Esperimenti con SPARC: lasing e seeding

L. Giannessi
ENEA – C.R. Frascati
On behalf of the SPARC collaboration

Frascati, 19/2/2008

Seeding @ SPARC

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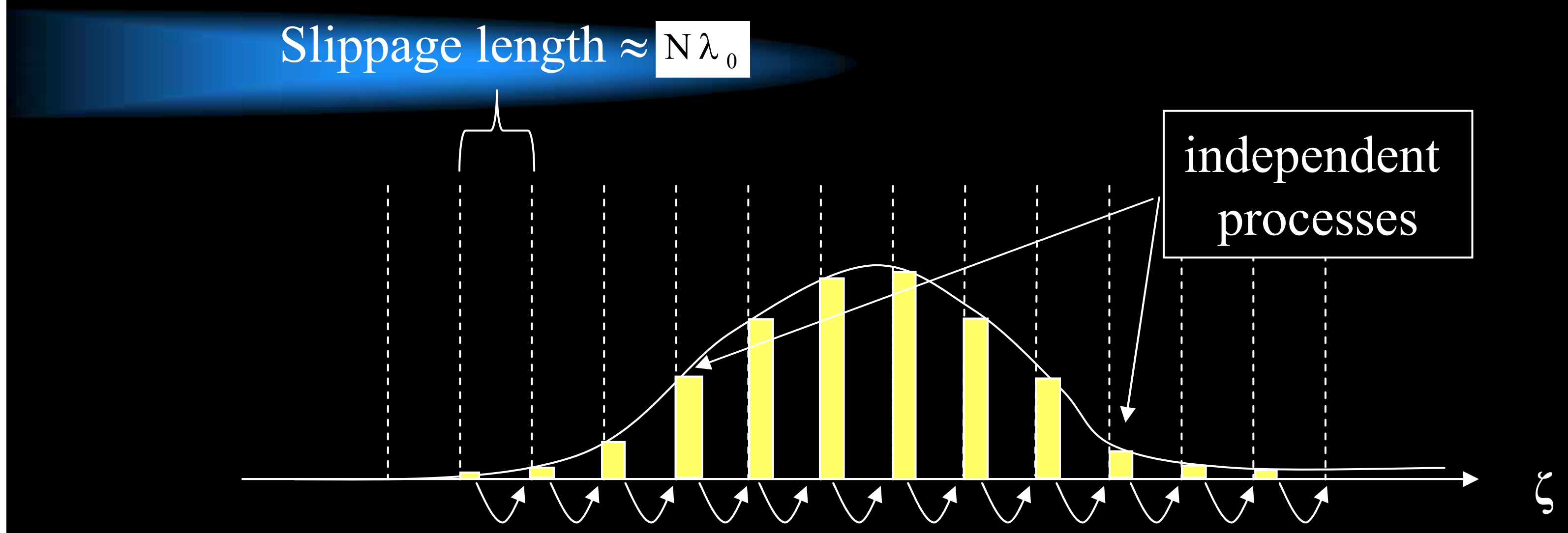
Outline

- Why seeding an FEL amplifier
- Seeding experiments
  - Seeding with high harmonics generated in gas
  - The harmonic cascade
  - The fresh bunch injection technique
- Self seeding

Longitudinal coherence

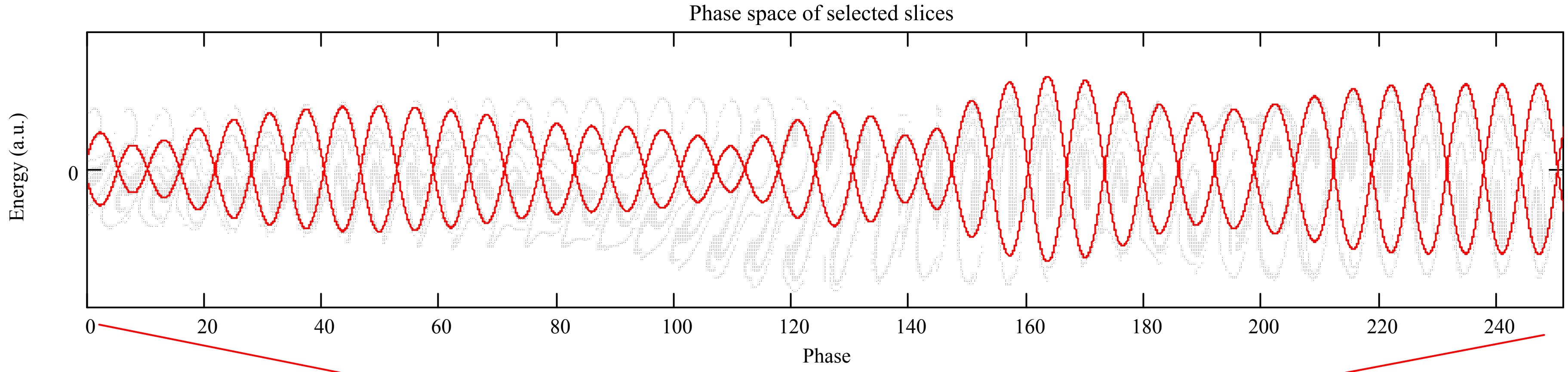


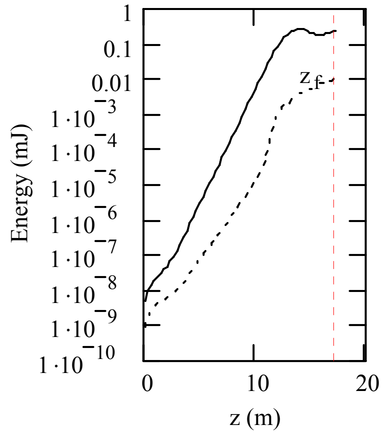
- The radiation "slips" over the electrons for a distance $N\lambda_0$
- SPARC:
  - N ~ 500
  - λ_0 ~500 nm
  - $N\lambda_0$ ~ 250 μm

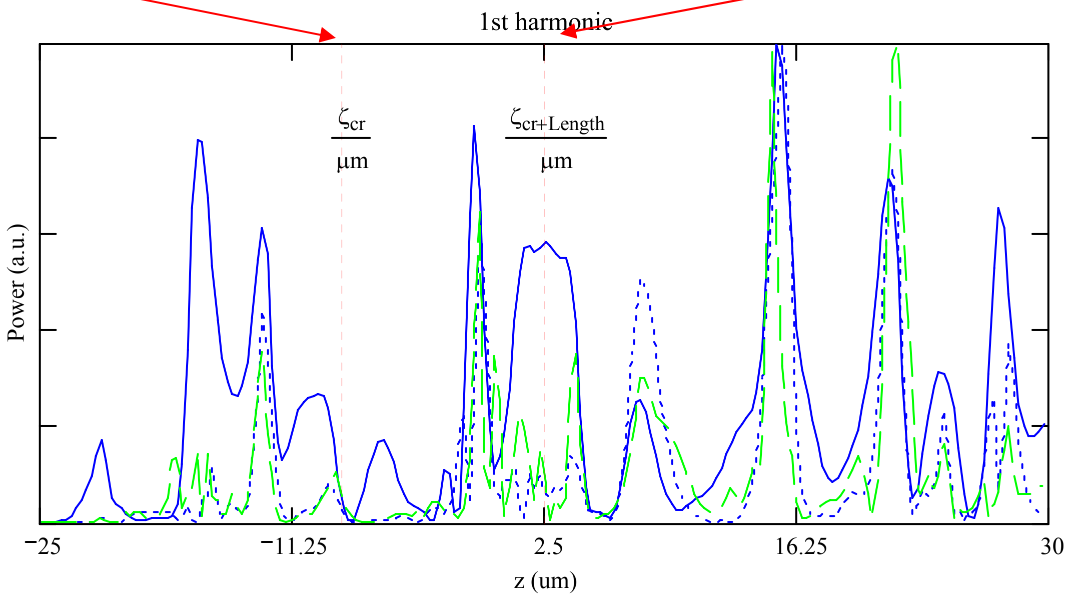
Bunch length ~ 2.6 - 2.8 ps (rms) → 7- 8 independent regions

(*the gain process increases this number*)

