ANALYSIS OF THE PROCESS OF AMPLIFICATION IN A SINGLE PASS FEL OF HIGH ORDER HARMONICS GENERATED IN GAS

L. Giannessi, M. Quattromini, ENEA C.R. Frascati, Italy

P. Musumeci, INFN Sez. Roma I, Roma, Italy

G. Sansone, S. Stagira, M. Nisoli e S. De Silvestri, Politecnico di Milano, Italy

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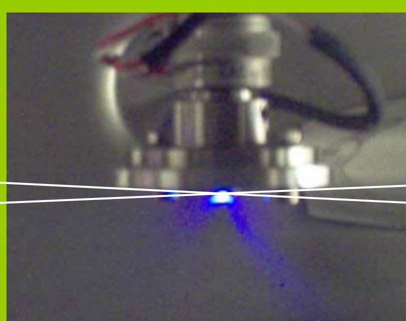
OUTLINE

"Start to end" SIMULATION from the FIELDS point of view

1

Harmonic generation



2

Matching to the FEL

- Optically
- Numerically

3

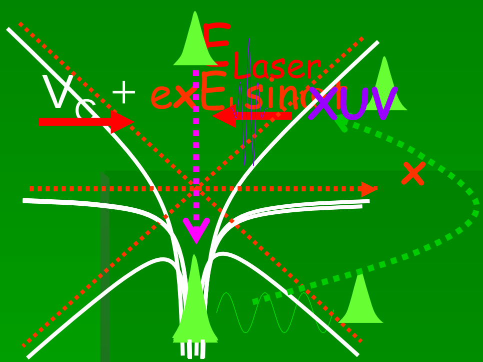
FEL Amplification
(GENESIS 1.3)

SINGLE PASS FEL

Picture taken at CEA during preliminary tests of the SPARC HHG chamber, SEE Tcherbakoff et al., MOPPH047

Temporal-spectral structure of XUV emission

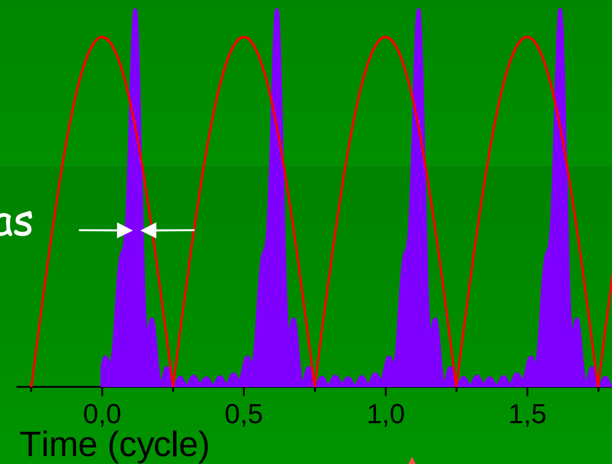
- "Three-step" model



2: Acceleration in the laser field

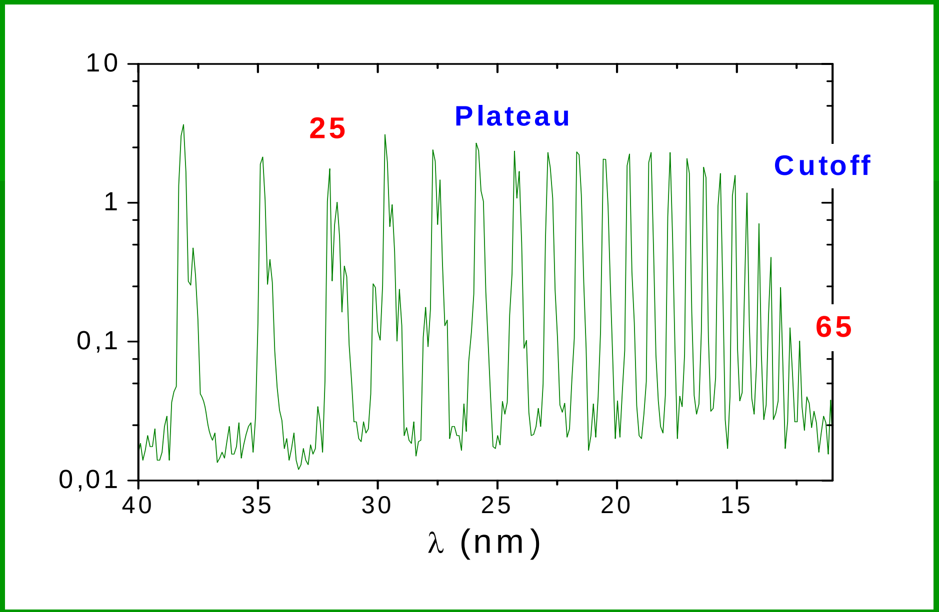
- Multi-cycle laser pulse

Mairesse et al. SCIENCE (2003)



