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Future Development of Accelerator Based Light Sources

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Phys55300-10-FEL

十年樹木，百年樹人

Important Notes to Students: The sole purpose of this lecture notes is meant for educational use only. Some photographs and graphic illustrations are adapted from various reference literatures, which are **NOT** to be distributed beyond the classroom.

[Further Readings]

1. H. Wiedemann, *Particle Accelerator Physics , 3rd ed.* (Springer, 2007)

2. A. W. Chao et al. (eds), *Handbook of Accelerator Physics and Engineering, 2nd ed.* (World Scientific, 2012)

3. Physical Review Accelerators and Beams, https://journals.aps.org/prab/

Outline

- Storage Ring Based Light Sources
- Linac Based Light Sources
- Dreams for Taiwan?

•Storage Ring Based Light Sources

1. Beam emittance

Beam emittance ε_x of e^- storage ring ~ $E^2\,\theta^3$ → smaller bending angle

critical photon energy ε_c [keV]= 0.665 **B**[T] E^2[GeV]

larger circumference

determined by requirements of scientific research

fundamental undulator radiation: $\varepsilon_1[keV] = \dfrac{0.950E^2[GeV]}{\lambda_u[cm](1+K^2/2+\gamma^2\theta^2)}$

$$\varepsilon_x = \frac{C_q}{J_x}\frac{\gamma^2}{\rho} < H >_{dipole} \qquad C_q = 3.8318\times 10^{-13} m\ ,\gamma = \frac{E}{m_0 c^2}$$

$$\boxed{\varepsilon_x = \frac{C_q}{J_x}\gamma^2\theta^3 F}$$

$$J_x = 1 - \frac{1}{2\pi\rho^2}\int_{bend} D_x(s)ds - \frac{2}{2\pi\rho^2}\int_{bend} D_x(s)\frac{\rho}{B_0}\boxed{\frac{dB_y}{dx}}ds$$

J_x is larger ← *negative gradient, i.e. vertical focusing*

the emittance is smaller !

2. Figure of merits for light sources

Flux: $$\frac{number\ of\ \ photons}{\Delta t(0.1\%\ \ fractional\ bandwidth)}$$ more beam current

Brightness:

$$\frac{number\ of\ \ photons}{4\pi^2\Sigma_x\Sigma_{x'}\Sigma_y\Sigma_{y'}\Delta t(0.1\%\ \ fractional\ bandwidth)}$$

more beam current

smaller beam sizes

$$\Sigma_i = \sqrt{\sigma_i^2 + \sigma_r^2}, \Sigma_{i'} = \sqrt{\sigma_{i'}^2 + \sigma_{r'}^2}$$

Coherent Fraction (CF):

$$CF = \frac{\left(\sigma_r \sigma_{r'}\right)^2}{\Sigma_x\Sigma_{x'}\Sigma_y\Sigma_{y'}}$$

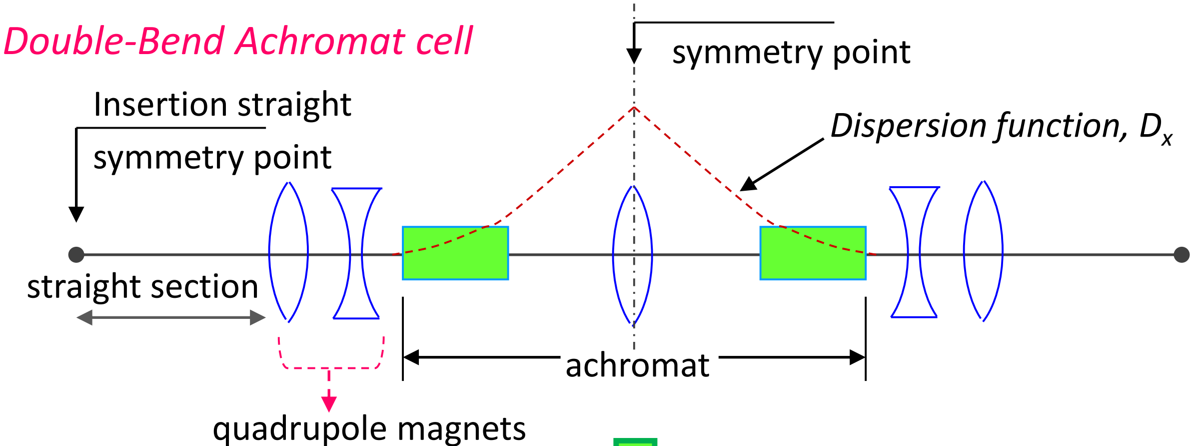
Diffraction limited beam emittance: $\lambda/4\pi$

To approach the diffraction limit and increase the brightness of radiation, you need