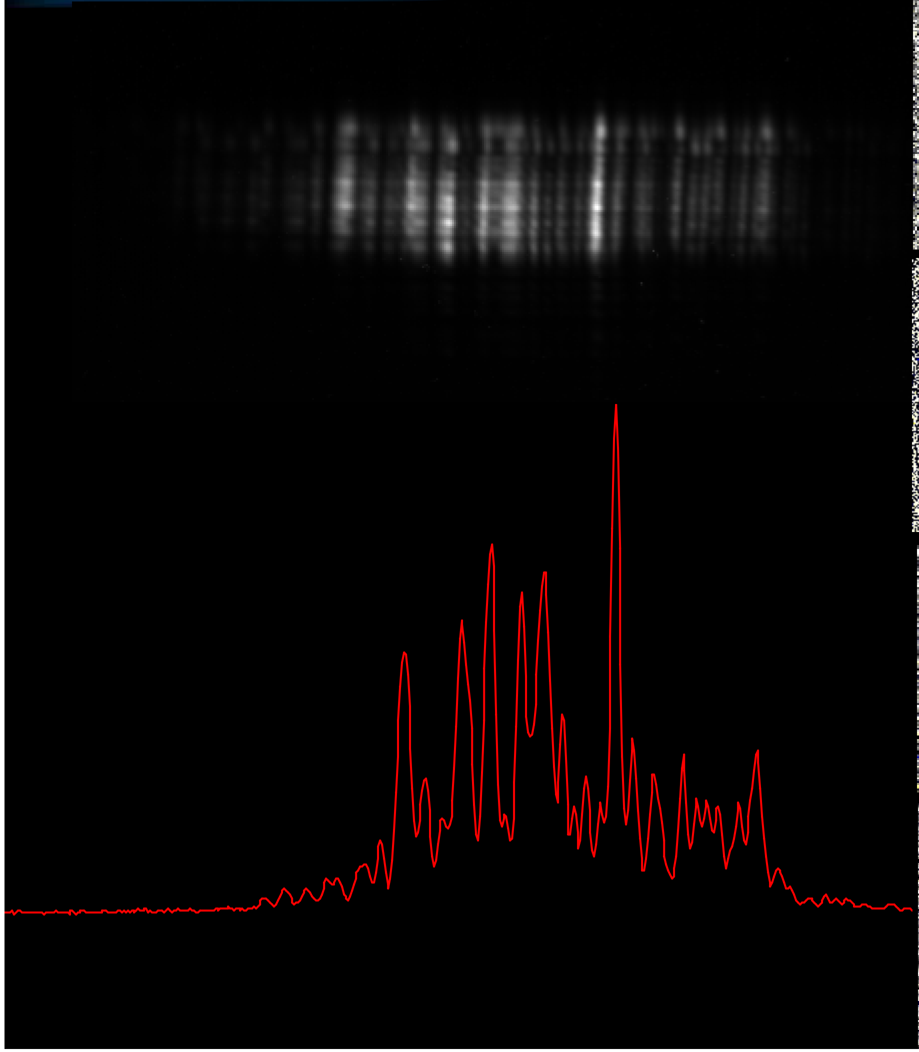
Phase space at saturation

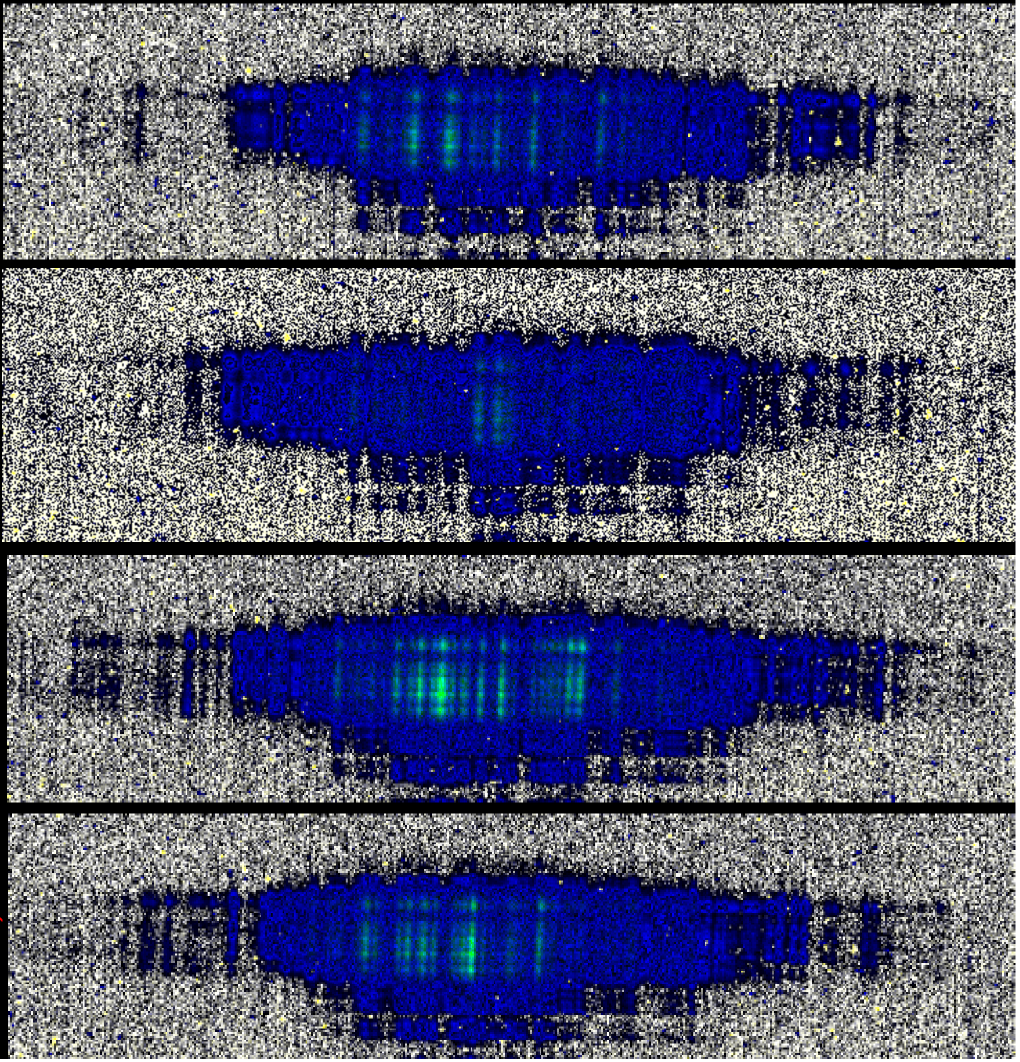




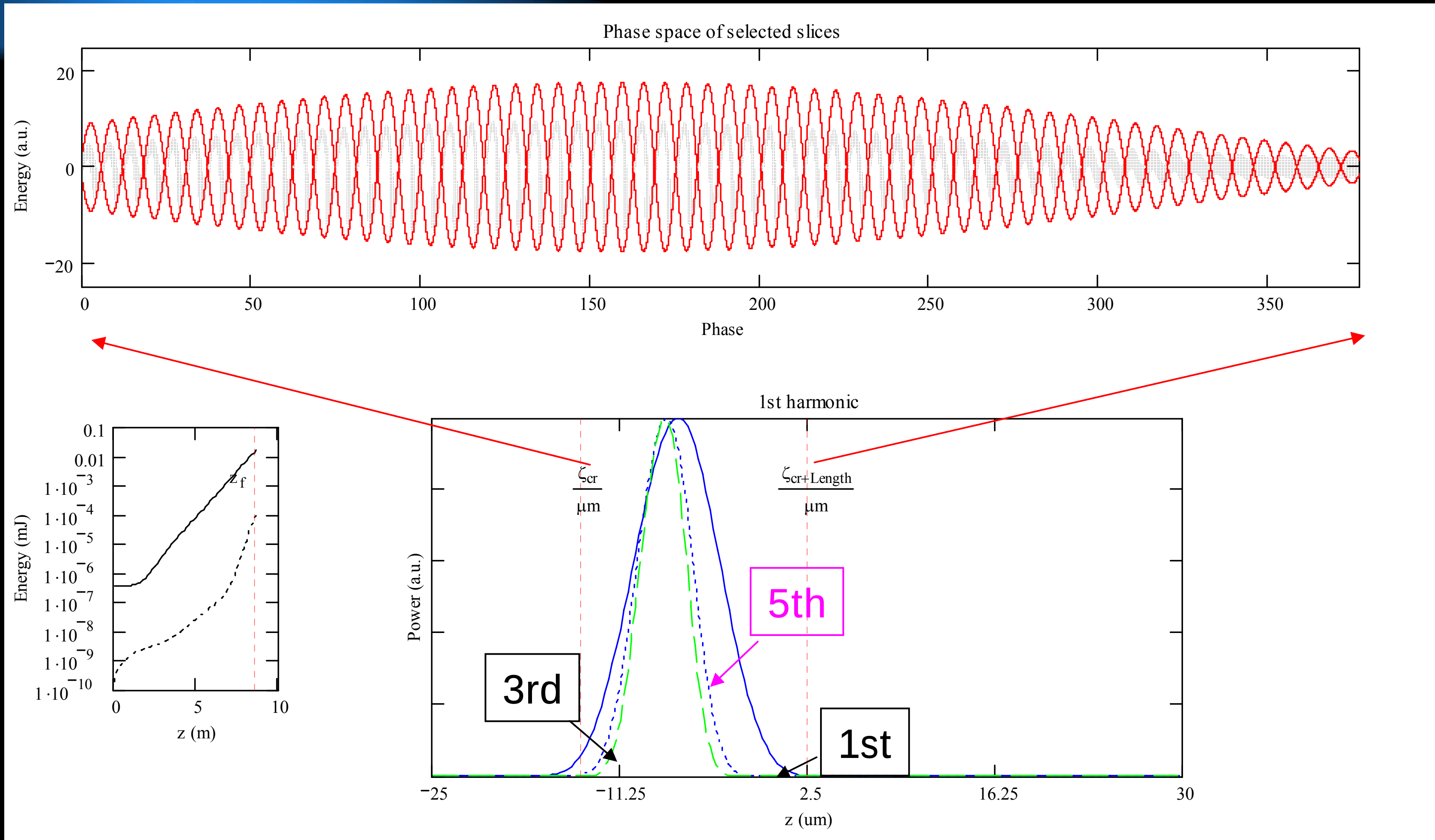


SPARC spectra (18.02.2009 … or 19.02.2009 ??)





Seeded FEL – Phase space @ exit of modulator



Luca Giannessi LIFE meeting
Frascati, 19/2/2008

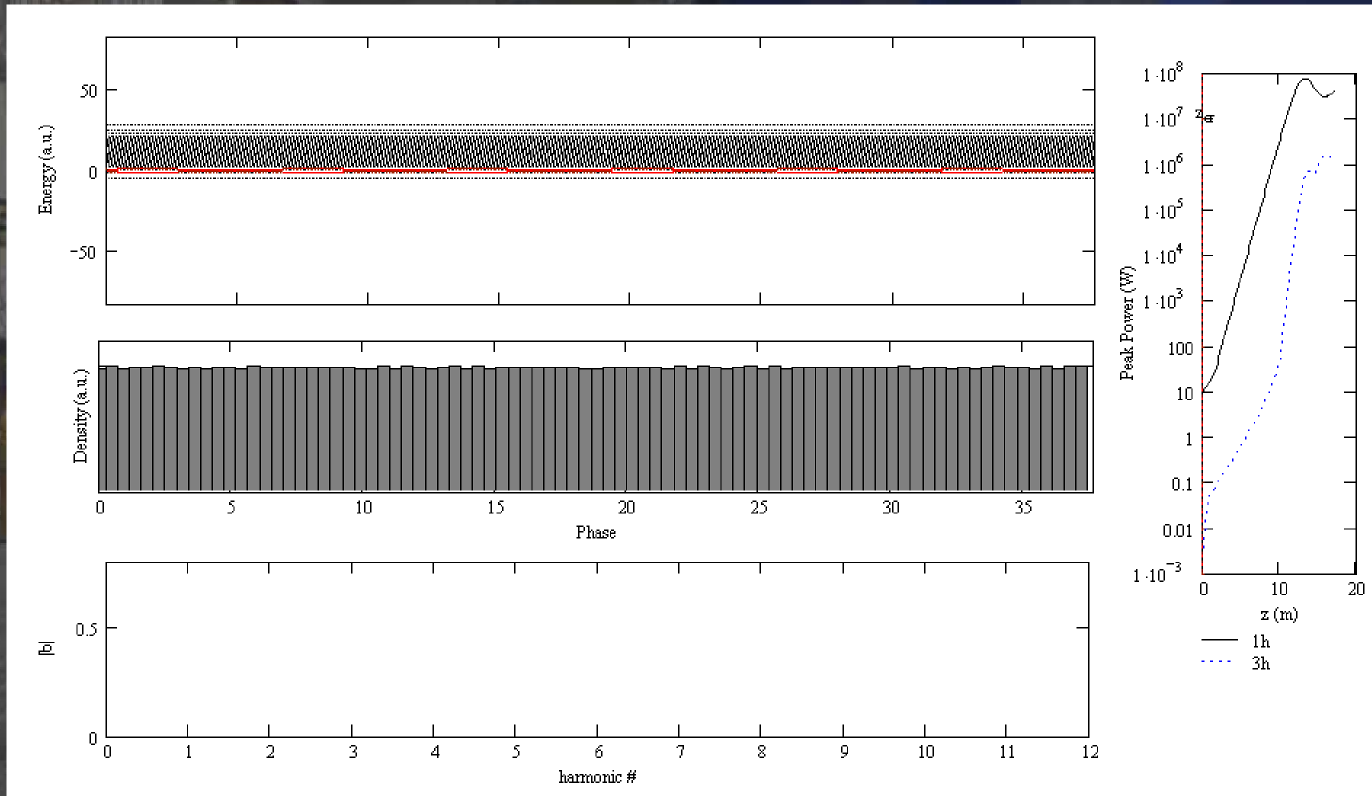
Coherence length determined by the seed

Higher order harmonics:
A close look at the bunching process

Phase space
Energy/position

Longitudinal density ρ

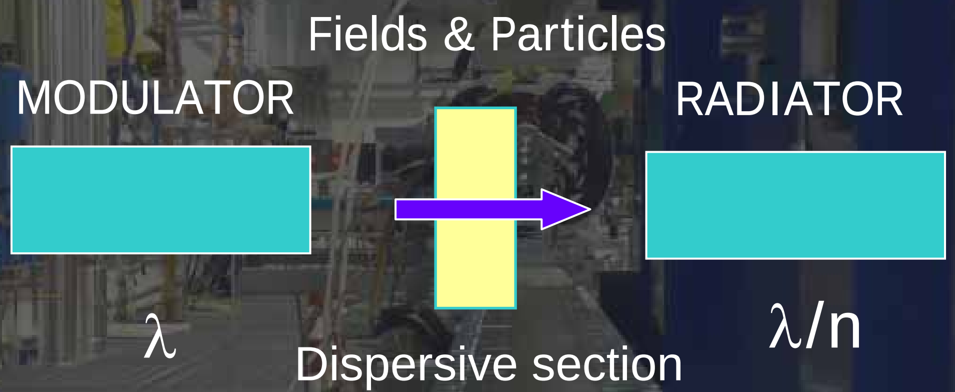
n^{th} Fourier coefficients of ρ



$$\frac{2\pi}{\lambda_0}\int_0^{\lambda_0/2\pi}\rho(\zeta)\exp(2\pi n i\zeta/\lambda_0)d\zeta$$

Higher order harmonics

Cascaded FEL configuration



Optical klystron operating on a higher order harmonic in the second section

I.Boscolo, V. Stagno, Il Nuovo Cimento 58, 271 (1980)
… and several other authors

