Brilliant Monochromatic X-rays at the Munich Compact Light Source

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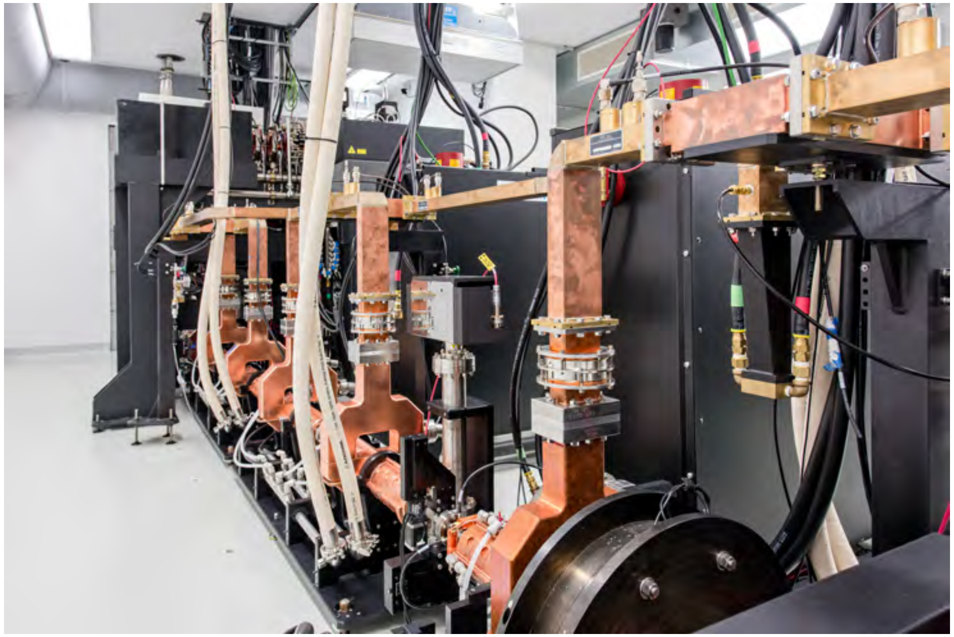
Outline

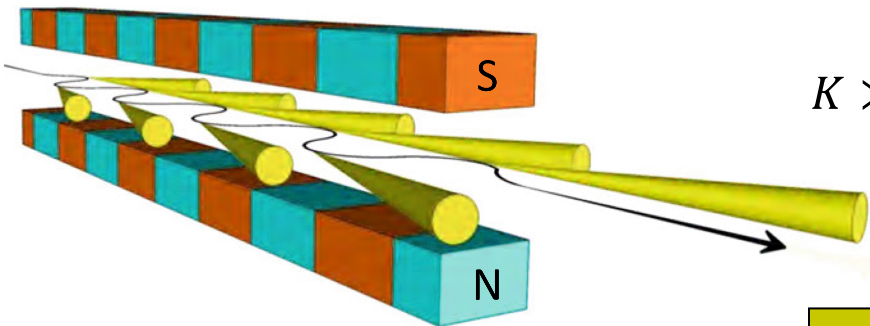
- Inverse Compton Scattering
- MuCLS Design
- Beam Characteristics at MuCLS
- Radiation Shielding



Synchrotron

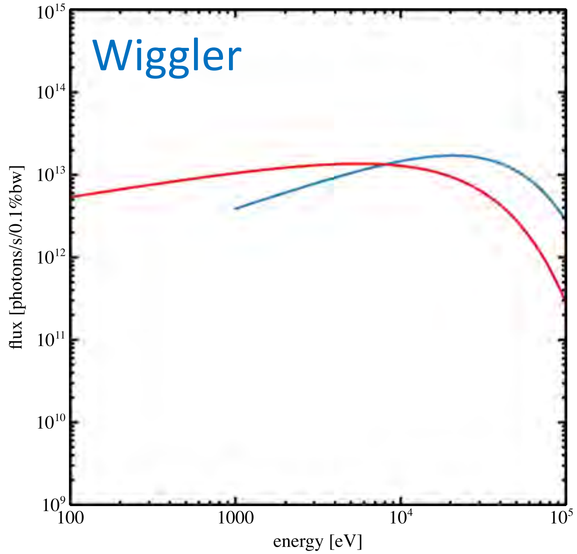
www.esrf.eu

Wiggler

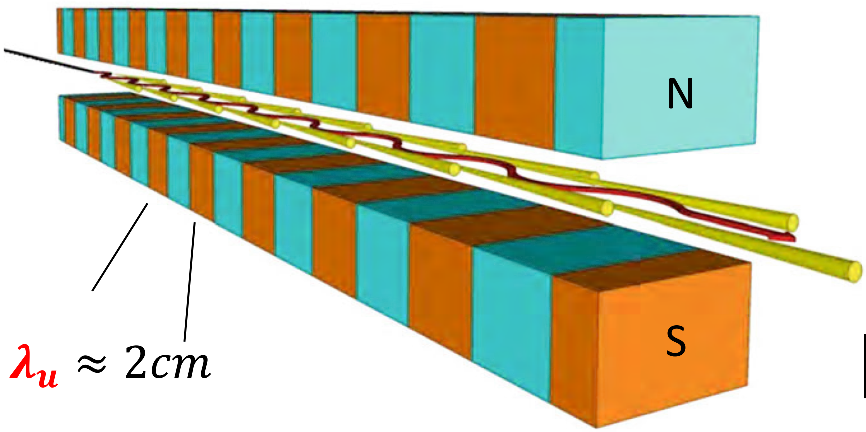


$K \gg 1$

add intensities



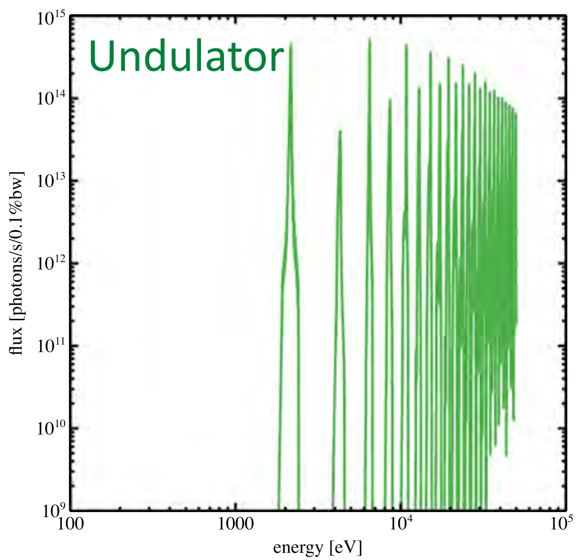
Undulator



$\lambda_u \approx 2cm$

$K \leq 1$

add amplitudes

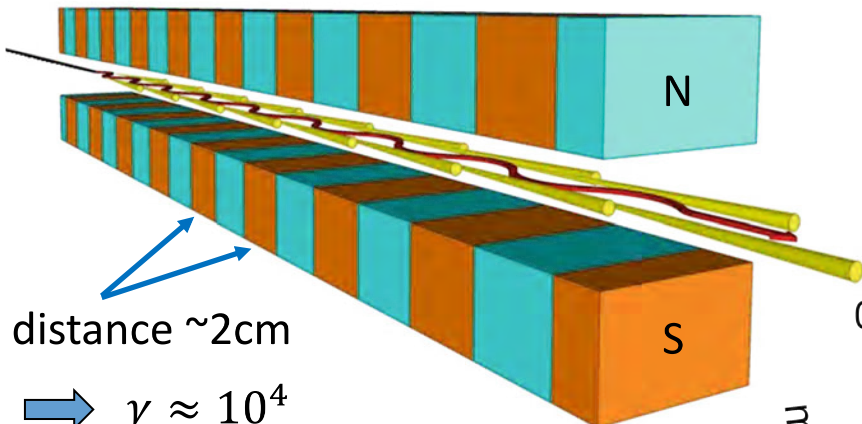


$$\lambda_{rad} = \frac{\lambda_u}{2\gamma^2} \cdot \left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

$$\gamma = \frac{total\ energy\ of\ electron}{rest\ energy\ of\ electron} \approx 10^4$$

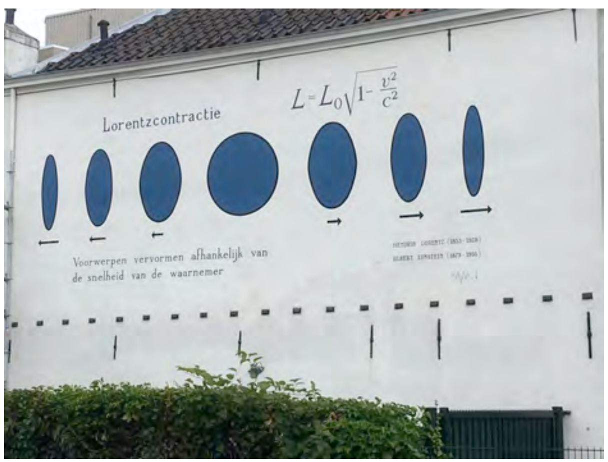
Inverse Compton Scattering

exchange undulator dipole magnets by the electro magnetic field of a laser



distance ~2cm

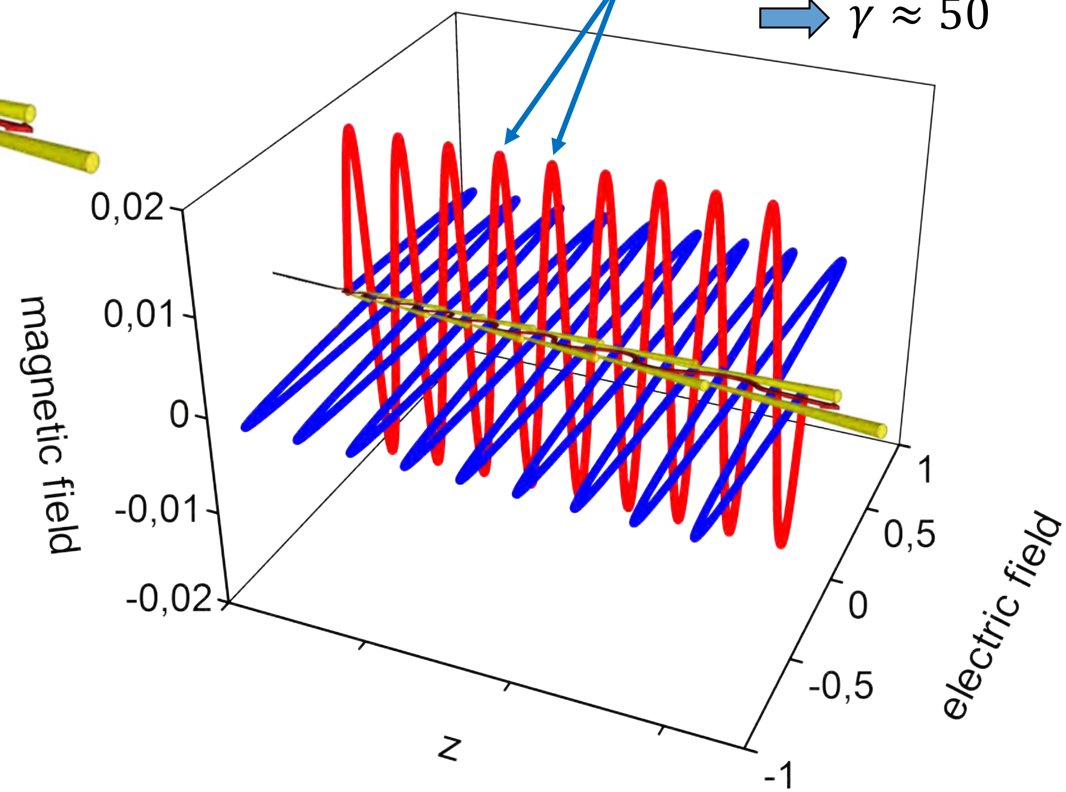
$\Rightarrow \gamma \approx 10^4$



Lorentz contraction on a wall in Leiden

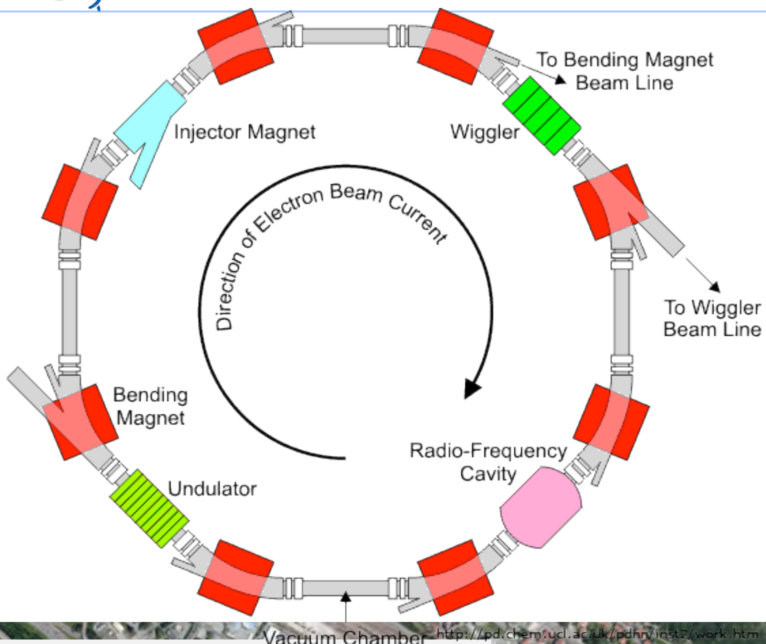
distance ~0.0001cm

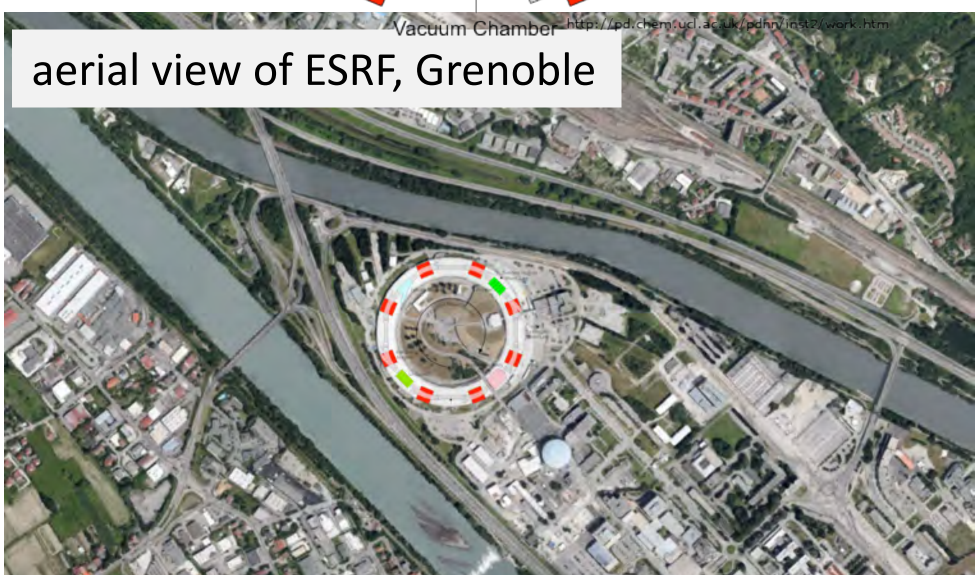
$\Rightarrow \gamma \approx 50$

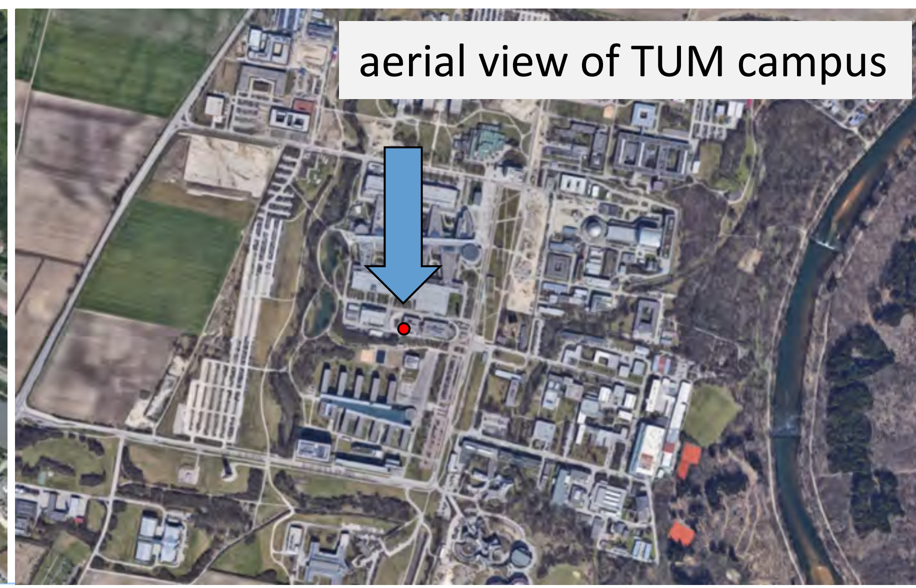


$$\lambda_{rad} = \frac{\lambda_{IR}}{4\gamma^2} \cdot \left(1 + \frac{a_0^2}{2} + \gamma^2\theta^2\right)$$

