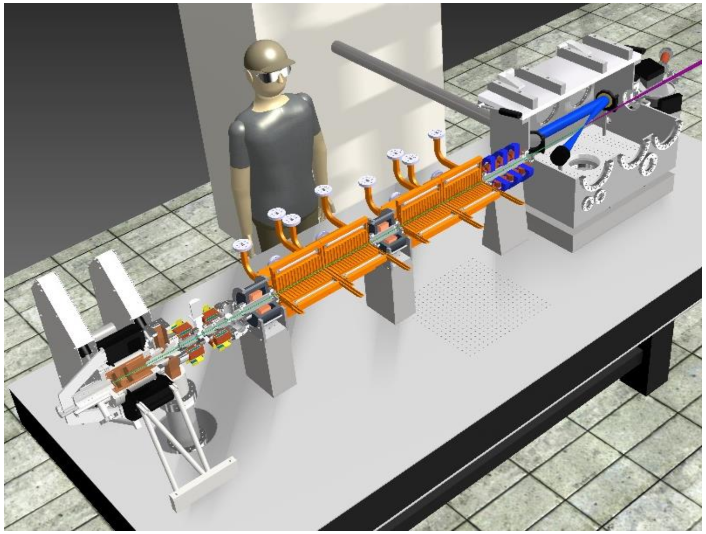
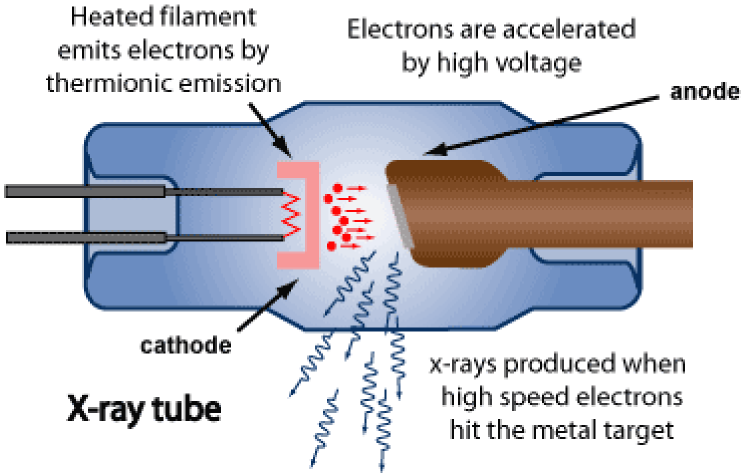
Inverse Compton Scattering X-ray source

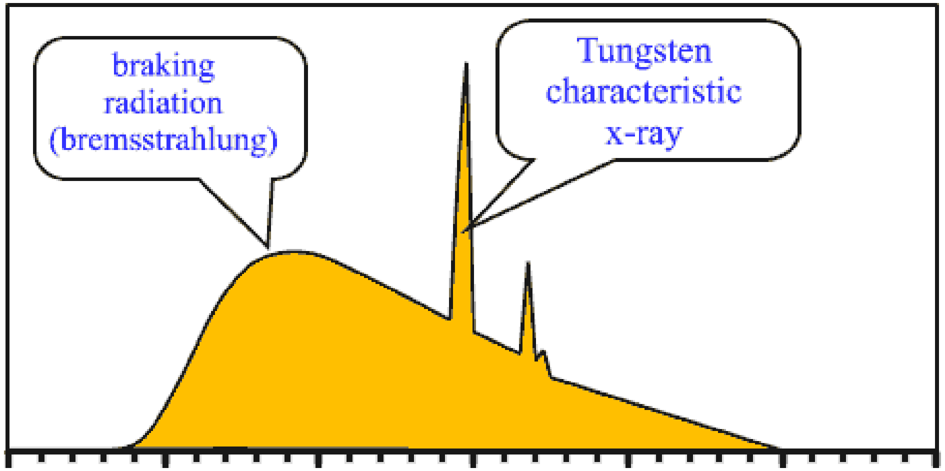


Jom Luiten – TU Eindhoven
Xavier Stragier – TU Eindhoven
Koen Janssens – Un. Antwerpen
Joris Dik – TU Delft

TU Delft Delft University of Technology | Universiteit Antwerpen | TU/e Technische Universiteit Eindhoven University of Technology

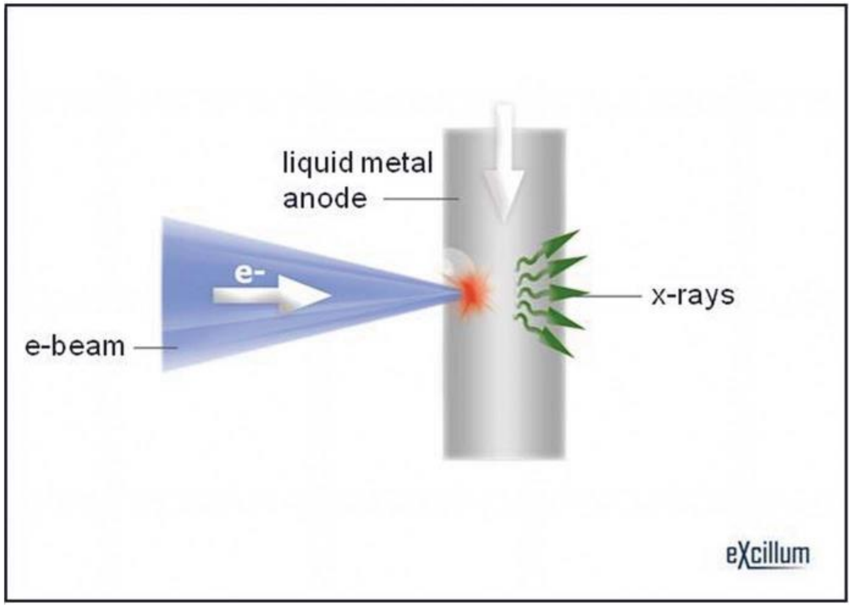
Current lab X-ray sources



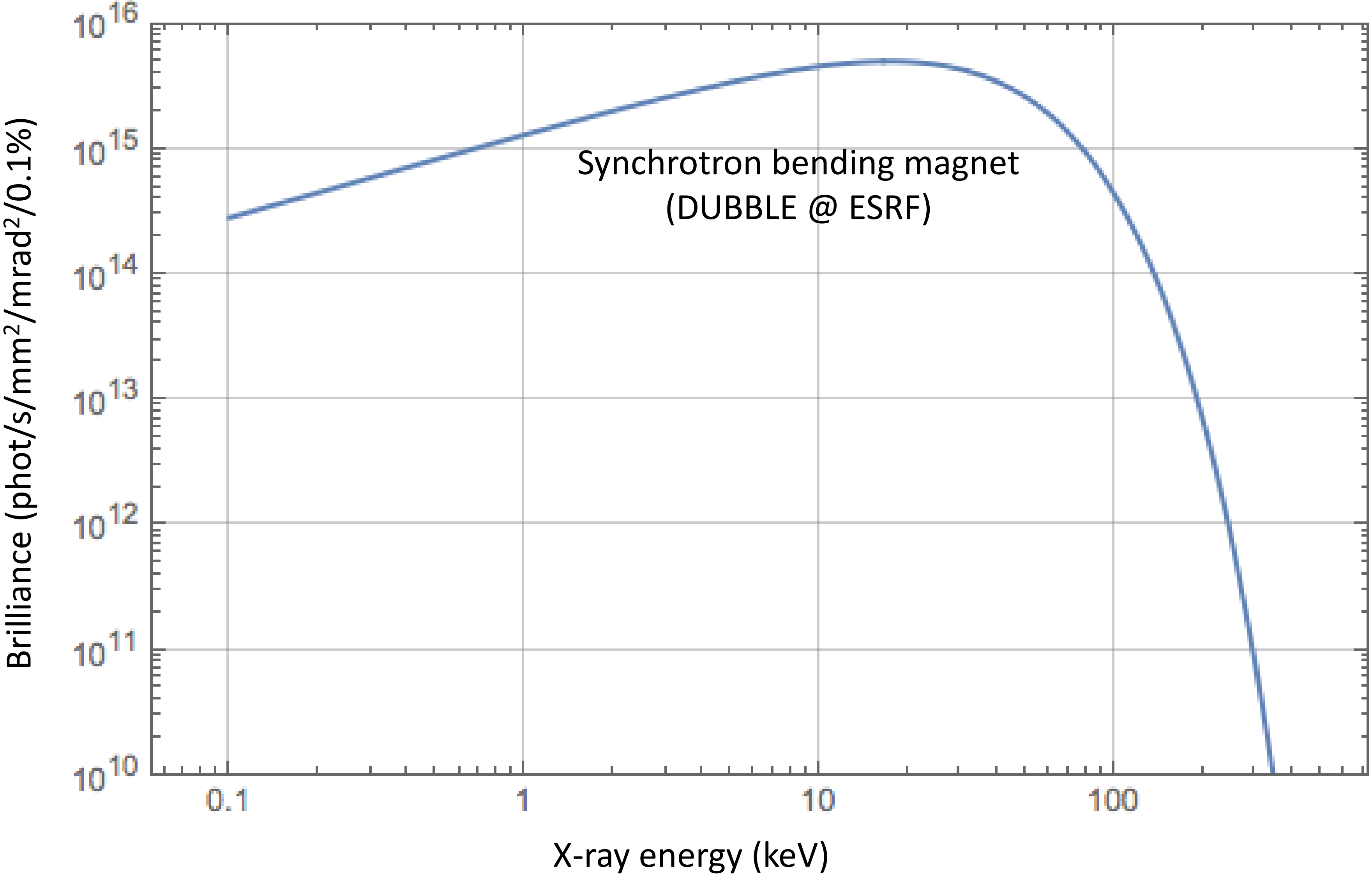


- Broadband with few characteristic lines
- Large photon flux but limited brilliance

