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Generation and Measurement of Intense Few-Femtosecond Superradiant Soft X-Ray Free Electron Laser Pulses

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on behalf of the FERMI team

Elettra Sincrotrone Trieste

MOTIVATIONS

- **Pulse duration of FEL1 ≈40-90fs*. Pulse duration of FE2 ≈20-40fs**
- **Many important new science opportunities become accessible in the ~10 fs (i.e. 5-15 fs)**
- **Among many others**
  - **Improvement of many present pump probe experiments**
  - **Many non-linear experiments by beating the core- hole lifetime**
  - **Study of conical intersection in photochemistry process**

* *P.Finetti et al. Phys Rev X 7, 102043 2016*

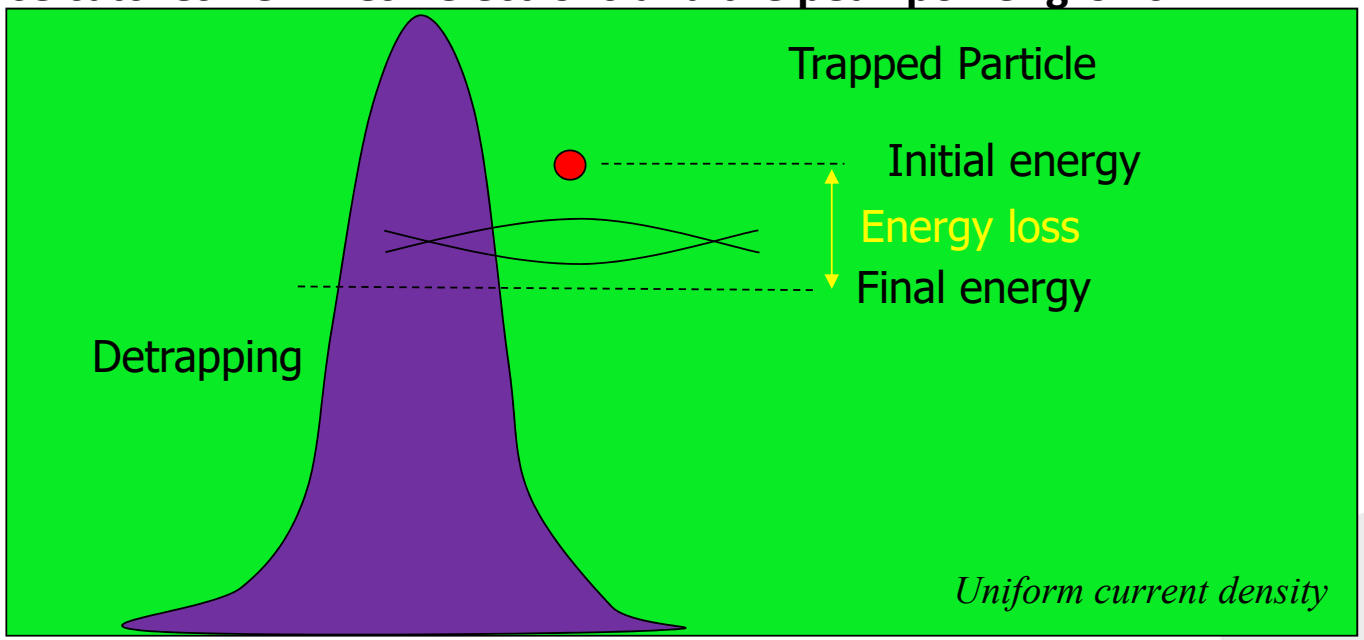
PROPOSED OPTIONS

- **Shortening the seed pulse: The shortening of the seed pulse down to 40 fs would permit to produce 10-15fs pulses on FEL2**
- **CPA: Demonstrated in FEL1 with a reduction of the pulse duration by a factor 2. This technique has the potentiality to reach a pulse duration of 5fs and below. Pulse compressors have low transmission efficiency (<5%) limiting the pulse energy available for experiments. It is still not verified on FEL2**
- **Shaping of the gain along the electron beam**
- **Electron Beam scraping (first tests done)**
- **Superradiance: This technique can produce pulses shorter than 10fs with a peak power>1GW on both FEL1 and FEL2**

Shorter pulse at FERMI, Luca Giannessi, Elettra-Sincrotrone Trieste
MACHINE ADVISORY COMMITTEE & SCIENTIFIC ADVISORY COUNCIL: Future of FERMI workshop

FEL NON LINEAR DYNAMICS: SUPERRADIANCE

- **Saturation: When the FEL laser power reaches ~ *1.6 ρ·Pbeam*, saturation occurs. After saturation → cyclic energy exchange between electrons and field (in steady state regime)**
- **Slippage: The light advances over the electrons of a distance *Nλ* in *N* undulator periods**
- **positive and negative energy exchange take place at different positions along the pulse if the pulse length is comparable with the distance covered in a synchrotron period**
- **The pulse catches new fresh electrons and the peak power grows**