Inverse Compton Scattering

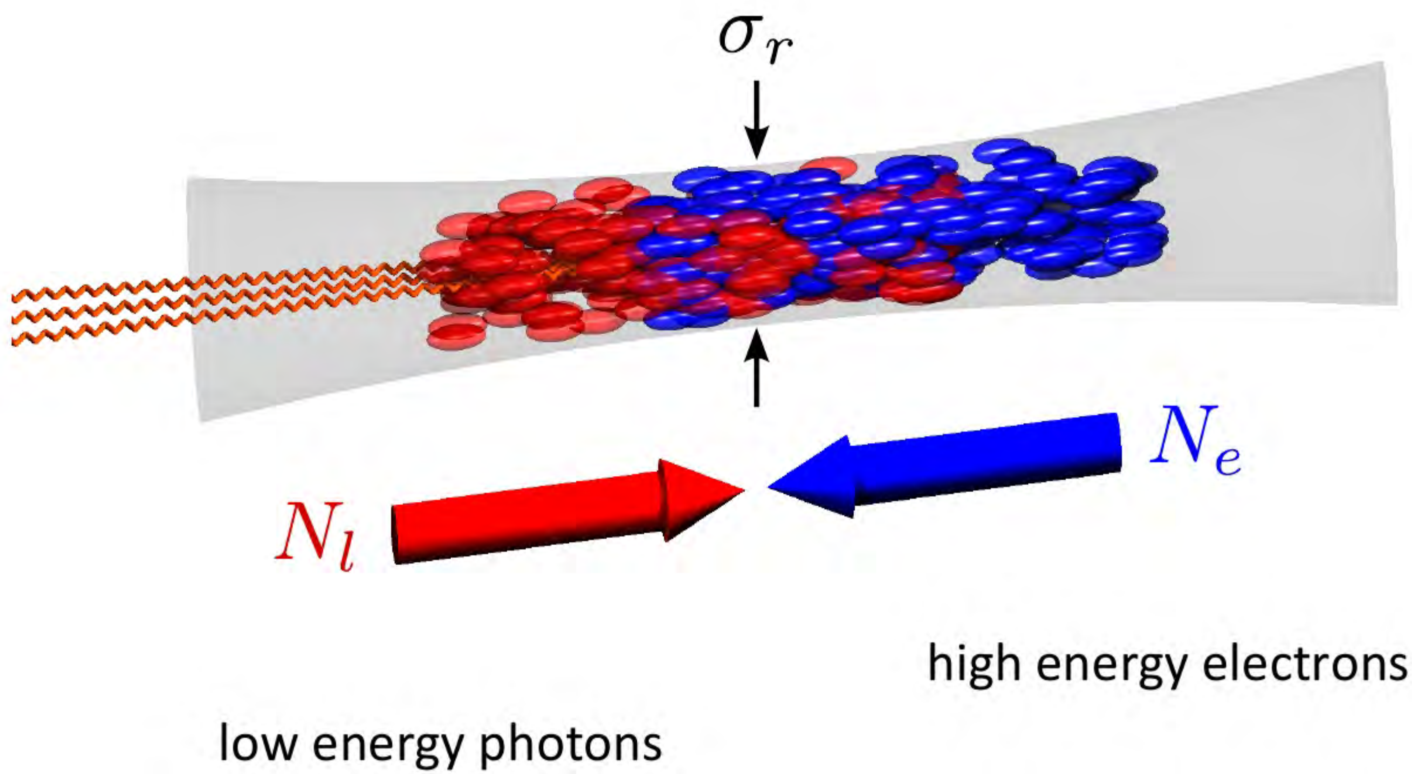




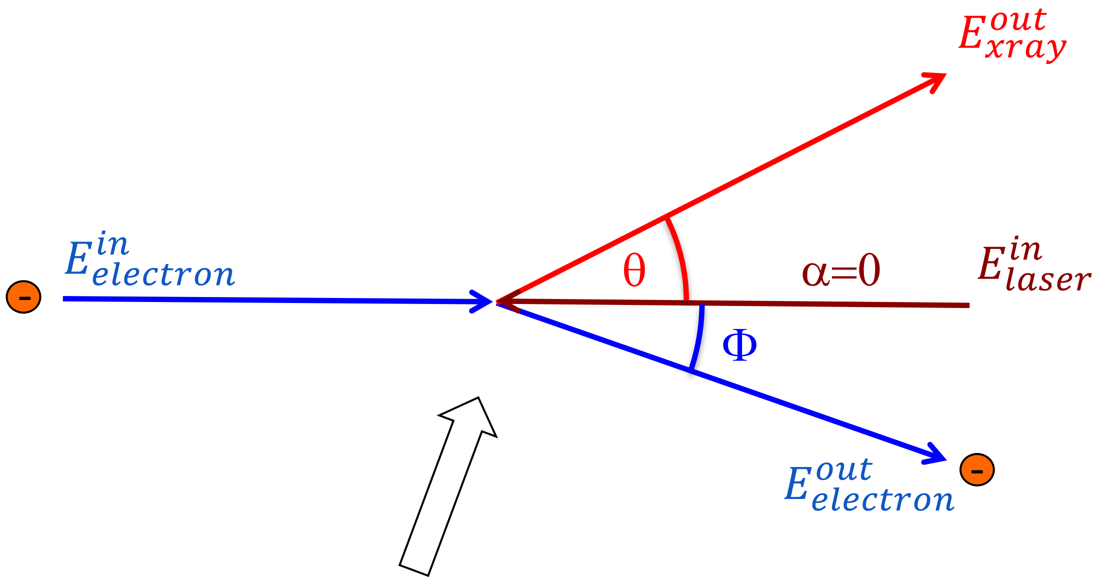


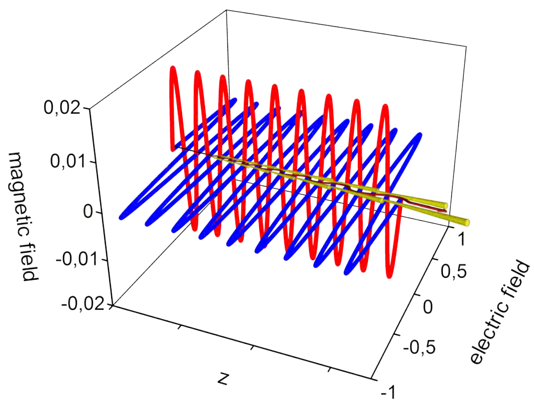
1	2
3	4

1: pd.chem.ucl.ac.uk/pdnn/inst2/work.htm ; 3,4: google maps

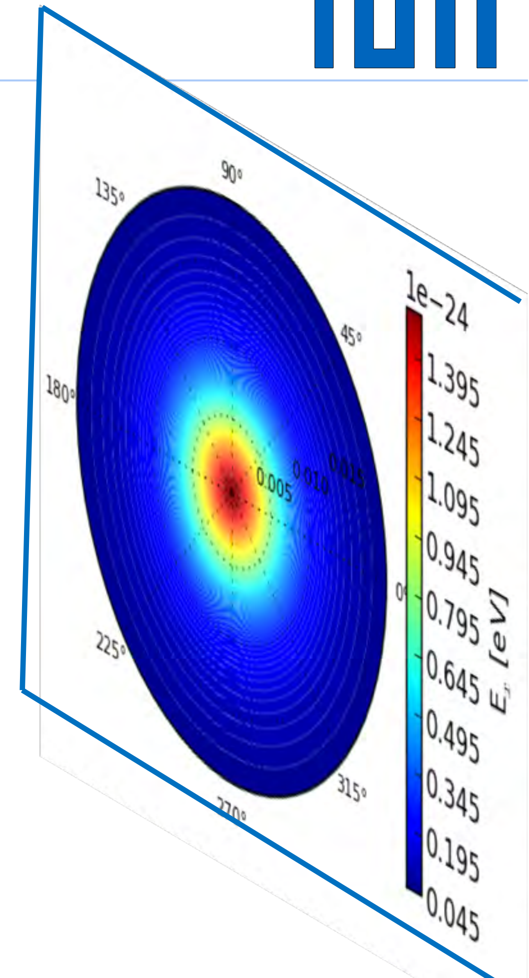

σ_r
N_e
N_l
high energy electrons
low energy photons

Inverse Compton Scattering





$$\lambda_{rad} = \frac{\lambda_{IR}}{4\gamma^2} \cdot \left(1 + \frac{a_0^2}{2} + \gamma^2\theta^2\right)$$



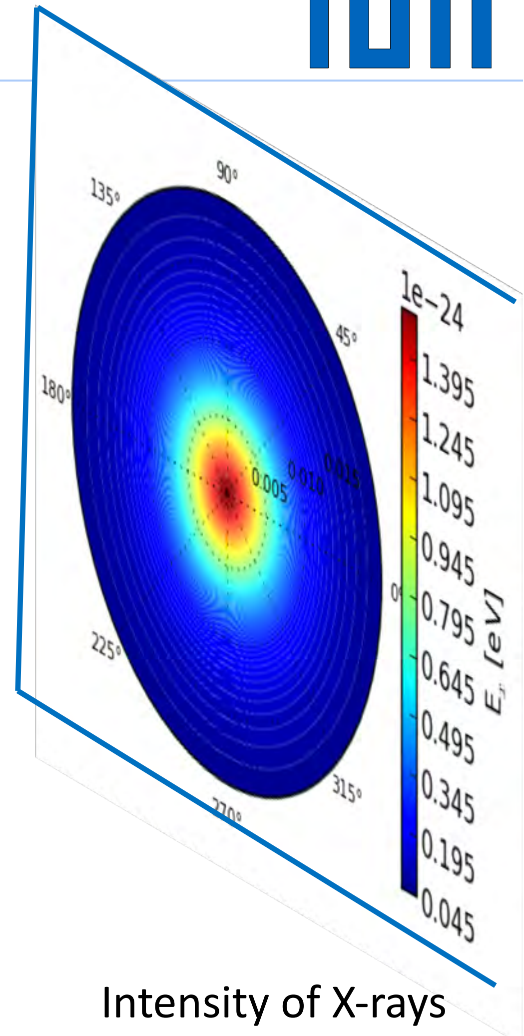
Intensity of X-rays on a detector

$$\lambda_{rad} = \frac{\boldsymbol{\lambda_{IR}}}{4\gamma^2} \cdot \left(1 + \frac{a_0^2}{2} + \gamma^2\theta^2\right)$$

$$a_0 = 0.22 \cdot \frac{\lambda_{IR}}{r_s} \cdot \sqrt{P_{IR}[GW]}$$

$$= 2.9 \cdot 10^{-4}$$

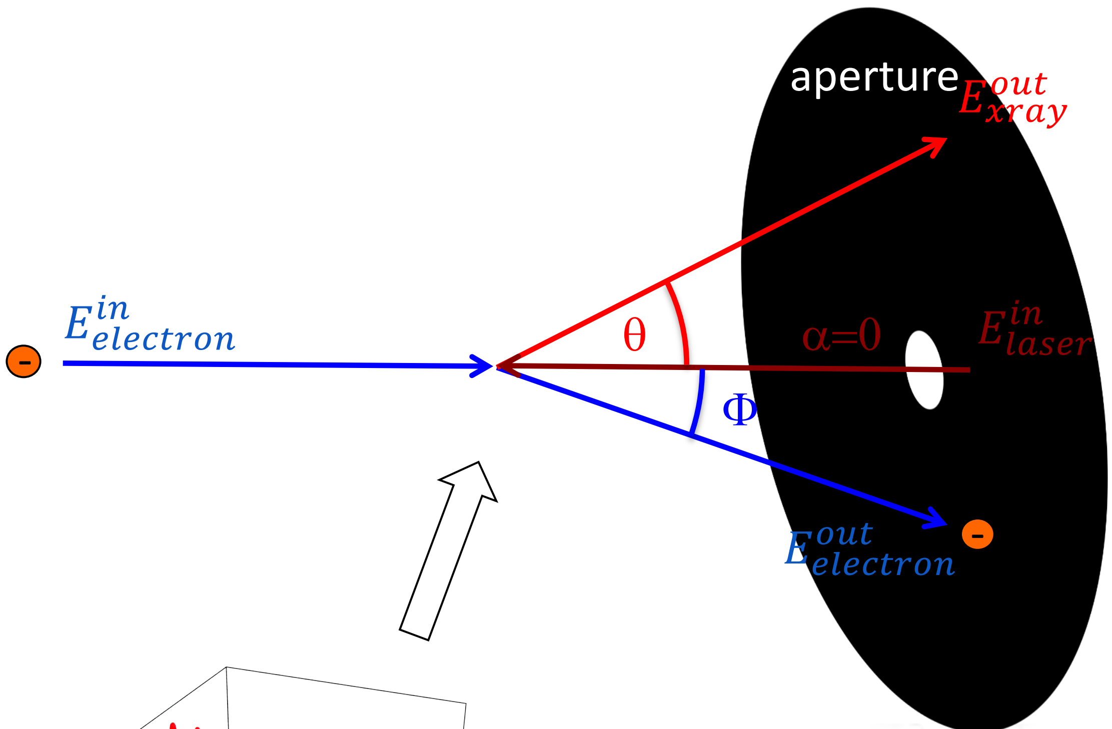
(for λ=1064 nm; Power of 300 kW)