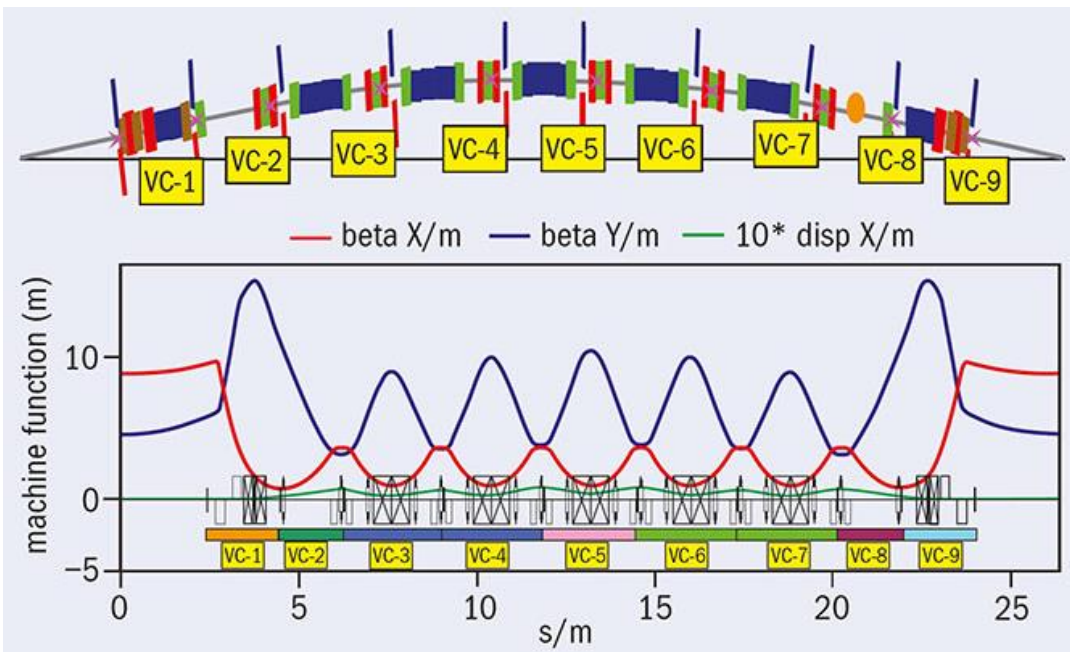
- smaller electron beam emittance
- better matching of photon beam and electron beam

3. Developing trend of lattice design for storage ring

• *Double-Bend Achromat cell*



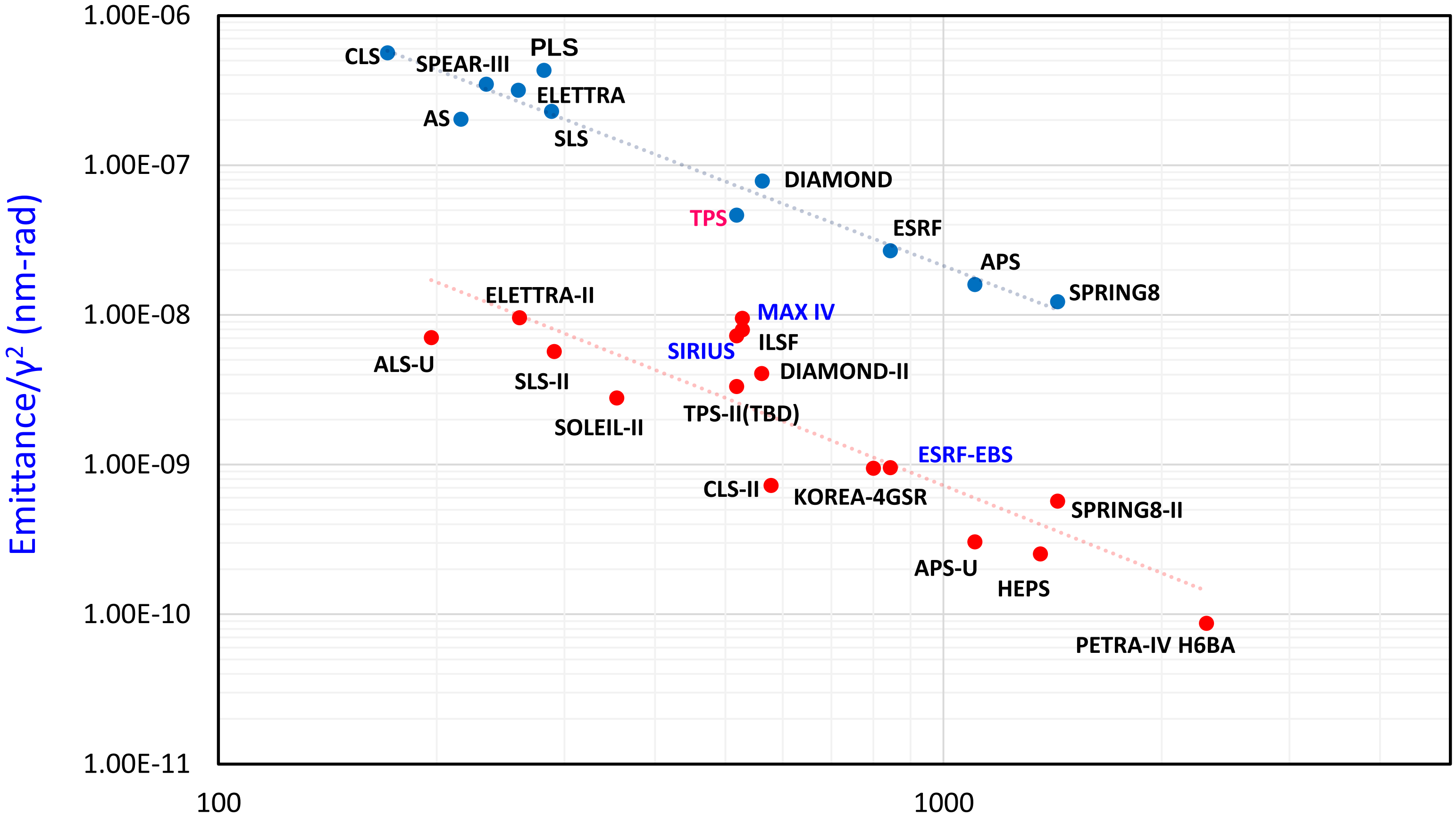
• *Multi-Bend Achromat cell*



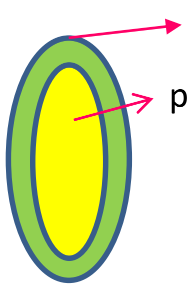
more bending magnets!

