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
  - Evaluate simulated beams and assist in design of undulator section
  - Demonstrate FEL gain from plasma accelerated beams
  - Target photon production in the water window (<4 nm)
- Betatron radiation
  - Evaluate potential as a photon source in the keV range
- Inverse Thomson Scattering
  - Evaluate potential as a photon source in the MeV range

Group collaborators

Group Coordinators: C. Schroeder, M. Streeter

DESY: C. Behrens, J-P. Schwinkendorf, M. Streeter, J. Zamella

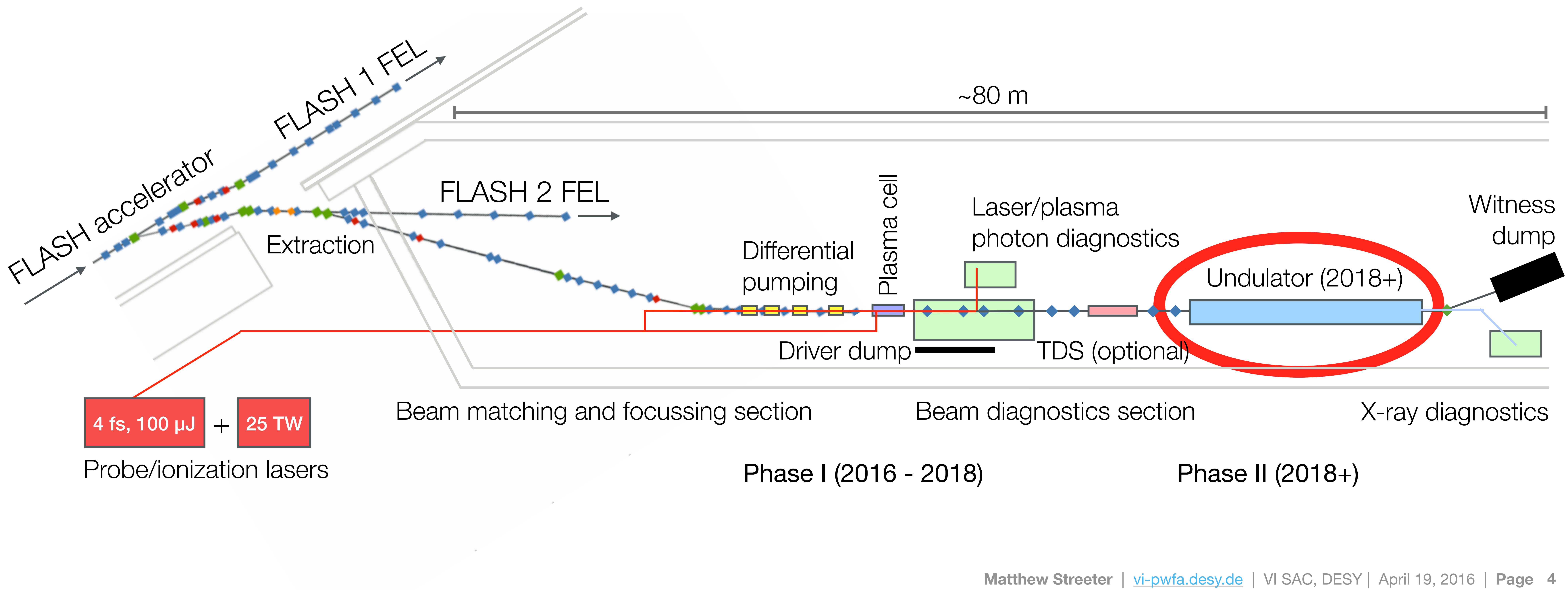
Hamburg University: A Maier, V. Wacker, (F. Pannek), B. Hidding

John Adams Institute: L. Campbell, G. Cheung, S. Hooker, S. Mangles, B. McNeill

LBNL: C. Schroeder

Undulator installation in FLASHForward Phase II

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



Target beam parameters for FEL: beam energy

> **We have the possibility to install 13.5 m (3 × 4.5 m) of Tesla Test Facility (TTF) undulators**

- We target an FEL gain of 100 fold, in order to demonstrate lasing

> **Undulator parameters:**

- Tesla-Test-Facility (TTF) undulators:

$$K = 1.21 \quad \lambda_u = 27.3 \text{ mm}$$

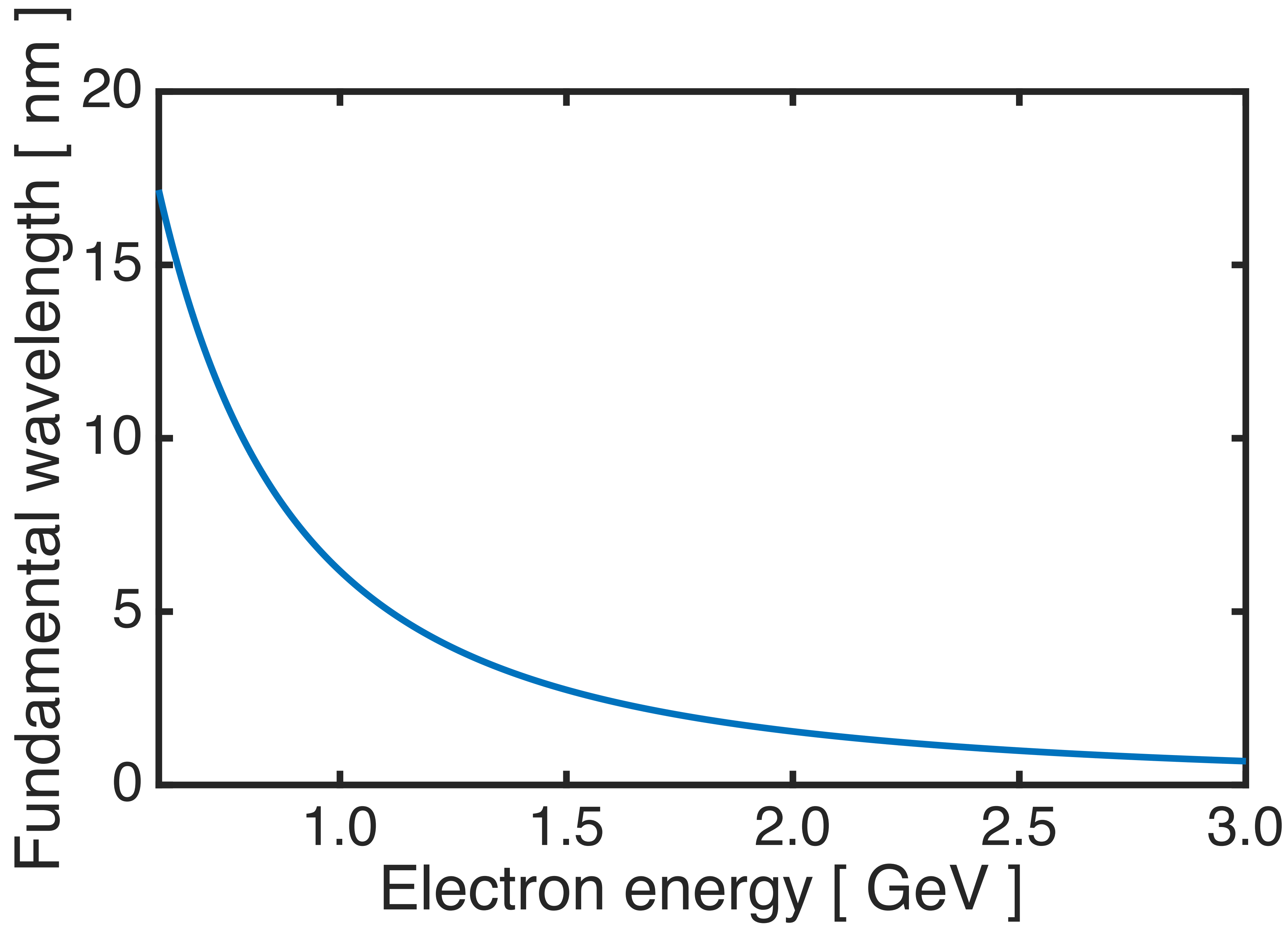
- Likely focusing FODO lattice

$$\beta \approx \mathbf{5 - 10} \text{ m}$$

> **Beam energy**:

- Goal: FEL gain at photon energies comparable to FLASH

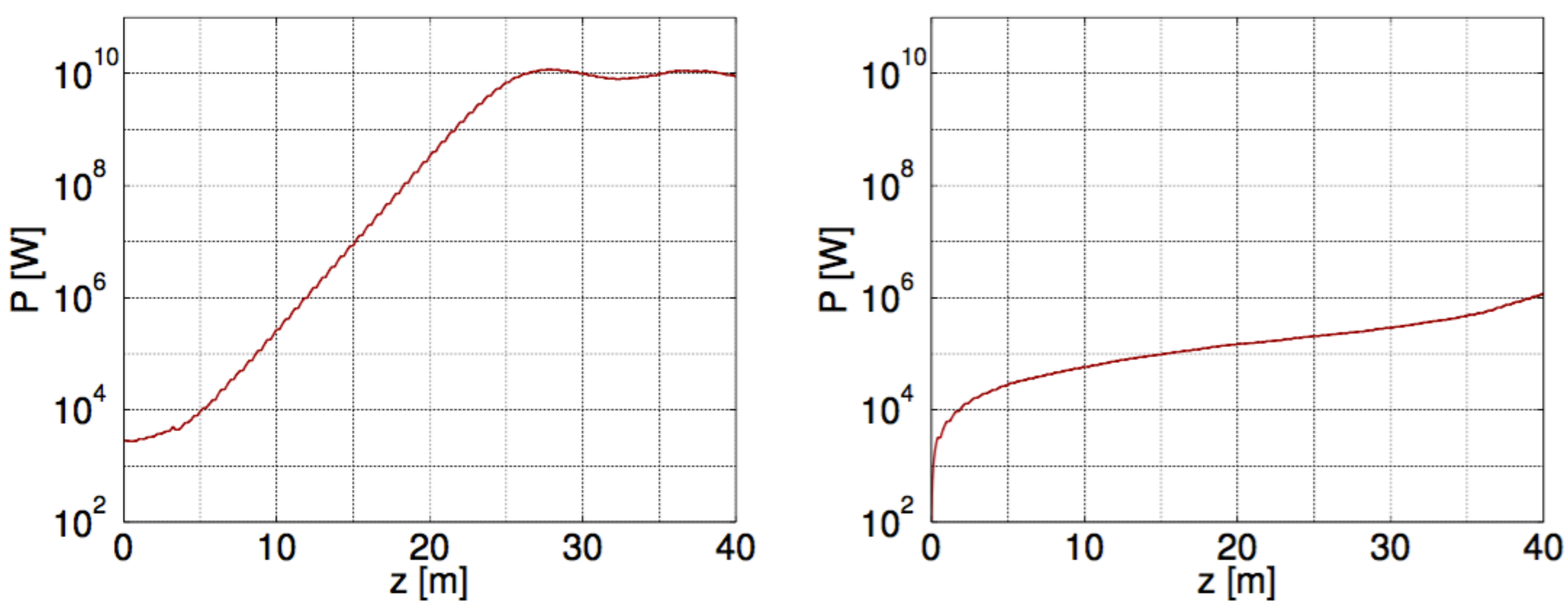
$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + K^2/2\right)$$



