X-FELs driven by GeV and 10s of GeV electrons from density downramp injection

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X-FELs driven by plasma-based acceleration (PBA)

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- Beam quality requirements to drive a X-FEL

(1) Emittance & Current: $\rho = \frac{1}{\gamma_b}\left[\left(\frac{K_u f_c}{4k_u}\right)^2 \frac{\gamma_b}{\beta\epsilon}\frac{I_b}{I_A}\right]^{1/3}$

$$L_{sat} \approx \frac{\lambda_u}{\rho}, P_{sat} \approx \rho P_{beam}$$

(2) Energy spread: $\frac{\sigma_{E_b}}{E_b} < \rho$ (10^{-3}~10^{-4})

- ➢ Typical energy spread from PBA: ~1%
  - Stretch the beam longitudinally[1]
  - Stretch the beam transversely + Transverse-Gradient Undulator[2]
- ➢ Control the injection and acceleration processes

(3) Energy: ~GeV to reach 1nm wavelength $\lambda_r = \frac{\lambda_u}{2\gamma_b^2}\left(1 + \frac{K^2}{2}\right)$

[1]A. R. Maier et al., PRX 2.031019 (2012);
[2]Zhirong Huang et al., PRL 109, 204801 (2012).

- High power: 1~10 TW and more $P_{sat} \approx \rho P_{beam} \propto I_0^{4/3}$

  → High current: 10s of kA and more

- Short wavelength: 1nm~0.01nm and shorter $\lambda_r = \frac{\lambda_u}{2\gamma_b^2}\left(1+\frac{K^2}{2}\right)$

  → High energy: GeV ~10s of GeV

- Short duration: attosecond

  → Short beam/Controlled chirp for further compression

- …

Controlled Injection schemes:

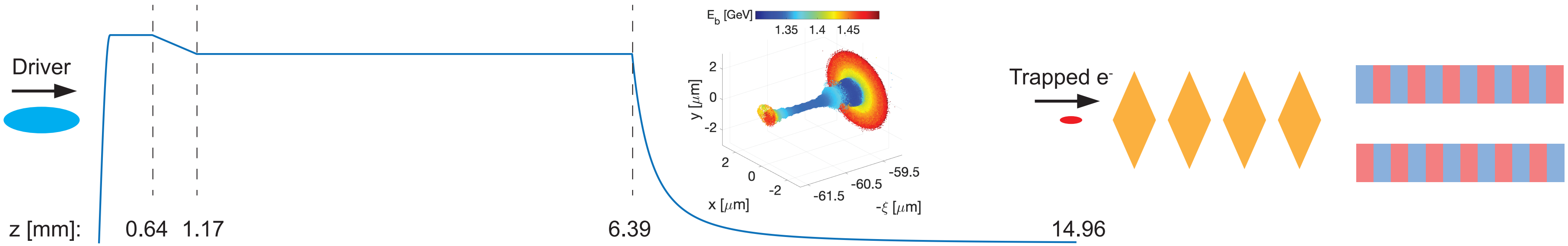
- Ionization-based injection[1]: 10s of nm, ~kA
- Density downramp injection[2]: 10s of nm, ~10s of kA

[1]B. Hidding et al., PRL 108, 035001 (2012); F. Li et al, PRL 111, 015003 (2013); X. L. Xu et al., PRL 112, 035003 (2014); G. G. Manahan et al., 10.1038/ncomms15705 (2017);
[2]J. Grebenyuk et al., NIMA 740, 264 (2014); X. L. Xu et al., PRAB 20, 111303 (2017).

X-FELs based on density downramp injection

OSIRIS | QuickPIC | Elegent | Genesis

Injection | Acceleration | Plasma Matching | Magnetic quadrupoles | Undulator



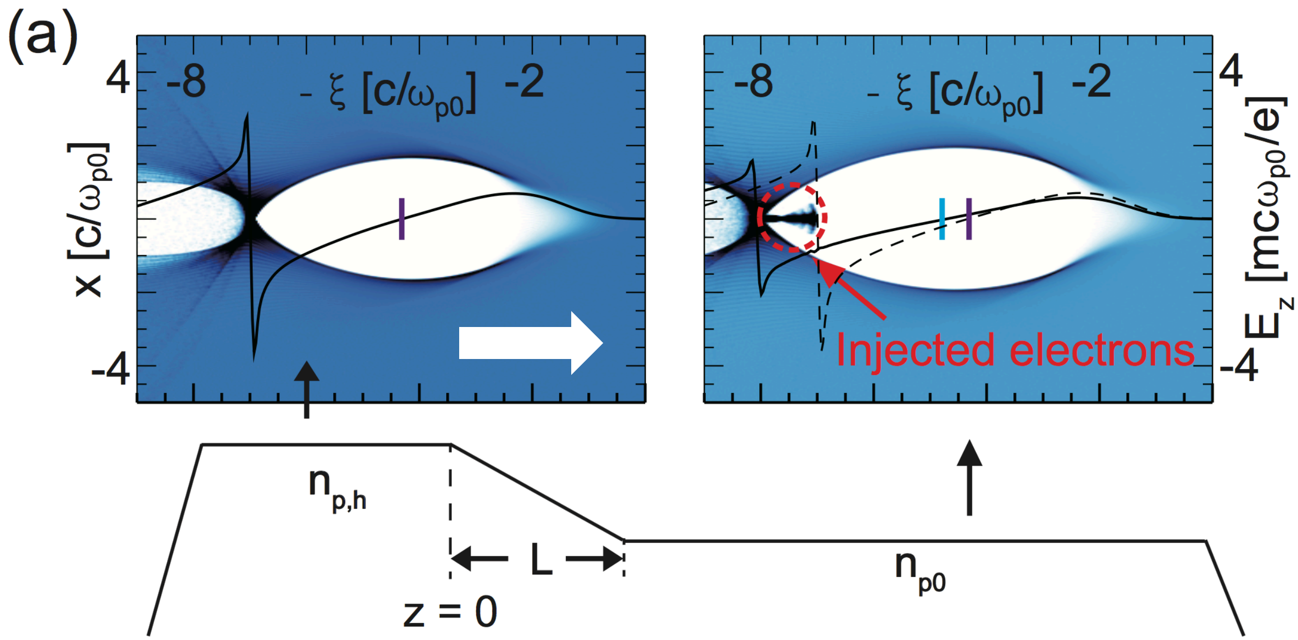
$\beta_{x,y} \approx 0.5$ mm → $\beta_{x,y} \approx 0.01$ m → $\beta_{x,y} \approx 0.4$ m

