Acceleration of electrons
by
Inverse Free Electron Laser
interaction

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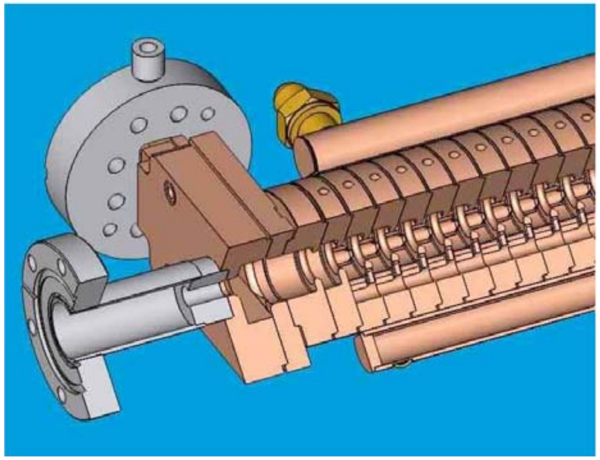
Outline

- Laser accelerators
- Brief IFEL introduction
- Inverse-Free-Electron-Laser accelerators around the world
- Neptune IFEL experiment
- Higher Harmonic Inverse Free Electron Laser interaction
- SPARC/Xino IFEL
- Conclusion

Laser acceleration (1)

- **Accelerator-based High Energy Physics beyond 3 TeV**
  - Gradients of 1 GeV/m or better are needed to limit total linac length
  - Superconducting option (recently chosen as “The” LC technology by ITRP) does not scale well because of the intrinsic low gradient
    - 24 MV/m TESLA 500 GeV,
    - 35 MV/m TESLA 800 GeV,
    - ~42 MV/m theoretical limit



High gradient normal conducting traveling wave linac

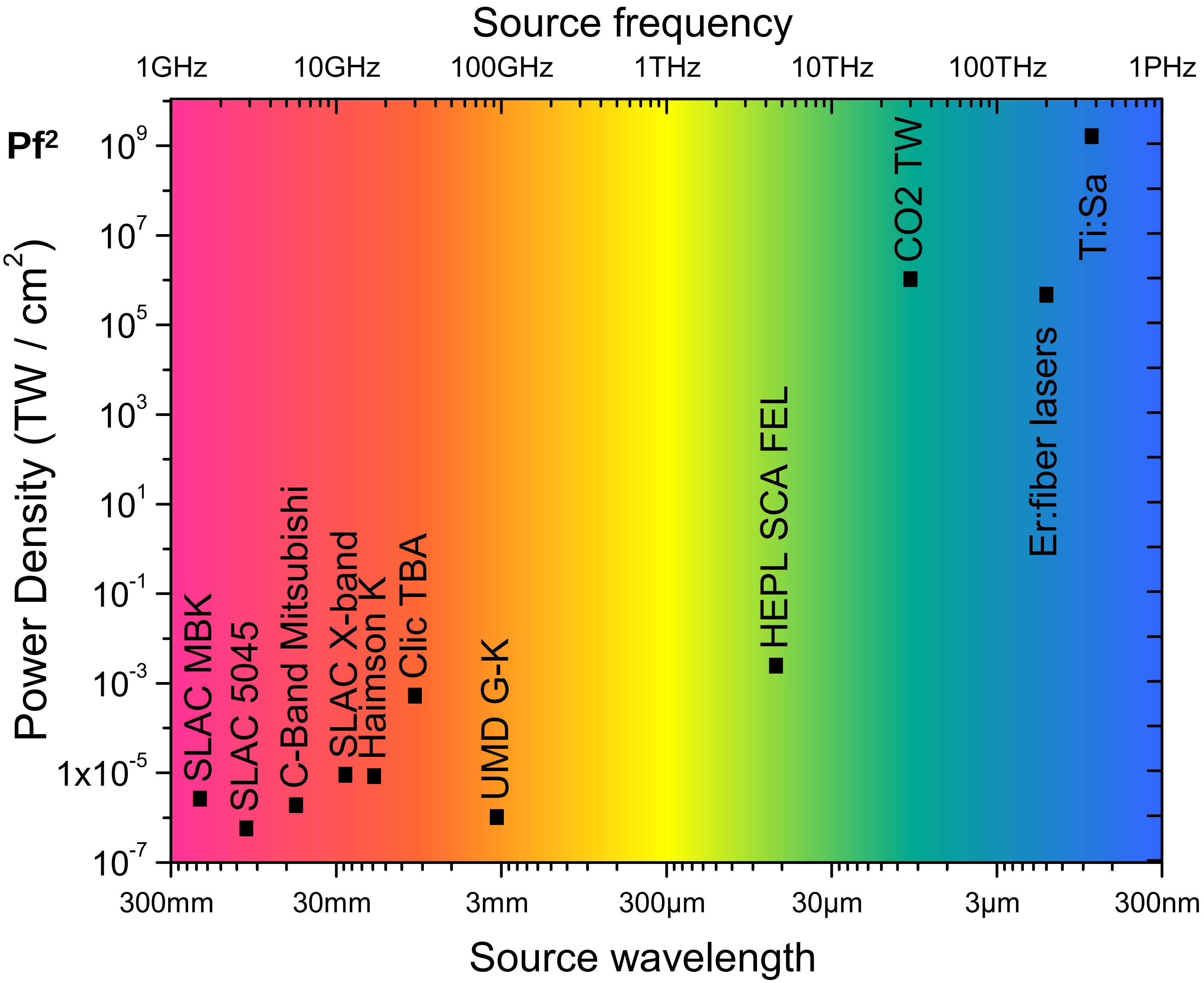
Superconducting, L-band standing wave cavity

Time

Laser acceleration (2)

- **Very high fields**
  - Very high peak powers. PetaWatt lasers exists and more will be developed.
  - ~ 50 MV/m is the gradient in conventional accelerators.
  - Laser field in a focus can be much higher (~ GV/m)
- **Short wavelengths**
  - Temporal characteristics of all charged particle beams strongly related to the waves used in the acceleration process
- **Novel radiation and particle sources**
  - Compact, inexpensive accelerators for university- and industry-sized particle and radiation sources
  - Versatility and cost/reliability
  - Linear laser acceleration naturally leads to attosecond, point-like electron bunches, potentially applicable for femtochemistry.

High power density→ high field strength



Quest for EM power sources

- As the accelerators benefit in the 20th century from the WWII-driven RF technology R&D, the history can repeat itself with the industry strongly driven laser development.

- Lasers are a $ 4.8B/year market (worldwide), with laser diodes accounting for 59%, DPSS lasers $ 0.22B/year, and CO_2 lasers $0.57B/year.

- In contrast, the microwave power tube market is $ 0.6 B/year, of which power klystrons are just $0.08 B/year.

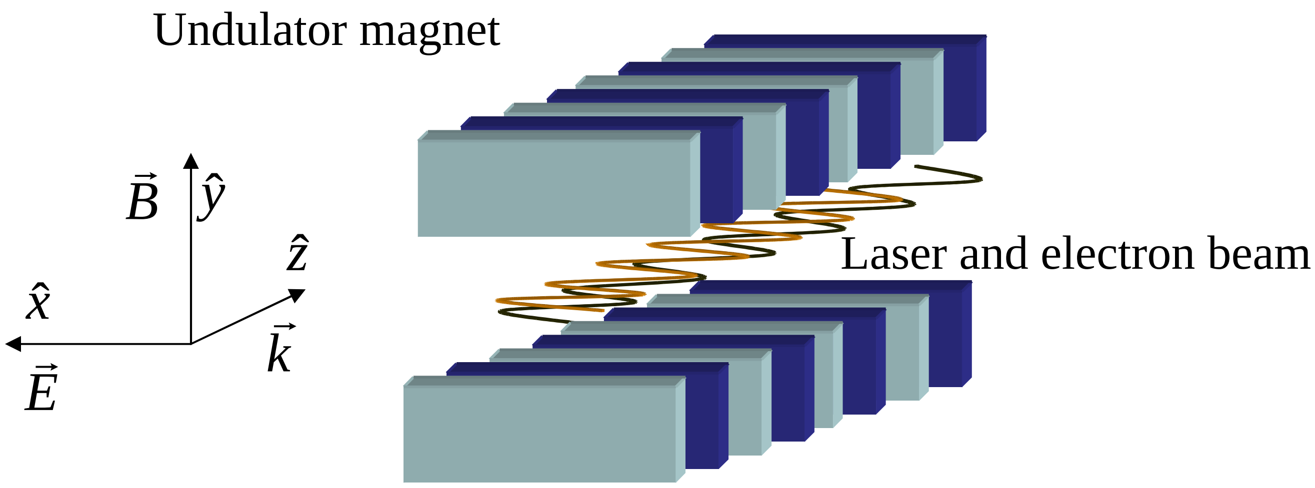
- Peak Powers of TW, average powers of kW are available from commercial products
- The market’s needs and accelerator needs overlap substantially: Cost, reliability, shot-to-shot energy jitter, coherence, mode quality are needed by both

Lawson-Woodward Theorem

- ***Colloquial version:*** If an electron with v≅c interacts with a laser field in vacuum over an infinite region (z = -∞ to ∞), the net energy gain is zero.
- One of more of the assumption of the LW theorem must be violated in order to achieve a non zero net energy gain by using laser fields in vacuum:
  - Laser fields in vacuum with no walls or boundaries present
  - The electron is highly relativistic along the acceleration path
  - No static or electric magnetic fields are present
  - The region of interaction is infinite
  - Ponderomotive effects (non linear forces, **v** x **B** forces) are neglected.
- **Schemes which do not violate Lawson-Woodward:**
  - Inverse Free Electron Laser (magnetic field present)
  - Inverse Smith-Purcell (boundary within λ)
  - Ponderomotive Acceleration (second-order process)
  - Inverse Cerenkov (gas present to slow v_{ph})
  - Crossed laser beam VLA (region of interaction is finite)
  - Non-linear Compton Scattering (multi-order process)

IFEL Interaction

Undulator magnetic field to couple high power radiation with relativistic electrons