Seeded configurations

FEL Amplifier

Seed

λ

FEL Harmonic Generation

Seed

λ_1

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

Modulator

Radiator

FEL Harmonic Cascade

Seed

λ_1

$\lambda_2 = n\lambda_1/m$, es. $m=4$, $n=3$

Modulator

Radiator

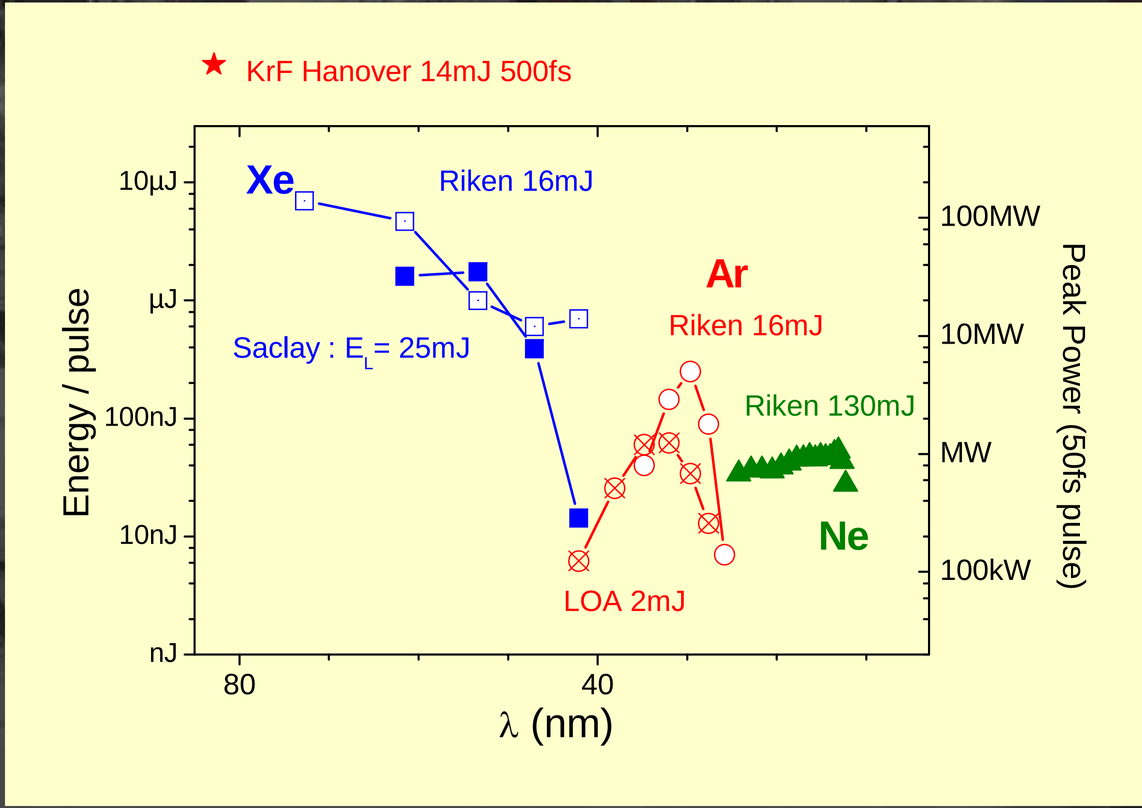
Fresh Bunch injection technique

Seed

λ=400nm | λ=200nm | λ=380-390nm | λ=200nm | λ=100nm

Modulator | Radiator | Dispersion | Modulator | Radiator

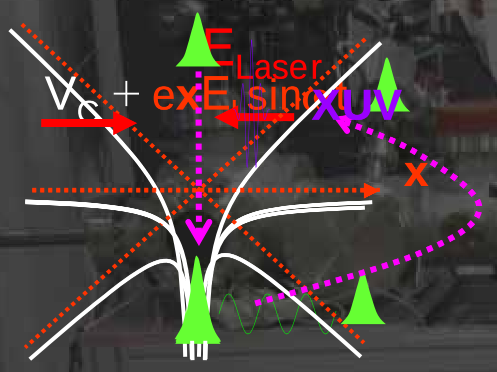
Seeding with high order harmonics generated in gas



Temporal-spectral structure of XUV emission

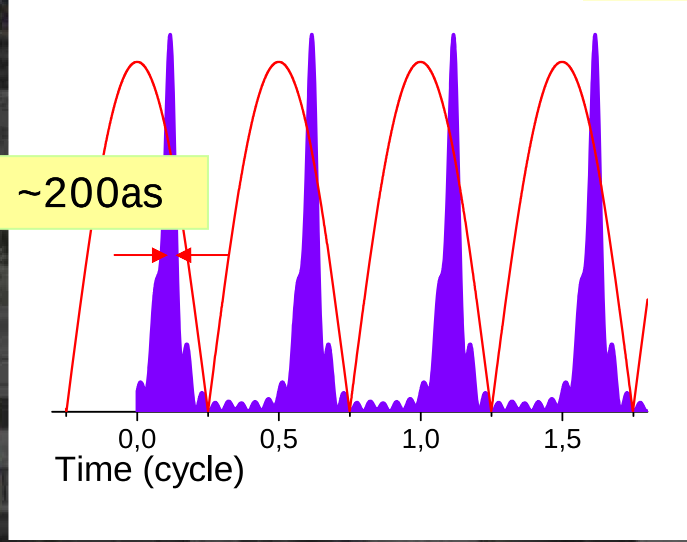
Courtesy of B. Carrè

- **"Three-step" model**



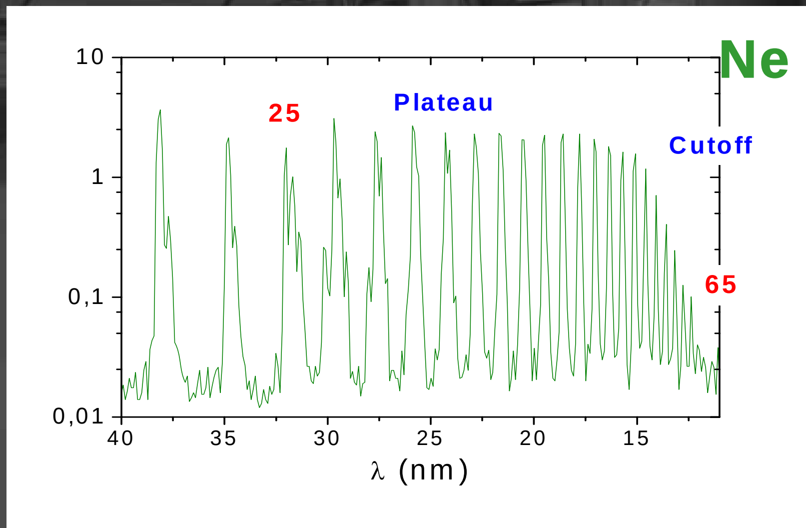
- **Multi-cycle laser pulse**

Mairesse et al. SCIENCE (2003)



Train of XUV "atto" pulses

Discrete odd harmonics

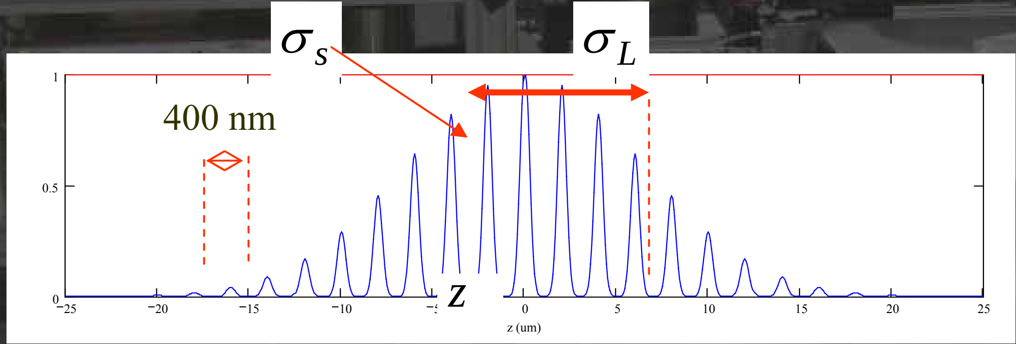


Seeding with HHG generated in gas

Simple model of an HHG pulse

$$E(t) = a(z-ct)e^{i(\omega t - kz)}$$

$$\omega = \frac{2\pi c}{\lambda}, \qquad \lambda = 114\text{nm}$$



$$\sigma_L = 30\,fs$$
$$\sigma_s = 100as$$

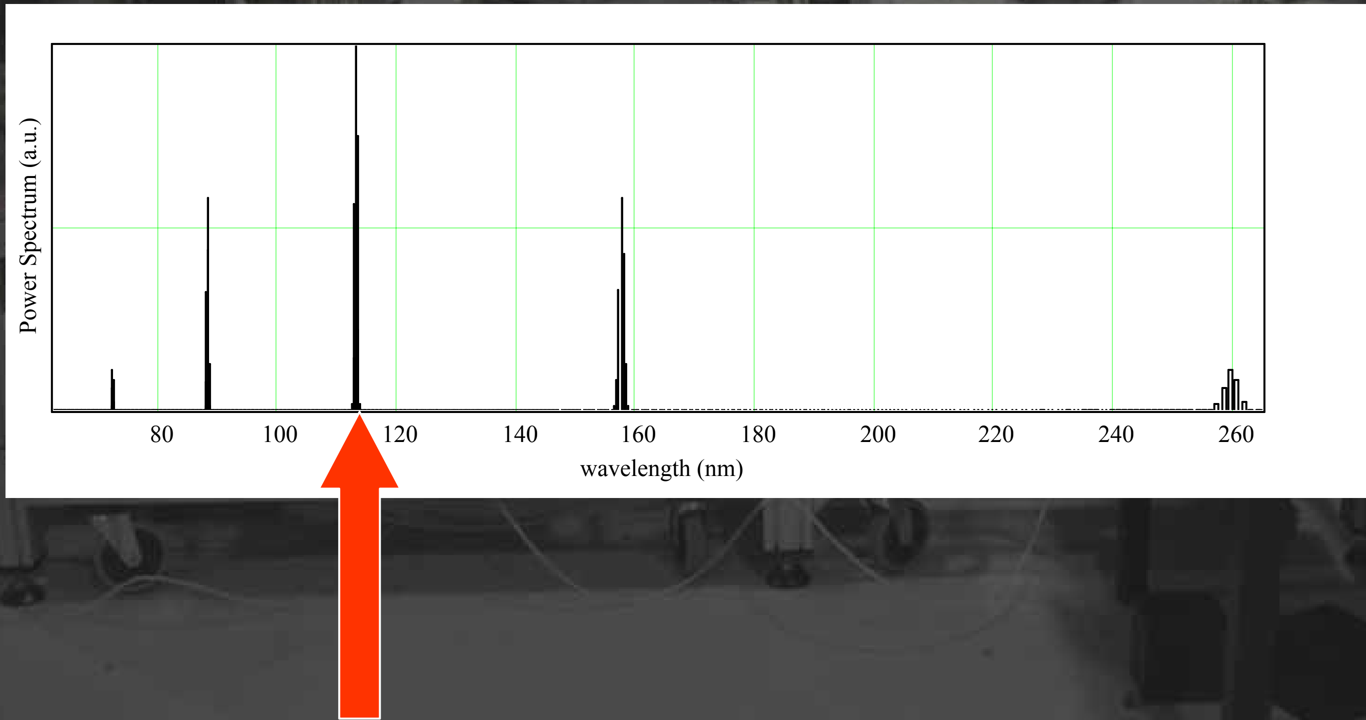
Phase shift between different peaks

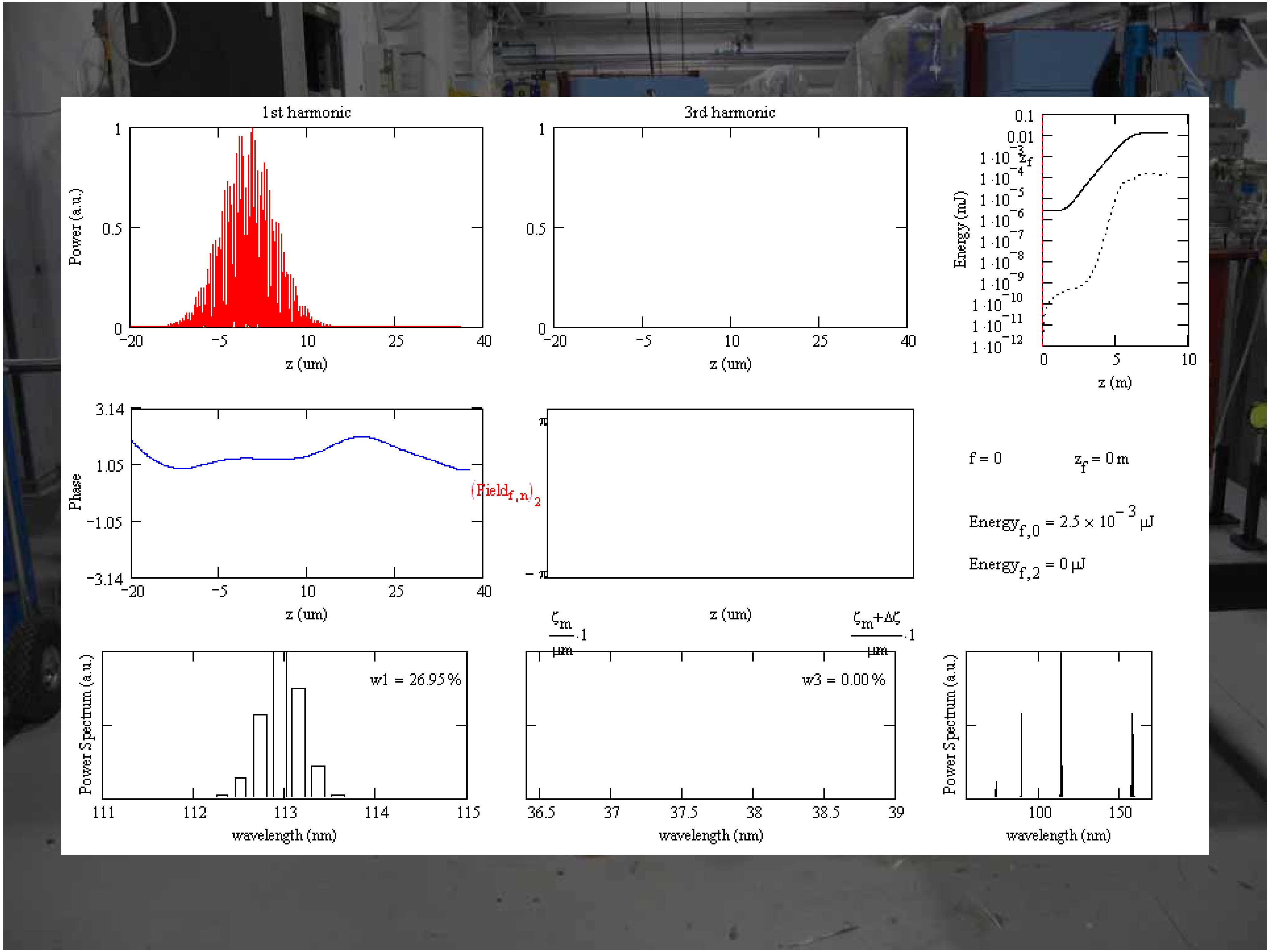
$$a(z) = |a(z)| \exp(i\phi(z))$$
$$\phi(z) = \sum_k s_j \sin(kz) + c_j \cos(kz)$$

