Seeding and harmonic generation in Free Electron Lasers

37th ICFA Beam Dynamics Workshop Future Light Sources
15 – 19 May 2006 DESY, Hamburg, Germany

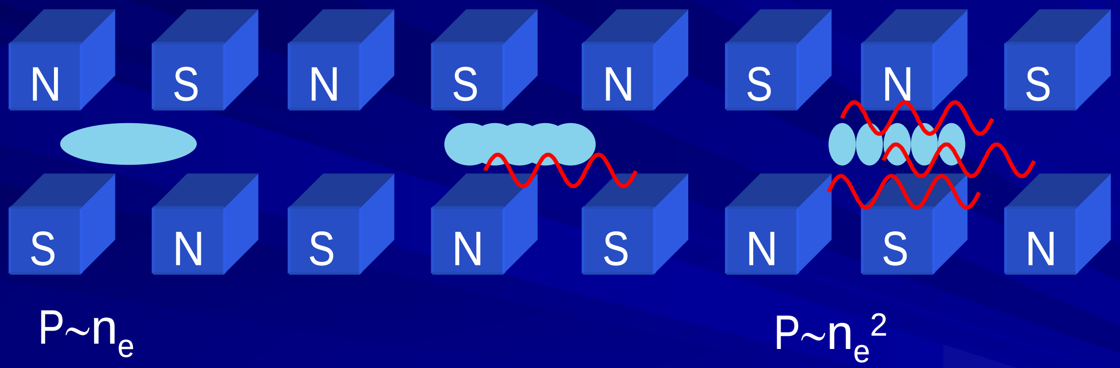
Luca Giannessi

May 17th 2006

Outline

- Harmonic Generation in FELs
- Cascaded configurations
- Multiple stage cascade and the energy budget – The Fresh bunch injection tecnique
- Superradiant cascade & Harmonic cascade
- Overview of proposed and existing projects
- Seeding with Ti:Sa harmonics generated in gas
- Conclusions

Single pass Free Electron Laser

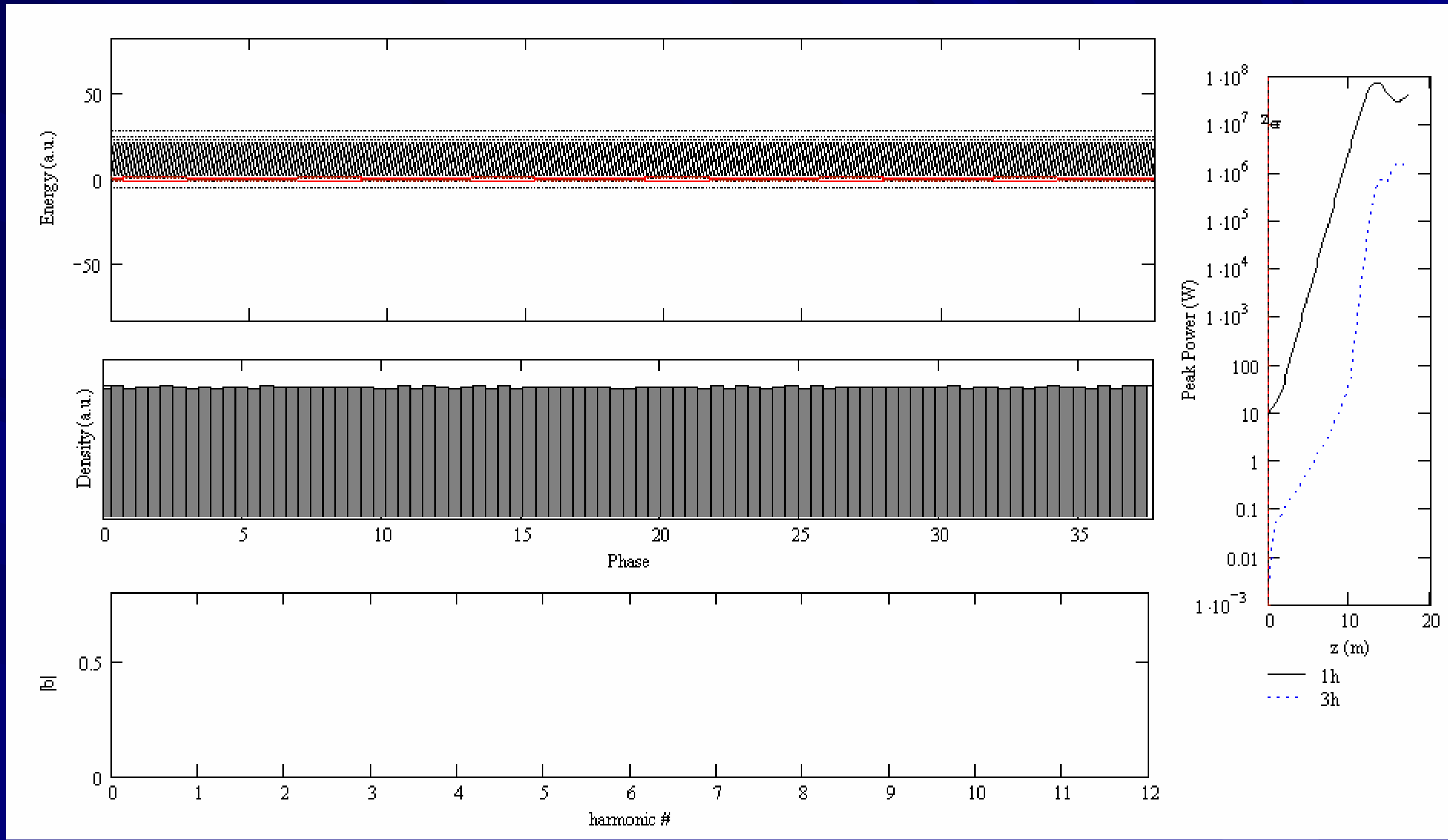


A close look at the bunching process

Phase space
Energy/position

Longitudinal density ρ

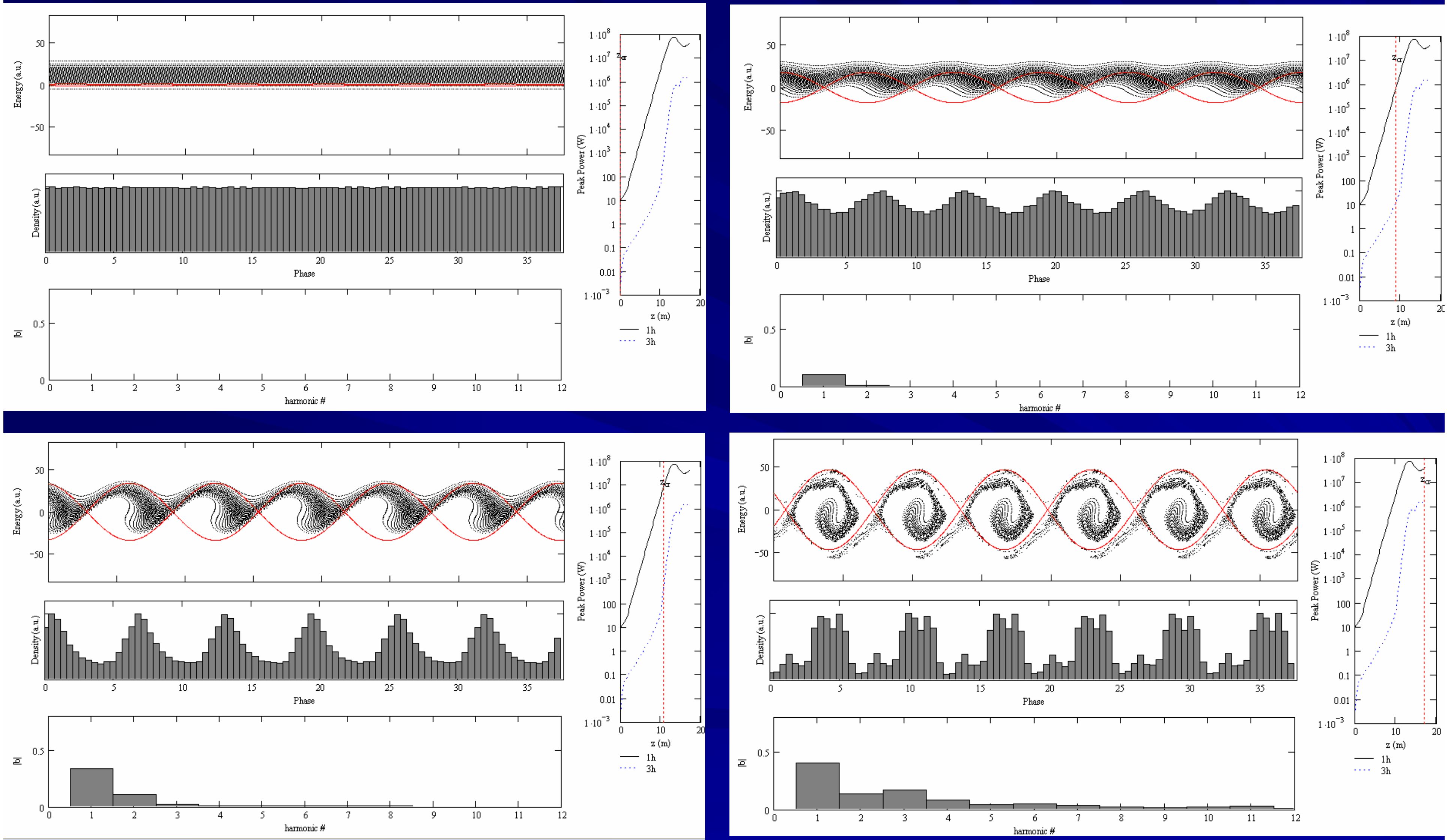
n^{th} Fourier coefficients of ρ



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

Higher order harmonics

Expanded Movie file: beam_bunching_2



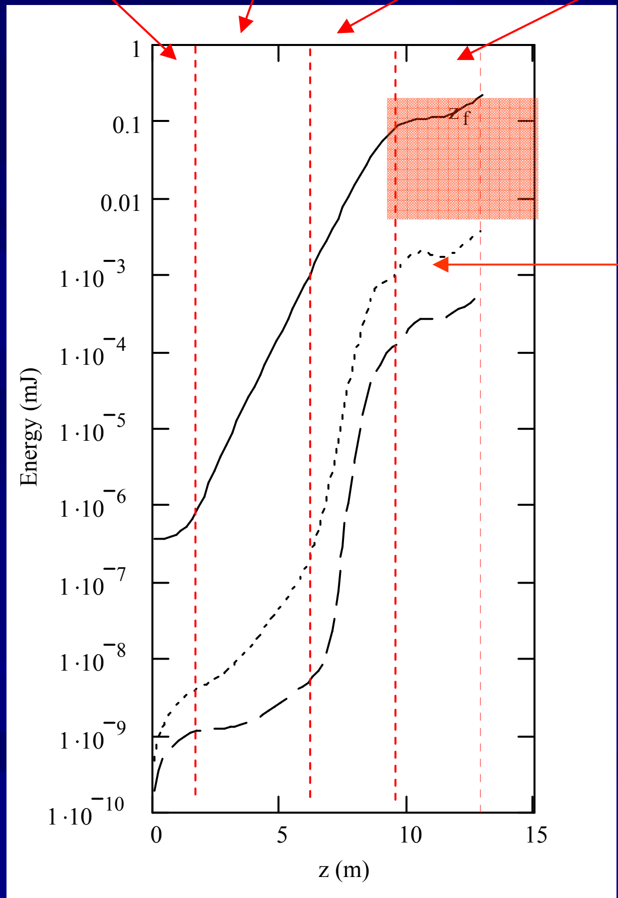
Cascaded FEL configuration

Energy modulation

Exponential

Saturaton

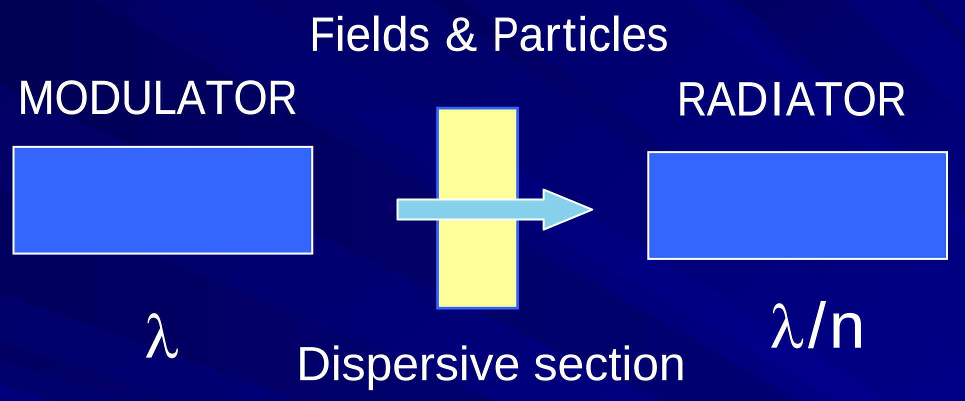
Deep Saturaton



Harmonic Saturation

Saturation of the harmonics signal is induced by overbunching at the first harmonic

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)

R. Bonifacio et al. NIM A296, 787 (1990)

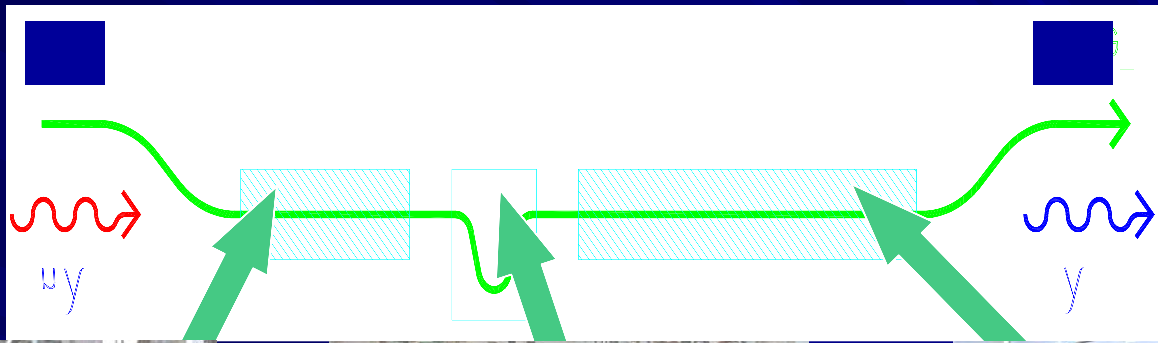
L. H. Yu, PRA 44, 5178 (1991)