Liquid gallium anode:
2.6×10^{10} photons s^{-1} mm^{-2} $mrad^{-2}$

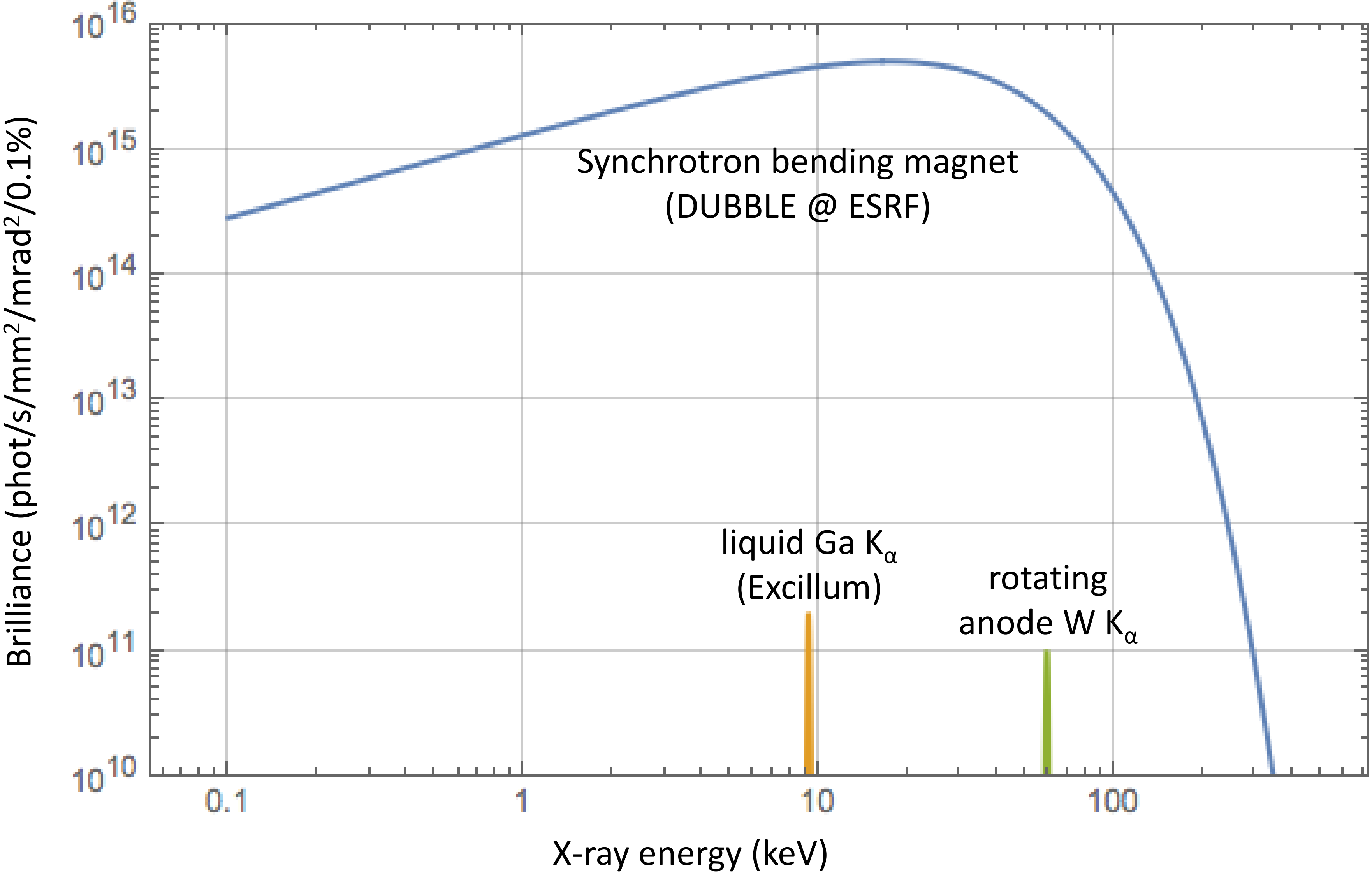


Brilliance



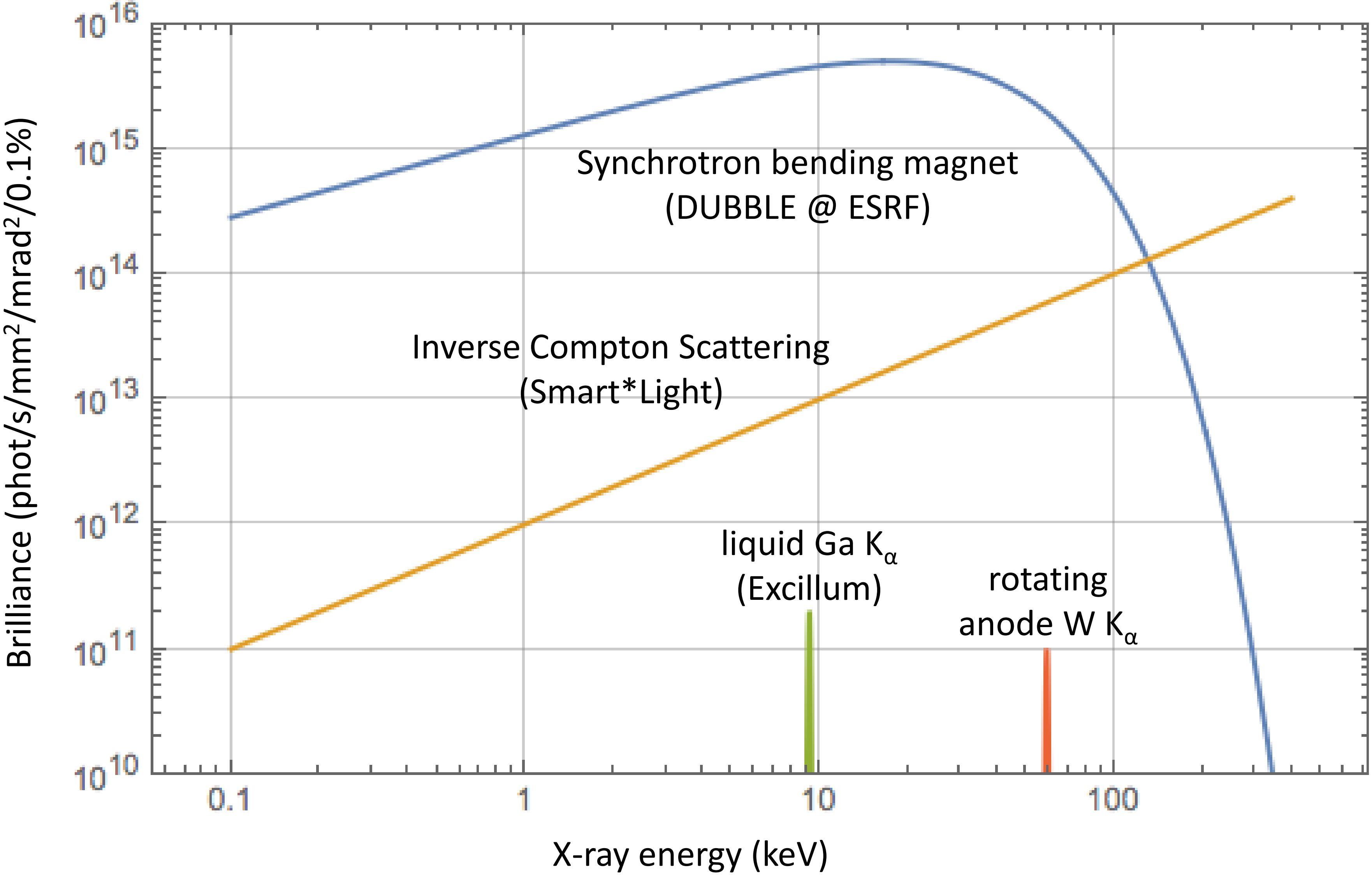
Synchrotron bending magnet
(DUBBLE @ ESRF)
Brilliance (phot/s/mm²/mrad²/0.1%)
X-ray energy (keV)
10^16
10^15
10^14
10^13
10^12
10^11
10^10
0.1
1
10
100

Brilliance



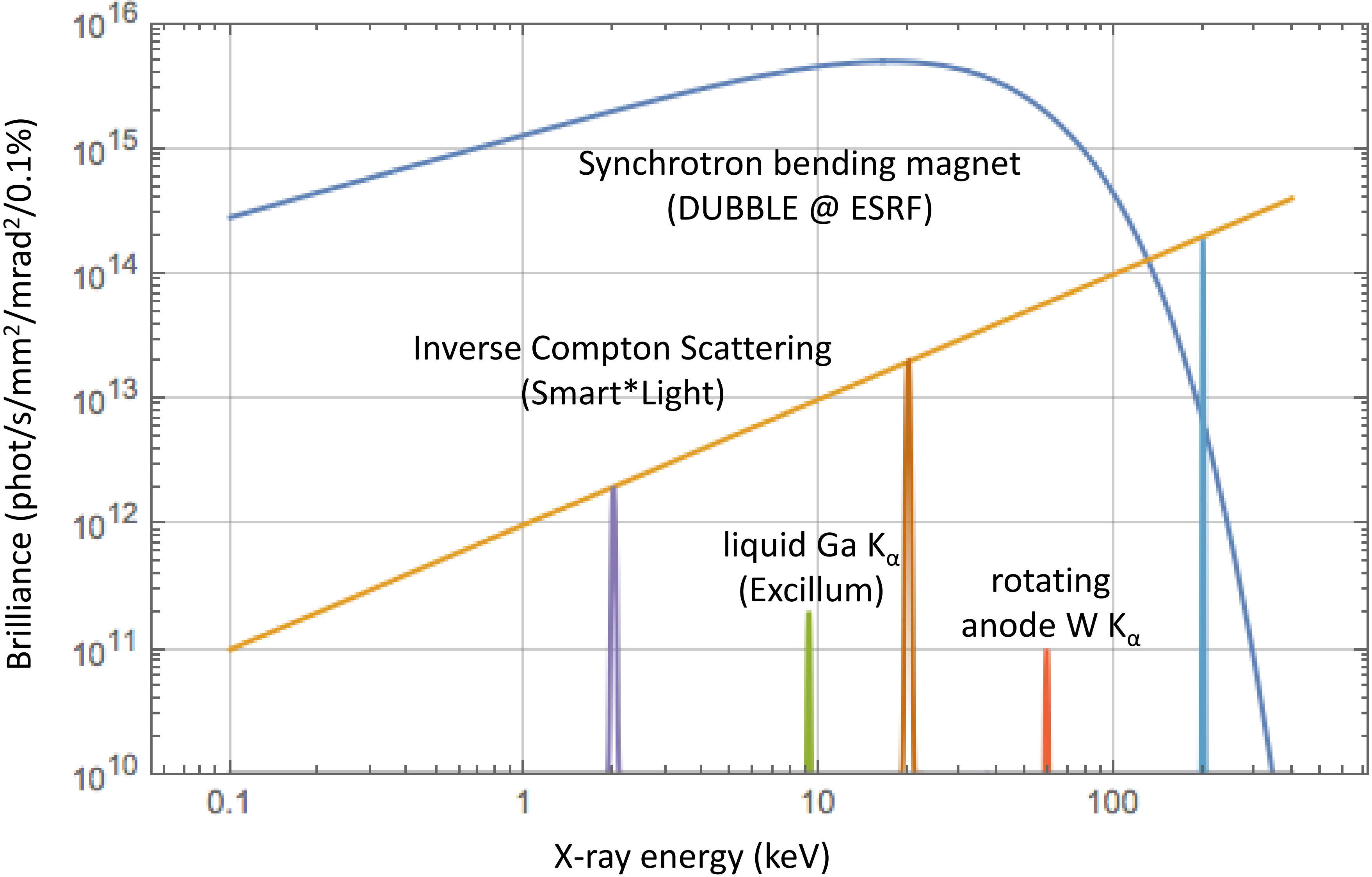
Brilliance (phot/s/mm²/mrad²/0.1%)
10^16
10^15
10^14
10^13
10^12
10^11
10^10
Synchrotron bending magnet
(DUBBLE @ ESRF)
liquid Ga Kα
(Excillum)
rotating
anode W Kα
0.1
1
10
100
X-ray energy (keV)

Brilliance



Synchrotron bending magnet
(DUBBLE @ ESRF)
Inverse Compton Scattering
(Smart*Light)
liquid Ga K_α
(Excillum)
rotating
anode W K_α
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
0.1
1
10
100
Brilliance (phot/s/mm^2/mrad^2/0.1%)
X-ray energy (keV)

Brilliance



Brilliance (phot/s/mm²/mrad²/0.1%)
10^16
10^15
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Synchrotron bending magnet
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Inverse Compton Scattering
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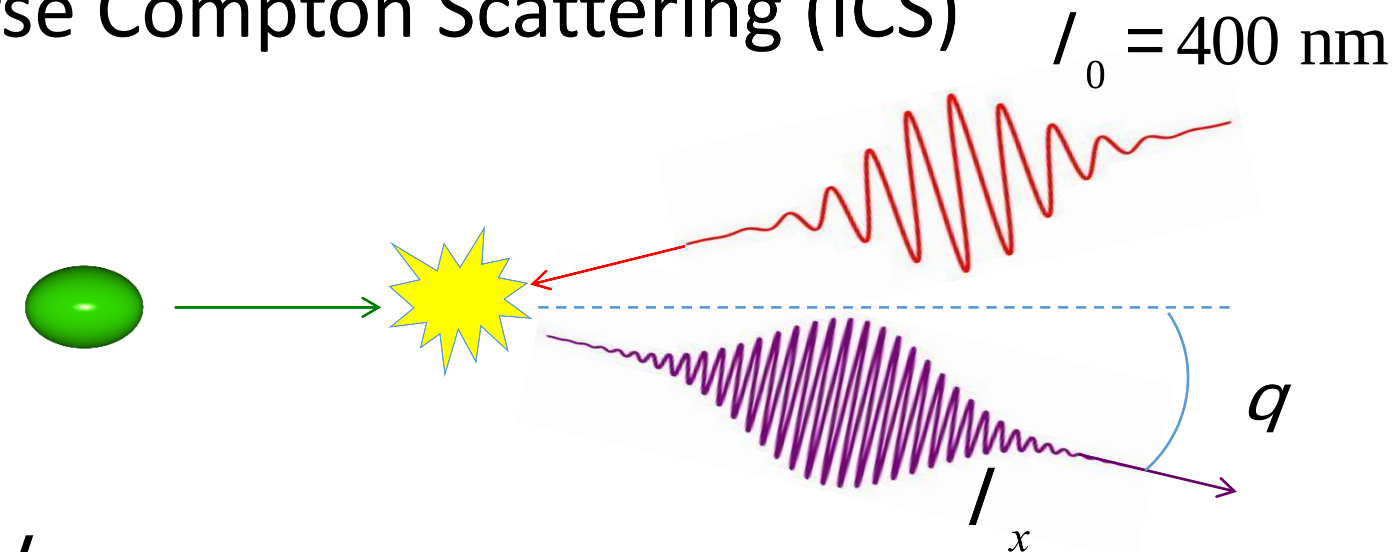
liquid Ga Kα
(Excillum)
rotating
anode W Kα
0.1
1
10
100
X-ray energy (keV)

Inverse Compton Scattering (ICS)



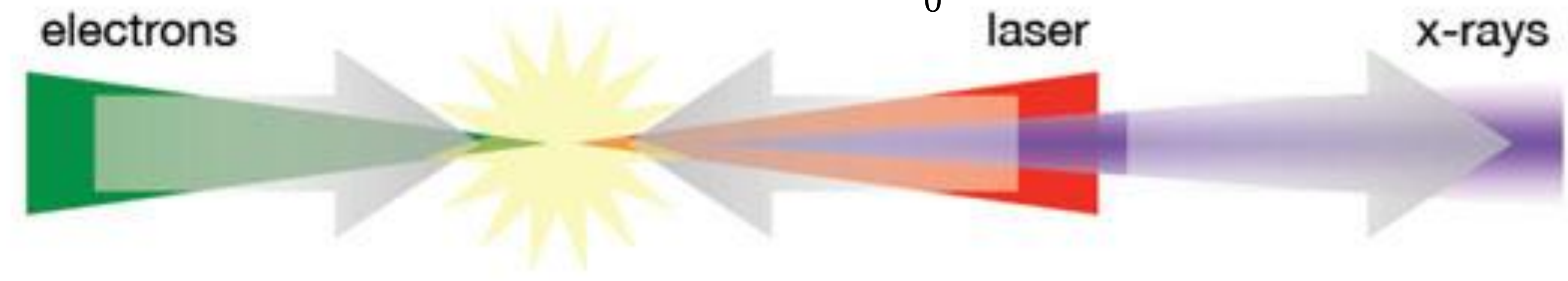
$$\lambda_x = \frac{\lambda_0}{4\gamma^2}(1+\gamma^2\theta^2)$$