Credit: CERN Courier, Aug. 2016

4. Plot of beam emittance vs. accelerator circumference



adapted from R. Bartollini, Courtesy of Nuan-Ya Huang



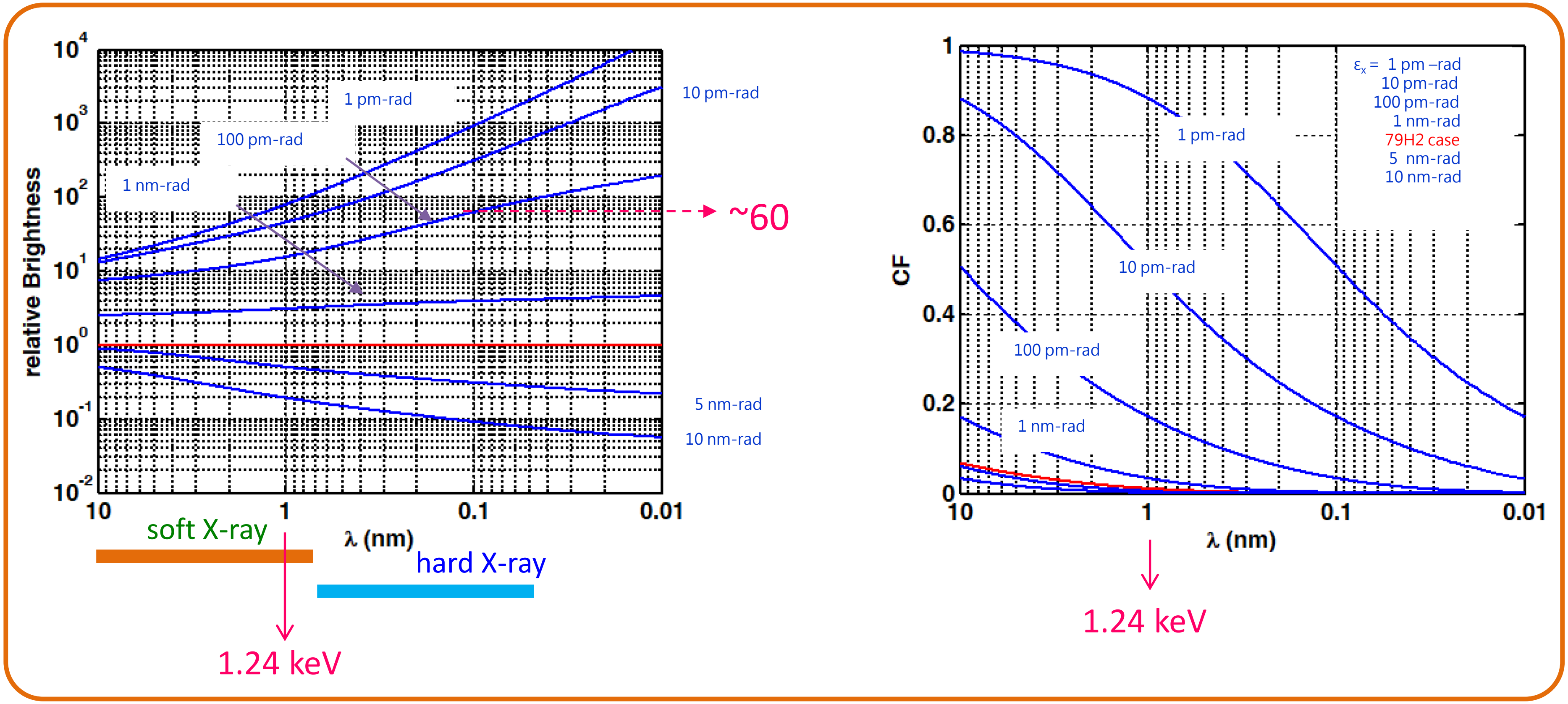
electron beam emittance

photon beam emittance

- *Better matching of phase space is more important than a smaller e- emittance → higher brightness*

5. What if we upgrade the existing TPS?

Baseline lattice: case, β_x = 5.35 m, β_y = 1.73 m, η_x = 0 m, σ_E =1e-3, ε_x = 1.6e-9, $\varepsilon_y/\varepsilon_x$ = 1%
Assumptions: L_{ID} = 3 m, η_x = 0 m, the same spectral flux (same beam current)