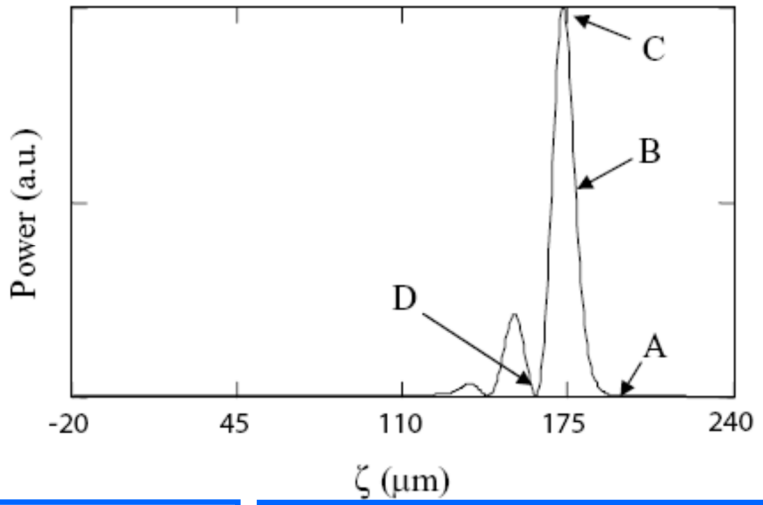
ELECTRON PHASE SPACE ALONG THE PULSE

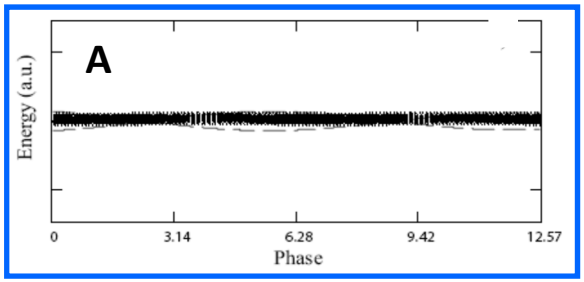
A) Fresh part of the electron beam. Initial energy spread and no modulation

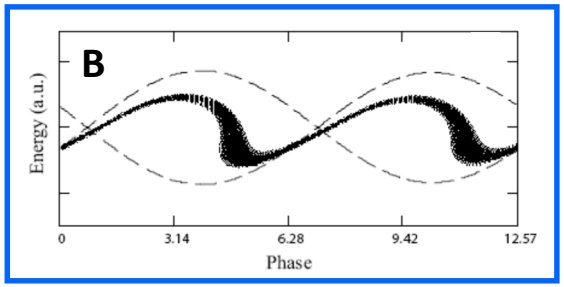
B) Region of the electron beam interacting with the radiation. Strong energy and density modulation. The electrons give energy to the light

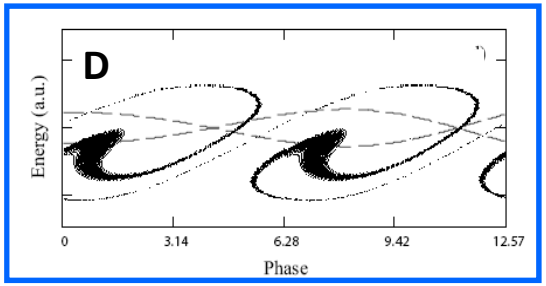
C)Peak of the super-radiant pulse. The electrons have reached the bottom of the bucket and start to gain energy from the light field.

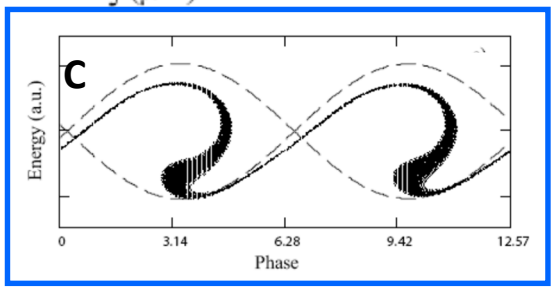
D)Minimum of the laser power. The phase space is deeply saturated and the electrons are de-trapped.