Train of XUV "atto" pulses

Discrete odd harmonics



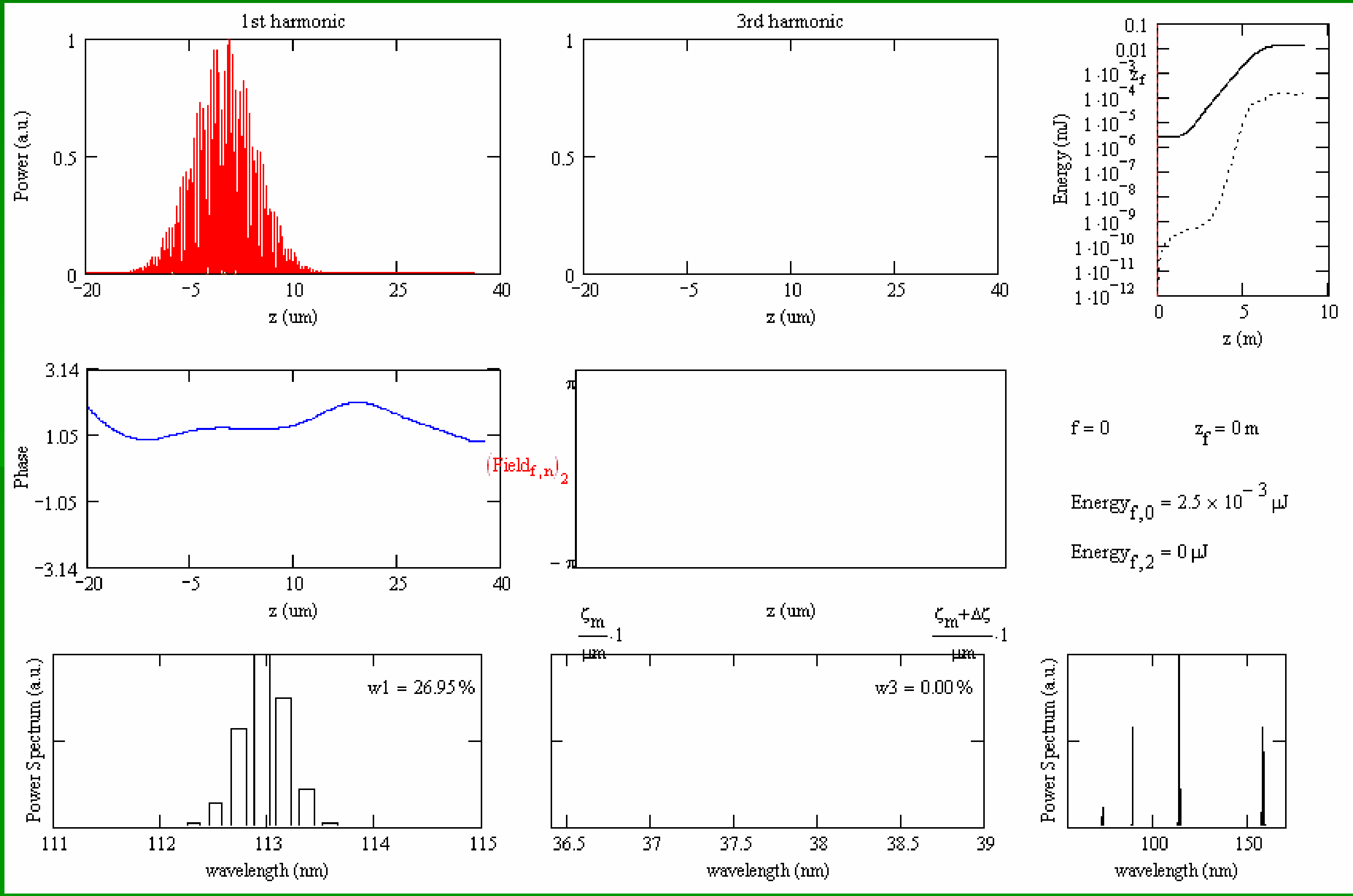
Waterwindow [4.4 – 2.7nm]
He, order ~300

Chang et al. *PRL* (1997)
Spielmann et al. *Science* (1997)

Courtesy of Bertrand Carrè

SPARC FEL seeded @114nm

- Ideal Field: superposition of Gaussian distributions shifted in z by half of the Ti:Sa wavelength
- 1D simulation (Perseo)



3-D Numerical propagation code

- **Single atom response**
  - ⇒ **Lewenstein model generalized to non adiabatic effects**

    (M. Lewenstein *et al.*, Phys. Rev. A **49**, 2117 (1994))
  - ⇒ **Non-linear dipole moment $x_{NL}(r,z,t)$**

- **Ionization effects and ground state depletion**
  - ⇒ **ADK model: free electron density $n_e(r,z,t)$**

- **Propagation of the fundamental field E_f**

$$\Delta_\perp E_f(r,z',t') - \frac{2}{c}\frac{\partial^2 E_f(r,z',t')}{\partial z'\,\partial t'} = \frac{\omega_p^2(r,z',t')}{c^2} E_f(r,z',t')$$

- **Harmonic field E_h**

$$\Delta_\perp E_h(r,z',t') - \frac{2}{c}\frac{\partial^2 E_h(r,z',t')}{\partial z'\,\partial t'} = \mu_0 \frac{\partial^2 P_{nl}(r,z',t')}{\partial z'\,\partial t'}$$

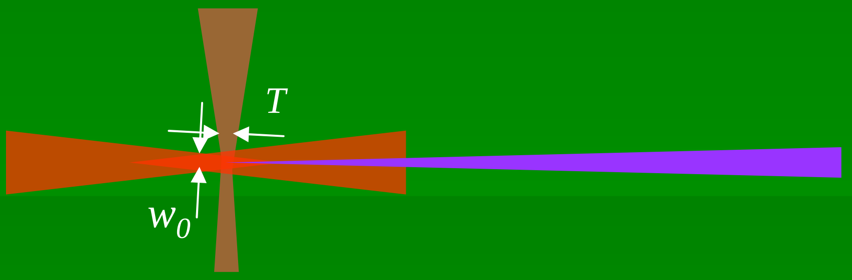
- **Power spectrum of harmonic field E_h**