Harmonics Spectrum

SPARC

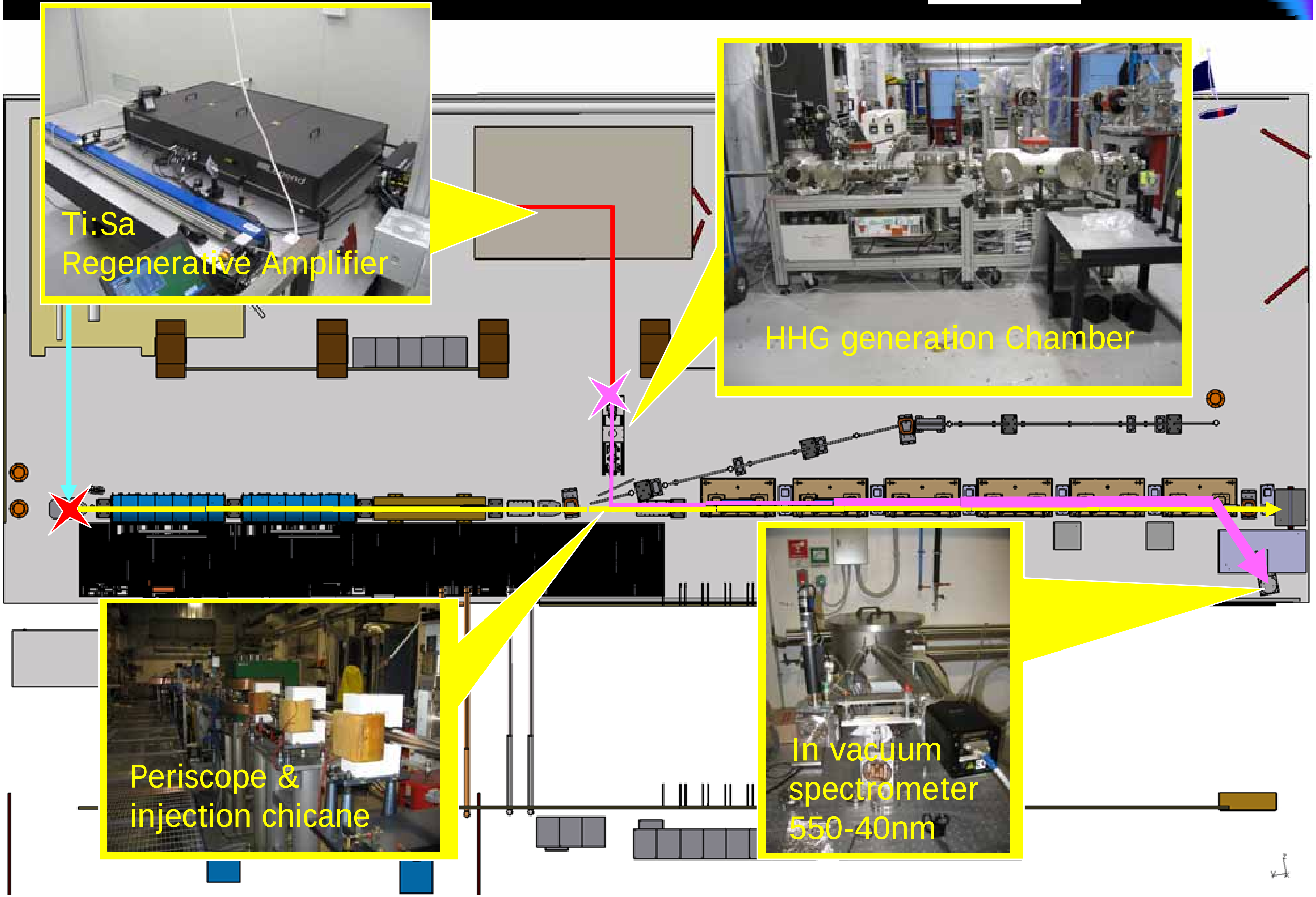
(www.sparc.it)

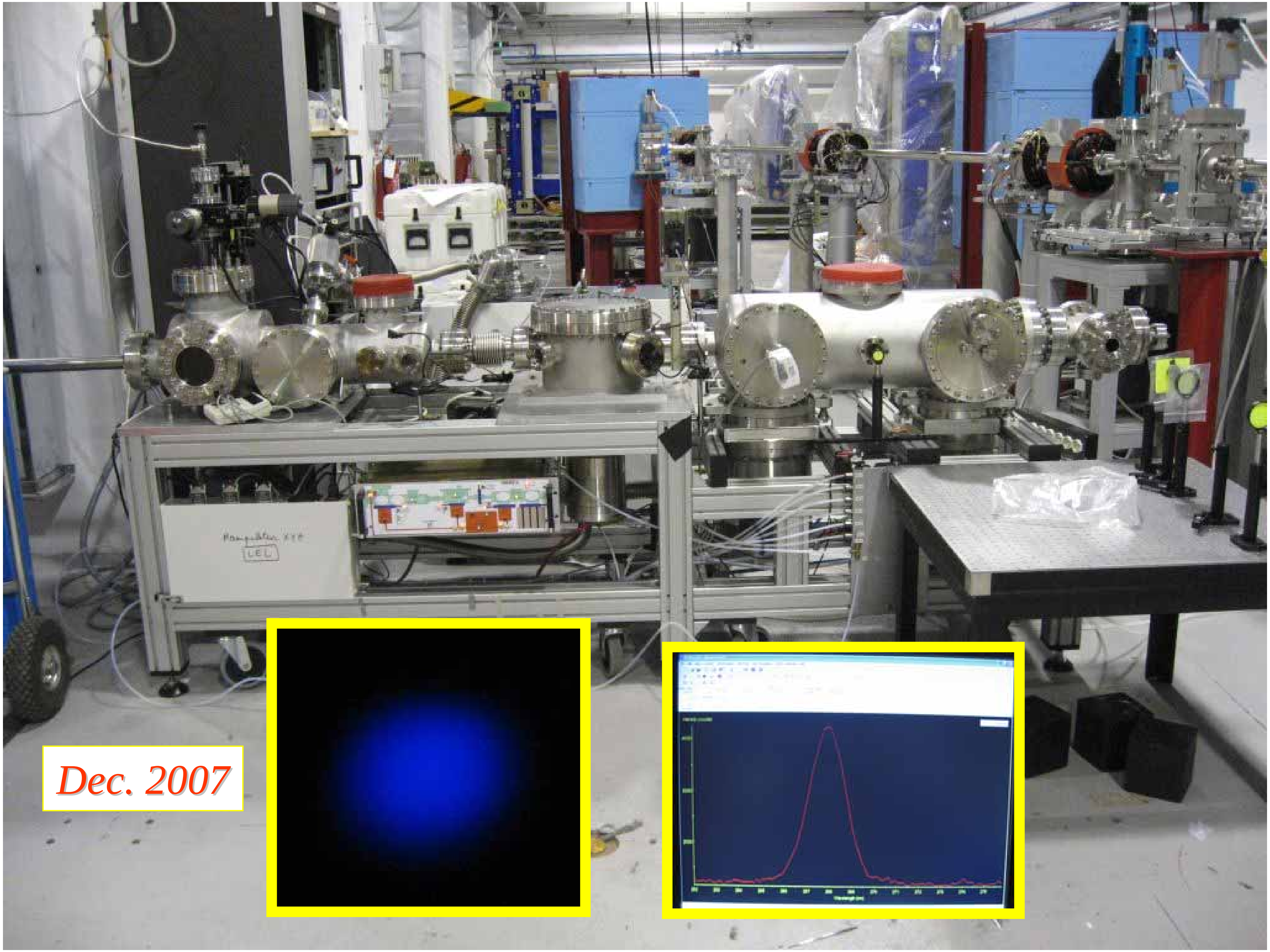



1st harmonic
Power (a.u.)
z (um)
3rd harmonic
z (um)
Energy (mJ)
z (m)
Phase
z (um)
$(Field_{f,n})_2$
f = 0
z_f = 0 m
$Energy_{f,0} = 2.5 \times 10^{-3}$ μJ
$Energy_{f,2}$ = 0 μJ
z (um)
w1 = 26.95 %
Power Spectrum (a.u.)
wavelength (nm)
w3 = 0.00 %
wavelength (nm)
Power Spectrum (a.u.)
wavelength (nm)

