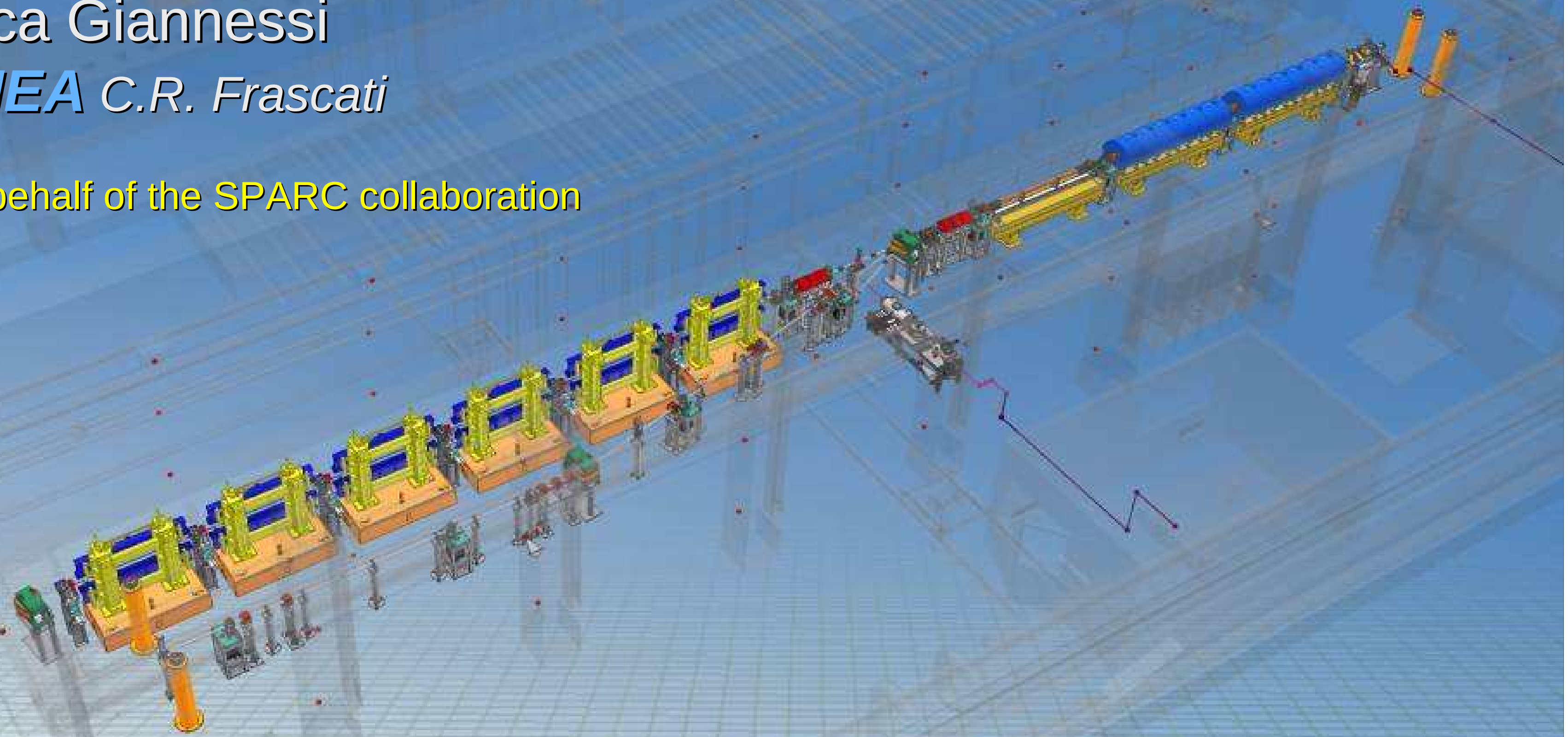
# Seeding the SPARC Free electron laser amplifier


Luca Giannessi

***ENEA*** *C.R. Frascati*

On behalf of the SPARC collaboration

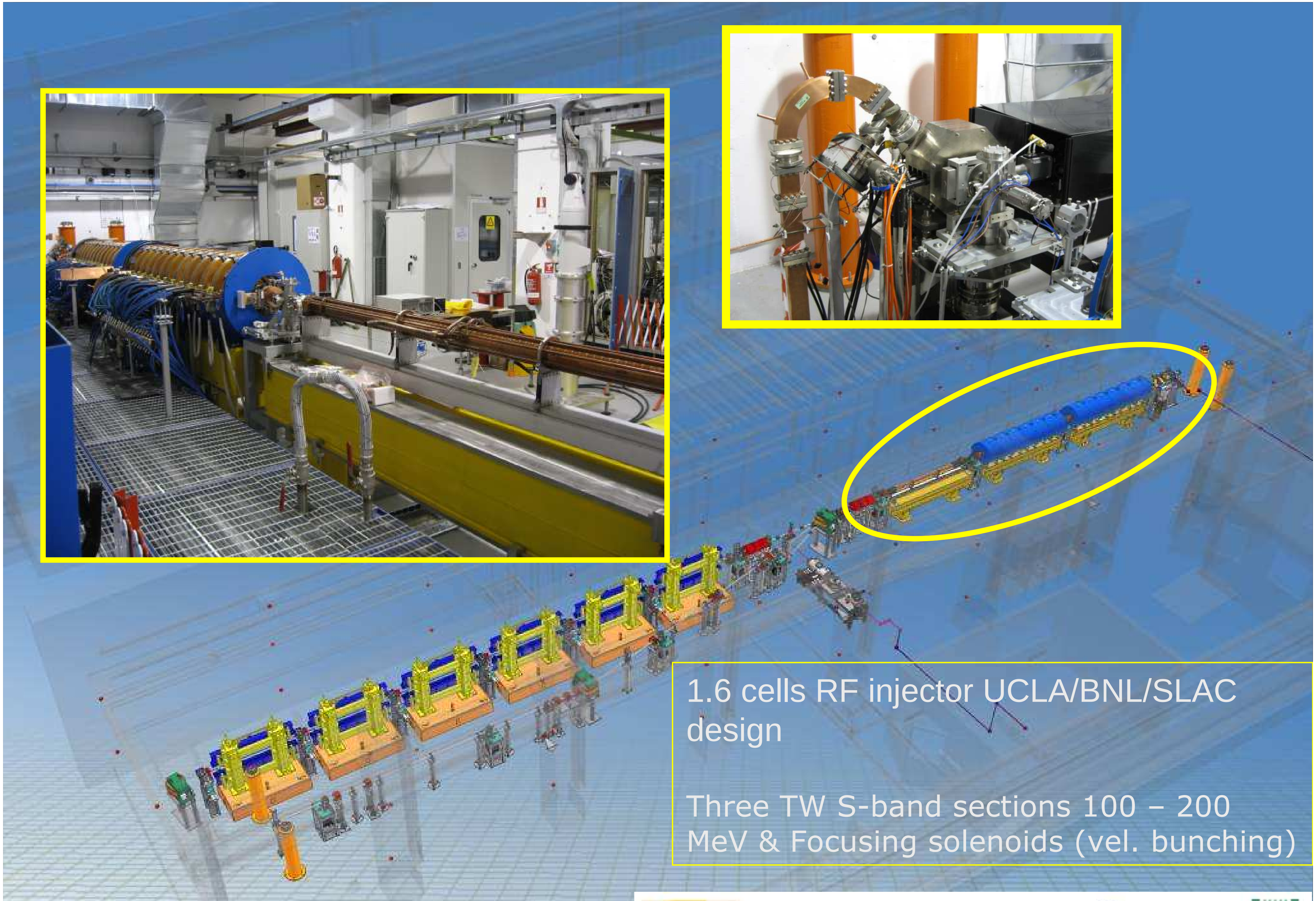



SPARC

*DESY, 11-02-2011*

# Outline

- SPARC Overview
- SPARC Seeding Layout
- Low power seeding: amplification of harmonics generated in gas
  - Direct seeding
  - Single stage cascade 266nm -> 133nm
- High power seeding
  - High harmonics generation
  - Superradiant cascade



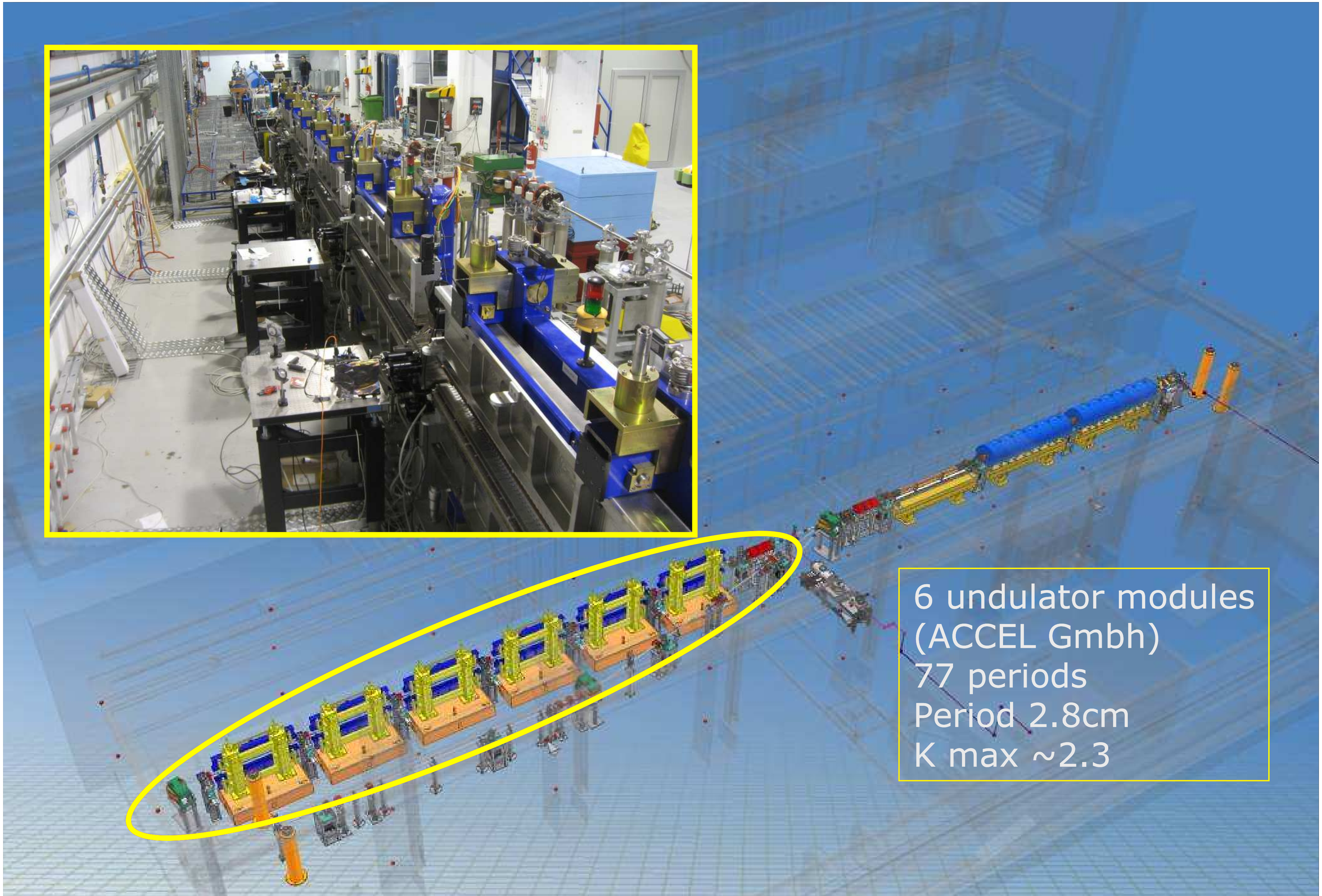

SPARC

Consiglio Nazionale delle Ricerche

ENEA C.R. Frascati

INFN Istituto Nazionale di Fisica Nucleare

Tor Vergata




SPARC

Consiglio Nazionale delle Ricerche

ENEA C.R. Frascati

INFN Istituto Nazionale di Fisica Nucleare

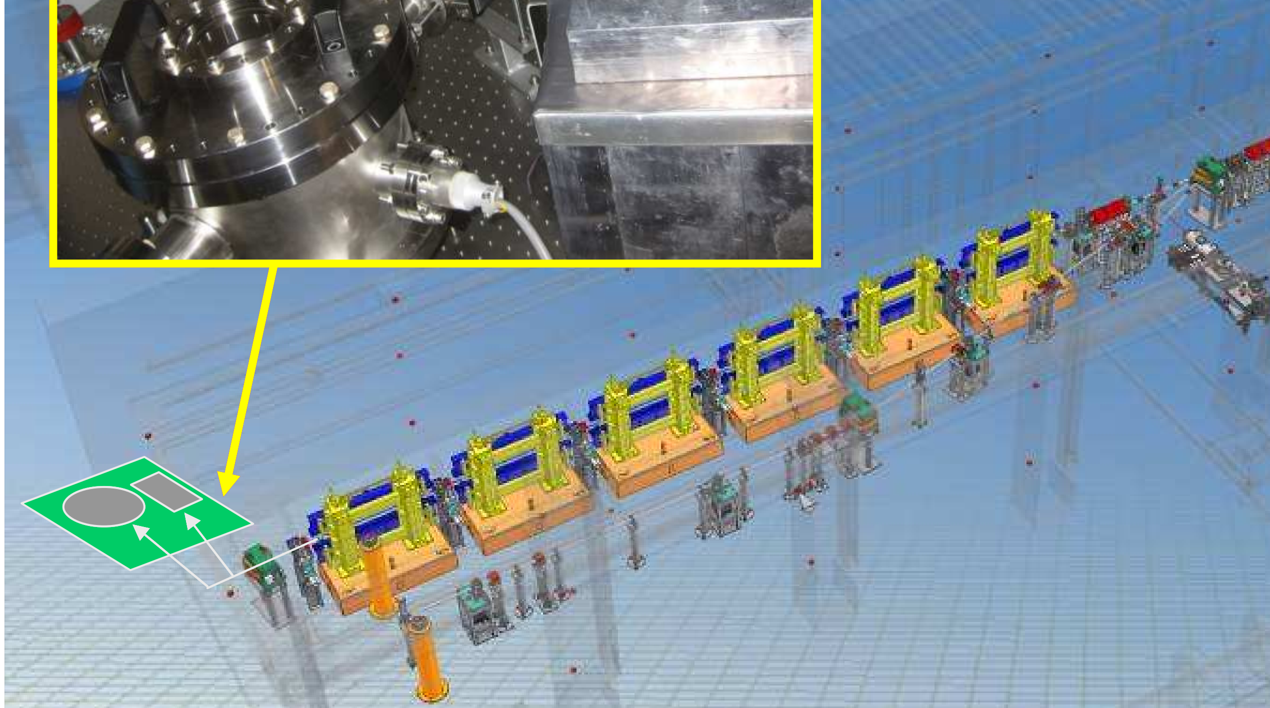
Streak Camera

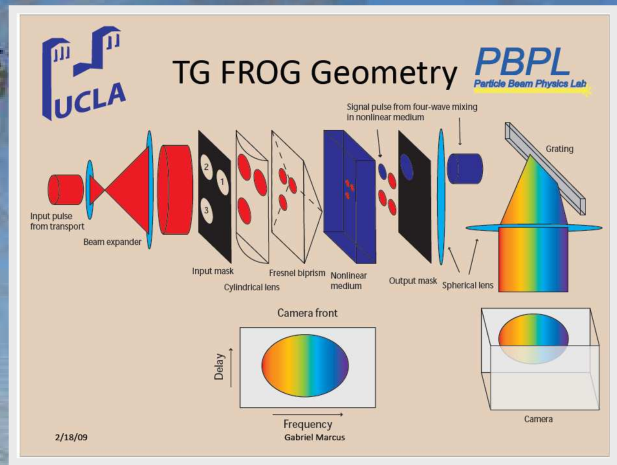
In vacuum spectrometer (Luxor)