Relative strength

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

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

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

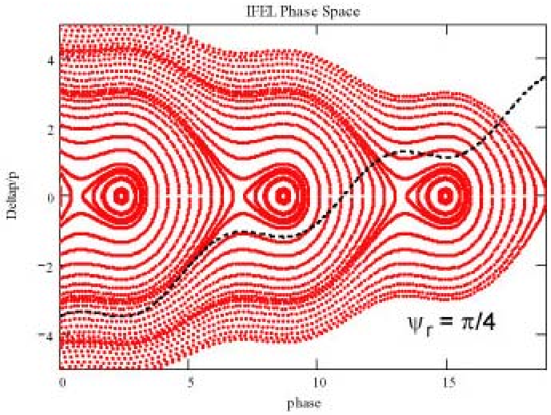
$$\boxed{\gamma_r^{\,2} \cong \frac{\lambda_w}{2\cdot\lambda}\cdot\left(1+\frac{K^{\,2}}{2}\right)}$$

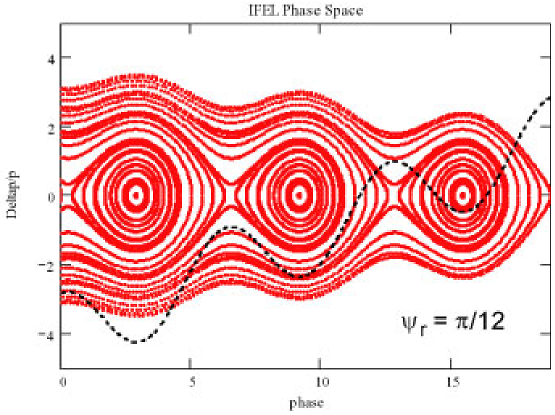
Resonant condition

- Fundamental IFEL interaction
  - The slippage in one undulator period is equal to one laser wavelength so that the transverse velocity and the EM wave keep always the same phase relationship.
  - In the rest frame of the electrons the undulator-induced wiggling is (for small *K*) a non relativistic dipole oscillation with the same frequency of the Doppler-shifted EM wave.

- To keep the resonance condition we need tapering of the undulator parameters, $\lambda_w(z)$, $K(z)$.
- The stable region in phase space shrinks increasing the acceleration rate (increasing ψ_r)

$$\boxed{\frac{d\gamma_r}{dz} = \frac{kK_l K}{\gamma_r}\cdot\frac{JJ(K)}{2}\sin(\psi_r)}$$


IFEL Phase Space


IFEL Phase Space

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

IFEL interaction users

Efficient way to transfer energy and/or information from high power lasers to relativistic electron beams

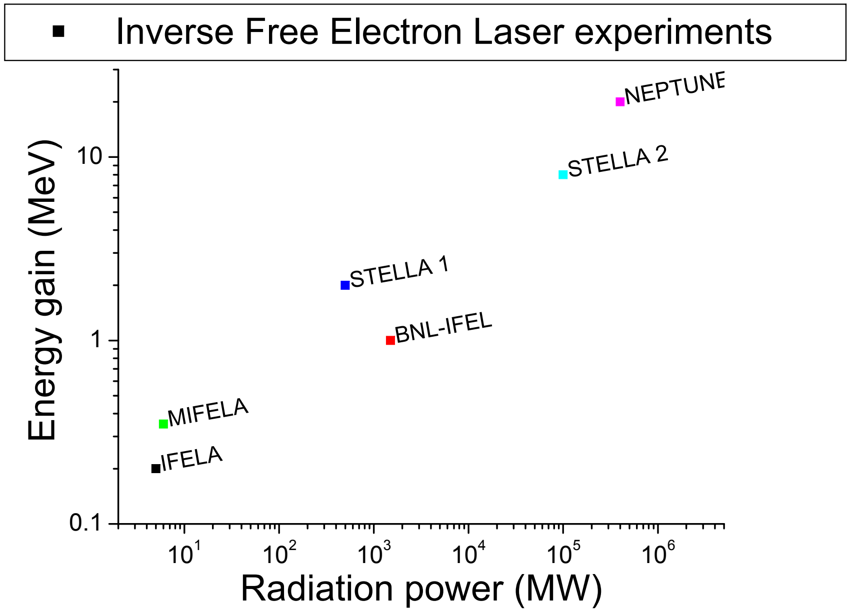
- Optical Stochastic Cooling (Zolotorev, PRE **50**, 3087, 1994)
- Laser slicing (Zholents, PRL **76**, 912, 1996)
- FEL seeding (Yu, Science, 289, 932, 2000)
- Advanced Accelerator pre-buncher (Kimura, PRL 86, 4041, 2001)
- SASE enhancement scheme (Fawley, FEL2004 Proc.)

IFEL Experiments

- IFELA: Wernick & Marshall 1992 (*PRA, 46, 3566)*
  - First proof-of-principle IFEL experiment
  - 5 MW at λ = 1.6 mm, gradient 0.7 MV/m, gain 0.2 MeV
- BNL-IFEL: Van Steenbergen, Gallardo et al. 1996 (***PRL 77, 2690)***
  - Microbunching observed 1998 (***PRL, 80 4418)***
  - 1-2 GW at λ = 10.6 μm, gradient 2.5 MV/m, gain 1 MeV
- MIFELA: Yoder, Marshall, Hirshfield 2001 ***(PRL, 86, 1765)***
  - All electrons accelerated, phase dependency of the acceleration
  - 6 MW at λ = 10 cm, gradient 0.43 MV/m, gain 0.35 MeV
- STELLA: Kimura et al. 2001 ***(PRL, 86, 4041)***
  - First staging of two IFEL modules.
  - 0.1-0.5 GW at λ = 10.6 μm, gain up to 2 MeV
- STELLA 2 : Kimura et al. 2003 ***(PRL, 92, 054801)***
  - Monoenergetic laser acceleration (80 % of electrons accelerated, energy spread less than 0.5 % FWHM)
  - ~30 GW,at λ = 10.6 μm, gain up to 17 % of initial beam energy

Motivation

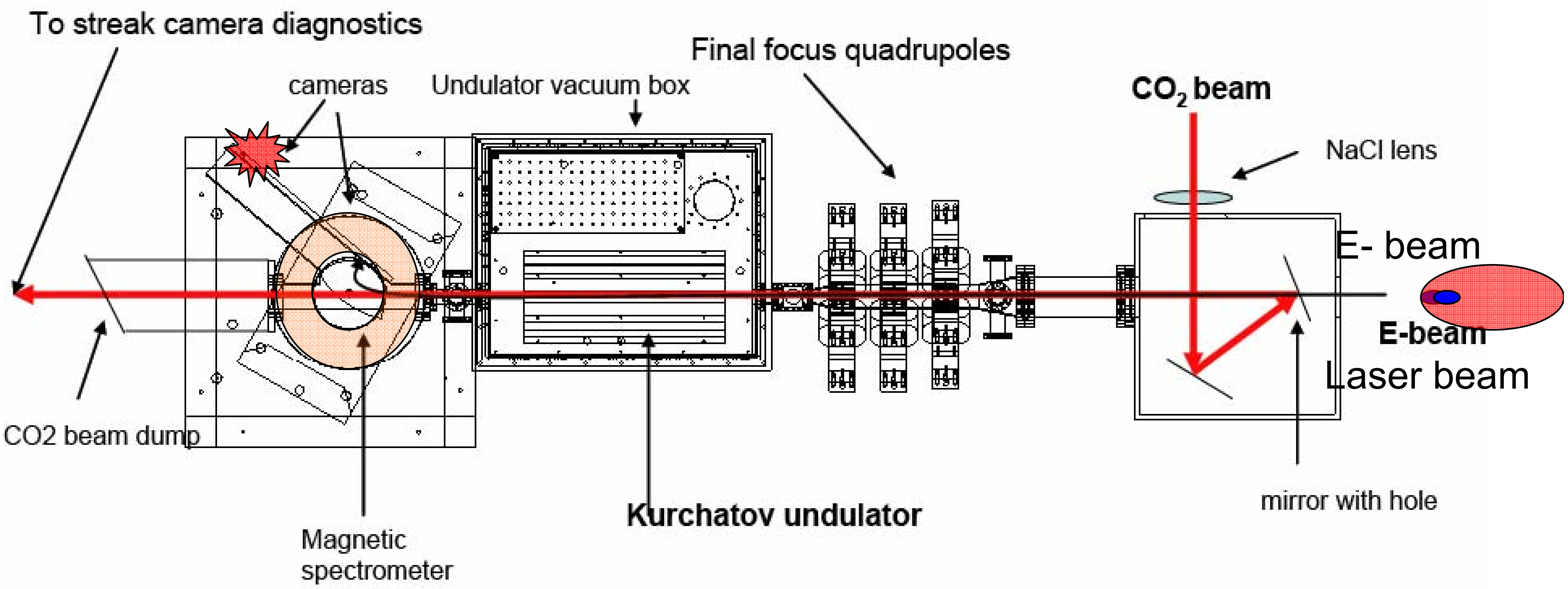
- Proof-of-principle experiments successful
- Upgrade to significant gradient and energy gain
  - Technical challenges:
    - very high power radiation
    - strong undulator tapering
  - Physics problems:
    - include diffraction effects in the theory
    - beyond validity of period-averaged classical FEL equation
- The Neptune Laboratory at UCLA has a high-power laser and a high-brightness electron beam



Neptune Laboratory

- Once upon a time a nuclear reactor for scientific research in the heart of L.A. (closed in '84 before the Olympic Games)
- Now Advanced Accelerator laboratory at UCLA
- Other Advanced Accelerator Concepts:
  - Plasma Beat-Wave Acceleration, Longitudinal phase space manipulations, Plasma WakeFields experiments
- Perfect location for IFEL experiment. High power laser and high brightness electron beam

Experimental Layout

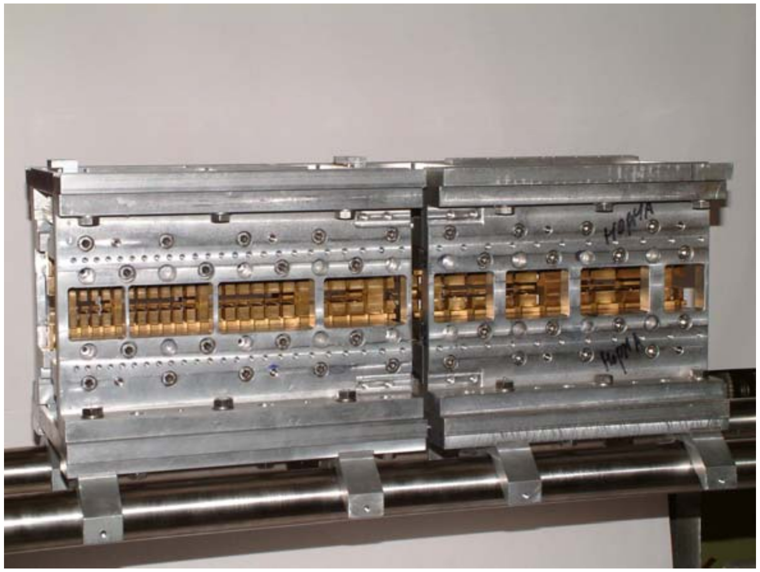


Neptune IFEL Design Parameters

Laser Power	400 GW
Laser wavelength	10.6 μm
Laser beam size (w_0)	340 μm
Rayleigh range	3.5 cm

