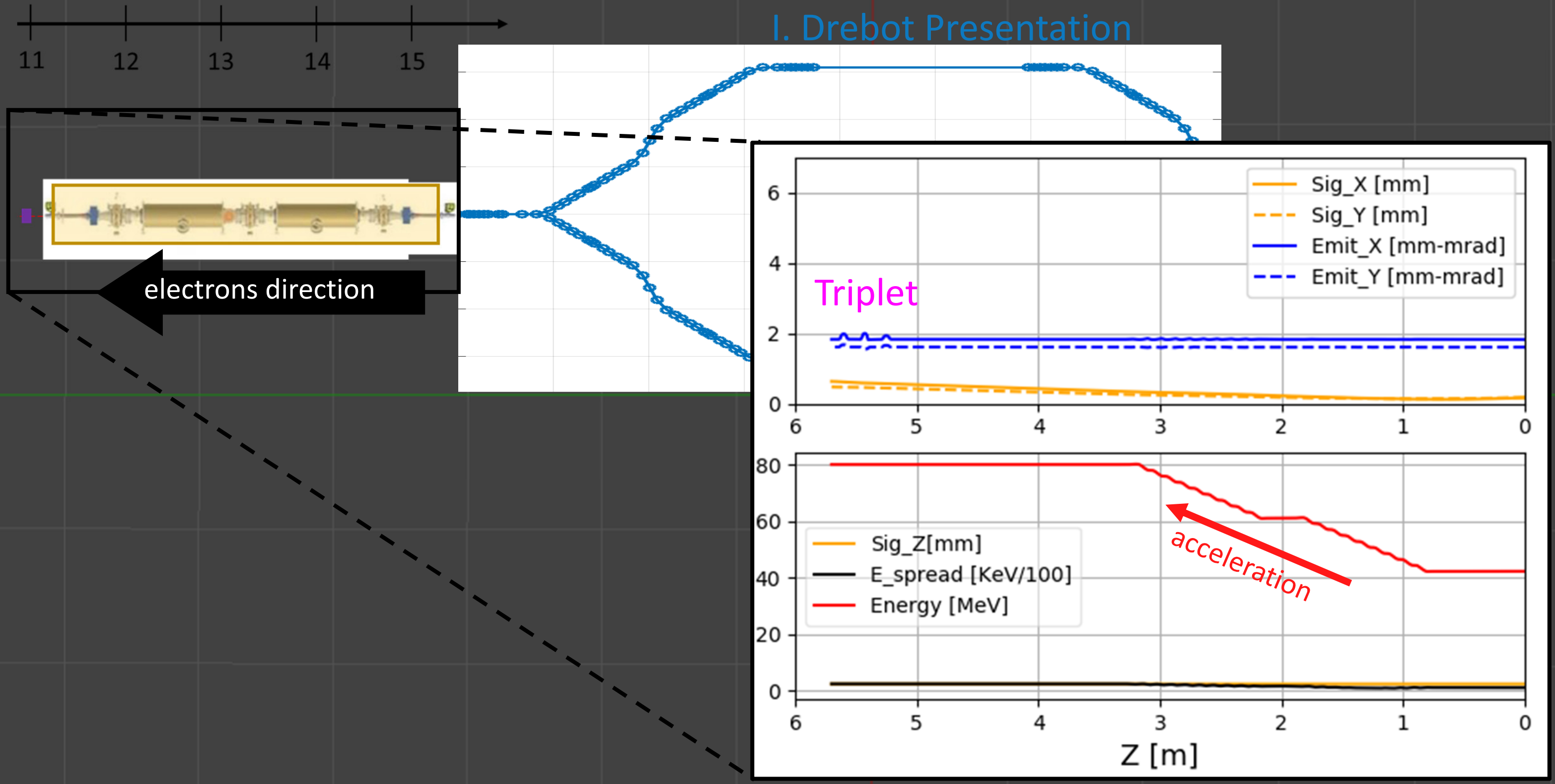
I. Drebot Presentation



1) Backward direction ERL case

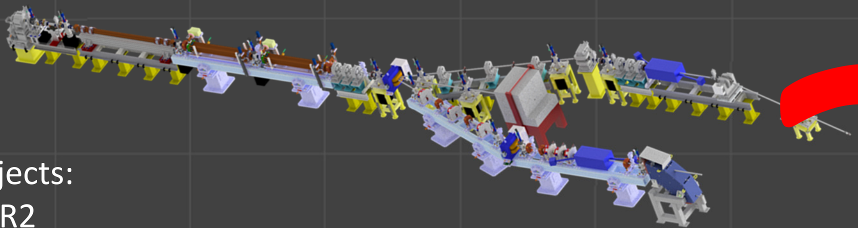


2) Backward direction MariX test case



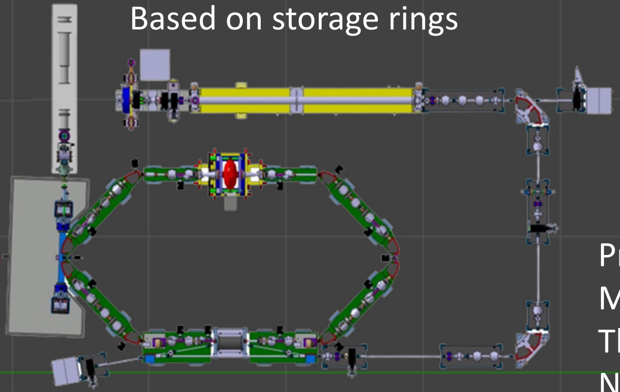
Two main conception of light source based on ICS

Based on linear accelerators



Projects:
STAR2
SMART*LIGHT

Based on storage rings



Projects:
MuCLS
ThomX
NESTOR

Number of scattering photons:

$$N = \frac{A_y A_x A_z}{2\pi\sqrt{\sigma_{y1}^2+\sigma_{y2}^2}} \frac{\sigma N_1 N_2 f}{\sqrt{\sigma_{x1}^2+\sigma_{x2}^2+(\sigma_{z1}^2+\sigma_{z2}^2)\tan(\frac{\alpha_0}{2})^2}}$$

$$N \sim \frac{\sigma_c f N_e N_L}{\sigma^2}$$

Advantage:
- Small emittance 2-3 mmrad
- Possibility to focus beam at 5-10 µm
- Hight flexibility in tuning

