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.

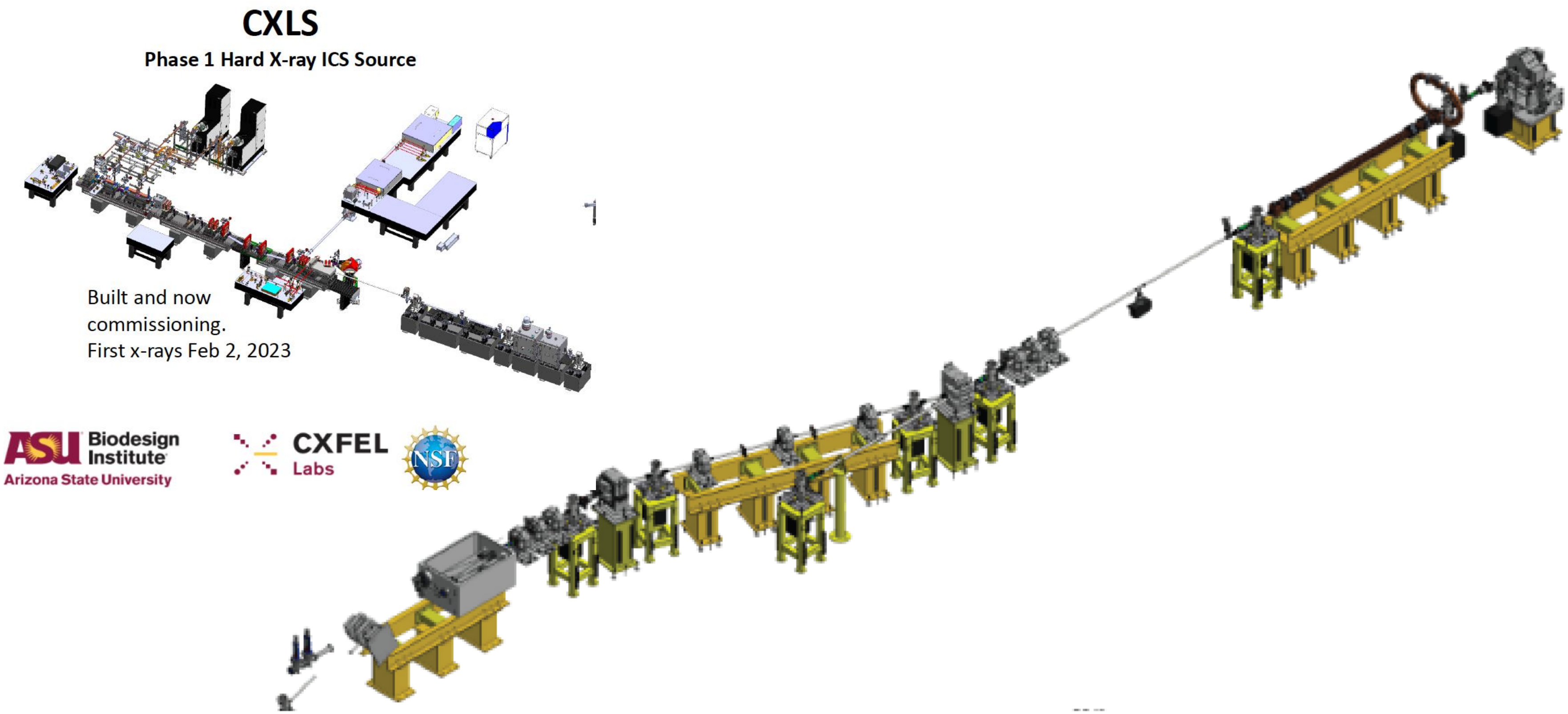


***Fig.2** – STAR machine as an example of Paradigm A. Overall length about 12 m.*

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€.

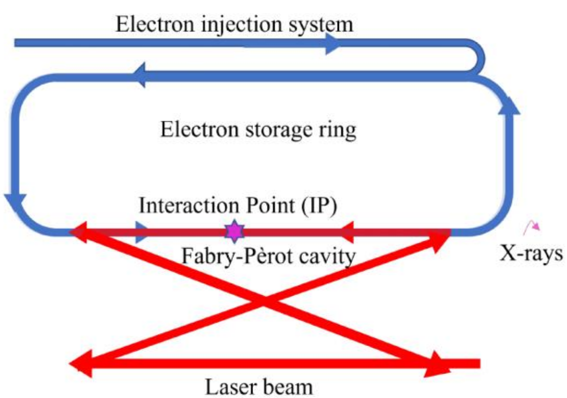


Figure 2. The typical scheme of source based on Paradigm (ii). Size is about 100 m^2. Overall length about 12 m.

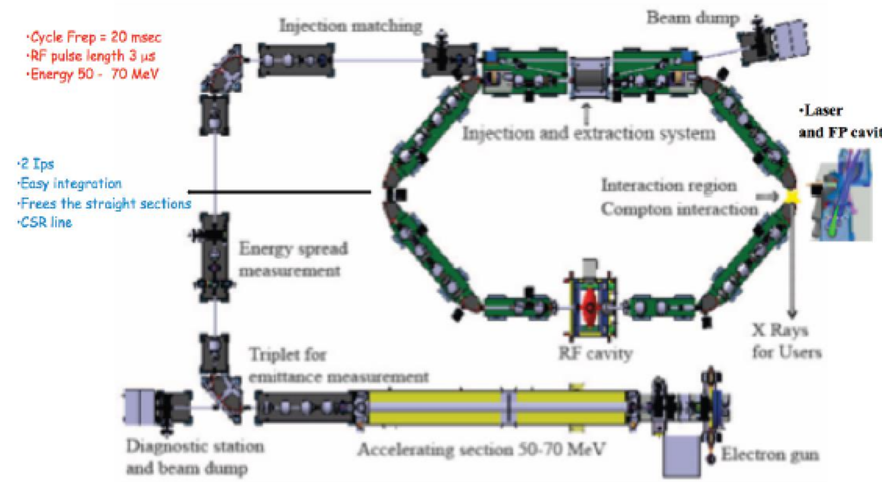
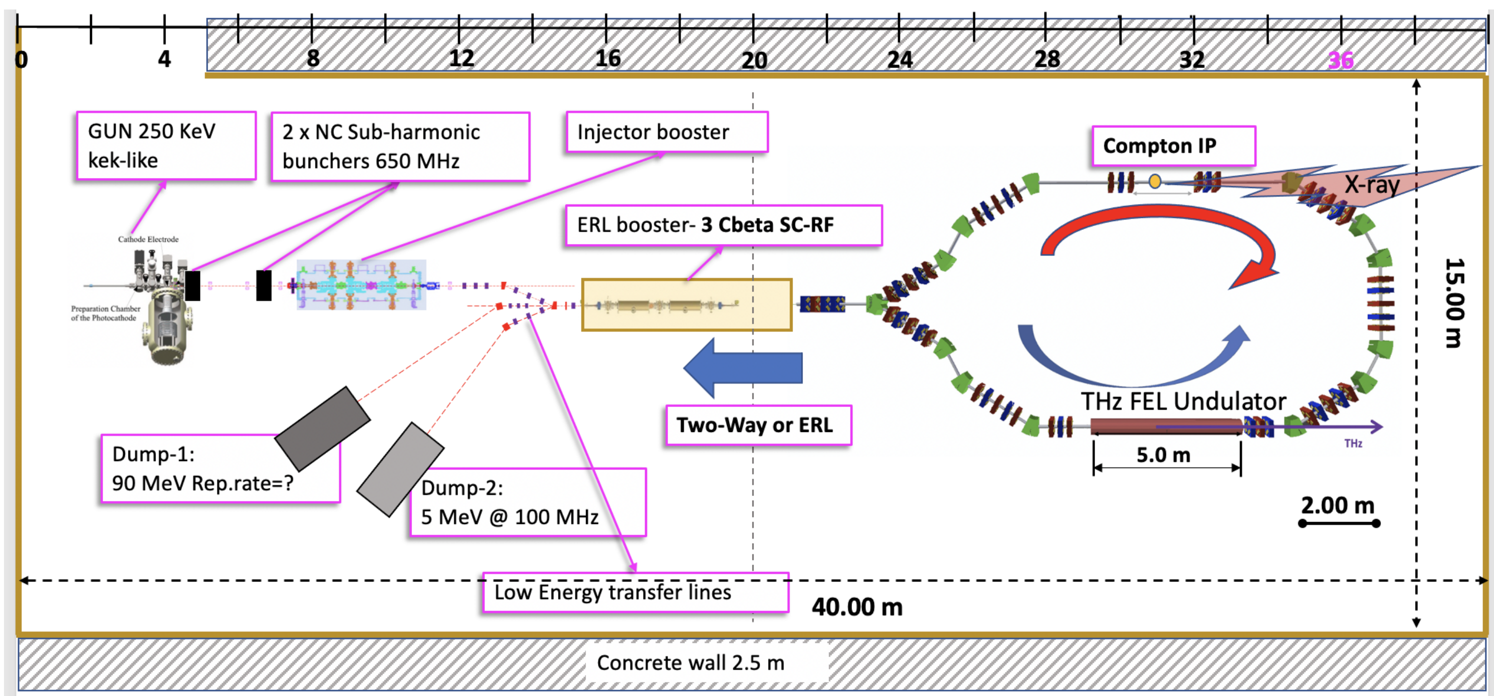


***Fig.3** – ThomX as an example of Paradigm B. Size is about 10x10 m^2.*

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).