	E_d [GeV]	I [kA]	σ_r [um]	σ_z [um]	ε_n [um]	Q [nC]
Driver beam	2	34 (Λ=4)	2.7	5.3	5.3	1.5

	$n_{p,h}$ [cm^{-3}]	n_{p0} [cm^{-3}]	L_{ramp} [mm]	L_{acc} [mm]	Initial T [eV]
Plasma	1.1e18	1e18	0.53	5.22	[0.5, 0.5, 0.5]

Density downramp injection

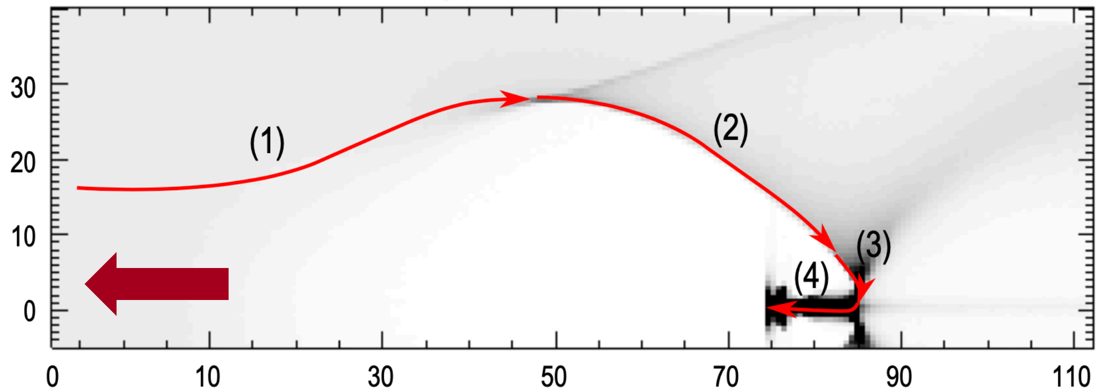
- Injection mechanism: decreasing the phase velocity of the wake by a density downramp.

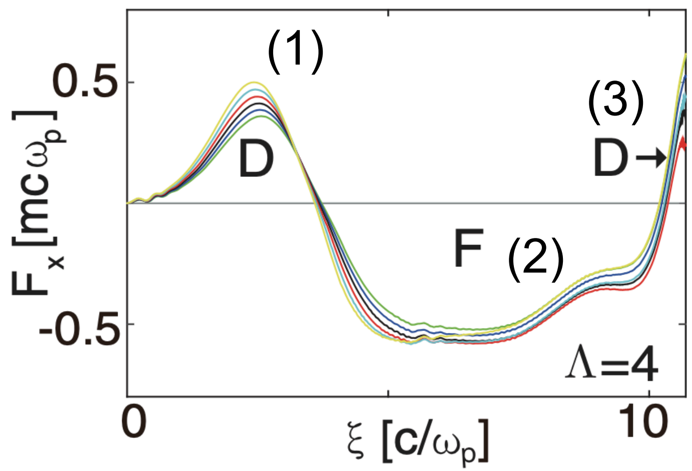


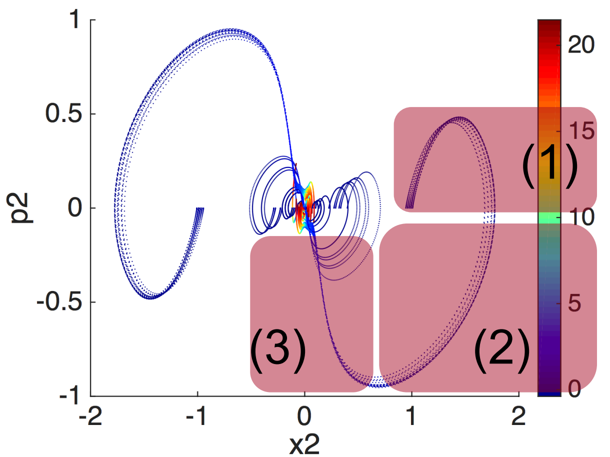
[1]S. Bulanov, et al., Phys. Rev. E 58, R5257 (1998); [2]H. Suk, et al., Phys. Rev. Lett. 86, 1011 (2001);

Generation of low emittance electrons

- “Transverse Deceleration” when the e⁻ move to the tail of the wake.

