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Double Stage Seeded FEL With Fresh Bunch Injection Technique at FERMI

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on behalf of the FERMI commissioning team

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Outline

- Seeded Free Electron Lasers
  - Benefits and possibilities
  - Seeded FEL facilities
- High Gain Harmonic Generation
  - Bunching and HGHG optimization
  - Double stage HGHG
- HGHG experimental results at FERMI
  - Coherence properties
  - Spectral characterization
- Conclusions

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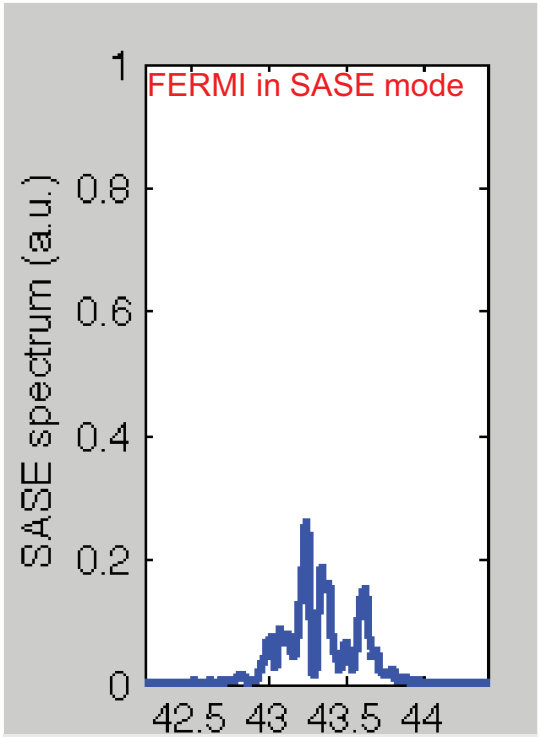
Why seeding?



SASE can give access to **very powerful pulses** but there is **little margin to control** pulse quality. In some cases this may be a limitation.

FERMI in HGHG mode

Seeding, self-seeding, and other **methods** (i-SASE, p-SASE) have been **studied** to have a **better control** of the **process** and improve the FEL properties.

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Seeded high gain FELs

Seeding **controls** the start-up of the FEL pulse within the electron bunch and helping to produce:

- **Temporal coherence** of the FEL pulse.
- Control of the **time duration**, **wavelength** and **bandwidth** of the coherent FEL pulse.
- Close to **transform-limit** pulses that provide excellent resolving power without monochromators.
- Natural **synchronization** of the FEL pulse to the seed laser.
- Reduction in **undulator length** needed to achieve saturation.
- High peak flux and **brightness**.

Benefits of seeding strongly **depend** on the **electron beam quality**. Seeded FELs are more sensitive to electron beam energy and phase space distortion than SASE.

Seeding sources

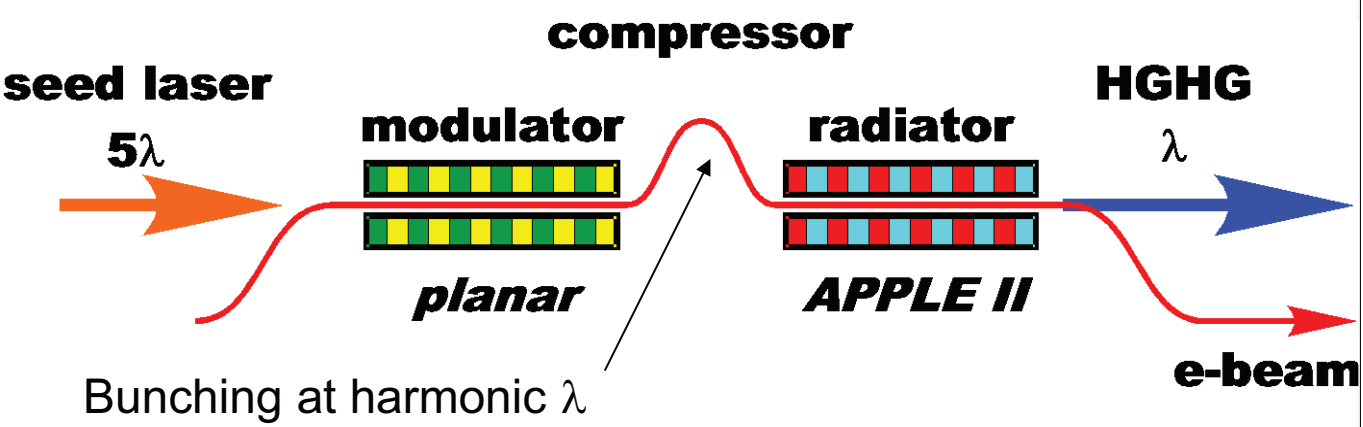
A suitable seeding source for FELs must be a **coherent** and stable source in the **wavelength range** where one is interested to operate the FEL or at **longer wavelength** if one use the **harmonic conversion** in the FEL.

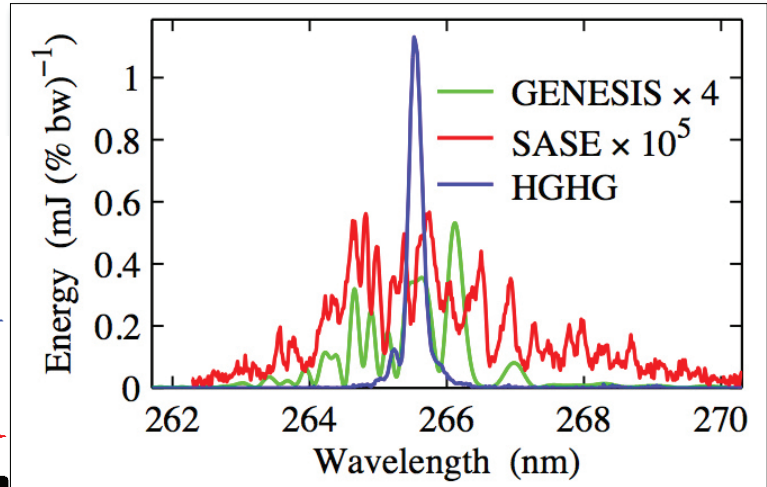
Possible sources are:

1. An external **laser** (visible to UV)
   - Prebunched by the seed laser, the FEL coherently emits at a higher harmonic in a radiator undulator (CHG) followed by high gain (HGHG, EEHG).
2. Harmonic emission produced by lasers, **HHG** (UV-VUV)
   - Weak coherent pulses are amplified by the FEL process.
3. A **free electron laser** (IR-X-ray)
   - Radiation from a FEL is used as a seed for another FEL (self seeding, two stages HG, oscillator seeding, …)

High Gain Harmonic Generation

The HGHG scheme of L.H. Yu was proposed after preliminary works(*) on FEL harmonic generation to solve the lack of seeding sources at short wavelengths.





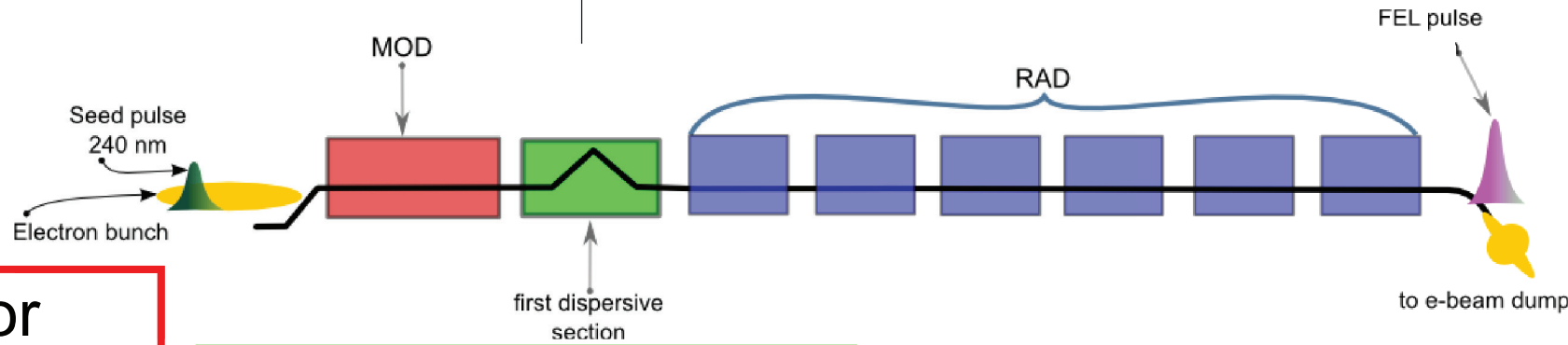
L.H. Yu et al. PRL 91, 074801 (2003)

FIG. 4: Single shot HGHG spectrum for 30 MW seed (blue), single shot SASE spectrum measured by blocking the seed laser (red) and simulation the SASE spectrum after 20 m of NISUS structure (green). The average spacing between spikes in the SASE spectrum is used to estimate the pulse length.