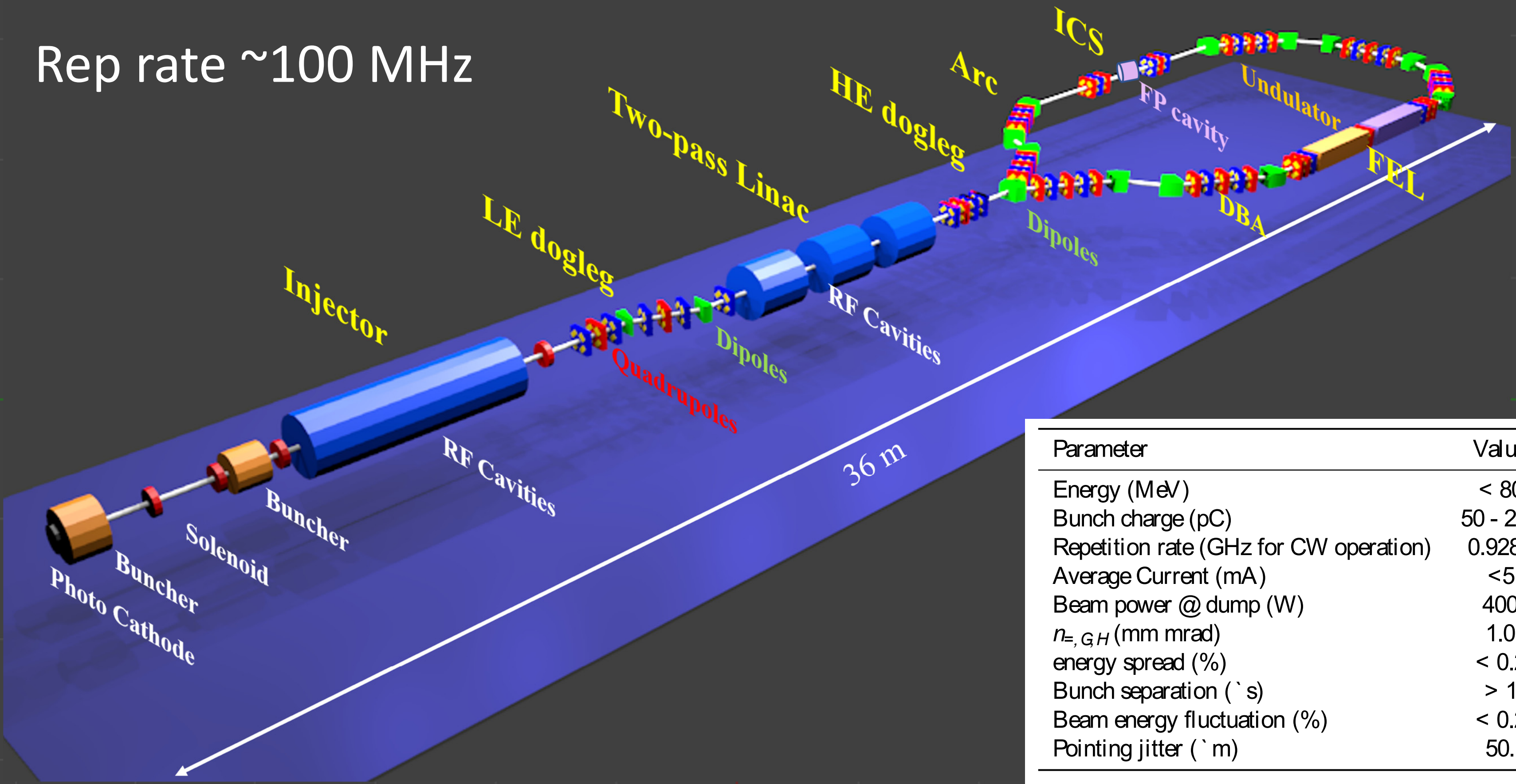
Disadvantage
- Low repetition rate 100 Hz

Advantage:
- Hight repetition rate 17.8 MHz

Disadvantage
- Bigger emittance 60 mmrad
- Bigger transvers size at IP ~70 µm

BriXSinO

Rep rate ~100 MHz



Parameter	Value
Energy (MeV)	< 80
Bunch charge (pC)	50 - 200
Repetition rate (GHz for CW operation)	0.9286
Average Current (mA)	<5
Beam power @ dump (W)	400
$n_{=,G,H}$ (mm mrad)	1.0
energy spread (%)	< 0.2
Bunch separation (`s)	> 1
Beam energy fluctuation (%)	< 0.2
Pointing jitter (`m)	50.

INFN MILANO BriXSinO

IPAC22

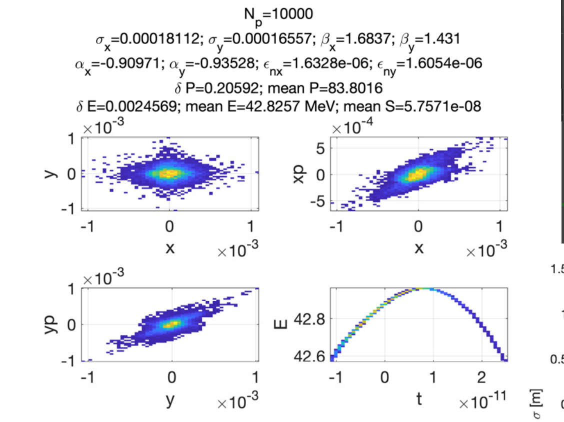
Table 1.1: A Comparison concerning efficiency and sustainability among Plasma Linacs (a), RT-Linacs (b), SC-RF Linacs (c), ERLs (d), Storage Rings (e), High power Cyclotrons (f). (*limited by beam dump **power emitted in synchrotron radiation *** 10 h life-time (360 MJ / 36,000 s))

ACCELERATOR	Energy Energy	Average current	Beam power	AC power	Efficiency b-t-p	Beam availability (beam power)	True efficiency
EuPRAXIA@SPARC_LAB (a)	5 GeV	0.3 nA	1.5 W	2 MW	7.5×10^{-7}	100% (1.5 W)	7.5×10^{-7}
BELLA (a)	7.8 GeV	5 pA	40 mW	200 kW	2.0×10^{-7}	100% (40 mW)	2.0×10^{-7}
STAR (b)	150 MeV	100 nA	15 W	400 kW	3.8×10^{-5}	100% (15 W)	3.8×10^{-5}
MariX (c)	3.8 GeV	50 µA	190 kW	17 MW	1.1%	100% (190 kW)	1.1%
Euro XFEL (c)	19 GeV	32 µA	608 kW	17.8 MW	3.4%	100% (608 kW)	3.4%
BriXSinO (d)	45 MeV	5 mA	225 kW	450 kW	50%	10% (22 kW)*	4.9%
Elettra (e)	2 GeV	310 mA	620 MW	4.0 MW	n.a.	0.015% (90 kW)**	2.3%
LHC (e)	7 TeV	540 mA	3.8 TW	120 MW	n.a.	3.2×10^{-9} (10 kW)***	$\sim 10^{-4}$
PSI Cyclotron (f)	590 MeV	2.4 mA	1.4 MW	10 MW	14%	100% (1.4 MW)	14%

