Inverse Free Electron Laser accelerator for advanced light sources

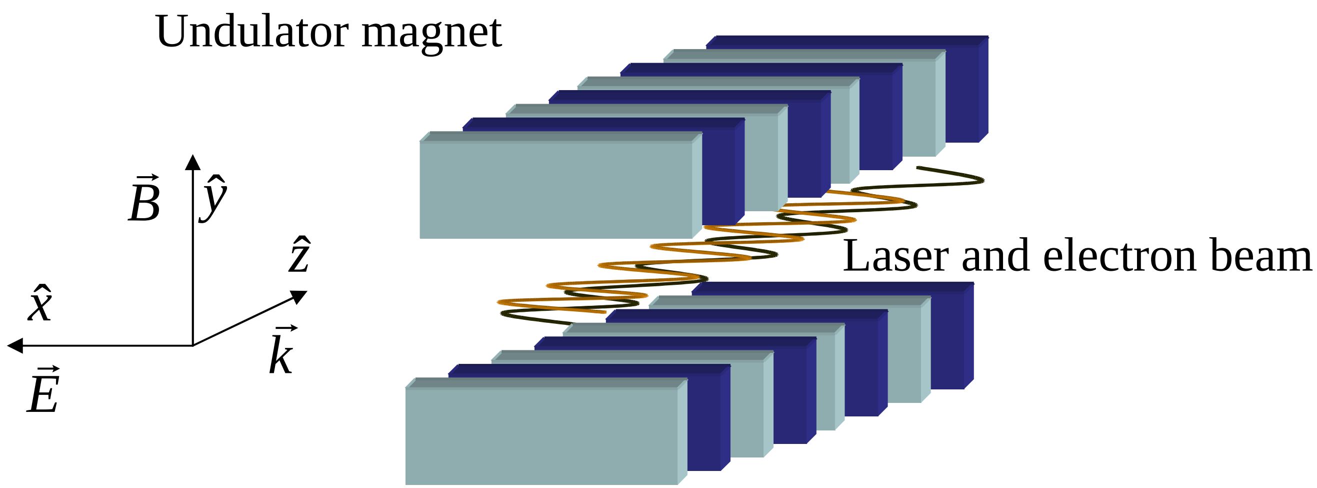
P. Musumeci

Outline

- Laser acceleration
  - High gradients
  - Ultra-short pulses
- Inverse Free Electron Lasers
- Experimental results achieved by IFELs
- Design of a compact laser accelerator suitable for injector for an advanced light source
- An example of IFEL-driven FEL
- Conclusions

IFEL Interaction

Undulator magnetic field to couple high power radiation with relativistic electrons



Relative strength

$$K = \frac{eB}{mck_w}$$

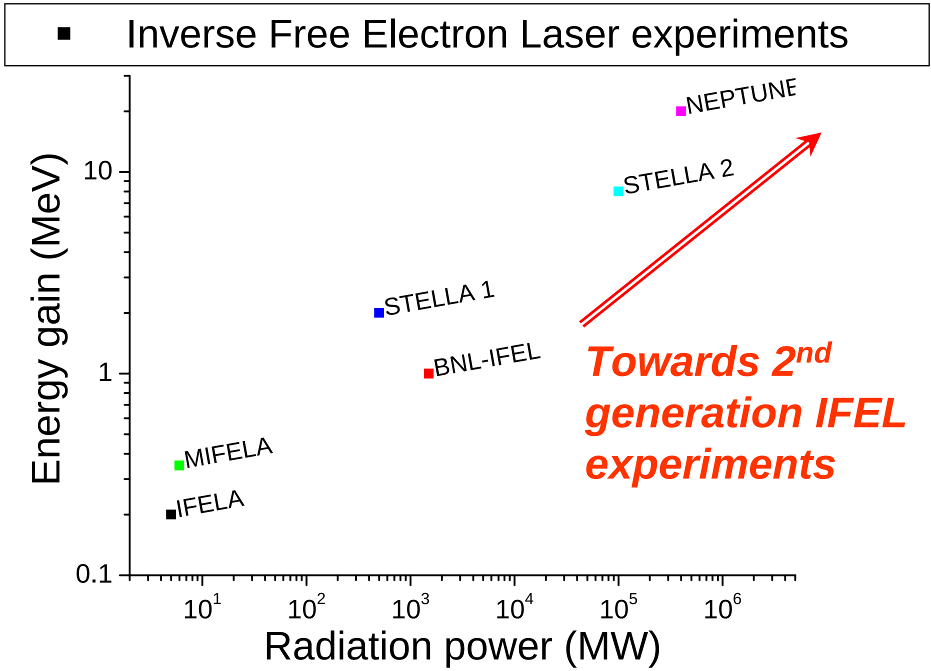
$$K_l = \frac{eE_0}{mc^2 k}$$

Significant energy exchange between the particles and the wave happens when the resonance condition is satisfied.

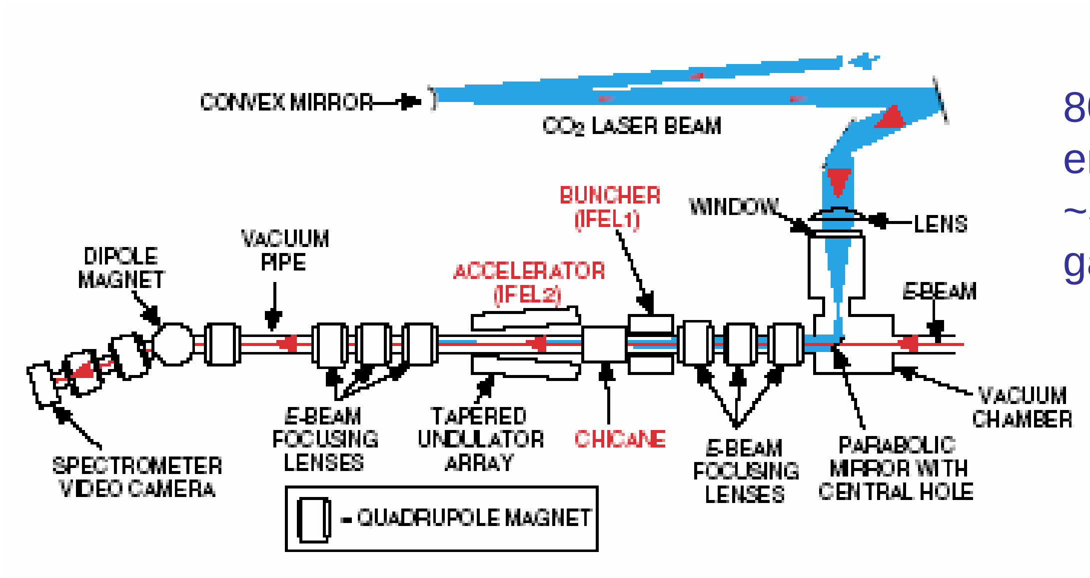
$$\boxed{\gamma_r^2 \cong \frac{\lambda_w}{2 \cdot \lambda} \cdot \left(1 + \frac{K^2}{2}\right)}$$

IFEL characteristics: a mature Advanced Accelerator

- Laser accelerator: high gradients
- Microbunching: control and manipulation of beams at the optical scale
- Vacuum accelerator: good output beam quality
- Efficient mechanism to transfer energy from laser to electrons
- State of the art requirements on laser and magnet technology
- Synchrotron losses at high energy (can be controlled by appropriate tapering of undulator)
- Gradient is energy dependent.