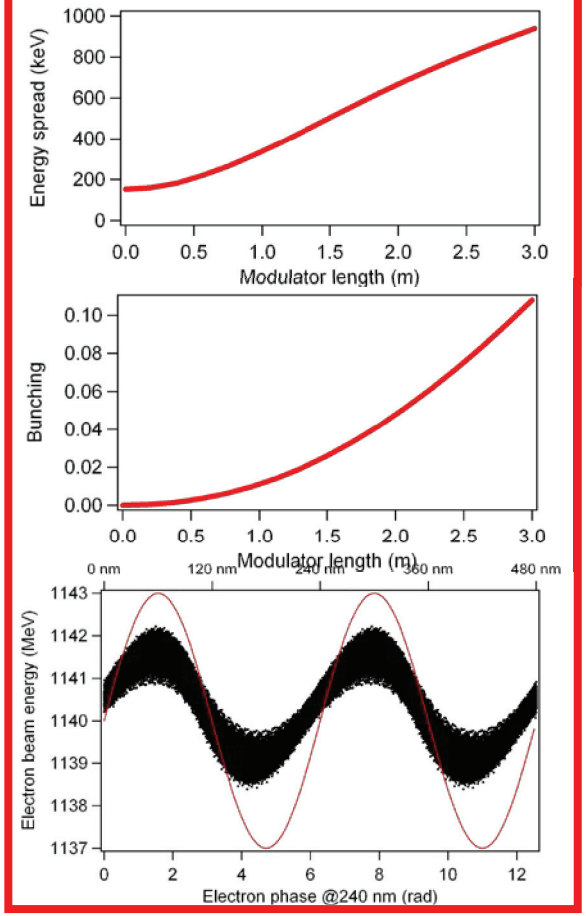
Compared to SASE devices, the HGHG approach is more compact and produces nearly fully temporally coherence output; spectral parameters easily controlled (e.g., pulse length, chirp).

(*)I. Boscolo et al. Il Nuovo Cimento 58, 271 (1980); B. Girard et al. Phys. Rev. Lett. 53, 2405 (1984),

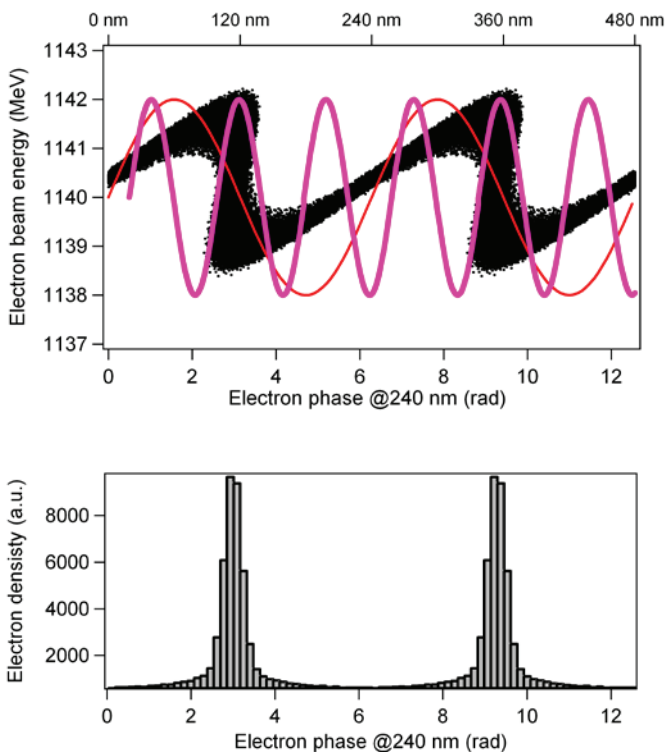
HGHG mechanism



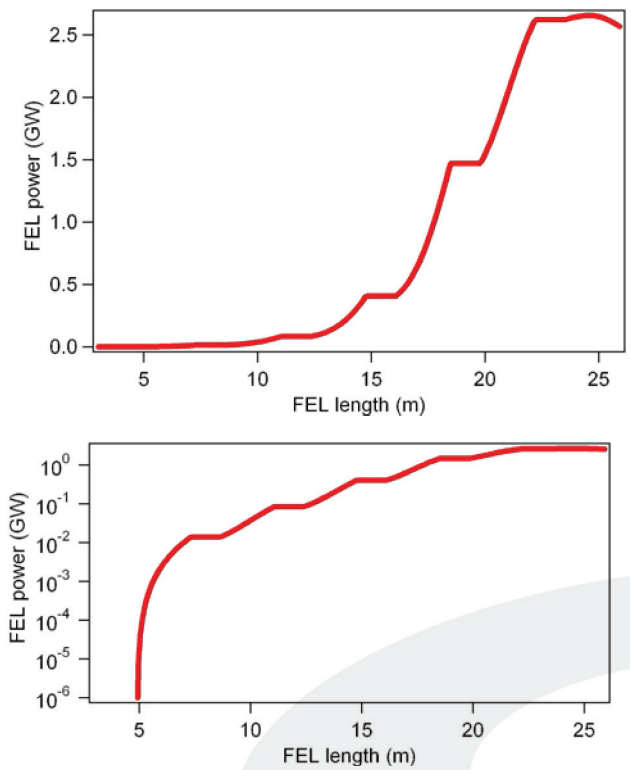
Modulator



Dispersive section



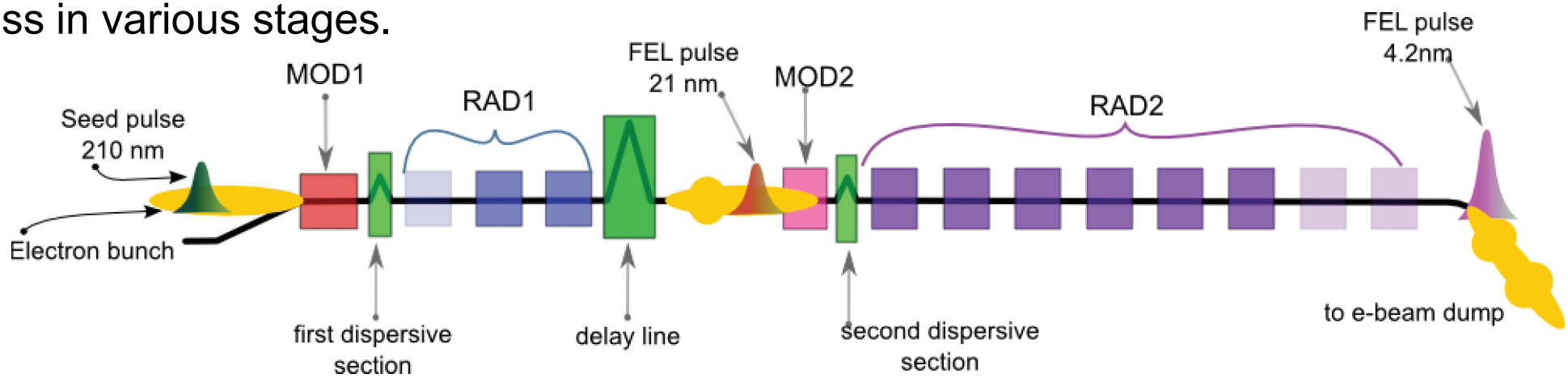
Radiator



The HGHG cascade

HGHG has a practical **short wavelength limit** with the maximum harmonic $\mathbf{H_{max} \sim \rho/\sigma_E}$.