… and several other authors

Courtesy of I. Ben Zvi

The HGHG Experiment

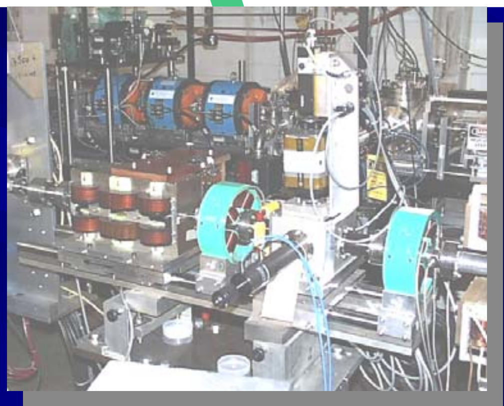
Seed Laser
λ=10.6μm
P_{pk}=0.7 MW



HGHG FEL
λ=5.3 μm
P_{pk}=35 MW

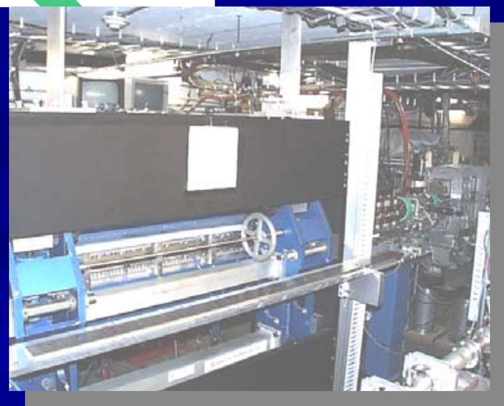
Modulator Section

B_w=0.16T λ_w=8cm L=0.76 m



Dispersion Section

L=0.3 m



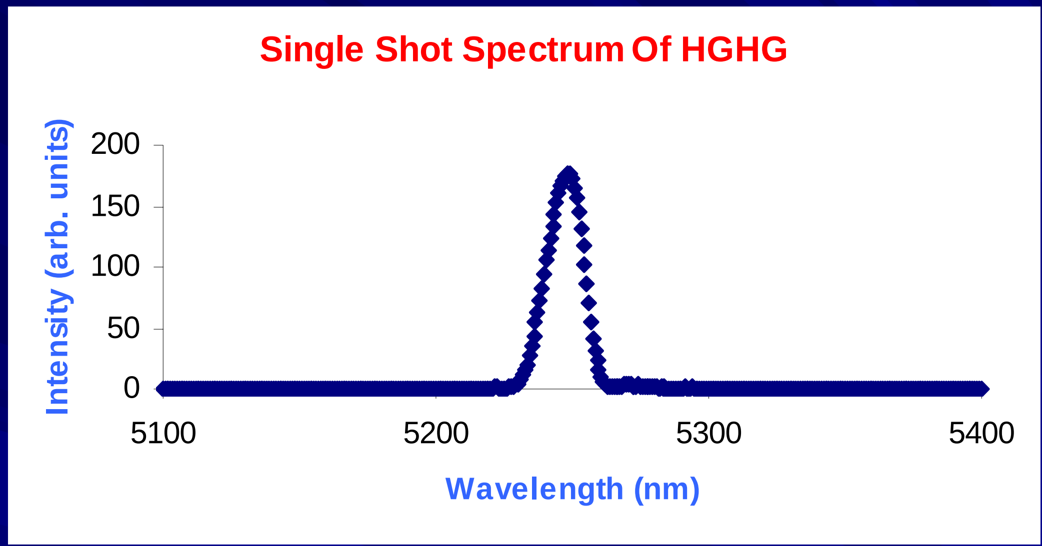
Radiator Section

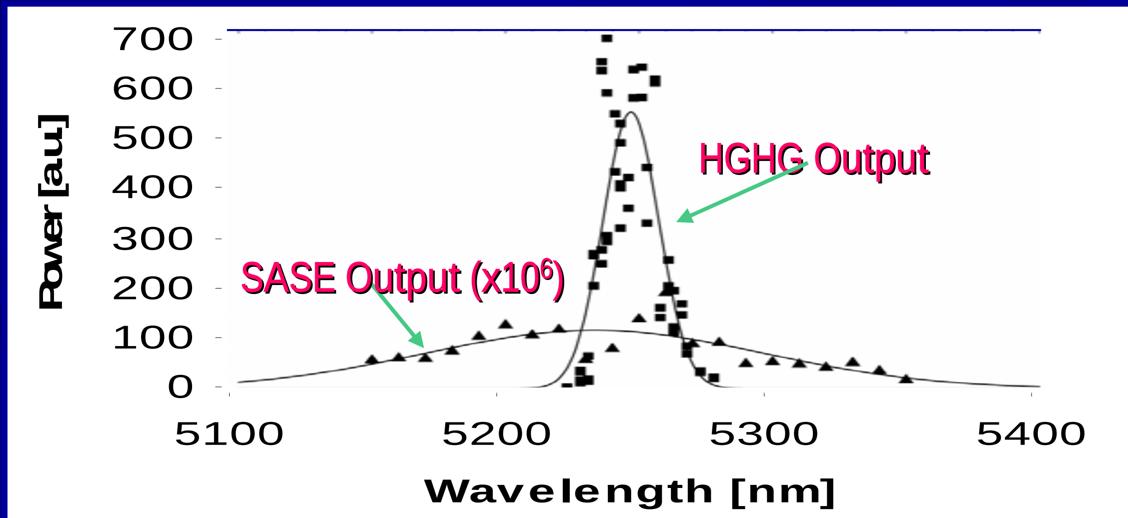
B_w=0.47T λ_w=3.3cm L=2 m

Electron Beam Input Parameters: E= 40 MeV

ε_n= 4π mm-mrad $d\gamma/\gamma$=0.043% I = 110A τ_e= 4 ps

The HGHG Experiment





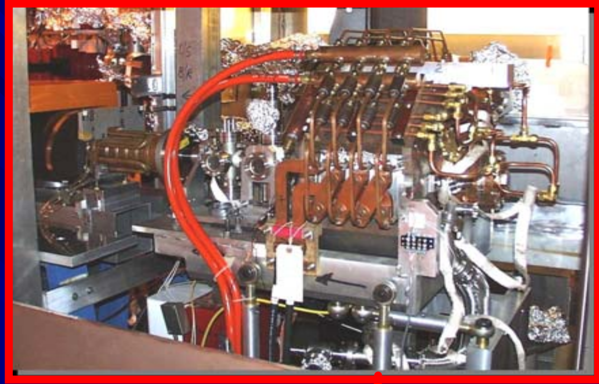
L. H. Yu et al. Science **289** (2000) 932

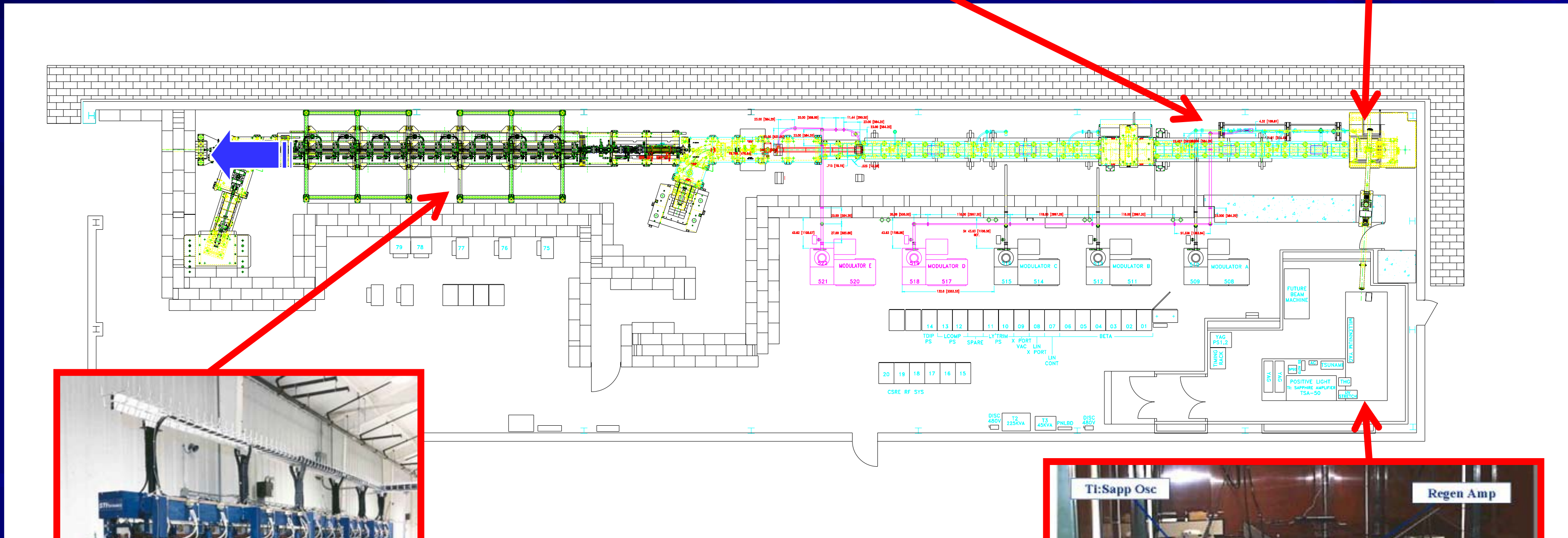
Courtesy of J.B. Murphy

NSLS SDL

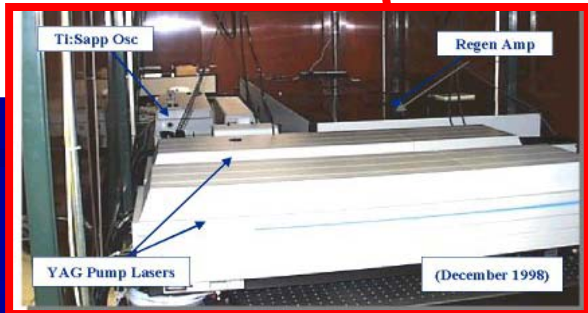
300 MeV S-Band Linac

BNL Photoinjector IV





10 m NISUS Wiggler



Titanium Sapphire Laser

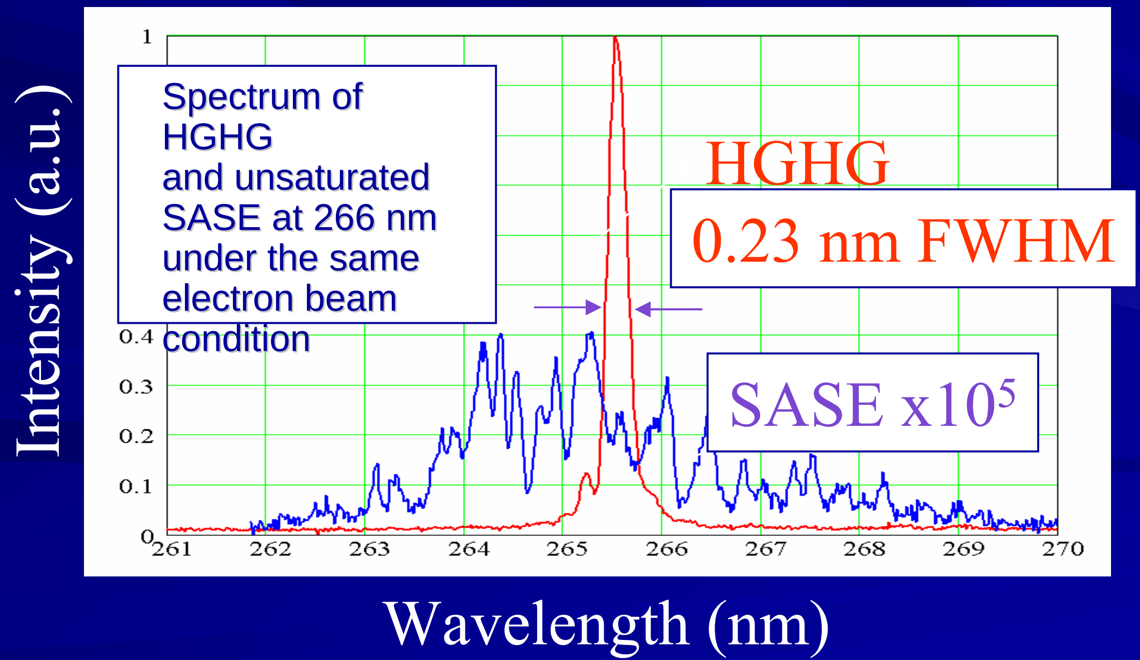
Seeding @ 800 nm

VOLUME 91, NUMBER 7 PHYSICAL REVIEW LETTERS week ending 15 AUGUST 2003

First Ultraviolet High-Gain Harmonic-Generation Free-Electron Laser

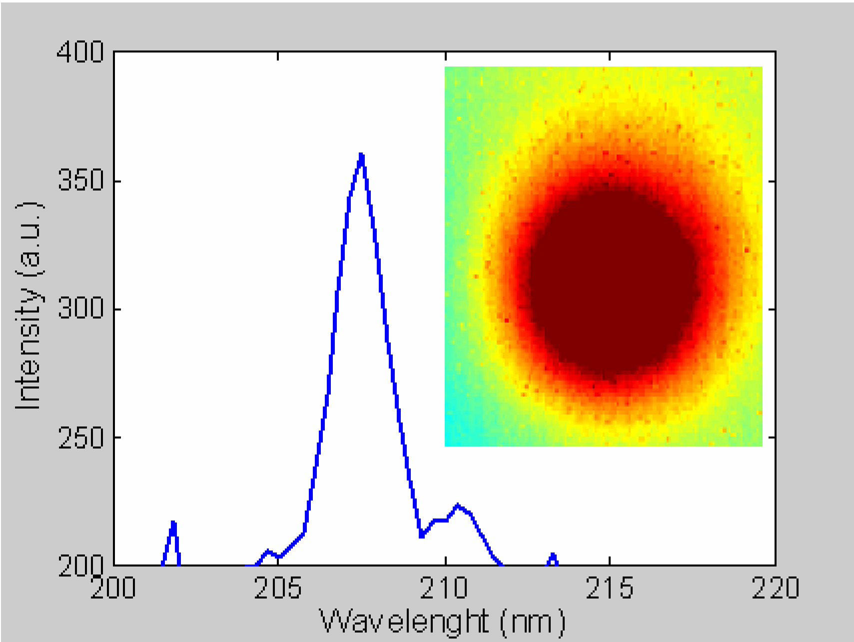
L. H. Yu,* L. DiMauro, A. Doyuran, W. S. Graves,† E. D. Johnson, R. Heese, S. Krinsky, H. Loos, J. B. Murphy, G. Rakowsky, J. Rose, T. Shaftan, B. Sheehy, J. Skaritka, X. J. Wang, and Z. Wu

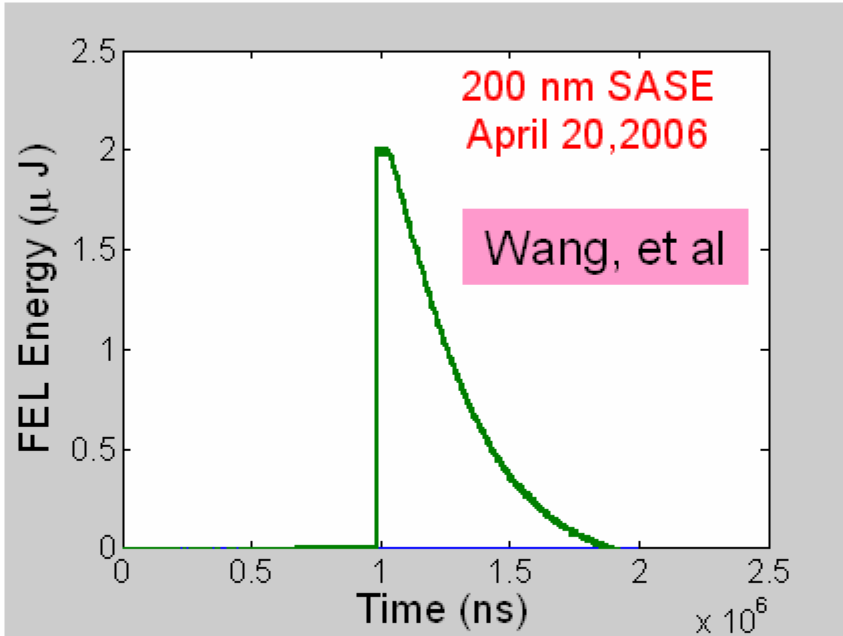
800 -> 266



Ultra-Violet FEL Operation

SDL Shortest Fundamental λ was 266 nm





HGHG 800 → 200 nm

with 10 μJ output measured

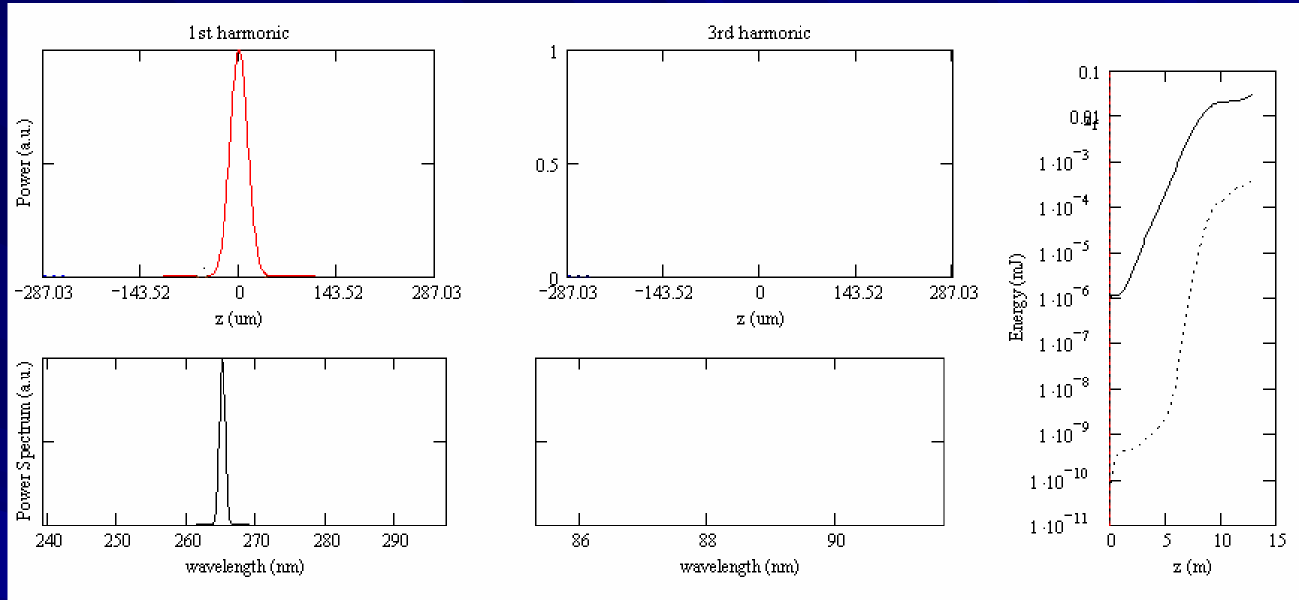
Office of Science
U.S. DEPARTMENT OF ENERGY

Courtesy of J.B. Murphy, X.J. Wang

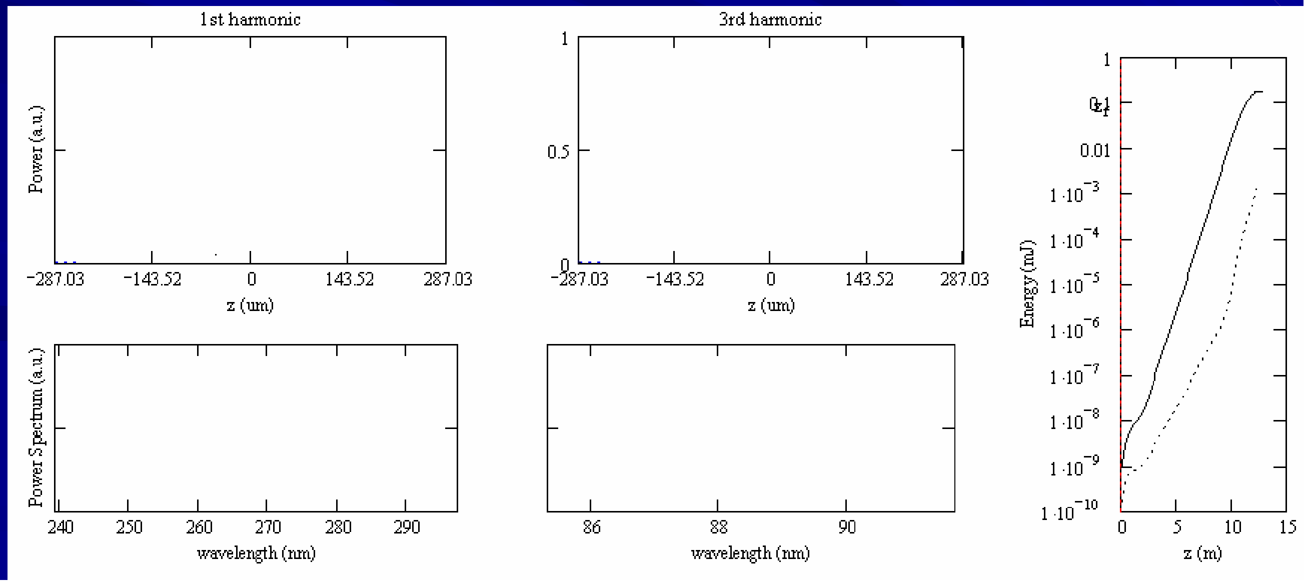
BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

