FLASHForward▸▸ Photon Generation and Applications

Report from Working Group 4

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Mission of Working Group 4

> **Investigate existing and novel techniques for photon generation using FLASHForward electron beams**

> Free Electron Lasers

- Main aim to demonstrate FEL gain — from FLASHForward scientific mission statement, "assess the feasibility of femtosecond FEL gain at photon energies inside and beyond the water window"
- FEL design to accommodate the properties of plasma-accelerated beam
- Requires effective beam transport and matching into undulator
  - Chirp and divergence mitigation

> Betatron radiation

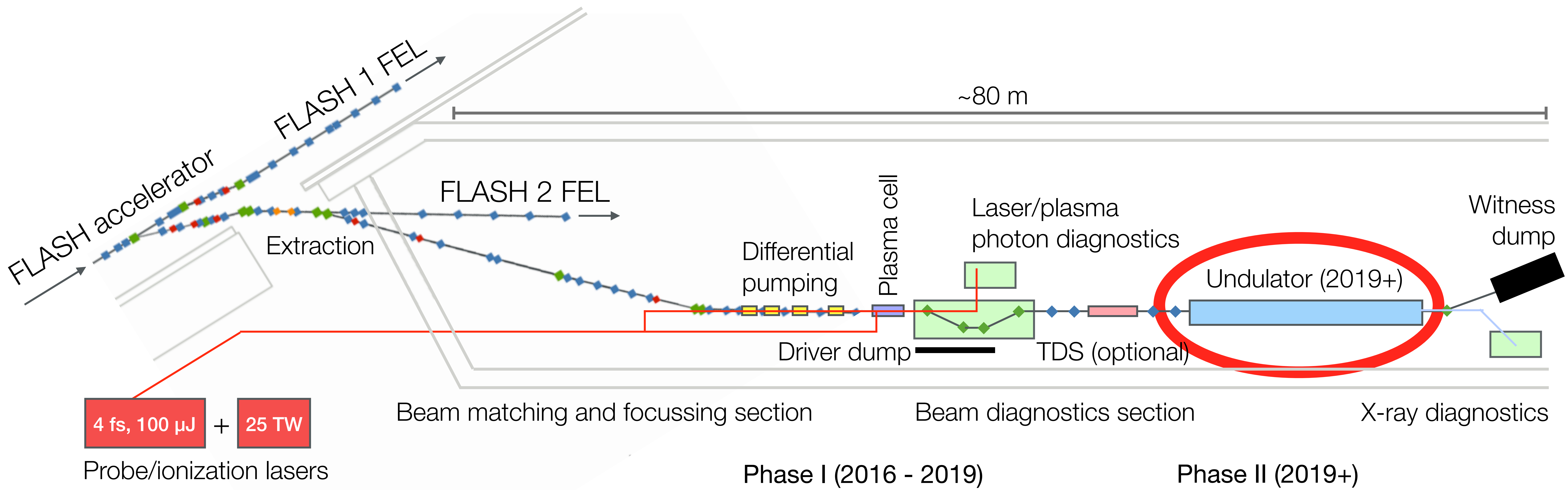
- Diagnostic of driving and accelerated electron beams
- Source of keV photons for pump-probe experiments

> Inverse Thomson Scattering

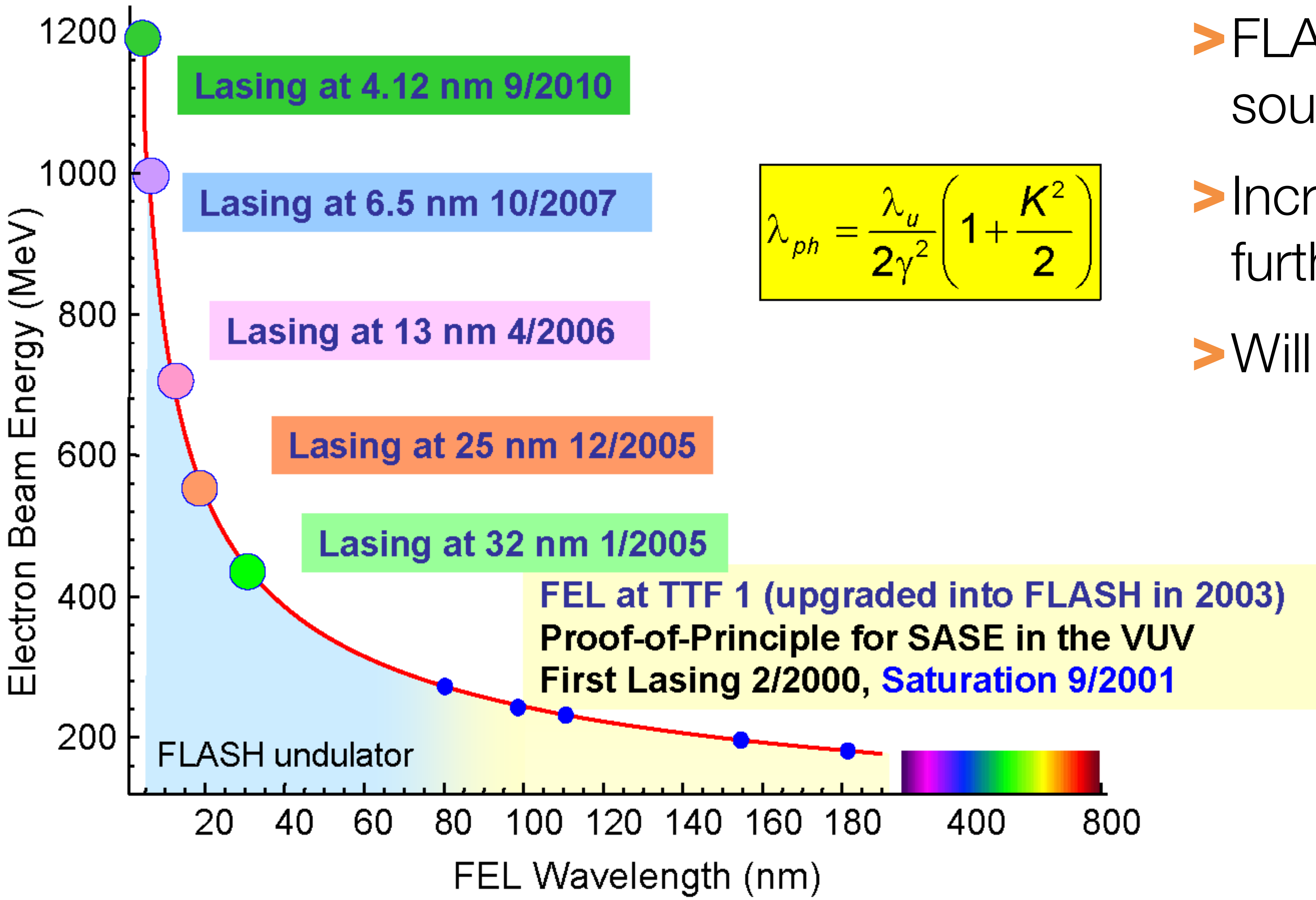
- Transverse probe pulse geometry for longitudinal properties of electron beams
- Characterize source for applications (photo-fission, SNM detection, etc.)
- Diagnostic development - detectors and spectrometers for multi-MeV range

Undulator installation in FLASHForward Phase II

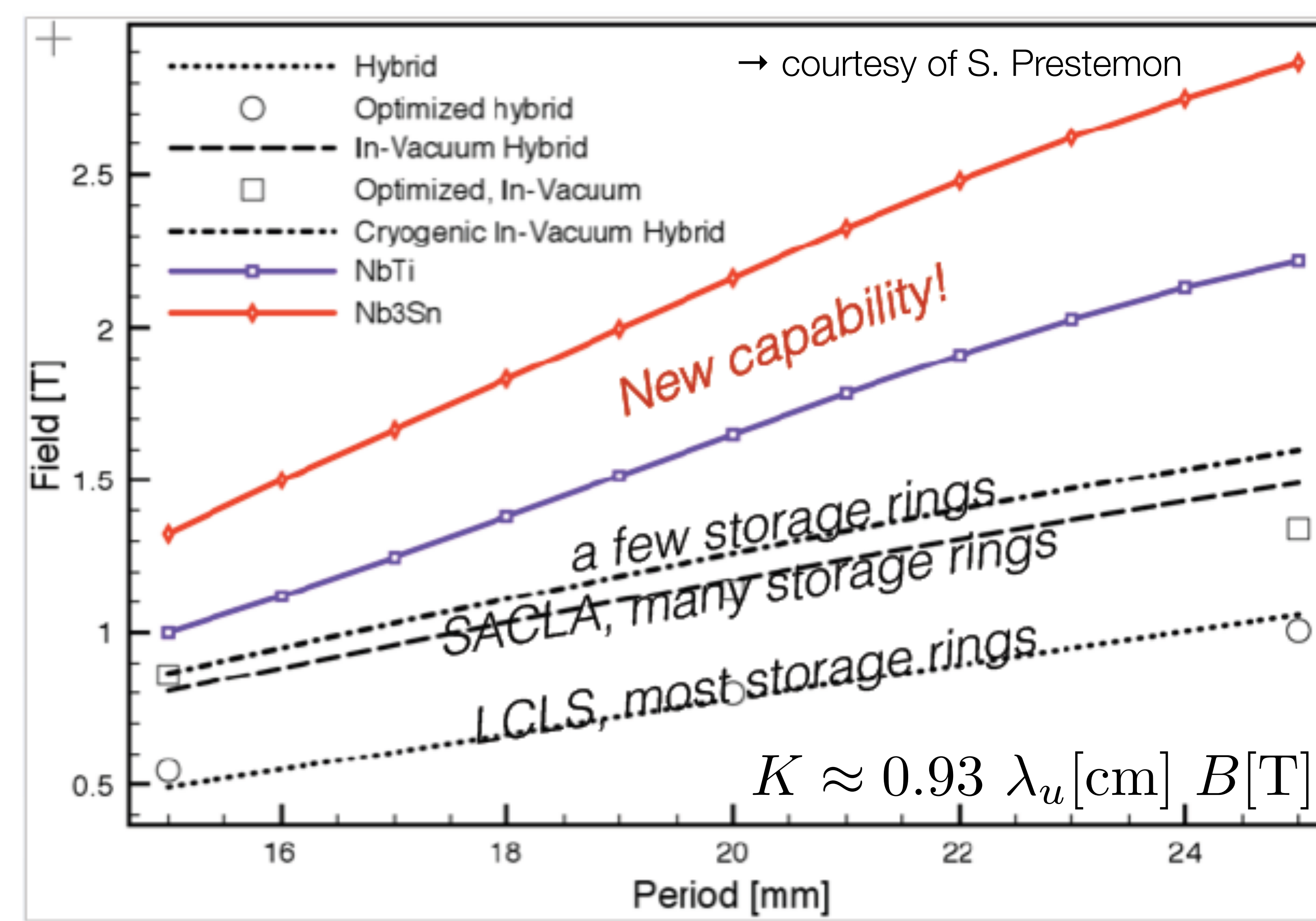
- Phase II operation 2019-2021
- Demonstrate FEL gain with FLASHForward beams



