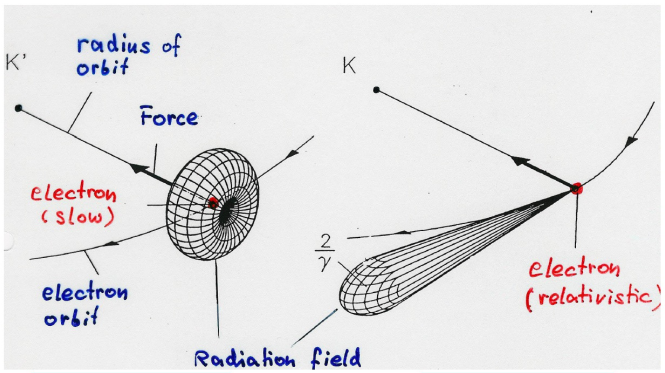
What is needed to build a CLS based research infrastructure like STAR and what are the enabled applications towards users

Luca Serafini – *INFN-Milan*

- **Brief recap of ICS physics (linear model) to explain technological challenges, performances and limitations of ICS based Compact Light Sources vs. Synchrotron Light Sources**
- **3 ICS paradigma: Linac-based (moderately easy), Storage ring (difficult) and Energy Recovery Linac (most challenging)**
- **STAR Project: an ICS based user facility in South Italy (Calabria) – its challenges, its evolution and present status close to commissioning/operation**
- **Inspiration to develop an African regional user facility for advanced X-ray applications, also helps igniting the AfLS initiative with a first step/first brick**

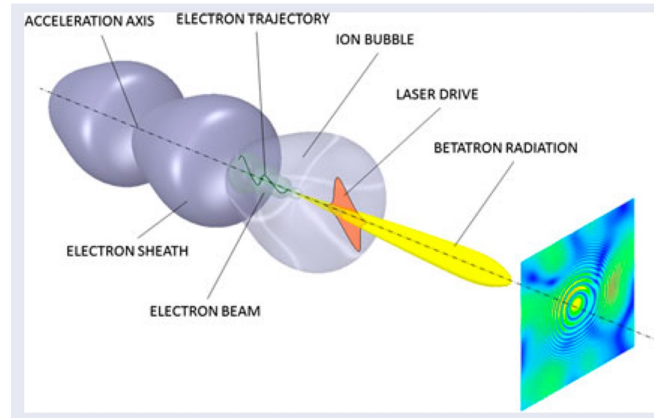
From wave-like, undulatory radiation towards collisional radiation

Spontaneous undulatory radiation (synchrotron, undulator, wiggler, *betatron*, *channeling*)



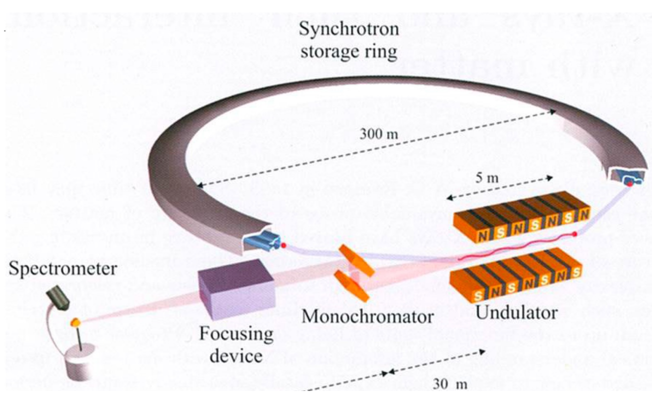
v << c

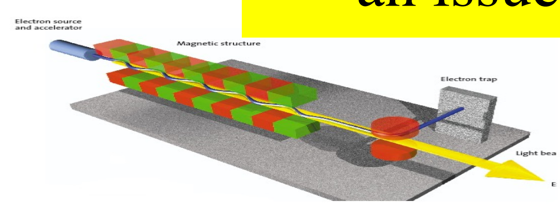
v ≈ c



$$E_X = f(\gamma^2\vartheta^2)$$

Energy angular correlation is an issue

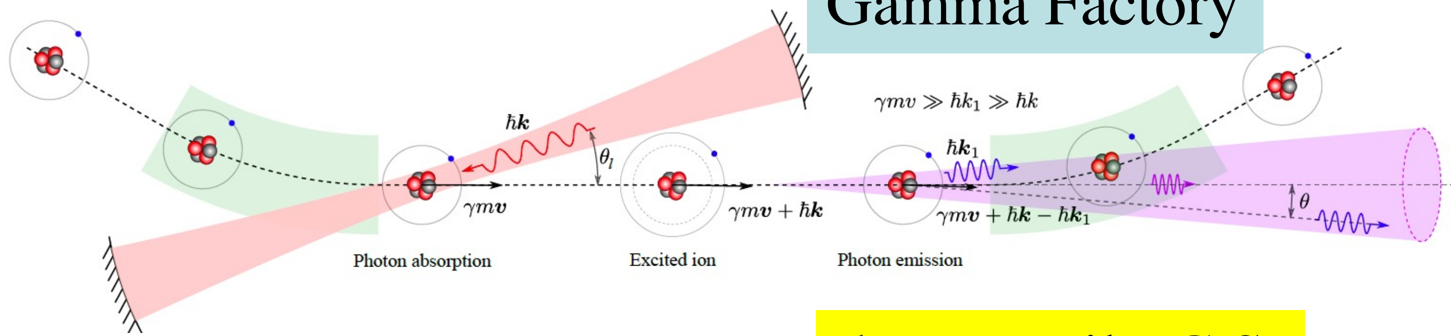




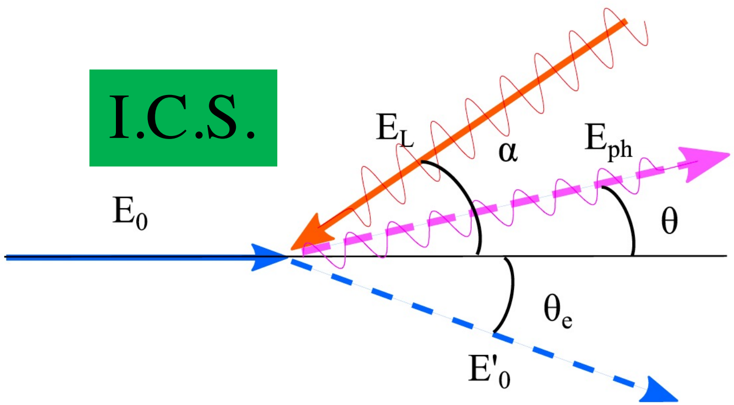
Collisional radiation

(Relativistic Rayleigh Scattering aka Gamma Factory, Inverse Compton Scattering, Large Recoil ICS, Symmetric Compton Scattering)

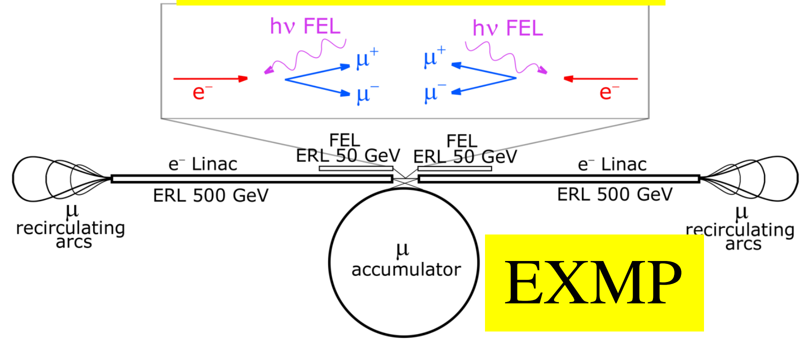
Gamma Factory



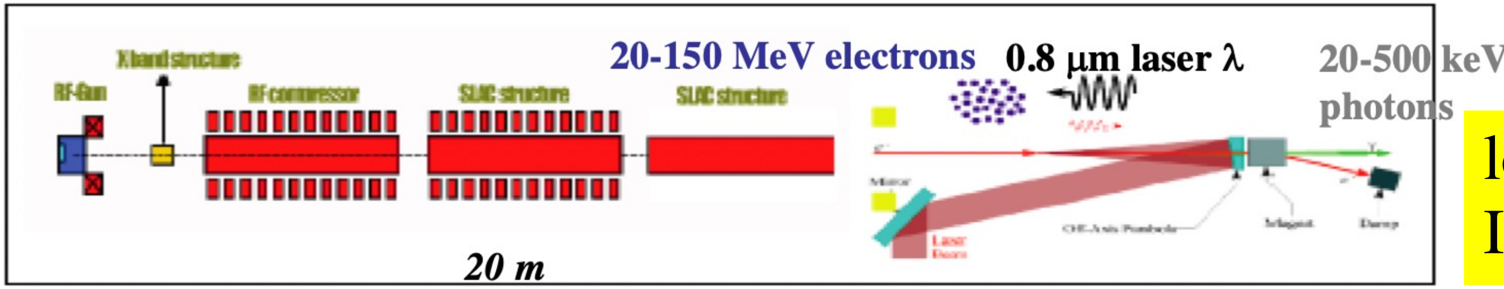
I.C.S.



deep recoil I.C.S.



EXMP

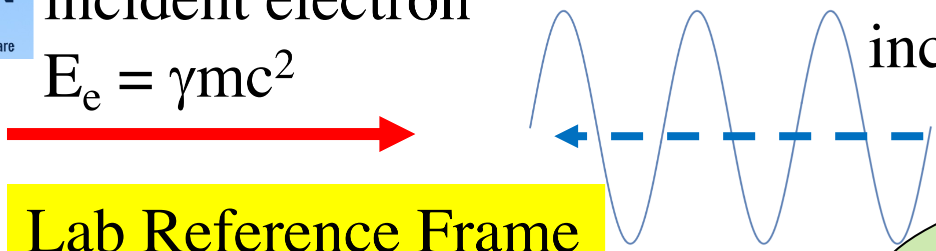


low recoil
I.C.S. - STAR

Kinematics of Inverse Compton Scattering a Cartoon

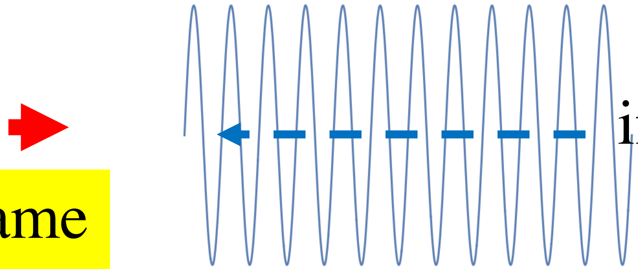
incident electron

$E_e = \gamma mc^2$



incident photon E_{ph}

Lab Reference Frame



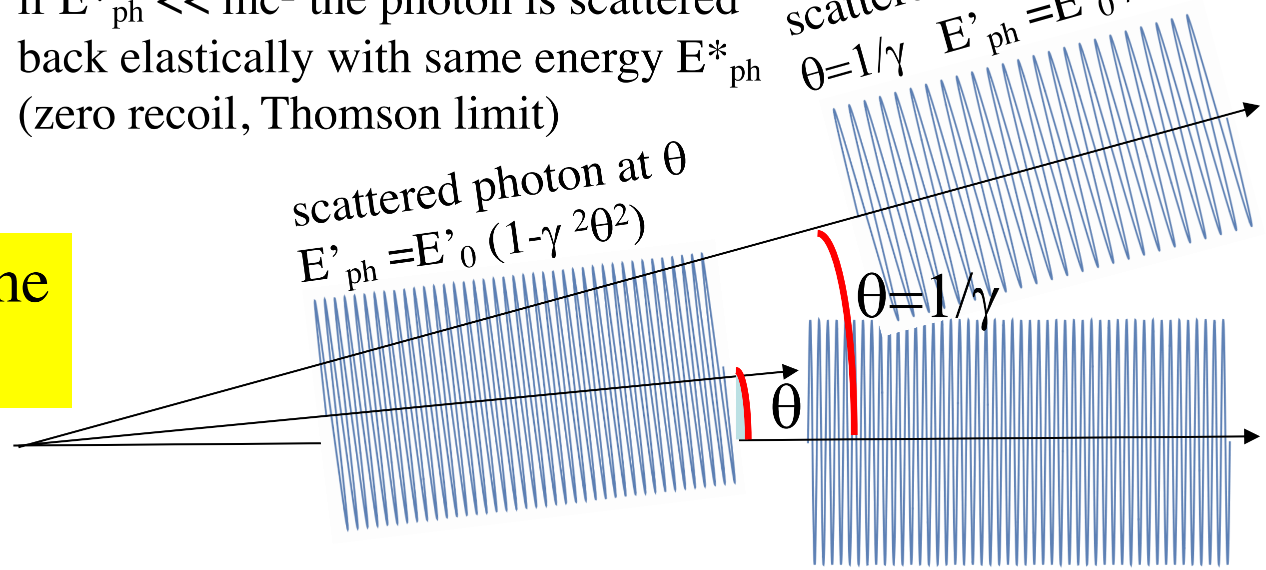
incident photon $E^*_{ph} = 2\gamma\, E_{ph}$

Electron rest frame

$E^*_e = mc^2$

if $E^*_{ph} \ll mc^2$ the photon is scattered back elastically with same energy E^*_{ph} (zero recoil, Thomson limit)

Lab Reference Frame after Scattering



scattered electron

$E'_e = \gamma mc^2 + E_{ph} - E'_{ph}$

energy of scattered photon at $\theta=0$ $E'_0 = 2\gamma\, E^*_{ph} = 4\gamma^2 E_{ph}$

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Istituto Nazionale di Fisica Nucleare

…y of scattered photon at θ

…ft at θ≠0

All I.C.S. X/γ ray Sources work at X<1
STAR (350 keV) $X_{STAR} < 2.6 \cdot 10^{-3}$
ELI-NP (20 MeV) $X_{ELI\text{-}NP} < 0.026$

X>>1 is for the next generation X-γ-ray Sources with photon cooling and spectral purification

scattered electro…

$E'_e = \gamma mc^2 + E_{ph}$…

ELSEVIER
Fundamental Plasma Physics
Available online 6 October 2023, 100026
In Press, Journal Pre-proof What's this?

Original research article

Symmetric Compton Scattering: a way towards plasma heating and tunable mono-chromatic gamma-rays

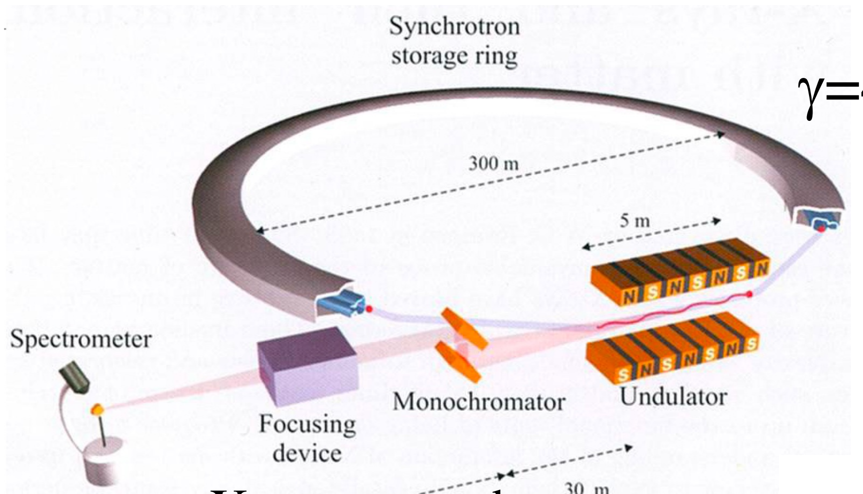
L. Serafini [a b], A. Bacci [a b], C. Curatolo [a b], I. Drebot [a b], V. Petrillo [a c], A. Puppin [a c], M. Rossetti Conti [a b], S. Samsam [a b]

[a] INFN-Section of Milan, Via G. Celoria 16, Milan, 20133, Italy
[b] INFN-LASA, Via F. Cervi 201, Segrate, 20090, Italy
[c] University of Milan, Via G. Celoria 16, Milan, 20133, Italy

Received 11 July 2023, Revised 18 September 2023, Accepted 3 October 2023, Available online 6 October 2023.

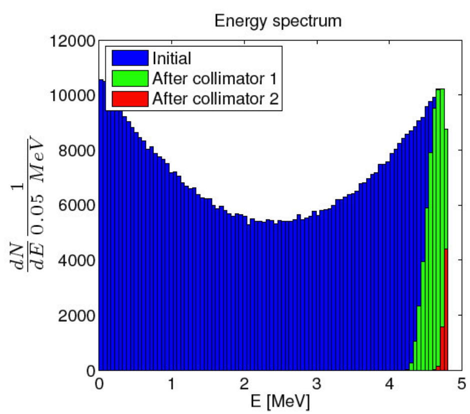
X = recoil … seen
by the elec… to mc^2

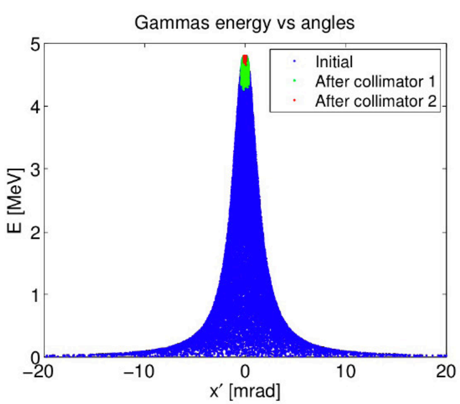
Poli-chromaticity implies using mono-chromators of different kinds (bragg-reflectors, collimators) to select a narrow bandwidth line from a broad-band spectrum



X-ray monochromator

γ=4000-10000 $\Rightarrow$ $\theta < 50$ μrad





γ=50-2000 $\Rightarrow$ θ = 0.1-10 mrad

ELI-NP-GBS γ–beam collimator (2-19 MeV)

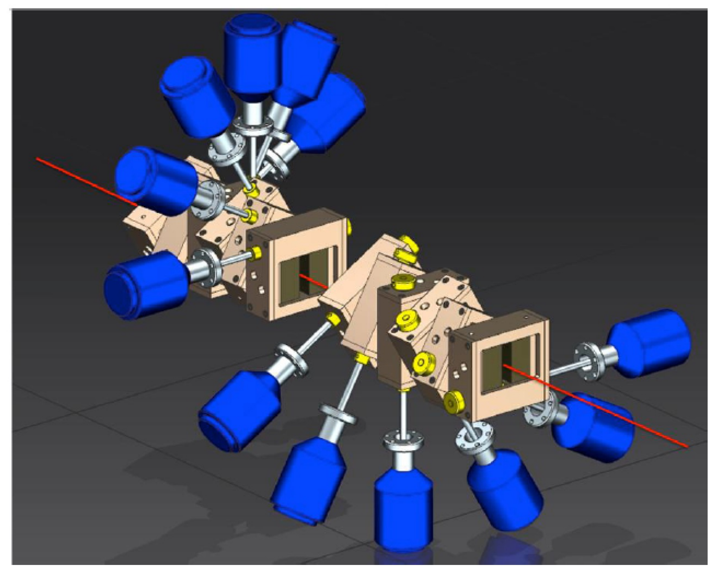
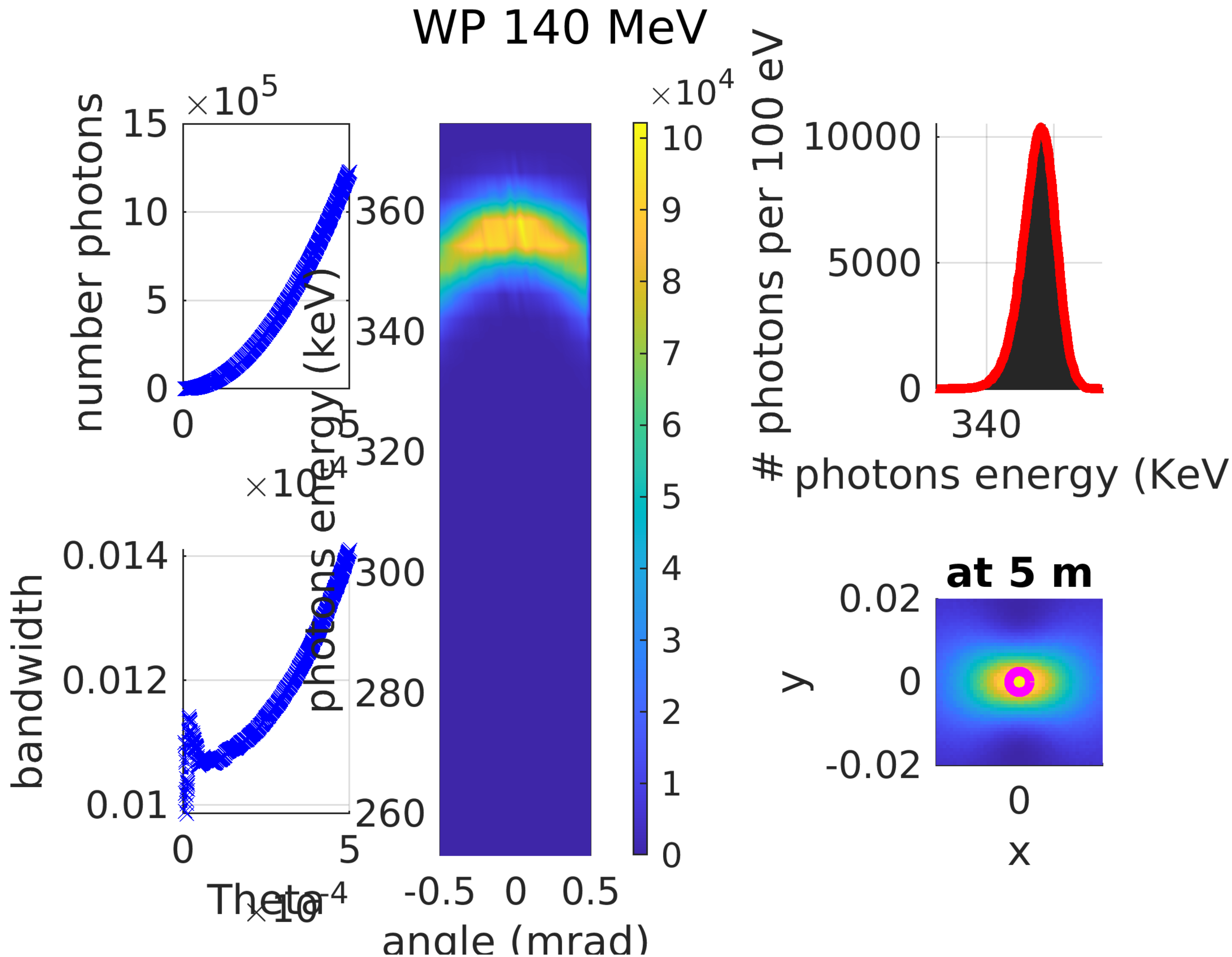
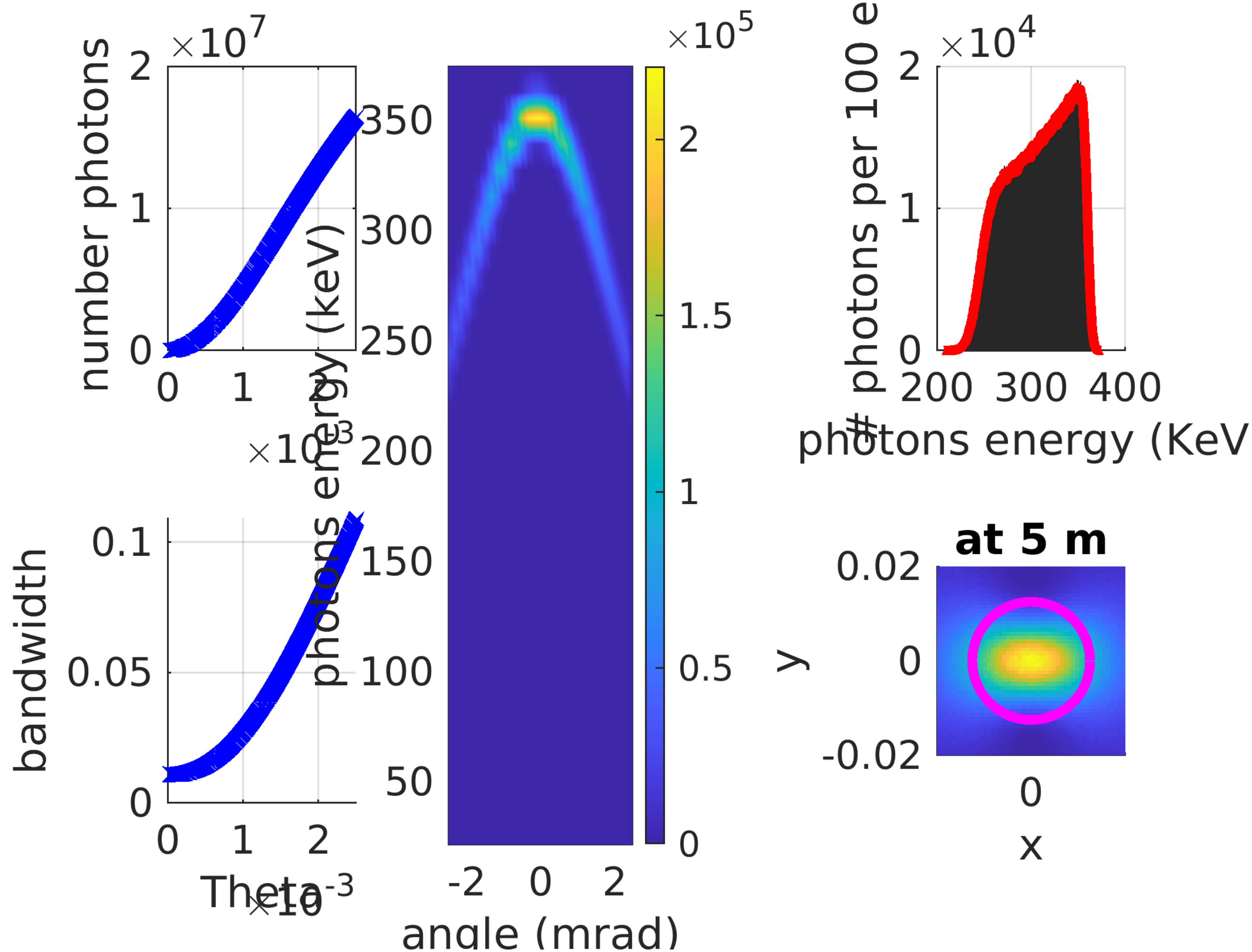