- X-rays emitted in narrow cone, half angle γ^{-1}
- X-ray energy dependent on emission angle
- 1% energy spread if $\theta < 0.1\ \gamma^{-1}$

Electron energy	Lorentz factor γ	X-ray wavelength	X-ray energy	Emission angle $0.1\ \gamma^{-1}$
5 MeV	11	8.6 Å	1.4 keV	9 mrad
15 MeV	30	1.1 Å	11 keV	3 mrad
30 MeV	60	0.28 Å	44 keV	1.7 mrad
45 MeV	89	0.13 Å	98 keV	1.1 mrad

Inverse Compton Scattering (ICS)

$\lambda_0 = 400 \text{ nm}$



$$\lambda_x = \frac{\lambda_0}{4\gamma^2}(1+\gamma^2\theta^2)$$

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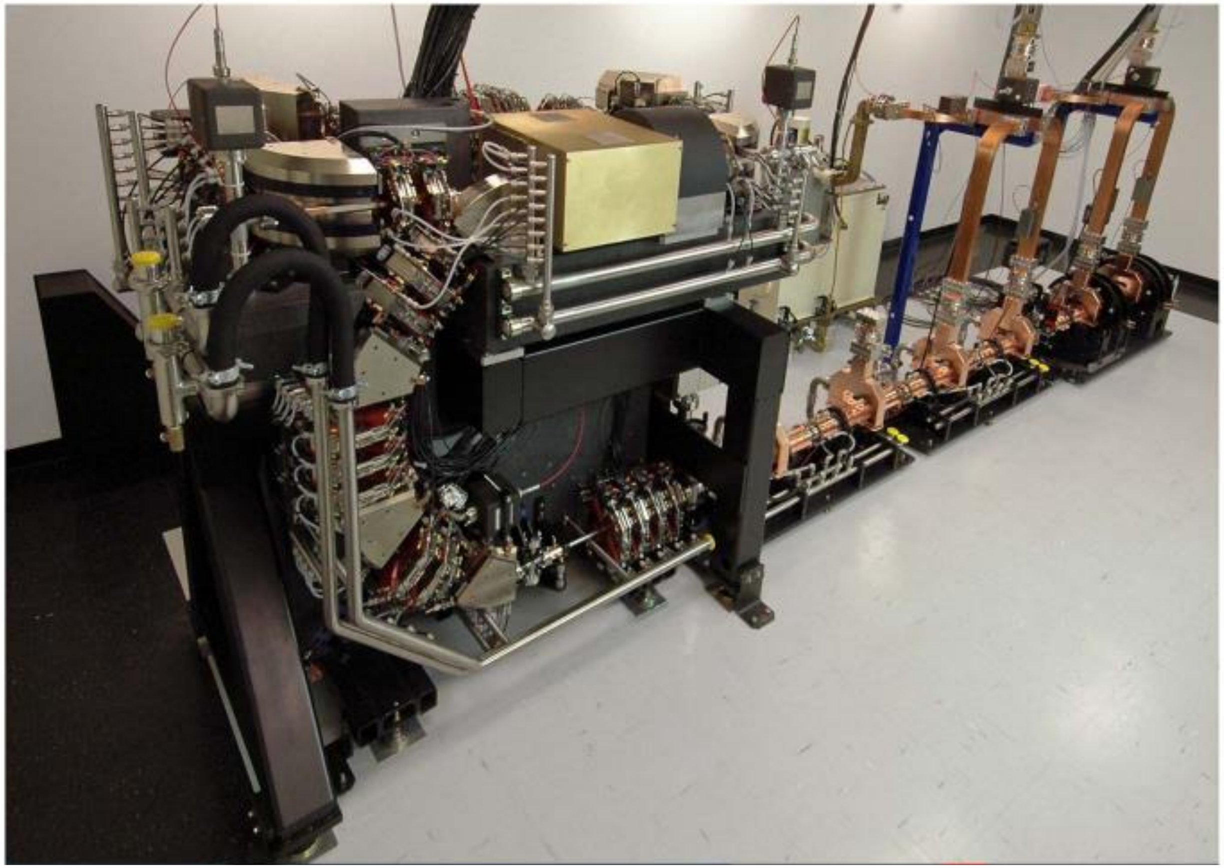
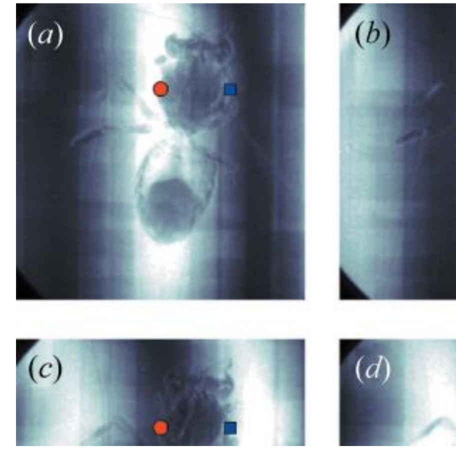
30 MeV	60	0.28 Å	44 keV	1.7 mrad
45 MeV	89	0.13 Å	98 keV	1.1 mrad

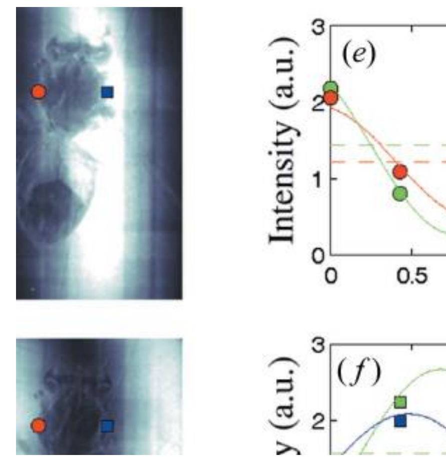
ICS sources: Lyncean

first commercial ICS source





absorption image



phase-contrast image

Journal of
Synchrotron Radiation

ISSN 0909-0495

Received 6 September 2008
Accepted 23 October 2008

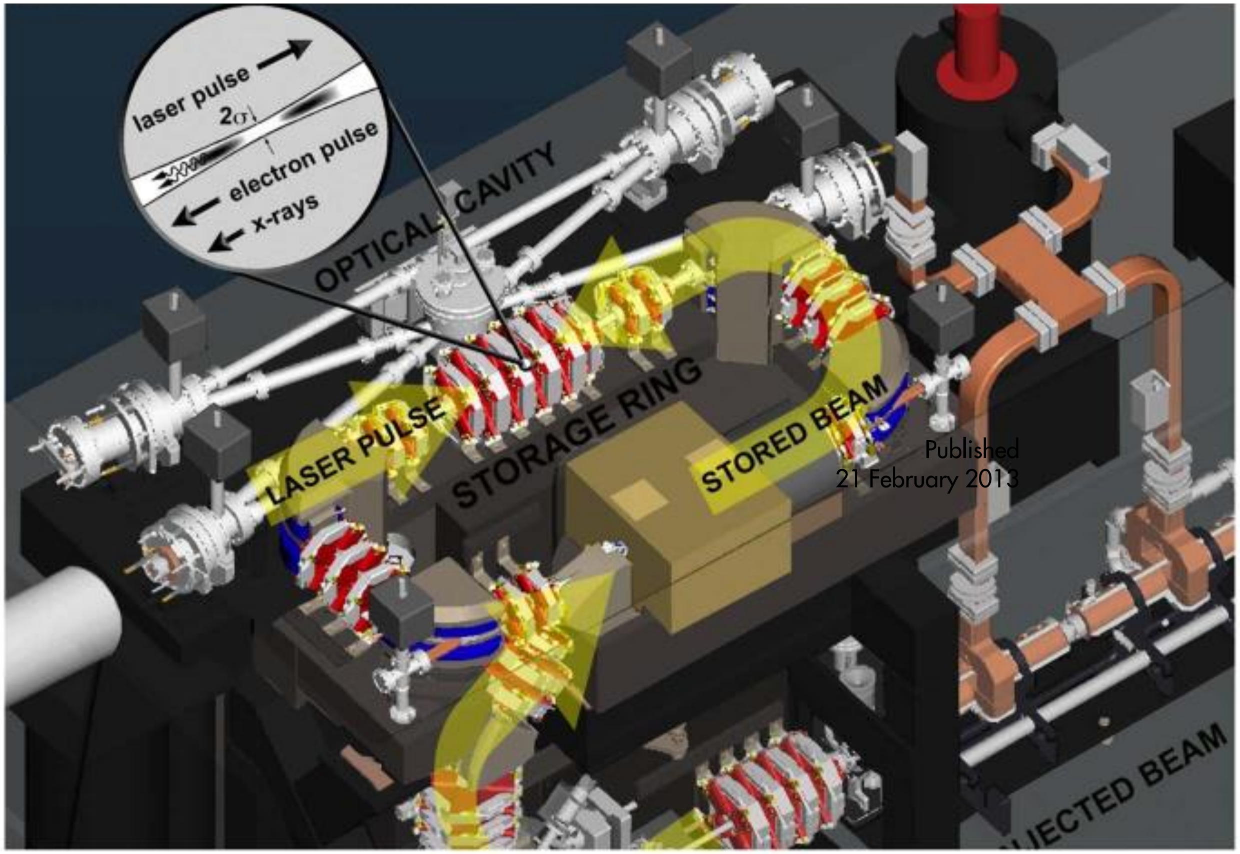
Hard X-ray phase-contrast imaging with the Compact Light Source based on inverse Compton X-rays

Martin Bech,[a]* Oliver Bunk,[b] Christian David,[b] Ronald Ruth,[c,d] Jeff Rifkin,[c] Rod Loewen,[c] Robert Feidenhans'l[a] and Franz Pfeiffer[b,e]*

Lyncean TECHNOLOGIES, INC.

ICS sources: Lyncean

first commercial ICS source



- 80 µm source size
- 15-36 keV x-ray energy
- 4×10^{9} ph/s flux in 3% BW

absorption computer tomography of a mouse

SCIENTIFIC REPORTS

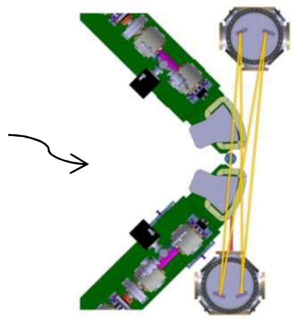
Monochromatic computed tomography with a compact laser-driven X-ray source

K. Achterhold[1], M. Bech[1], S. Schleede[1], G. Potdevin[1], R. Ruth[2], R. Loewen[3] & F. Pfeiffer[1]

Published
21 February 2013

ICS sources: ThomX

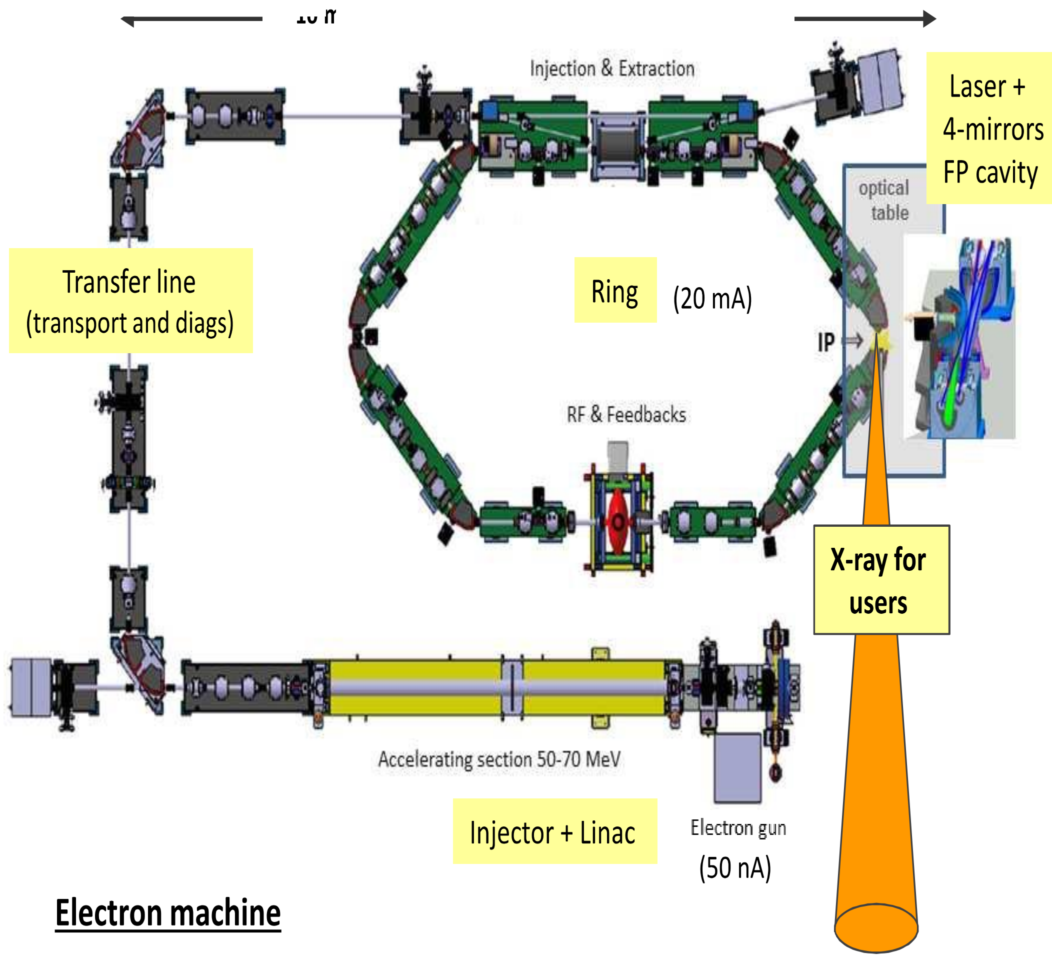
under construction



Laser /Cavity system

- Pulsed laser : ps , ~ 1W average
- Optical fiber amplification
  → (100 W) 2-3 µJ/pulse
- Optical FP cavity amplification
  → (gain 10000)