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

FROG diagnostic (UCLA)

PBPL Particle Beam Physics Laboratory






SPARC

Consiglio Nazionale delle Ricerche

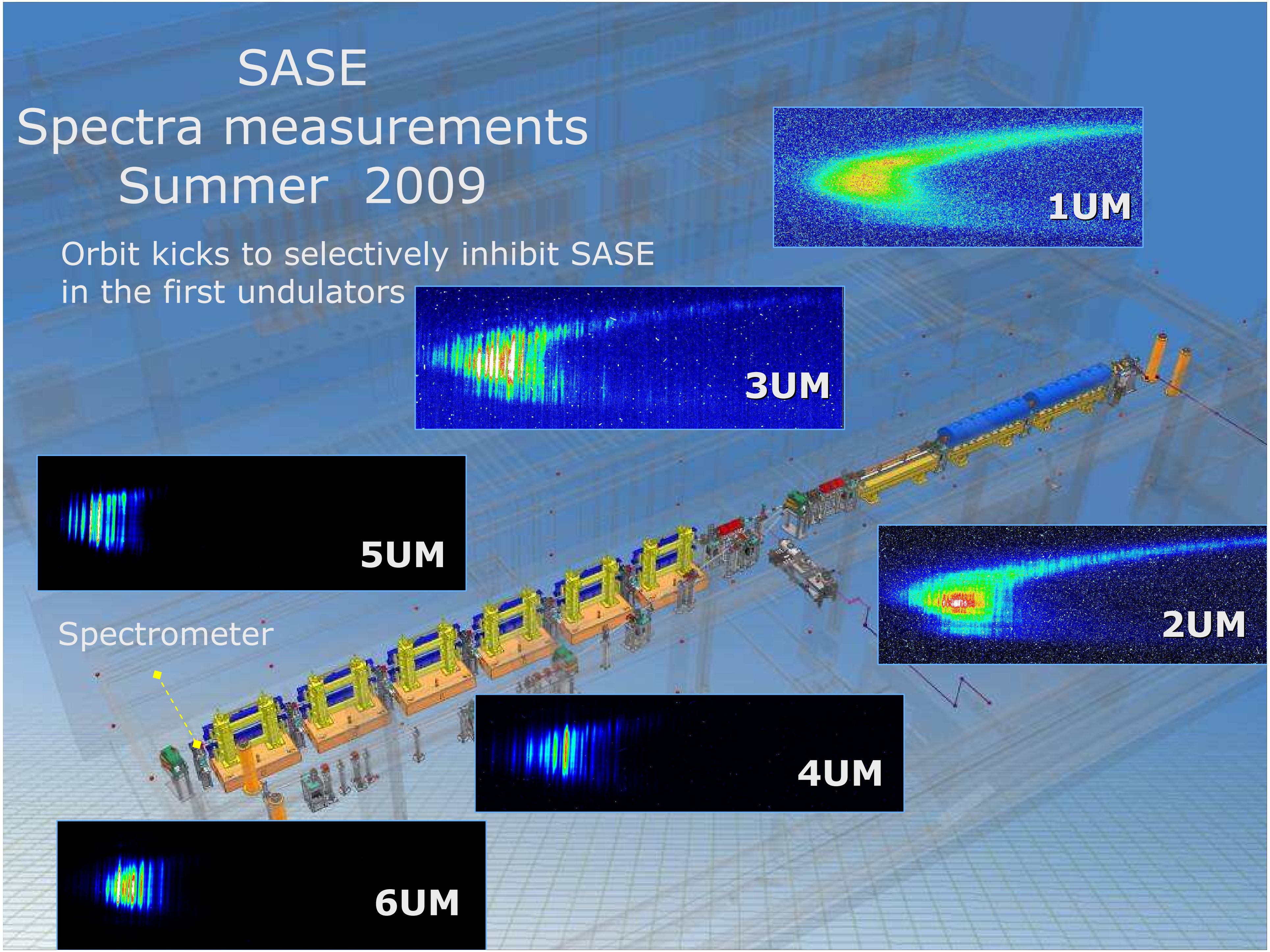
ENEA C.R. Frascati

INFN Istituto Nazionale di Fisica Nucleare

Università degli Studi di Roma Tor Vergata

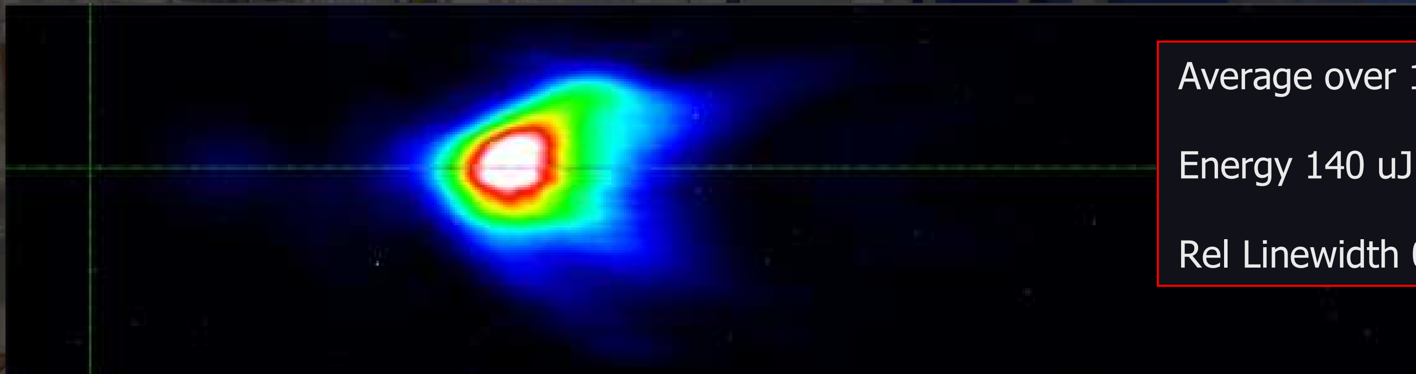
# SASE
# Spectra measurements
# Summer 2009

Orbit kicks to selectively inhibit SASE
in the first undulators



# SASE experiments in 2010 …

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

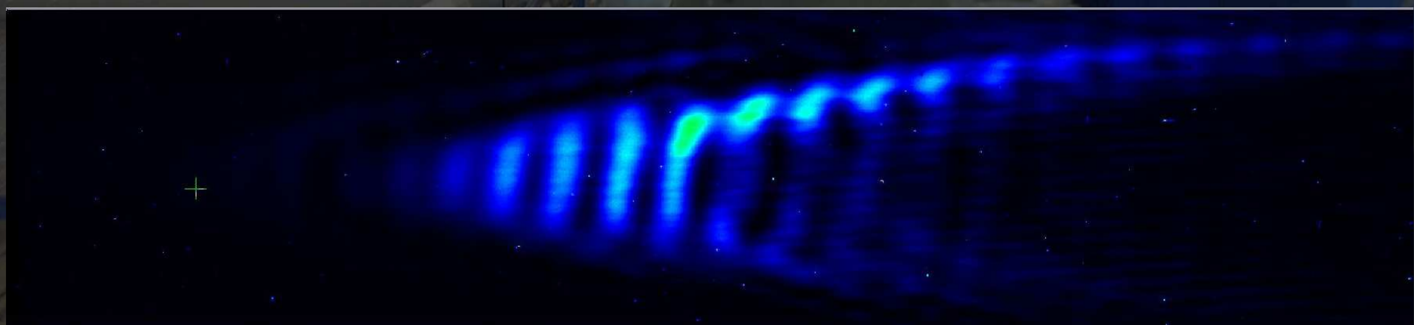


Average over 100 spectra:

Energy 140 uJ (max 380 uJ)

Rel Linewidth 0.8% rms

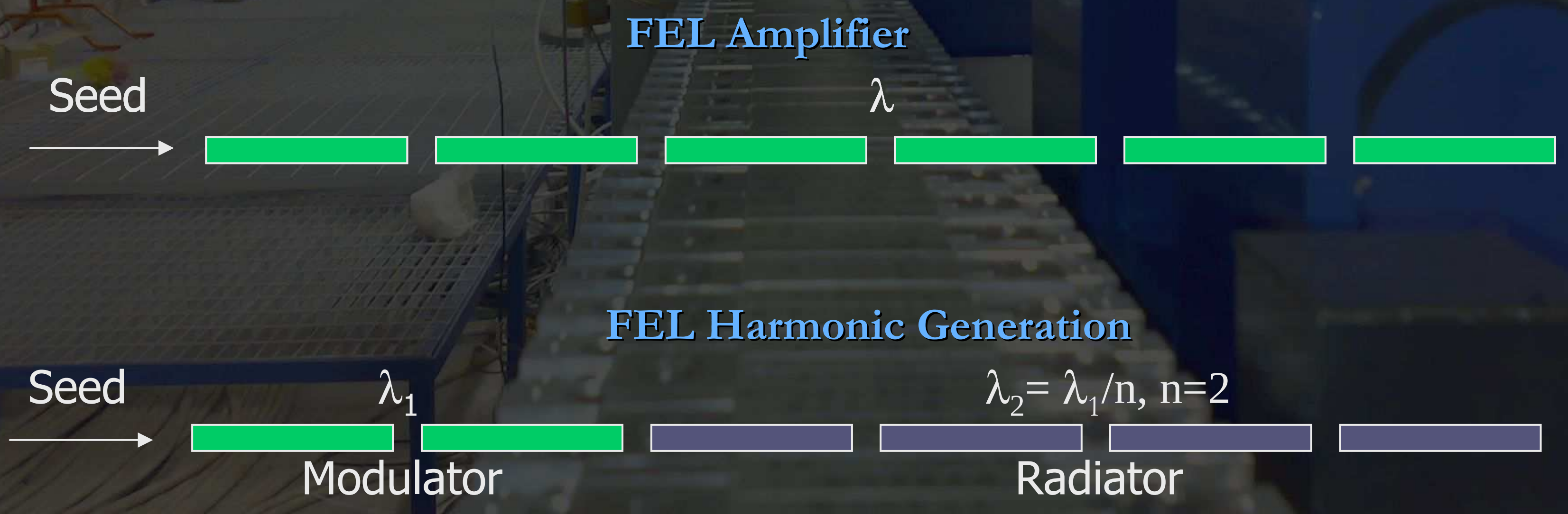
## TWINS (Two simultaneous spikes ~500 fs separation)



~40 nm

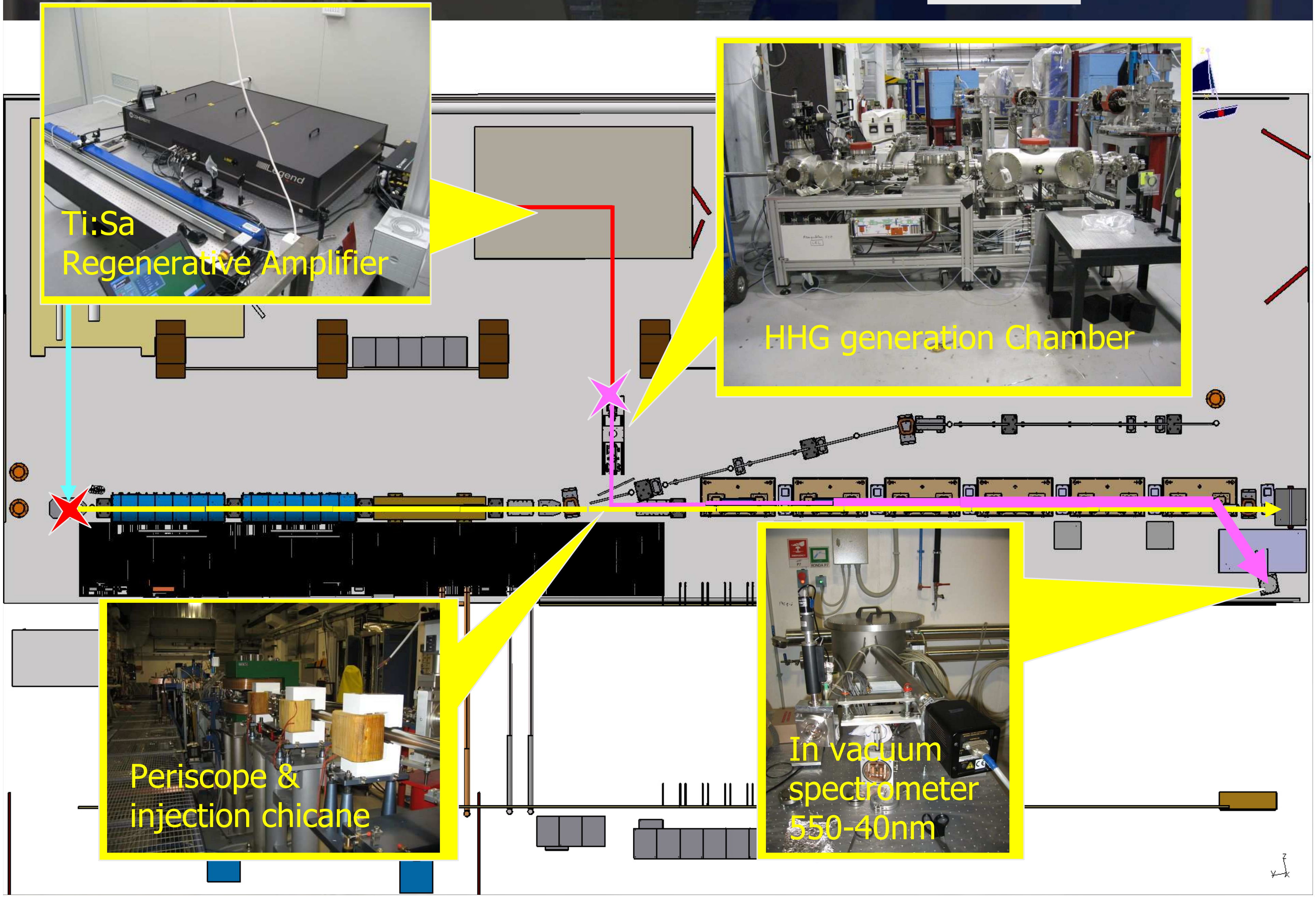
# Seeded Operation

- Seed modes:
  - Low pulse energy seeding: 266 nm & 160 nm generated in gas
  - High pulse energy seeding: 400 nm in BBO crystal