A way to **extend the HGHG** to **higher harmonics** is to **repeat** several times the process in various stages.



In a two stage, HGHG cascade FEL, the first stage generates a high quality FEL pulse at shorter wavelength (e.g., 20 nm).

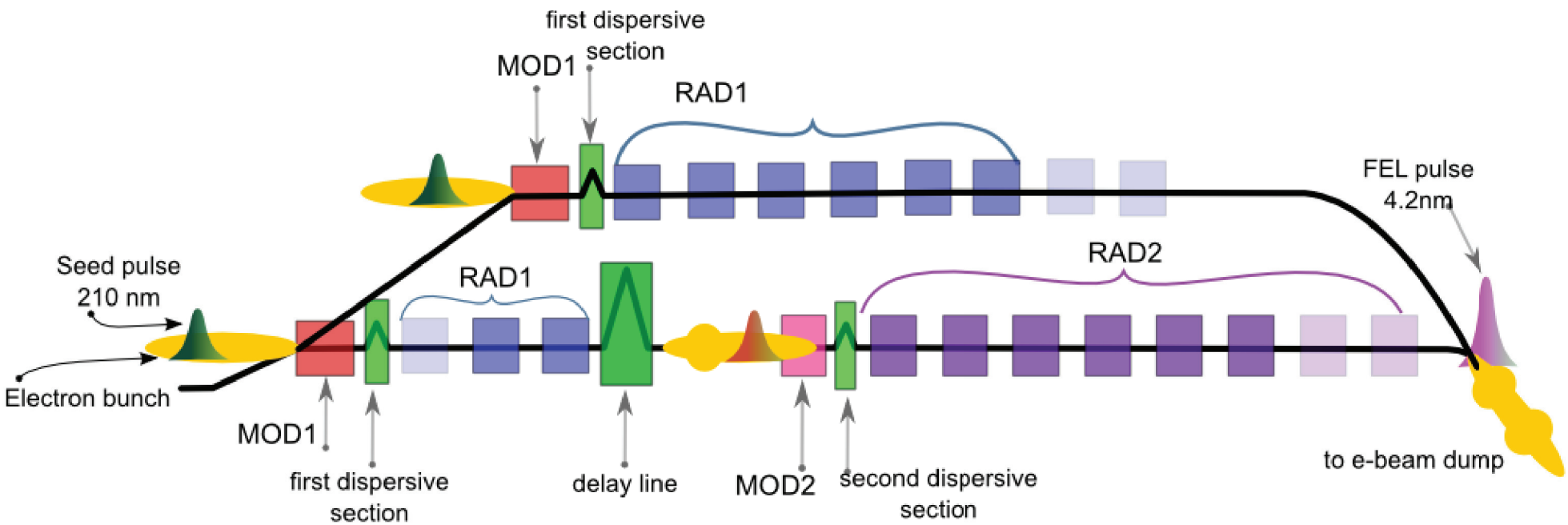
This **pulse** then **seeds** the **second HGHG** stage, creating coherent bunching, and eventual FEL output at an even shorter wavelength (e.g., 4 nm).

The "**fresh bunch**" technique is used to have the seeding always occurring in a part of the **electron beam** that has **not** been **spoiled** by previous FEL interaction.

In this configuration **an FEL** is used as a **seed for the second FEL**. The scheme can in principle be repeated to reach even shorter wavelengths.

FERMI FELs

FEL-1, based on a single stage high gain harmonic generation scheme initialized by a UV laser, covers the spectral range from ~80 nm down to 20nm.



FEL-2, in order to be able to reach the wavelength range from 20 to ~4 nm starting from a seed laser in the UV, is based on a double cascade of harmonic generation. The nominal layout uses a magnetic electron delay line in order to improve the FEL performance by using the fresh bunch technique. Other FEL configurations are also possible in the future (e.g., EEHG).

FERMI FEL-1 results

Successful operation of HGHG in the VUV has been demonstrated and reported.

Currently FEL-1 is operated for user dedicated beamtimes and first results are coming out.

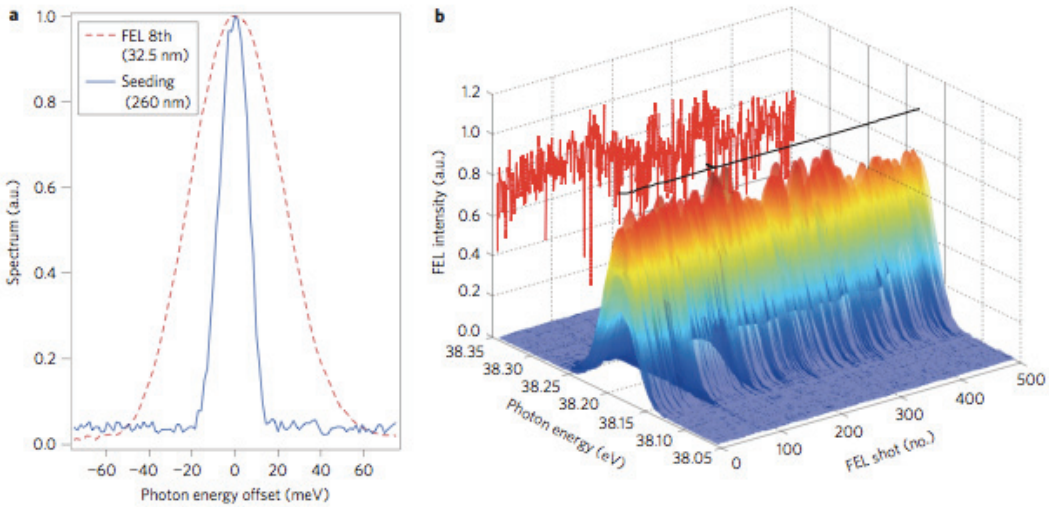


Figure 4 | Single-shot and multi-shot spectra at 32.5 nm. a, Measured FEL and seed laser spectrum (dashed red and continuous blue lines respectively). **b**, Acquisition of 500 consecutive FEL spectra.

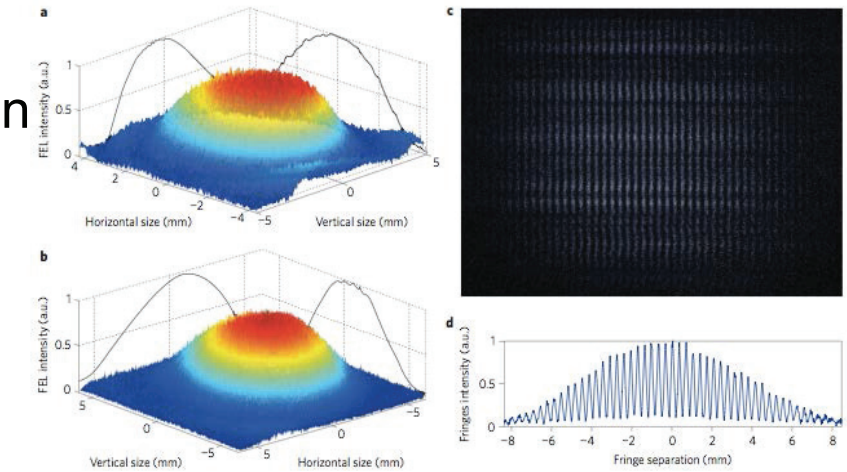


Figure 3 | Measured beam profiles and double slit diffraction pattern. a, FEL spot size measured on a YAG screen positioned 52.4 m downstream from the radiator exit. The main signal is well reproduced by a Gaussian profile and is characterized by a second moment of ~2 mm in both the vertical and horizontal directions. **b**, FEL spot size measured on a second YAG screen positioned 72.5 m downstream from the radiator exit. In this case the measured horizontal and vertical beam dimensions are 2.6 mm and 2.4 mm, respectively. **c,d**, Image and projection of the interference pattern recorded on the second YAG screen when the FEL beam propagates through two 20 μm slits, separated by 0.8 mm, placed ~8.5 m before the screen.