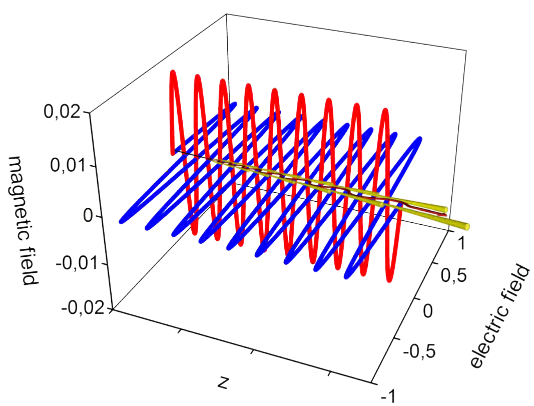


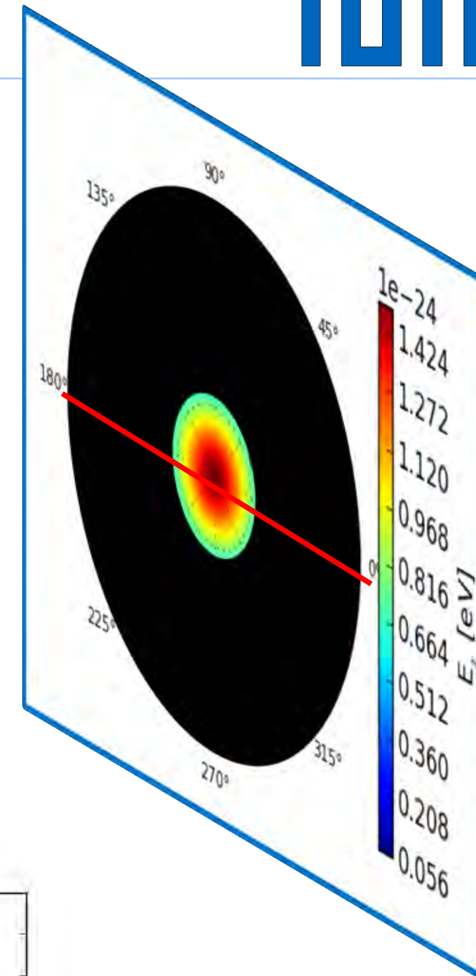
→ small amplitude transverse oscillation
→ no higher harmonics