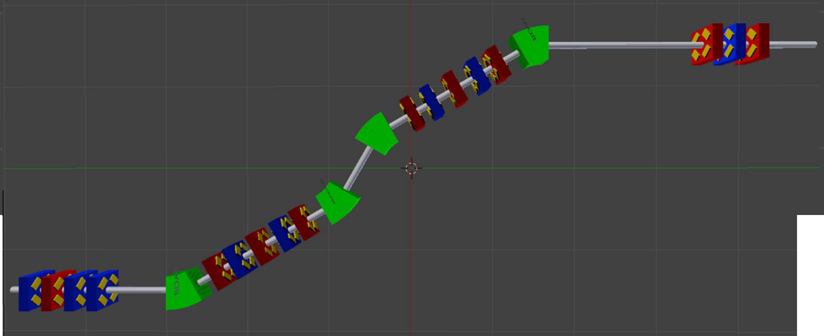
BriXSinO

Star to end simulation

Beam from linac



Simulation in ASTRA code
by A. Bacci



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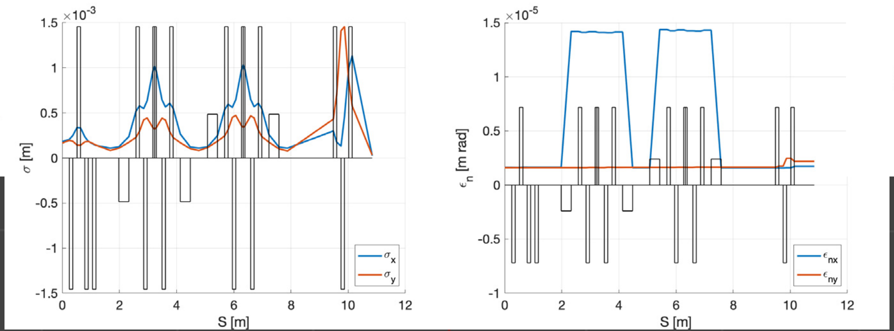
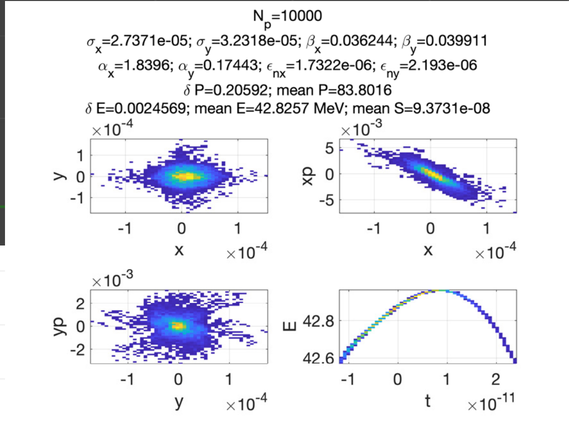
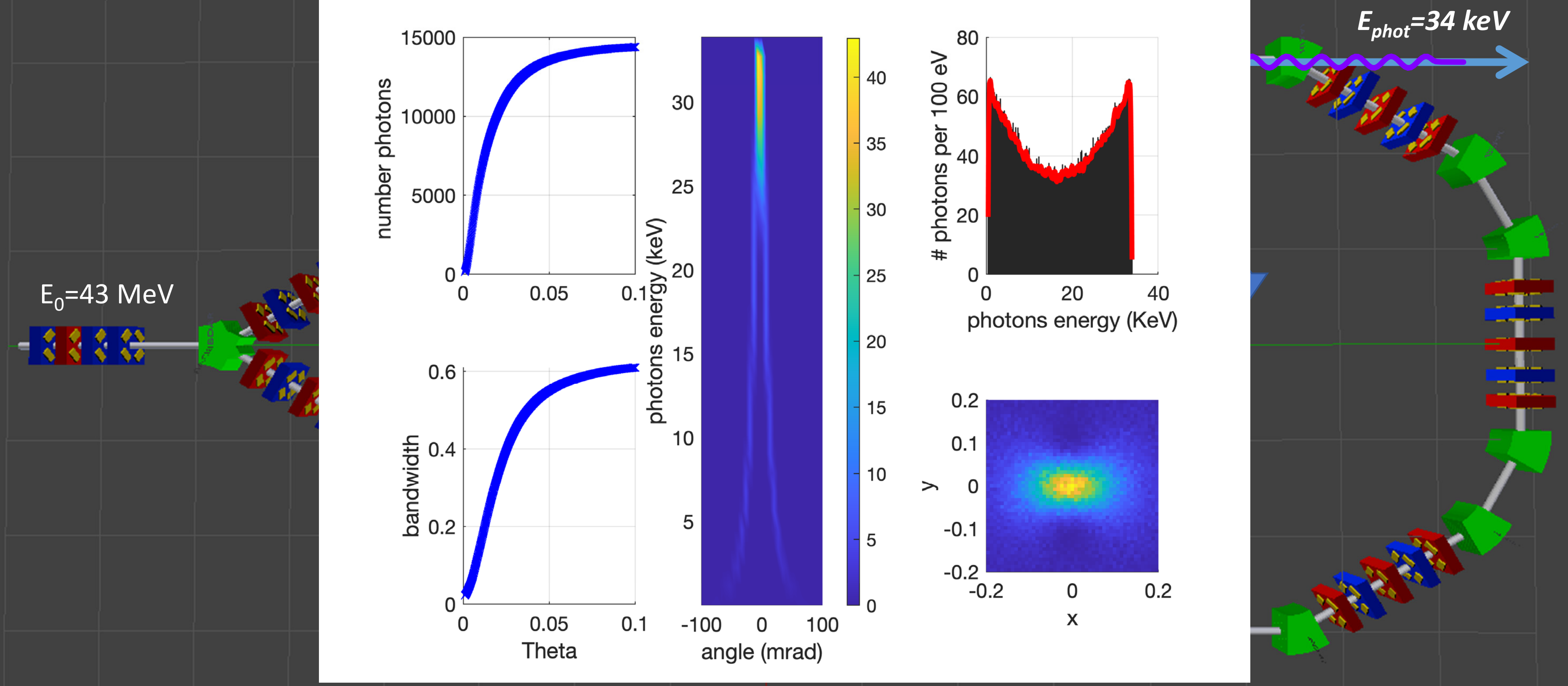