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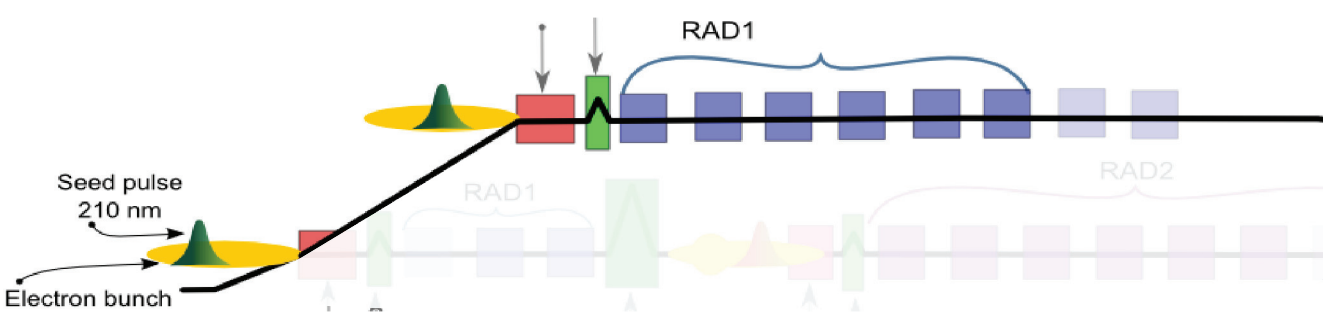
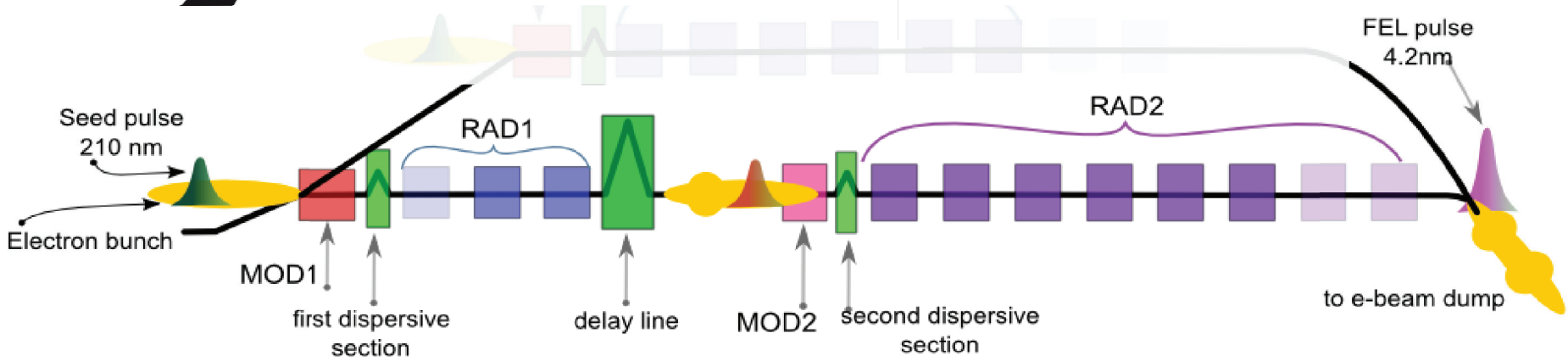
Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet

E. Allaria *et al.**

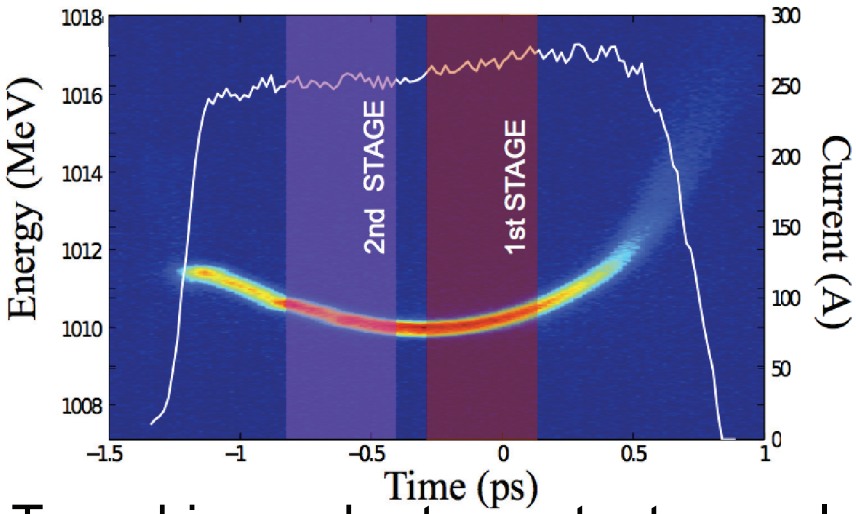


FEL-2: two stages HGHG

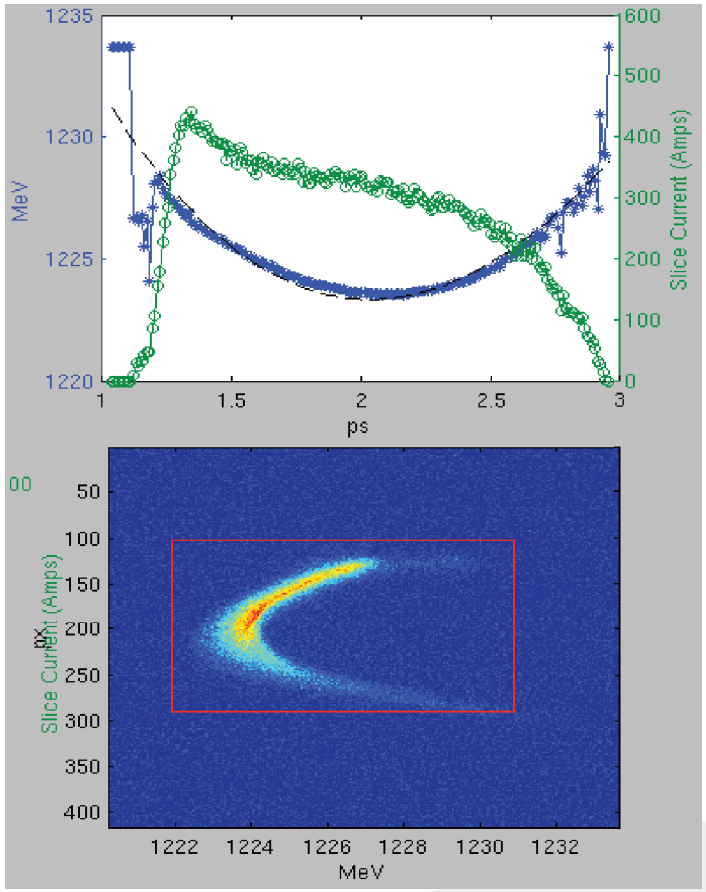


- Activity on FEL-2 started in May 2012 with first FEL emission from the first stage.
- In October 2012 we successfully operate the full, two stage cascade using the fresh bunch technique and produced narrow bandwidth, reasonably low jitter pulses down to 10.8 nm wavelength (1.0 GeV electron beam energy).
- In March 2013 we extended the short wavelength limit down to 8.4 nm (1.2 GeV) and in June 2013 to 4.7 nm (1.4 GeV) with significant coherent pulse energies (>= 1 μJ) to wavelengths as short as 4.3 nm.

Used electron beams



First FEL-2 operation has been with **1 GeV** electron beam with moderate compression (single bunch compressor). Electron beam current **~250 A**.



To achieve shorter output wavelengths, the electron beam energy was increased first to **1.2GeV** and then to **1.4GeV.**

Peak current has been in the range **300-500 A** depending on the used compression scheme.

Despite the quite good current profile, we have seen that in some cases the **FEL** may be **affected** by the **quadratic curvature** of the electron beam **phase space.**

FEL **bandwidth** and wavelength **stability** may be compromised in case of a large and not controlled electron beam **energy chirp** or modulation.