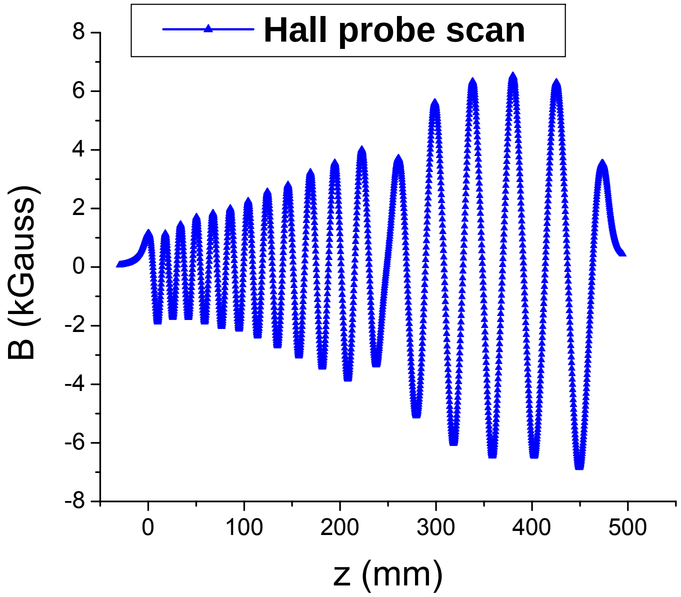
Energy	14.5 MeV
Energy spread (rms)	0.5 %
Charge	300 pC
Pulse length (rms)	4 ps
Rms transverse Emittance	10 mm-mrad
Rms beam size at the focus	150 μm

Kurchatov IFEL Undulator



	Initial	Final
Period	1.5 cm	5.0 cm
Field Amplitude	0.12 T	0.6 T
Peak K parameter	0.2	2.8
gap	12 mm	12 mm

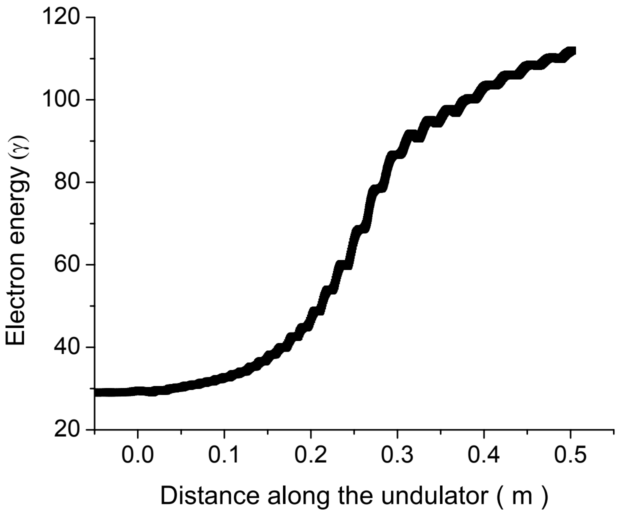
- Unique “double tapered” 50 cm long undulator.
  - Final resonant energy 250 % bigger than initial
- Hall Probe measurements.
- Pulse Wire tuning.

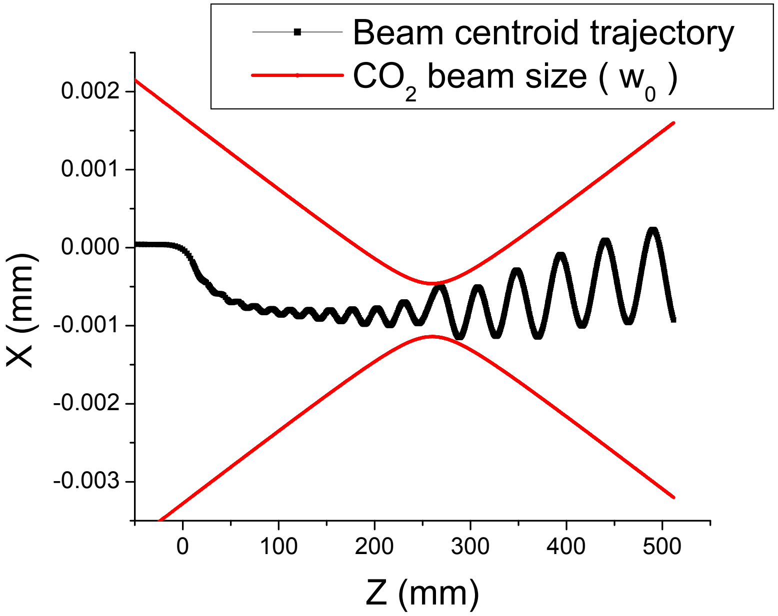


Diffraction Dominated Interaction

$$\frac{d\gamma}{dz} = \frac{K}{\gamma}\cdot\frac{kK_l}{\sqrt{1+\frac{(z-z_w)^2}{z_r^2}}}\frac{JJ(K)}{2}\sin(\psi)$$

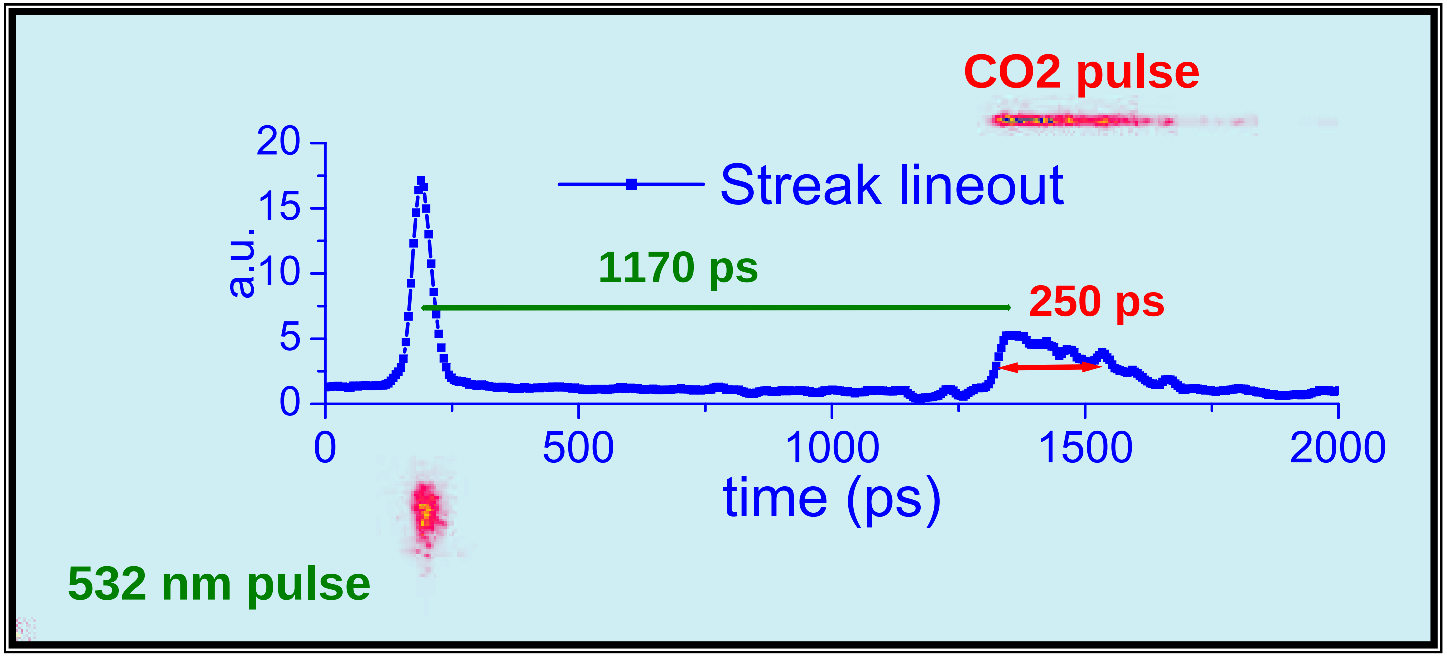
$$\frac{d\psi}{dz} = k_w + k - \frac{k}{\left(1-\frac{1+\frac{K^2}{2}+\frac{K_l^2}{2}+KK_l\cdot JJ(K)\cdot\cos(\psi)}{\gamma^2}\right)^{1/2}} - \frac{1}{z_r\left(1+\frac{(z-z_w)^2}{z_r^2}\right)}$$



