Life Meeting @ LNF December 9, 2010

SPARC FEL Experiments

Luca Giannessi
ENEA C.R. Frascati

On behalf of the SPARC collaboration

Ministero dell'Università e della Ricerca

Consiglio Nazionale delle Ricerche

ENEA C.R. Frascati

INFN Istituto Nazionale di Fisica Nucleare

Tor Vergata

PBPL Particle Beam Physics Laboratory

cea

elettra Synchrotron Light Laboratory

Laboratory for UV and X-ray Optical Research LUXOR CNR-INFM

SOLEIL SYNCHROTRON

SPARC

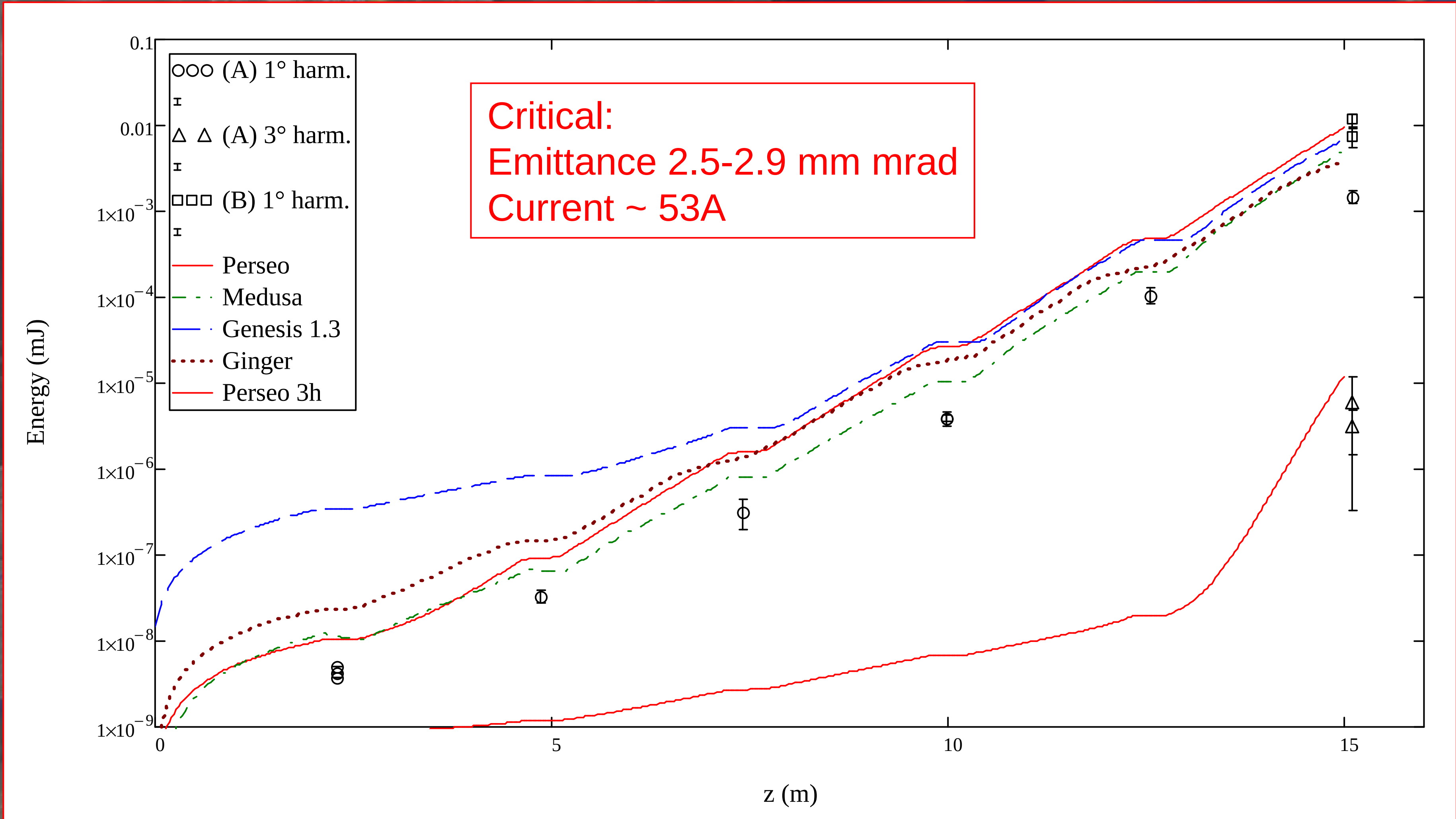
Contributors

A. Petralia, G. Dattoli, F. Ciocci, M. Del Franco, M. Quattromini, C. Ronsivalle, E. Sabia, I. Spassovsky, V. Surrenti ENEA C.R. Frascati, IT. D. Filippetto, G. Di Pirro, G. Gatti, M. Bellaveglia, R. Boni, D. Alesini, M. Castellano, E. Chiadroni, L. Cultrera, M. Ferrario, L. Ficcadenti, A. Gallo, A, Ghigo, N. Marchetti, E. Pace, B. Spataro, C. Vaccarezza, INFN-LNF, IT. A. Bacci, V. Petrillo, A.R. Rossi, L. Serafini INFN-MI, IT. M. Serluca, M. Moreno INFN-Roma I, IT. L. Poletto, F. Frassetto CNR-IFN, IT. J.V. Rau, V. Rossi Albertini ISM-CNR, IT. A. Cianchi, UN-Roma II TV, IT. A. Mostacci, M Migliorati, L. Palumbo, Un. Roma La Sapienza, IT. G. Marcus, P. Musumeci, J. Rosenzweig, UCLA, CA, USA. S. Spampinati, ST, IT, M. Labat, F. Briquez, M. E. Couprie, SOLEIL, FR. B. Carré, M. Bougeard, D. Garzella CEA Saclay, DSM/DRECAM, FR. G. Lambert LOA, FR. S. Reiche, C.Vicario PSI, CH.

FEL Experiments in 2010

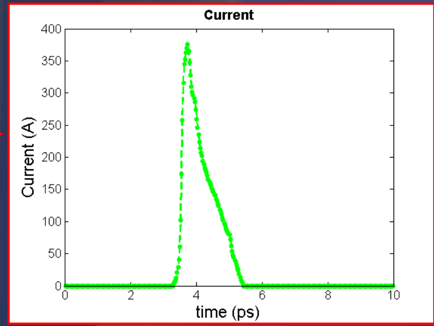
- SASE
  - FEL Comb – Simultaneous lasing of two FEL pulses
  - Lasing with chirped beam combined with tapered undulator
- Seeded
  - Seeded amplifier with the generation of high order harmonics
  - Cascaded FEL operating above saturation 400nm -> 200nm
  - FEL seeded with harmonics generated in gas
  - Cascaded FEL seeded with harmonics generated in gas

SASE – 24.07.2009

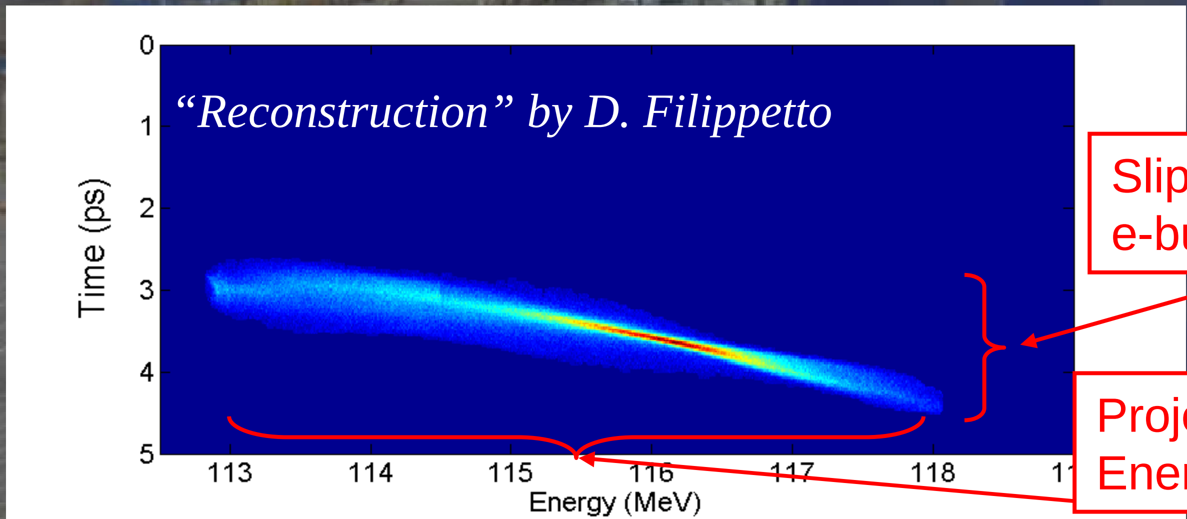


SASE with chirped & compressed beam

- Compression with “Velocity Bunching”
  - High peak current (up to 380A)



