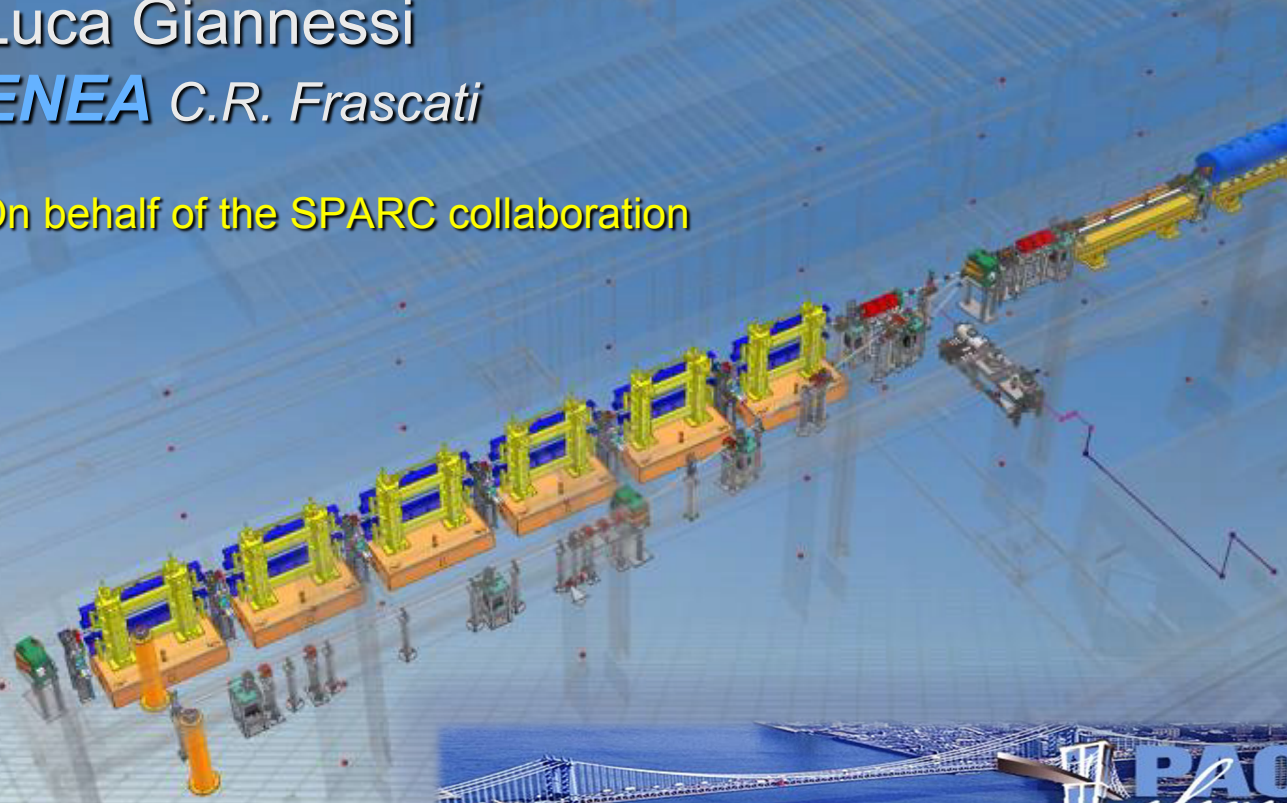
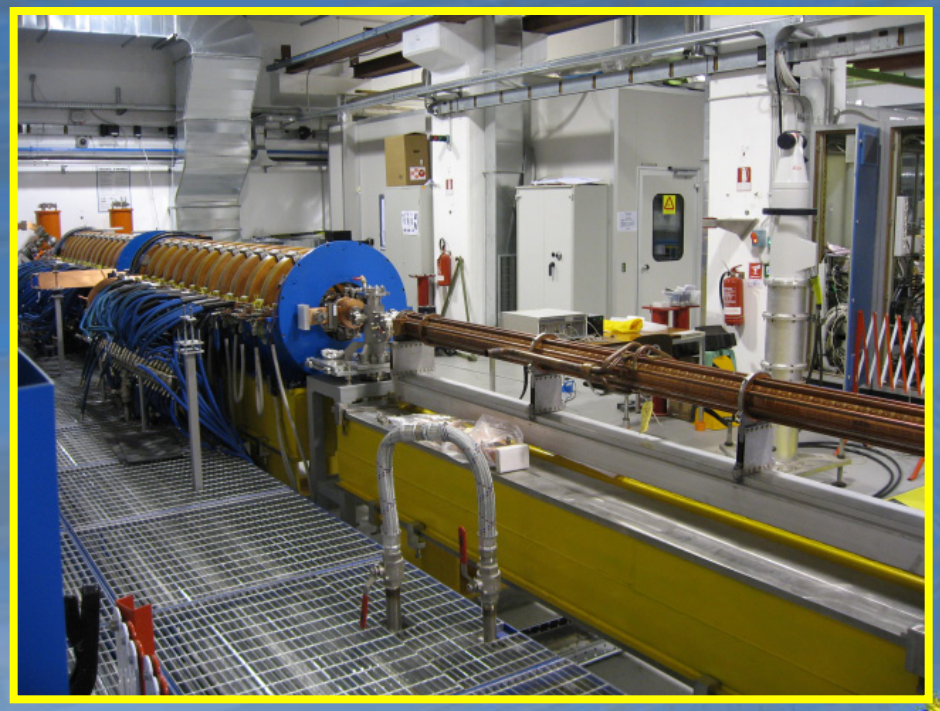
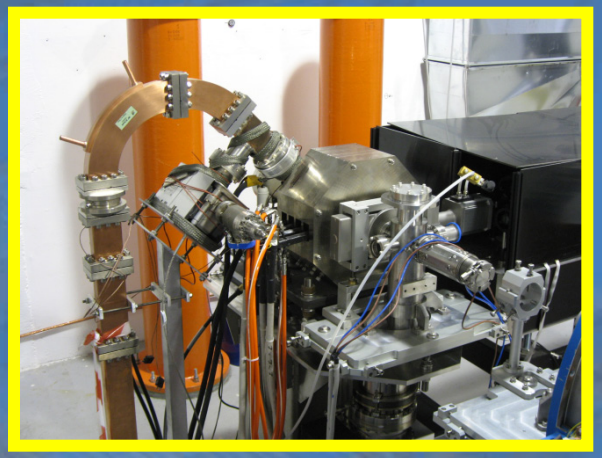
Free Electron Laser Seeding experiments at SPARC