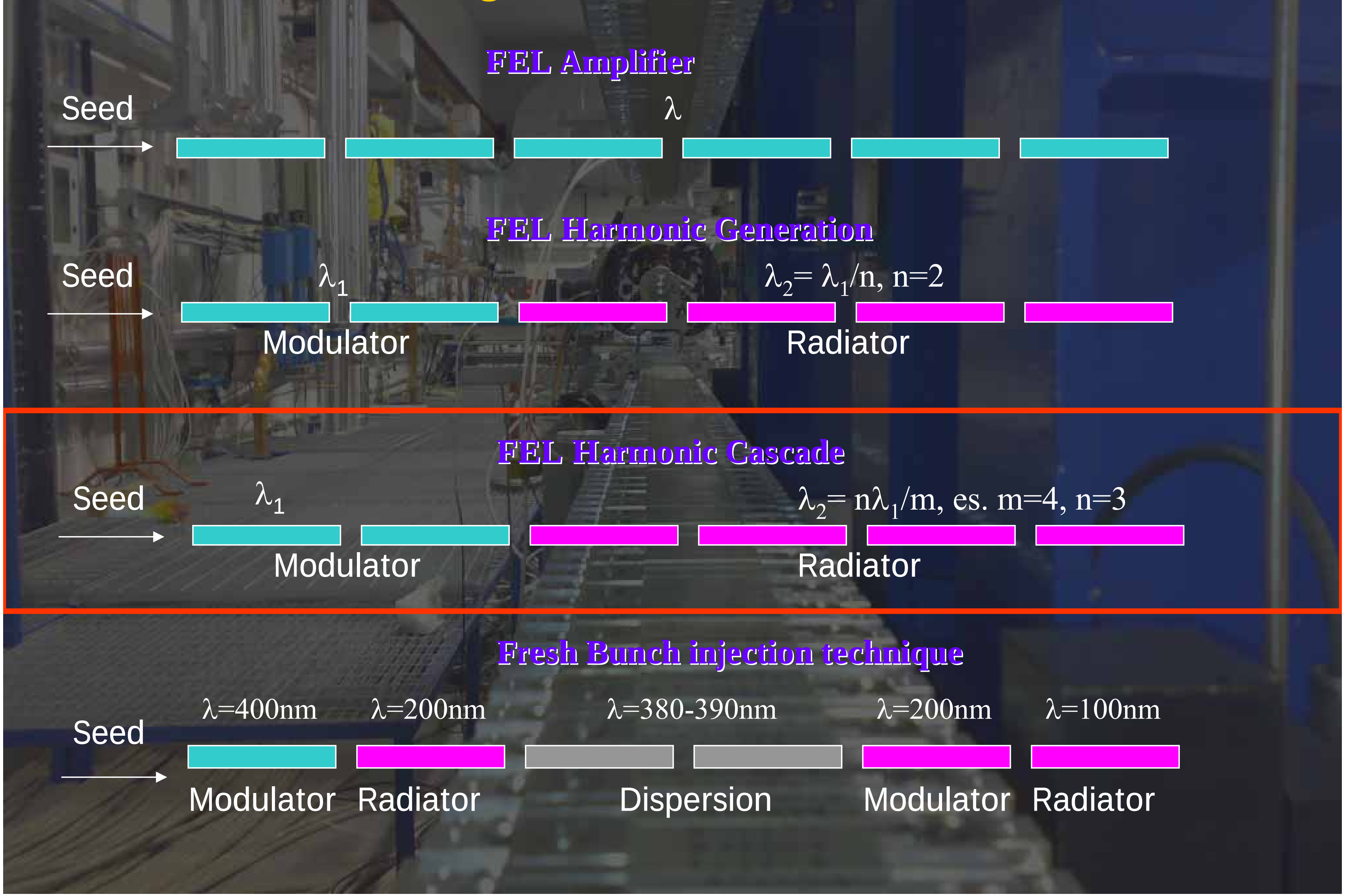
Seeded SPARC Layout

EURO FEL + MUR




Dec. 2007

Seeded configurations



Harmonic Cascaded FEL

Resonant at λ_1

Resonant at $\lambda_2 = \frac{m}{n}\lambda_1, \quad m \neq n$

UM1 → UM2

Emitted wavelength: $\lambda_m = \frac{\lambda_2}{m} = \lambda_n$

Bunching at $\lambda_n = \frac{\lambda_1}{n}$

Harmonics Spectra of the two undulators

1° Undulator

2° Undulator

+

Superradiamt regime

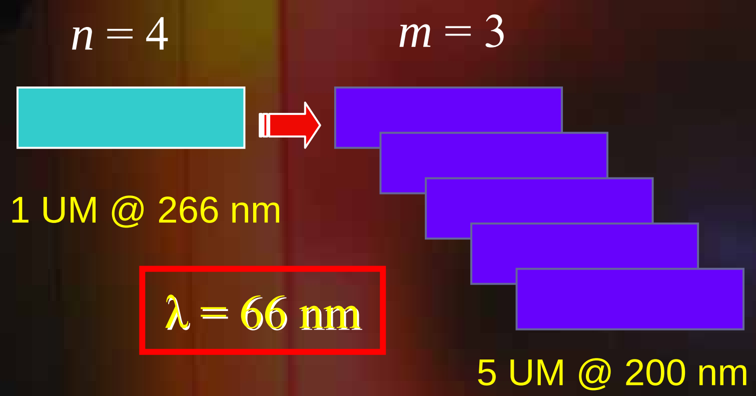
a) Anticipate SASE saturation

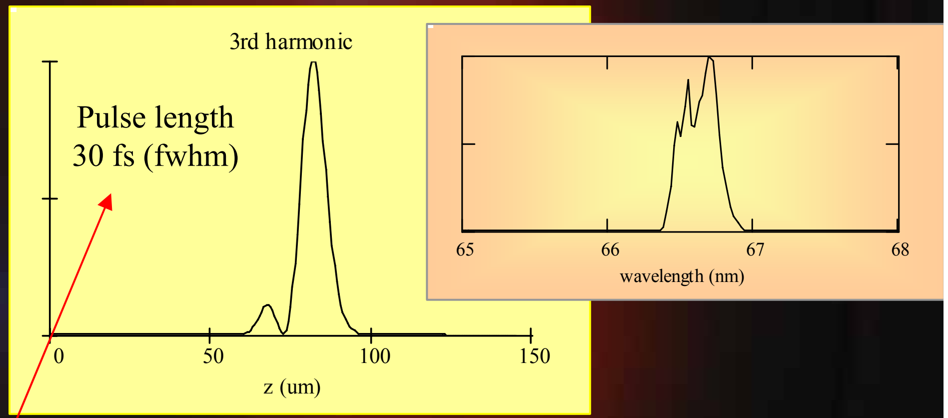
b) Increase efficiency
(eff. proportional to slippage)

L.Giannessi, P. Musumeci, *New Journal of Physics* **8** (2006) 294

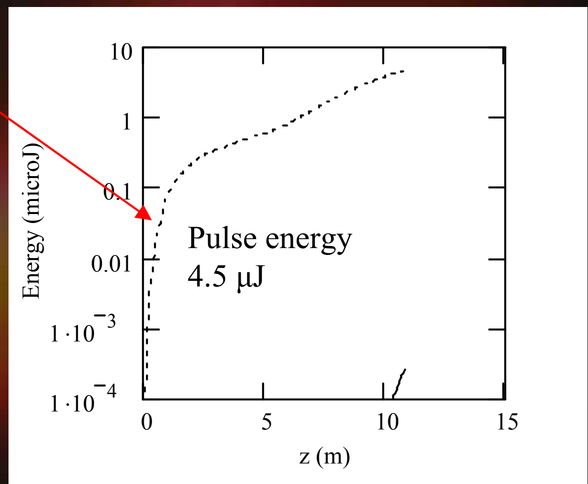
Example with *Sparc* undulator/beam parameters

1D *Perseo* simulation *(http://www.perseo.enea.it)*





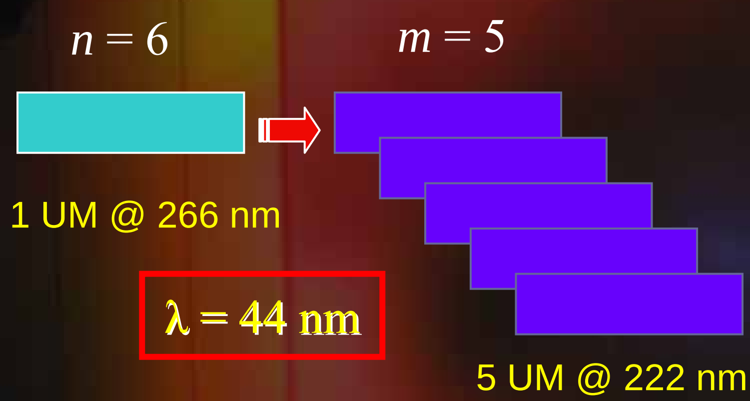
Peak power ≈ 130 MW



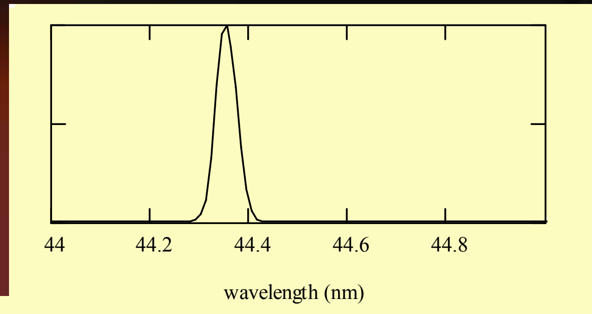
Main parameters

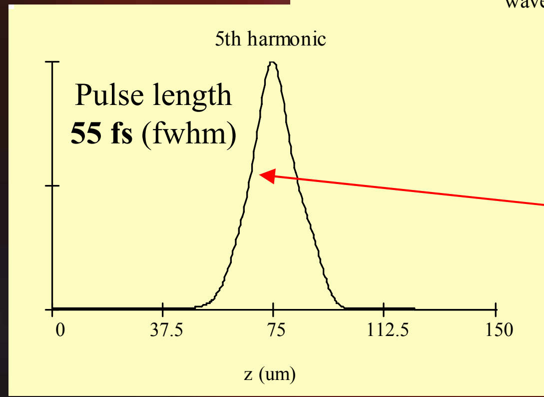
Undulator period	2.8 cm
Undulator K (UM1/UM2)	1.95 / 1.53
Number of periods	77 / 77*5
Beam energy	200 MeV
Res. wavelength (nm)	266 / 200
E-beam current	110 Amp
Energy spread	10^{-4}
Emittance	1 mm-mrad
Input Laser power	2 MW
Input pulse length (fwhm)	100 fs

n = 6 and m = 5

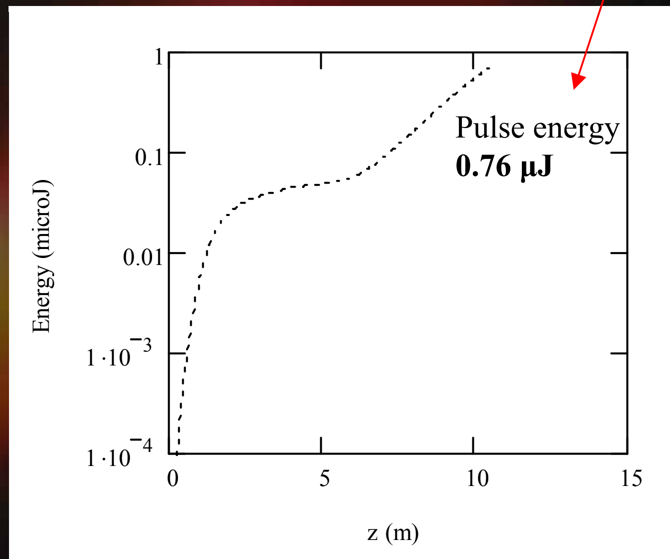


λ = 44 nm



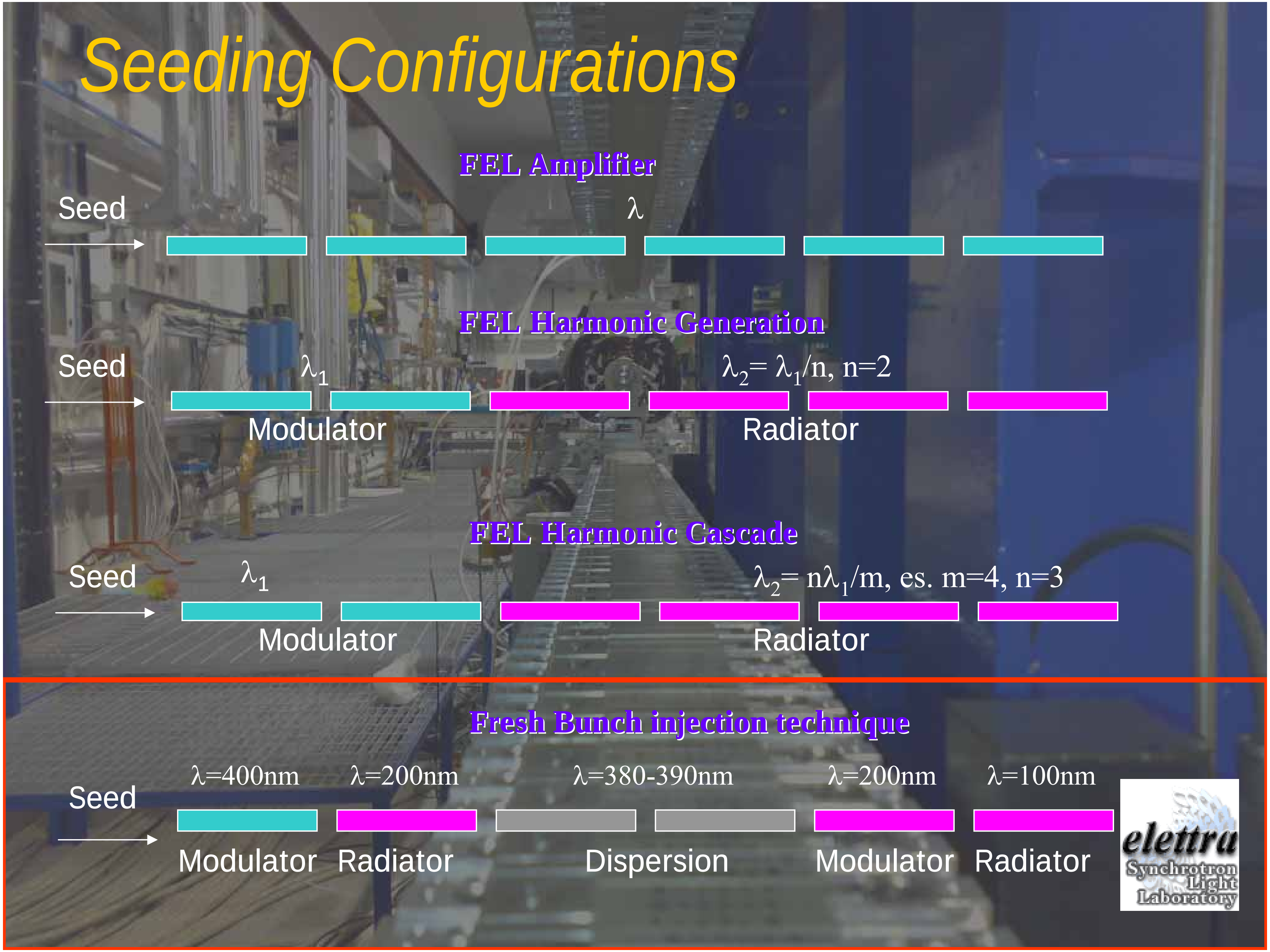


Peak power ≈ 12 MW



Main parameters

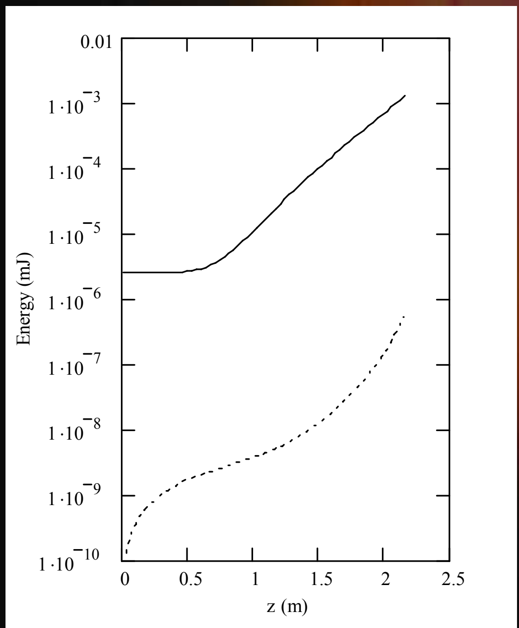
Undulator period	2.8 cm
Undulator K (UM1/UM2)	1.95 / 1.69
Number of periods	77 / 77*5
Beam energy	200 MeV
Res. wavelength (nm)	266 / 222
E-beam current	110 Amp
Energy spread	10^{-4}
Emittance	1 mm-mrad
Input pulse length (fwhm)	100 fs