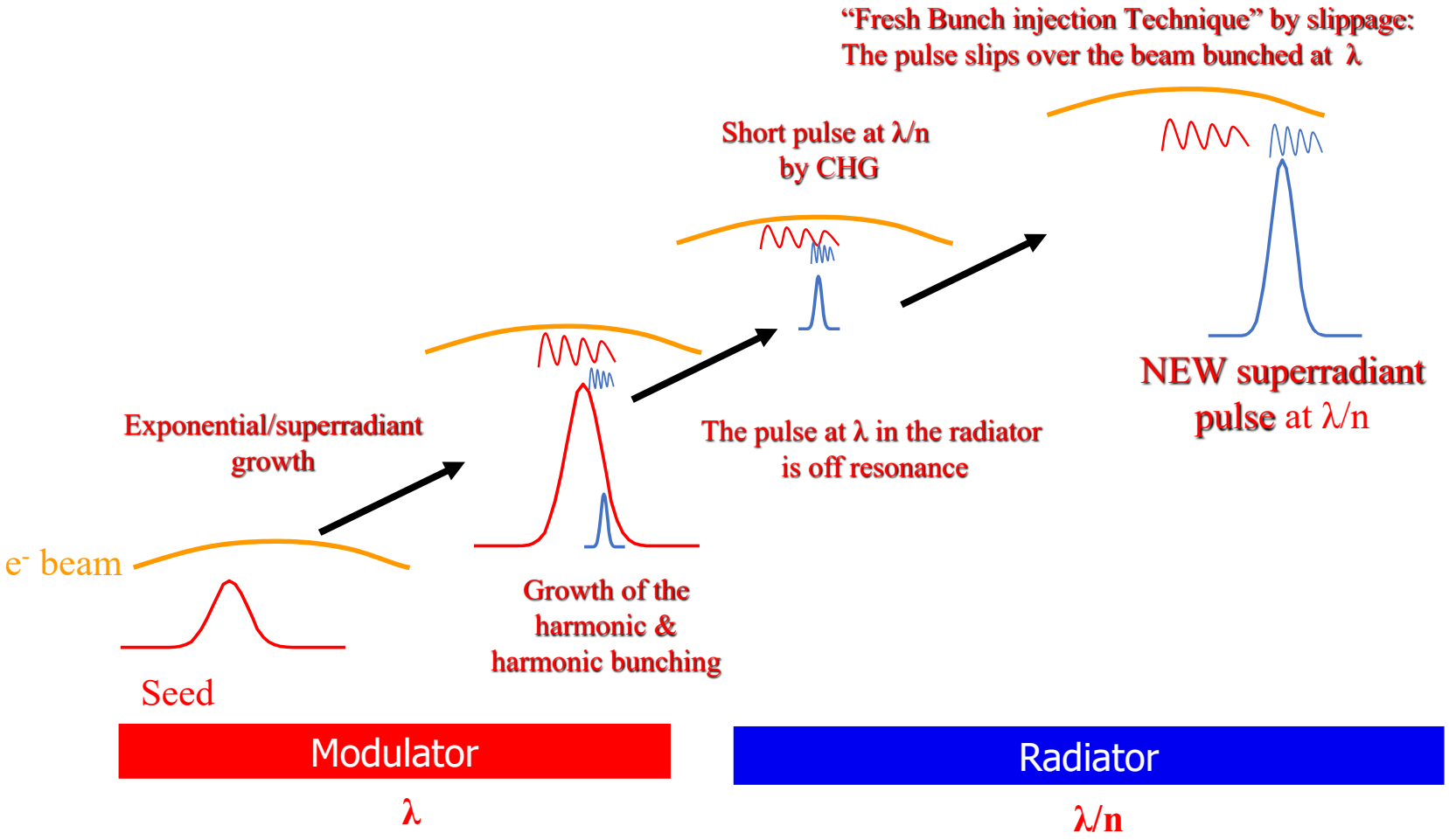






L.Giannessi, P. Musumeci, S. SpampinatiJ. Appl. Phys 98(4) 043110 2005

CASCADE EVOLUTION

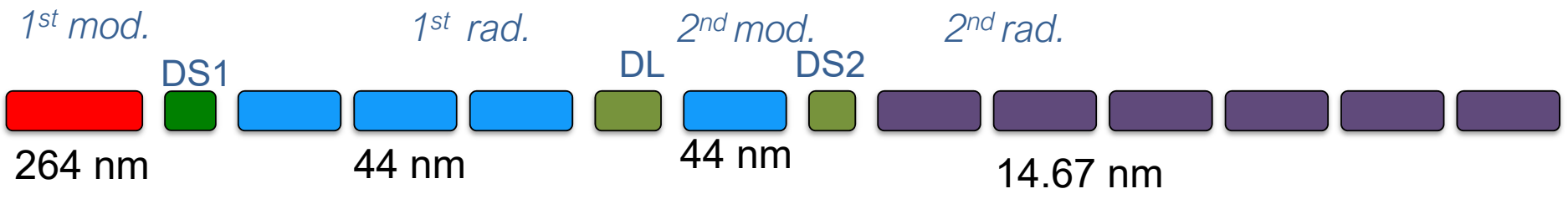


L.Giannessi, P. Musumeci, S. SpampinatiJ. Appl. Phys 98(4) 043110 2005

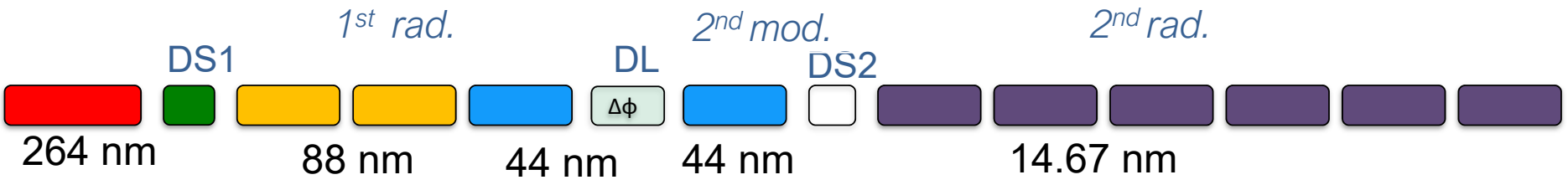
SUPERADIANT CASCADE EXPERIMENT AT FERMI

The experiment was done at 14.67nm with a 750 MeV beam on FEL2