First test case demonstrated that bunch length is critical to FEL gain

- **Slippage**: sub-micron electron beams suppresses FEL instability (at soft-x-ray wavelengths)
  - Beam slips with respect to radiation, one wavelength per undulator period
  - To avoid strong slippage effects: require bunch length longer than slippage length (undulator period multiplied by number of oscillations) $\sigma_\mathbf{z} > \lambda_\mathbf{u} \mathbf{N_u}$

Genesis simulations of 230 nm length PWFA ionisation injection beam



Time-independent Time-dependent

Using Ming Xie formalism used to evaluate FEL suitability of beams from PIC simulations

> Goal: minimize FEL power gain length (maximize FEL parameter):

$$P(z) \propto \exp\left(z/L_g\right) \qquad L_g = \frac{\lambda_u}{4\pi\rho}\left[1 + \left(\frac{\sigma_\gamma}{\gamma\rho}\right)^2\right] \qquad \rho = \frac{1}{4\gamma}\left[\frac{I}{I_A}\left(\frac{K[JJ]\lambda_u}{\pi\sigma_x}\right)^2\right]^{1/3}$$

> Conditions for exponential power growth:

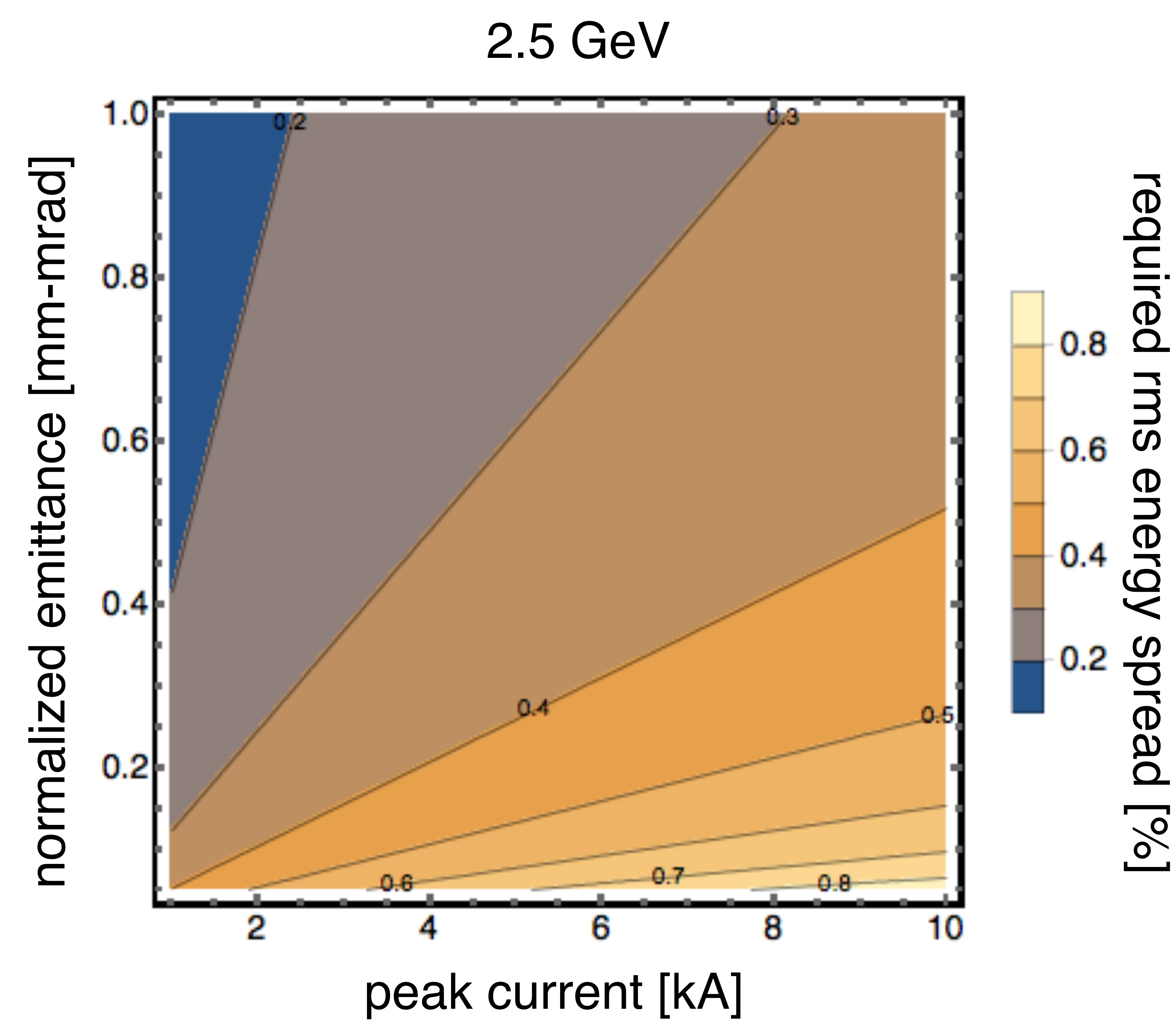
- Beam emittance < photon emittance: $\epsilon_n < \gamma\lambda/4\pi$
- Undulator length > gain length: $N_u\lambda_u > L_g$
- Gain length < Rayleigh length: $L_g \ll Z_R \sim \pi\sigma_x^2/\lambda = \left(\frac{4\pi\epsilon_n}{\gamma\lambda}\right)\frac{\bar{\beta}}{4}$
- Beam energy spread (including effective spread from emittance) < FEL bandwidth ~ FEL parameter