Intensity of X-rays on a detector

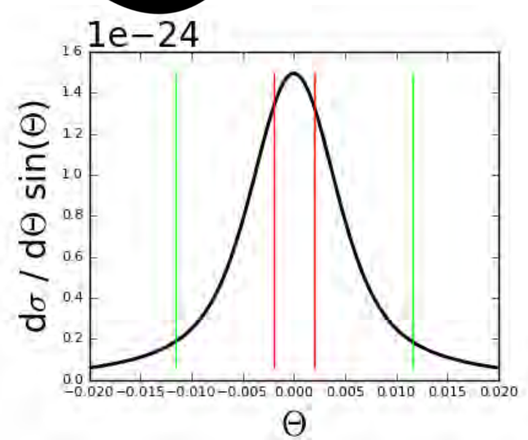
Inverse Compton Scattering





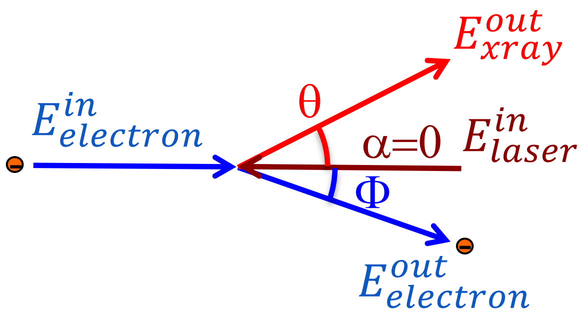


Intensity of X-rays on a detector

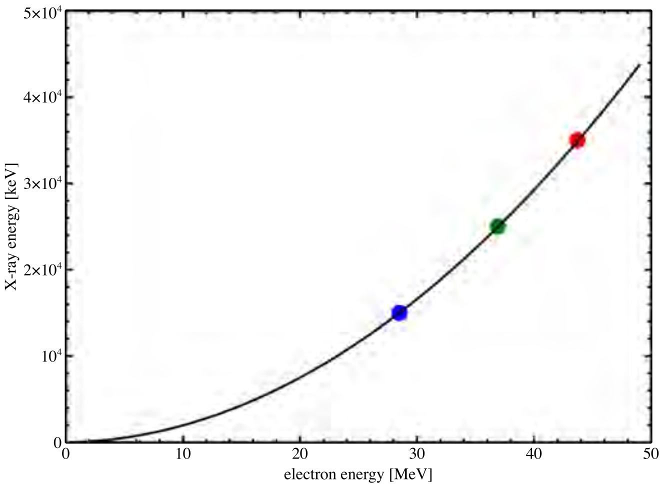


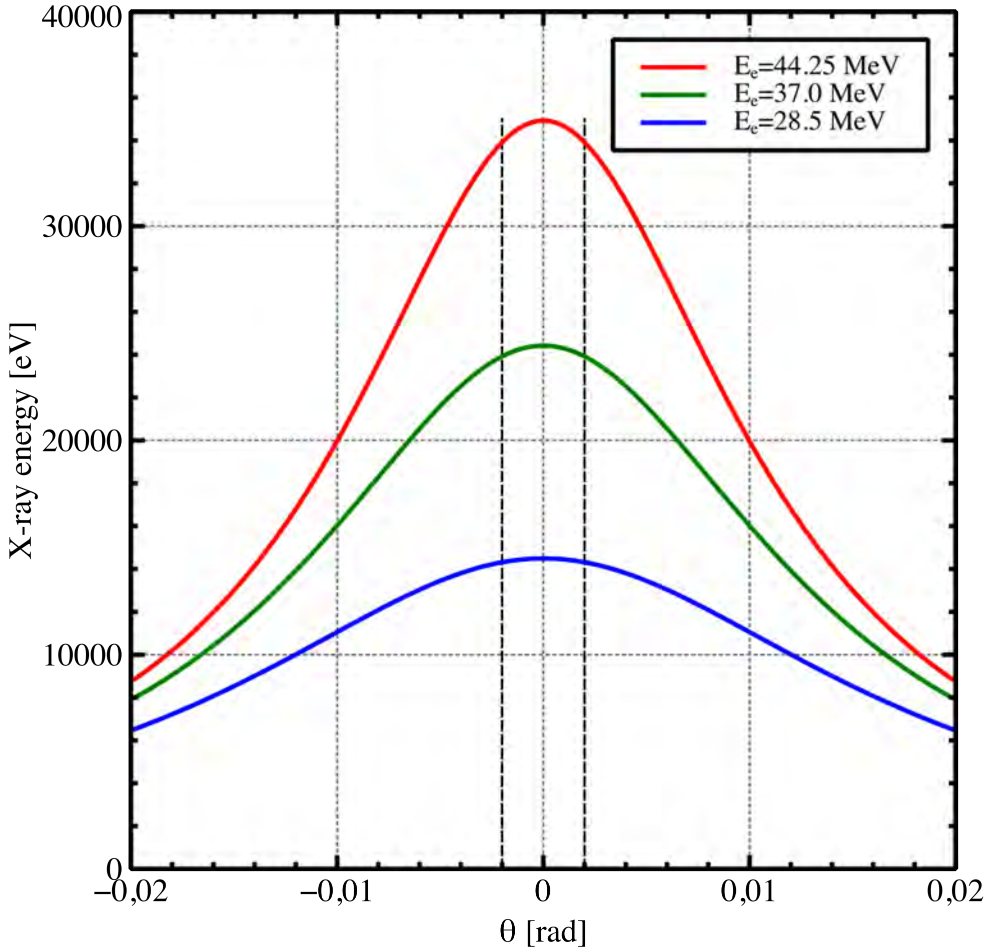
from Klein-Nishina equation

tuning the energy

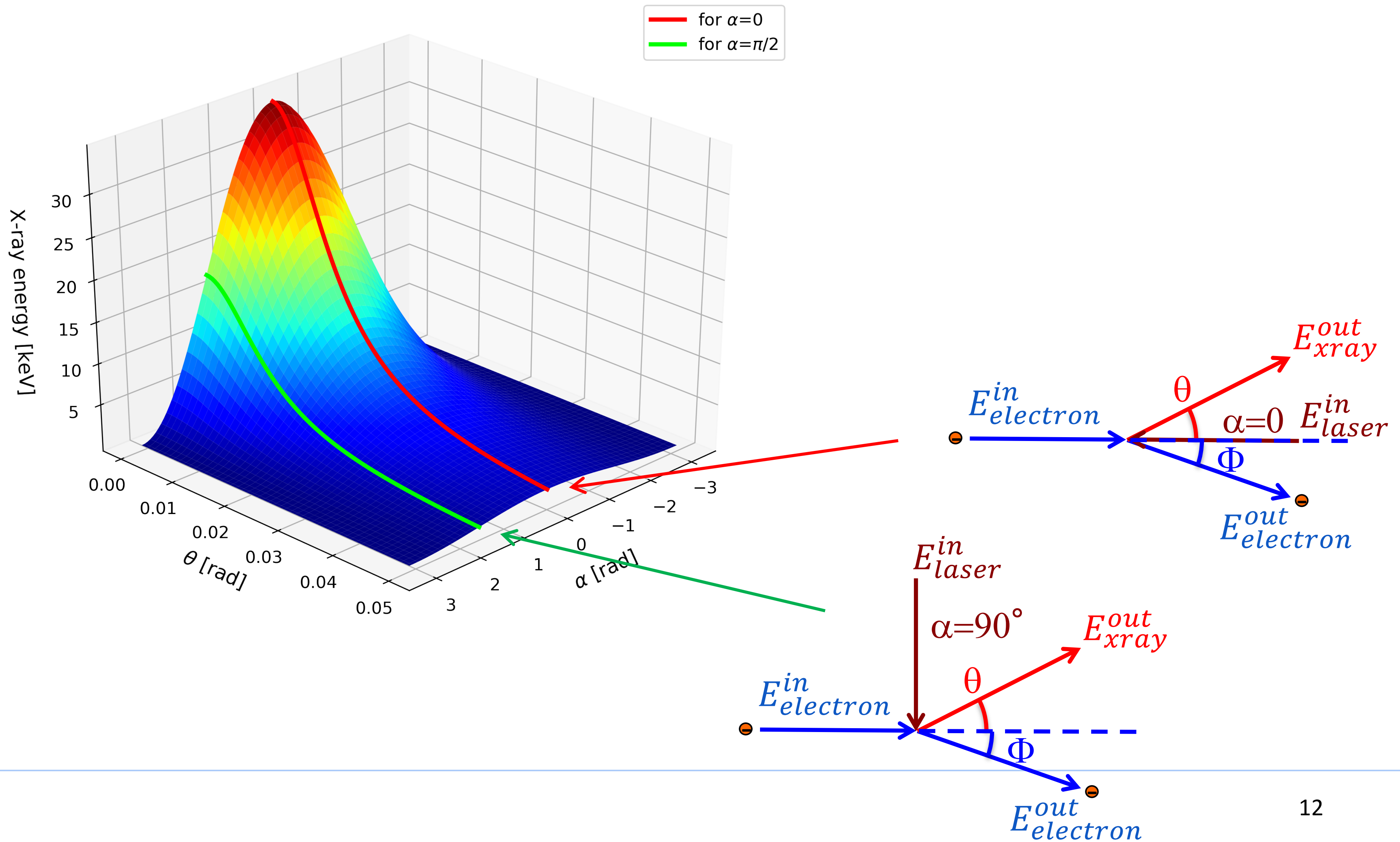


$$E_{xray} \propto E_{laser} \cdot E^2_{electron}$$

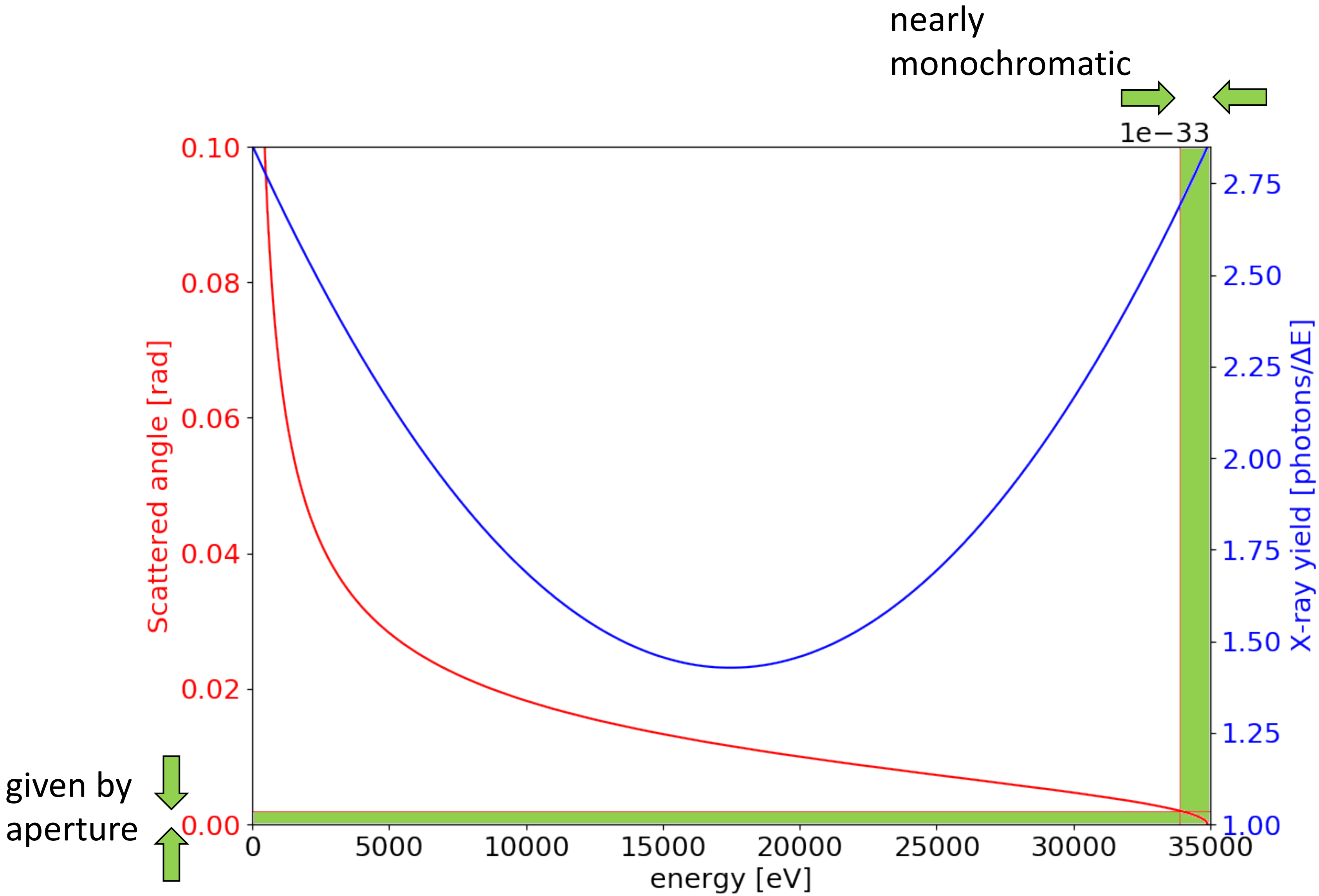




in case it's not a head-on collision



Inverse Compton Scattering

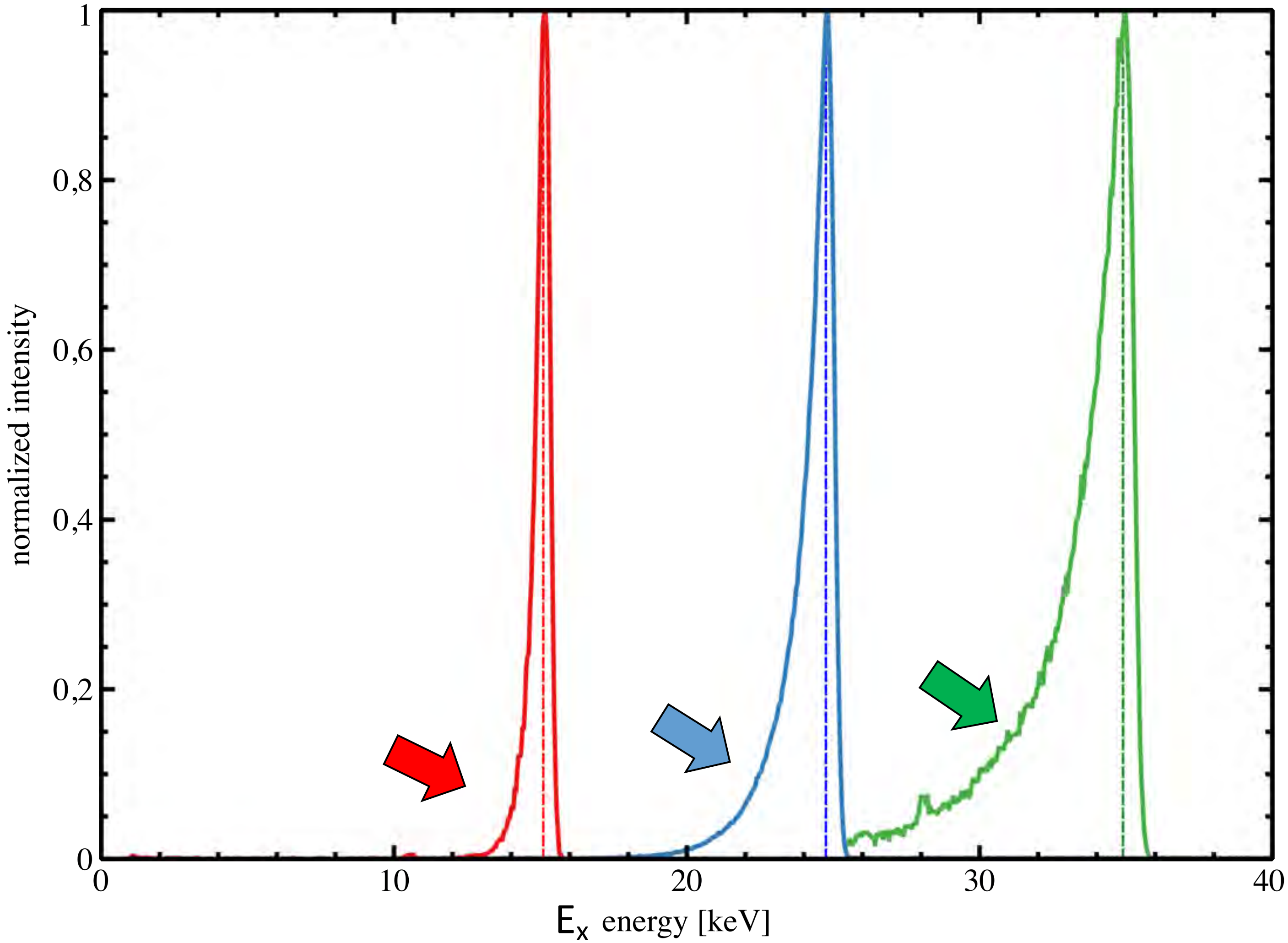


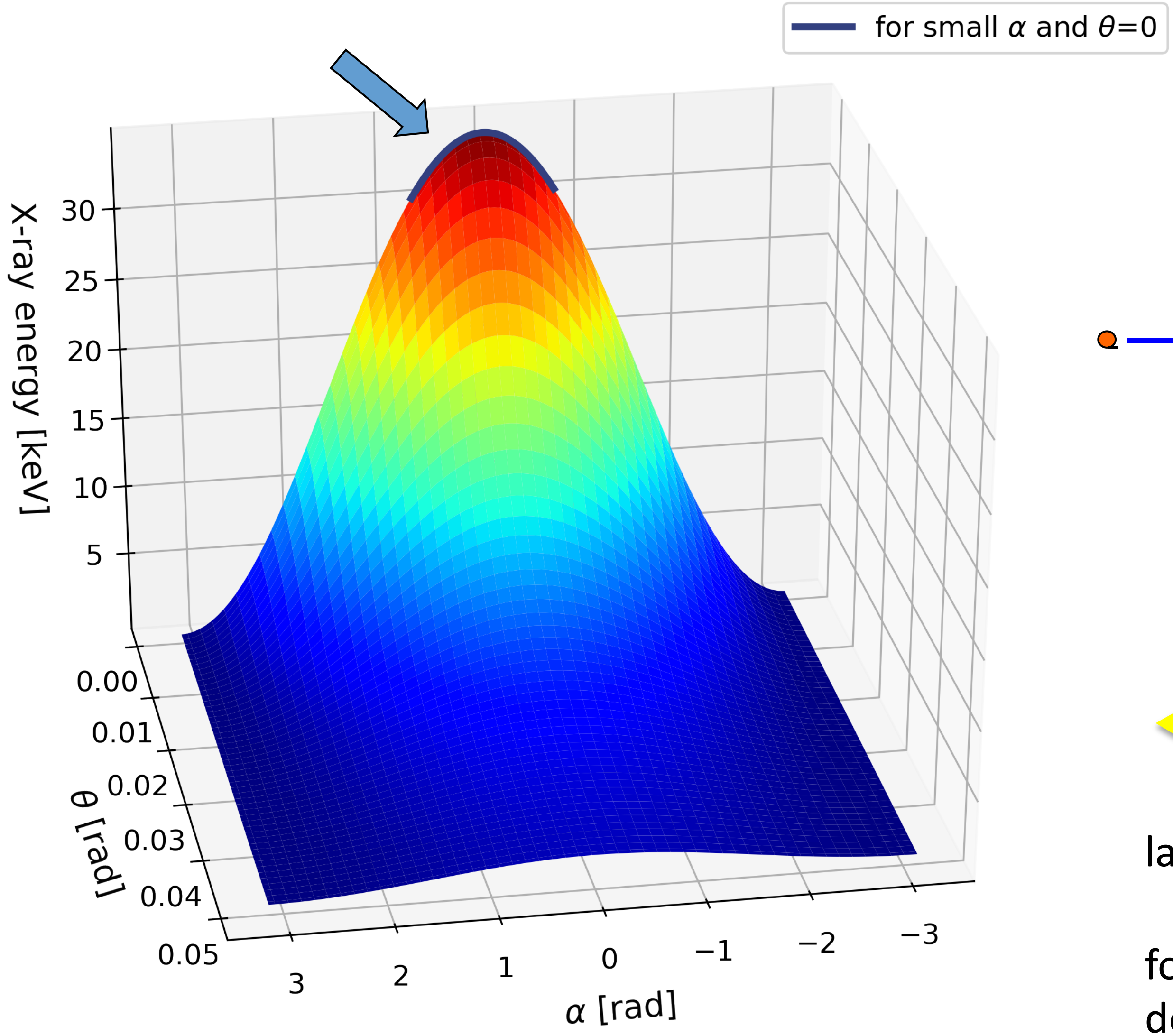
Spectrum of the X-rays

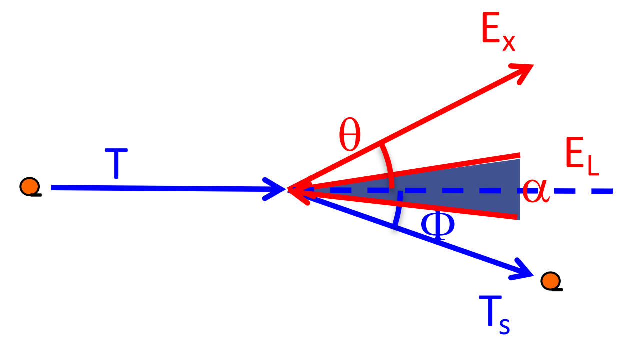
if collision is not head-on

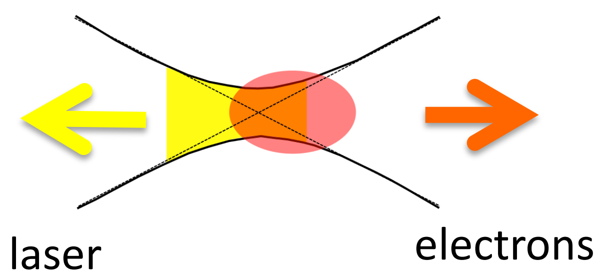
+/-Δα

- ΔE_x









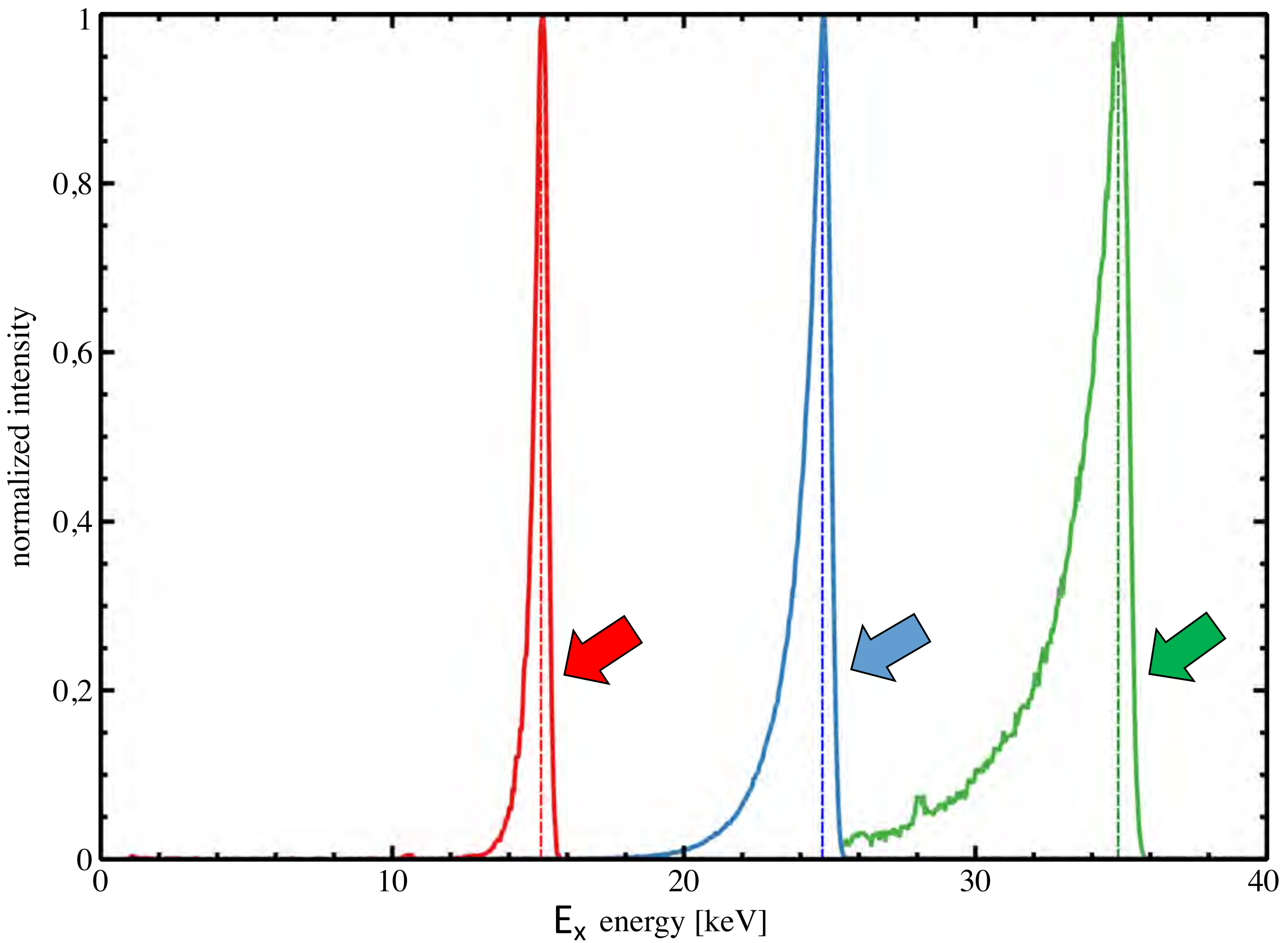
focus of laser and electrons <u>decreases</u> E_x