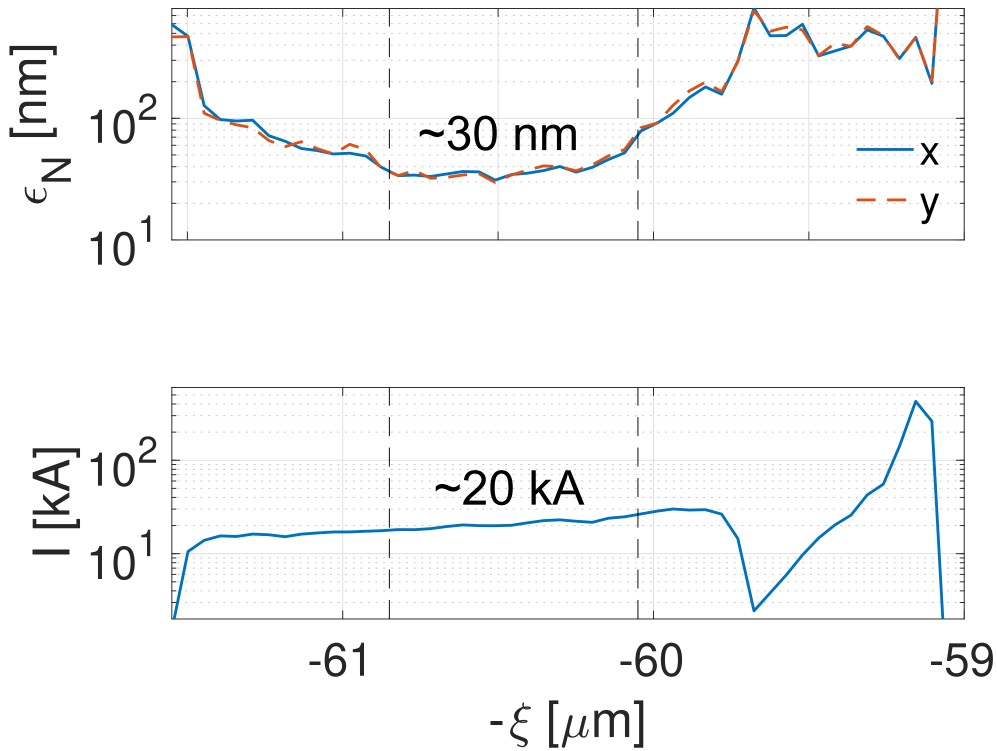


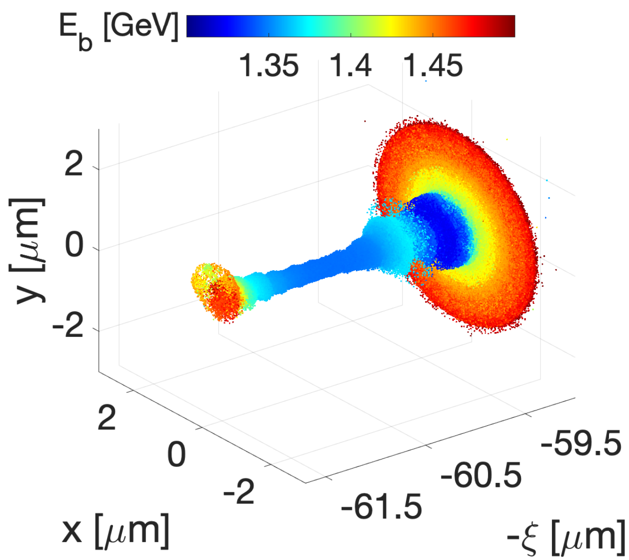




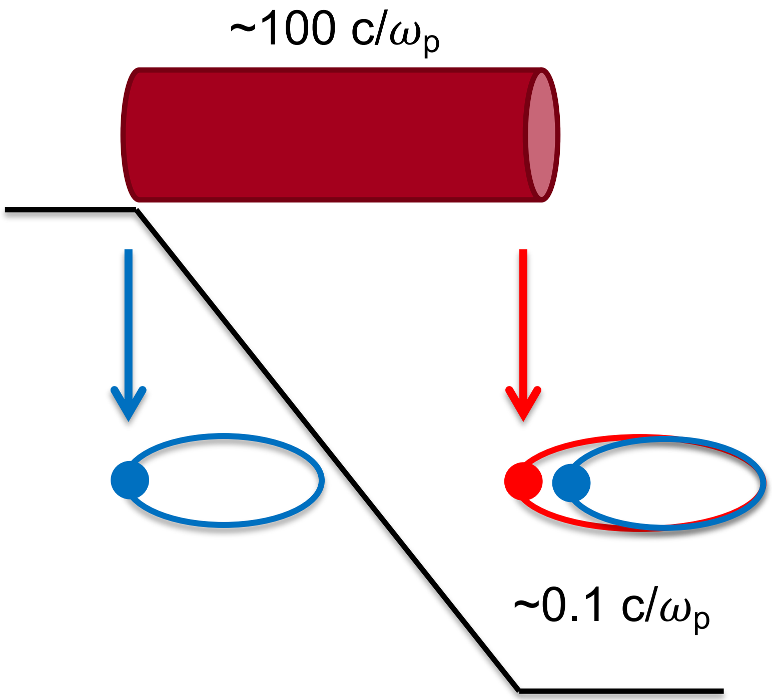
X. L. Xu et al., Phys. Rev. Accel. Beams. 20, 111303 (2017).

Generation of low emittance electrons



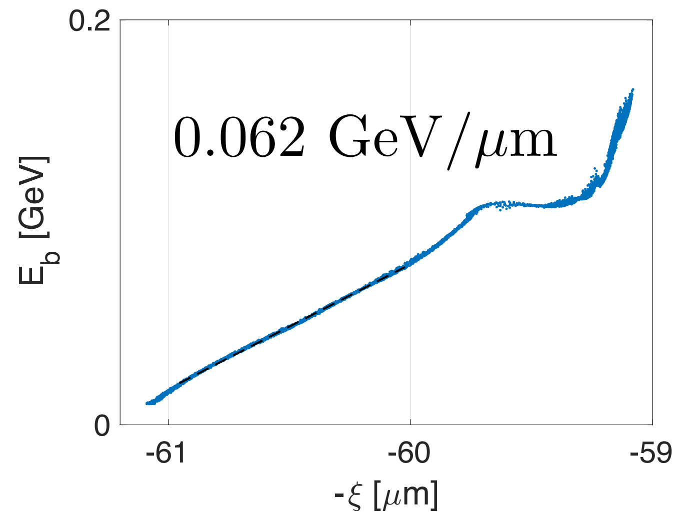


Longitudinal mapping



$$\frac{d\xi}{dz_i} \approx \frac{d\lambda_{wake}}{dz_i} \approx 2\frac{dr_m}{dz_i}$$

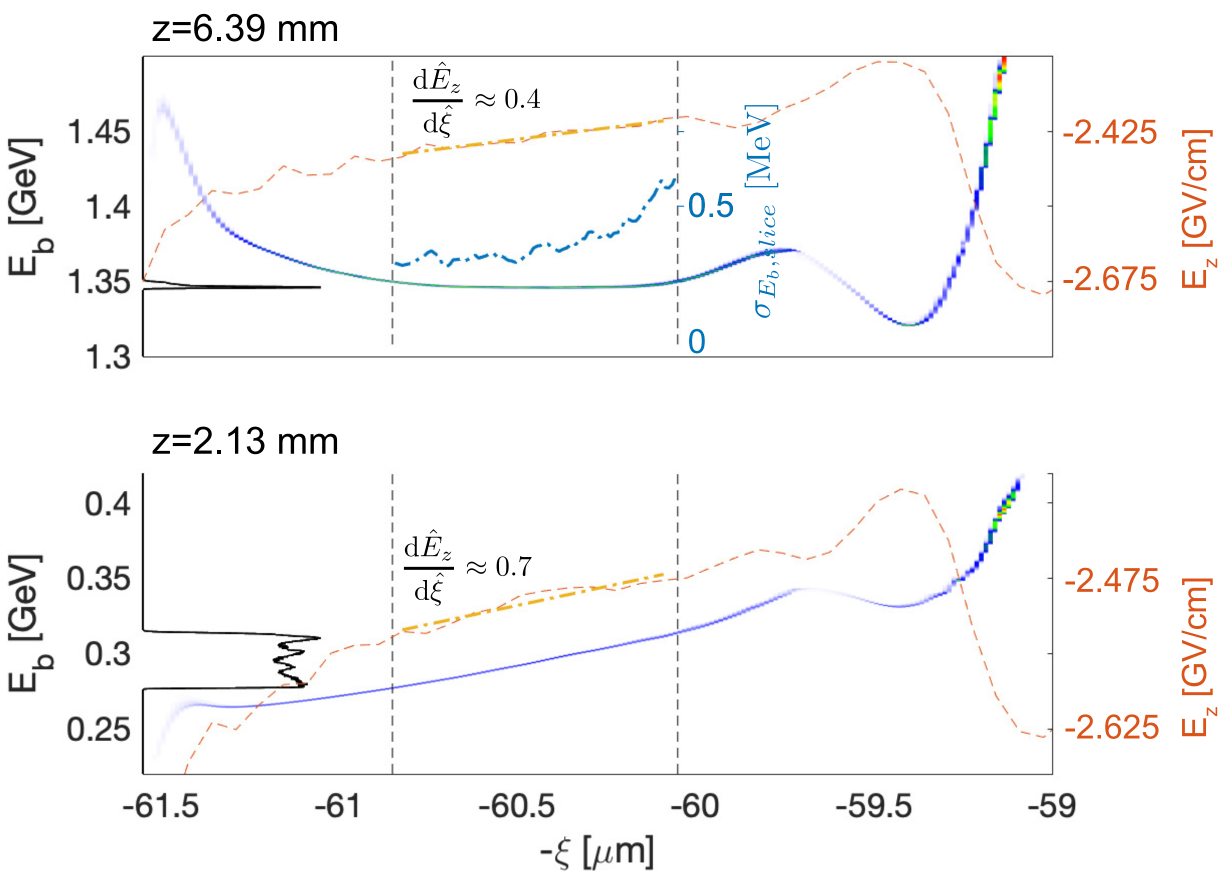
At the end of the ramp (z=1.17 mm)