Luca Giannessi
ENEA C.R. Frascati

On behalf of the SPARC collaboration







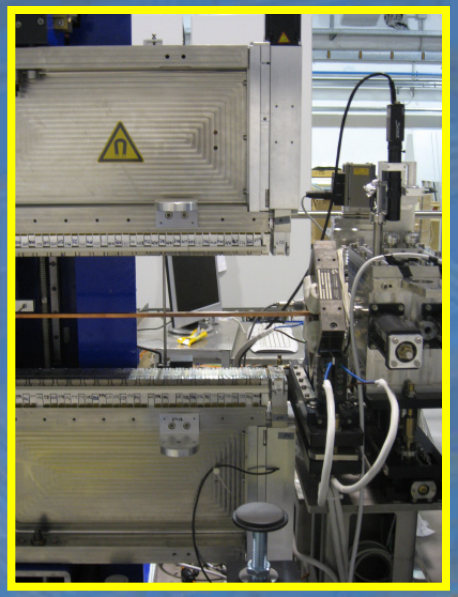
RF Gun & Solenoid

Linac modules & Solenoid

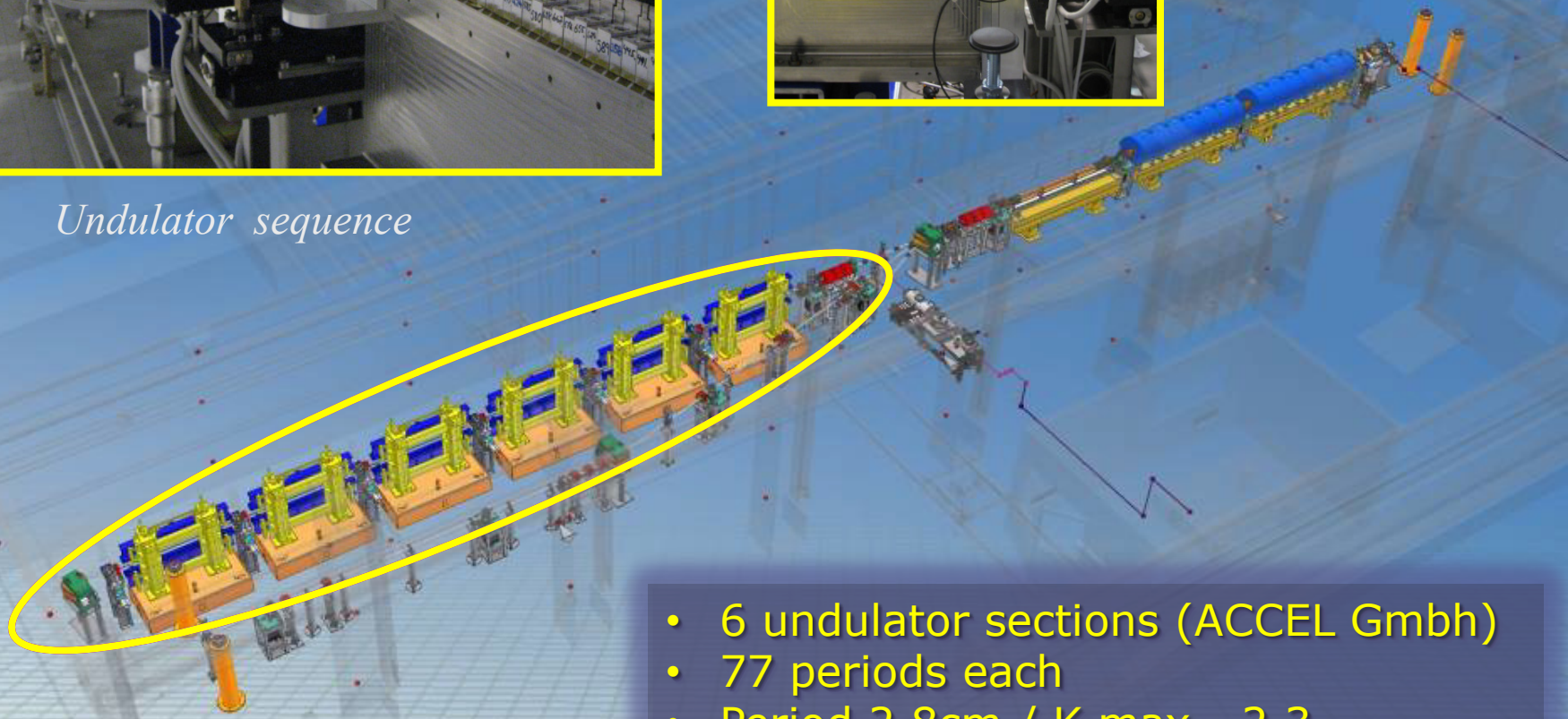
- UCLA/BNL/SLAC design 1.6 cells RF injector
- Three TW S-band modules
- Energy in the range 100MeV to 180 MeV
- Focusing solenoids on the first two modules (longitudinal compression via velocity bunching)

SPARC

Undulator sequence



Undulator termination with phase shifter



- 6 undulator sections (ACCEL Gmbh)
- 77 periods each
- Period 2.8cm / K max ~2.3
- Phase shifters between the modules

SPARC

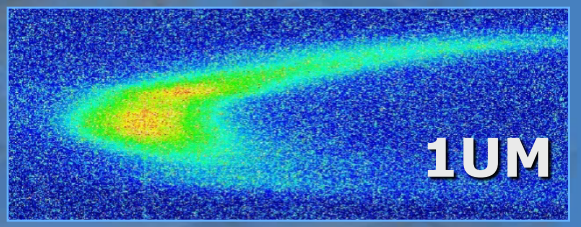
In Vacuum Spectrometer

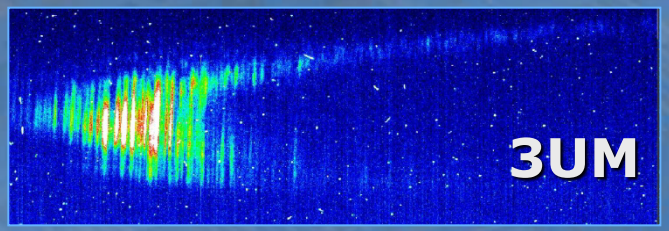
L. Poletto & F. Frassetto
Un. Padova

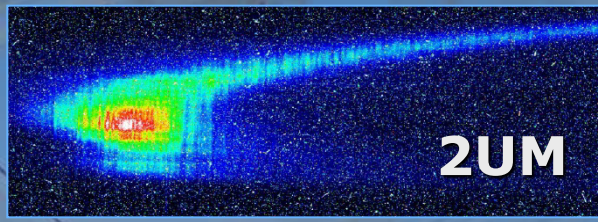
Entrance/exit arms: ≈ 1 m
Three gratings:
600 gr/mm, 214 - 560 nm - 0.034 nm/pixel
1200 gr/mm, 120 - 250 nm - 0.017 nm/pixel
2400 gr/mm, 36 - 150 nm - 0.0084 nm/pixel
CCD detector (Roper Scientific)
Pixel size 20 mm - 1340 × 1340 pixel

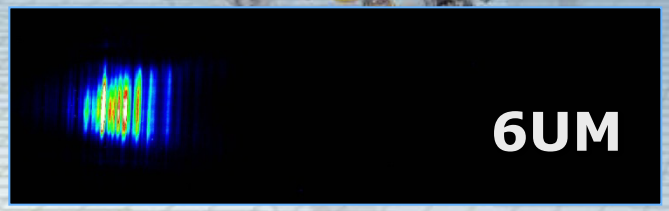
In Vacuum Spectrometer

SASE Spectra @ 500 nm
Orbit kicks to selectively inhibit SASE
in the first undulators





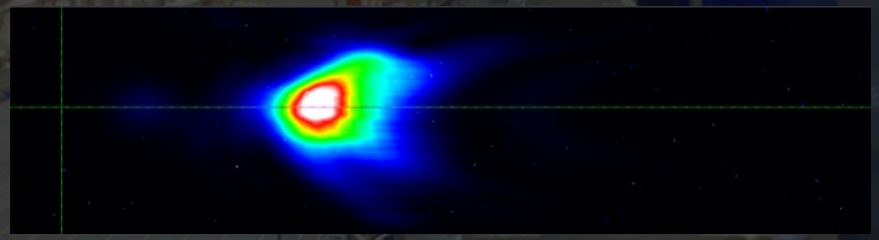




SASE experiments in 2010 …

***SASE**

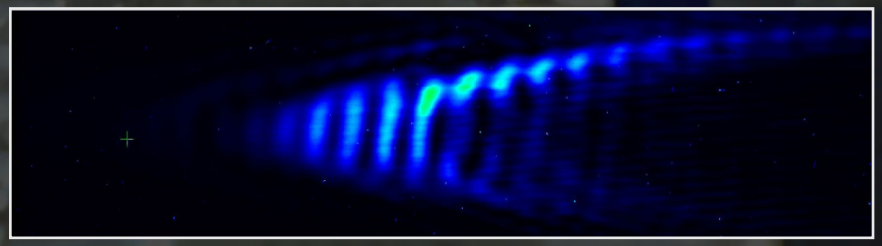
****SINGLE SPIKE**
(Combination of e-beam chirp & taper)



Substantial increase of
Pulse energy

Energy 140 uJ (max 380 uJ)
Rel Linewidth 0.8% rms

*****TWINS**
(Two simultaneous spikes ~560 fs separation)

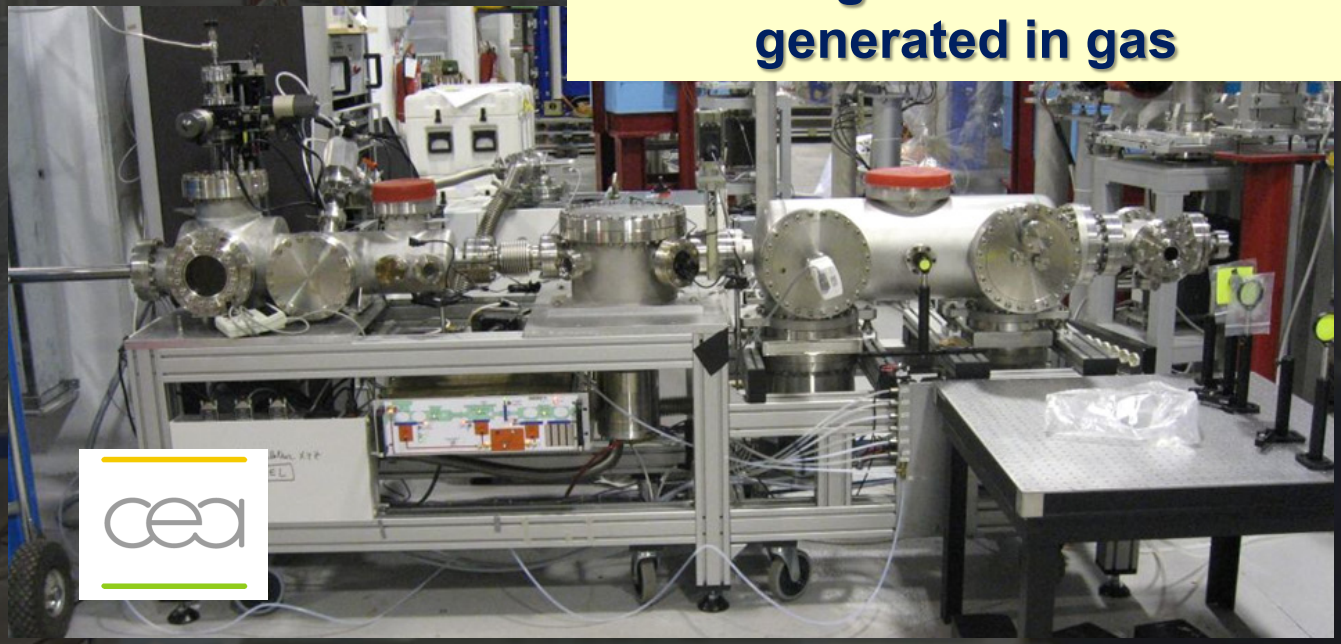


* *PRST-AB, submitted*
** *PRL, to be published*
*** *work in progress*

Seeded Operation (2010)