SASE & Seeded pulse & spectra

Seeded

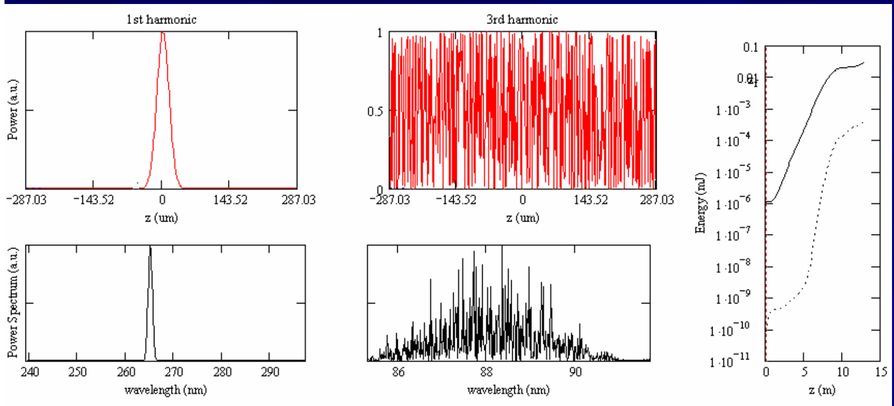


SASE

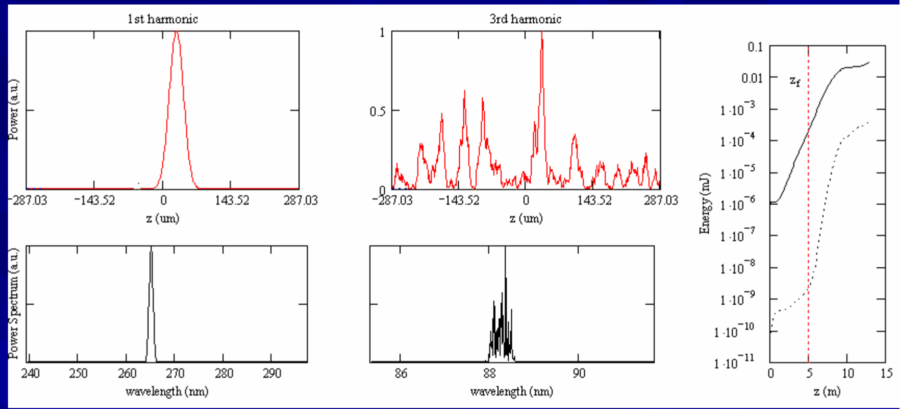


Seeded pulse & spectra, movie file: seed266.avi

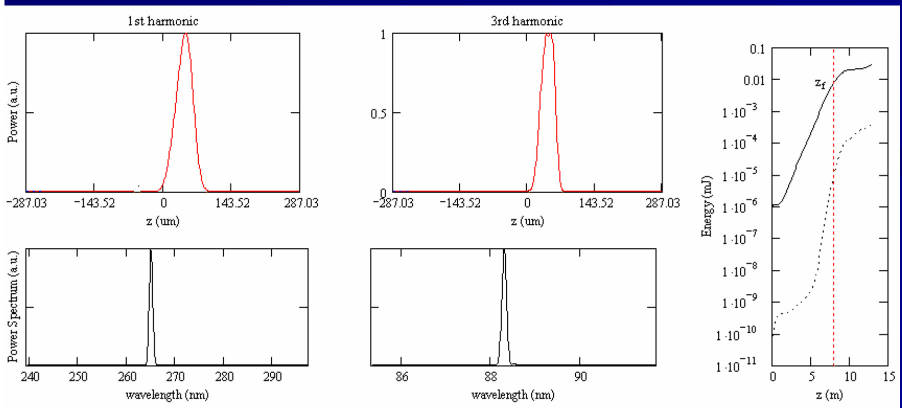
1



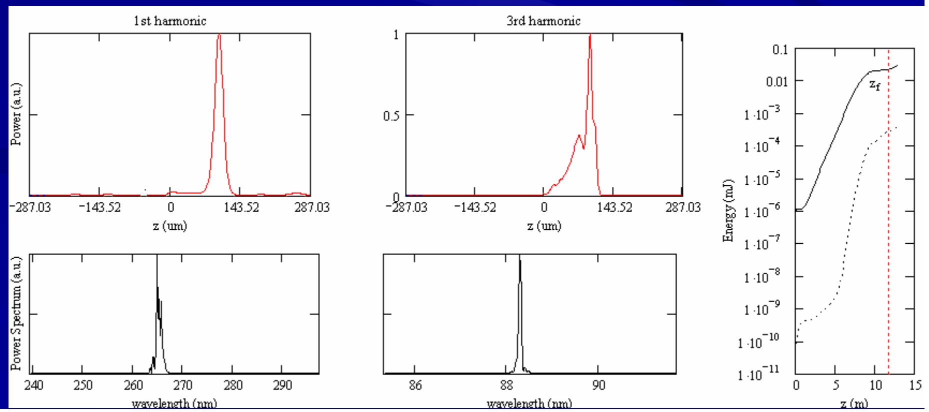
2



3



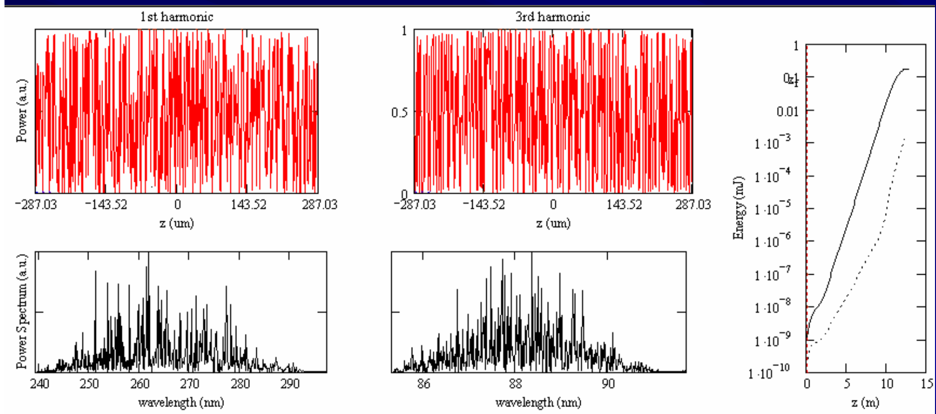
4



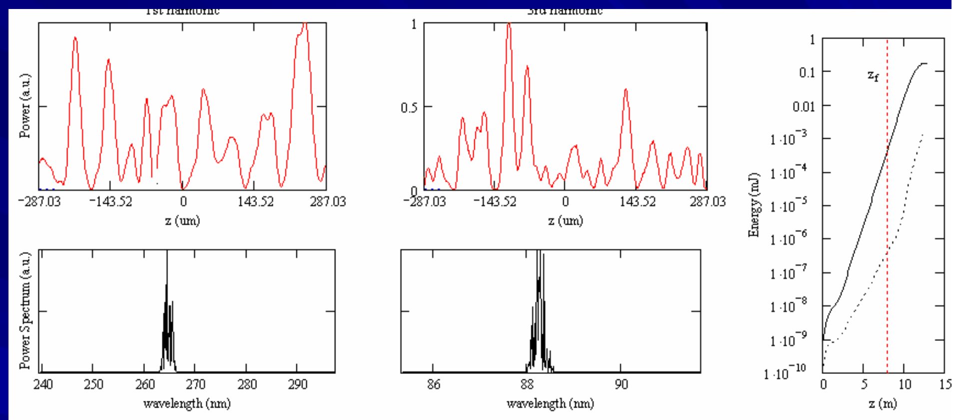
SASE pulse & spectra, movie file: seed266.avi

note the pulses structure from image 2 (3° Harm SASE) to image 3 (3° Harm induced by SASE on the fundamental harmonic)

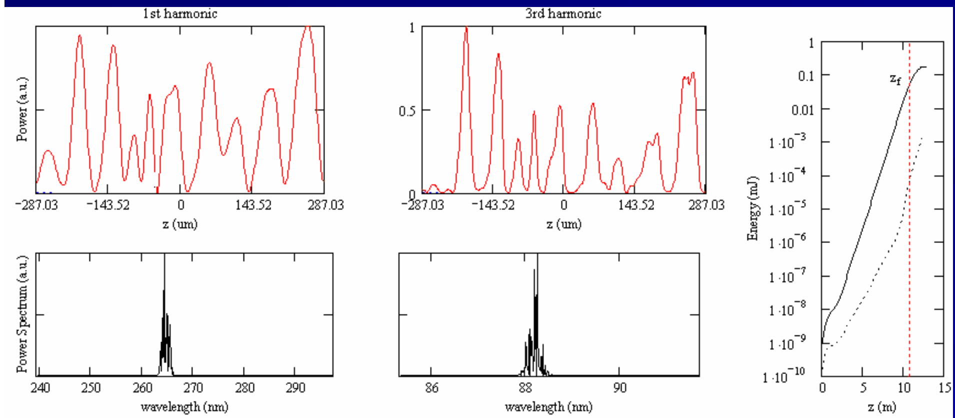
1



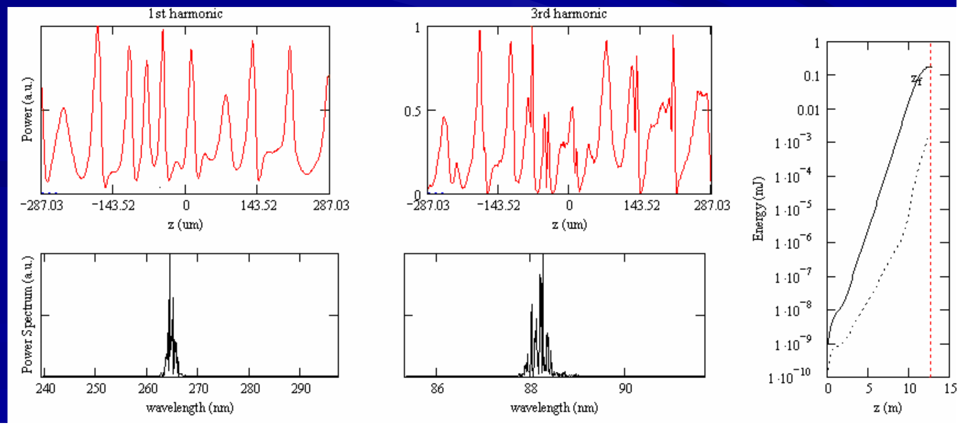
2

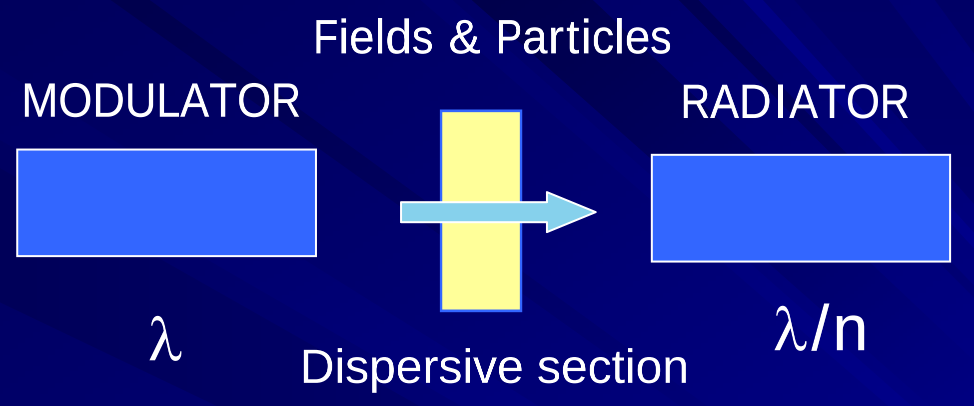


3



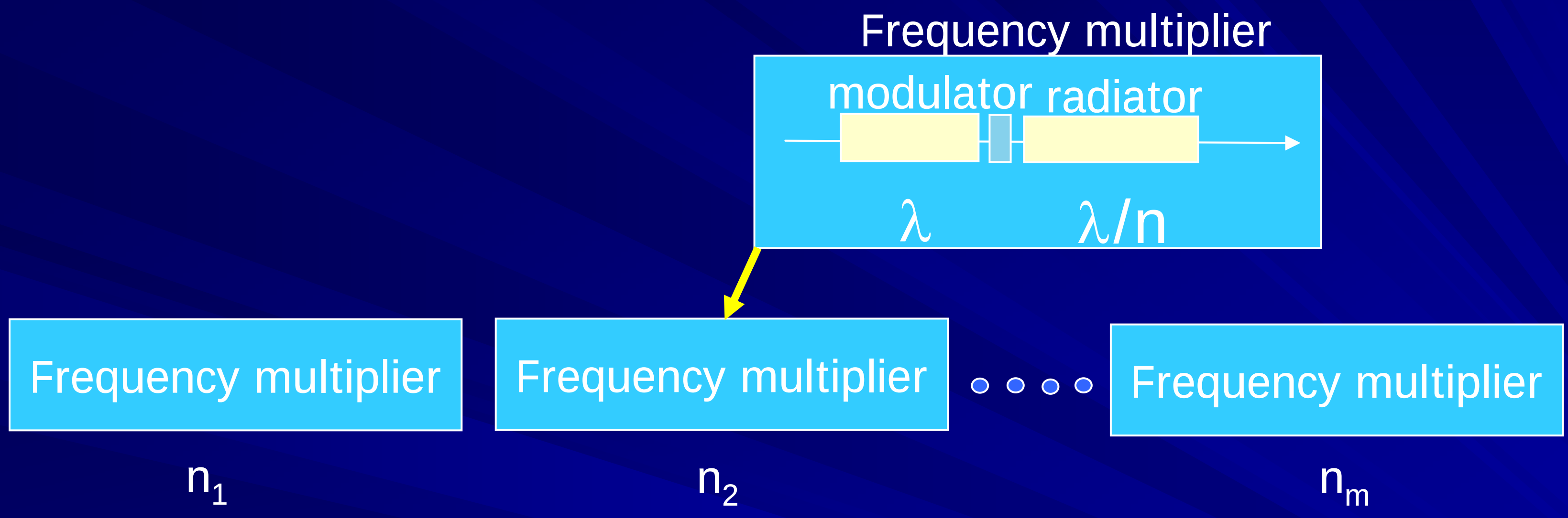
4





- Reduced intrinsic fluctuations
- Coherence properties (transverse/longitudinal) determined by the seed
- Narrow bandwidth limited by e-bunch length
- Coherent techniques, such as CPA and compression
- Wavelength tuning by bunch compression *(T.Shaftan, L. H Yu Phys. Rev. E **71**, 046501 (2005))*

Multiple stage cascade and the energy spread budget



- Required energy spread in order to bunch at the n^{th} harmonic (Liouville's theorem)

$$\sigma_{induced} \approx 2n\sigma_{initial}$$

- Effective number of periods in the radiator (dispersion)

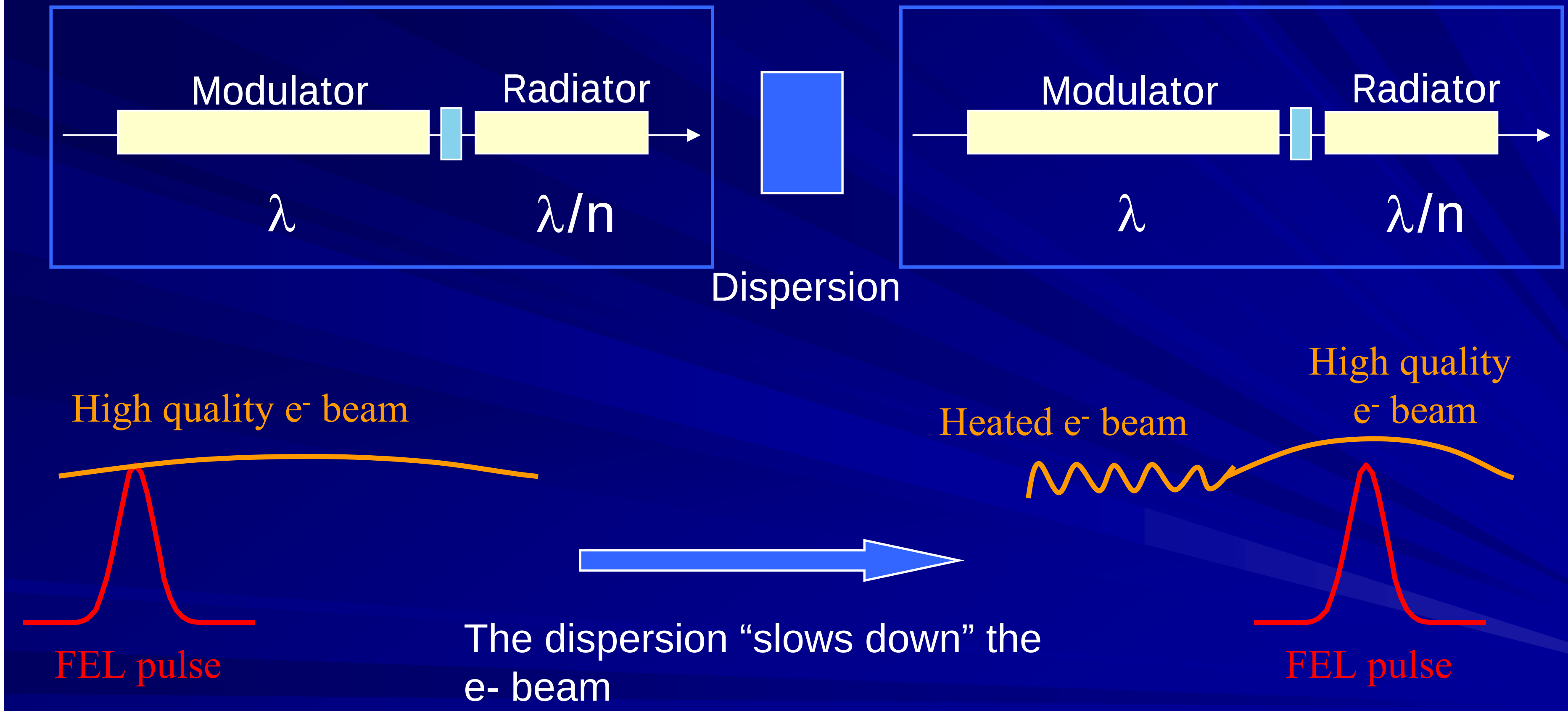
$$N \approx \frac{1}{8n\sigma_{initial}}$$