- Break the longitudinal phase mixing which leads to a low slice energy spread, O(0.1) MeV.
- Induce a energy chirp which leads to a high energy beam without chirp.
- Compress the beam which leads to a high current, 10s of kA (~0.5 I_d).

Longitudinal phase space rotation

L_{ramp}=0.532 mm, Δn_p=0.1n_{p0}



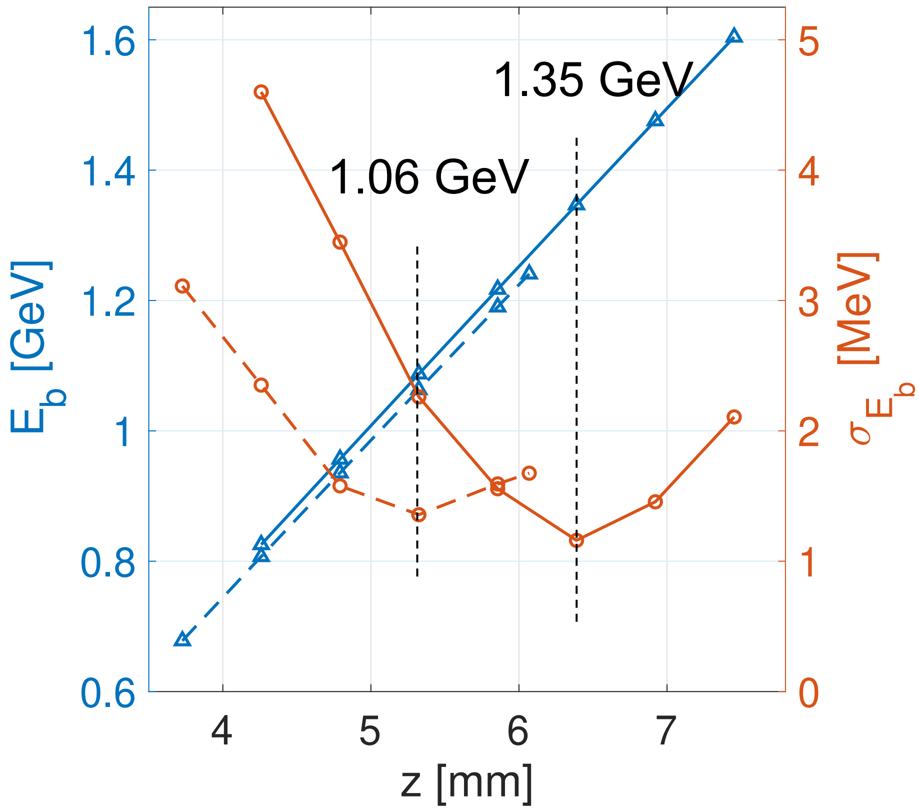
$$\frac{\sigma_{E_b,slice}}{E_b} = \frac{0.35\ \text{MeV}}{1.35\ \text{MeV}} \approx 3 \times 10^{-4}$$

$$\frac{\sigma_{E_b}}{E_b} = \frac{1.16\ \text{MeV}}{1.35\ \text{GeV}} \approx 8 \times 10^{-4}$$

Nonlinear energy chirp:

$$\sigma_{E_b,nl} \approx \sqrt{\sigma_{E_b}^2 - \sigma_{E_b,slice}}$$
$$\approx 1.09\ \text{MeV}$$

Evolution of the average energy and energy spreads



Solid lines: L_{ramp}=0.532 mm
Dashed lines: L_{ramp}=0.426 mm

$$g = \frac{\Delta \hat{n}_p}{\hat{L}_{ramp}}$$

Chirp after the ramp:

$$\frac{d\gamma_b}{d\hat{\xi}} \approx -\frac{\hat{E}_z}{2\sqrt{2I_d/I_A}}\left(\frac{d\hat{n}_p}{d\hat{z}}\right)^{-1}\hat{n}_p^{3/2} \approx -\frac{\hat{E}_z}{4g}$$

Acceleration gradient:

$$\hat{E}_z \approx \hat{E}_{z0} + \frac{d\hat{E}_z}{d\hat{\xi}}(\hat{\xi} - \hat{\xi}_b)$$

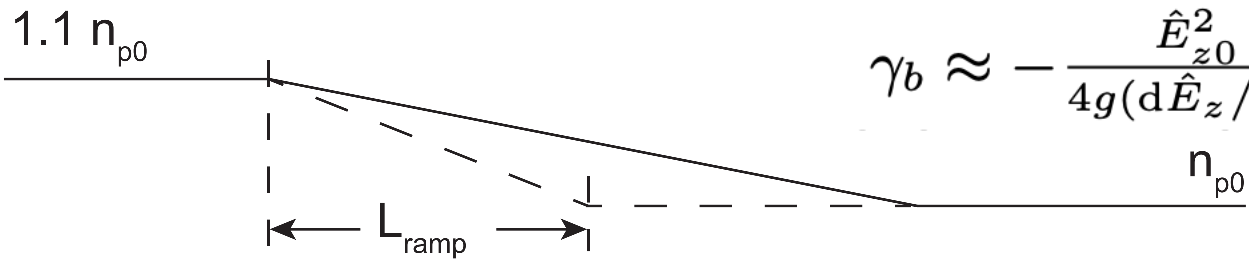
The projected energy spread achieves its minimum at $\hat{L}_a \approx \frac{\hat{E}_{z0}}{4g(d\hat{E}_z/d\hat{\xi})}$