Strong chirp / energy spread in the longitudinal phase space

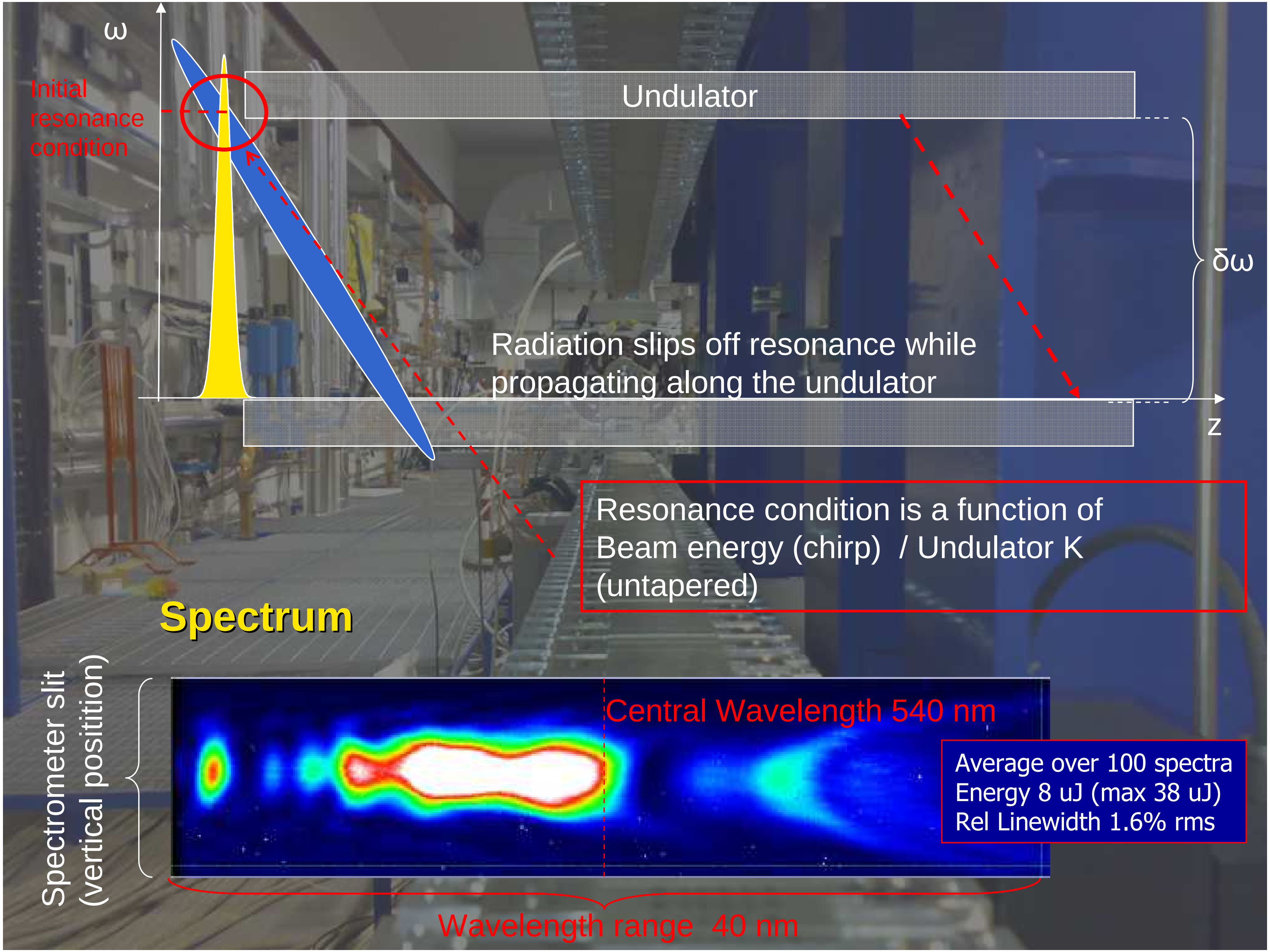


Slippage length ~ e-bunch length

Projected r.m.s. Energy spread ~ 1%

Compensation of the chirp with UM Taper

E. L. Saldin, E. A. Schneidmiller, and M.V. Yurkov, Self-amplified spontaneous emission FEL with energy-chirped electron beam and its application for generation of attosecond x-ray pulses, PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 9, 050702 (2006)


ω
Initial resonance condition
Undulator
δω
Radiation slips off resonance while propagating along the undulator
z
Resonance condition is a function of
Beam energy (chirp) / Undulator K
(untapered)
Spectrum
Spectrometer slit
(vertical posititon)
Central Wavelength 540 nm
Average over 100 spectra
Energy 8 uJ (max 38 uJ)
Rel Linewidth 1.6% rms
Wavelength range 40 nm

Compensation with Undulator taper

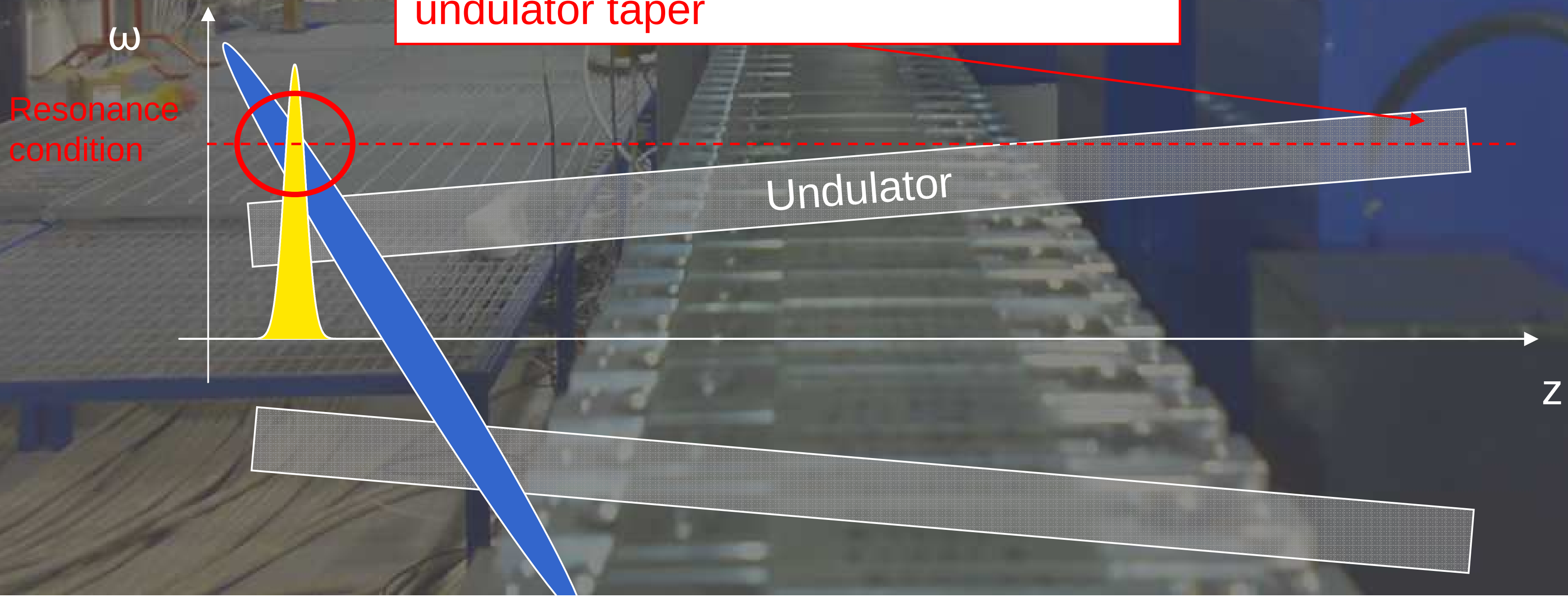
$$\omega_r = \frac{2\gamma^2}{1+\frac{K^2}{2}}\omega_u$$

$$\omega_u = \frac{2\pi c}{\lambda_u}$$

Chirp $\bar{\gamma} = \bar{\gamma}(s) = \gamma_0 + \alpha(s - s_0)$

Taper $K = K(z) = K_0 + \alpha_k(z - z_0)$

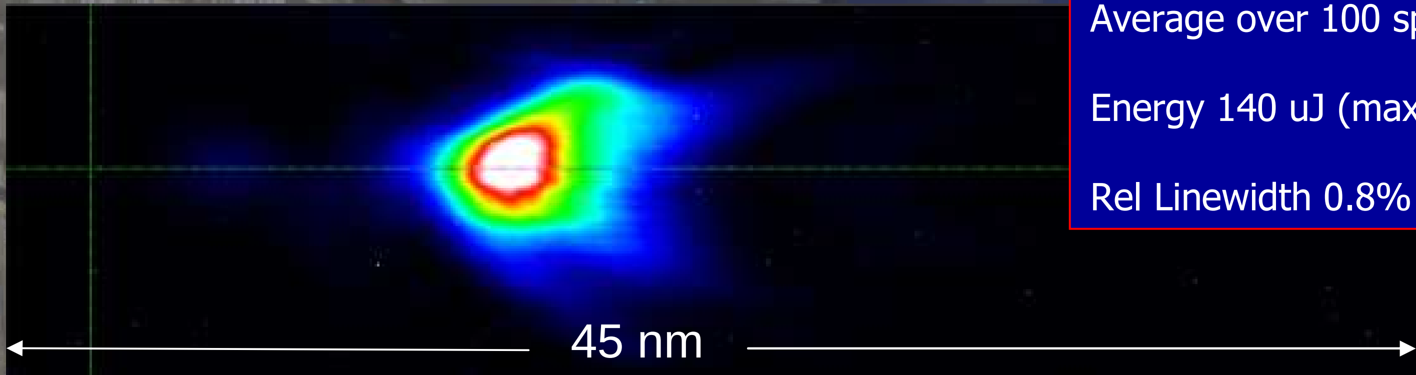
Resonance is maintained by tuning the undulator taper



Average over 100 spectra:

Energy 140 uJ (max 380 uJ)

Rel Linewidth 0.8% rms

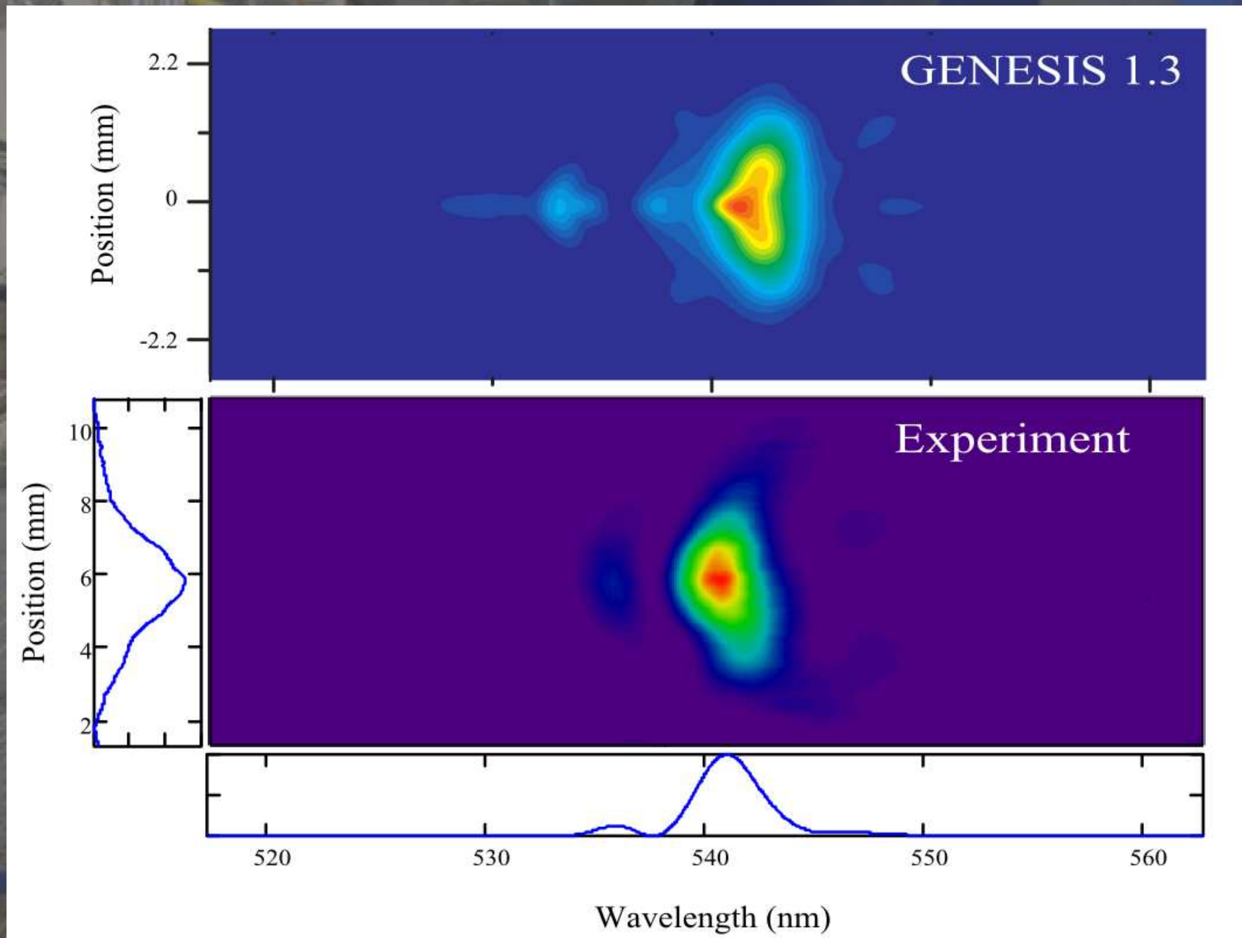


Single cooperation length observed in many spectra (as the one shown above)