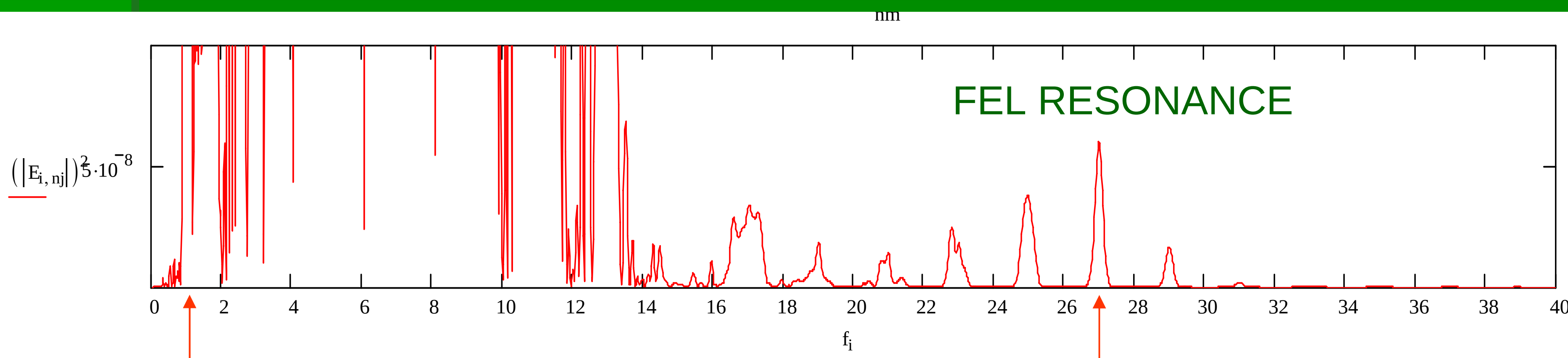
$$I_h(\omega) \propto \int_0^\infty |\mathrm{E}_h(r, z_{out}, \omega)|^2\, 2\pi r\, dr$$

E. Priori *et al*., Phys. Rev. A 61, 63801 (2000)

Harmonics spectrum on axis

Pulse duration	30 fs
Peak intensity	10^{14} W/cm^2
Waist	w_0 = 50µm
Geometry	3mm before Ne gas jet, thickness T = 1 mm





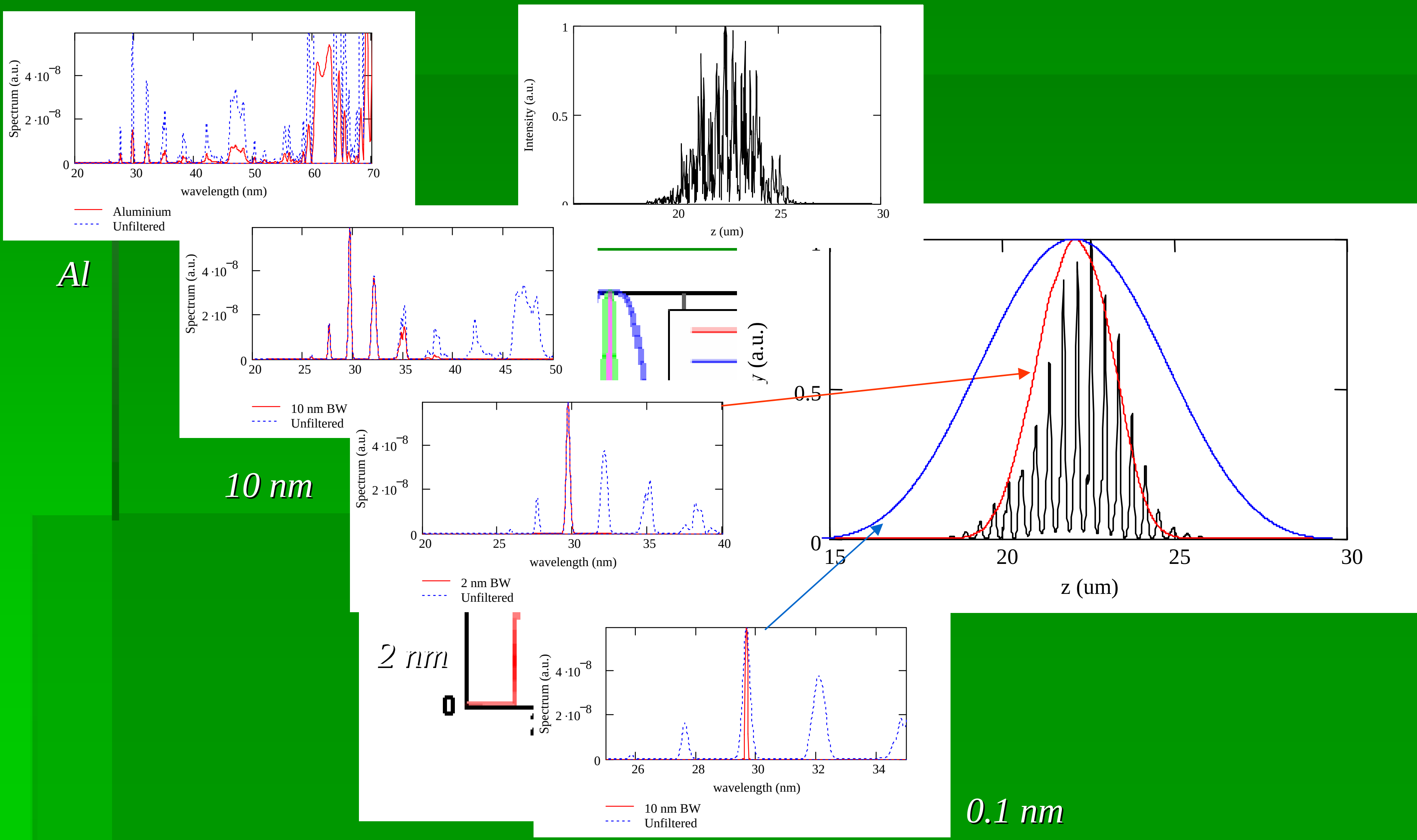
800 nm

FEL central wavelength λ_0~29.7 nm

Output data obtained without the Slowly Varying Envelope Approximation (SVEA). In order to load in GENESIS:

- Filter in bandwidth around λ_0
- Multiply by a phase factor exp($-i2\pi z/\lambda_0$)