BriXSinO



photons within normalized acceptance angle $\Psi = \gamma \cdot \theta_{acc}$

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

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

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

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

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)

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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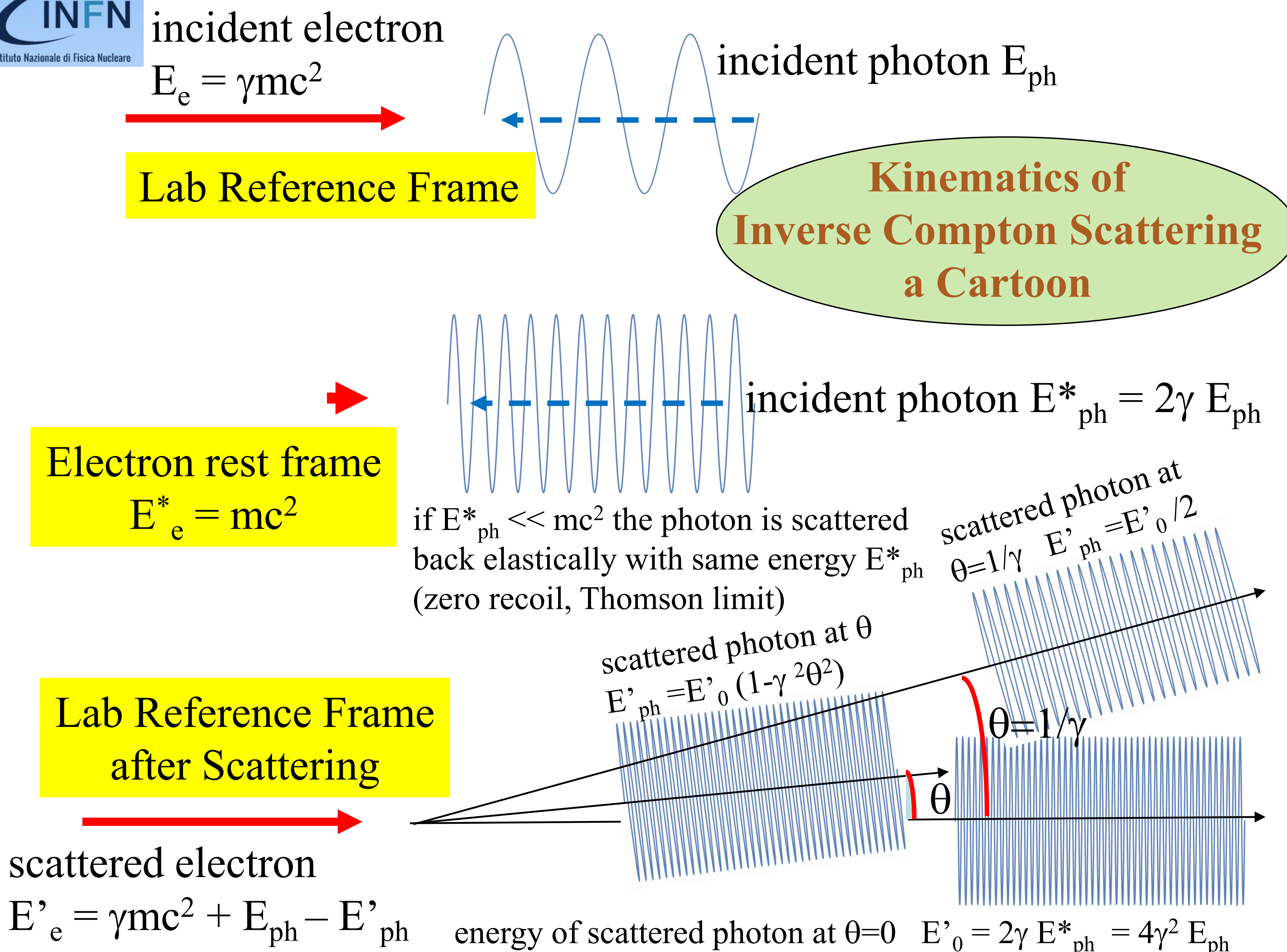
† These authors contributed equally to this work.

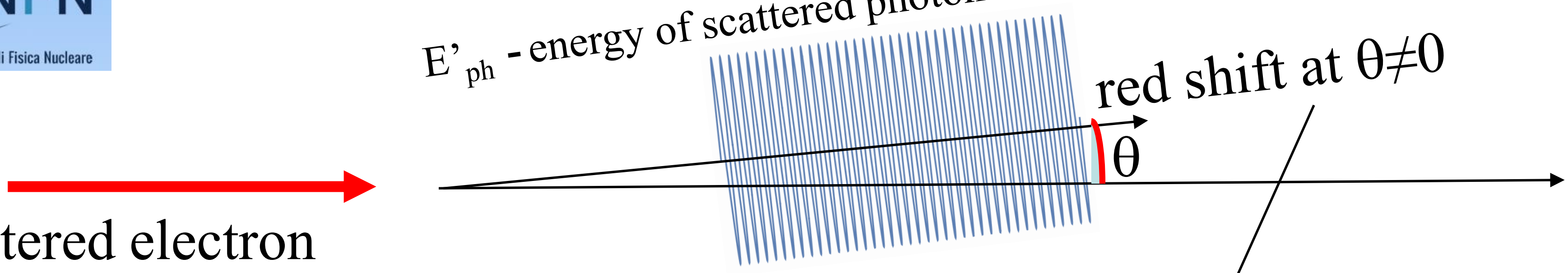
Abstract: In this paper, we present the generalities of the Compton interaction process; we analyse the different paradigms of Inverse Compton Sources, implemented or in commissioning phase at various facilities, or proposed as future projects. We present an overview of the state of the art, with a discussion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

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

Additional Slides



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 $E^*_{ph} << mc^2$ the photon is scattered back elastically with same energy E^*_{ph} (zero recoil, Thomson limit)
scattered photon at $\theta=1/\gamma$ $E'_{ph} = E'_0/2$
scattered photon at θ
$E'_{ph} = E'_0 (1-\gamma^2\theta^2)$
$\theta=1/\gamma$
θ
Lab Reference Frame after Scattering
scattered electron
$E'_e = \gamma mc^2 + E_{ph} - E'_{ph}$
energy of scattered photon at $\theta=0$ $E'_0 = 2\gamma E^*_{ph} = 4\gamma^2 E_{ph}$



scattered electron

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

$$E'_{\rm ph}(\theta) = \frac{4E_{\rm ph}\gamma^2}{1 + X + \gamma^2\theta^2}$$

$$X = \frac{4E_e E_{\rm ph}}{\ } = \frac{4\gamma E_{\rm ph}}{\ } = 4\gamma^2 \frac{E_{\rm ph}}{\ }$$