→ **for review of FEL theory, see C. Pellegrini et al., Rev. Mod. Phys. (2016)**

Minimising slice energy spread is critical to minimising FEL gain length

> **Energy spread**:
- Approximate (1D) scaling: $L_g \approx L_{g0}\left[1+\left(\frac{\sigma_\gamma}{\gamma\rho}\right)^2\right]$
- Slice energy spread < FEL parameter: $\sigma_\gamma/\gamma < \rho$
- Required **rms slice energy spread** function of beam current and transverse emittance:

$$\boxed{\left(\frac{\sigma_\gamma}{\gamma}\right)[\%] < \frac{0.3}{(E_b[\mathrm{GeV}])^{2/3}}\left(\frac{I[\mathrm{kA}]}{\epsilon_n[\mu\mathrm{m}]}\right)^{1/3}}$$



- Note: a "slice" is approximately the slippage length over a gain length (i.e., cooperation length):

$$l_c[\mu\mathrm{m}] \sim \frac{\lambda}{4\pi\rho} = \frac{0.2}{(E_b[\mathrm{GeV}])^{4/3}}\left(\frac{I[\mathrm{kA}]}{\epsilon_n[\mu\mathrm{m}]}\right)^{-1/3}$$

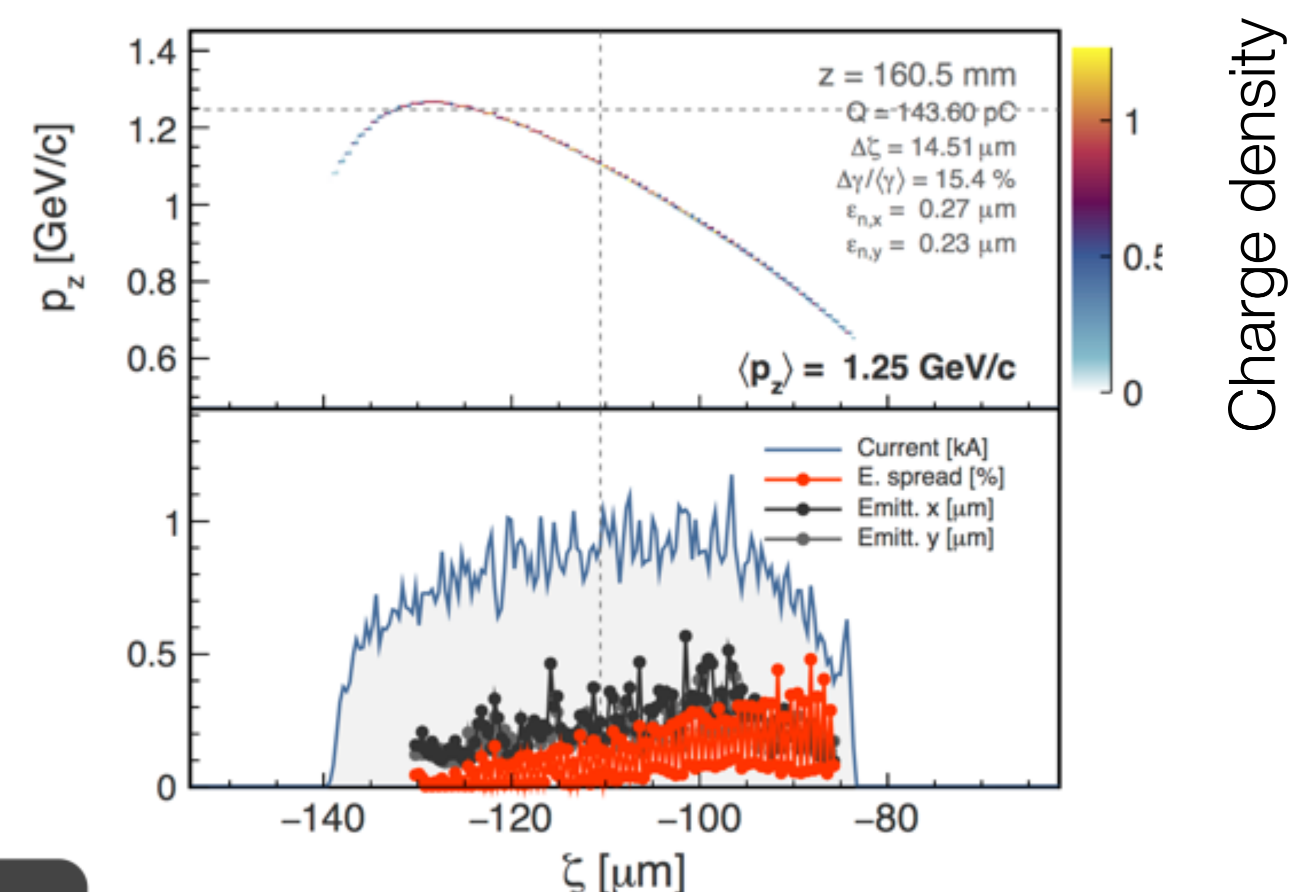
~ 20 nm for 2.5 GeV, 5 kA, 0.3 mm-mrad emittance

