PSI

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SYNCHROTRONS AND FREE ELECTRON LASERS

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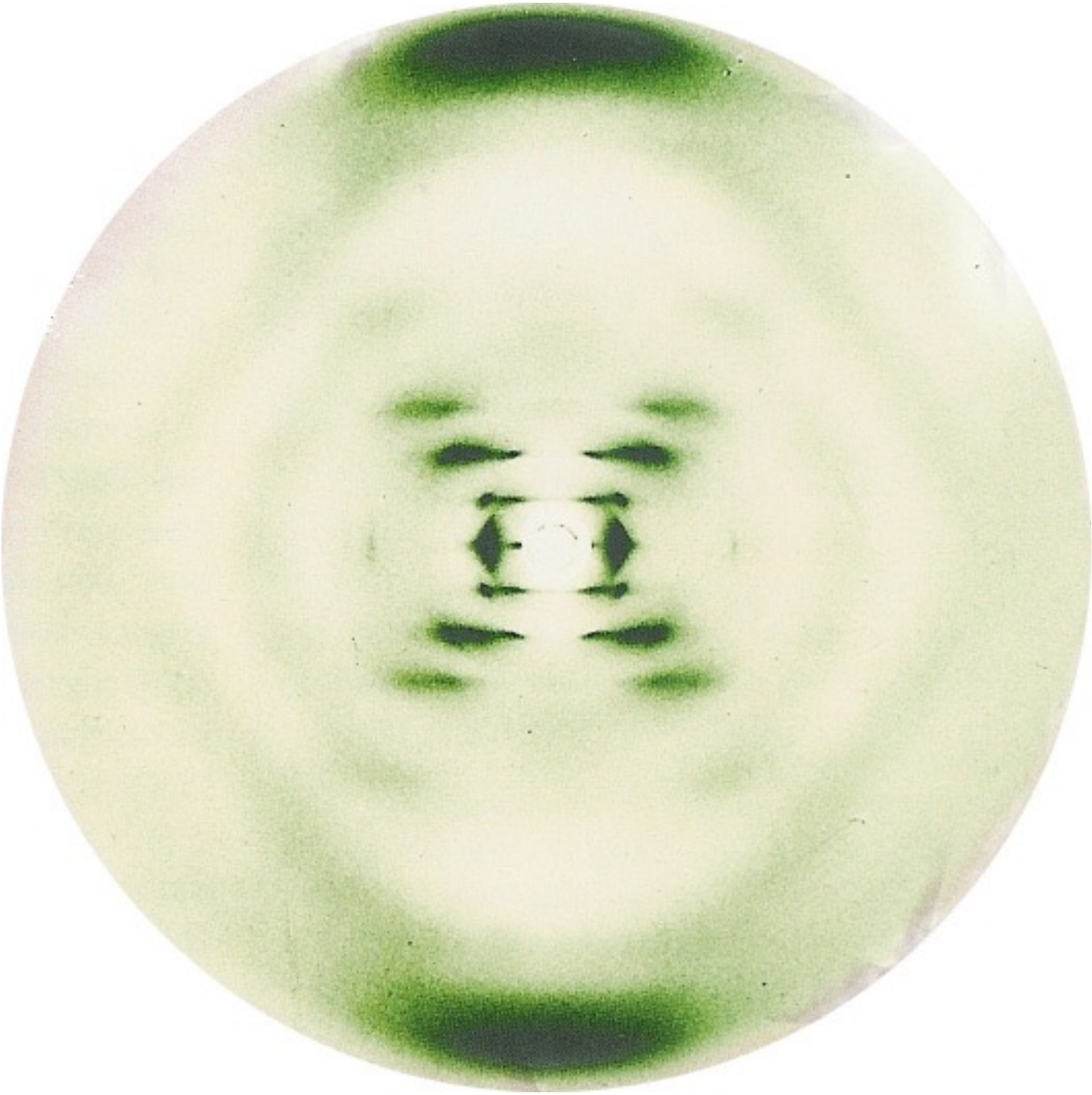
PHOTO 51 — RAYMOND GOSLING, ROSALIND FRANKLIN



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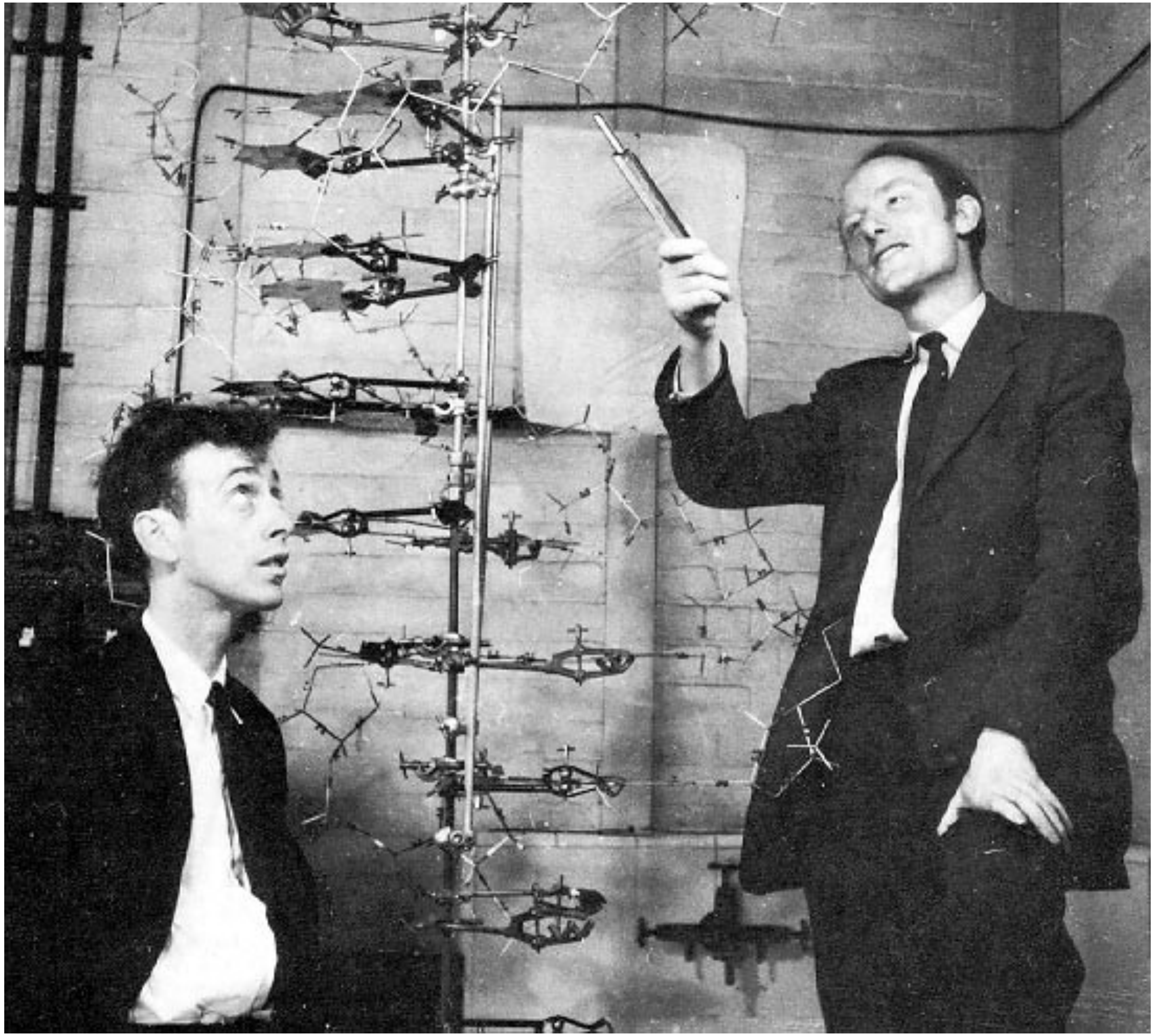
STRUCTURE OF DNA — JAMES WATSON, FRANCIS CRICK