All I.C.S. X/γ ray Sources work at X<1 and A » 1

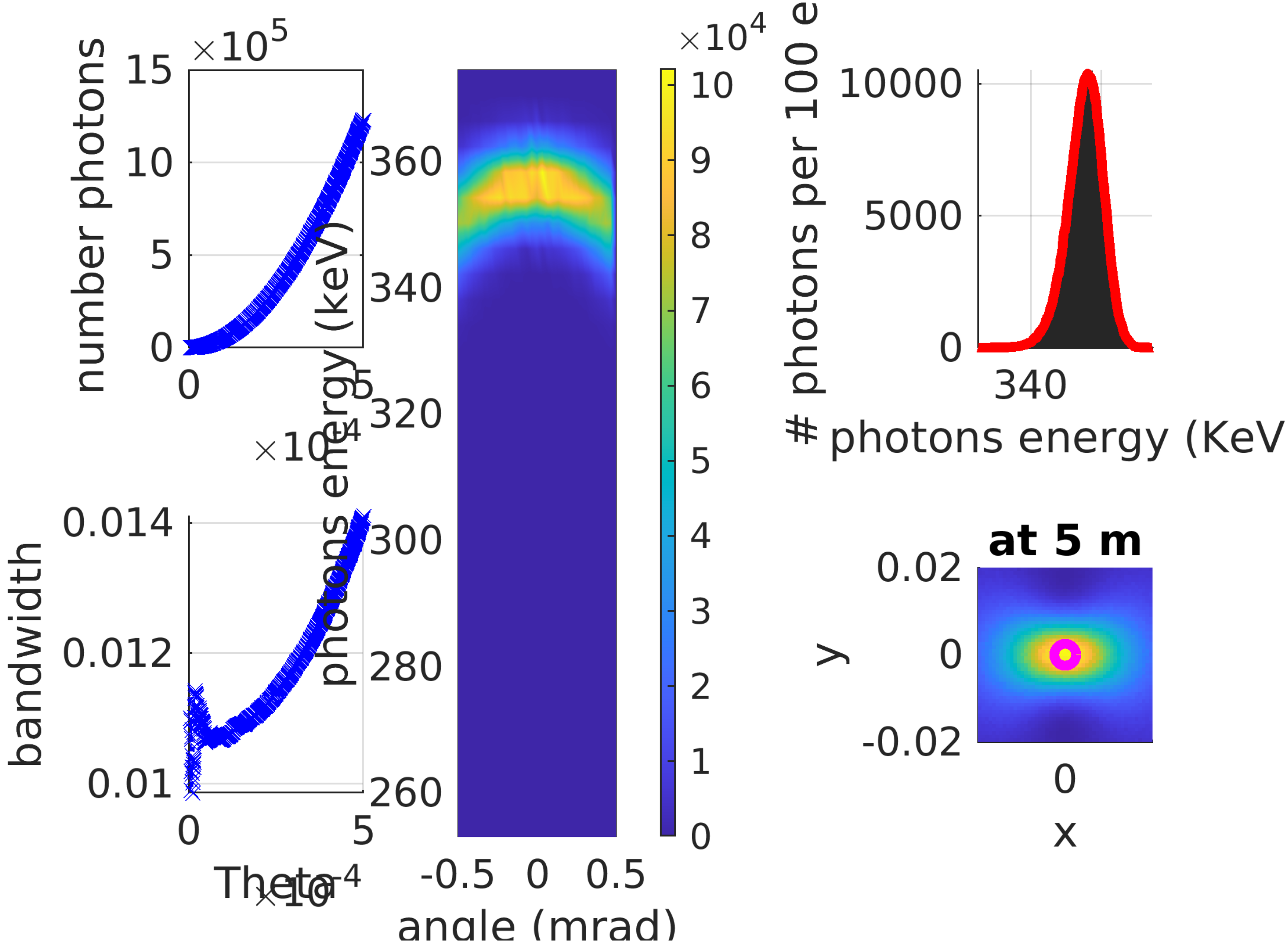
STAR (350 keV) $X_{STAR} < 2.6 \cdot 10^{-3}$ $A_{STAR} > 10^4$