FEL with plasma-accelerated beams

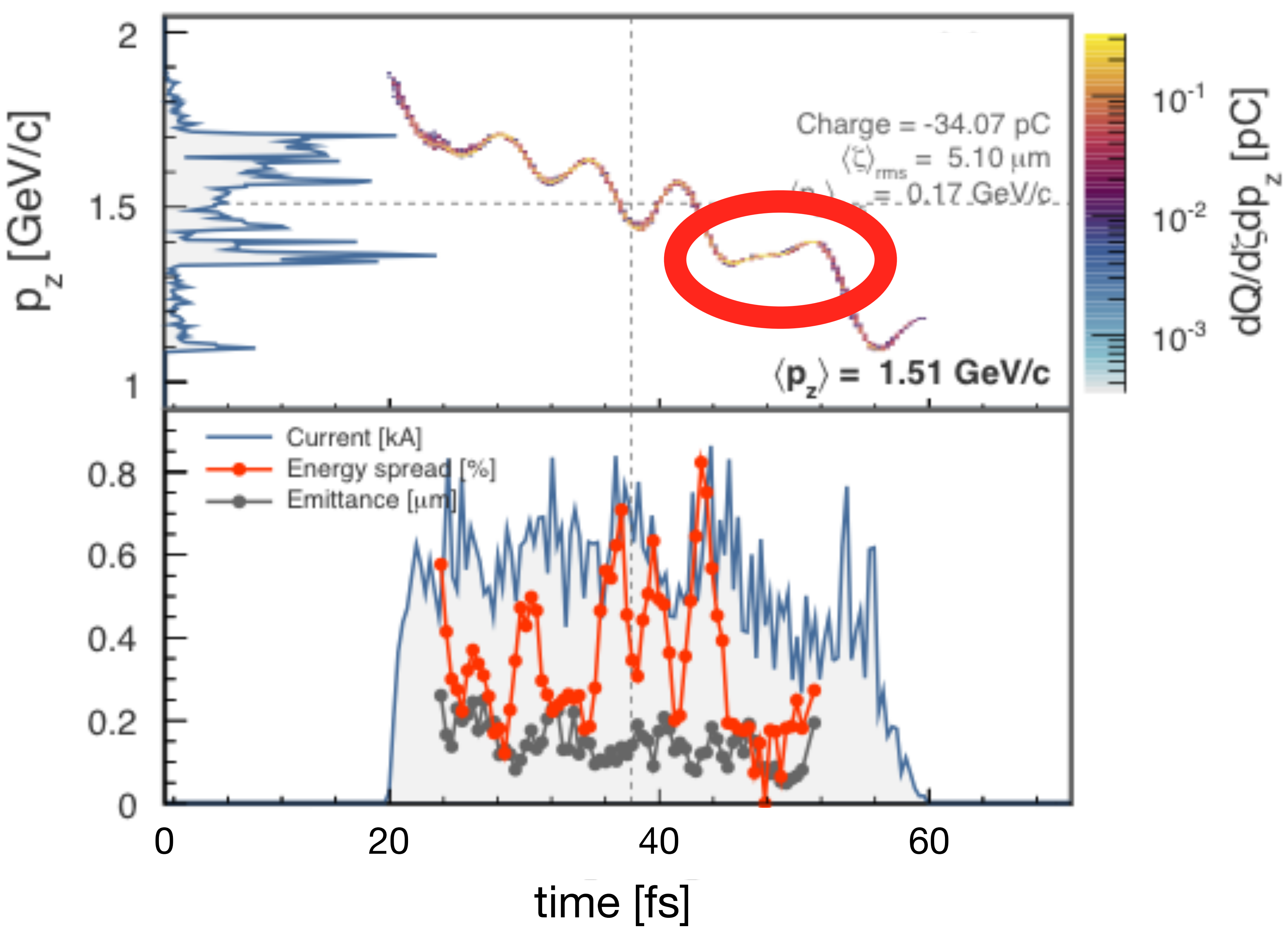


- FLASH has been continually developing VUV sources since 2000
- Increasing the electron energy allows for further reduction in the produced wavelength
- Will allow new experiments and applications.



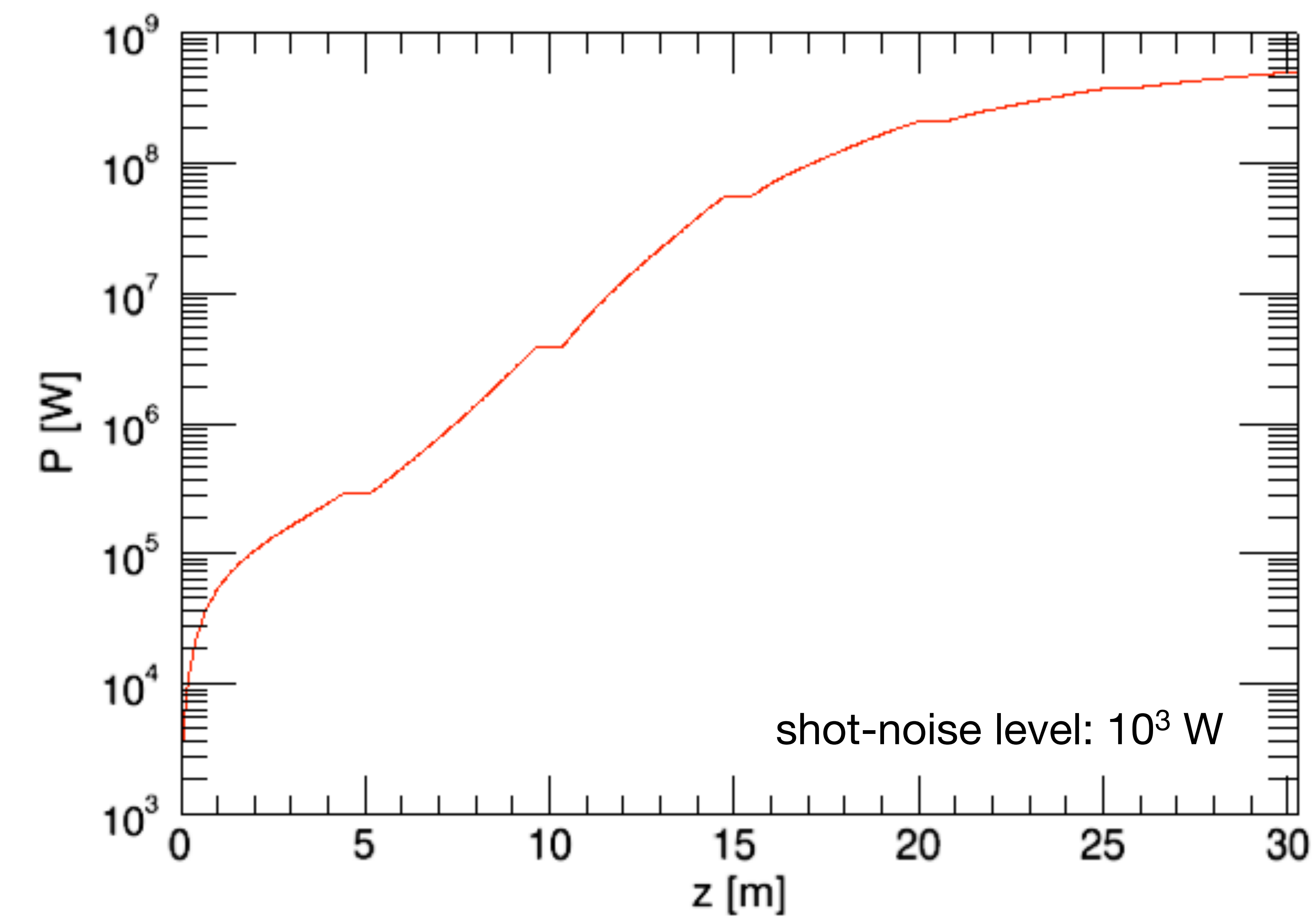
Simulated PWFA beams show significant FEL gain

J. Grebenyuk et al., NIM A (2014)



3D OSIRIS particle-in-cell simulation
of density-gradient injection

→ simulations by C. Behrens



3D time-dependent GENESIS simulation

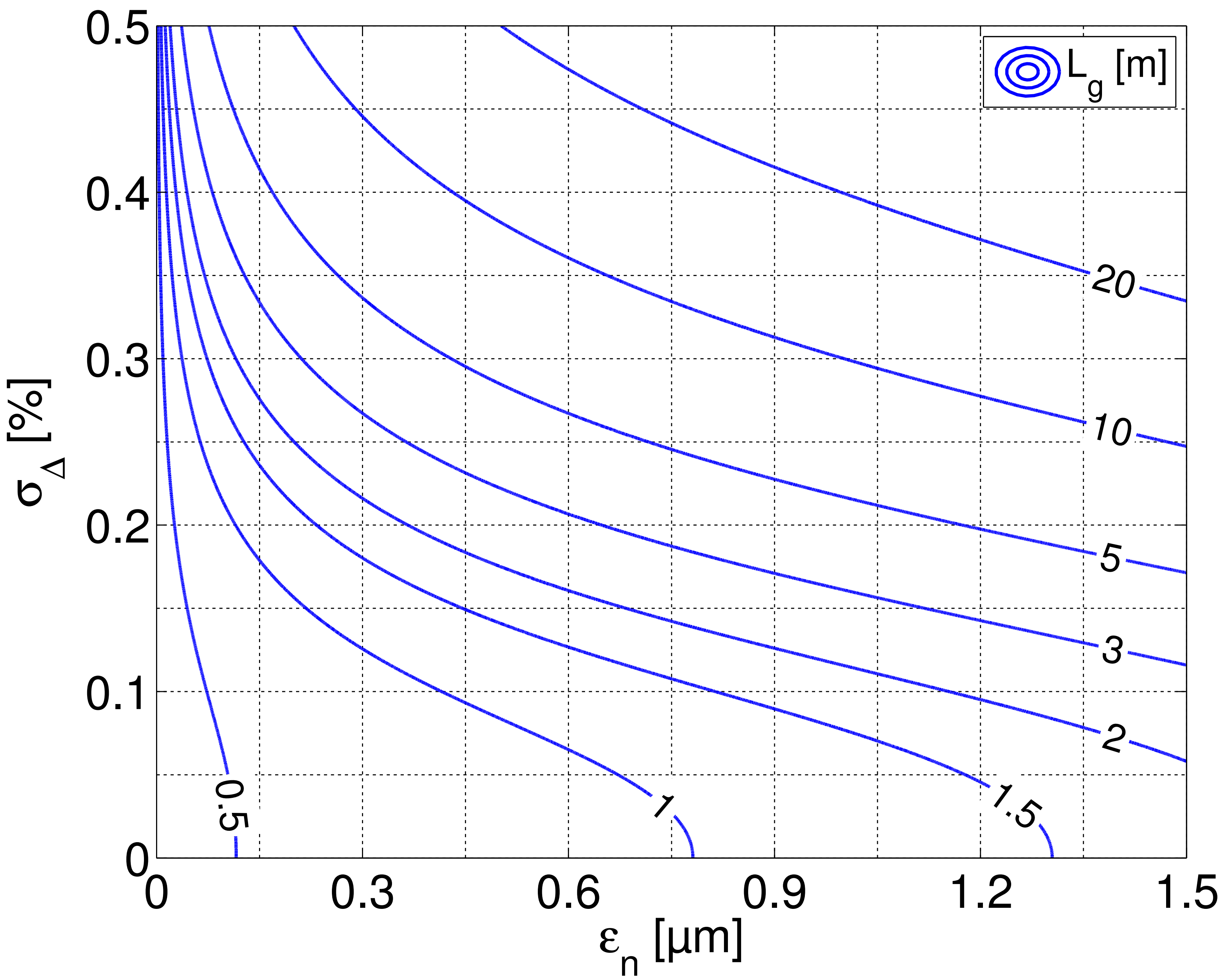
- part of beam matched through FLASH-type undulators
- gain length 1.7 m
- FEL signal at 3 nm ± 1 nm