Example:

$$\sigma_{initial} = 3\times10^{-4}$$
$$n = 4\times3 = 12$$
$$N \approx 26$$

Alternative:
the Fresh bunch injection Technique

The Fresh bunch injection technique

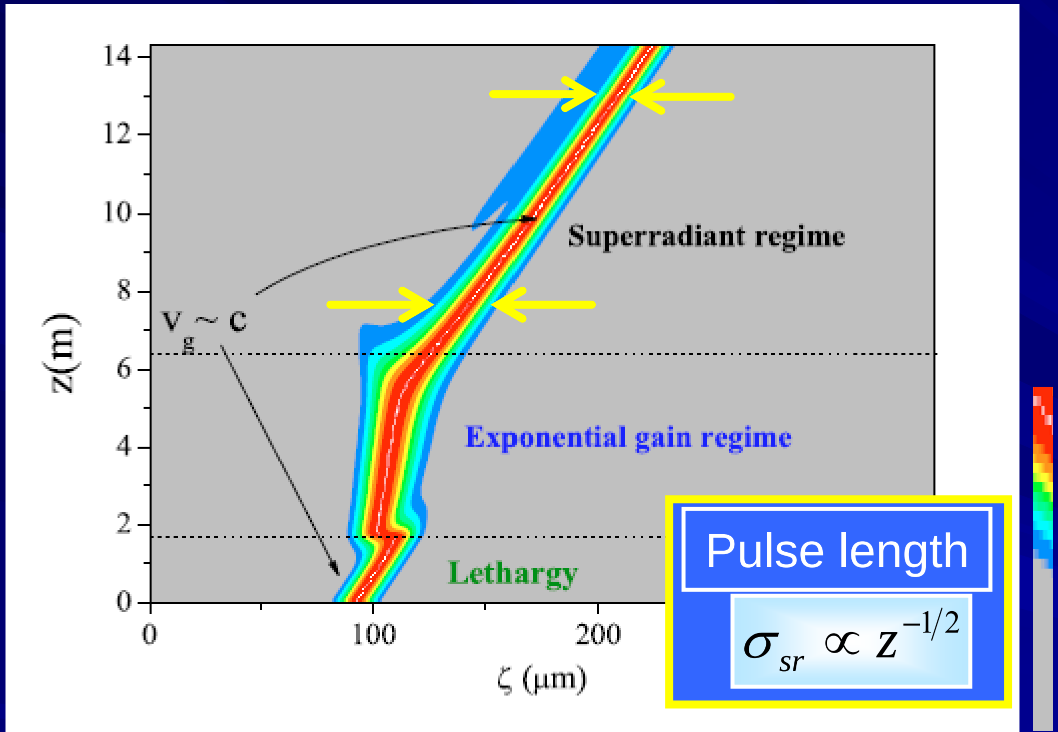


*L. H. Yu, I. Ben-Zvi NIM A**393** (1997) 96*

Short pulses and the Superradiant regime

(Genesis 1.3)

Distance along the undulator



Pulse length

$\sigma_{sr} \propto z^{-1/2}$

Distance along the e-bunch

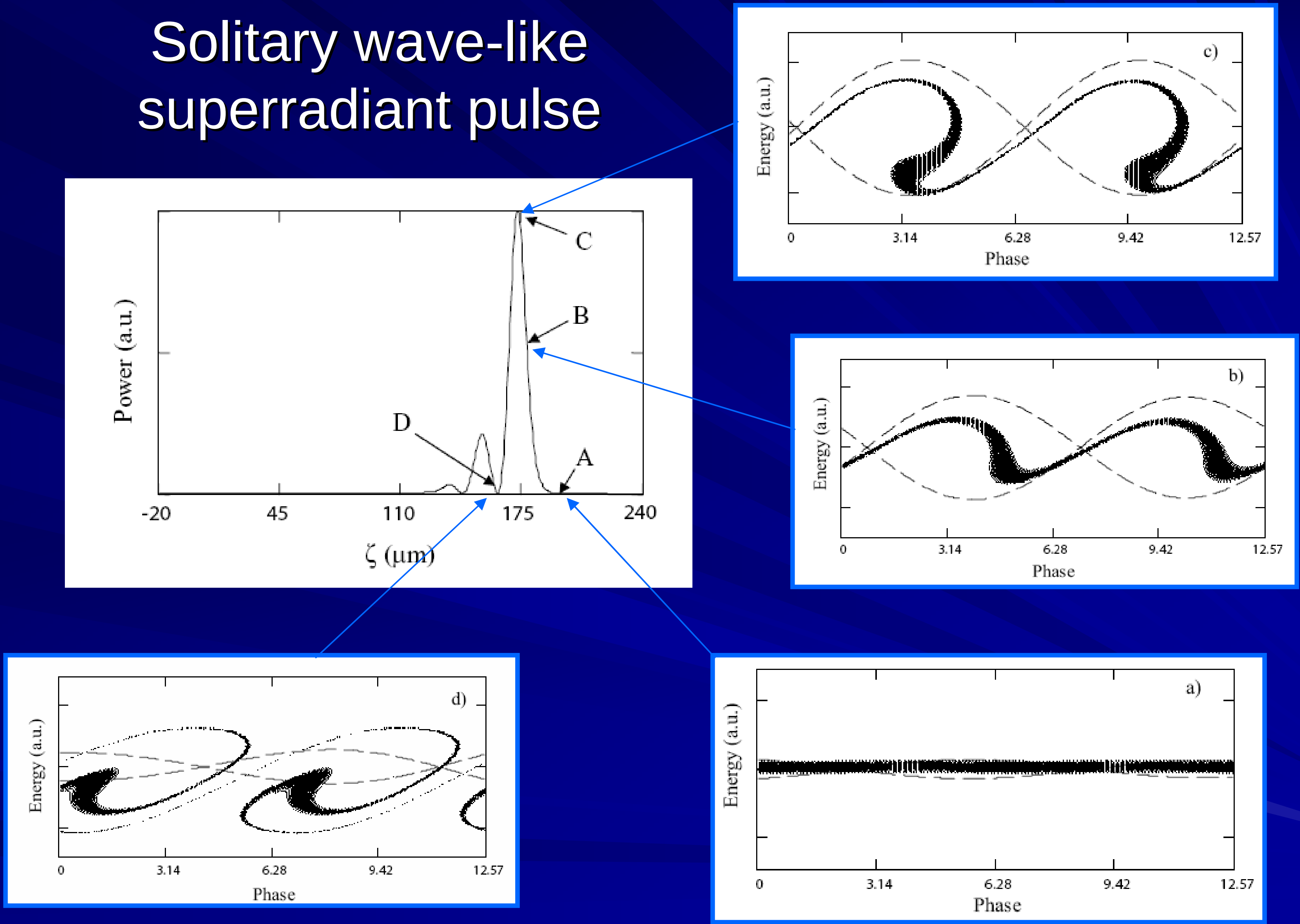
Relation pulse length/Power

$$\tau = \frac{\lambda}{2}\frac{\sqrt{1+K^2/2}}{\sqrt{2 f_B(\xi)} K K_R} \propto \frac{\lambda}{P_L^{1/4}}$$

$$P_L \propto z^2$$

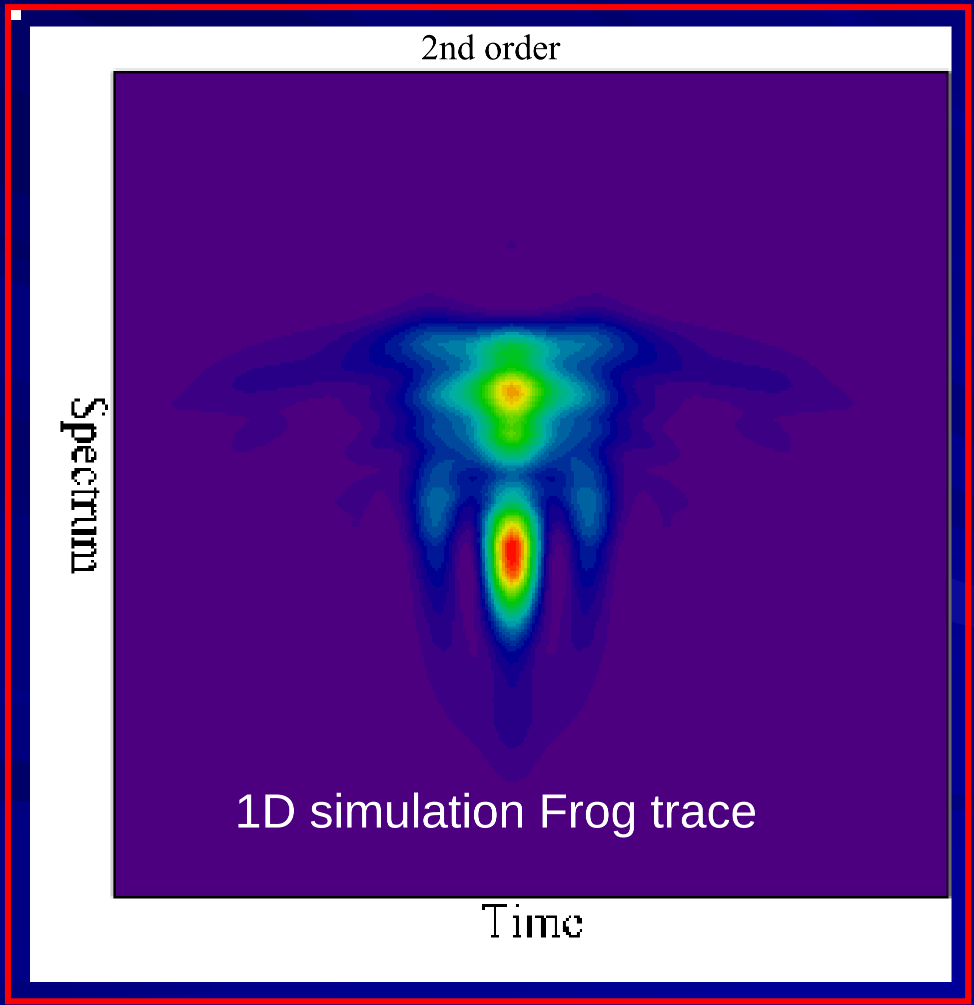
R. Bonifacio, B. W. J. Mc Neil, P. Pierini, PRA 40, 4467 (1989)
N. Piovella, Opt. Comm. 83, 92 (1991)

Solitary wave-like superradiant pulse



2° order FROG trace of the superradiant pulse,

reconstructed from 1D PERSEO simulation



Femto-second FEL Pulse Characterization

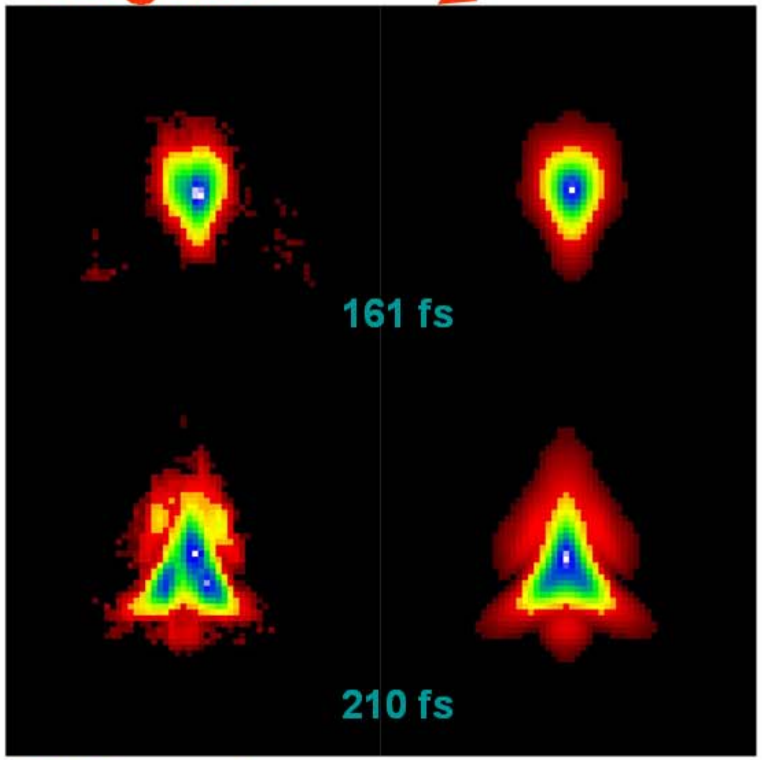
From Exponential Growth to Superradiance