ELI-NP (20 MeV) $X_{ELI\text{-}NP} < 0.026$ $A_{ELI\text{-}NP} > 2.4 \cdot 10^5$

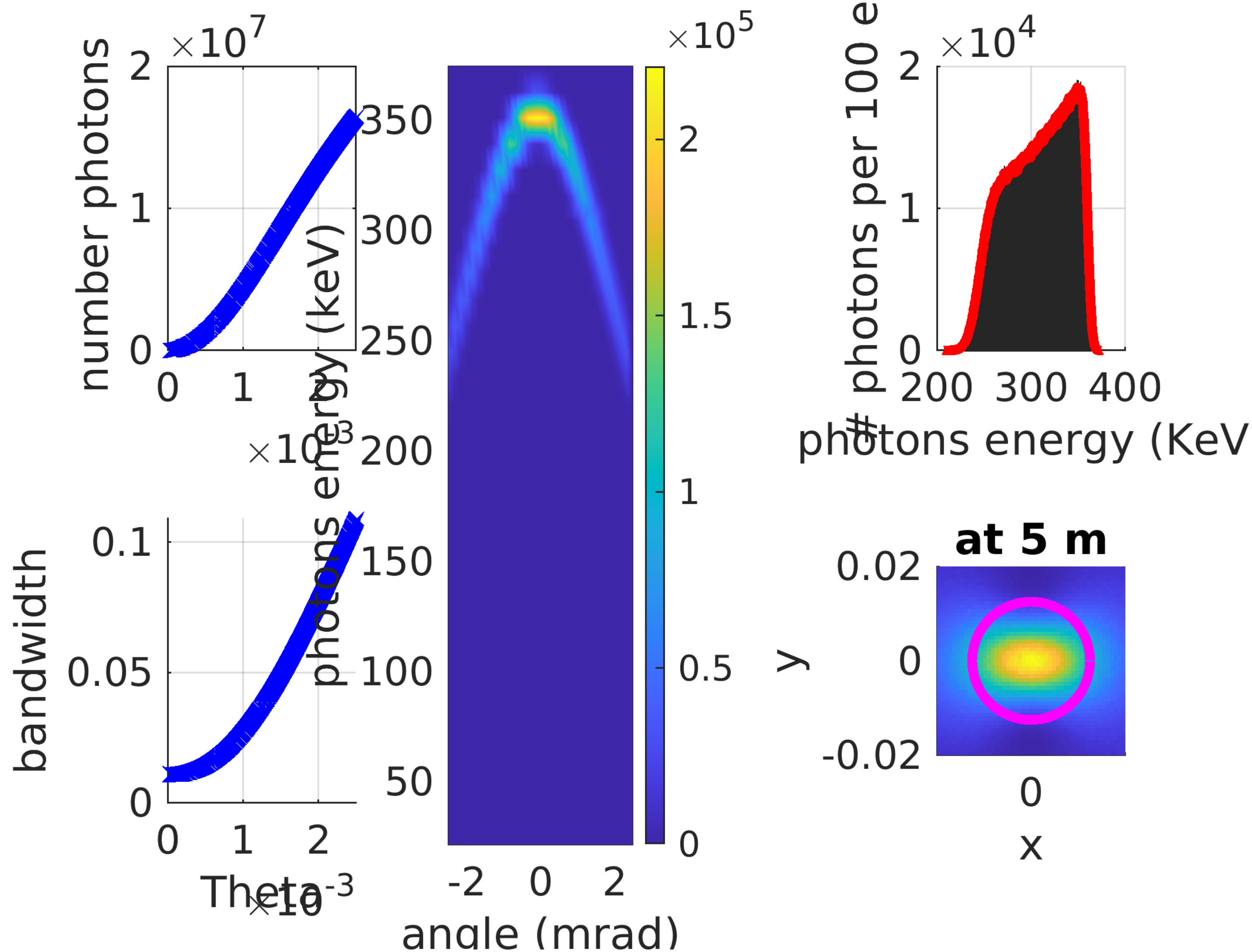
X = recoil … n seen

by the ele … d to mc^2

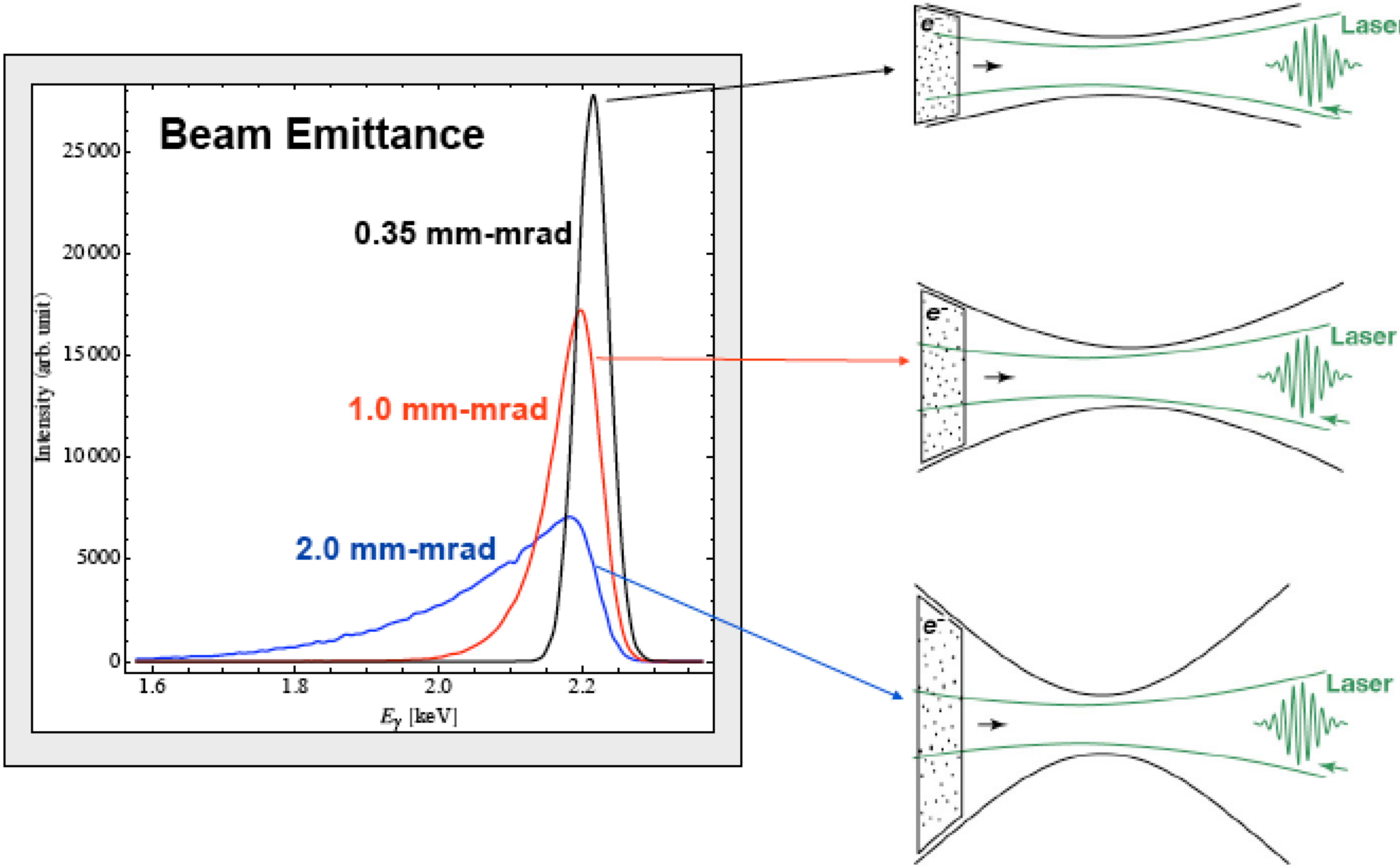
WP 140 MeV


number photons
×10^5
15
10
5
0
0
5
bandwidth
×10^-4
0.014
0.012
0.01
0
5
Theta
×10^-4
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
0
340
photons energy (KeV
at 5 m
y
0.02
0
-0.02
0
x

WP 140 MeV



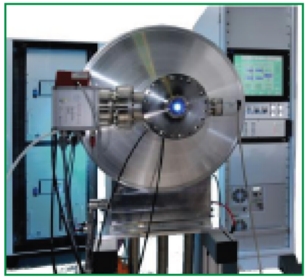
number photons
×10^7
bandwidth
Theta
×10^-3
photons energy (keV)
angle (mrad)
×10^5
photons per 100 eV
×10^4
photons energy (KeV)
at 5 m
y
x