→ **1 MW stored inside the cavity**
  → (20-30 mJ/pulse)



Electron machine

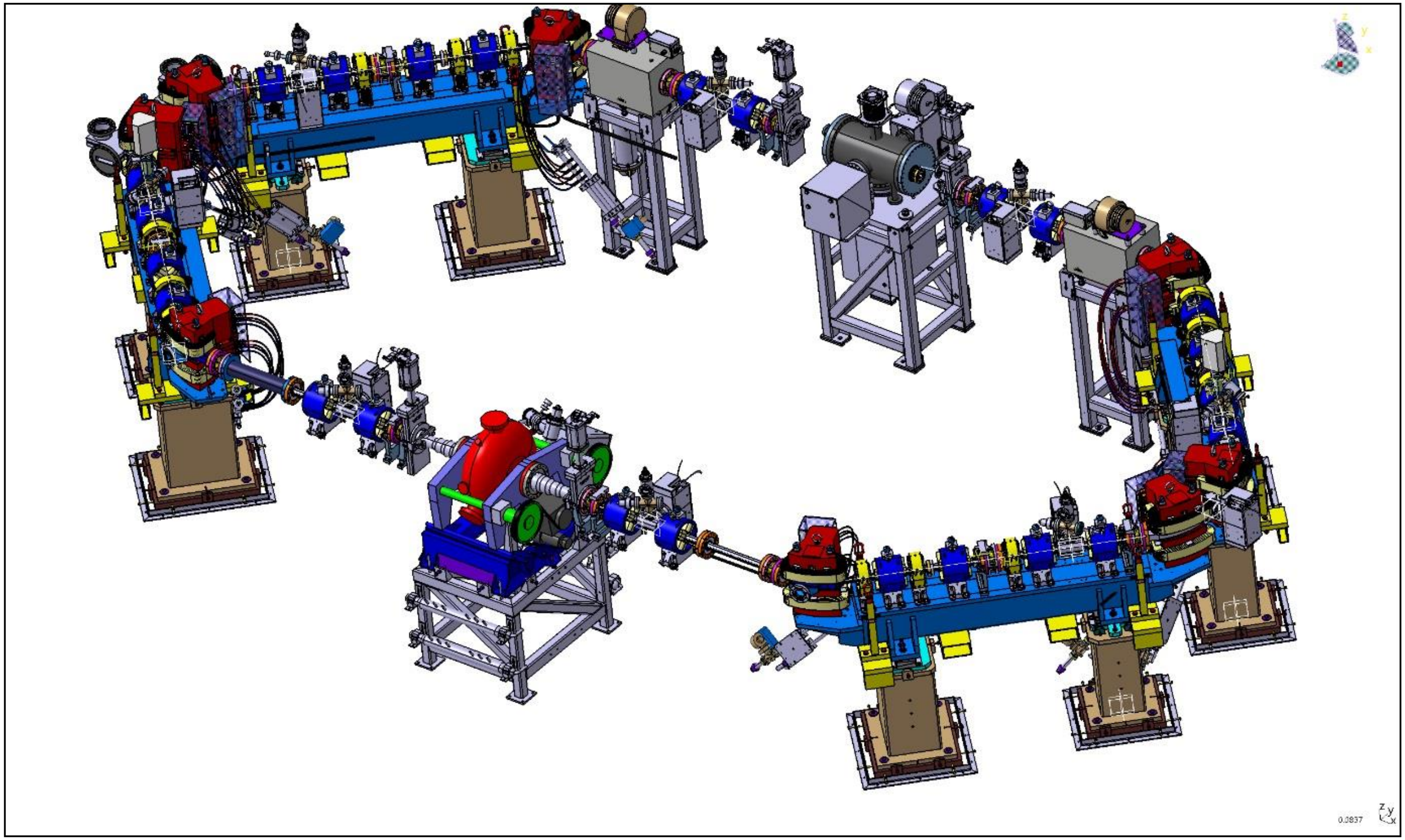
- 1 nC / bunch , 50 Hz inj. freq.
- **50-70 MeV**
- Ring, 20 MHz frep.
- **σ_e ~ 70 µm**
- **ε_N ~ 4 mm.mrad**
- τ_e ~ 10-20 ps

X-ray beam

Flux	**10^{13}**
Brigthness	**10^{11}**
Transv. size	**70 µm**
E_X	**20-90 KeV**

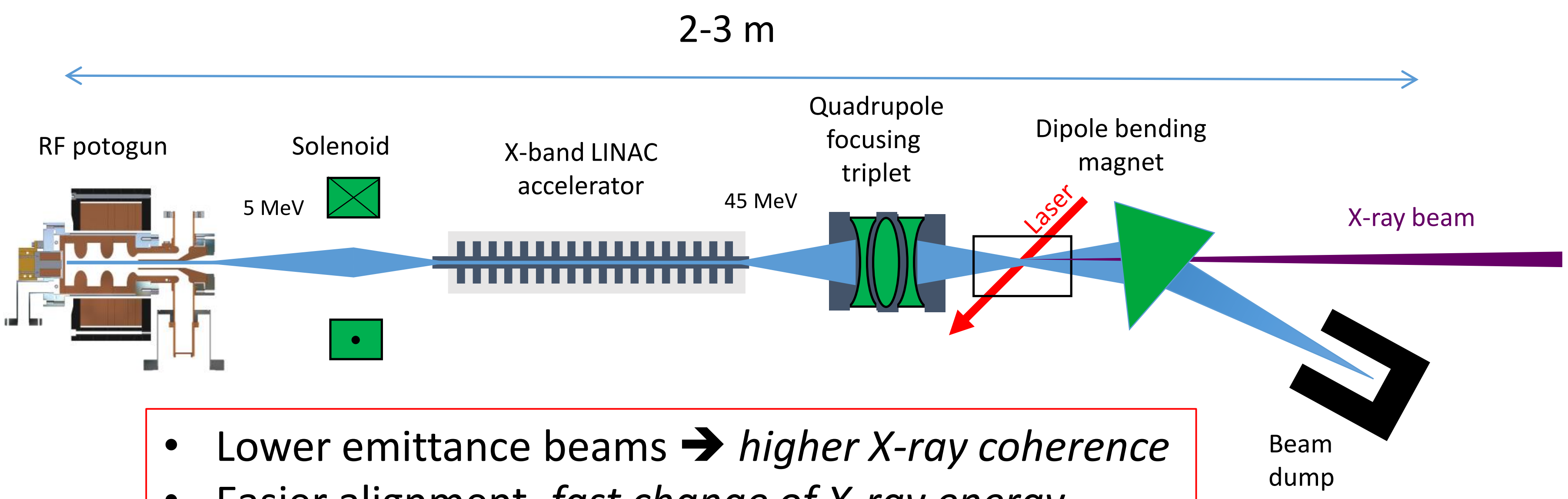
ICS sources: ThomX

under construction

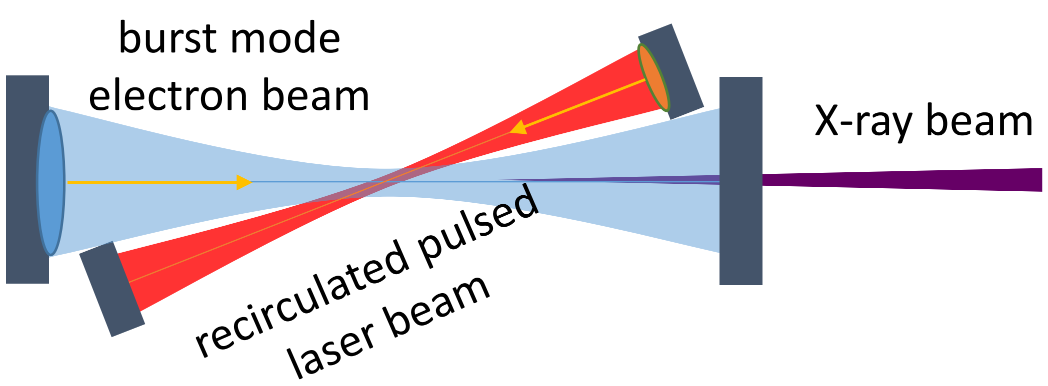


- 2017: installation & commissioning
- 2018: first X-ray users

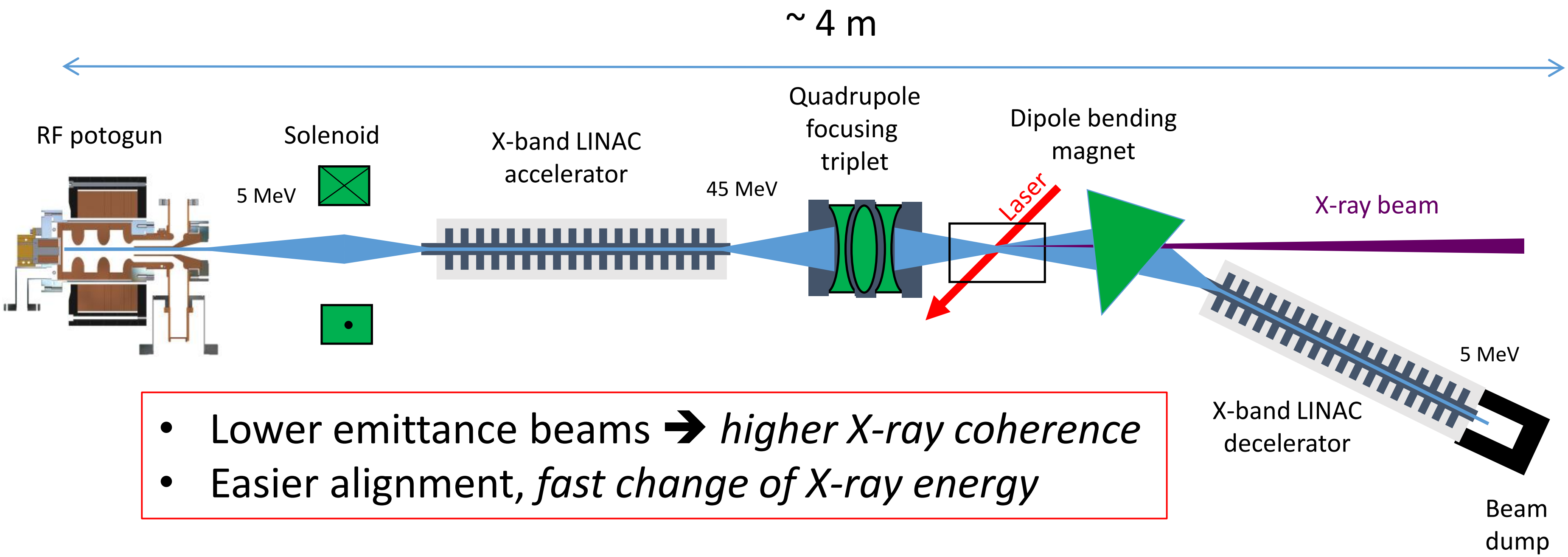
LINAC-based ICS sources: why?



- Lower emittance beams ➔ *higher X-ray coherence*
- Easier alignment, *fast change of X-ray energy*



LINAC-based ICS sources: why?