Beam at IP



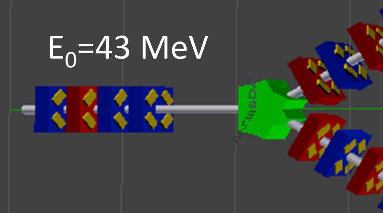
E_0=43 MeV

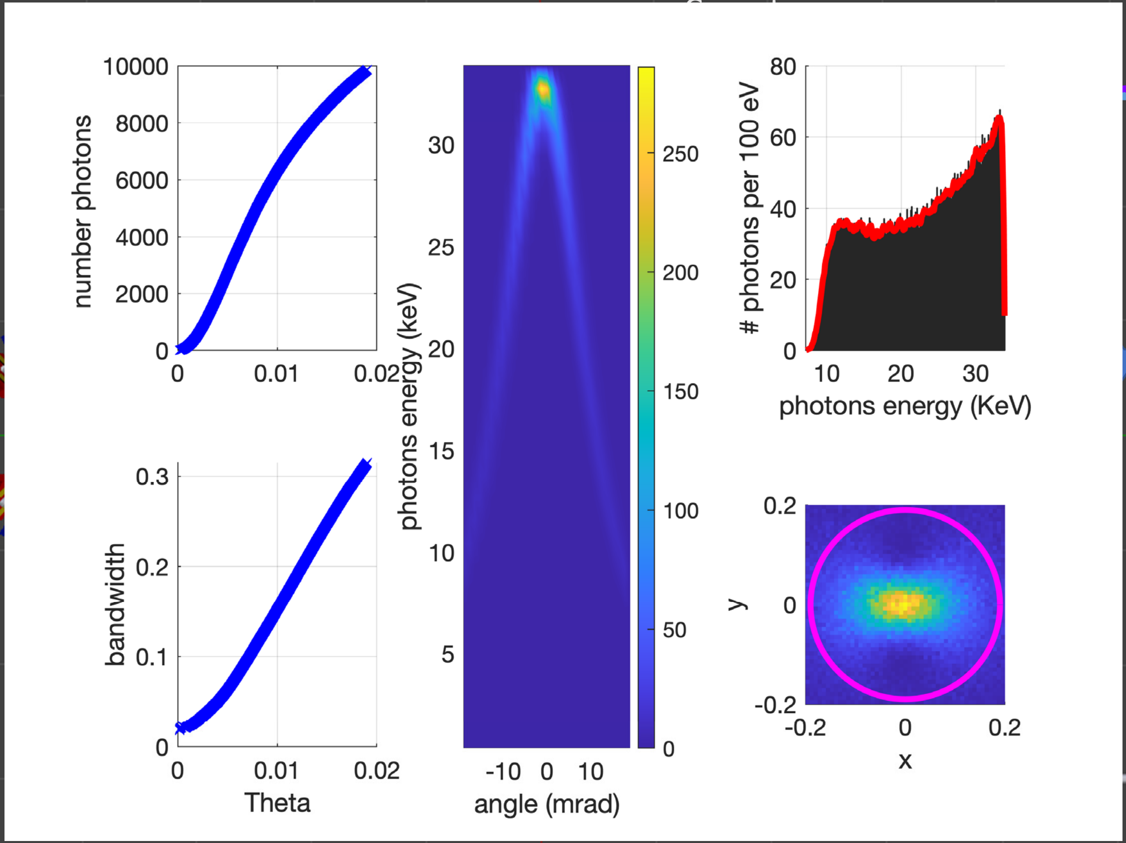
E_{phot}=34 keV

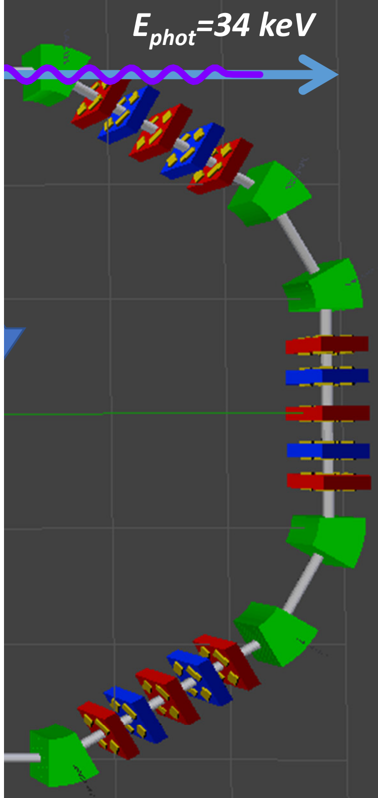


The energy angular correlation - tunability

BriXSinO

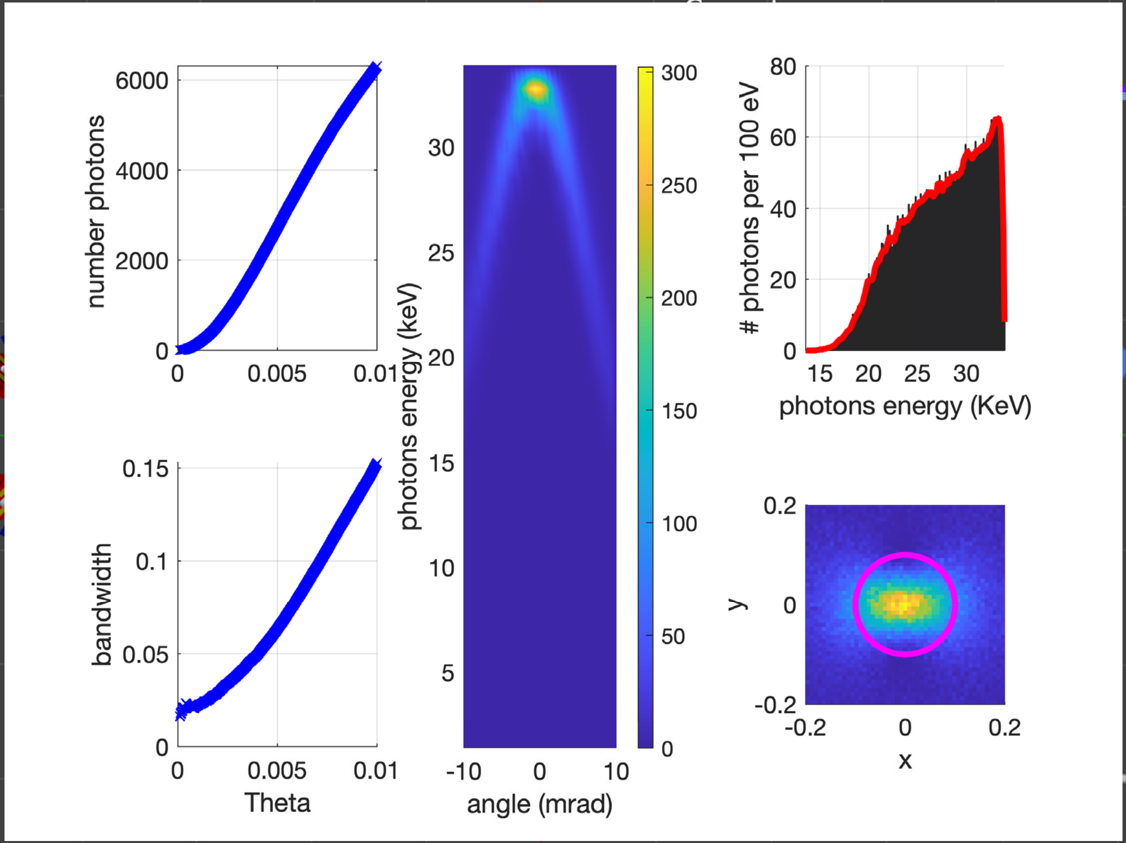






