Progress towards seeded LWFA-based FEL and lessons learned

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On behalf of the COXINEL collaboration

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erc European Research Council Established by the European Commission

The COXINEL collaboration

I. Andriyash, S. Corde, O. Kononenko, G. Lambert, V. Malka, S. Smartzev, C. Thaury et al.

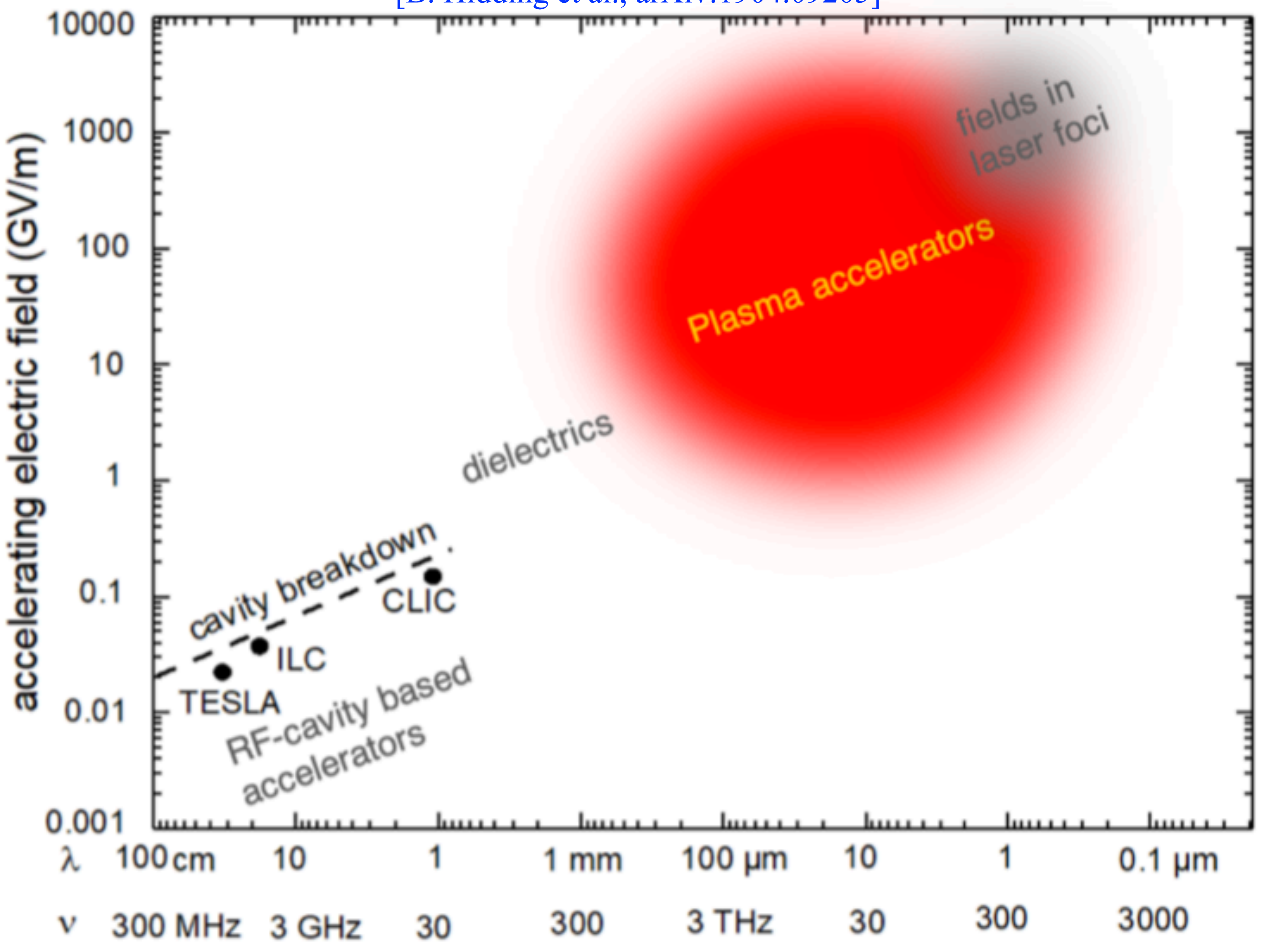
T. André, M. E. Couprie, A. Ghaith, M. Labat, A. Loulergue, D. Oumbarek et al.

S. Bielawski, E. Roussel et al.

Introduction to LWFA-based FEL

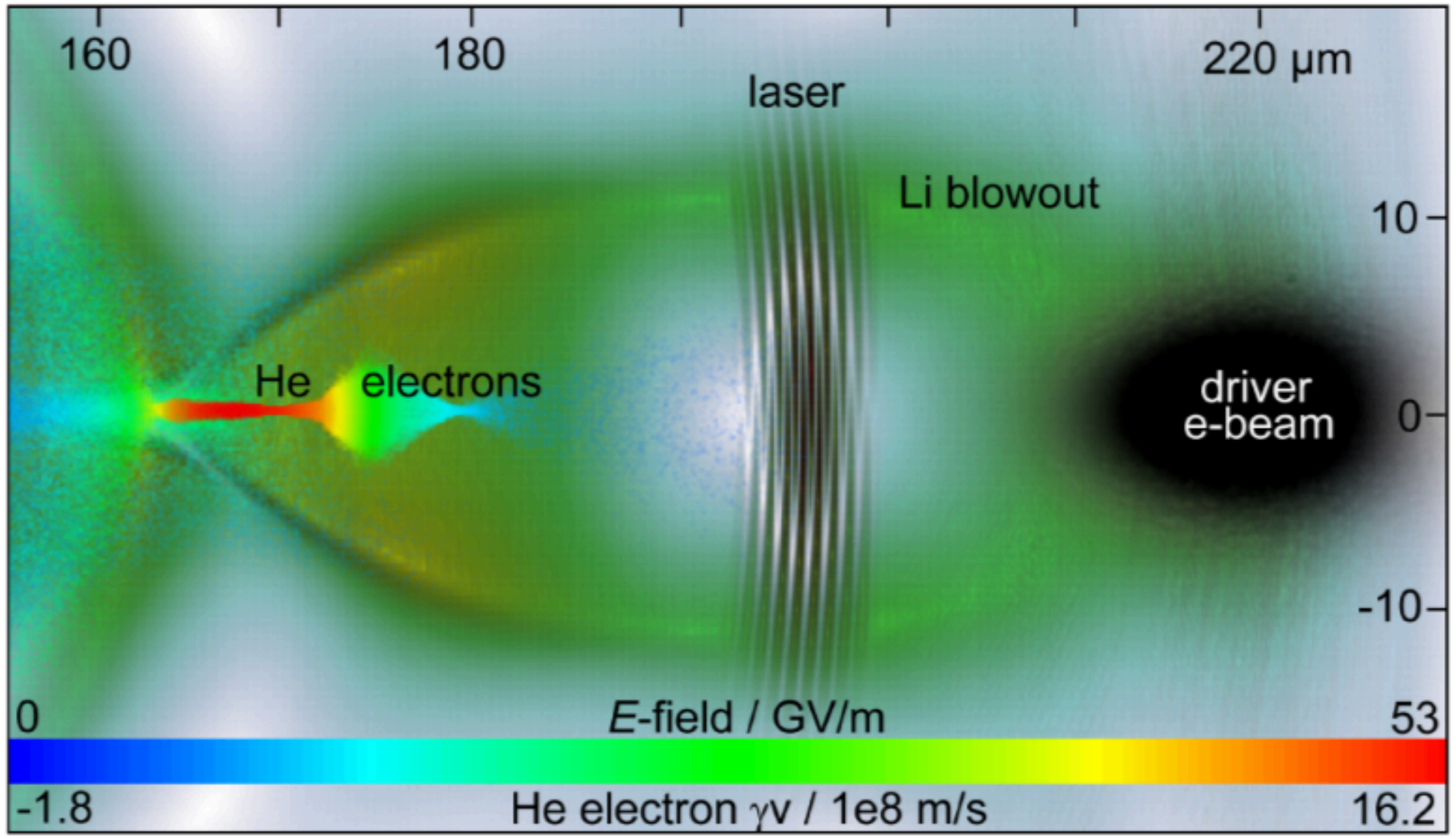
Towards compact accelerators and higher brightness