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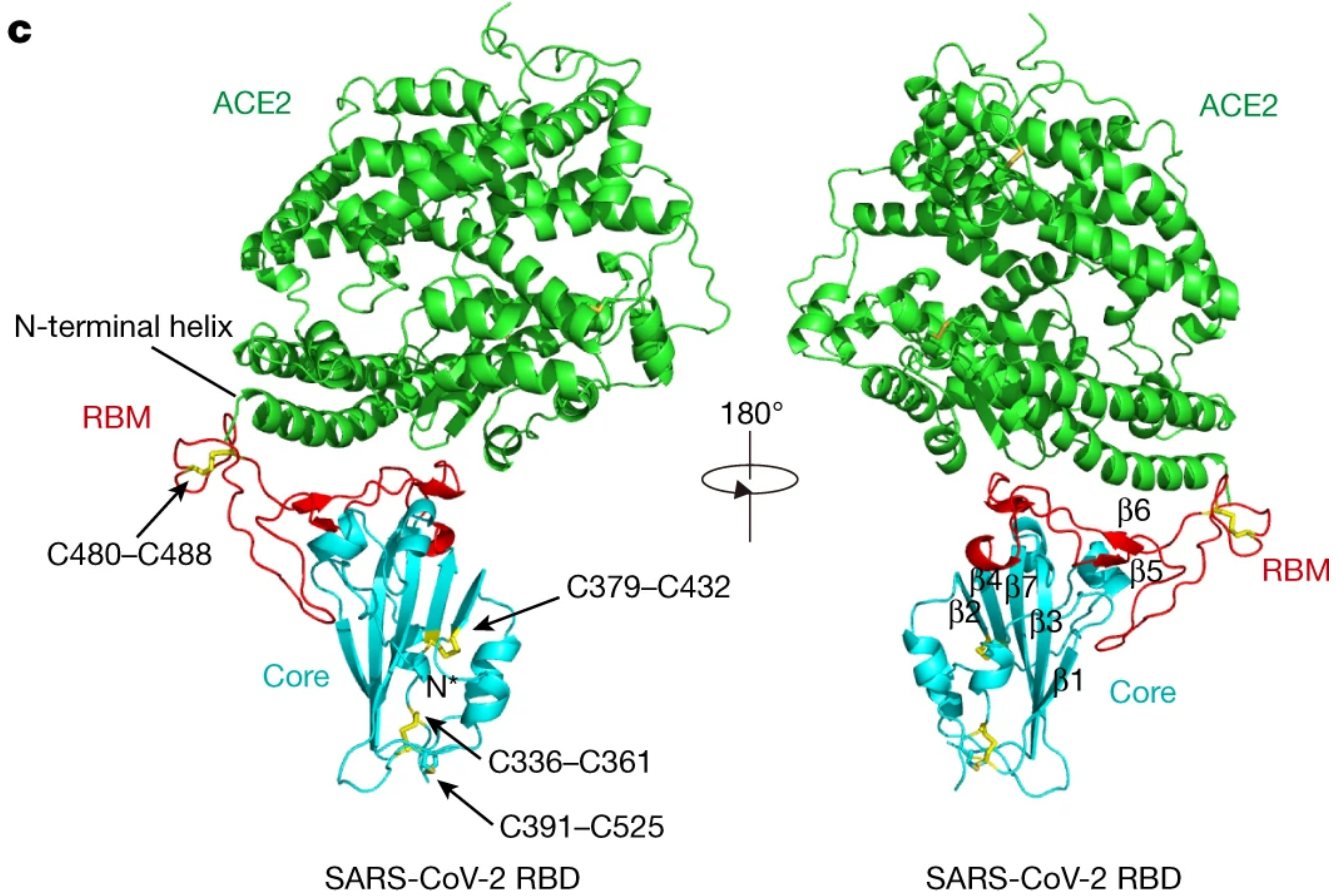
RECEPTOR BINDING DOMAIN OF SARS-CoV-2



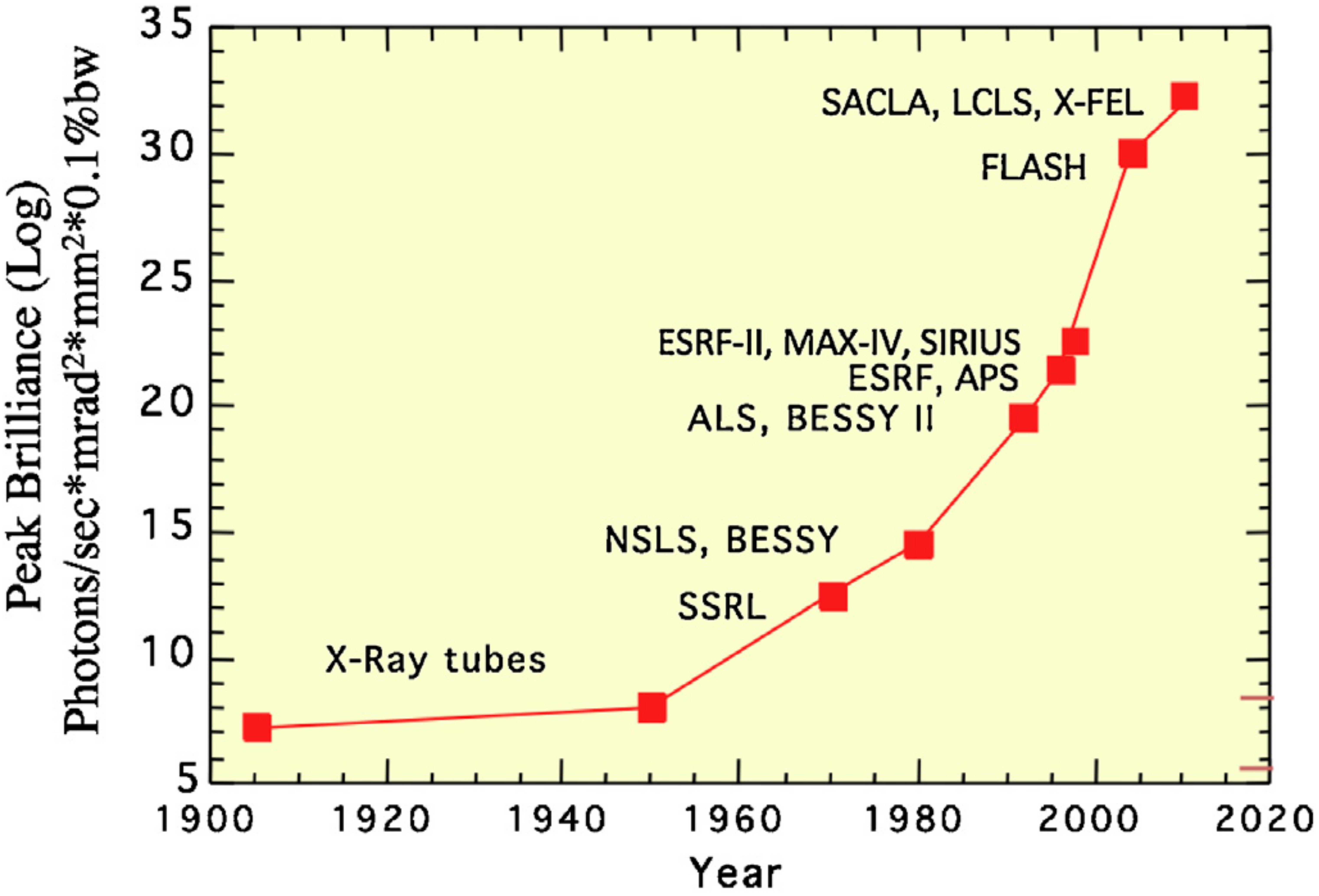
Lan et al., Nature 581, 215–220 (2020)

BRILLIANCE OF X-RAY SOURCES

- Key figure of merit comparing different photon sources

$$\mathcal{B} = \frac{\dot{N}_\gamma}{4\pi^2 \sigma_x \sigma_y \sigma_{x'} \sigma_{y'} (0.1\%\mathrm{BW})}$$