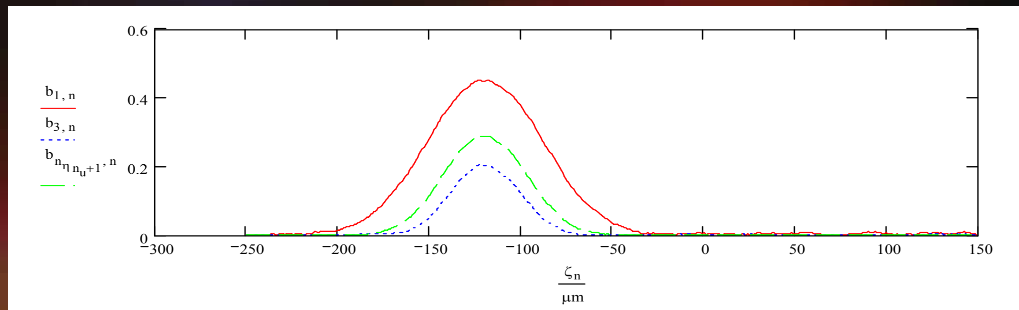

Seeding Configurations
FEL Amplifier
Seed
λ
FEL Harmonic Generation
Seed
λ_1
$\lambda_2 = \lambda_1/n$, n=2
Modulator
Radiator
FEL Harmonic Cascade
Seed
λ_1
$\lambda_2 = n\lambda_1/m$, es. m=4, n=3
Modulator
Radiator
Fresh Bunch injection technique
Seed
λ=400nm
λ=200nm
λ=380-390nm
λ=200nm
λ=100nm
Modulator
Radiator
Dispersion
Modulator
Radiator
elettra
Synchrotron Light Laboratory

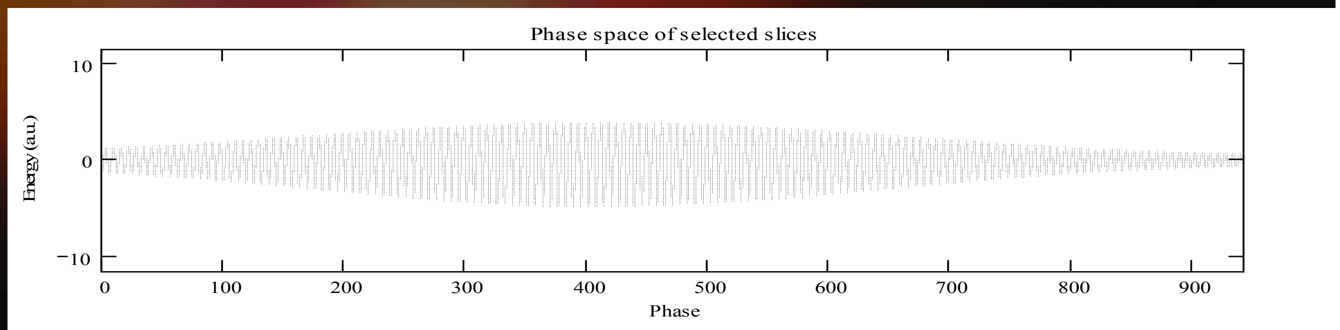
Double stage FEL cascade

Beam energy	175 MeV
Peak current	100 A
Input seed	20 kW
Pulse length (rms)	100 fs