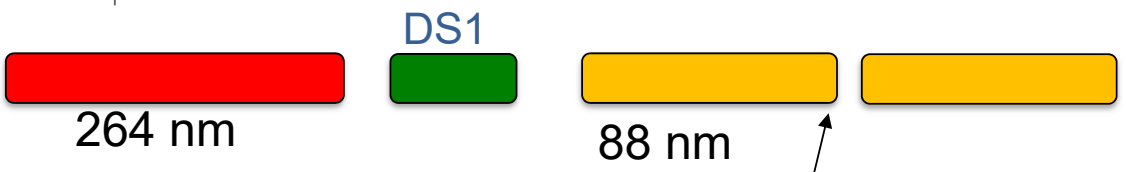
FEL 2 LAYOUT



SUPERRADIANT CASCADE LAYOUT



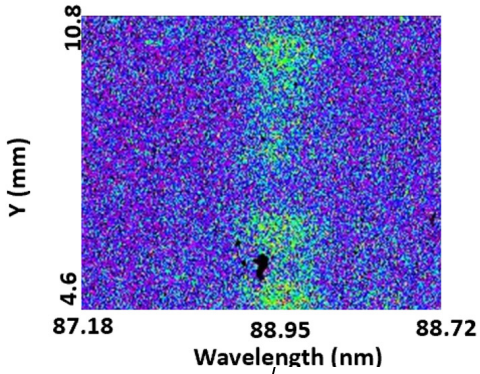
FEL2 SUPERRADIANT CASCADE: STAGE 1

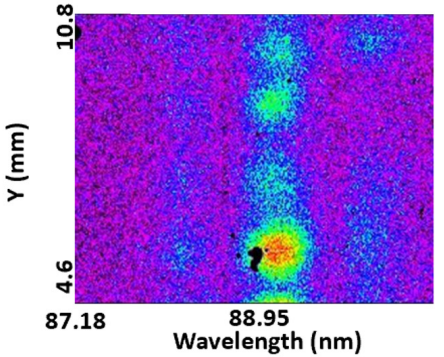


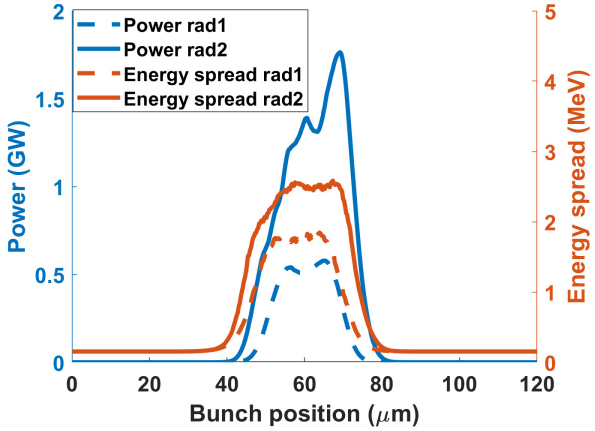
Seed pulse duration 55fs

- **The pulse grows towards saturation**
- **Saturation and slippage start to deform the pulse shape**
- **Growth of energy spread**