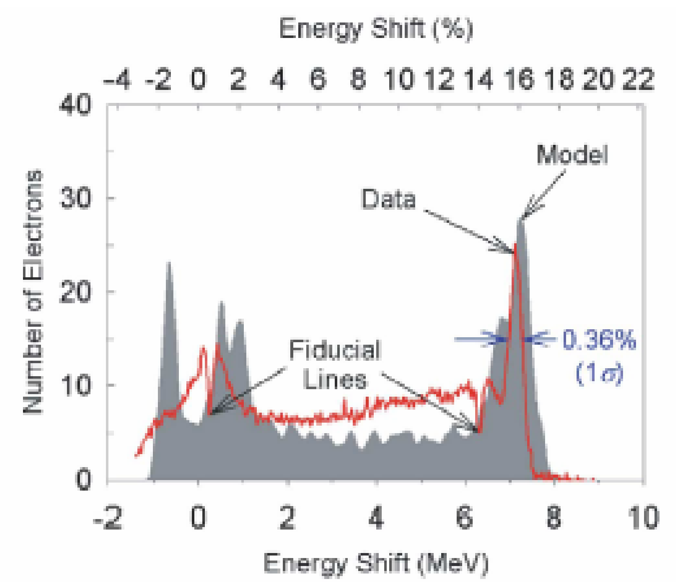


STELLA2 experiment



80 % of electrons accelerated,
energy spread less than 0.5 % FWHM
~30 GW@ λ = 10.6 μm,
gain up to 17 % of initial beam energy

W. Kimura et al. First demonstration of high trapping efficiency and narrow energy spread in a laser accelerator,
PRL, 92, 154801 (2004)



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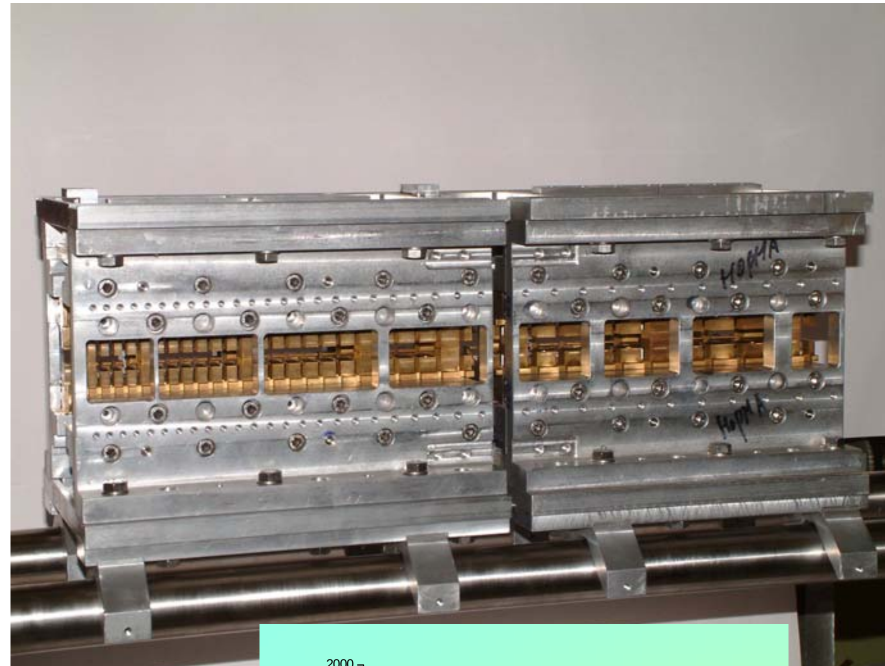
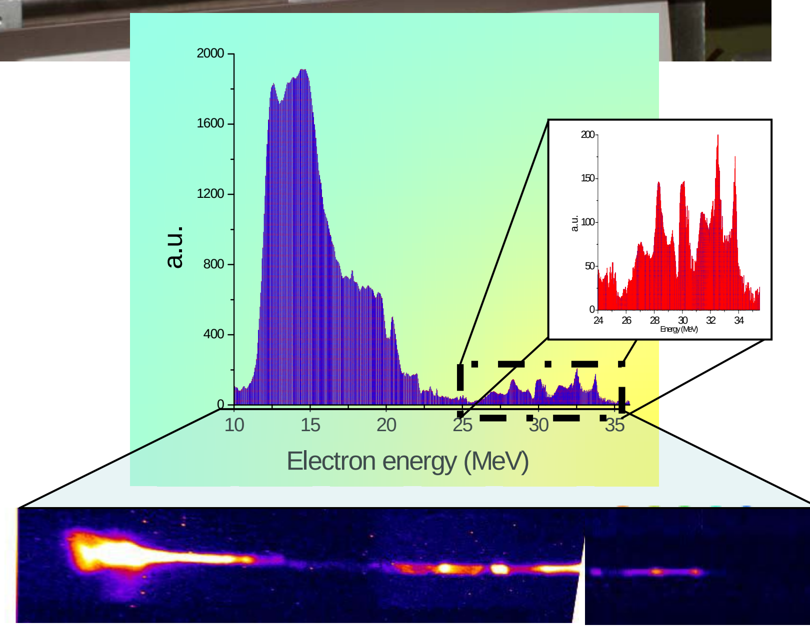
Diffraction dominated IFEL @ UCLA

- IFEL Advanced Accelerator at the Neptune Laboratory
- 0.5 TW 10.6 μm laser
- Strongly tapered Kurchatov undulator
- Highest recorded IFEL acceleration
  - 15 MeV beam accelerated to over 35 MeV in 25 cm
  - Relative energy gain 150 %
  - Accelerating gradient ~70 MeV/m !
  - Observation of higher harmonic IFEL interaction