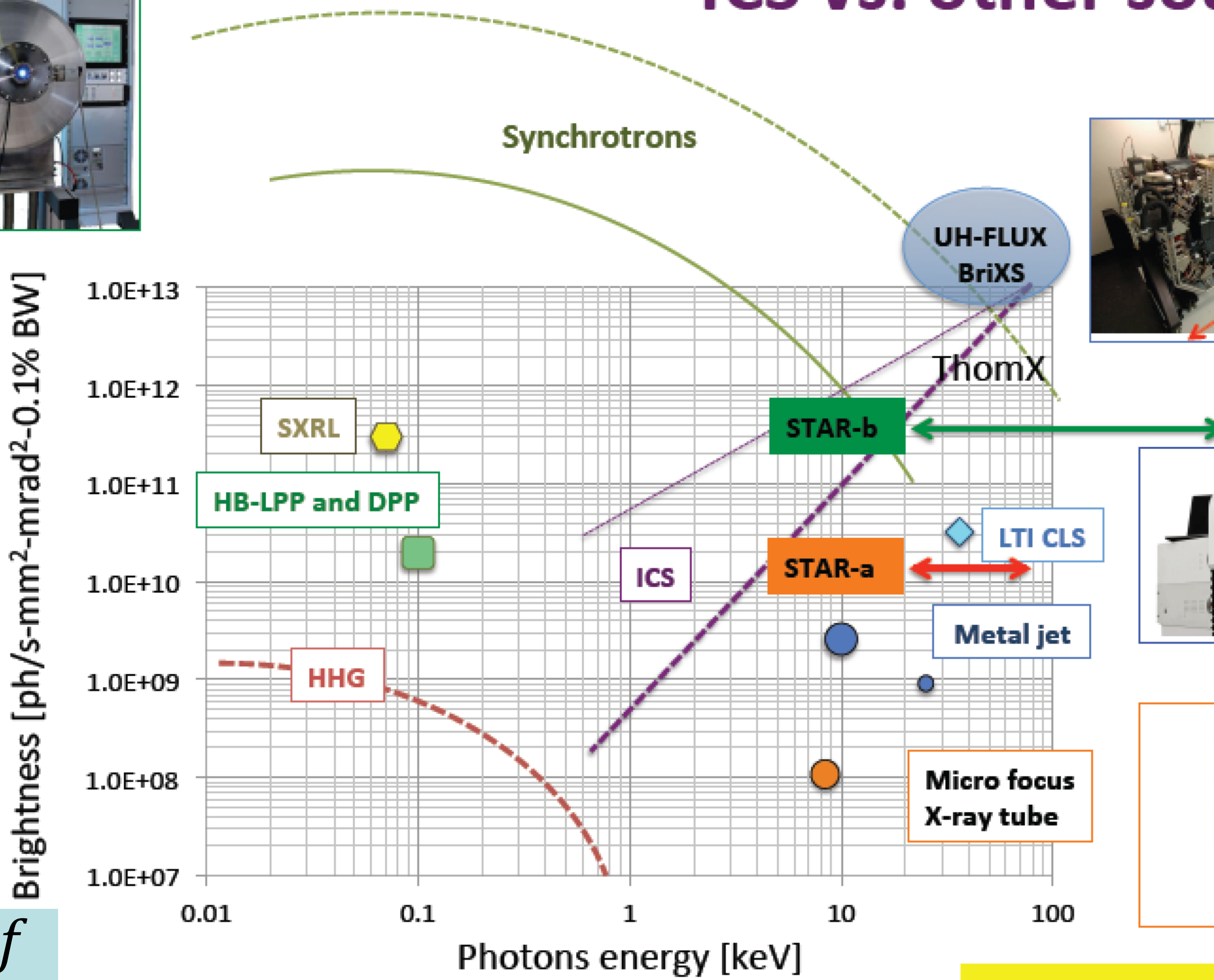


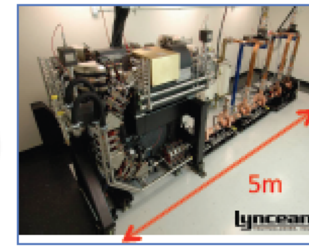
Courtesy C. Barty - LLNL

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

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

$s_t = 10 - 20 \;\; fs$

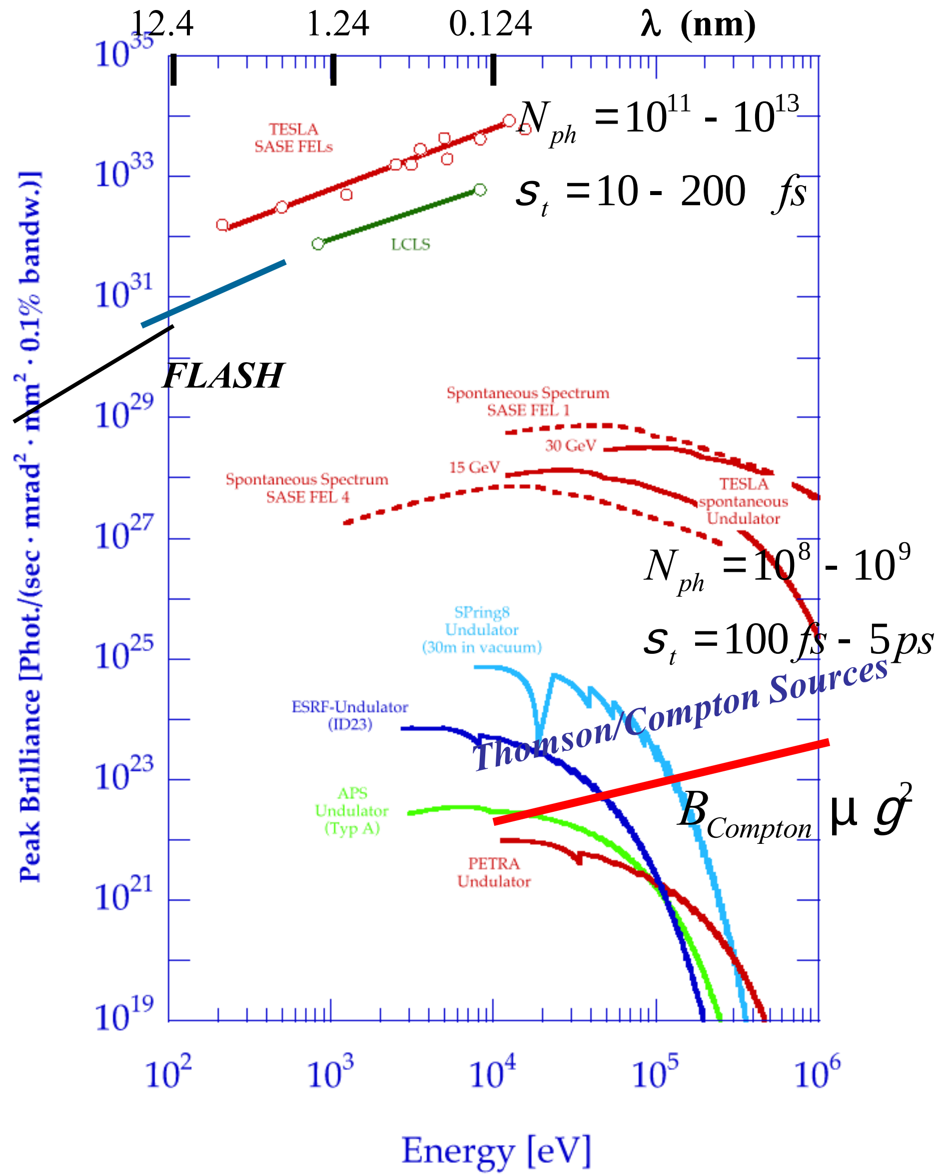
$$B = \frac{N_{ph}}{\sqrt{2\pi}\sigma_t\left(M^2\lambda\right)^2 \frac{\Delta\lambda}{\lambda}}$$

ELI

BELLA

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

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



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 is relevant to microscopy/spectroscopy)

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

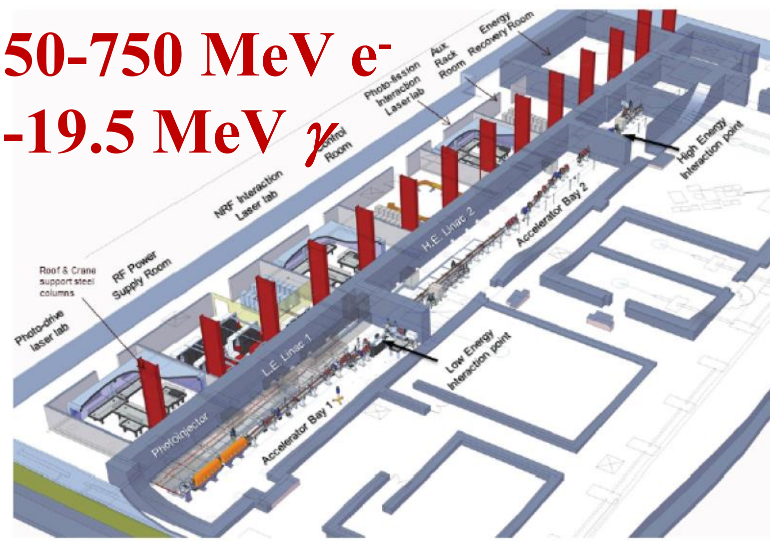
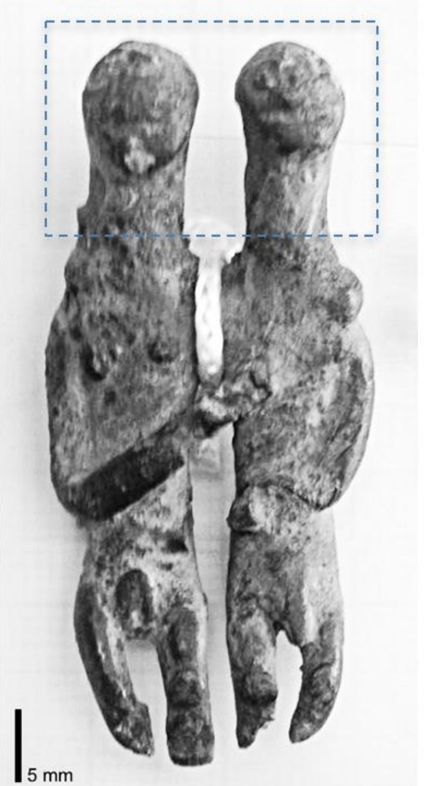


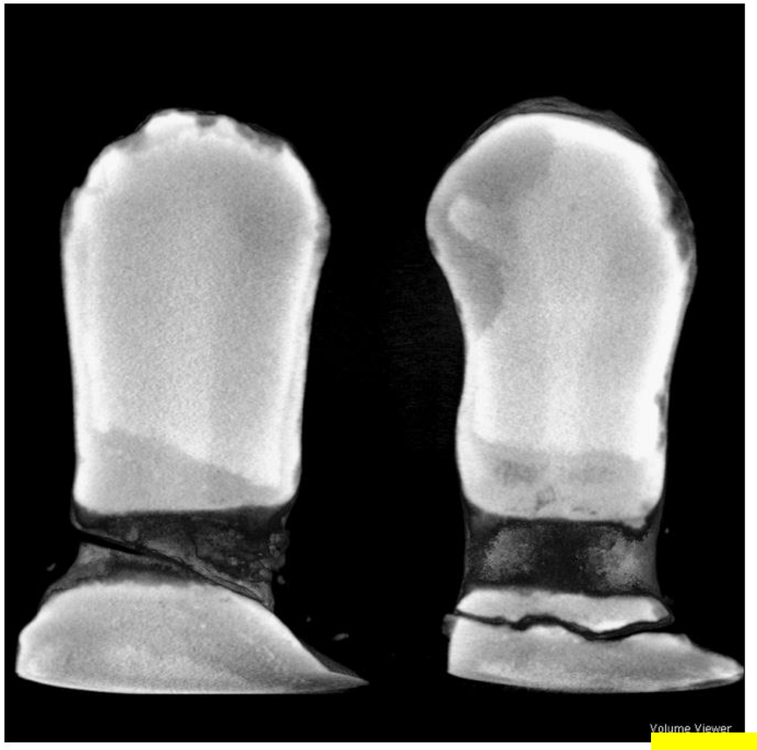
Fig. 197. Isometric 3D view of Building Layout of the Accelerator Hall & Experimental Areas

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**.



Campione ROS 1 - Bucita - RS 001



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.