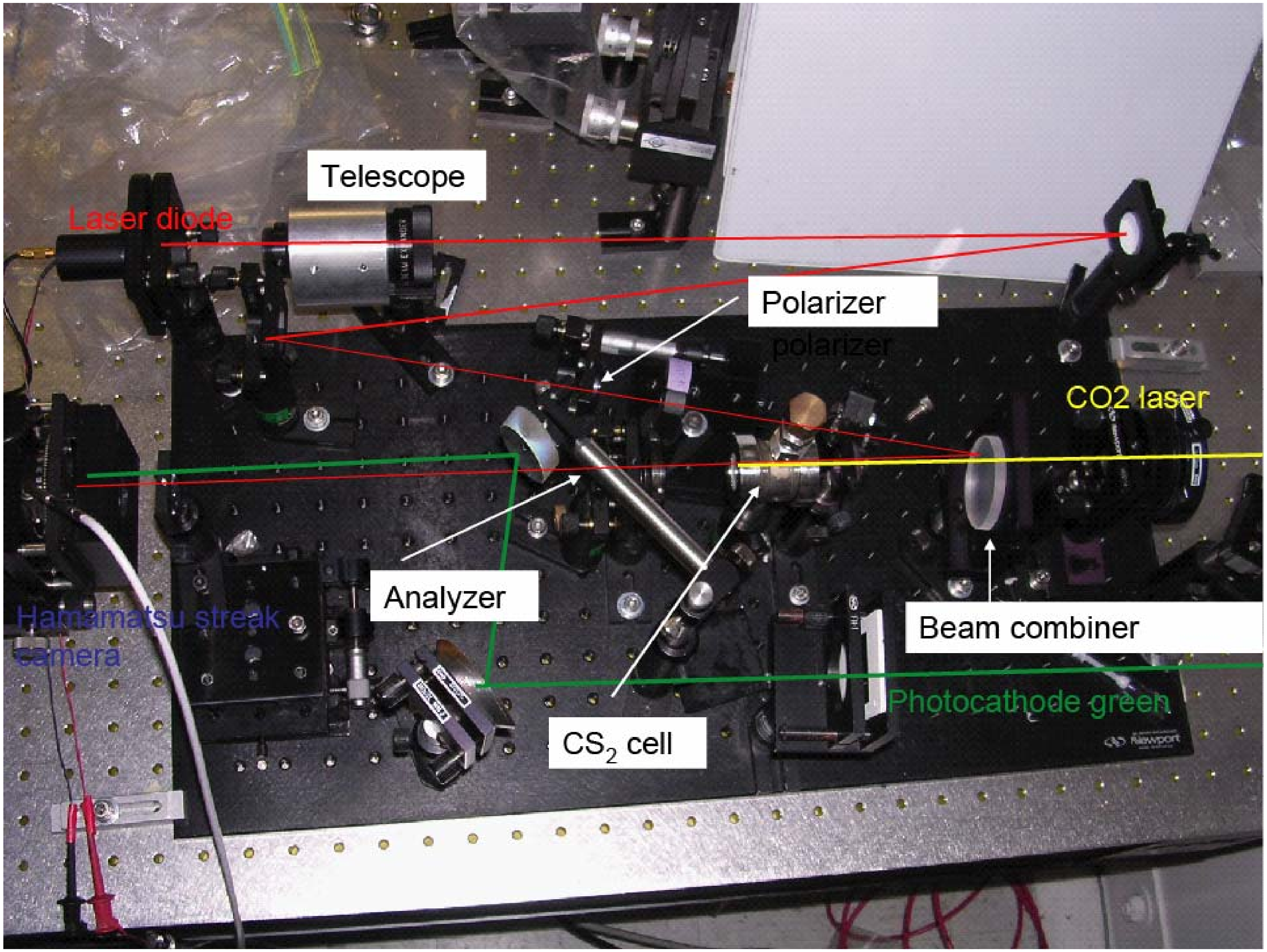


Streak camera: "Live from the bunker"

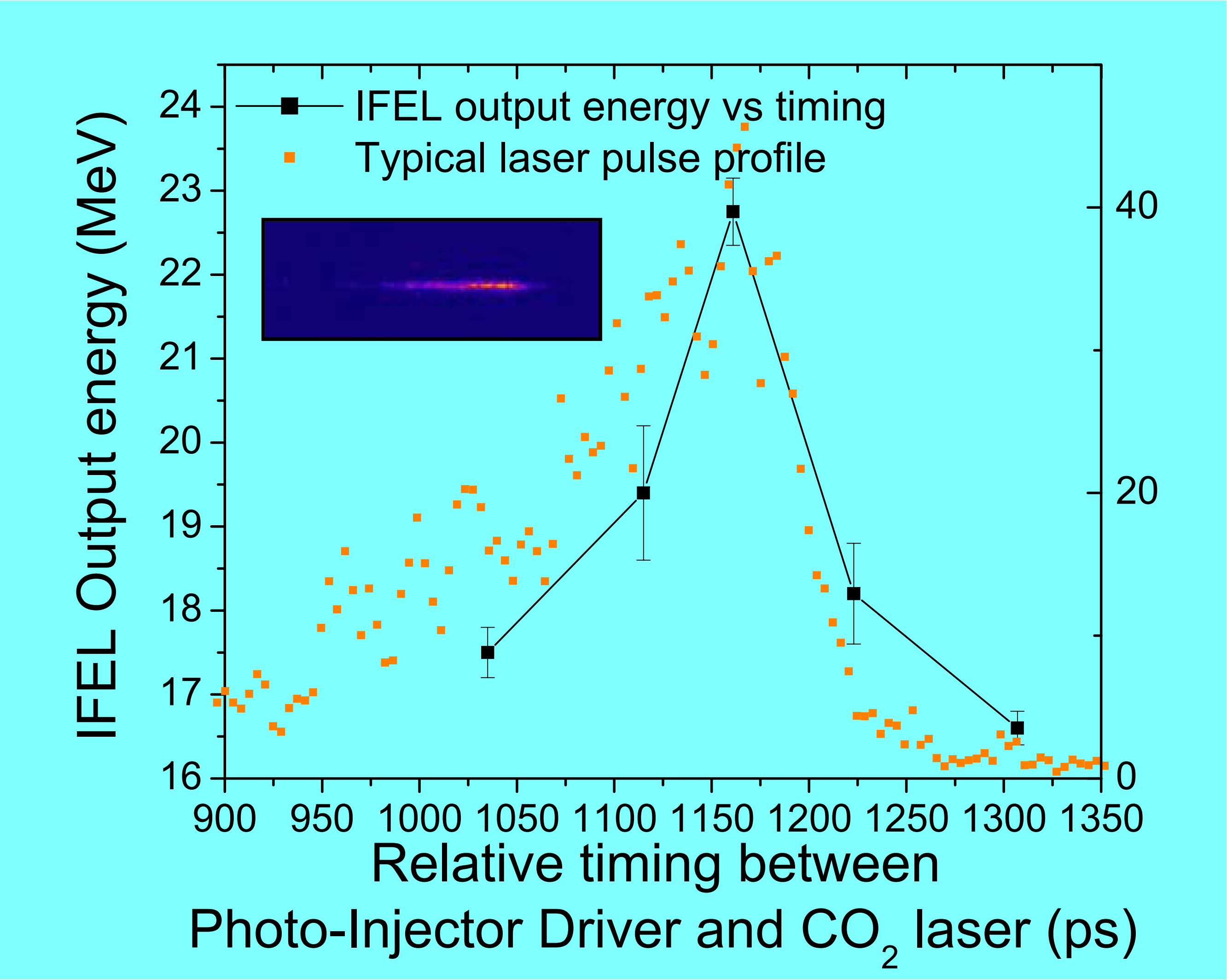
- Shot-to-shot measurements of the laser pulse length and the timing between two pulses necessary because of the complex dynamics of the final amplification of the CO_2 pulse.
- Optical Kerr Effect (OKE) to get CO_2 streaks
- E-beam reference pick off the photocathode drive laser