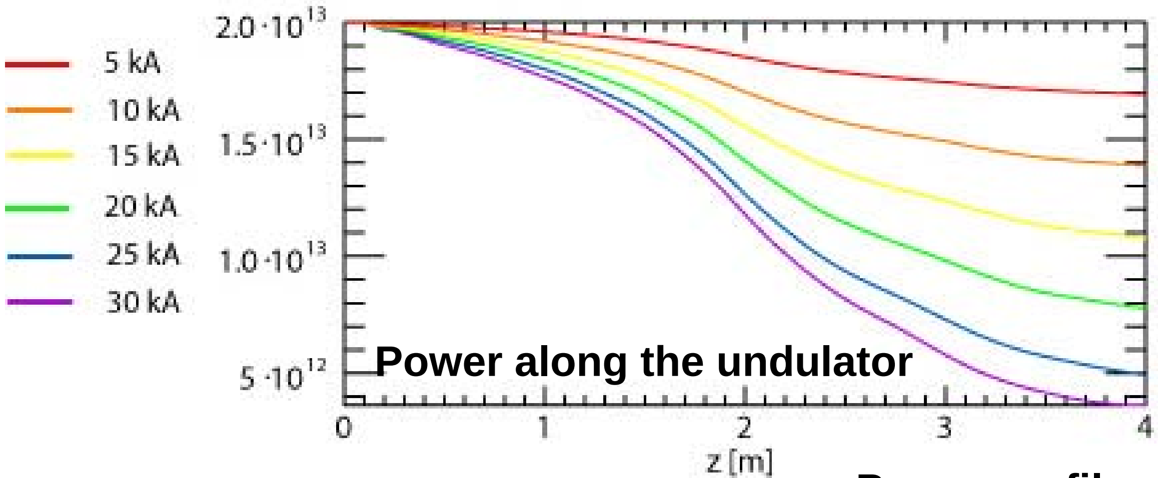




P. Musumeci et al.,High energy gain of trapped electrons in a tapered diffraction-dominated IFEL **PRL,** 94, 154801 (2005)

IFEL efficiency

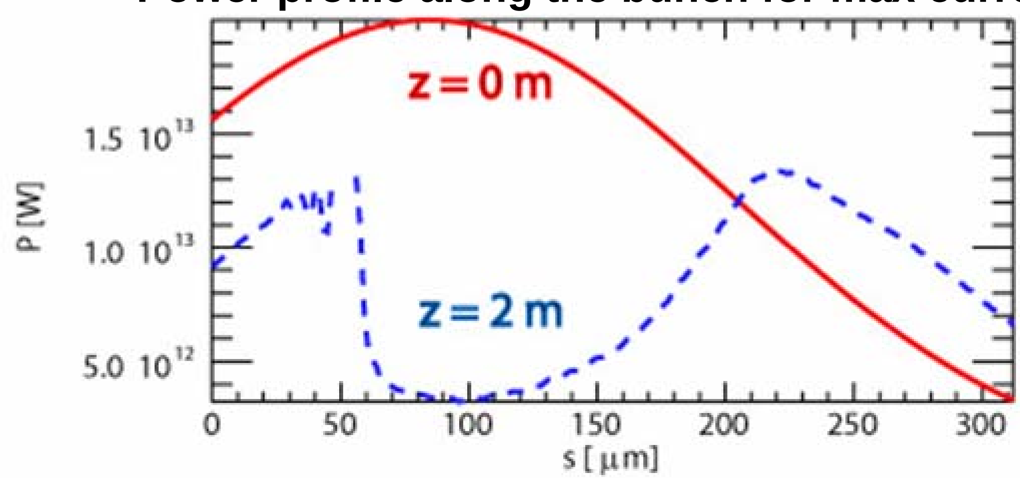
- Beam loading or pump depletion effects for high accelerated beam charge (1 nC @ 1GeV = 1 J of energy).



- Simulate radiation (and particle) IFEL dynamics with GENESIS 1.3

- Energy extraction very efficient (> 80%) adjusting tapering to compensate for peak power variation along the undulator.

Power profile along the bunch for max current



Future of Inverse Free Electron Laser acceleration

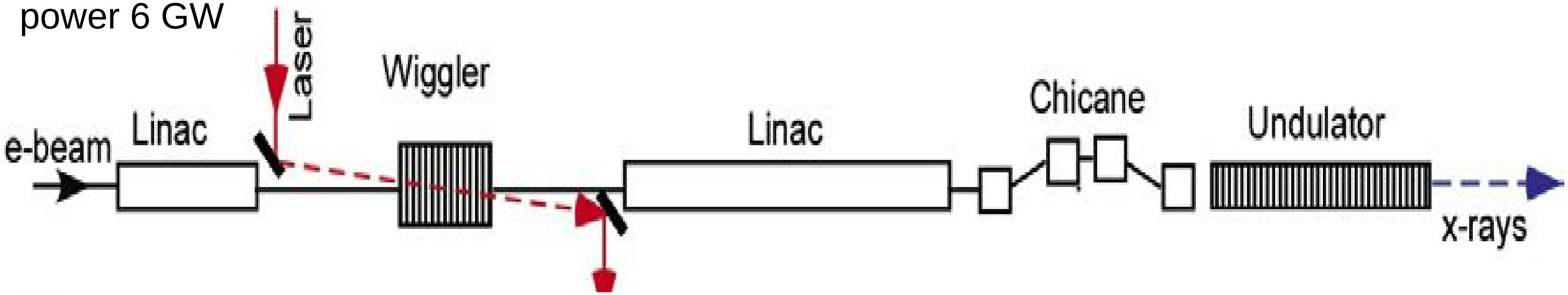
- There is no laser wavelength preference intrinsic in the IFEL equations
  - NIR lasers advantages
    - Commercial high power sources available
    - Table-top-sized laser systems.
    - Mitigated diffraction effects
- With the high-power laser wavelengths today available IFEL scales optimally for energies up to few GeVs.
- Manipulation of longitudinal phase-space at the laser wavelength scale.
- Injector for other kinds of advanced accelerators
- Injector for advanced light sources

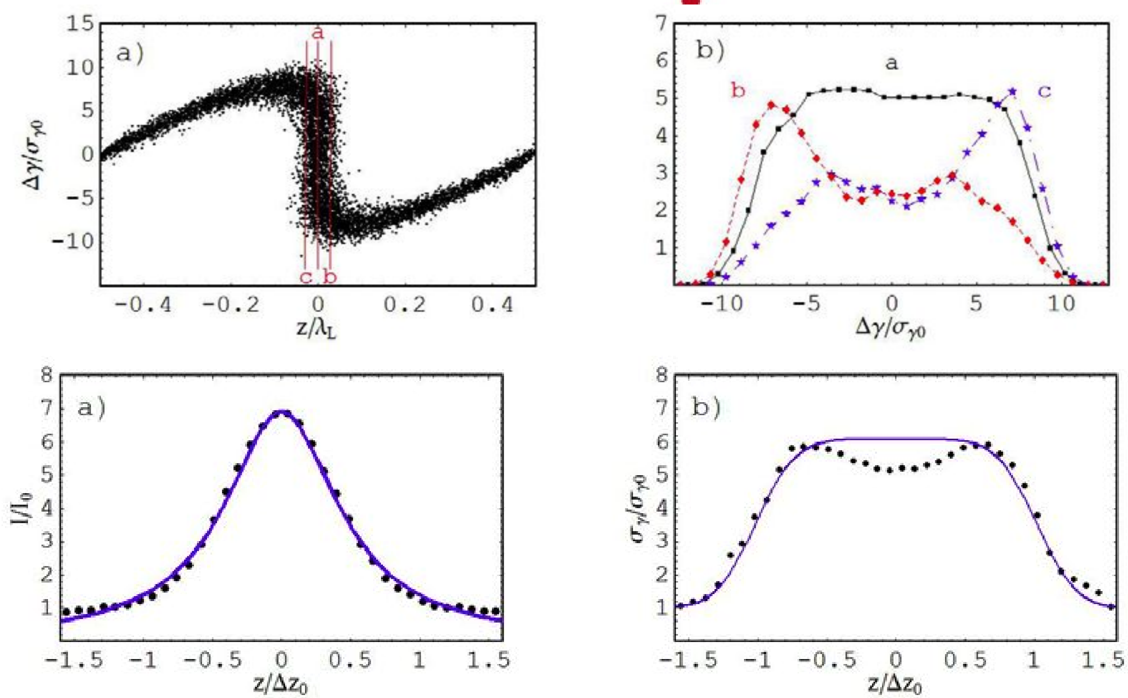
GeV-class IFEL design:

- Application of IFEL scheme as 4th generation light source driver
- Compact-size accelerator
- ESASE benefits intrinsic
  - Exponential gain length reduction
  - Absolute timing synchronization with external laser
  - Control of x-ray radiation pulse envelope
- Need control of energy spread !!!
- Design exercise aimed to extend the energy and wavelength reach of planned SPARC linac
- First Advanced Accelerator driven/ radiation source

Enhanced SASE.
A. Zholents, LBNL-55938 and PRL 92, 224801 (2004)

Modulating Laser at wavelength 2.2 μm,
power 6 GW

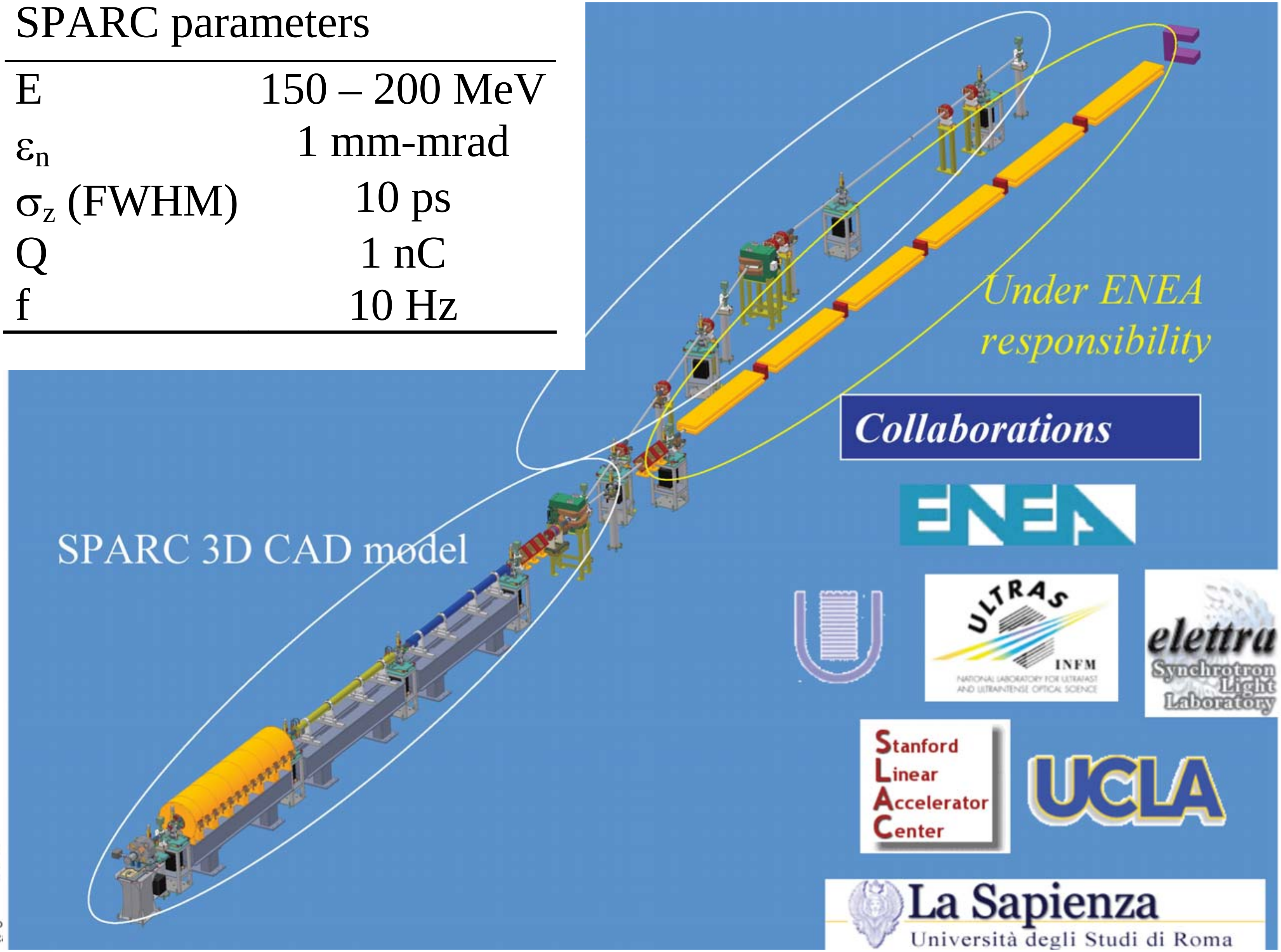




- FEL parameter, of modulated beam $8\text{x}10^{-4}$ twice as large as the non modulated beam.
- FEL radiation at 0.15 nm, with peak power of 230 GW and pulse length of 0.2 fs.

The SPARC project

SPARC parameters	
E	150 – 200 MeV
ε_n	1 mm-mrad
σ_z (FWHM)	10 ps
Q	1 nC
f	10 Hz



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Sorgente Pulsata Amplificazione Radiazione Coerente

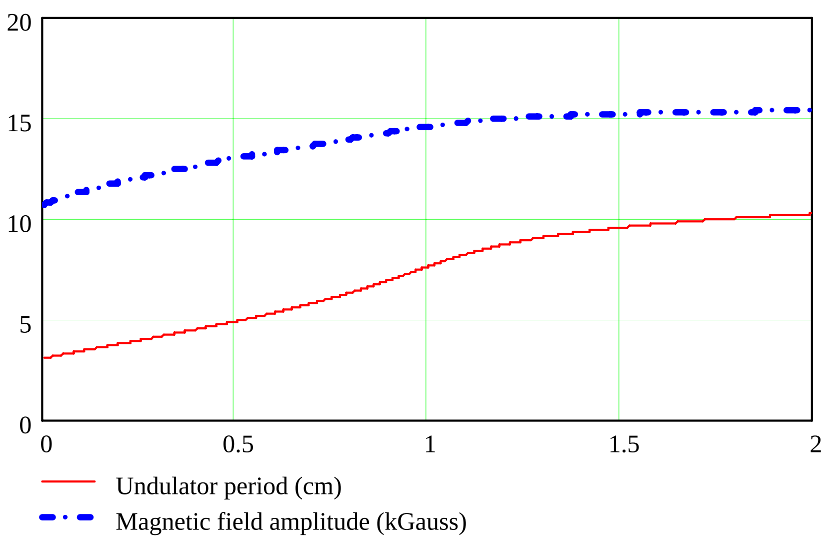
- SPARC is a SASE-FEL project in the visible range of the spectrum
  - SASE saturation length <15 m at 532 nm.
- R&D for shorter wavelength radiation source.
- Advanced beam dynamics. High brightness beams, emittance-o-meter, dynamically optimized beam regime, velocity bunching.
- Initial commissioning results (see M. Bellaveglia, THPPH031 & L. Catani THCAU03)
- Photoinjector driver Ti:Sa laser system will be upgraded to ultra high power laser (Plasmon-X). Unique facility for advanced schemes experiments.