where the energy is

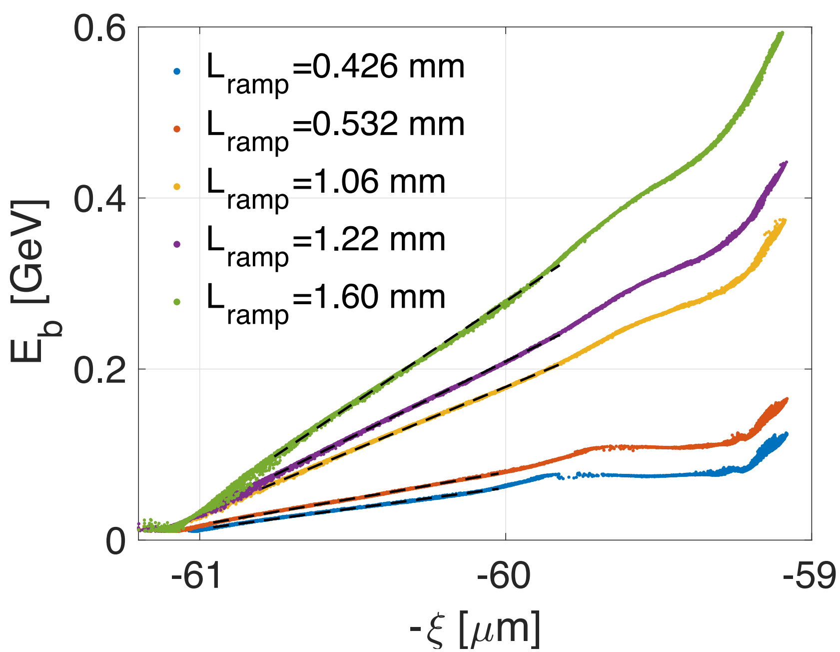
$$\gamma_b \approx -\frac{\hat{E}_{z0}^2}{4g(d\hat{E}_z/d\hat{\xi})}$$

Put the numbers in, L_a≈6 mm (5.2 mm from simulations).

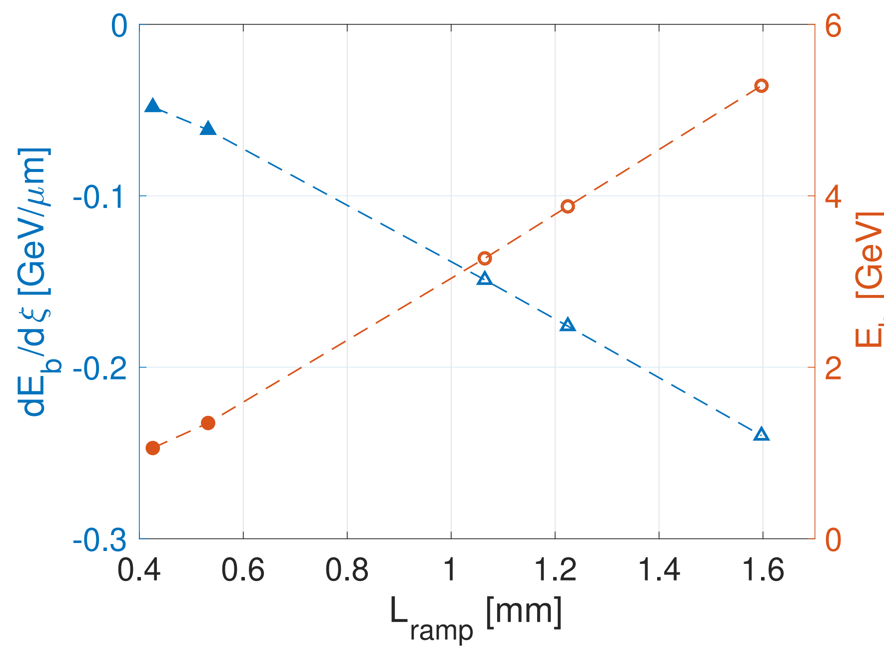
Improve the energy by increasing the ramp length



$$\gamma_b \approx -\frac{\hat{E}_{z0}^2}{4g(\mathrm{d}\hat{E}_z/\mathrm{d}\hat{\xi})} \qquad g = \frac{\Delta \hat{n}_p}{\hat{L}_{ramp}}$$



At the end of the ramp



Improve the energy to 10s of GeV

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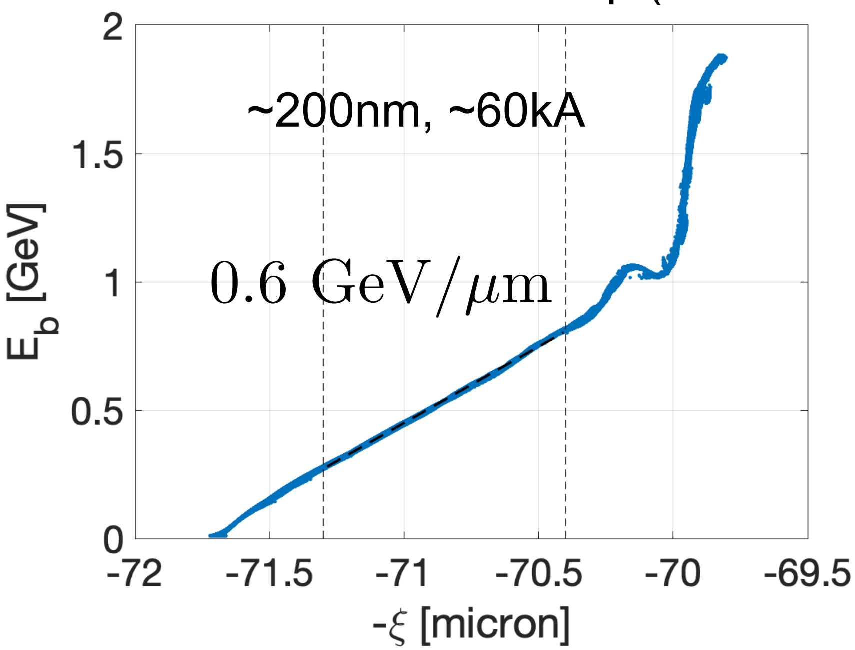
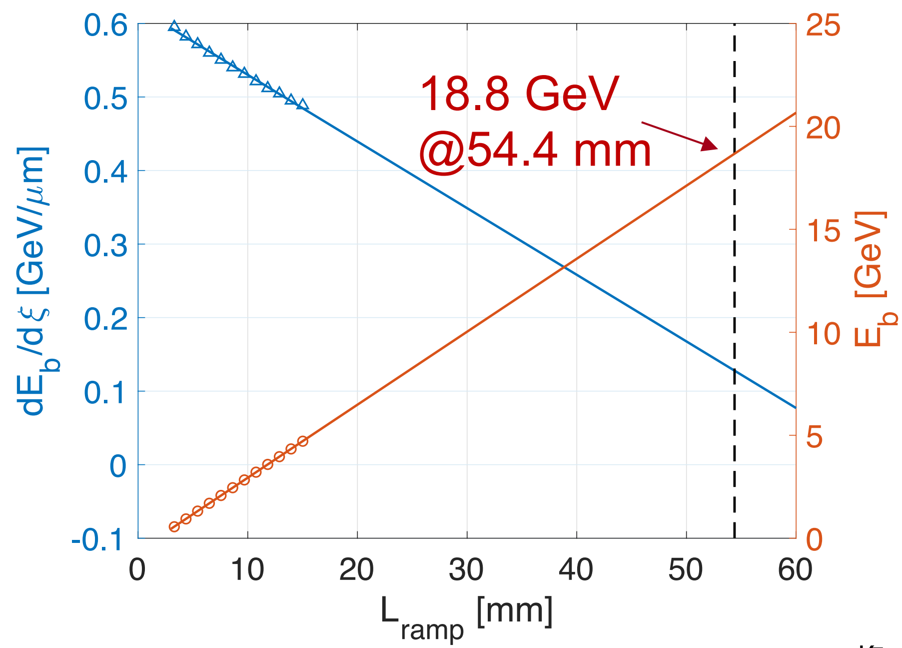
	E_d [GeV]	I [kA]	σ_r [um]	σ_z [um]	ε_n [um]	Q [nC]
Driver beam	10	68 (Λ=8)	0.85 (matched)	5.3	12.7	3