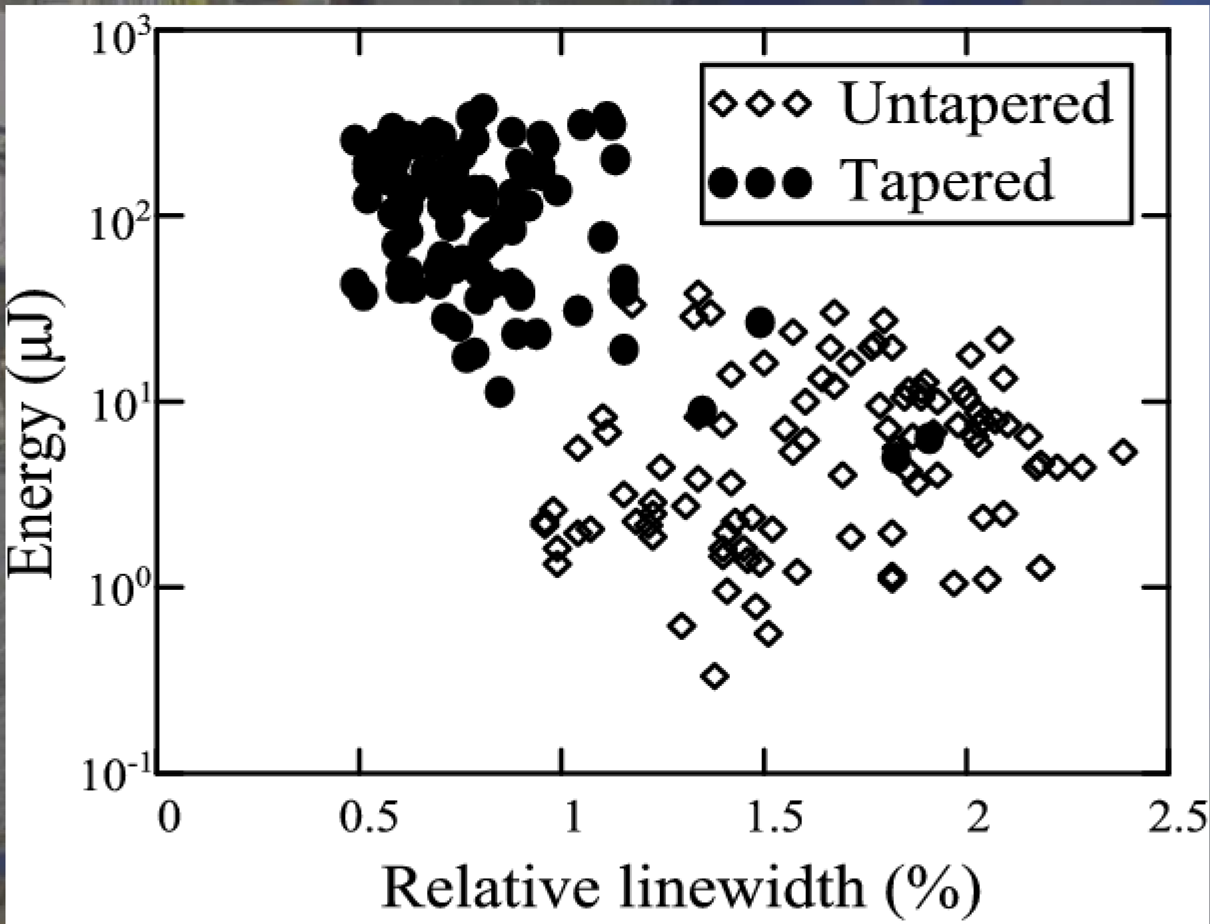
Average energy per pulse 18 times higher !!!

… in a narrower bandwidth (~1/2)

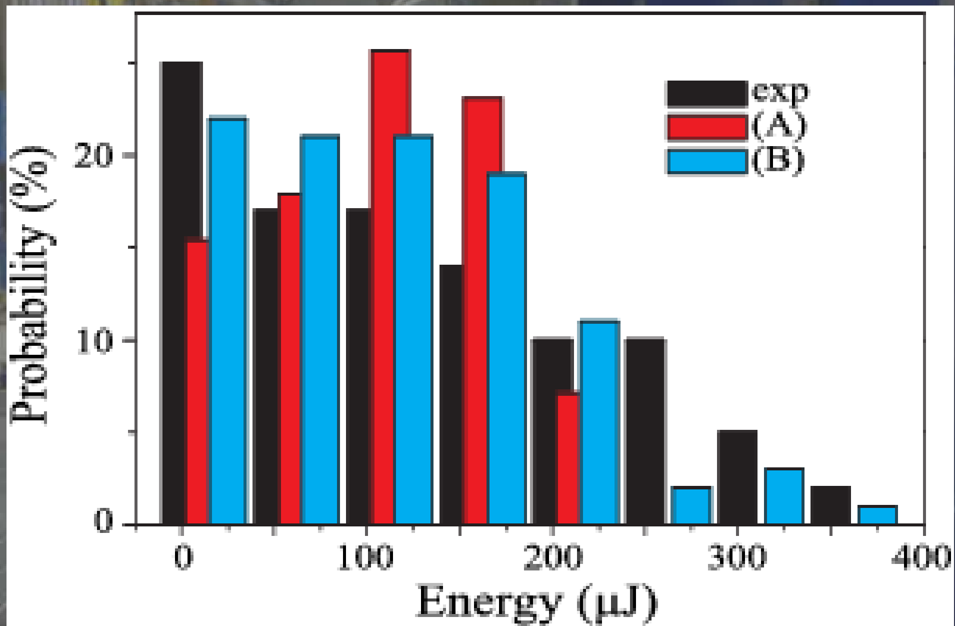
Comparison with GENESIS 1.3 simulations (1)



Comparison with GENESIS 1.3 simulations (2)



Comparison with GENESIS 1.3 simulations (3)



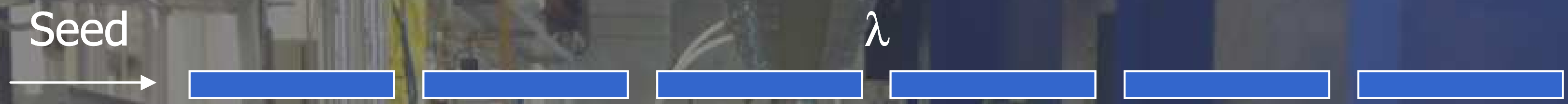
Experiment

Simulation including Jitter in phase/length/current/

Simulation including Jitter in phase/length/current/energy spread/emittances

Seeded Operation

FEL Amplifier



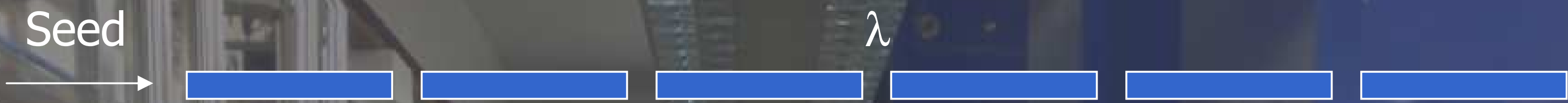
FEL Harmonic Generation

- Seed Sources:

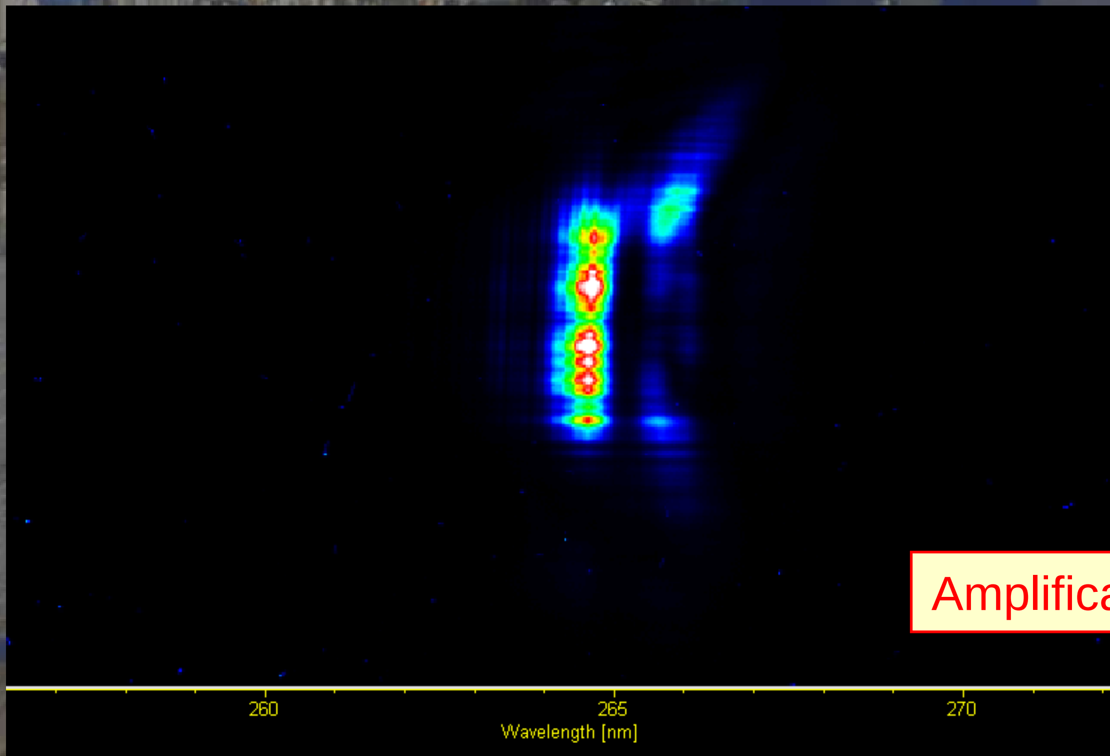
  - 400 nm in BBO crystal (high seed energy)
  - 266 nm & 160 nm generated in gas