Study of performance of standard FLASH undulators with plasma-accelerated beams

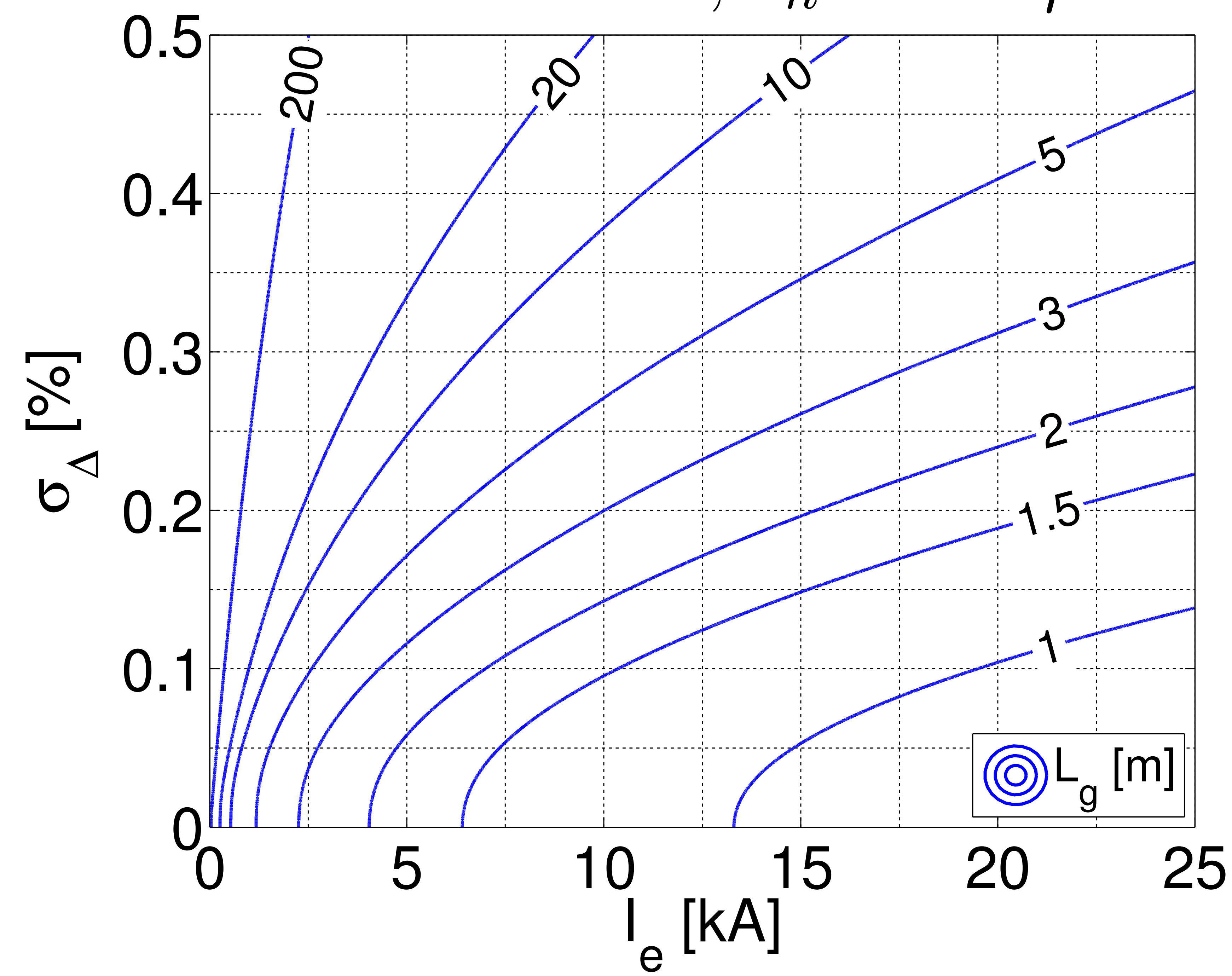
→ by Fabien Pannek et al.

- Study of Tesla-Test-Facility (TTF) undulators with 2.5 GeV FLASHForward beams (wakefield-Induced Ionization Injection beam)
- FODO focusing lattice with $\bar{\beta} = 5$ m
- Undulator parameters: $\lambda_u = 27.3$ mm, $K_0 = 1.21$, $L = 13.5$ m
- FEL power gain length: $P(z) \propto \exp(z/L_g)$

$E = 2.5$ GeV, $I_e = 5$ kA



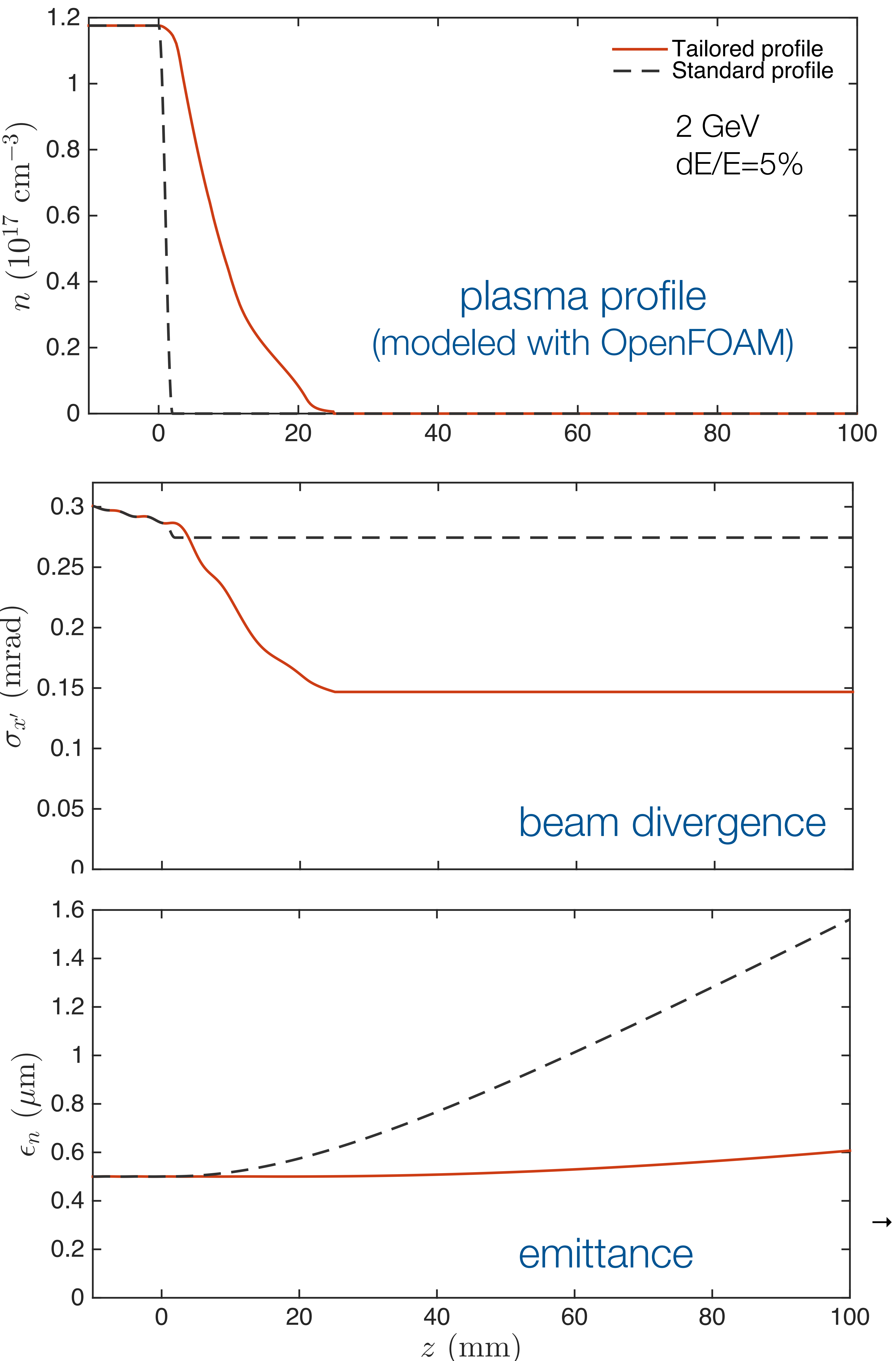
$E = 2.5$ GeV, $\epsilon_n = 1.5\ \mu$m



Issues and challenges for FEL lasing using plasma-accelerated electron beams

- Energy spread
  - Requires slice energy spread < FEL parameter $\rho = 0.0038$
  - Plasma de-chriper path to reduced energy spread
- Emittance
  - sub-micron emittance preservation required for FEL application
  - Plasma tailoring to extract beam with reduced divergence
- Brightness
  - Use injection scheme that maximizes e-beam brightness: $B_{6\mathrm{D}} = \dfrac{N}{\epsilon_{nx}\epsilon_{ny}\epsilon_{nz}} \approx \dfrac{(I/I_A)}{r_e \epsilon_n^2 \sigma_\gamma}$
- Slippage: $\sigma_z \sim N_u \lambda$
  - sub-micron electron beams suppresses FEL instability (at soft-x-ray wavelengths)
  - Decompression possible solution (provided sufficient charge density)

Extraction and emittance preservation with tailored plasma density profile



→ courtesy of Timon Mehrling

- *Problem*: Coupling of energy spread and large beam divergence leads to chromatic emittance growth:

$$\epsilon_n^2 \simeq \left(\sigma_\gamma^2 \sigma_{x'}^4 z^2 + \langle\gamma\rangle^2\ \epsilon\right)$$