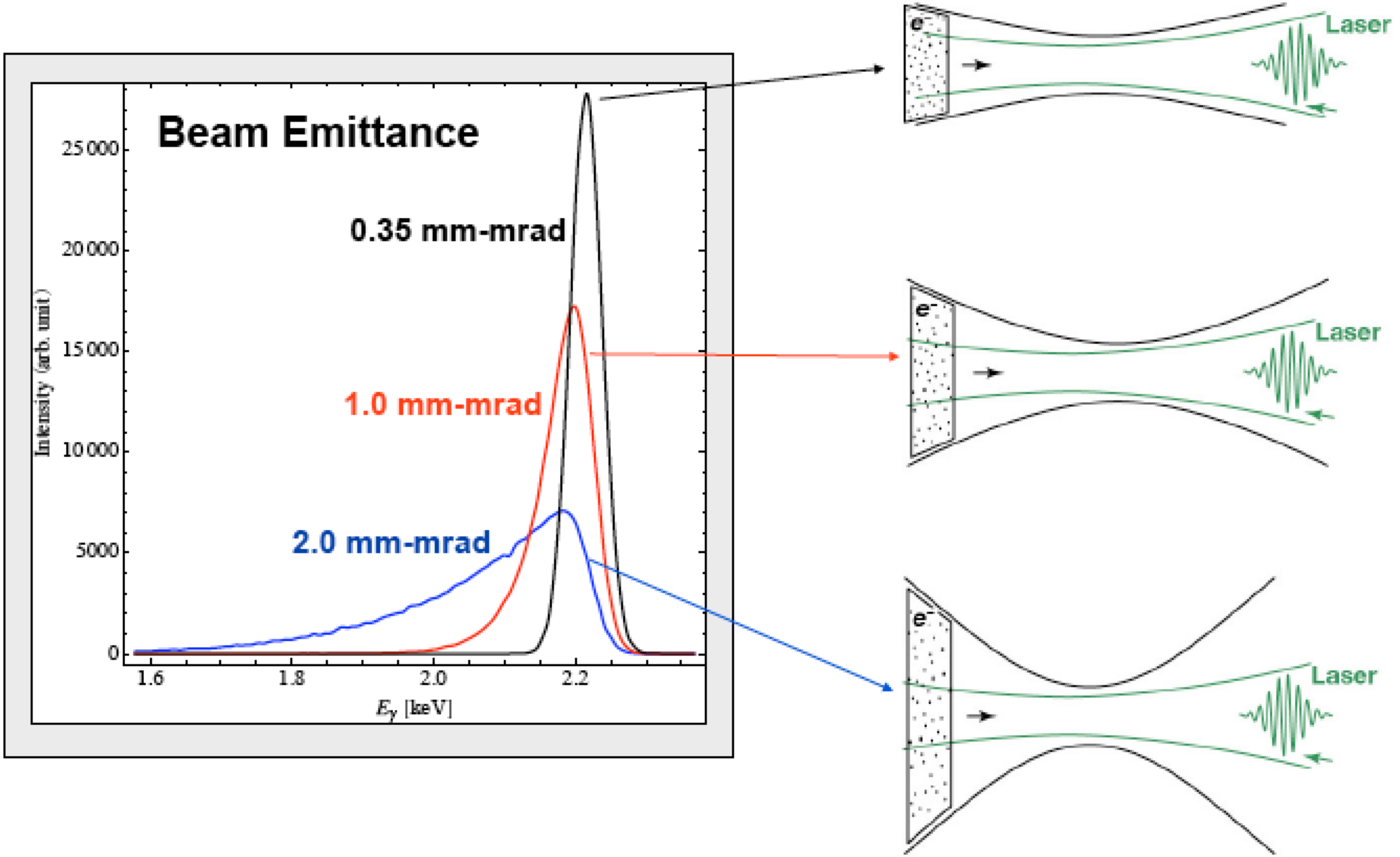
Fig. 184. Drawing of the configuration of low energy collimator made up of 12 tungsten adjustable slits with a relative 30° rotation each


WP 140 MeV
number photons
×10^5
15
10
5
0
0
5
bandwidth
×10^-4
0.014
0.012
0.01
Theta
photons energy (keV)
360
340
320
300
280
260
-0.5 0 0.5
angle (mrad)
×10^4
10 9 8 7 6 5 4 3 2 1 0
photons per 100 eV
10000
5000
340
photons energy (KeV
at 5 m
0.02
-0.02
y
x

WP 140 MeV



number photons
×10^7
Theta ×10^-3
bandwidth
photons energy (keV)
×10^5
angle (mrad)
photons per 100 eV
×10^4
photons energy (KeV)
at 5 m
y
x



Courtesy C. Barty - LLNL

Istituto Nazionale di Fisica Nucleare

Petrillo-Serafini for ICS photon beam bandwidth

$$\frac{\delta\nu_\gamma}{\nu_\gamma} \cong \sqrt{\left[\left(\frac{\gamma^2\vartheta^2/\sqrt{12}}{1+\gamma^2\vartheta^2/2} + \frac{2\varepsilon_n^2/\sigma_x^2}{1+\sqrt{12}\,\varepsilon_n^2/\sigma_x^2}\right)\frac{1}{1+\Delta}\right]^2 + \left(\frac{2+\Delta}{1+\Delta}\frac{\delta\gamma}{\gamma}\right)^2 + \left(\frac{1}{1+\Delta}\frac{\delta\nu}{\nu}\right)^2 + \left(\frac{M^2\lambda_L}{2\pi w_0}\right)^4 + \left(\frac{a_0^2/3}{1+a_0^2/2}\right)^2}$$

collimation

electron beam phase space

laser beam phase space

laser collective effects

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 080701 (2017)

Analytical description of photon beam phase spaces in inverse Compton scattering sources

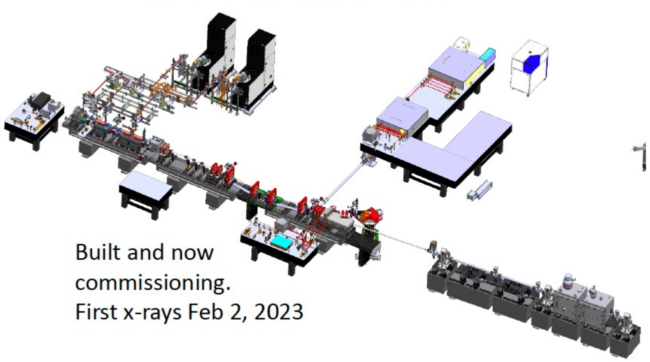
C. Curatolo,[1,*] I. Drebot,[1] V. Petrillo,[1,2] and L. Serafini[1]
[1] *INFN-Milan, via Celoria 16, 20133 Milano, Italy*
[2] *Università degli Studi di Milano, via Celoria 16, 20133 Milano, Italy*
(Received 9 March 2017; published 3 August 2017)

Presently there are 3 main Paradigms for high performance ICS:

A) RF Photo-injector producing a high charge 1-2 nC electron bunch against a J-class laser pulse delivered by an amplified *Yb:Yag* laser system, tightly focused down to 10-20 *μm*, running collisions at 100 Hz. Best example of this model is STAR [9] (Southern europe Thomson source for Applied Research), in construction as a dedicated user facility at the University of Calabria (Italy) by a collaboration INFN-ST-CNISM-UniCal. Maximum achievable fluxes in excess of $3 \cdot 10^{11}$ with maximum photon energy 200 keV.

CXLS

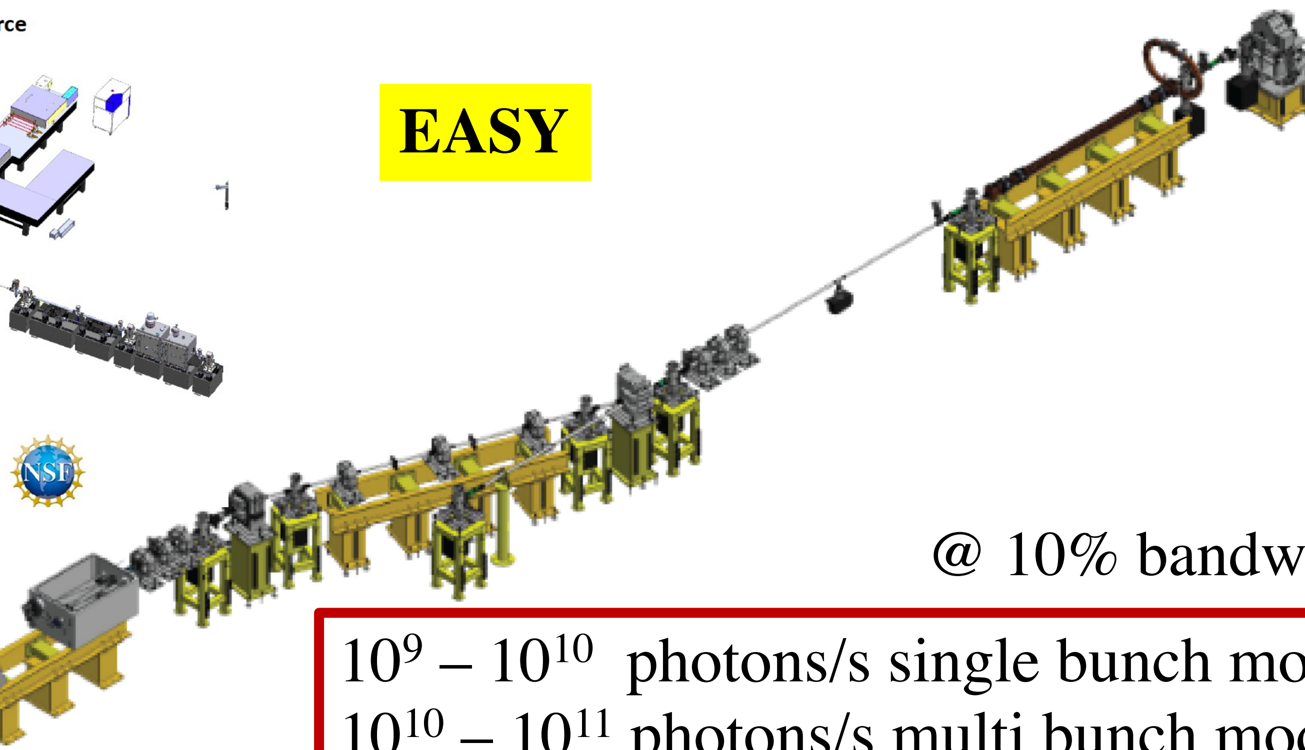
Phase 1 Hard X-ray ICS Source



Built and now commissioning.
First x-rays Feb 2, 2023

ASU Biodesign Institute Arizona State University — CXFEL Labs — NSF

EASY



@ 10% bandwidth

$10^{9} – 10^{10}$ photons/s single bunch mode
$10^{10} – 10^{11}$ photons/s multi bunch mode

Fig.2 – STAR machine as an example of Paradigm A. Overall length about 12 m.

B) Compact Storage Ring for the electron beam, colliding at a high repetititon rate (up to 25 MHz, *i.e.* an average beam current of 15 mA) a moderately high charge electron bunch with a mJ-class laser pulse stored in an optical Fabry-Perot Cavity [17], focused to 70 μm spot size at collision. Best example of this category is ThomX, in construction at Orsay-LAL by a collaboration IN2P3-Universite' de Paris Sud. Maximum achievable fluxes about $5 \cdot 10^{12}$. Maximum photon energy 90 keV [10]. A commercially available ICS of this type is currently available from the company Lyncean Tech., named LTI-CLS: its performances are a maximum photon flux of $5 \cdot 10^{10}$ and a maximum photon energy of 35 keV. The unofficially declared cost of such a system is about 8-10 M€.

DIFFICULT

$10^{11} - 10^{12}$ photons/s

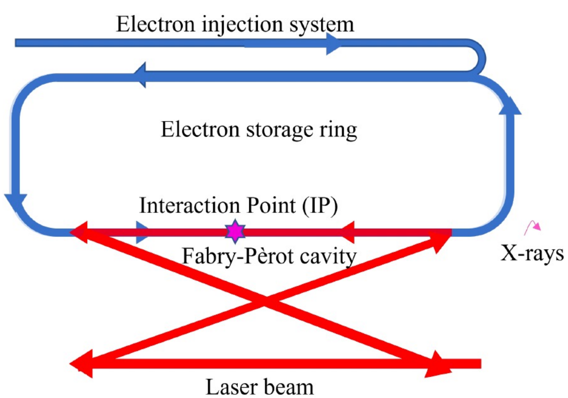


Figure 2. The typical scheme of source based on Paradigm (ii). Size is about 100 m^2. Overall length about 12 m.

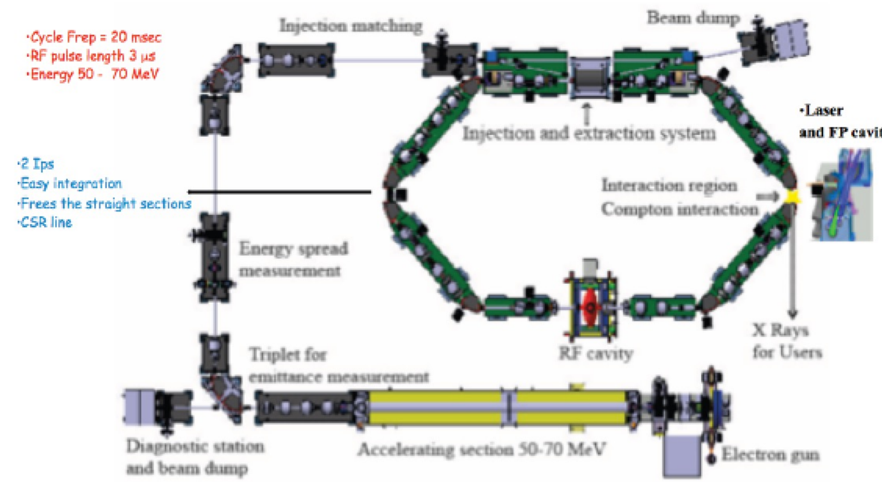


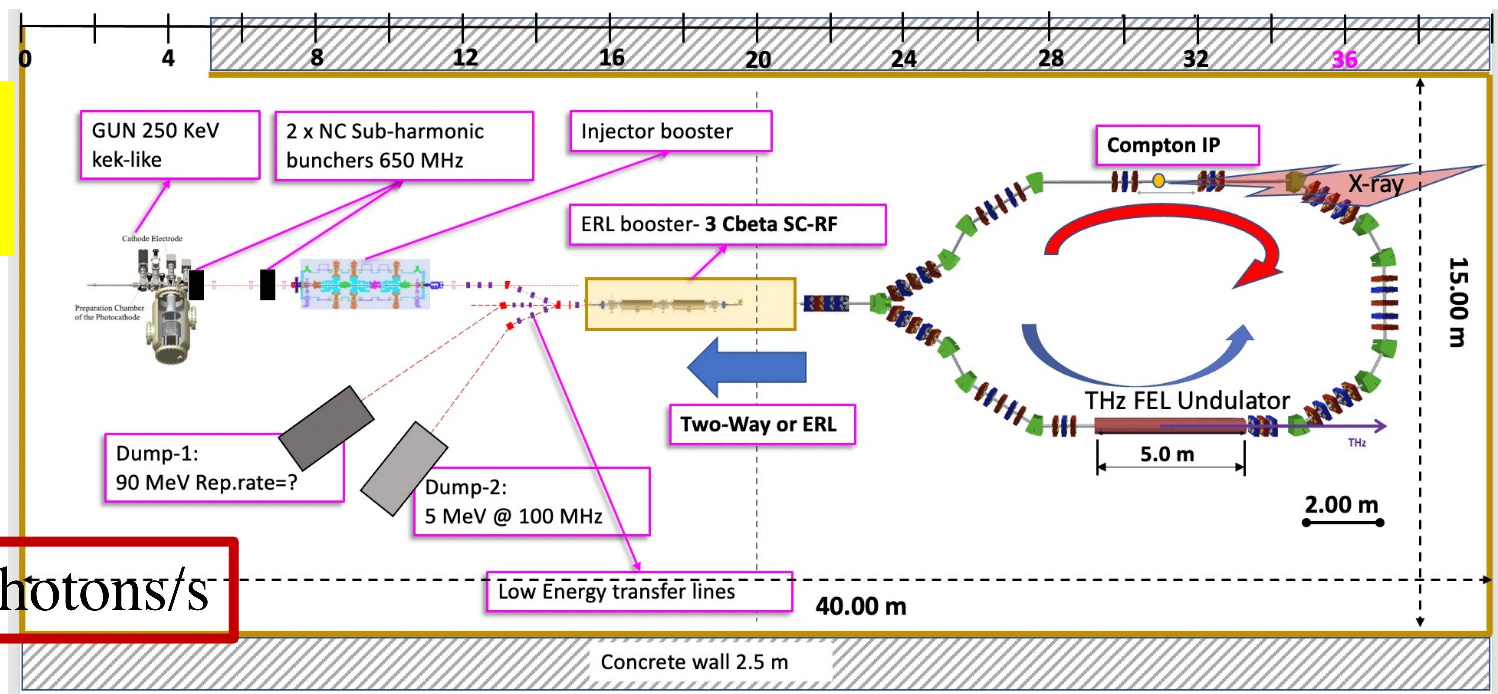
Fig.3 – ThomX as an example of Paradigm B. Size is about 10x10 m^2.

The Energy Recovery Linac based ICS: a technology in its demonstration phase promising the best performances

C) Super-Conducting RF Photo-Injector delivering a low charge (tens of pC) electron bunch at a very high rep. rate (up to 100 MHz), colliding with a mJ-class laser pulse stored in an optical Fabry-Perot Cavity (up to 1 MW stored laser power), focused to 20-30 μm spot size at collision. Maximum achievable fluxes about $3.5 \cdot 10^{12}$ without energy recovery (average electron beam current 1 mA) while in excess of an impressive 10^{15} with energy recovery at an average electron current of 100 mA. Maximum photon energy 200 keV. BriXS would belong to this type of ICS, together with UH-FLUX, a similar project [11] in development in UK (with energy recovery) and CUBIX, an ongoing project [12] at MIT (without energy recovery).

VERY DIFFICULT

BriXSinO



$10^{12} - 10^{13}$ photons/s

STAR was designed adopting a common paradigm with ELI-NP-GBS: both are e-γ linear collider based on 100 Hz amplified J-class lasers interacting with high brightness RF photo-injector. The design strategy applies Petrillo-Serafini criterion for maximum spectral density.

strong focusing of high brightness (peak & average) to maximize Luminosity according to Petrillo-Serafini criterion

$$S \propto \frac{\langle I_e \rangle U_{las}}{\varepsilon_n^2 E_x} \propto \frac{B_n U_{las}}{E_x}$$

true for all collisional radiation

Spectral Density *S (# photons per sec per eV bdw)* relevant to X-ray imaging (Brilliance B_{AV} is relevant to microscopy/spectroscopy)

$$B_{AV} \propto \frac{S}{\varepsilon_X^2} E_X \propto \frac{S}{\sigma_x^2 \theta_{coll}^2} E_X$$

30-150 MeV e$^-$
20-350 keV X

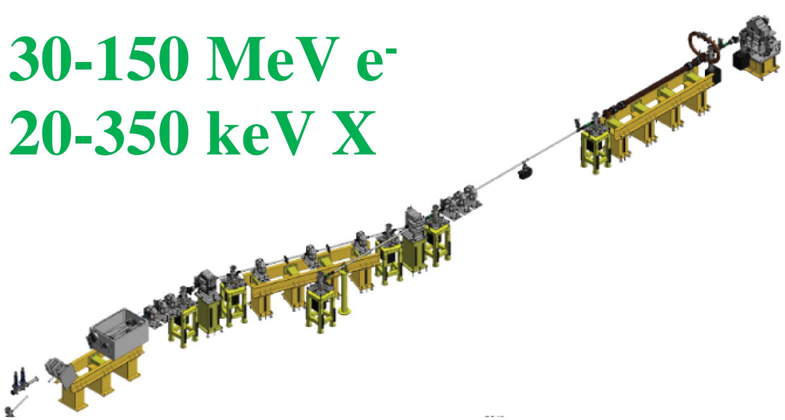


Fig.2 – STAR machine as an example of Paradigm A. Overall length about 12 m.

250-750 MeV e$^-$
1-19.5 MeV γ

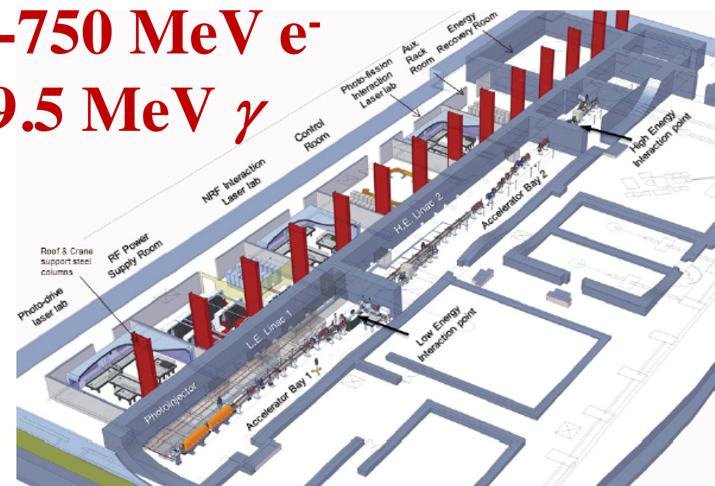


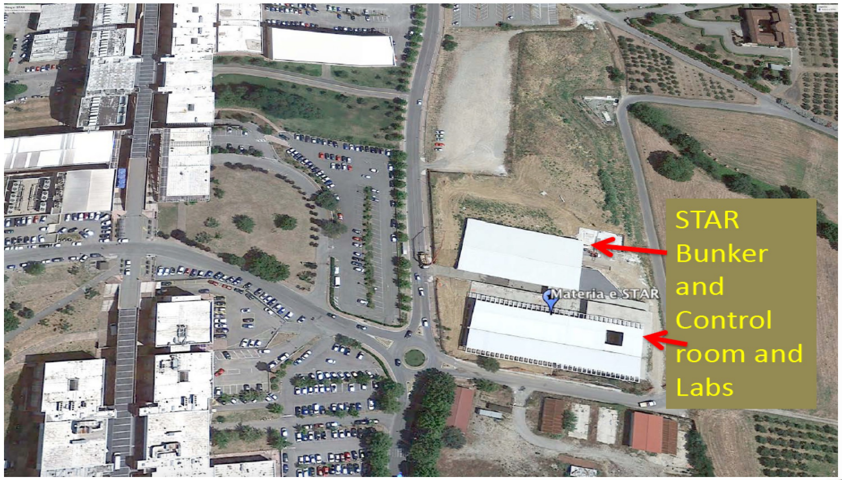
Fig. 197. Isometric 3D view of Building Layout of the Accelerator Hall & Experimental Areas

ICS for X-rays: Storage Rings or Linacs, Pros and Cons (a personal point of view)

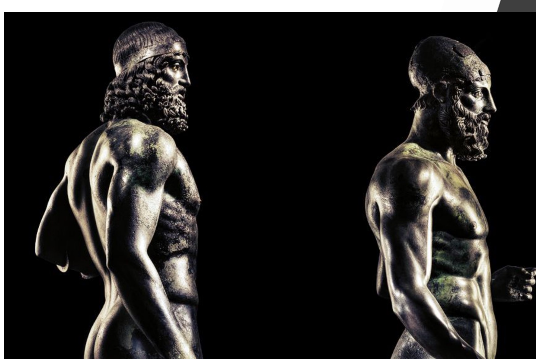
- **Storage Ring based ICS can attain larger fluxes, but you need a Laser Guru for the Fabry-Perot MW-class optical cavity. Linac based ICS use commercially available psec J-class laser systems**
- **Storage Ring based ICS can host only one photon beam line. Linac based ICS can serve several beam lines (minimum 2, à la STAR, or up to 4-5 in multi-bunch mode)**
- **Linac based ICS can generate X-ray beams from smaller spot-sizes (10-20 microns, vs. 50-100 microns of Storage Rings), better boosting phase contrast imaging applications**
- **Linac based ICS cost less (same photon energy) than St. Ring based ICS (need anyway a full energy Linac for beam injection)**