# Seeded SPARC Layout

EURO FEL + MUR



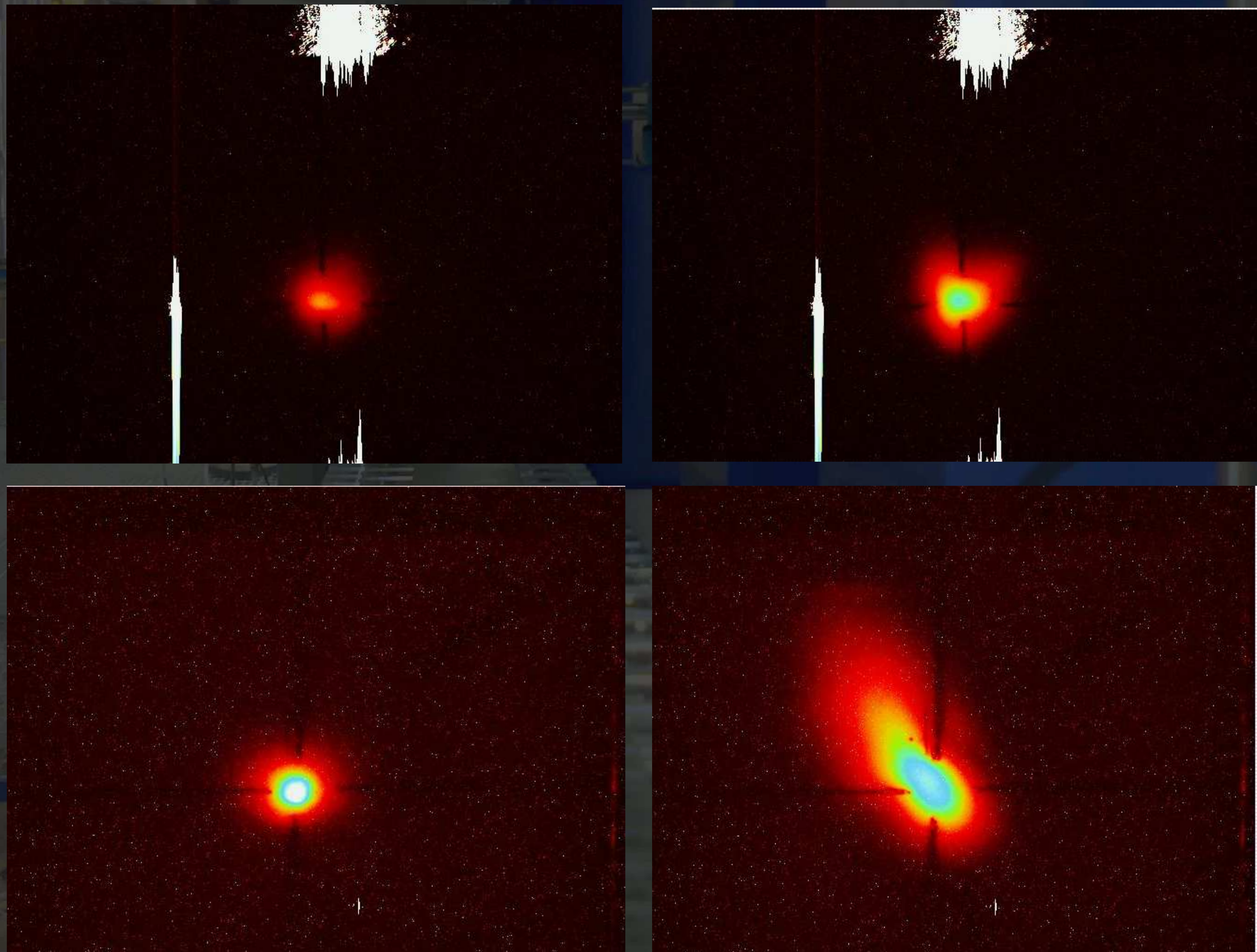
# Transverse Alignment

e-

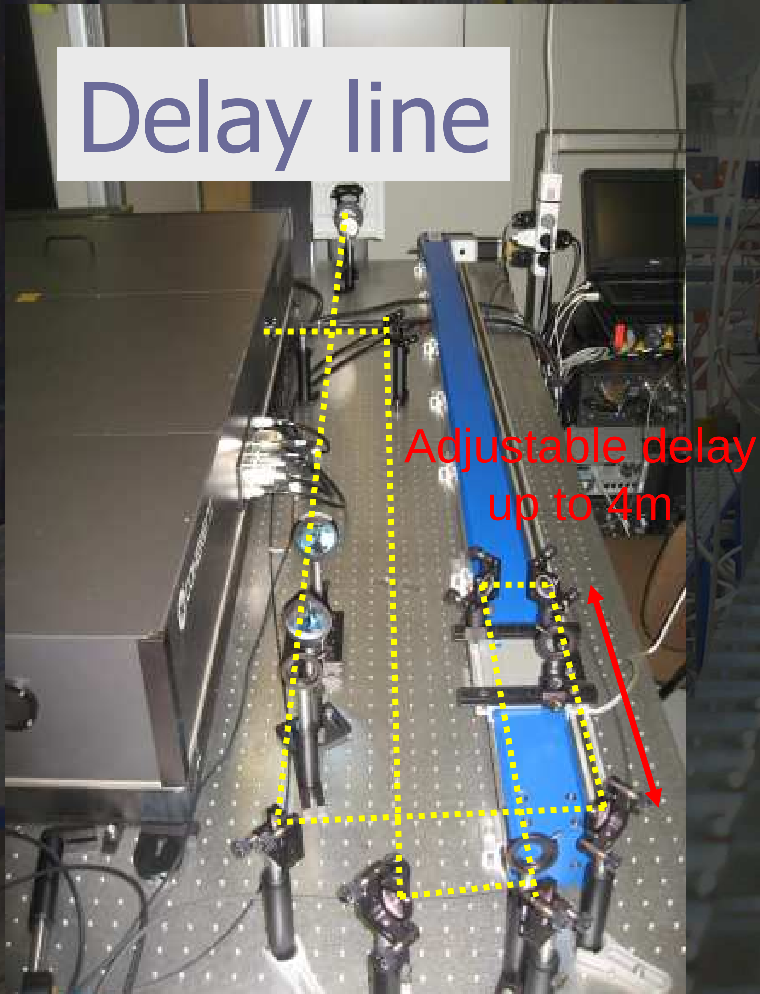
400nm

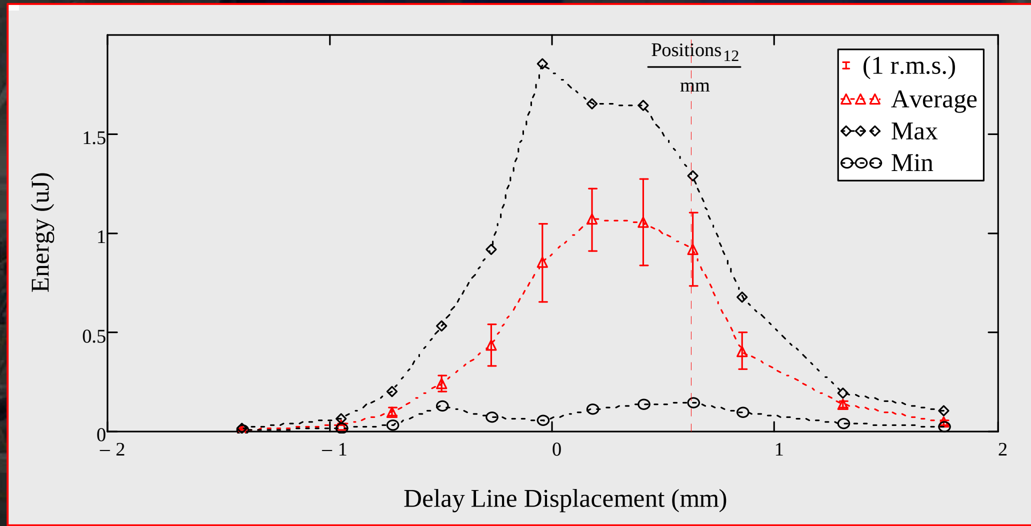
FLAG1
(after first UM)

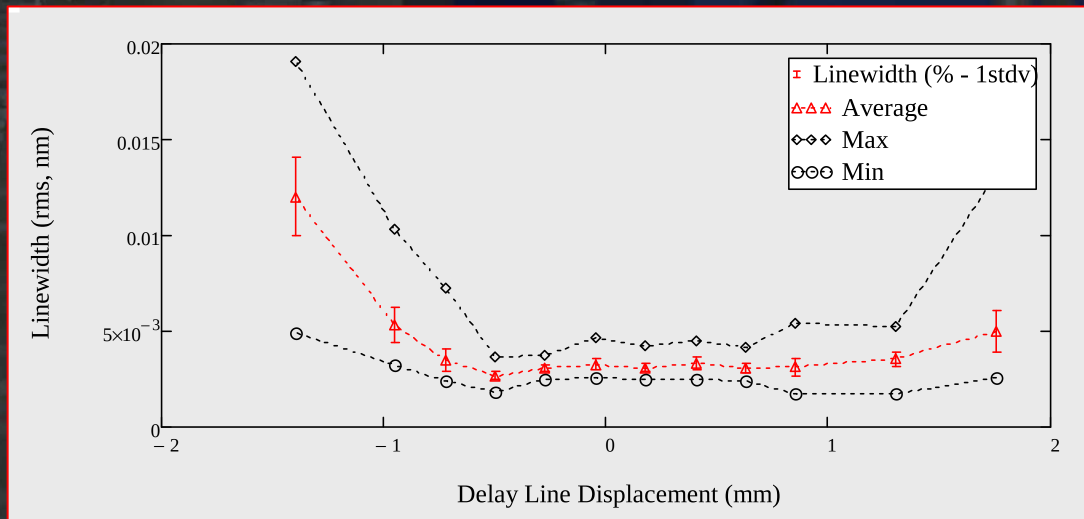
FLAG2
(after second UM)