[B. Hidding et al., arXiv:1904.09205]



Higher fields in plasma

[B. Hidding et al., PRL 108, 053001 (2012)]



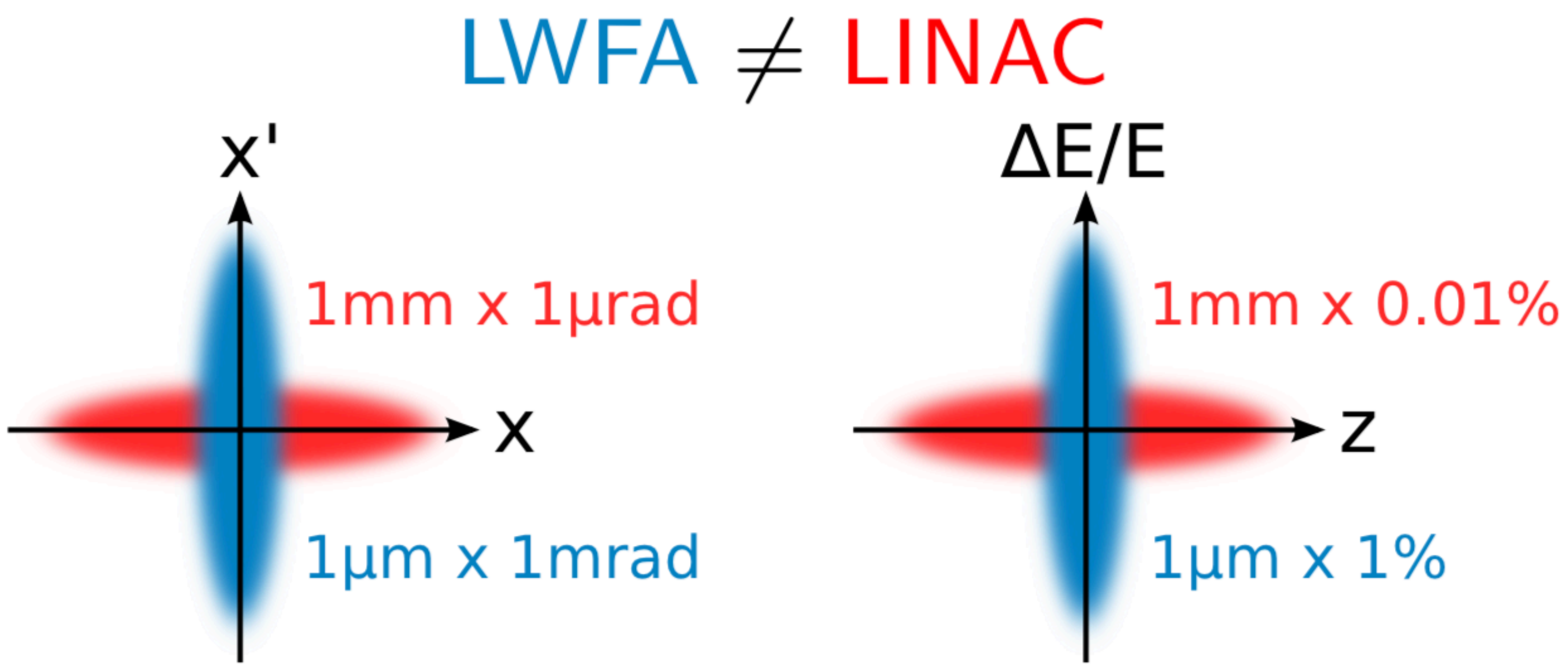
Higher brightness from plasma photocathode

One major objective for plasma accelerators: a plasma-based FEL, so-called 5th generation light source

Using laser-driven plasma accelerators: LWFA-based FEL

Electron beam from LWFA

Characteristic electron beam properties:



transverse and longitudinal phase-space

Chromatic effect:

$$\gamma\varepsilon_{total} = \sqrt{\gamma^2\varepsilon_0^2 + \gamma^2\varepsilon_{chrom}^2}$$

$$\varepsilon_{chrom} \propto \sigma'^2\ \sigma_\gamma/\gamma$$

Bunch lengthening effect:

$$\sigma_s^2 \approx \sigma_{s0}^2 + (r_{56}\frac{\sigma_\gamma}{\gamma})^2 + (r_{522}\sigma_{x0}'^2 + r_{544}\sigma_{z0}'^2)^2.$$

FEL Pierce parameter

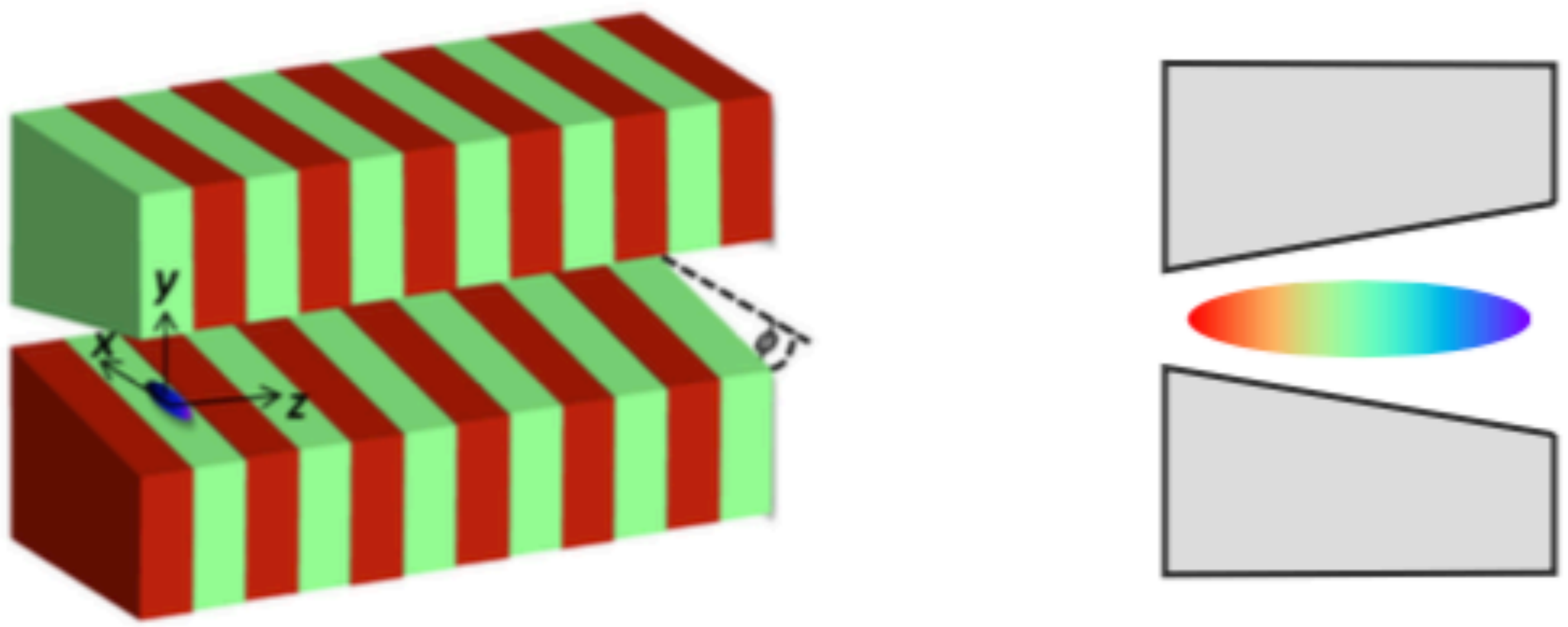
$$\rho = \left[\left(\frac{I}{I_A}\right)\left(\frac{\lambda_u K_u[JJ]}{2\sqrt{2}\pi\sigma_x}\right)^2\left(\frac{1}{2\gamma_0}\right)^3\right]^{1/3}$$