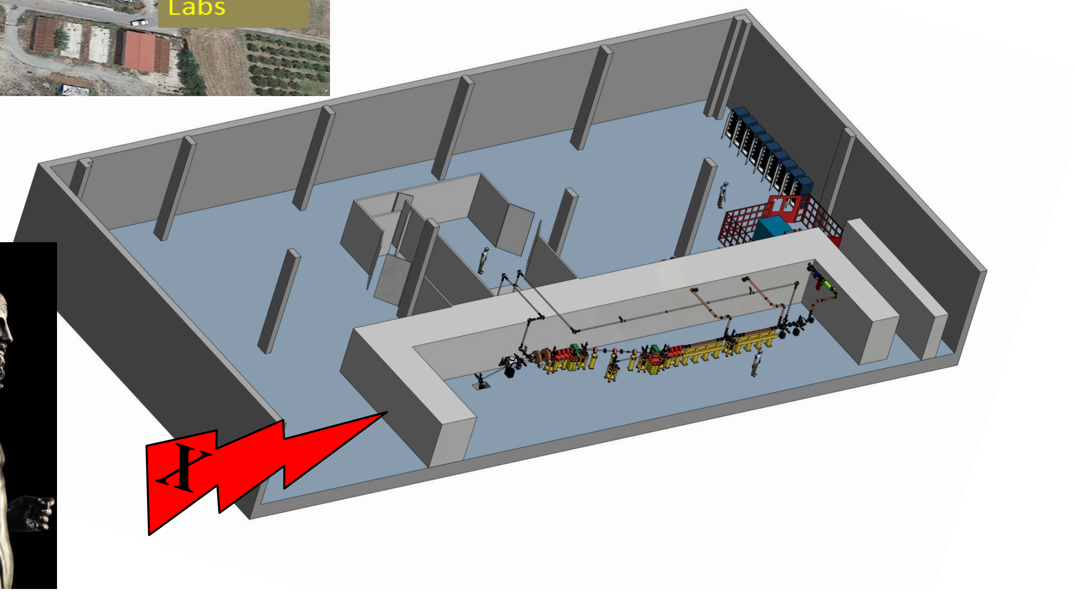
STAR in Calabria (South Italy)

STAR @UNICAL



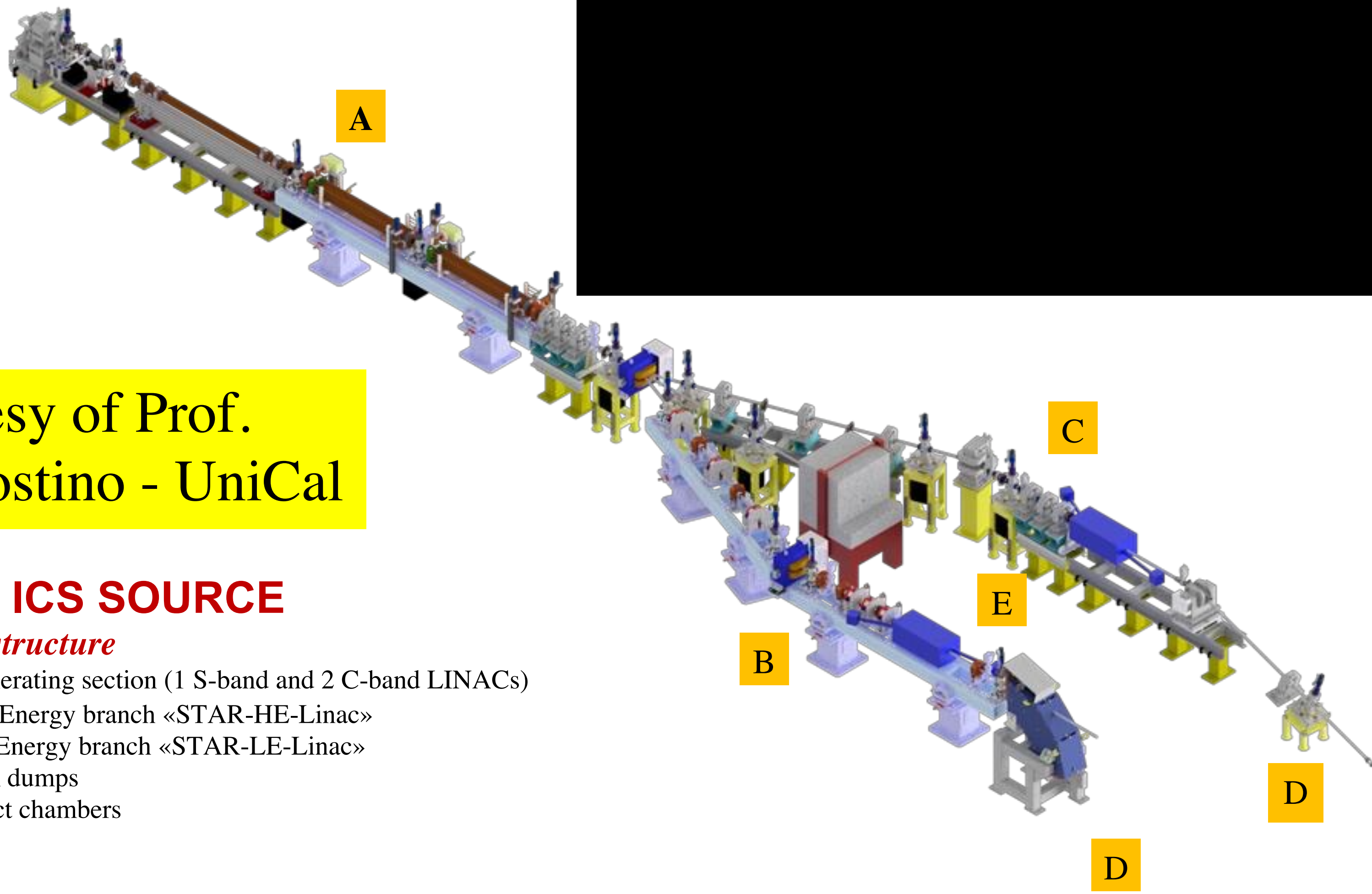
STAR : Southern europe Thomson source for Applied Research





- **STAR (Southern europe Thomson source for Applied Research) is a Compton Source of mono-chromatic X-rays tunable in the range 20-350 keV, devoted to advanced non-invasive diagnostics of cultural heritage/archeological samples.**

STAR ICS SOURCE



Courtesy of Prof. R. Agostino - UniCal

STAR ICS SOURCE

e- infrastructure

A. Accelerating section (1 S-band and 2 C-band LINACs)
B. High Energy branch «STAR-HE-Linac»
C. Low Energy branch «STAR-LE-Linac»
D. Beam dumps
E. Impact chambers

- *A. Bacci et al., The Star project, Proceedings of IPAC2014, Dresden, Germany*
- *A. Bacci et al., Status of the Star project, Proceedings of IPAC2016, Busan, Korea*
- *A. Bacci et al., Photoinjector Emittance Measurement at STAR", Proceedings of IPAC2017, Copenhagen, Denmark*
- *A. Bacci et al., STAR HE-Linac Complete Detailed Design Report, arXiv:2109.10351*

STAR ICS SOURCE

	HE-linac	LE-linac
Energy range [MeV]	40-150	23-65
Rap. rate [Hz]	100	
Bunch charge range [pC]	100 – 500 (bf:2000)	
Normalized emittance (x,y) [μm]	2.0 (bf: 1.0)	
Bunch energy spread [%]	0.5 (bf: 0.2)	
Bunch length – rms [ps]	≤ 5	
Bunch spot dimension at IP [μm]	40 (bf: 20)	

Courtesy of Prof. R. Agostino - UniCal

- *A. Bacci et al., The Star project, Proceedings of IPAC2014, Dresden, Germany*
- *A. Bacci et al., Status of the Star project, Proceedings of IPAC2016, Busan, Korea*
- *A. Bacci et al., Photoinjector Emittance Measurement at STAR", Proceedings of IPAC2017, Copenhagen, Denmark*
- *A. Bacci et al., STAR HE-Linac Complete Detailed Design Report, arXiv:2109.10351*

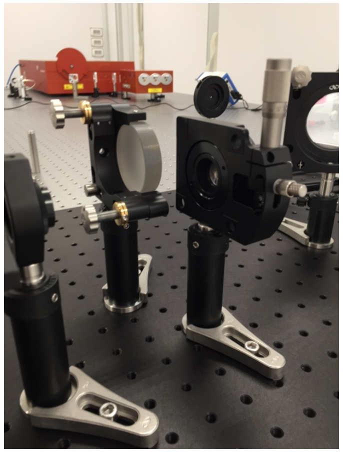
INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

STAR INFRASTRUTTURA DI RICERCA

STAR ICS SOURCE

Laser infrastructure

Interaction laser system	
Repetition rate (Hz)	100 +/- 1
Output Energy (mJ)	≥ 500
Wavelength (nm)	1030 +/- 1
Bandwidth (nm)	< 4
Pulse duration (ps FWHM)	< 5
M^2	< 1.4
Linear polarization (%)	> 99
Spot size at IP (µm)	40



Amplitude

Courtesy of Prof. R. Agostino - UniCal

STAR INFRASTRUTTURA DI RICERCA

STAR ICS SOURCE

X-ray beam features

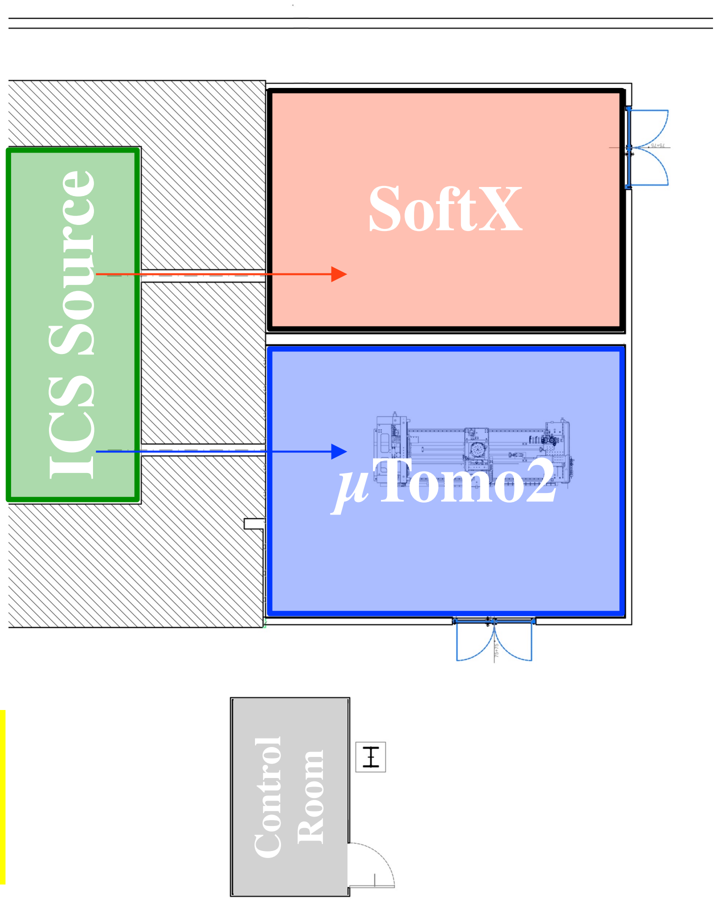
- X-ray energy **tuneable** on a wide range up to hard X-rays
- **Controlled BW** (<1% - 10%)
- Low (controlled) divergence (1-10 mrad)
- Time structure on the **ps-scale**
- **Linear polarization** up to 99% - pulse-to-pulse switchable
- Circular **20/40 μm-sized x-ray source**
- **(Pseudo-)coherence →** Phase-contrast and diffraction-enhanced imaging

$$L_s = \frac{\lambda l}{2S} = \frac{\lambda}{2\alpha}$$

- *Possible evolution to higher energies and fluxes*

Courtesy of Prof.
R. Agostino - UniCal

STAR BEAMLINES



Courtesy of Prof. R. Agostino - UniCal

*HE-LINAC → **μTomo2** - Elettra Sincrotrone Trieste*

Elettra Sincrotrone Trieste

*LE-LINAC → **SoftX** - ASF Metrology*

ASF metrology

STAR INFRASTRUTTURA DI RICERCA

Courtesy of Prof. R. Agostino - UniCal

STAR BEAMLINES

µTomo2: Imaging system

Elettra Sincrotrone Trieste

Parameter	Value
Running (Stroke)	300 mm
Load capacity	300 kg
Encoder resolution	< 1 um
Minimal movement	< 1 um
Repeatability	< 5 um
Linearity	< 30 µm
Flatness	< 25 µm

Source translation system

Parameter	Value
Maximum axial load	>40 kg
Speed	> 60 RPM
Radial error	< 2 um LSC
Axial error	< 2 um LSC
Precession	< 2 urad
Angular accuracy	±10 arcsec

Parameter	Value
Running	50 x 50 mm
Load capacity	10 kg
Minimal movement	1 um

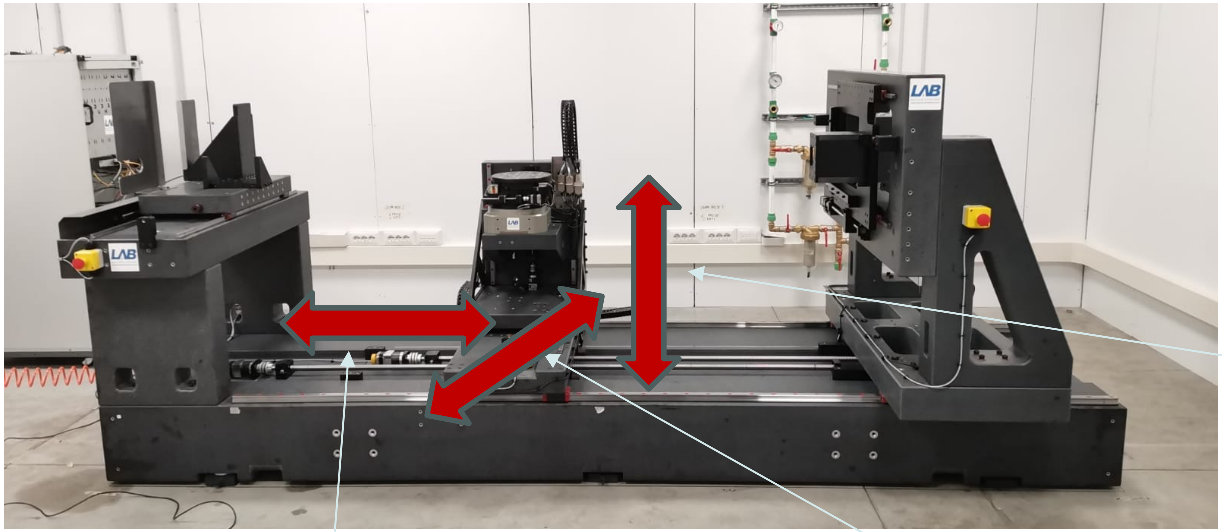
Rotator system

STAR INFRASTRUTTURA DI RICERCA

Courtesy of Prof. R. Agostino - UniCal

STAR BEAMLINES

µTomo2: Imaging system



Elettra Sincrotrone Trieste

Parameter	Value
Running (Stroke)	300 mm
Load capacity	100 kg
Encoder resolution	< 1 um
Minimal movement	< 1 um
Repeatability	< 1 um
Linearity	< 20 µm
Flatness	< 20 µm

Z-axis sample translation

Parameter	Value
Running (Stroke)	2000 mm
Load capacity	300 kg
Encoder resolution	< 1 um
Minimal movement	< 1 um
Repeatability	< 1 um
Linearity	< 30 µm
Flatness	< 30 µm

Y-axis sample translation

Parameter	Value
Running (Stroke)	300 mm
Load capacity	200 kg
Encoder resolution	< 1 um
Minimal movement	< 1 um
Repeatability	< 1 um
Linearity	< 20 µm
Flatness	< 20 µm

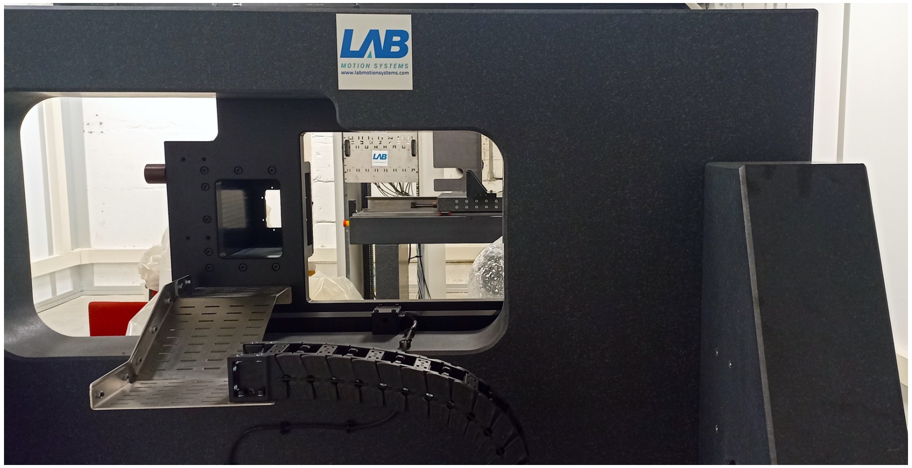
X-axis sample translation

STAR INFRASTRUTTURA DI RICERCA

Courtesy of Prof. R. Agostino - UniCal

STAR BEAMLINES

µTomo2: detectors



Elettra Sincrotrone Trieste

Varex XRD 3025N-G45-C CT grade

SENSOR

Panel .... Single substrate amorphous silicon active TFT-diode array
Scintillator .... Direct deposition CsI:Tl or various Gd_2O_2S:Tb (Gadox)
Pixel Matrix .... 3008 × 2512 @ 100 µm pixel pitch
Total Area .... 300 × 250 mm²

ELECTRONICS

Charge Amplifier ... Low noise ASICs with six user selectable gain settings
ADC 16-bit

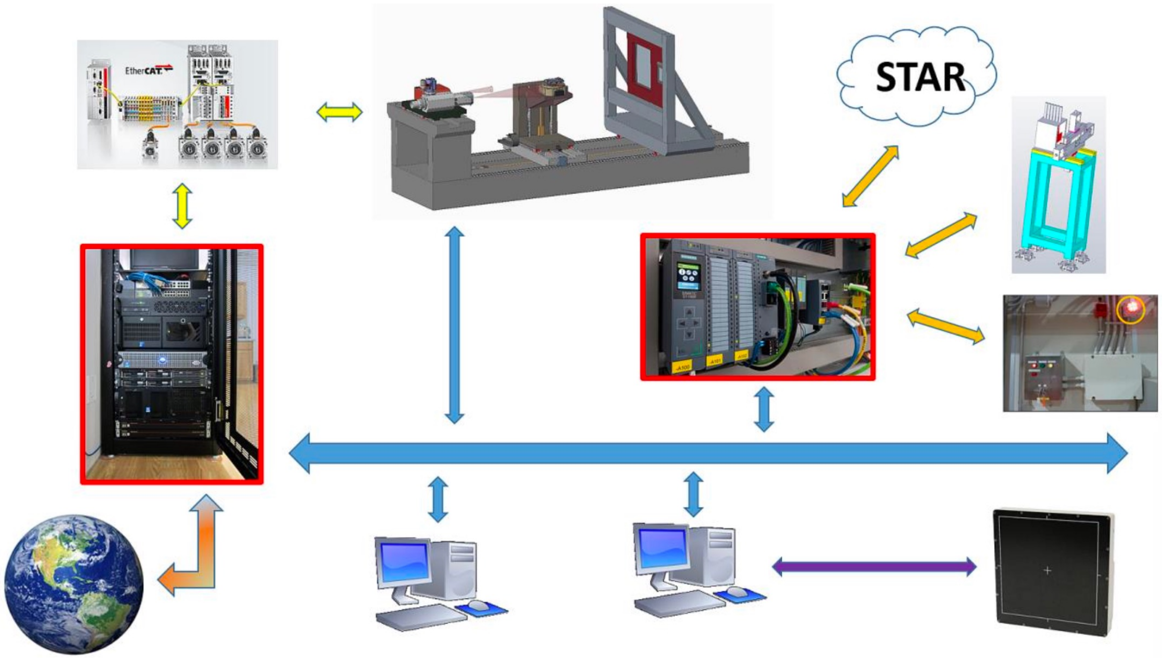
Read-out Modes	Matrix	Pixel (µm²)	fps
	3008 × 2512	100 × 100	5.5
	1504 × 1256	200 × 200	11
	752 × 628	400 × 400	20

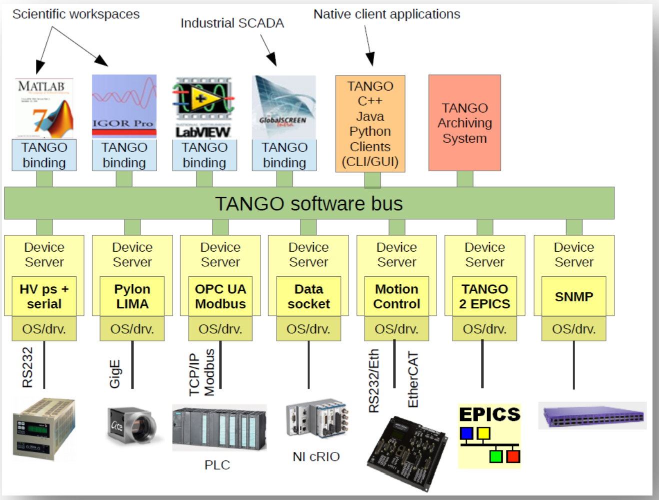
Gpixel GSENSE6060 (grade 1)

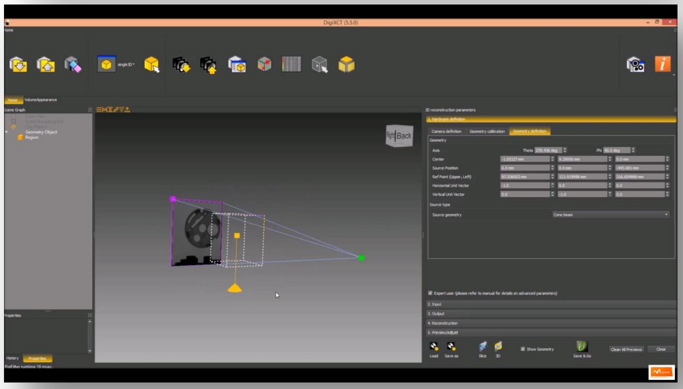
Specifications

Photosensive area	61.44 mm x 61.44 mm
Pixel size	10 µm x 10 µm
Number of active pixels	6144 x 6144
Full well capacity	128 ke- @ LG
Temporal noise	4.6 e- @ HG
Dynamic Range	89 dB @ 12bit HDR mode
Peak QE	71.6% @ 550nm

STAR BEAMLINES
μTomo2: control hardware and software







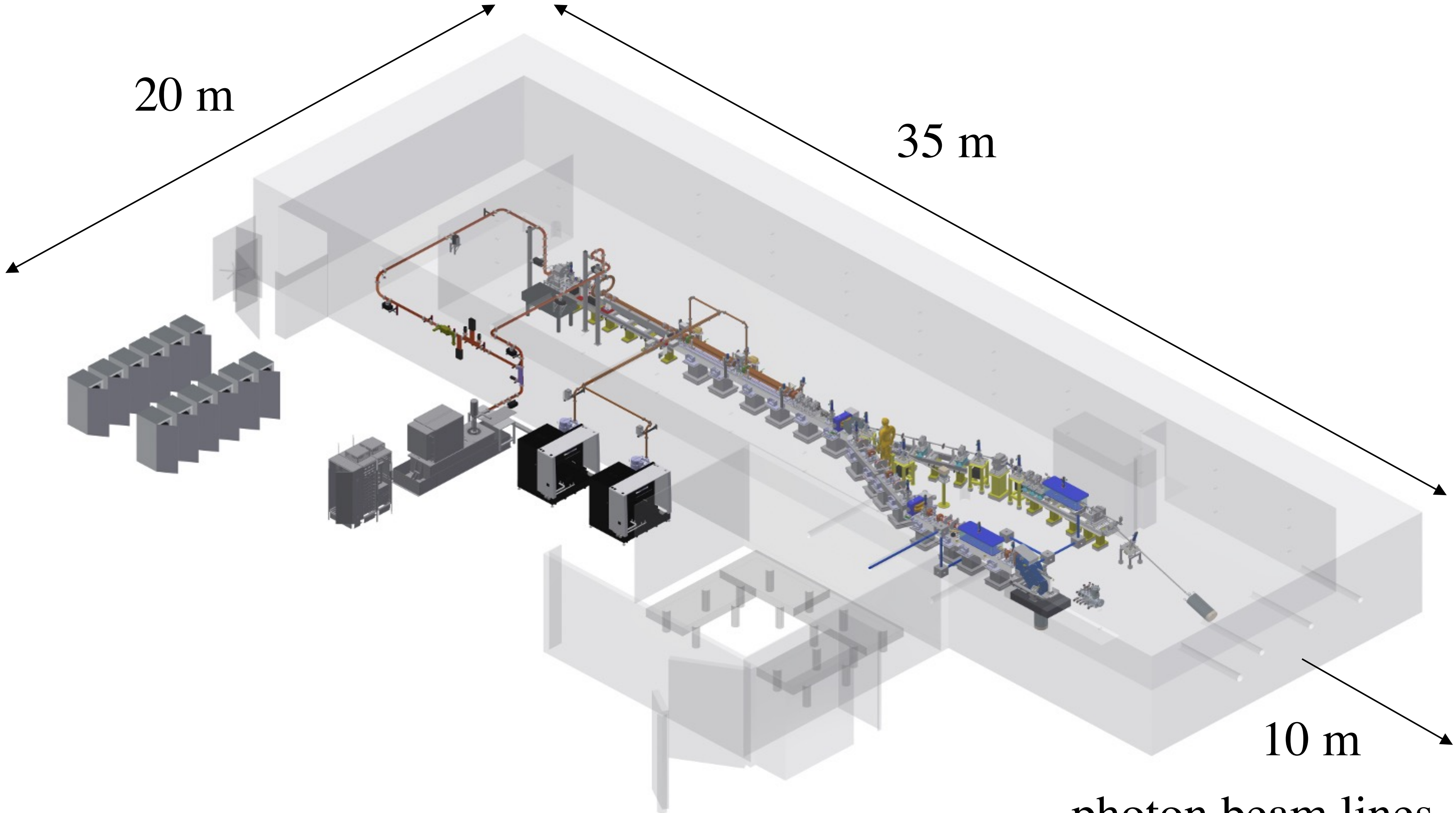
Data Storage and Image Processing

- High performance workstation for image acquisition and processing
  - *control PC*
  - *Workstation for tomographic reconstruction*
  - *Workstation for visualisation and data analysis*
- High-speed network
- Local Network Attached Storage
- Software
  - *Reconstruction software from Digisens*
  - *Processing software from Avizo*

Elettra Sincrotrone Trieste

STAR INFRASTRUTTURA DI RICERCA

150 MeV High Brightness Electron Linac + Laser	12 M€
Bunker/building + ancillary equipm.	4 M€
2 X-ray beam lines for micro-tomography	3 M€



Schematic Budget for a
170 keV X-ray ICS to be built from scratch

100 MeV Linac+Laser (170 keV) - 9 M€
Bunker/building + ancillary equipm. 4 M€
2 X-ray beam lines (fully equipped) 3 M€
TOTAL 16 M€

Injector for AfLS (100 MeV Linac) 5-6 MeV
Bunker/building + ancill. equipment used also for AfLS

Cost specific to ICS (9-5) + 3 = 7 M€

Operational Team requested by a ICS-CLS

STAFF MEMBERS

1. Radio-Frequency
2. Diagnostics/Electronics
3. Laser
4. Beam Dynamics/Optics
5. Magnets/Vacuum
6. Control System
7. Beam Lines / Detectors

TECHNICIANS

1. Radio-Frequency
2. Diagnostics/Electronics (2)
3. Magnets/Vacuum (2)
4. Control System
5. Ancillary Plants

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Thank you for your attention

https://youtu.be/vHK77Mk2Dp4

applied sciences

MDPI

Article

State of the Art of High-Flux Compton/Thomson X-rays Sources

Vittoria Petrillo [1,2,*,†], Illya Drebot [1,†], Marcel Ruijter [1,†], Sanae Samsam [1,†], Alberto Bacci [1], Camilla Curatolo [1], Michele Opromolla [1,2], Marcello Rossetti Conti [1], Andrea Renato Rossi [1] and Luca Serafini [1,†]

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* Correspondence: vittoria.petrillo@mi.infn.it
† These authors contributed equally to this work.