	$n_{p,h}$ [cm^{-3}]	n_{p0} [cm^{-3}]	L_{ramp} [mm]	Initial T [eV]
Plasma	1.05e18	1e18	2.66	0.5

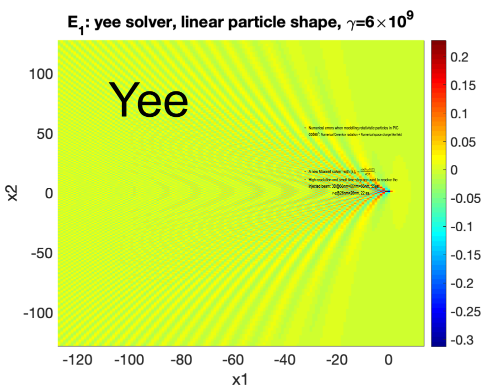
At the end of the ramp (z=3.3 mm)

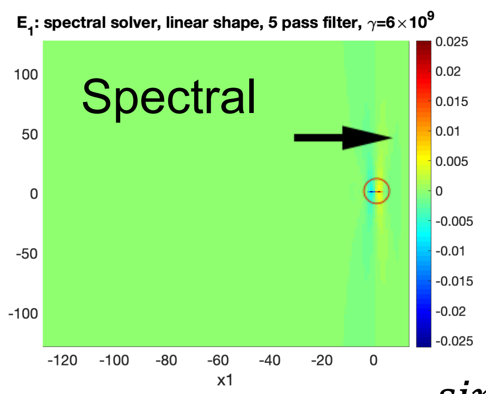


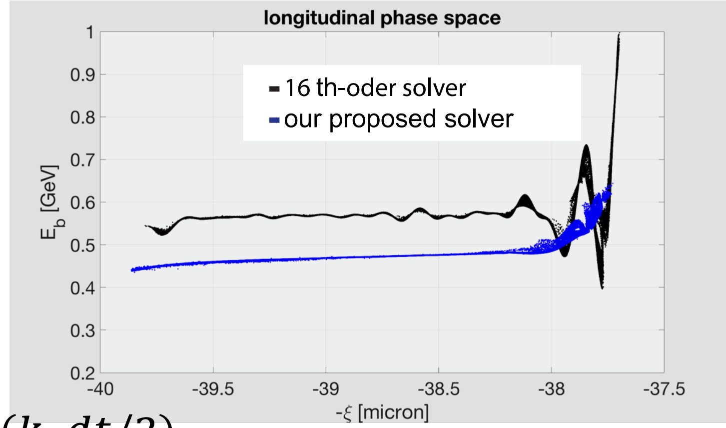


Simulation challenges

- Numerical errors when modelling relativistic particles in PIC codes[1]: Numerical Cerenkov radiation + Numerical space charge like field



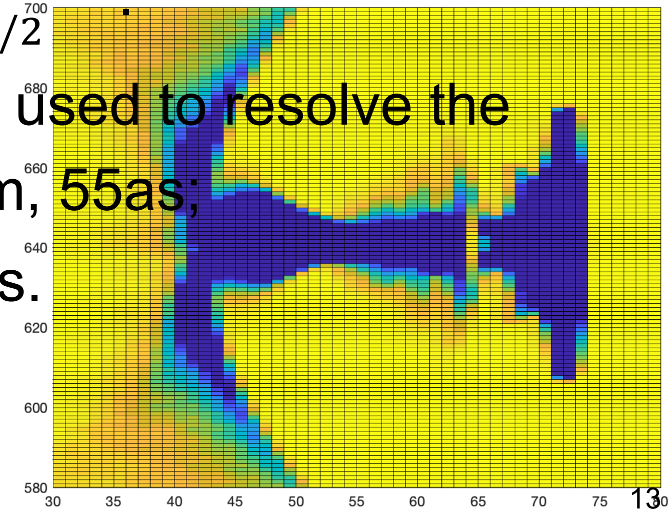




- A new Maxwell solver[1] with $[k]_1 = \frac{sin(k_1 dt/2)}{dt/2}$

- High resolution and small time step are used to resolve the injected beam: 3D@66nm×66nm×66nm, 55as;

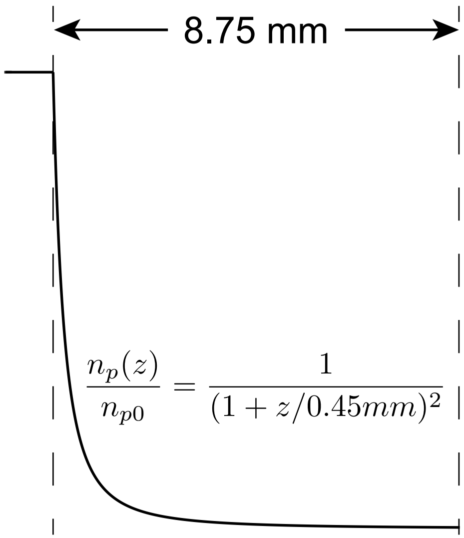
  r-z@26nm×26nm, 22 as.