Effect of frequency filtering



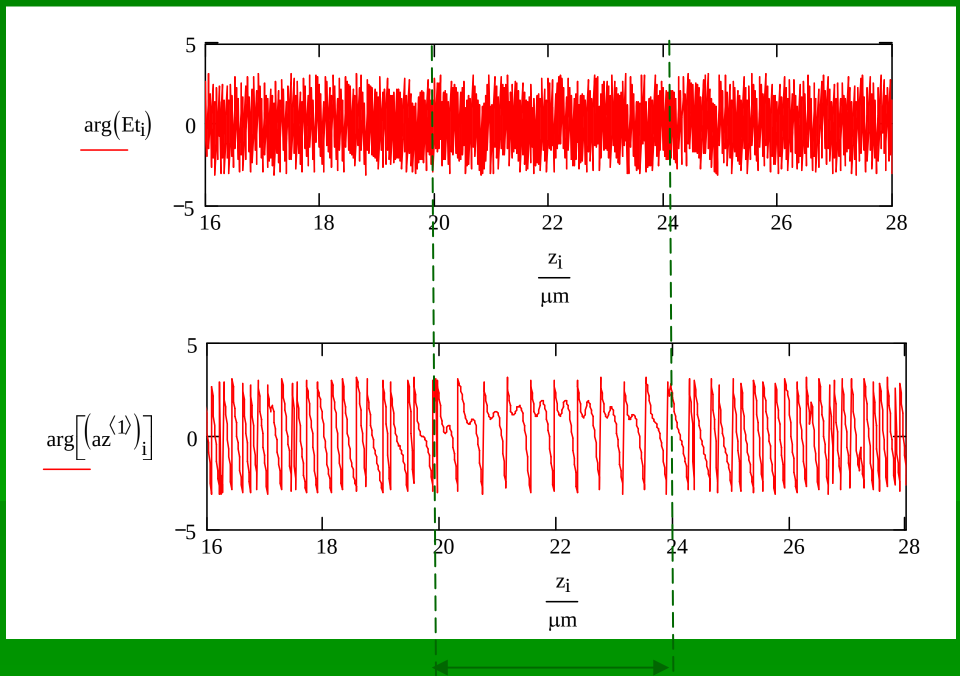
SVEA

Phase vs. longitudinal coordinate along the e-bunch

Field data

“Slow” field component

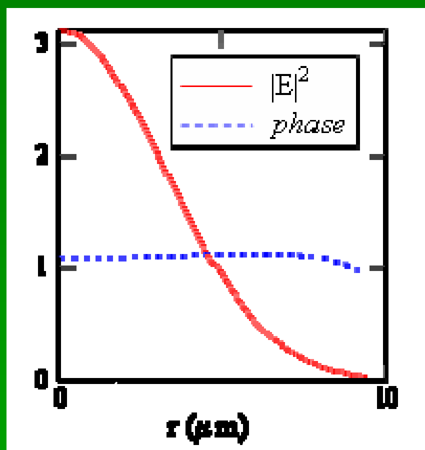
$$a(z) = Et(z)\exp(-ik_0 z)$$

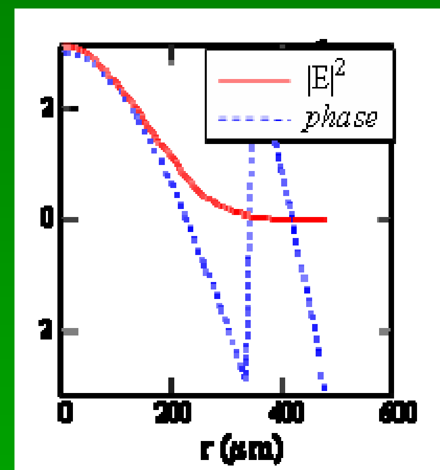


Harmonic pulse position

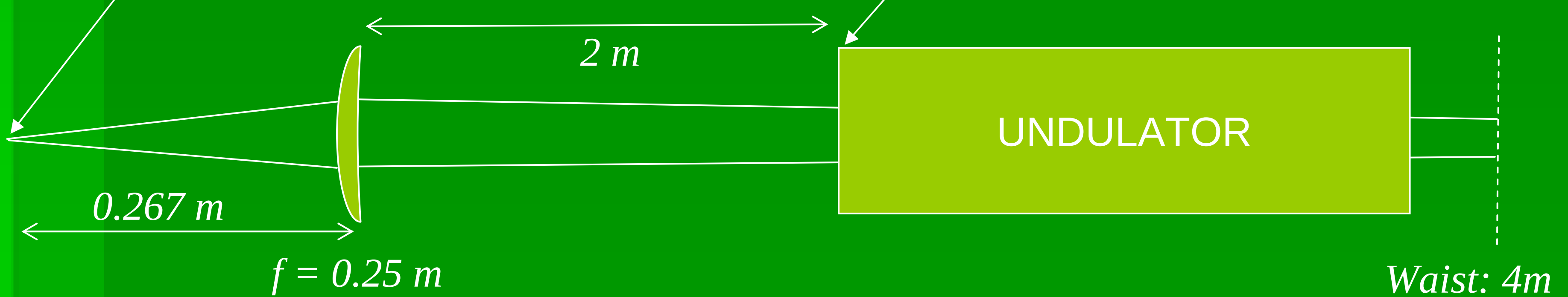
Transverse matching

“average” field and phase at the waist