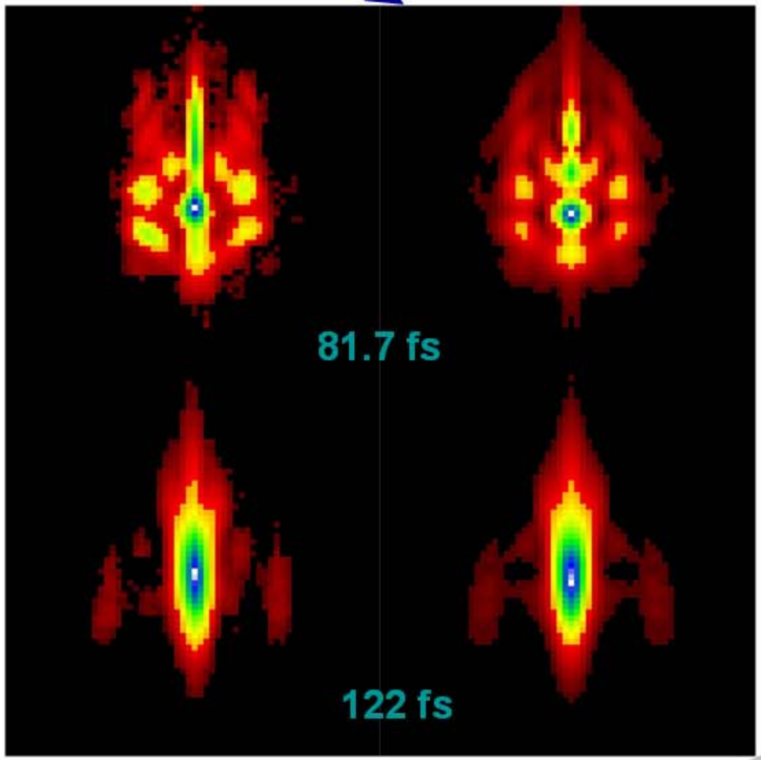
With 150 fs Seed Laser

Exponential Regime

EXPERIMENT

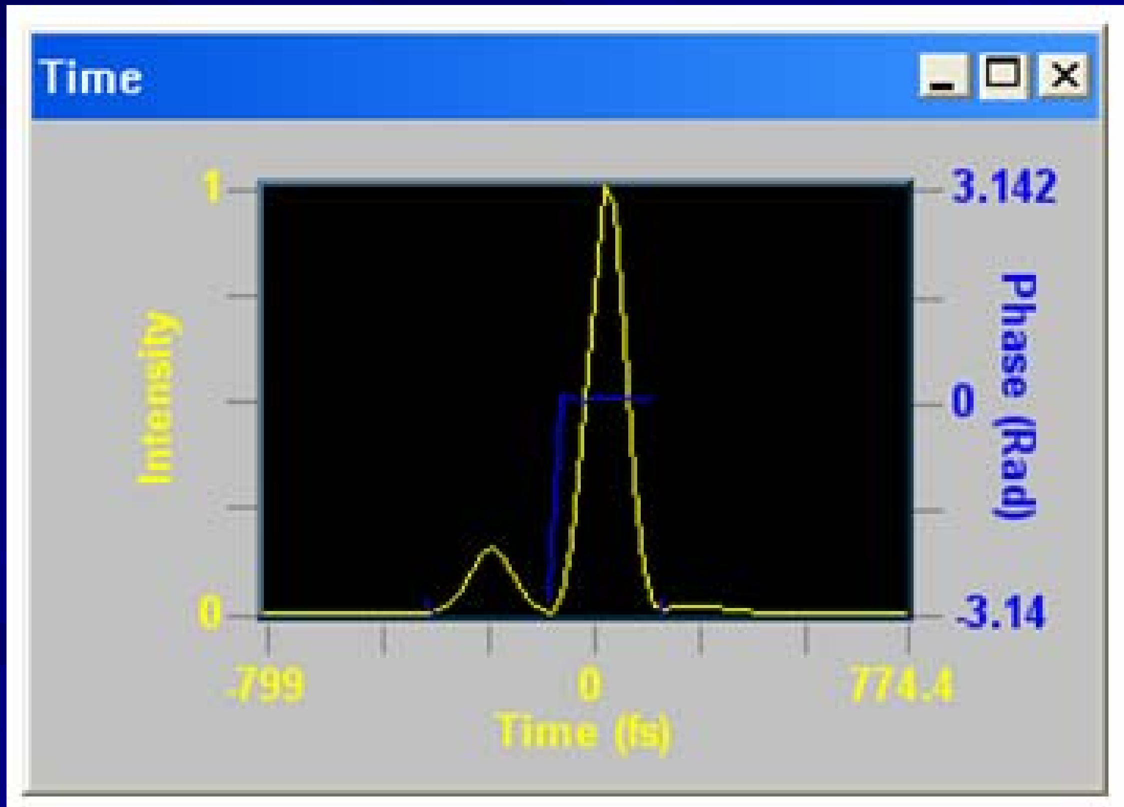
Superradiance

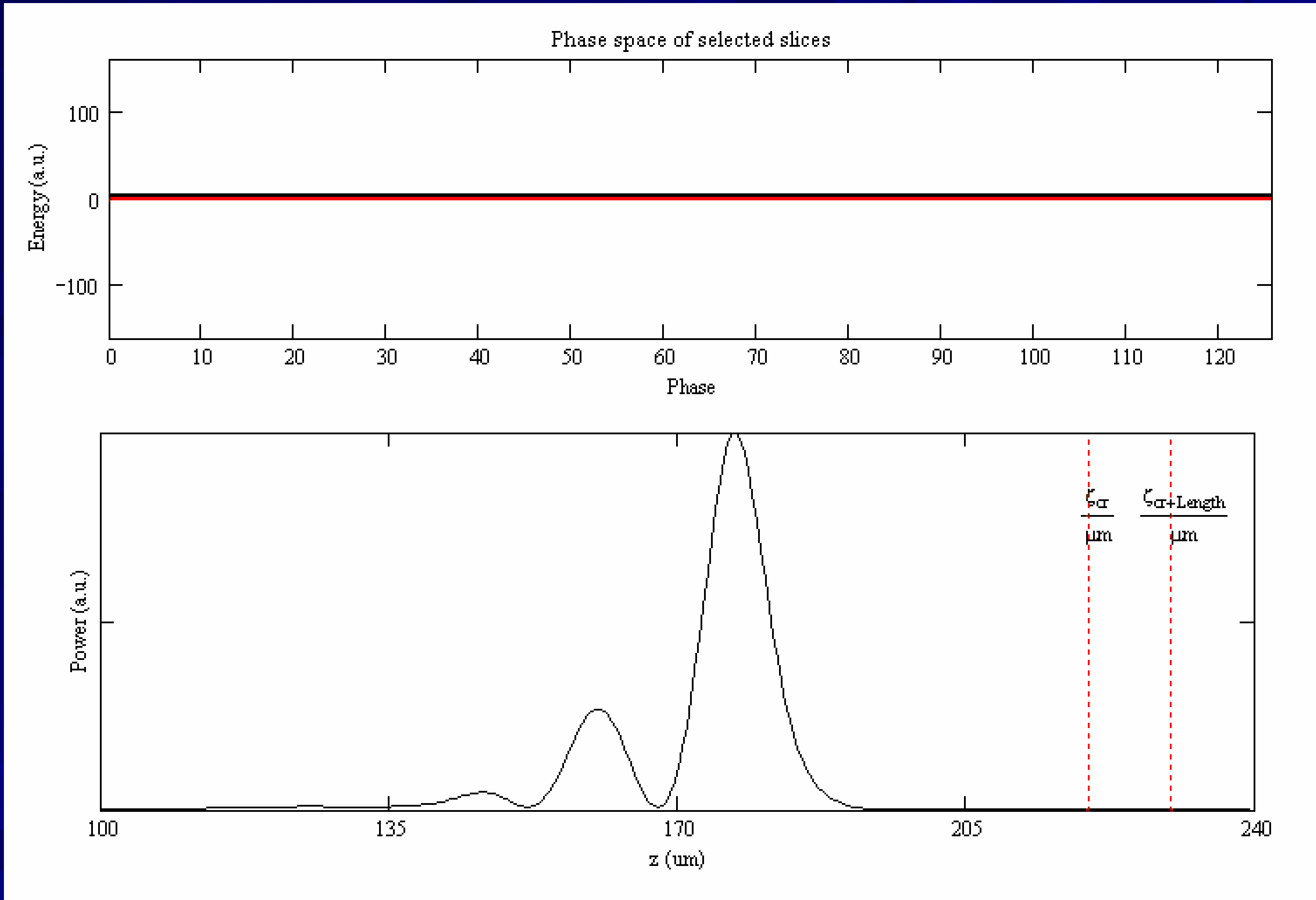




Courtesy of J.B. Murphy, X. Wang, T. Watanabe

SUPERRADIANT PULSE reconstructed from measured FROG traces

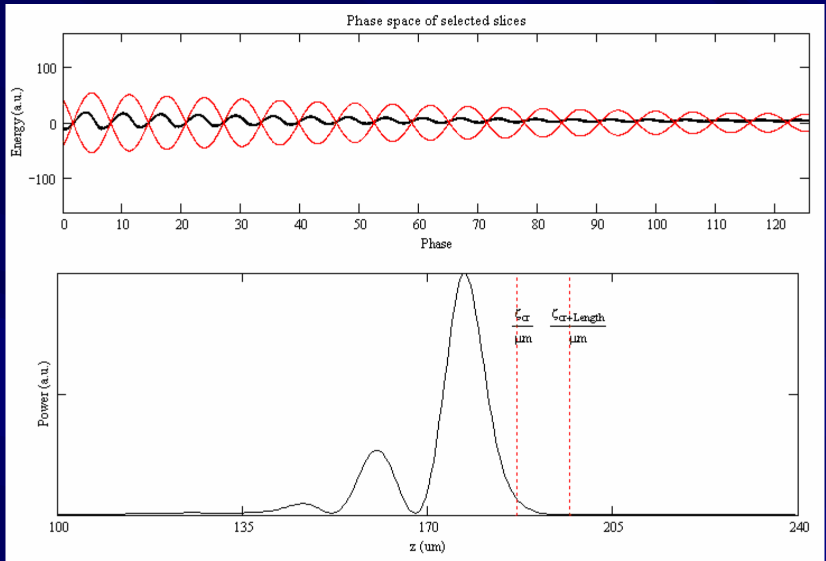


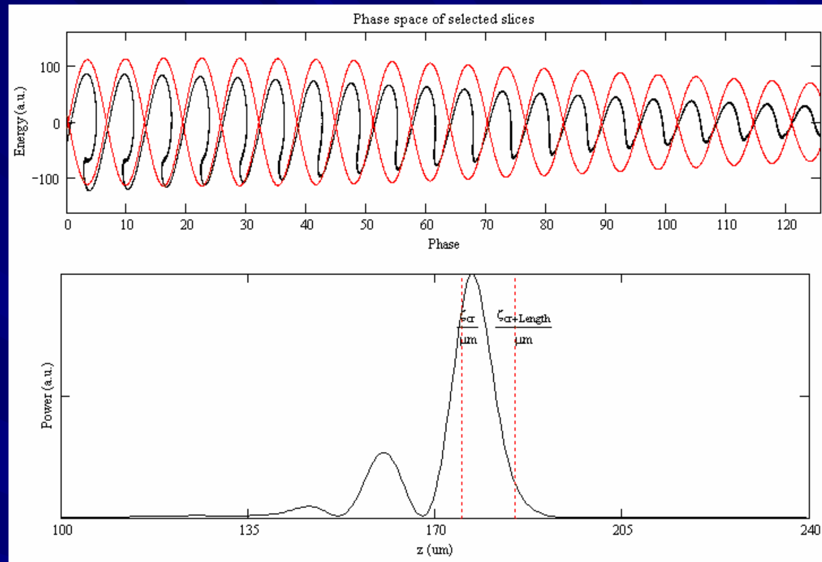


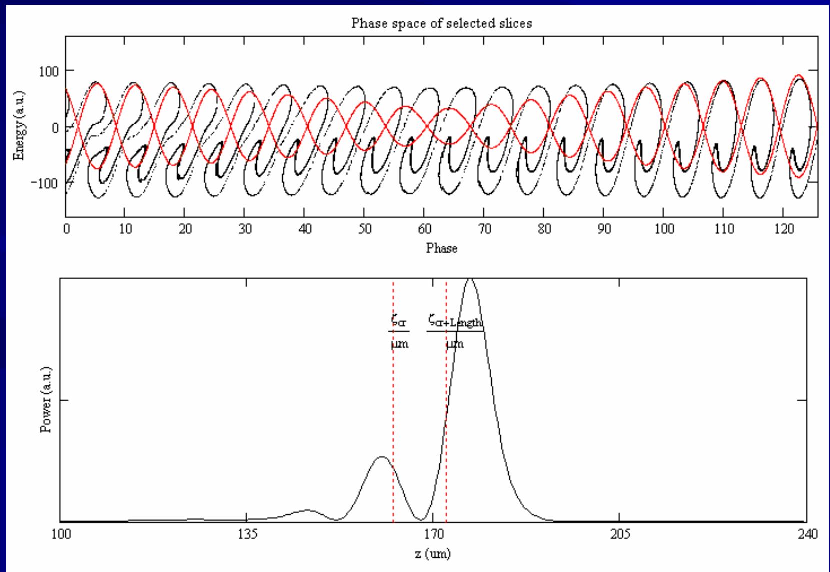
Phase space of selected slices
Energy (a.u.)
100
0
−100
0
10
20
30
40
50
60
70
80
90
100
110
120
Phase
Power (a.u.)
ζcr
µm
ζcr+Length
µm
100
135
170
205
240
z (um)

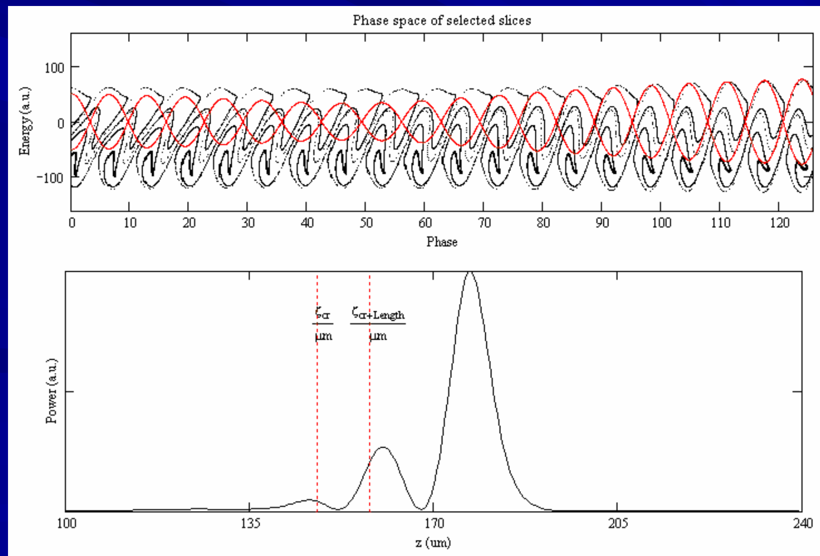
Phase spaces corresponding to different parts of the superradiant pulse

Movie file: particlesvs bunch.avi

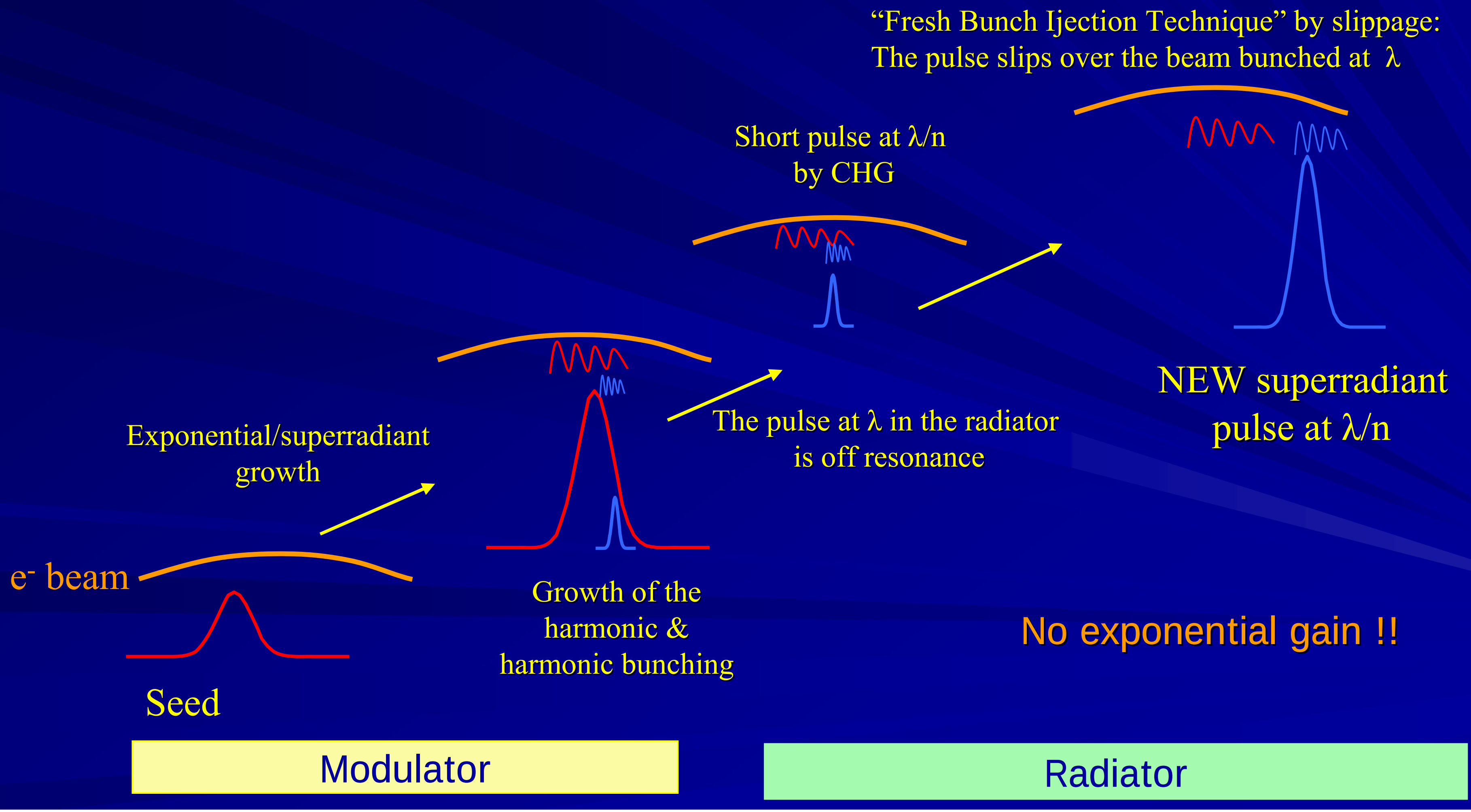








Evolution of a superradiant pulse in a cascade



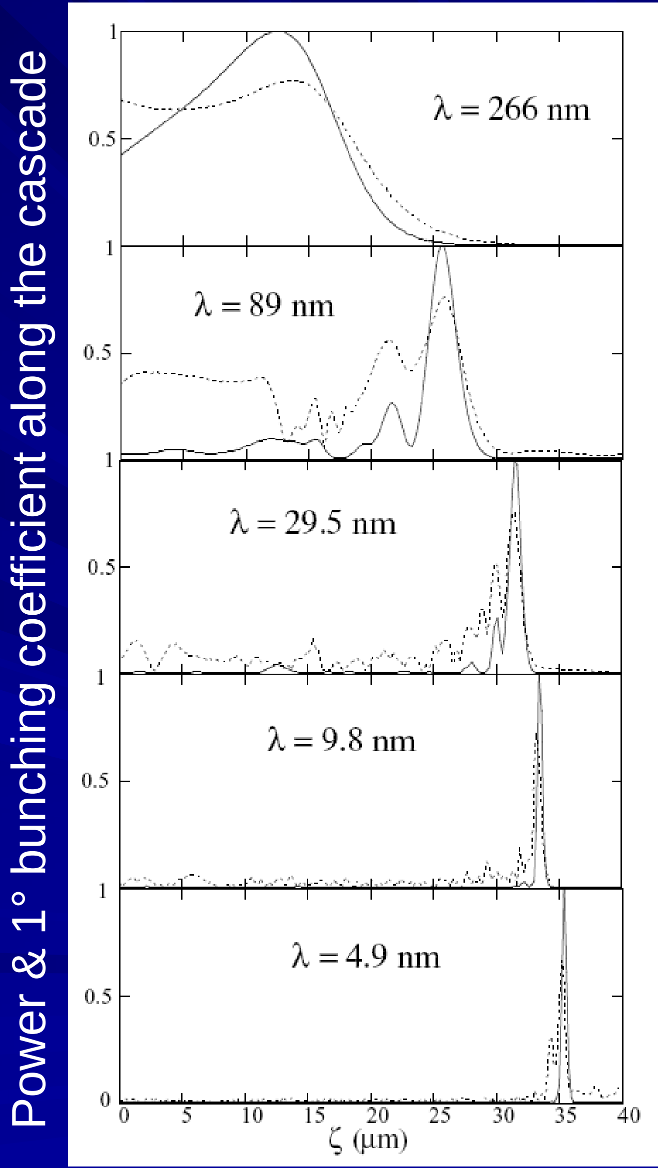
FEL cascade in SRmode

TABLE II: Radiation seed and electron beam parameters

Electron beam energy	800 MeV
Current	1 KA
Emittance	1 mm-mrad
Average β	4 m
$\delta\gamma/\gamma$	$5 \cdot 10^{-4}$
Seed wavelength λ	266 nm
Seed power	41 MW
Seed pulse width (rms)	15 fs

TABLE III: Parameters of the FEL Cascade.

