Very high energy gain at the Neptune IFEL experiment

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Advanced Accelerator Concepts

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Outline

- Brief IFEL introduction
- Inverse-Free-Electron-Laser accelerators around the world
- Neptune IFEL project
  - Overview of Neptune Laboratory setup
    - Electron beam
    - Kurchatov Undulator
    - CO_2 laser
- Experimental results
- Conclusion

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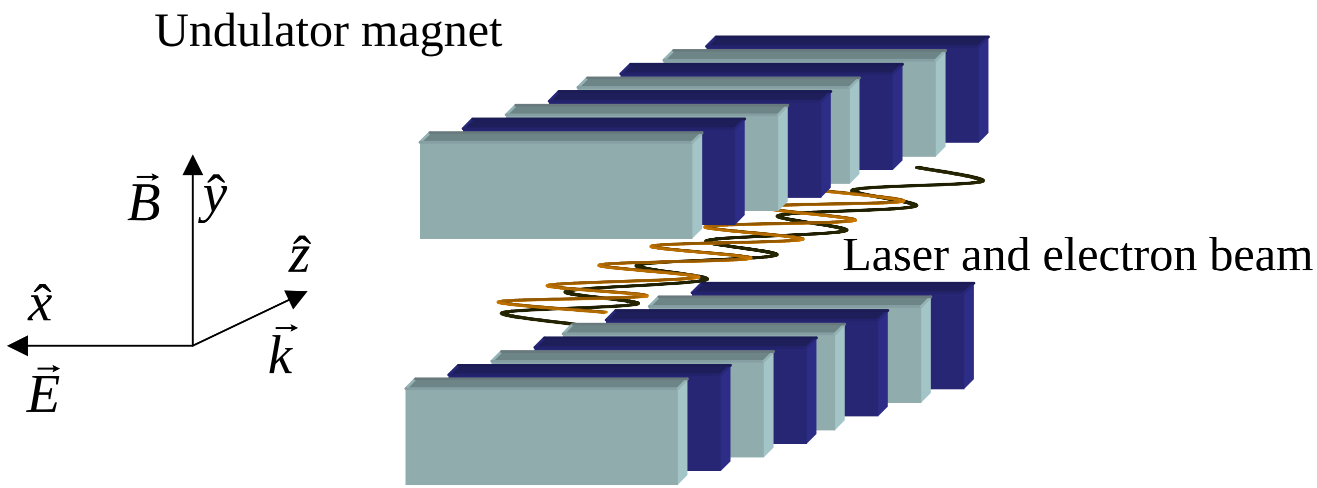
IFEL Interaction

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.

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

IFEL characteristics: a solid and reliable Advanced Accelerator

- Laser accelerator: high gradients
- Vacuum accelerator: good output beam quality
- Microbunching: control and manipulation of beams at the optical scale
- 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

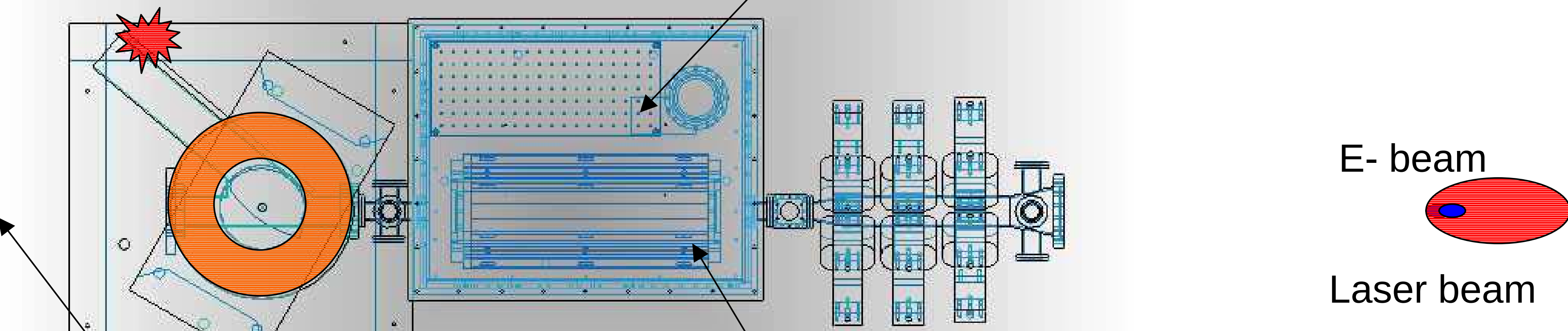
IFEL Experiments

- 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

Experimental Layout



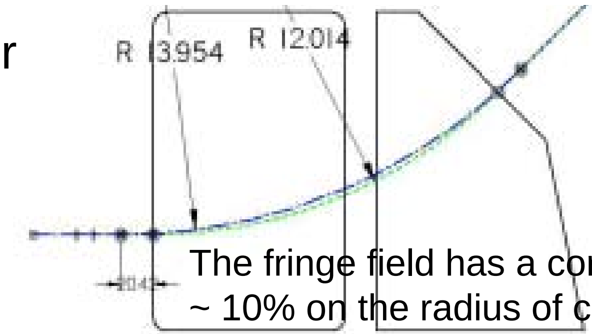
Neptune IFEL Design Parameters

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

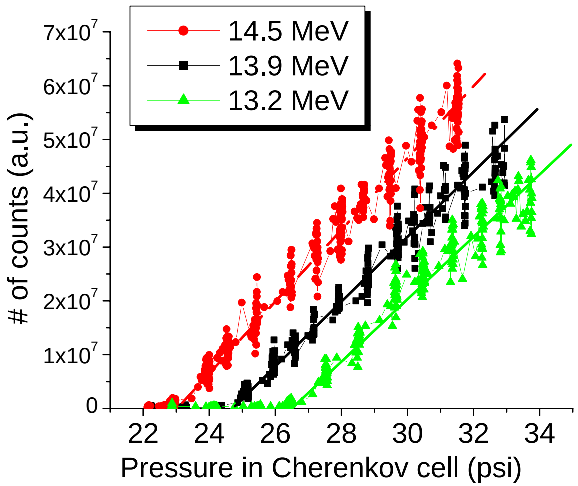
Energy	14.5 MeV
Energy spread (rms)	0.5 %
Charge	300 pC
Pulse length (rms)	4 ps
Rms transverse Emittance	10 μ
Rms beam size at the focus	150 μm

e-beam delivery

- Calibration of 45 º two dipoles spectrometer
  - Alignment errors
  - Fringe field issue