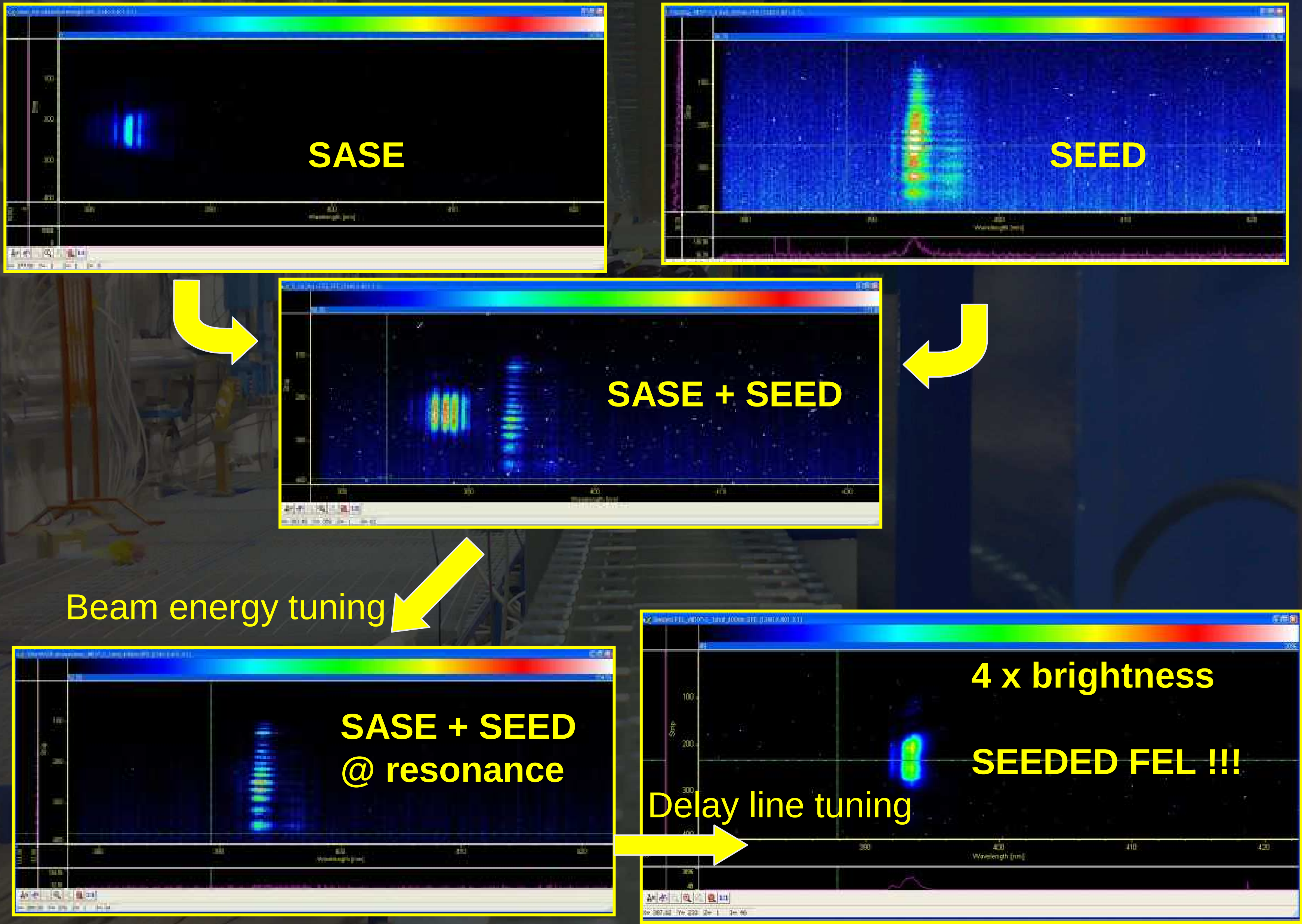
# Temporal alignment



# Energy “alignment” (11-02-2010)

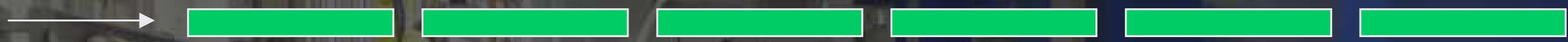


# Seeding with harmonics generated in gas

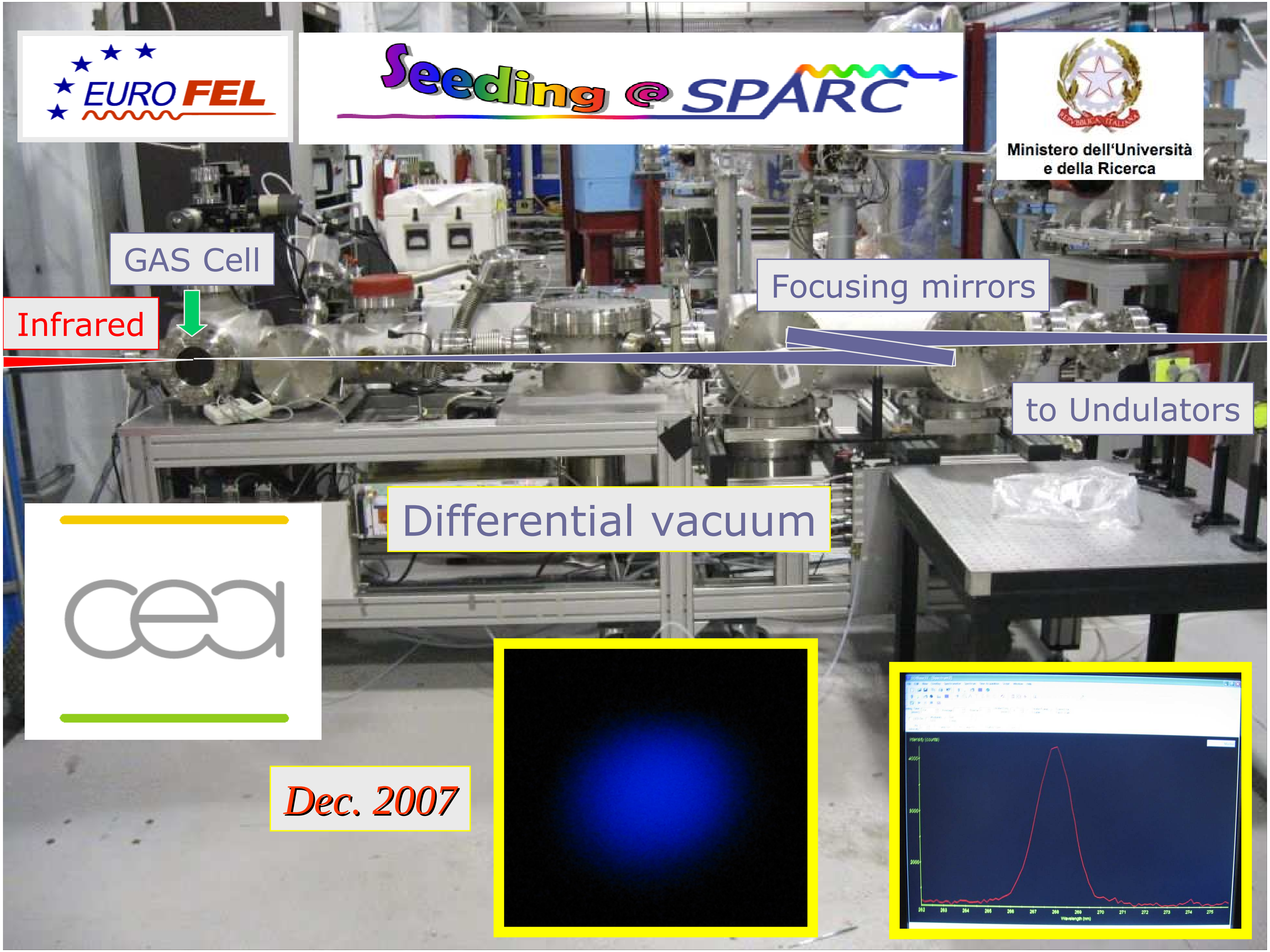
FEL Amplifier

Seed

λ

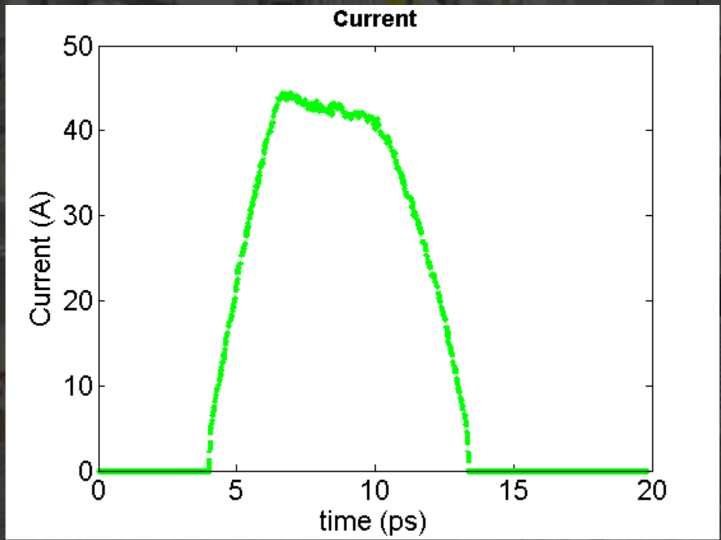


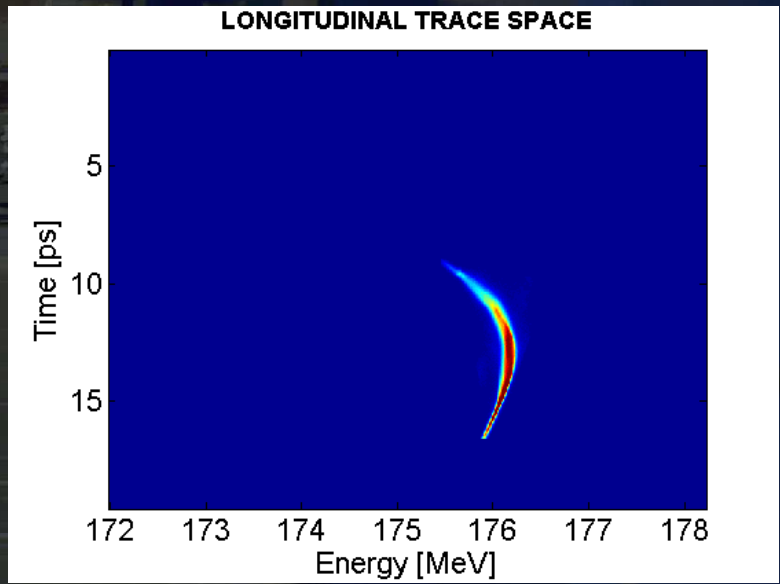
Seed generated in gas


EURO FEL
Seeding @ SPARC
Ministero dell'Università e della Ricerca
GAS Cell
Infrared
Focusing mirrors
to Undulators
Differential vacuum
cea
Dec. 2007

# Seeding - Beam parameters (3-4/6/2010)

Transverse emittances ~ 2 mm mrad

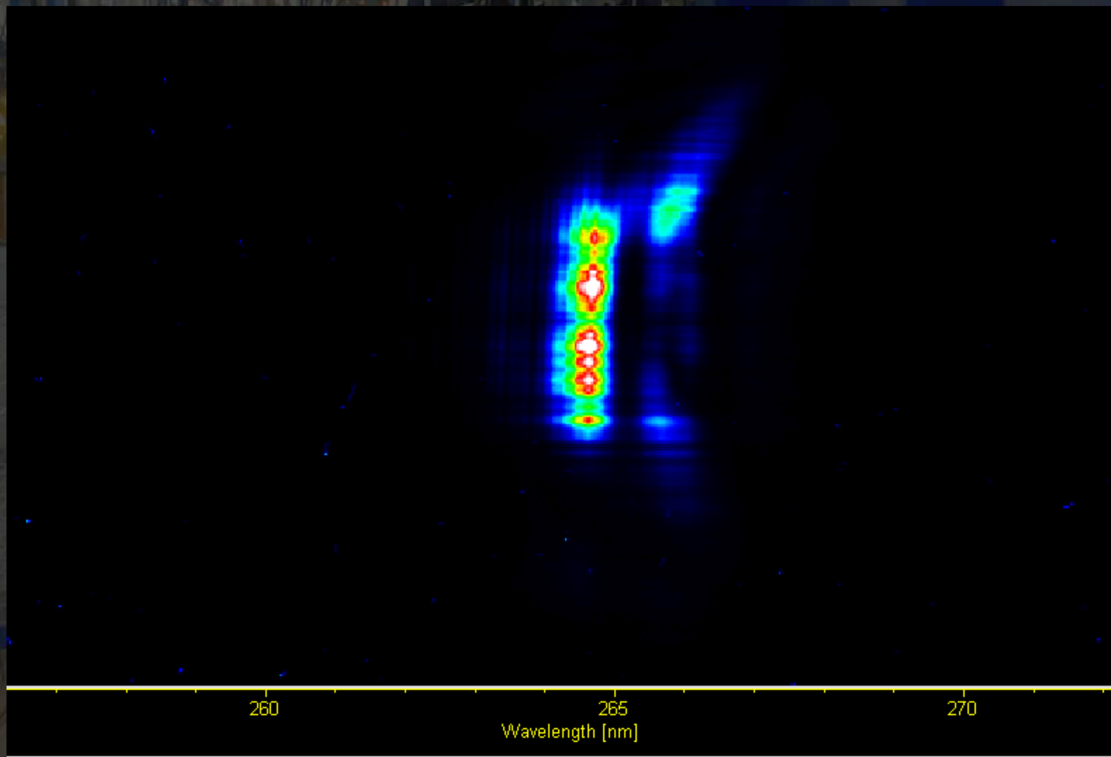



Low peak current, but relatively good beam quality

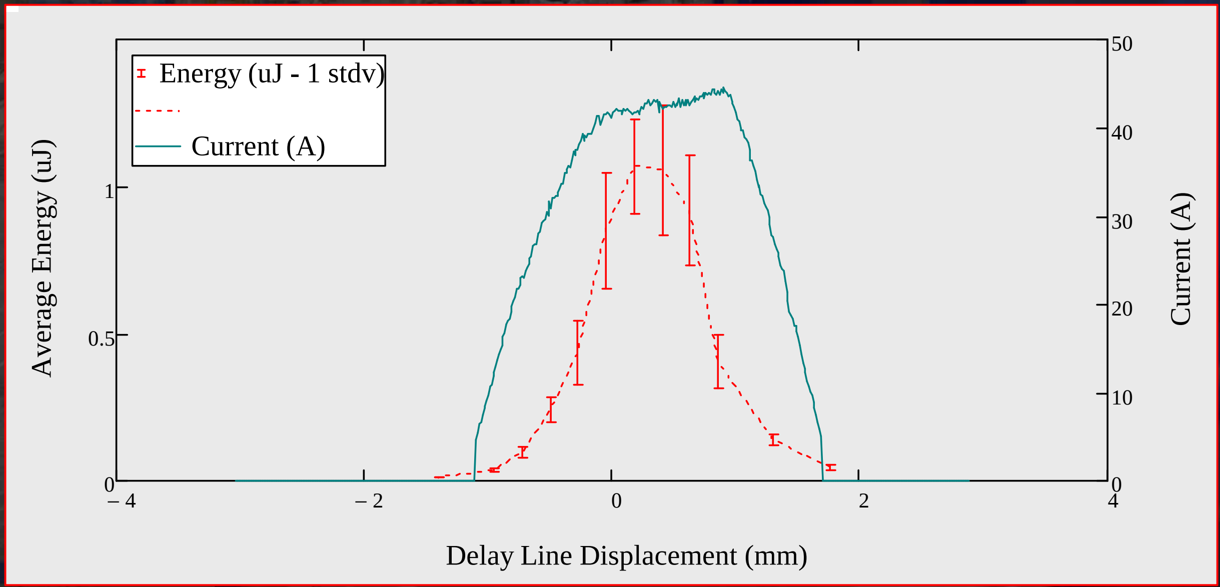
Seed @ 266 nm (Ar), ~50 nJ (±20nJ)
6 UM 266 nm

Spectrometer slit @ 5 um
CCD saturated with nbw filter @ 266nm, 17% T



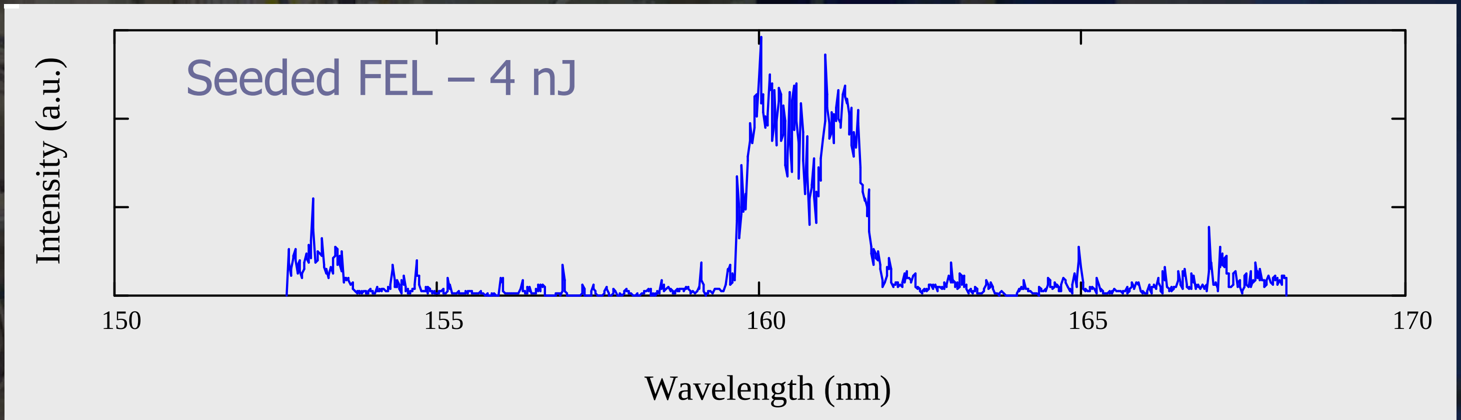
# Comparison of current shape measured with RF deflector &