“average” field and phase at the undulator entrance



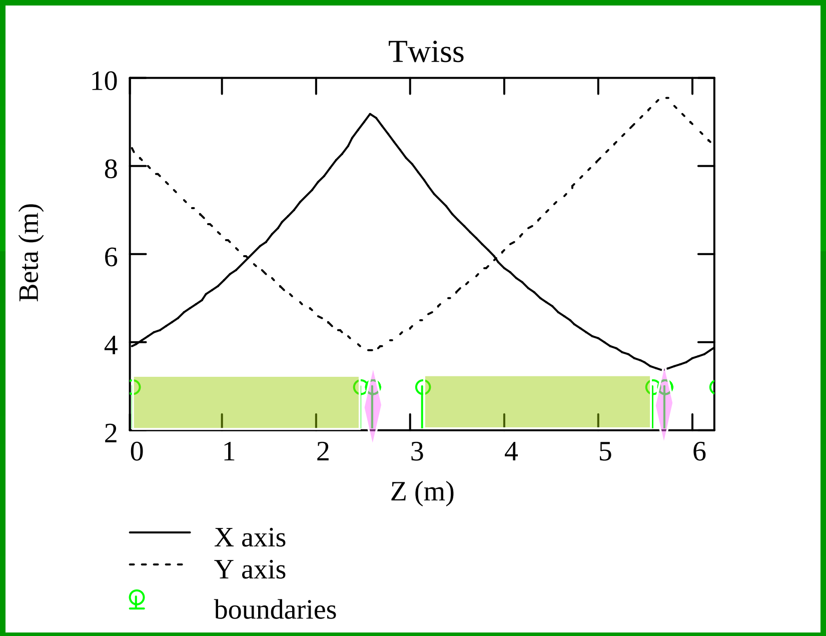
The FEL amplifier

FODO Lattice

… 21 m

FEL parameters

Beam Energy (GeV)	1
Peak current (A)	1000
Energy Spread (%)	0.06
Emittance (mm-mrad)	1
Average β_T (m)	6
Undulator period (cm)	4.2
K (peak)	2.97
Periods per section	58
Sections	7

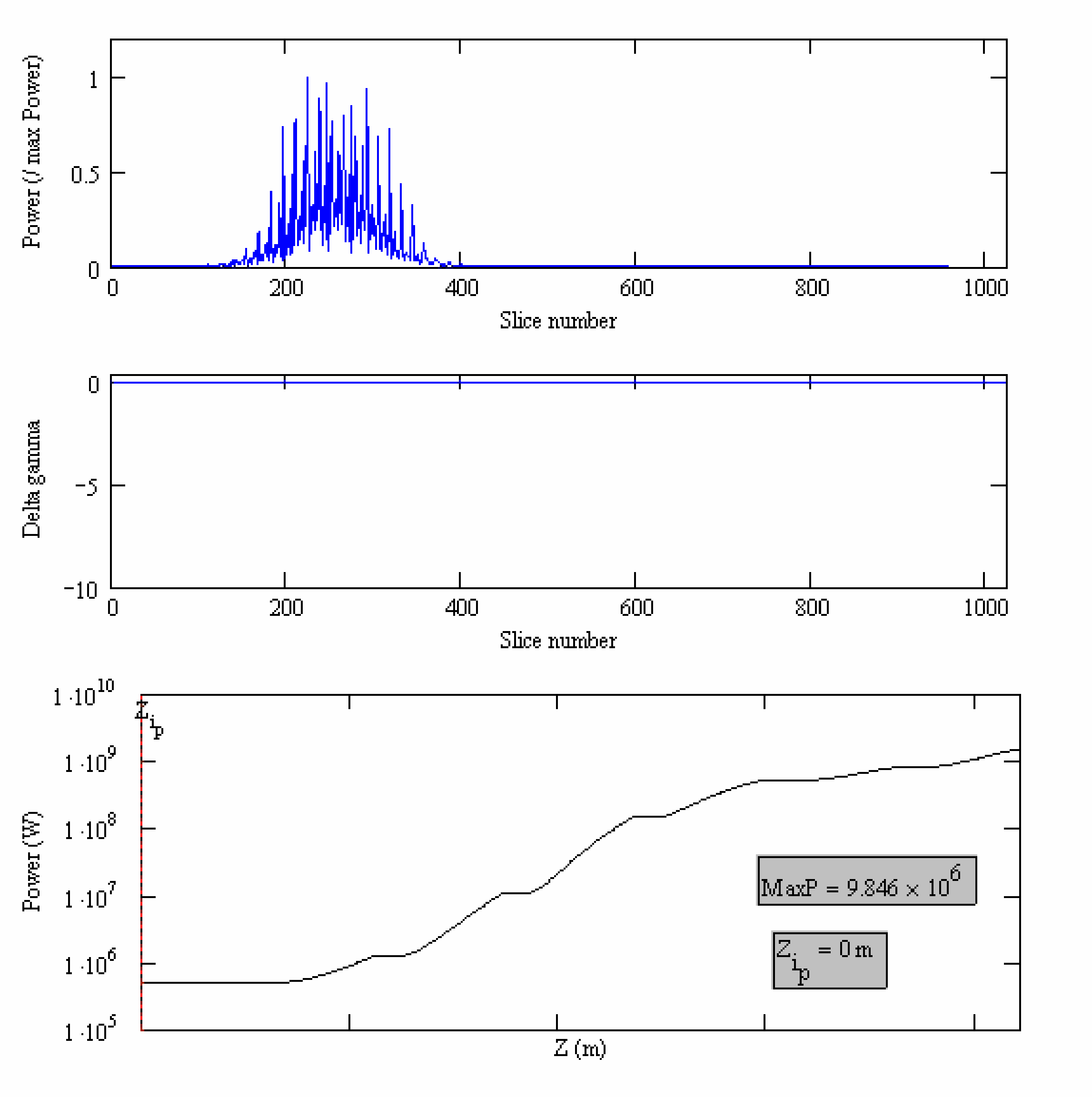


σ_x-σ_y ~ 40 – 60 μm

Aluminium 0.6 μm, broadband (45 nm)