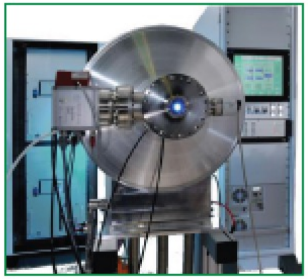
Abstract: In this paper, we present the generalities of the Compton interaction process; we analyse the different paradigms of Inverse Compton Sources, implemented or in commissioning phase at various facilities, or proposed as future projects. We present an overview of the state of the art, with a discussion of the most demanding challenges.

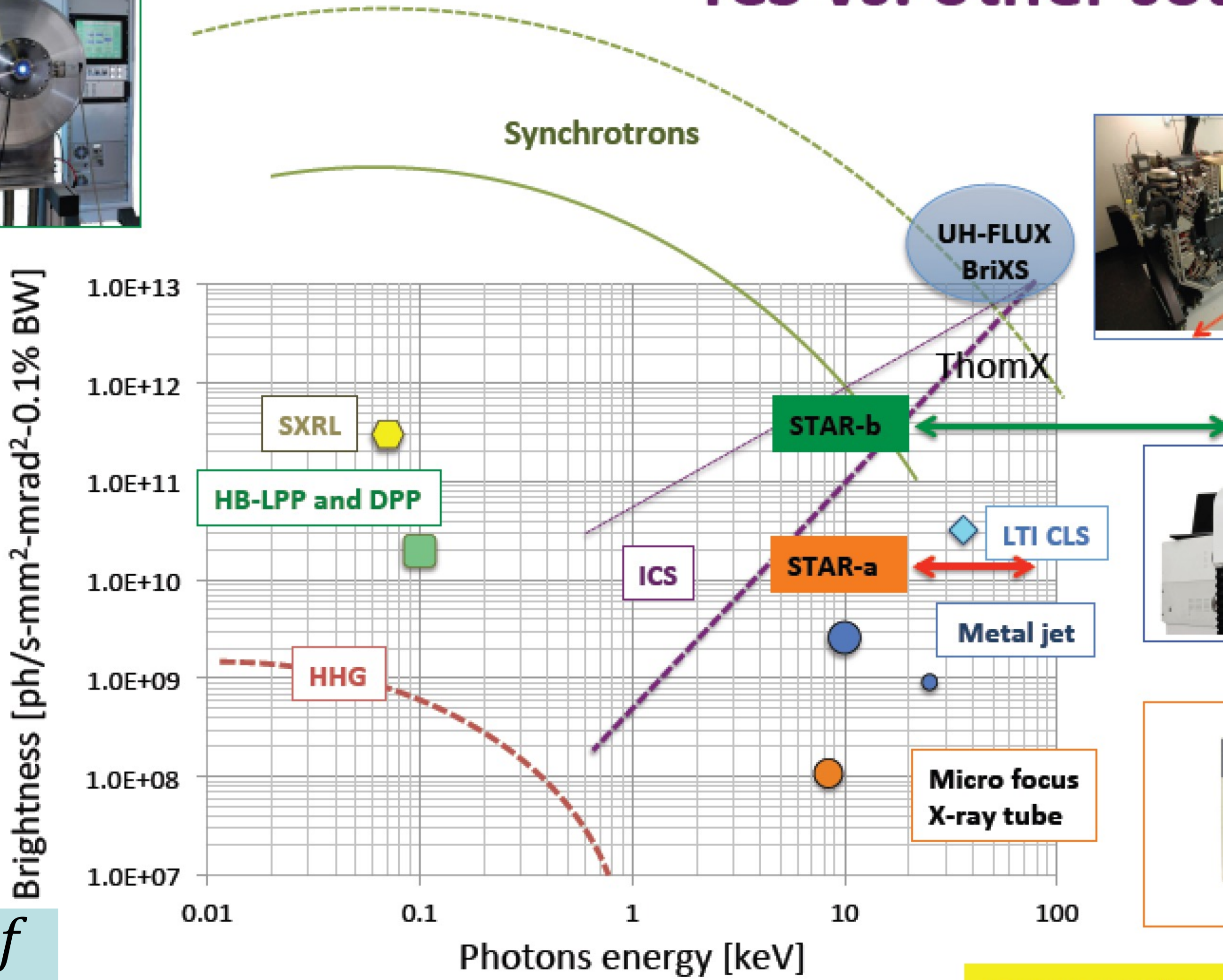
Keywords: thomson scattering; compton scattering; synchrotron radiation; X-rays; radiation sources

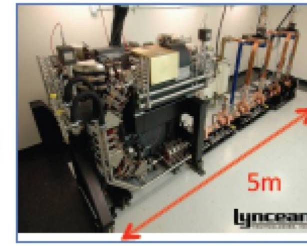
Additional Slides

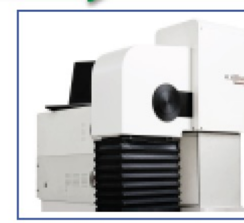
Rivaling with Synchr. Light Sources for energies above 50 keV

ICS vs. other sources









$$B_{av} = \frac{N_{ph} f}{\varepsilon_x^2 \frac{\Delta E_X}{E_X}}$$

Courtesy of A. Murokh
RadiaBeamTechnology

Brilliance of Lasers and X-ray sources

$$N_{ph} = 10^{19} - 10^{20}$$

$$\sigma_t = 10 - 20 \quad fs$$

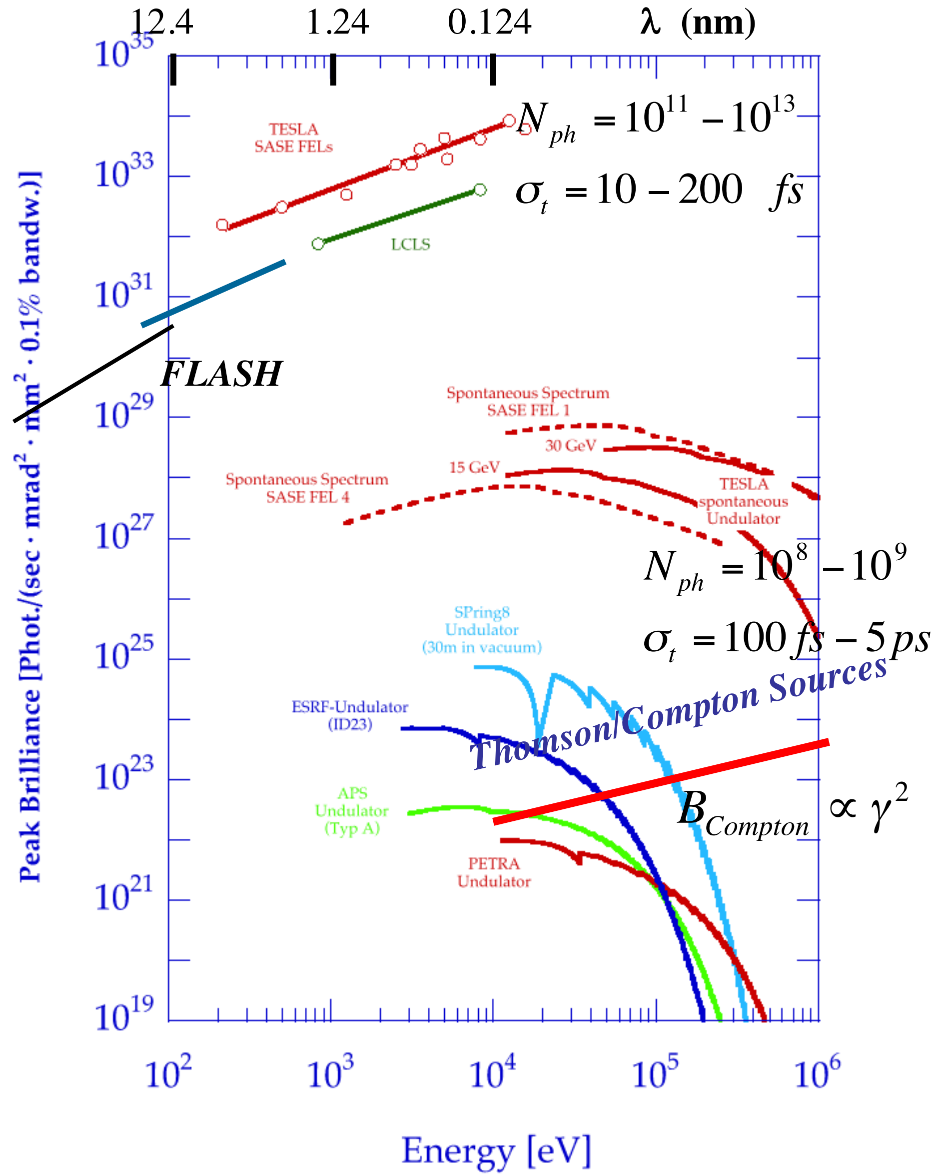
$$B = \frac{N_{ph}}{\sqrt{2\pi}\sigma_t \left(M^2\lambda\right)^2 \frac{\Delta\lambda}{\lambda}}$$

ELI

BELLA

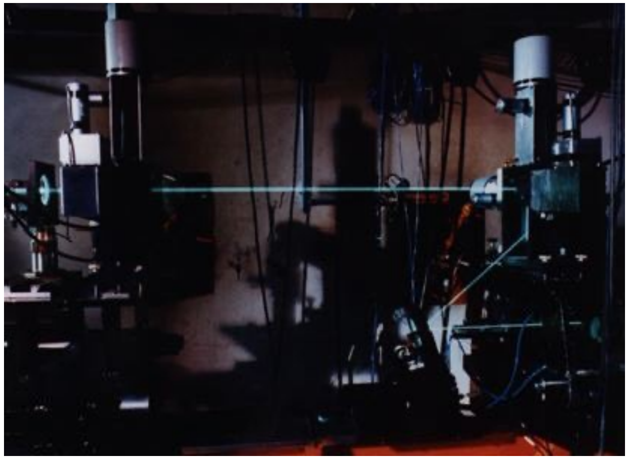
$$B_{peak} = \frac{N_{ph}}{\sqrt{2\pi}\sigma_t \varepsilon_x^2 \frac{\Delta E_X}{E_X}}$$

$$B_{av} = \frac{N_{ph} f}{\varepsilon_x^2 \frac{\Delta E_X}{E_X}}$$



Compton back-scattering (later renamed ICS) was experimentally observed firstly at Frascati National Lab. of INFN

Hadronic Physics was the original motivation for Compton back-scattering experiments (cfr. Ladon at INFN-LNF, Graal at ESRF): single photon per bunch collision at energies > 50 MeV



L. Federici, G. Giordano, G. Matone, G. Pasquariello, P. G. Picozza, et al. **Backward compton scattering of laser light against high-energy electrons: the Ladon photon beam at Frascati**. Il Nuovo Cimento B (1971-1996), 59(2):247–256, 1980.

An ICS based *X*-ray User Facility in operation in Germany

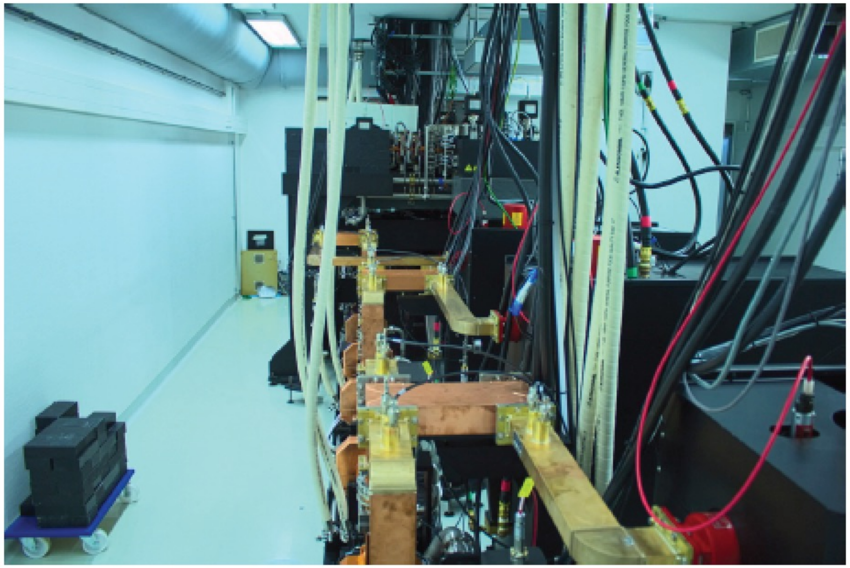
E17 Lehrstuhl für Biomedizinische Physik

Technische Universität München

Biomedical imaging with the lab-sized laser-driven synchrotron source Munich Compact Light Source

Klaus Achterhold

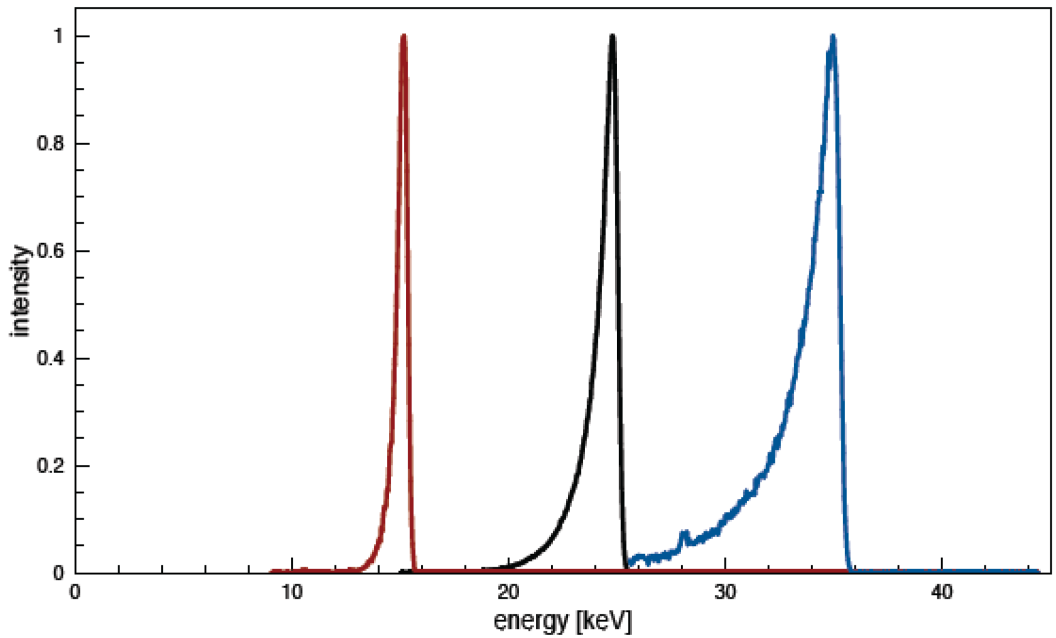
Biomedical Physics, Physics-Department E17, Technische Universität München



Compact machine
10x10 m^2
In operation since early 2015

Klaus.Achterhold@tum.de

$$E_x(\Theta,\alpha,E_L,T)=\frac{(1+\beta\cos\alpha)E_L}{1-\beta\cos\Theta+(E_L/mc2)(1+\cos(\Theta+\alpha))}$$



measured Spectrum of X-rays into +/- 2 mrad

↓

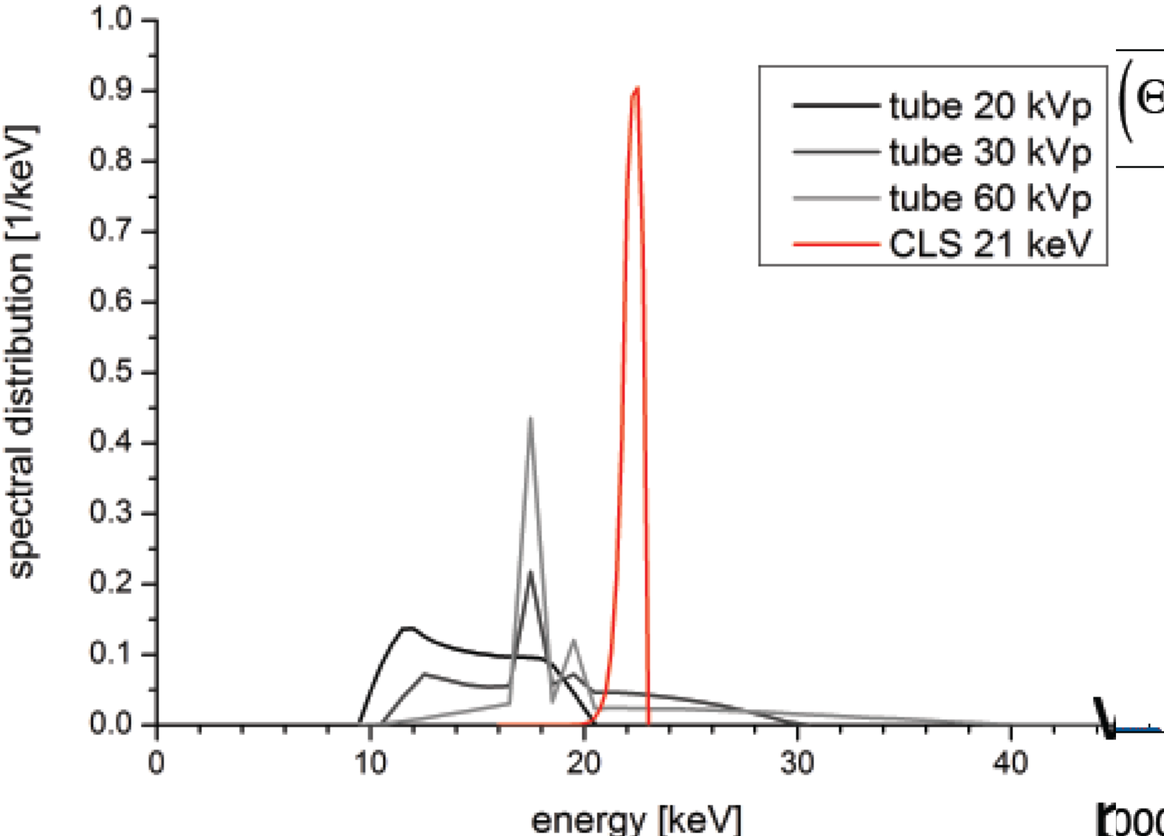
Bandwidth

$35000+0.0016\cdot\Delta T$ with $\Delta T/T=0.3\%$

$35000+30000\cdot\Delta E_L$ with $\Delta E_L/E_L=10^{-12}$

$35000-9000\cdot\Delta\alpha^2$ with $\Delta\alpha=0.03$

Measured $5\cdot10^{10}$ ph/sec with 20 mA



measured Spectrum of X-rays into +/- 2 mrad

Bandwidth

$(\Theta+\alpha))$

000+0.0016 · ΔT with ΔT/T=0.3%

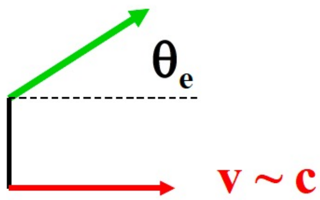
35000+30000 · ΔE_L with $\Delta E_L/E_L=10^{-12}$

35000-9000 · $\Delta\alpha^2$ with $\Delta\alpha=0.03$

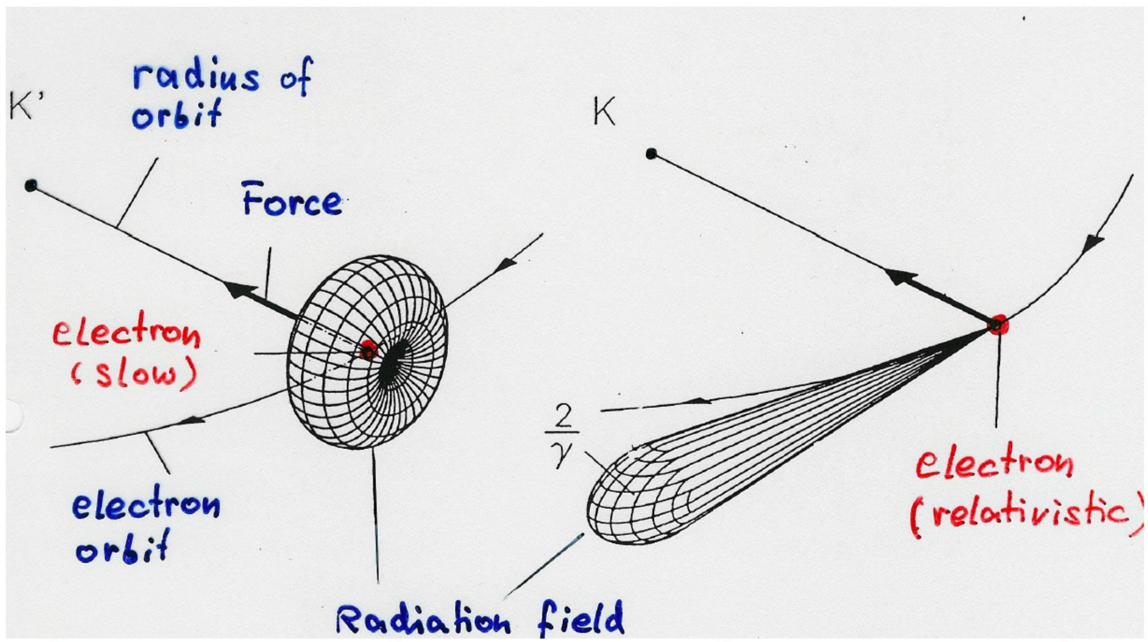
Measured $5\cdot10^{10}$ ph/sec with 20 mA

Also synchrotron radiation is affected by the $\gamma^2\theta^2$ red shift

Radiation is emitted into a narrow cone



$$\theta = \frac{1}{\gamma} \cdot \theta_e$$



v << c

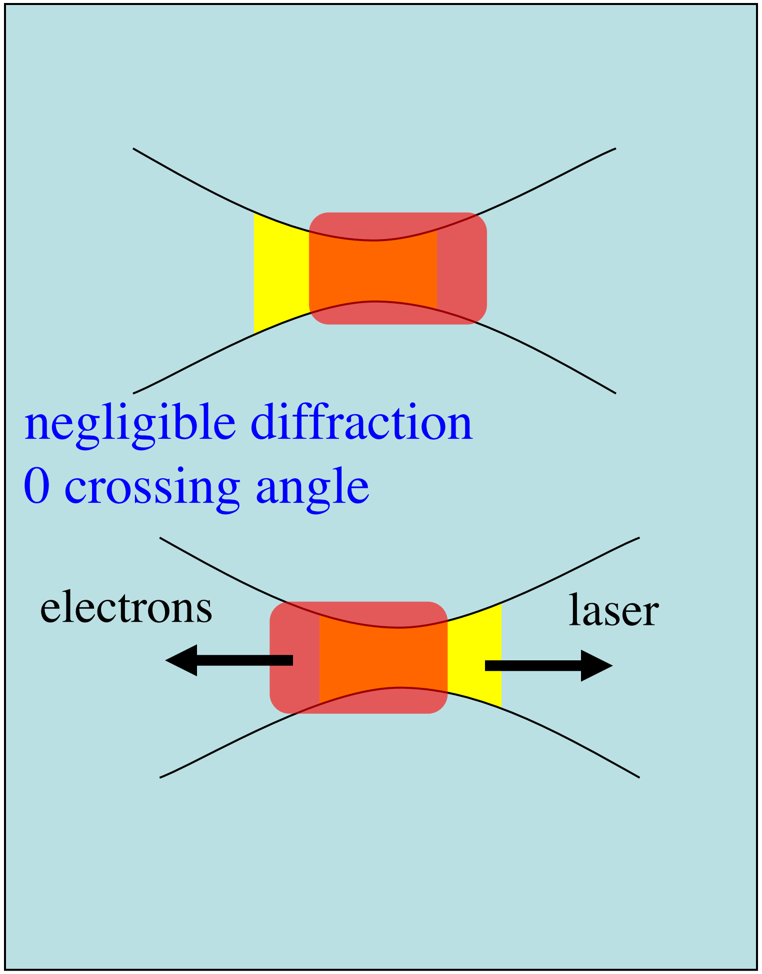
v ≈ c

Courtesy L. Rivkin

ICS sources are better described as colliders. They are actually mini-colliders of electron-photon beams to generate secondary beams of photons.

unlike undulatory radiation sources, where the collision is with virtual photons, ICS involves collision with real photons that carry energy and momentum

$\sigma_T = 0.67 \cdot 10^{-24} cm^2 = 0.67 \ \ barn$

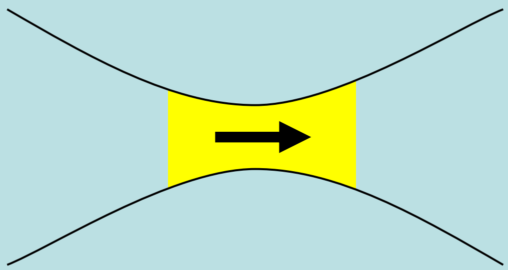


- Scattered flux $N_\gamma = \mathbf{L}\sigma_T$ $\quad \sigma_T = \frac{8\pi}{3} r_e^2$
- Luminosity as in HEP collisions
  - Many photons, electrons
  - Focus tightly $\quad \mathbf{L} = \frac{N_L N_{e-}}{4\pi\sigma_x^2} f$
  - ELI-NP-GBS $\quad L_S \equiv \frac{L}{\Delta\nu_\gamma}$

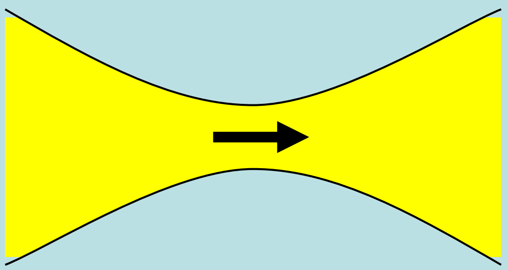
$$L = \frac{1.3 \cdot 10^{18} \cdot 1.6 \cdot 10^9}{4\pi(0.0015cm)^2} 3200(s^{-1}) = 2.5 \cdot 10^{35} cm^{-2} s^{-1}$$

cfr. LHC 10^{34}, Hi-Lumi LHC 10^{35}

Matching Laser Pulse Length and Focus Size



Laser pulse length matched to focus size (Rayleigh length).