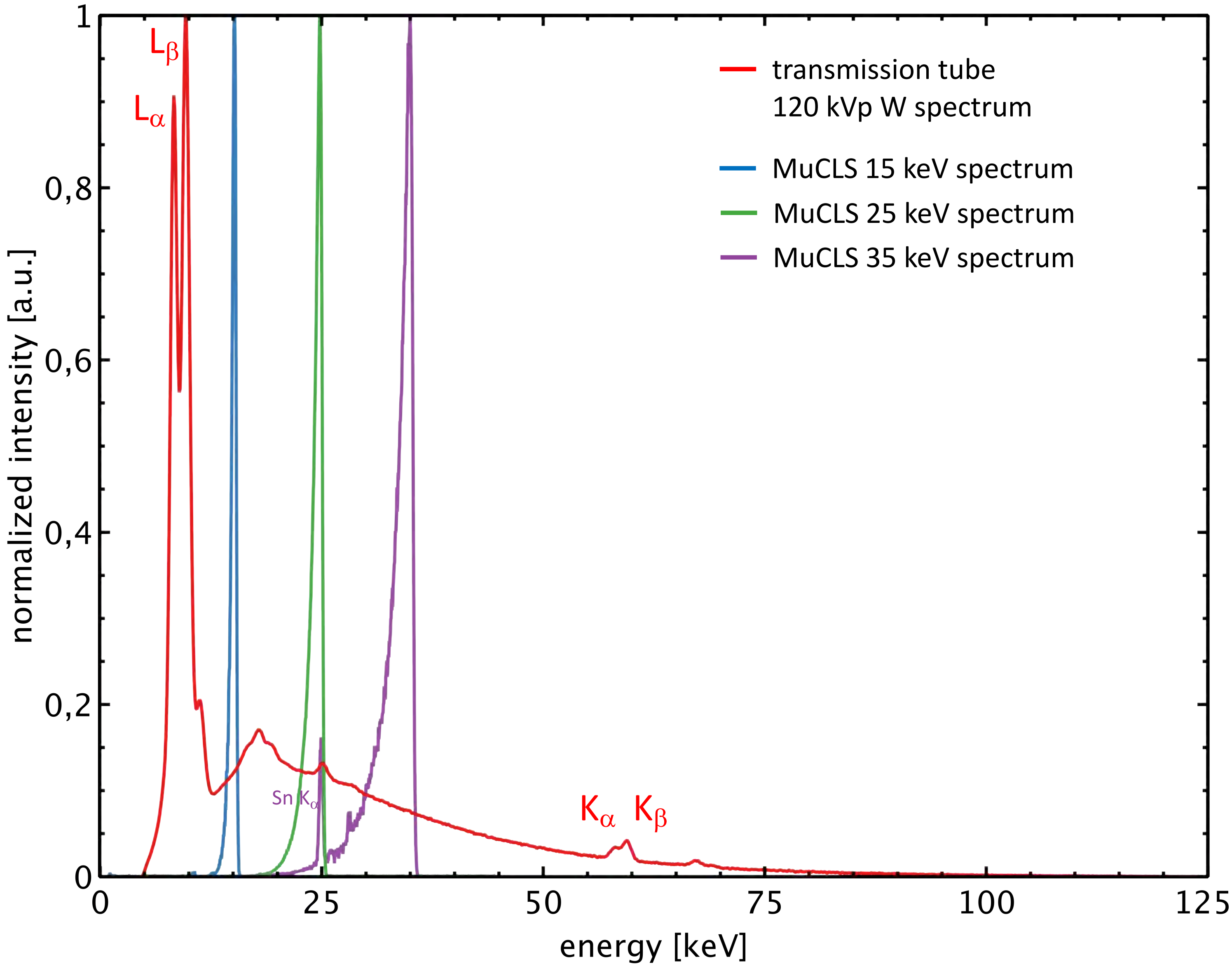
Spectrum of the X-rays

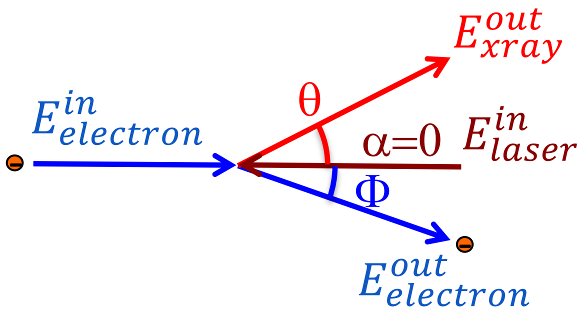
mainly due to

$$\frac{\Delta E_e}{E_e}$$

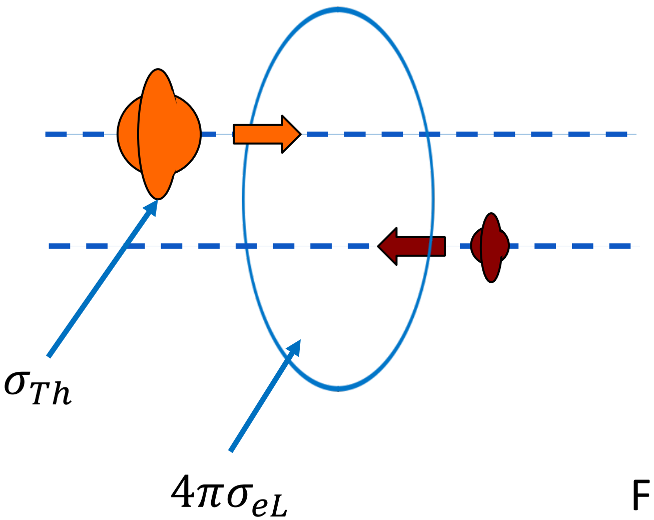
$$\pm \Delta E_x$$




transmission tube
120 kVp W spectrum
MuCLS 15 keV spectrum
MuCLS 25 keV spectrum
MuCLS 35 keV spectrum
L_β
L_α
Sn K_α
K_α
K_β
normalized intensity [a.u.]
energy [keV]
0
0,2
0,4
0,6
0,8
1
0
25
50
75
100
125



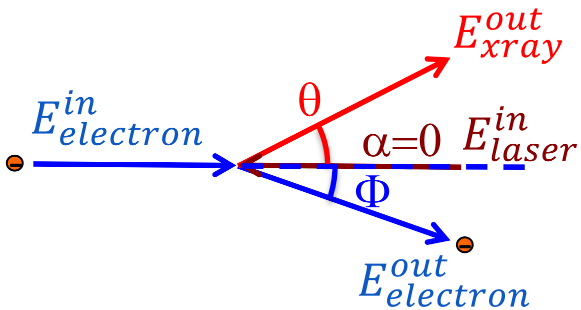
How many X-ray Photons do we generate per second?

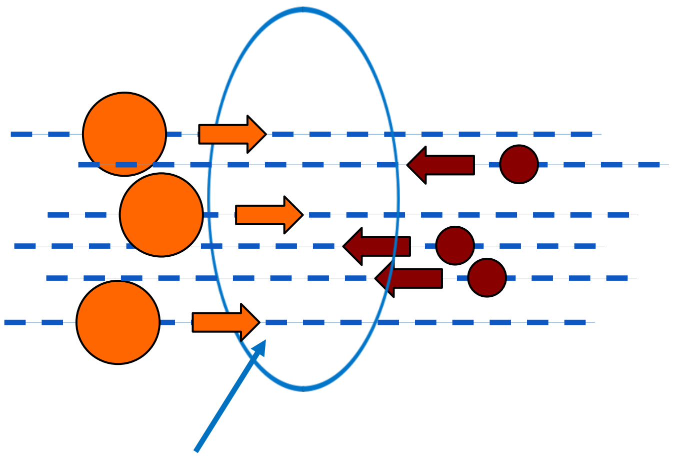


$$\sigma_{Th} = \frac{8\pi}{3} r_e^2 = 6.65 \cdot 10^{-29}\ m^2$$

Flux of X-ray photons $\dot{N}_x = \sigma_{Th} \cdot \mathcal{L} = \sigma_{Th} \cdot \frac{1}{4\pi\sigma_{eL}^2}$

+ small size of interaction area

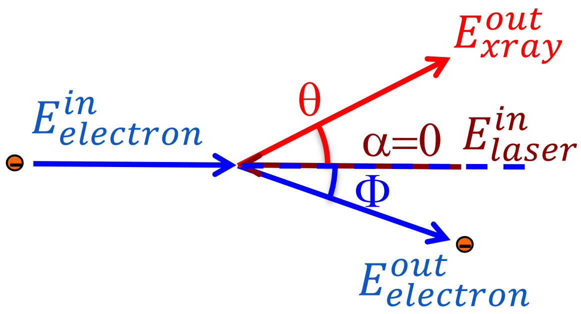


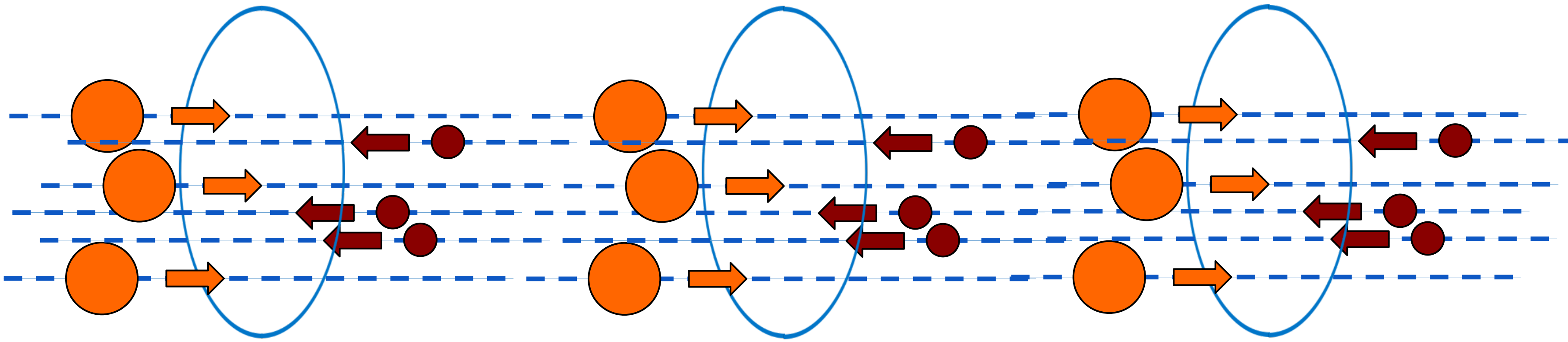


$$\sigma_{Th} = \frac{8\pi}{3} r_e^2 = 6.65 \cdot 10^{-29}\ m^2$$

Flux of X-ray photons $$\dot{N}_x = \sigma_{Th} \cdot \frac{N_e N_L}{4\pi\sigma_{eL}^2}$$