- Seed modes:
  - Low intensity seeding (HHG): 266 nm & 160 nm generated in gas (Ar)
  - High pulse intensity seeding (saturation & superradiance): 400 nm in BBO crystal

Seeding with harmonics generated in gas



EURO FEL

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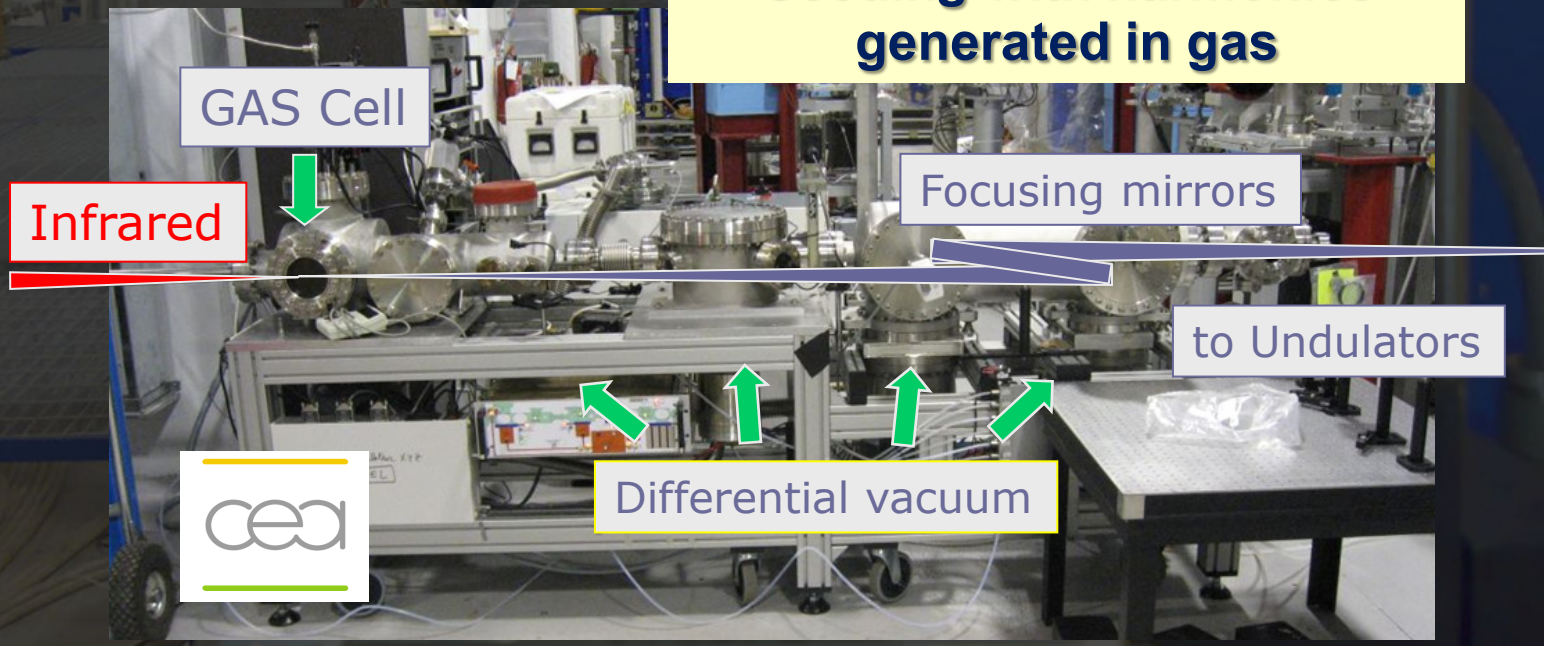

EURO FEL

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Seeded Operation (2010)

- Seed modes:
  - Low intensity seeding (HHG): 266 nm & 160 nm generated in gas (Ar)

Beam parameters	
Energy	177.2 MeV
Peak Current	45 A
Rel. En. Spread (slice)	< 2 x 10-4
Projected Emitt.	2 mm-mrad

Wavelength 266 nm (3° harmonic of Ti:Sa in Ar, E_{seed}~50 nJ (±20nJ) – Amplified > 1 uJ)

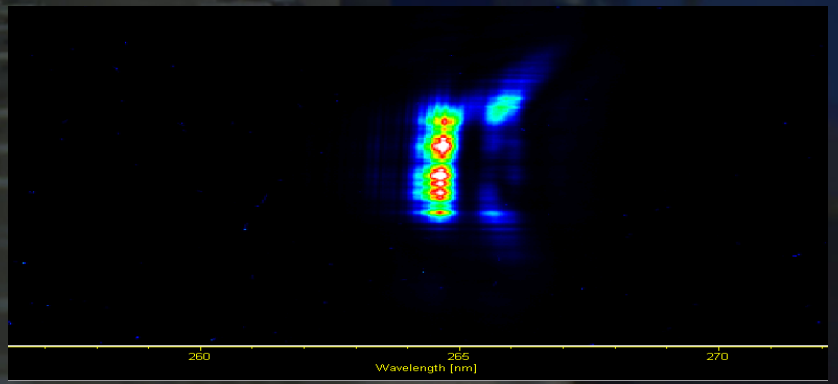
Wavelength 160nm (5° harmonic of Ti:Sa in Ar, E_{seed}<< 1nJ – Amplified ~ 4 nJ)

Seeded Operation (2010)

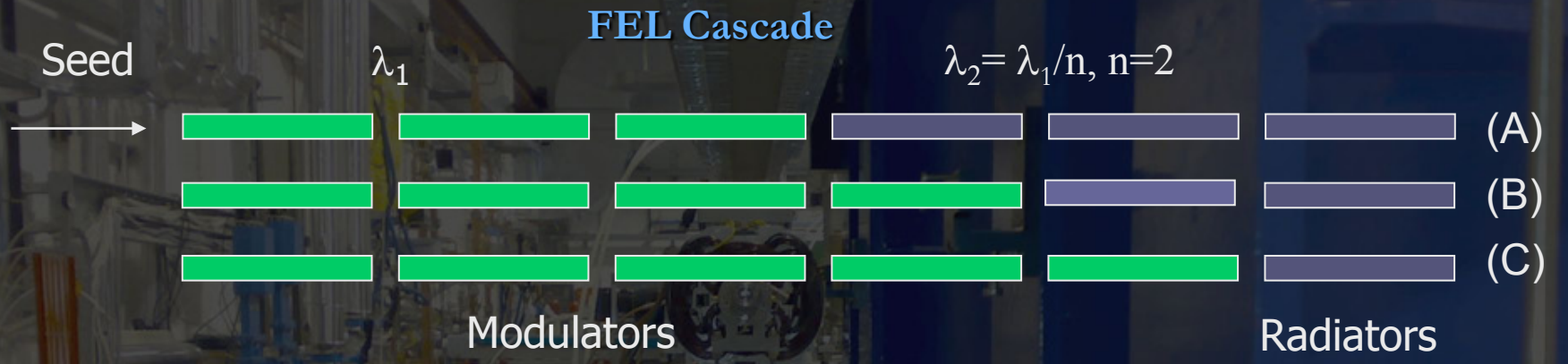
- Seed modes:
  - Low intensity seeding (HHG): 266 nm & 160 nm generated in gas (Ar)

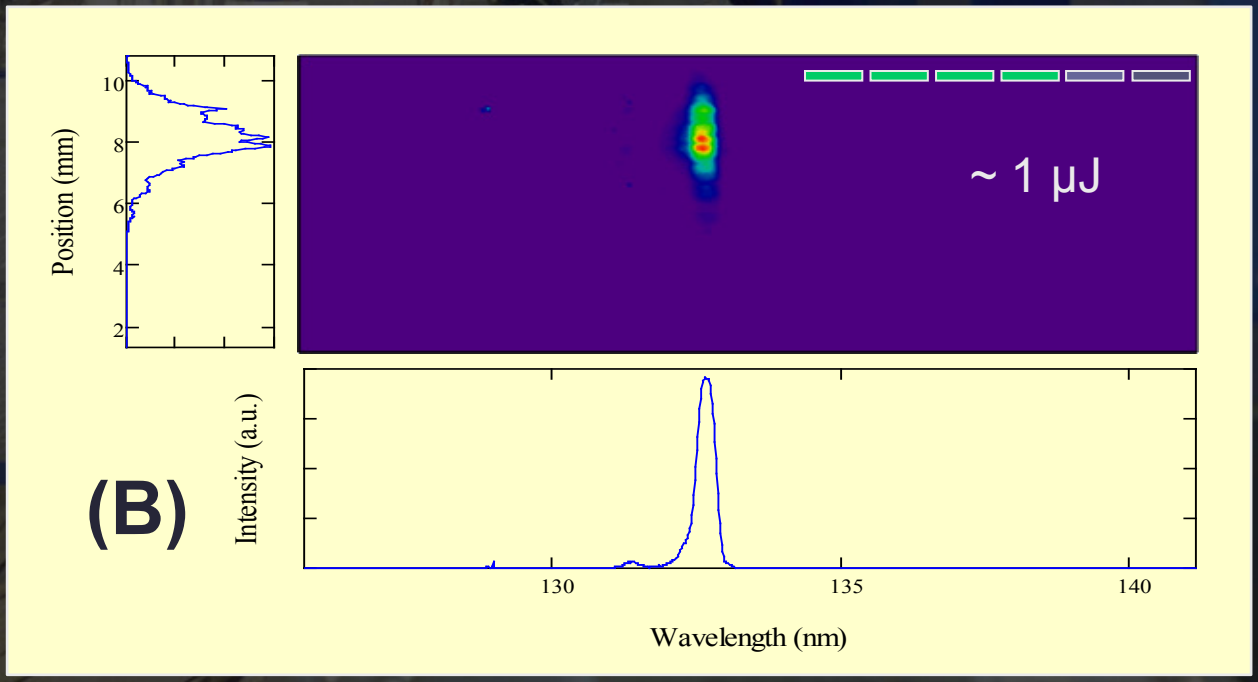
Beam parameters	
Energy	177.2 MeV
Peak Current	45 A
Rel. En. Spread (slice)	< 2 x 10-4
Projected Emitt.	2 mm-mrad