Laser pulse too long for small focus size.

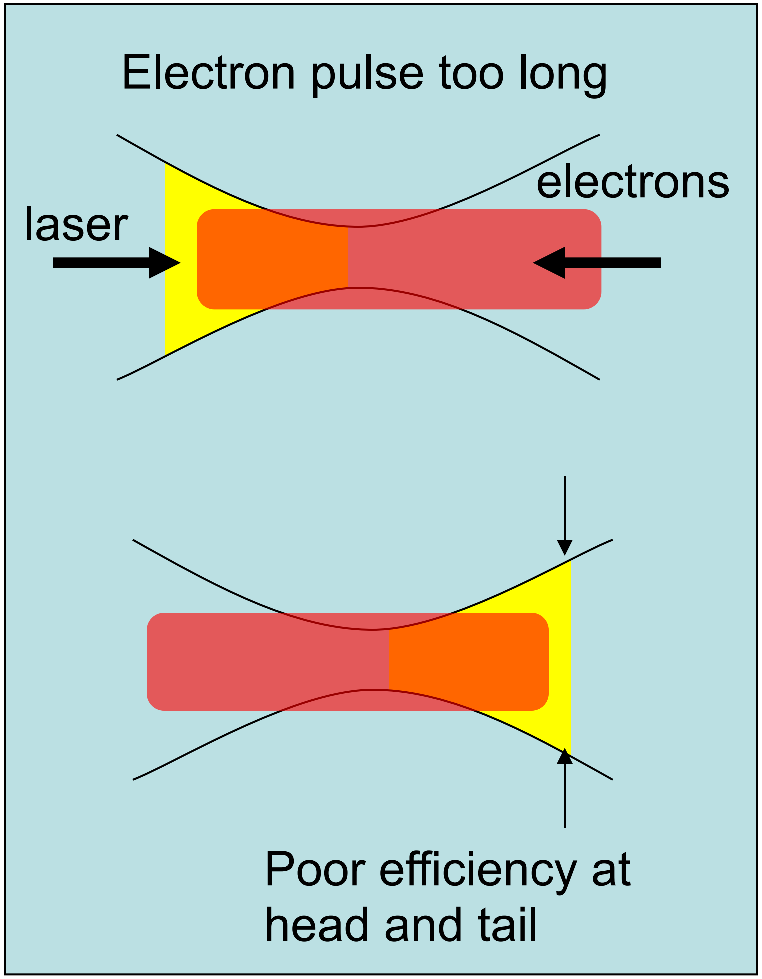
Laser pulse must be short compared to Rayleigh length so that whole pulse is focused simultaneously.

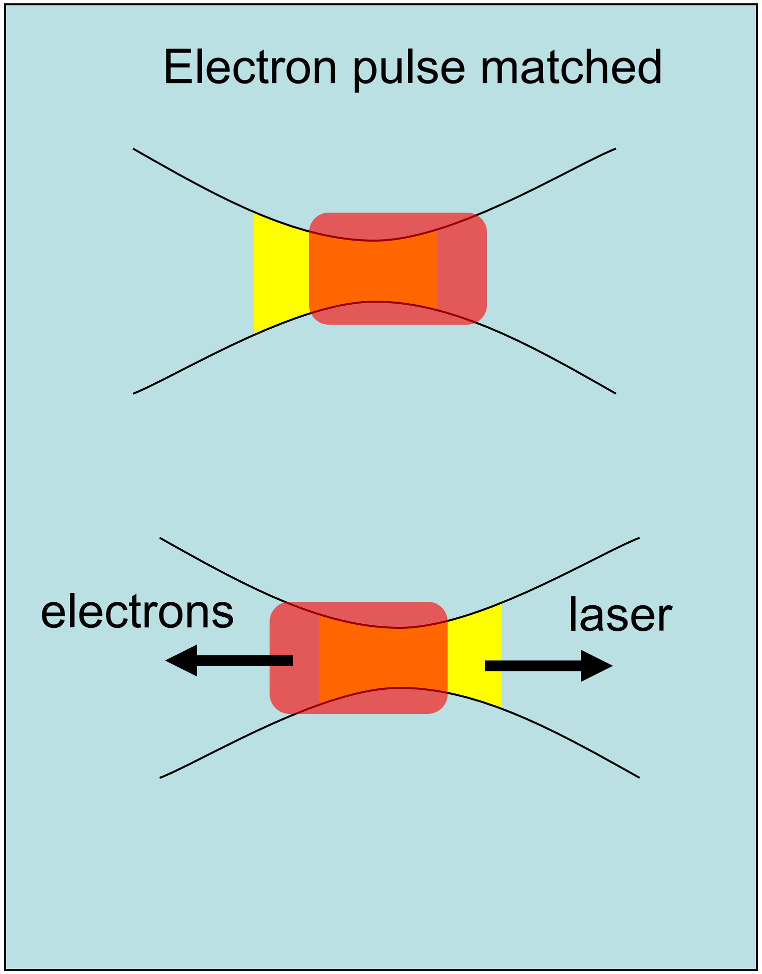
Laser may be shorter than Rayleigh length, but less than 0.5 ps is not practical, and could lead to non-linear effects that broaden the spectral line

courtesy of D. Moncton

$$L = \frac{N_{el} N_{las}}{2\pi\left(\sigma_0^2 + w_0^2/4\right)} f$$

Electron Bunch Length Matched to Rayleigh Length





courtesy of D. Moncton

3^{rd}-4^{th} Generation Light Sources

- Synchrotron light sources: < 50 keV, > 50 ps (100 m, 300 M$)
- X-ray FEL (LCLS): energy ≤25 (50?) keV, 1-100 fs (1 km, 1 G$)

- **Inverse Compton Scattering sources (ICS) 20-400 keV , sub-ps, (10 m , 10 M$)**

photons within normalized collimation angle $\Psi = \gamma \cdot \theta_{coll}$

$$\mathcal{N}^{\Psi} = 6.25 \cdot 10^{8} \frac{U_L(J)\, Q(pC)\, r}{E_L(eV)\, (\sigma_x^2(\mu m) + \sigma_L^2(\mu m))} \cdot \frac{\left(1 + \sqrt[3]{X}\,\Psi^2/3\right)\Psi^2}{(1 + (1 + X/2)\Psi^2)\,(1 + \Psi^2)},$$

Spectral Density S relevant to X-ray imaging and nuclear photonics

$$S = \frac{\mathcal{N}^{\Psi}}{\sqrt{2\pi}\, 4\, E_L \gamma_{CM}^2 \, \frac{\Delta E_{ph}}{E_{ph}}}.$$

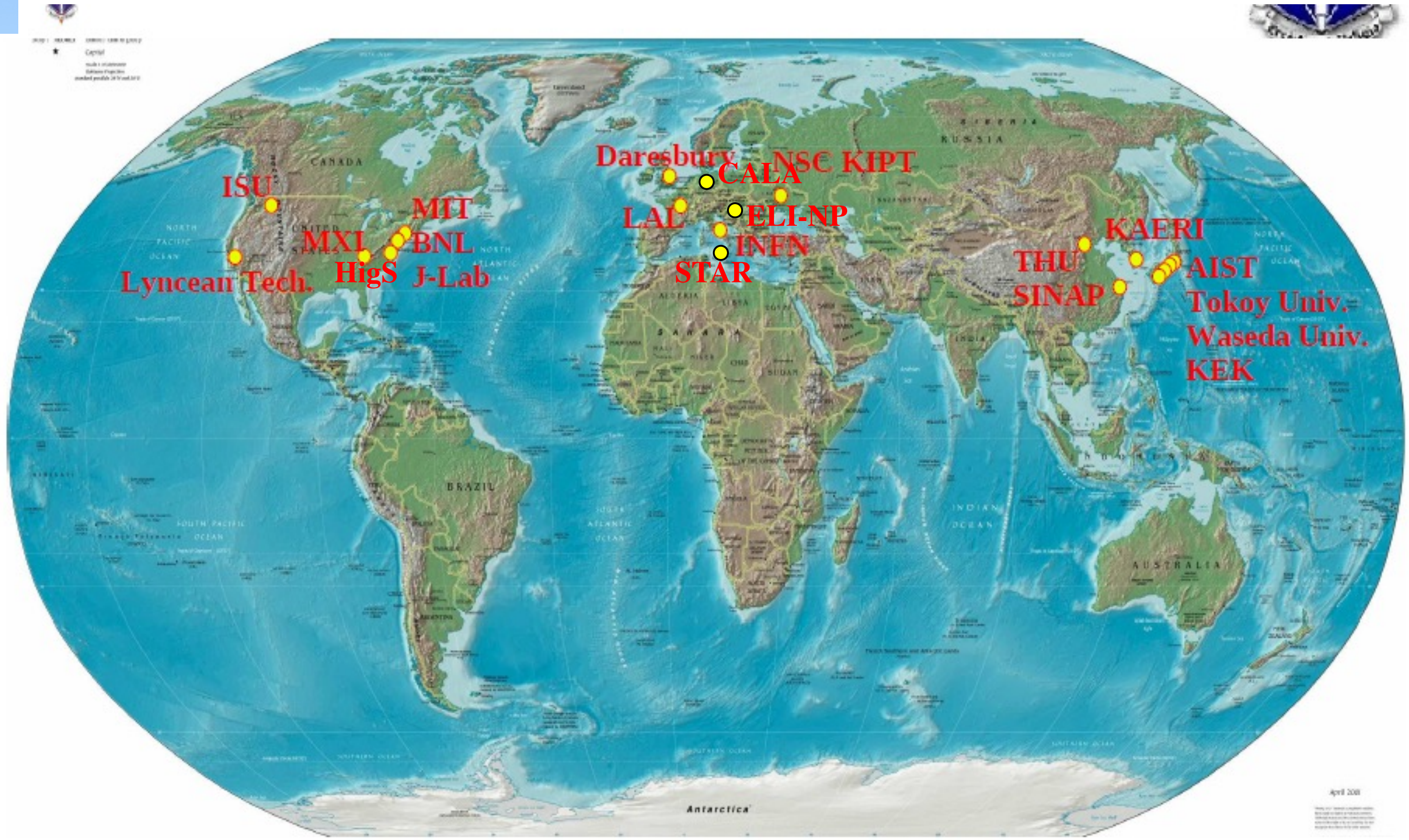
Serafini-Petrillo criterion

$$S \propto \frac{\langle I_e \rangle U_{las}}{\varepsilon_n^2 E_x}$$

Average Brilliance relevant to microscopy/ spectroscopy

$$B_{AV} \propto \frac{S}{\varepsilon_X^2} E_X \propto \frac{S}{\sigma_x^2 \theta_{coll}^2} E_X$$

$$\varepsilon_X \propto \sigma_x \theta_{coll}$$



ICS are the most effective "photon accelerators" **(boost twice than FELs)**

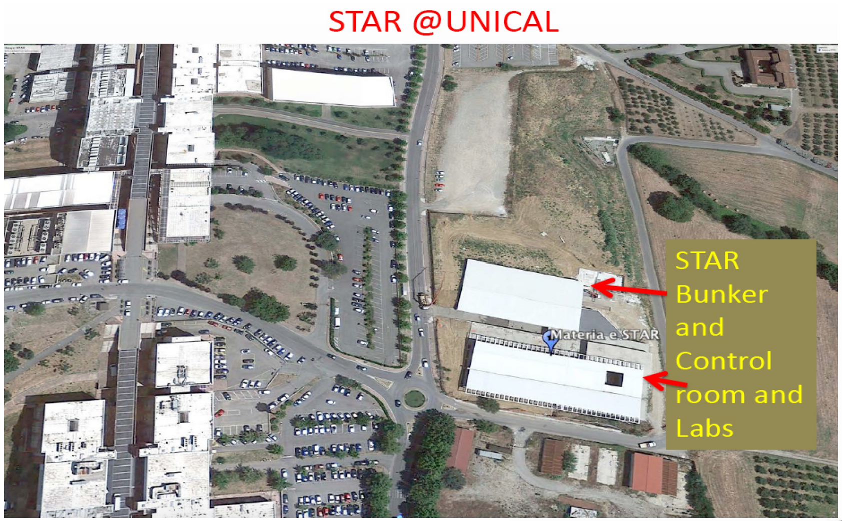
"4γ² boost effect" $E_{X/\gamma} = 4\gamma^2 E_{laser}$

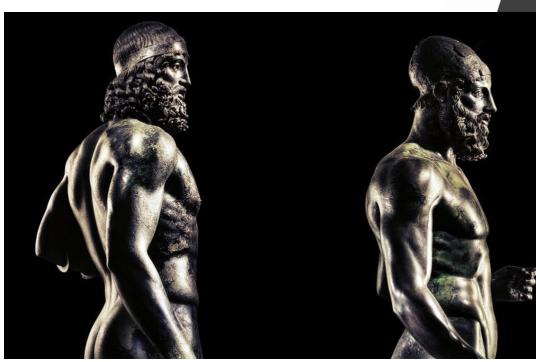
$$with\ T = 100\,MeV\ (\gamma = 197)\ E_{laser} = 1.2\ eV \Rightarrow E_{X/\gamma} = 186\ keV$$

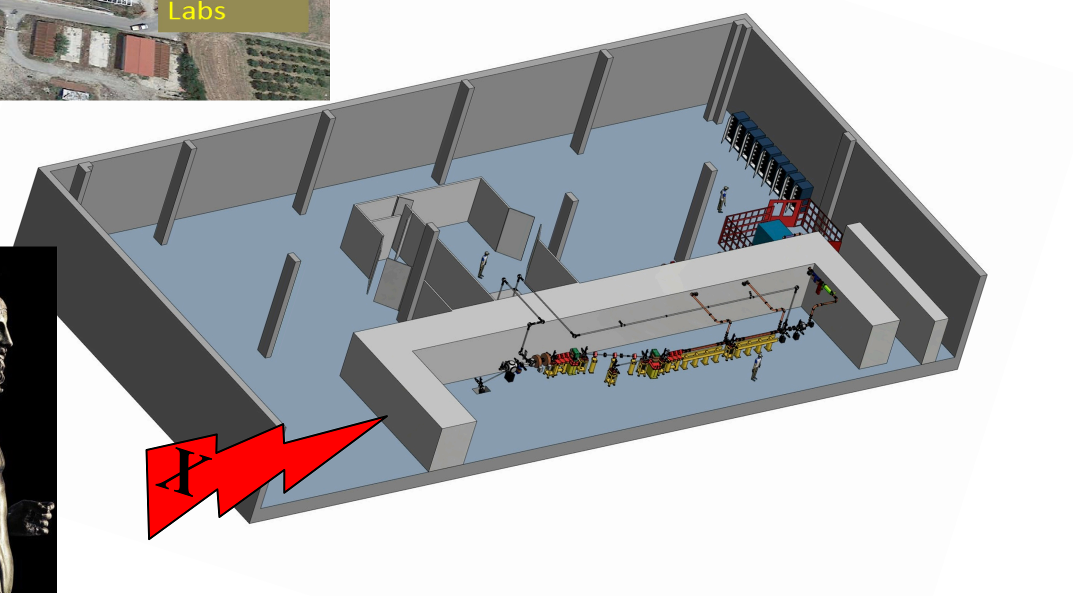
Courtesy A. Variola

STAR in Calabria (South Italy)

STAR : Southern europe Thomson source for Applied Research

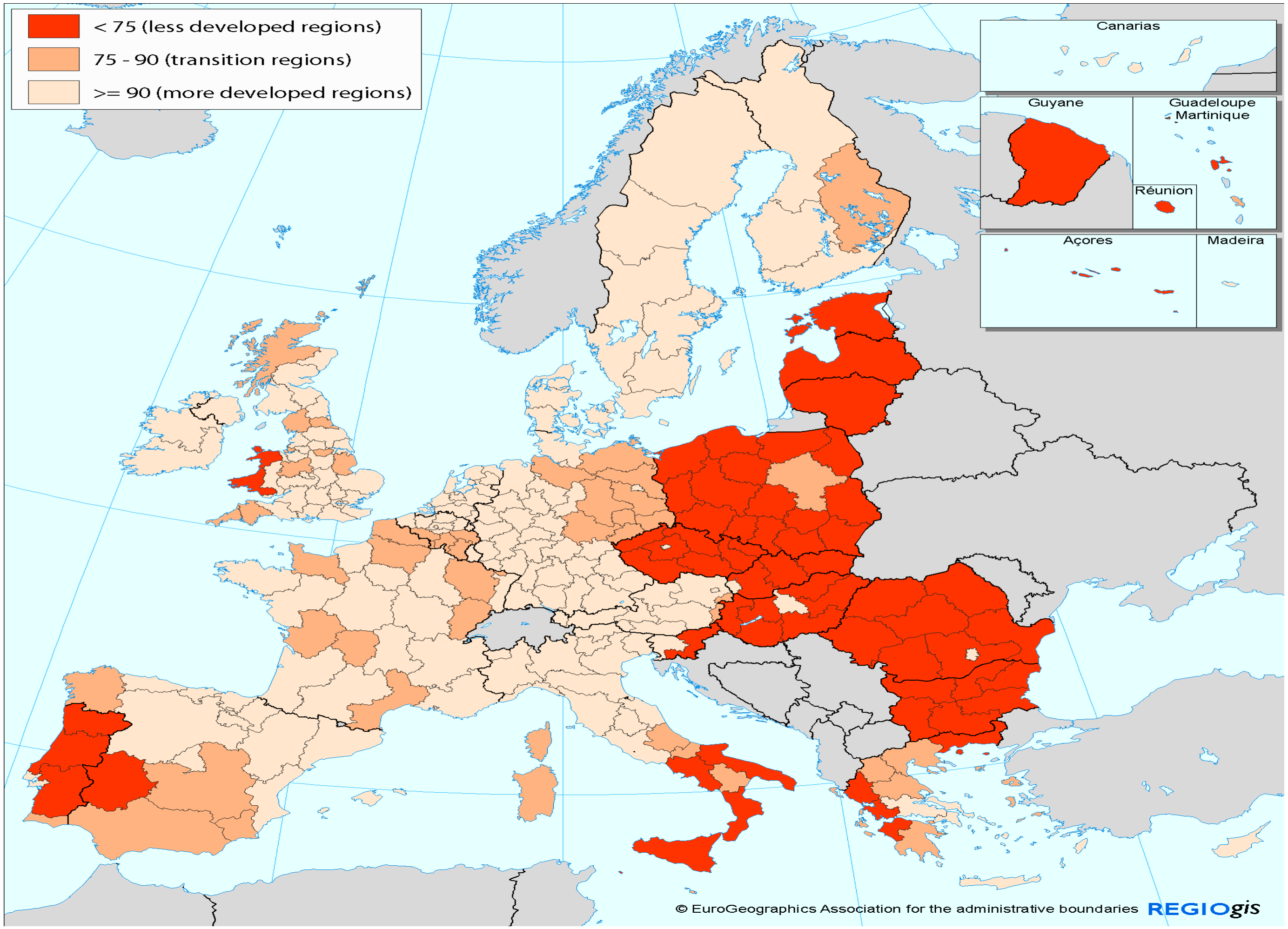






- **STAR (Southern europe Thomson source for Applied Research) is a Compton Source of mono-chromatic X-rays tunable in the range 20-350 keV, devoted to advanced non-invasive diagnostics of cultural heritage/archeological samples.**

about 30 M€ allocated to Univ. of Calabria to build a research infrastrucutre based on ICS, from EU Govt. in the frame of funding programs to Convergence Regions



2014-2020

(**EU Commission Official Regional Map**)

Convergence Regionss

Transition Regions

Developed Regions

STAR : Southern europe Thomson source for Applied Research

STAR X-ray beamlines foreseen applications

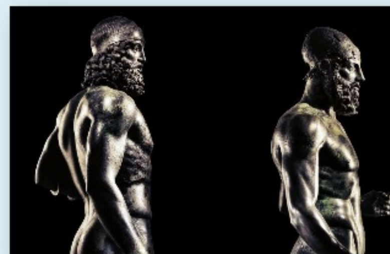
Calabria: rich in archaeological sites and findings

List of Calabrian's museums:

1)
2)
3)
4)
5)
6)
7)
8)
9)
10)
11)

List of archaeological sites or area

1) Area archeologica di Casignana
2) Area archeologica di Monasterace
3) Sito archeologico di Castiglione di Paludi
4) Sito archeologico di Francavilla Marittima
5) Sito archeologico di Punta Alice
6) Area archeologica di Vibo Valentia
7) Area archeologica di Capo Colonna
8) Area archeologica di Locri Epizefiri
9) Area archeologica di Sibari
10) Area archeologica di Scolacium

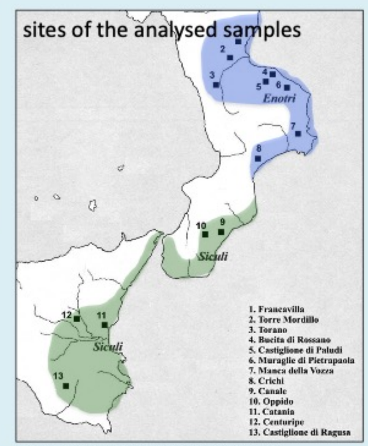


PEACE SYMBOLS IN CALABRIA BEFORE GREEK COLONIZATION (A preliminary study @ STAR µTomo)

1. - Pendaglio a coppia antropomorfa da Francavilla Marittima tipo A (lato 1 e 2).

2. - Pendaglio a coppia antropomorfa da Francavilla Marittima tipo B (lato 1 e 2).

- Bronze anthropomorphic couples as pendants.
- Burial goods in calabrian area (VIII sec B.C.)
- Two sets: type-A (30 findings);type-B (2 findings)

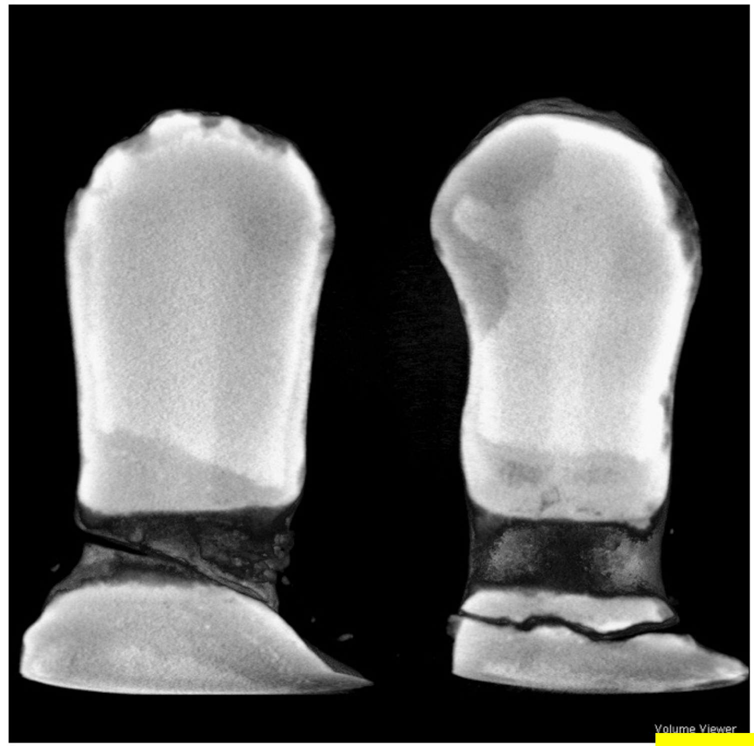


6. - Carta di distribuzione dei pendagli a coppia antropomorfa.