- Independent of the distance to the source



W. Eberhardt / Journal of Electron Spectroscopy and Related Phenomena 200 (2015) 31–39

EMITTANCE

- Particles in the beam are described with the Hamiltonian formalism

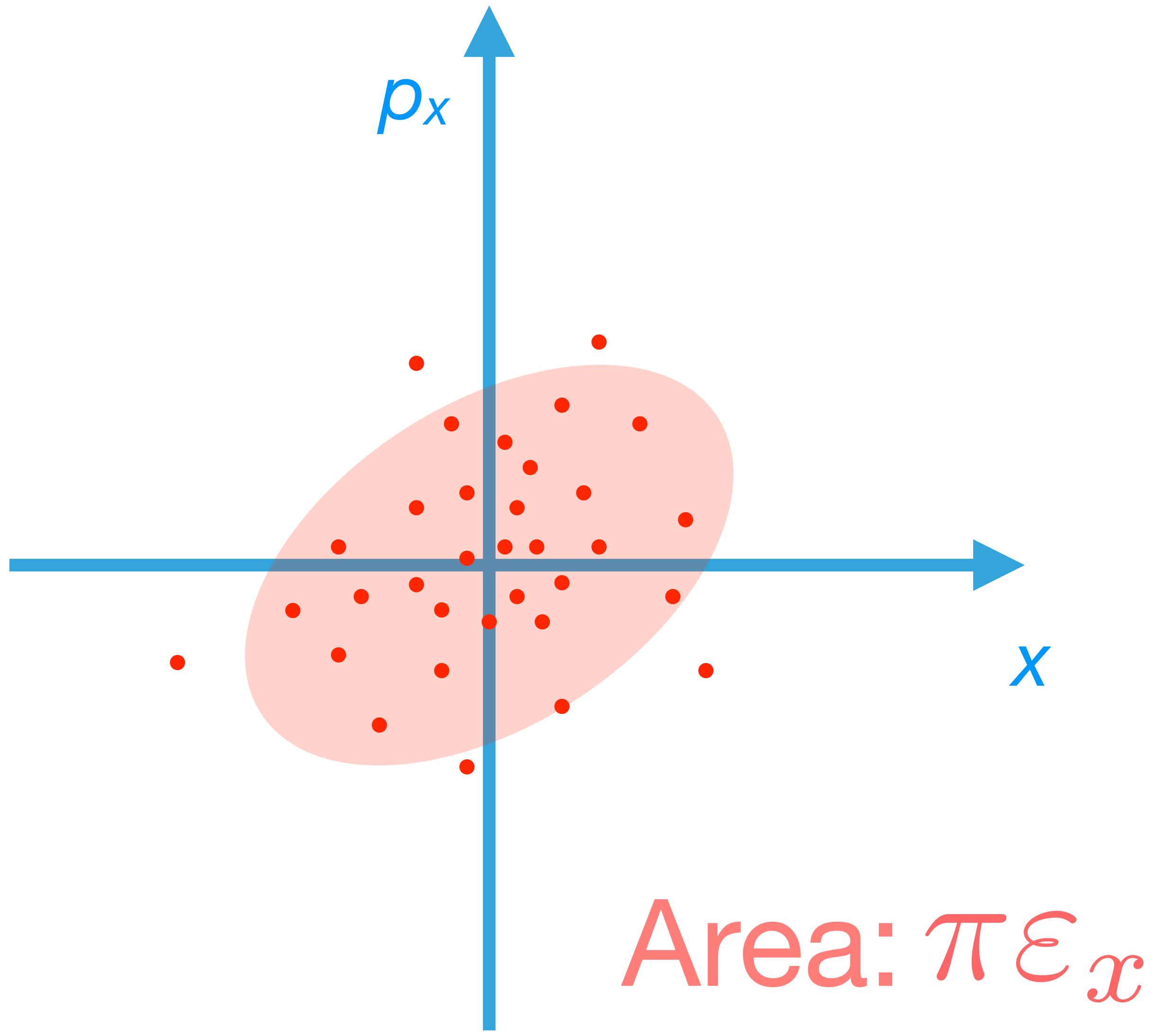
$$\mathcal{H} = E = T + V$$

$$(x, p_x), \quad (y, p_y), \quad (z, p_z)$$

$$\frac{dx}{dt} = \frac{\partial \mathcal{H}}{\partial p_x}$$
$$\frac{dp_x}{dt} = -\frac{\partial \mathcal{H}}{\partial x}$$


William Rowan Hamilton

- Phase space area in the transverse coordinates is called *emittance*

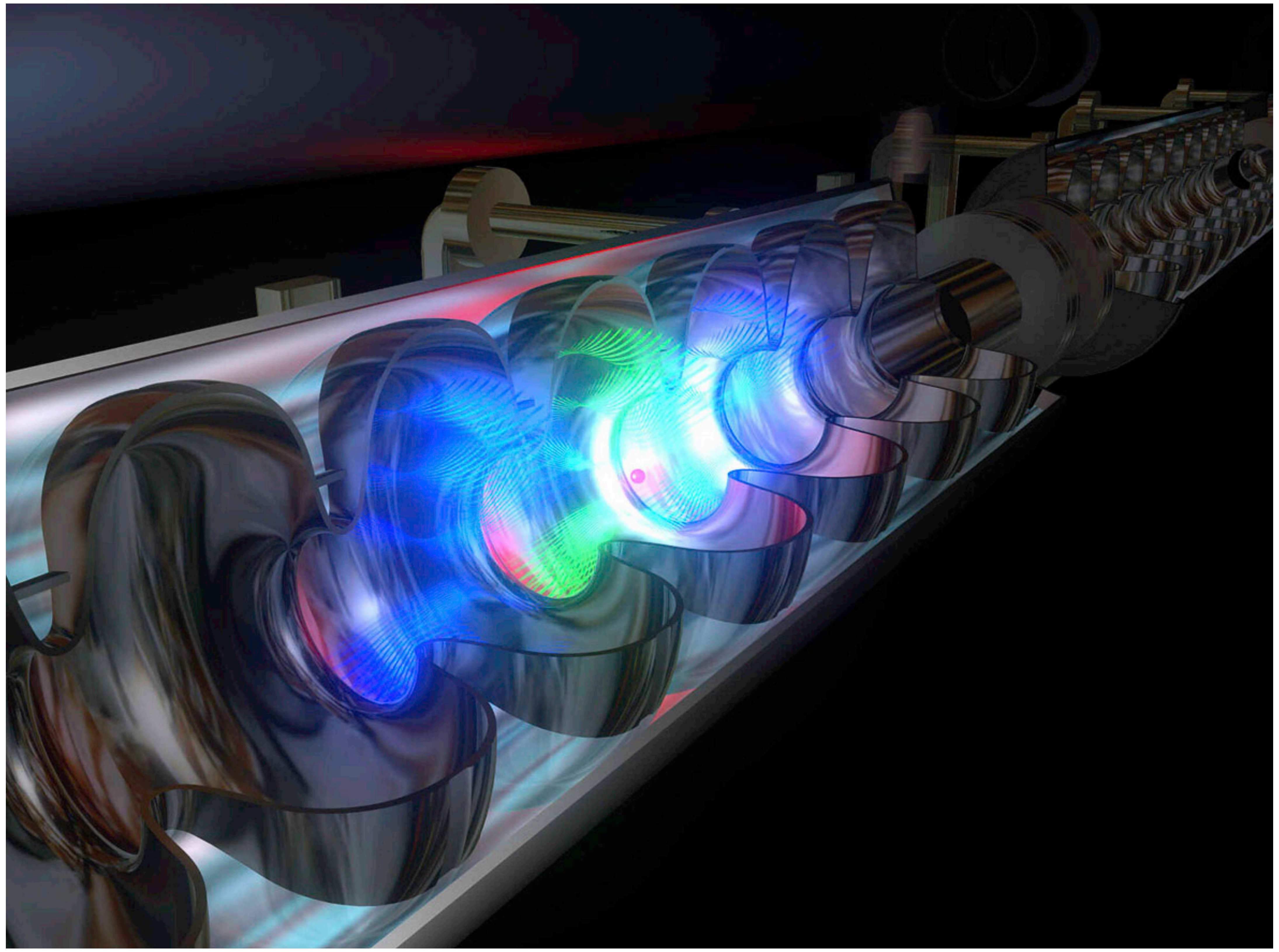


EMITTANCE IN A LINEAR ACCELERATOR

- Emittance decreases with acceleration
  - Accelerating structures increase the longitudinal momentum, but leave the transverse momentum unchanged

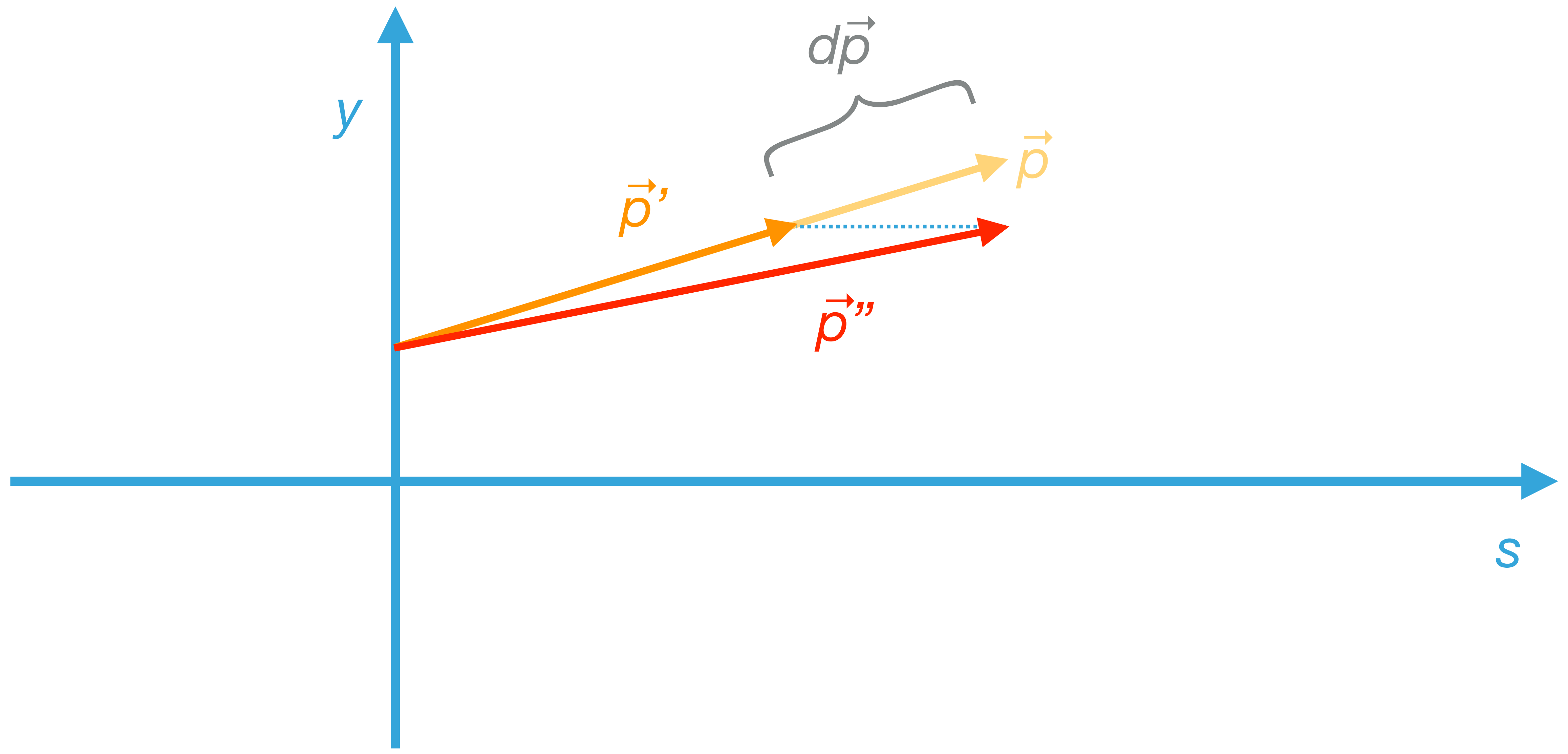
- In the absence of non-linear forces, the normalized emittance is constant