Spectrometer slit @ 5 um & nbw filter @ 266nm, 17% T - Energy > 1 uJ – Sidebands (saturation)

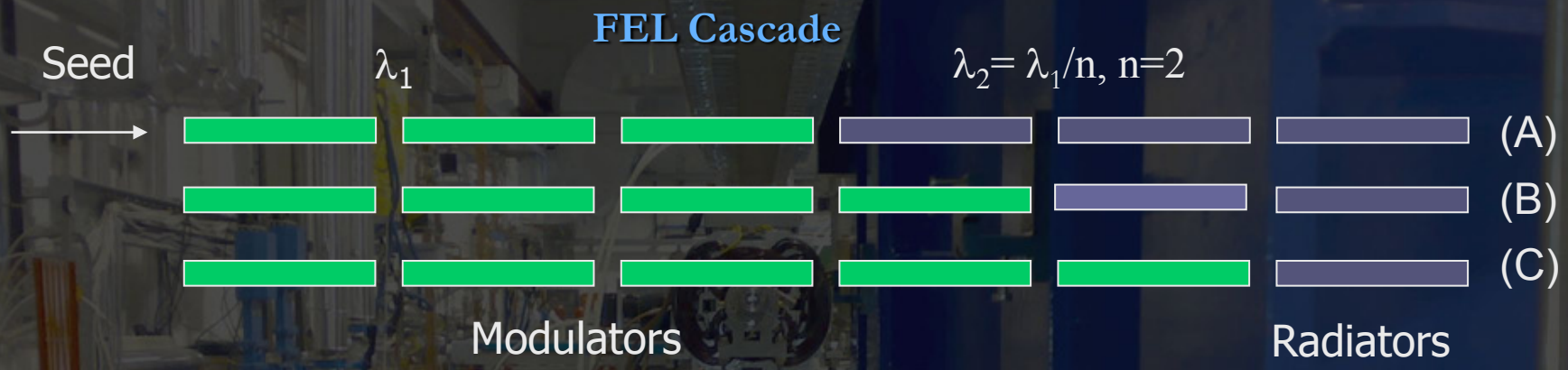


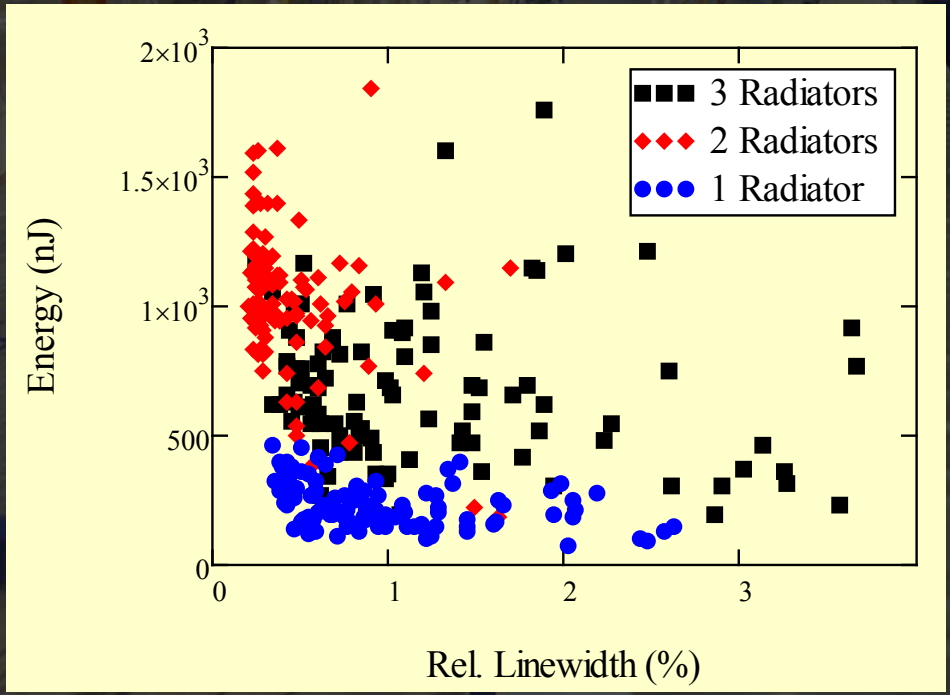
FEL cascade seeded by HHG





FEL cascade seeded by HHG





Rad./Mod.	Energy (μJ)	LW (%)
3/3	0.7	1.3
2/4	1.0	0.44
1/5	0.23	1.0

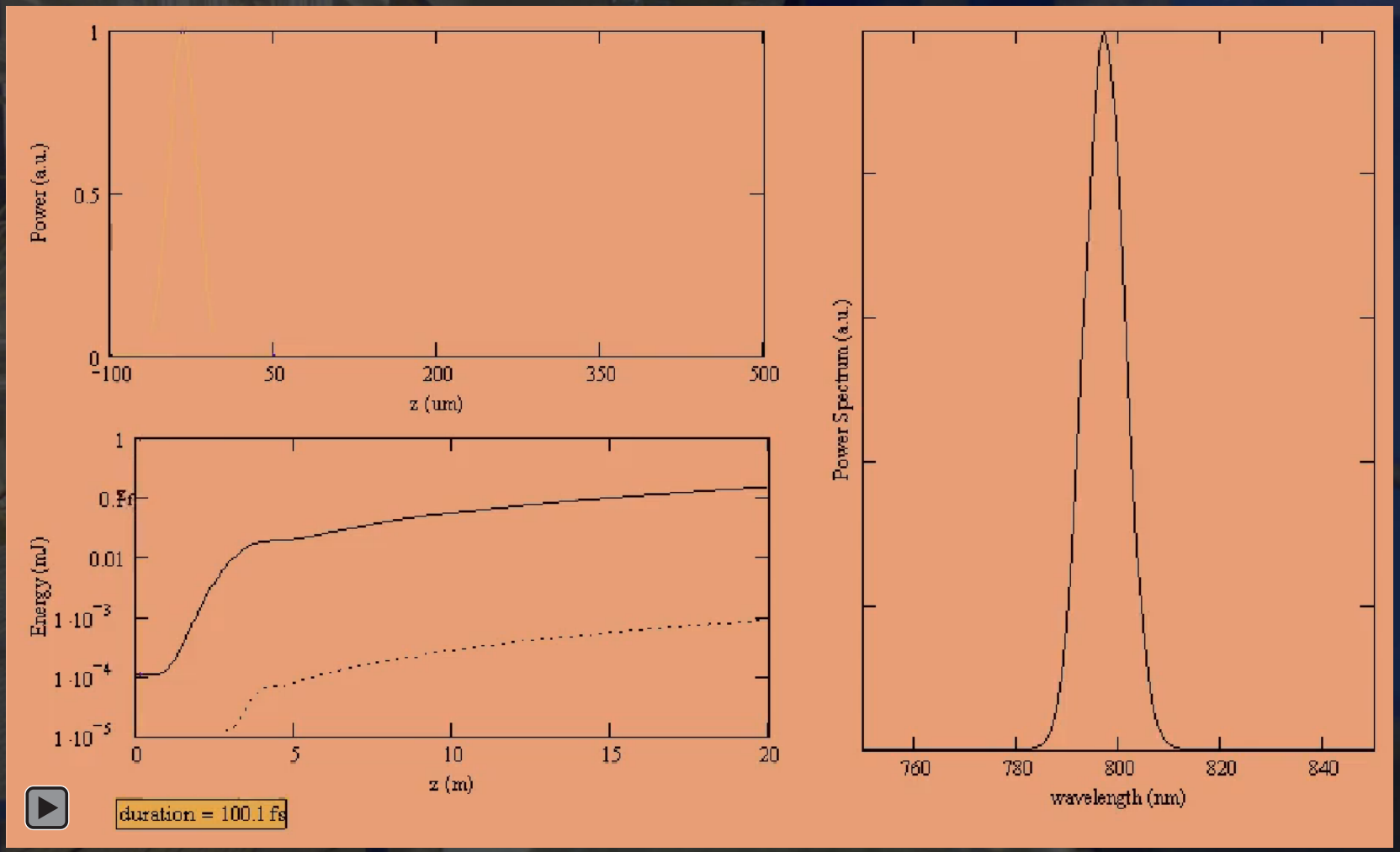
High intensity seeding:
Superradiance & harmonic generation

- *Emission from a "coherent" electronic state*
  Dicke, PR 93, 99 (1954)
- *In FELs, regime of "field/particles" evolution with*
  - *Power scaling typical of superradiance a la "Dicke"* $\boldsymbol{P \alpha n_e^2}$
  - *Peak power exceeding the saturation threshold*
  - *Longitudinal self-focusing*
  - *Solitary wave-like pulse propagation*
  - *High Harmonics Generation*