# "gain" profile measured with cross correlation

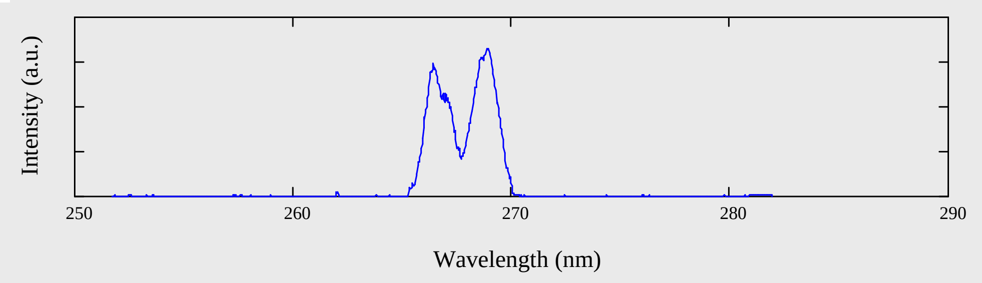


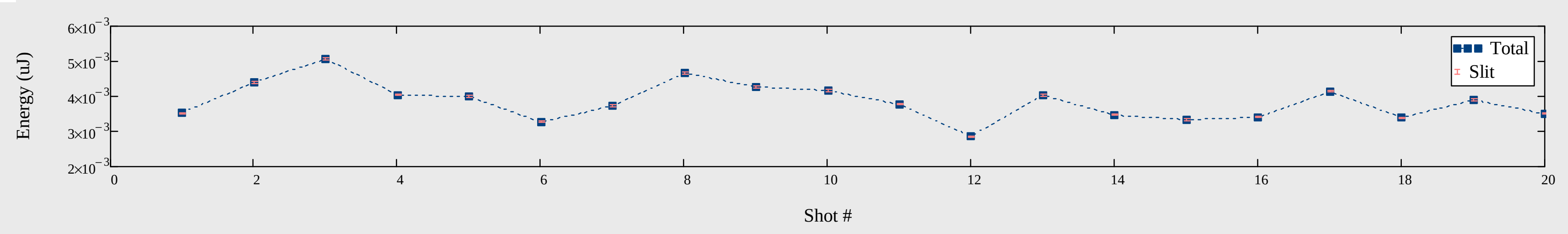
# (2010/06/04) Seed @ 160nm

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



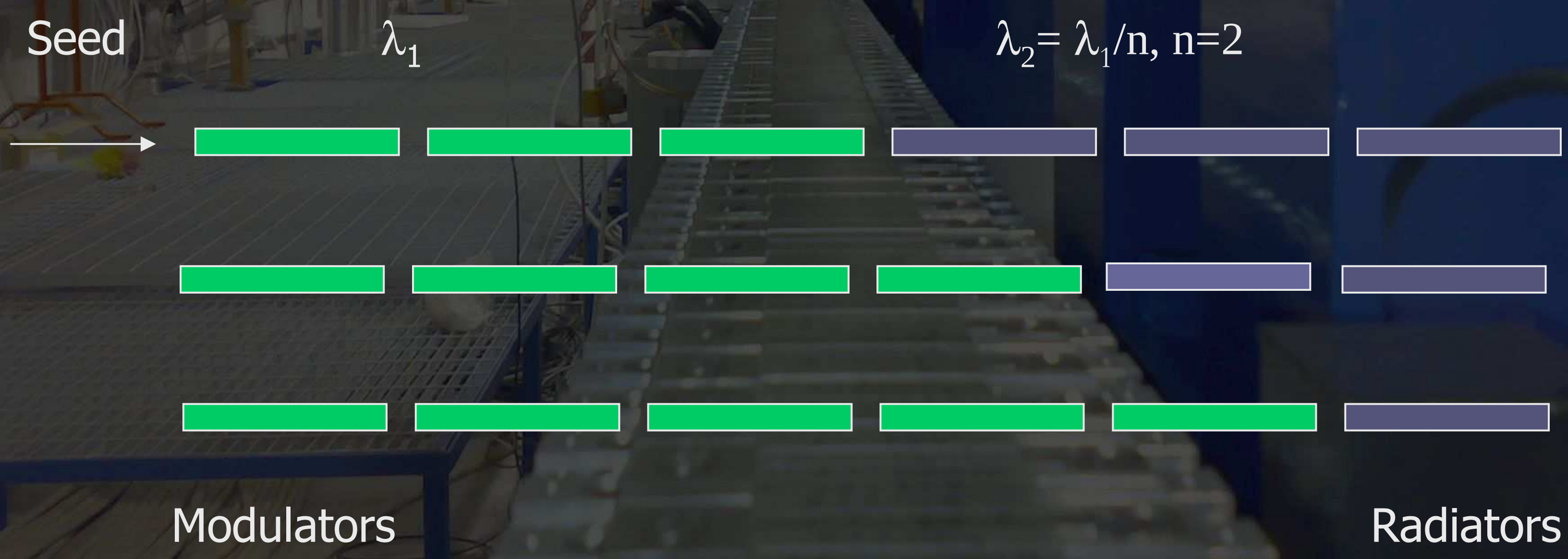

The seed @ 266 measured 1 day before shows the same double peak structure



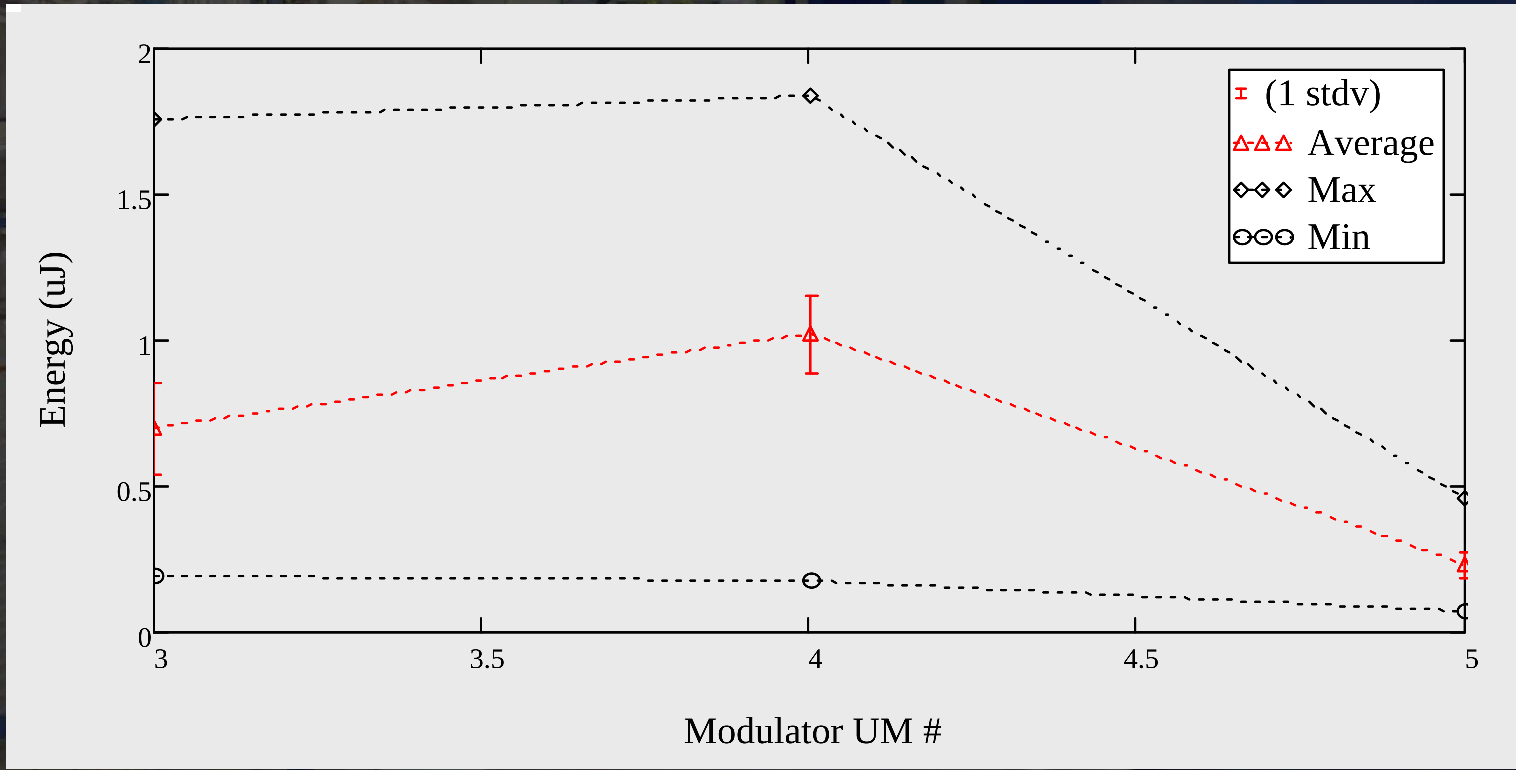



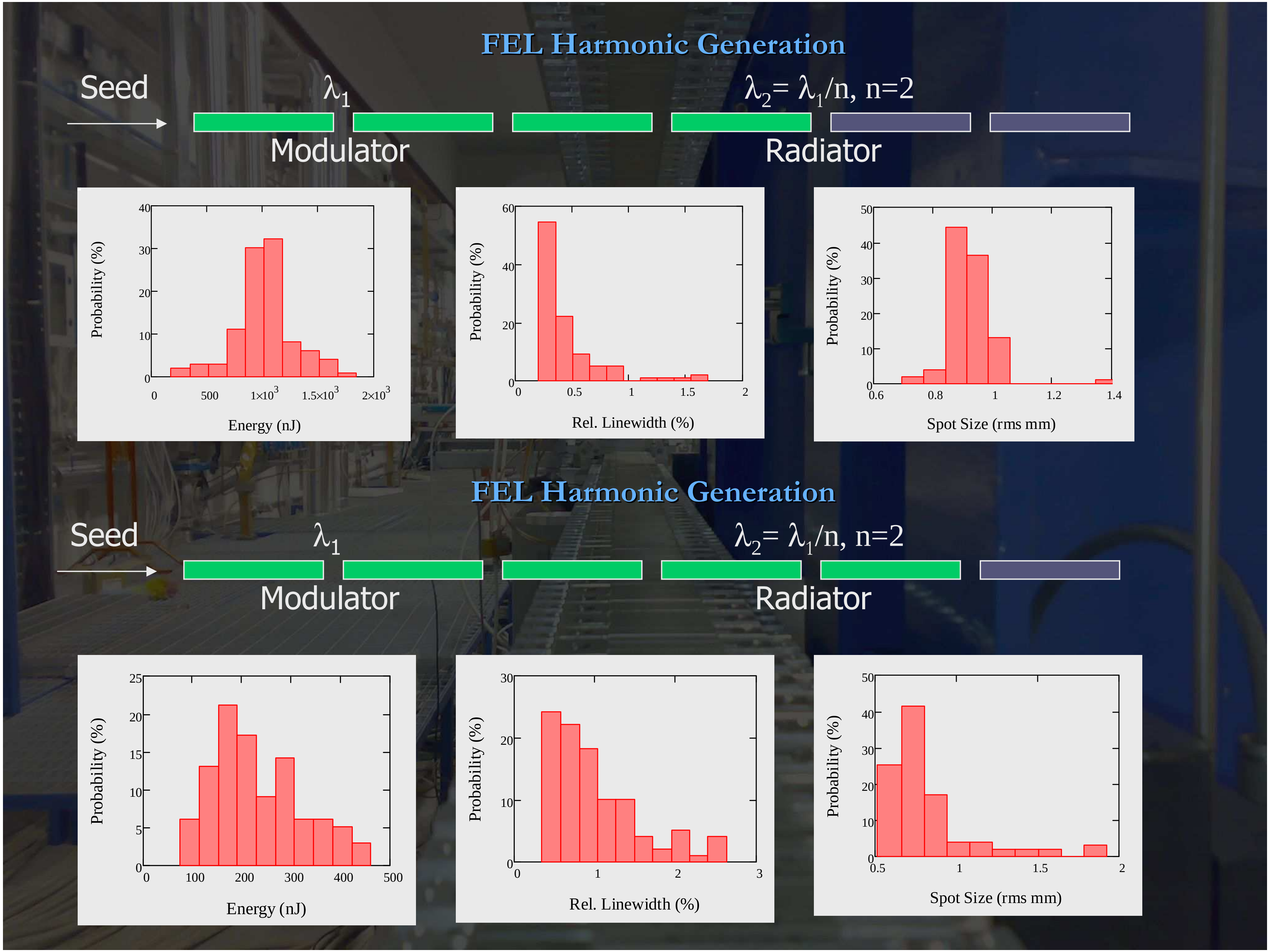
# Cascaded FEL seeded with harmonics generated in gas

- Seed @ 266 nm / ~50 nJ
- 5-4-3 UM tuned @ 266 nm / 1-2-3 UM tuned @133 nm



# Output energy (@133nm) as a function of modulators/radiators #





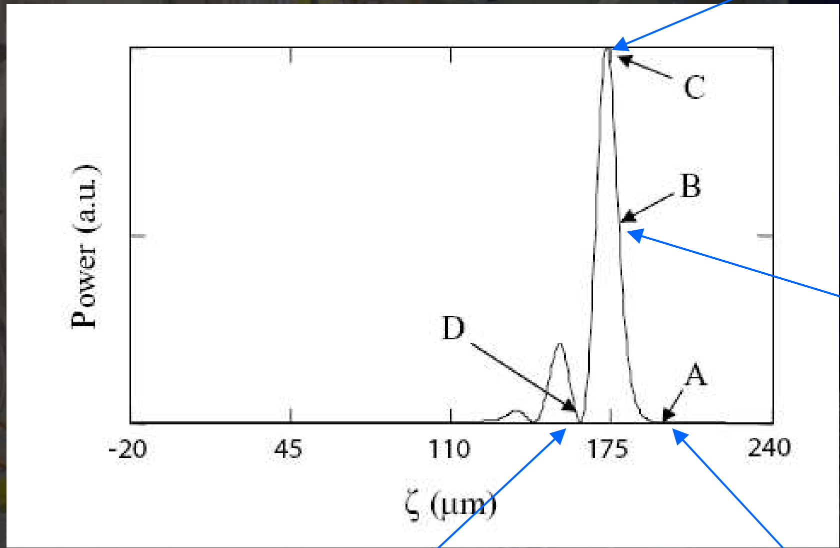
FEL Harmonic Generation
Seed
λ1
λ2= λ1/n, n=2
Modulator
Radiator
Probability (%)
Energy (nJ)
Probability (%)
Rel. Linewidth (%)
Probability (%)
Spot Size (rms mm)
FEL Harmonic Generation
Seed
λ1
λ2= λ1/n, n=2
Modulator
Radiator
Probability (%)
Energy (nJ)
Probability (%)
Rel. Linewidth (%)
Probability (%)
Spot Size (rms mm)

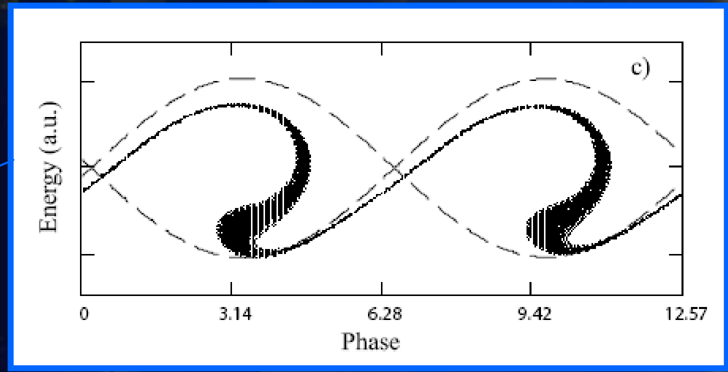
# High intensity seeding of a single pass amplifier at SPARC