The energy angular correlation - tunability

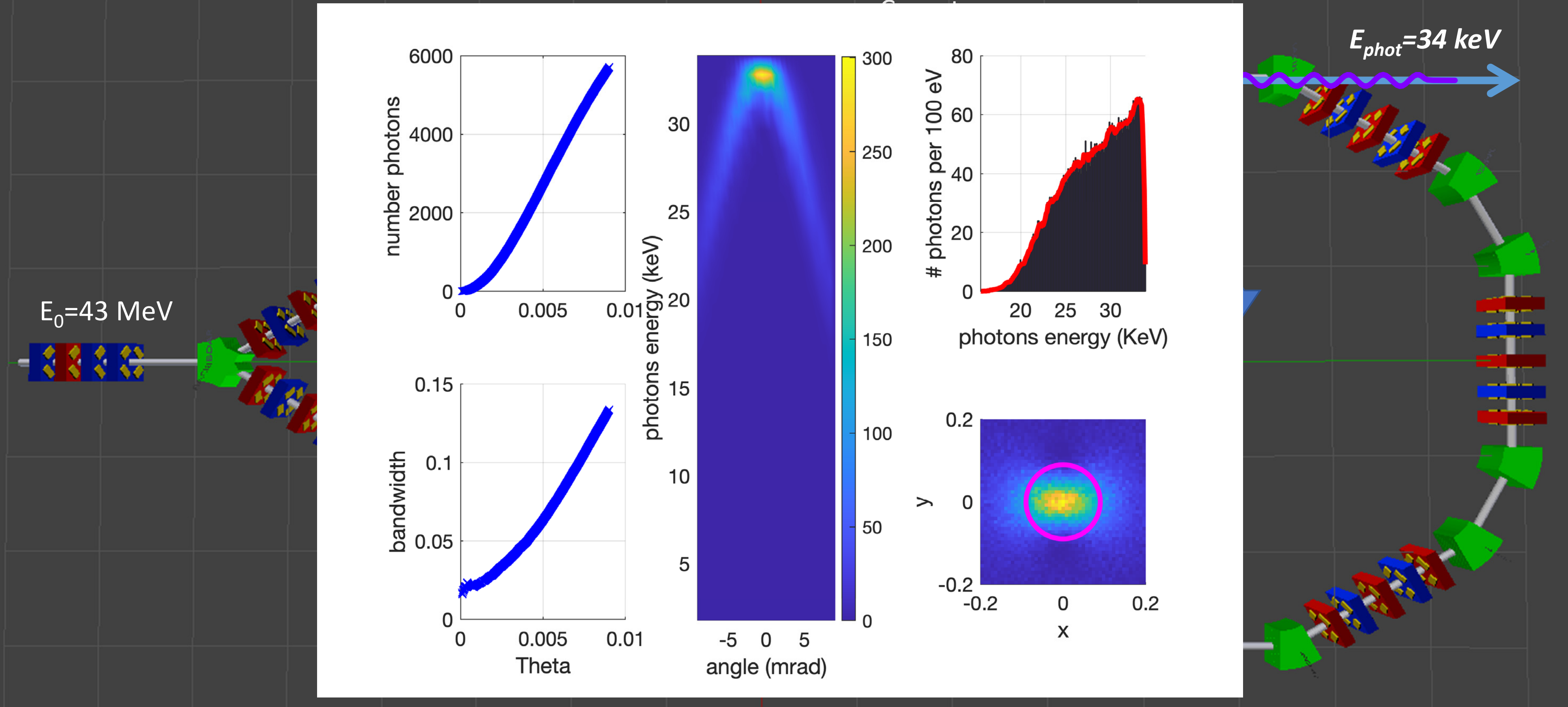
E_0=43 MeV



E_{phot}=34 keV

Why we so like Compton back scattering? The energy angular correlation - tunability

BriXSinO

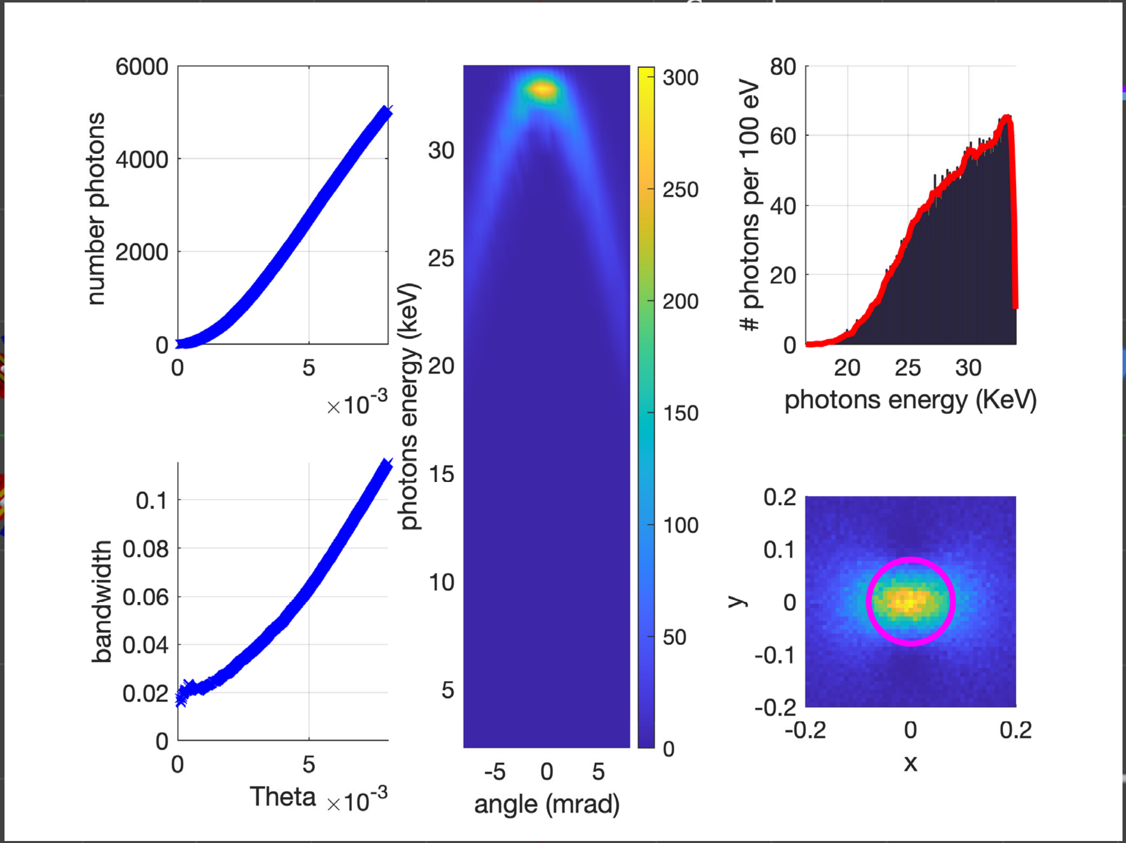


Why we so like Compton back scattering?