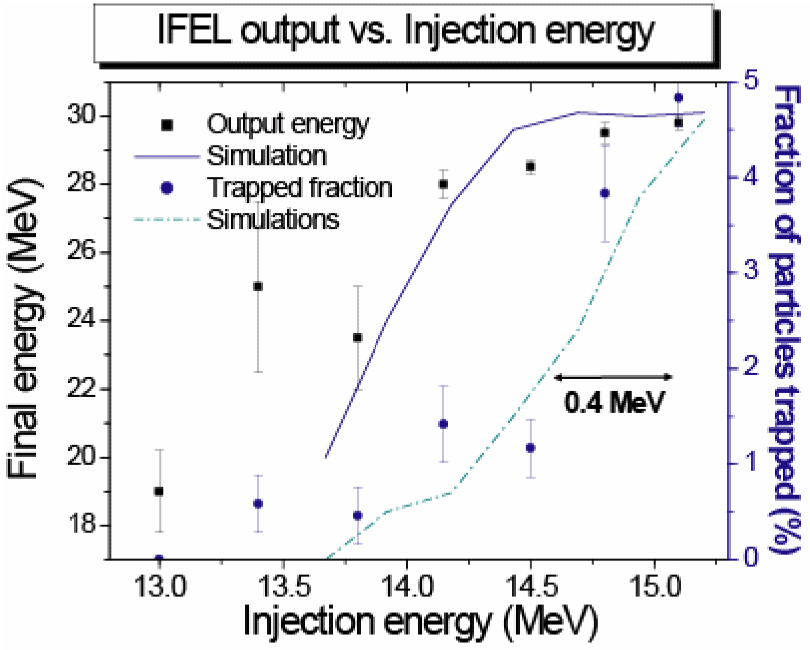
OKE setup for streak camera

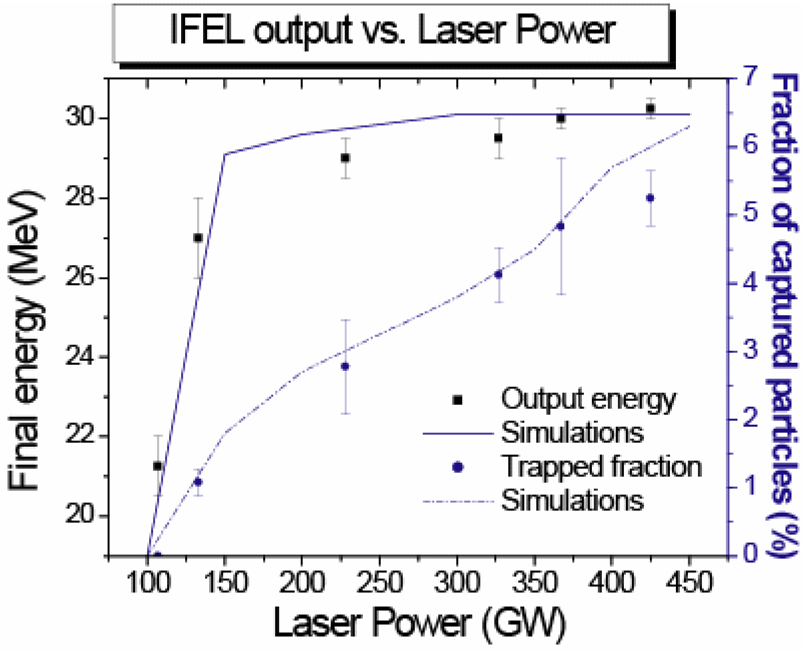


Measurement of timing between CO2 and e beam

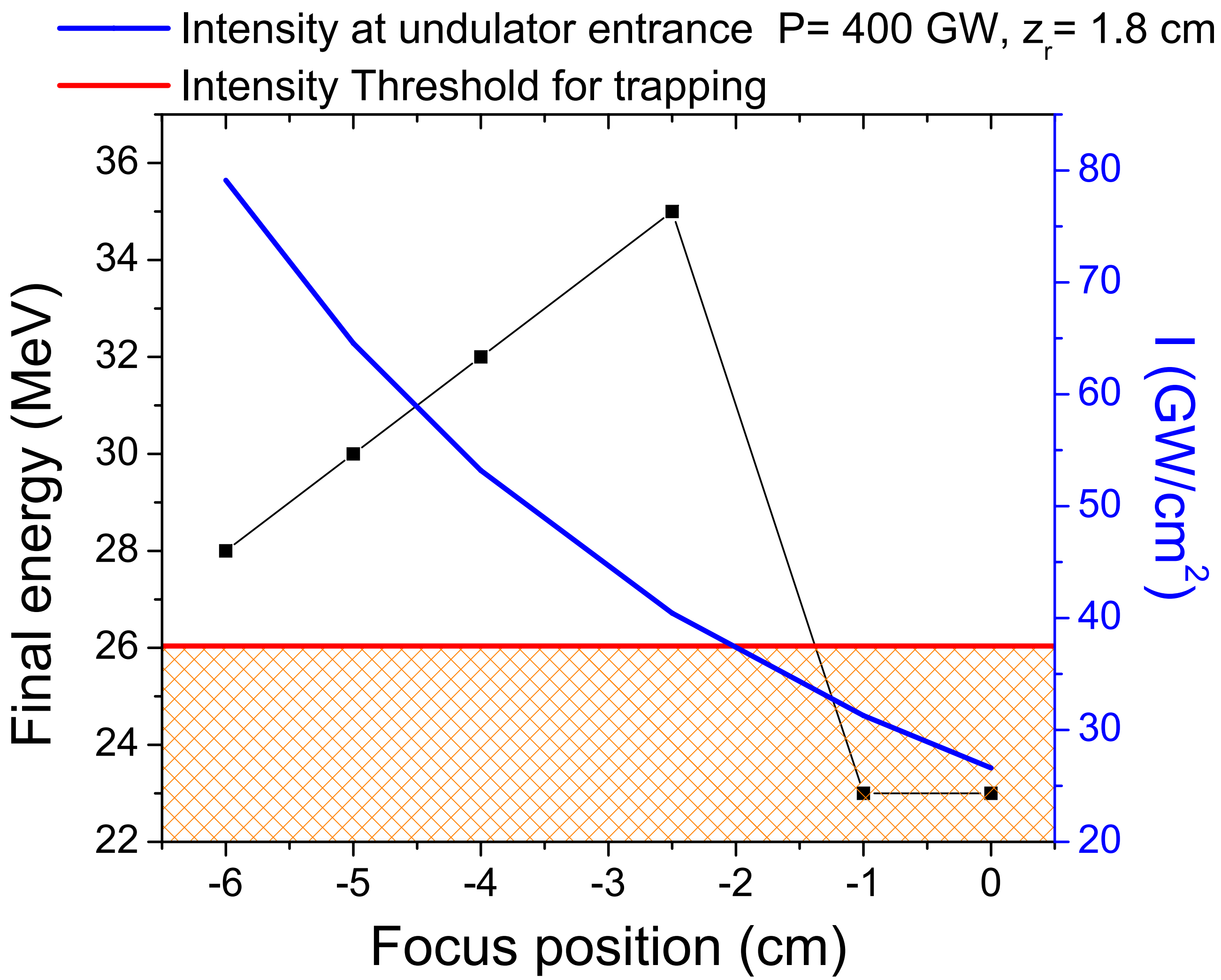


Optimization of IFEL output

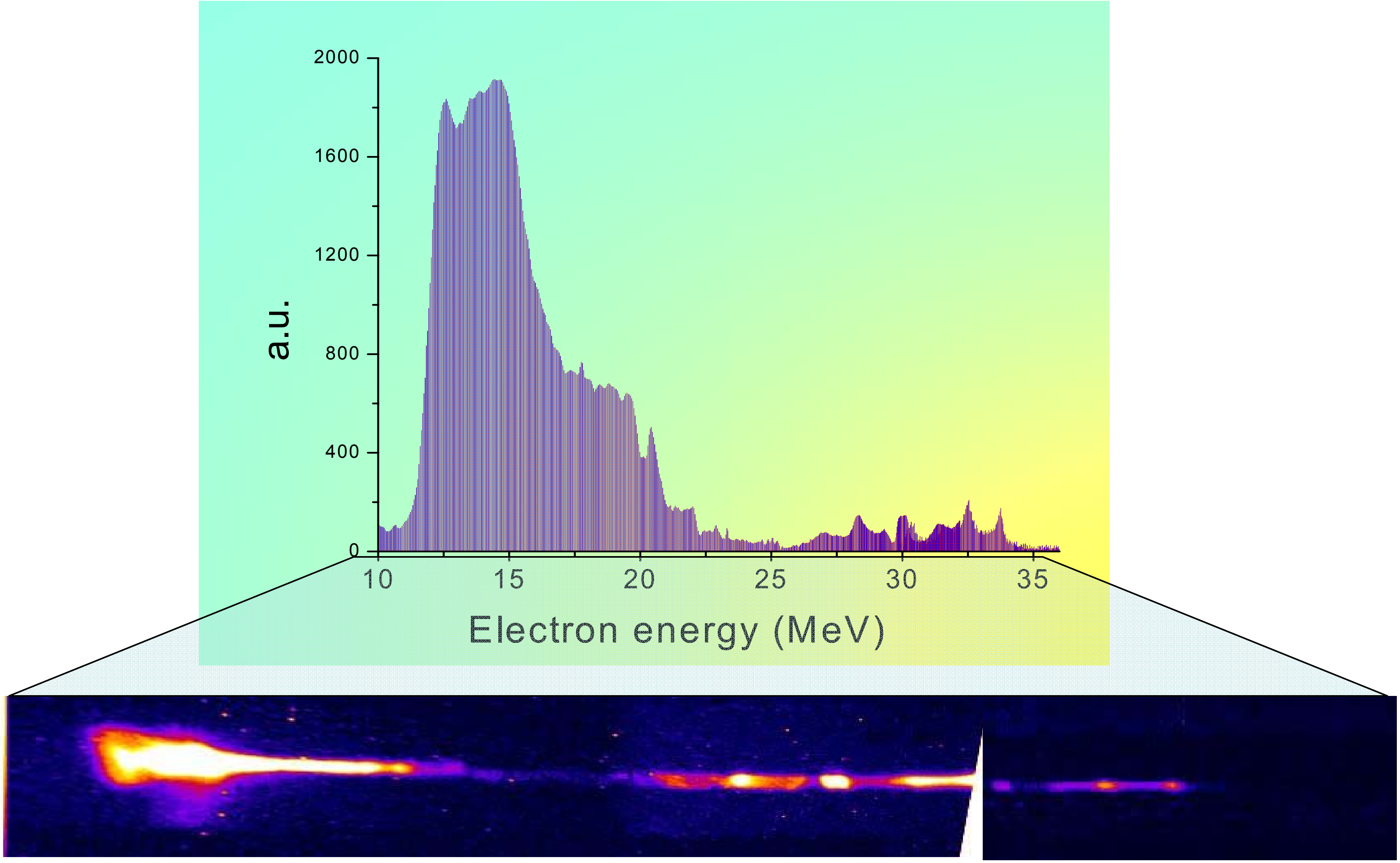




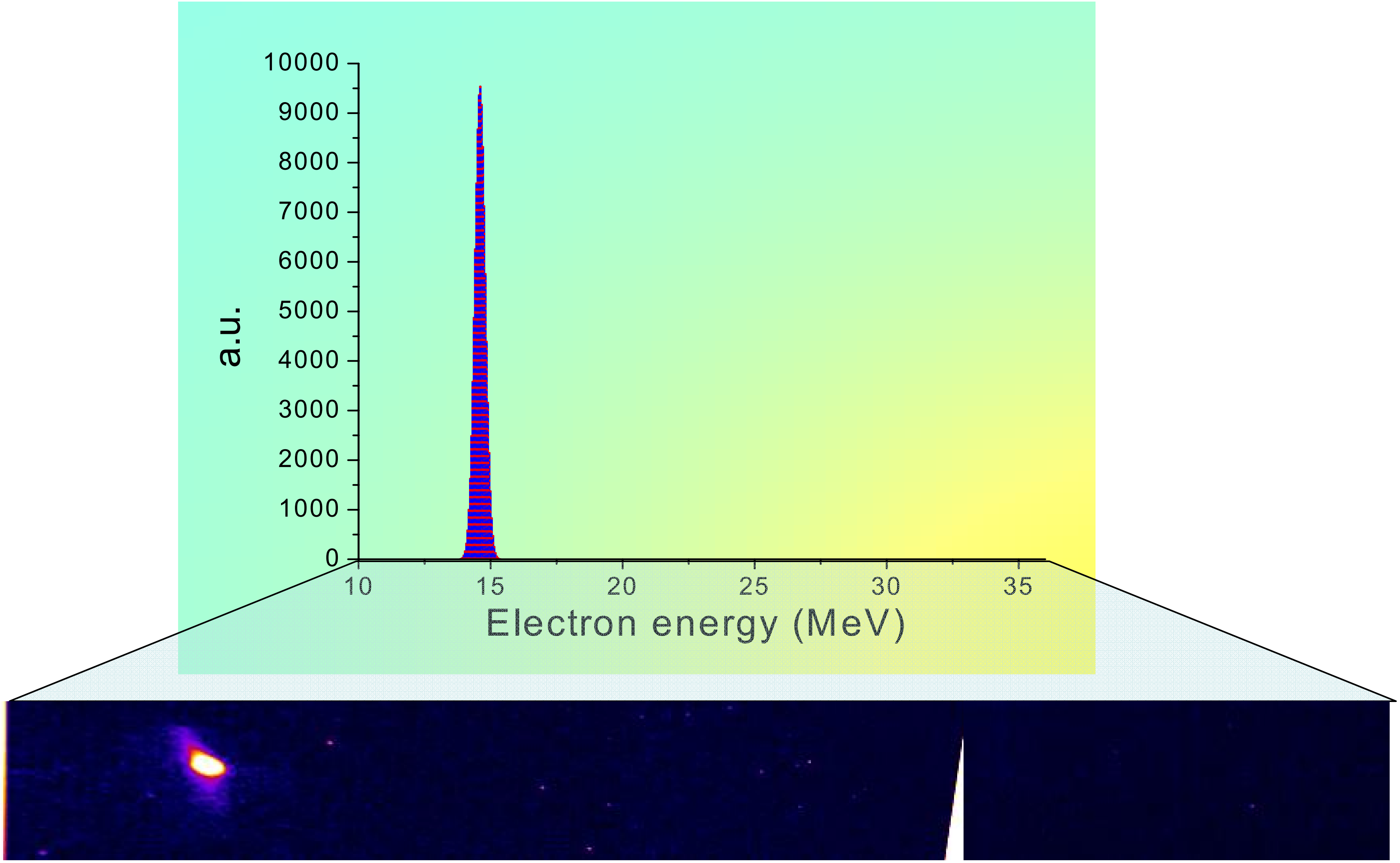
Output energy vs. focus position



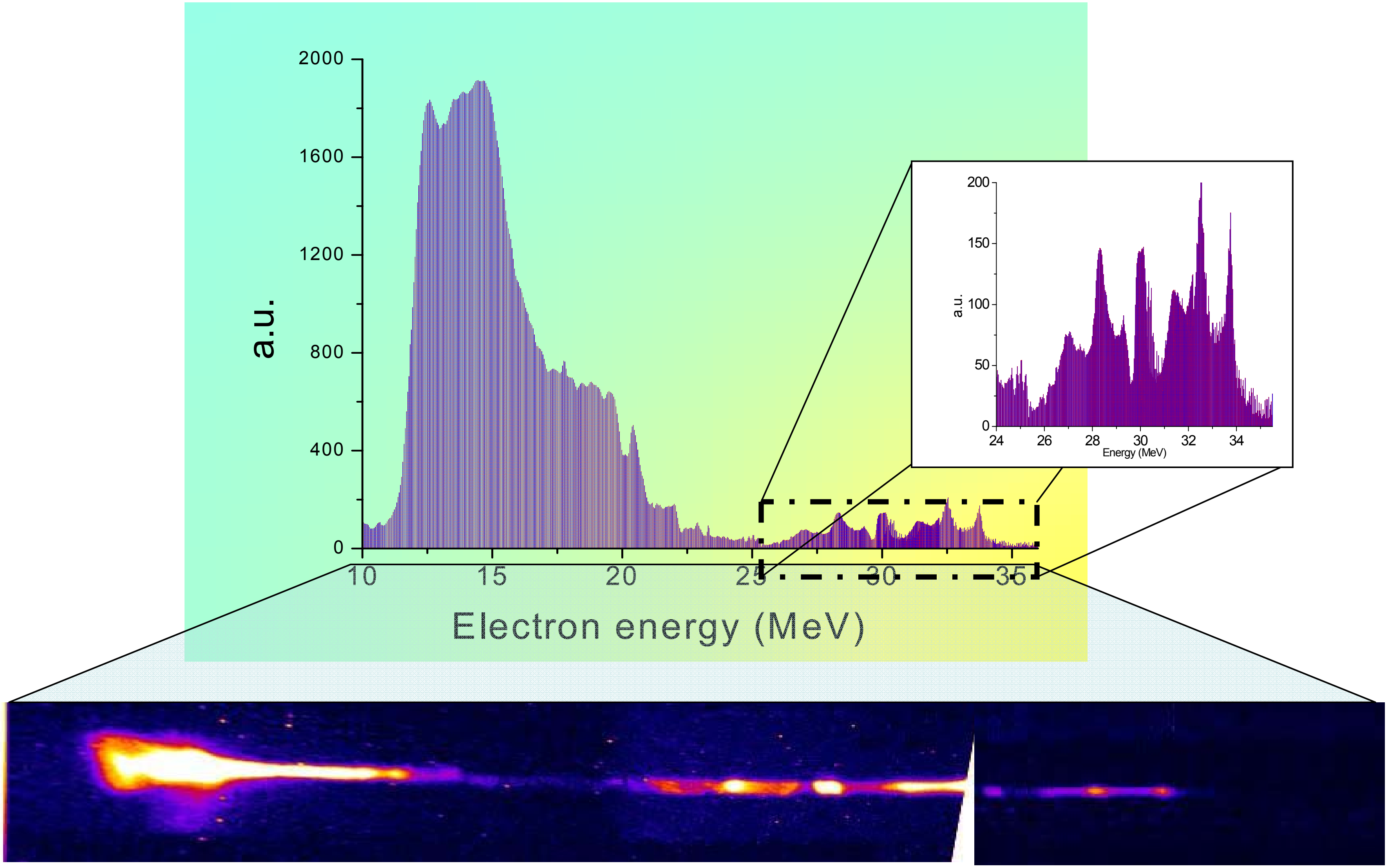
Single shot spectrum (laser on)



Single shot spectrum (laser polarization 90° off)



Single shot spectrum (laser on)

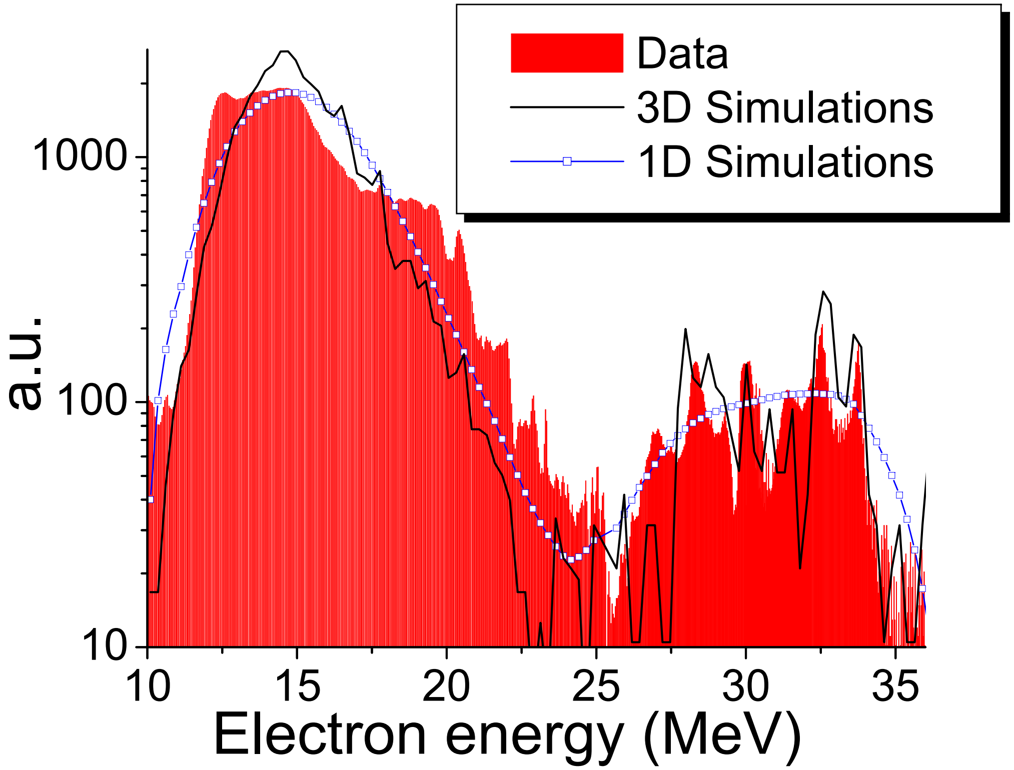


IFEL Simulation tools

- 1D simple FEL-like equations solver
  - Quick exploration of parameter space in the design phase
  - Benchmarked against with 3D simulations results
- TREDI: Lienerd-Wiechert potential based 3D code
  - Need more than FEL approximation for the equation, because of violent acceleration: Lorentz Force solver.
  - 3d magnetic field map from magnetostatic field solver RADIA
  - Analytical laser fields (TEM Hermite-Gaussian modes)