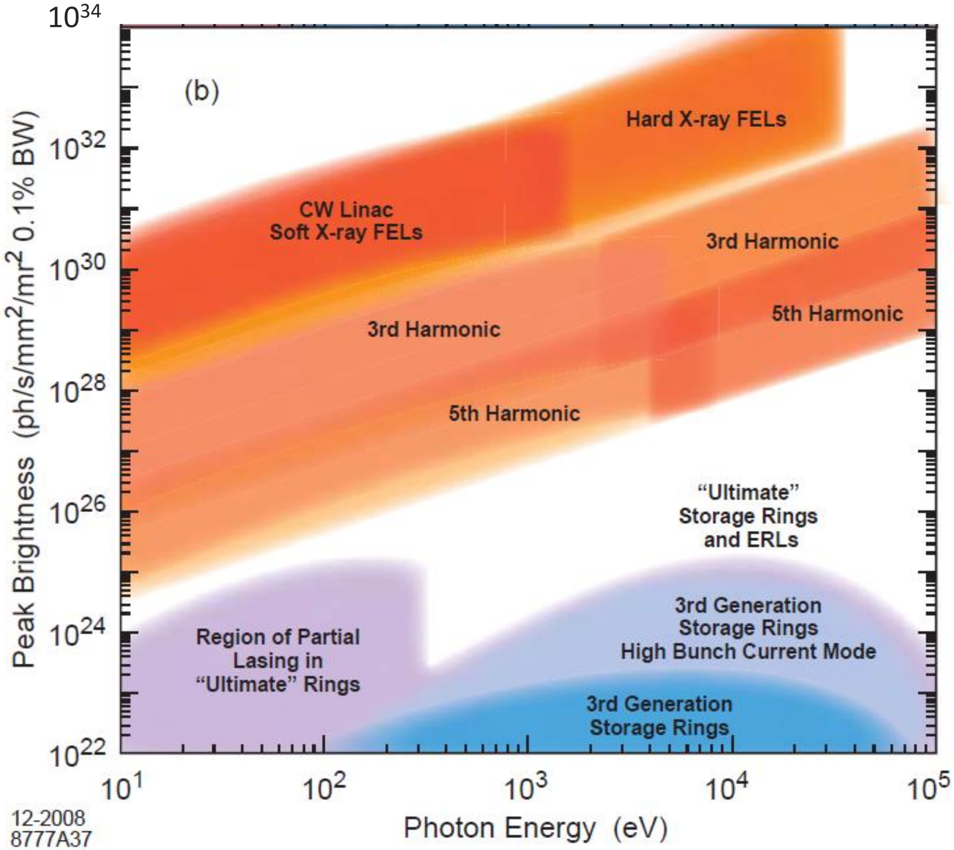


Courtesy of Nuan-Ya Huang

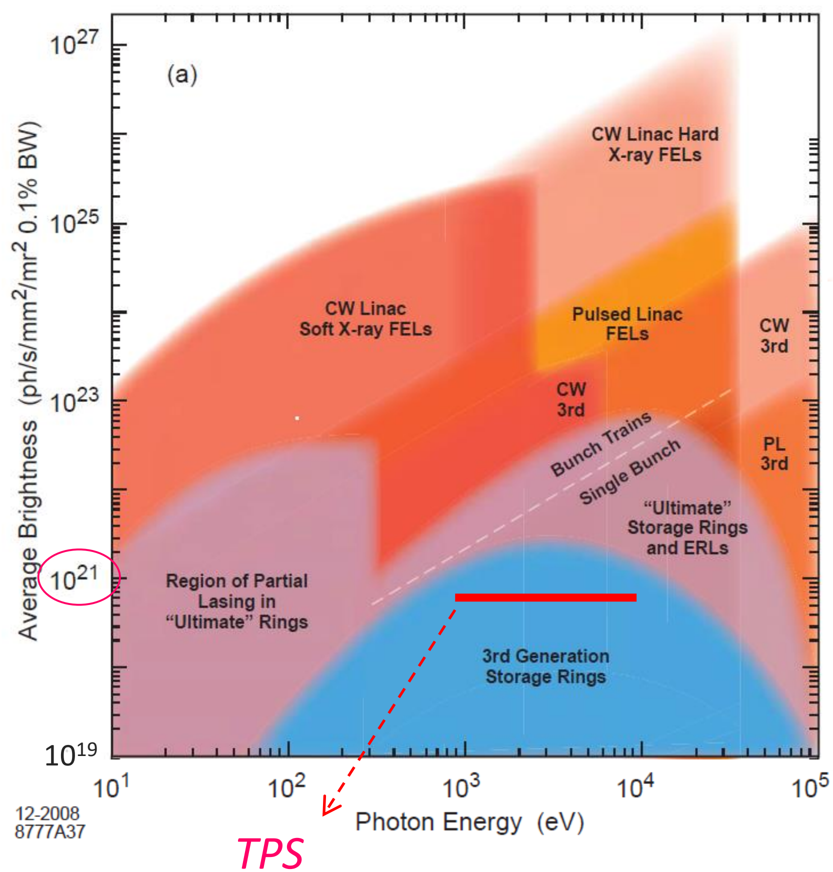
- Increase of brightness and coherent fraction, especially for hard X-ray.
- Is this expensive investment worth it?