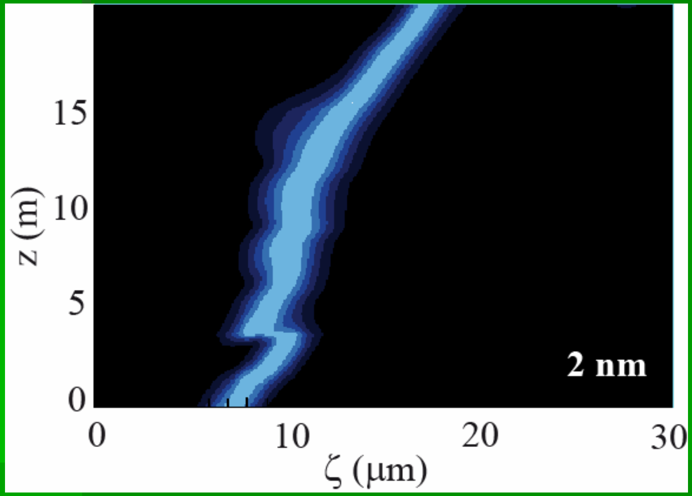
Pulse energy
50 nJ

Energy in 2ρ: 0.8 nJ

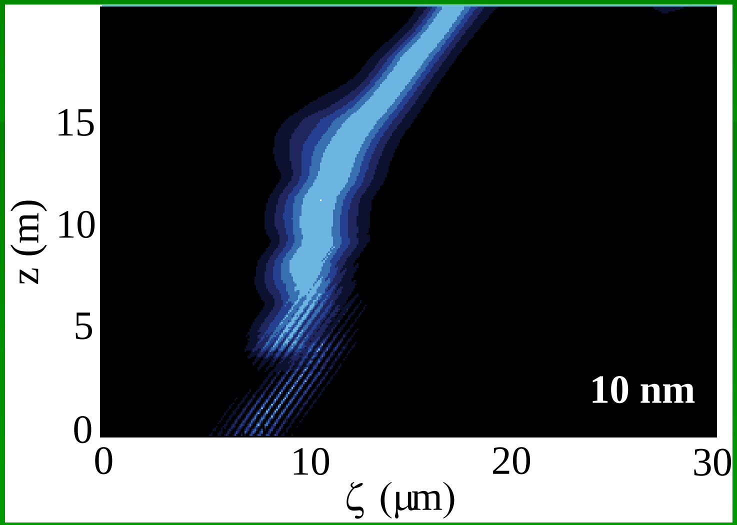


Results at different filter bandwidth

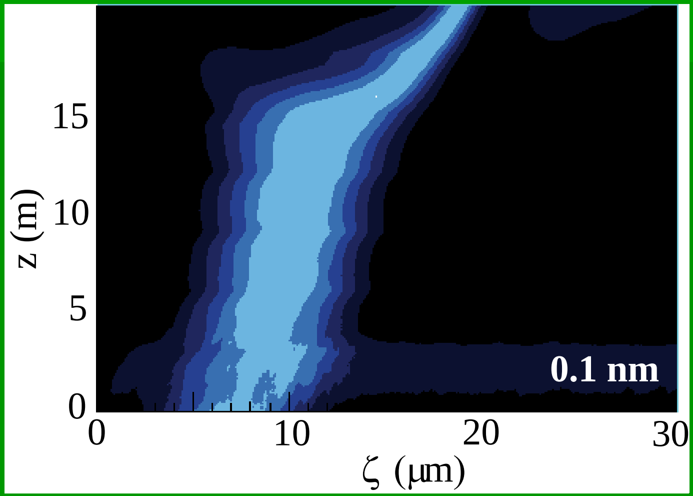
1 nJ, ~0.5 nJ in 2ρ



2.5 nJ, ~0.5 nJ in 2ρ



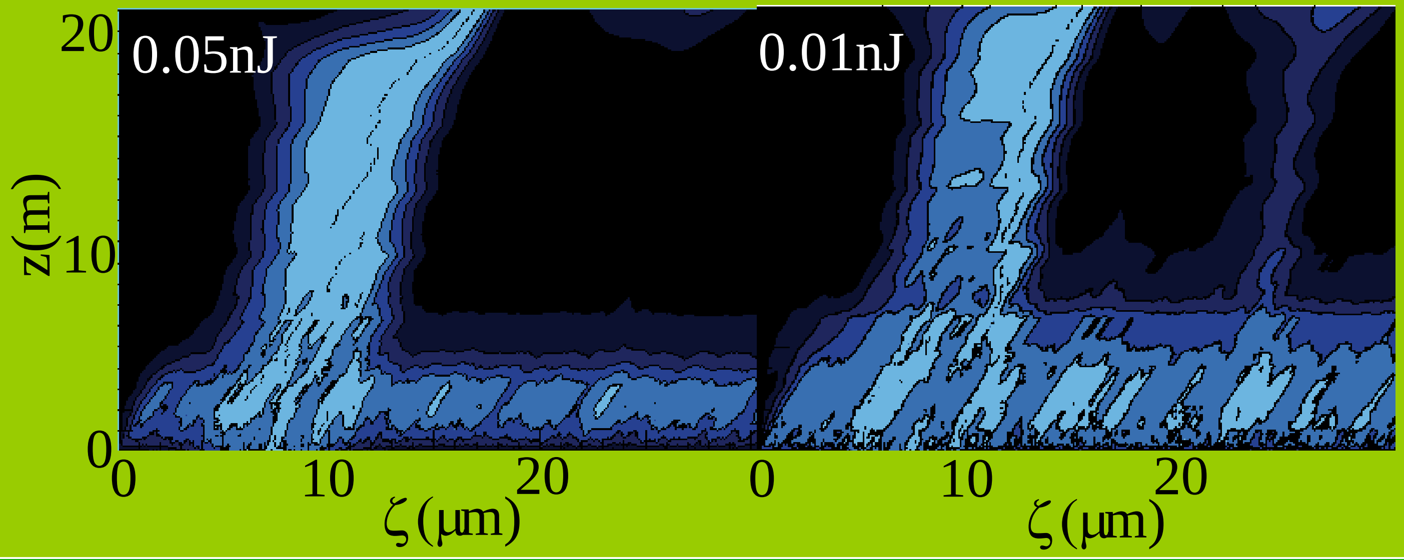
0.5 nJ, ~0.5 nJ in 2ρ



*Threshold for overcoming shot noise**

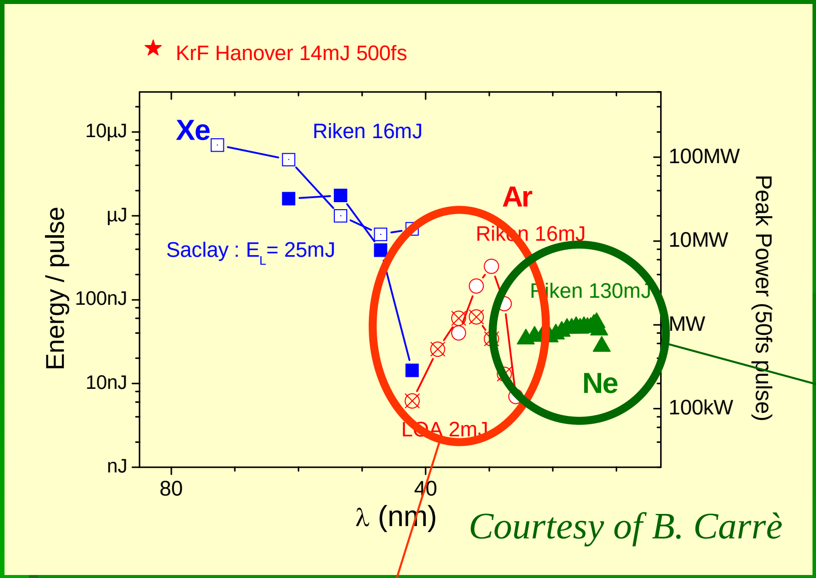
$$I_0 \approx \frac{4}{5}\rho^2\omega_0 \frac{E_{beam}}{\Sigma_b} \approx 300\, kW/cm^2$$

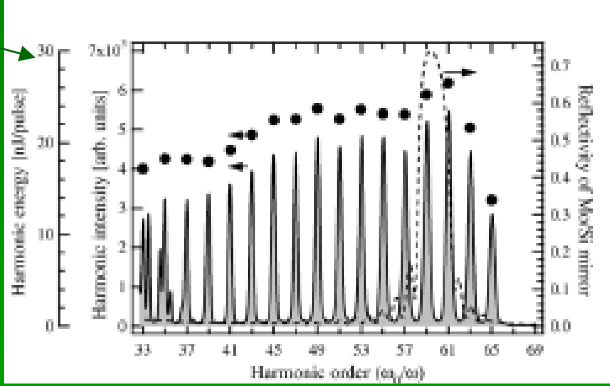
@ threshold, 300 kW/cm² *below threshold,60 kW/cm²*