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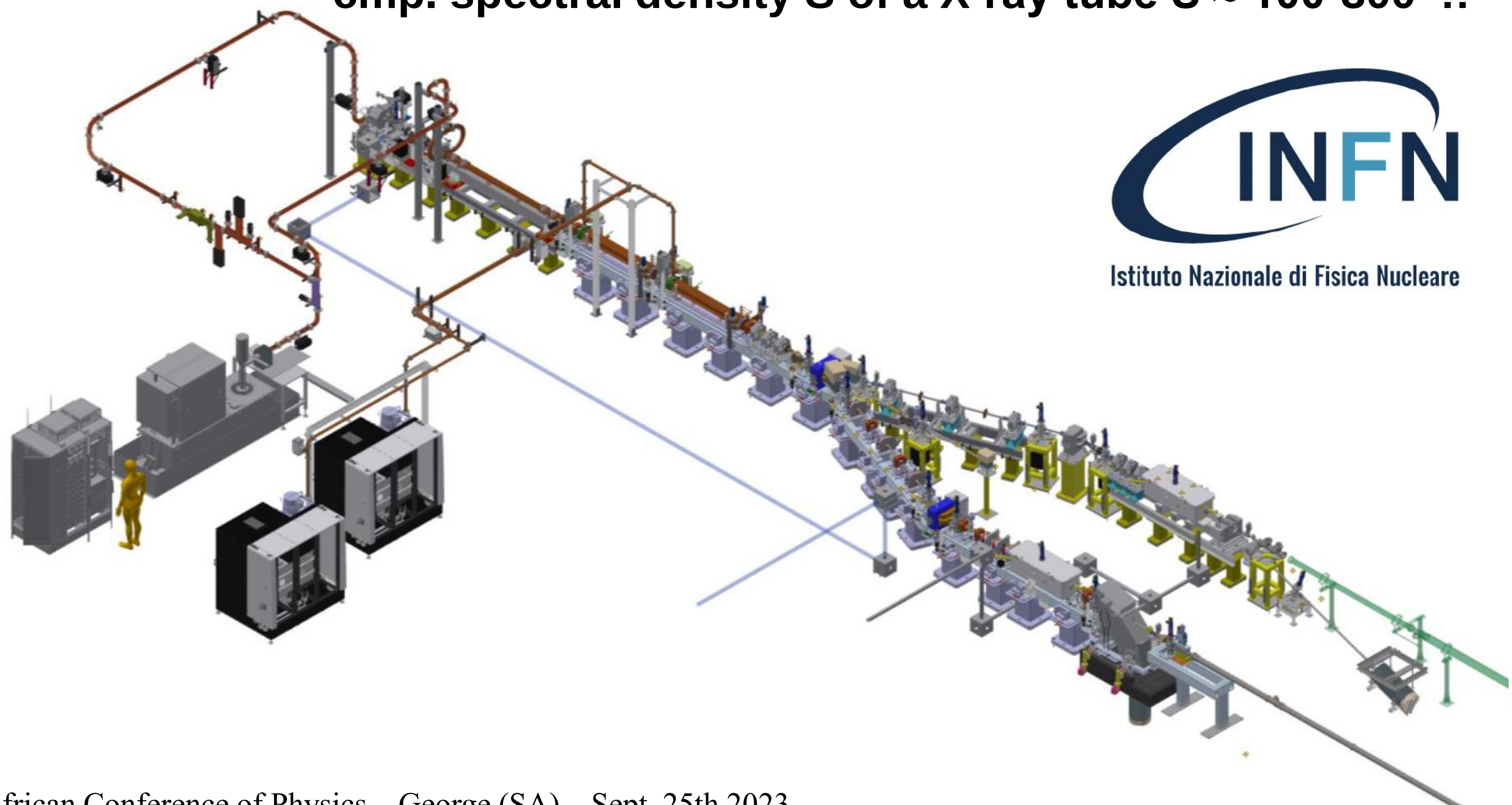
N_{ph} (s^{-1}) = $5 \cdot 10^{10}$ (10% bdw) S @ 30keV ($s^{-1}eV^{-1}$)= $1.5 \cdot 10^{7}$

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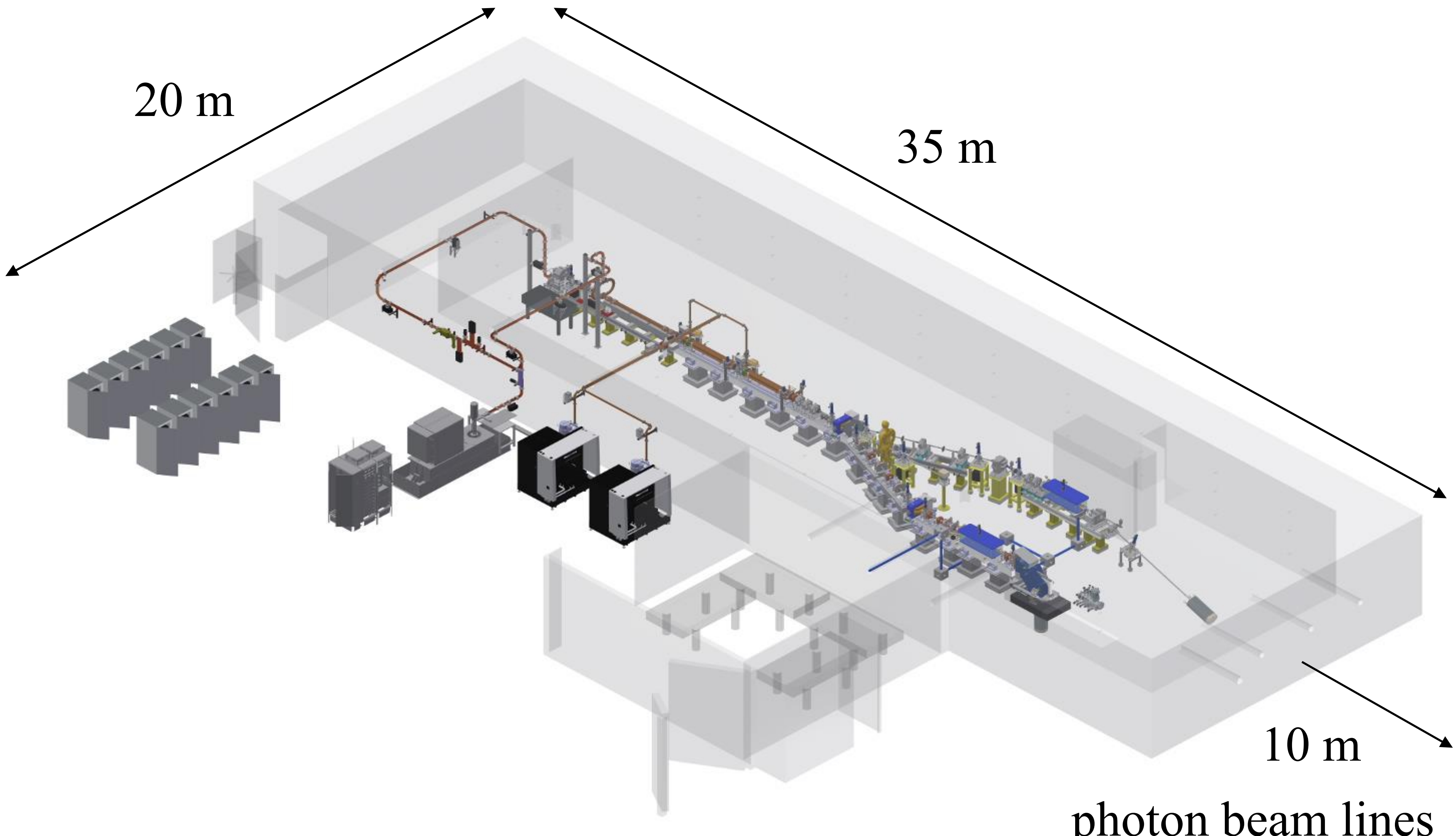
150 MeV High Brightness Electron Linac + Laser 12 M€
Bunker/building + ancillary equipm. 4 M€
2 X-ray beam lines for micro-tomography 3 M€



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

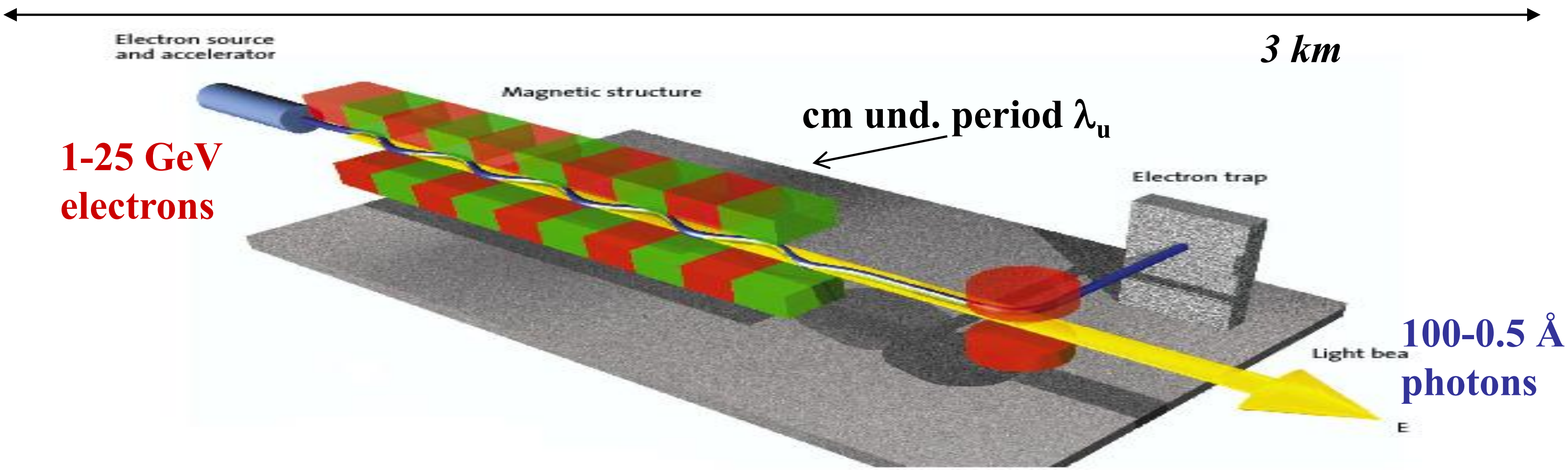
100 MeV Linac+Laser (170 keV) - 9 M€
Bunker/building + ancillary equipm. 4 M€
2 X-ray beam lines (fully equipped) 3 M€
TOTAL 16 M€