First evidence of seeding on second stage

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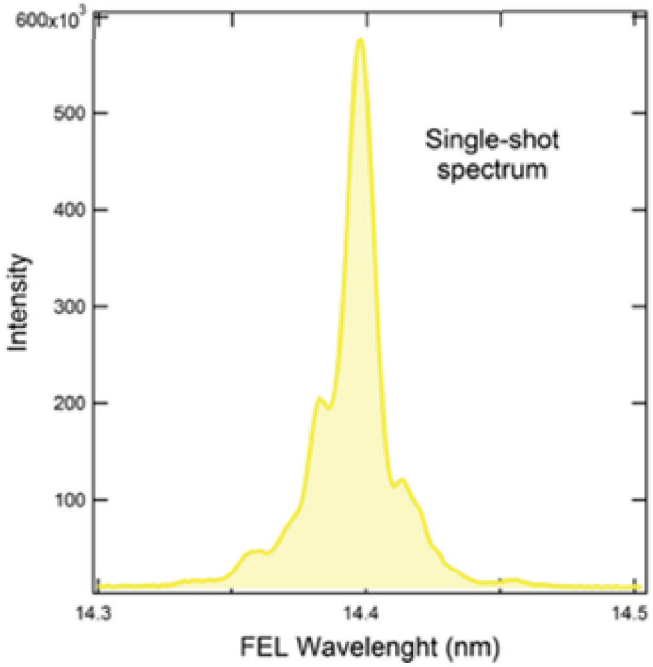
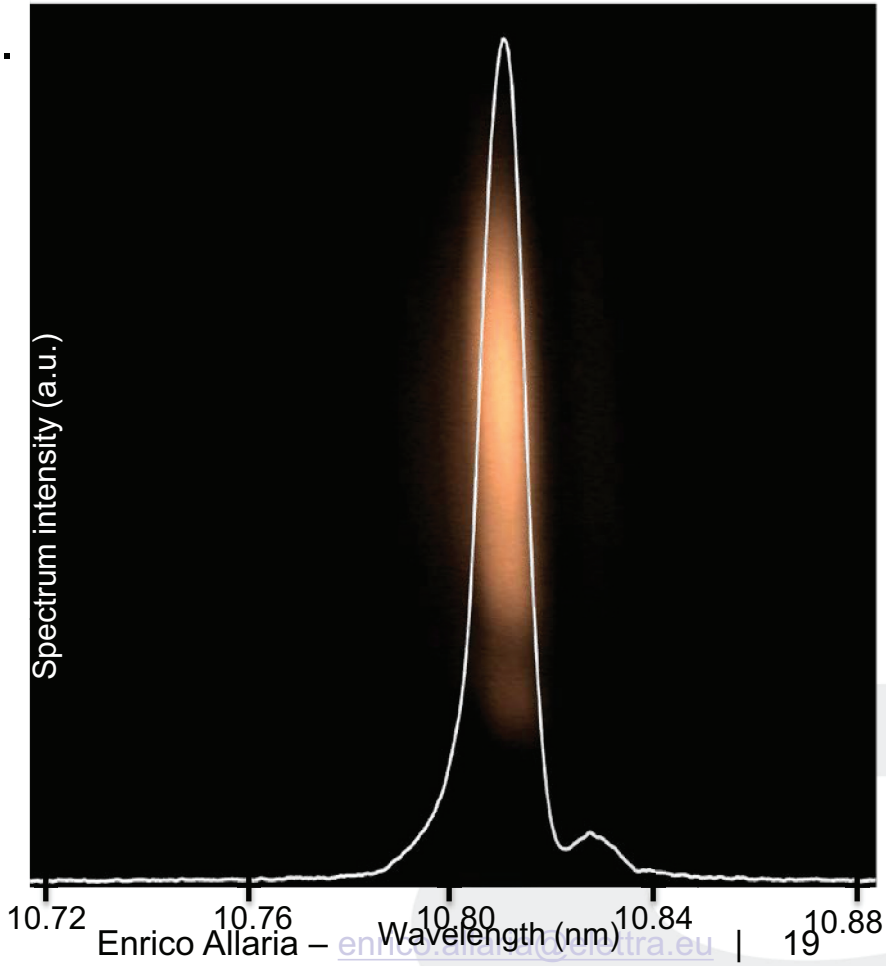


After few days of operations in October we had the first evidence of seed-induced coherent emission from the second stage.

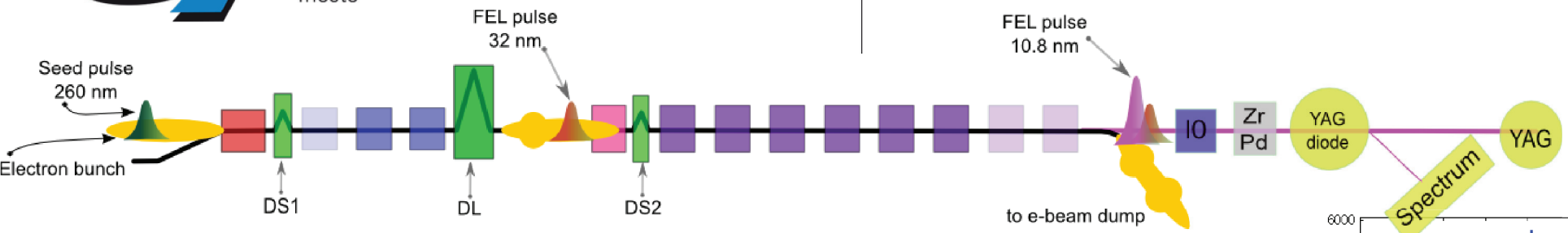
October '12 operations have been focused at ~1GeV electron beam energy permitting operation of the FEL in the 15-9 nm spectral range.

After the first evidence of lasing at the 3rd harmonic of the 6th (260→43.3→14.4 nm) we focused our efforts to shorter wavelength.

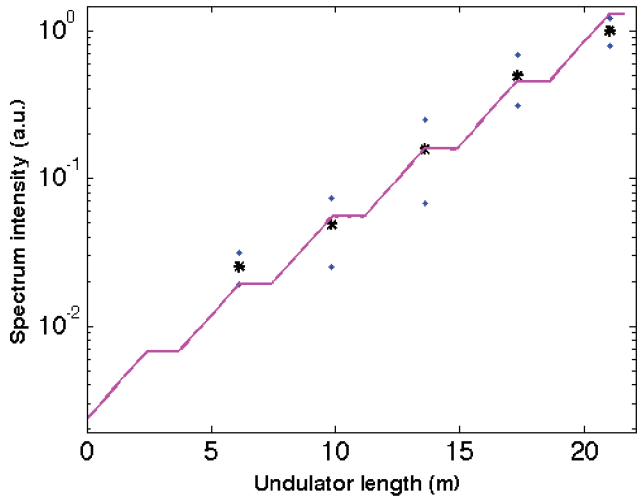
Most of October '12 results have been obtained at 10.8nm that has been produced both as the 4th harmonic of the 6th (260 →43.3→10.8 nm) and the 3rd harmonic of the 8th (260→32.5→10.8nm) .