•Science and Technology of Future Light Sources— A White Paper (SLAC-R-917)

Peak Brightness



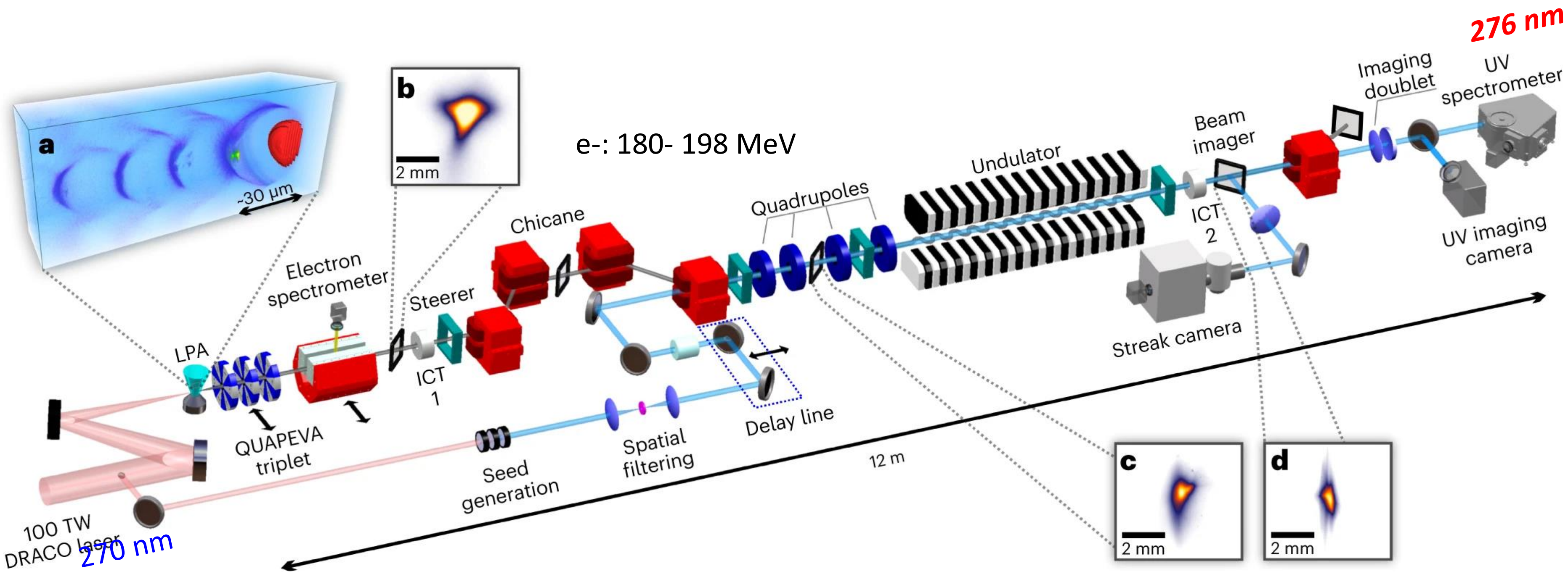
Average Brightness



[Ref.] SLAC-R-917, https://doi.org/10.2172/948040

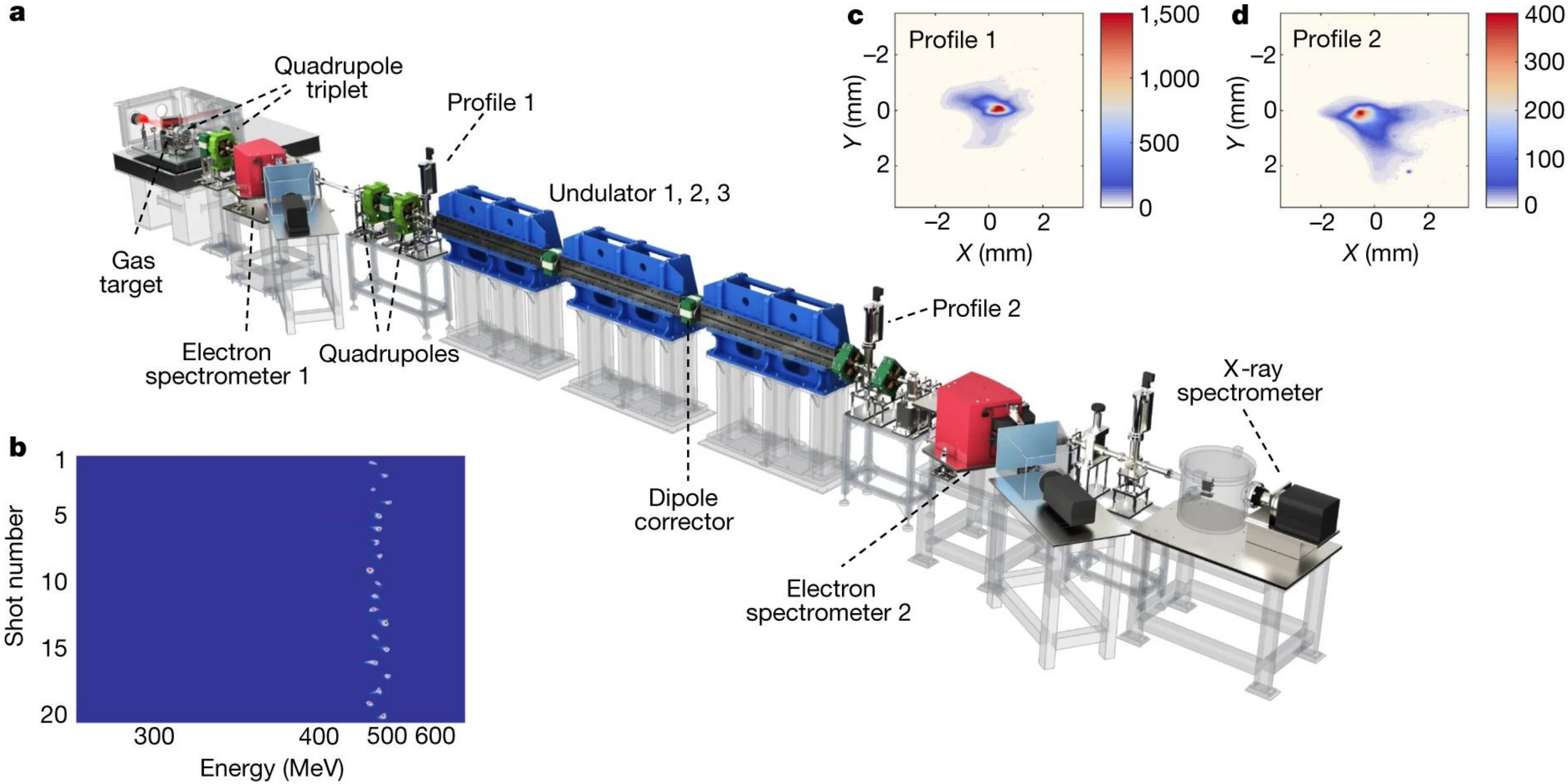
•Linac Based Light Sources

1. FEL driven by a compact laser plasma accelerator (seeded FEL, 276 nm)