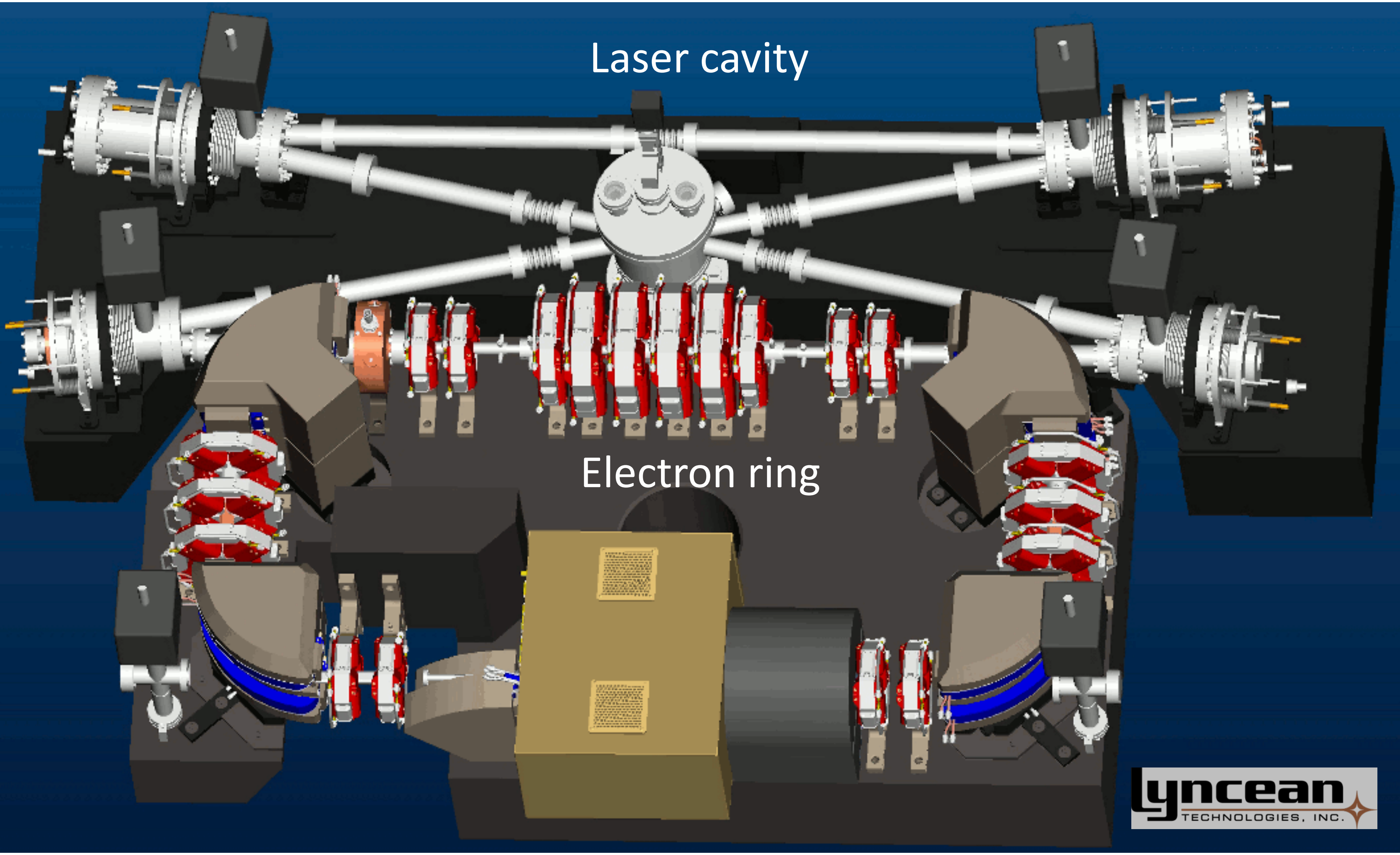
+ many electrons
+ many laser photons



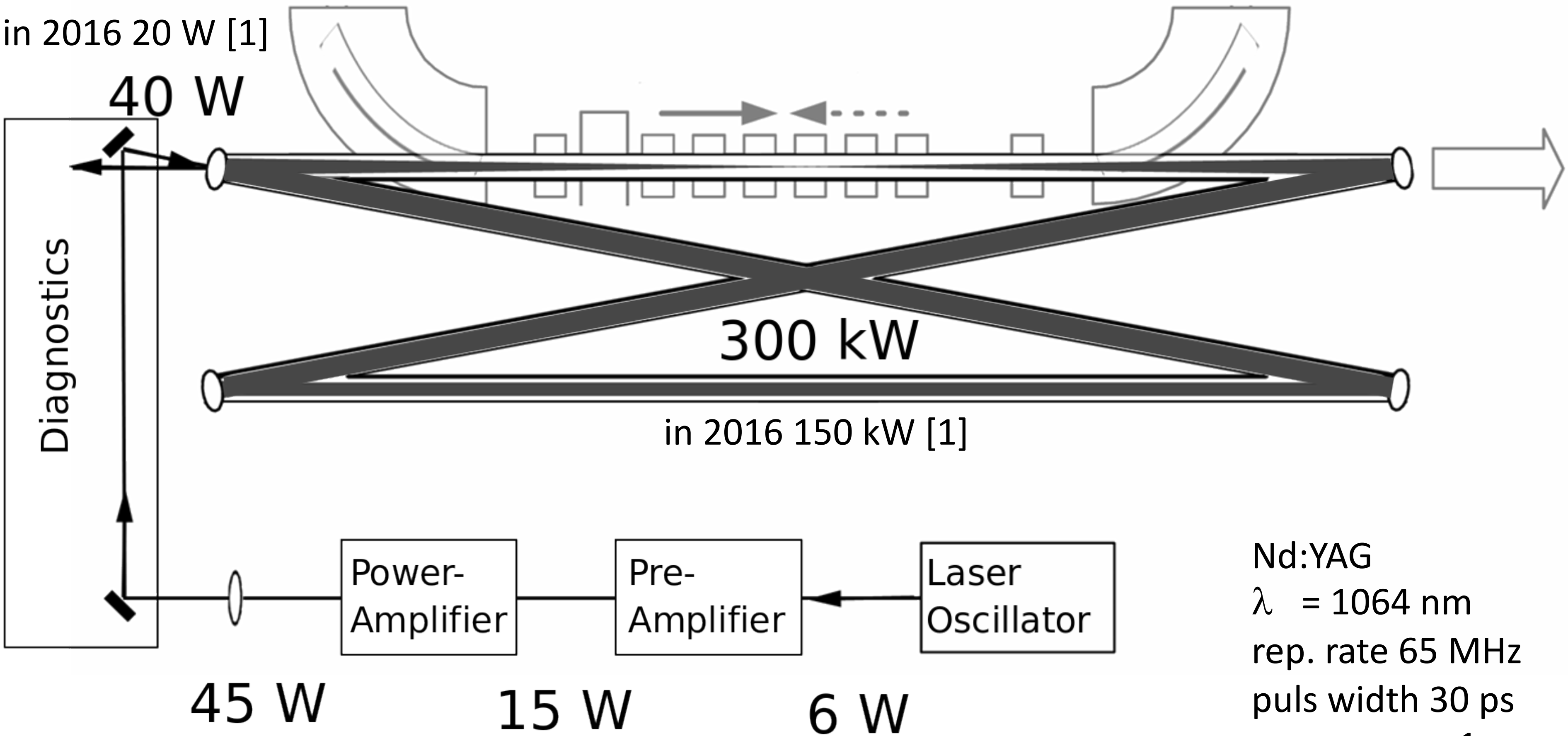


Flux of X-ray photons $$\dot{N}_x = \sigma_{Th} \cdot \frac{N_e N_L}{4\pi\sigma_{eL}^2} \cdot f_{CLS}$$

+ high repetition rate

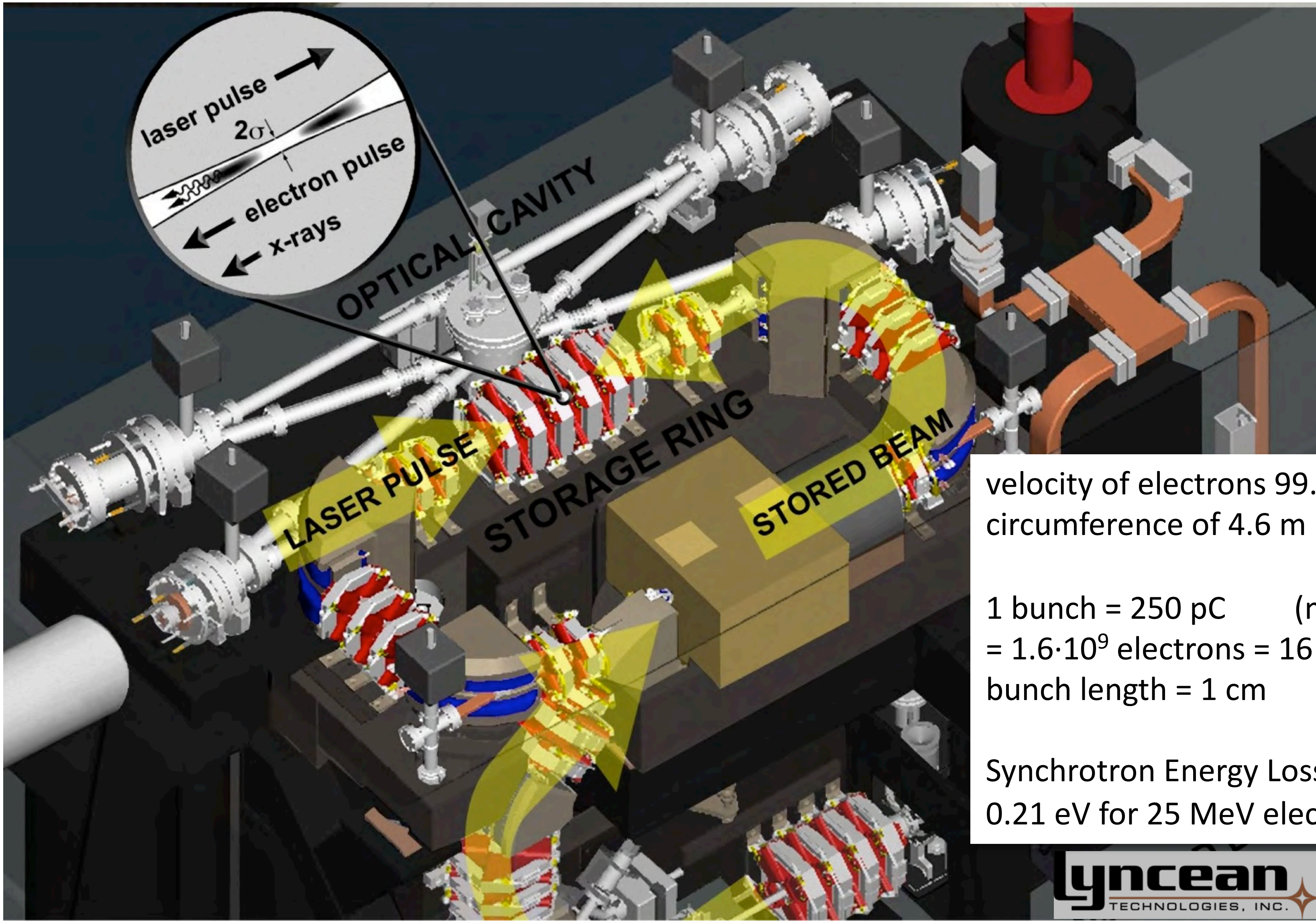

Laser cavity
Electron ring
lyncean
TECHNOLOGIES, INC.

Laser Enhancement Cavity



Nd:YAG
λ = 1064 nm
rep. rate 65 MHz
puls width 30 ps
< 1 cm

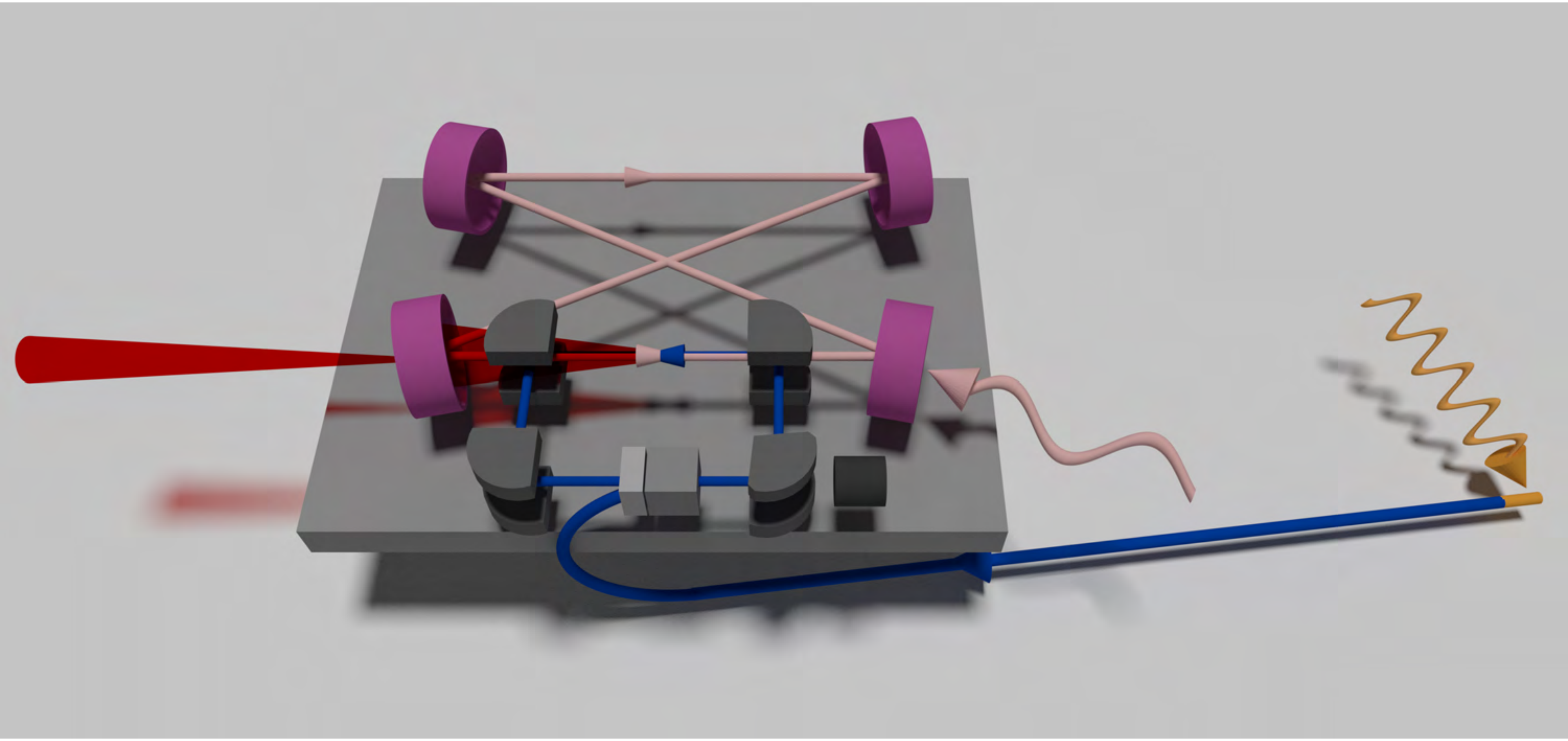
[1] E. Eggl, M. Dierolf, K. Achterhold, Ch. Jud, B. Günther, E. Braig, B. Gleich, F. Pfeiffer,
The Munich Compact Light Source: initial performance measures, J. Synch. Rad. 23 (2016)

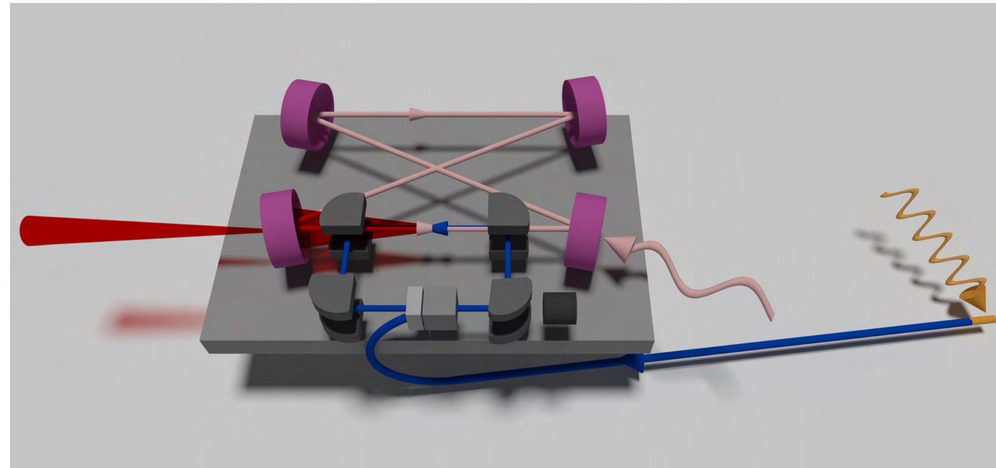


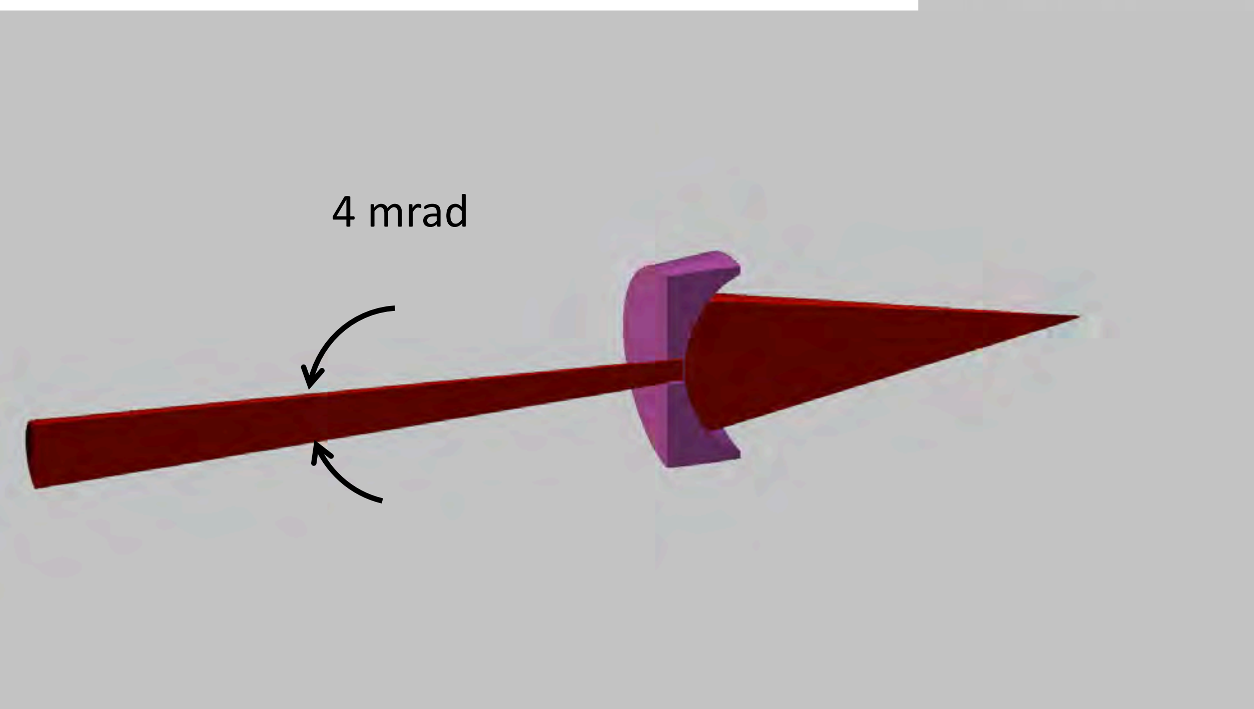
velocity of electrons 99.99 % of c
circumference of 4.6 m → 65 MHz

1 bunch = 250 pC (max 1.2 nC)
= $1.6 \cdot 10^9$ electrons = 16 mA
bunch length = 1 cm