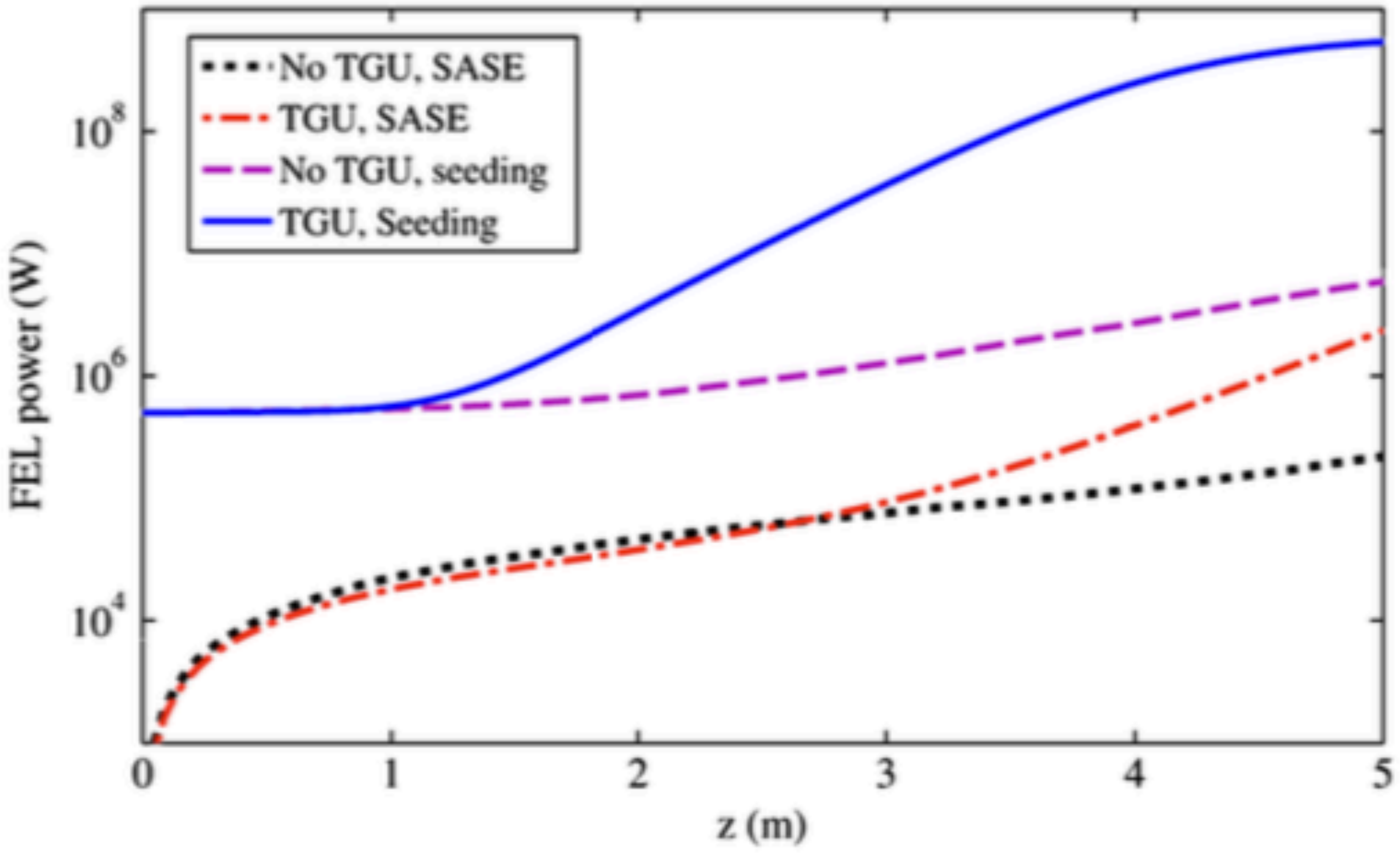
For FEL gain, need small slice/effective energy spread:

$$\sigma_\delta < \rho$$

Strategies for energy spread mitigation

1. transverse-gradient undulator (TGU)





- vertical undulator field
  $\Delta K/K_0 = \alpha x$
- horizontal dispersion
  $x = \eta \Delta\gamma/\gamma_0$

effective e-spread

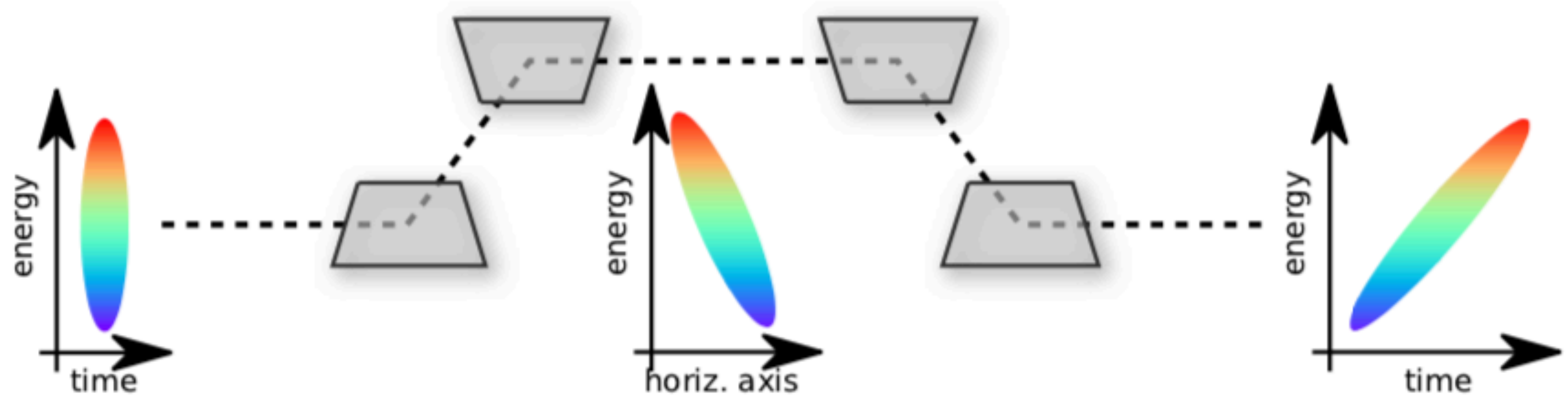
$$\sigma_\delta^{eff} = K_0^2/(2+K_0^2)\alpha\sigma_x$$

[Z. Huang, et al., Phys. Rev. Lett. **109**, 204801 (2012)]

→ Strongly sensitive to transverse pointing fluctuations ! ☹

Strategies for energy spread mitigation

❷ bunch stretching in a magnetic chicane



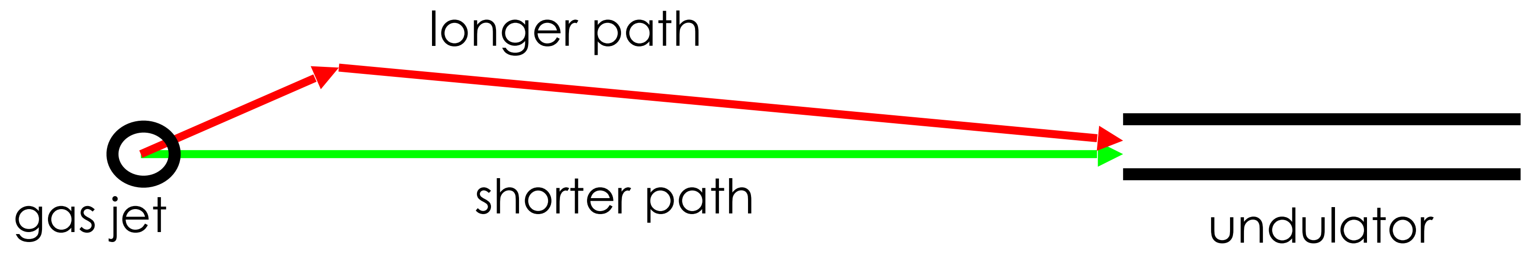
▷ longitudinal energy sorting
$\Delta z = R_{56}\sigma_{\delta 0}$

slice e-spread

$$\sigma_\delta \simeq \sqrt{\sigma_{z0}^2 + 2(R_{522}\sigma_{x'0}^2)^2 + 2(R_{544}\sigma_{y'0}^2)^2} / R_{56}$$