STAR Thanks to R. G. Agostino on behalf of STAR-UNICAL team

Tomografia in Archeometria.

La microtomografia è sfruttata in modo ottimale in indagini **archeometriche** e **paleontologiche**. Inoltre, la sua applicazione può supportare **restauratori** e conservatori a comprendere le tecniche di costruzione di un'opera d'arte o individuare restauri di scarsa qualità o, ancora, **contraffazioni**.



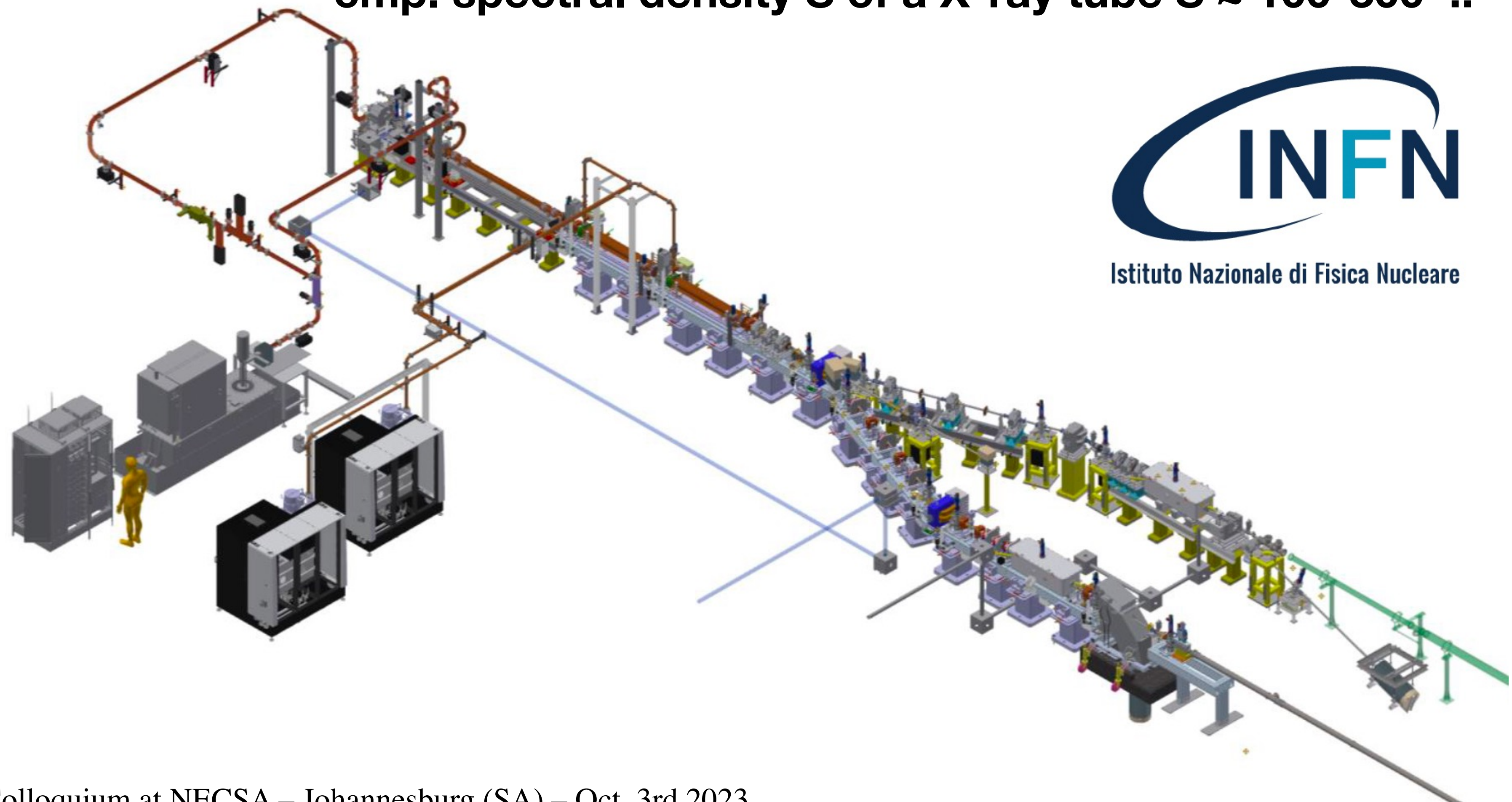
Courtesy R. Agostino

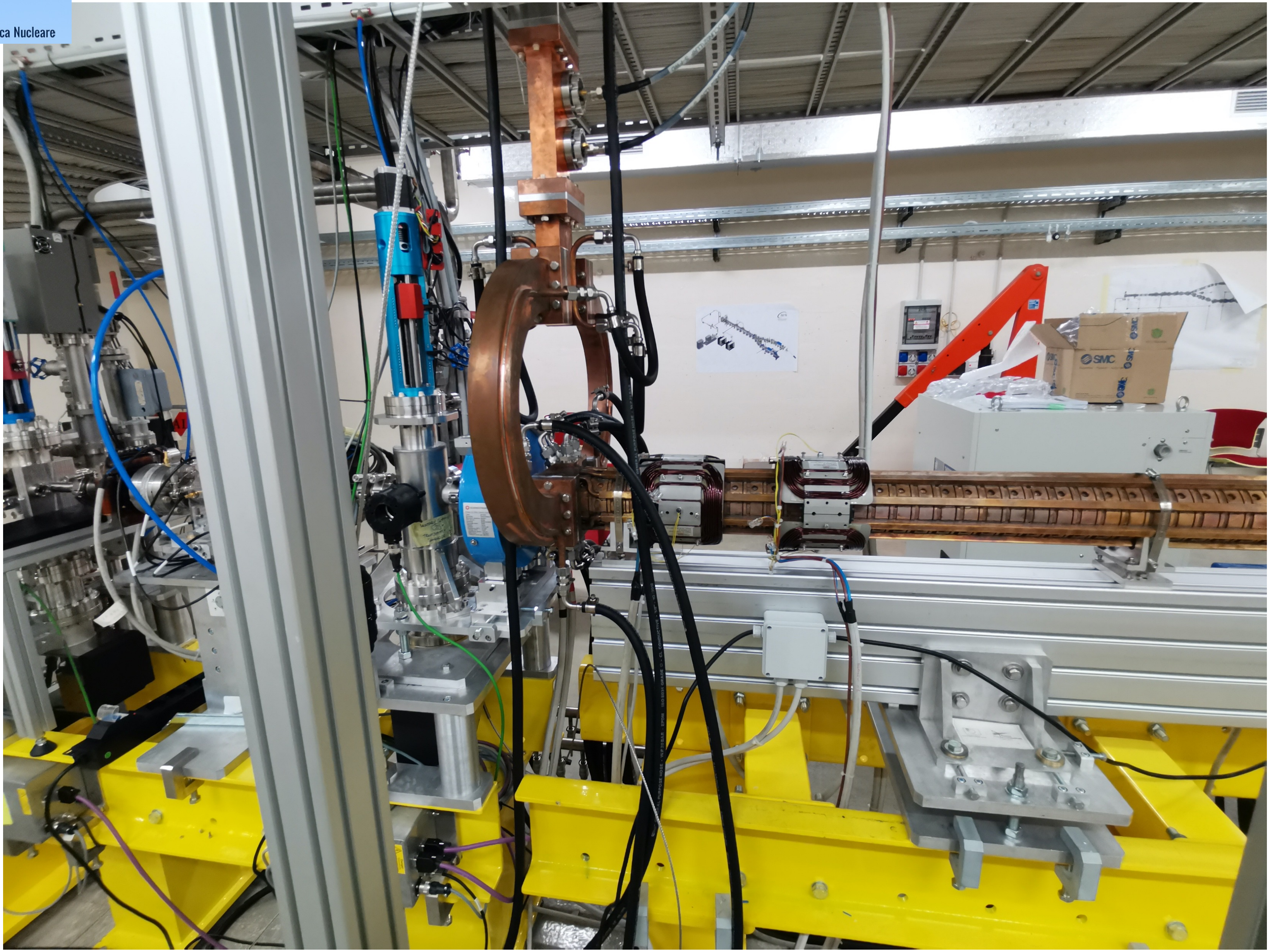
Abbiamo sottoposto a microtomografia una coppietta in bronzo dell'VIII sec. a.C. (*). Le sezioni mostrano una serie di elementi che permettono di ipotizzare tecniche di realizzazione e stabilire quale sia lo stato di conservazione del reperto. Nella sezione tomografica a destra, un particolare delle teste in cui si individua un foro passante alla base delle stesse e una frattura restaurata attraverso l'utilizzo di resine.

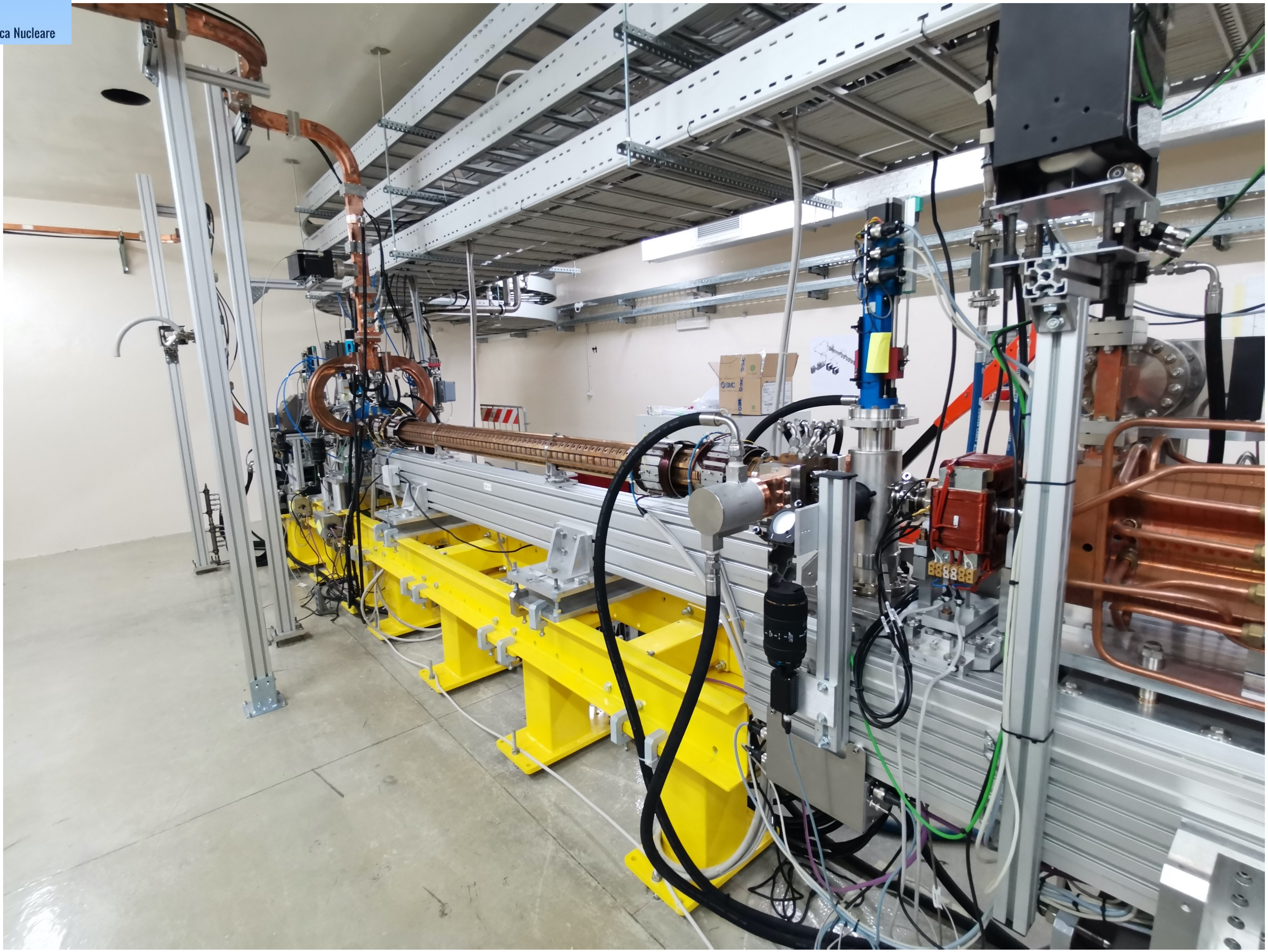
N_{ph} (s^{-1}) = $5{\cdot}10^{10}$ (10% bdw) S @ 30keV ($s^{-1}eV^{-1}$)= $1.5{\cdot}10^{7}$

STAR-multi-bunch N_{ph} (s^{-1}) = $5{\cdot}10^{11}$ (10% bdw)
S @ 30 keV ($s^{-1}eV^{-1}$)= $1.5{\cdot}10^{8}$

cmp. spectral density S of a X-ray tube S ≈ 100-300 !!







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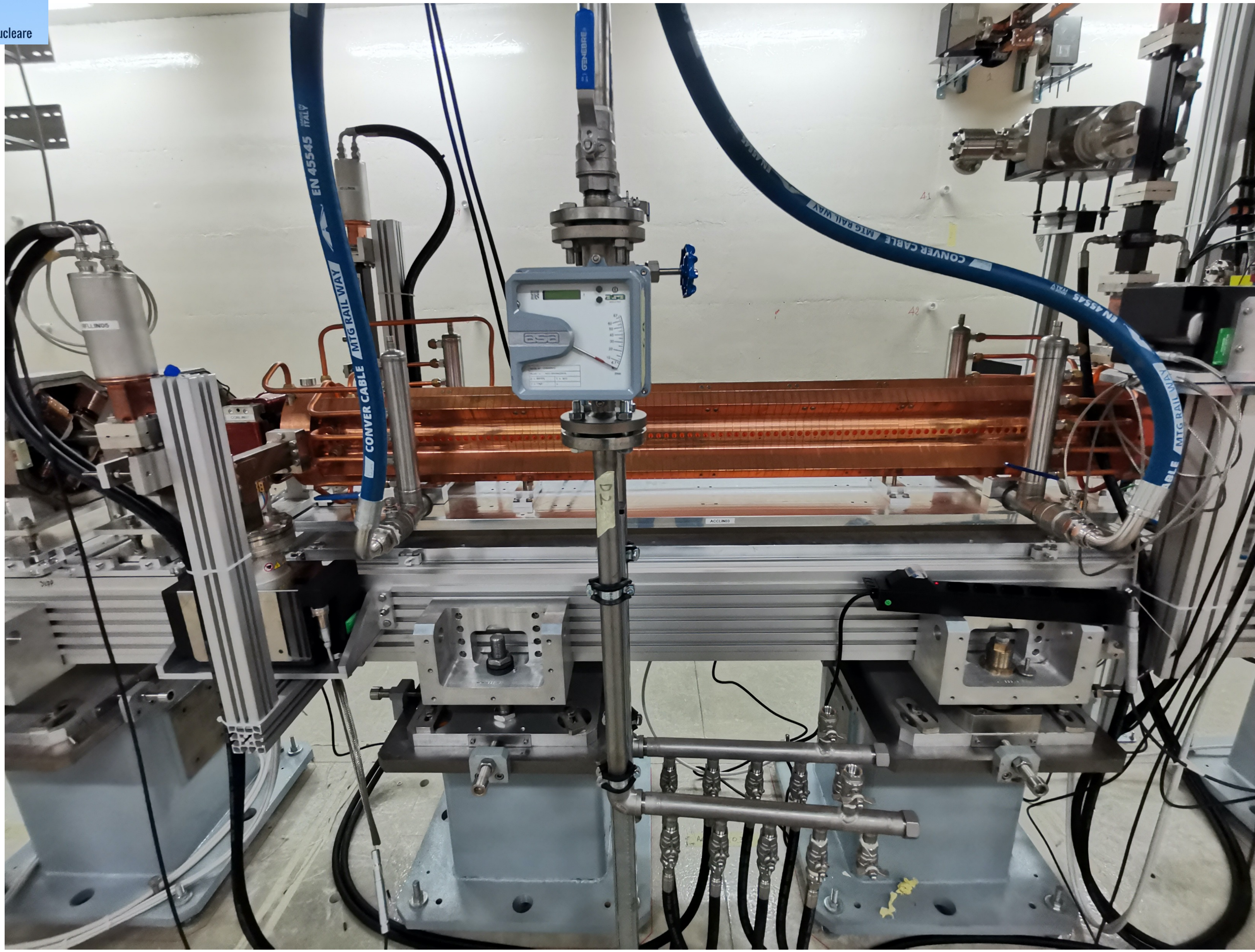


DANFYSIK

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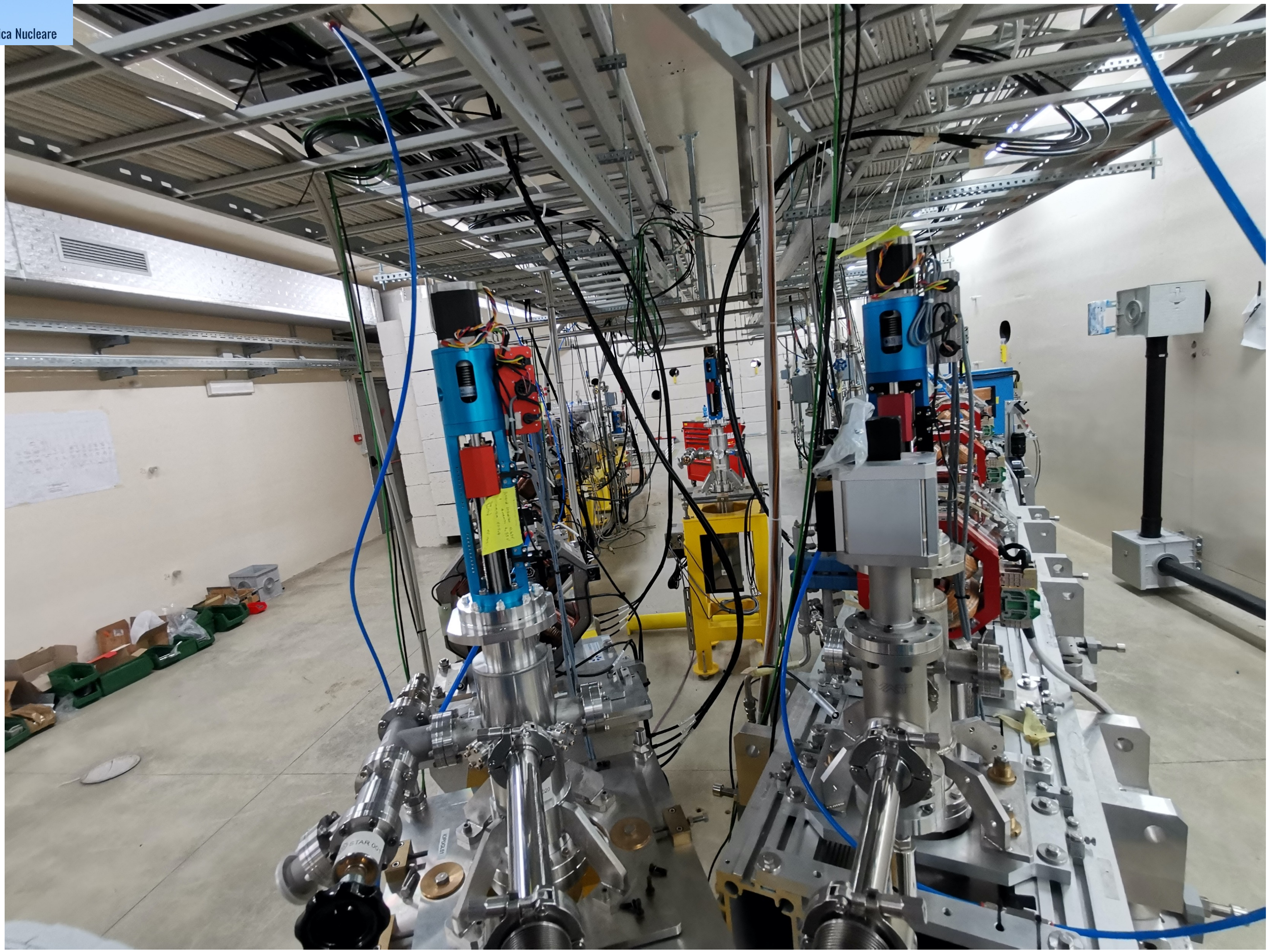

Additional Slides

SP criterion: quality factor $\mathbf{Q_S = \langle I_e \rangle U_L / \varepsilon_n^2}$

ThomX Nph (s^{-1}) = 10^{12} (10% bdw) S at 30 keV ($s^{-1}eV^{-1}$) = $3*10^8$
max 80 keV **QS = 3.2** (16 mA * 20 mJoule / 10 mm·mrad)

MuCLS Nph (s^{-1}) = 10^{11} (10% bdw) S at 30 keV ($s^{-1}eV^{-1}$) = $3*10^7$
max 40 keV **QS = 0.3** (10 mA * 3 mJoule / 10 mm·mrad)

STAR Nph (s^{-1}) = $5*10^{10}$ (10% bdw) S at 30keV ($s^{-1}eV^{-1}$) = $1.5*10^7$
max 350 keV **QS = 0.16** (100 nA * 1 Joule / 0.8 mm·mrad)
STARmb Nph (s^{-1}) = $5*10^{11}$ (10% bdw) S at 30 keV ($s^{-1}eV^{-1}$) = $1.5*10^8$
QS = 1.6 (1 microA * 1 Joule / 0.8 mm·mrad)

CXLS Nph (s^{-1}) = $4*10^{10}$ (10% bdw) S at 30keV ($s^{-1}eV^{-1}$) = $1.3*10^7$
max 20 keV **QS = 0.13** (25 nanoA * 200 mJoule / 0.2 mm·mrad)

BriXSinO Nph (s^{-1}) =$2*10^{12}$ (10% bdw) S at 30 keV ($s^{-1}eV^{-1}$) = $6*10^8$
max 40 keV **QS = 6.4** (5 mA * 2 mJoule / 1.25 mm·mrad)

Large Recoil in ICS damps the effect of large bandwidth incident photon beams onto the bandwidth of scattered photons

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 080701 (2017)

Analytical description of photon beam phase spaces in inverse Compton scattering sources