New test cases from PIC simulations with TTF undulators: Aiming for gain length < 2.9 m

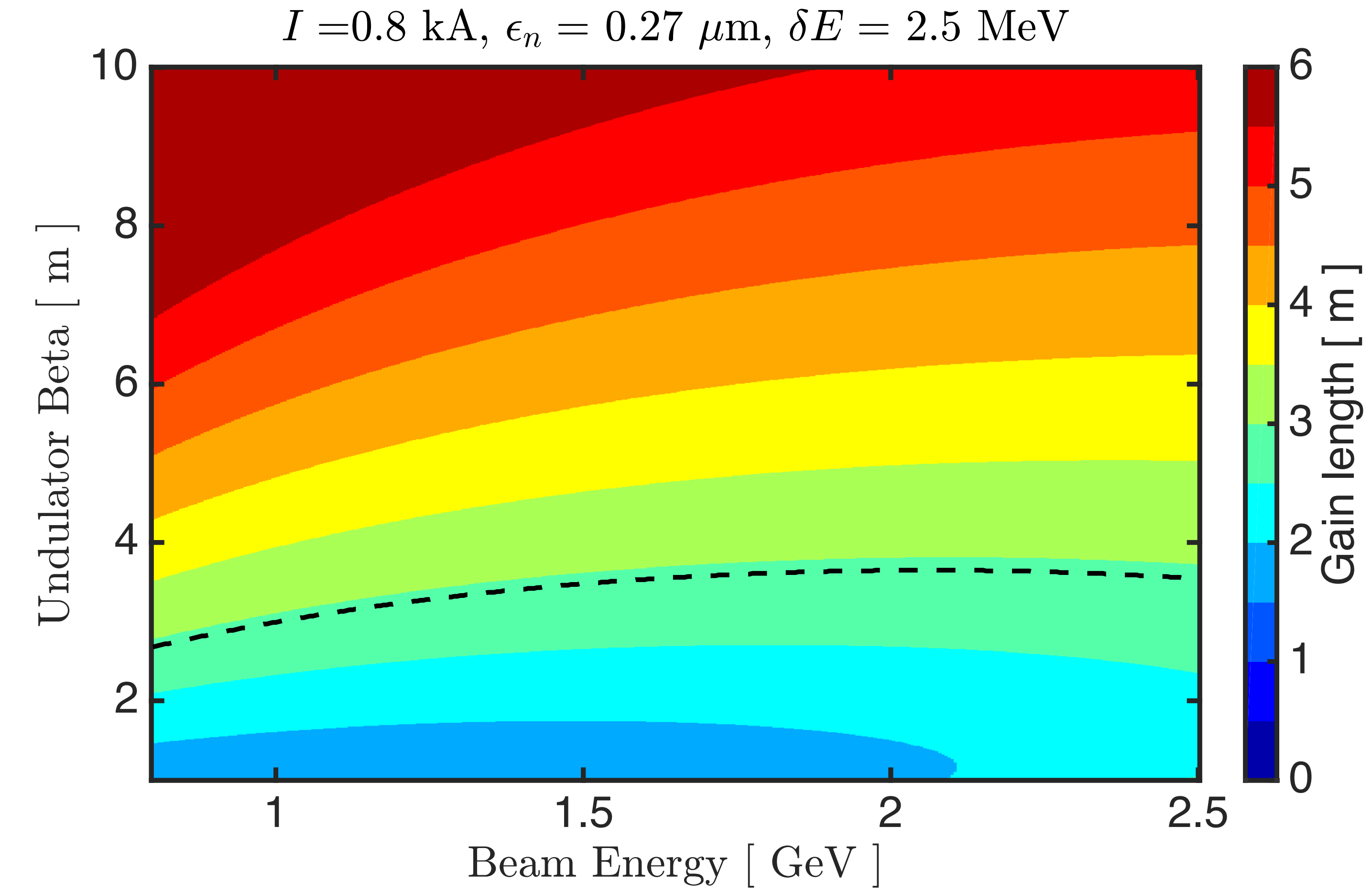
Electron Beam properties

Ming Xie based calculations (does not include chirp)