The energy angular correlation - tunability

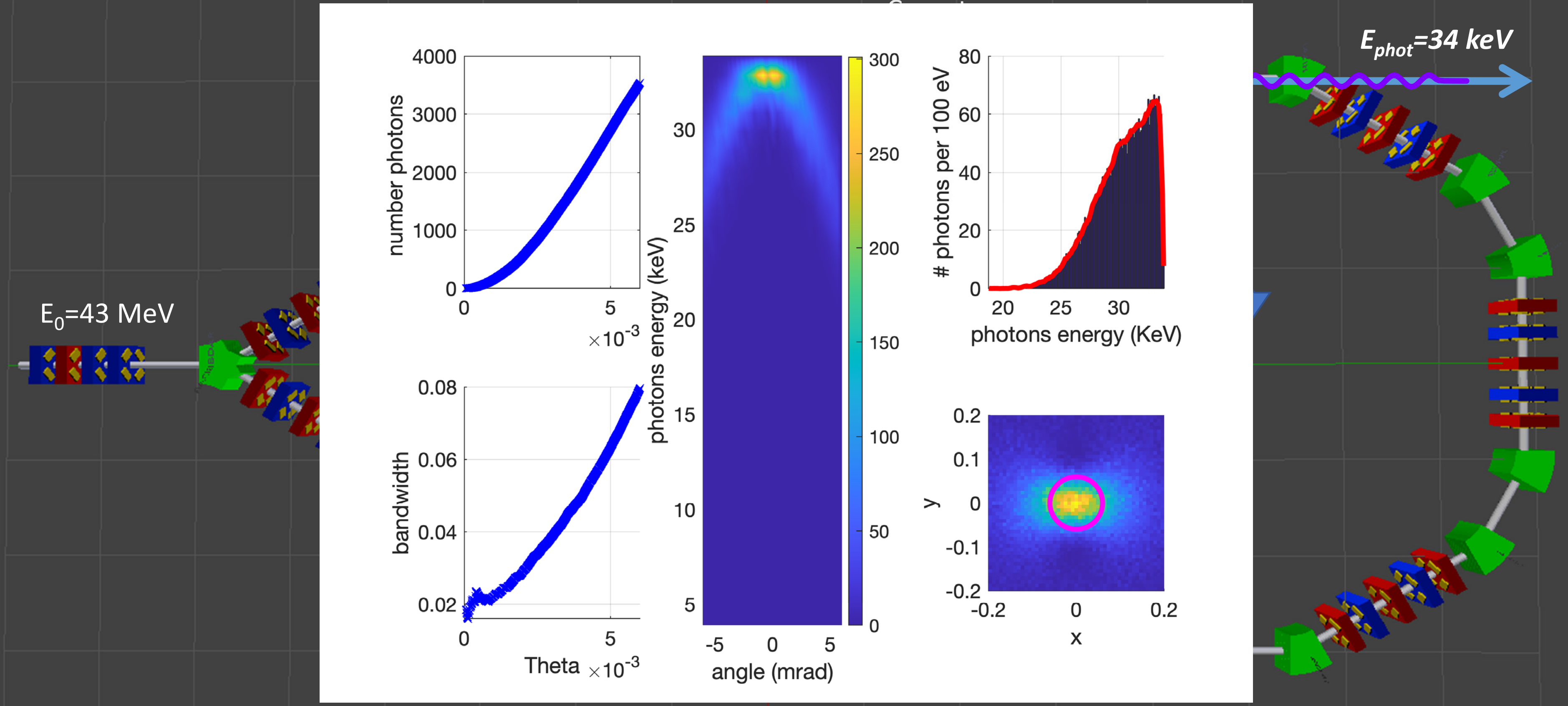
E_{phot}=34 keV

E_0=43 MeV



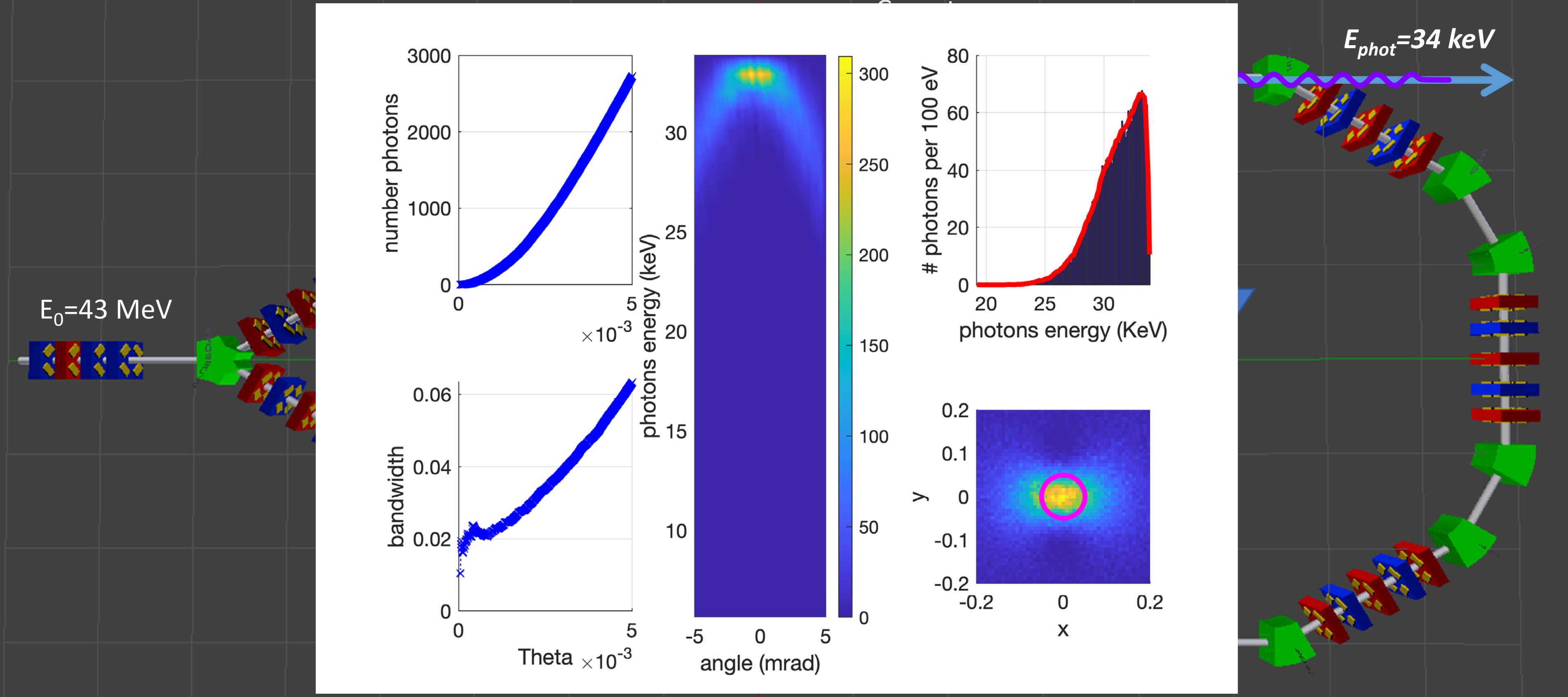
The energy angular correlation - tunability