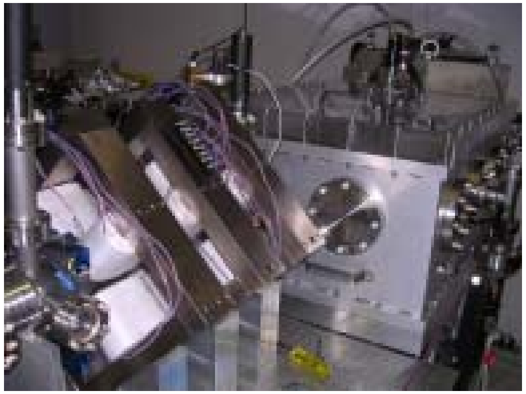


The fringe field has a correction of ~ 10% on the radius of curvature

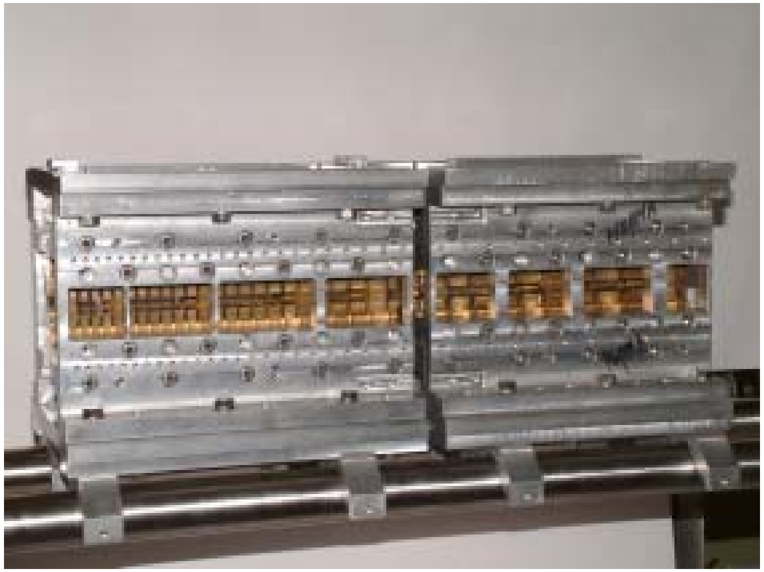


- Cherenkov cell
  - Vary CO_2 pressure to find threshold for Cherenkov emission

- New quadrupole magnets with larger (2.625”) aperture to avoid CO_2 clipping
  - Up to 7 T/m
  - 9.1 cm effective length

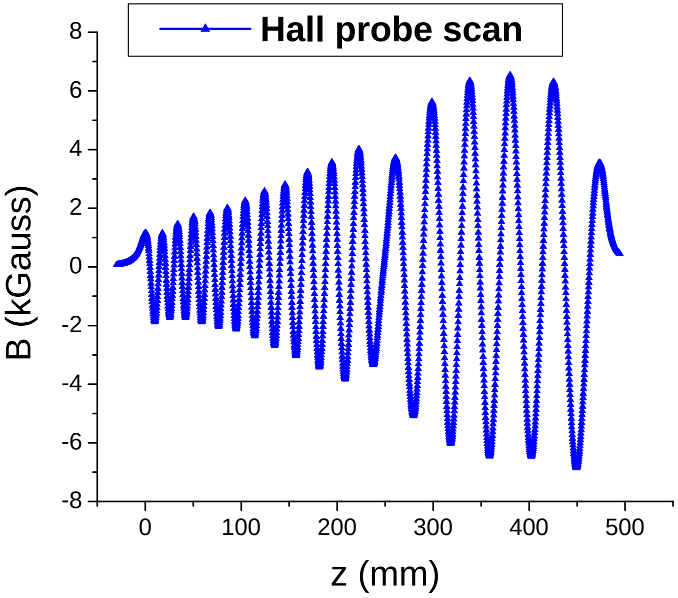


Kurchatov IFEL Undulator



	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

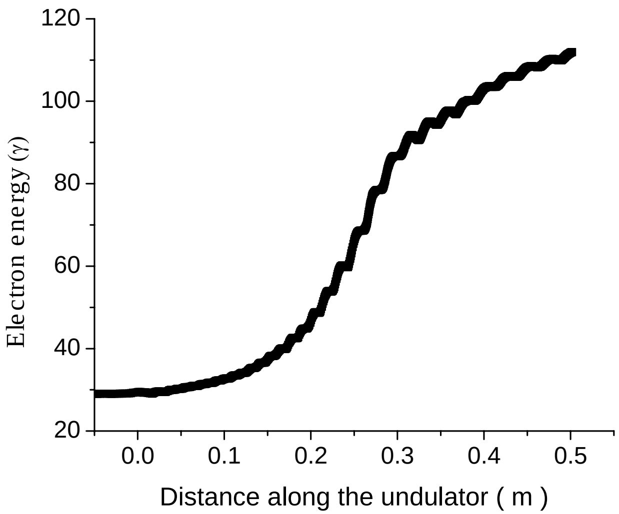
- Unique “double tapered” 50 cm long undulator.
  - Final resonant energy 250 % bigger than initial
- Hall Probe measurements.
- Pulse Wire tuning.

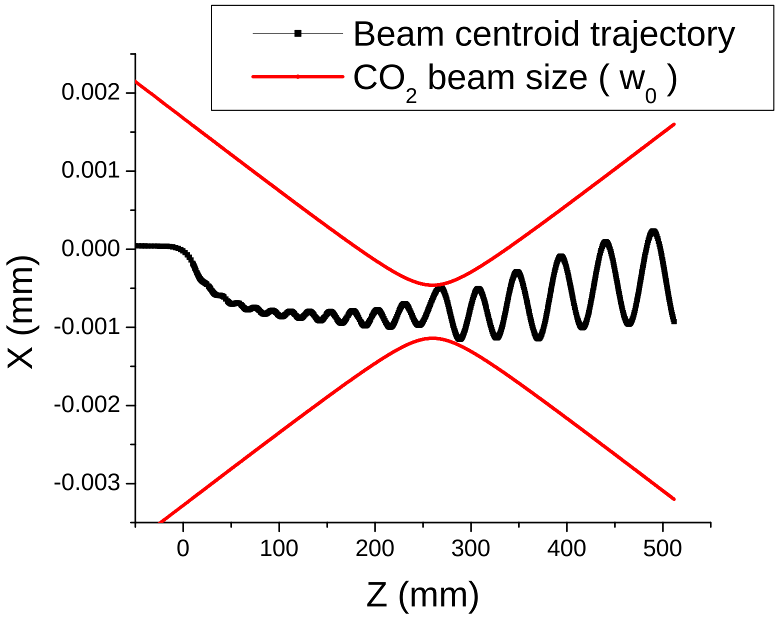


Diffraction Dominated Interaction

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

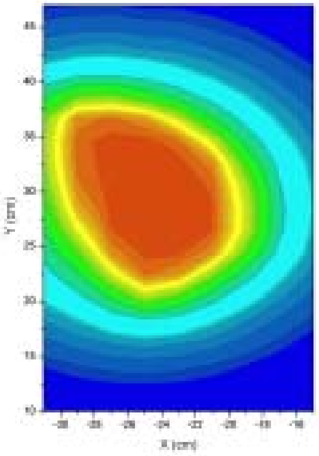
$$\frac{\partial \psi}{\partial z} = k_w + k - \frac{k}{\left(1 - \frac{1 + \frac{K^2}{2} + \frac{K_l^2}{2} + KK_l \cdot JJ(K) \cdot \cos(\psi)}{\gamma^2}\right)^{1/2}} - \frac{1}{z_r\left(1 + \frac{(z - z_w)^2}{z_r^2}\right)}$$