Cascaded FEL tested with both seed configurations

FEL Amplifier

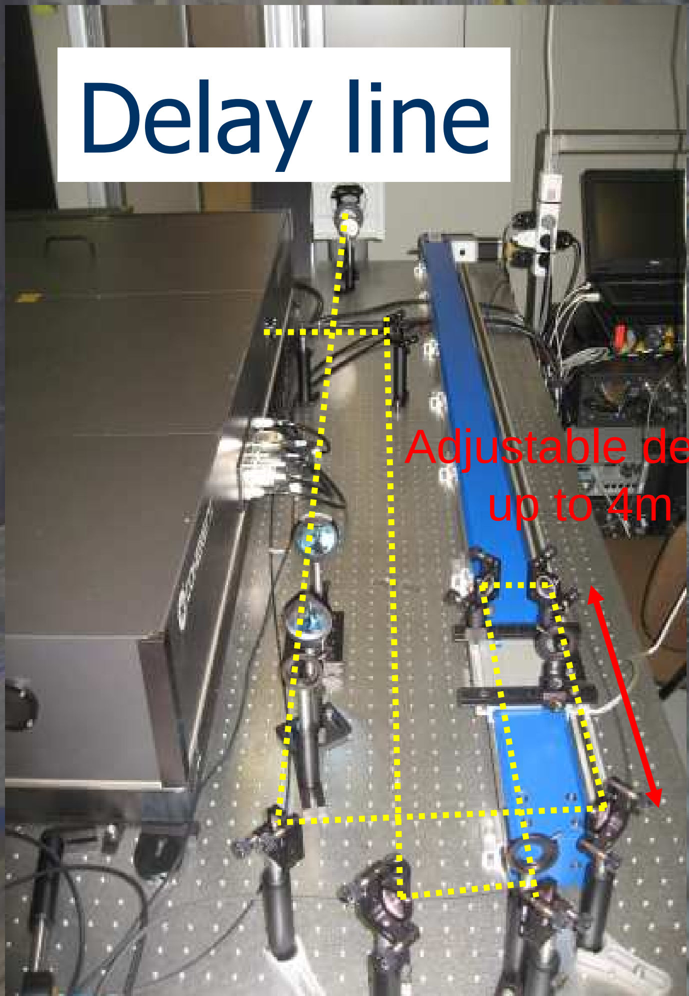


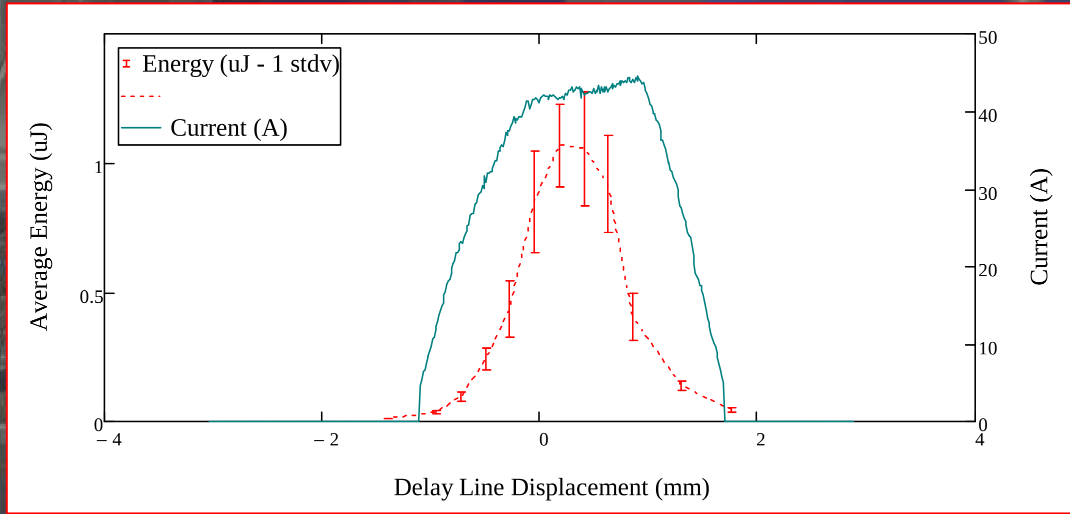
Seed @ 266 nm generated in Ar, ~50 nJ (±20nJ)
6 UM 266 nm
Spectrometer slit @ 5 um - CCD saturated with nb filter @ 266nm, 17% T