References

R. Bonifacio, B. W. J. Mc Neil, P. Pierini, PRA 40, 4467 (1989)
R. Bonifacio, L. De Salvo Souza, P. Pierini, N. Piovella, NIM A296, 358 (1990)
L. Giannessi, P. Musumeci, S. Spampinati, J. of Appl. Phys. 98, 043110 2005
T. Watanabe et al. Phys. Rev. Lett. 98, 034802 (2007)

Seeded Amplifier at saturation



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

Brookhaven - SDL 2006

Longitudinal focusing

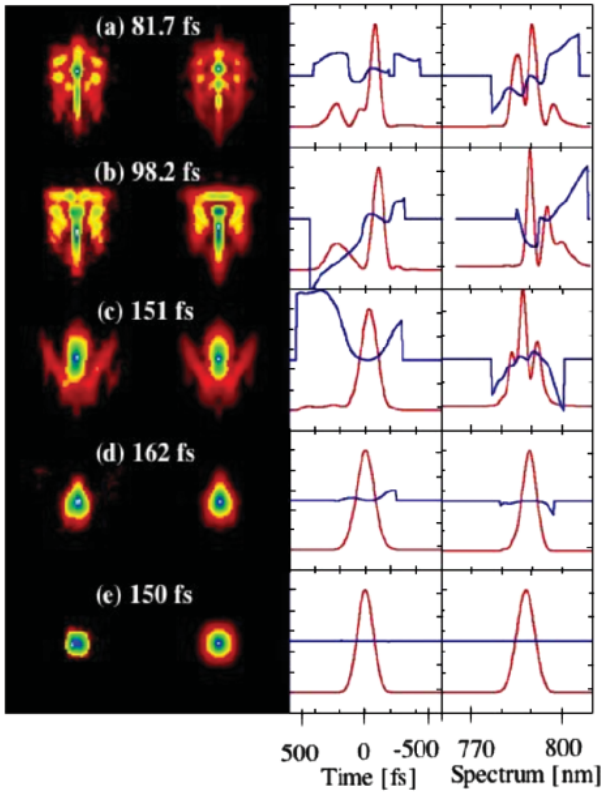


FIG. 3 (color). Each FROG result is a row in the figure labeled by the FWHM of the main temporal peak. Starting from the left, the four columns are: raw and retrieved FROG images, temporal and spectral distributions including phase. Amplitudes (red) are normalized and phase (blue) are plotted from −6 to +6 radians.

PRL 98, 034802 (2007) PHYSICAL REVIEW LETTERS week ending 19 JANUARY 2007

Experimental Characterization of Superradiance in a Single-Pass High-Gain Laser-Seeded Free-Electron Laser Amplifier

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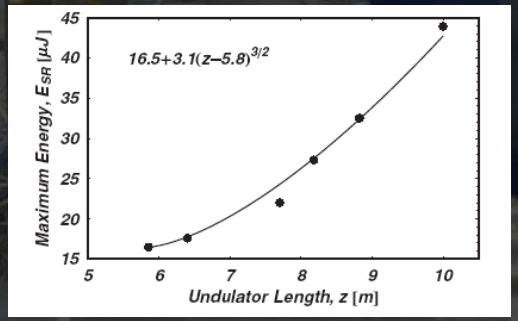
[3]*ENEA C.R. Frascati, Via E. Fermi 45, 00044 Frascati, Italy*
[4]*INFN c/o Dipartimento di Fisica, Università di Roma "La Sapienza", Piazzale Aldo Moro 2, 00185 Roma, Italy*
[5]*Department of Physics and Astronomy, UCLA, Los Angeles, California 90095, USA*
(Received 15 September 2006; published 19 January 2007)

Pulse energy scaling



Pulse shape and spectrum

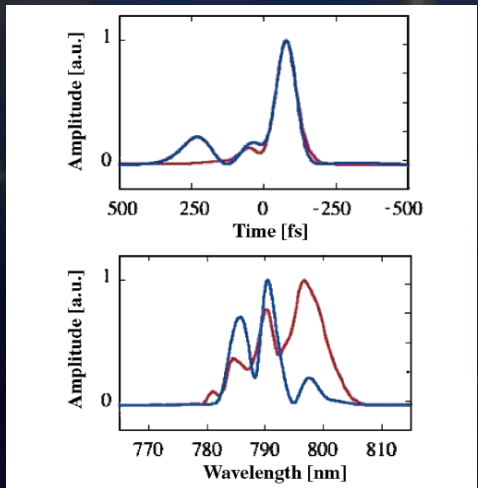
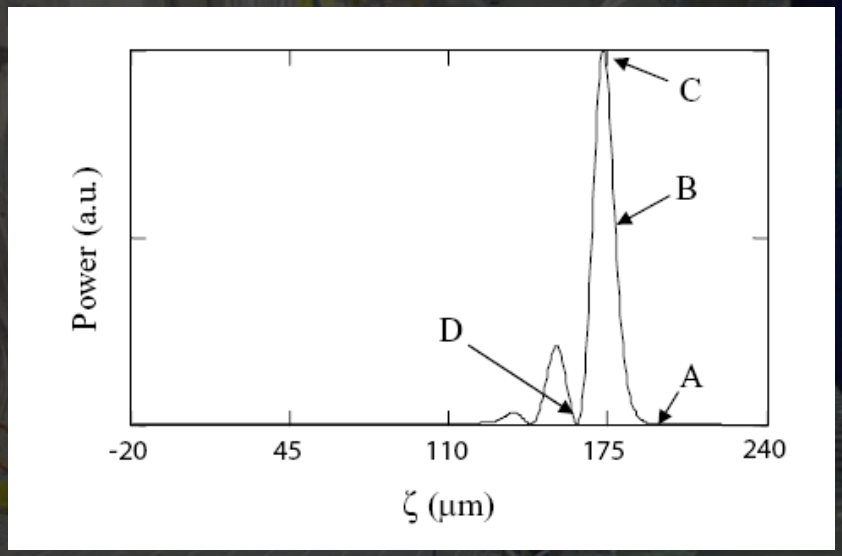
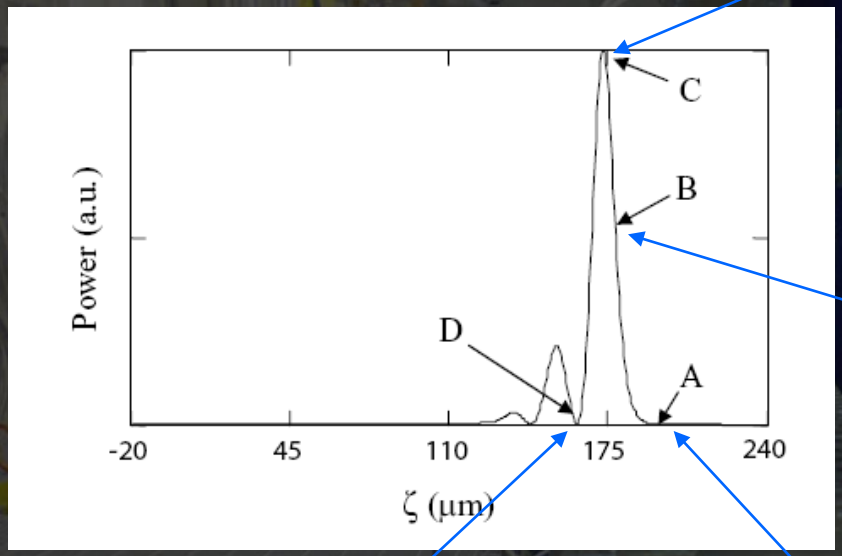


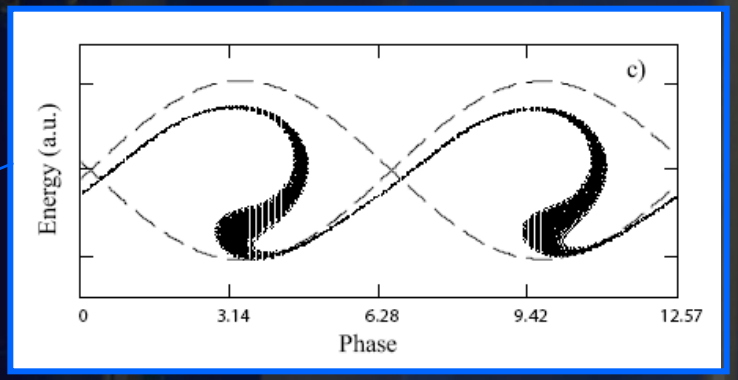
FIG. 4 (color). Measured FROG results of the first row of Fig. 3 (blue) and GENESIS1.3 simulation results (red). For the temporal distribution, toward the right is the head and left is the tail of the pulses.