- *Solution*: Tailor plasma density profile at exit to decrease focusing forces (reducing divergence) and early capture of beam

$$k_\beta \propto n^{1/2}$$

$$\sigma_{x'} = (k_\beta \epsilon_n/\gamma)^{1/2}$$

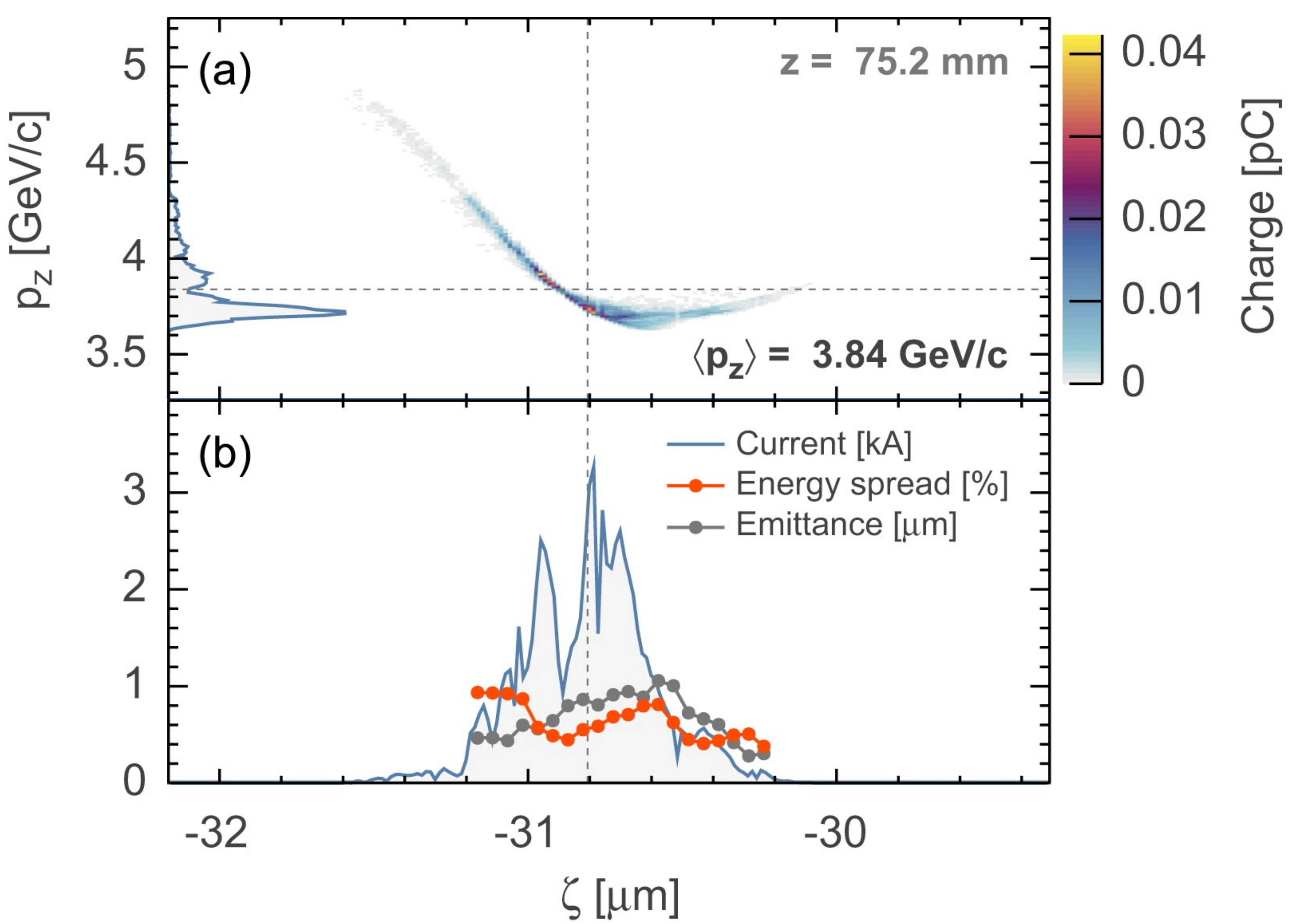
Beam chirp mitigation with plasma wakefields

→ courtesy of Violetta Wacker

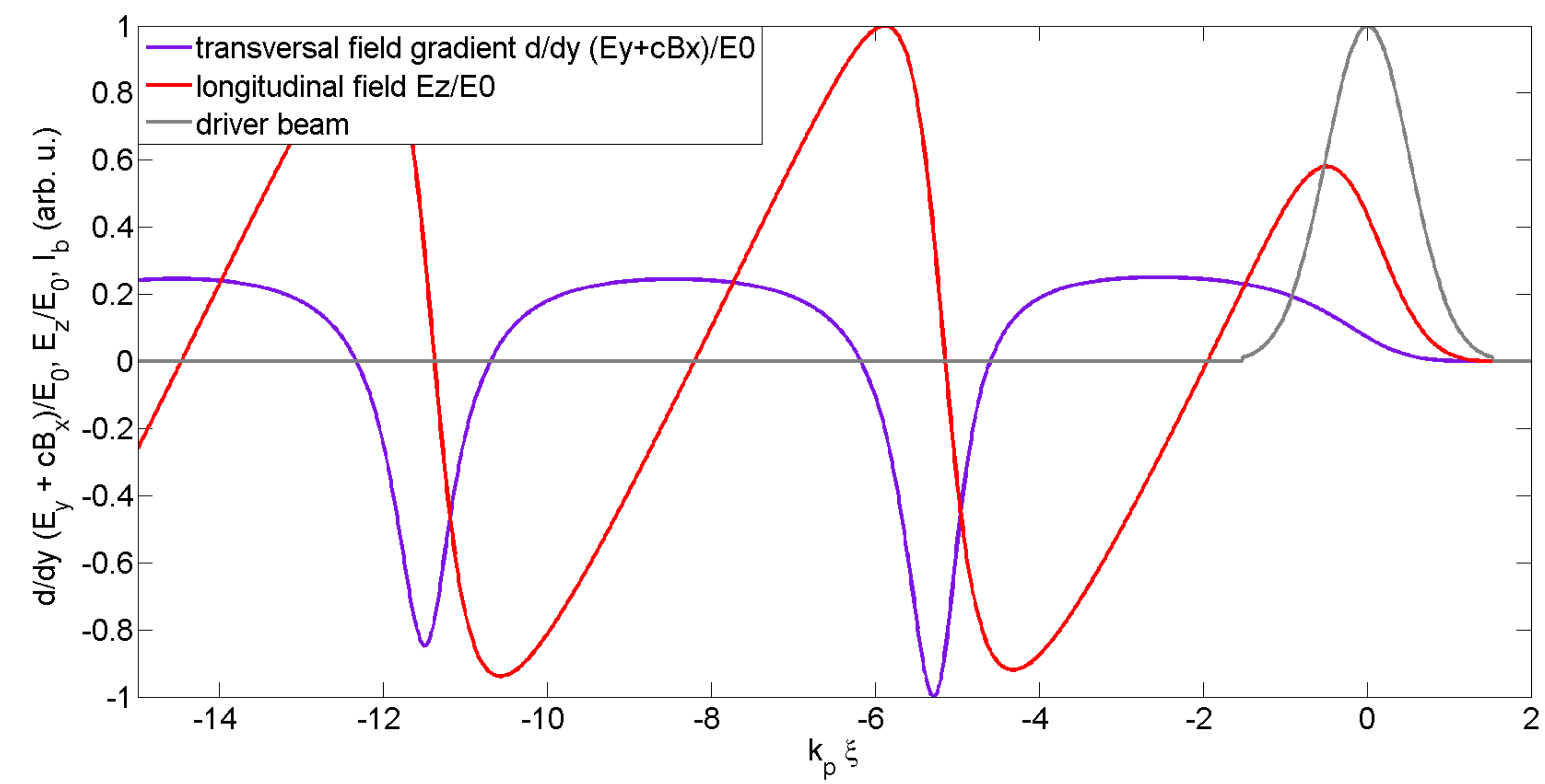
- Typical plasma generated electron beams exhibit large energy chirp
- For beam-driven wakes: $\gamma_{\text{tail}} > \gamma_{\text{head}}$

- Chirp created in wakefield can also be compensated by driving a wakefield with the accelerated beam