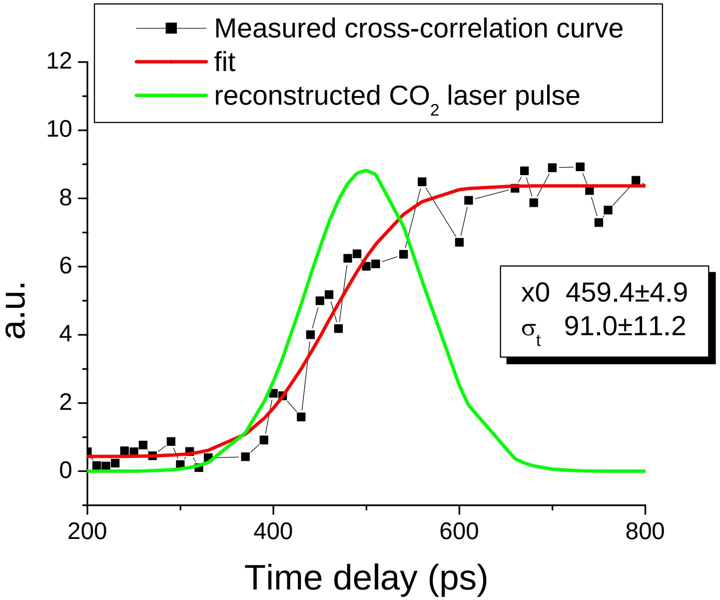


Diagnostics

- Charge
  - ICT in the folding box and Faraday Cup at the end of beamline.
- Energy spectrometer
  - Browne and Buechner geometry to have the energy spectrum over as wide a range of energies as possible.
  - 1.5” pole gap for CO_2 dump
  - 11º edge angle for controlling vertical size of the beam
- Spatial and temporal synchronization
  - Mid-of undulator graphite-coated phosphorous screen
  - Ge crystal on the beam path for temporal synchronization using e-beam controlled transmission of CO_2



Experimental 2d field map of Browne-Buechner poles



Pulse propagation in a CO_2 amplifier

Classical $V_{gr} = c/(n+\nu dn/d\nu)$

$$n_{\text{active medium}} = n_{\text{res}} + n_{\text{nonres}}$$

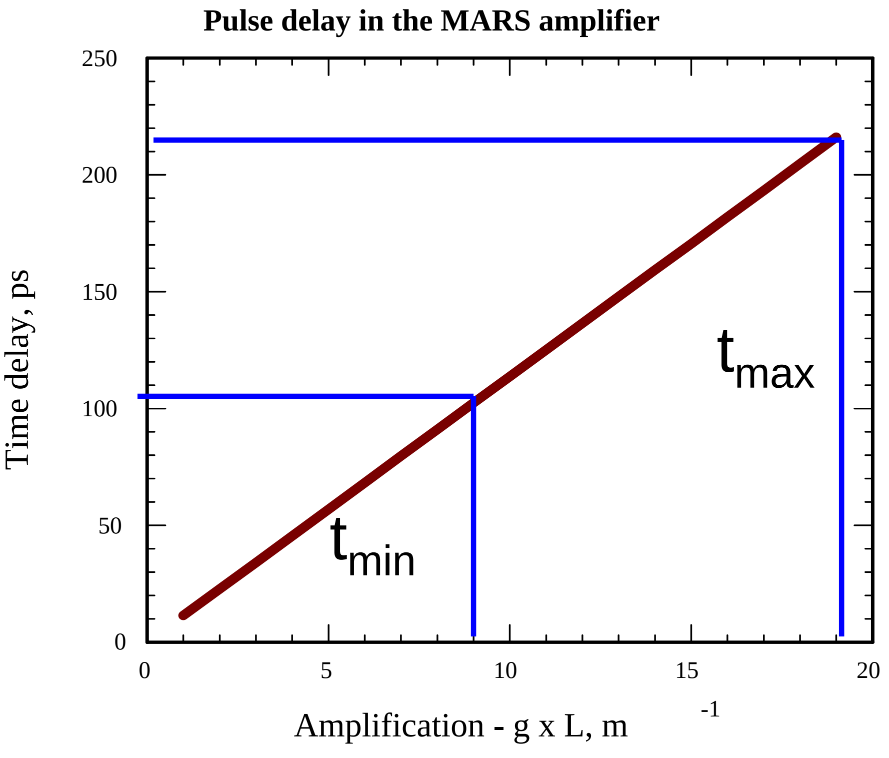
$$n_{\text{nonres}} = 1 + 2\pi \sum_m N_m \alpha_m + \Delta n_{vibr} - \Delta n_e$$

$$m = CO_2, N_2$$

$$n_{\text{res}}(\nu) = n_0 + \frac{c(\nu - \nu_0) g(\nu)}{2\pi\nu\Delta\nu}$$

$$\text{Vgr} = \frac{c}{n_0 + \frac{c g_0}{2\pi\Delta\nu}}$$

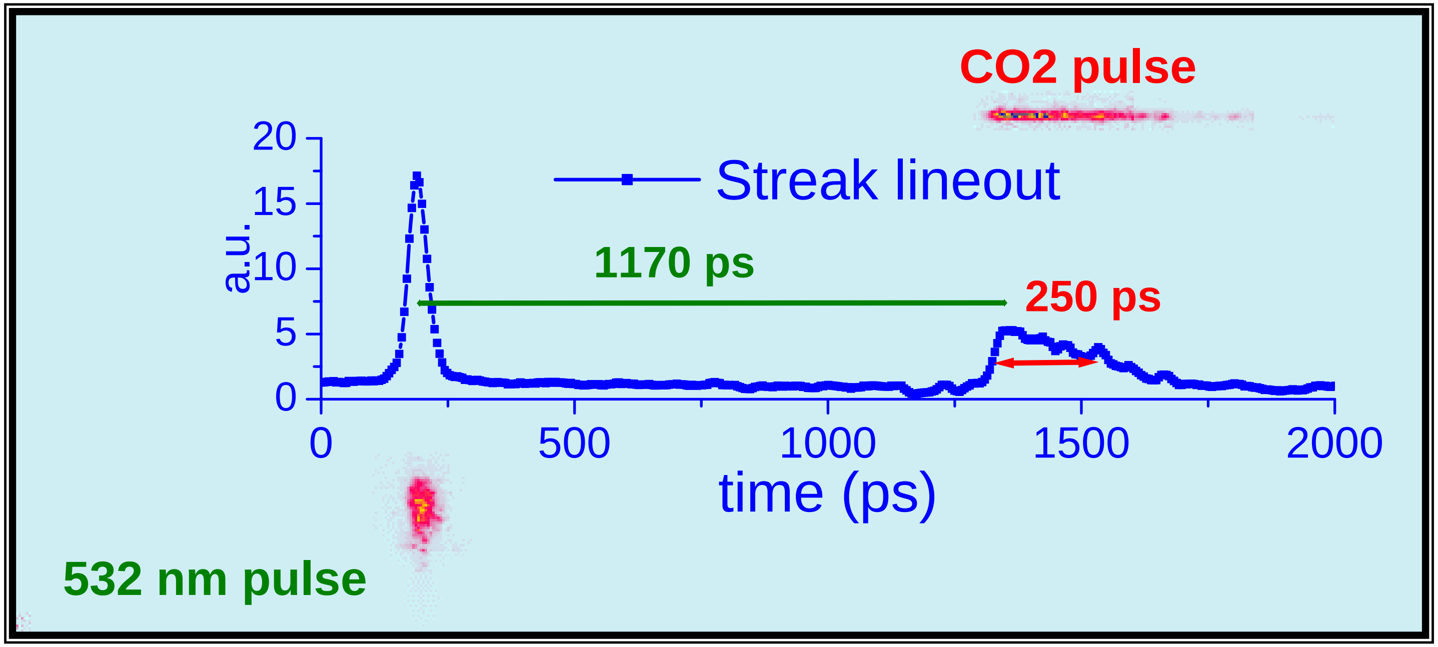
$$t_{\text{delay}} = \frac{L g_0}{2\pi\Delta\nu}$$