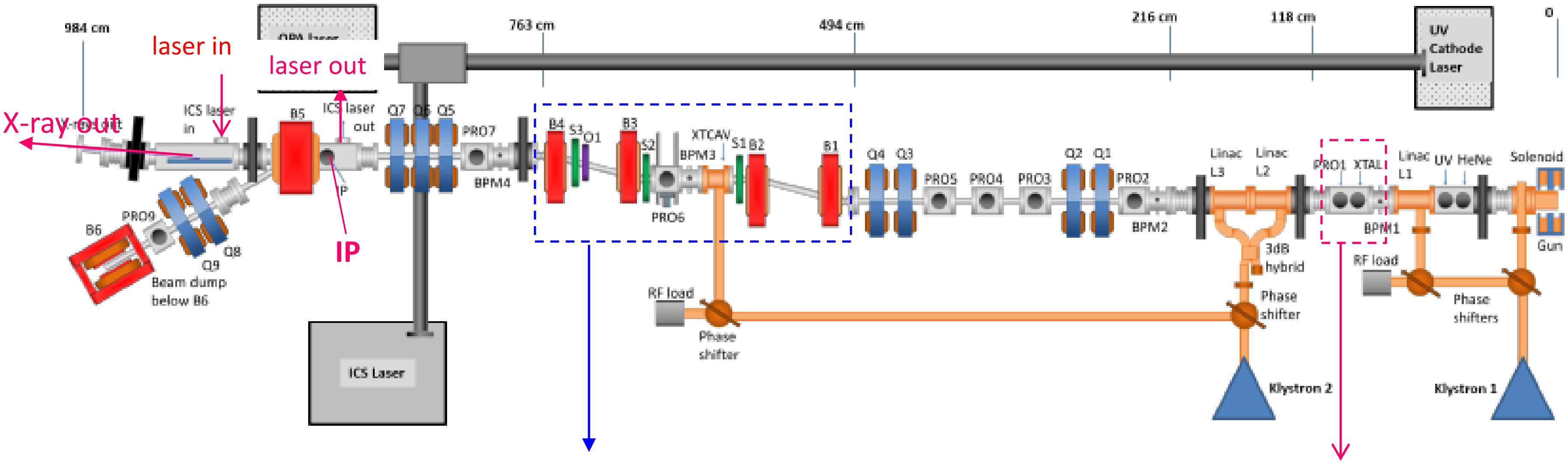
[Ref.] Nature Photonics **17**, 150-156 (2023), https://doi.org/10.1038/s41566-022-01104-w

2. FEL driven by a compact laser plasma accelerator (SASE FEL, 27 nm)



[Ref.] Nature **595**, 516-520 (2021), https://doi.org/10.1038/s41586-021-03678-x