A. Martinez de la Ossa et al., NIM A (2014)

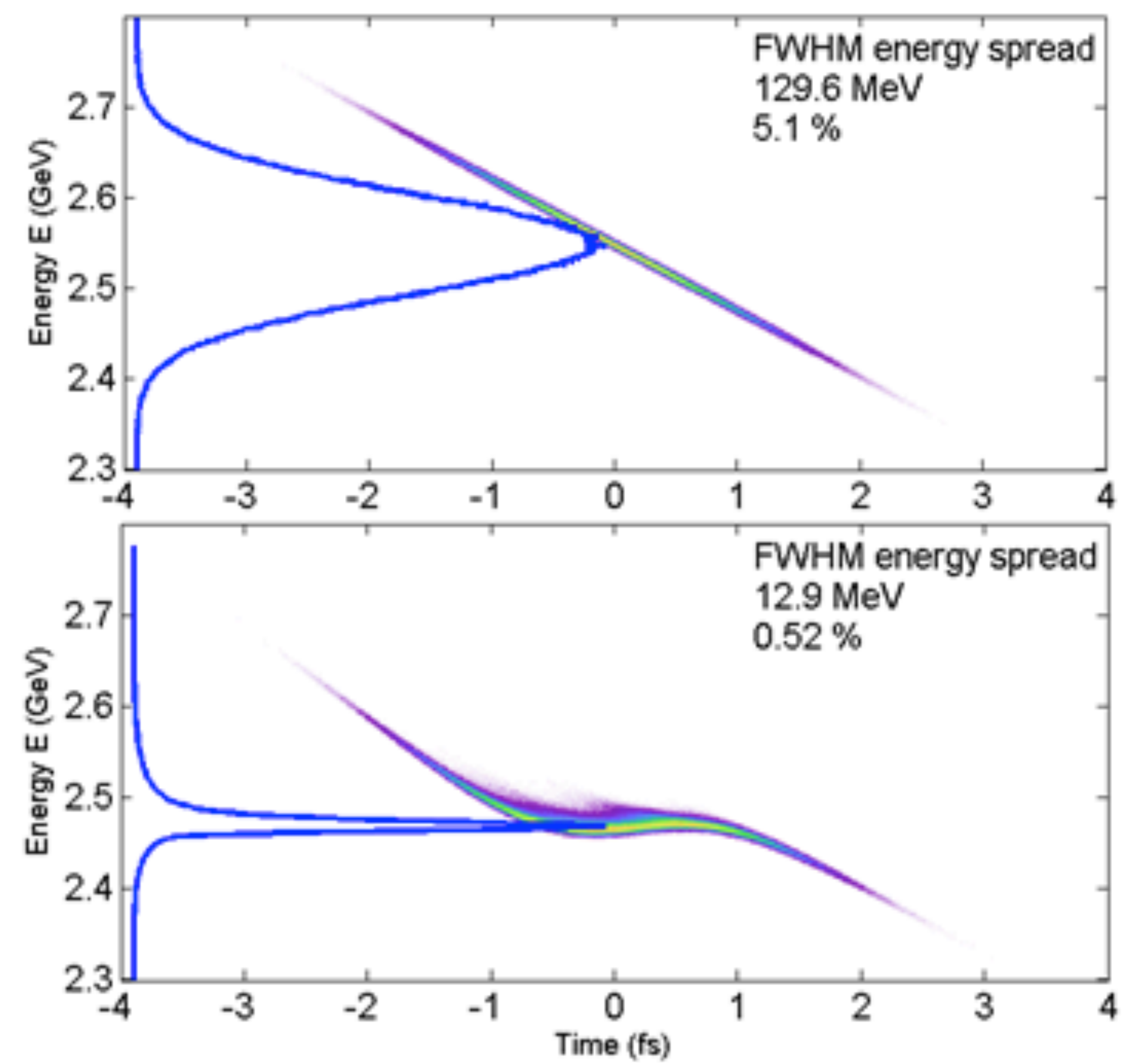


3D OSIRIS particle-in-cell simulation of ionization injection



Beam chirp mitigation with plasma wakefields

→ courtesy of Violetta Wacker

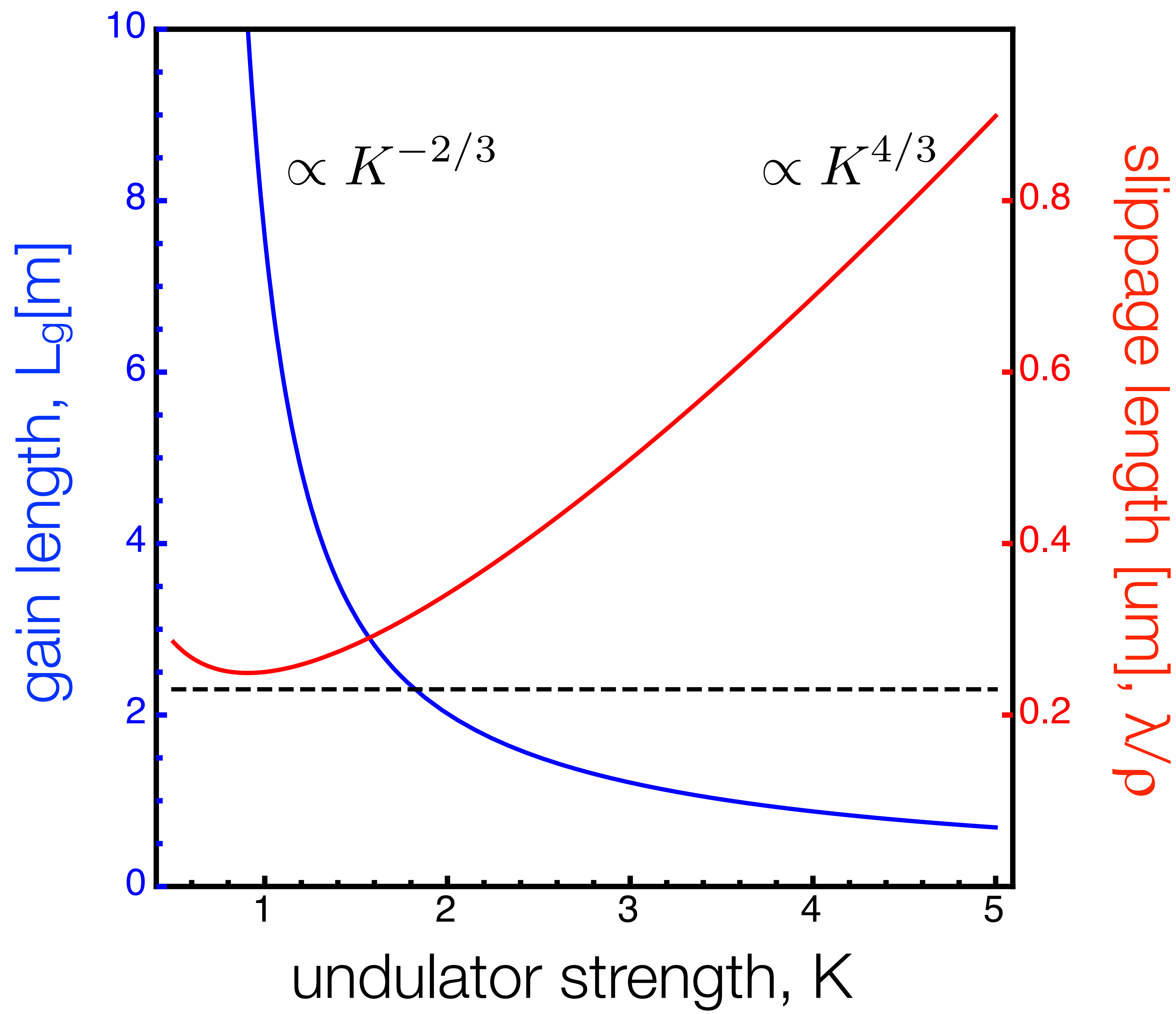


- Realized experimentally by density up-ramp at the end of the acceleration section
- Drive beam loses resonance with plasma wave
- Witness beam drives wake

Undulator design: undulator strength parameter

- Undulator parameters to minimize FEL power gain length: $P(z) \propto \exp\left(z/L_g\right)$

$$\sigma_z = 0.23\ \mu\text{m}$$
$$E = 2.5\ \text{GeV}$$
$$I_e = 5\ \text{kA}$$
$$\epsilon_n = 0.3\ \mu\text{m}$$
$$\sigma_\Delta = 0.5\ \%$$
$$\bar{\beta} = 1\ \text{m}$$
$$\lambda_u = 27.3\ \text{mm}$$

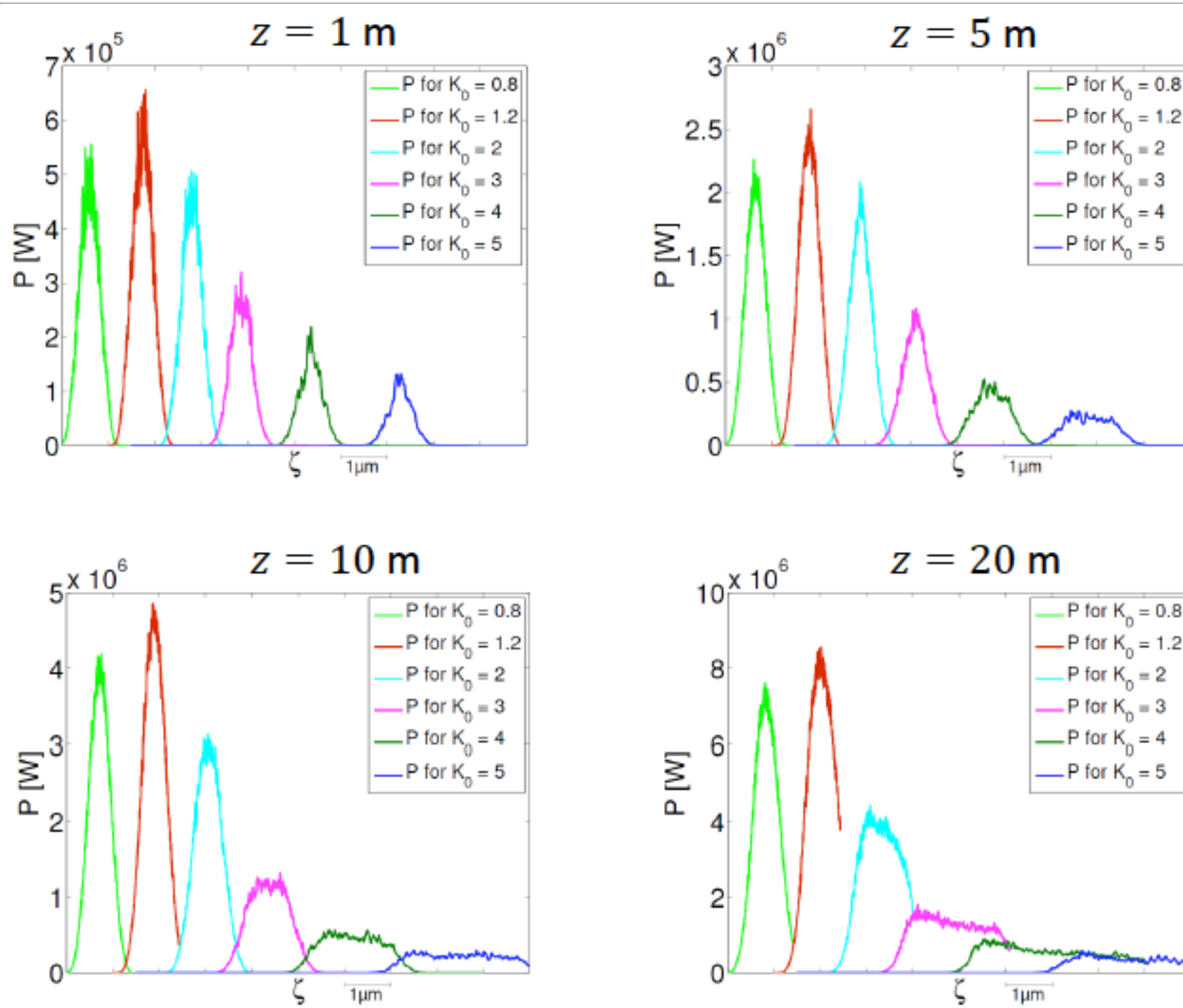


Undulator design: Slippage critical issue for sub-micron beams at soft-x-ray wavelengths

→ by Fabien Pannek et al.

$$\lambda_u = 4 \text{ cm}$$
$$\bar{\beta} = 1 \text{ m}$$

$$\sigma_z = 0.23 \ \mu\text{m}$$
$$E = 2.5 \text{ GeV}$$
$$I_e = 5 \text{ kA}$$
$$\epsilon_n = 0.3 \ \mu\text{m}$$
$$\sigma_\Delta = 0.5 \ \%$$



Decompression possible path to improved FEL performance

- Decompression
  - Mitigates slippage
    - larger FEL radiation bandwidth
  - Reduces gain length
    - reduces slice energy spread:

$$\sigma_\Delta < \rho$$

    - reduces peak current:

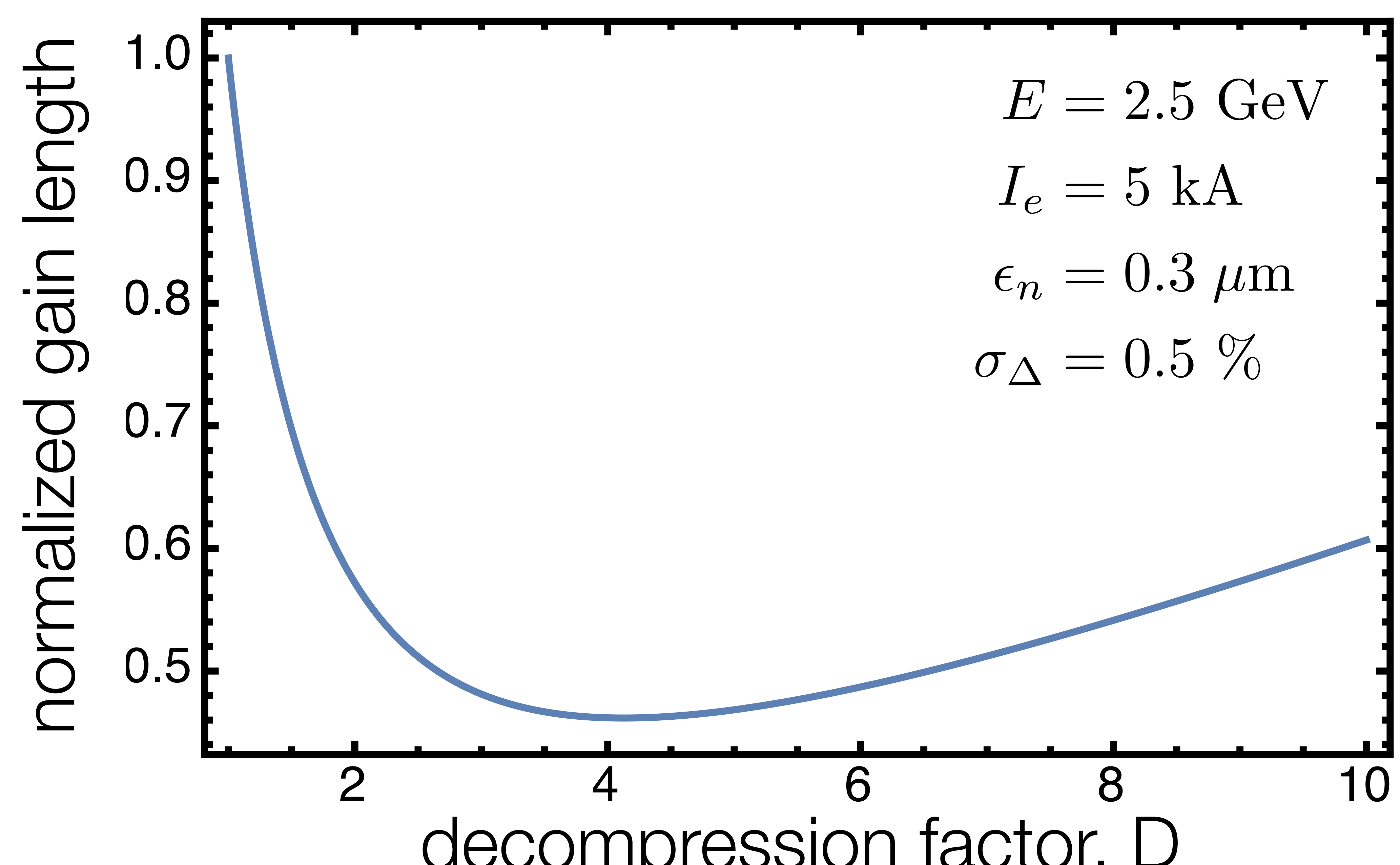
$$\rho \propto I^{1/3}$$

- (Ming Xie) gain length formula:

Diffraction / *angular spread* / *energy spread*

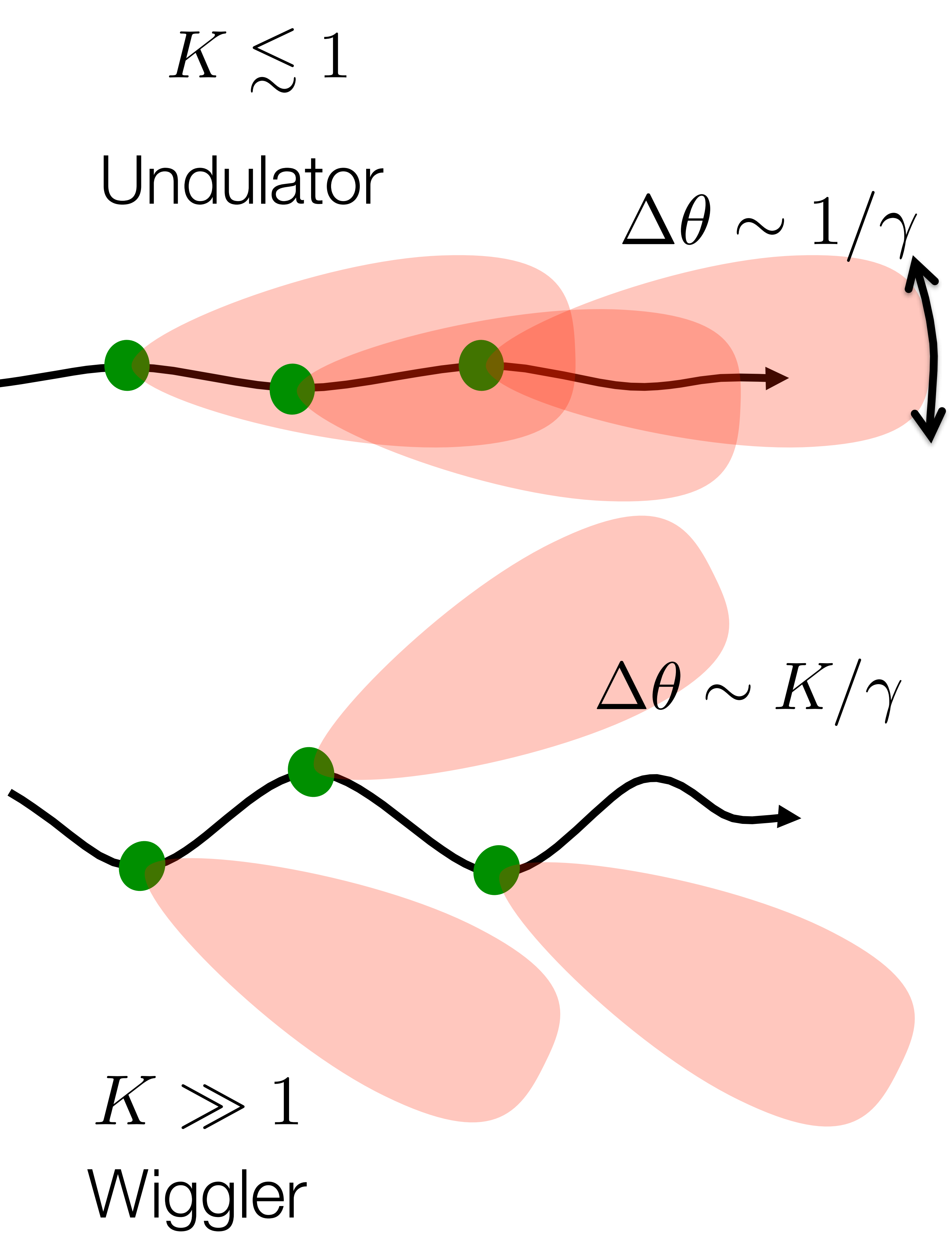
$$L_g = \left(\frac{\lambda_u}{4\pi\sqrt{3}\rho}\right) D^{1/3}\left[1 + \Lambda\left(D^{1/3}\eta_d, D^{1/3}\eta_\epsilon, D^{-4/3}\eta_\gamma\right)\right]$$

→ Schroeder et al., Proc FEL 2013



$\bar{\beta} = 1$ m
$\lambda_u = 27.3$ mm
$K = 1.21$
$\rho = 0.0038$
$\lambda = 1$ nm

Betatron radiation from oscillating charge in plasma wake



> Radiation generated by transverse oscillation of electrons in (strong) focusing fields of wakefield

> Spectrum depends on particles energies, field strength and oscillation amplitude.

$$\omega_c \simeq 3K\gamma^2\omega_\beta \propto \gamma^2 n_e r_\beta$$

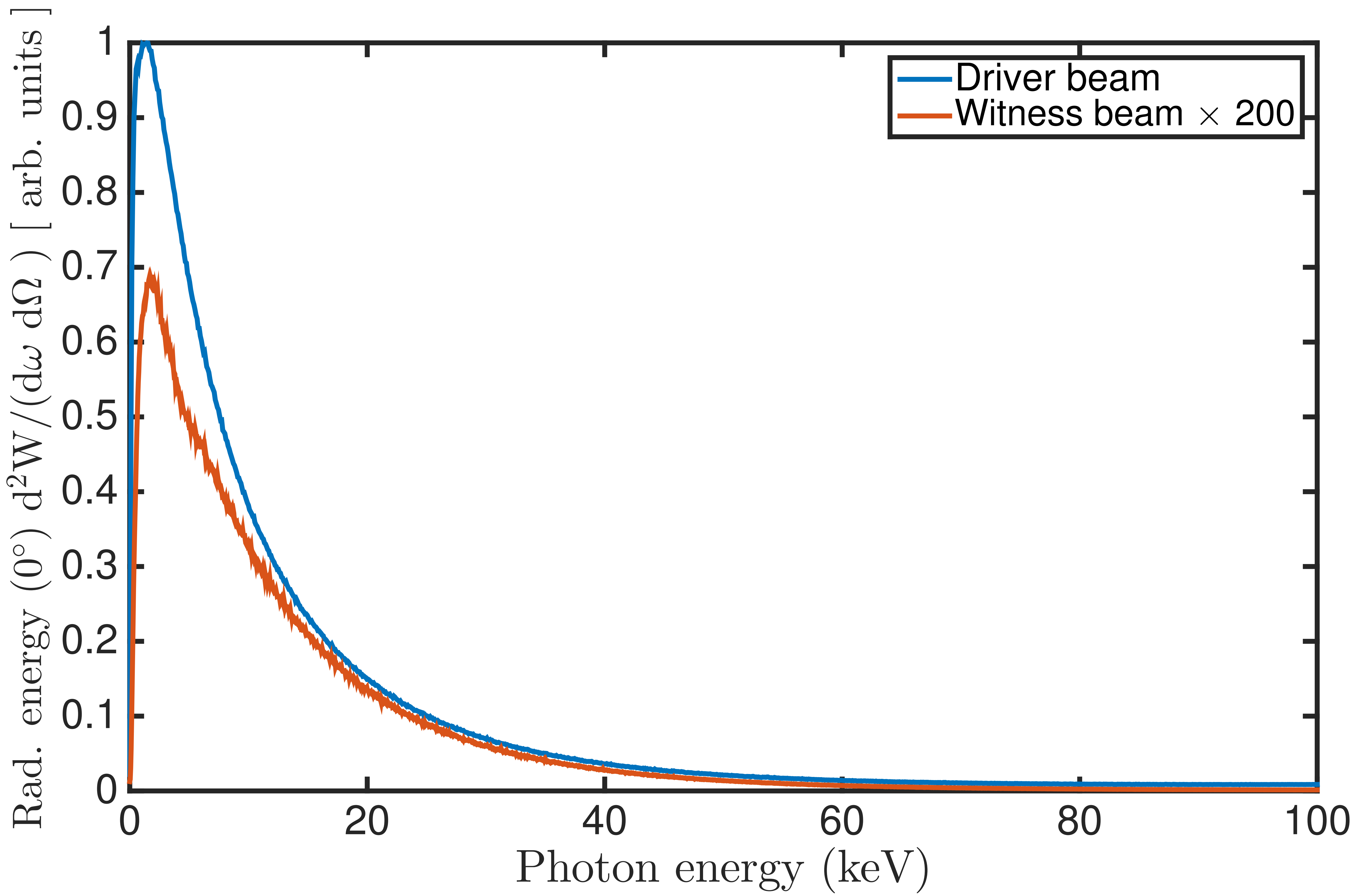
> Can operate in undulator or wiggler regime, depending on parameters:

→ courtesy of Jan-Patrick Schwinkendorf

	Driver	Witness (ext)	Witness (RAKE)	LWFA (Gemini)
$K \sim r_\beta (\gamma\ n_e)^{1/2}$	6.5 – 20.8	9.3 – 29.4	0.9 – 2.9	5 – 10
$h\nu_c$ [keV]	3.1 – 31	12.5 – 125	1.8 – 12.5	20 – 50
λ [Å]	4.0 – 0.4	1.0 – 0.1	6.9 – 1.0	0.6 – 0.2
θ=K/γ [mrad]	2.7 – 8.5	1.9 – 6.0	0.2 – 0.6	20 x 10
Photons	10^9	10^9	10^7	10^9
	1.25 GeV 1 nC r~10 um	2.5 GeV 0.5 nC r~10 um	2.5 GeV 50 pC r~1 um	

Betatron radiation as diagnostic of driver beam

→ courtesy of J.P. Schwinkendorf



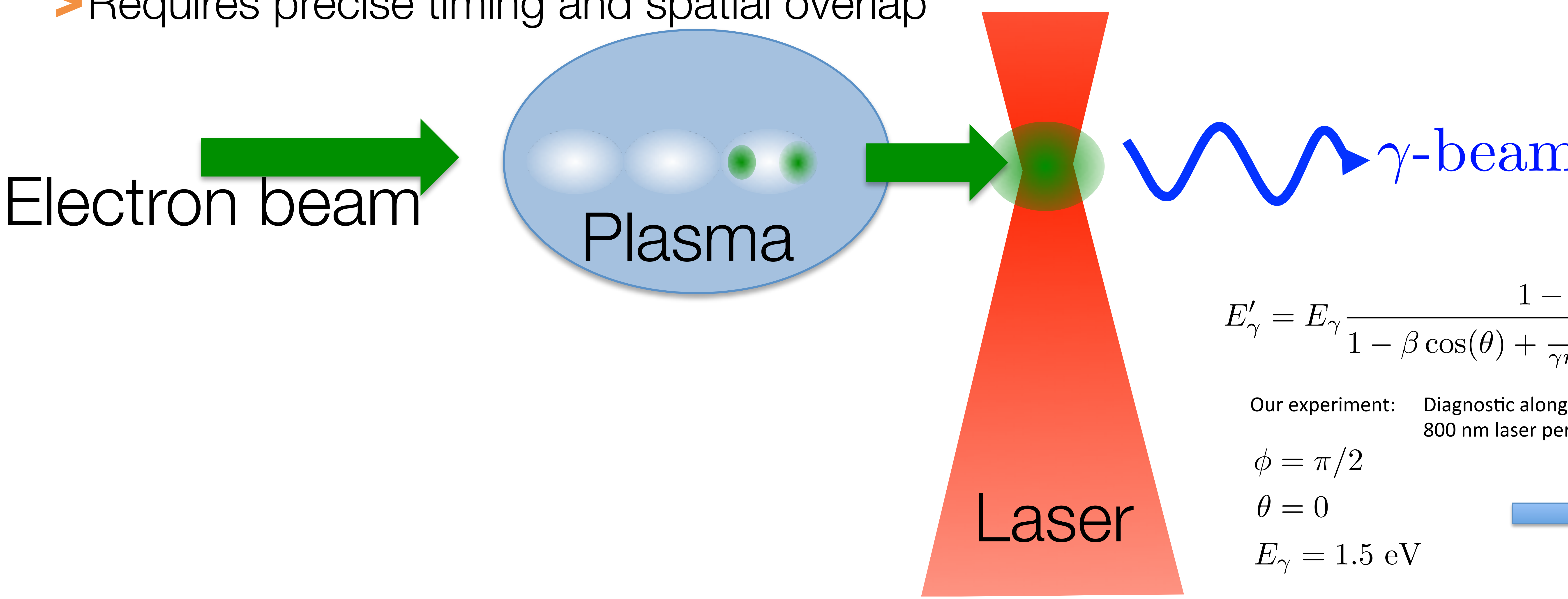
- Betatron spectrum calculated from particle trajectories in PIC code
- Drive beam emission likely to dominate, due to higher charge
- Diagnostic can reveal transverse properties of driver, e.g., head-to-tail tilt (WG 2)

Betatron radiation from driver and witness beam

- It may be possible to distinguish drive beam from witness via spectral or angular resolution
- Diagnostics under development with WG2
- Correlated to injected charge, energy, and oscillation amplitude
- Low betatron emission from high charge accelerated bunch indicative of high quality, low emittance beam
- Spatial measurements can also reveal size of emission region
- Potential source for pump-probe experiments (x-ray time structure for drive and witness beams: two-pulse ~5 um and ~1 um, separated by ~85 um)

Inverse Compton Scattering

- Scattering of laser beam from FLASHForward electron beam
- Transverse geometry allows probing of longitudinal structure of electron beams if nonlinear effects are avoided ($a_0 \ll 1$)
- Requires precise timing and spatial overlap



$$E'_\gamma = E_\gamma \frac{1-\beta\cos(\phi)}{1-\beta\cos(\theta)+\frac{E_\gamma}{\gamma m_e c^2}\left(1-\cos\left(\theta-\phi\right)\right)}$$

Our experiment: Diagnostic along electron beam axis.
800 nm laser perpendicular to electron beam.