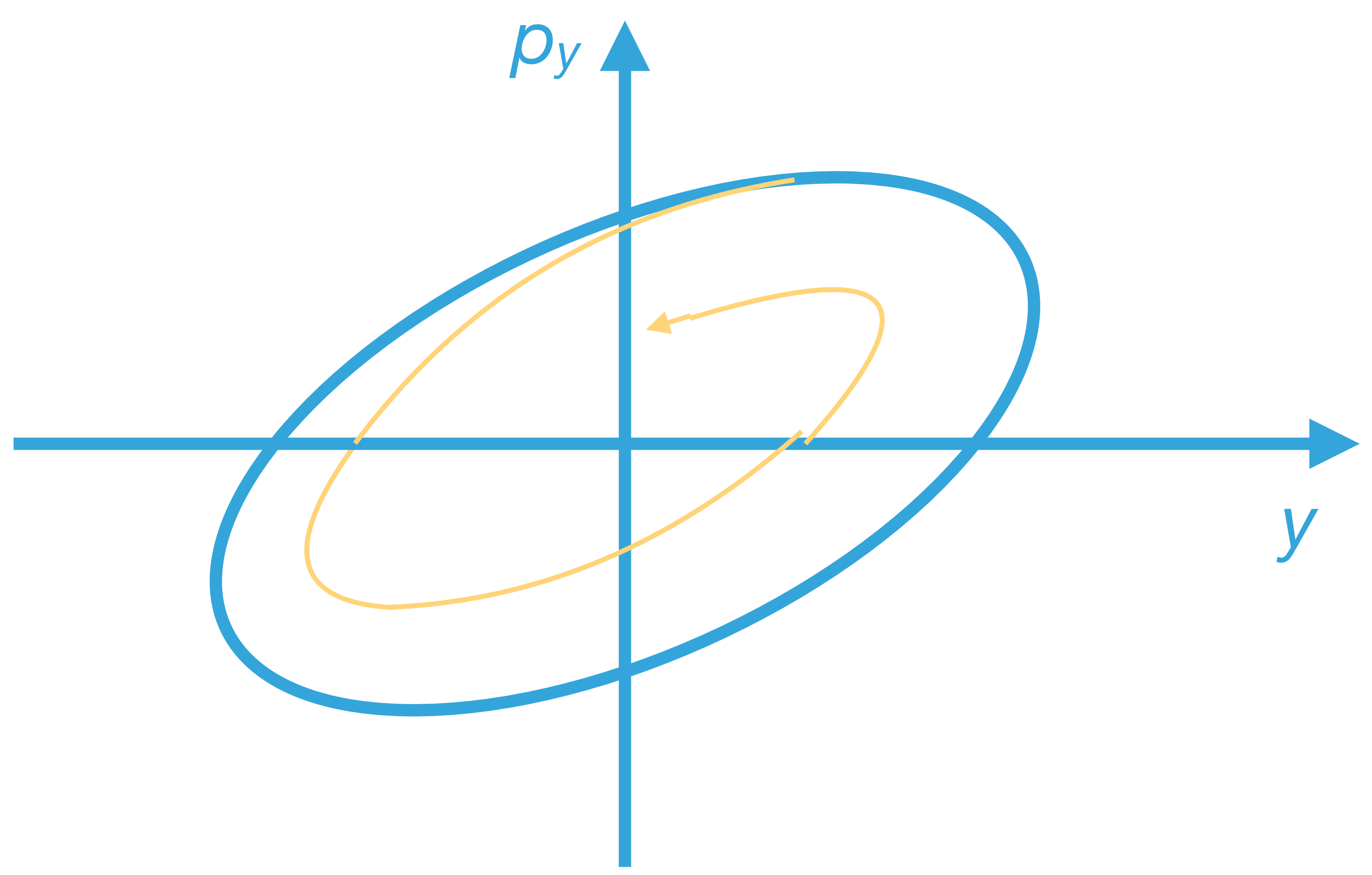
$$\varepsilon_n = \gamma\varepsilon$$



EMITTANCE IN A STORAGE RING

- Emittance is damped by the emission of synchrotron radiation





$$\varepsilon(t) = \varepsilon(0) \exp\left(-2\frac{t}{\tau}\right) + \varepsilon(\infty)\left[1 - \exp\left(-2\frac{t}{\tau}\right)\right].$$

- The equilibrium emittance is determined by quantum mechanics

RADIATION DAMPING AND QUANTUM EXCITATION

- Horizontal equilibrium emittance in a storage ring

$$\varepsilon_{x,\infty} = \frac{55}{32\sqrt{3}} \frac{\hbar}{m_e c} \gamma^2 \frac{\oint \frac{\gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_{px} + \beta_x \eta_{px}^2}{|\rho|^3} \mathrm{d}s}{\left(1 - \frac{\oint \frac{\eta_x}{\rho} \left(\frac{1}{\rho^2} + 2 \frac{e}{P_0} \frac{\partial B_y}{\partial x}\right) \mathrm{d}s}{\oint \frac{1}{\rho^2} \mathrm{d}s}\right) \oint \frac{1}{\rho^2} \mathrm{d}s}$$

where:
h is Planck's constant,
m_e is the electron mass,
c is the speed of light,
γ is the Lorentz factor,
the integrals are ring integrals around the storage ring, along the longitudinal coordinate *s*,
α_x, β_x and γ_x are the Twiss parameters, which characterize the beam optics,
η_x *and* η_{px} are the dispersion, i.e. the dependence of position and angle on beam energy,
ρ is the (local) radius of curvature,
–*e* is the charge of the electron,
P_0 is the nominal momentum of the particles, and
B_y is the vertical component of the magnetic field

RADIATION DAMPING AND QUANTUM EXCITATION

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Magnet lattice

≡ a detailed description of the magnets around the ring

Special relativity

Quantum mechanics

$$\varepsilon_{x,\infty} = \frac{55}{32\sqrt{3}} \frac{\hbar}{m_e c} \gamma^2 \frac{I_5}{j_x I_2}$$

$$\varepsilon_{x,\infty} = \frac{55}{32\sqrt{3}}\frac{\hbar}{m_e c}\gamma^2\frac{I_5}{j_x I_2}$$