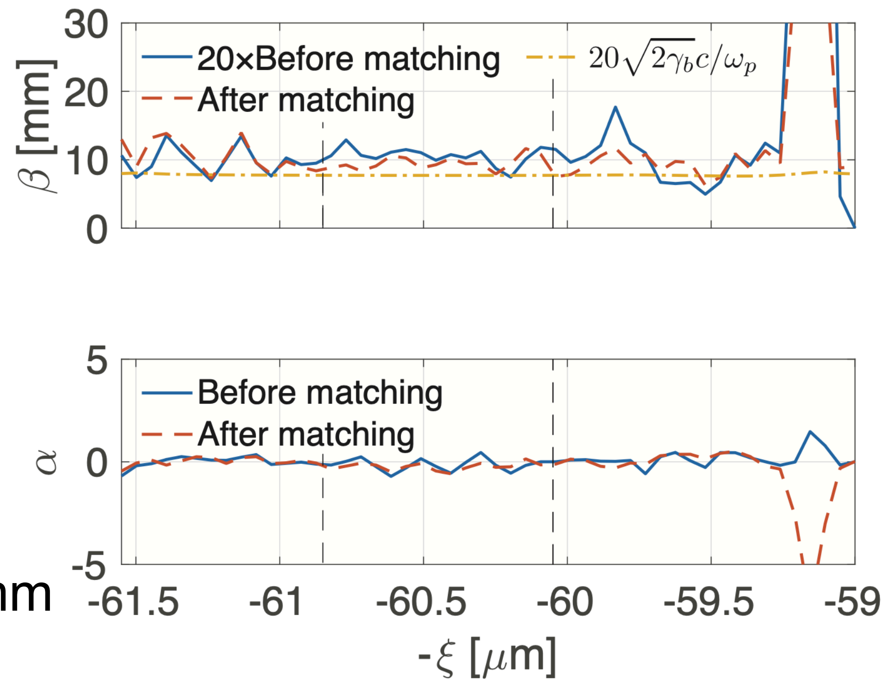
[1]Xinlu Xu et al., arXiv:1910.13529.

Matching: Plasma matching section + Magnetic Quads

- Goal: Enlarge the beam size while preserving the beam quality (emittance, peak current and energy spreads)



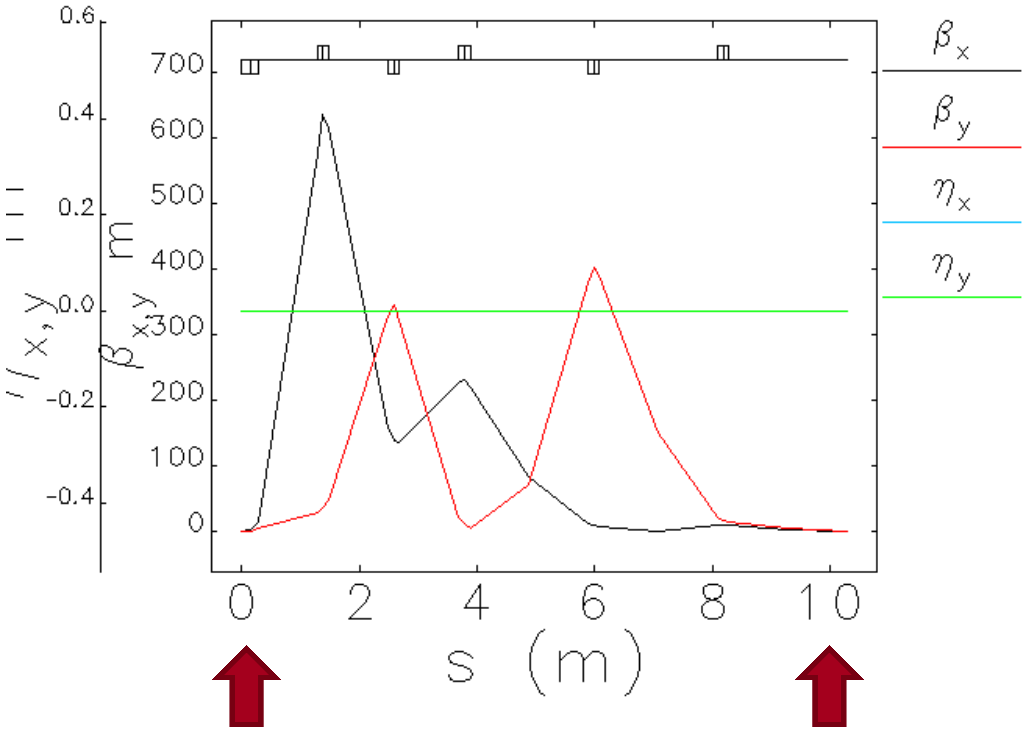
$\beta_{x,y}$≈0.5 mm ➡ $\beta_{x,y}$≈10 mm



- Energy change: -3.7 MeV (1347 MeV -> 1343 MeV);
- Other parameters (current, energy spreads) vary little.

Matching: Plasma matching section + Magnetic Quads

- Designed and simulated using Elegant.