[M.E. Couprie, et al., J. of Phys. B: AMO Phys. **47**, 234001 (2014)], [A.R. Maier et al., Phys. Rev. X **2**, 031019 (2012)]

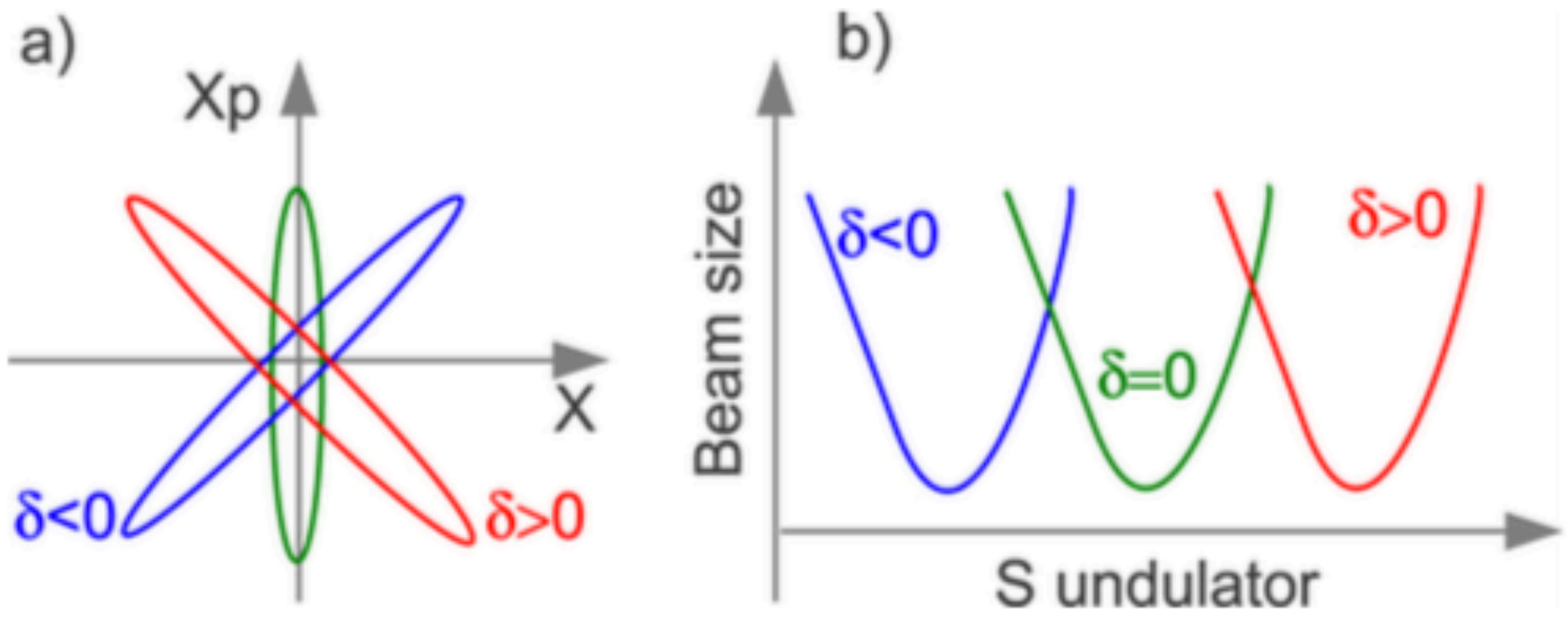
→ Large divergence increases the slice e-spread ! ☹