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[1]*INFN-Milan, via Celoria 16, 20133 Milano, Italy*
[2]*Università degli Studi di Milano, via Celoria 16, 20133 Milano, Italy*
(Received 9 March 2017; published 3 August 2017)

equivalent to FELs Kim-Pellegrini crit. on 3D inhomogeneous effects on photon bandwidth

$$\frac{\Delta E_{\rm ph}}{E_{\rm ph}} \simeq \sqrt{\left[\frac{\Psi^2/\sqrt{12}}{1+\Psi^2}+\frac{\bar{P}^2}{1+\sqrt{12}\bar{P}^2}\right]^2+\left[\left(\frac{2+X}{1+X}\right)\frac{\Delta\gamma}{\gamma}\right]^2+\left(\frac{1}{1+X}\frac{\Delta E_L}{E_L}\right)^2+\left(\frac{M^2\lambda_0}{2\pi w_0}\right)^4+\left(\frac{a_0^2/3}{1+a_0^2/2}\right)^2}$$

collimation angle

beam emittance

beam en. spread

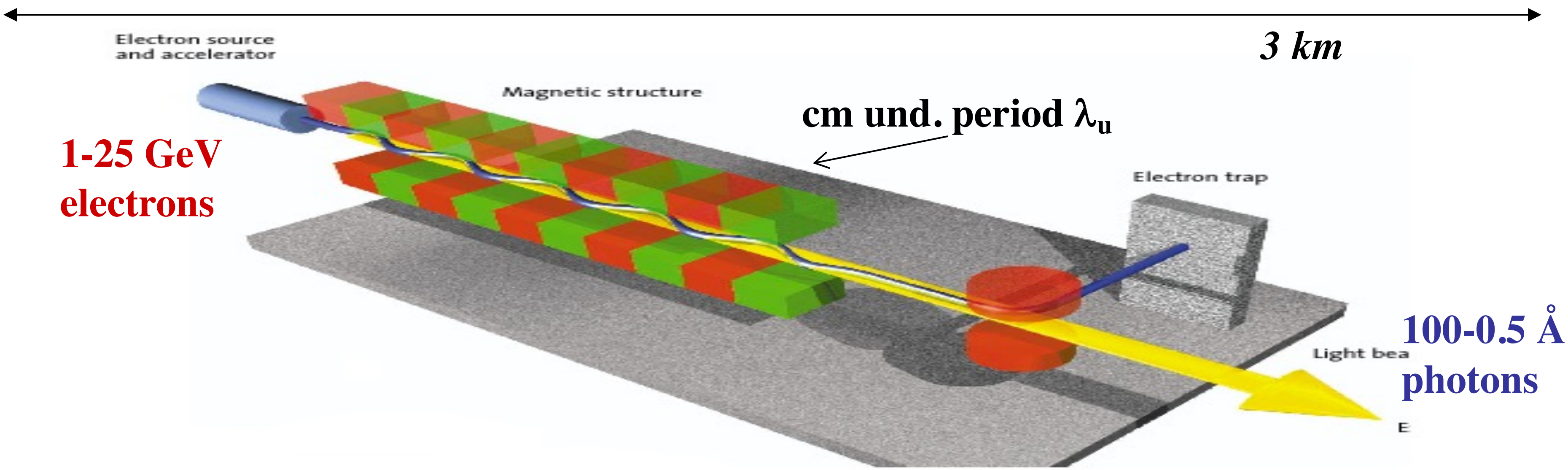
incident photons en. spread

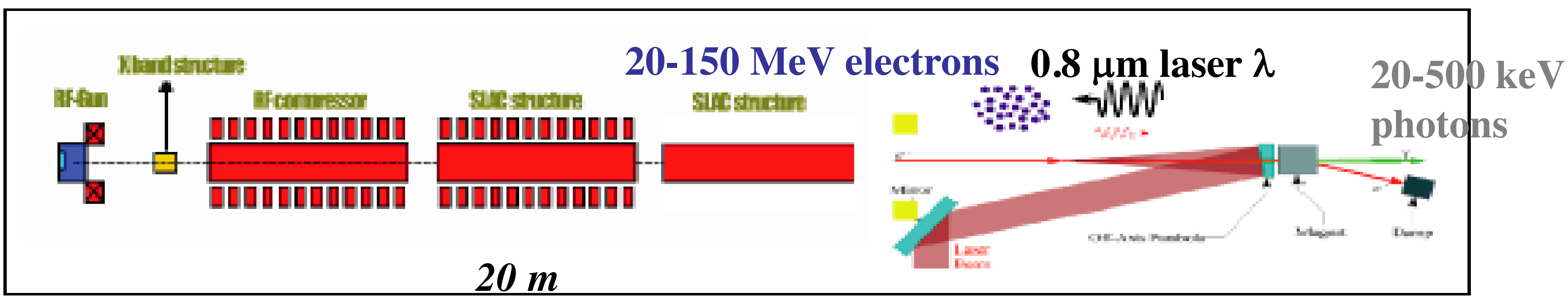
diffraction

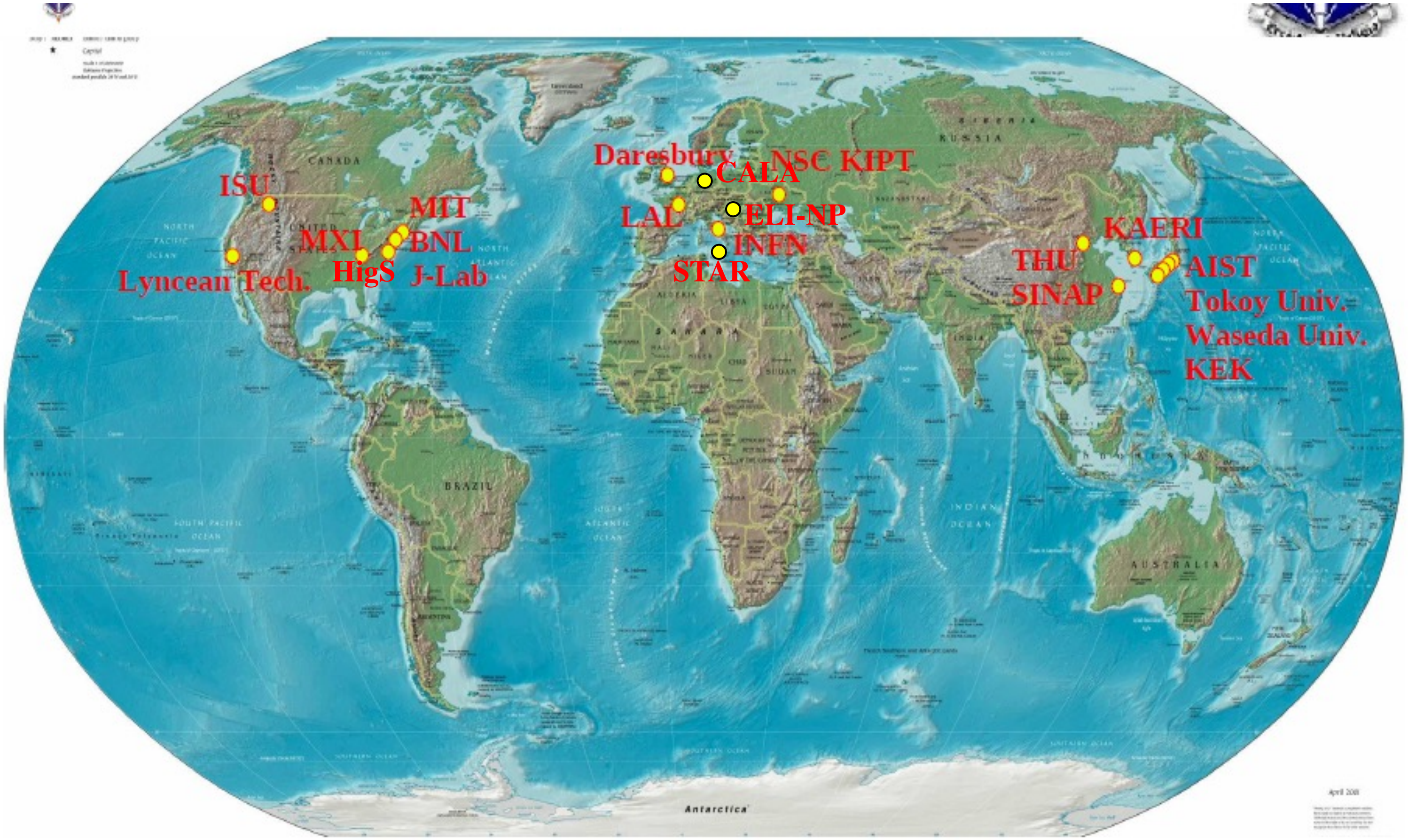
non linearity

The Classical E.M. view (Maxwell eq.): Thomson Sources as synchrotron radiation sources with electro-magnetic undulator

FEL's and Thomson/Compton Sources common mechanism:
collision between a relativistic electron and a (pseudo)electromagnetic wave







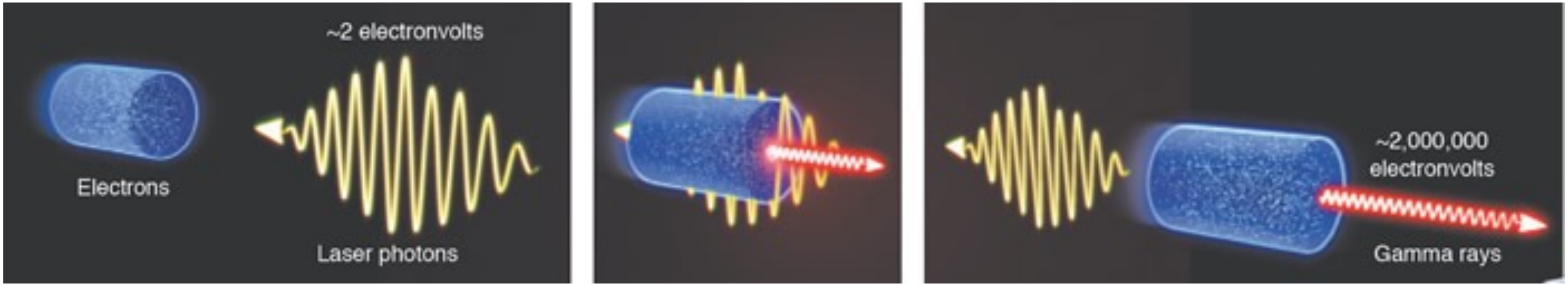
ICS are the most effective "photon accelerators" **(boost twice than FELs)**

"4γ² boost effect" $E_{X/\gamma} = 4\gamma^2 E_{laser}$

$$with\ T = 100 MeV\ (\gamma = 197)\ E_{laser} = 1.2\ eV \Rightarrow E_{X/\gamma} = 186\ keV$$

Courtesy A. Variola

I.C.S. : Inverse Compton Scattering

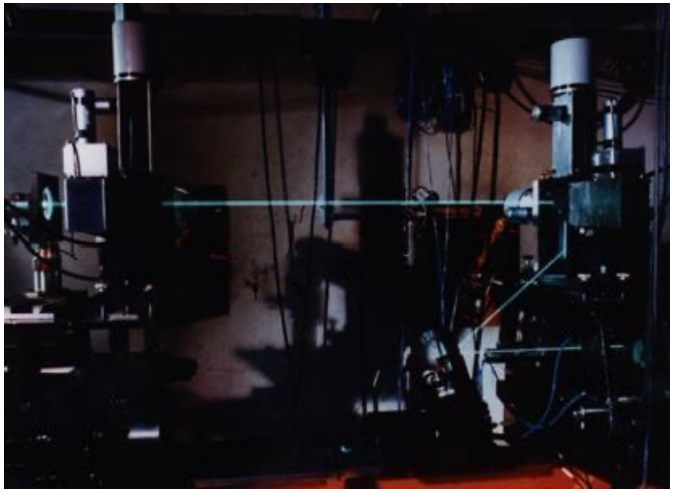


Inverse Compton Scattering: why Inverse?

(direct) Compton Scattering is performed by an energetic photon (X-rays) interacting with an atomic electron (eV)

Inverse Compton Scattering is performed by an energetic electron (MeV-GeV) onto a visible (eV) photon ("inverse" refers to the reaction kinematics, not the dynamics)

- **Hadronic Physics was the original motivation for Compton back-scattering experiments (cfr. Ladon at INFN-LNF, Graal at ESRF, etc): single photon per bunch collision at energies > 50 MeV with tagging (quite popular decades ago)**



L. Federici, G. Giordano, G. Matone, G. Pasquariello, P. G. Picozza, et al. **Backward compton scattering of laser light against high-energy electrons: the ladon photon beam at frascati**. Il Nuovo Cimento B (1971-1996), 59(2):247–256, 1980.

Second Series *May, 1923* *Vol. 21, No. 5*

THE PHYSICAL REVIEW

The change in wave-length due to scattering.—Imagine, as in Fig. 1*A*,

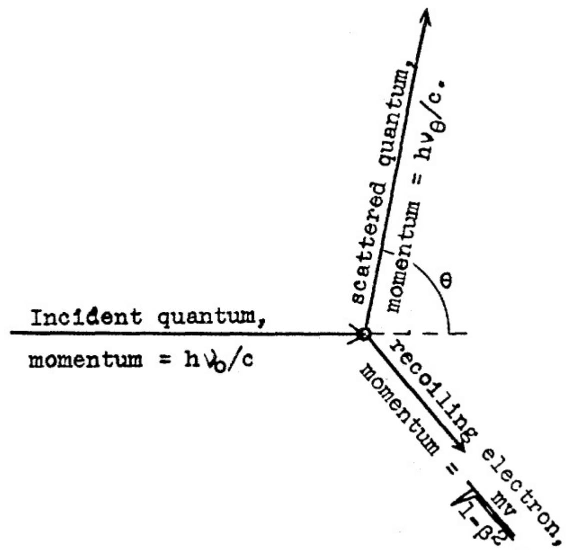


Fig. 1 A

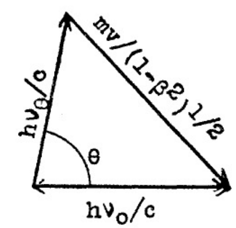


Fig. 1 B

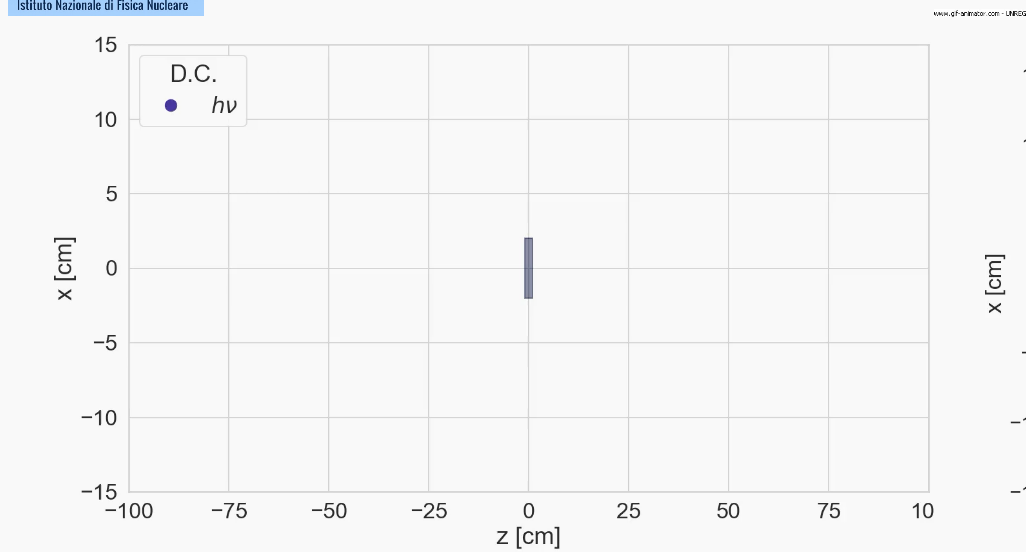
that an X-ray quantum of frequency ν_0 is scattered by an electron of mass m. The momentum of the incident ray will be $h\nu_0/c$, where c is

where is the Continental Divide
between
Compton Scattering
and
Inverse Compton Scattering?

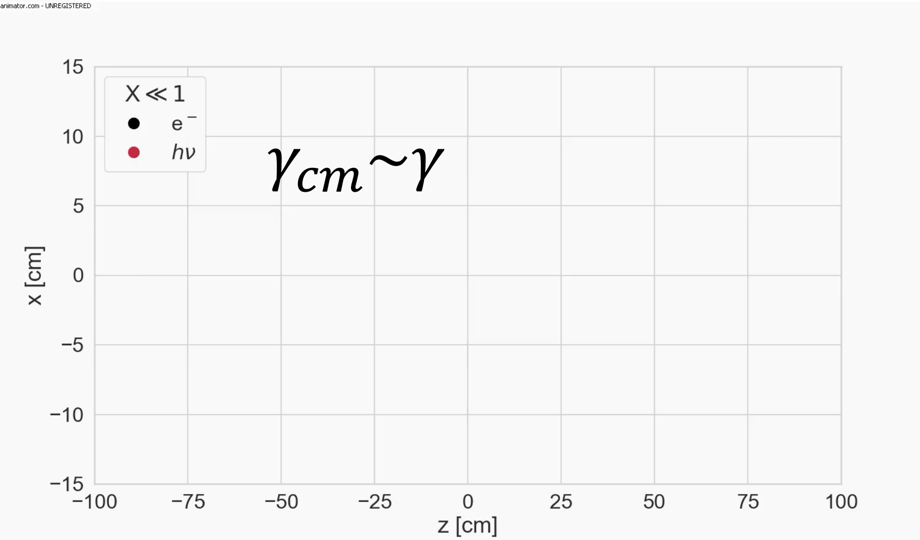
when the electron becomes
a projectile (as in ICS)
instead of
a target (as in Compton)?

Does it depend only on electron energy?
No, it depends only on asymmetry in colliding momenta

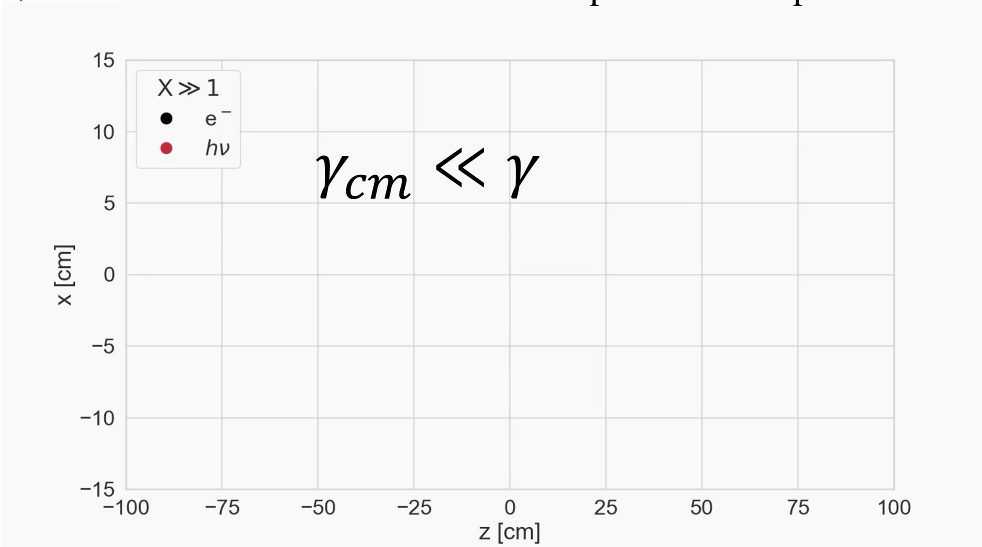
CM rest frame moves with
the photon in Direct Compton



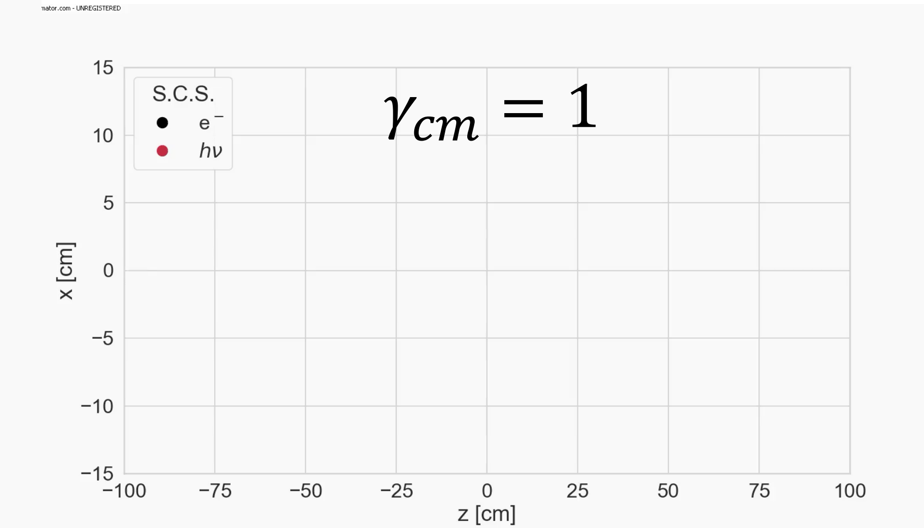
CM rest frame moves with the electron in
Inverse Compton, FEL, Synchrotron light

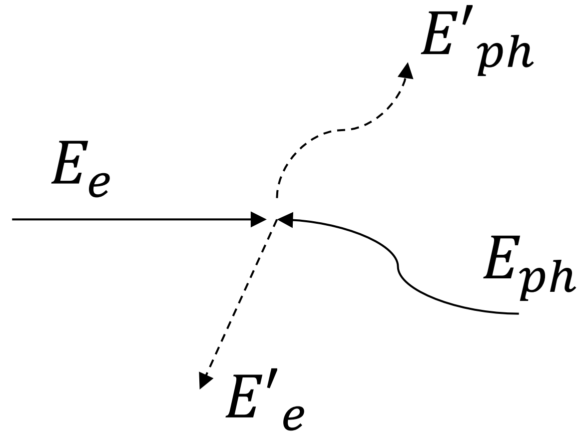


CM rest fr. slows down in Inv. Compton with deep recoil



CM rest frame is steady in Symmetric Compton





I.C.S. low recoil X<<1

$$E'_{ph-max} = 4\gamma^2 E_{ph}$$

I.C.S. large recoil X>>1

$$E'_{ph-max} = \left(1 - \frac{1}{X}\right) E_e$$

S.C.S. (A=0) or quasi-SCS (A<<1)

$$\begin{cases} E'_{ph} = E_{ph}\left(1 + \dfrac{2A}{(1+\beta)\gamma^2}\right) \\ E'_e = E_e - E_{ph}\dfrac{2A}{(1+\beta)\gamma^2} \end{cases}$$

Commissioning the STAR Inverse Thomson Scattering X-ray source: progress report

Marcel Ruijter[1], Adolfo Esposito[2], Alberto Bacci[1], Luigi Faillace[2], Alessandro Gallo[2], Alessandro Vannozzi[2], Andrea Ghigo[2], Angelo Stella[2], Dario Giannotti[1], Alesini David[2], Ezio Puppin[3], Fabio Cardelli[2], Francesco Prelz[1], Gaetano Catuscelli[2], Gianluca Luminati[2], Giorgio Scarselletta[2], Illya Drebot[1], Luca Piersanti[2], Luca Serafini[1], Luigi Pellegrino[2], Marcello Rossetti Conti[1], Marco Bellaveglia[2], Sanae Samsam[1], Sandro Vescovi[2], Simone Bini[2], Simone Tocci[2], Vittoria Petrillo[4]

[1] INFN – Sezione di Milano, Italy
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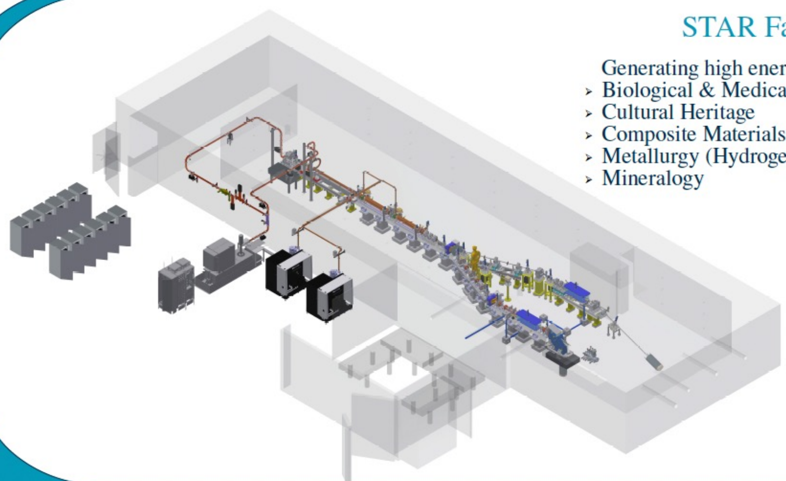
Abstract

The Southern European Thomson back-scattering source for Applied Research (STAR) is a high energy photon facility located on the campus of the University of Calabria (UniCal). The facility was designed for its first phase to operate with an electron and photon energy up to 85MeV and 140keV respectively. For the second phase of the project the energy of the electrons, and thereby the photons, would be increased up to 150MeV and 300keV respectively. The Italian Institute for Nuclear Physics (INFN) was awarded the project for installing, testing and commissioning the energy upgrade of the electron beamline. Here we will outline the progress made regarding the RF system and the Control System Software (CSS). The former consists out of two C-band linacs connected to their individual RF power stations for which the site acceptence test has recently been performed. For the latter the network of the STAR site has been extended to allow the EPICS based CSS to be further developed, including top level GUIs and IT security infrastructure.