Fresh Bunch injection technique



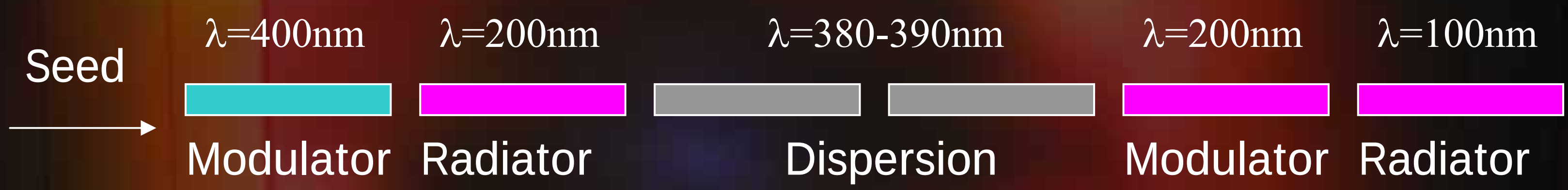


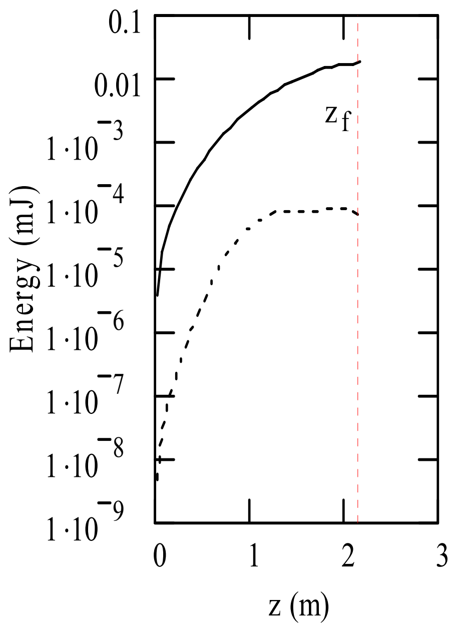


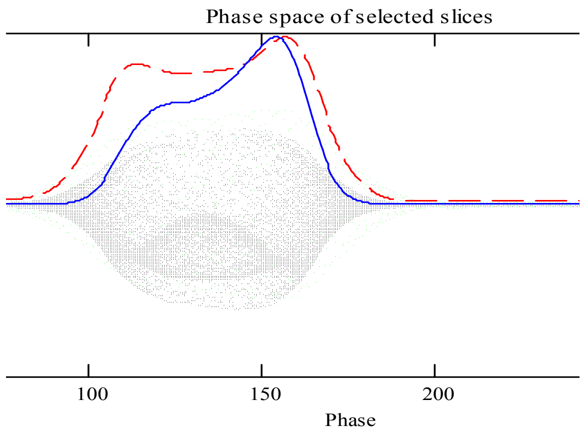
Double stage cascade

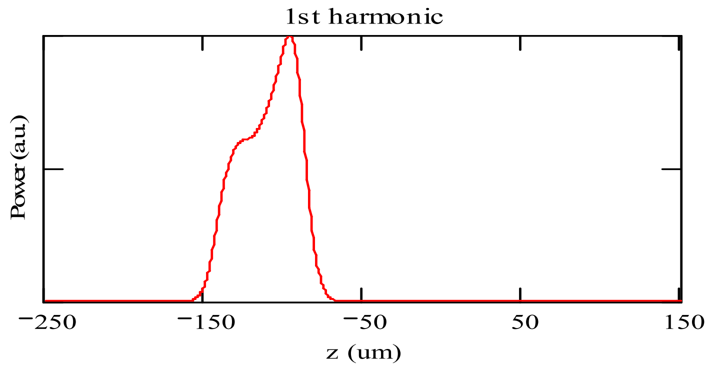
AFTER THE FIRST RADIATOR

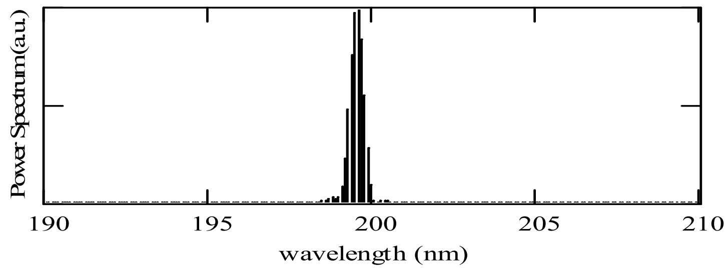
Fresh Bunch injection technique







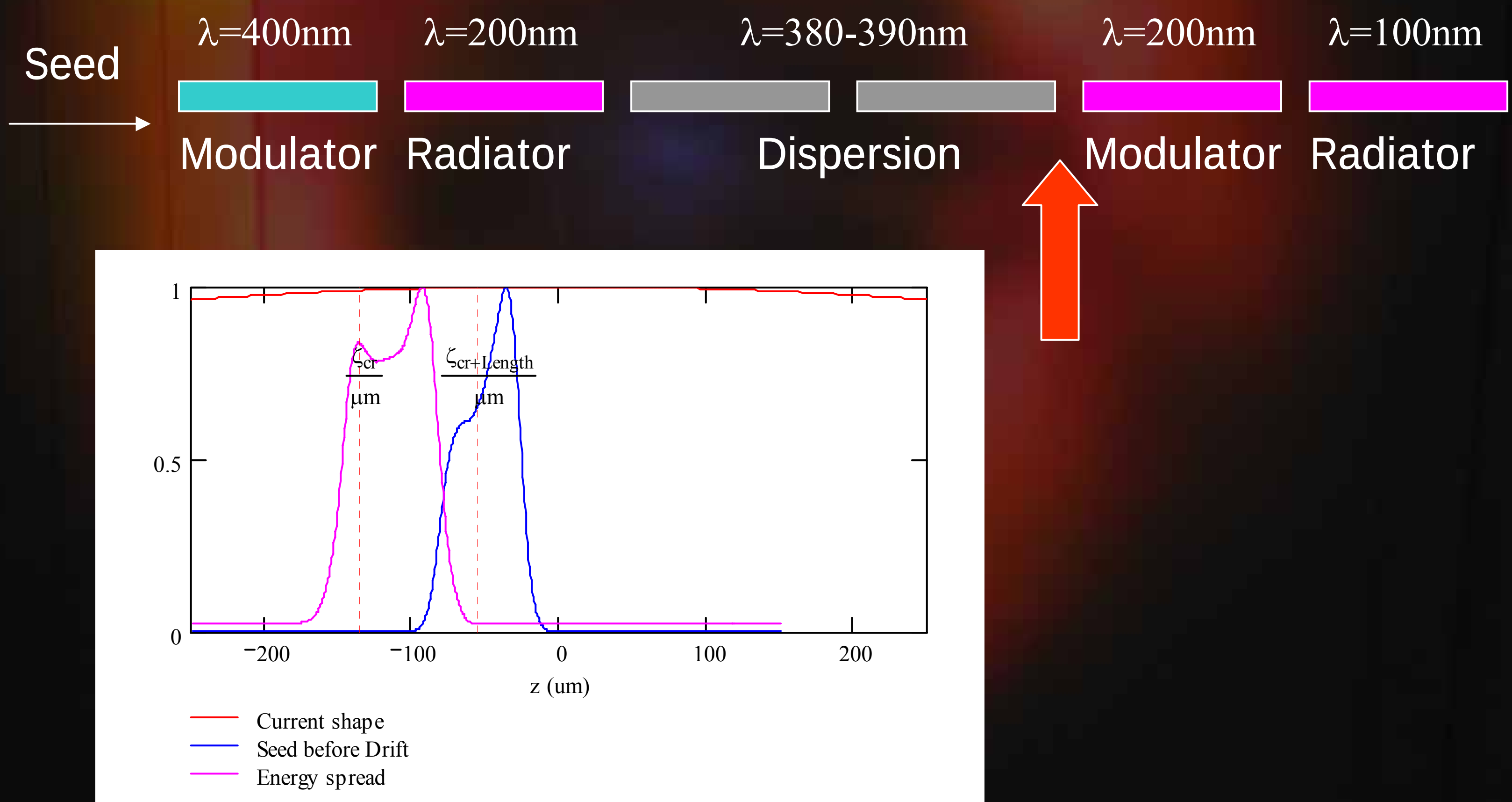




Double stage cascade

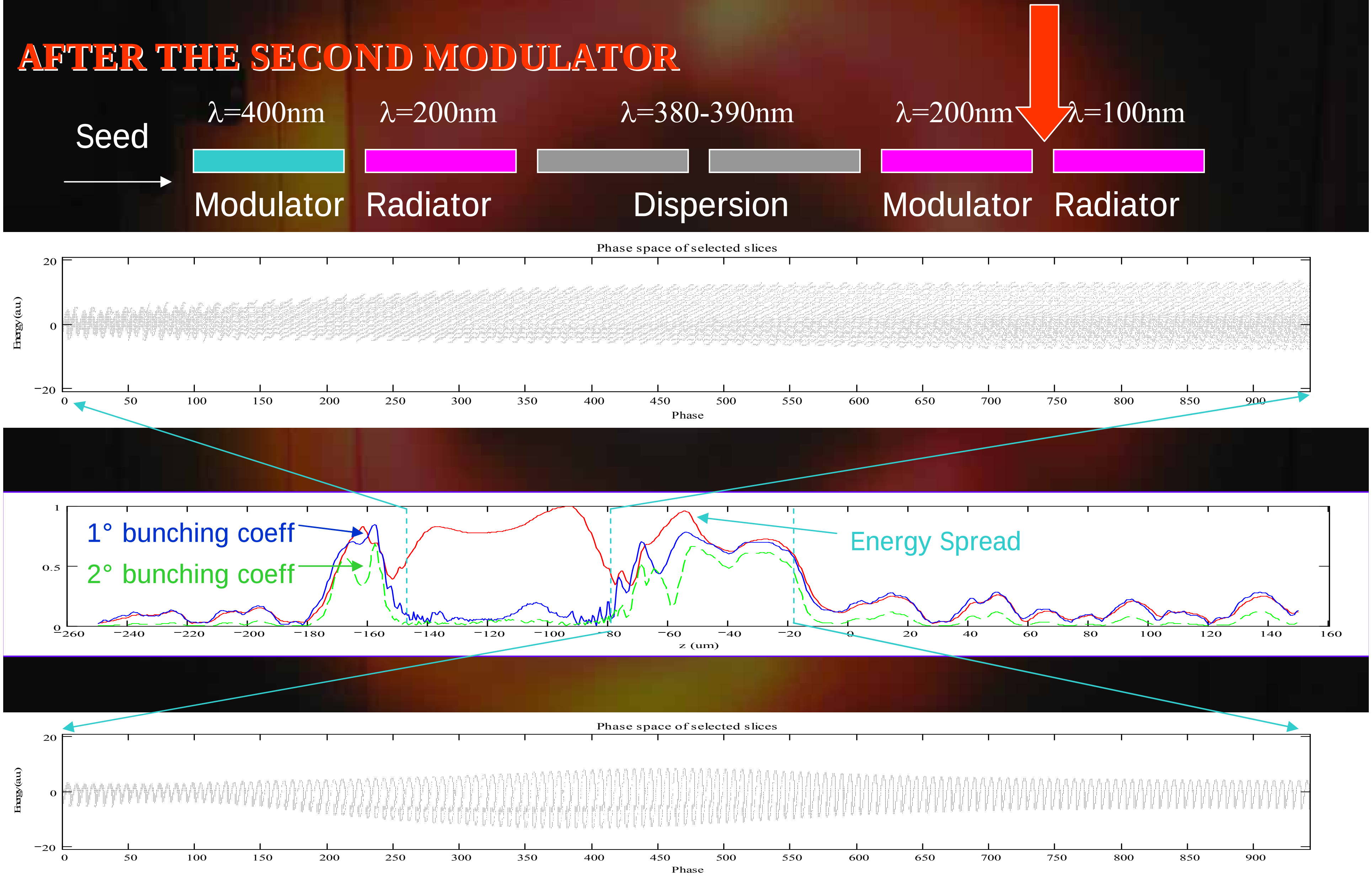
AFTER THE DISPERSIVE SECTION

Fresh Bunch injection technique



Double stage cascade

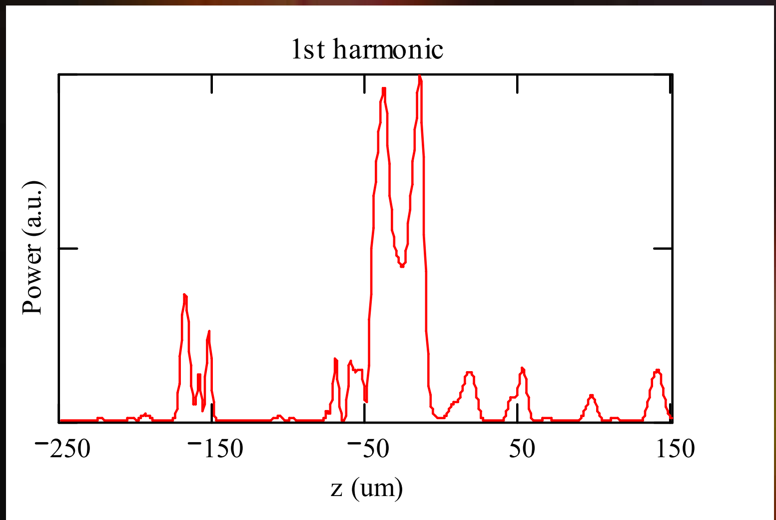
AFTER THE SECOND MODULATOR

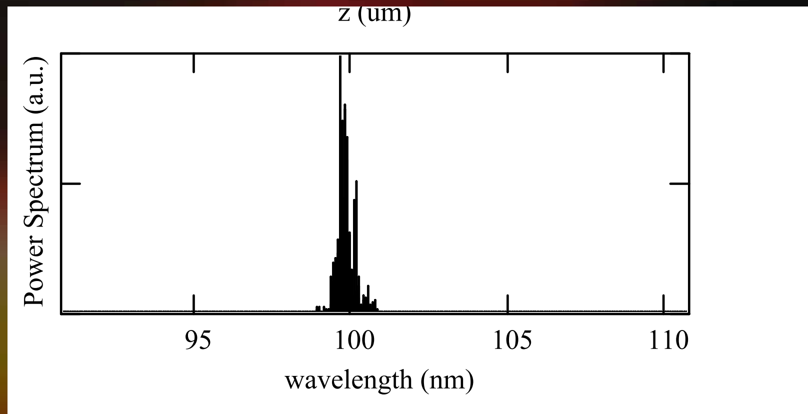


Double stage cascade

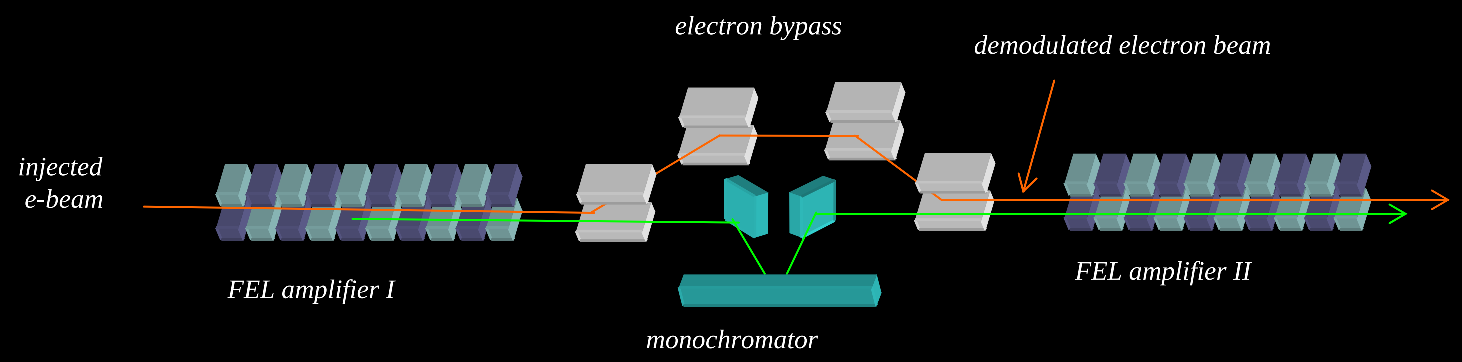
Fresh Bunch injection technique

Seed → λ=400nm Modulator | λ=200nm Radiator | λ=380-390nm Dispersion | λ=200nm Modulator | λ=100nm Radiator





Self seeding: Regenerative amplifier

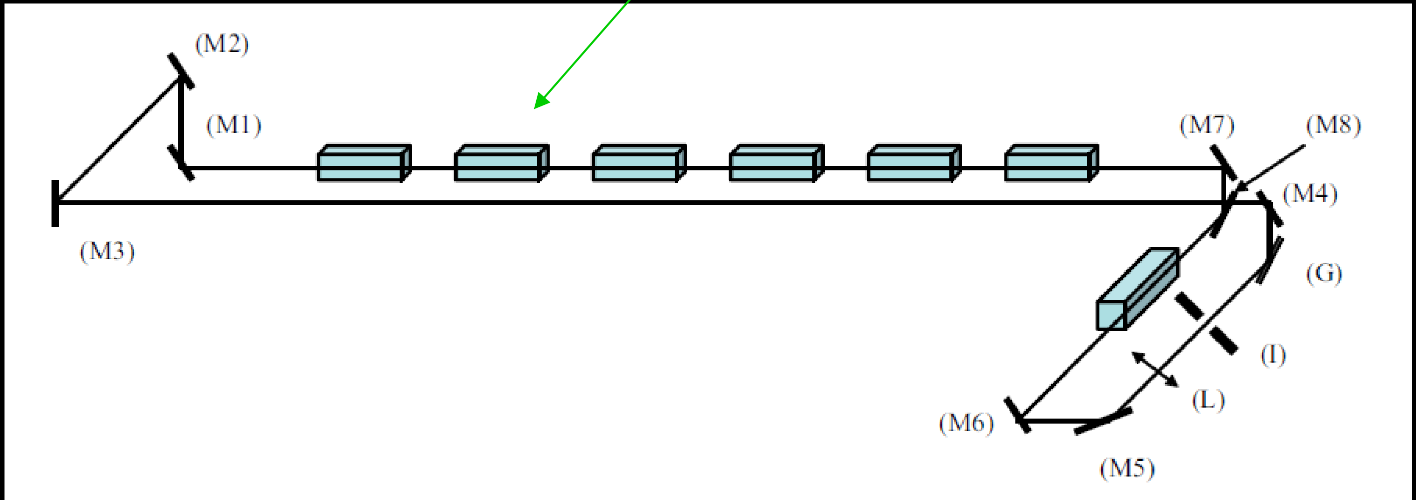


DESY

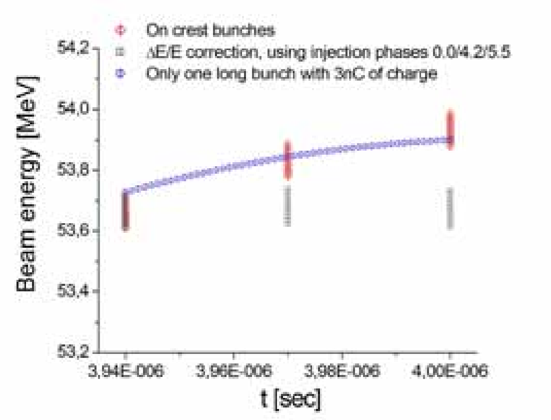
Same concept @ SPARC

Report: A. Bacci, L. G., M. Labat, B. Spataro SPARC-FEL-09/001

SPARC undulators



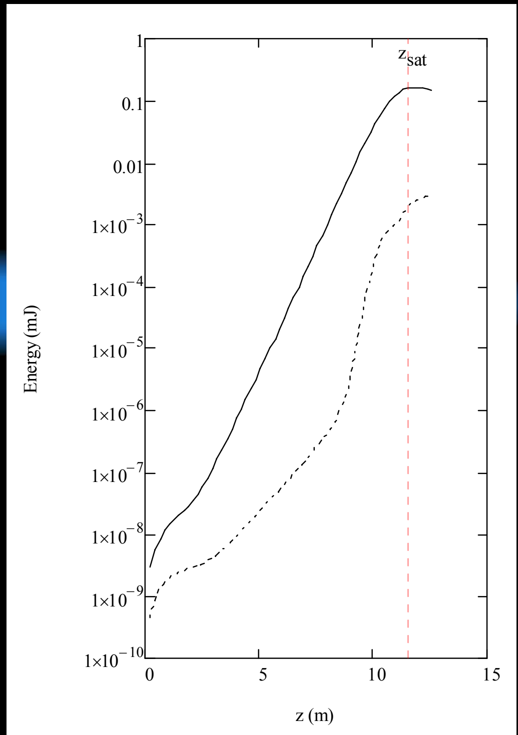
Small fraction of SASE re-injected as a seed



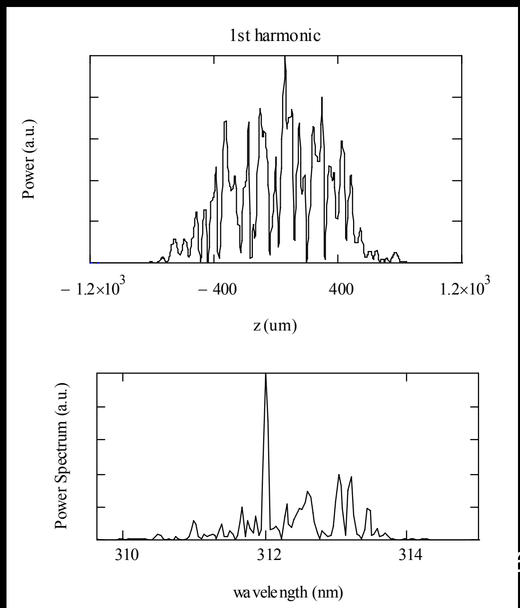
Simulation parameters

Electron beam	
Beam Energy	175 MeV
Beam Energy spread	4 10^{-4}
Beam Emittance	1.1
Peak current	100
Undulator	
Period	2.8 cm
Strength (K)	1.8
Periods/Module	75
Modules	6
Average Twiss β	1.8 m
Radiation	
Central wavelength	312.7 nm
Injection coupling	10^{-3}
Filter width (relative)	10^{-4}