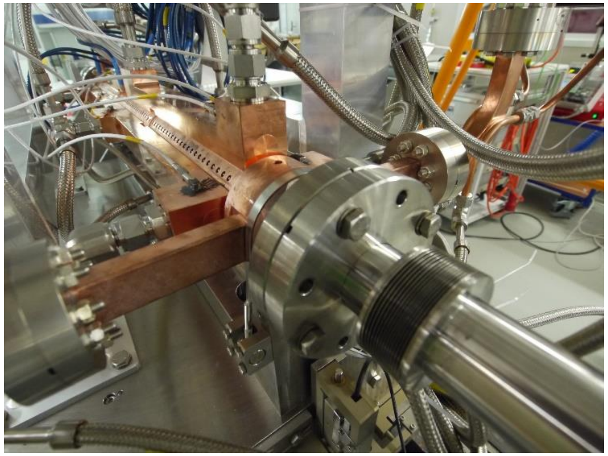


- Lower emittance beams ➔ *higher X-ray coherence*
- Easier alignment, *fast change of X-ray energy*

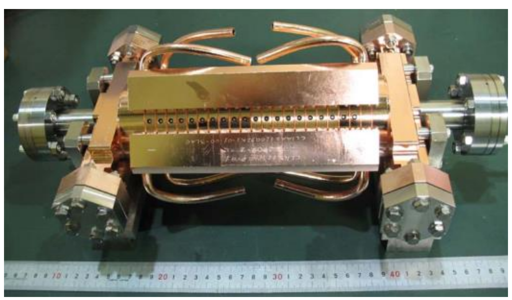
- Deceleration option: strongly *reduced shielding requirements*
- *Will fit into sea container*

Enabling technology: compact 12 GHz X-band LINAC

Developed by CERN, PSI and VDL-ETG collaboration



X-band test facility @ PSI



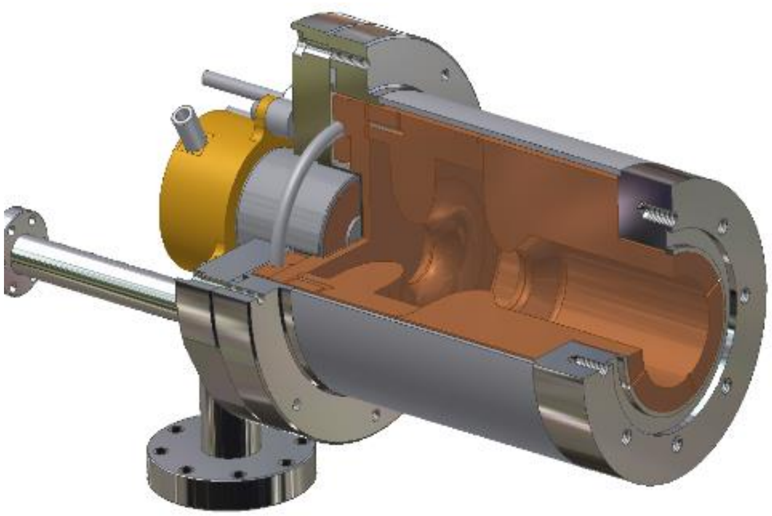
- 12 GHz accelerator structure
- 40 MeV/m average gradient

1 m long accelerator structure sufficient for generating up to ~100 keV monochromatic X-ray beams

Enabling technology: electron guns, pulsed lasers

Coherence X-ray beam ultimately limited by emittance electron gun

5 MeV low-emittance RF photogun developed at TU/e



Spectacular development industrial pulsed fiber laser technology

Commercially available compact, high-power, femtosecond fiber lasers
200 fs, 2mJ @ 10 kHz

Enabling technology: high-power optical circulator

DESIGN AND OPTIMIZATION OF A HIGHLY … Phys. Rev. ST Accel. Beams **17,** 033501 (2014)

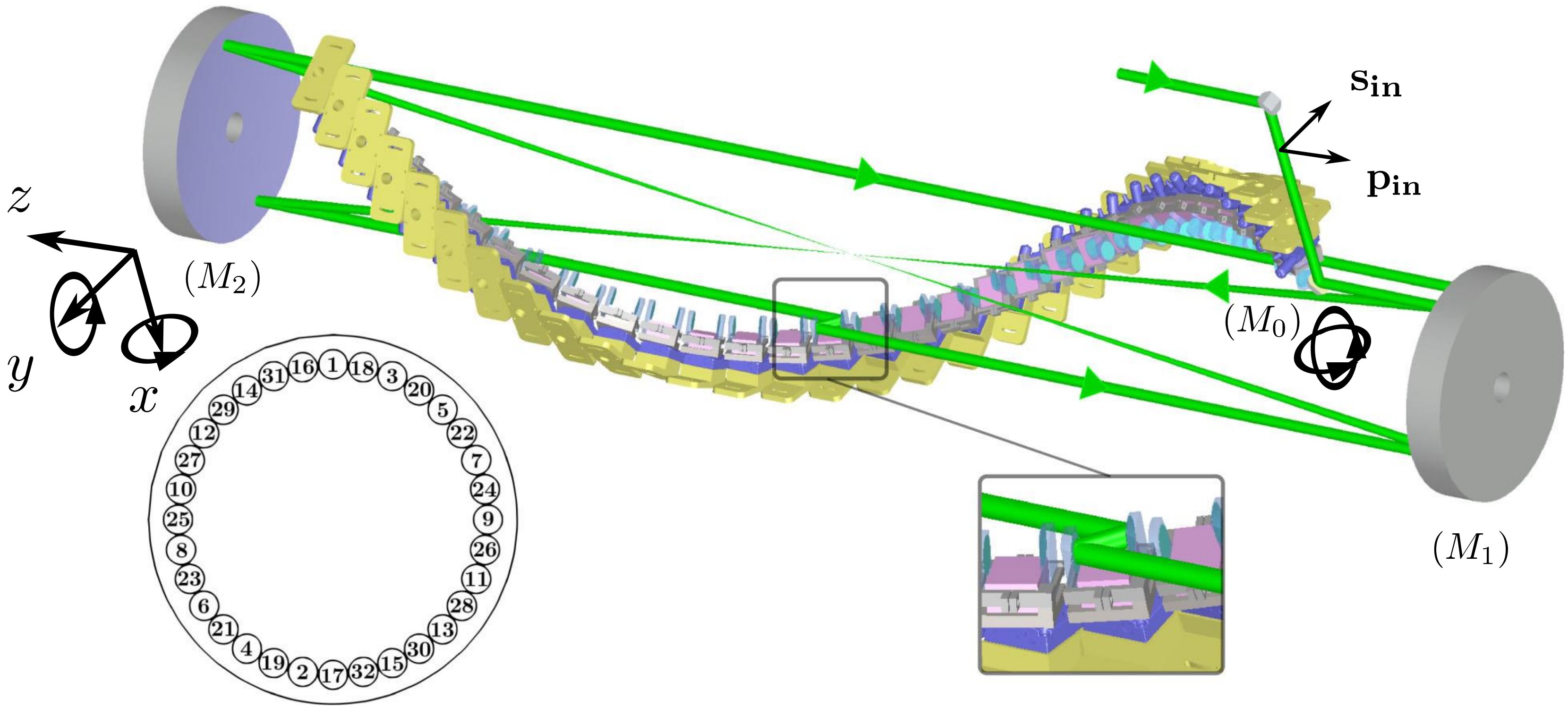


FIG. 2. Isometric view of ELI-NP-GBS recirculator. The mirror M_0 is used to inject the incident laser beam. The mirror-pair system (structures positioned on a circular helix) and the laser beam paths (green lines) are located between two parabolic mirrors M_1, M_2. Two of the 32 recirculation passes (green lines) are drawn. The polarization vectors $\mathbf{s}_{in}$ and $\mathbf{p}_{in}$ related to the incoming laser beam are also shown. The 7 degrees of freedom for the mirror motions are sketched: two tilts for M_0; two tilts and three translations for M_2. The inset scheme shows the optical pass ordering.

LINAC-based ICS sources: CXLS

W.S. Graves et al., funded

TABLE I. Estimated performance at 0.1% and 5% bandwidth for 12.4 keV x rays from the compact source.

Parameter	0.1% bandwidth	5% bandwidth	Units
Photon energy	12.4	12.4	keV
Average flux	2×10^{10}	5×10^{11}	phot/s
Average brilliance	7×10^{12}	2×10^{12}	photons/(sec mm^2 mrad^2 0.1%)
Peak brilliance	3×10^{19}	9×10^{18}	photons/(sec mm^2 mrad^2 0.1%)
rms horizontal opening angle	3.3	4.3	mrad
rms vertical opening angle	3.3	4.3	mrad
rms horizontal source size	2.4	2.5	μm
rms vertical source size	1.8	1.9	μm
rms pulse length	490	490	fs
Photons/pulse	2×10^5	5×10^6	···
Repetition rate	100	100	kHz

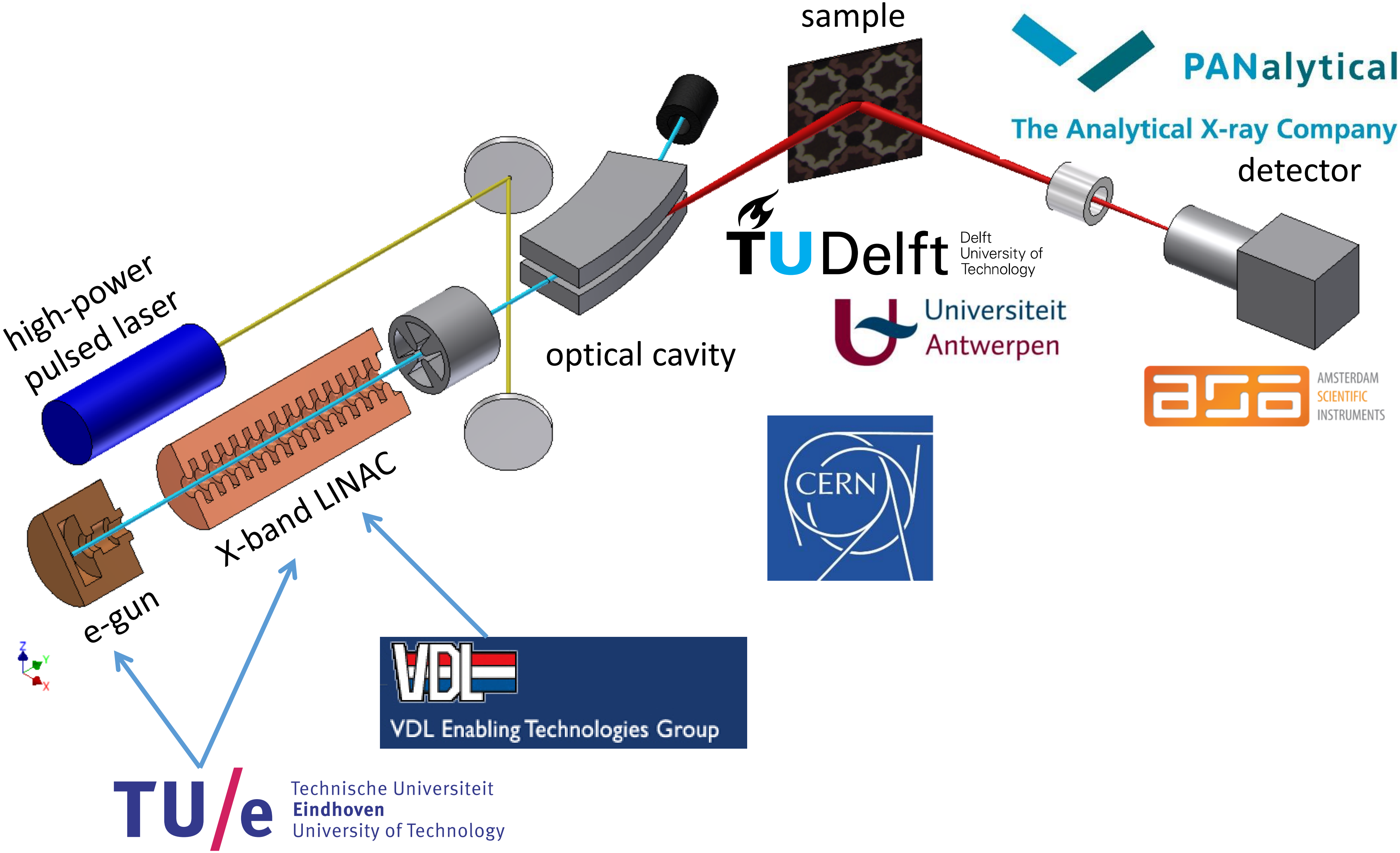
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **17,** 120701 (2014)

Compact x-ray source based on burst-mode inverse Compton scattering at 100 kHz

W. S. Graves,[1,*] J. Bessuille,[2] P. Brown,[2] S. Carbajo,[3] V. Dolgashev,[4] K.-H. Hong,[1] E. Ihloff,[2] B. Khaykovich,[1] H. Lin,[1] K. Murari,[3] E. A. Nanni,[1] G. Resta,[1] S. Tantawi,[4] L. E. Zapata,[1,3] F. X. Kärtner,[1,3] and D. E. Moncton[1]