Cascade stage	1	2	3	4	5
ρ $(\cdot 10^{-3})$	11	5.8	3.3	1.9	1.3
K	4.9	3.92	2.88	1.8	1.2
Period $\lambda_w (cm)$	10	5	2.8	1.8	1.4
Resonant Wavelength λ (nm)	266	89	29.5	9.8	4.9
Peak power (GW)	1.2	4.8	7	2.5	3.1
Pulse energy (μJ)	63	72	35	4.6	5.3
Pulse width (fwhm - fs)	53	8.4	3.4	1.5	1.4
Undulator periods	60	100	180	200	480



L. Giannessi, P. Musumeci, S. Spampinati J. Appl. Phys 2005

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

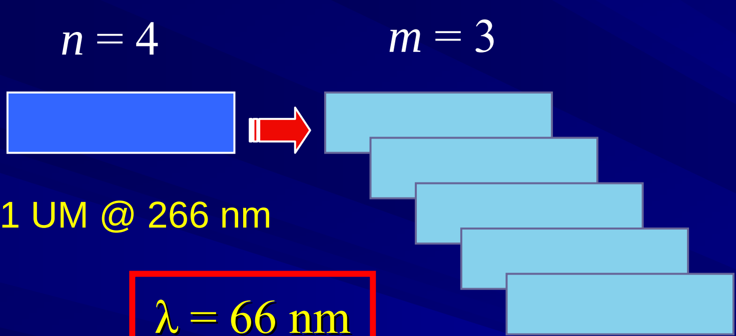
Harmonics Spectrum of the two undulators

1° Undulator — 2° Undulator

L. Giannessi, P. Musumeci, in proc. 2005 ICFA Erice

Example with *Sparc* undulator/beam parameters

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



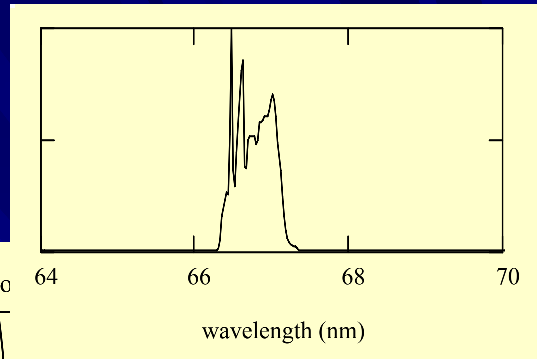
1 UM @ 266 nm

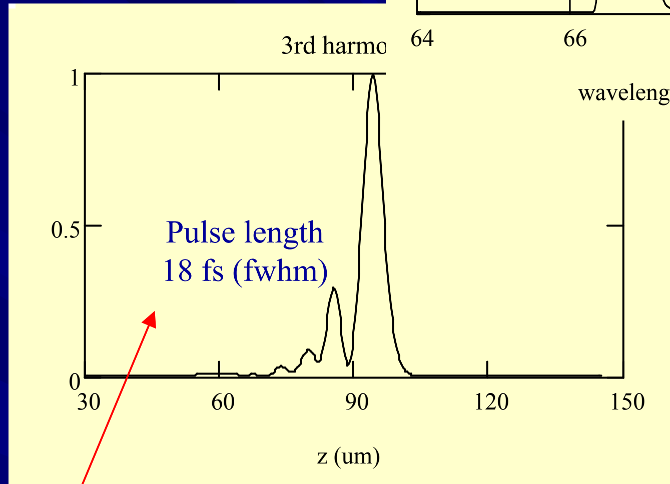
$\lambda = 66$ nm

5 UM @ 200 nm

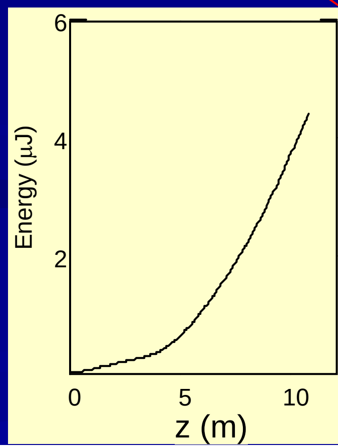
Main parameters

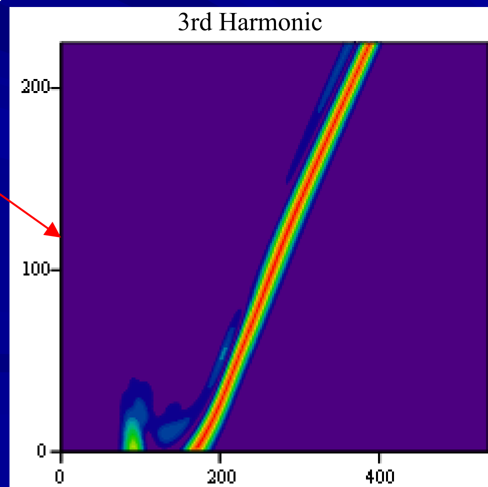
Undulator period	2.8 cm
Undulator K (UM1/UM2)	1.95 / 1.53
Number of periods	77 / 77*5
Beam energy	200 MeV
Res. wavelength (nm)	266 / 200
E-beam current	110 Amp
Energy spread	10^{-4}
Emittance	1 mm-mrad
Input Laser power	10 MW
Input pulse length (fwhm)	100 fs





Peak power
>200 MW

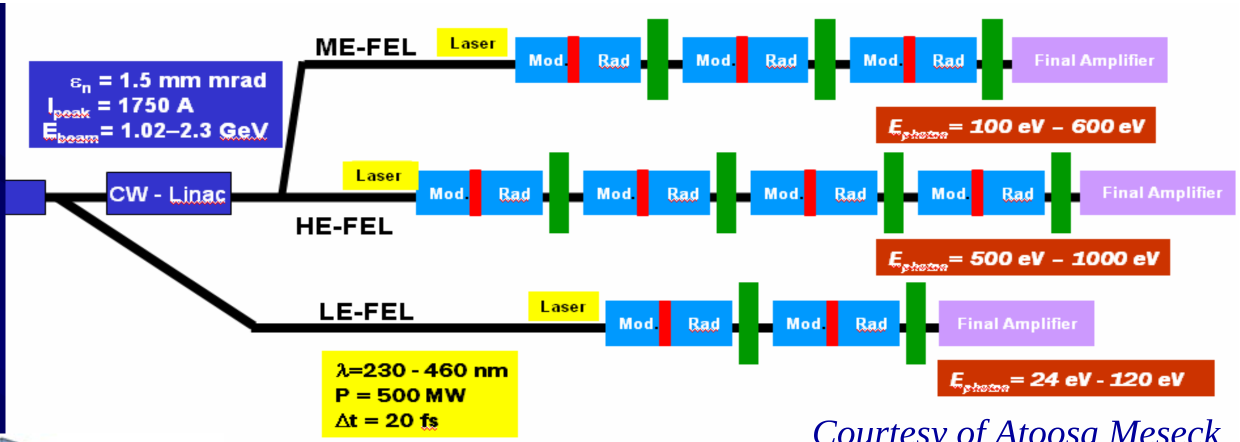




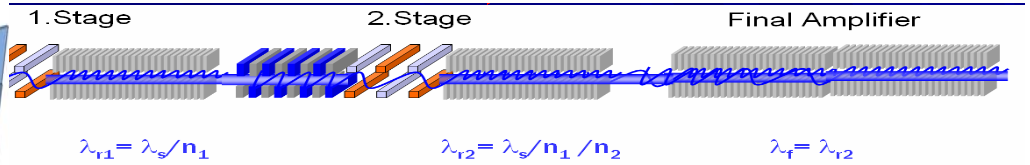
Pwn2

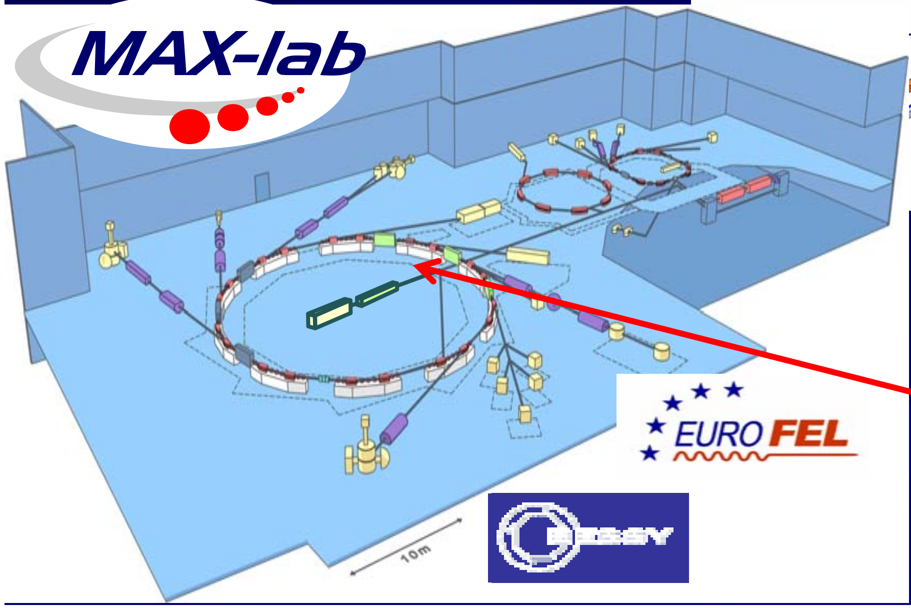
Existing and Proposed seeded HG FELs

Project	λ_{FEL}, (nm)	P.len. (fs)	Accel. type
• 4GLS	IR-XUV		ERL
• ARC-EN-CIEL	200-0.82	~20	SC-Linac
• BESSY	51-1	~20	ERL
• DESY	6-0.1	~100	SC-Linac
• FERMI	100-10	~100	Linac
• MAX-4	260-10	~50	Linac
• SparC	400 – 66	~50-100	Linac
• SDL (BNL)	800-200	600-80	Linac
• LUX (LLBL)	240-1	200-10	ERL
• MIT-BATES	100-0.3	50/1	Linac
• SDUV-FEL(Shanghai)	264, 88		Linac
• SCSS (Phase 1)	80-40		Linac

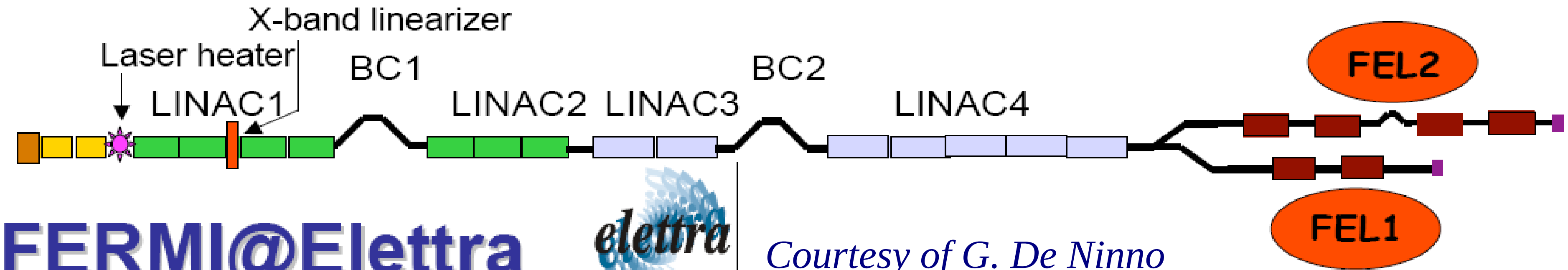


Courtesy of Atoosa Meseck





Test facility
Seeding and HG tests (3rd harmonic, 90 nm)
on the current MAX injector



FERMI@Elettra

Courtesy of G. De Ninno

Stability

- A seeded FEL is not affected by intrinsic fluctuations as SASE

BUT

Any change in the input parameters as seed power, beam energy, current, beam quality (slice-full), alignment, time jitters, induces output fluctuations

Resonant process

$$\lambda_0 = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

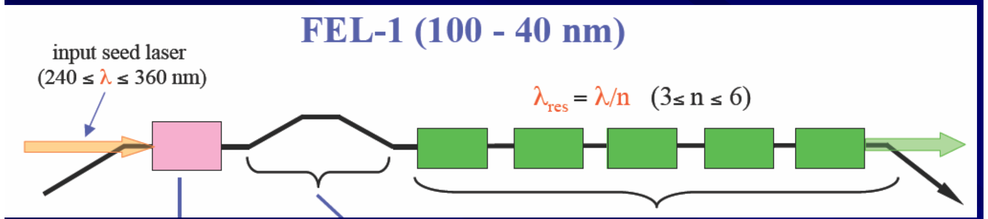
$$\lambda_0 \cong \lambda_{seed}$$

- The fluctuations are amplified in the multi stage configuration.

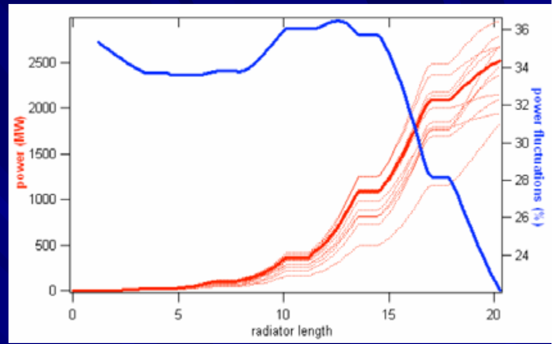
FERMI@Elettra

Single Stage

Courtesy of G. De Ninno



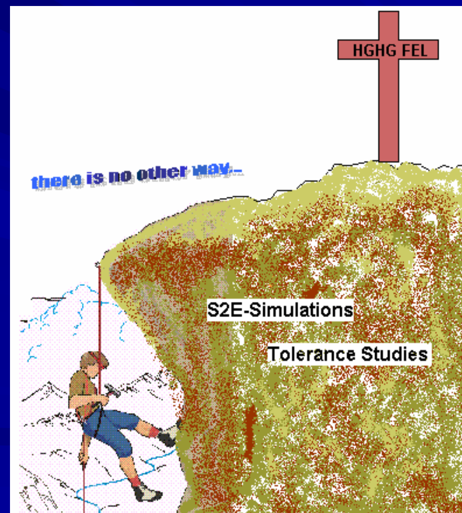
Parameter	*Shot-to-shot variation (rms)*
Emittance	10 %
Peak current	10 %
Mean energy	0.1 %
Energy spread	10 %
Seed power	5 %



Output
30% pulse to pulse stability

Experience from Bessy
B. Kuske

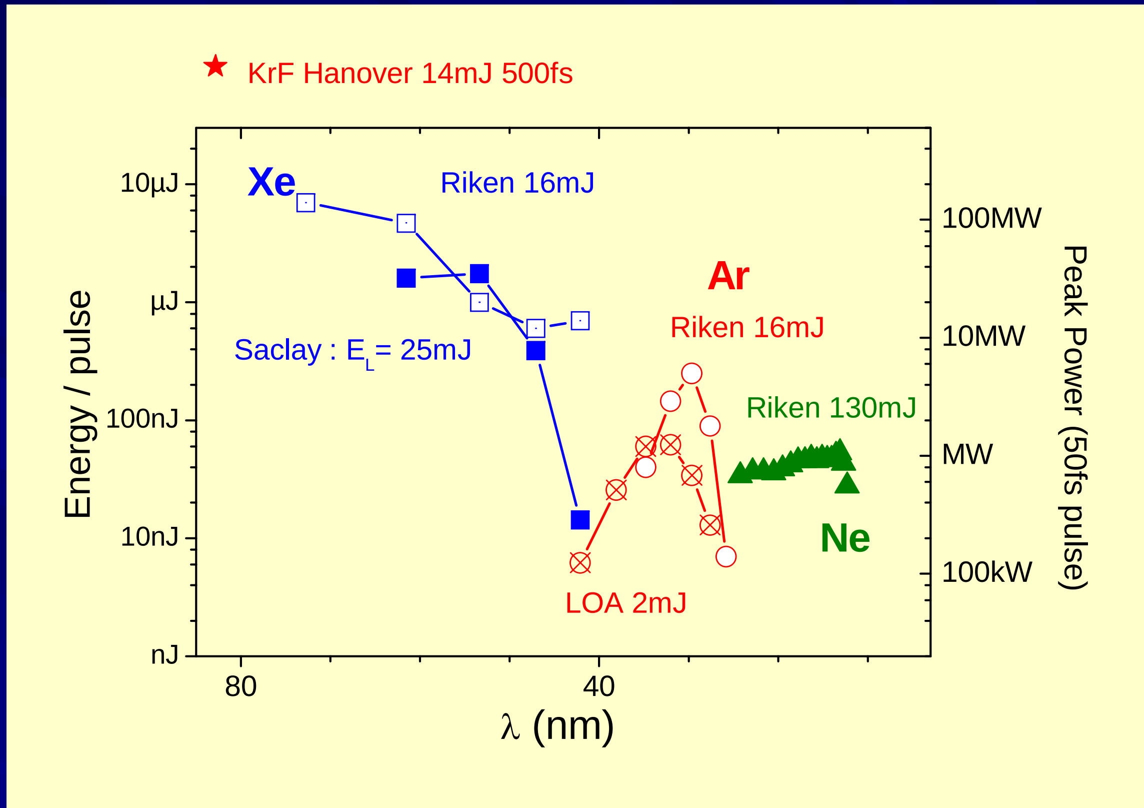
- **S2E simulations necessary in HGHG cascades to predict local bunch parameters**
- **Big effect on the radiator output power**
- **Tunable hardware necessary to adjust to varying bunch properties**
- **Tolerance studies directly influence hardware layout**
- **Longer devices to make up for reduced coupling of imperfect bunches to radiation**



The cross is commonly found on top of mountains. Nobody is buried there.