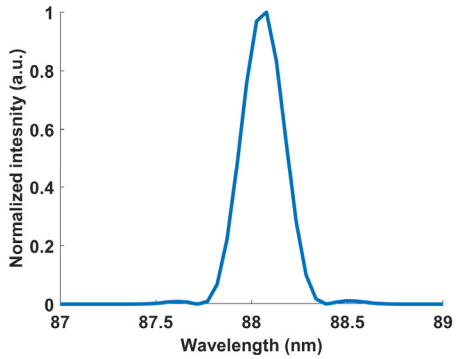
EXPERIMENT

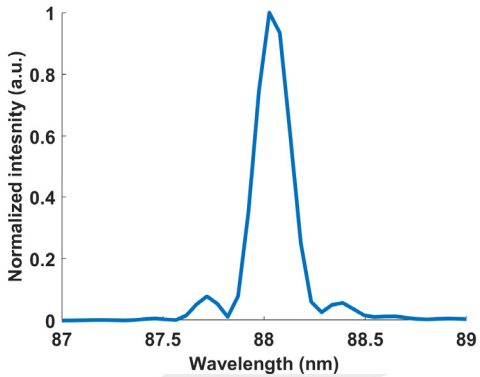






GENESIS simulation



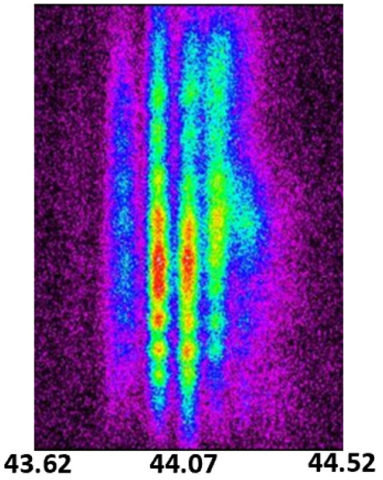


FEL2 SUPERRADIANT CASCADE: STAGE 2

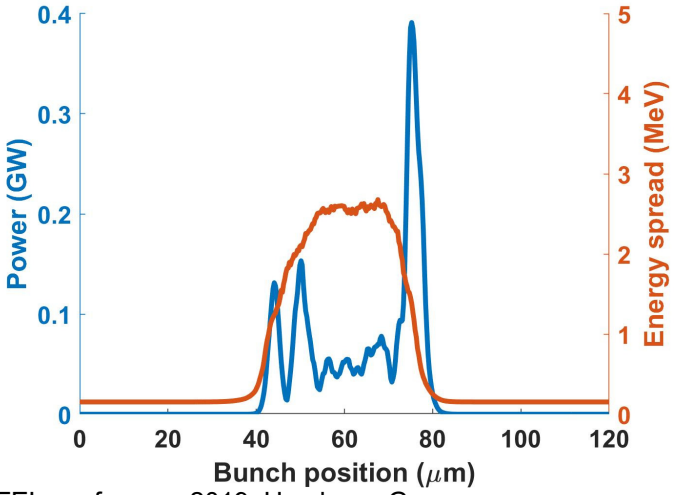
Seed pulse duration 55fs

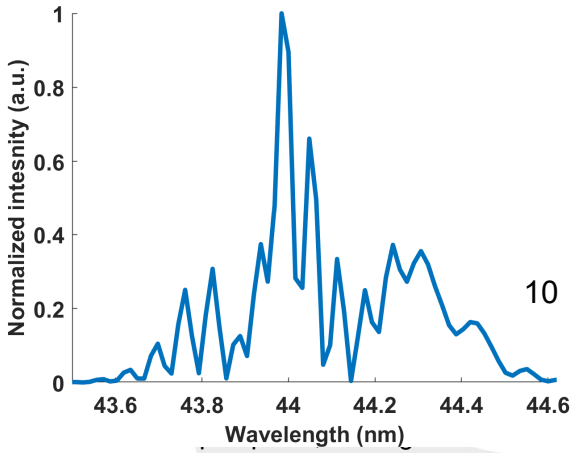
- **The energy spread accumulated in the previous stage is too high for higher harmonic emission in the core of the modulated region**
- **The front peak slips on fresh electrons and grows**