EINSTEIN AND PLANCK IN ONE EQUATION

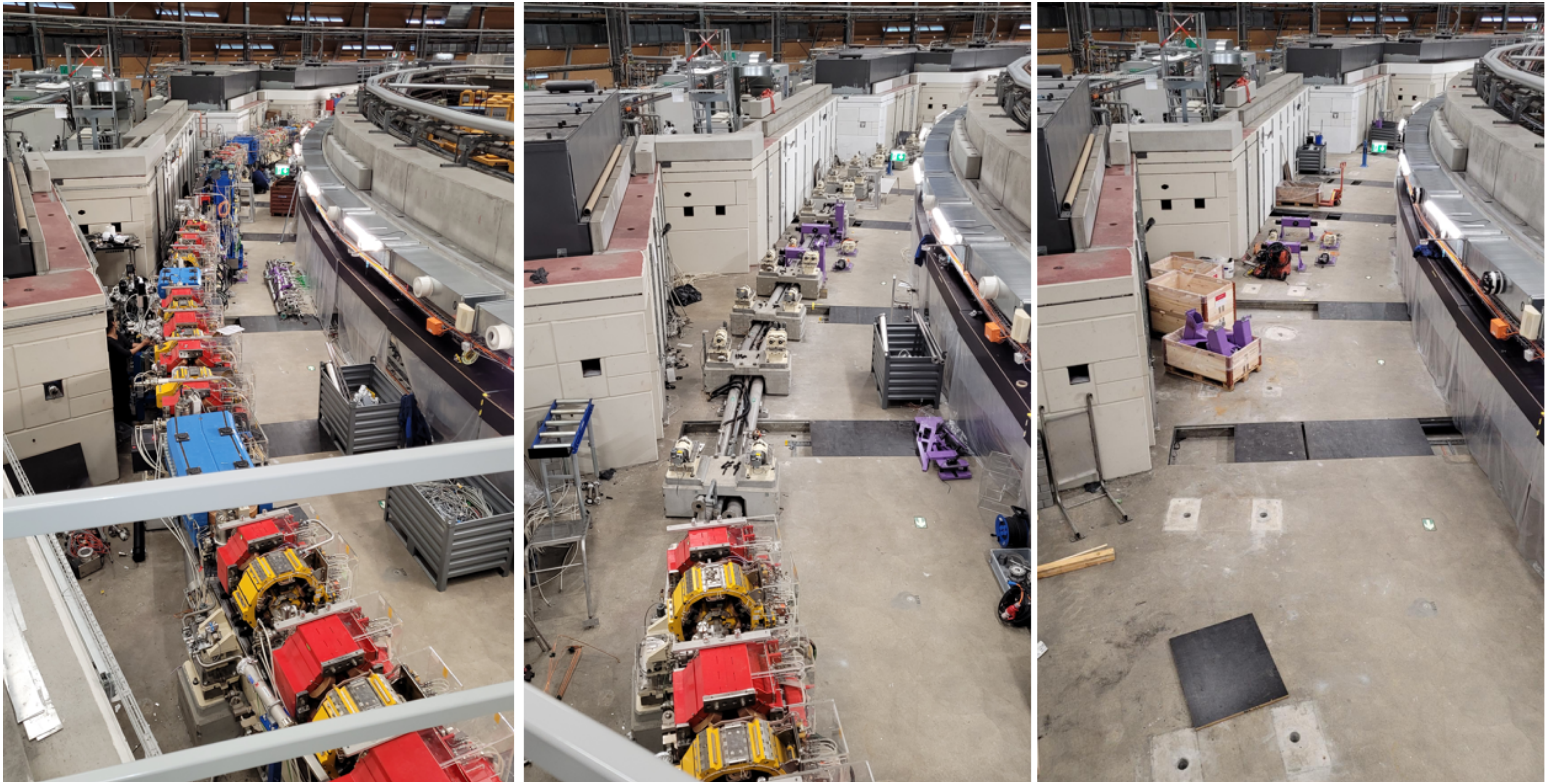
EMITTANCE OF X-RAY SOURCES

- Synchrotrons
  - emittance determined by radiation damping

- Free electron lasers
  - (normalized) emittance determined by source

SYNCHROTRON UPGRADE

SLS DISMANTLING



October 2023 → November 2023

SLS 2.0 CONSTRUCTION

January 2024

→

Mid-February 2024

INSTALLATION PROGRESS

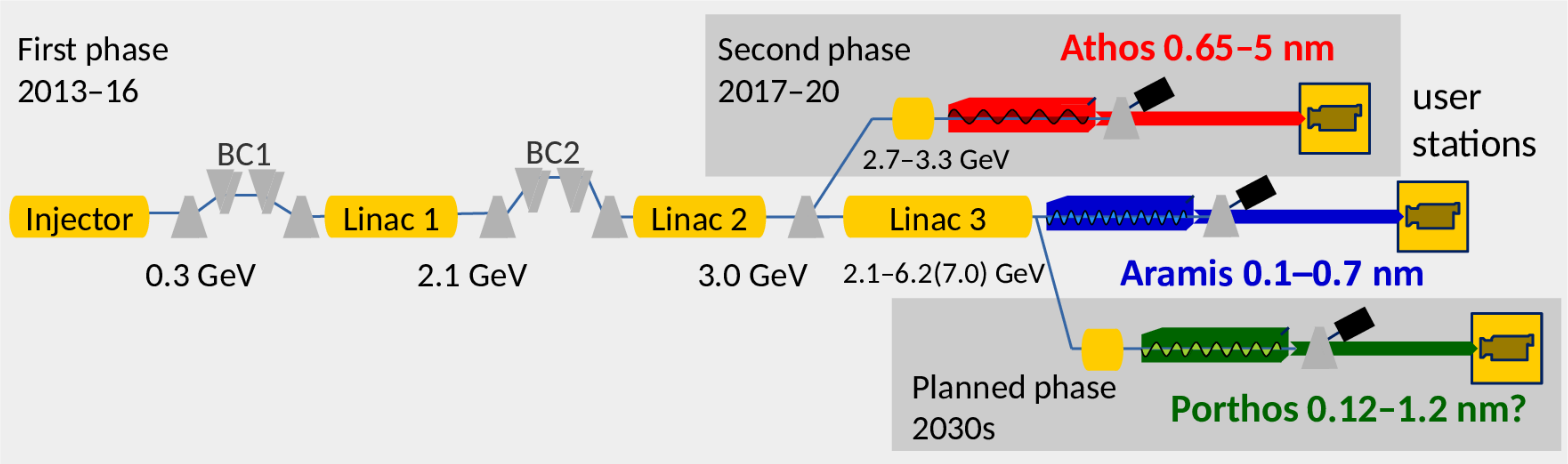
March 2024

TARGET BEAM PARAMETERS

	SLS today	SLS 2.0 CDR	SLS 2.0 TDR
Lattice type	TBA	7-BA	7-BA
Circumference [m]	288	290.4	288
Periodicity (arc geometry)	3	12	3
Energy [GeV]	2.411	2.400	2.700
Beam current [mA]	400	400	400
Natural emittance [pm.rad]	5630	102	158
Energy spread [10^{-3}]	0.88	1.03	1.16
Radiation loss per turn [keV]	549	554	688
Momentum compaction factor [10^{-4}]	6.04	–1.33	1.05
Working point Q_x, Q_y	20.43, 8.74	39.20, 15.30	39.37, 15.22
Chromaticity ξ_x, ξ_y	–67.3, –21.0	–95.0, –35.2	–99.0, –33.4
Total gross straight length [m]	79.9	66.3	83.6
Vertical emittance in operation [pm.rad]	~5	10	10
Beam lifetime in operation [h]	~9		9.5

FEL UPGRADE

SwissFEL



Linac:

Pulse duration : 1–20 fs

Electron energy : up to 6.2 GeV
(7 GeV after upgrade)

Electron bunch charge: 10–200 pC

Repetition rate: 100 Hz, 2 bunches
(3 bunches after upgrade)

Aramis:

Hard X-ray FEL, λ = 0.1–0.7 nm

Linear polarization, in-vacuum, variable-gap undulators

First users 2018

Porthos:

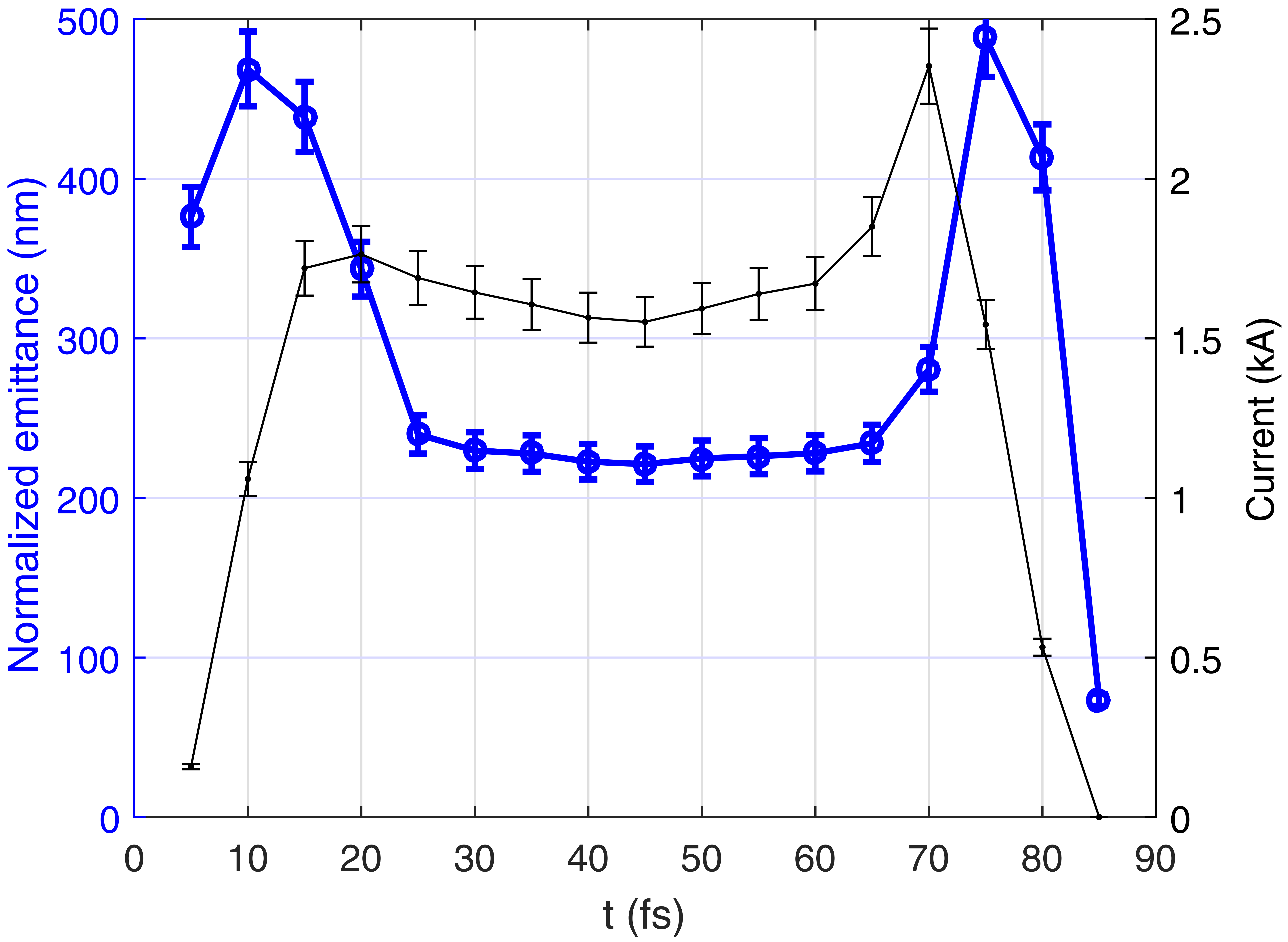
Hard X-ray FEL, λ = 0.12–1.2 nm?