Comparison with experimental data

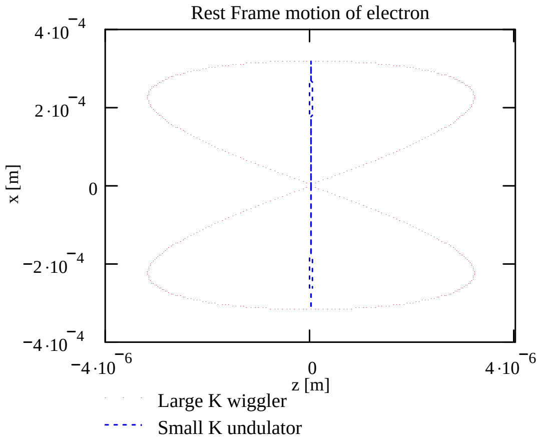
- Excellent agreement in
  - Maximum energy gain
  - Fraction of captured particles
  - Peaky structure
- Low energy side difference maybe due to experimental misalignment or not Gaussian phase fronts.



Resonant condition

- Fundamental interaction
  - The slippage in one undulator period is equal to one laser wavelength so that the transverse velocity and the EM wave keep always the same phase relationship.
  - In the rest frame of the electrons the undulator-induced wiggling is (for small K) a non relativistic dipole oscillation with the same frequency of the Doppler shifted EM wave.

- Higher Harmonic interaction
  - The slippage in one period can be equal to n laser wavelengths
  - In the electron rest frame, the oscillations induced by a large K wiggler have multipole components



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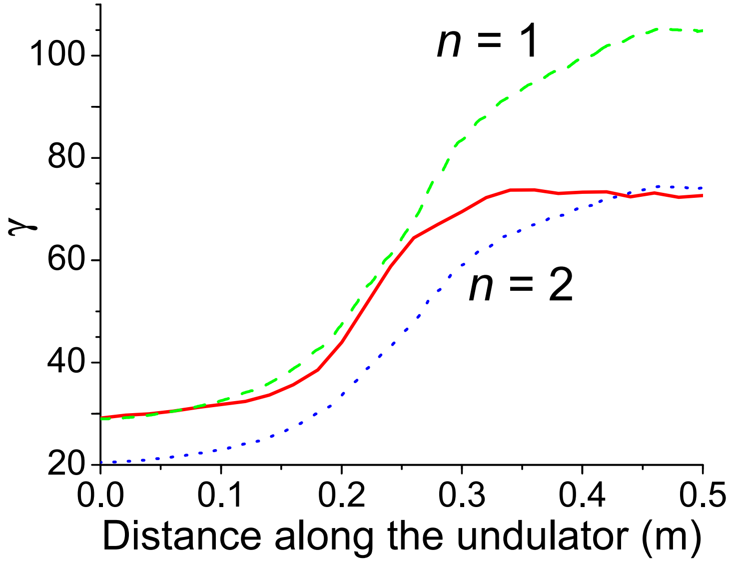
Where are the energy peaks coming from?