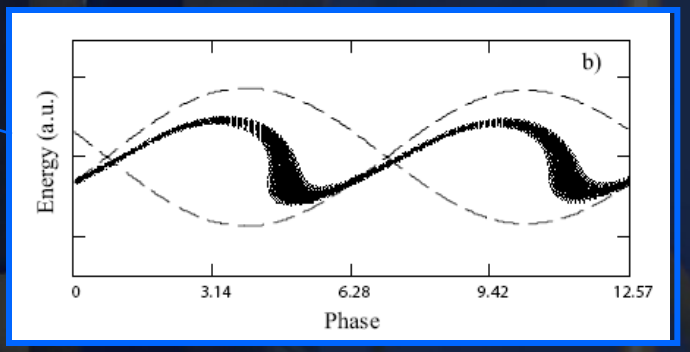
Solitary wave-like superradiant pulse

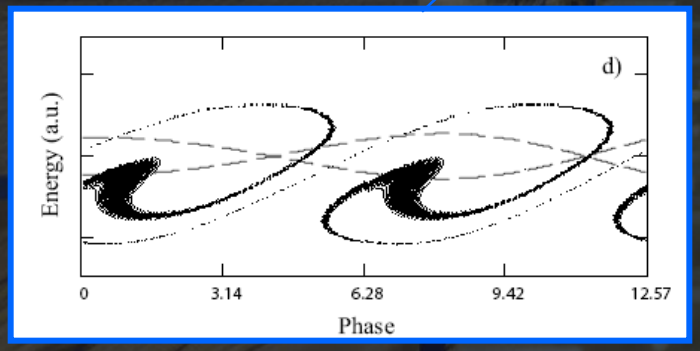


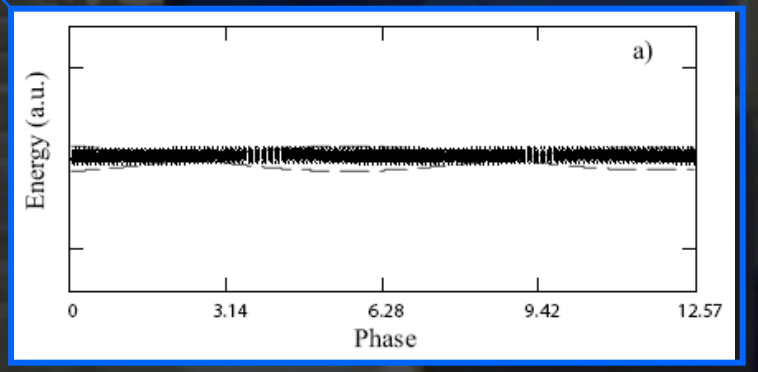
Solitary wave-like superradiant pulse





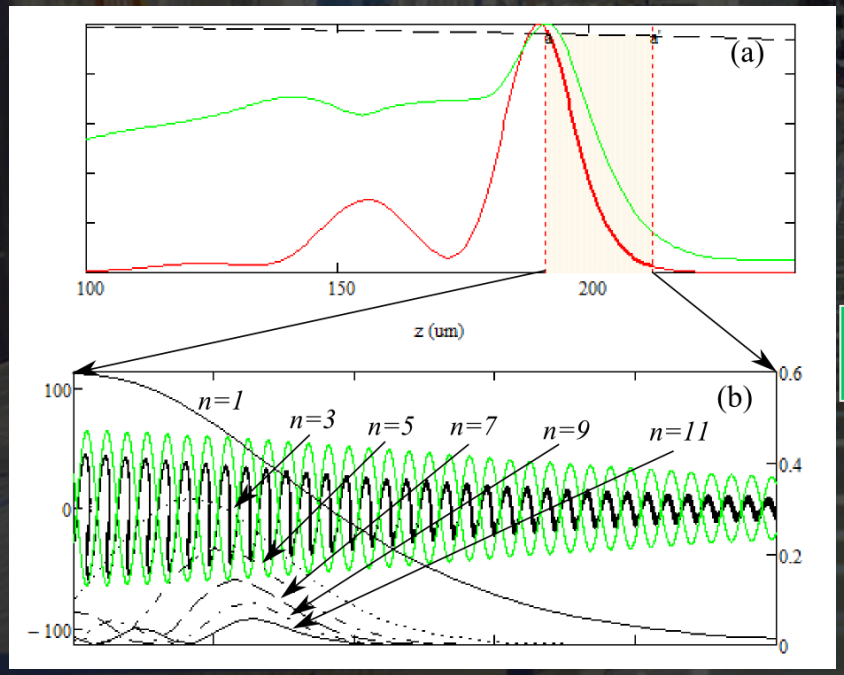


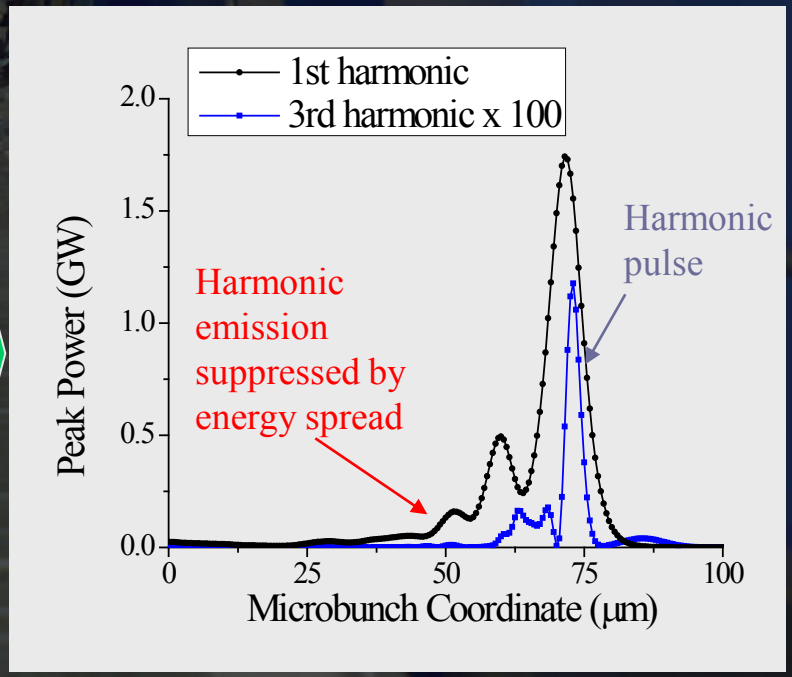




Bunching coefficients in the front side of the pulse: Harmonics

- Bunching peaks at the higher order harmonics
- Short bursts of harmonic radiation in the front side of the pulse
- Bunching structure preserved by the "solitary wave" behavior of this solution

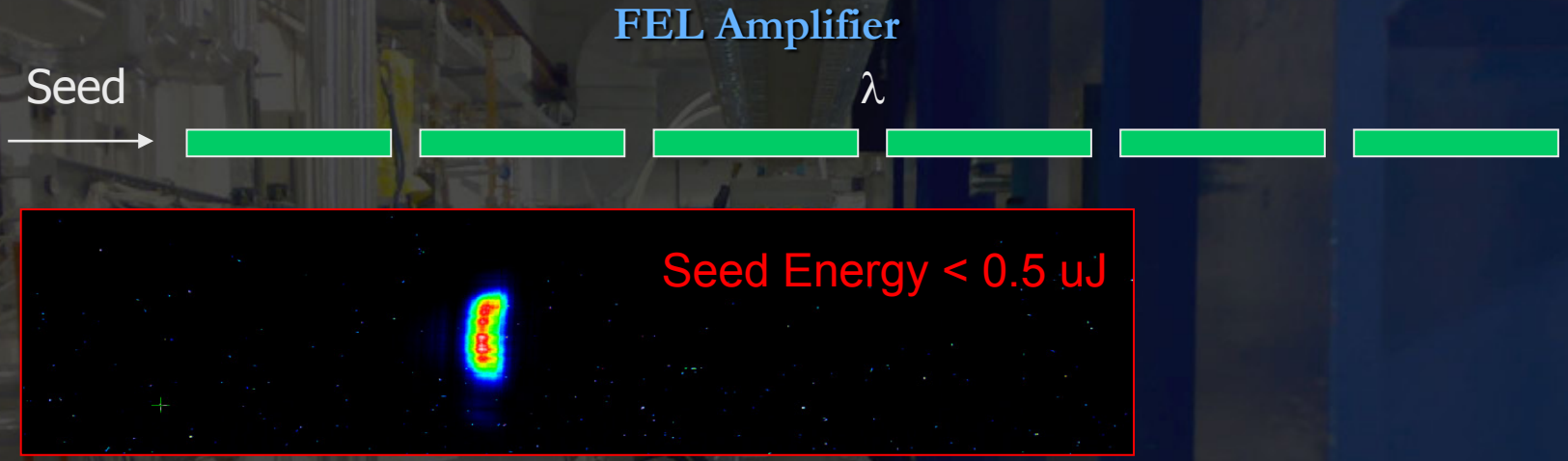




Expected very efficient generation of high order harmonics

Direct seeding @400 nm - (30/6/2010)

Seed @ 400 nm, <0.5 uJ – 9 uJ - 6 UM tuned at 400 nm



Beam parameters	
Energy	178 MeV
Peak Current	50 A
Rel. En. Spread (slice)	< 2 x 10-4
Projected Emitt.	2.5/2.9 mm-mrad