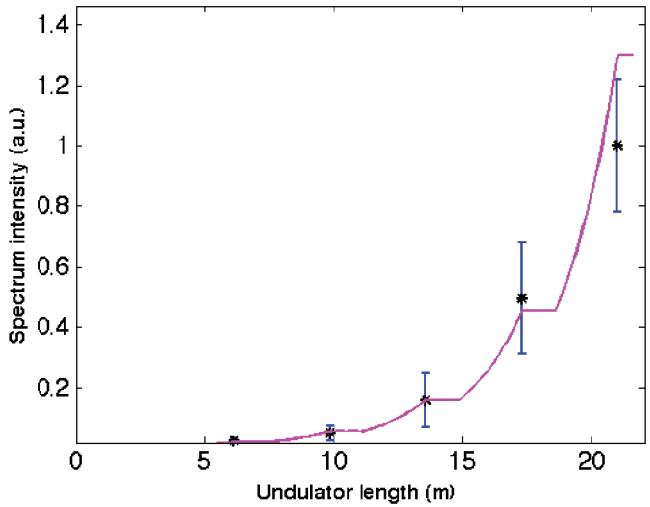


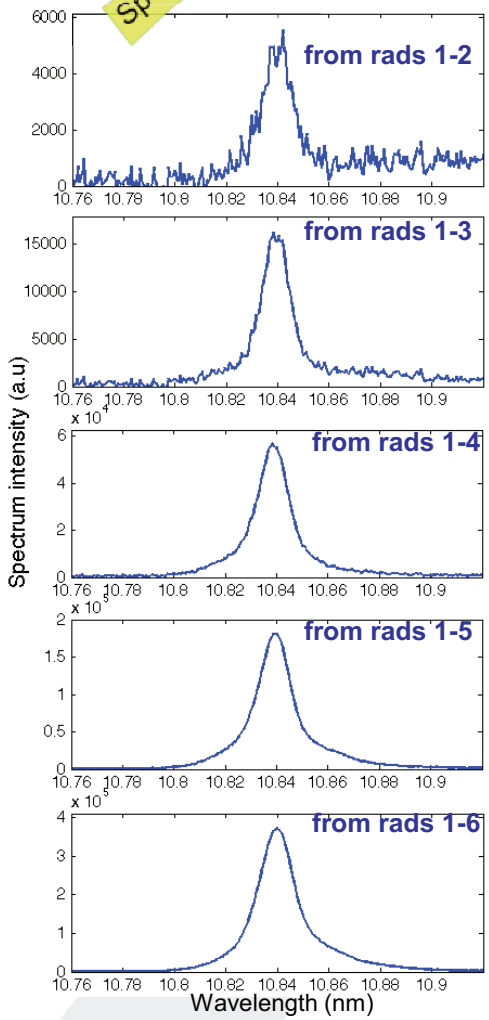
FEL gain



Second stage at 3rd harmonic of the 8th (260→32.5→10.8nm) .



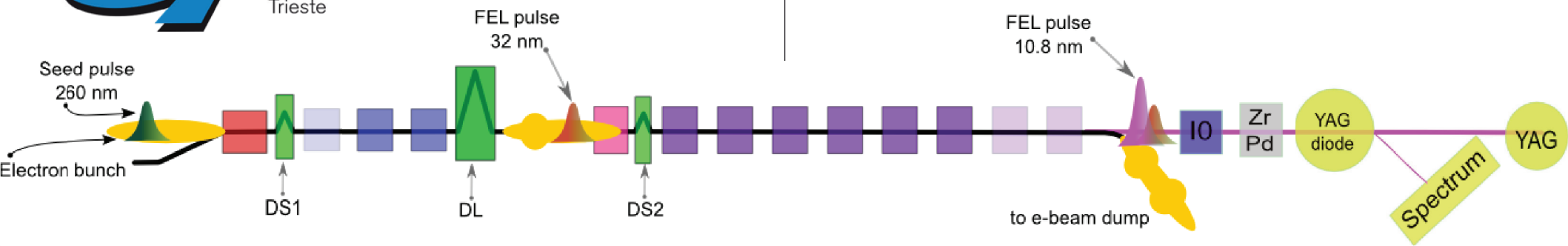


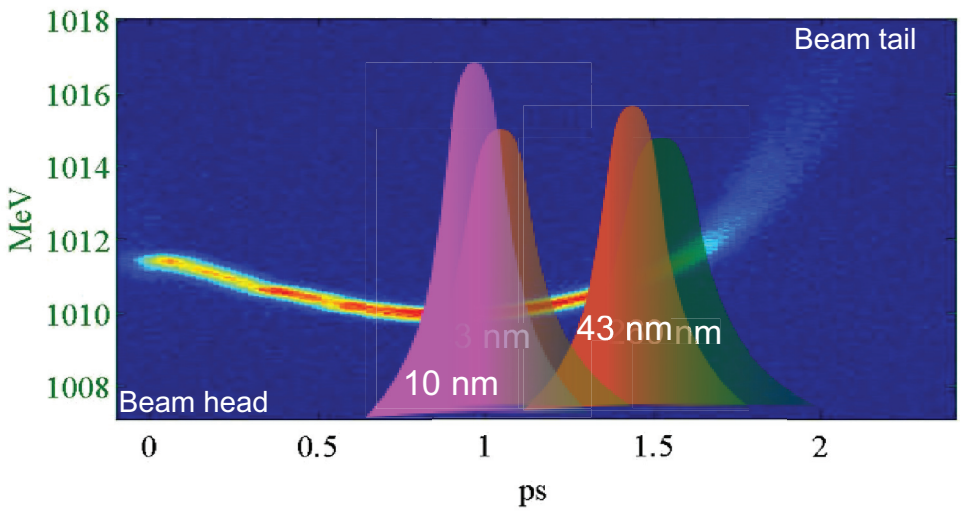


Data fit well with an **exponential curve** characterized by a **gain length** of ~**2.2 m**. L_g =2.2 m can be obtained from a beam that has the characteristic of the one used for the experiment:

I=300A, E=1.0GeV, σE=600keV, ε=1 mm mrad, β=15 m

Fresh bunch: Seed delay

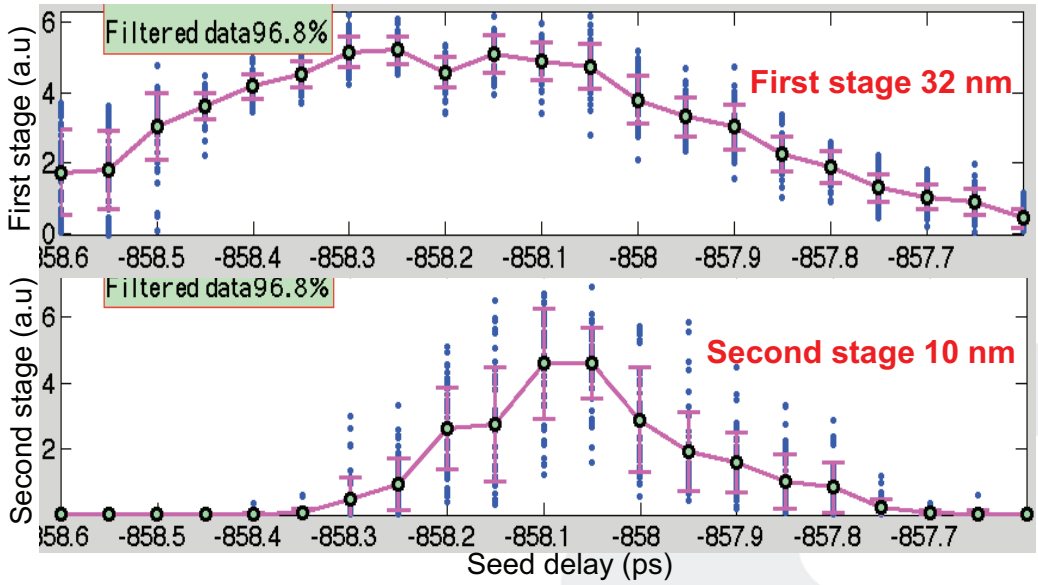




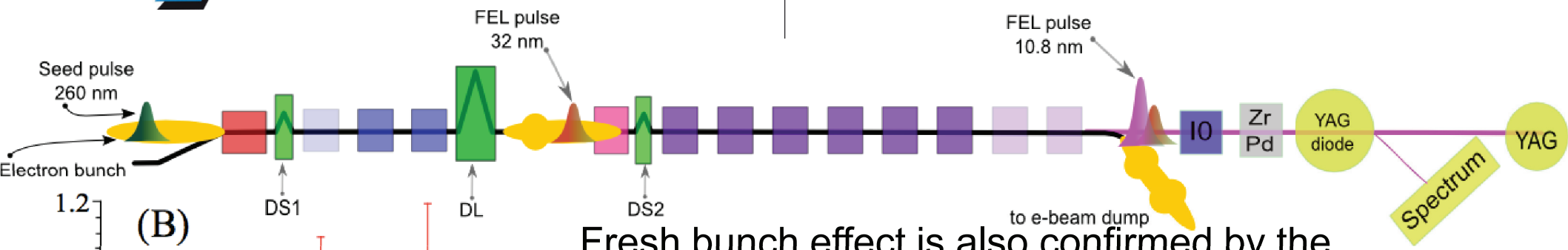
Because of the **fresh bunch scheme**, the **second stage** radiation is produced few hundreds of fs **toward** the **head** of the bunch.