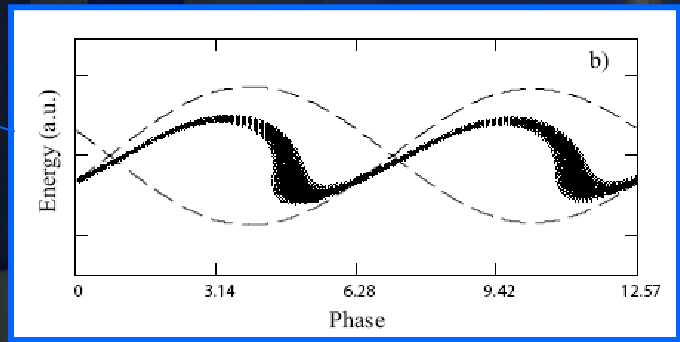

Wavelength 400nm (II harmonic of Ti:Sa)

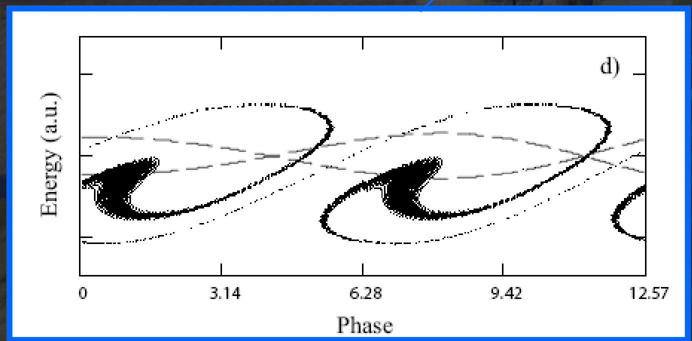
Tuned laser energy in the range  0.2 - 9 uJ

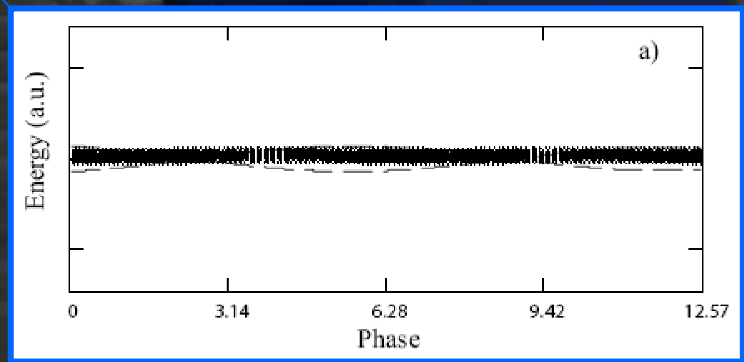
# Solitary wave-like superradiant pulse



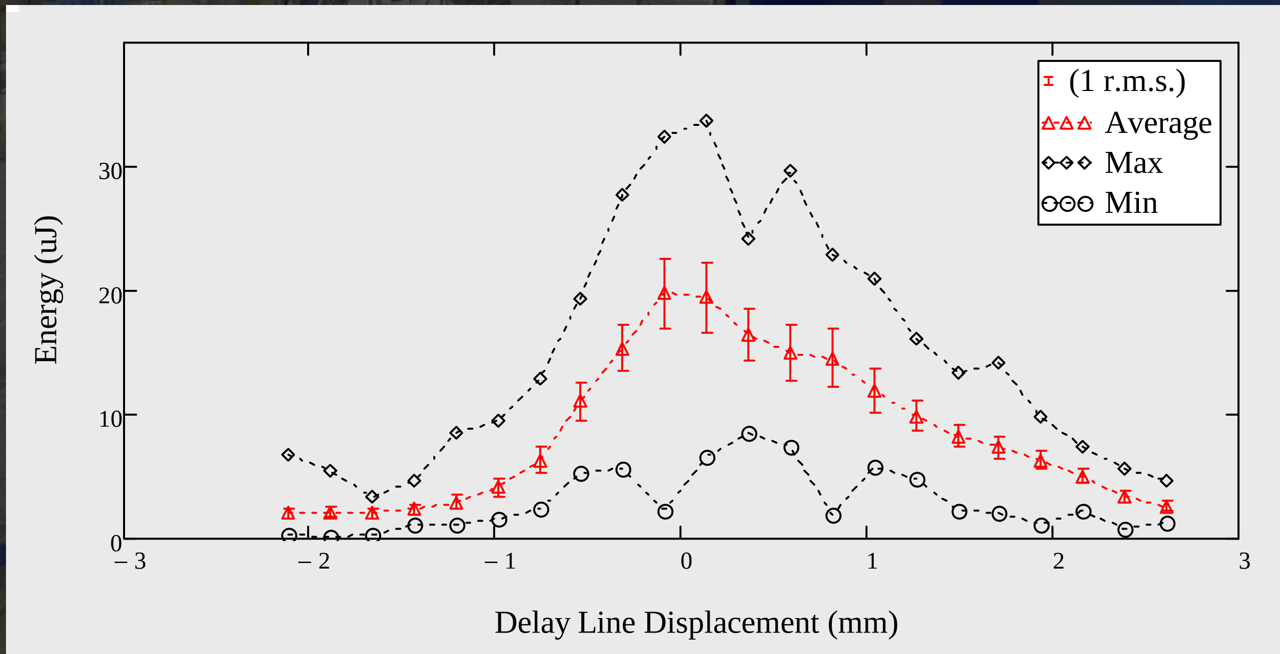



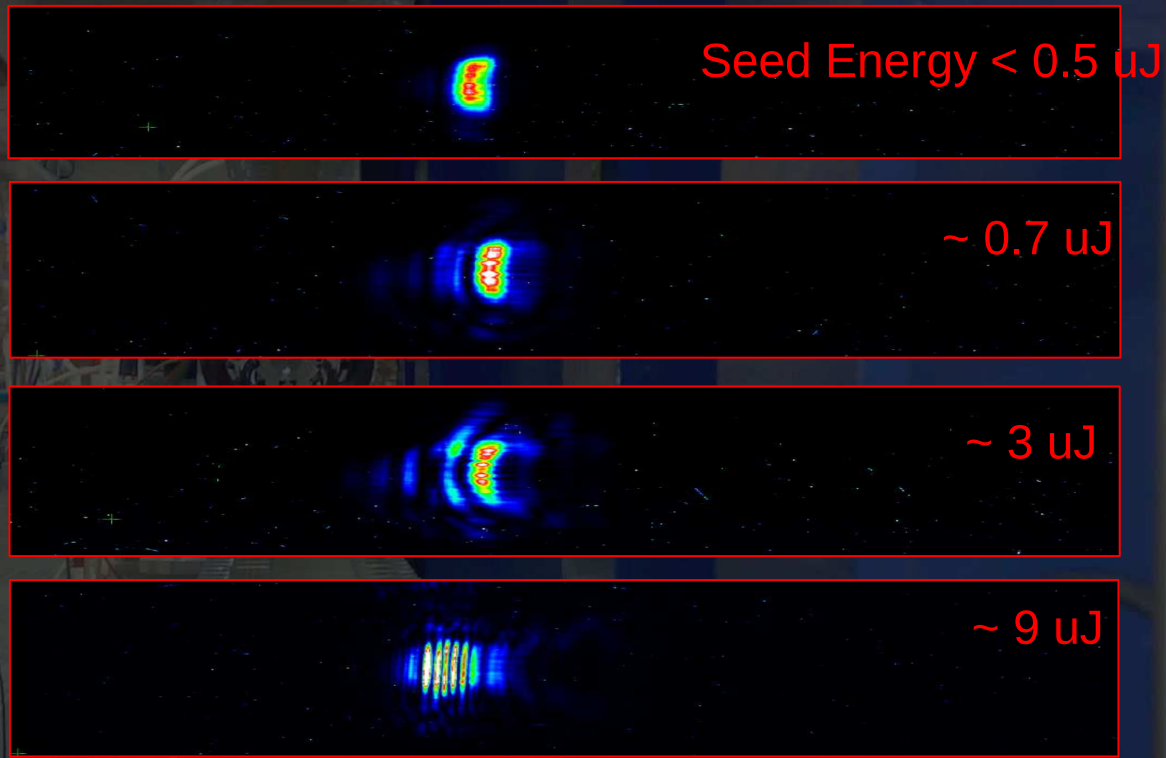
# High harmonics in an FEL (30/6/2010)

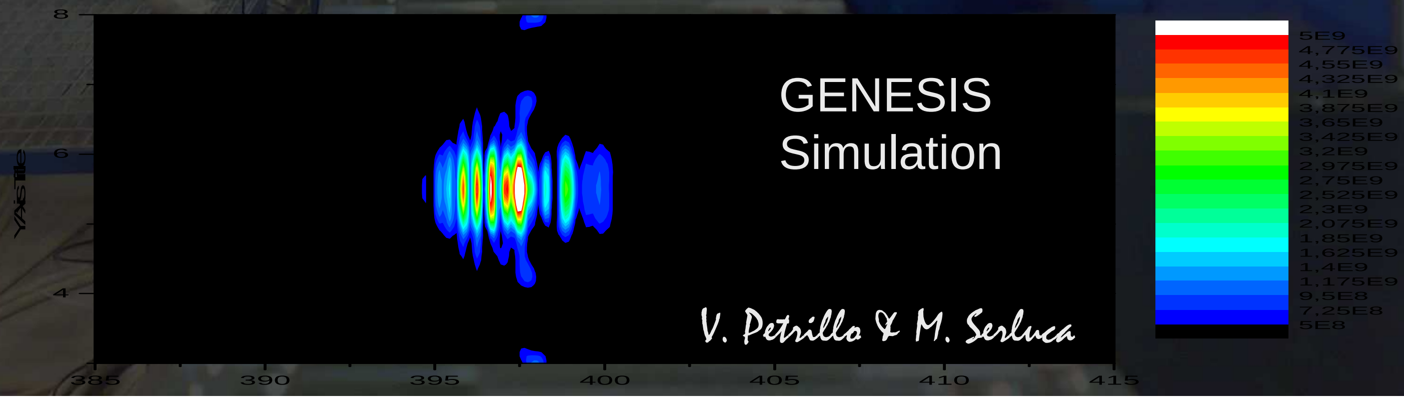
Seed @ 400 nm, 5 uJ - 1 UM tuned at 400 nm – 5 UM tuned @ 200nm

- Higher charge (420 pC)
- Longer e-bunch
- Larger emittances (3 mm mrad)