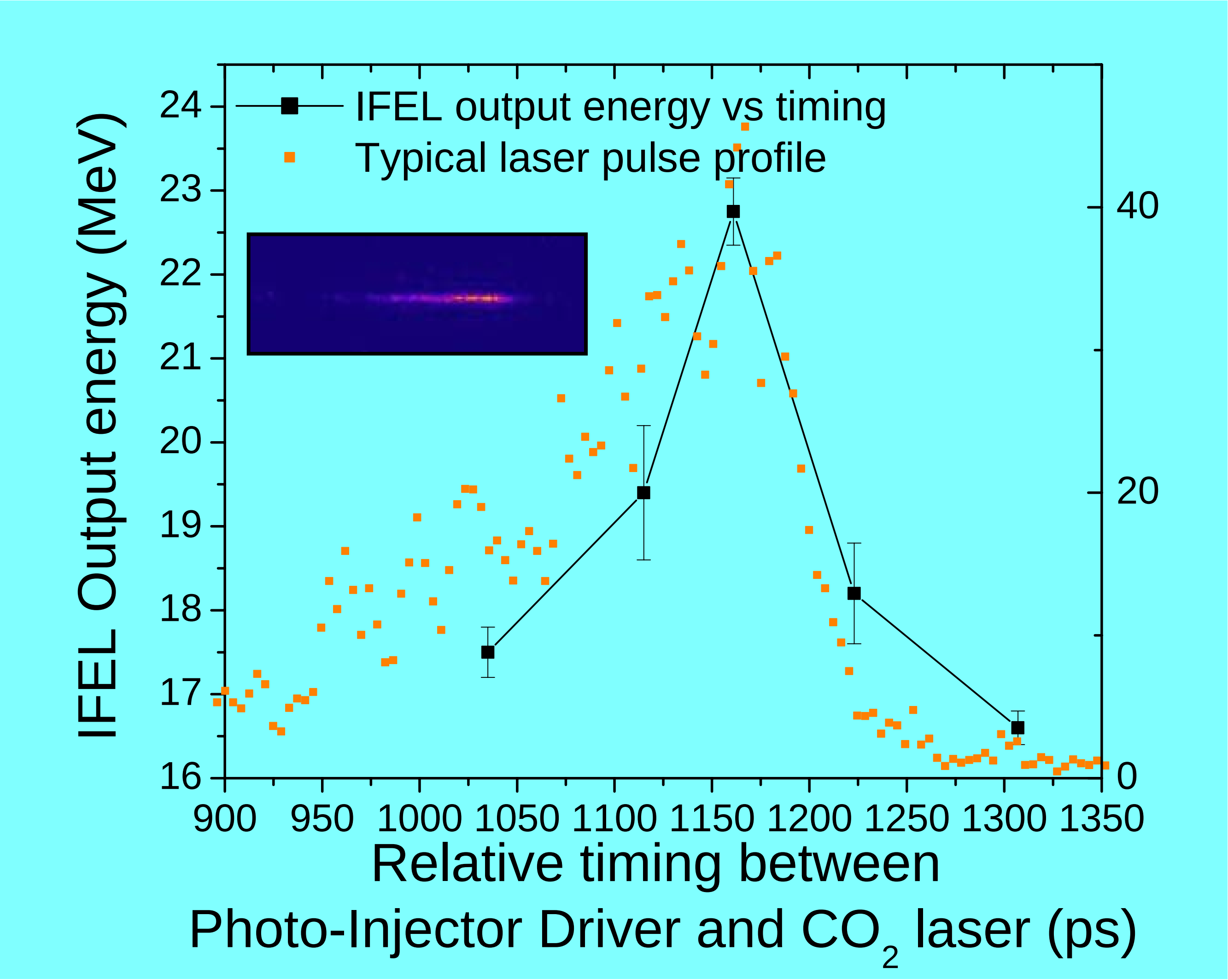
Time delay of 100 ps < t_{delay} < 220 ps in the active medium of MARS high-power amplifier has to be compensated.

Streak camera: “Live from the bunker”

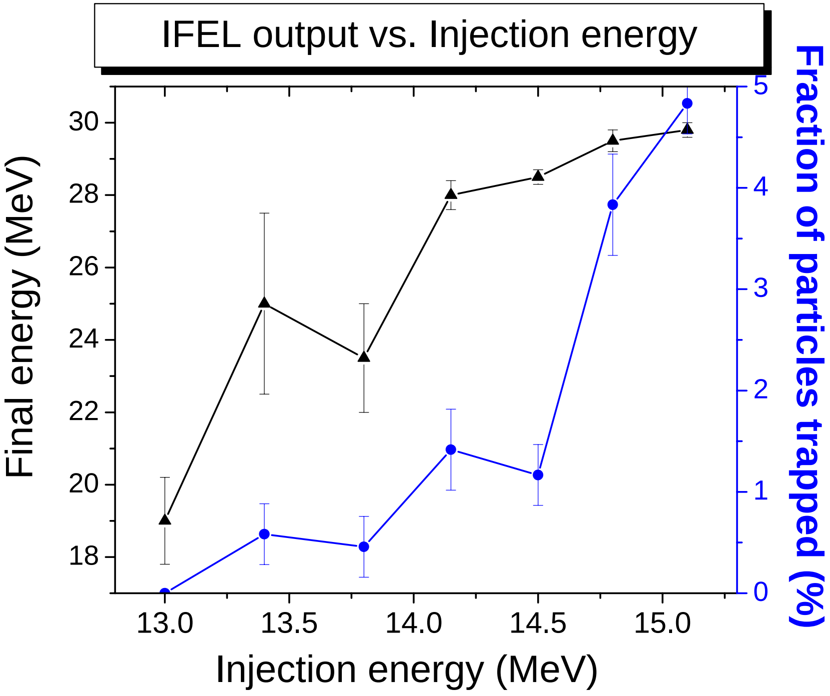
- Shot-to-shot measurements of the laser pulse length and the timing between two pulses necessary because of the complex dynamics of the final amplification of the CO_2 pulse.
- Optical Kerr Effect to get CO_2 streaks
- E-beam reference pick off the photocathode drive laser