Seeding with high order harmonics generated in gas

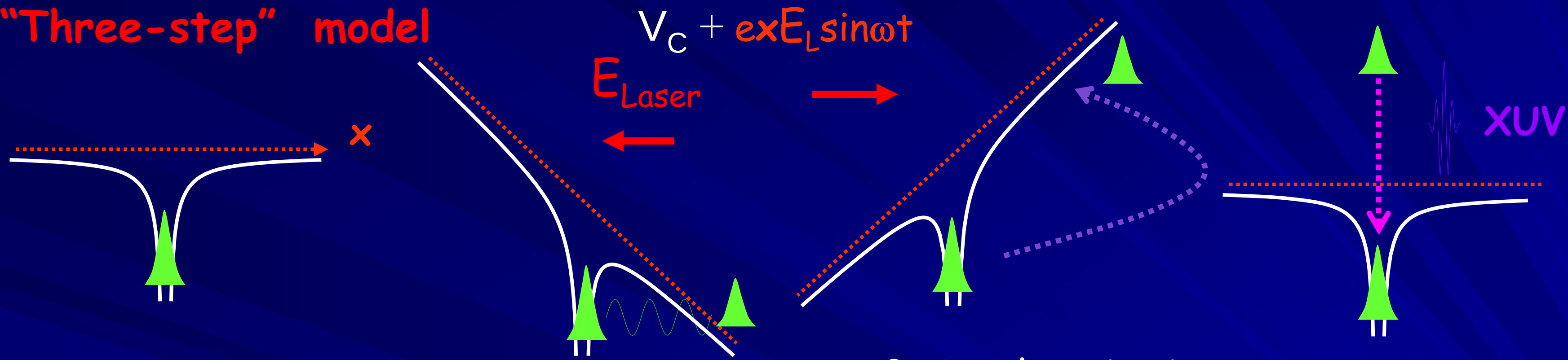
- Arc En Ciel
- 4GLS
- SCSS
- SPARC/X



Temporal-spectral structure of XUV emission

Courtesy of B. Carrè

- "Three-step" model



Initial state (t=0)

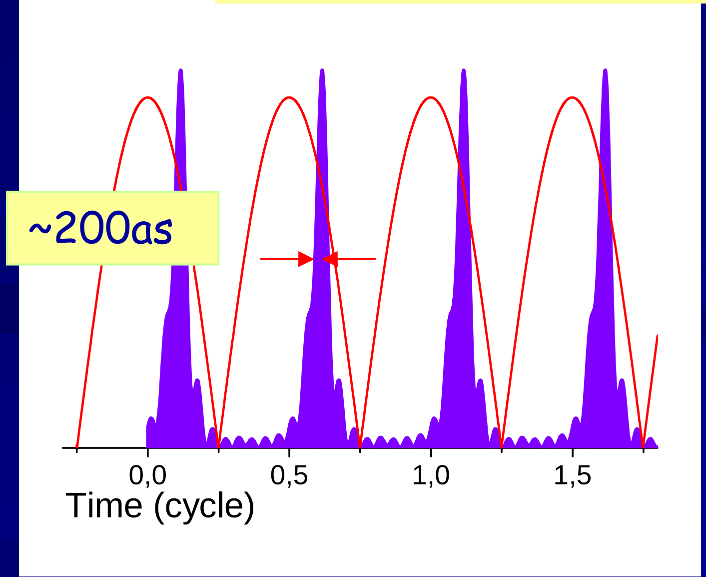
1: Tunnel ionization (OFI)

2: Acceleration in the laser field

3: Recombination

- Multi-cycle laser pulse

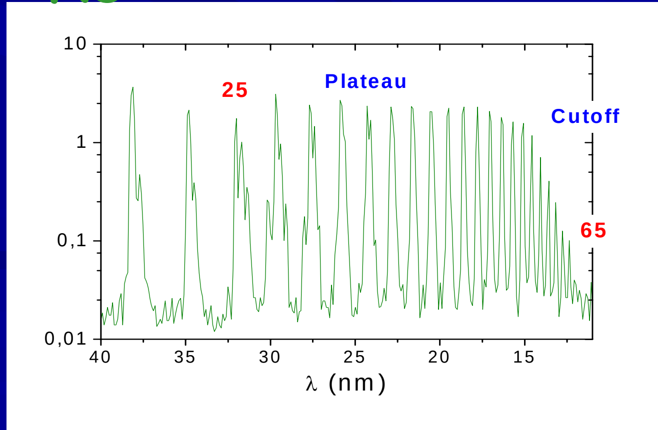
Mairesse et al. SCIENCE (2003)



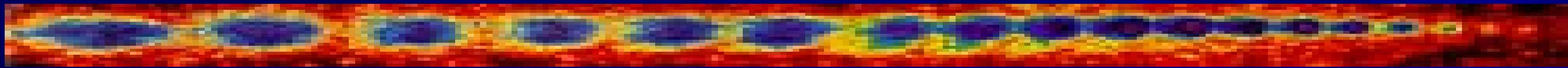
Train of XUV "atto" pulses

Discrete odd harmonics

Ne



Seeding with HHG generated in gas

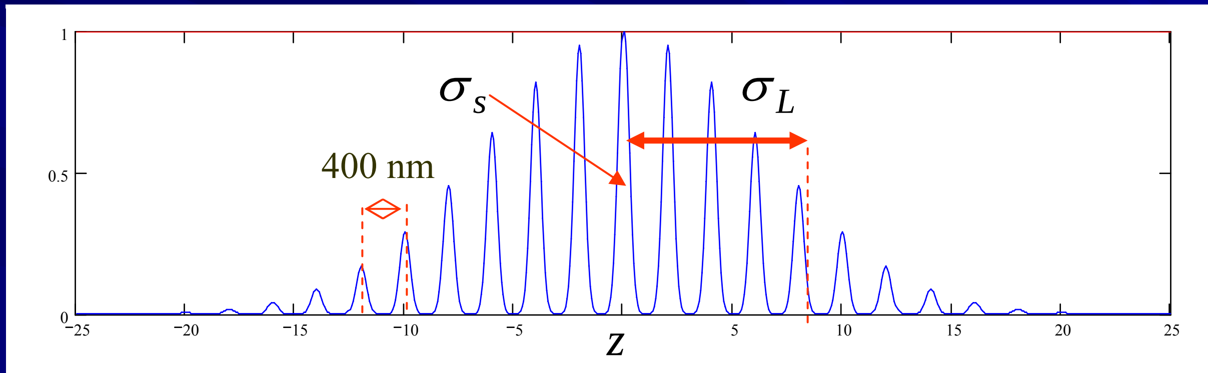


Simple model of an HHG pulse

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

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

$|a(z)|$



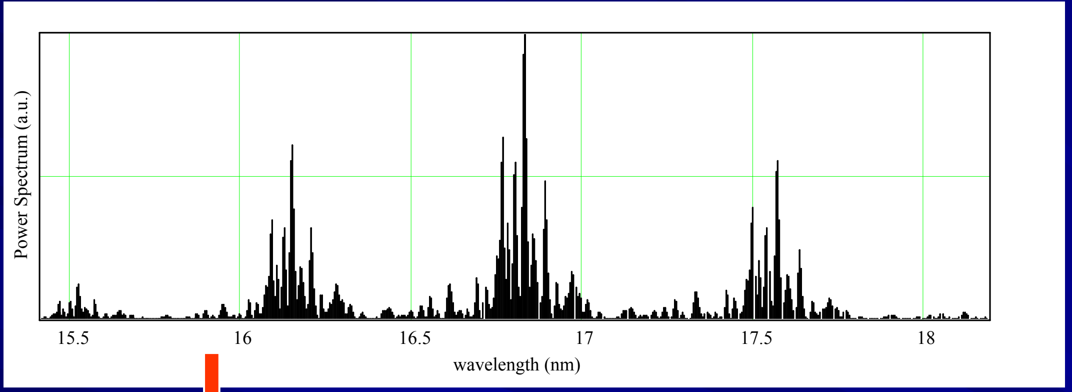
$$\sigma_L = 30\, fs$$
$$\sigma_s = 100 as$$

Phase shift between different peaks

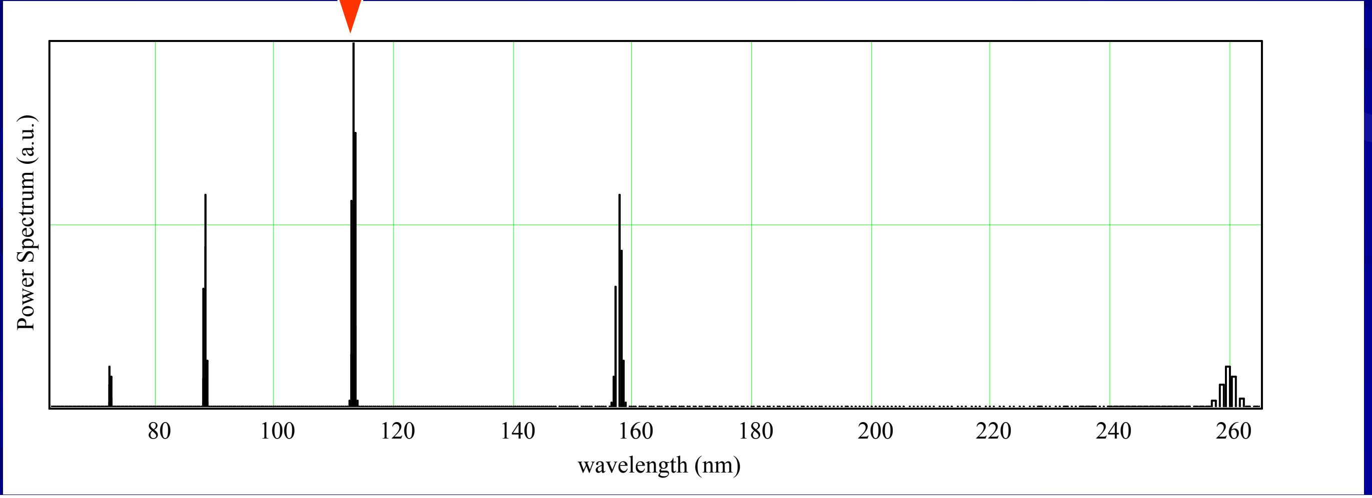
$$a(z) = |a(z)| \exp(i\phi(z))$$
$$\phi(z) = \sum_k s_j \sin(kz) + c_j \cos(kz)$$

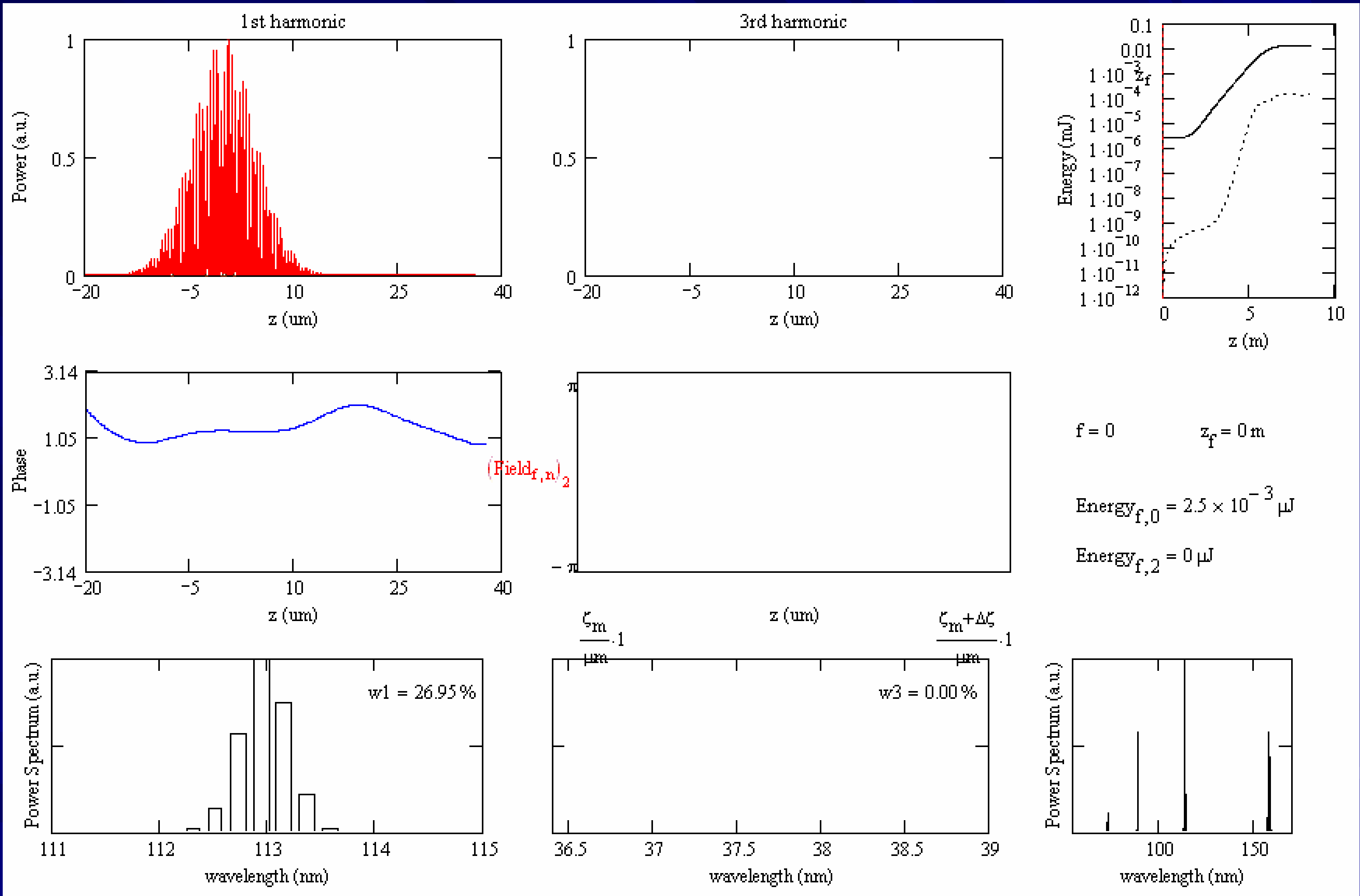
Harmonics Spectrum

(www.sparc.it)



Simulation wavelength

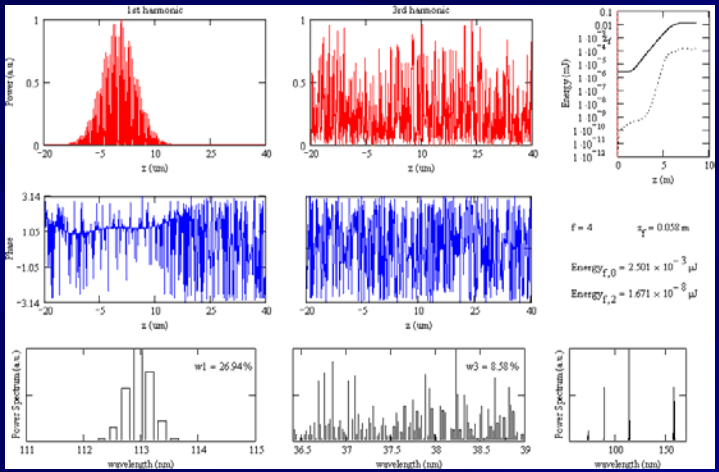



1st harmonic
3rd harmonic
Power (a.u.)
z (um)
Energy (mJ)
z (m)
Phase
(Field f,n) 2
f = 0
z f = 0 m
Energy f,0 = 2.5 × 10^-3 μJ
Energy f,2 = 0 μJ
Power Spectrum (a.u.)
w1 = 26.95 %
w3 = 0.00 %
wavelength (nm)

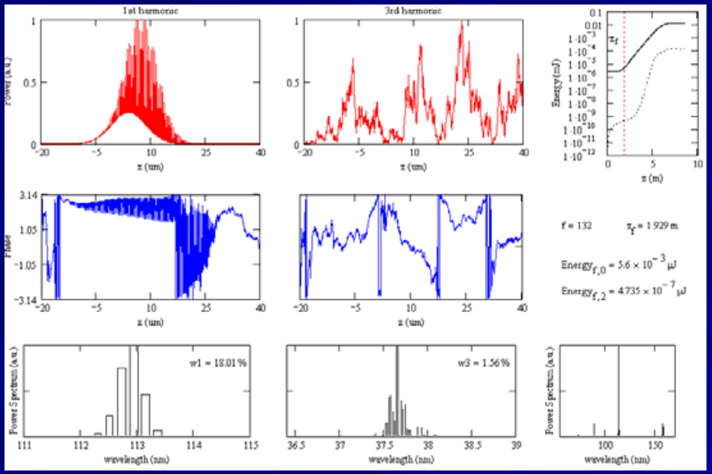
Movie of pulse amplification in a FEL amplifier. Movie file: Sparxino - 114nm - seeded - narrow - time & spectrum - 3.avi