Resonant conditions for energy transfer between particles and EM wave: Higher Harmonic IFEL

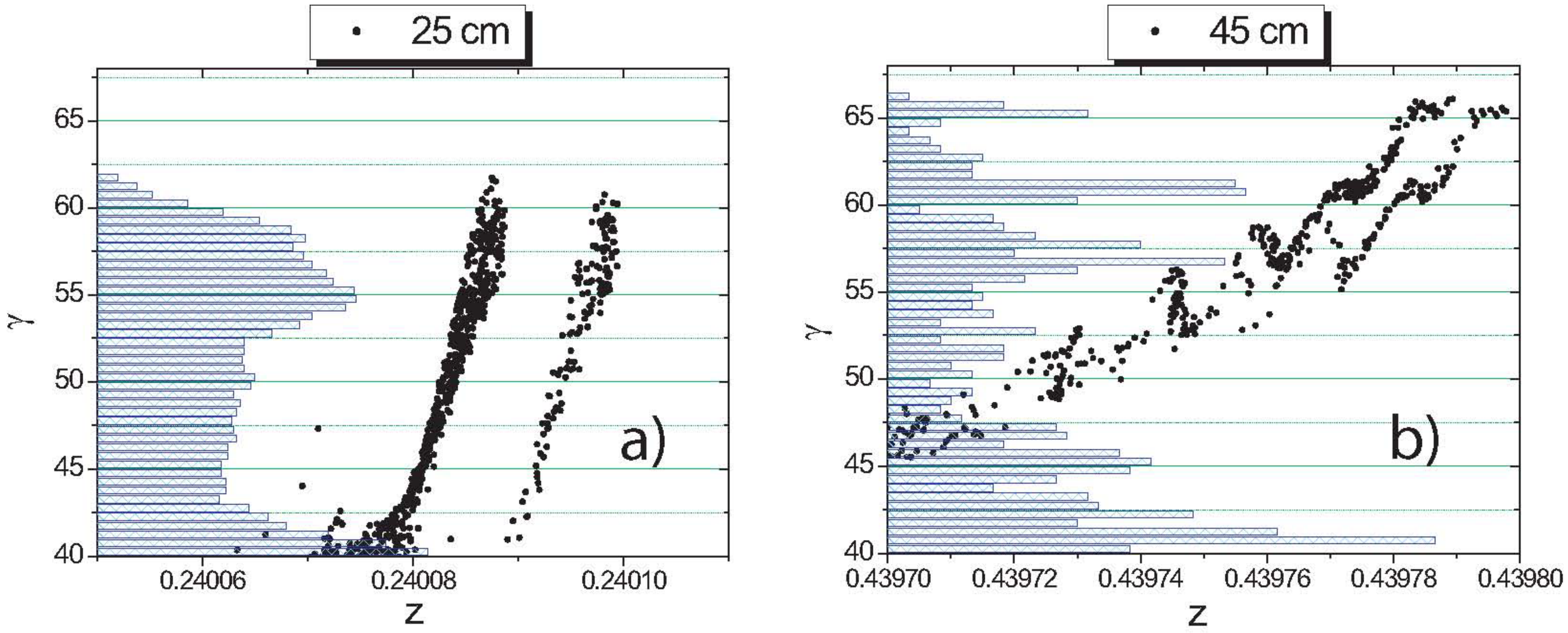
$$\gamma_{res,n}^2 = \frac{\lambda_w \cdot \left(1 + \frac{K^2}{2}\right)}{2\lambda \cdot n}$$



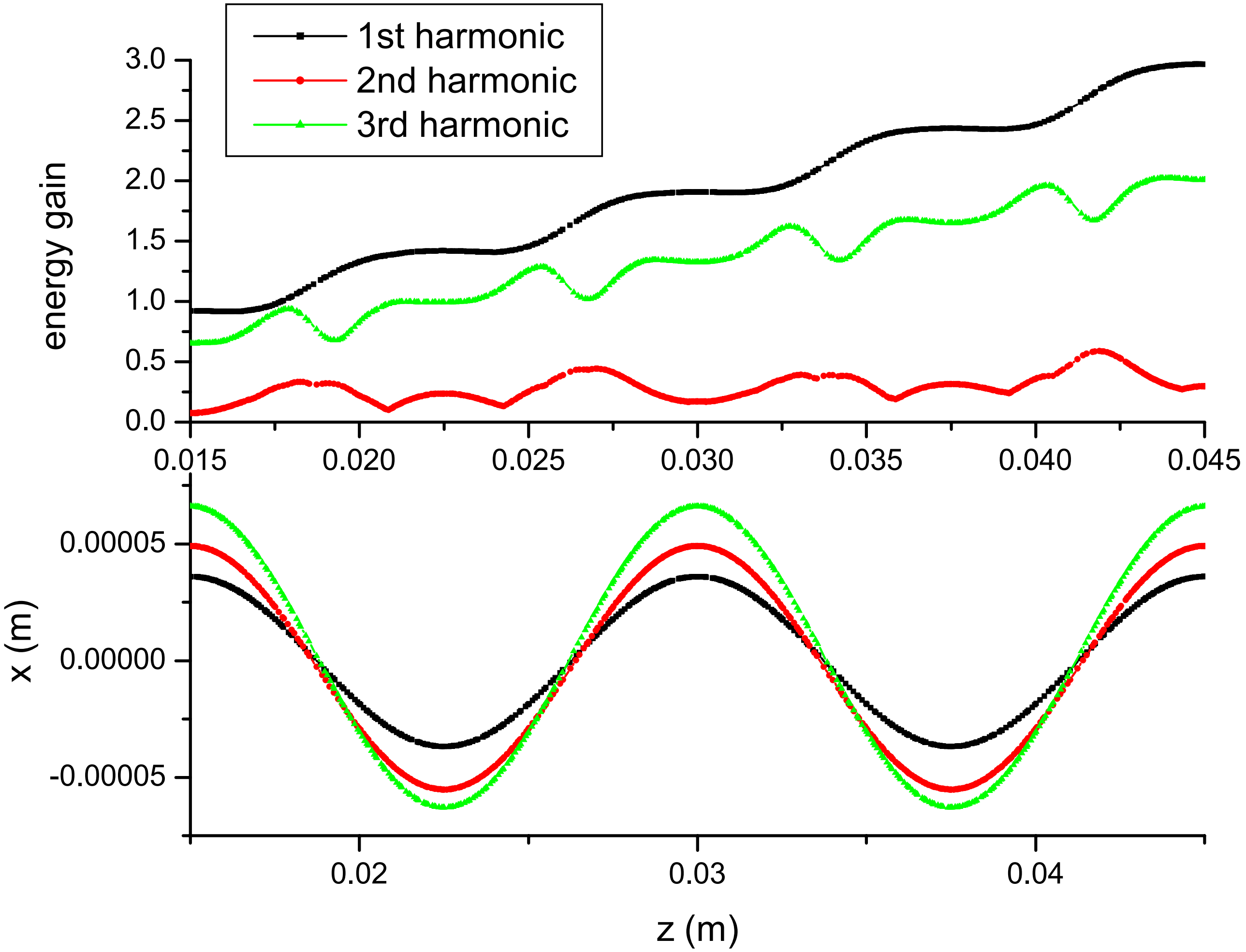
Unfortunately we were not able to follow the green curve because of missing laser intensity, but if you slip out of the first resonance, the undulator is tapered enough that electrons can start to exchange energy with 10.6 μm photons through second harmonic coupling !!!

3d simulation

- Energy gain is in the first section of undulator. (20 MeV in 25 cm !!)
- Higher Harmonic IFEL in the second section



Energy gain in one undulator wavelength



Higher Harmonic IFEL theory

$$\boxed{\frac{d\gamma}{dz} = kK_l \cdot \sum_n \frac{JJ_n(K)}{2} \cdot \frac{K}{\gamma} \sin\left(k_w z(1+n) + kz - \omega t + \varphi\right)}$$

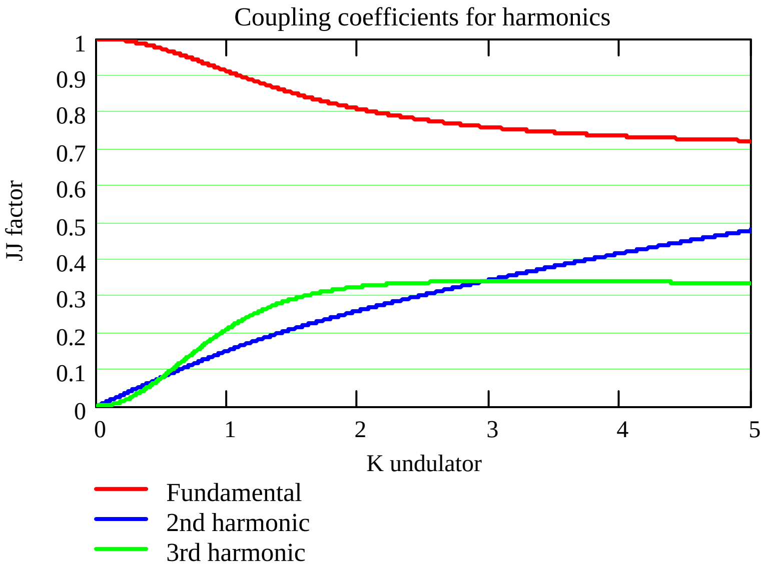
$$JJ_n(K) = \sum_{m=-\infty}^{\infty} J_m\left(\xi(K)\right) \cdot \left(J_{2m+n+2}\left(\sigma(K)\right) + J_{2m+n}\left(\sigma(K)\right)\right)$$

where $\xi(K) = \dfrac{K^2}{4\left(1+\dfrac{K^2}{2}\right)}$ $\qquad \sigma(K) = \dfrac{K}{\gamma k_w w}$

The even harmonics are coupled through σ a parameter that is a measure of how three dimensional is the problem (diffraction angle, misalignments).

In the limit σ(K)→0 we found the known result for odd harmonics.

Higher Harmonic IFEL gives a lot of flexibility in undulator design !!!