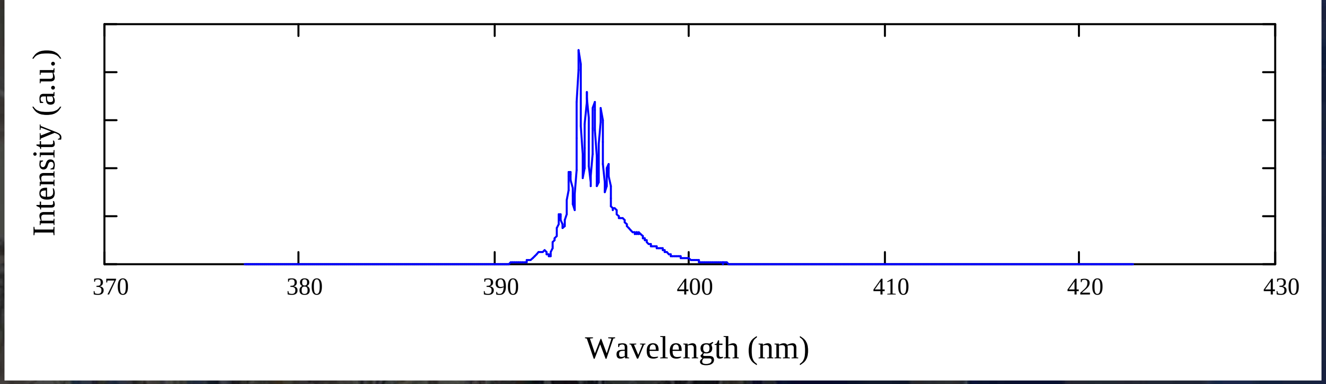


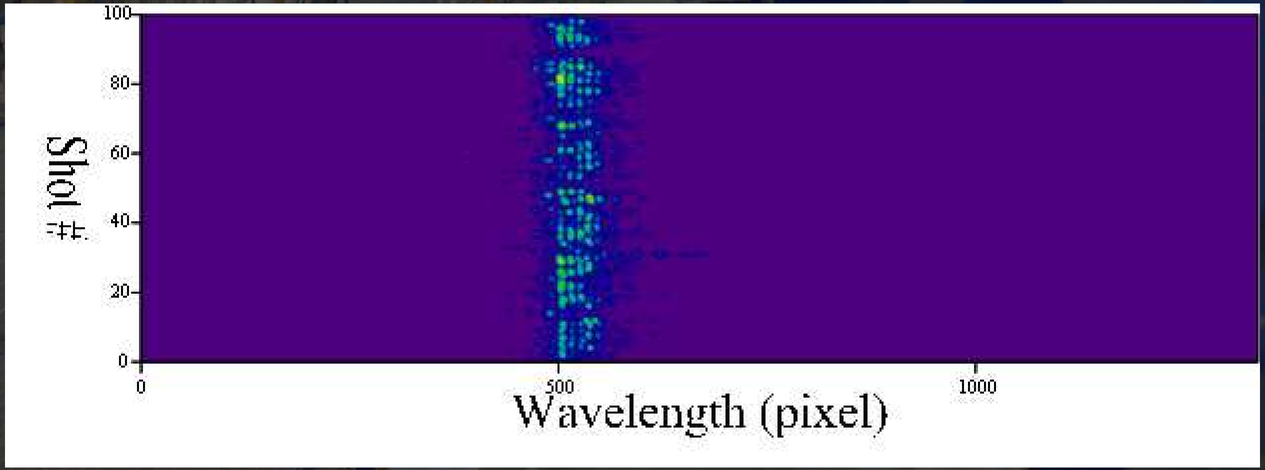
# Direct seeding above saturation



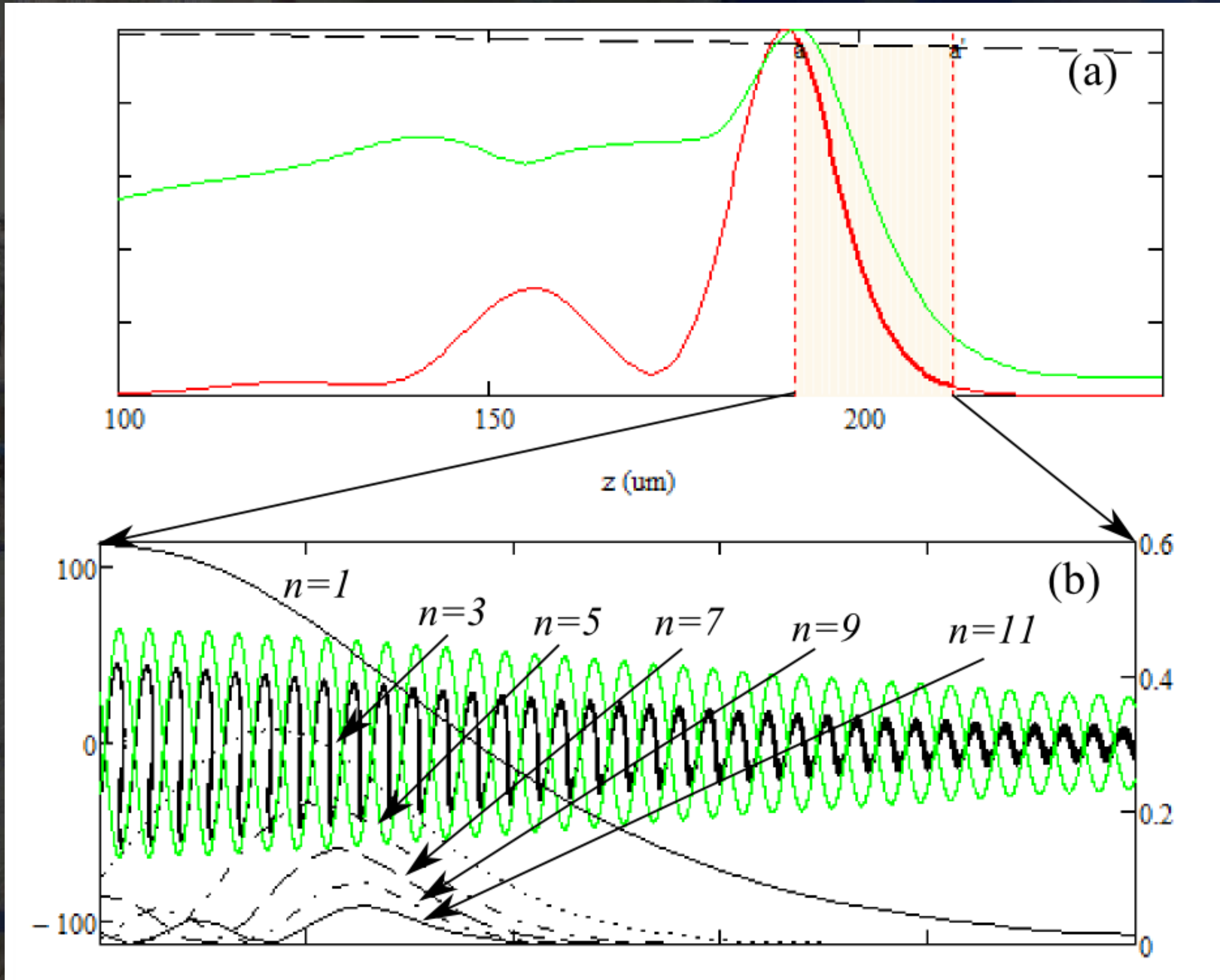
# Mean spectrum




Regular pattern depending on the laser pulse structure & saturation position along the undulator

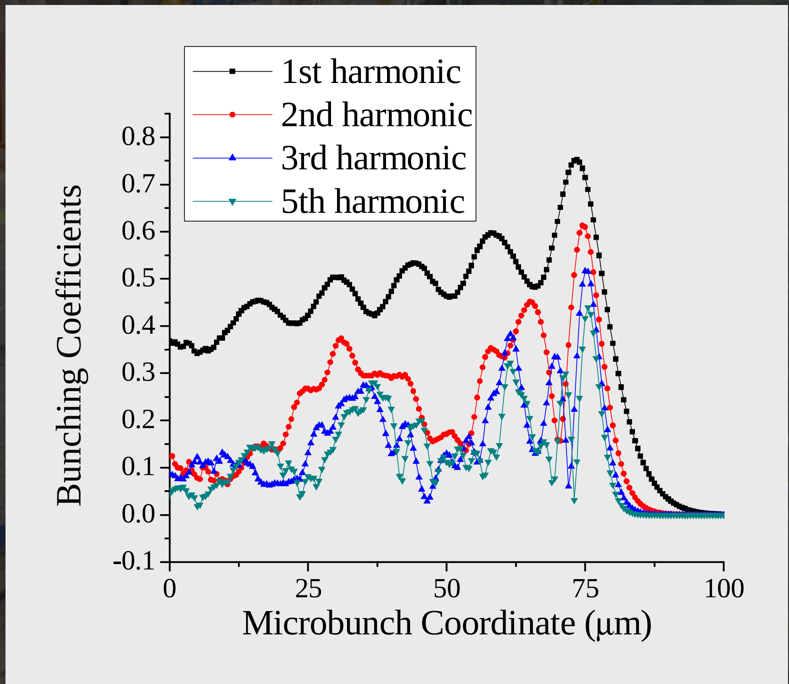
# Bunching coefficients in the front side of the pulse

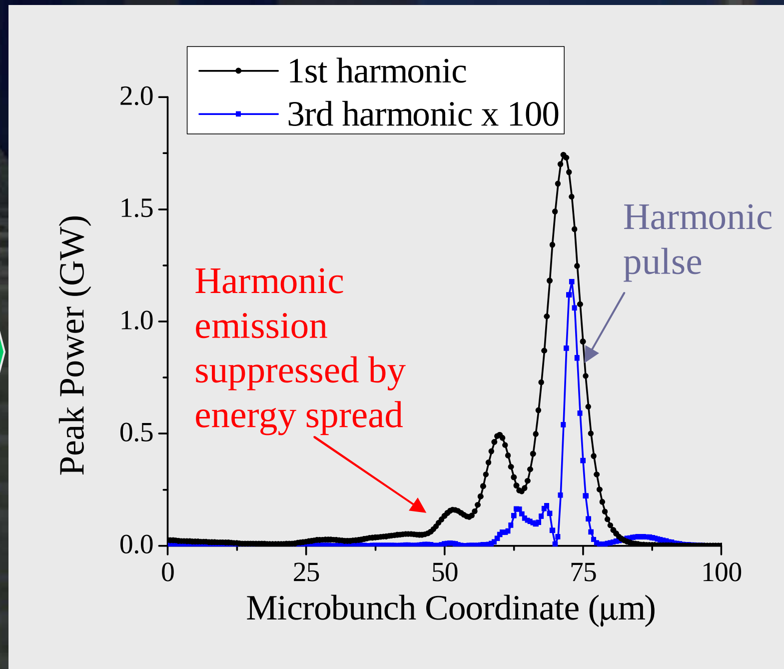



Expected very efficient generation of high order harmonics

# harmonics

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



# High harmonics down to 37 nm

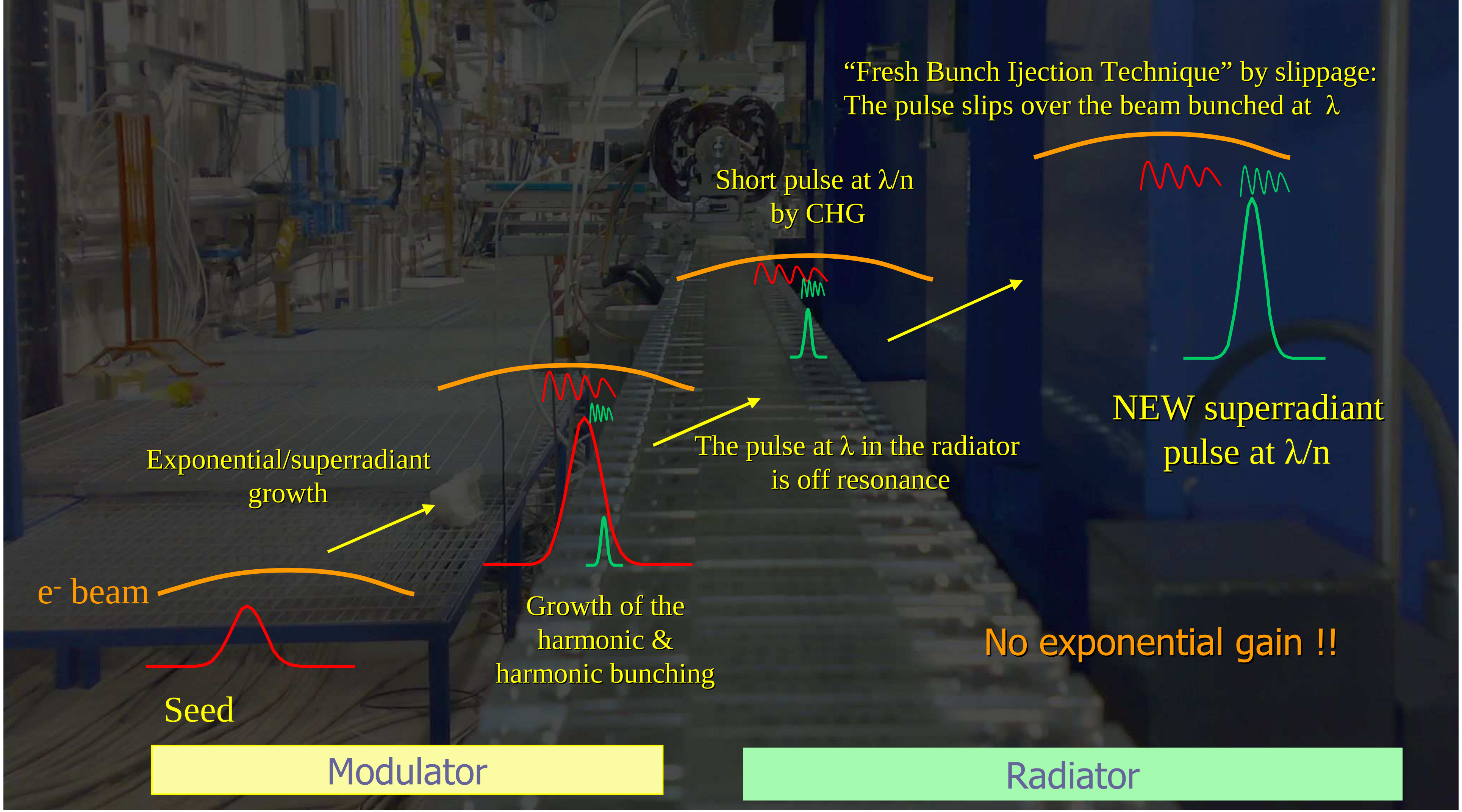


Measured energy per pulse, spot size & and bandwidth of the first 11° harmonics

# High intensity seeding in a cascaded FEL at SPARC

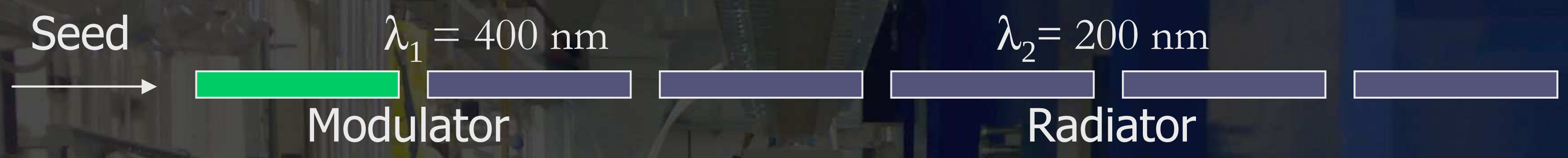
Tuned laser energy in the range  0.2 - 9 uJ

# Evolution of a superradiant pulse in a cascade

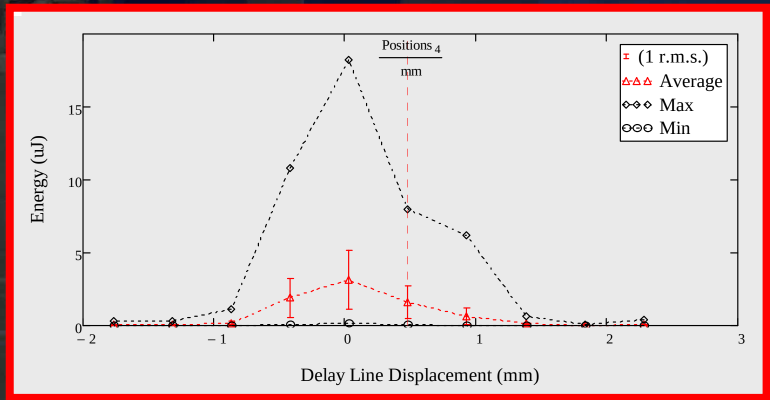


## (4/6/2010) Seed @ 400 nm

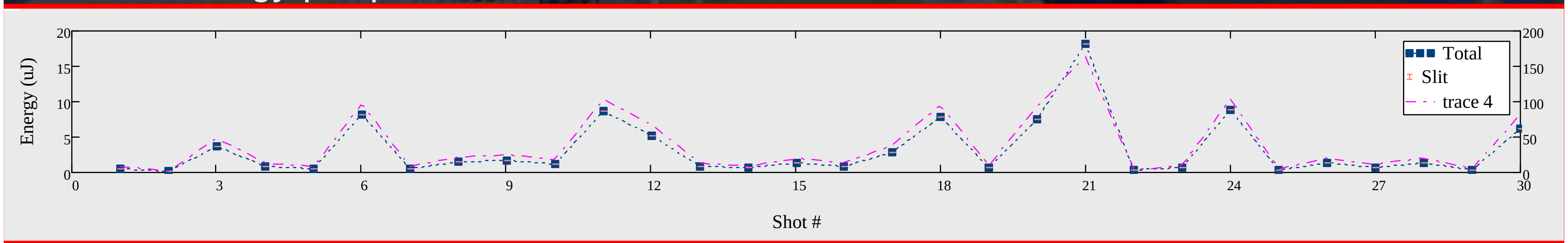
### 2 uJ - 1 UM tuned at 400 nm – 5 UM tuned @ 200nm




Delay line Scan

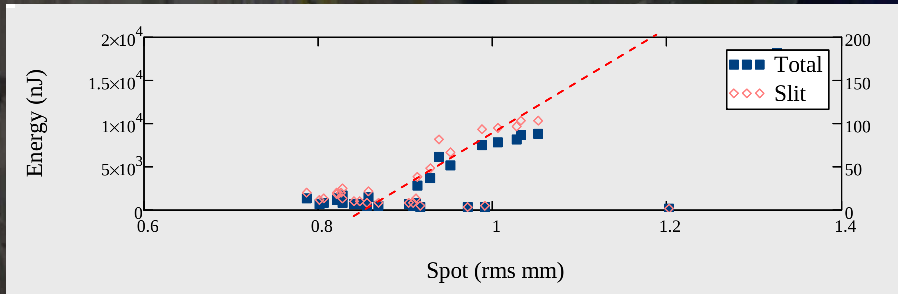



Energy per pulse @ 200nm

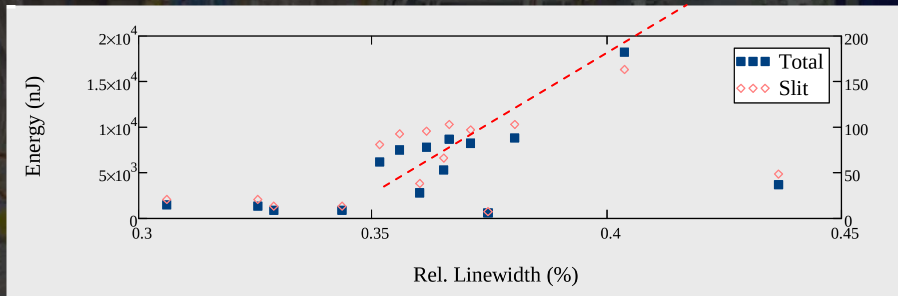


# Indication of saturation at 200nm

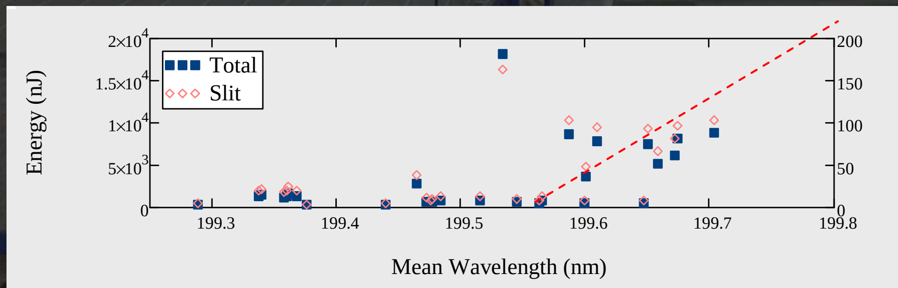
Large energy jitter –> large energy fluctuations