Observe the pulse "cleaning" in fig 3 and the third harmonic that follows in fig 4

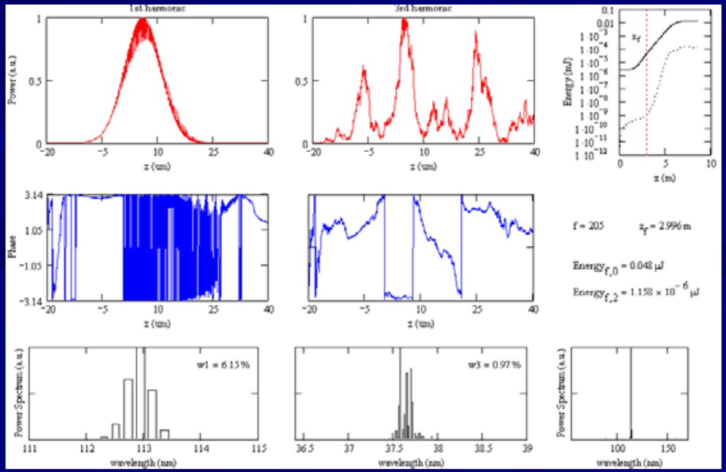
1



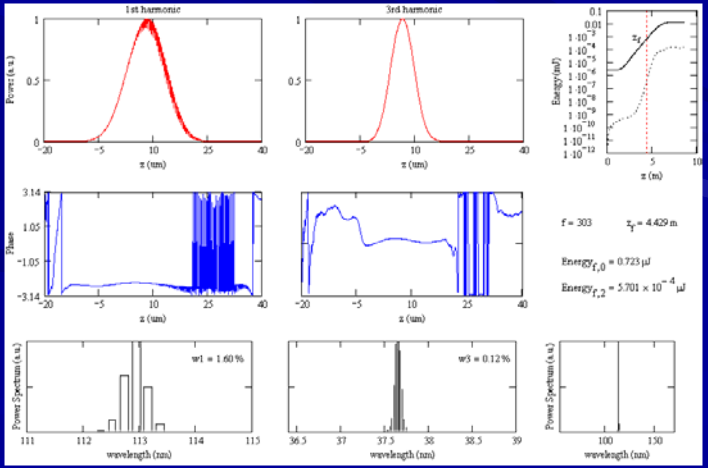
2

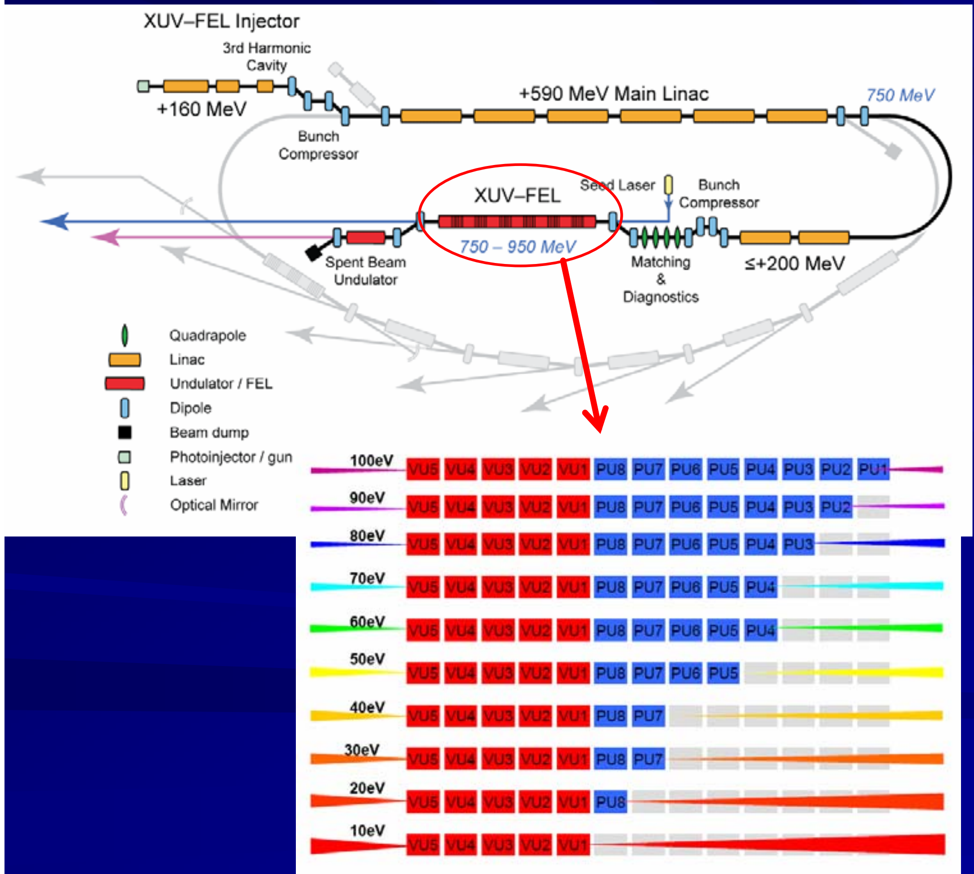


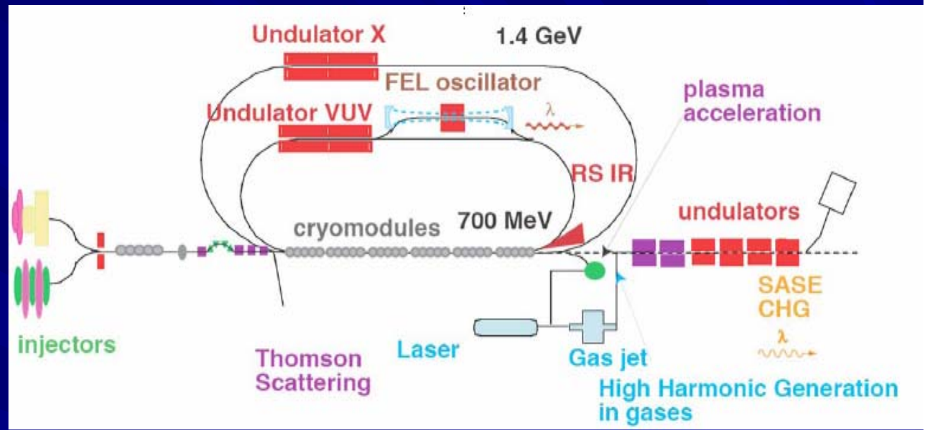
3



4



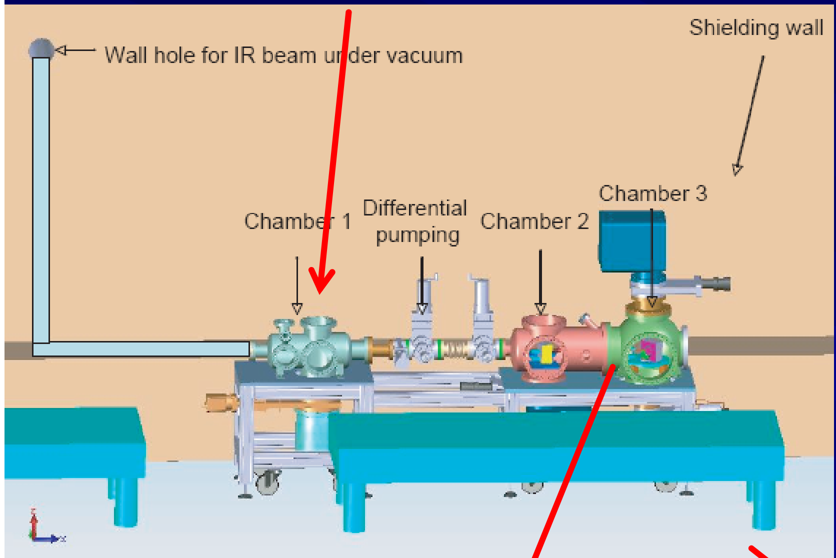

XUV–FEL Injector
3rd Harmonic Cavity
+160 MeV
Bunch Compressor
+590 MeV Main Linac
750 MeV
XUV–FEL
Seed Laser
Bunch Compressor
750 – 950 MeV
Spent Beam Undulator
Matching & Diagnostics
≤+200 MeV
Quadrapole
Linac
Undulator / FEL
Dipole
Beam dump
Photoinjector / gun
Laser
Optical Mirror
100eV
90eV
80eV
70eV
60eV
50eV
40eV
30eV
20eV
10eV
VU5 VU4 VU3 VU2 VU1
PU8 PU7 PU6 PU5 PU4 PU3 PU2 PU1

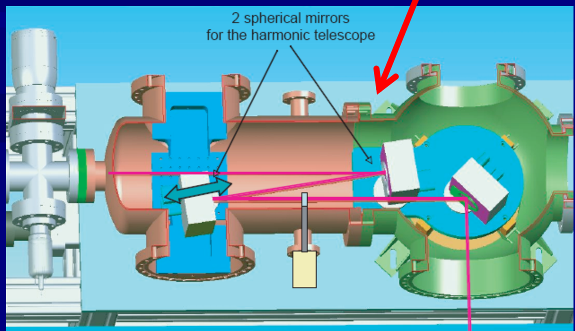

Undulator X
1.4 GeV
FEL oscillator
Undulator VUV
plasma acceleration
RS IR
cryomodules
700 MeV
undulators
injectors
SASE
CHG
Thomson Scattering
Laser
Gas jet
High Harmonic Generation in gases

SCSS Seeding with harmonics generated in gas

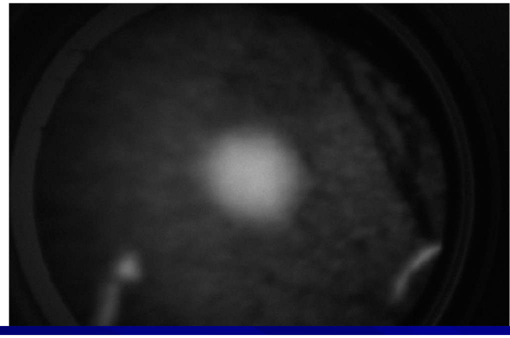
Guillaume Lambert, Michel Bougeard, Willem Boutu, Bertrand Carré, David Garzella, Marie Labat (CEA, Gif-sur-Yvette), Toru Hara, Hideo Kitamura, Tsumoru Shintake (RIKEN Spring-8 Harima, Hyogo), Oleg Chubar, Marie-Emmanuelle Couprie (SOLEIL, Gif-sur-Yvette)

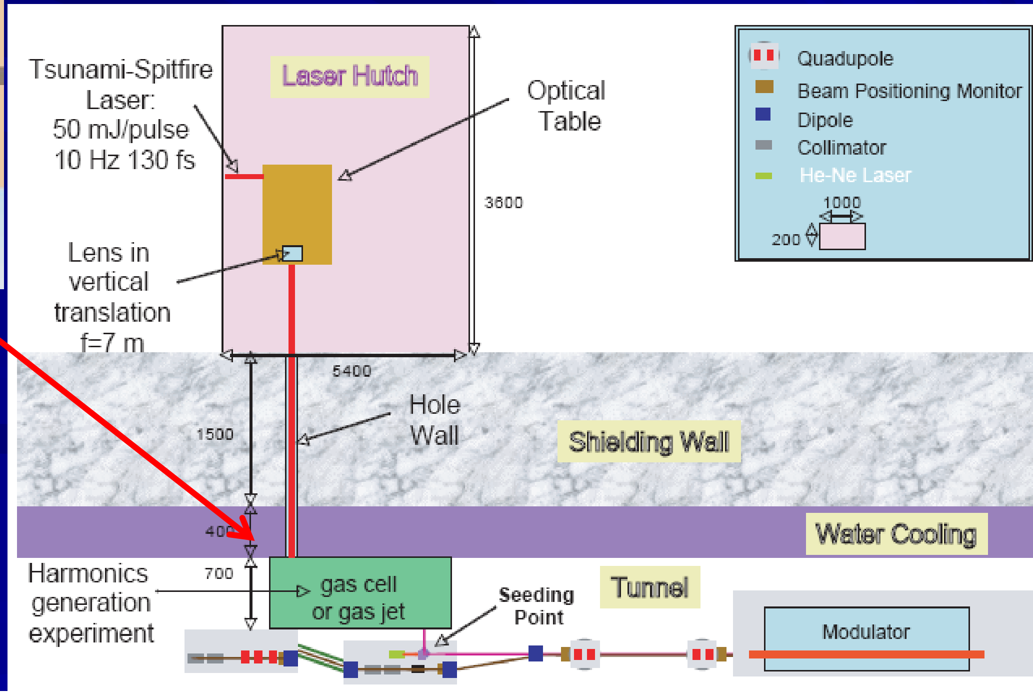
GAS CELL

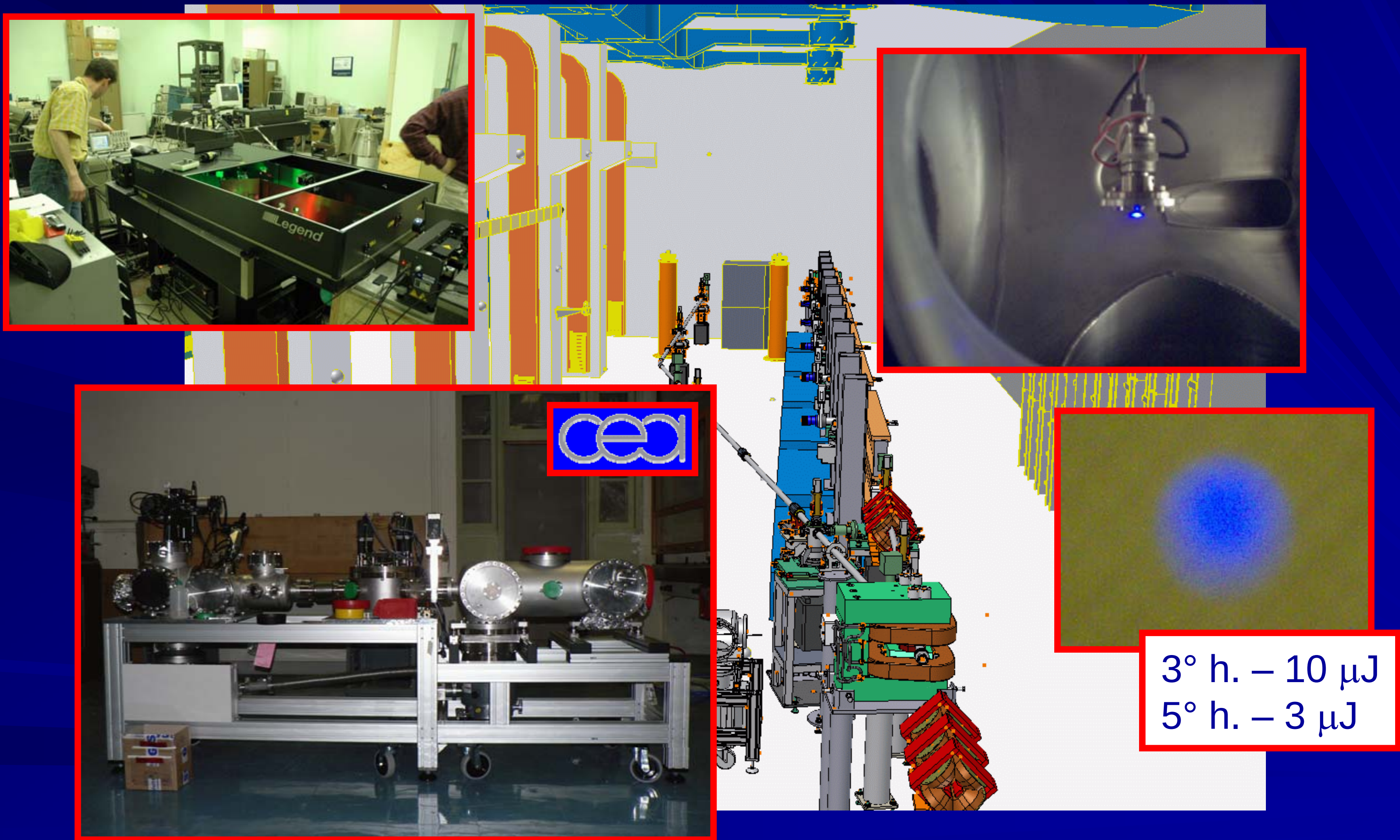




Measurement of H13 (60 nm) on the MCP







Service des Photons, Atomes et Molécules Saclay, DSM-DRECAM CEA
O. Tcherbakoff, M. Labat, G. Lambert, D. Garzella, M.E. Couprie, M. Bougeard, P. Breger, P. Monchicourt, H. Merdji, P. Salières, B. Carré

Conclusions

- Computing and s2e simulations are precious tools in exploring new possibilities and in the design of new facilities
- New ideas are coming: Mantain flexibility in machine design
- The experiments on seeded FELs combined to harmonic generation have provided confirmations to theory and deeper understanding on the FEL amplification process (credit to BNL)
- Several new experiments are required and some are foreseen in the next future:
  - The Fresh Bunch injection technique
  - The multiple stage cascade
  - Superradance in a cascade
  - FEL amplification from a HHG source/harmonic generation
  - …

  MAKE EXPERIENCE !!!
- Conventional lasers and FEL are merged in a single device. Collaboration with laser people community is becoming fundamental in short wavelength FEL research
- New advances in the field of harmonic generation from conventional laser sources could provide means to extend the cascade wavelength operation range in the future