**L. Giannessi in Proceedings FEL 2004, Trieste*

- *Derived in “ideal” conditions*
- *Checked with 1D simulations in Perseo*





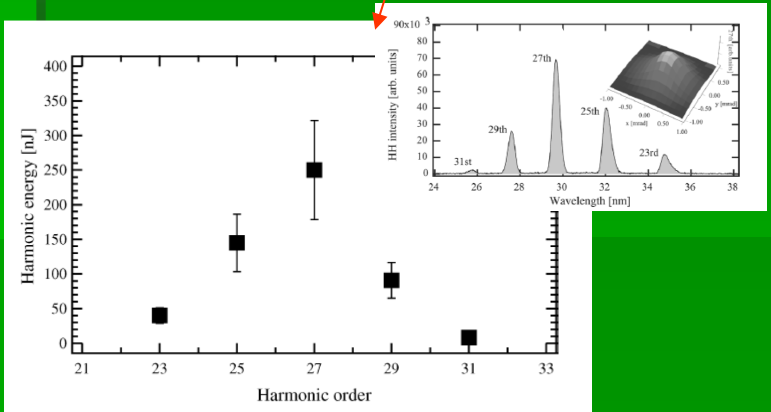


Fig. 3. Harmonic energy yield per shot for a 10-cm medium with 1.8-torr Ar gas.

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Generation of Strong Optical Field in Soft X-Ray Region by Using High-Order Harmonics

Eiji J. Takahashi, Yasuo Nabekawa, Hiroki Mashiko, Hirokazu Hasegawa, Akira Suda, *Member, IEEE*, and Katsumi Midorikawa, *Senior Member, IEEE*