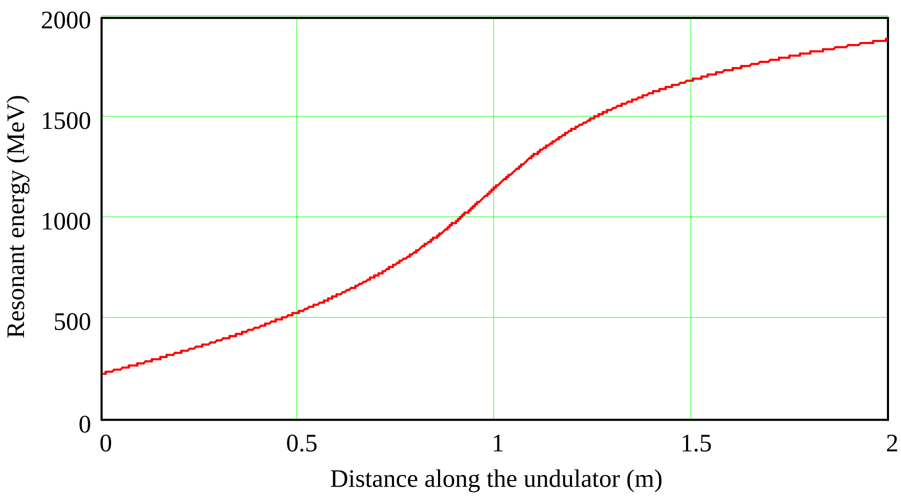
Parameters

Parameter	Fixed Value
Initial *e*-beam energy (γ value)	210 MeV
Initial *e*-beam intrinsic energy spread	0.1% (1σ)
Initial *e*-beam current	1 kA
Laser wavelength	800 nm
Laser peak power	20 TW
Nominal length of wiggler, L_w	200 cm
Rayleigh range	20 cm
Location of laser waist inside wiggler	100 cm
Resonant phase angle ψ for wiggler	*var*

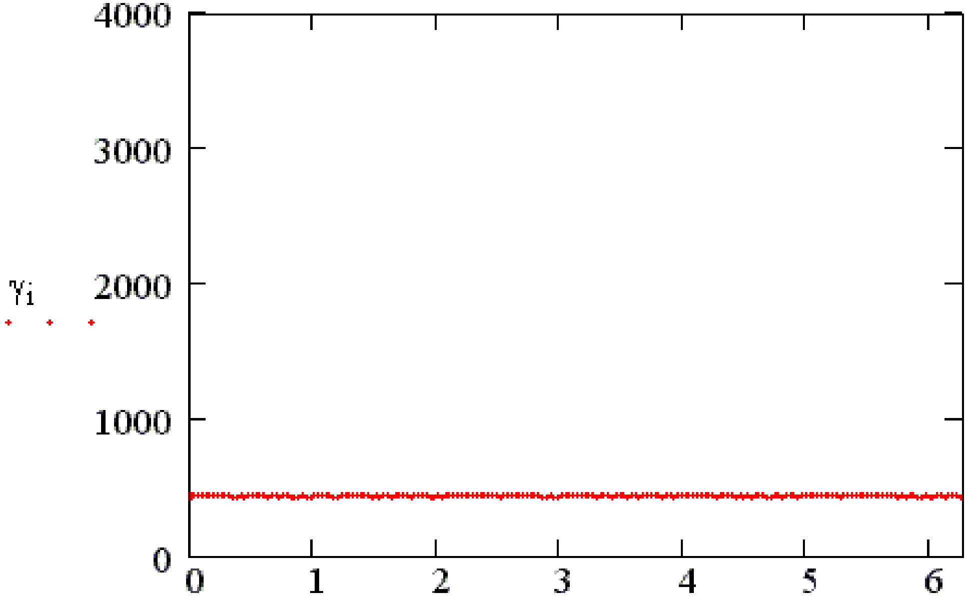
Tapering optimization

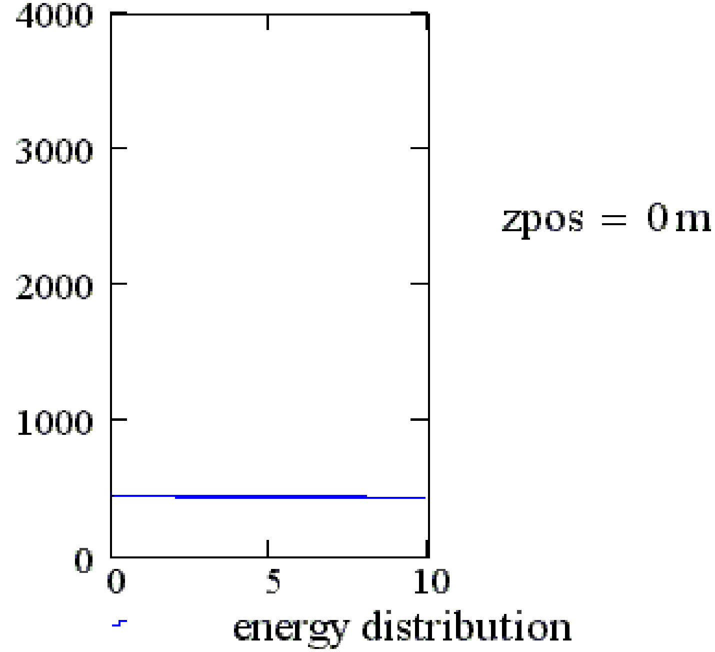
- Helical undulator to maximize energy exchange (interaction always ON).
- Keep magnetic field amplitude well under the Halbach limit for a gap = 6 mm to ensure technical feasibility.
- Captured fraction up to 90 % with a prebuncher section.
- The undulator period and magnetic field amplitude are changed trying to control the resonant phase of acceleration and the longitudinal phase space parameters (final energy spread <0.6 %).