1° pass

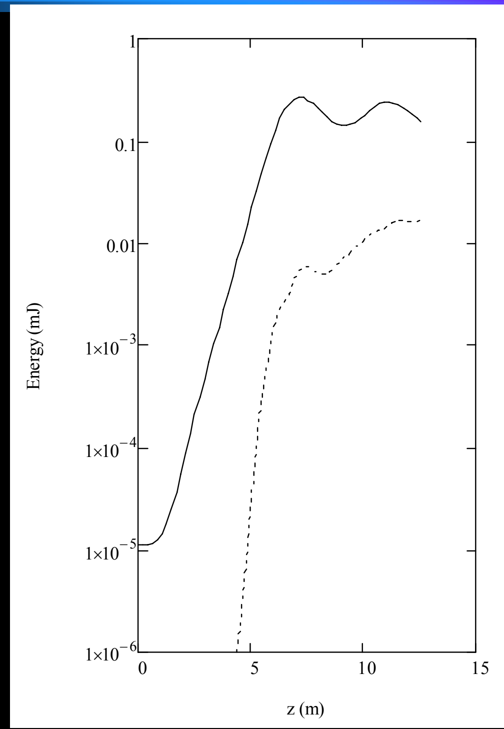


Energy (mJ)
z (m)
z_sat

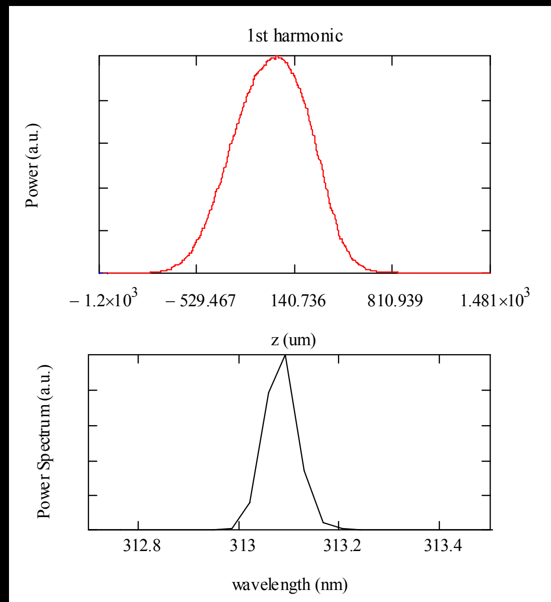


1st harmonic
Power (a.u.)
z (um)
Power Spectrum (a.u.)
wavelength (nm)

2° pass



Energy (mJ)
z (m)



1st harmonic
Power (a.u.)
z (um)
Power Spectrum (a.u.)
wavelength (nm)

Seeded SPARC wavelengths

Harmonics

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

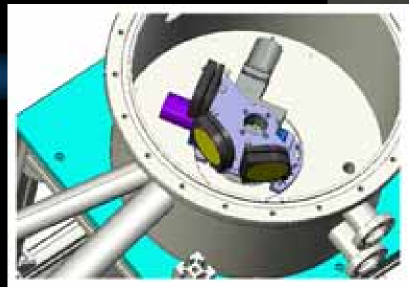
Seed/Fundamental

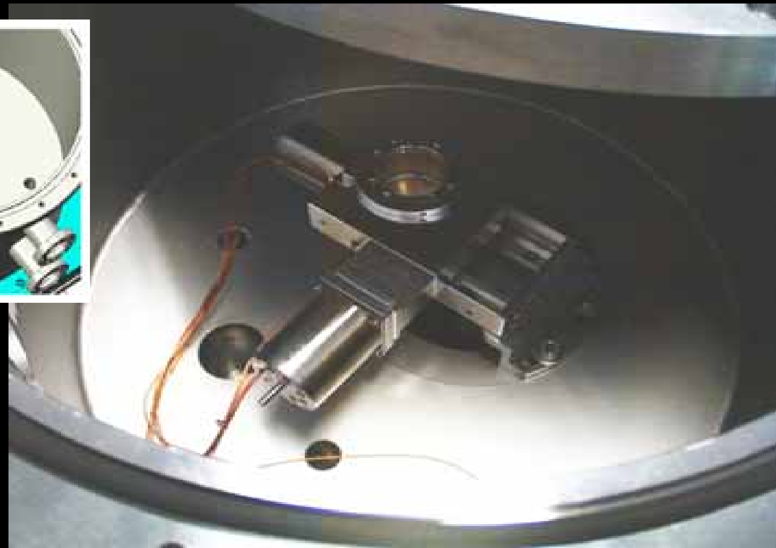
Laboratory for UV and X-ray Optical Research

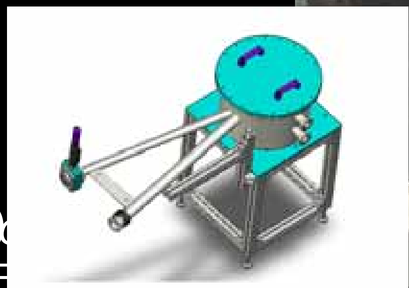
LUXOR

CNR-INFM

- Entrance slit:
  - minimum aperture 20 mm,
  - maximum aperture 2 mm
- Entrance/exit arms: ≈1 m
- Three gratings:
  - 600 gr/mm, 150-550 nm
  - 1200 gr/mm, 100-350 nm
  - 2400 gr/mm, 50-150 nm
- Acceptance
  - 25 mrad × 25 mrad (1.4 deg × 1.4 deg)
- CCD detector (Roper Scientific)
  - Thinned and back illuminated
  - Pixel size 20 mm
  - 1340 × 1340 pixel
- Resolving element
  - 0.034 nm/pixel (600 gr/mm)
  - 0.017 nm/pixel (1200 gr/mm)
  - 0.0084 nm/pixel (2400 gr/mm)

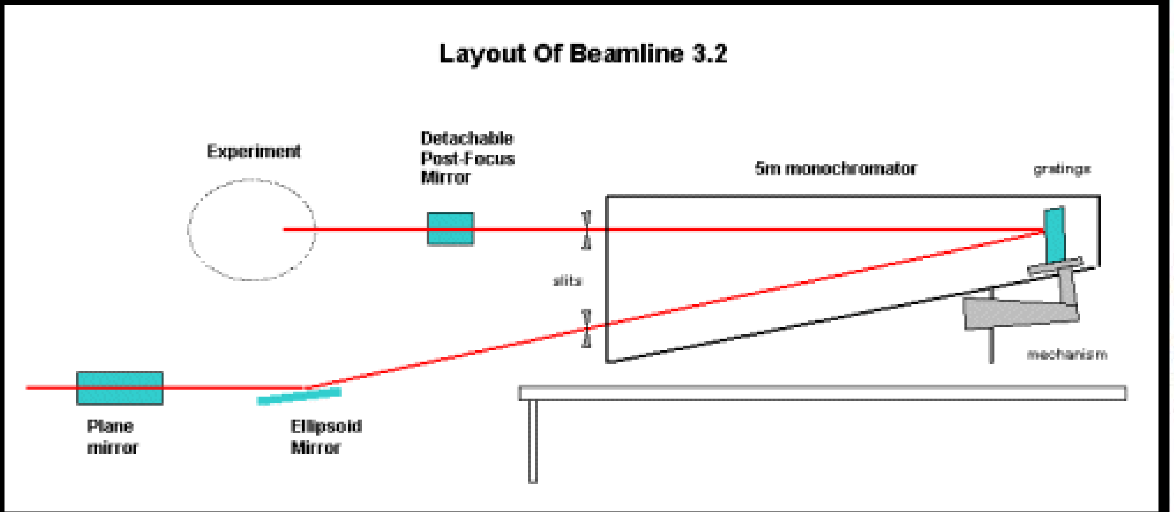




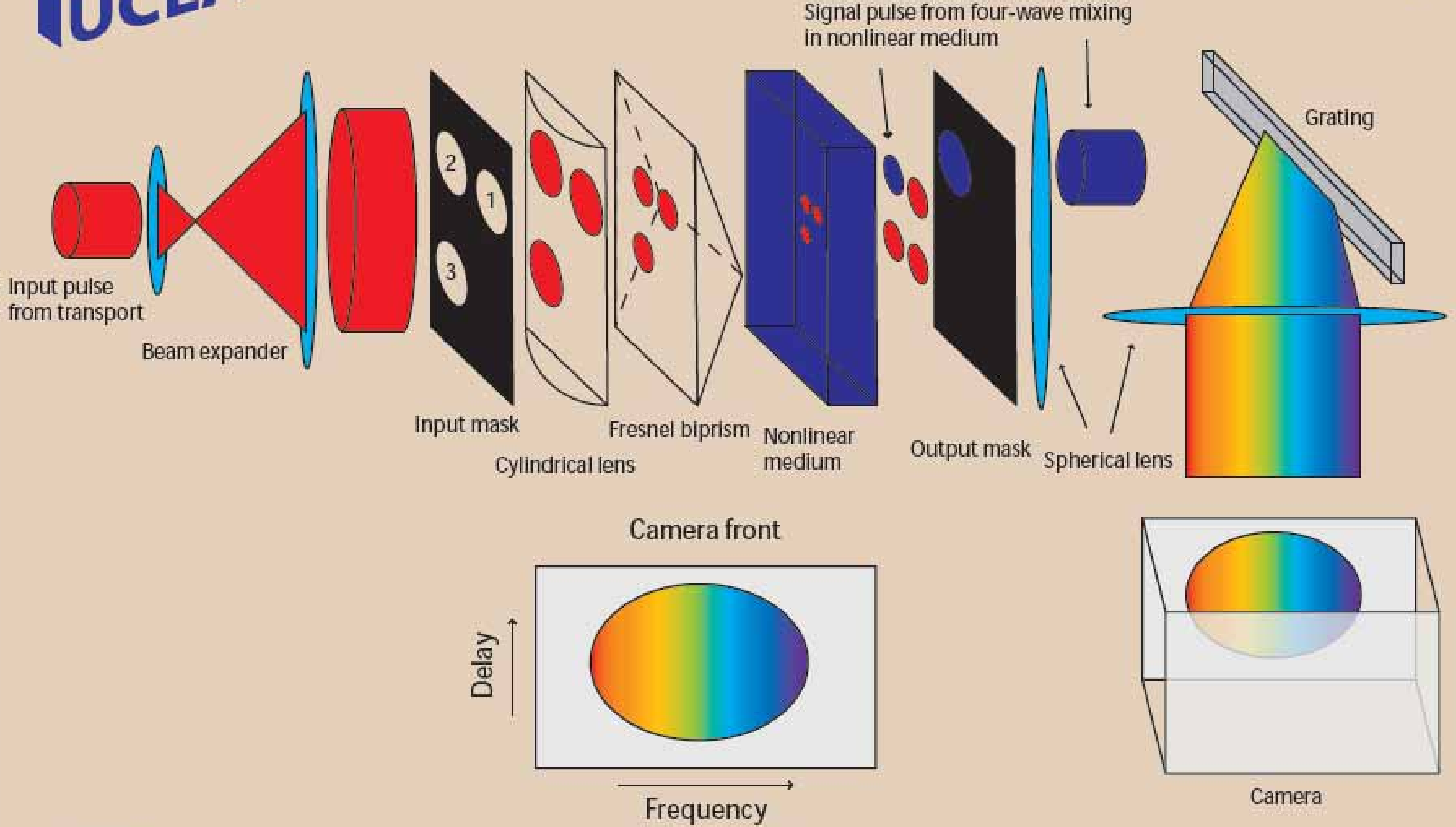


5m McPherson HiRes UV-VUV monochromator

Available for spectroscopy and photon diagnostics from SRS-Daresbury, beamline 3.2
2 concave gratings, 300 - 2500 Å, resolution < 0.05 Å
ref. Holland, NIM B **44** (1989) 233-241



TG FROG Geometry



2/18/09

Gabriel Marcus

Collaborazioni

- CEA/SOLEIL Seeding e generazione armoniche in gas
- Luxor Spettrometro VUV
- UCLA Diagnostiche ottiche (FROG UV)
- ST – short period undulators & Fresh bunch technique experiment
- Spettrometro 5m Daresbury ?

Conclusions and perspectives

- SPARC is an ideal test bench for single pass FEL physics
  - Compatibility of Ti:Sa Harmonics generated in gas with FEL gain filtering & cascades
  - Pulse evolution in a FEL amplifier
  - Fresh Bunch Injection Technique (full double stage cascade)
  - Superradiance and superradiant cascade
  - Test of harmonic cascade concept
  - Demonstrate VUV wavelength generation with a “low energy” electron beam

SPARC is a great opportunity