1 GeV IFEL design: application to SPARC/Xino

- 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
- Control of energy spread !!!
- Extend the energy reach of planned linac
- First Advanced Accelerator driven/ radiation source

SPARC/Xino project

Parameter	Fixed Value
Initial *e*-beam energy (γ value)	210 MeV
Initial *e*-beam intrinsic energy spread	0.1% (1σ)
Laser wavelength	800 nm
Laser peak power	10 TW
Nominal length of wiggler, L_w	200 cm
Rayleigh range	40 cm
Location of laser waist inside wiggler	100 cm
Resonant phase angle ψ for wiggler	$\pi/4$

Laser Wavelength Pros and Cons

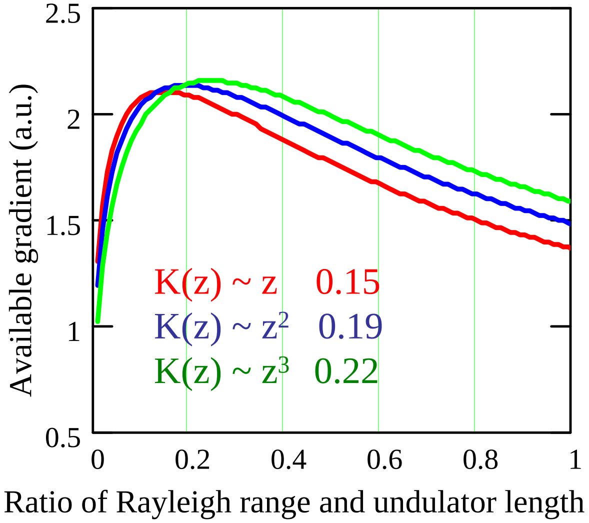
There is no laser wavelength preference expressed by the IFEL equations

- Short wavelength (typically solid state near infrared lasers systems) advantages:
  - The ultra short pulse length makes possible to reach very high peak power ~100 TW
  - Good pulse repetition rates available (e.g., 10 Hz)
  - The smaller amount of energy contained in the laser pulse makes the design less sensitive to fluence-induced optical damage;
  - In a free-space coupling configuration, the shorter wavelength makes the diffraction effects less important;
  - Table-top-sized laser systems.
- Long wavelength (typically CO2 laser systems) advantages:
  - A greater energy in the laser pulse makes possible to increase the amount of charge in the accelerated beam
  - Because of the longer pulse length, there are less slippage problems;
  - The alignment of the accelerator has less strict requirements
  - The synchronization and phase-locking of different accelerator stages has increased tolerances

Comments on Rayleigh Range

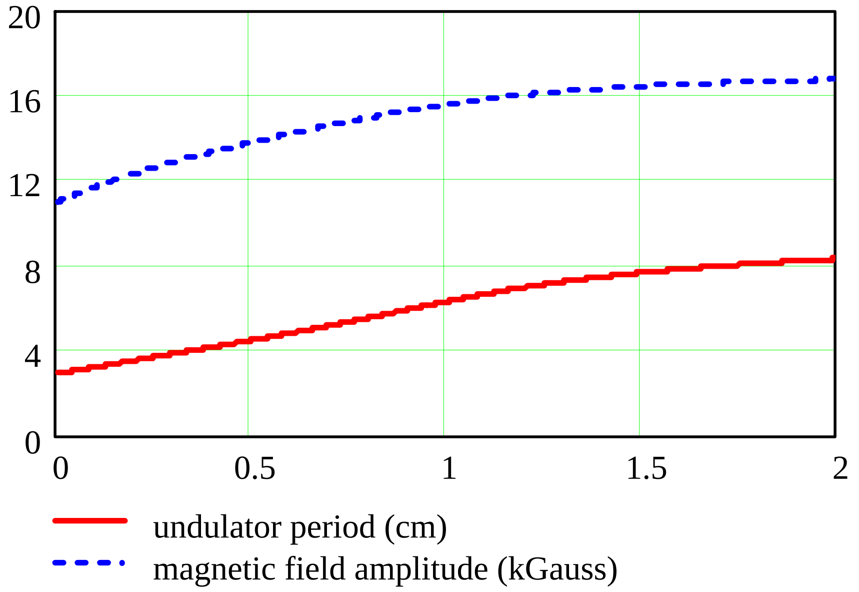
- Fixing the laser power available, there is an optimum choice for the focusing scheme
  - Focusing in a tighter spot increases the intensity and the electric field driving the interaction
  - A more gentle focus distributes more uniformly the intensity over the all undulator length
- The optimum ratio between the undulator length and the Rayleigh range is found maximizing the available IFEL gradient integrated along the accelerator and it is found to be 0.15-0.25 depending on how strong is the tapering of the undulator.

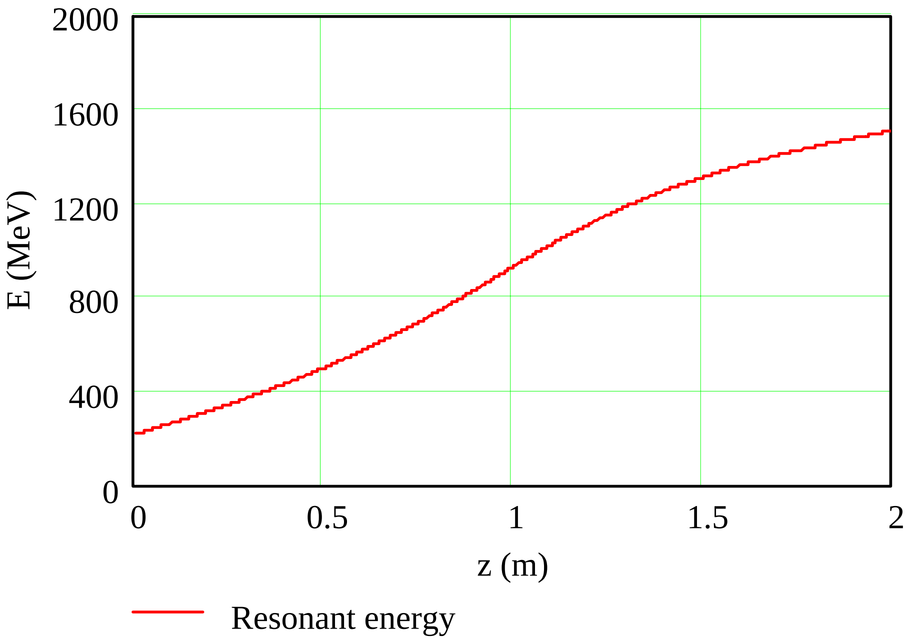
$$\boxed{\frac{\partial}{\partial z_r}\int_0^{L_w} K(z)E(z,z_r) = \frac{\partial}{\partial z_r}\int_0^{L_w} K(z)\sqrt{\frac{1}{z_r}\cdot\frac{1}{1+\left(\frac{z-\frac{L_w}{2}}{z_r}\right)^2}} = 0}$$



Tapering optimization

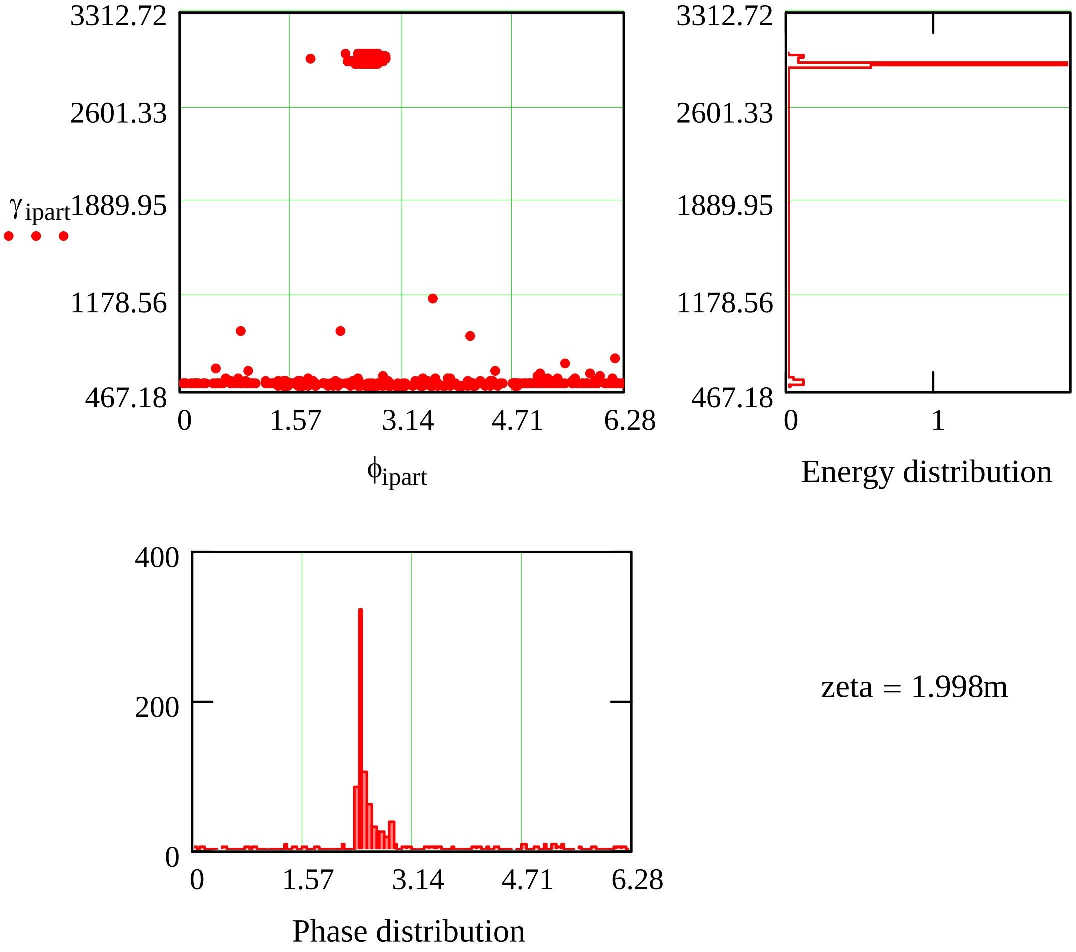
- Helical undulator to maximize energy exchange (interaction always ON)
- Keep magnetic field amplitude well under the Halbach limit
- Final energy spread ~1 %, to be decreased with appropriate exit-section tapering





IFEL phase space

IFEL longitudinal phase space



zeta = 1.998m

Final output parameters

Energy	**1.5 GeV**
Energy spread	<1 %
Microbunch length	**250 as**
Peak current	**> 4 kAmp**

Summary & Conclusion

- IFEL interaction is one of the most efficient way to transfer energy and/or information from a high power laser to a relativistic electron beam
- IFEL Advanced Accelerator at the Neptune Laboratory
  - > 20 MeV energy gain (+ 150 %) !!
  - trapped up to 10 pC in accelerating buckets !
  - accelerating gradient ~70 MeV/m !
- First experimental study of Strong Tapering & Diffraction Effects in IFELs
- Observation of Harmonic IFEL interaction in second section of undulator.
- Bright future for laser acceleration and IFEL !!!