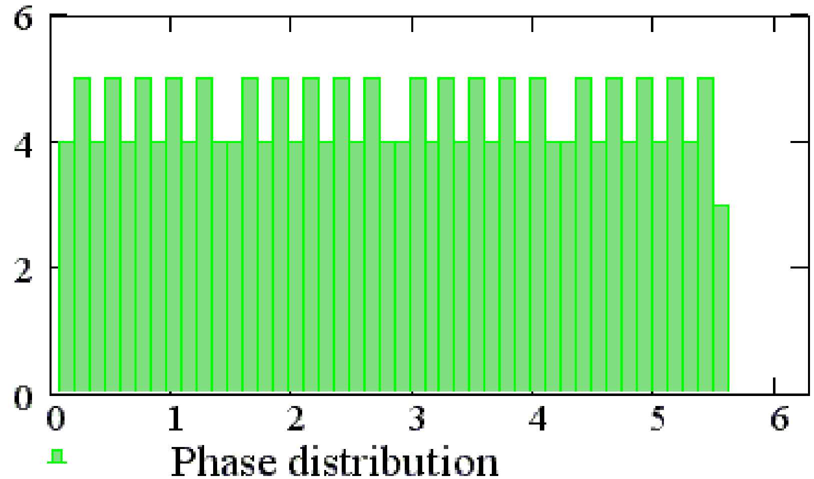




IFEL longitudinal phase space





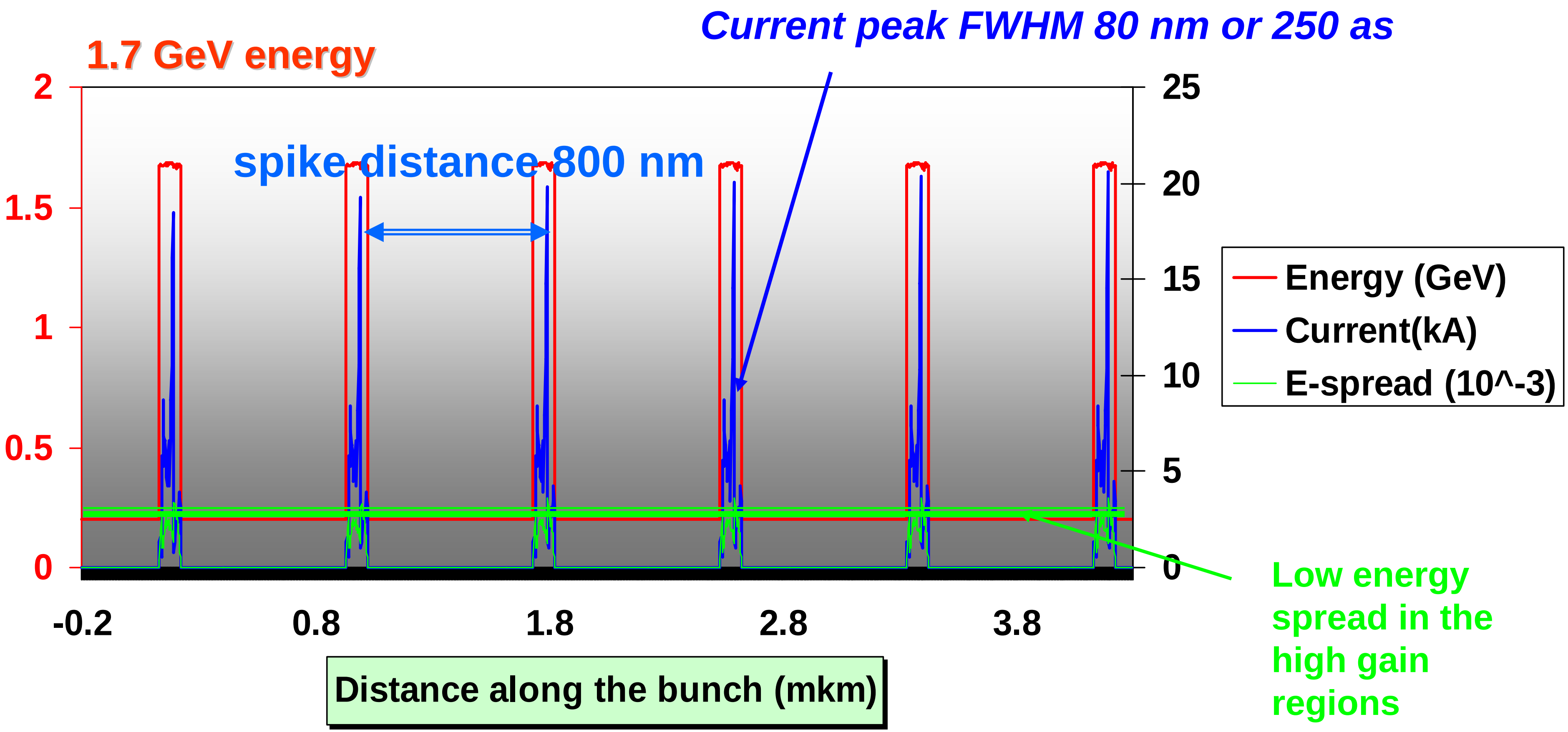


Final output parameters

Energy	**1.7 GeV**
Energy spread	< 0.5 %
Microbunch length	**250 as**
Peak current	**> 6 kAmp**
Avg. gradient	**750 MeV/m**