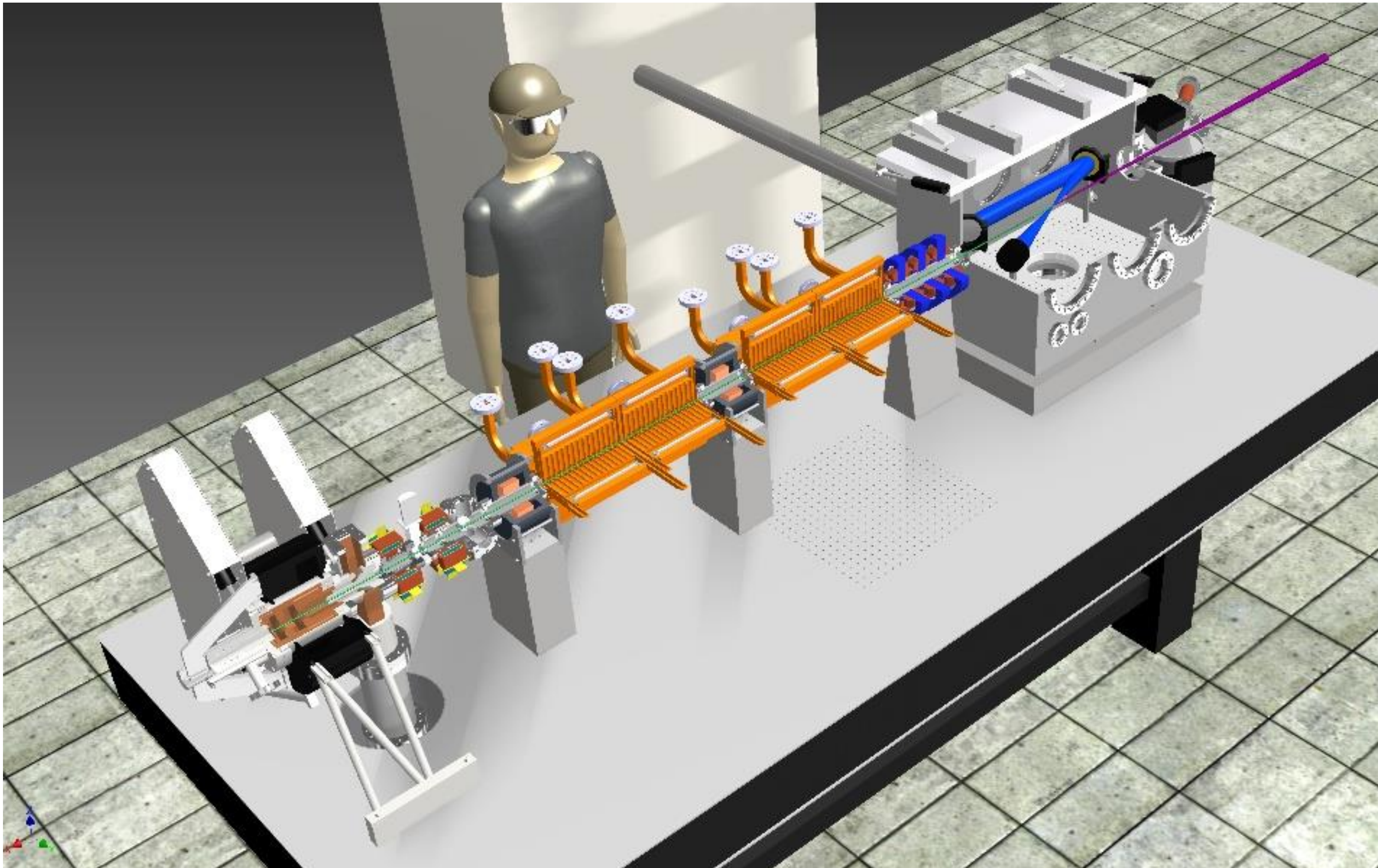
LINAC-based ICS sources: Smart*Light

starts in 2017



LINAC-based ICS sources: Smart*Light

starts in 2017



LINAC-based ICS sources: Smart*Light

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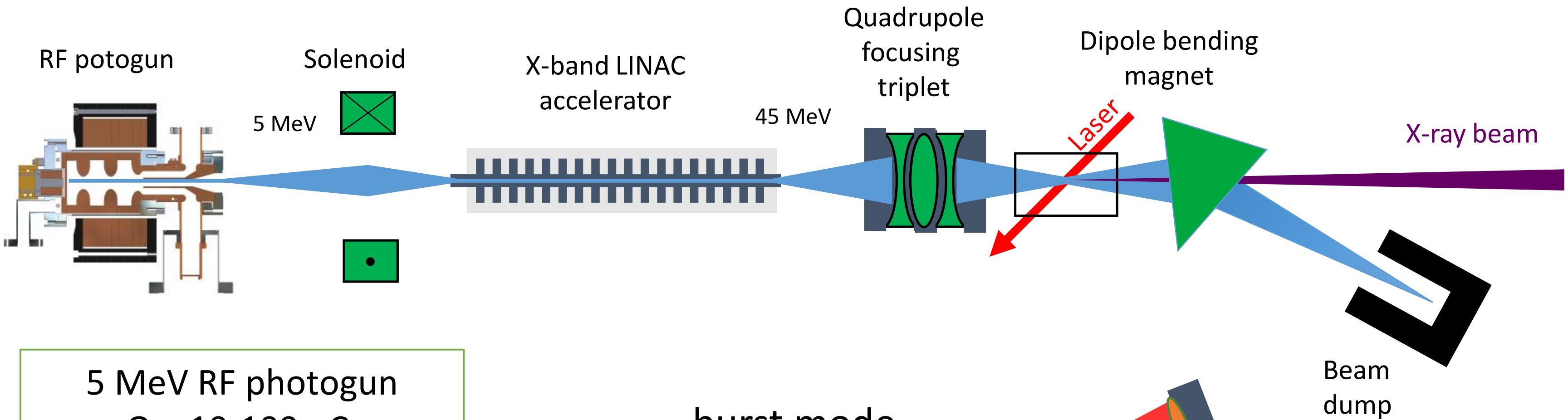
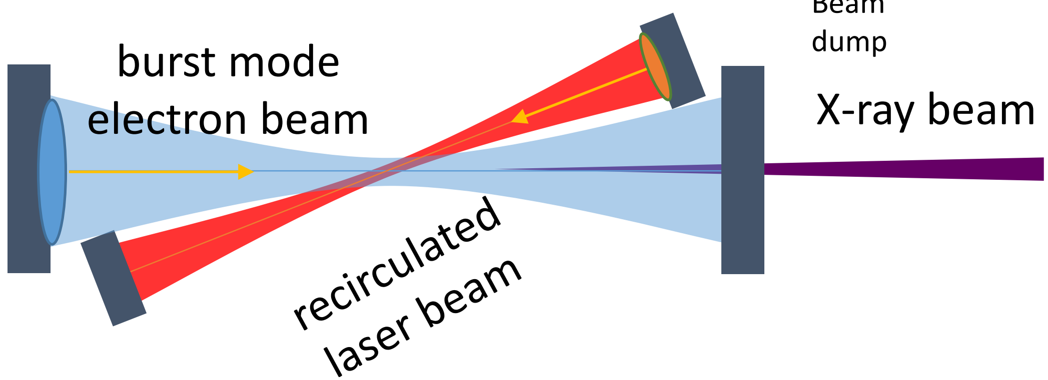


5 MeV RF photogun
Q = 10-100 pC,
ε_n = 0.15-0.5 mm mrad
1 kHz RF pulses
100 bunches/RF pulse



1 kHz, 10 mJ laser
100× recycled in optical cavity
➔10^5 colliding pulses/sec
in 5 µm laser beam waist

X-ray photon flux and brilliance

Total number of X-ray photons produced: $$N_{x,total} = N_e N_0 \frac{\sigma_T}{2\pi w_0{}^2}$$

$$\left.\begin{array}{l} \text{Thomson cross section}: \sigma_T = 6.6\times 10^{-29}\ \text{m}^2 \\ \text{10 mJ laser pulse}: N_0 = 2\times 10^{16} \\ \text{bunch charge } Q = 10\ \text{pC} \Rightarrow N_e = 6\times 10^{7} \\ \text{laser beam waist } w_0 = 5\ \mu\text{m} \end{array}\right\} \Rightarrow N_{x,total} = 5\times 10^{5}\ \text{photons per pulse}$$

How many photons per second?

- LINAC operates at 1 kHz rep rate
- amplified pulsed laser operates at 1 kHz
- 100 electron bunches per RF pulse
- recycle laser pulses 100 times in optical cavity
- ➔ 10^5 pulses per second

Þ $N_{x,total} = 5$´ 10^{10} ph×s^{-1}

Few micron spot size, few mrad divergence

~10^{14} photons s^{-1} mm^{-2} mrad^{-2}

X-ray photon flux and brilliance

Total number of X-ray photons produced: $$N_{x,total} = N_e N_0 \frac{\sigma_T}{2\pi w_0^{\ 2}}$$

$$\left.\begin{array}{l} \text{Thomson cross section}: \sigma_T = 6.6\times10^{-29}\ \text{m}^2 \\ 10\ \text{mJ laser pulse}: N_0 = 2\times10^{16} \\ \text{bunch charge } Q = 10\ \text{pC} \Rightarrow N_e = 6\times10^7 \\ \text{laser beam waist } w_0 = 5\ \mu\text{m} \end{array}\right\} \Rightarrow N_{x,total} = 5\times10^5 \text{ photons per pulse}$$

Few micron spot size, few mrad divergence

~10^{14} photons s^{-1} mm^{-2} $mrad^{-2}$

Liquid gallium anode:

2.6×10^{10} photons s^{-1} mm^{-2} $mrad^{-2}$

X-ray photon flux and brilliance

Total number of X-ray photons produced: $$N_{x,total} = N_e N_0 \frac{\sigma_T}{2\pi w_0^{\,2}}$$

Number of photons per bandwidth:

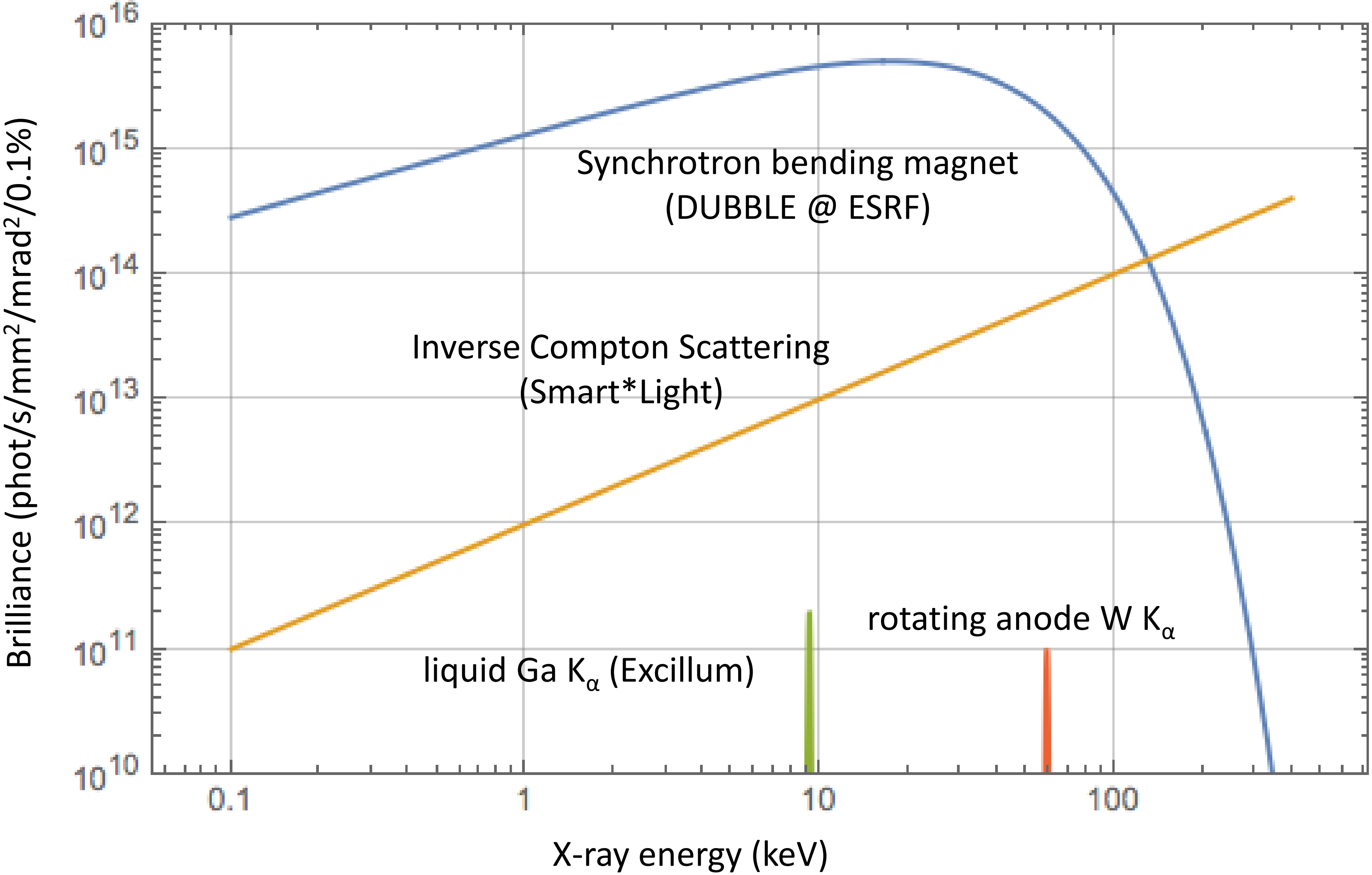
$$N_x = N_{x,total} \cdot \frac{12}{\pi} \frac{\Delta E}{E} \approx 0.004 \cdot N_{x,total} \text{ in } 0.1\% \text{ bandwidth}$$

Theoretically achievable brilliance:

$$B \approx 10^{12} - 10^{13} \text{ ph} \cdot \text{s}^{-1} \cdot \text{mm}^{-2} \cdot \text{mrad}^{-2} \cdot (0.1\% \text{ BW})$$

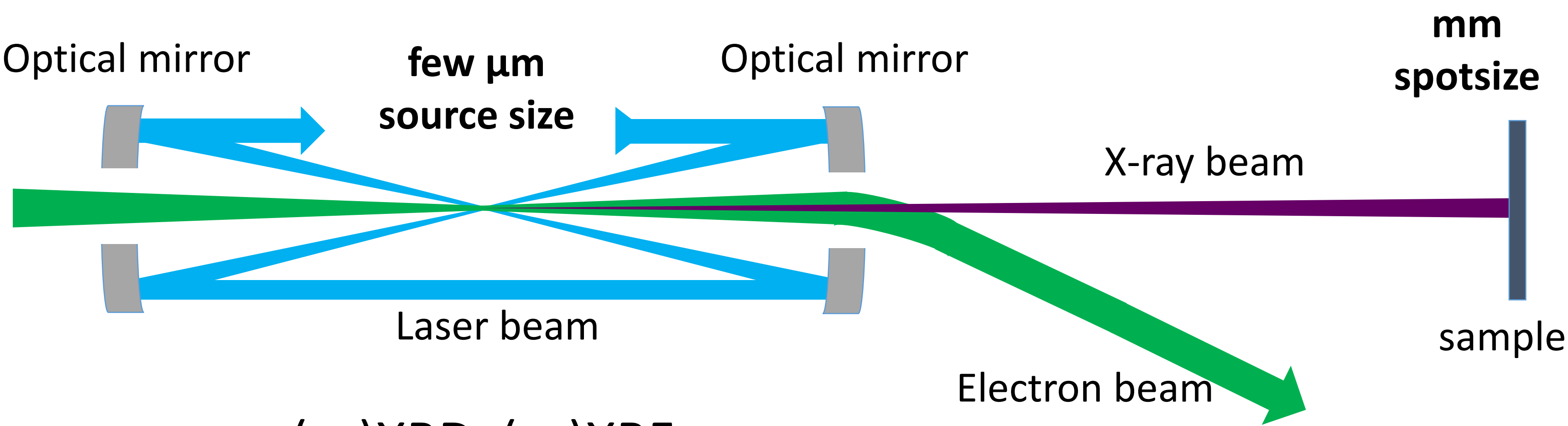
- Brilliance comparable to synchrotron bending magnet radiation (DUBBLE @ ESRF);
- Full calculation complicated due to interplay energy spread, emittance, pulse length, bunch length and Rayleigh length, etc;
- W.S. Graves et al., PR-STAB **17**, 120701 (2014): detailed feasibility study.