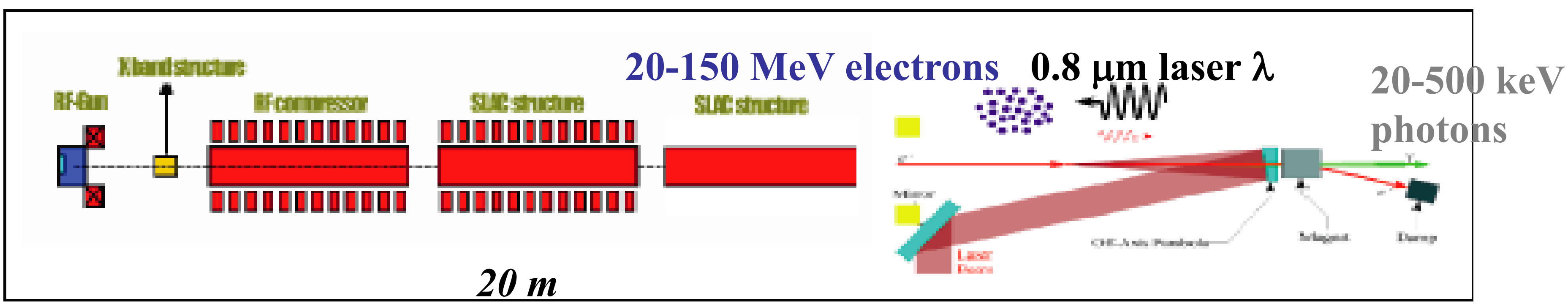
Injector for AfLS (100 MeV Linac) 5-6 MeV
Bunker/building + ancill. equipment used also for AfLS

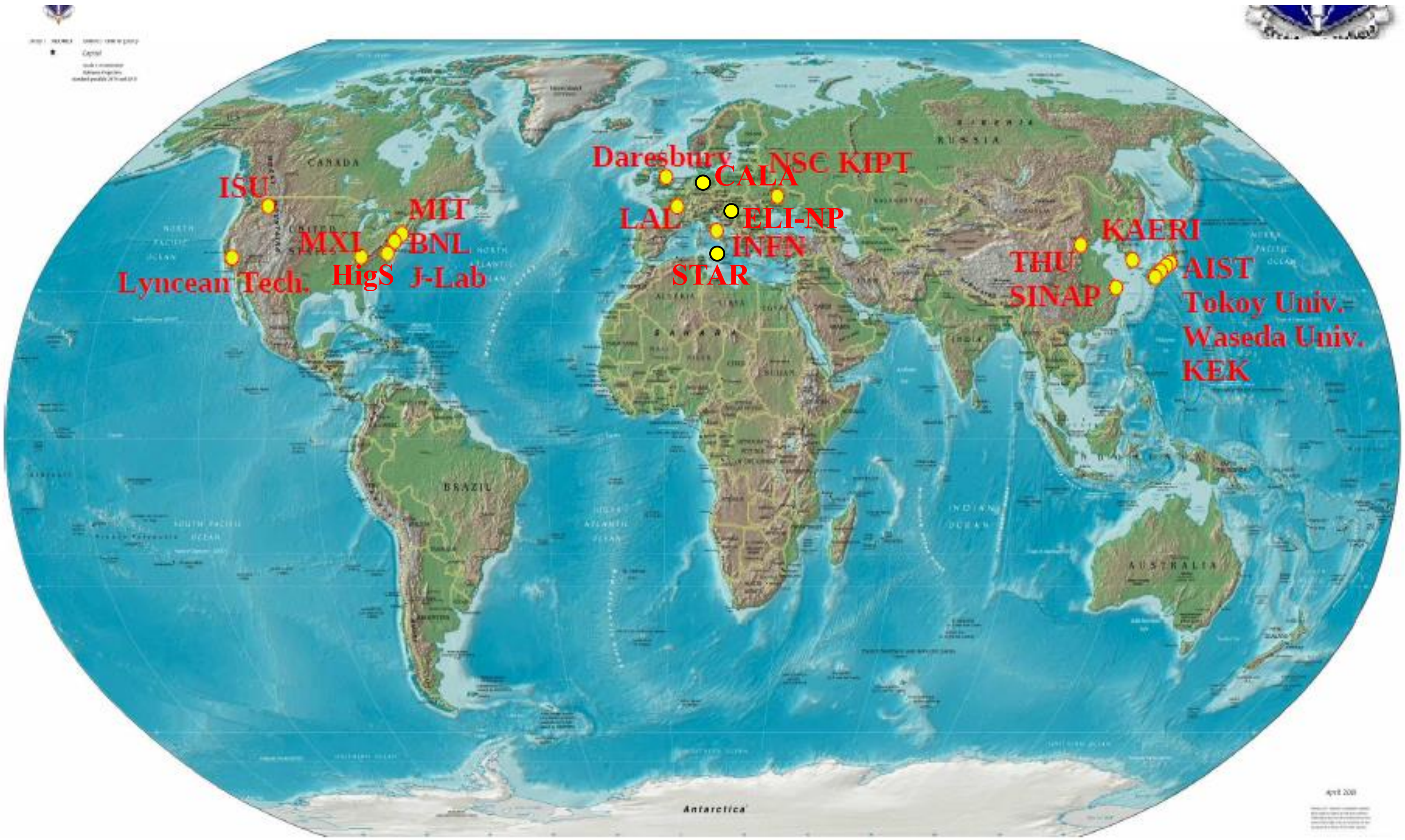
Cost specific to ICS (9-5) + 3 = 7 M€

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

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]

Istituto Nazionale di Fisica Nucleare

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[3] Politecnico di Milano, Italy
[4] Università degli Studi di Milano, Italy

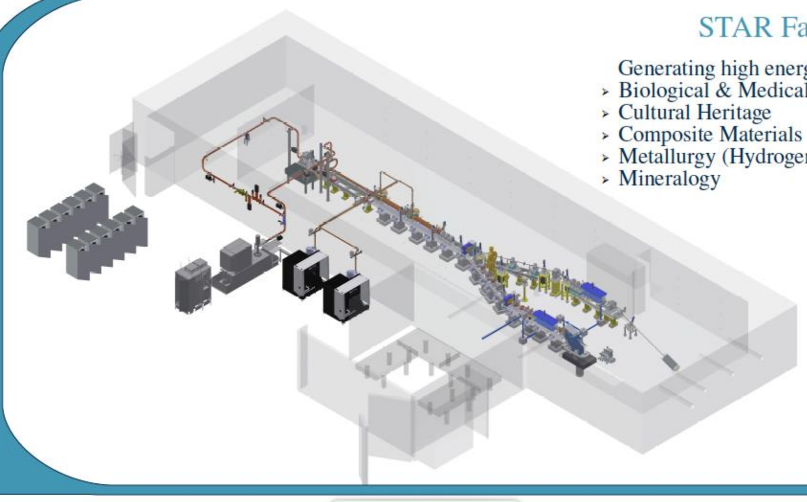
Abstract

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

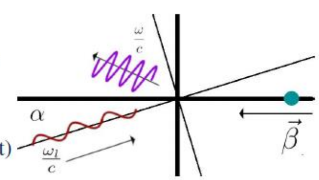
Upgrade to High Energy line (HE-line) consist out of:

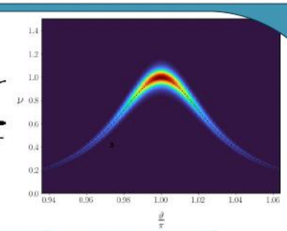
- Installation of soilenoid (8 cm) in front of S-band cavity for emittance control
- Installation of two C-band RF cavities incl. powerstations, for higher beam energy
- Cooling system upgrade
- Electric system upgrade, incl. backup power, power supplies and cabeling
- IT infrastructure & control system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

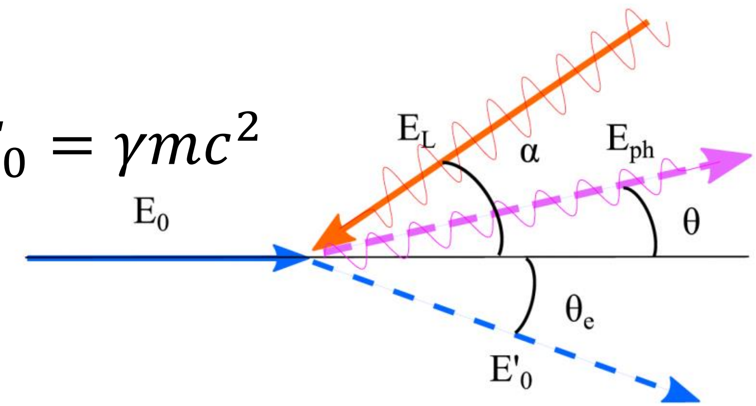
Electrons
- Emittance : 1 [mm mrad]
- Charge : 100 – 500 [pC]
- Bunch length : < 0.7 [mm]
- Energy spread : 0.1 %, 0.05%