Variable-polarization undulators (technology to be decided)

Construction: 2030s

REQUIREMENTS ON THE ELECTRON BEAM

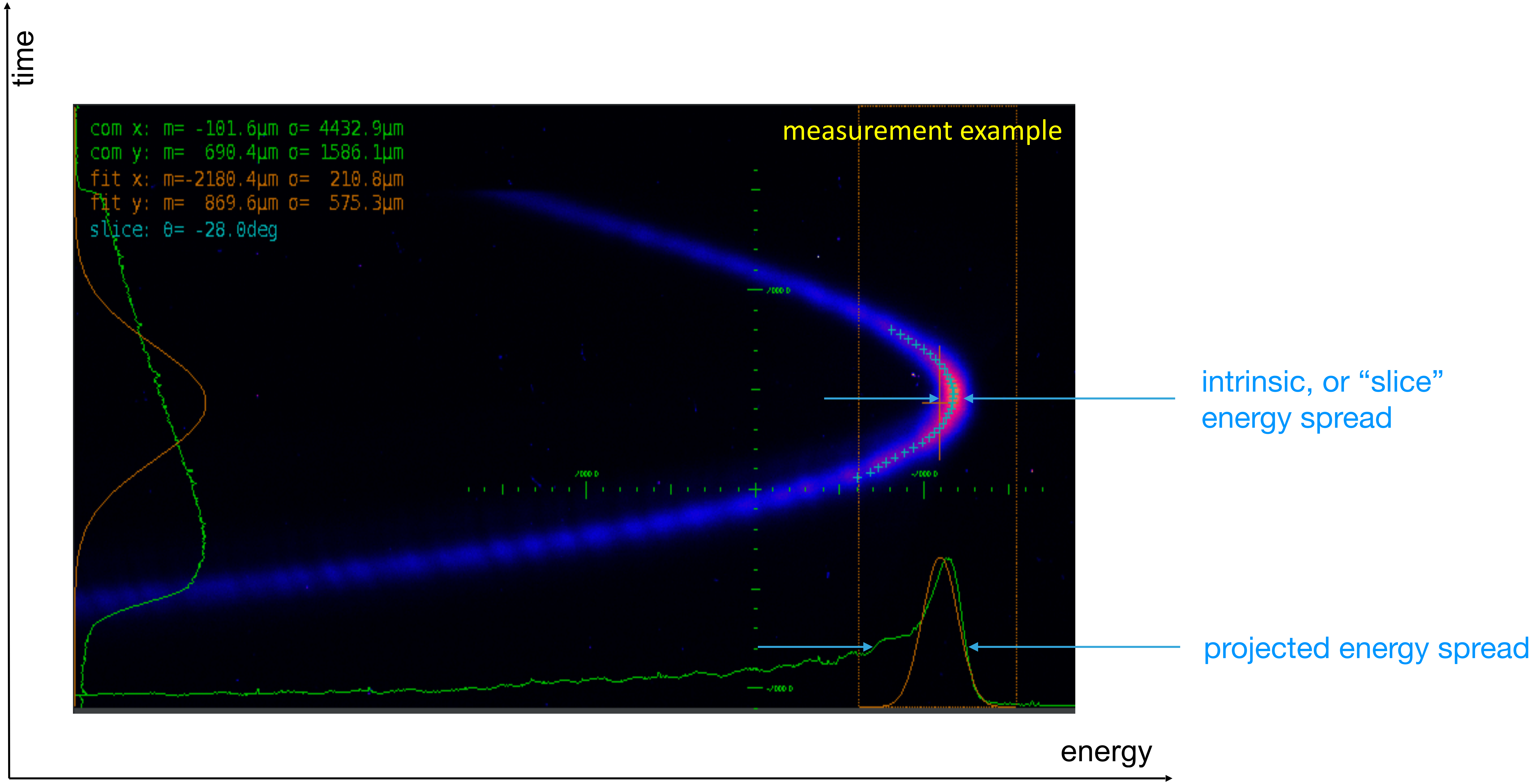
- Transverse normalized slice emittance:
  - predicted:
    - @ 10 pC: 180 nm
    - @ 200 pC: 430 nm
  - measured:
    - @ 10 pC: 100 nm
    - @ 200 pC: 220 nm



Prat et al., PRL 123, 234801 (2019)

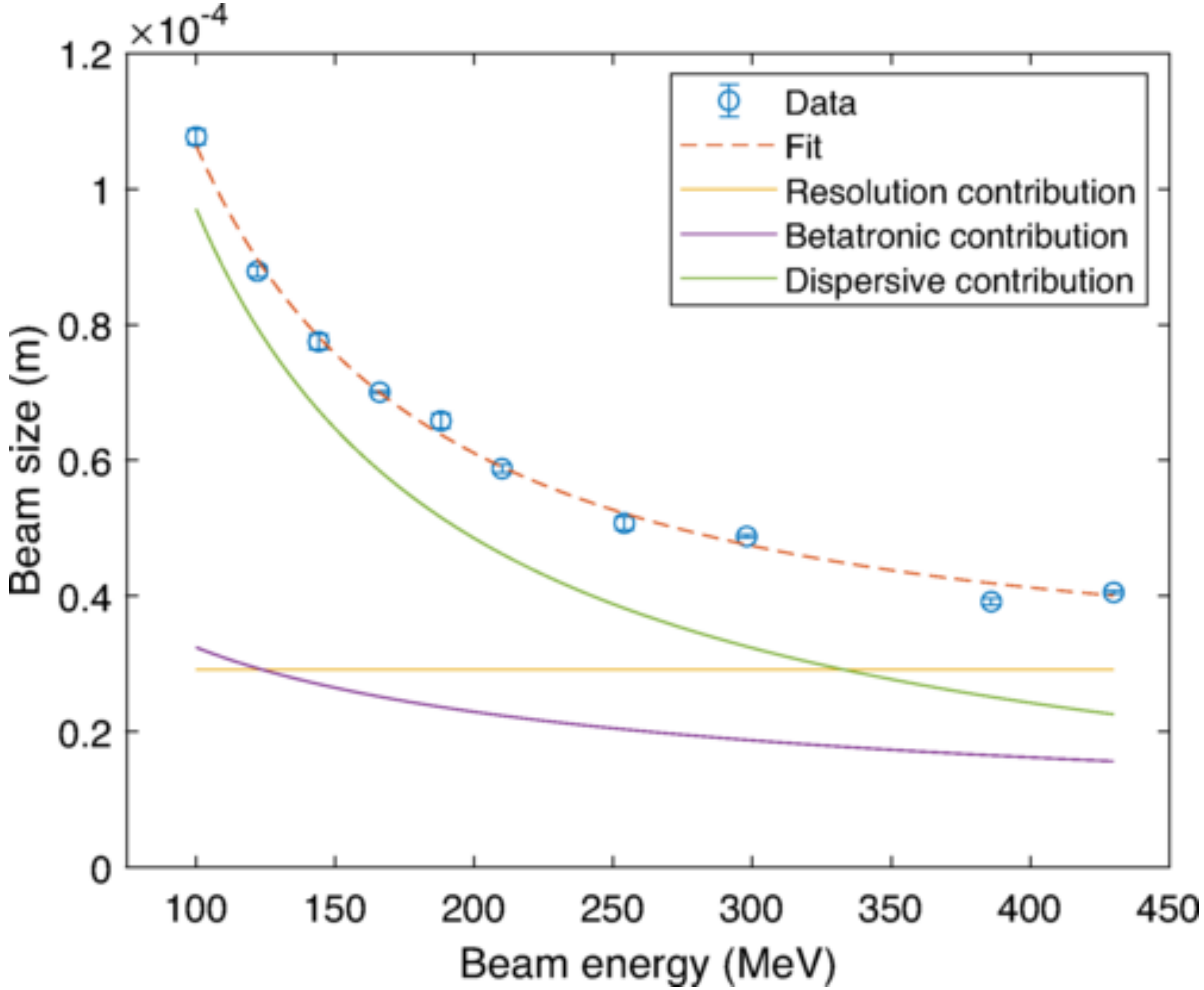
REQUIREMENTS ON THE ELECTRON BEAM

- Slice energy spread of the SwissFEL electron source



SLICE ENERGY SPREAD OF SWISSFEL

- From ASTRA simulations: < 1 keV
- Measured:
  - @ 10 pC: 6.5 ± 0.5 keV
  - @ 200 pC: 15.0 ± 0.3 keV