X-ray photon flux and brilliance



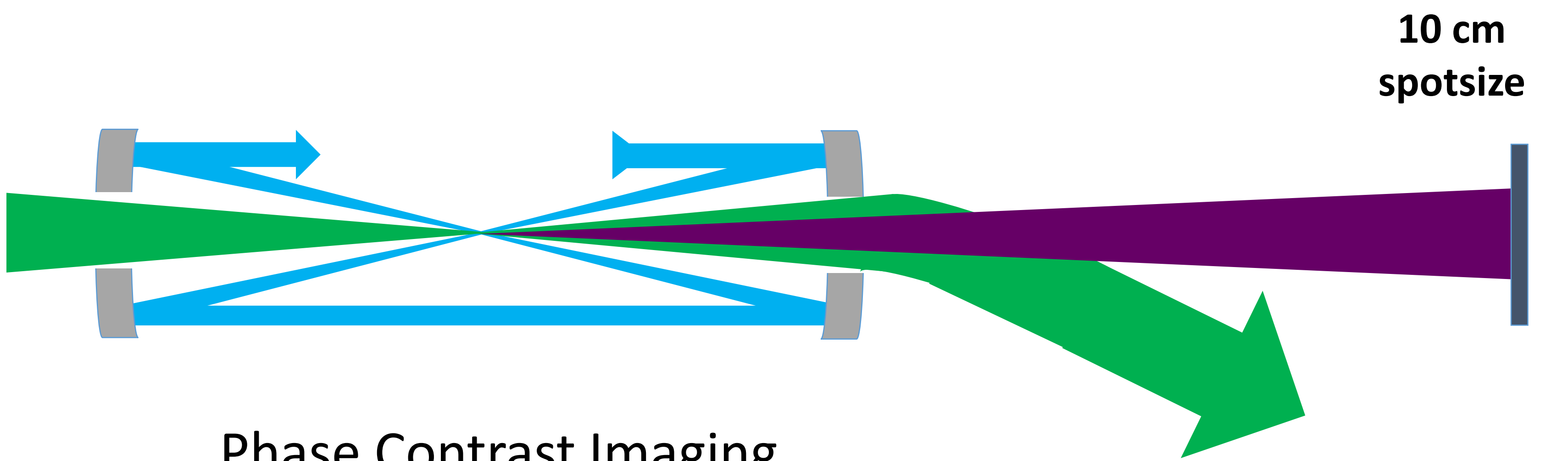
Two scenarios:

A



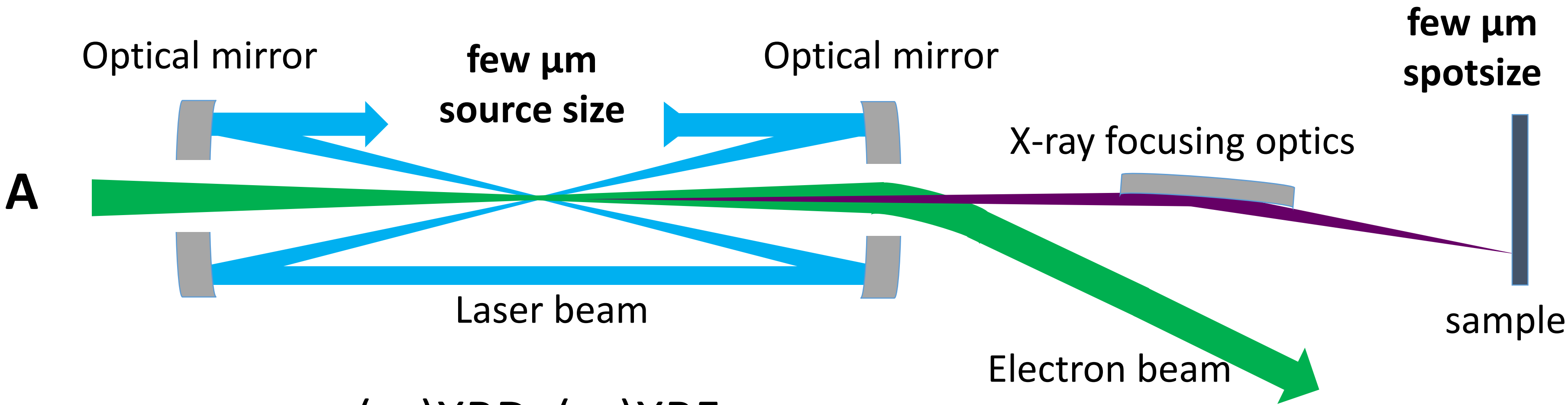
(μ-)XRD, (μ-)XRF

B

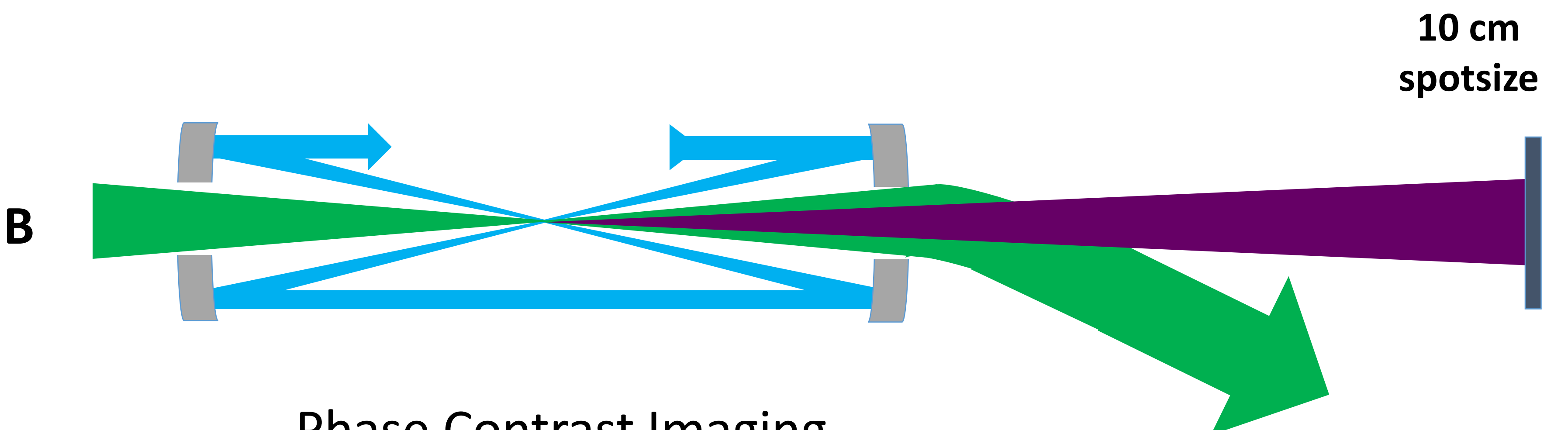


Phase Contrast Imaging

Two scenarios:



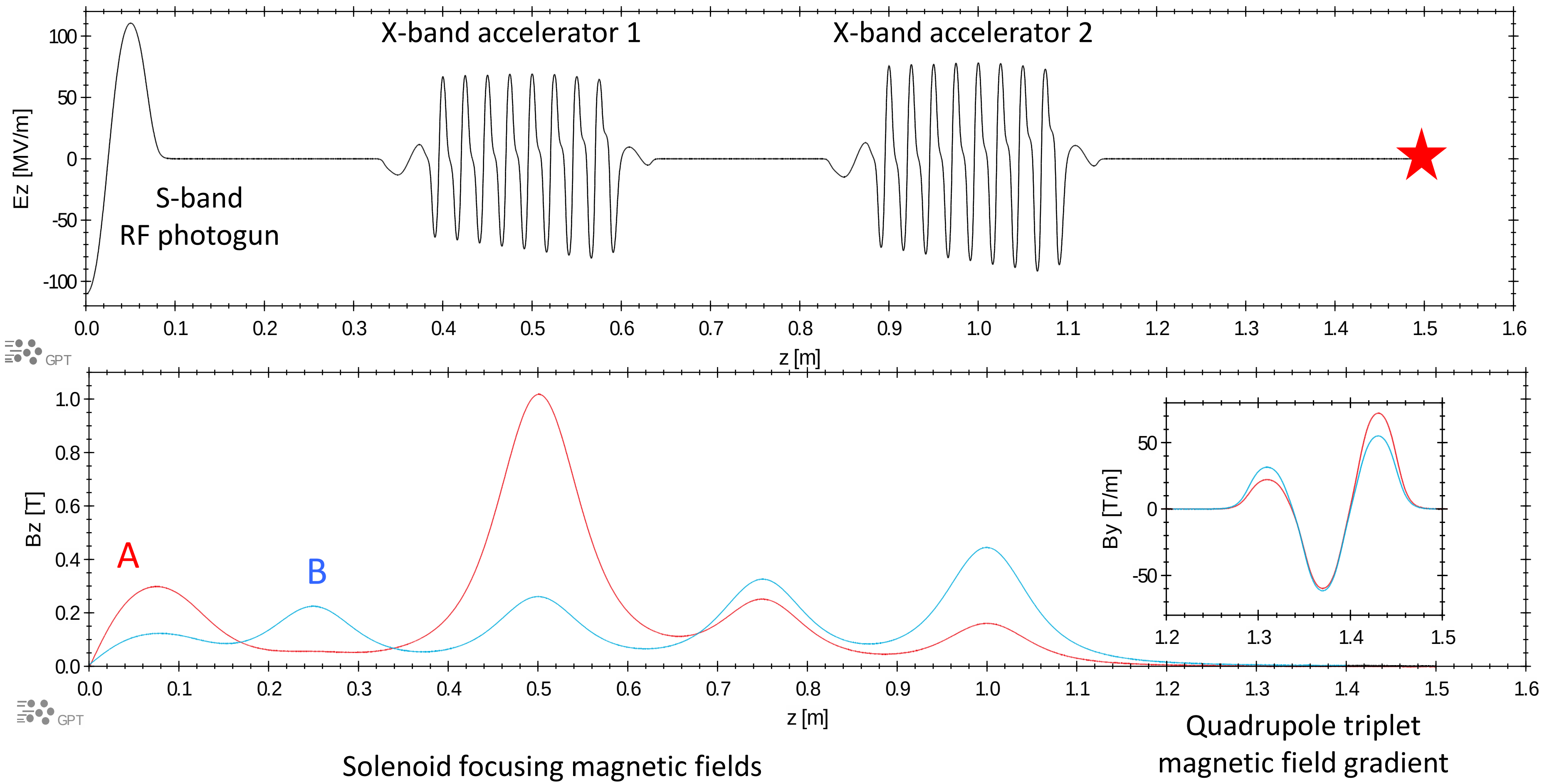
(µ-)XRD, (µ-)XRF



Phase Contrast Imaging

Two scenarios:

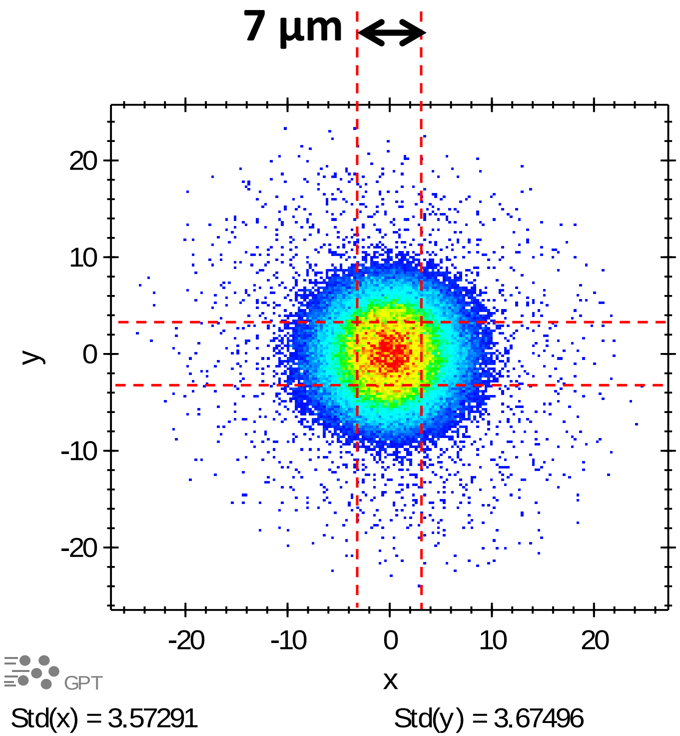
(A): (μ-)XRD, (μ-)XRF; (B) Phase Contrast Imaging