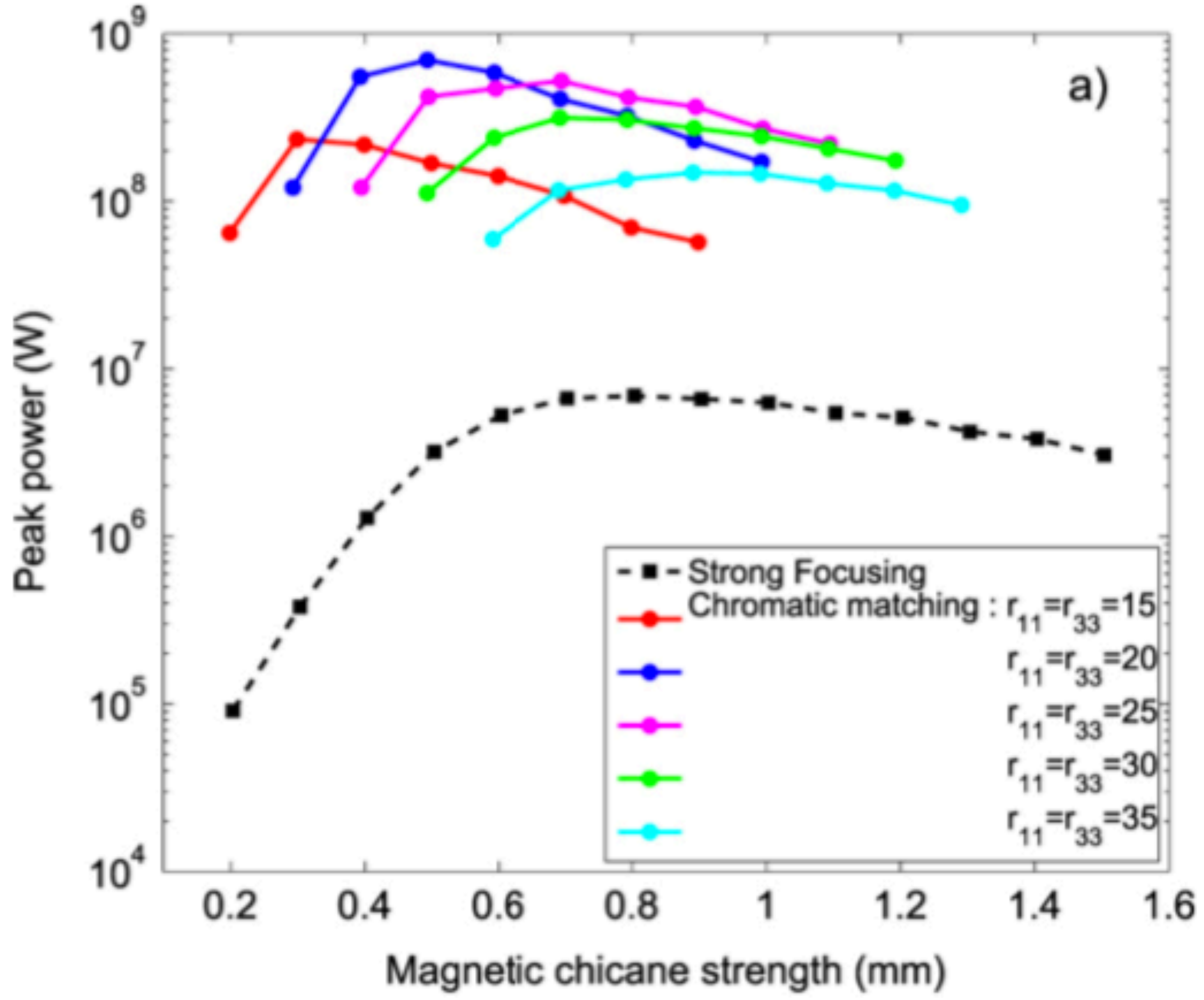


$$\Longrightarrow R_{522} \simeq R_{544} \simeq 0.3 \text{ m}$$

Chromatic matching

- synchronization of the e-beam size in the undulator with FEL slippage



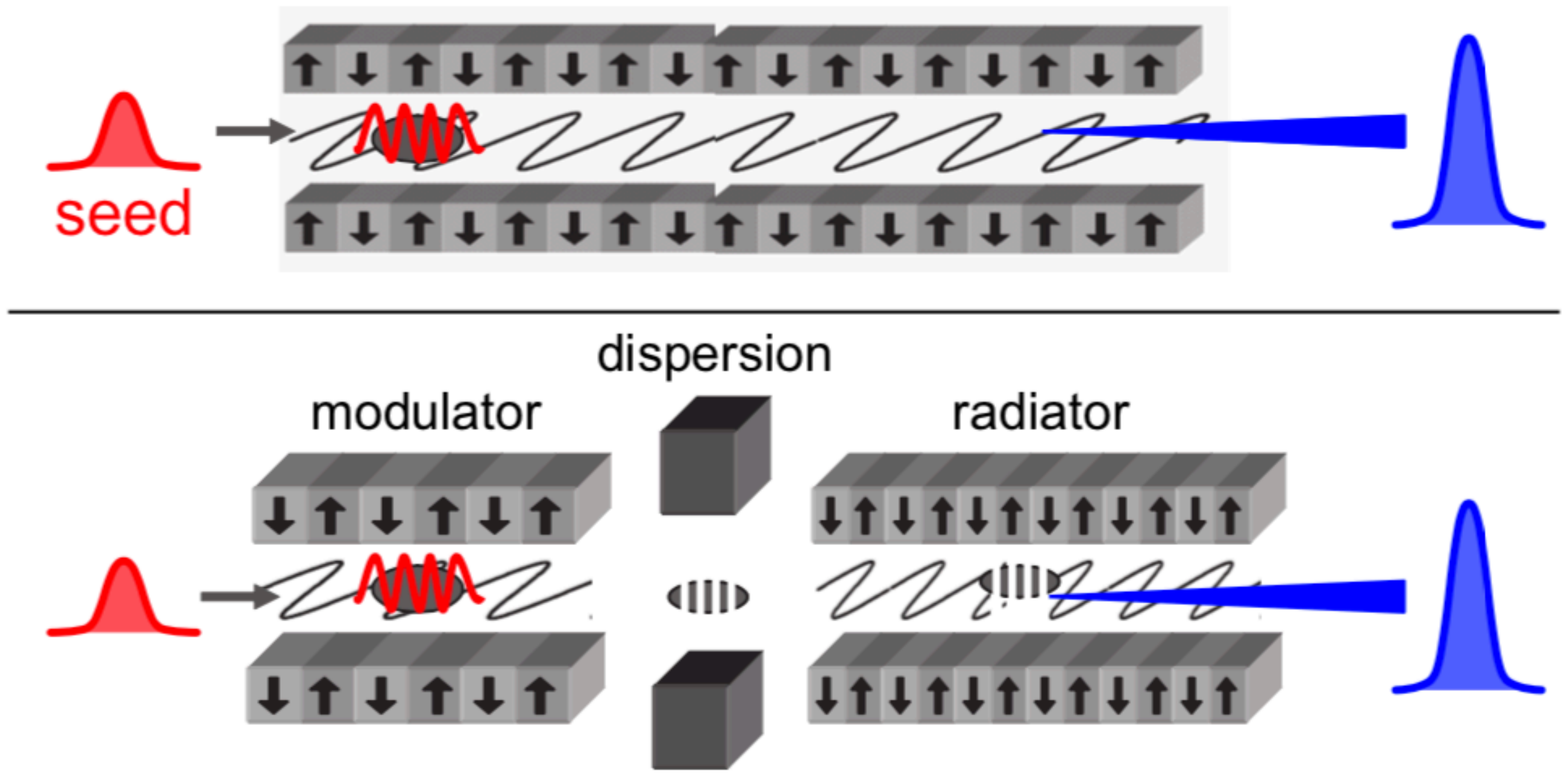


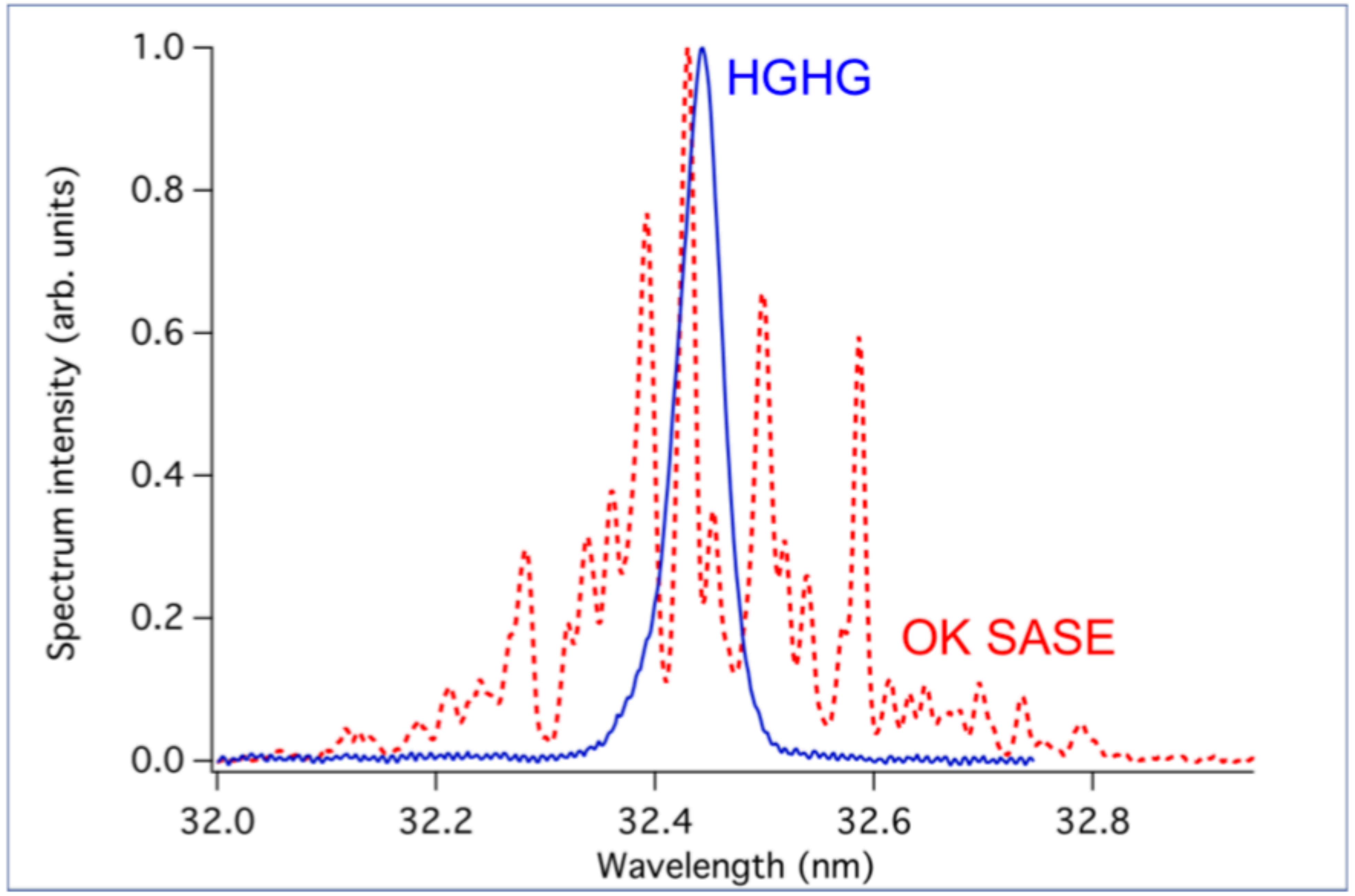
- ▷ condition for the chicane strength
  $R_{56} = -R_{11} R_{126} \lambda_R / (3\lambda_U)$

[A. Loulergue et al., New Journal of Physics **17**, 023028 (2015)]

SASE vs seeding

- External seeding: control the electron distribution within the bunch using an external laser
  $\rightarrow$ reduction of undulator chain to reach saturation + spectro-temporal control of FEL properties