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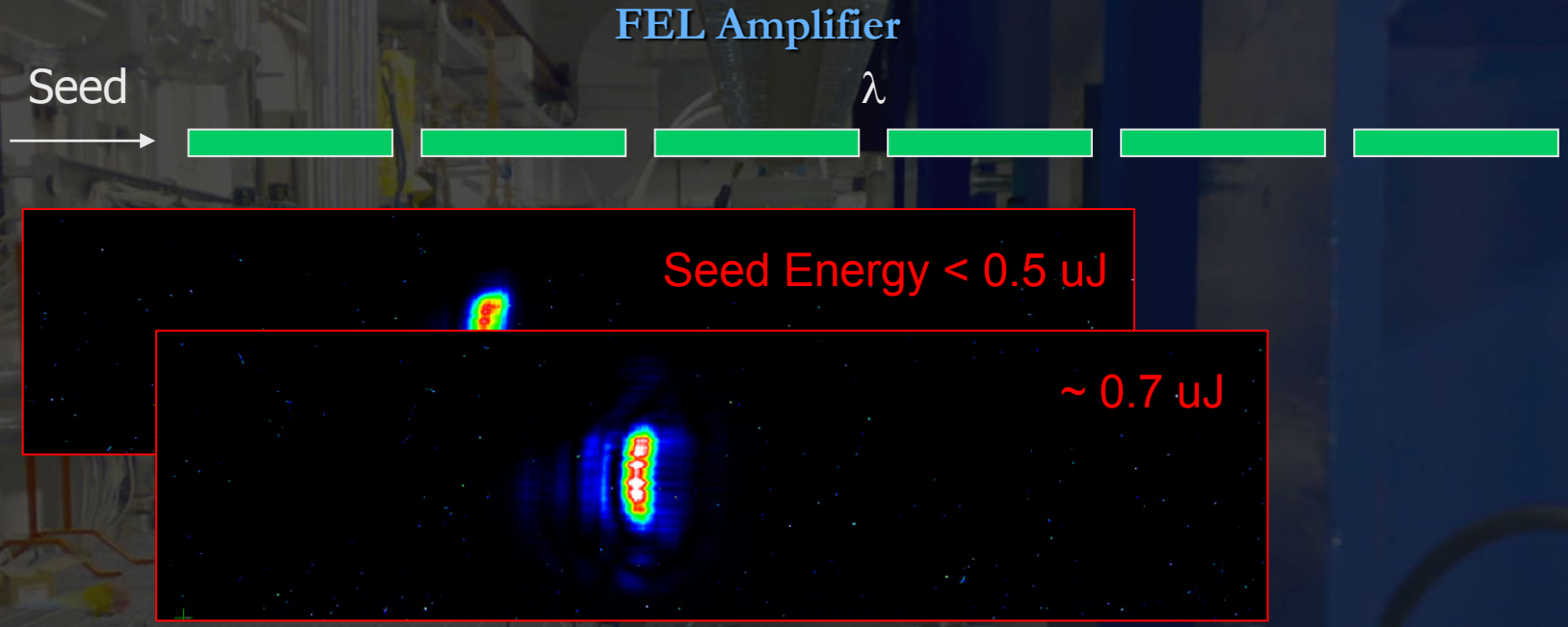

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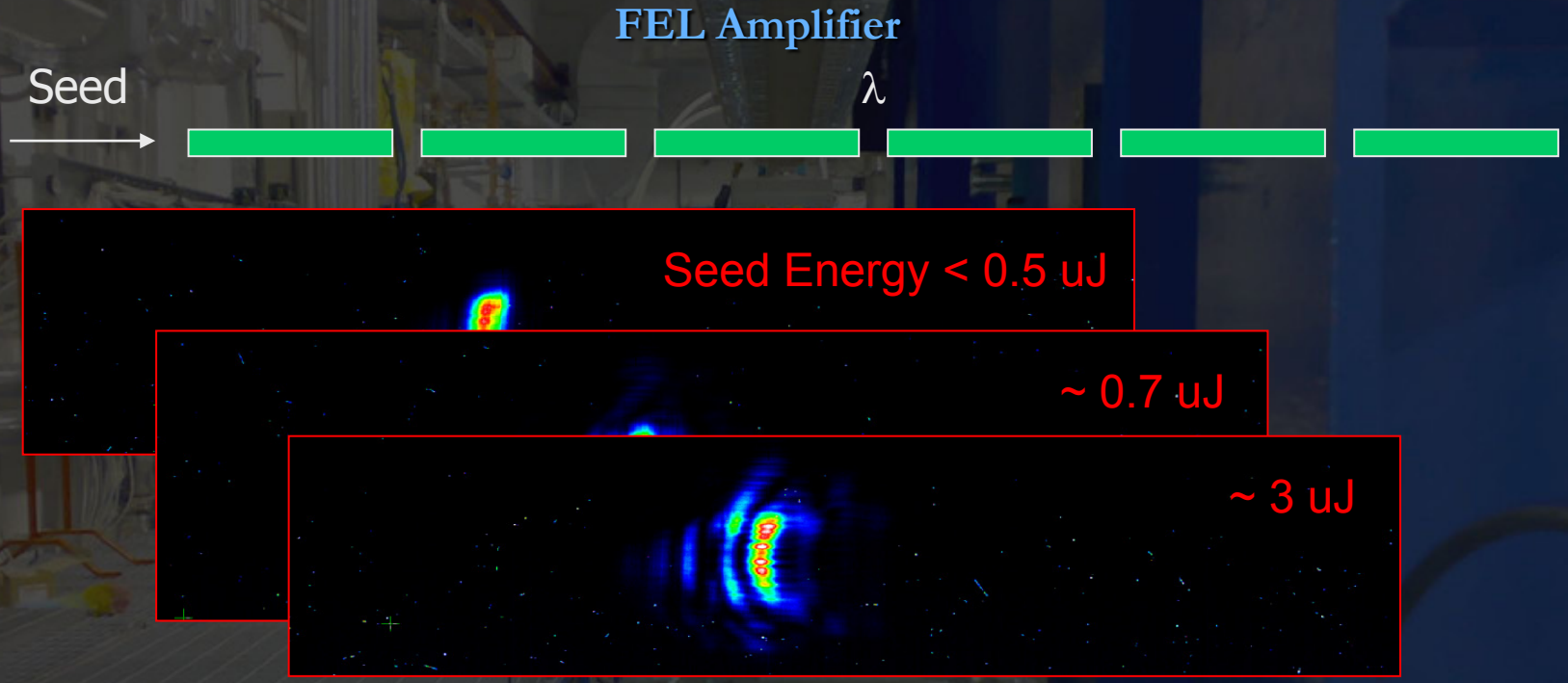

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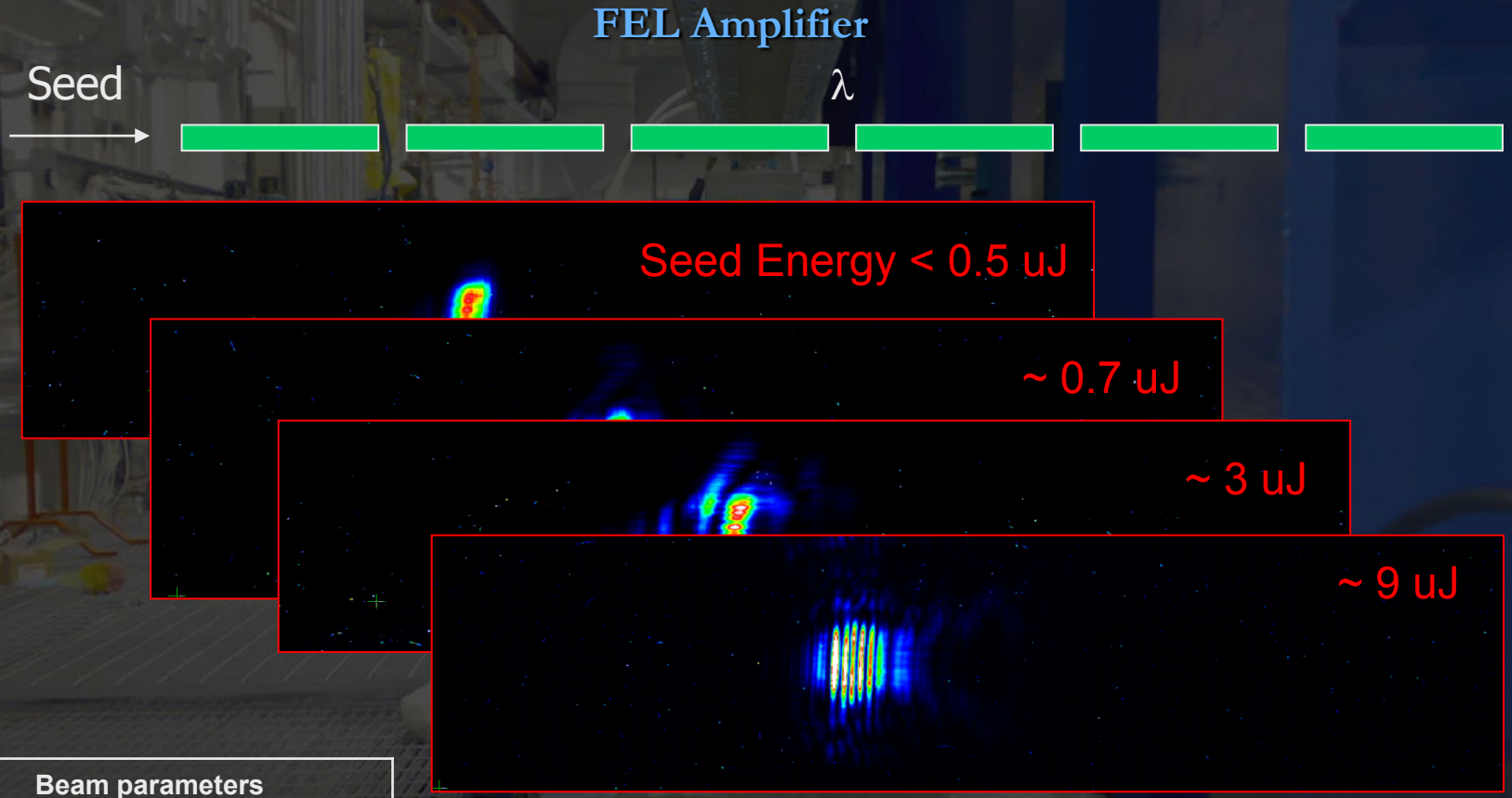