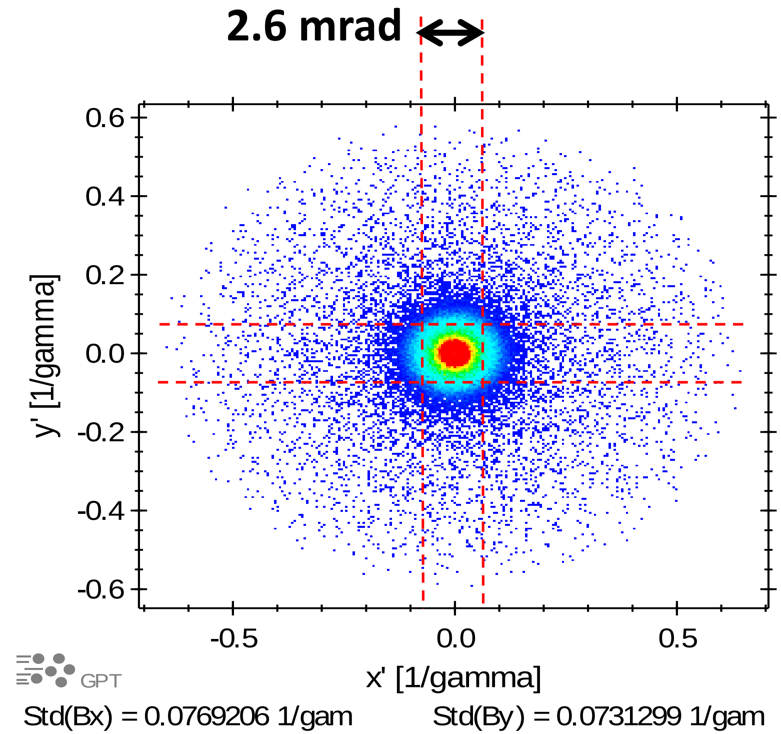
GPT simulations

A: Coherent & narrow-bandwidth pencil beam

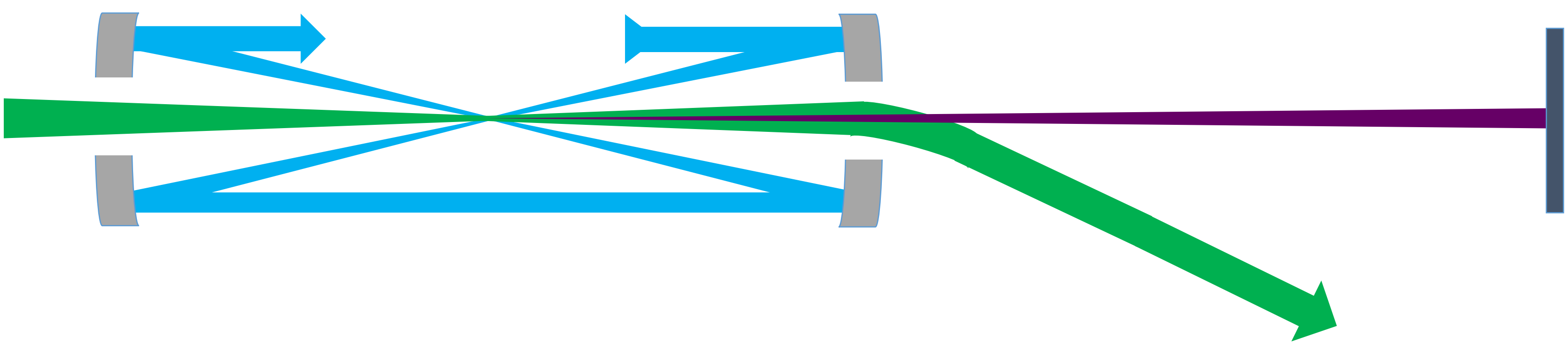
GPT simulations 30 MeV beam



source size

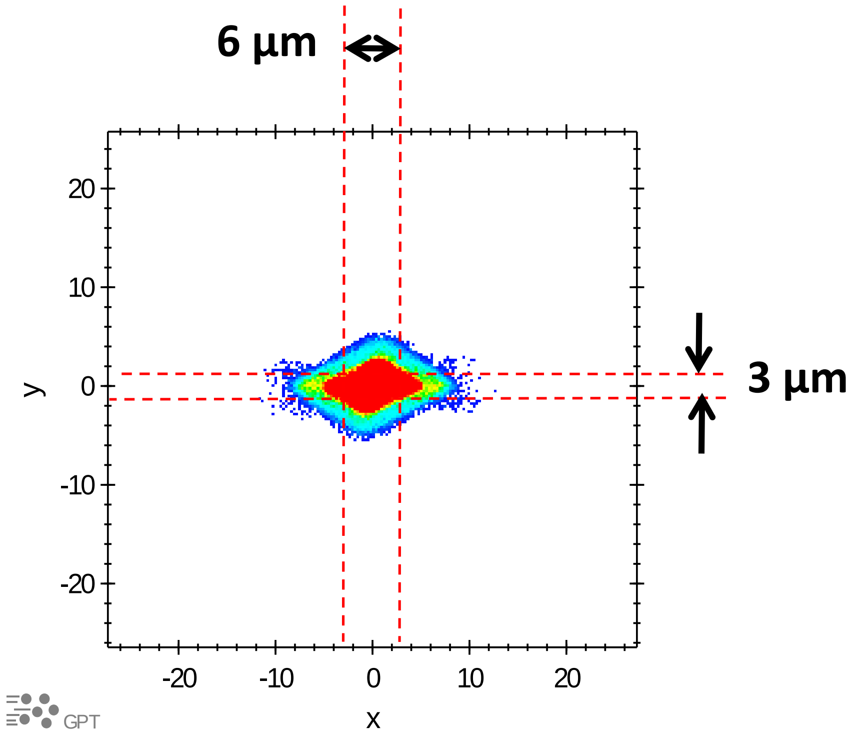


angular spread

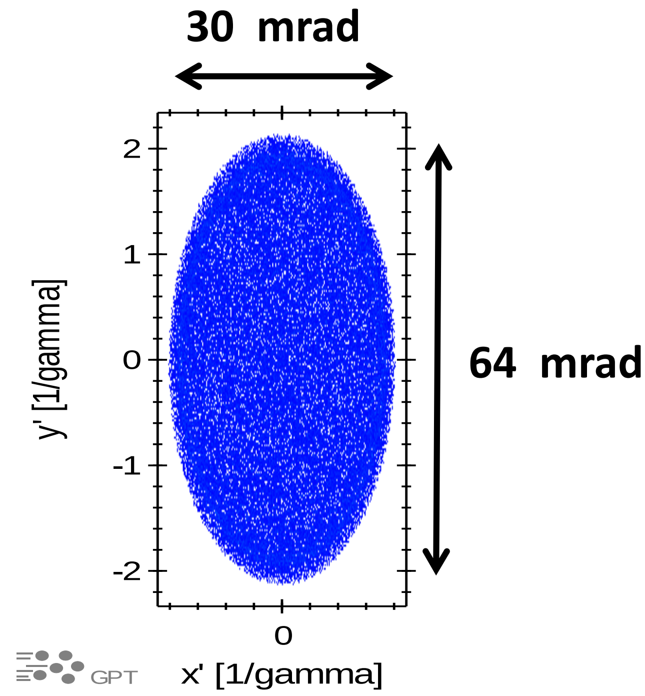


B: Coherent divergent beam

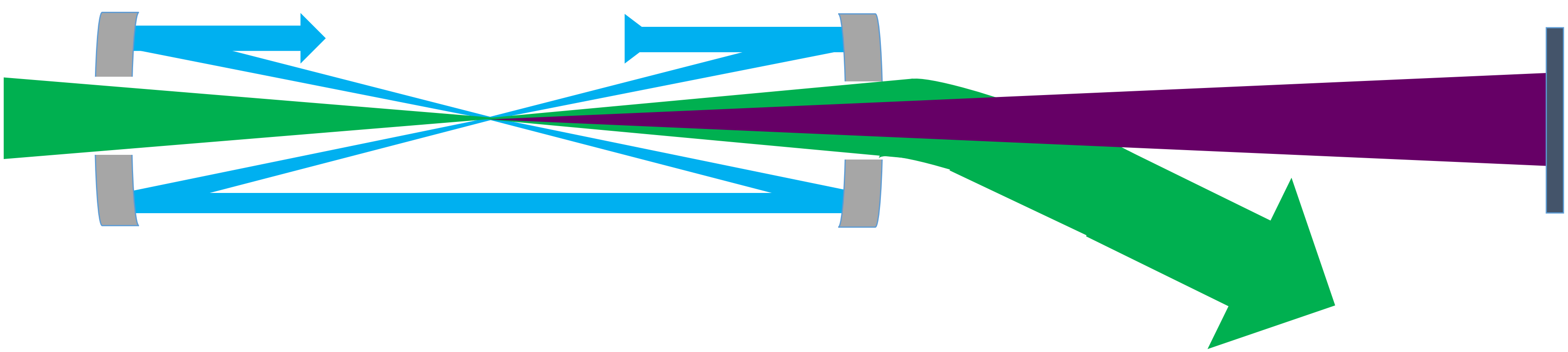
GPT simulations 30 MeV beam



source size

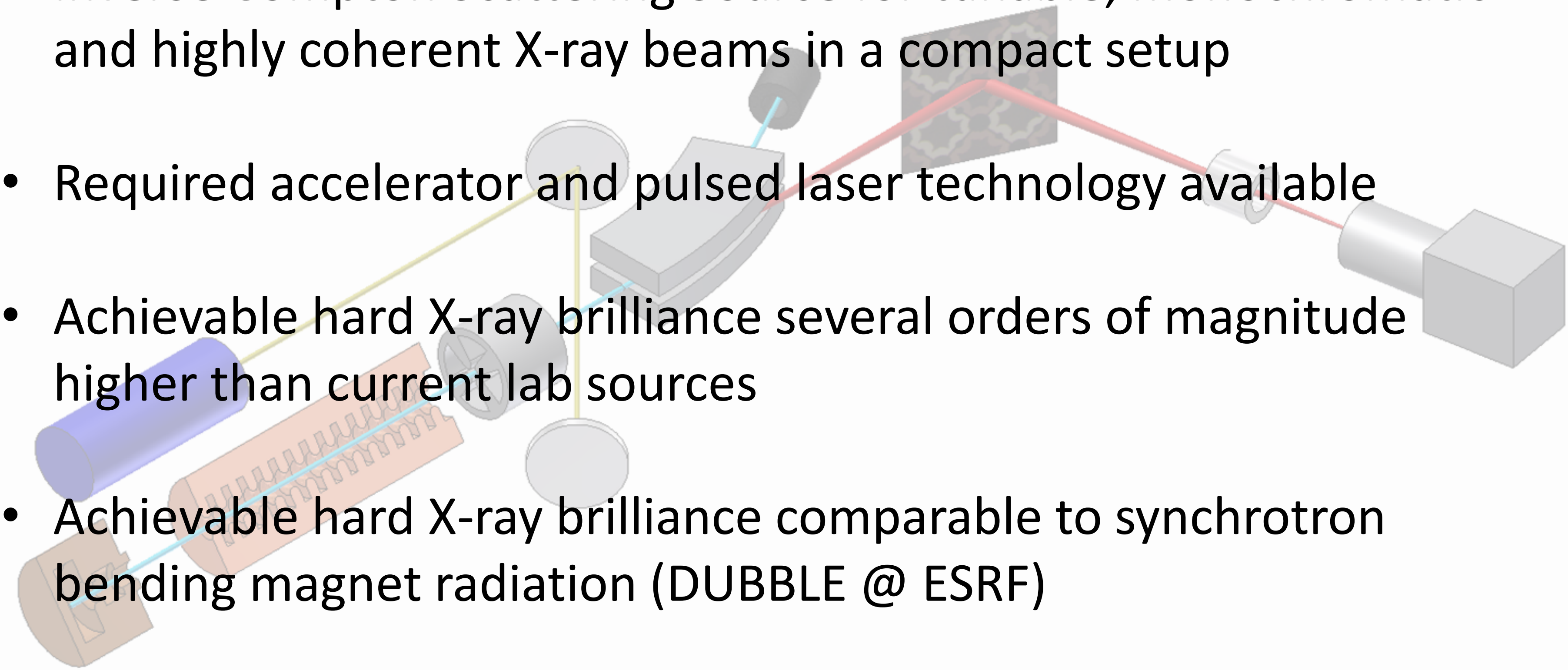


angular spread



Summary

- Inverse Compton Scattering Source for tunable, monochromatic and highly coherent X-ray beams in a compact setup
- Required accelerator and pulsed laser technology available
- Achievable hard X-ray brilliance several orders of magnitude higher than current lab sources
- Achievable hard X-ray brilliance comparable to synchrotron bending magnet radiation (DUBBLE @ ESRF)



TUDelft Delft University of Technology
Universiteit Antwerpen
TU/e Technische Universiteit Eindhoven University of Technology