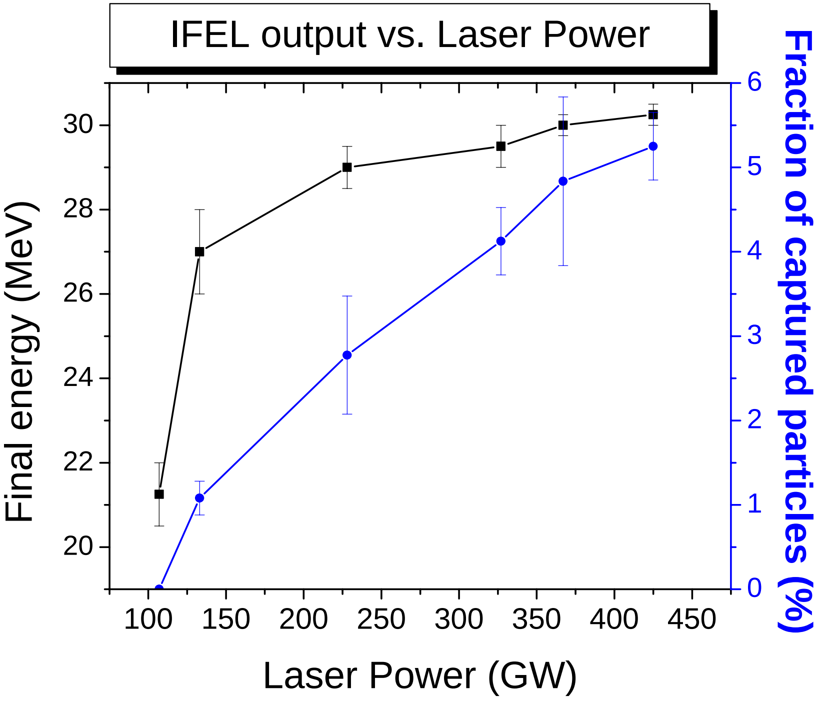


Measurement of timing between CO2 and e beam

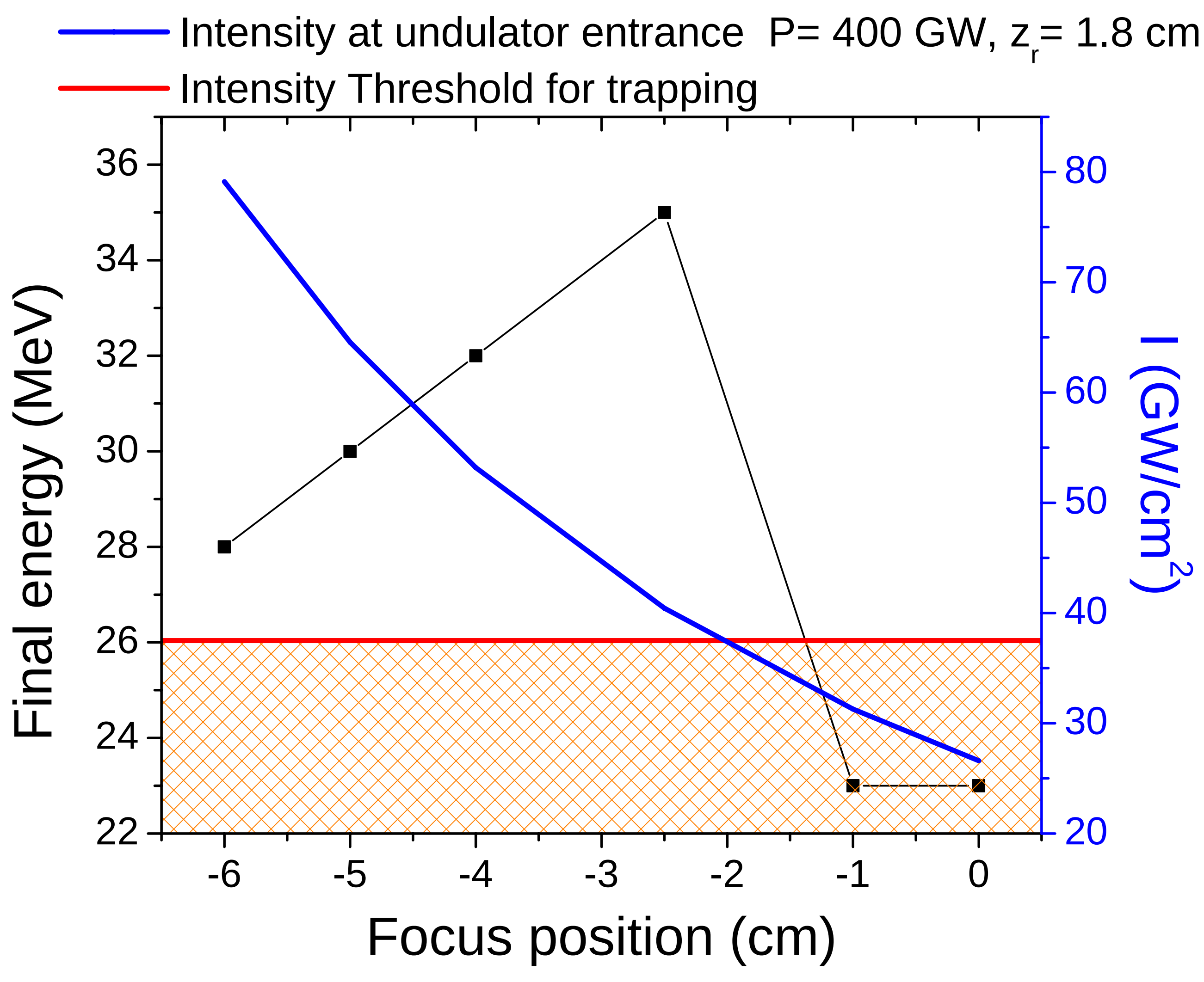


Optimization of IFEL output





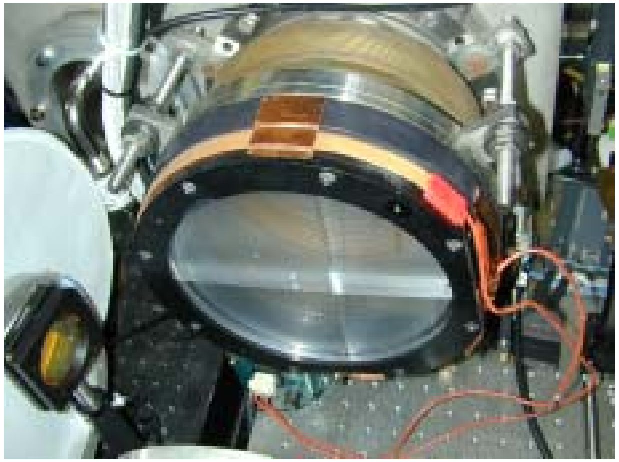
Output energy vs. focus position

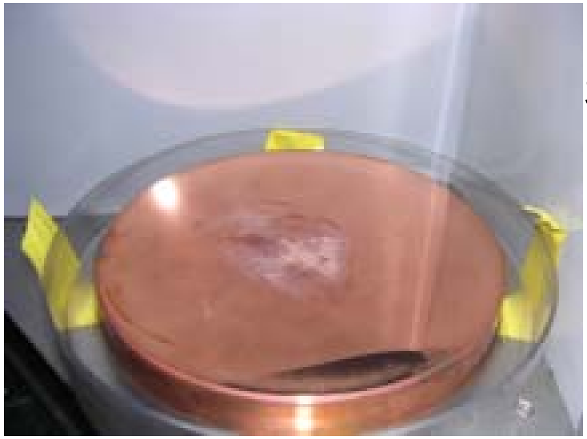


Side-effects of very high power laser beams

- Increase in laser intensity could be accomplished by increase in Rayleigh range, or increase of power in the pulse…