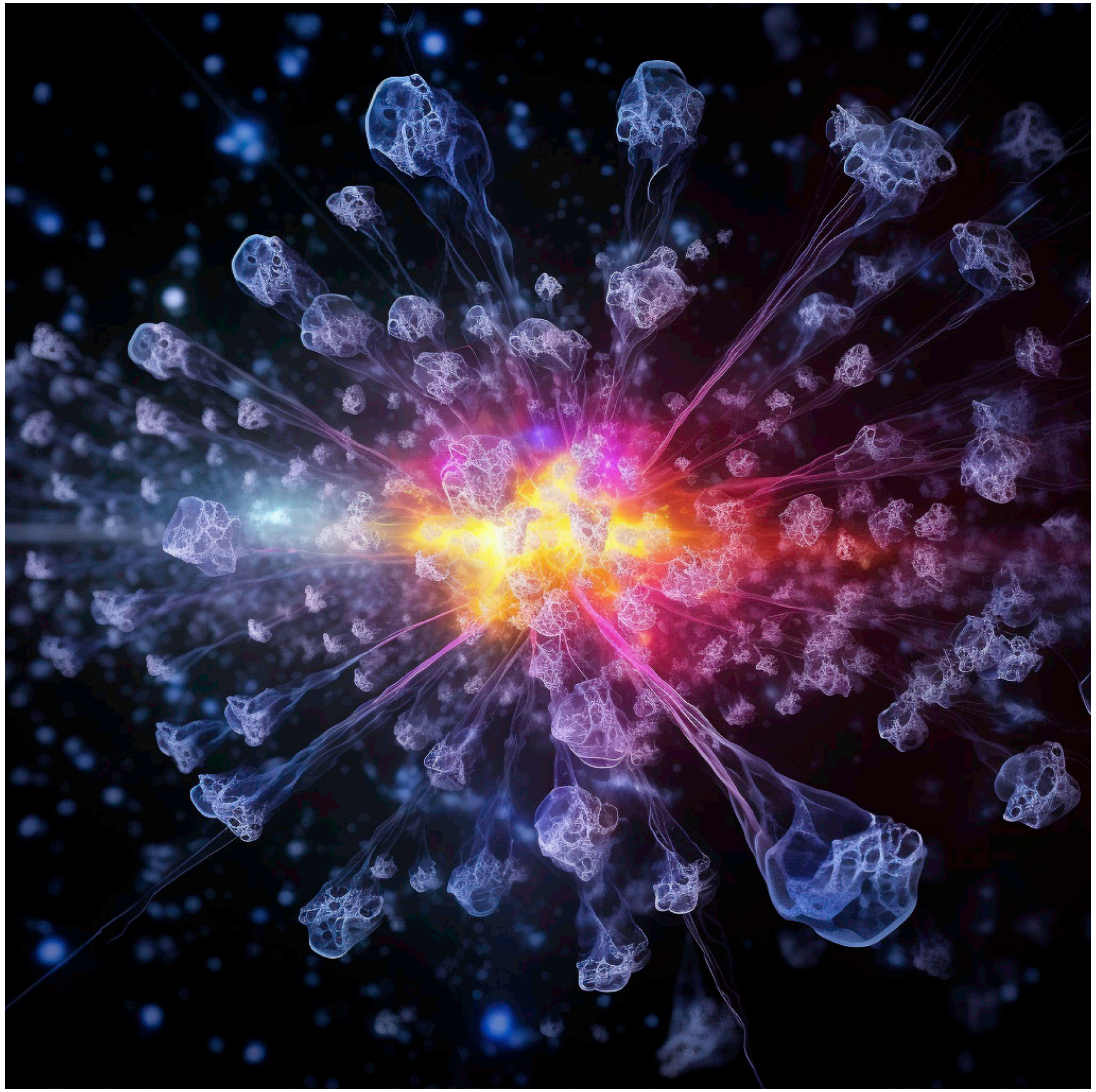
EFFECTS INCREASING THE ENERGY SPREAD

- Intra-beam scattering (IBS)

$$\sigma_E \sim \frac{I^{1/2} z^{1/2}}{\beta^{1/4} \varepsilon_n^{3/2}}$$

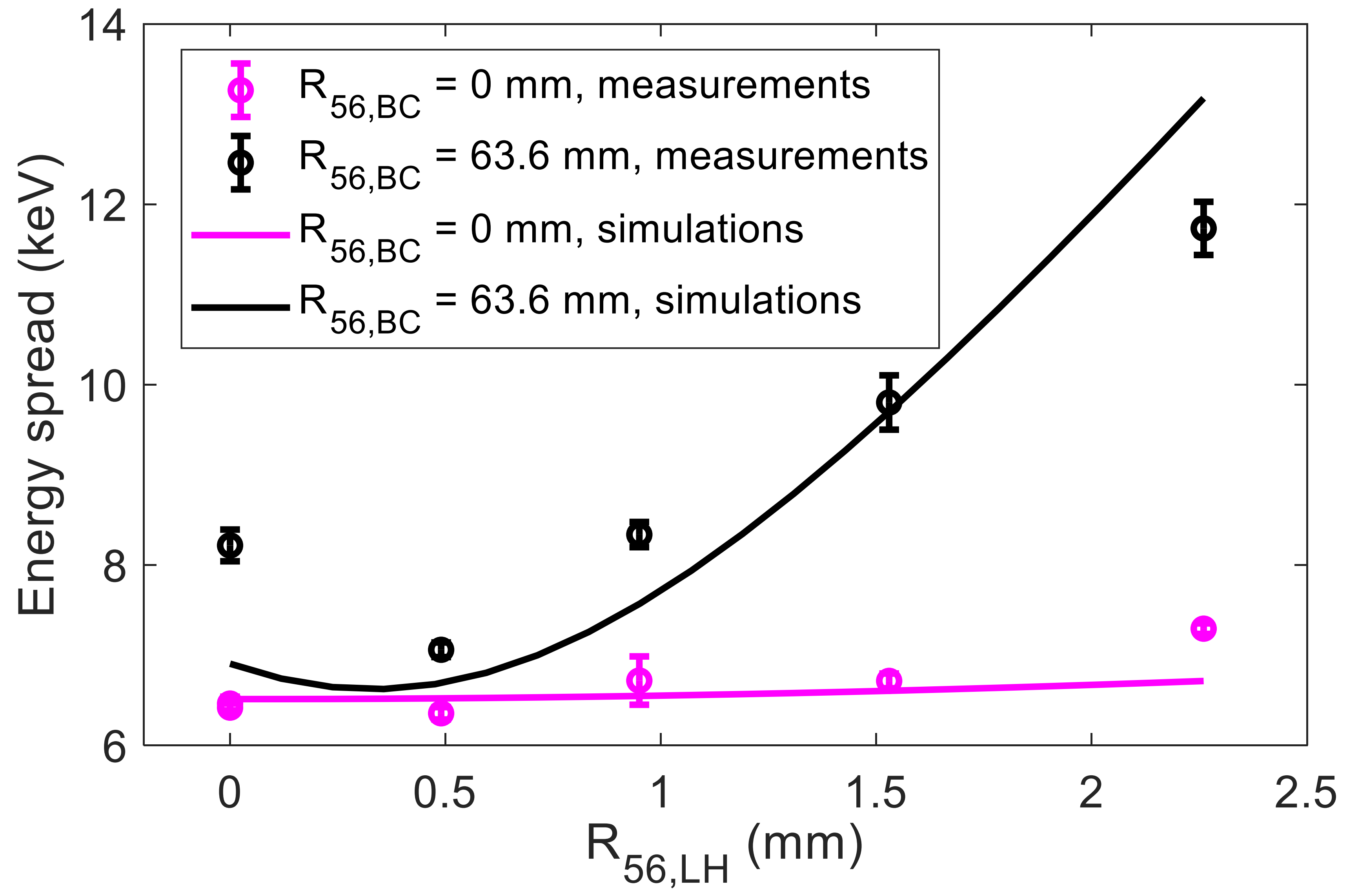
- Microbunching instability (MBI)