BriXSinO



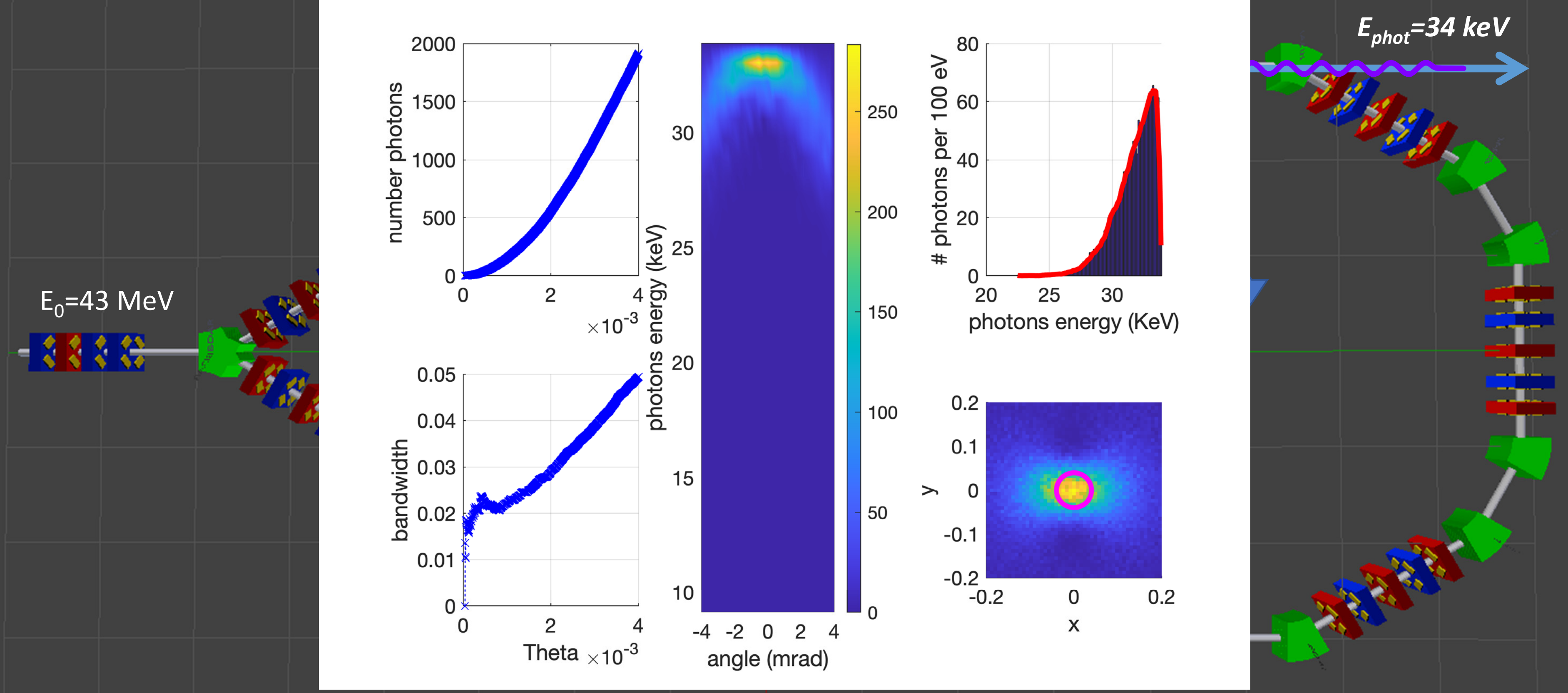
The energy angular correlation - tunability

BriXSinO



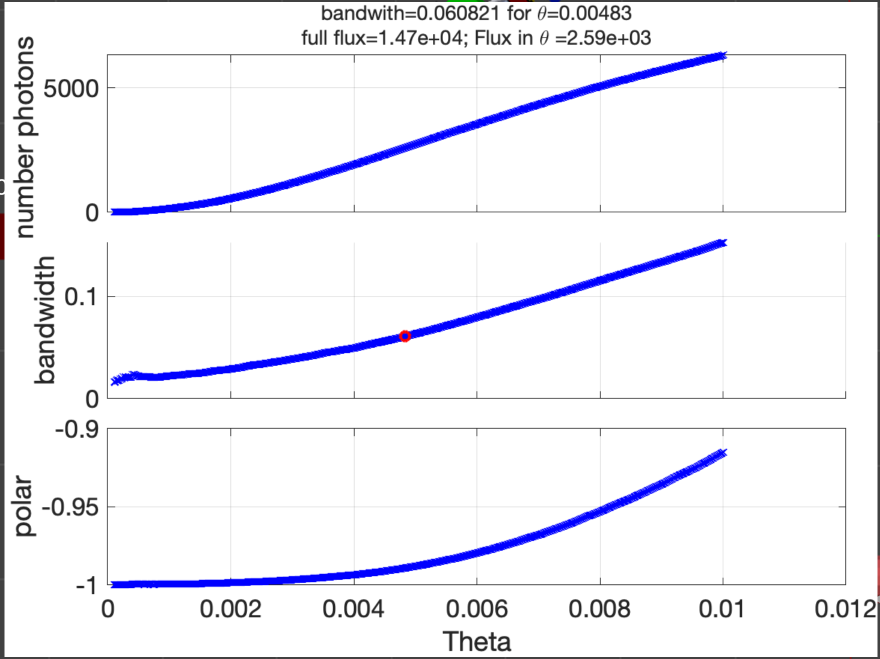
Why we so like Compton back scattering?

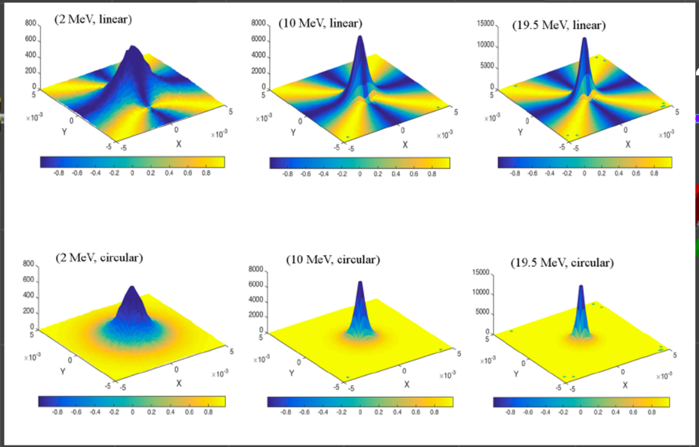
The energy angular correlation - tunability



BriXSinO

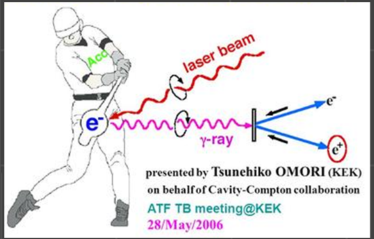
Why we so like Compton back scattering?
We get X-ray with given polarization linear or circular.