$\phi = \pi/2$

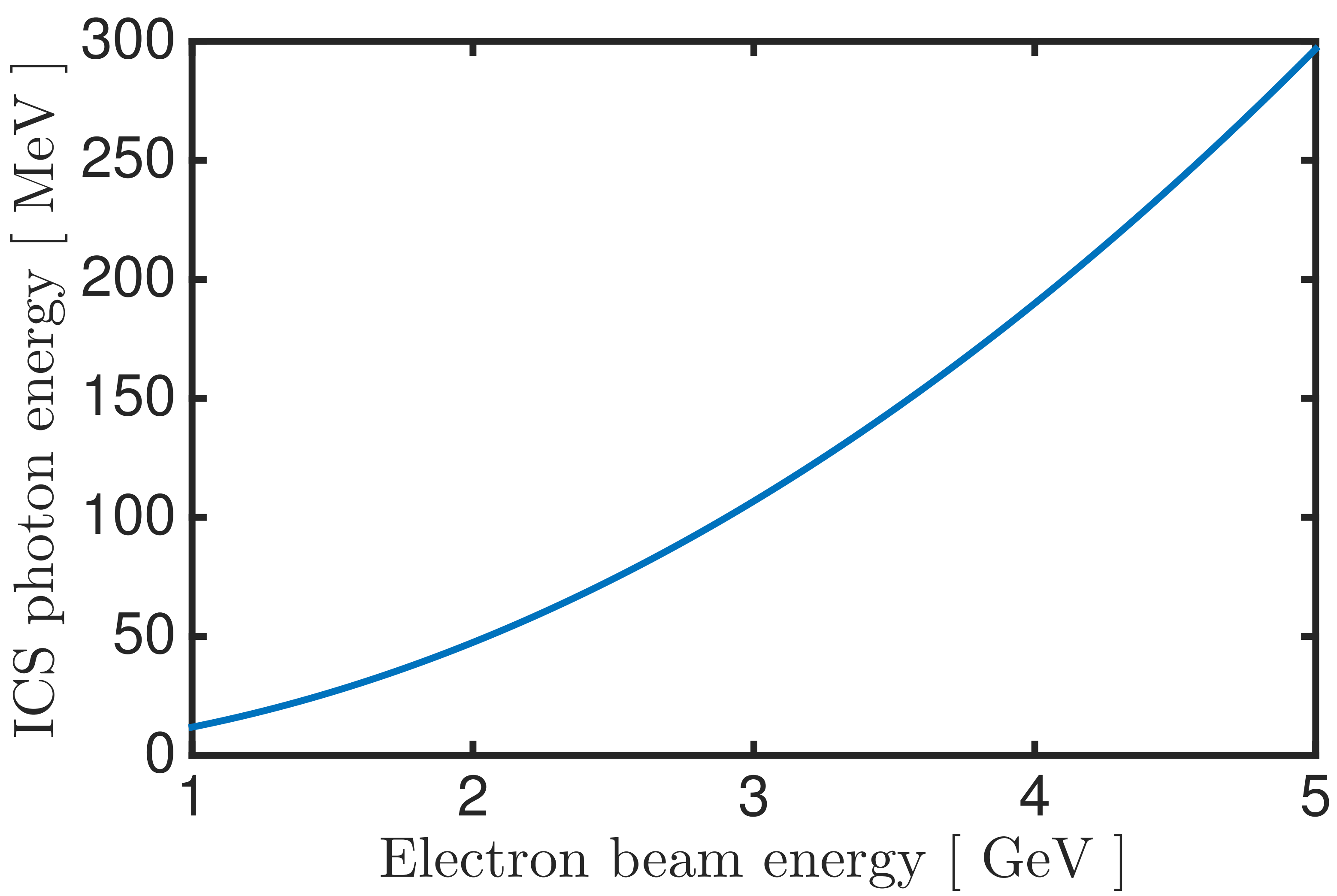
$\theta = 0$

$E_\gamma = 1.5\ \text{eV}$

$\Rightarrow \quad E'_\gamma \approx 2\gamma^2 E_\gamma$

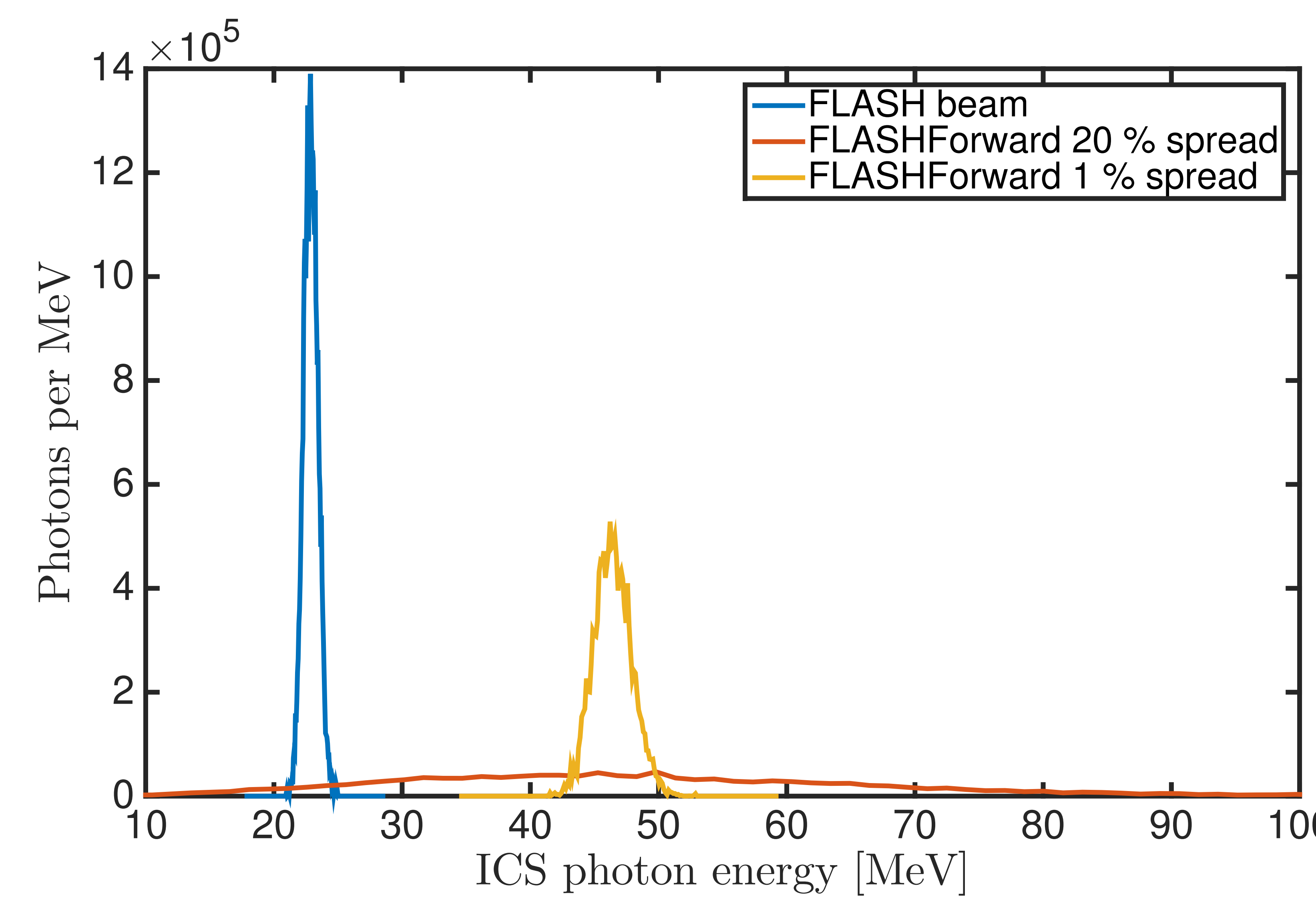
Inverse Compton Scattering as a photon source

- Gamma flux -> correlates to charge density and laser photon flux
- Spectrometer to determine particle energy distribution is a challenge
- Laser $a_0 \ll 1$ allows electron beam properties to be determined
- $a_0 \gtrsim 1$ non-linear effects increase photon energy



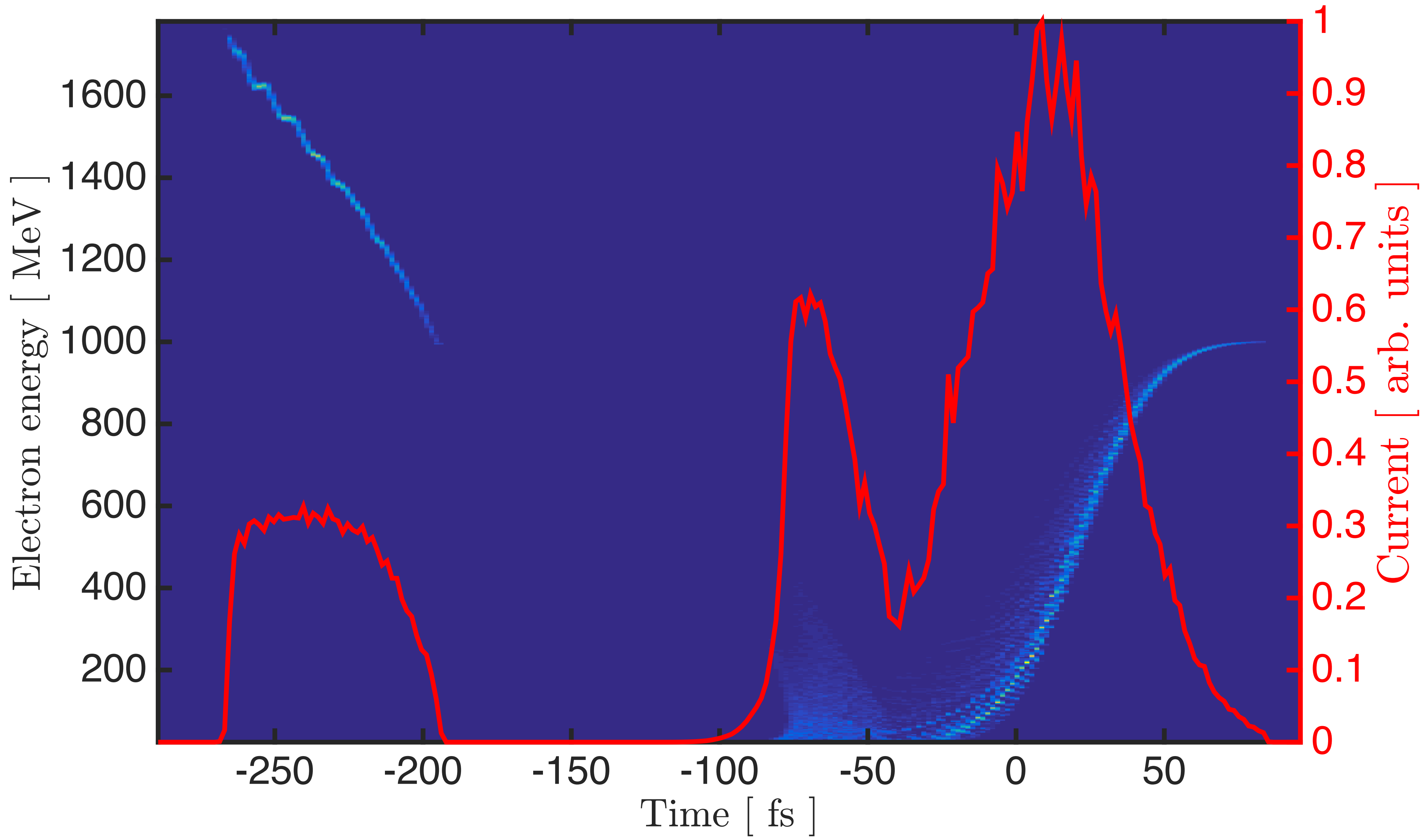
For $a_0 \ll 1$

Flux ~ 10^6 - 10^8 photons per shot

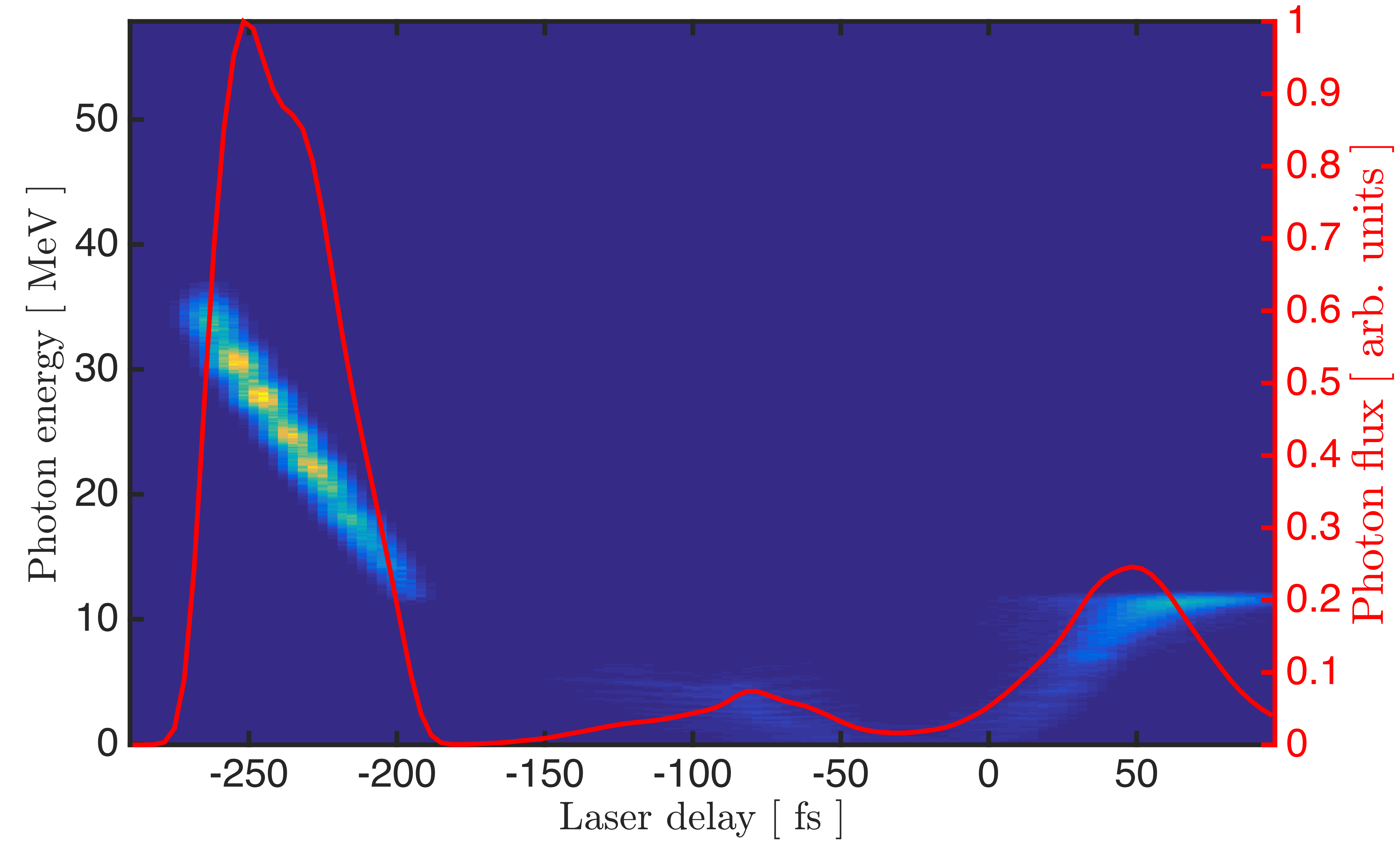


Inverse Compton Scattering as a diagnostic

- Electron distribution from FLASHForward simulation with density down-ramp injection



- Numerical calculation of photon distribution as a function of scattering laser
- Shows lower flux from driver due to large transverse spatial extend (lower density than witness).



WG4 to do list…

- Prepare for Phase II operation
- Free Electron Lasers
  - Start-to-End simulations with increased level of realism and consistency
  - Continue optimization of beam transport for FEL as beam parameters (from WG 1) evolve
  - Perform studies to minimize beam divergence and energy chirp
- Betatron radiation
  - Consider pump-probe possibilities (with undulator radiation)
  - Diagnostics development/testing (with WG2); testing with LWFA beamline
- Inverse Thomson Scattering
  - Continued modeling of expected source parameters
  - Diagnostic development/testing in progress (with WG 2), extend measurement range to 20-100 MeV gamma rays
  - Establish possible users for high-energy gamma-ray beams

Working Group collaborators

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