Density Downramp



Chirp would be an additional problem for this case

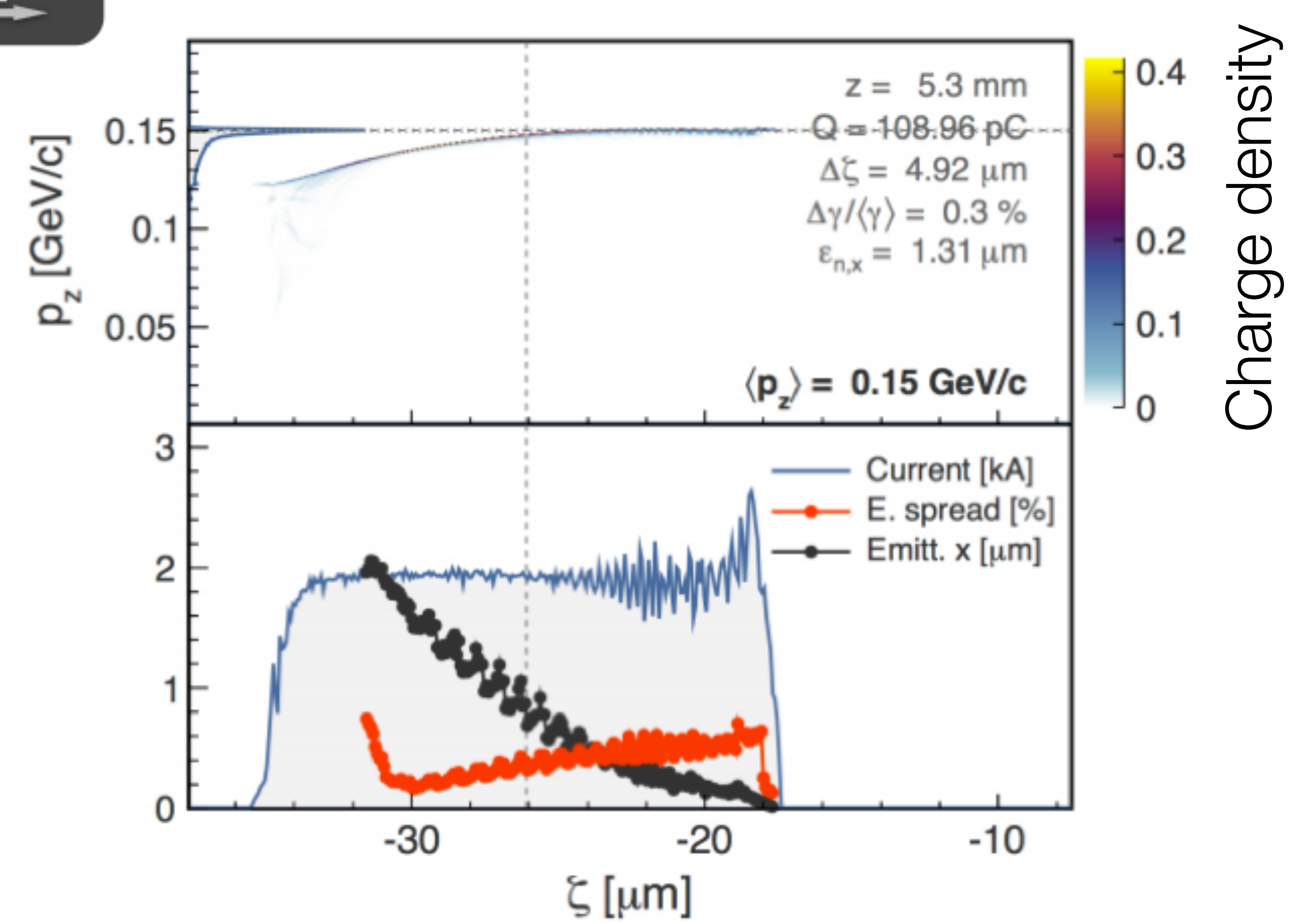


3D particle-in-cell (PIC) simulation

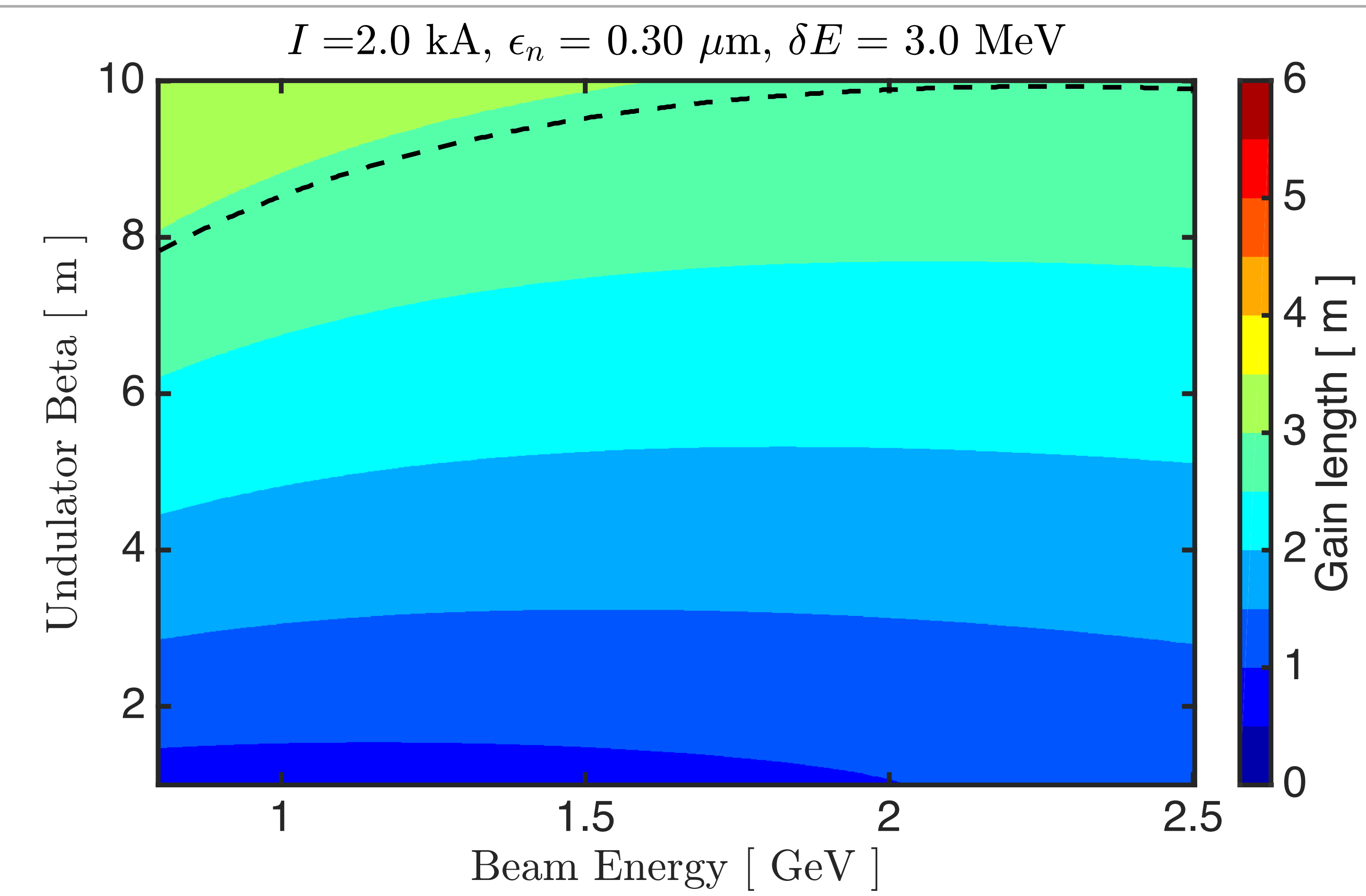