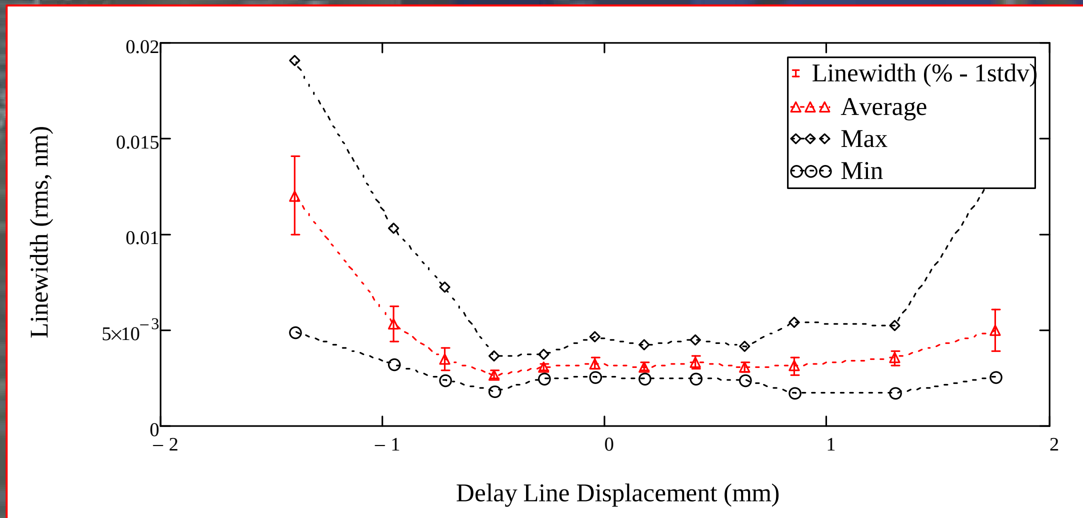


Amplification ≈ 20x

Delay line Scan



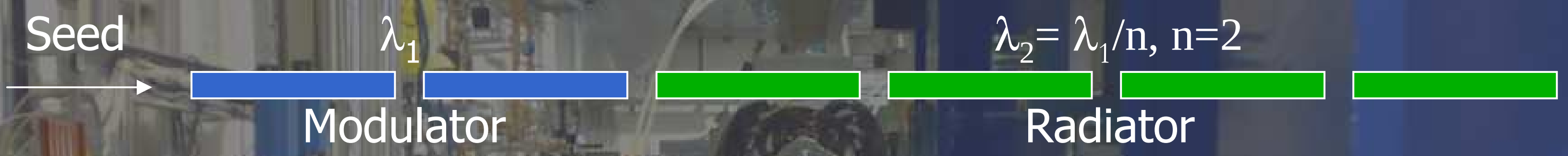


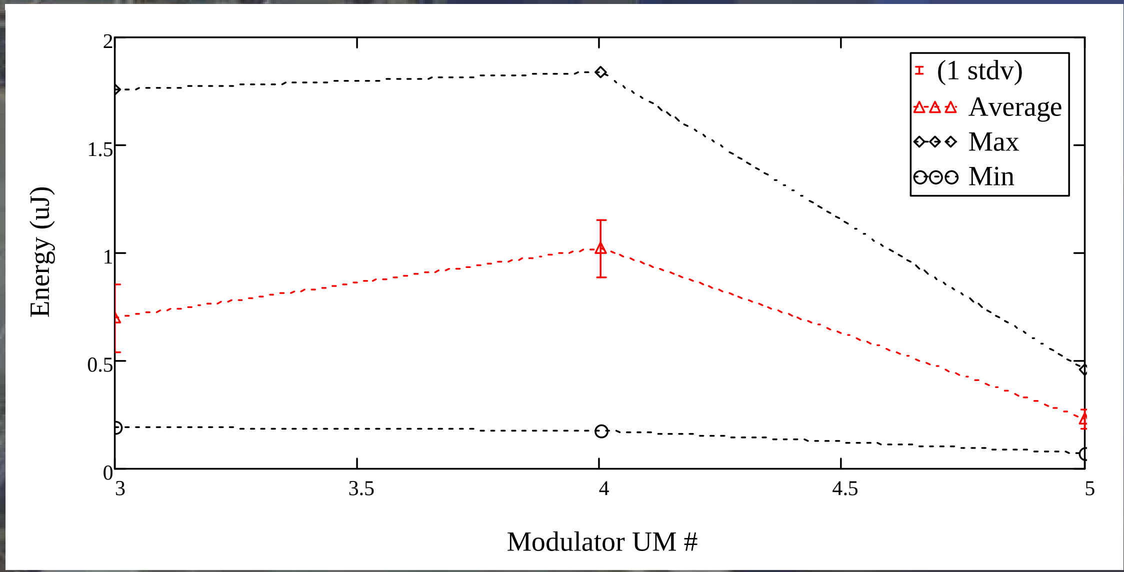


Cascaded FEL

- Seed @ 266 nm, 50 nJ 5-4-3 UM tuned @ 266 nm – 1-2-3 UM tuned @133 nm

FEL Harmonic Generation

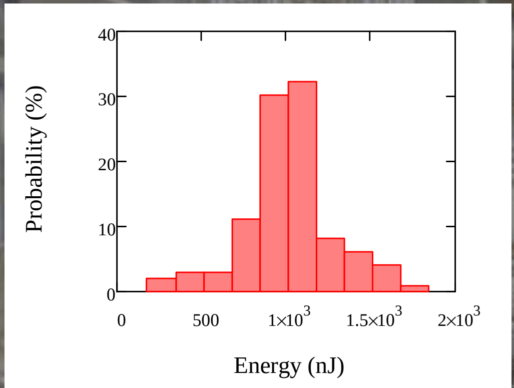


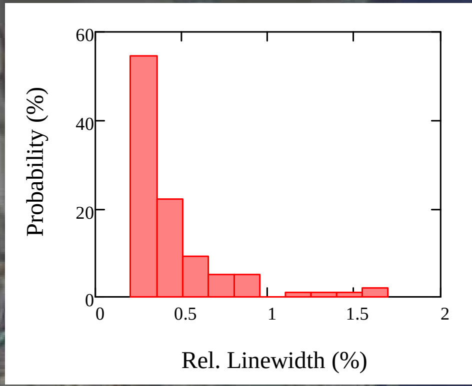


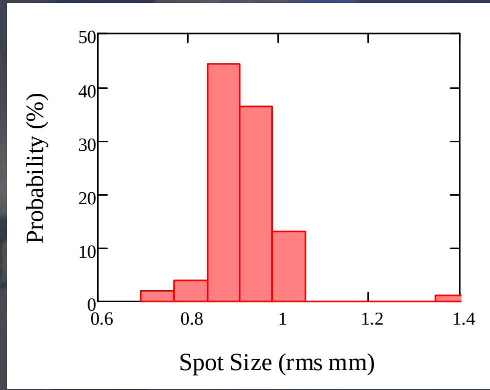
FEL Harmonic Generation

Seed λ_1 $\lambda_2 = \lambda_1/n$, n=2

Modulator Radiator



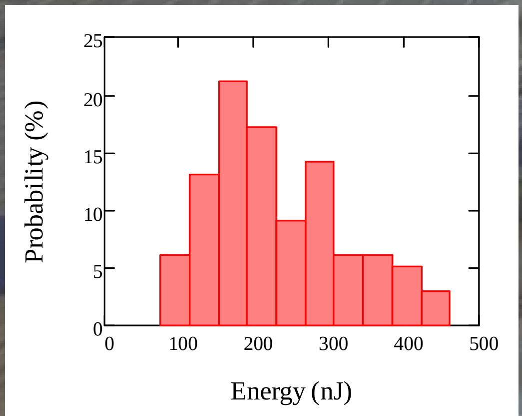


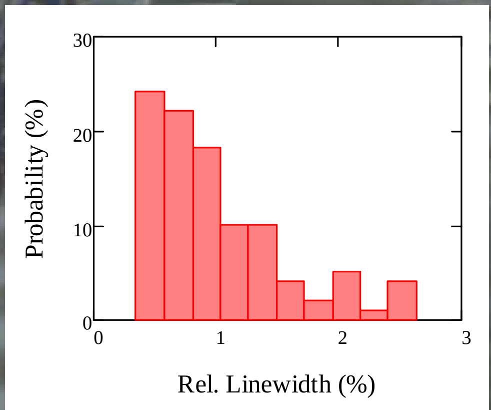


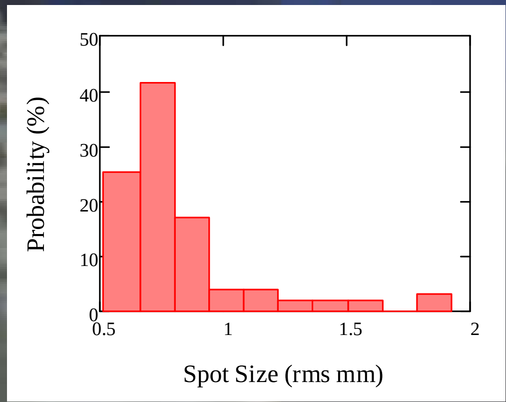
FEL Harmonic Generation

Seed λ_1 $\lambda_2 = \lambda_1/n$, n=2

Modulator Radiator

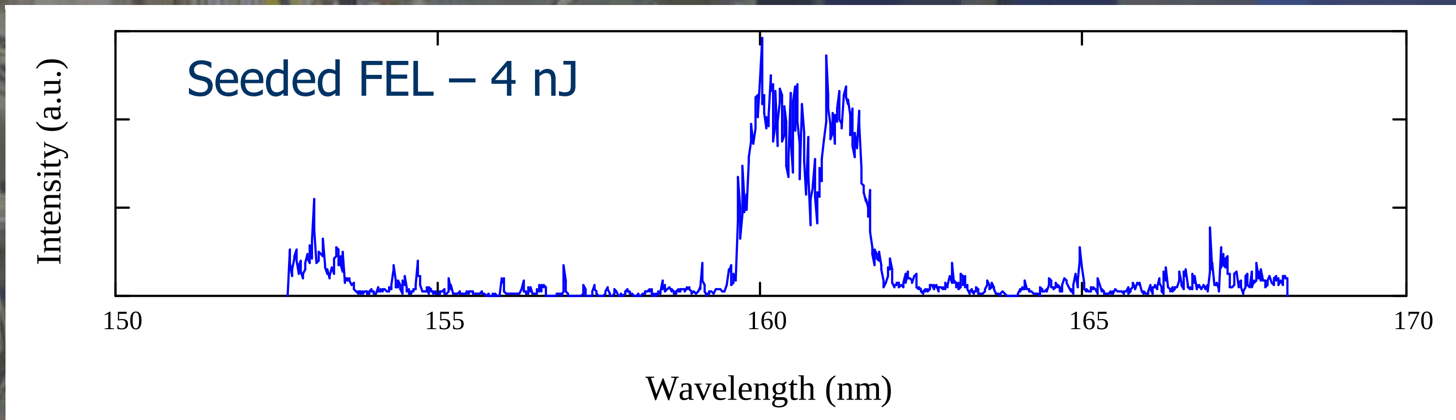




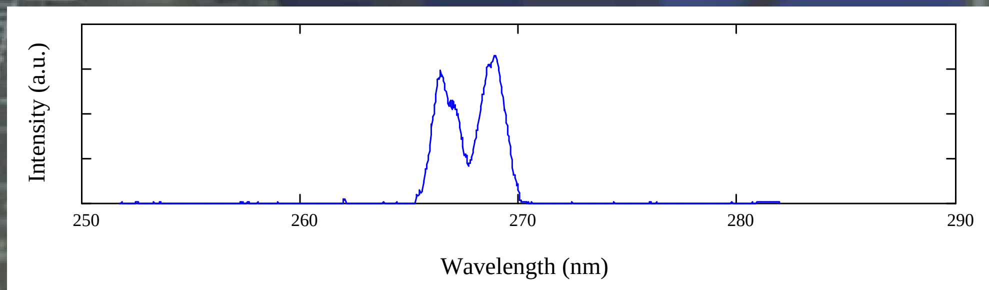


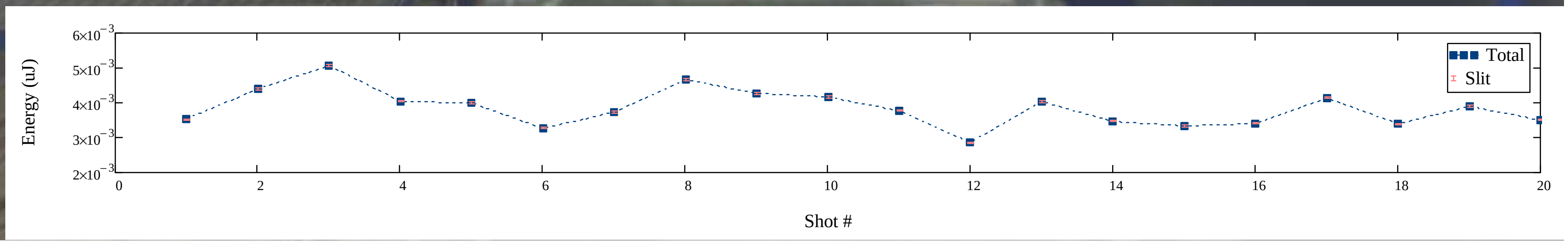
(2010/06/04) Seed @ 160nm

- Seed intensity & SASE too low to be detected at the spectrometer (< 1 nJ)