Upgrade to High Energy Line

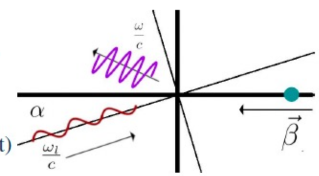
Upgrade to High Energy line (HE-line) consist out of:

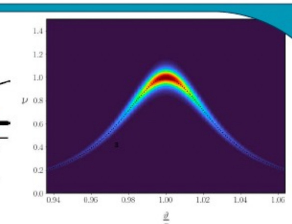
- Installation of soilenoid (8 cm) in front of S-band cavity for emittance control
- Installation of two C-band RF cavities incl. powerstations, for higher beam energy
- Cooling system upgrade
- Electric system upgrade, incl. backup power, power supplies and cabeling
- IT infrastructure & control system software



STAR Facility

Generating high energy radiation for
- Biological & Medical Imaging
- Cultural Heritage
- Composite Materials
- Metallurgy (Hydrogen embrittlement)
- Mineralogy





	Electron [Mev]	Photon [keV]
LE – line	23 -65	40 - 150
HE – line	40-150	25 - 350

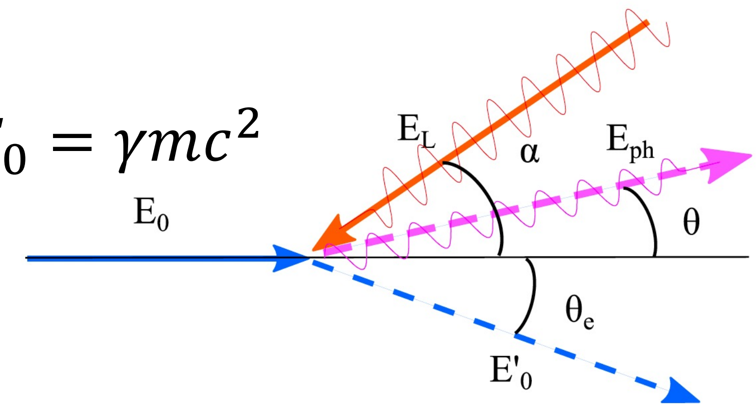
Electrons
- Emittance : 1 [mm mrad]
- Charge : 100 – 500 [pC]
- Bunch length : < 0.7 [mm]
- Energy spread : 0.1 %, 0.05%

(CPA) Laser
- Energy : > 0.5 [Joule]
- Wavelength : 1030 [nm]
- Bandwidth : 1 [nm]

The $\gamma^2\theta^2$ issue/disease

All radiation originated by a Lorentz Boost associated to relativistic emitting particles (electrons, heavy ions) is intrinsically poli-chromatic because of $\gamma\theta$ correlation (energy boost of scattered photons depends on scattering angle, at $\theta=1/\gamma$ photon energy is 50% of max photon energy at $\theta=0$) of single electron spectrum (on top of inhomogeneous effects)

$$E_0 = \gamma m c^2$$

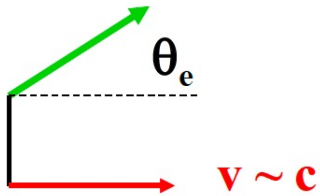


$$E_{ph} = \frac{4\gamma^2 E_l}{1 + X + \gamma^2\vartheta^2}$$

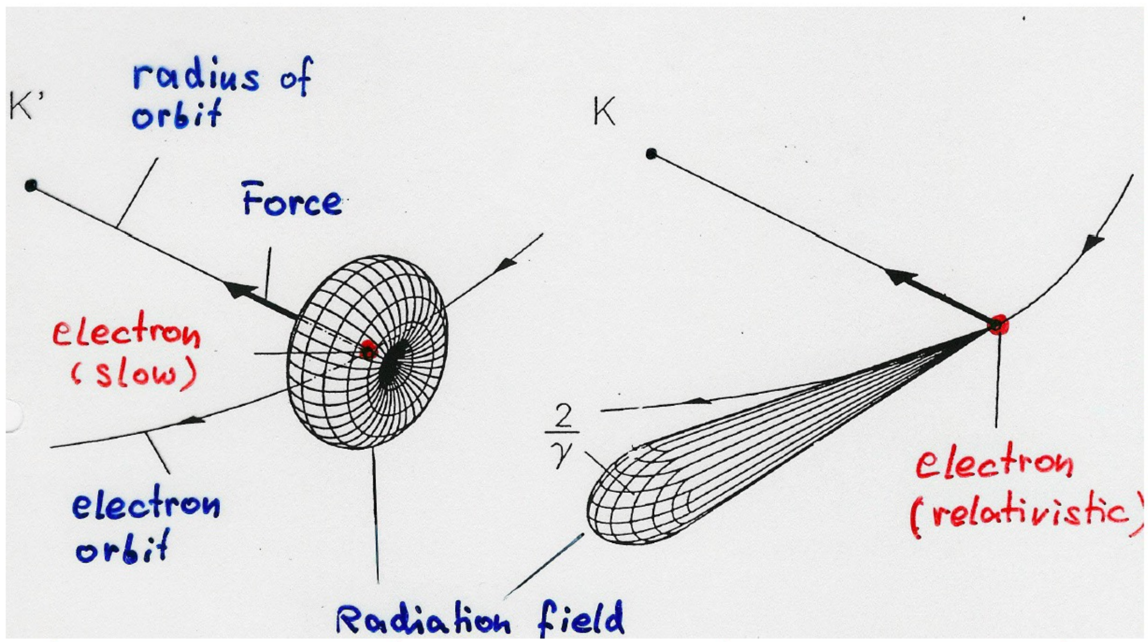
$$X \equiv \frac{4\gamma E_l}{mc^2} = \frac{2E_l^{ERF}}{mc^2}$$

True for all kinds of Undulatory and Collisional radiation (bremsstrahlung, wiggler/betatron, synchrotron, RRS, ICS), while resonant or amplified radiation (undulators, FELs), that are diffraction limited thanks to their beam quality, are not (or only partially) affected

Radiation is emitted into a narrow cone



$$\theta = \frac{1}{\gamma} \cdot \theta_e$$



v << c

v ≈ c

Courtesy L. Rivkin

To transform to the Lab ref. system we need to compute γ_{cm}

$$\gamma_{cm} = \frac{E_{lab}}{E_{cm}} = \frac{E_e + h\nu_L}{m_e c^2 \sqrt{1+\Delta}} \cong \frac{\gamma}{\sqrt{1+\Delta}}$$

Then apply a Lorentz transformation

$$\begin{cases} E_{ph} = p^*_{ph}\gamma_{cm}\left(1 + \sqrt{1 - \frac{1}{\gamma^2_{cm}}}\cos\theta^*\right) \\ p_{phx} = p^*_{ph}\sin\theta^*\cos\phi^* \\ p_{phy} = p^*_{ph}\sin\theta^*\sin\phi^* \\ p_{phz} = p^*_{ph}\gamma_{cm}\left(\sqrt{1 - \frac{1}{\gamma^2_{cm}}} + \cos\theta^*\right) \end{cases}$$

Deep Recoil I.C.S. helps attenuating the $\gamma^2\theta^2$ problem

strong focusing to maximize Peak Luminosity according to Petrillo-Serafini criterion

$$S_d \propto \frac{\langle I_e \rangle U_{las}}{\varepsilon_n^2 E_x}$$

30-150 MeV e⁻
20-350 keV X

$\Psi =$

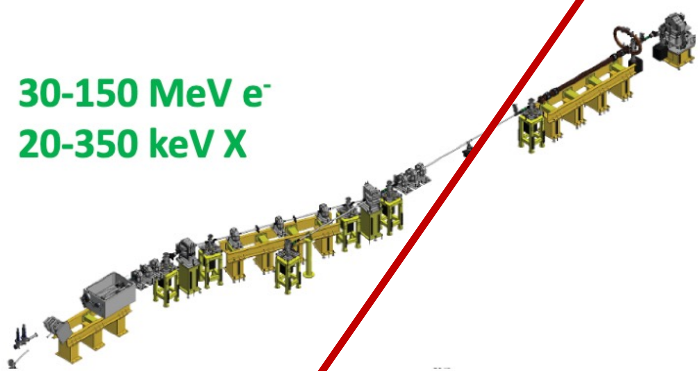


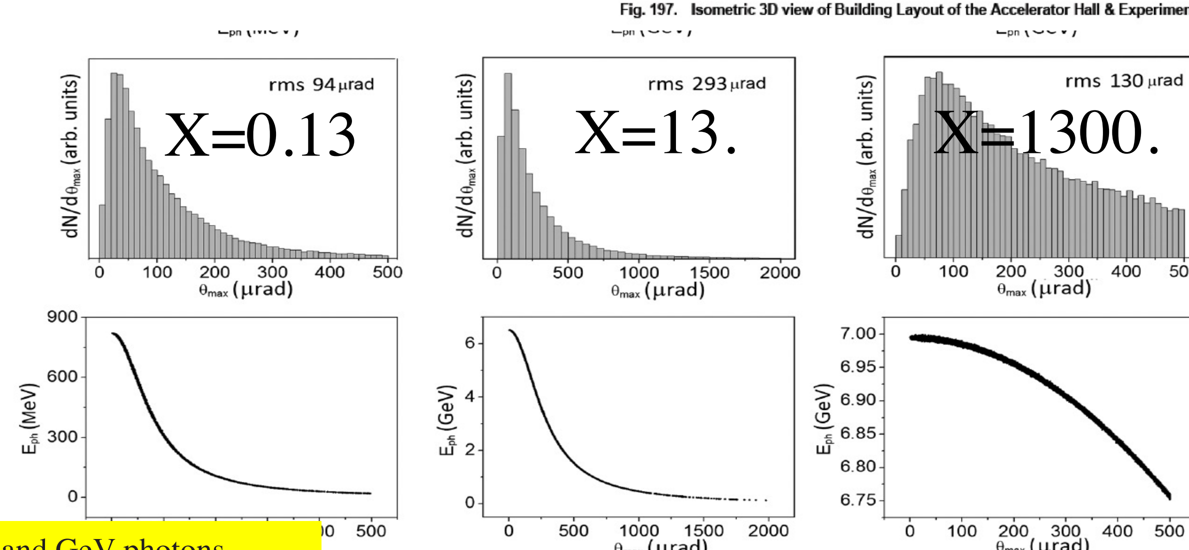
Fig.2 – STAR machine as an example of Paradigm A. Overall length about 12 m.

250-750 MeV e⁻
1-19.5 MeV γ

Fig. 197. Isometric 3D view of Building Layout of the Accelerator Hall & Experimental Areas

$$\bar{P} = \frac{\sqrt{2}\varepsilon_n}{\sigma_x\sqrt{1+X}}$$

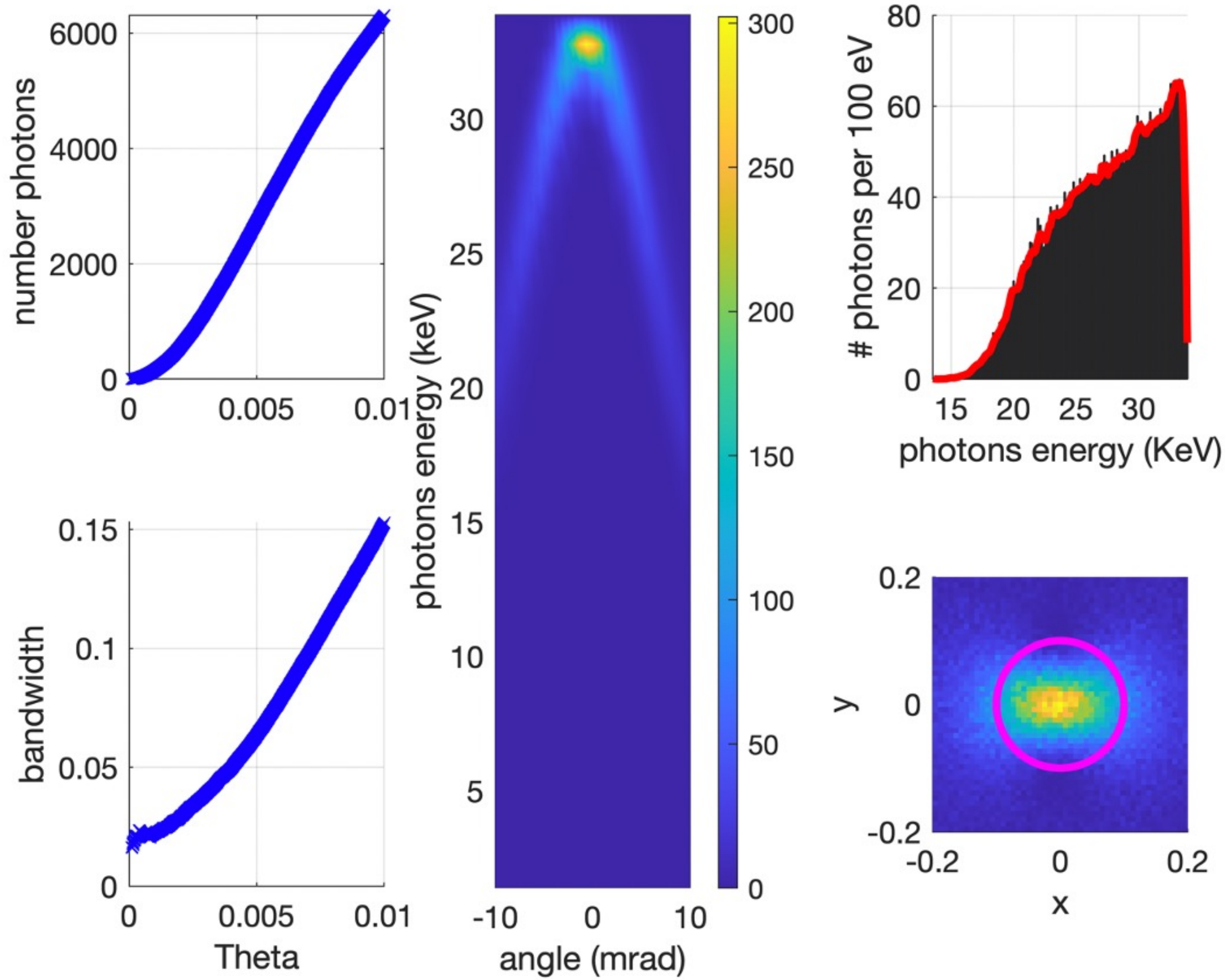
$$\gamma_{cm} = \frac{\gamma}{\sqrt{1+X}}$$



…, CAIN simulations. First line spectrum, second line angular distribution, third line energy as a …ft column, case E middle column, case F right column.

R. Hajima and M. Fujiwara, Narrow-band GeV photons generated from an x-ray free-electron laser oscillator, Phys. Rev. Accel. Beams 19, 020702 (2016). XFELO Project

BriXSinO's ICS source – Illya Drebot with CAIN – ICS Moustache



BriXSinO T.D.R. @ www.marix.eu

Inverse Compton Sources rivaling/overcoming Synchrotron Light Sources at photon energies above 80-100 keV

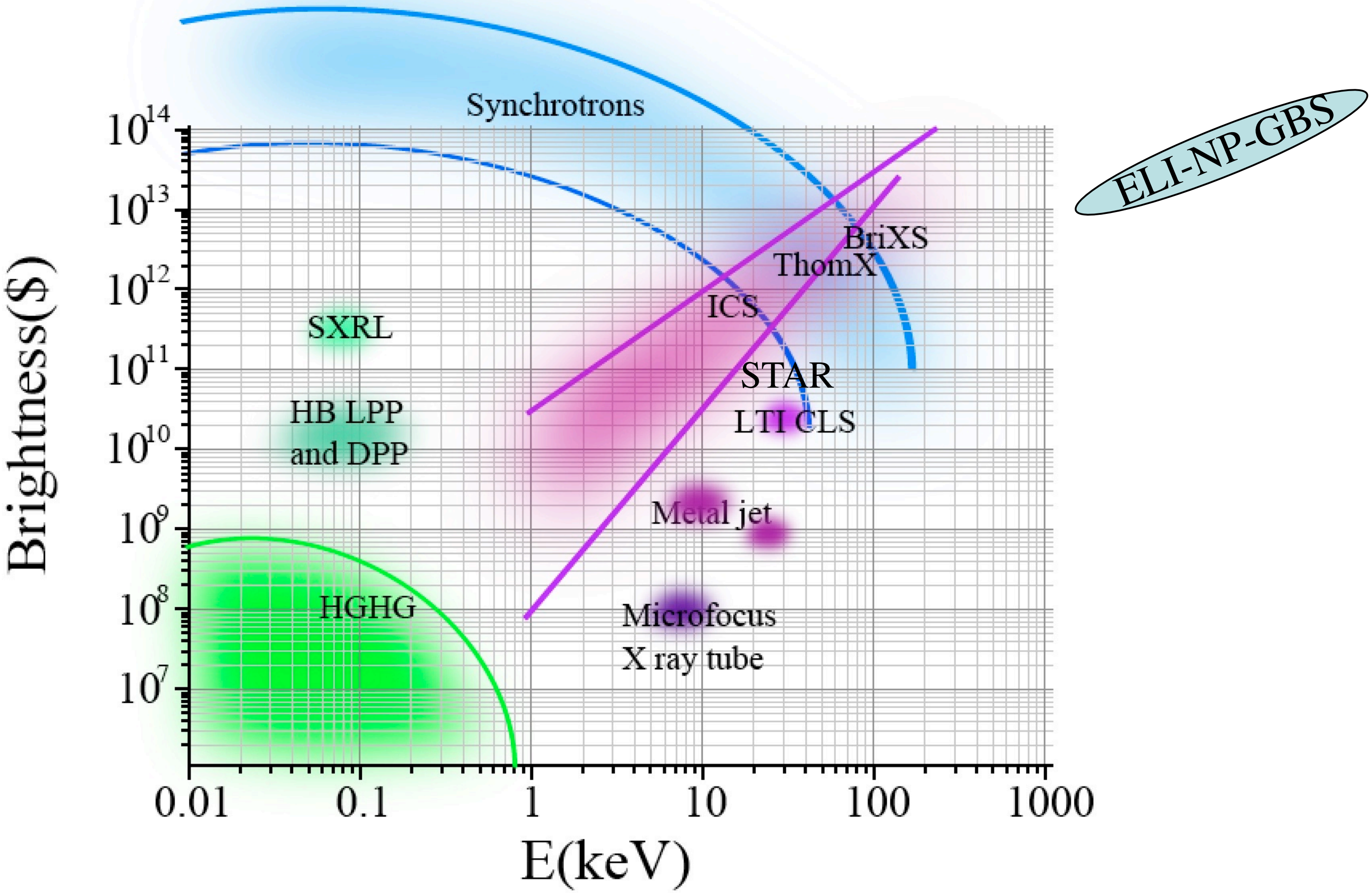


Figure 1: Brightness of several radiation sources as a function of the photon energy. $: Photon $number/s/mm^2/mrad^2/(0.1\%$.

I.C.S. Sources (LTI-CLS,ThomX, STAR, UH-FLUX and BriXS) are compared to Synchrotron Light Sources and the most performing X-ray tube so far (Metal Jet).

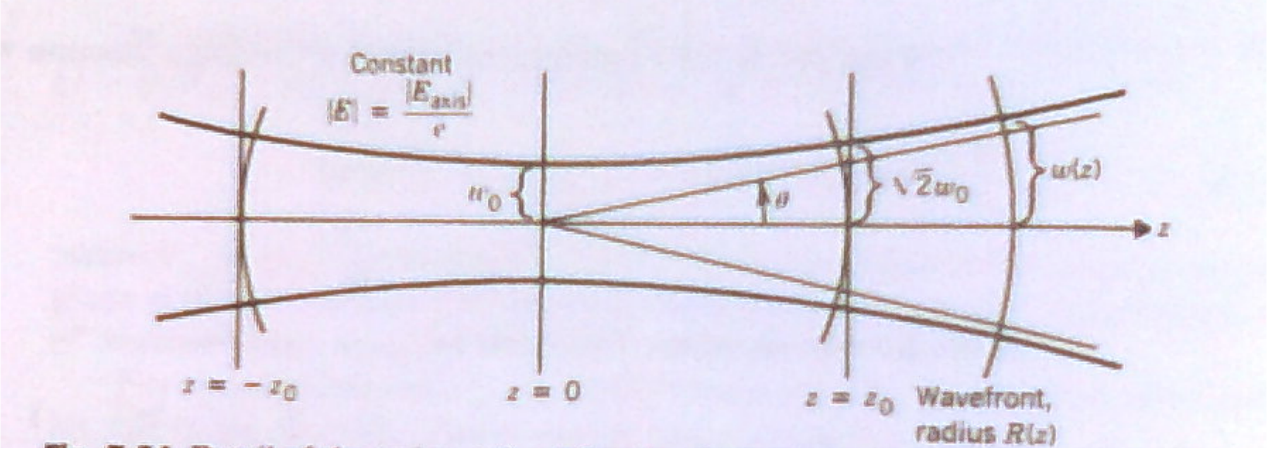
Inverse Compton Sources, Overview, Theory, Main Technological Challenges – Photonic Colliders

- **New Generation of *X*/γ ray beams via electron-photon beam collisions for advanced applications in medicine/biology-material science/cultural heritage/national security *and* fundamental research in nuclear physics and high energy physics (e-γ, γ-γ colliders, pol. e^+ beams, hadron. physics, etc)**
- **Inverse Compton Sources (ICS) are e^-/photon colliders aimed at producing secondary beams of photons**
- **Several Test-Facilities world-wide: after a decade of machine test&development we are entering the era of User Facilities in *X*-ray imaging and γ-ray Nuclear Physics and Photonics**

Challenges of *electron-(optical)photon colliders* as *X/γ* beam Sources using Compton back-scattering

- **Need of *high peak brightness/high average current* electron beams (cmp. FEL's drivers) *fsec-class* synchronized and *μm-μrad-scale* aligned to *high peak/average power* laser beams**
- **Main goal for Nuclear Physics and Nuclear Photonics:**
  Spectral Densities **> 10^4** ***N_{ph}/(s·eV)***
  photon energy range 1-20 MeV, *bandwidths* 10^{-3} class
- **Main goal for Medical Applications with *X*-rays: tunability in the 20-120 keV range, good mono-chromaticity (1-10 %), high flux (10^{11} min., 10^{12} for radio-imaging, 10^{13} for radio-therapy)**

Photon / Particle Beams: diffraction, envelope, matching, co-propagation.
Example: TEM_{00} Gaussian Laser mode (circ. pol. M^2=1 diffr. limited)



$$E_0(x,y,z,t) = A_0 e^{i\omega t} e^{-ikz} \frac{Z_0}{Z_0 - iz} \exp\left[-\frac{k\left(x^2+y^2\right)}{2} \frac{1}{Z_0 - iz}\right] \quad k = 2\pi/\lambda$$

$$\left|E_0(x,y,z,t)\right| = E_0 \frac{w_0}{w} e^{-\frac{x^2+y^2}{w^2}}$$

$$w = w_0\sqrt{1+\frac{z^2}{Z_0^2}} \qquad Z_0 = \frac{\pi w_0^2}{\lambda} \qquad \vartheta = \frac{w_0}{Z_0} = \frac{\lambda}{\pi w_0}$$

$$I \propto \left| E_0(x,y,z,t) \right|^2$$

LASER

PARTICLE BEAM

$$Z_0 = \frac{4\pi\left(\frac{w_0}{2}\right)^2}{\lambda} \quad \Longleftrightarrow \quad \beta^* = \frac{\sigma_0^2}{\varepsilon_n / \gamma}$$

$$\frac{w}{2} = \frac{w_0}{2}\sqrt{1+\frac{z^2}{Z_0^2}} \quad \Longleftrightarrow \quad \sigma(z) = \sigma_0\sqrt{1+\frac{z^2}{\beta^{*2}}}$$

$$\Downarrow$$

$$\frac{\lambda}{4\pi} = \frac{\varepsilon_n}{\gamma} \quad and \quad w_0 = 2\sigma_0$$

$$\varepsilon_n \le \frac{\lambda_{FEL}\gamma}{4\pi}$$

$$w(z) = 2\sigma(z) \quad and \quad \vartheta(z) = 2\sigma'(z)$$

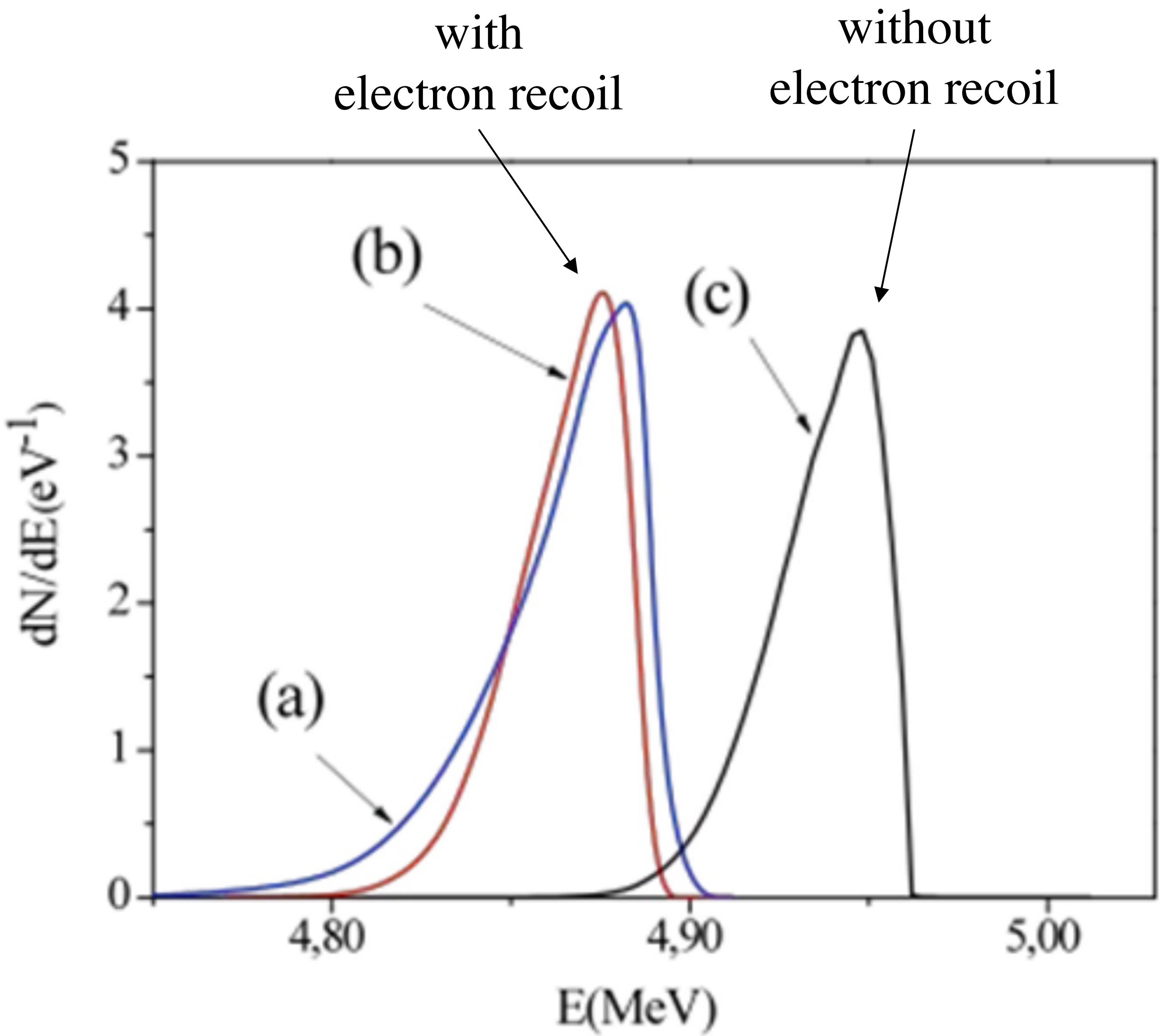


Fig. 5. **Spectra of the rays. (a) CAIN (b) Quantum model (c) Classical treatment in the case of beam (A) and for the laser parameter of Table 1 and interaction angle α=π ; rms acceptance angle θ_{rms} = 25μrad**