3. Compact X-ray FEL based on nanomodulated electron beams and inverse Compton scattering (ICS)

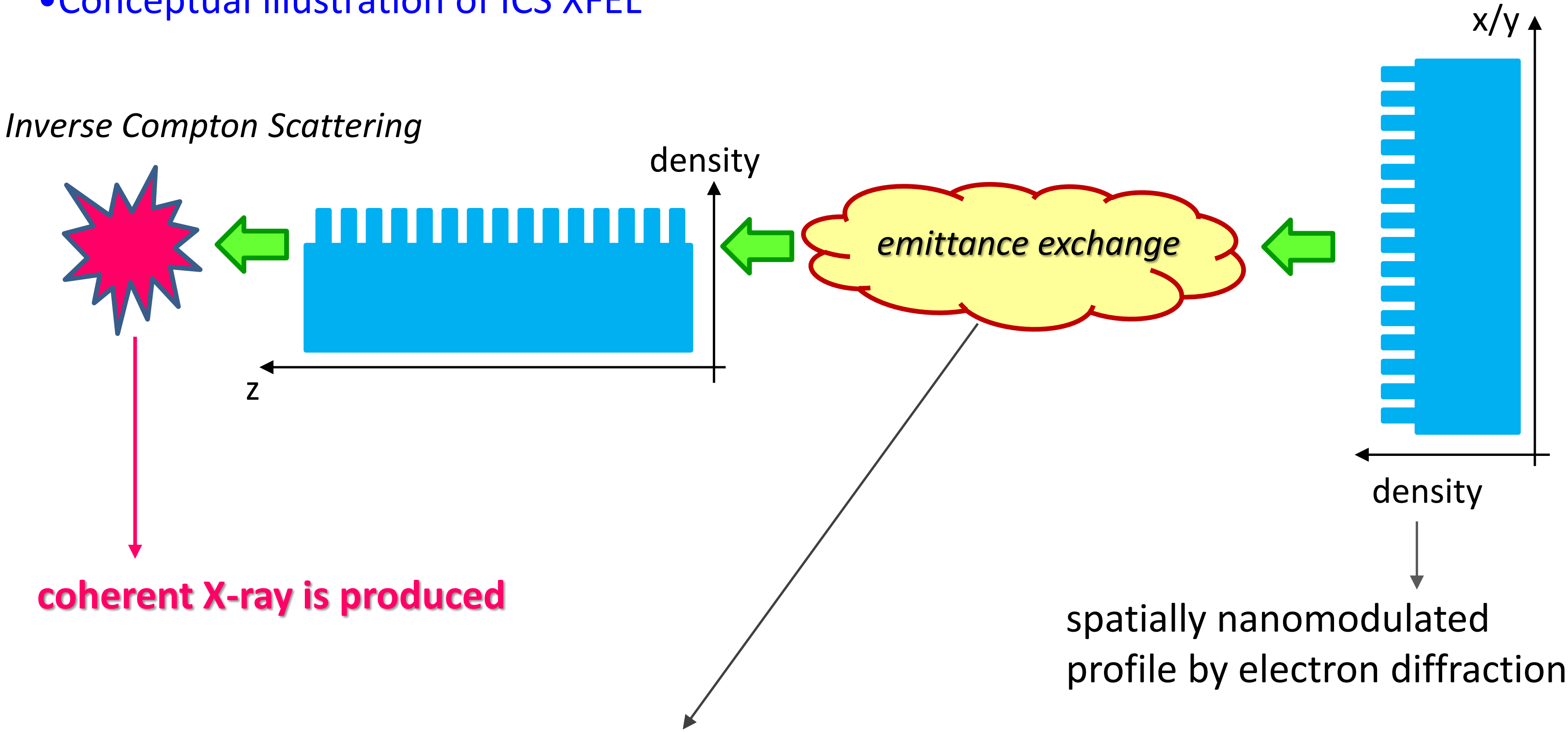


- transverse-to-longitudinal emittance exchange: transforming a spatial modulation to a coherent temporal modulation

- nanomodulated transverse beam profile by electrons been diffracted by single crystal Si grating

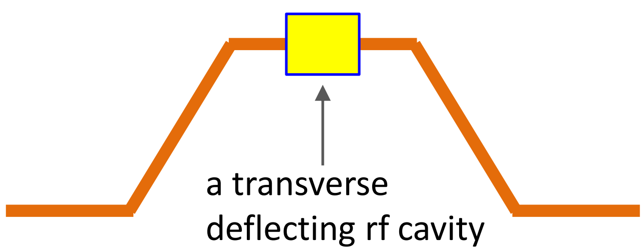
[Ref.] E.A. Nanni, W.S. Graves, and D.E. Moncton, PRAB 21, 014401 (2018)