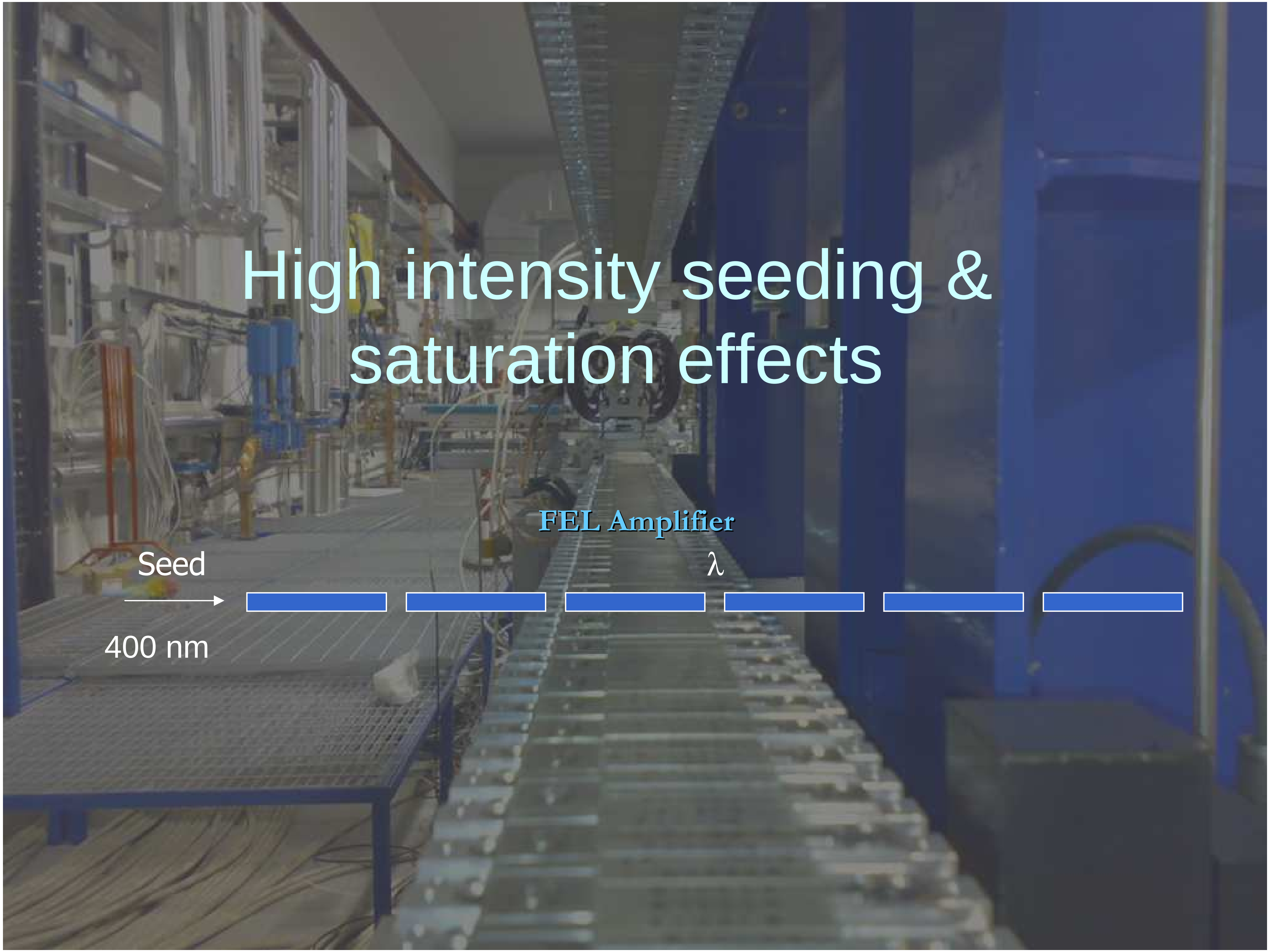


The seed @ 266 measured 1 day before shows the same double peak structure

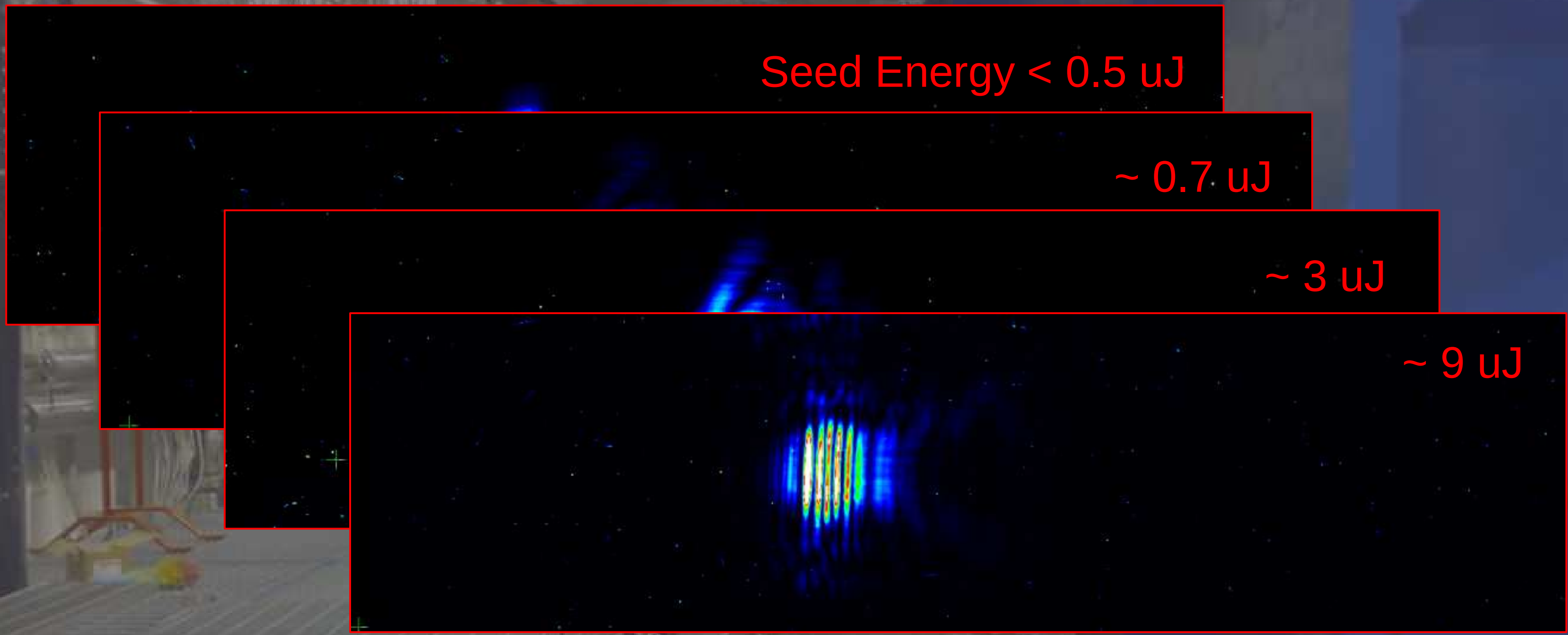


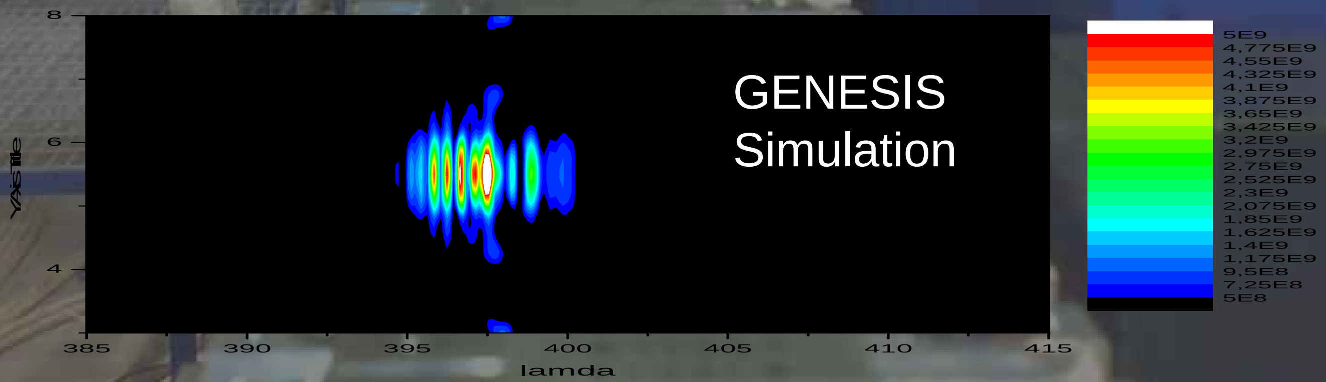


High intensity seeding & saturation effects

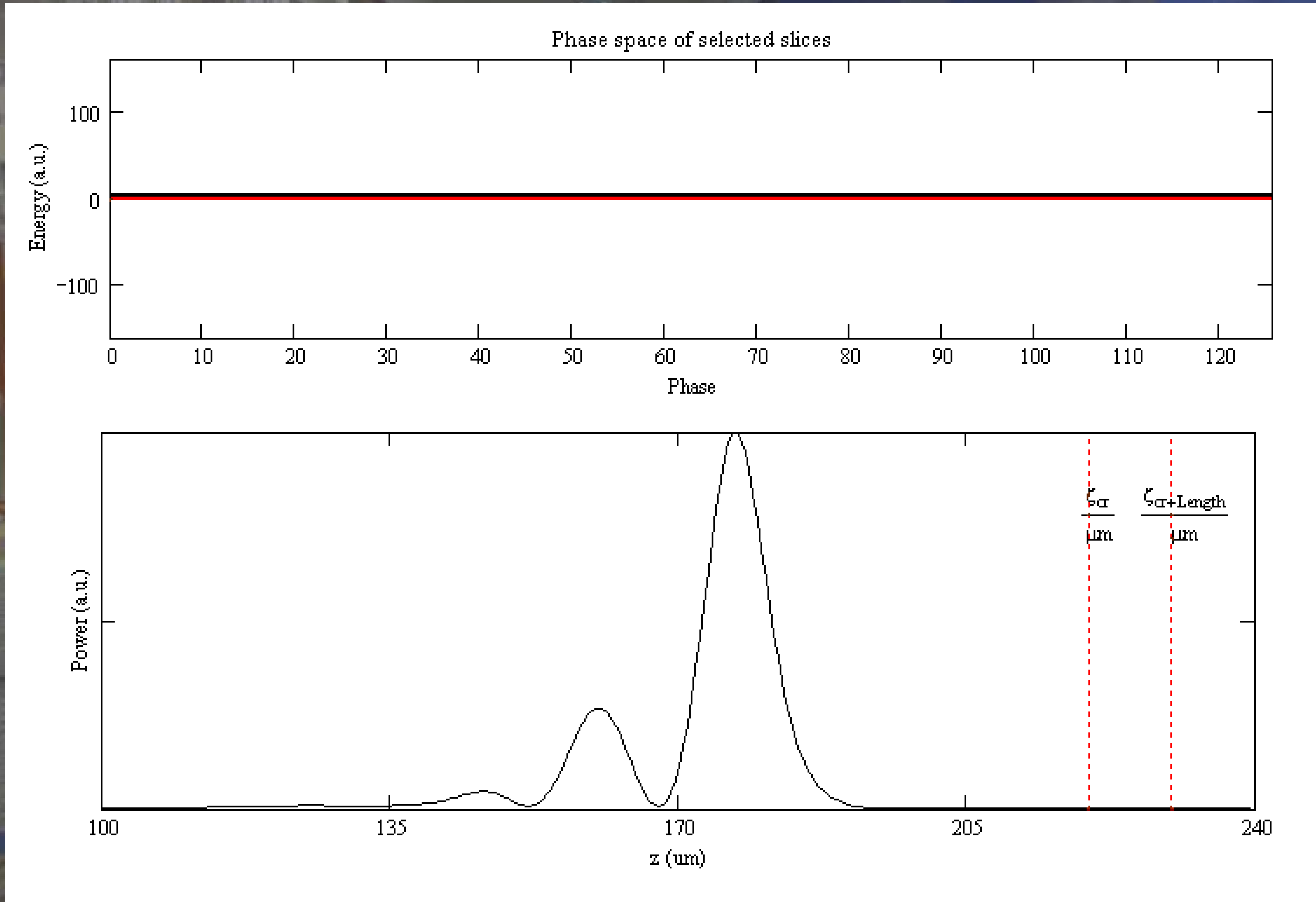


Effect of high intensity seed



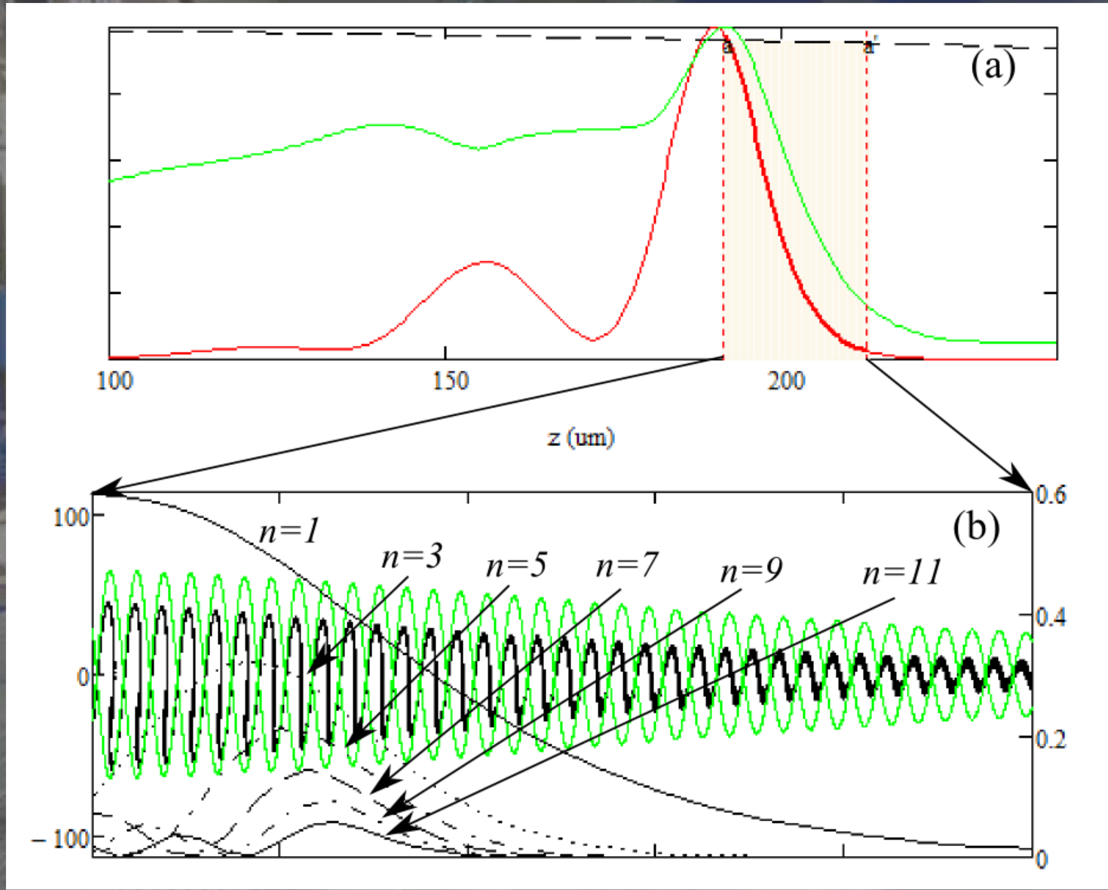


Seeded FEL: field intensity above saturation



Simulation with Perseo (www.perseo.enea.it)