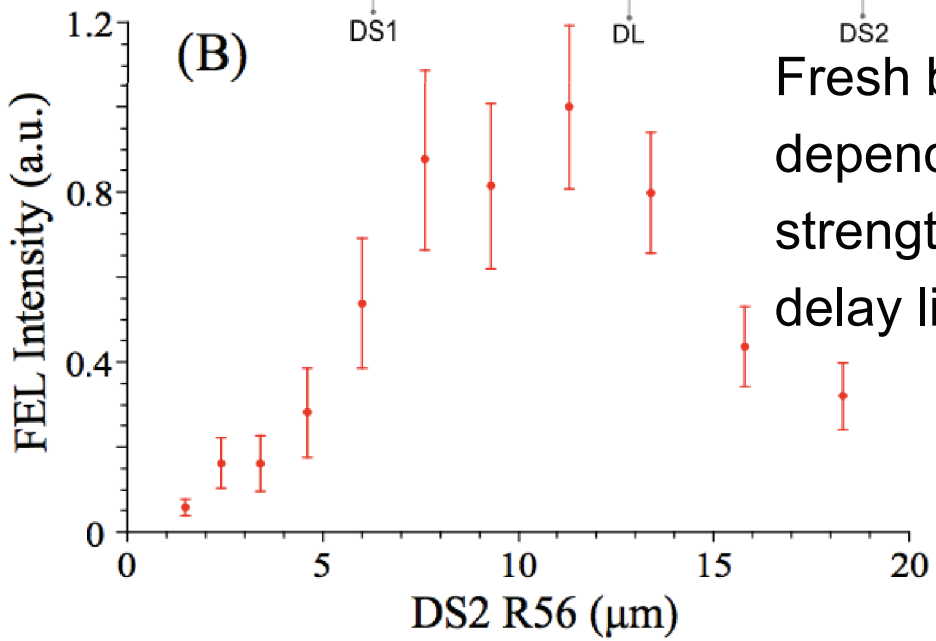
While **scanning the seed delay,** there is a region where radiation from **first stage is produced** but **not from the second stage**.

The results of the scans of the seed laser delay suggest that **second stage** radiation comes from the **fresh part of the beam** and not from the one pre-bunched by the seed laser.

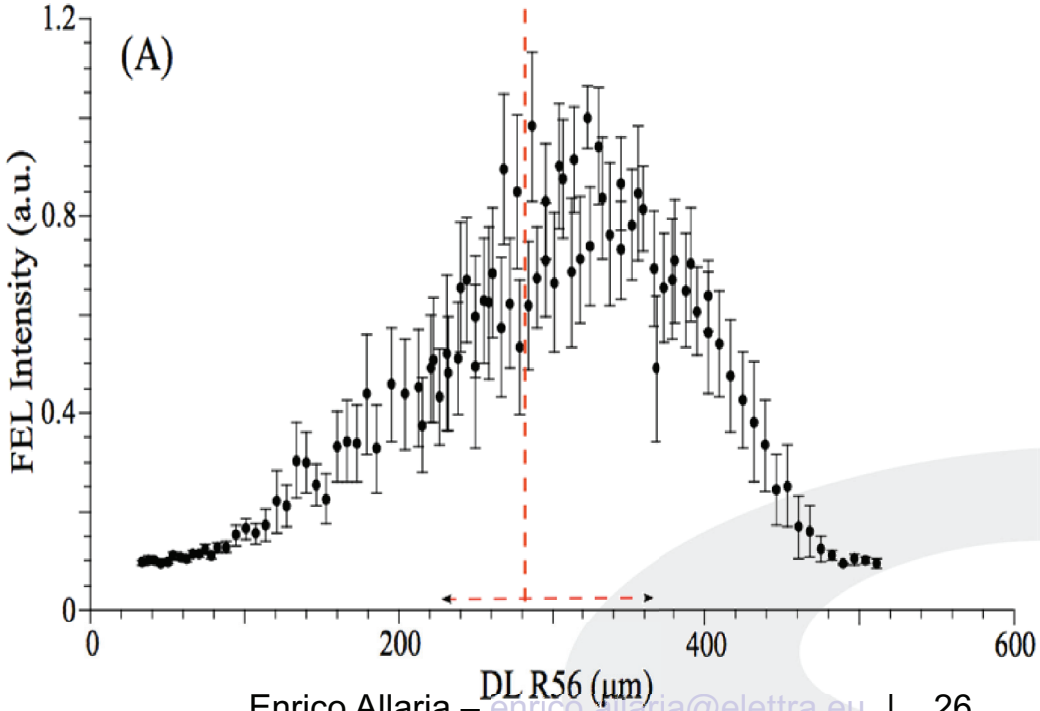


Fresh bunch: scan of the dispersive sections





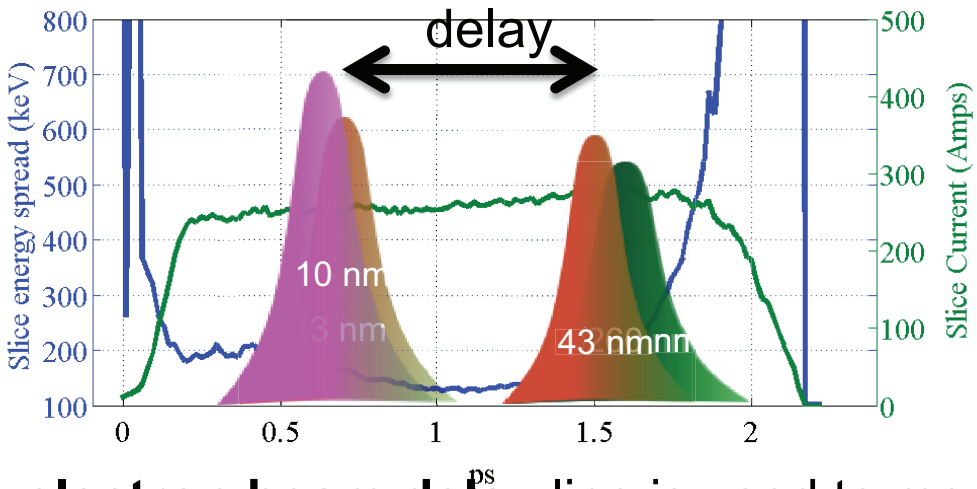
Fresh bunch effect is also confirmed by the dependence of the second stage emission from the strength of the second dispersive section (DS2) and the delay line that follow the first stage radiator (DL).