EXPERIMENT

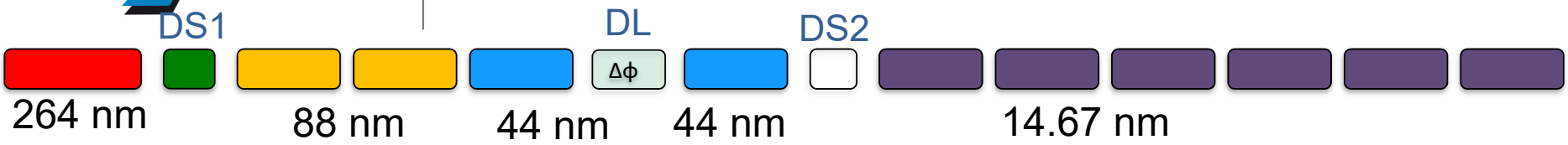


GENESIS SIMULATION





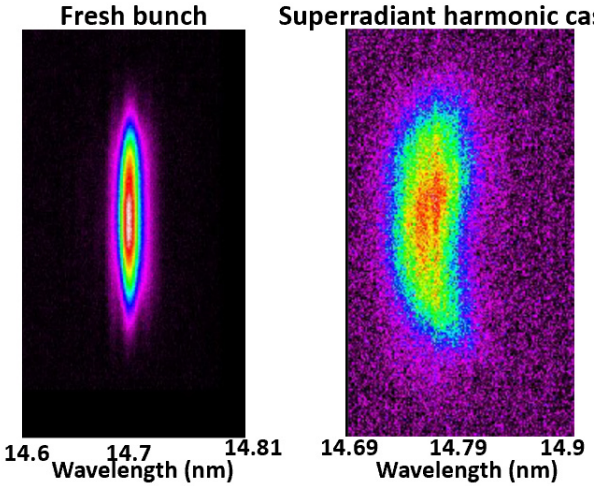
FEL2 SUPERRADIANT CASCADE: STAGE 3



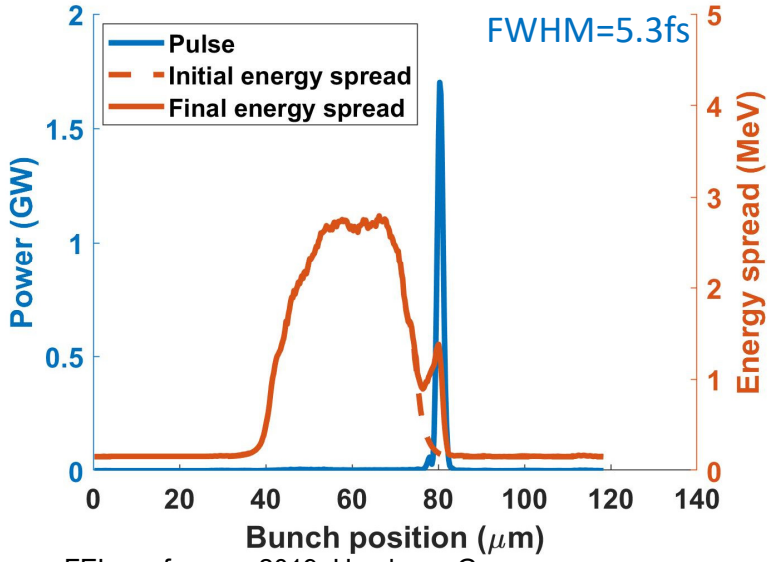
Seed pulse duration 55fs

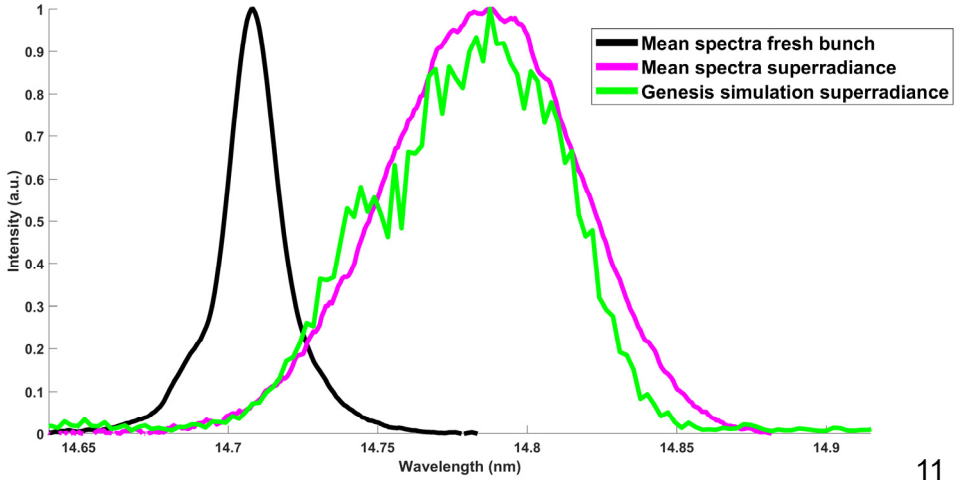
- **The tail is largely suppressed by energy spread**
- **Strong & short output spike**