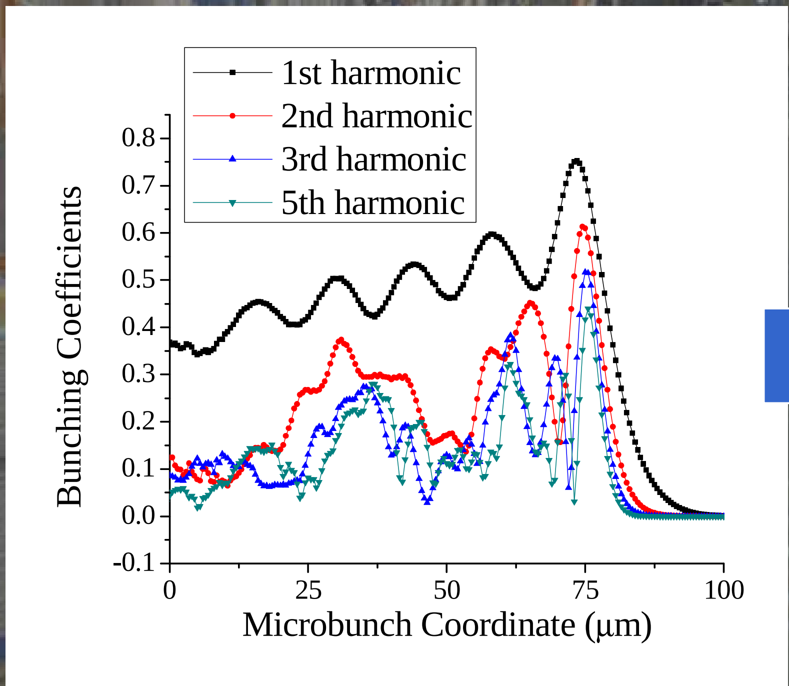
Bunching coefficients in the front side of the pulse

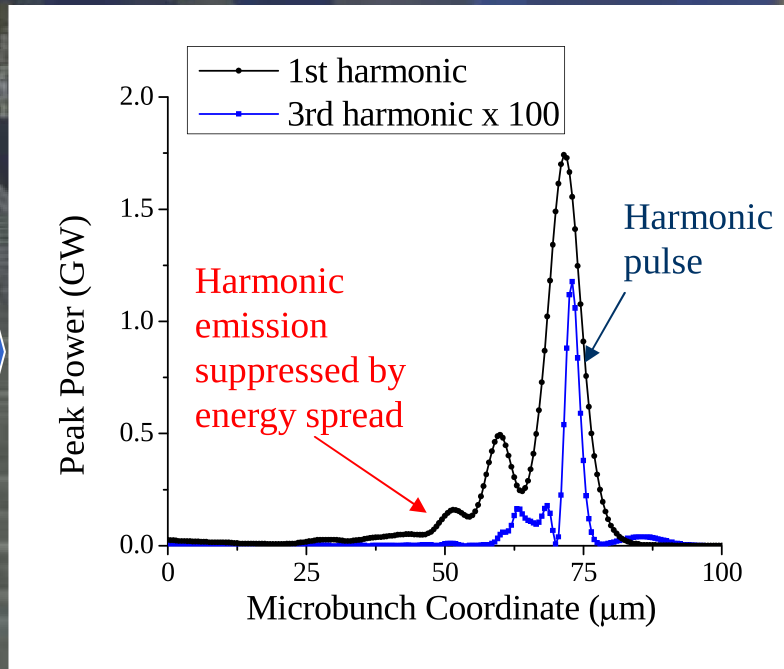


Expected very efficient generation of high order harmonics

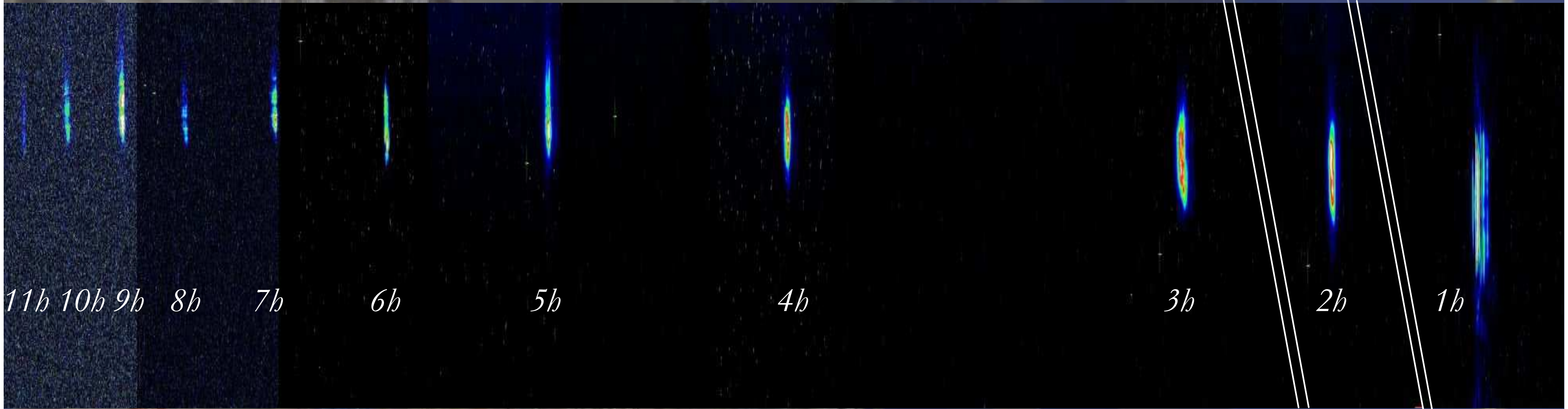
Harmonics in a Superradiant pulse

- Short bunching peaks on the pulse front side at the higher order harmonics
- Dynamics for non-linear harmonic evolution "faster" by the harmonic factor n. (i.e. $L_{g,n} \sim L_g / n$)
- Short bursts of harmonic radiation
- Pulse structre preserved by the "solitary wave" behavior of this solution



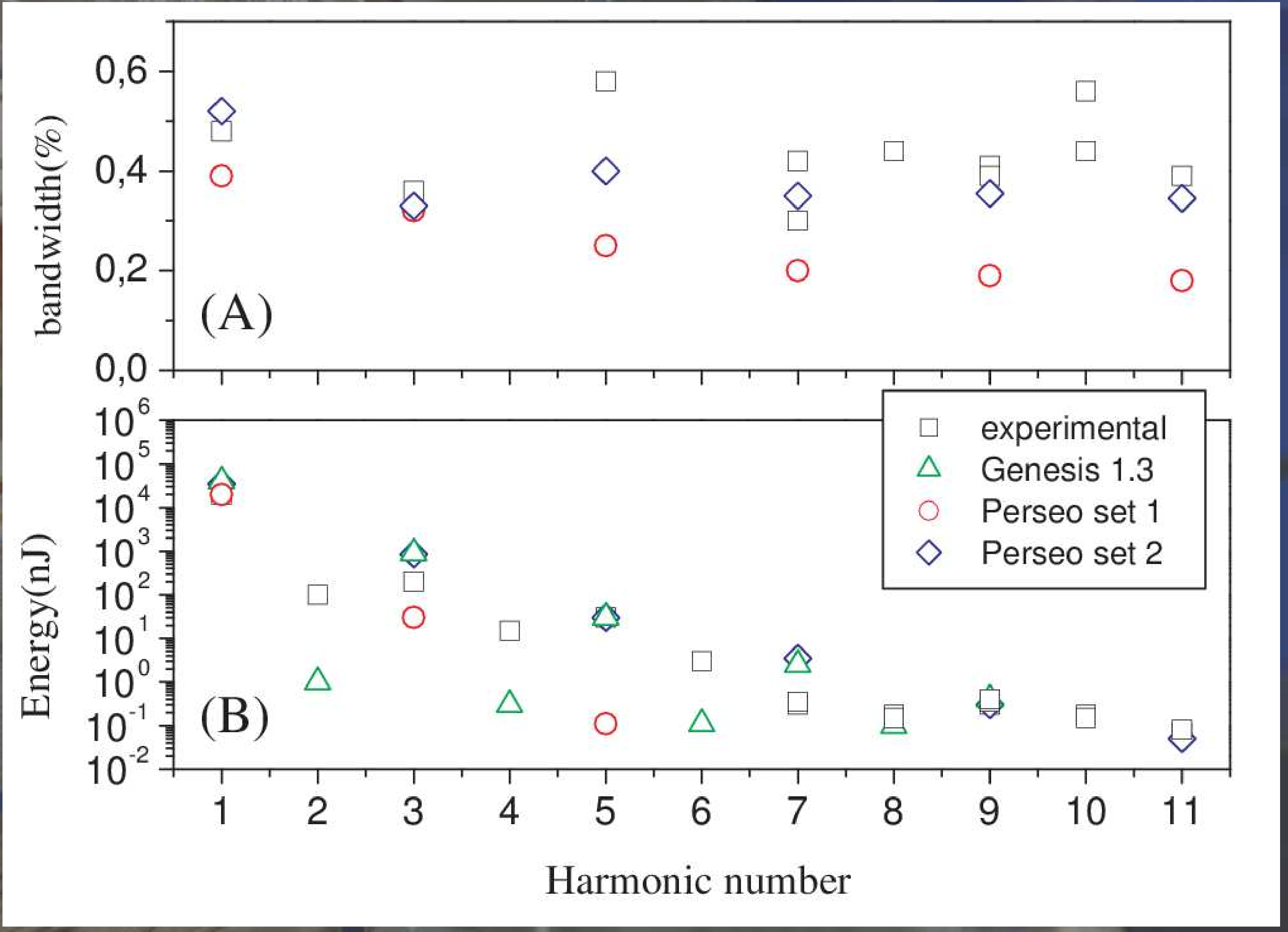


High harmonics down to 37 nm

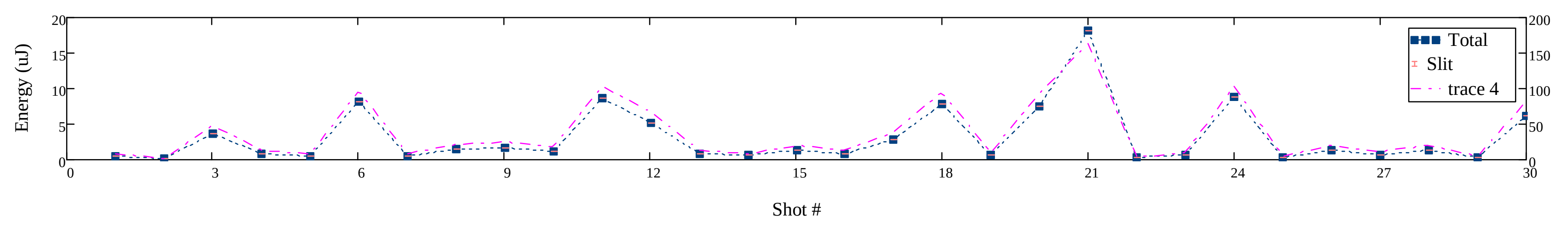


Measured energy per pulse, spot size & and bandwidth of the first 11° harmonics

Data on the high harmonics (to be published)