Synchrotron Energy Loss/Turn
0.21 eV for 25 MeV electron energy

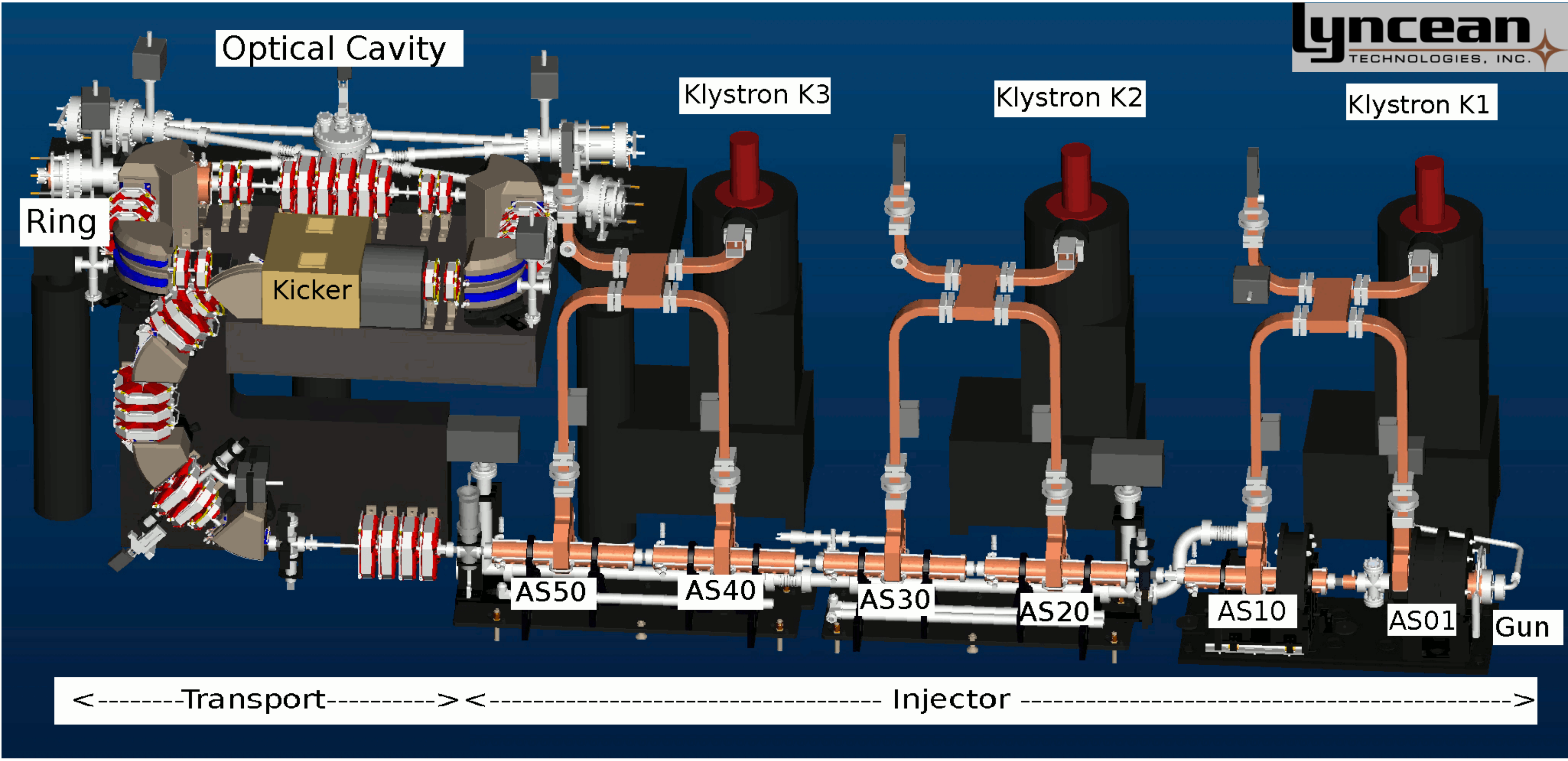






mirror thinned
in the middle area

MuCLS

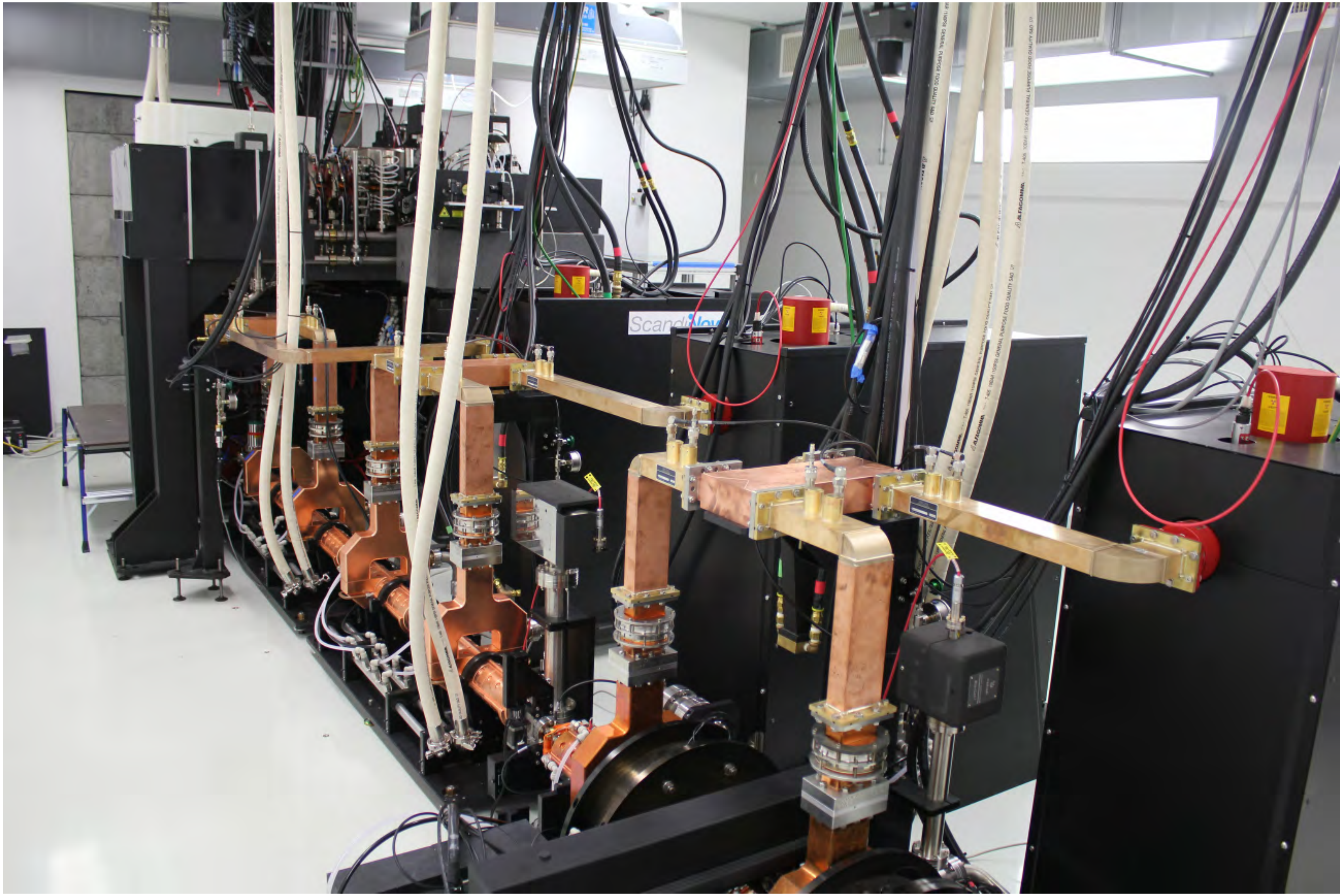


7,30 m

LINAC
standing wave
20 – 46 MeV

UV laser pulses
onto Cu cathode
P = 150 μJ; λ=262 nm
25 Hz repetition

MuCLS



© A. Heddergott

Flux

Expected flux $$\dot{N}_x = \sigma_{Th} \cdot \frac{N_e N_L}{4\pi\sigma_{eL}^2} \cdot f_{CLS}$$

with $$\sigma_{Th} = \frac{8\pi}{3} r_e^2 = 6.65 \cdot 10^{-29}\ m^2$$

N_e for 250 pC electrons in the ring is $1.6 \cdot 10^9$
N_L for 2.3 mJ puls energy in laser cavity: $1.2 \cdot 10^{16}$
f_{CLS} (repetition rate of ring and cavity): 65 MHz

$$\dot{N}_x = 2.2 \cdot 10^{12}\ s^{-1}$$

but with the
cross section
into +/- 2 mrad

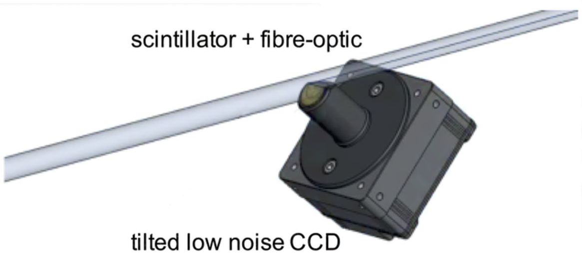
$$\sigma_{Th\pm 2} = 0.35 \cdot 10^{-29}\ m^2$$

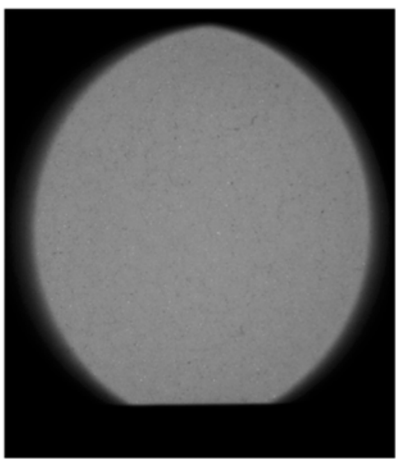
$$\dot{N}_x = 1.1 \cdot 10^{11}\ s^{-1}$$

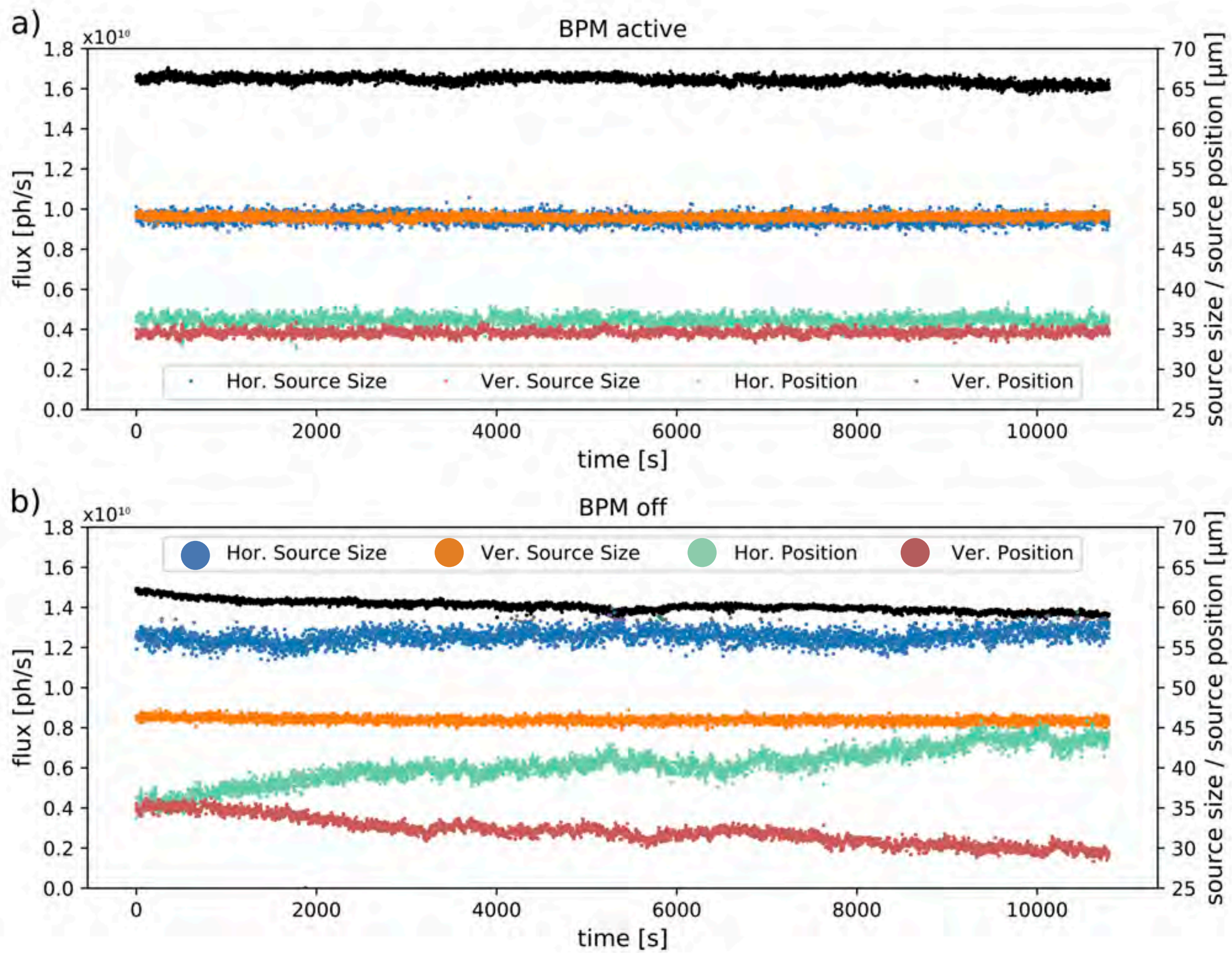
we have @35keV: $\dot{N}_x = 5 \cdot 10^{10}\ ph\ s^{-1}$ → brilliance: $1.1 \cdot 10^{10}\ phs^{-1}\ mm^{-2}\ mrad^{-2}\ 0.1\%BW^{-1}$