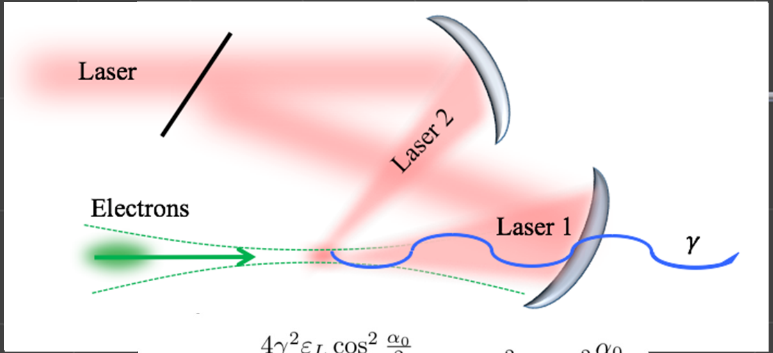
4 keV

E_0

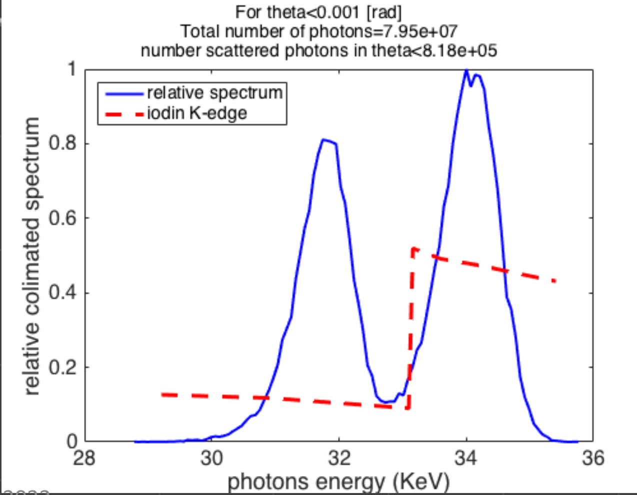


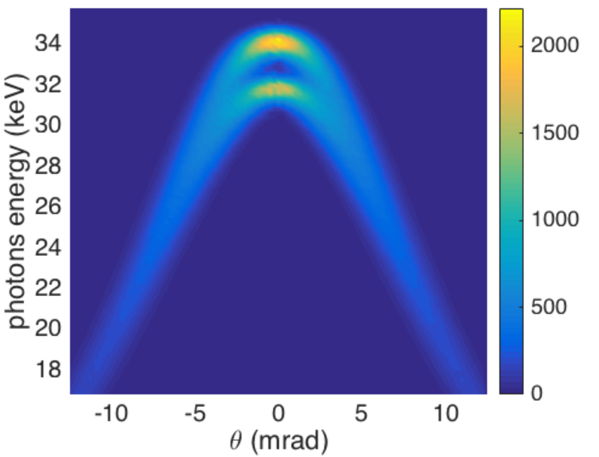
undulator 4 m

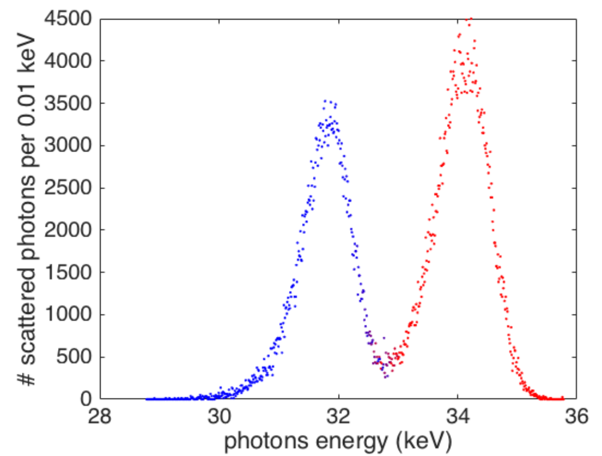
BriXSinO Two colour X-ray source

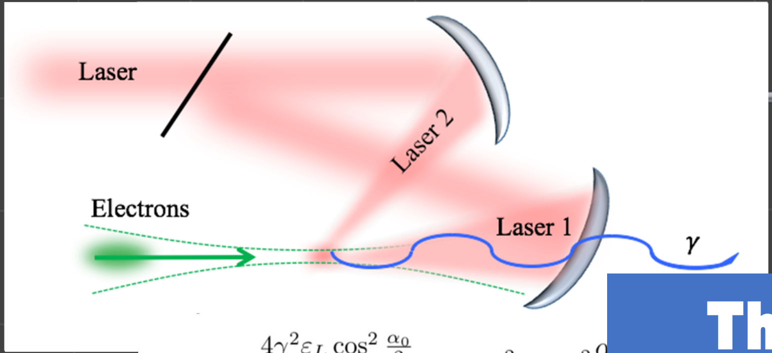


$$\varepsilon_{\gamma m} = \frac{4\gamma^2 \varepsilon_L \cos^2\frac{\alpha_0}{2}}{4\gamma\frac{\varepsilon_L}{mc^2}\cos^2\frac{\alpha_0}{2}+1} \approx 4\gamma^2\varepsilon_L cos^2\frac{\alpha_0}{2}$$

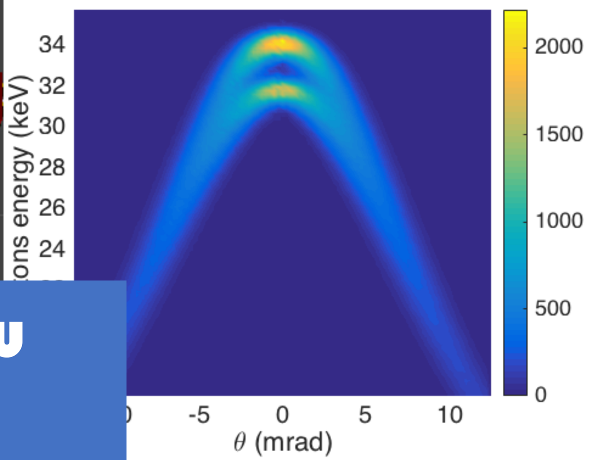


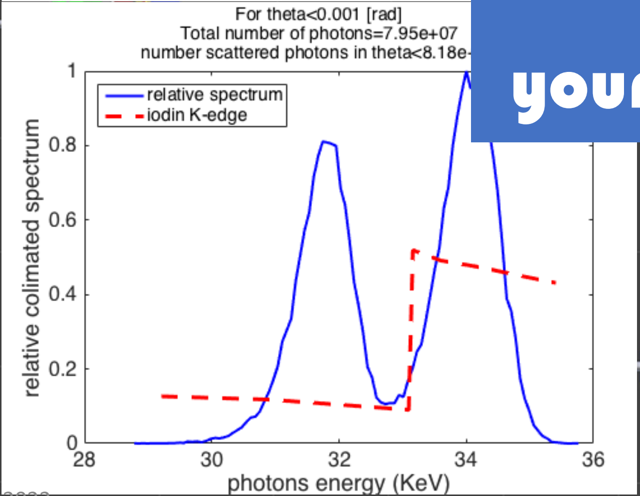


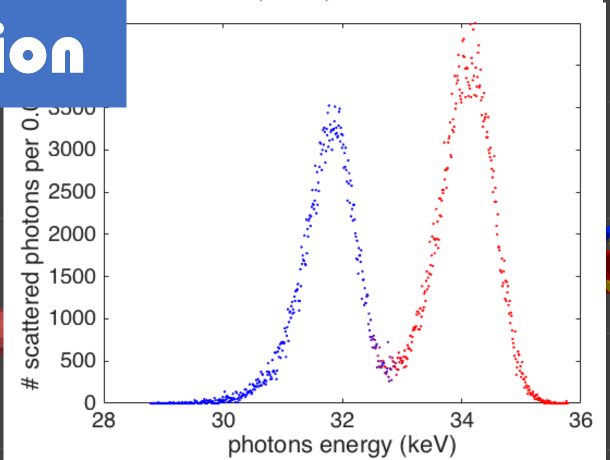




$$\varepsilon_{\gamma m} = \frac{4\gamma^2\varepsilon_L\cos^2\frac{\alpha_0}{2}}{4\gamma\frac{\varepsilon_L}{mc^2}\cos^2\frac{\alpha_0}{2}+1} \approx 4\gamma^2\varepsilon_L cos^2 \frac{\alpha}{2}$$







Thank you For your attention