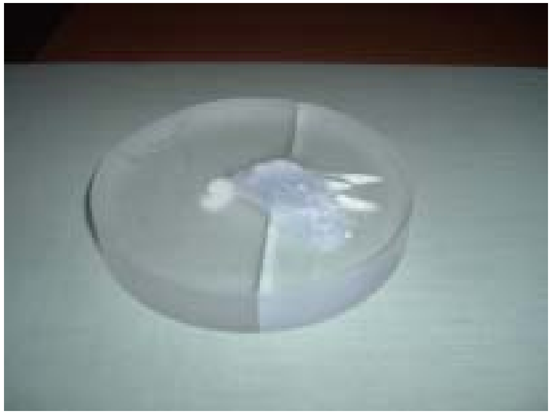
Single crystal NaCL lens



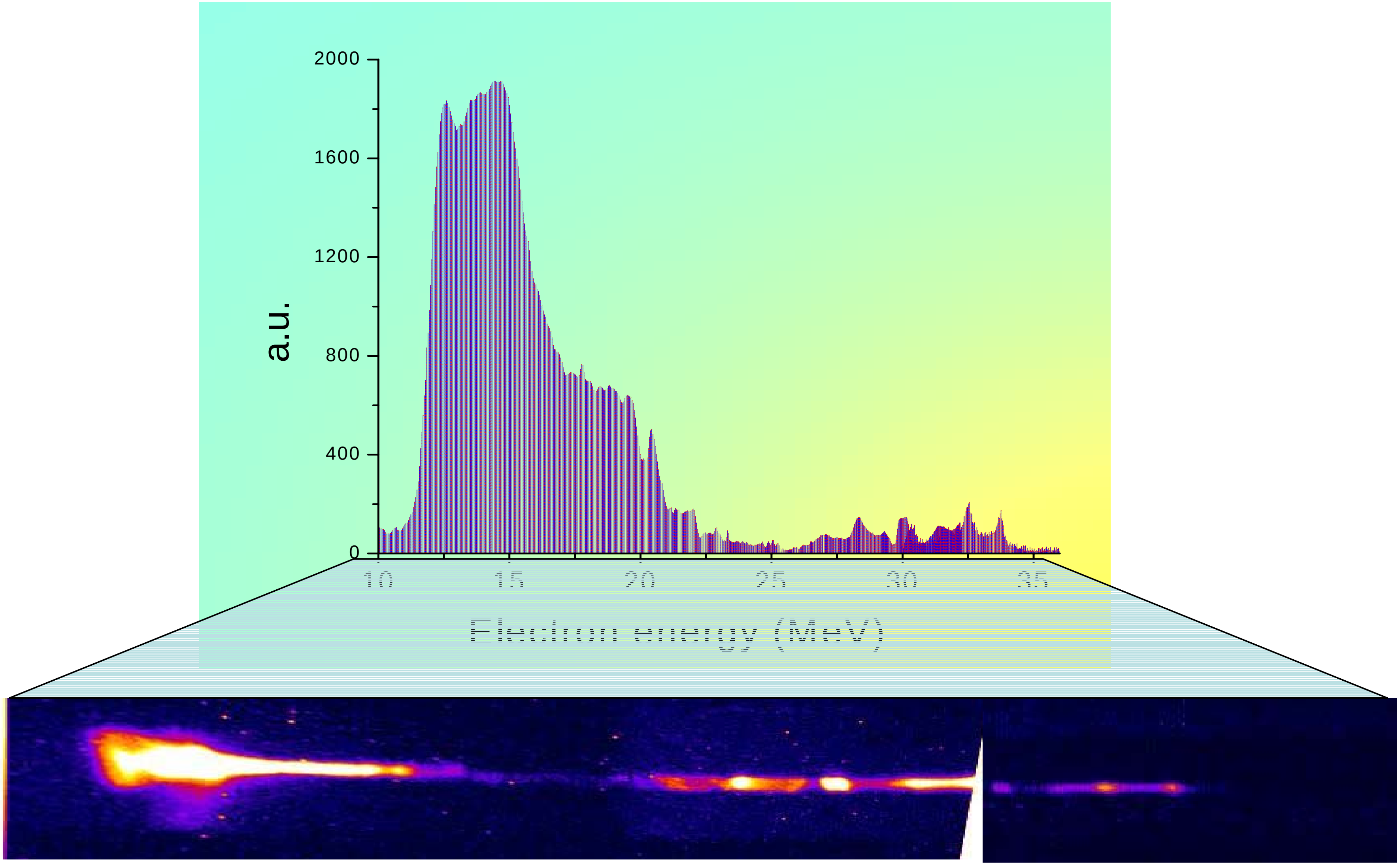


Copper mirrors

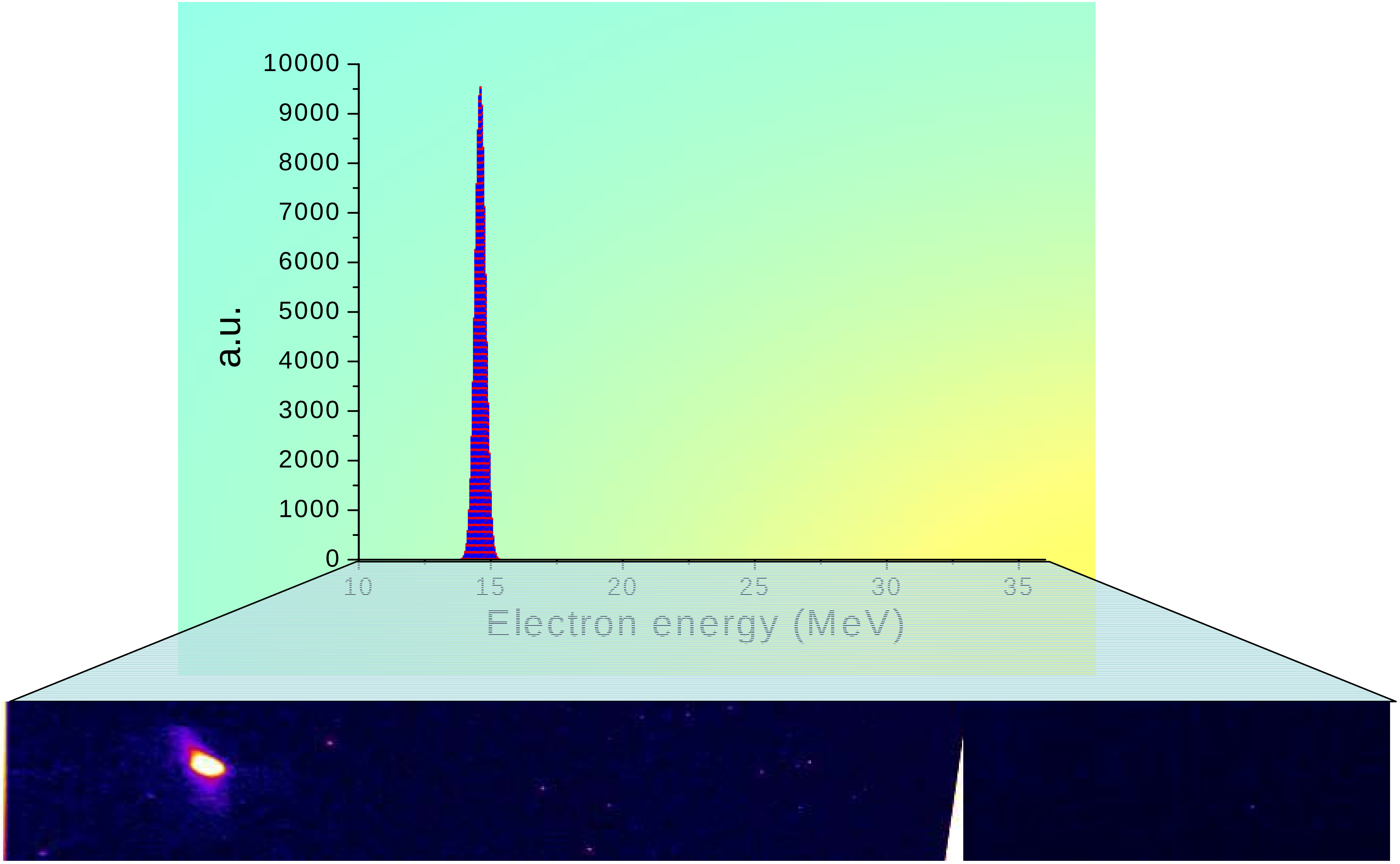
Single crystal NaCL windows