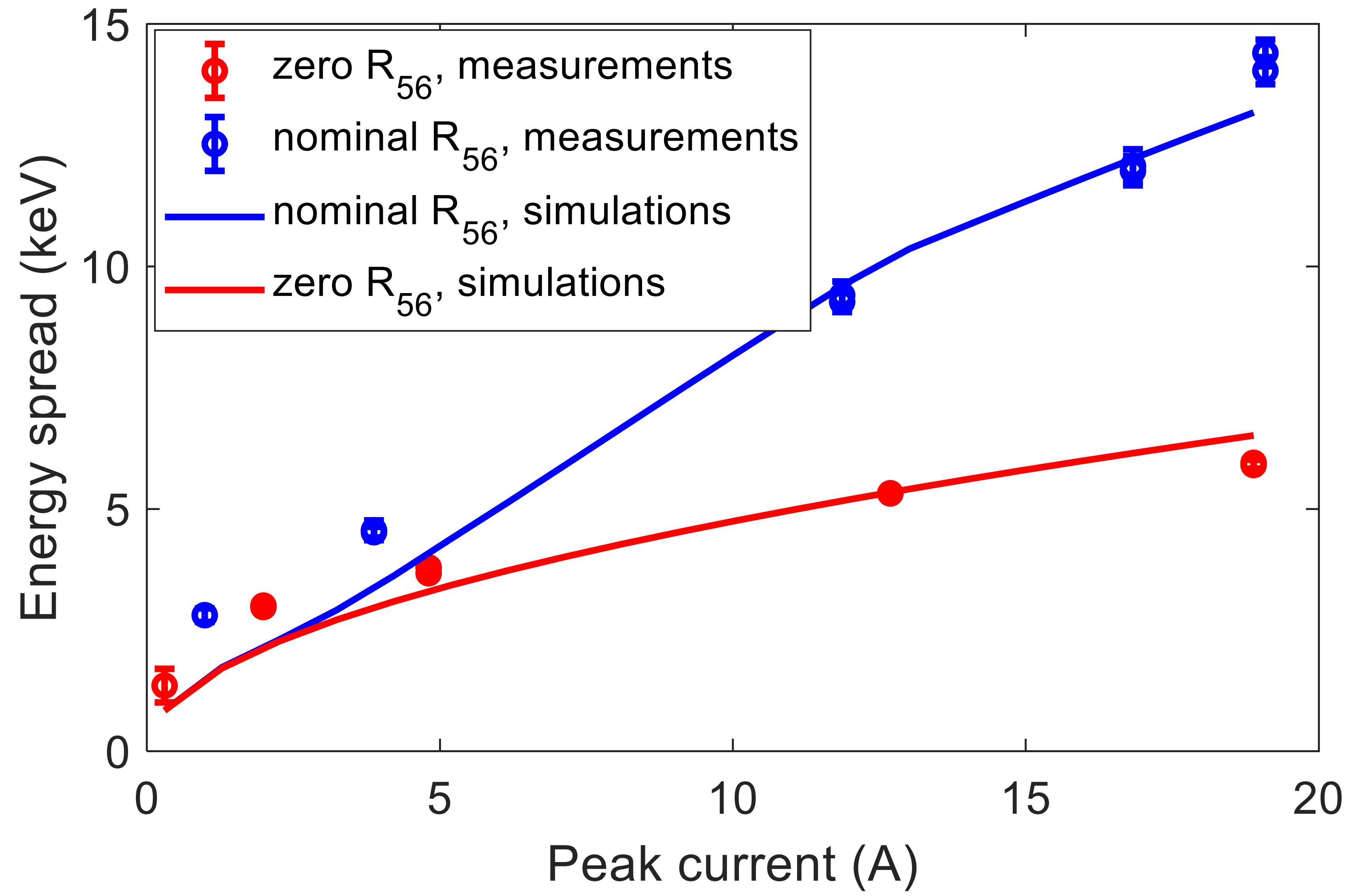
$$\sigma_E \sim I \beta z$$



Eduard Prat; Di Mitri et al, New J. Phys. 22, 083053 (2020) and references herein; Rasmus ⊕ Midjourney

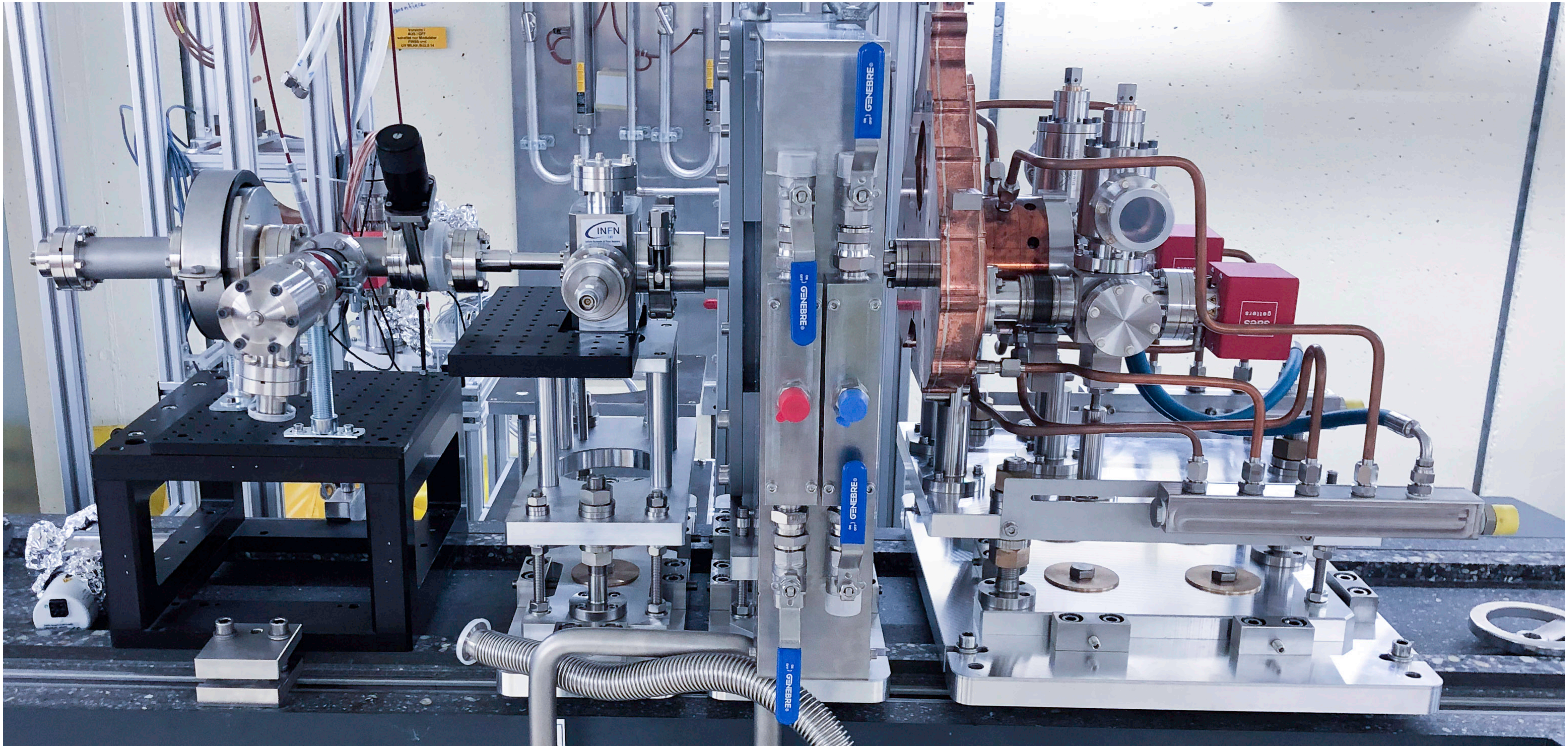
MEASUREMENTS OF ENERGY SPREAD



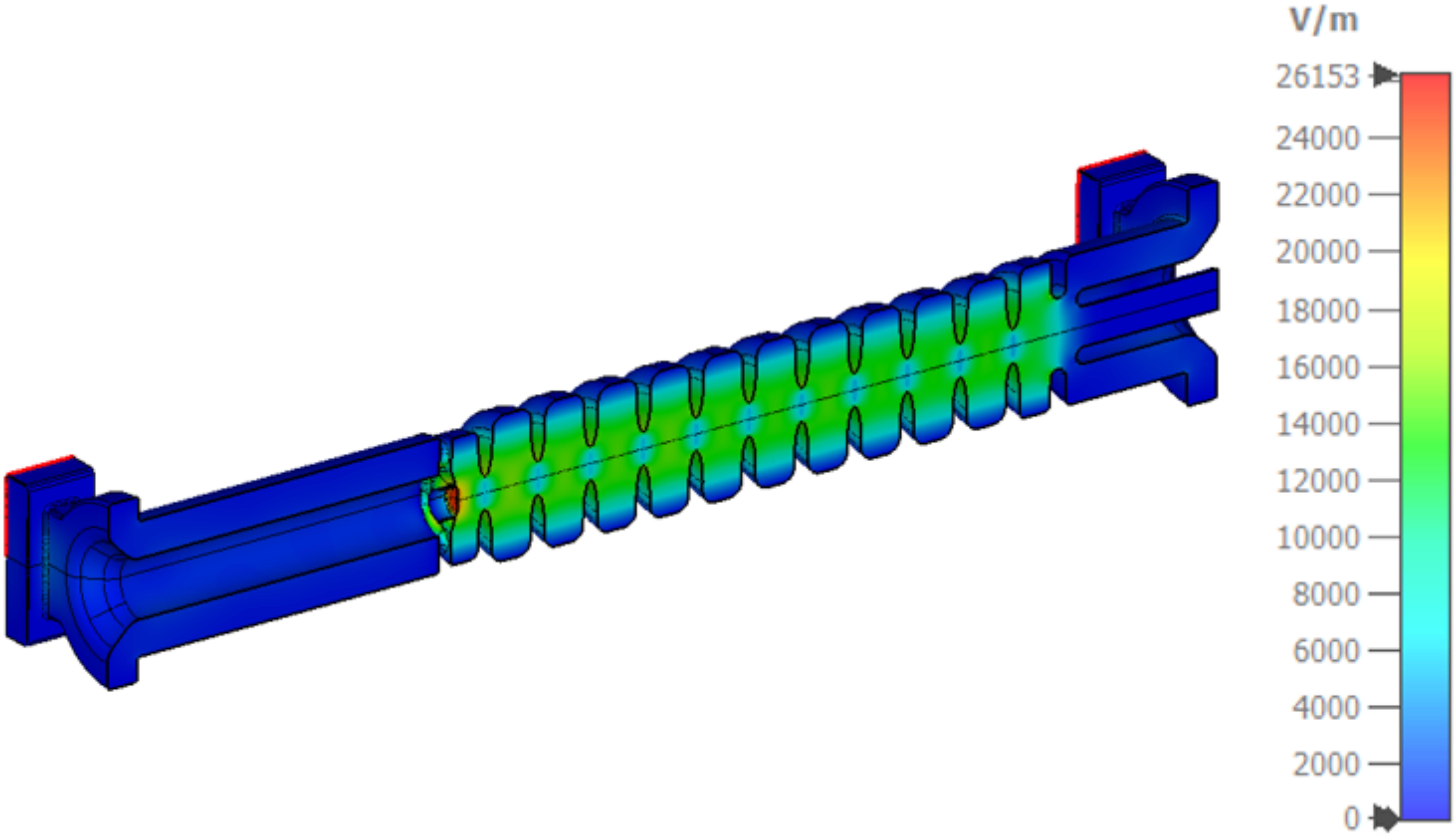


- Overall a good agreement!
- … but we require to increase IBS strength by a factor of ~2.4
- still, underestimation of energy spread for low peak currents and some R56 settings

ELECTRON SOURCE TEST STAND



TRAVELING WAVE C-BAND GUN




SINQ