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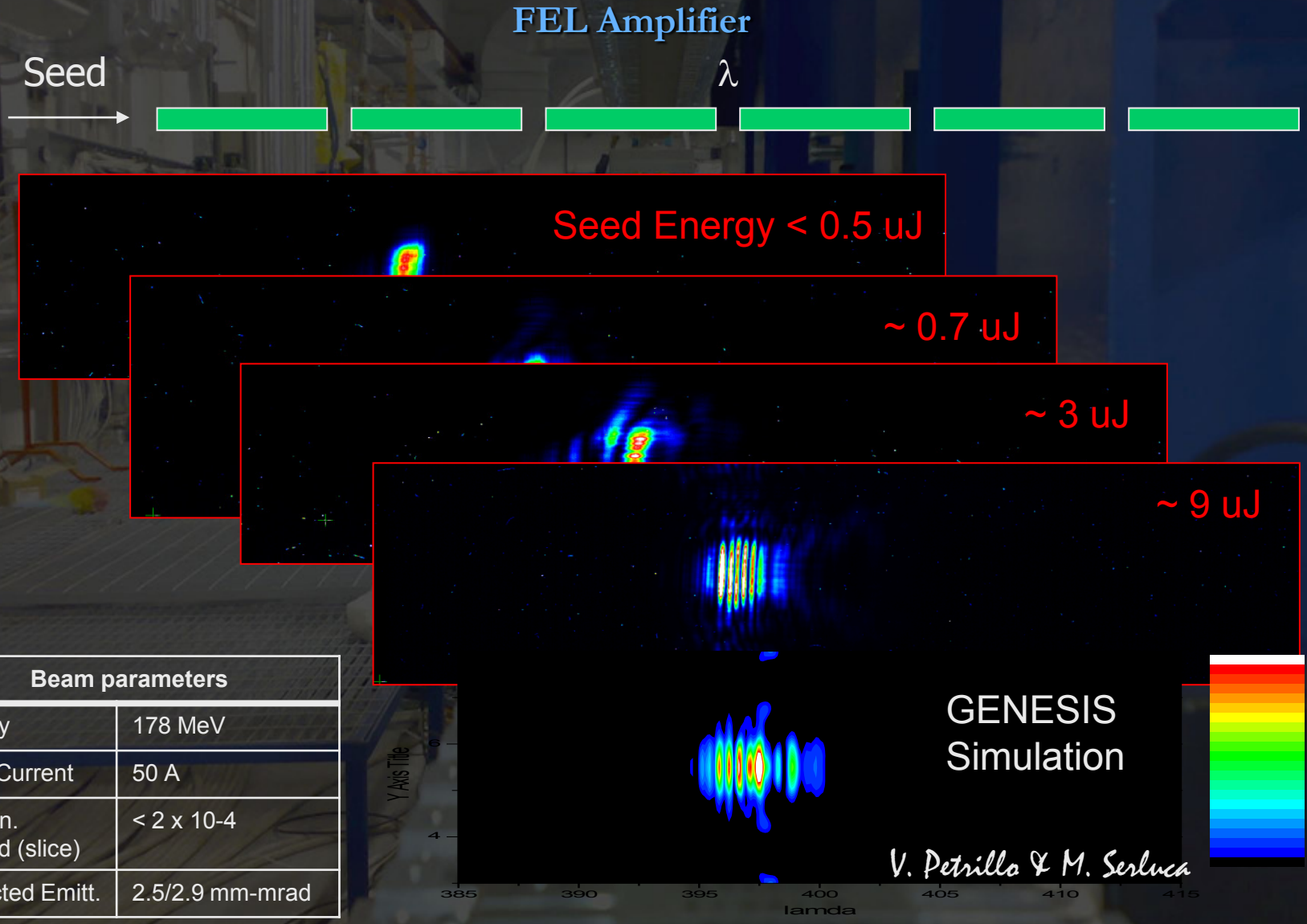
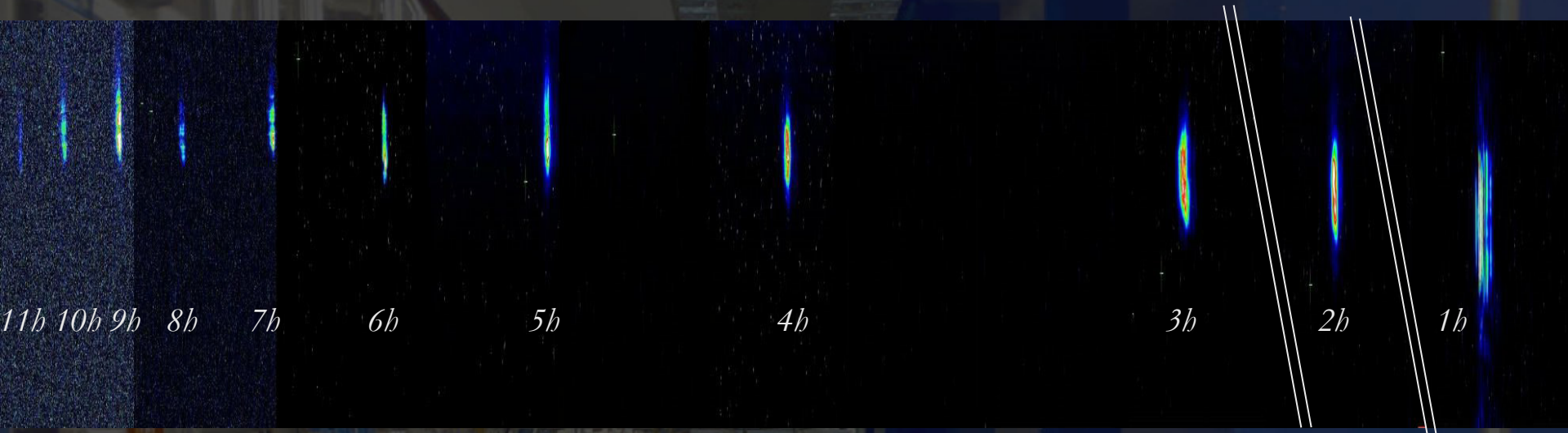
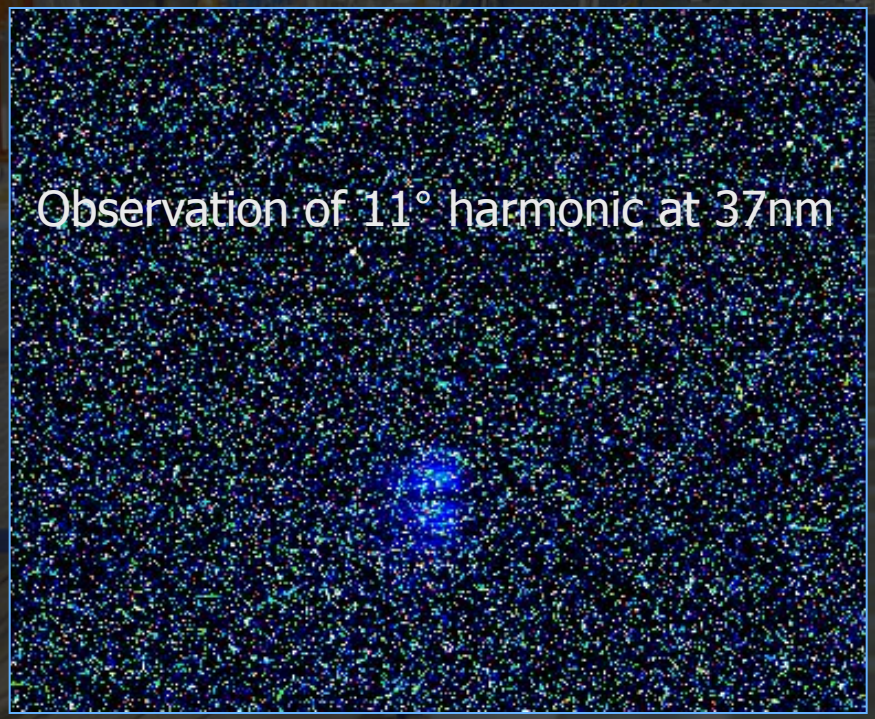


Beam parameters	
Energy	178 MeV
Peak Current	50 A
Rel. En. Spread (slice)	< 2 x 10-4
Projected Emitt.	2.5/2.9 mm-mrad

High harmonics down to 37 nm (E=178MeV)





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

Conclusions

- First FEL cascade seeded with harmonics generated in gas
  - Future development: energy boost to 240 MeV → seeding with higher order and even harmonics with two colors hhg in Ar.
- Harmonic generation in superradiance → generation of high harmonics in a FEL amplifier
  - Developments: Multistage cascaded FEL & Harmonic cascade

Observed pulse energies vs. wavelength (~ 50-60A / 178MeV)

Mode of operation	SASE	Seeded		
Wavelength	500 nm	200nm	133 nm	66nm*
Energy/pulse (~ 100 fs)	~100 μJ	~10 μJ	~1 μJ	~100 nJ
# photons	2.5×10^{14}	1×10^{13}	6×10^{11}	3×10^{10}

* FEL cascade operating in superradiance