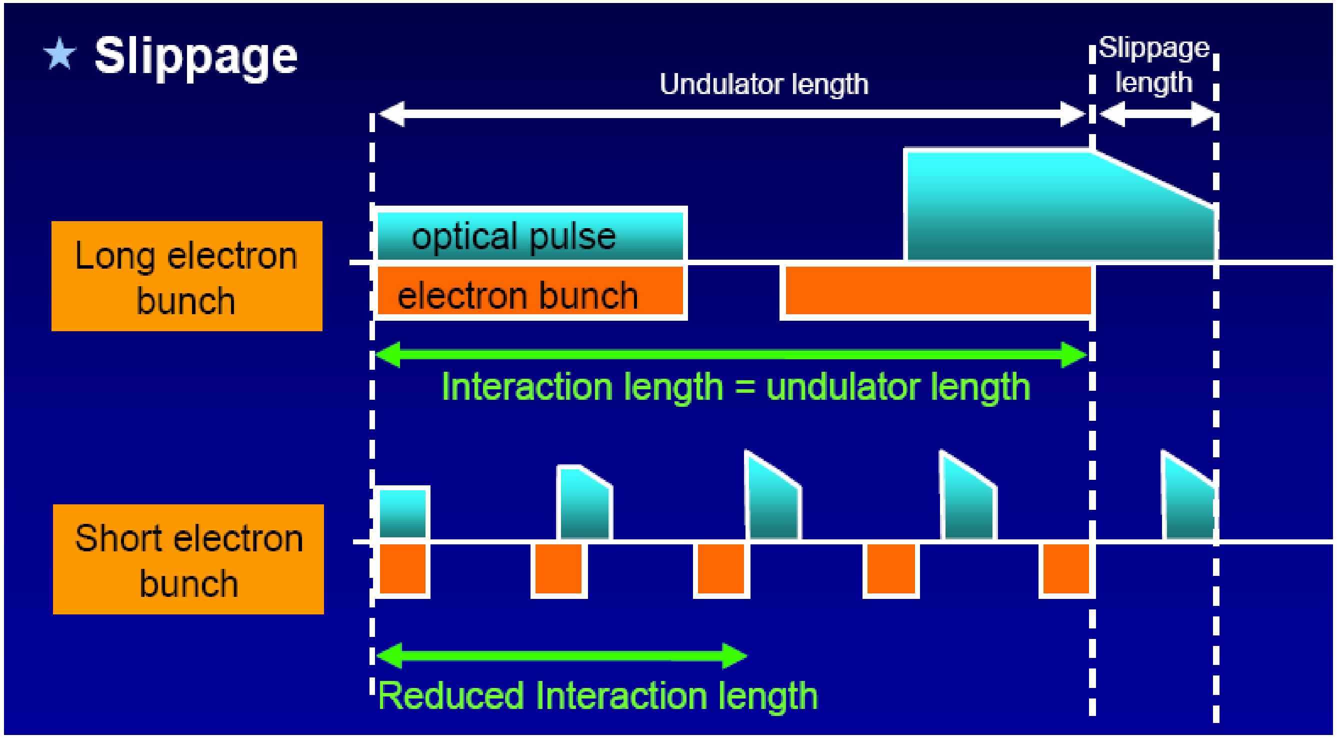
FEL radiation from IFEL accelerator

- Sending the IFEL beam into an undulator
  - FEL radiation @ λ = 3 nm (water window)
- Slippage dominated regime.
- Start-to-end simulations



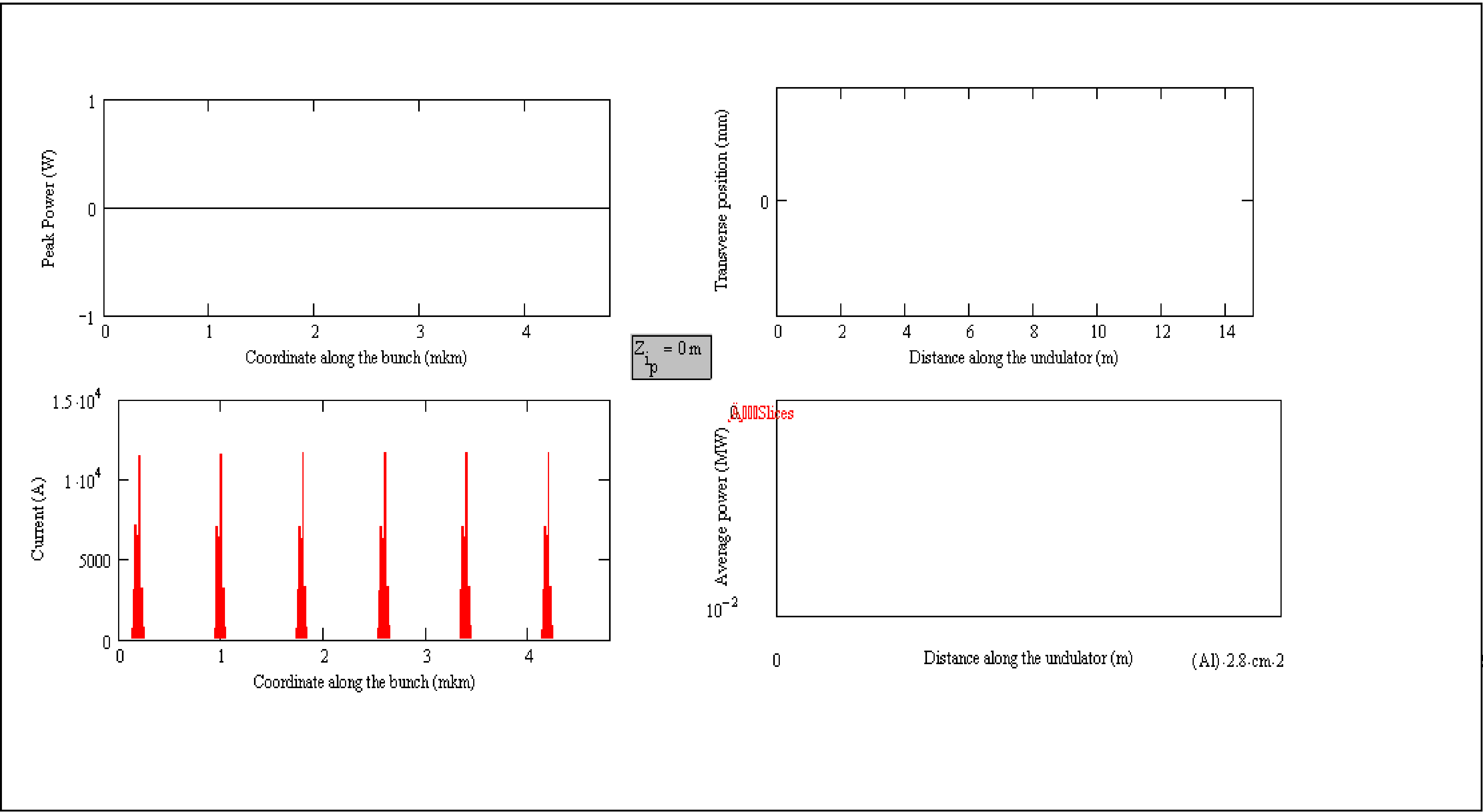
Slippage

- Slippage in the undulator $$L_s = \frac{L_u}{\lambda_w}\lambda = N\lambda$$
- Slippage in a gain length $$L_c = \frac{L_g}{\lambda_w}\lambda$$
- Different FEL dynamics (weak superradiance) when $L_b \sim L_c$