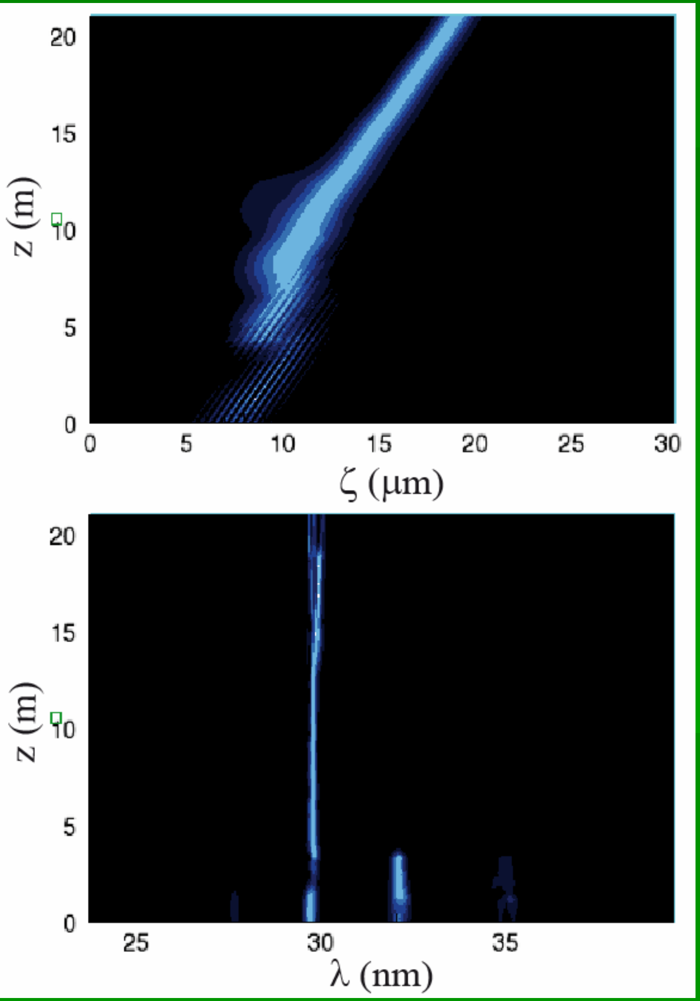
250 nJ @ 27° harmonic – 29.7 nm

25 nJ @ 65° harmonic : 12.3 nm

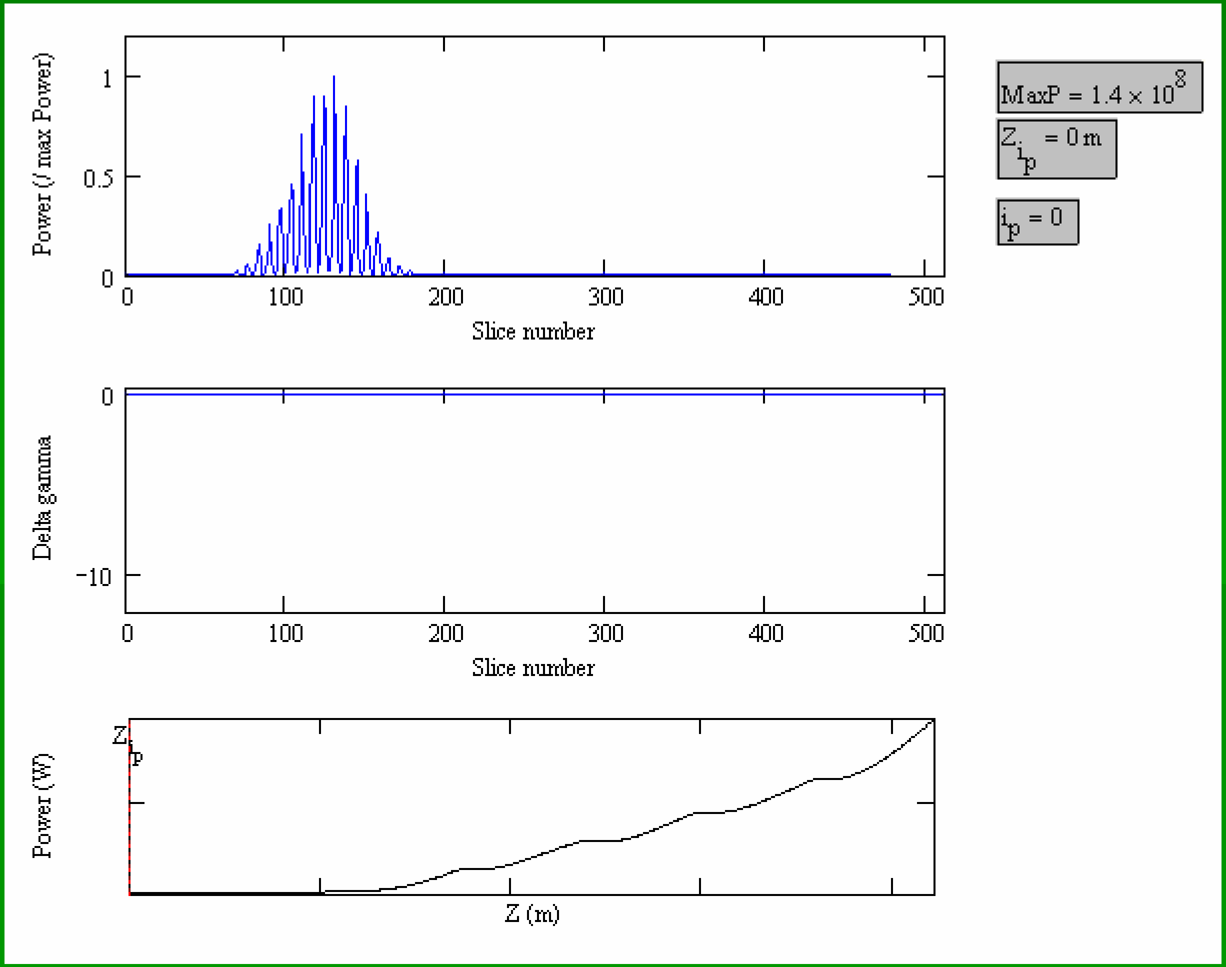
Energy 100 nJ

BW 10 nm

~20 nJ in 2ρ



Energy 100 nJ
BW 10 nm
~20 nJ in 2ρ



Conclusions

Seeding from high order harmonics generated in gas

- *Good transverse coherence properties, no problems in transverse matching with the e-beam*
- *Peculiar longitudinal distribution (naturally filtered by the FEL gain bandwidth)*
- *Additional frequency filtering required for increasing the coherence length*
- *Energy sufficient to seed an FEL @30 nm, and probably also @12nm (short pulses)*
- *Source available down to the water window …*