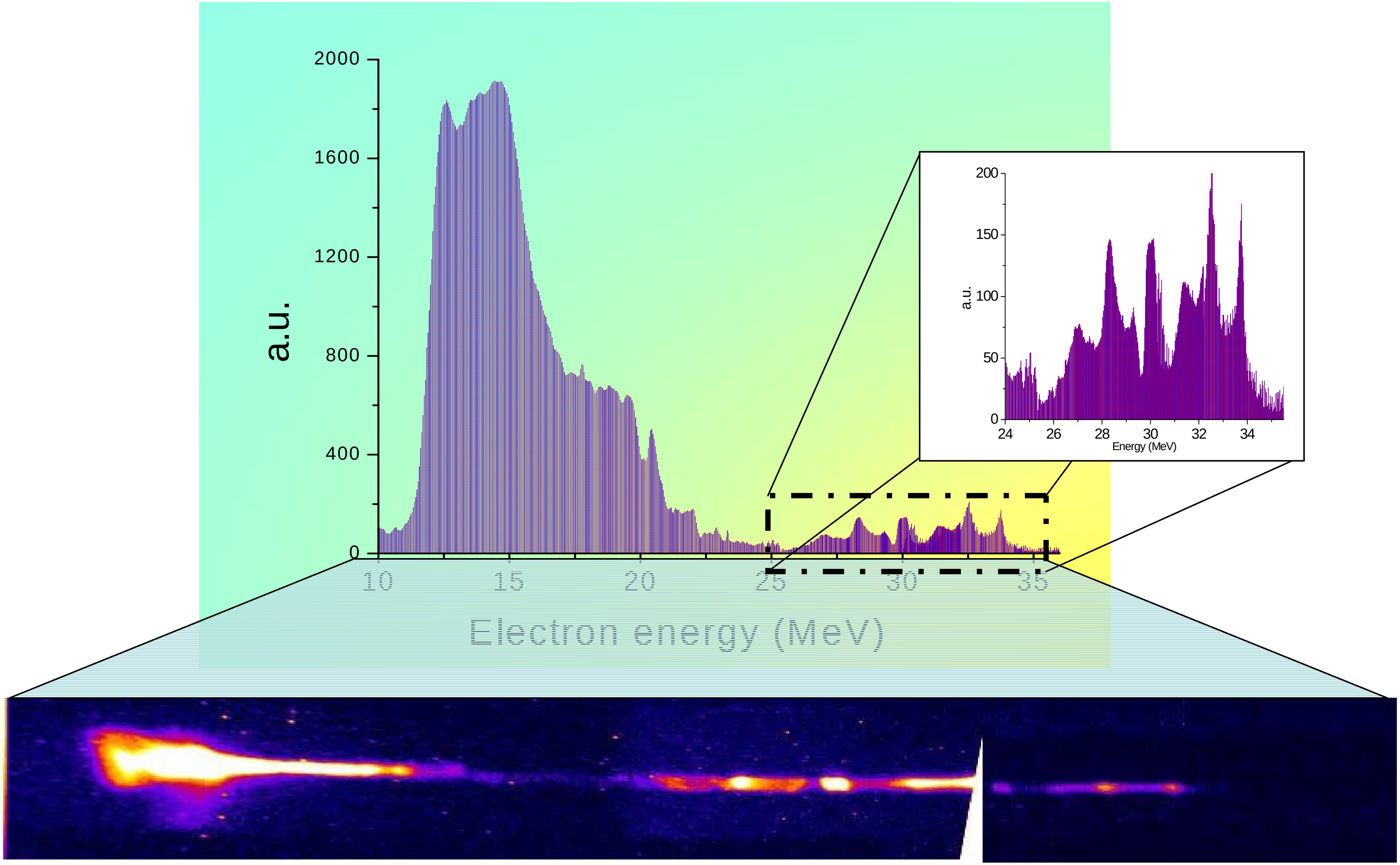
Single shot spectrum (laser on)



Single shot spectrum (laser polarization 90º off)



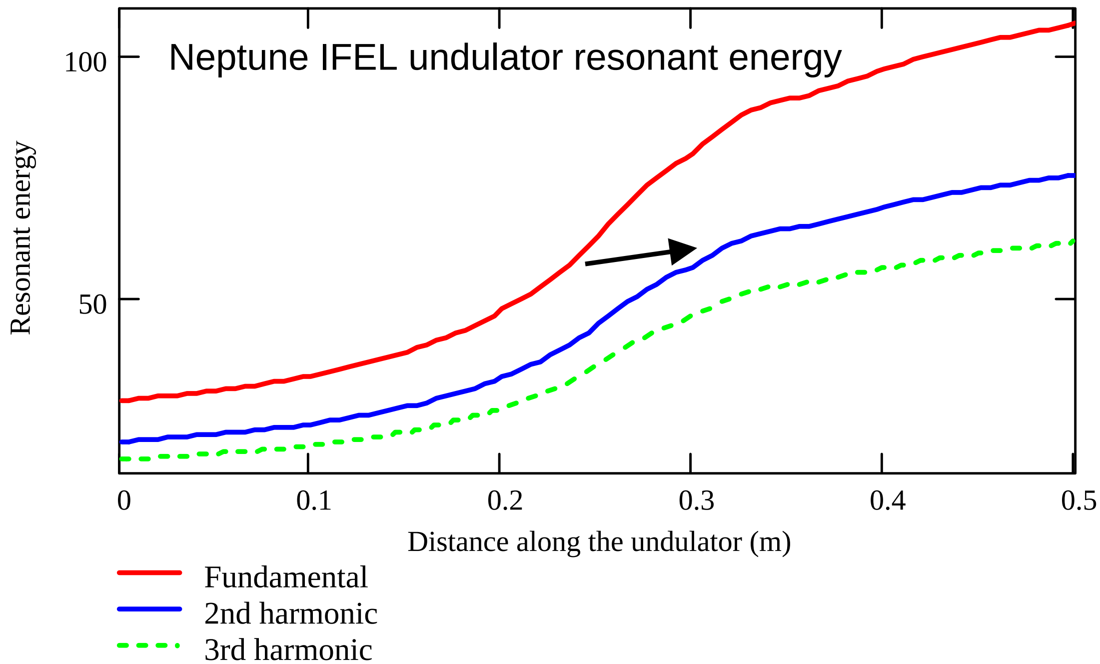
Single shot spectrum (laser on)