EXPERIMENT



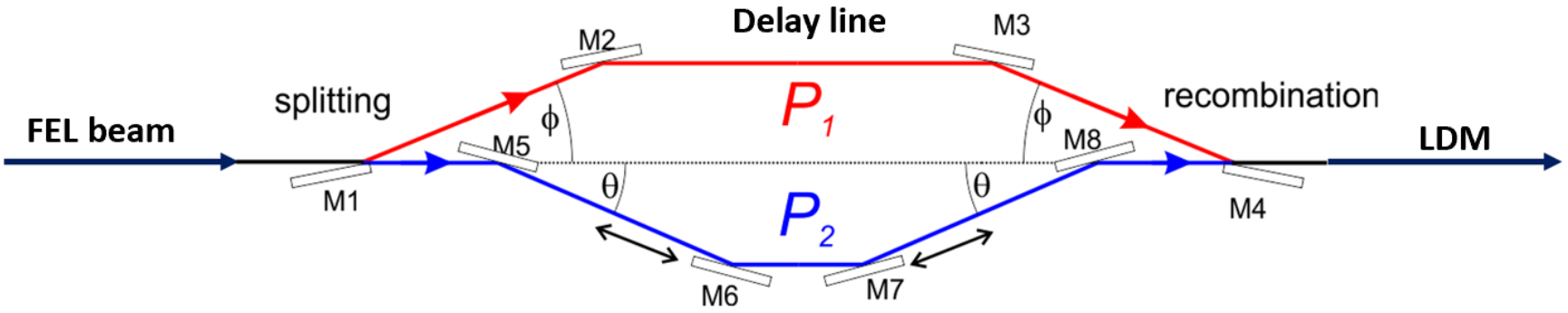
GENESIS SIMULATION



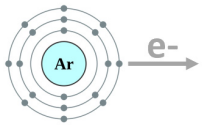


FEL PULSE DURATION MEASUREMENTS: METHODS

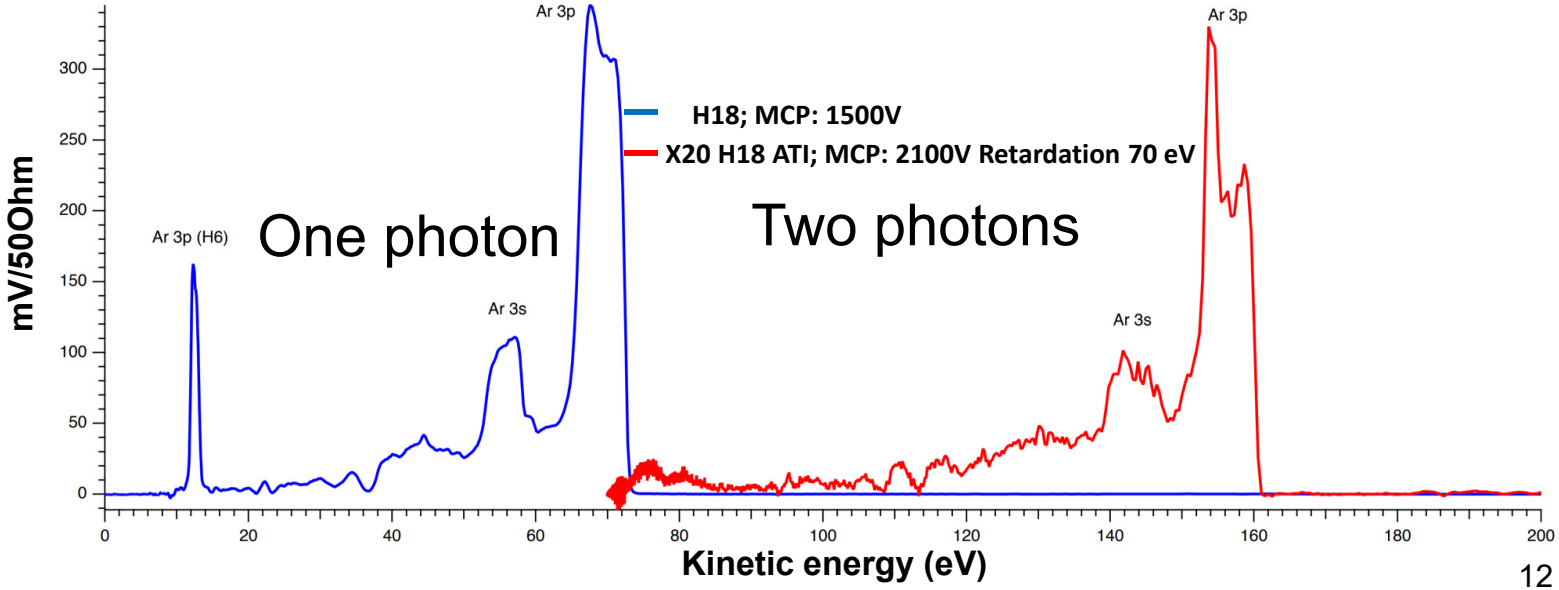
Autocorrelation of the FEL pulse by two photons above threshold ionization in Ar