osiris v2.0

HiPACE

Laser Assisted Trapping



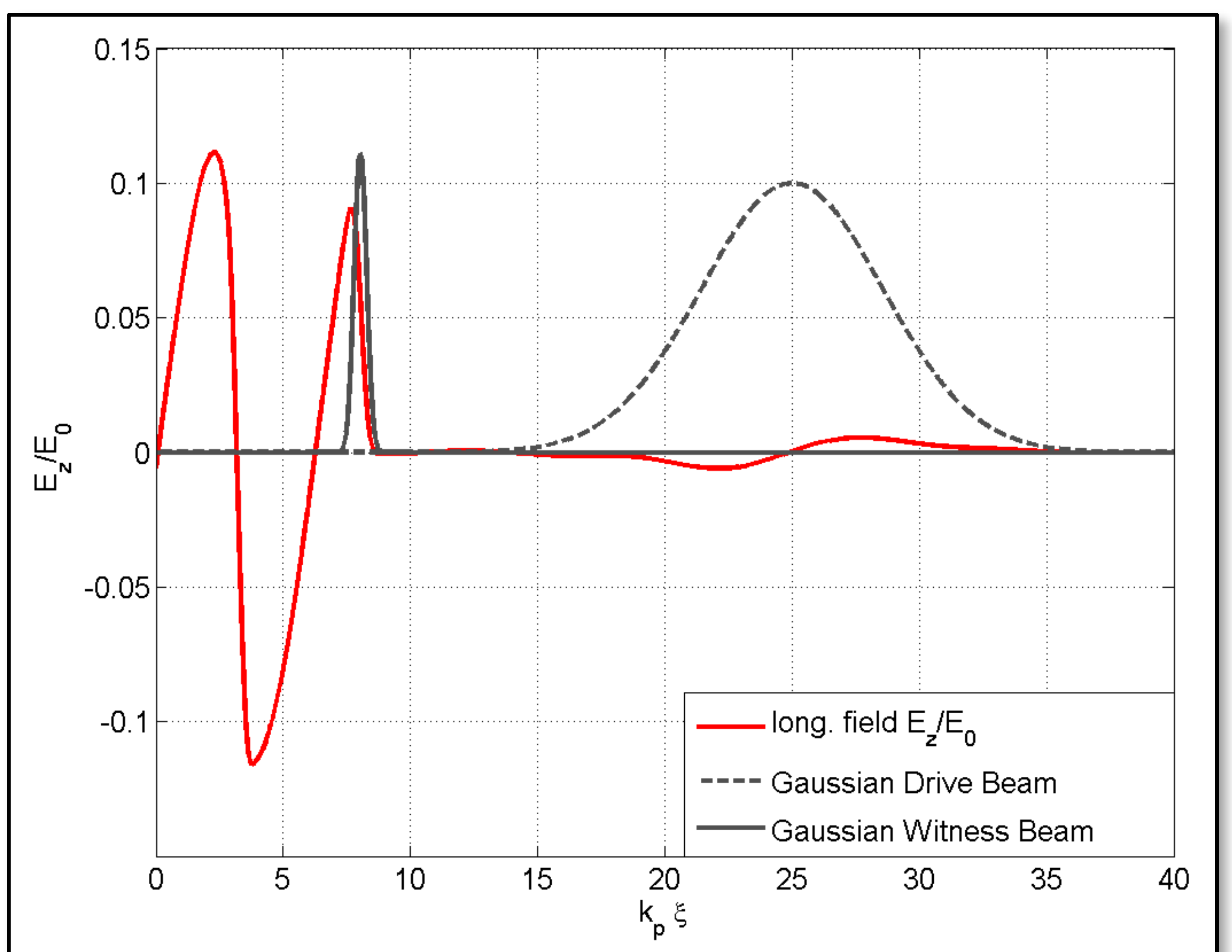
This case shows increased performance, mainly due to the higher beam current