Where are the energy peaks coming from?

Resonant conditions for energy transfer between particles and e.m. 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 red 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 μm photons through second harmonic coupling !!!

Higher Harmonic IFEL theory

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

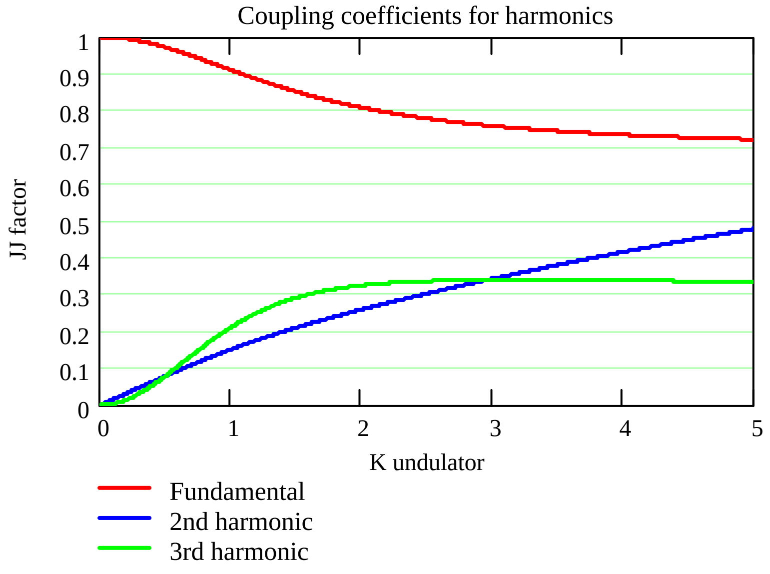
$$JJ_n(K) = \sum_{m=-\infty}^{\infty} J_m\left(\xi(K)\right) \cdot \left(J_{2m+n+2}\left(\sigma(K)\right) + J_{2m+n}\left(\sigma(K)\right)\right)$$

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

The even harmonics are coupled through the diffraction angle

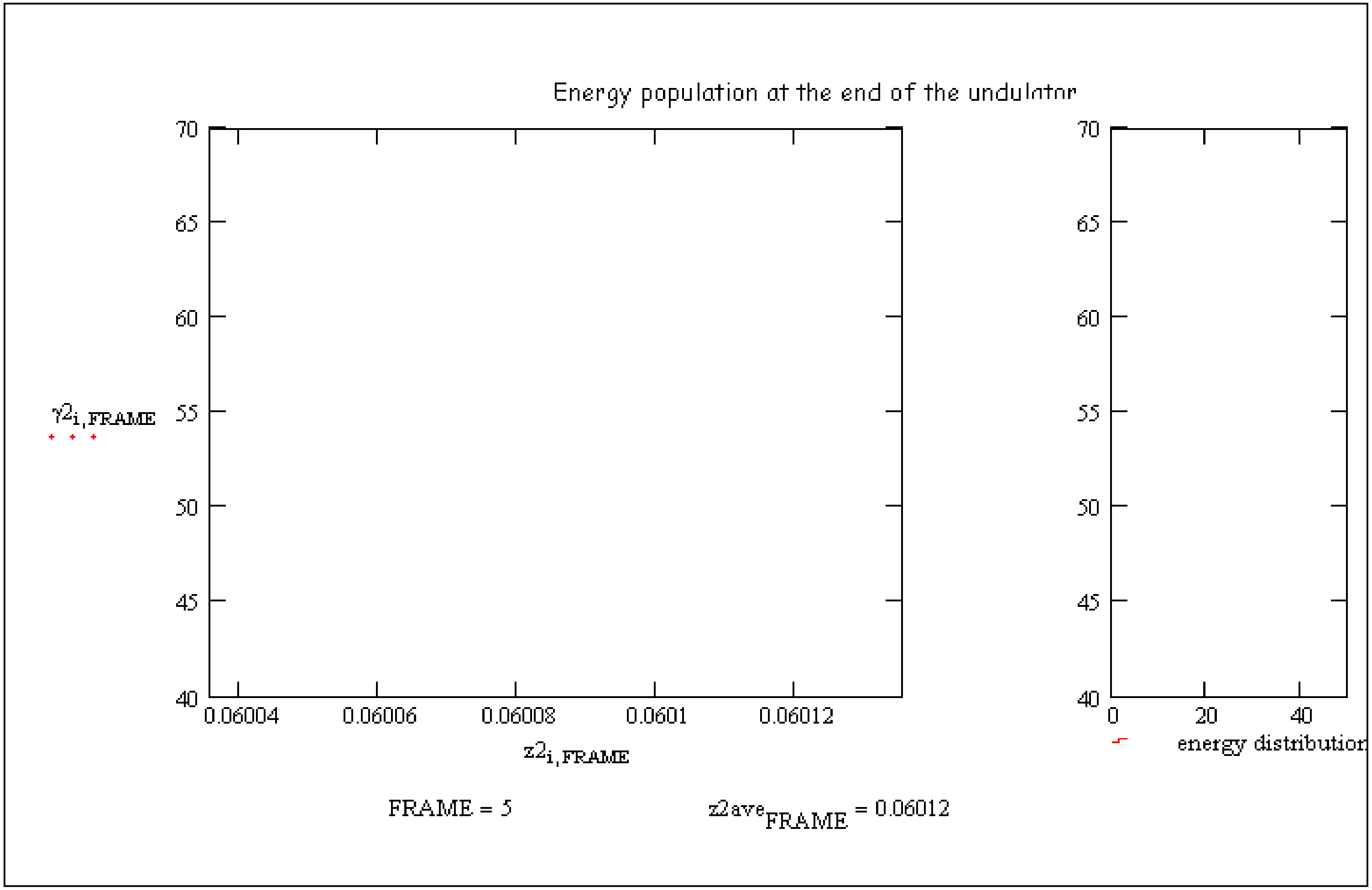
In the limit $\sigma(K) \rightarrow 0$ we found the known result for odd harmonics

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



3d simulation

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



Summary & Conclusion

- 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