• Conceptual illustration of ICS XFEL



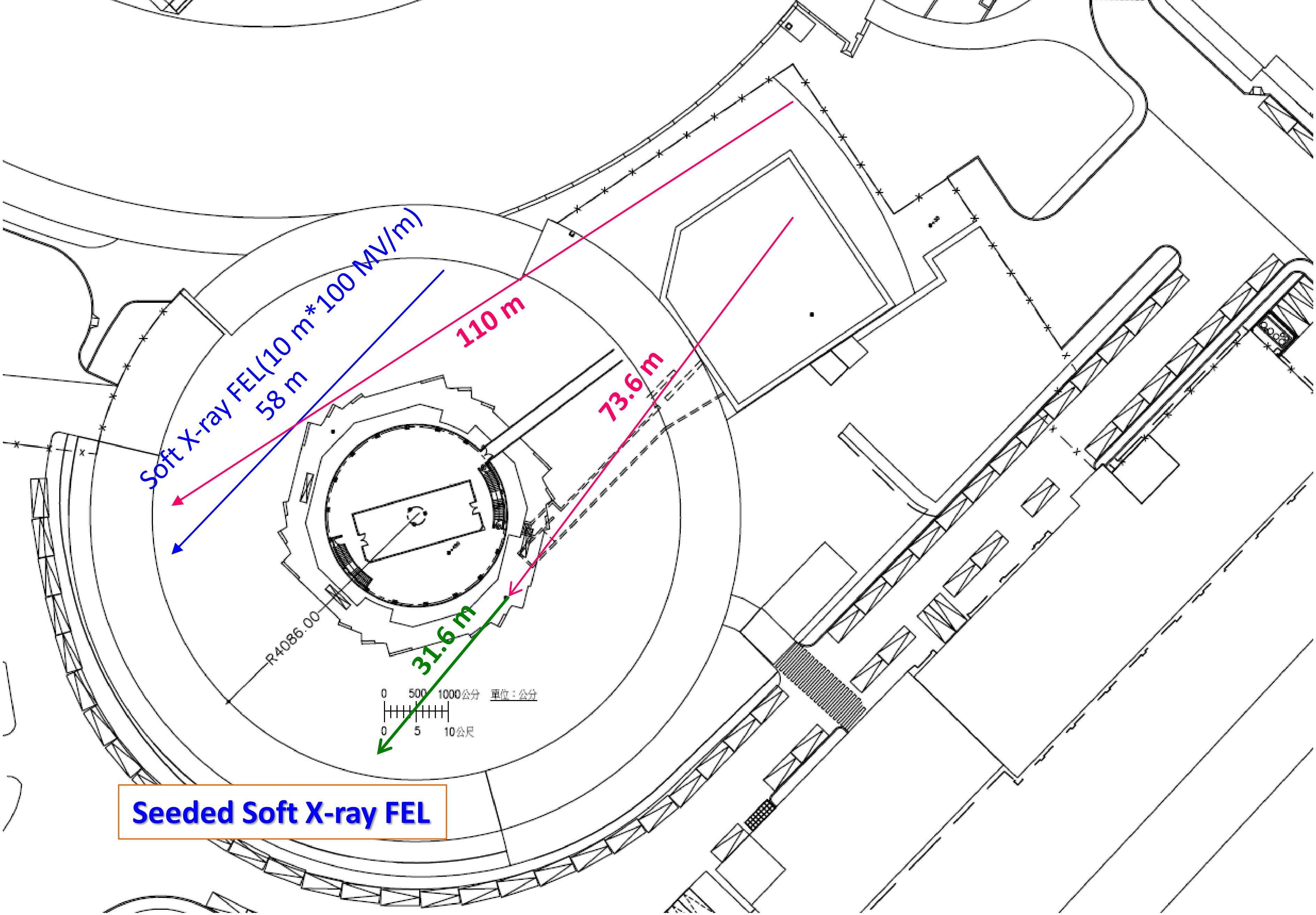
The generic configuration of emittance exchange:

a chicane with a transverse cavity at its center



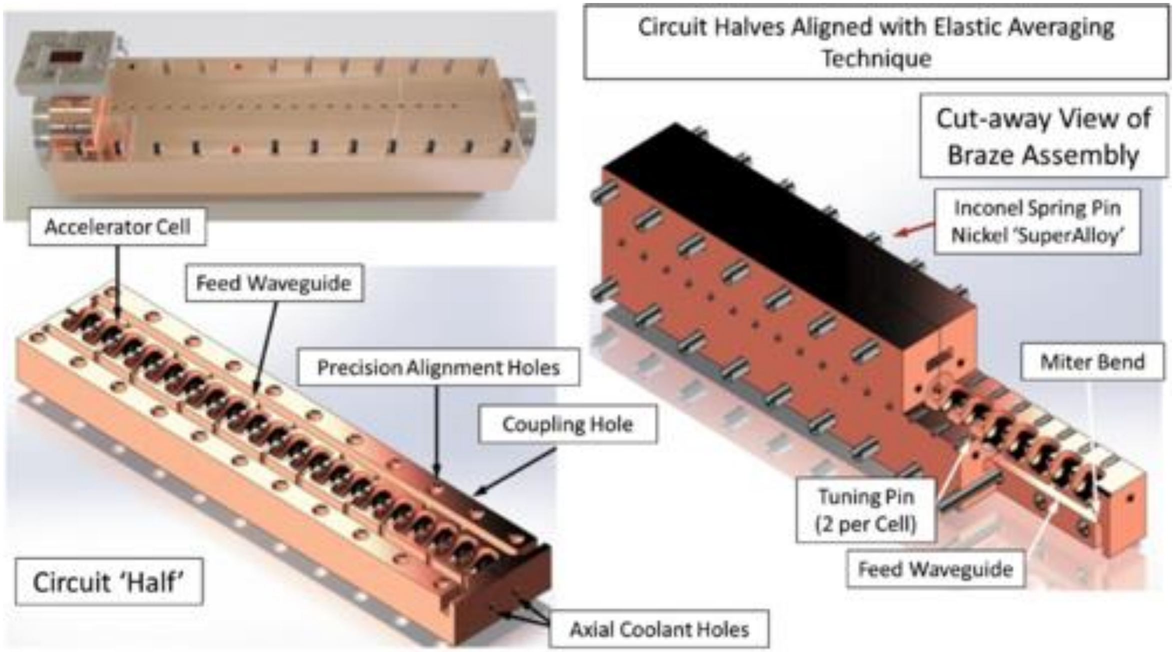
[Ref.] M. Cornacchia and P. Emma, PRST-AB **5**, 084001 (2002)

•Dreams for Taiwan?



Seeded Soft X-ray FEL

•Potential accelerator technology for compact FEL:
Cool **C**opper **C**ollider (C3), X-band 11.424 GHz, in 77 K liquid nitrogen



[Ref.] *Phys. Rev. Accel. Beams*, **23**, 092001 (2020),
Phys. Rev. Accel. Beams, **24**, 093201 (2021)

The accelerating gradient of 150 MV/m was experimentally demonstrated at SLAC