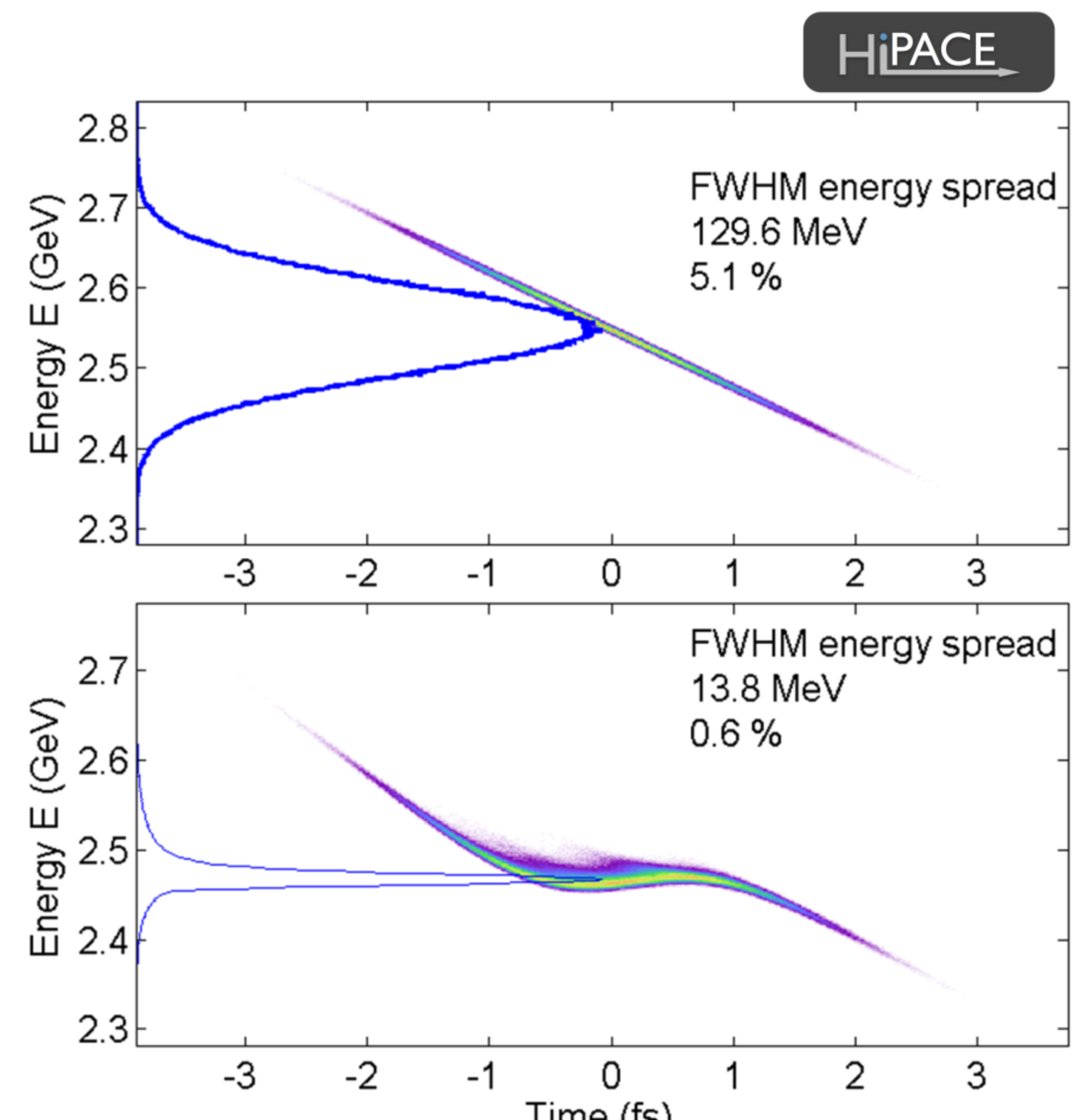


Longitudinal energy chirp will be a problem
Investigation underway exploring de-chirping techniques

→ courtesy of V. Wacker

- Theoretical and simulation work has revealed the potential to de-chirp the beam
- Proof of principle experiment planned at Brookhaven National Laboratory
- Main challenge to remove influence of drive beam
  - May be possible with control of target density and ionisation pulse for higher Z gas between driver and witness





Summary and conclusions

> Collaboration between VI members is resulting in good progress
  - Would like to add more people who can contribute actively to the research

> Free Electron Lasers
  - Recent work has lead to a change in how electron beams from simulations are evaluated
  - Starting to see simulated PWFA beams with potential for FEL gain
  - Latests beam distributions will be evaluated using the 3D code Genesis
  - Experimental and theoretical work in progress to determine possibilities for de-chirping

> Betatron radiation and Inverse Thomson Scattering
  - Most work on this currently falling within Working Group 2: Diagnostics