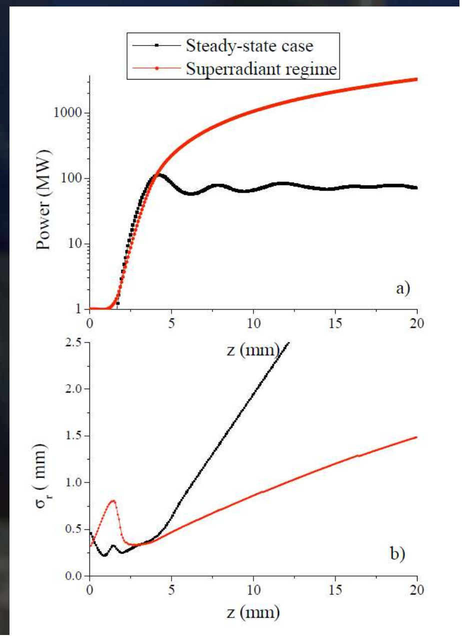

Correlation Energy – Spot size



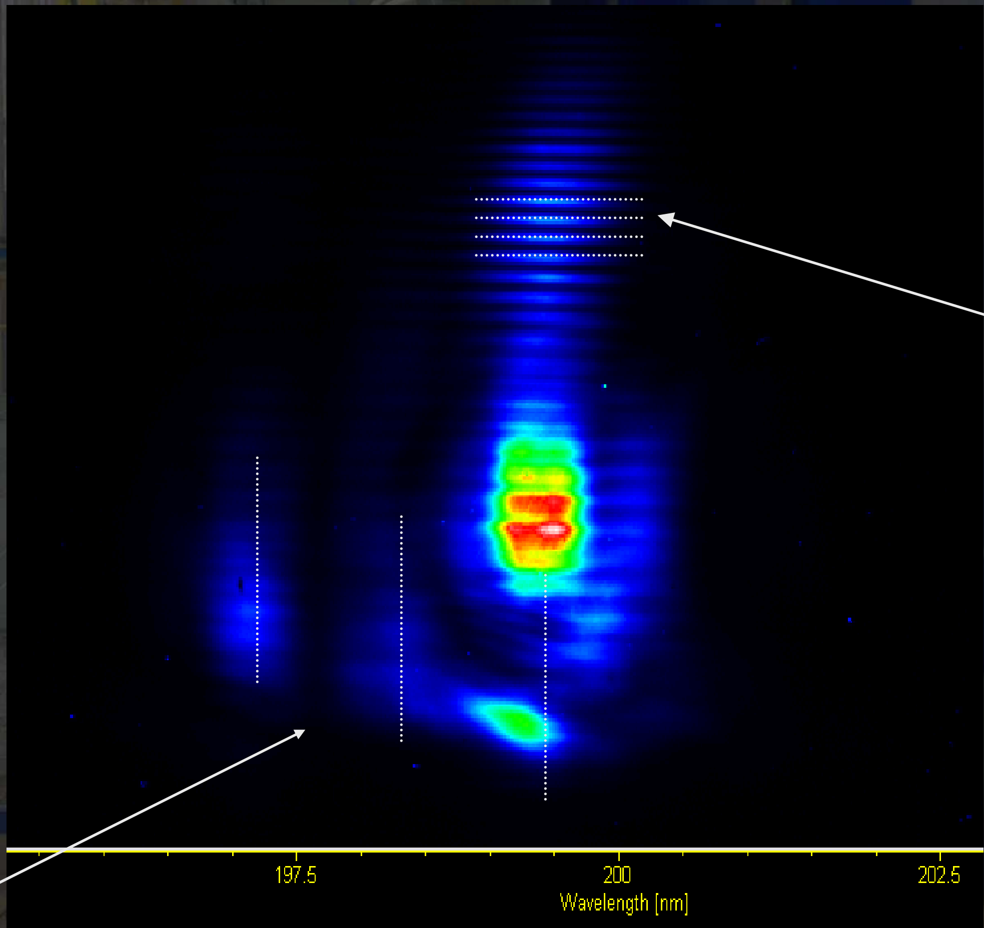

Correlation Energy – Linewidth




Redshift



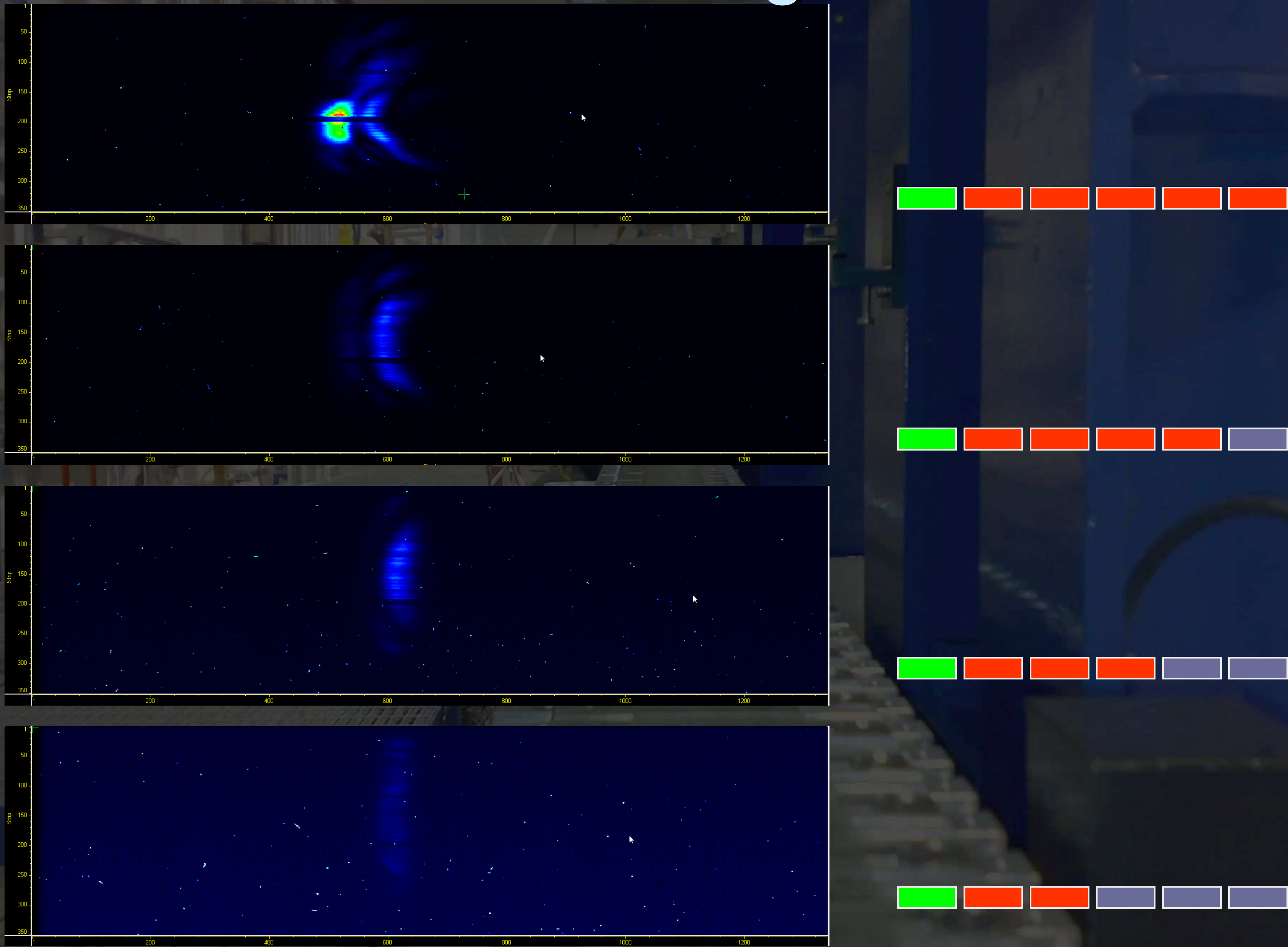
# 18 µJ - Structure in the spectrum




Typical diffraction from vacuum pipe

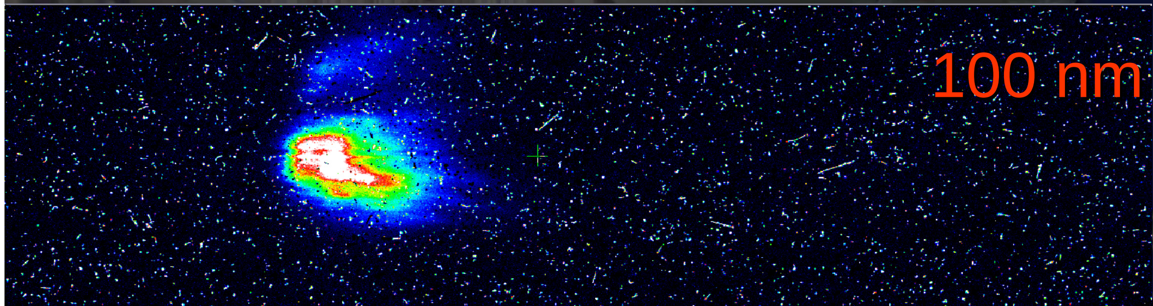
Saturation effect ? – confirmed 11/12/2010

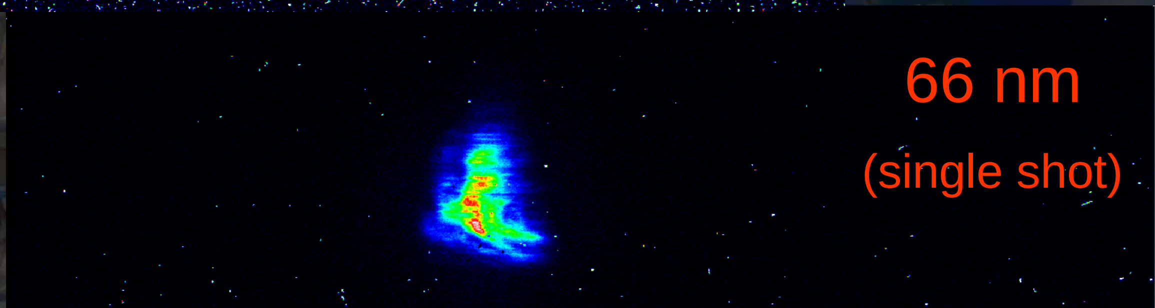
# 200 nm – single shot

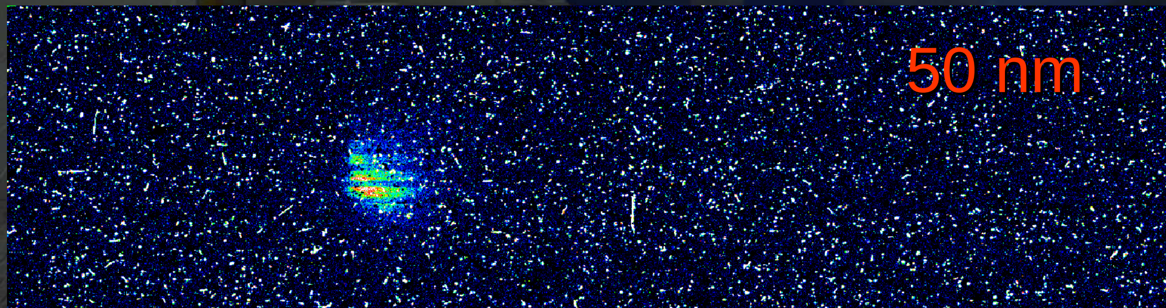


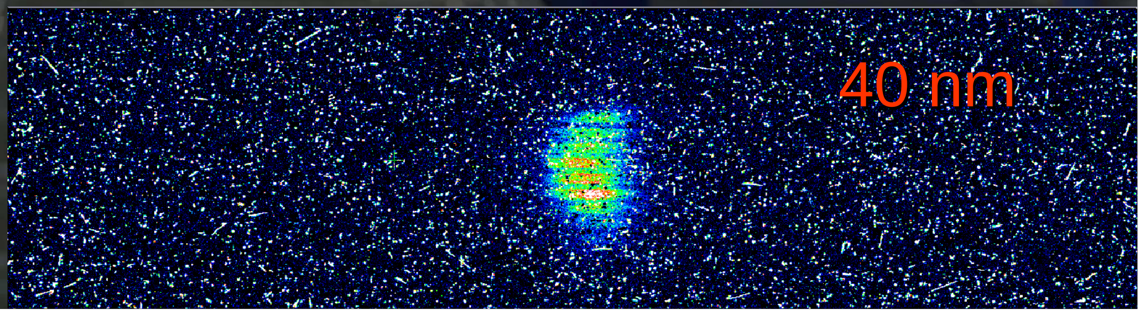
# Higher harmonics in the cascade

Shift of 10/12/2010
Preliminary data




(wavelength indicates the center of the window
Window width ~10nm)

# Seeded SPARC spectral range

Harmonics (columns); Fel generated harmonics (rows)

| 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

| 10 | 11 |
|---|---|
| 40 | 36.4 |

SPARC MAX ENERGY 178 MeV

# Conclusions

- SPARC represents an ideal test bed for studying single pass FEL and FEL cascades in SASE and seeded mode
- Conventional lasers and FEL are merged in a single device
- In vacuum spectrometer extend the observed SPARC spectral range down to 36nm - 540 nm

Observed pulse energy at different wavelengths ( ~ 50-60A / 178MeV )

| Wavelength | 500 nm | 200nm | 133 nm | 66nm |
|---|---|---|---|---|
| Energy/pulse (~ 100 fs) | ~100 µJ | ~10 µJ | ~1 µJ | ~100 nJ |

Future Experiments

Multistage cascade

The harmonic cascade

HHG even harmonics amplification