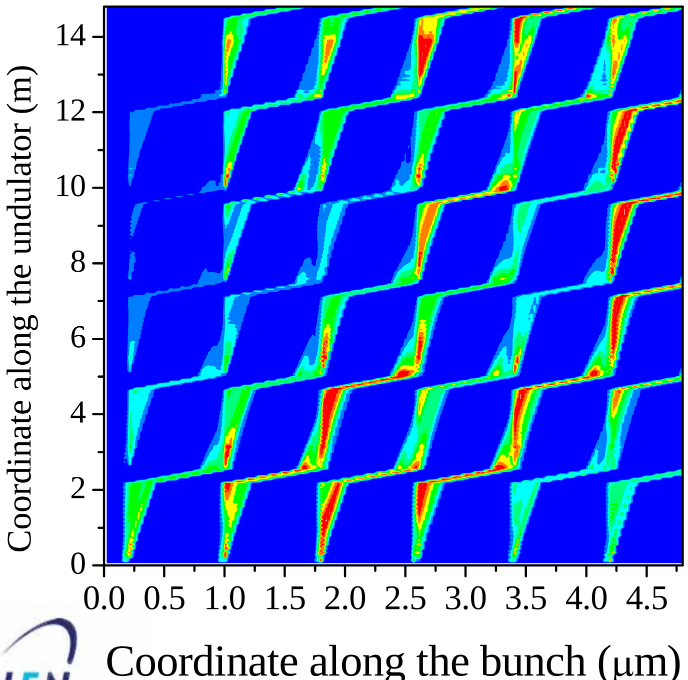
Enhanced SASE

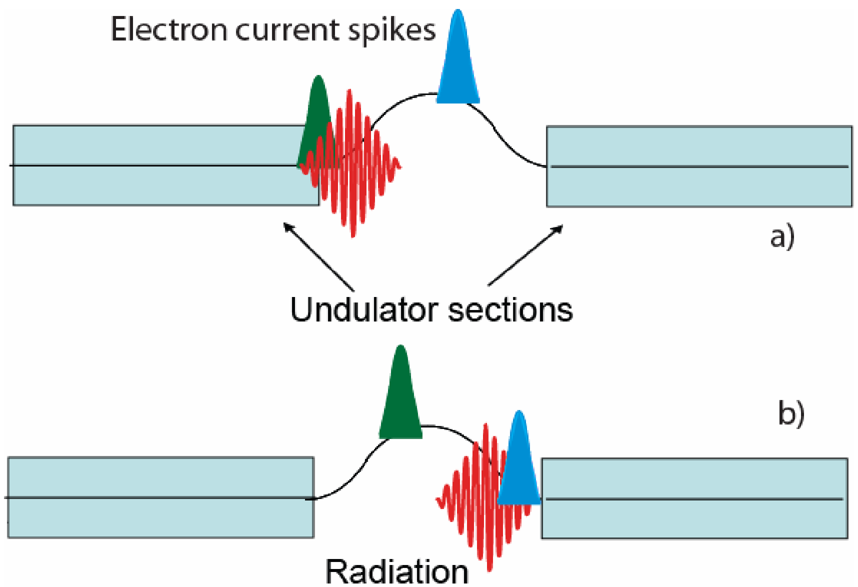
- SPARC 6 section undulator, $\lambda_w = 2.8$ cm, K = 1.65
- Effective power gain length = 3 m
- Spiky structure lost due to slippage.



Inserting slippage sections to increase radiation gain

- Between undulator section we insert a magnetic delay section for the electron beam to realign current and radiation spikes.
- Effective gain length 2.1 m
- The slippage section effectively is a positive R_{56} region that helps the conversion between energy modulation and bunching. Optical Klystron
- Need to seed for longitudinal coherence





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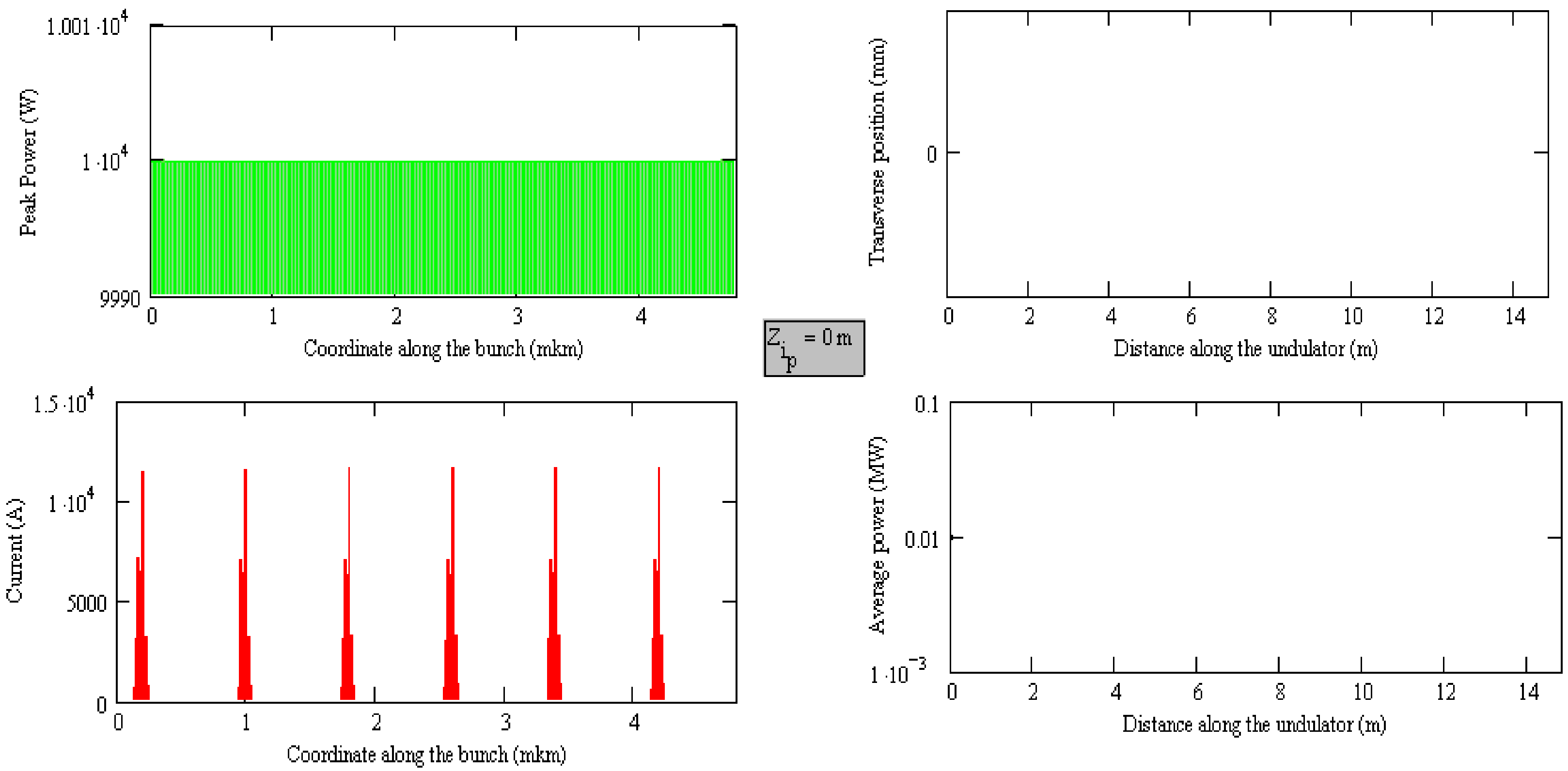
Seeding the spikes

- Using a long seed the phase in the different spikes is coherent and the FEL gain is maximized.
- Effective gain length 1.2 m



Conclusions

- Laser accelerators have made tremendous progress and will soon be competitive with more conventional machines.
- IFEL accelerator among these offers control of the longitudinal phase space.
- Preserving ultrashort pulse structure in FEL requires some precautions but can be done.
- The FEL scheme proposed is applicable to any laser accelerator beam structure.
- Ultrashort probe beams will come from a synergy between laser and accelerator worlds.