Ar jet



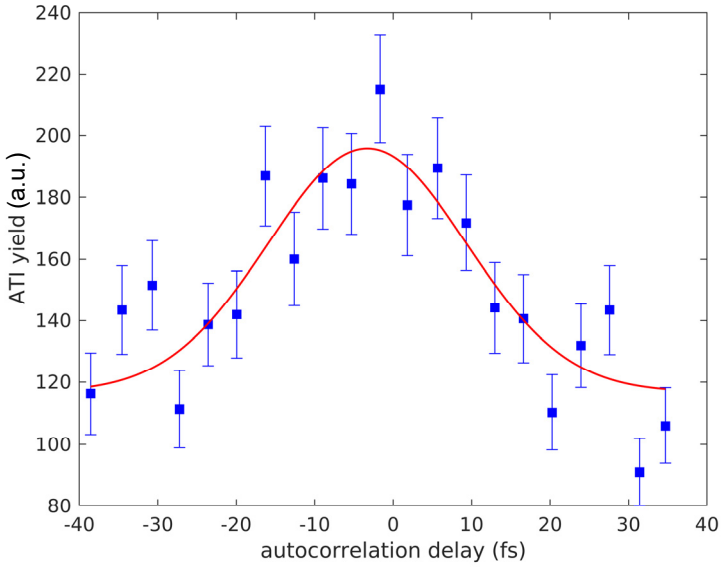
Photoelectron spectra



FEL PULSE DURATION MEASUREMENTS: RESULTS

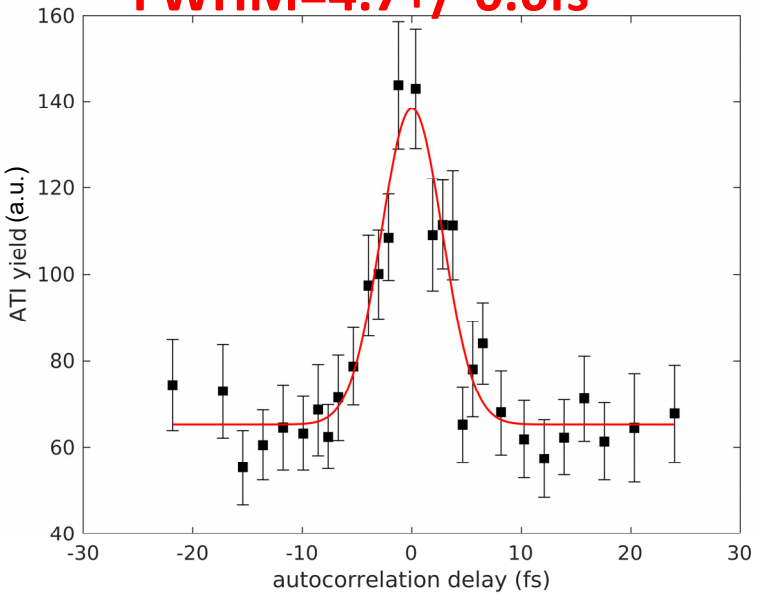
Fresh bunch

FWHM=22+/-4fs



Superradiance

FWHM=4.7+/-0.6fs



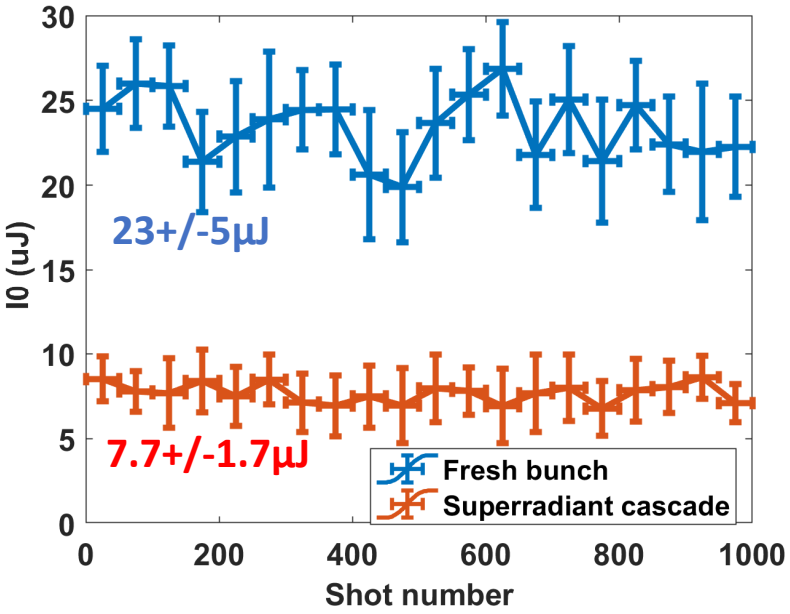
- Pulse Duration of Seeded Free-Electron Lasers P. Finetti *et al.* Phys. Rev. X 7, 021043
- considering saturation only in in the second stage we have $\sigma_{FEL} \approx \frac{7}{6}\sigma_{Seed}/(\sqrt[2]{6}\,\sqrt[3]{3})$=18fs

Participants:

- **FERMI machine physics**
- **PADRES group**
- **LDM team**
- **T. Mazza, European X-FEL,Hamburg**
- **R. Feifel, R. Squibb, University of Gothenburg**
- **X. Yang, Brookhaven National Laboratory**

FEL CHARACTERISTICS

- Less energy per pulse respect to two stage fresh bunch **but higher peak power (+50% in the experiment).** Same relative energy stability
- Broader spectrum - still single peak.
- Peak power > 1GW

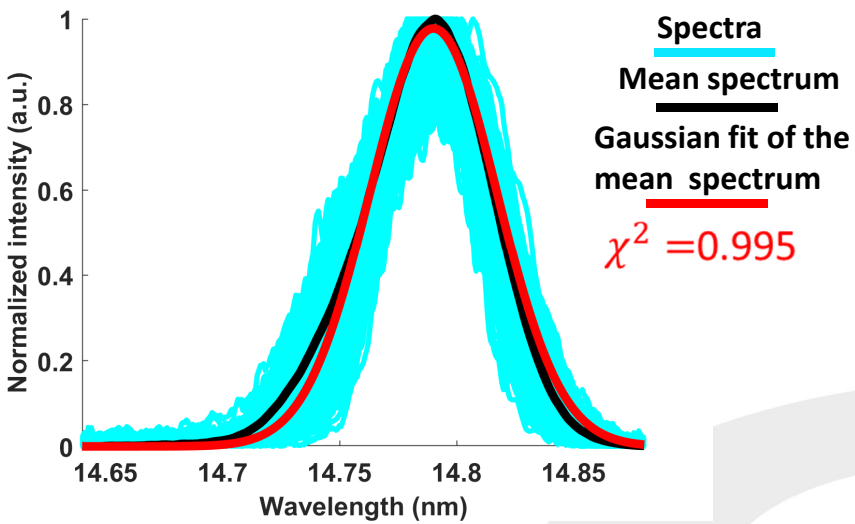


FWHM=0.064nm → 5fs

Fourier-limited pulse duration

From the Gaussian fitting of the mean spectra

Central wavelength jitter removed



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CONCLUSIONS

- **Autocorrelation of the FEL pulse with a resolution ~1fs in the wavelength range of FEL2**
- **Superradiant cascade scheme demonstrated on FEL2 at 14.79 nm with an electron beam energy of 750 MeV**

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Thank you!