Beam Position Monitor

closed-loop feedback adjusting the laser beam trajectory

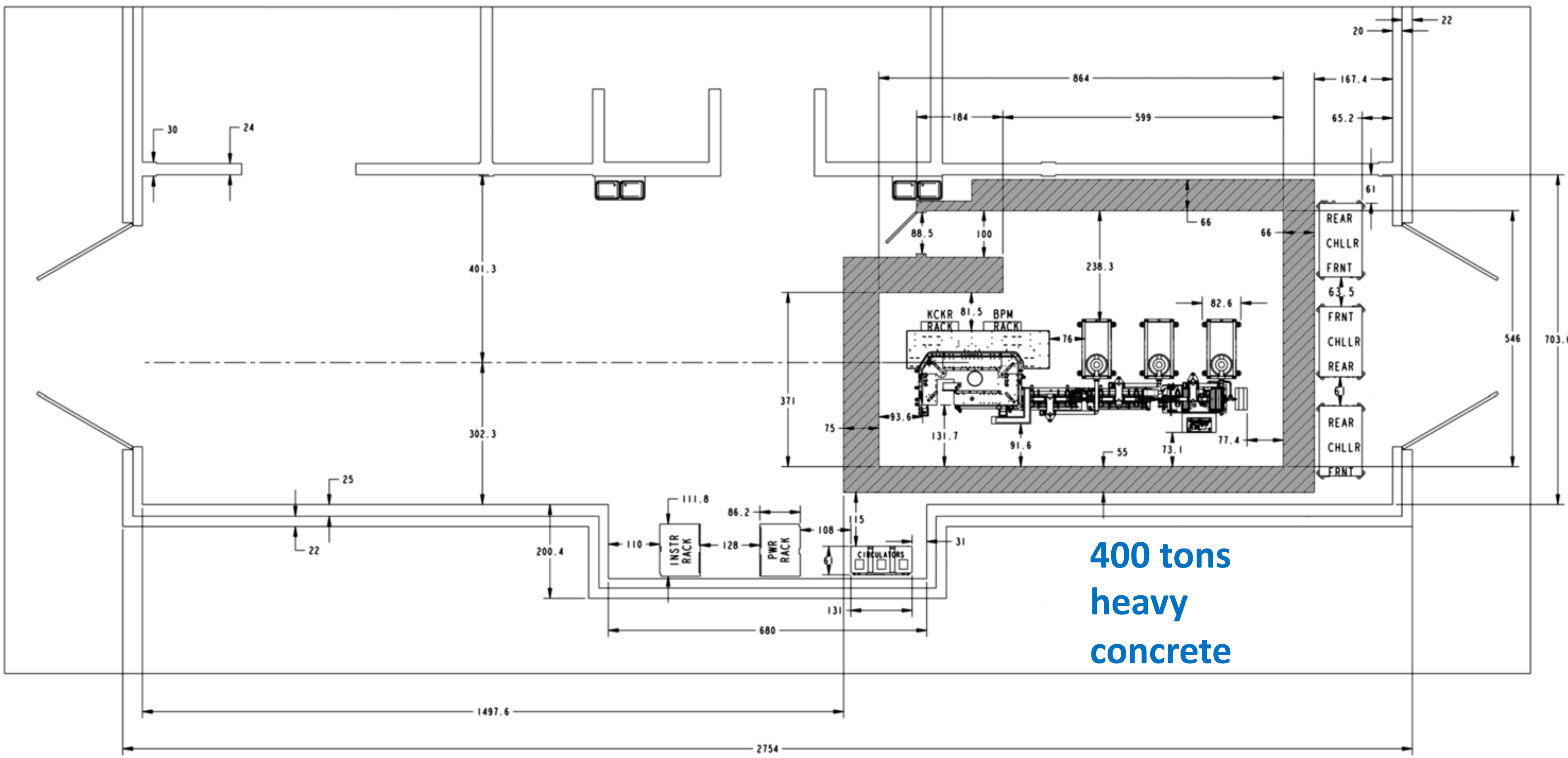




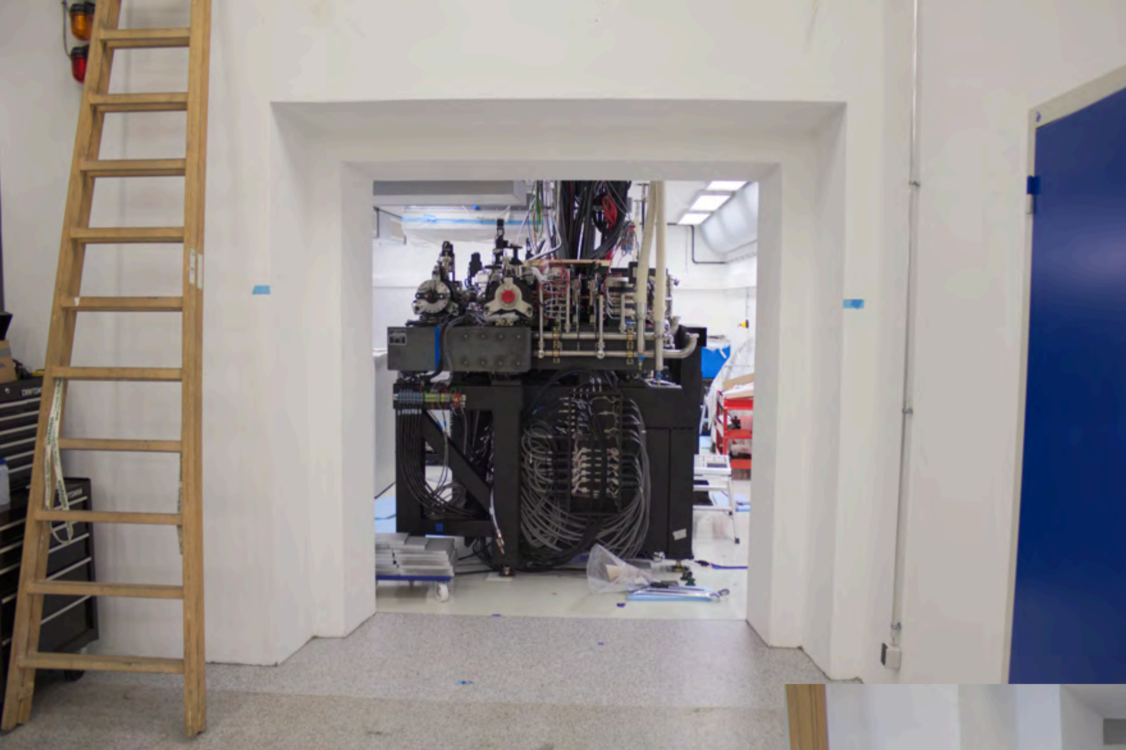


B. Günther, M. Dierolf, K. Achterhold, F. Pfeiffer, J Synchrotron Radiation 26 (2019) 1546–1553

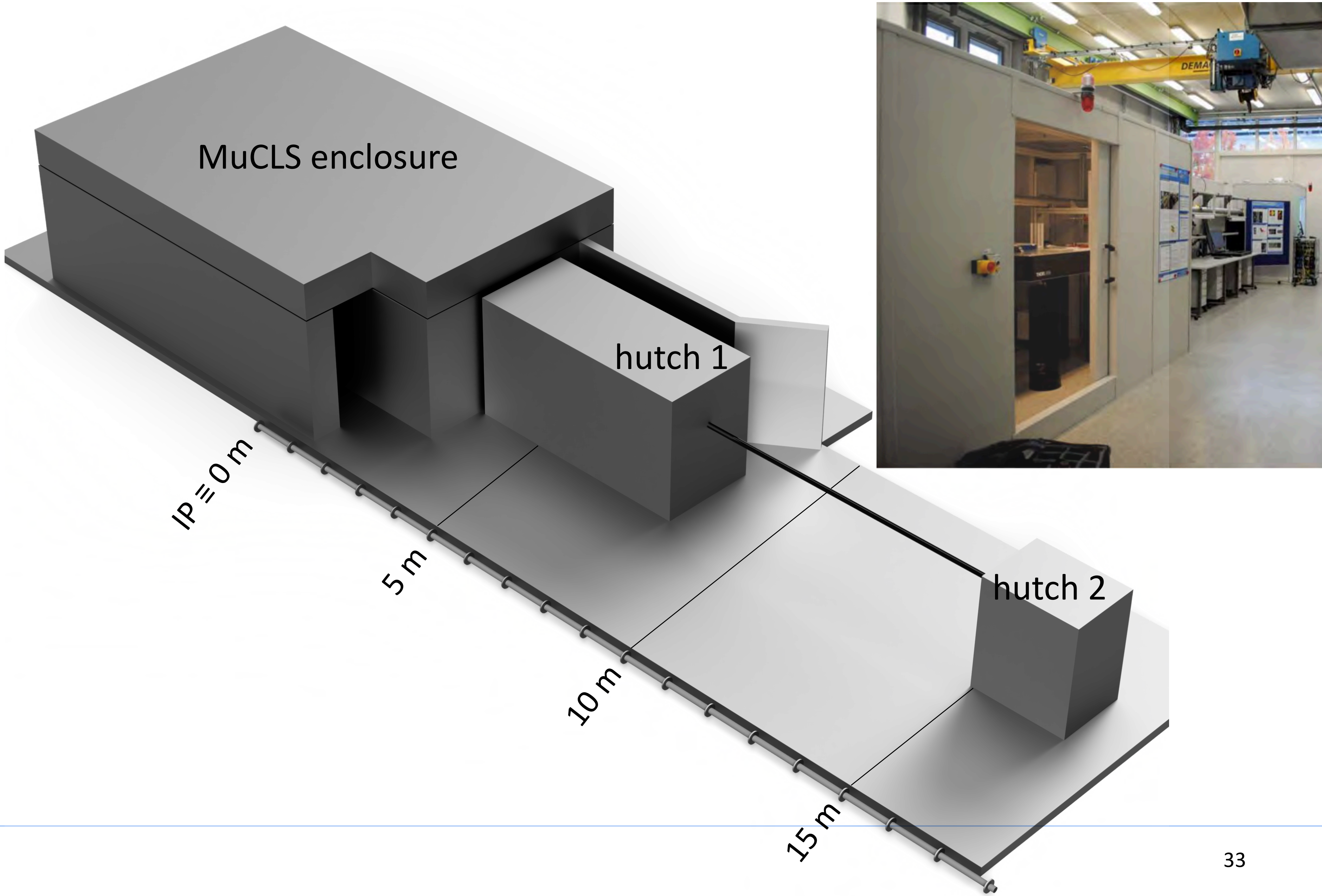
Radiation Shielding



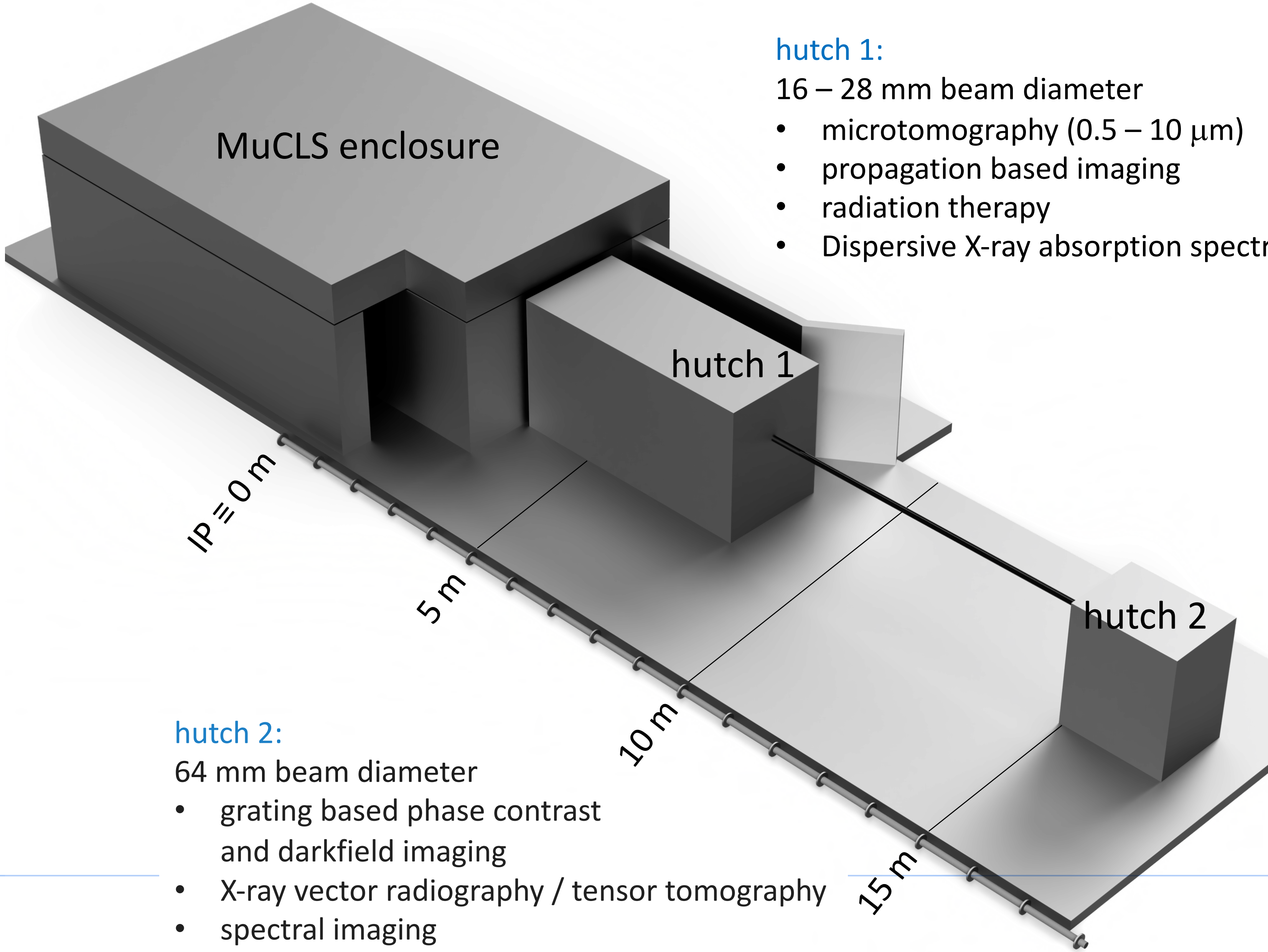
400 tons heavy concrete



Radiation Shielding



Radiation Shielding



hutch 1:

16 – 28 mm beam diameter

- microtomography (0.5 – 10 μm)
- propagation based imaging
- radiation therapy
- Dispersive X-ray absorption spectroscopy

hutch 2:

64 mm beam diameter

- grating based phase contrast and darkfield imaging
- X-ray vector radiography / tensor tomography
- spectral imaging

The Future

Parameter	CLS 1.1 (Munich CLS)	CLS 2.0 (Next system)	CLS Roadmap (Future)
Total Flux (~4% BW) – [ph/s]	>3 * 10^{10}	4 * 10^{11}	4 * 10^{12}
Source size [µm rms]	45	40	30
Source divergence [mrad] (Flattop Cone)	4	6	6
Source Brightness – Full Bandwidth [ph/s/mrad^2/mm^2/4% BW]	5 * 10^{11}	4 * 10^{12}	1 * 10^{14}
Tunable x-ray energy range [keV]	8-35 (IR 1um laser)	8-35 (IR 1um laser)	4-22 (IR – 2um) 8-50 (IR – 1um) 16-100 (Vis – 0.5um)
X-ray energy bandwidth [dE/E FWHM]	3-5%	3-5%	2-4%
X-ray Pulse Length (rms) [ps]	60		
X-ray Repetition Rate [MHz]	65		

Michael Feser, CEO Lyncean Technologies Inc., XRM 2018

www.e17.ph.tum.de
Franz Pfeiffer, Martin Dierolf, Benedikt Günther

Ronald Ruth, www.lynceantech.com
Roderick Loewen, Chris Juan, Martin Gifford,…

www.bioengineering.tum.de
Axel Haase, Bernhard Gleich

www.munich-photonics.de
DFG Cluster of Excellence Munich-Center for Advanced Photonics (DFG EXC-158)

Thank you for your attention