(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)

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

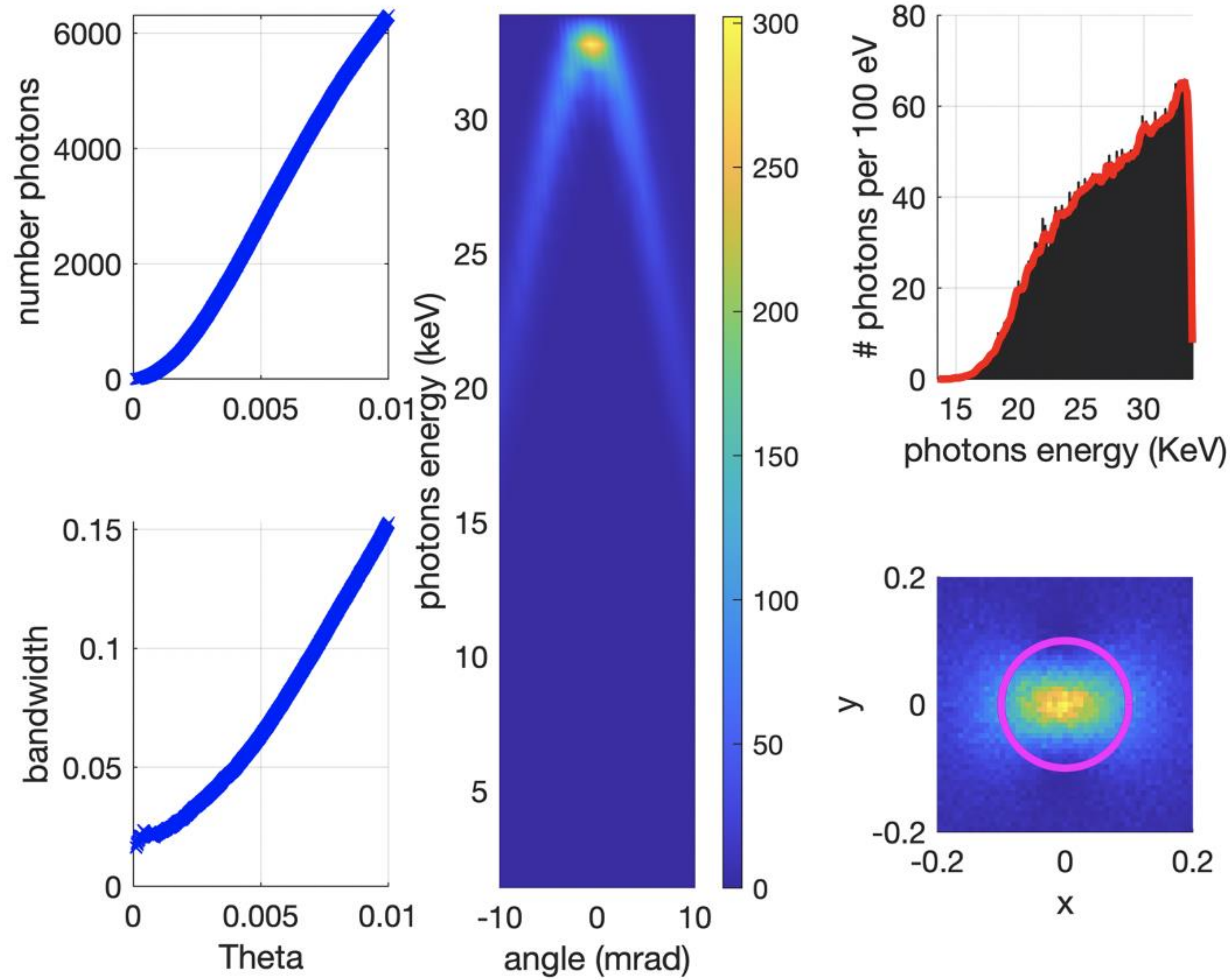


$$E_{ph} = \frac{4\gamma^2 E_l}{1 + X + \gamma^2\vartheta^2}$$

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

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

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

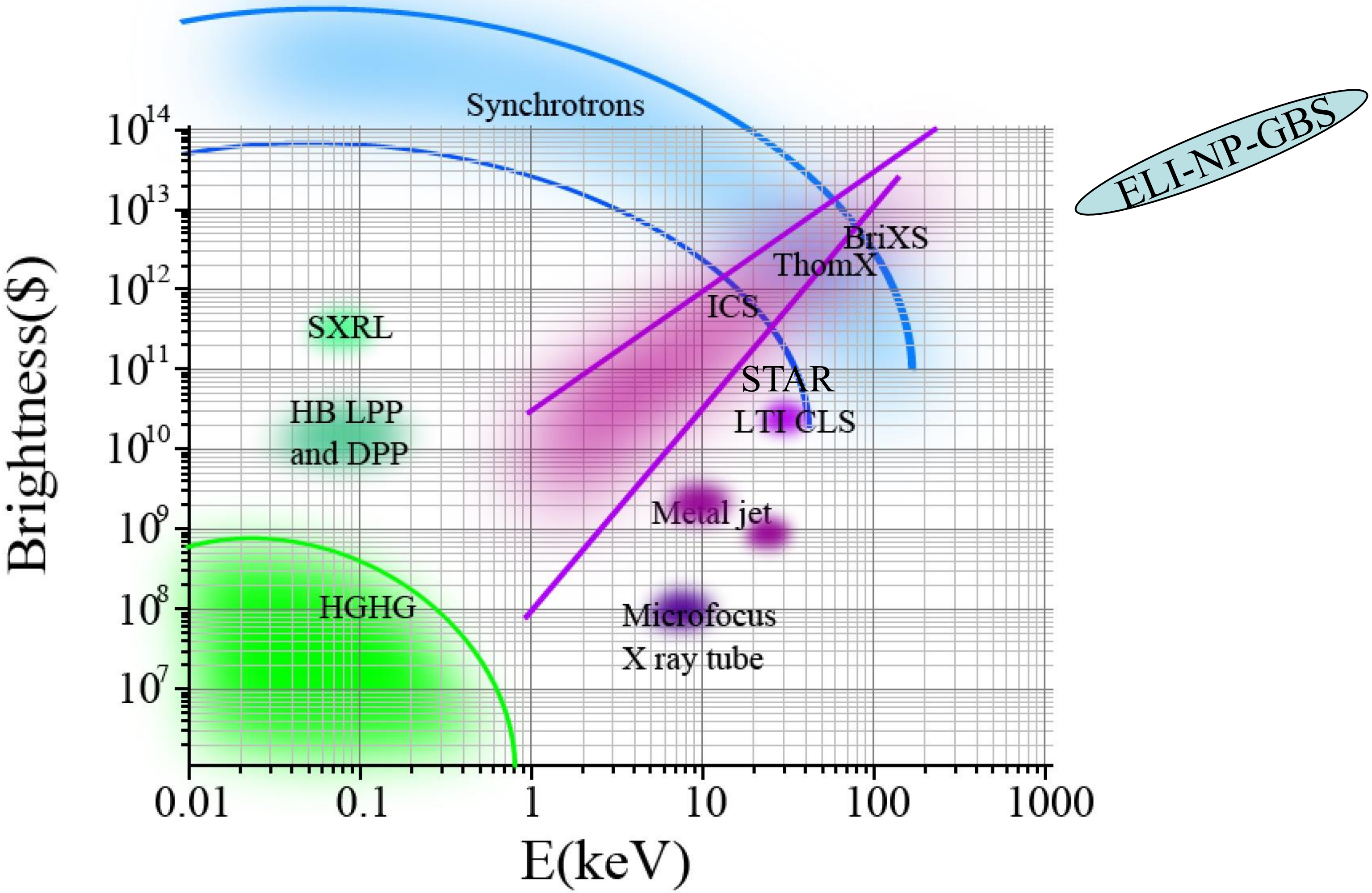


Figure 1: Brightness of several radiation sources as a function of the photon energy. $: Photon $number/s/mm^2/mrad^2/(0.1\%$.
I.C.S. Sources (LTI-CLS,ThomX, STAR, UH-FLUX and BriXS) are compared to Synchrotron Light Sources and the most performing X-ray tube so far (Metal Jet).