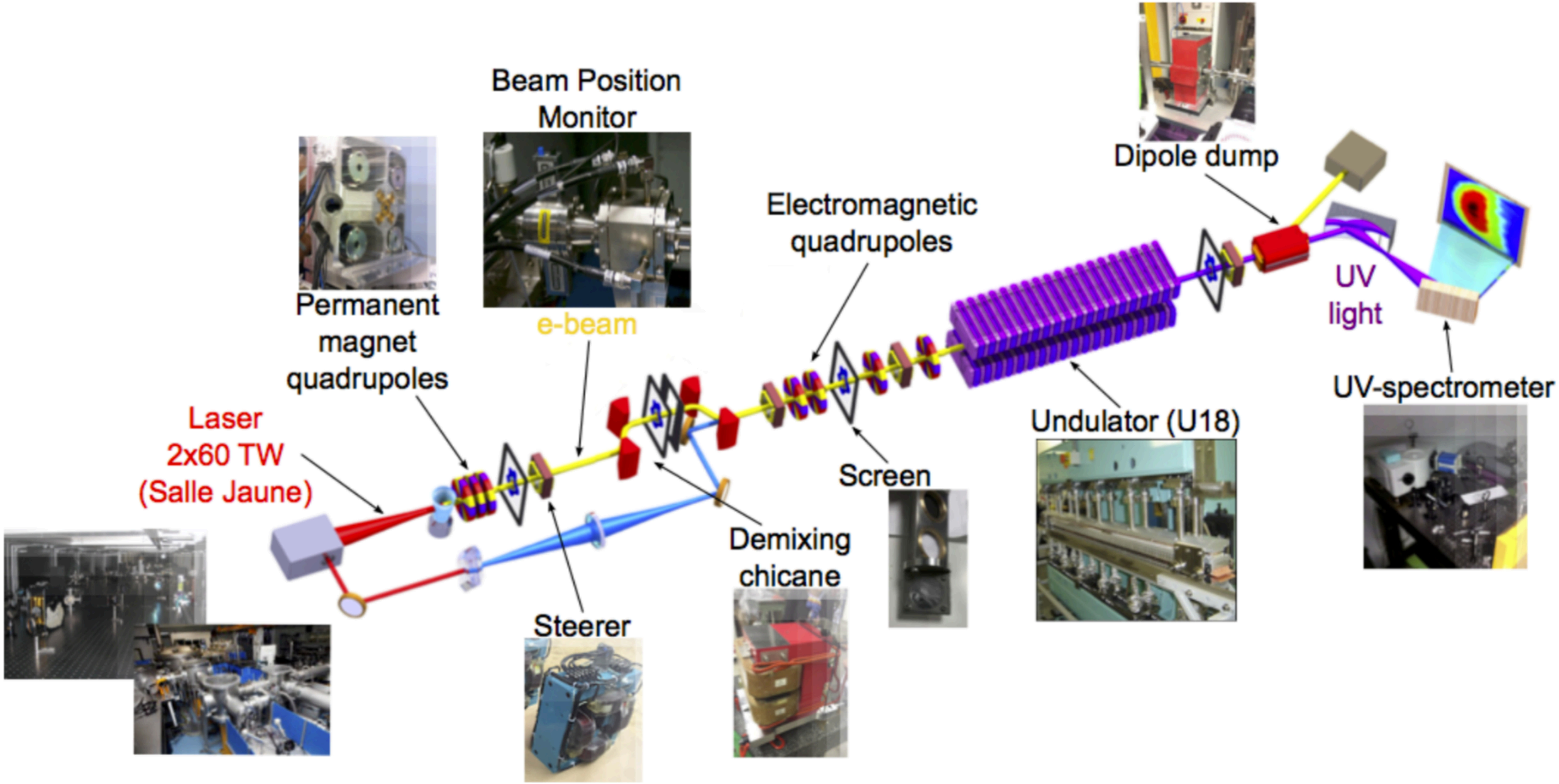




BUT… no external seeding sources at very short wavelength range ☹

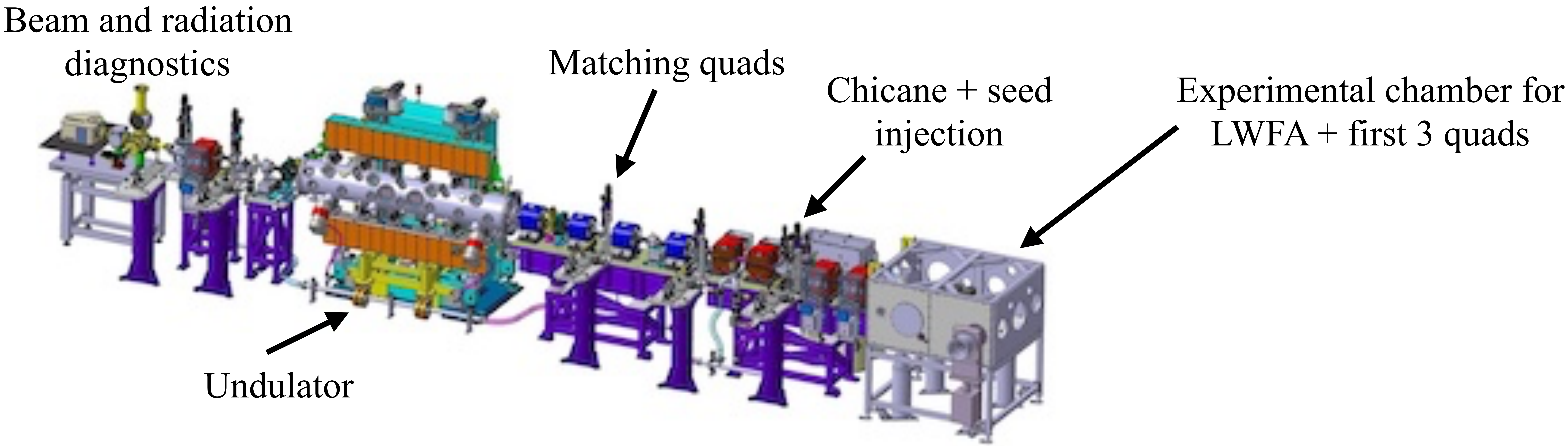
The COXINEL beamline

Schematic of the beamline



Operation parameters: 150-200 MeV electrons, UV seeding with harmonics of 800 nm (starting from H3)

Implementation of SOLEIL beamline in Salle Jaune (LOA)