High intensity seed in a cascaded configuration



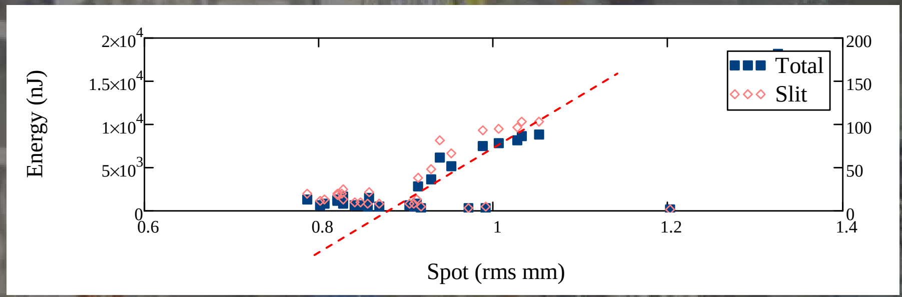
Energy jitter mainly due to e-beam energy jitter

Correlations

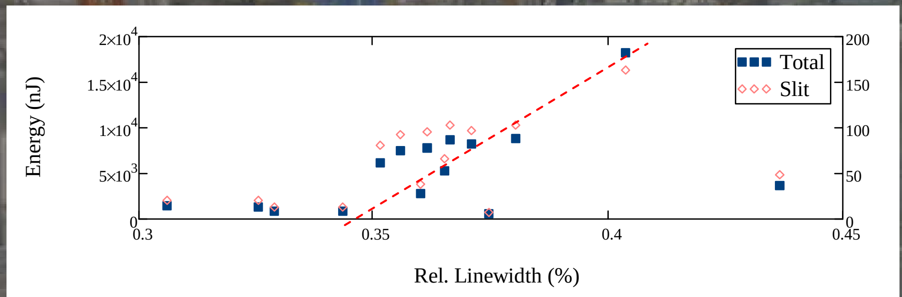
Large energy jitter –> large energy fluctuations

Indication of saturation @200 nm

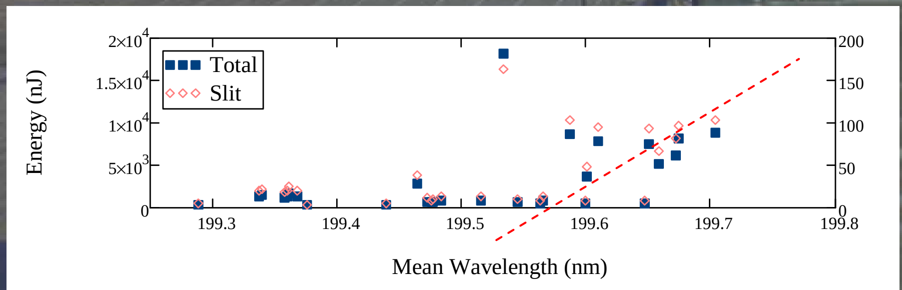
Correlation Energy – Spot size

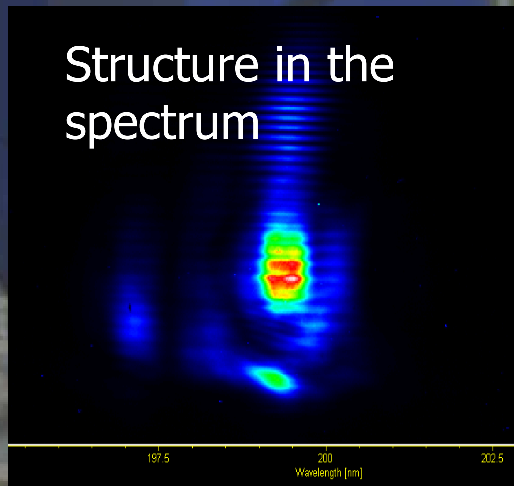


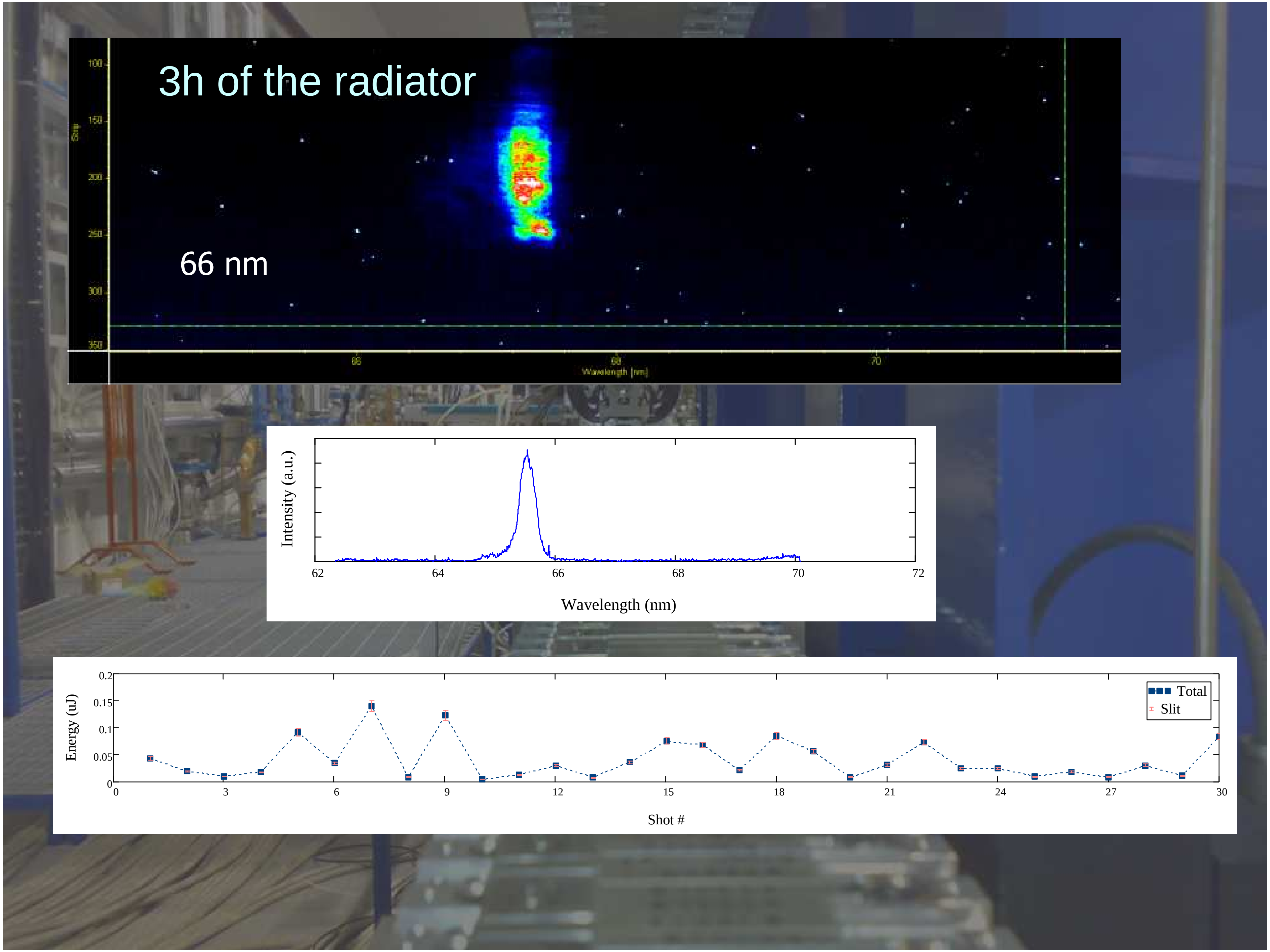
Correlation Energy – Linewidth



Redshift






3h of the radiator
66 nm
100
150
200
250
300
350
66
68
70
Wavelength [nm]
Intensity (a.u.)
62
64
66
68
70
72
Wavelength (nm)
Energy (uJ)
0.2
0.15
0.1
0.05
0
0
3
6
9
12
15
18
21
24
27
30
Total
Slit
Shot #

Seeded SPARC wavelengths

Fel generated harmonics

	1	2	3	4	5	6	7	8	9
→	400	200	133.3	100	80	66.7	57.1	50	44.4
→	266.7	133.3	88.9	66.7	53.3	44.4	38.1	33.3	29.6
→	160	80	53.3	40	32	26.7	22.9	20	17.8
→	114.3	57.1	38.1	28.6	22.9	19	16.3	14.3	12.7

Seed/Fundamental

Harmonics

+ 11

36.4

FEL Experiments SUMMARY

FEL Comb (18.5.2010 & 22-23.11.2010)

Observed double radiation pulses, control on energy separation

FEL SASE with chirped beam & taper (19.5.2010 & 16-18.12.2010)

Full saturation, single spike

Seeding @266nm with harmonics generated in gas (3.6.2010 e 1.7.2010 & February 2011)

Generation of 1uJ@133nm

Direct Seeding @160nm (4.6.2010)

Observed amplification

Cascaded FEL 2x @ 400nm (4.6.2010 e 2.7.2010 & 9-10.12.2010)

Indication of deep saturation @ 266nm & 3° harmonic: 100 nJ@66nm

Direct seeding @400nm generazione di armoniche di ordine elevato (30.6.2010 & 7.12.2010)

Radiation up the 11° harmonic observed

Seeding con fascio con chirp analisi FROG (15-23.07.2010 & 16-18.12.2010)

Beam too unstable – our hopes are in the next week shifts

SPARC FEL

Near term perspectives (2011?)

- Harmonic FEL cascade 400nm-200nm-100nm
- Amplification of harmonic generated in gas – generation & amplification of odd & even harmonics (Collaboration with M.E. Couprie, M. Labat, F. Briquetz, Soleil – B. Carrè M. Bougeard CEA, G. Lambert, ENSTA)
- Study of noise suppression for seeded FEL applications (Collaboration with A. Gover, A.Neuse, Tel-Aviv University) – Report available soon.
- Continue study of saturation in seeded and SASE FEL amplifiers
- FROG diagnostic of FEL radiation in seeded and SASE mode (Collaboration with G. Marcus, J. Rosenzweig – UCLA)
- Diagnostic of transverse coherence (specle, wavefront monitor)
- FEL amplification in exhotic undulators

Comments for the mid term perspectives

- SPARC started as a 500nm SASE FEL. The operation range has been extended by about an order of magnitude with seeding & harmonic generation

- The progresses in the beam/FEL dynamics scientific case ensured worldwide visibility (and leadership in some specific contexts) to this facility. There are the conditions to ensure a beneficial integration with the opportunities provided by FLAME.

- A high current/high brightness stable beam is the first step toward the completition of the listed experiments and a passepartout for their success

- Small upgrades of the existing SPARC configuration could extend the energy levels at the shortest wavelengths reached and further extend the spectral range.

- Any step toward new developments has to be commisurated to the human/financial resources

- This would allow to implement pilot experiments where specific properties of the light (pulse length/spectrum) could be used in user experiments to probe structure of matter.