$\beta_{x,y}$≈0.01m

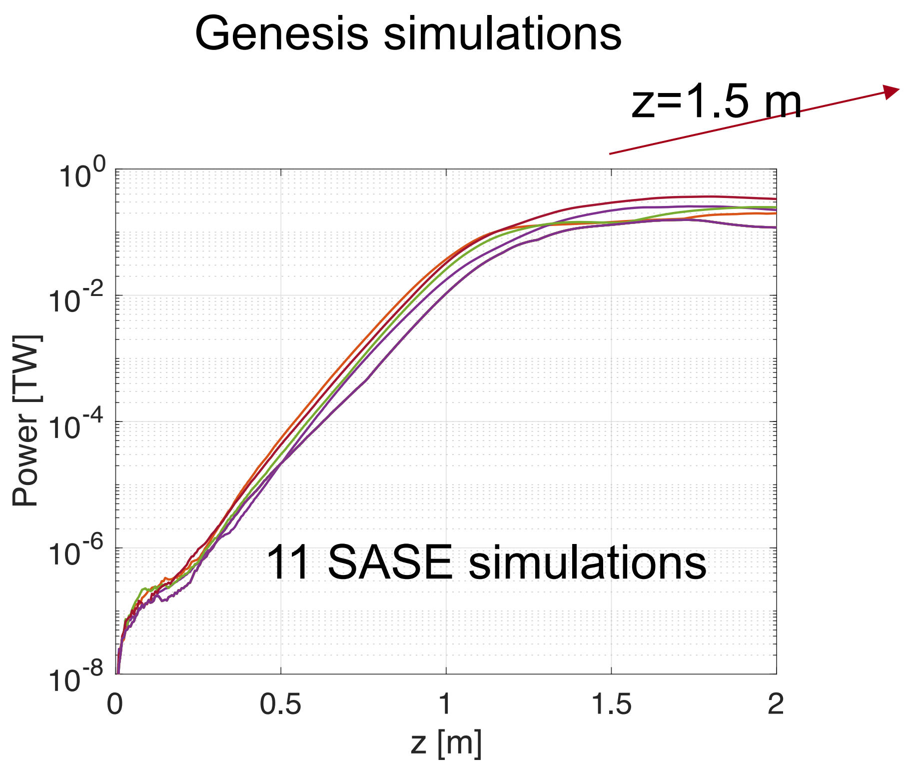
$\beta_{x,y}$≈0.4m

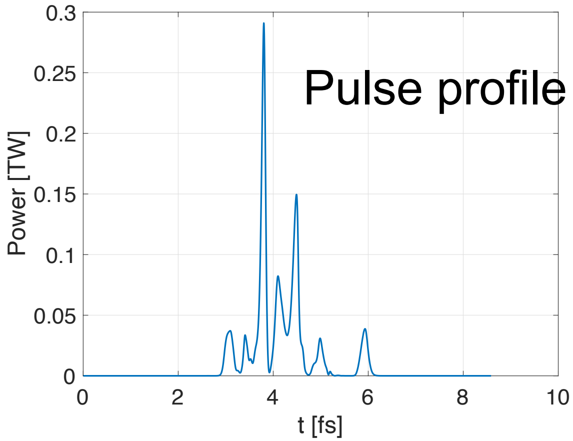
	L [m]	K [m^{-2}]
Q1	0.1	-20.0*
Q2	0.1	6.6
Q3	0.1	-6.43
Q4	0.1	2.54
Q5	0.1	-4.76
Q6	0.1	6.34

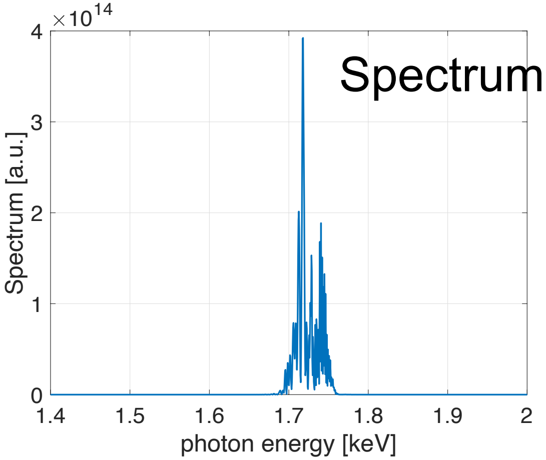
*Corresponding to 90T/m.

FEL radiation: ~1 nm, 100s of GW in meter long undulator

- Undulator: λ_u=0.5 cm, K=1.4, λ_r=0.716 nm (1.73 keV)

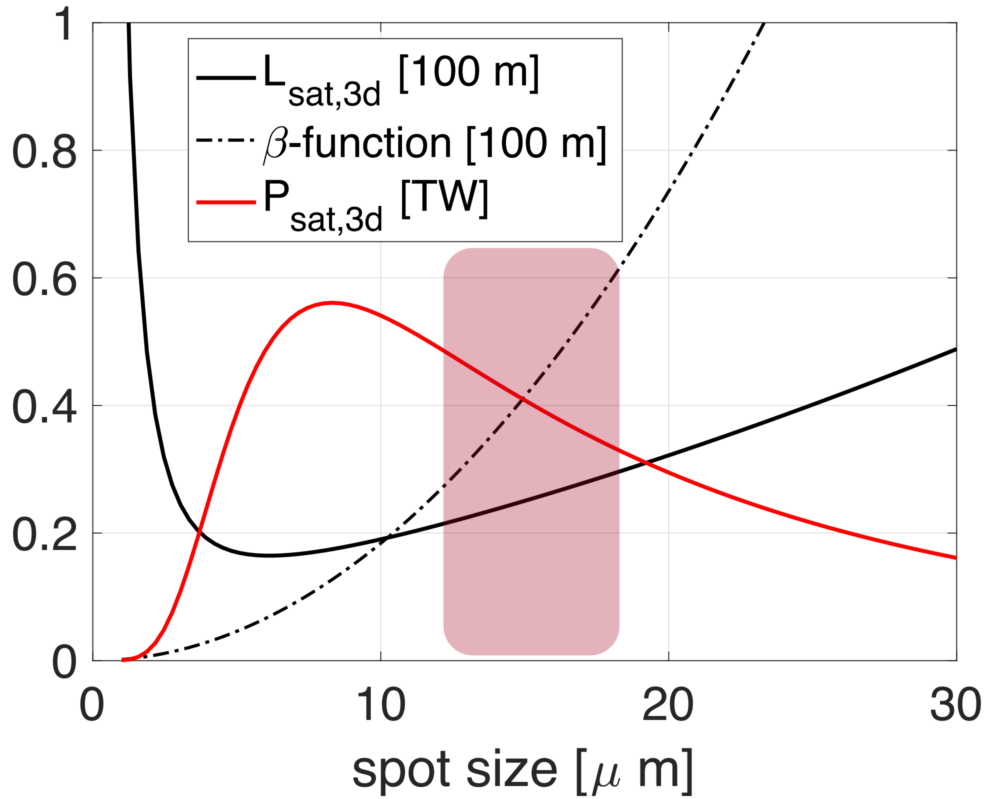






FEL radiation: ~0.01 nm, 100s of GW in 10s of meter undulator

- Beam: E_b=18.8 GeV, ε_N≈200 nm, I_b ≈60 kA, σ_{Eb} ≈4 MeV.
- Undulator: λ_u=1 cm, K=1.4, λ_r=0.00731 nm (0.17 MeV)



Calculations using MingXie's fitting formula[1].

[1]Ming Xie, Proc. 1995 PAC, pp. 183–185 (1996).

Conclusion

1. We studied generations of GeV high quality electrons in downramp injection and explored the possibility of generation of 10s of GeV electrons.
2. Start-to-end simulations are done to demonstrate how to drive a X-FEL (~1nm) using electrons from plasma accelerators.