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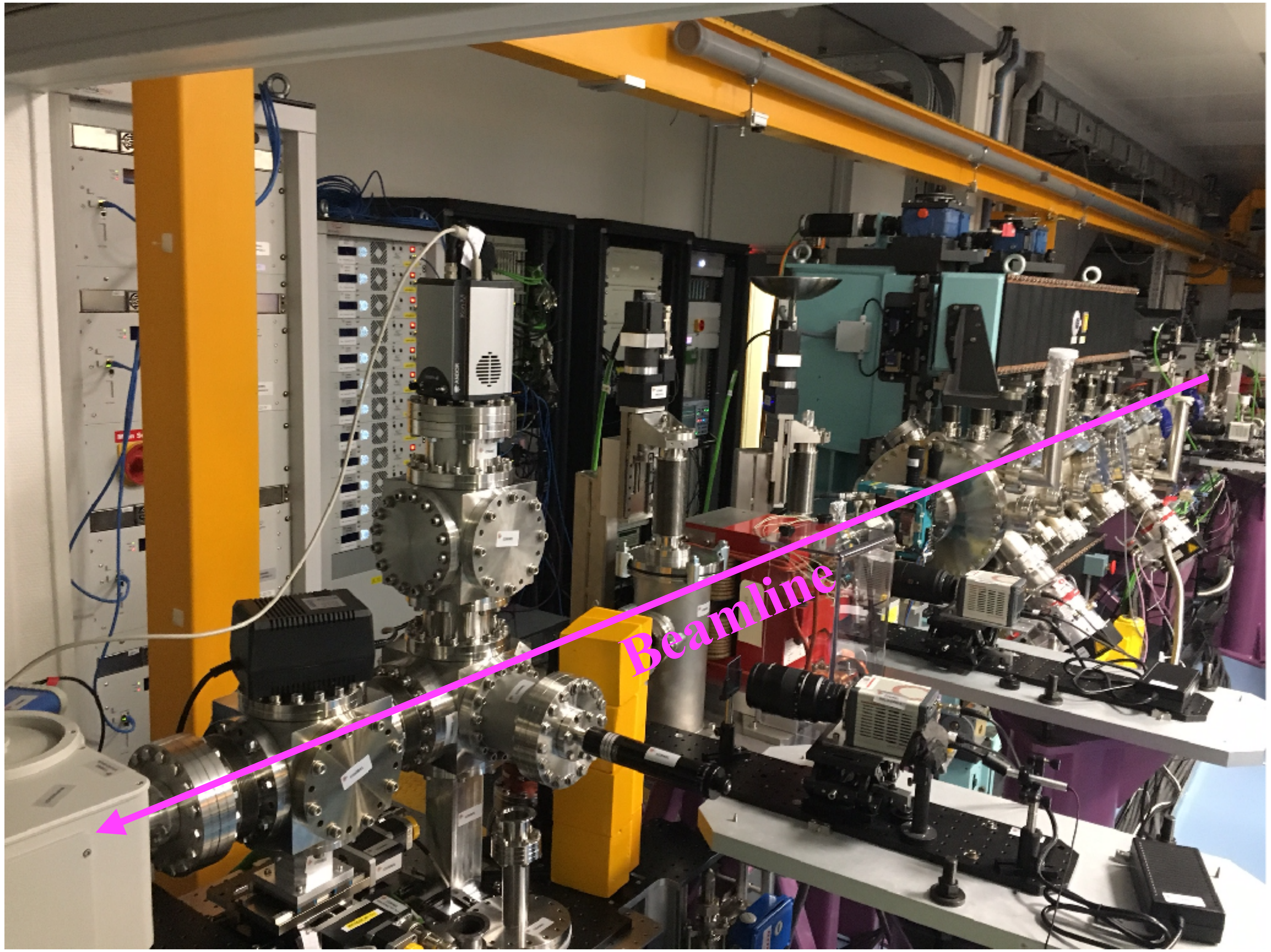
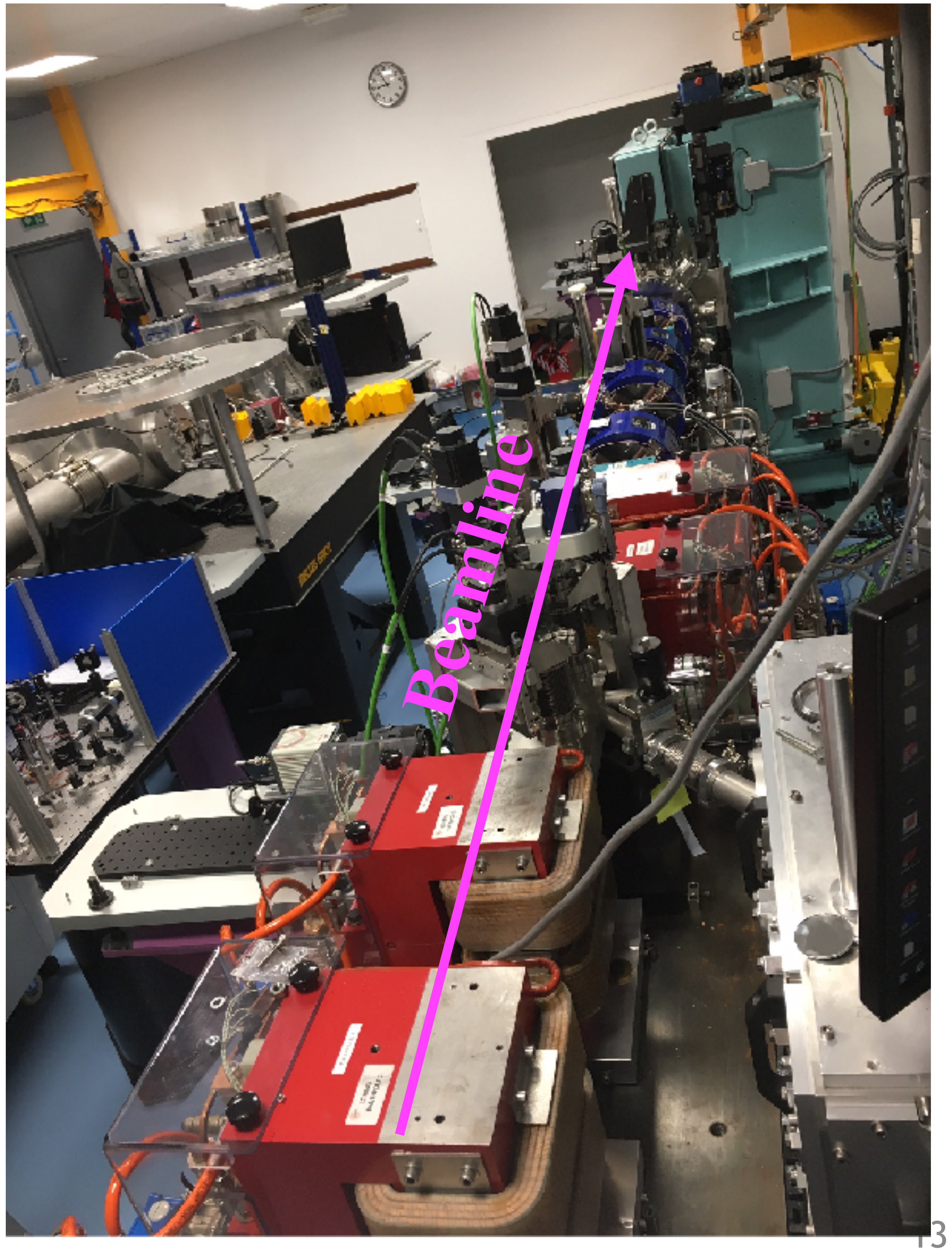
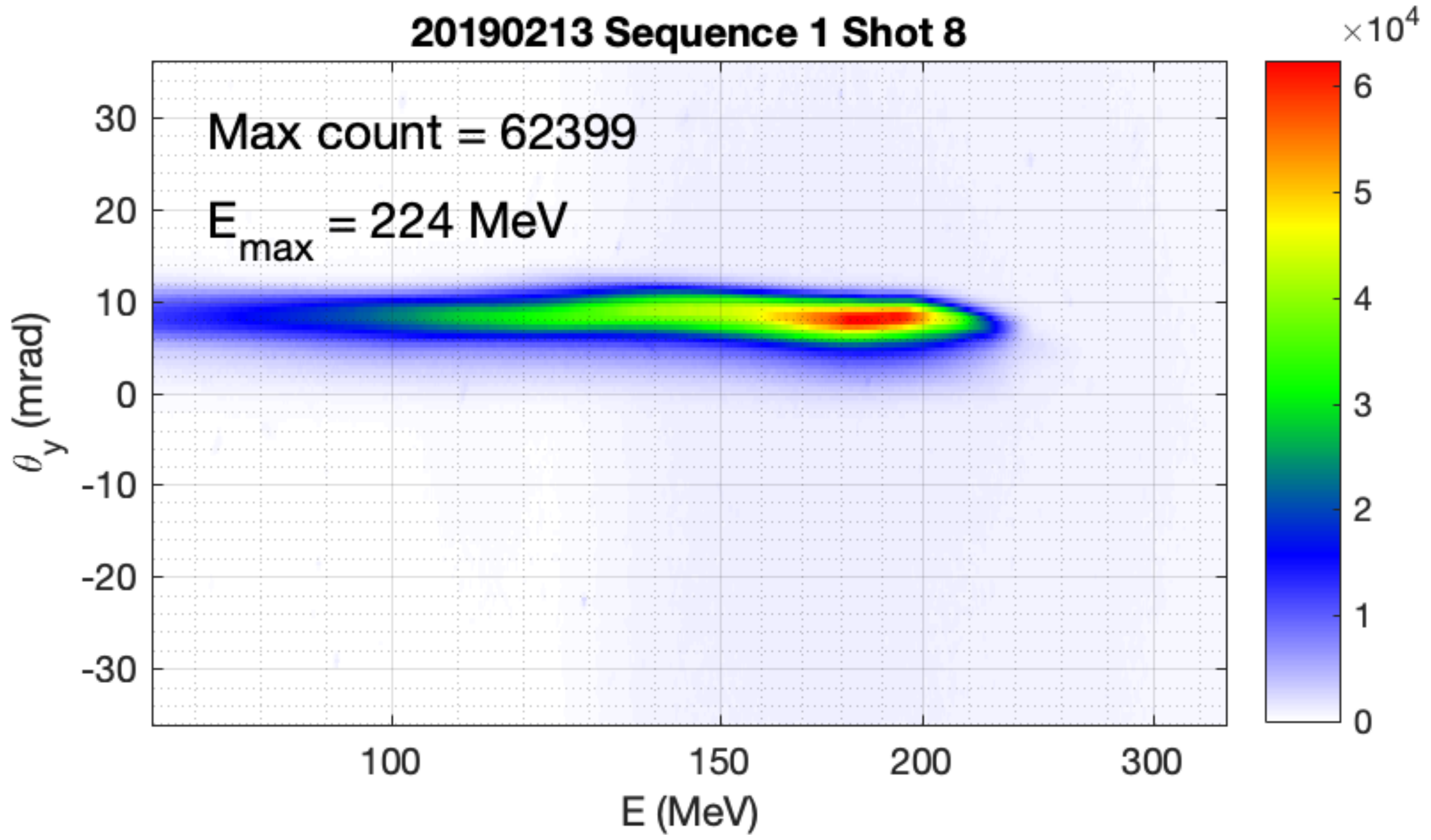


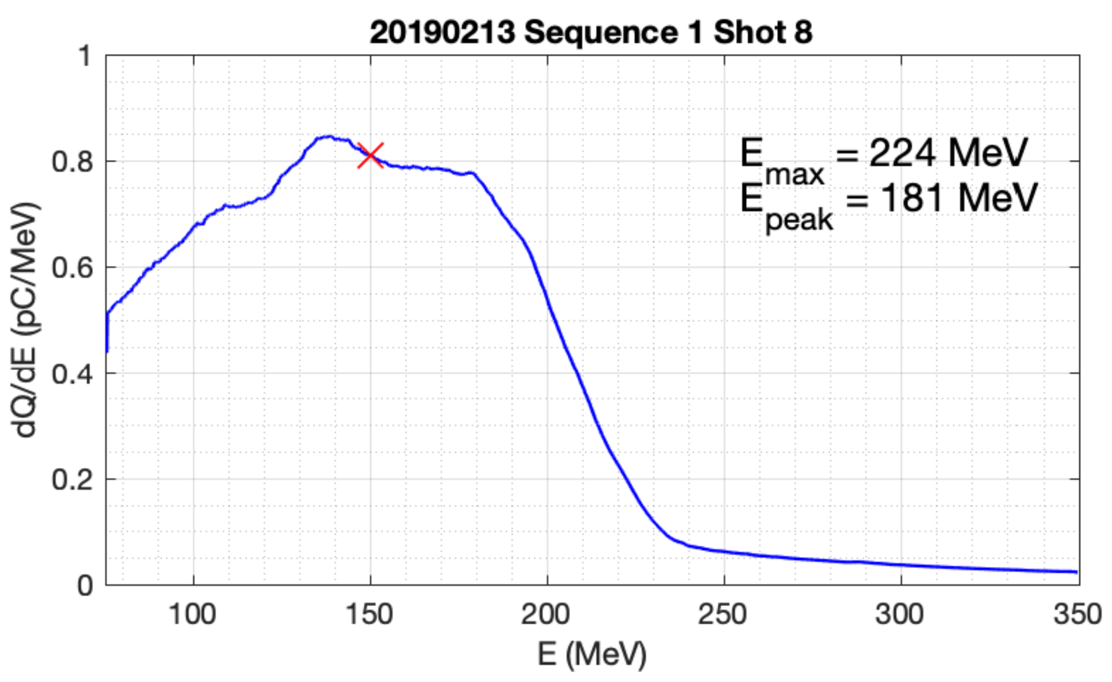


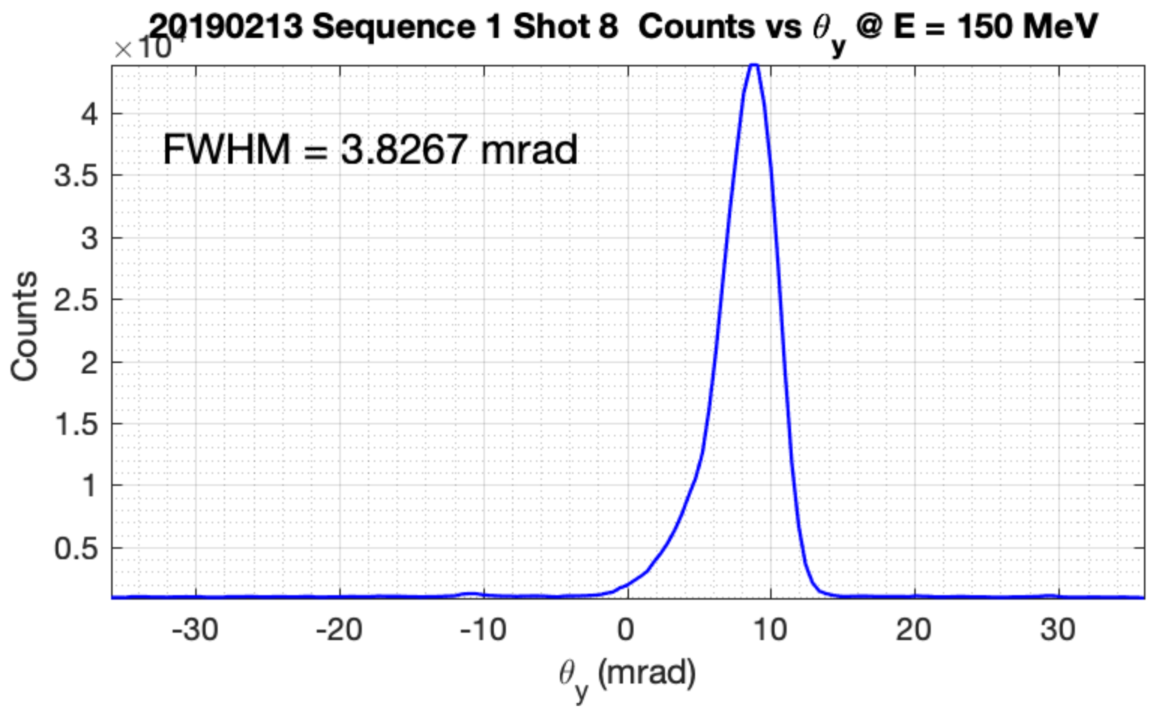
Electron beam at the LWFA source

Available on-target laser energy so far: 1.25-1.5 J

Electron beam generation from LWFA in ionisation injection regime:







- Spectral charge density of about 1 pC/%
- Divergence of 1.5-2 mrad (rms), 3-4 mrad (FWHM)
- Fluctuations: about 10% shot to shot
- Reproducible operation over the day

To increase spectral charge denisty, Salle Jaune is currently under upgrade to double the on-target laser energy to 2.5-3.5 J

Summary

- Spectral charge density and divergence are key parameters from LWFA; ongoing laser upgrade at LOA.
- Transport requires adequate controls: orbit and dispersion knobs, optimised focusing.
- Observation of the angulo-spectral distribution of spontaneous undulator radiation
- High-quality undulator radiation with optimised transport and using e-beam monochromator, wavelength and bandwidth control, second harmonic generation
- Work presented on behalf of the COXINEL collaboration:

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