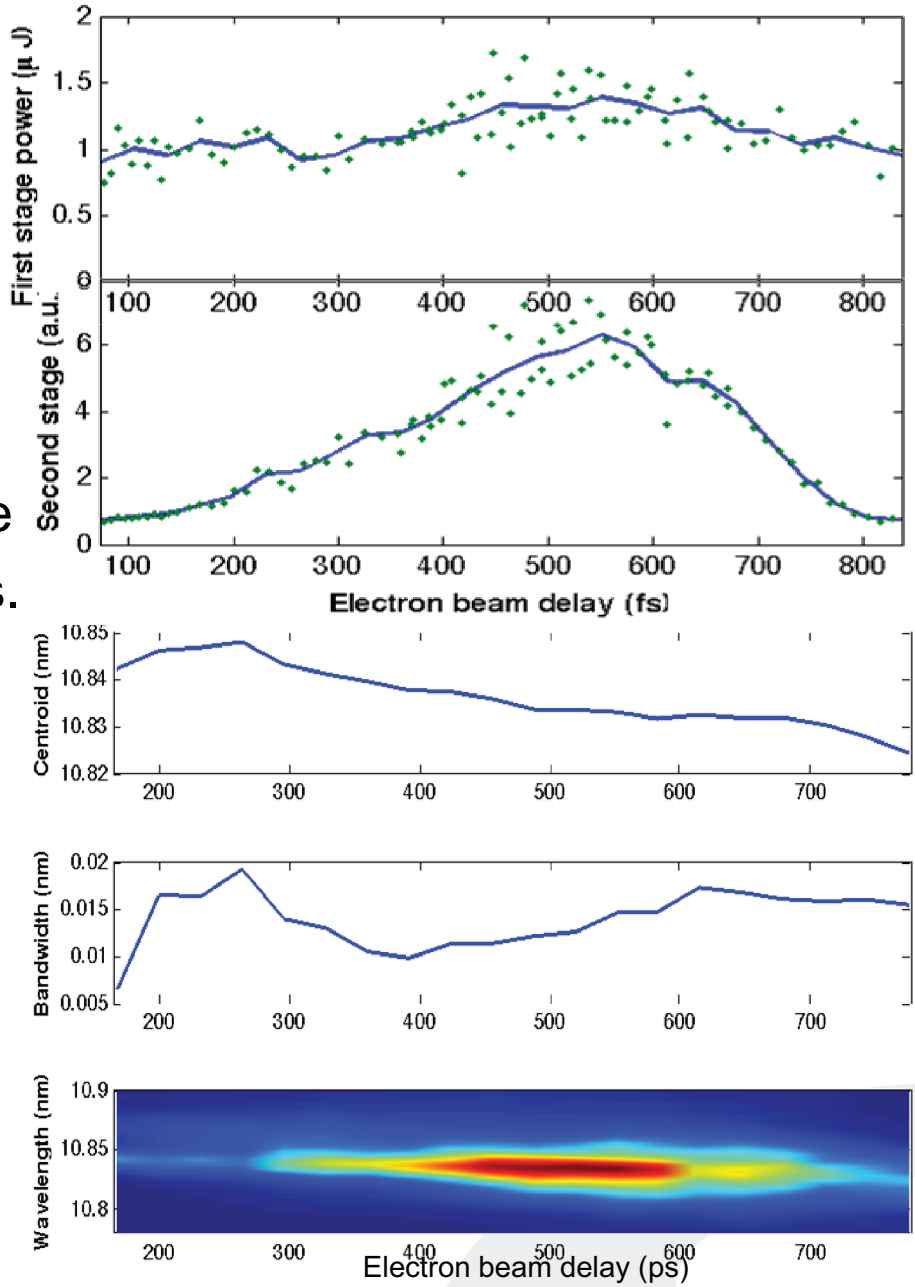


While changes of a few microns on the DS2 strength strongly affects the FEL output, the DL strength needs to be varied by hundreds of microns to show the same effect.

Second stage emission disappears if MOD2 detuned.

Effect of the e-beam delay line





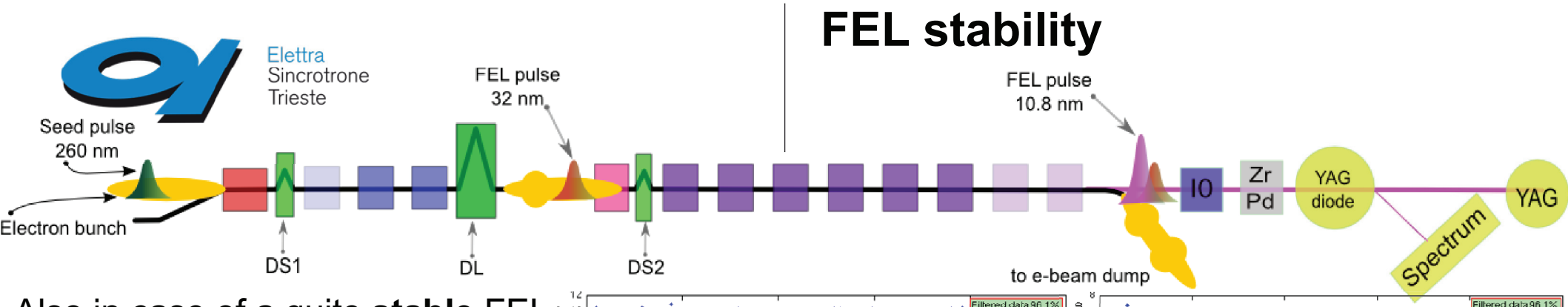
The **electron beam delay** line is used to move the first stage FEL pulse ahead toward fresh electrons. This is a **critical** parameter for **FEL optimization**.

As expected, for **small delays** the second stage seeding is **not efficient** (electrons partially involved on first stage).

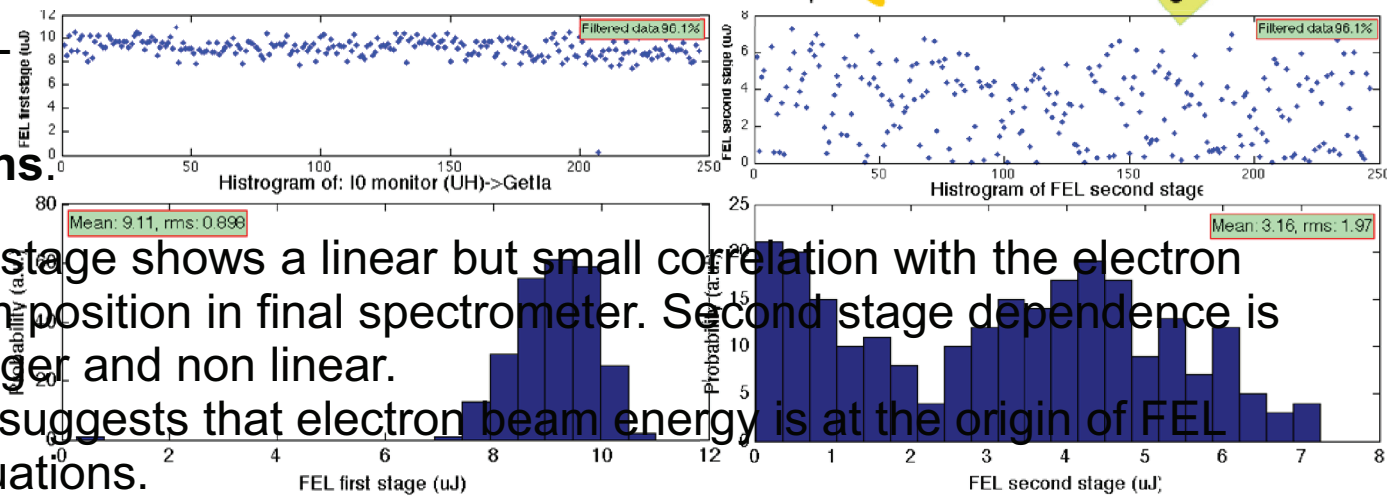
For too **large** a **delay**, the **second stage** is moved **outside** the good region of the beam.

The value of the **delay** line has an **impact** also on the final **FEL spectrum** (wavelength and bandwidth).

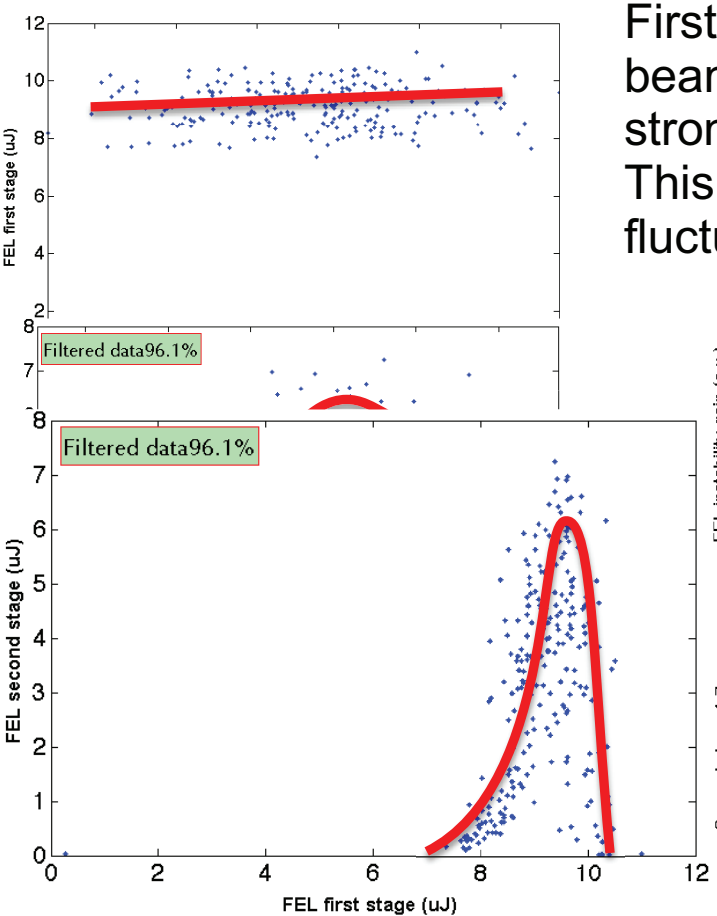
FEL stability

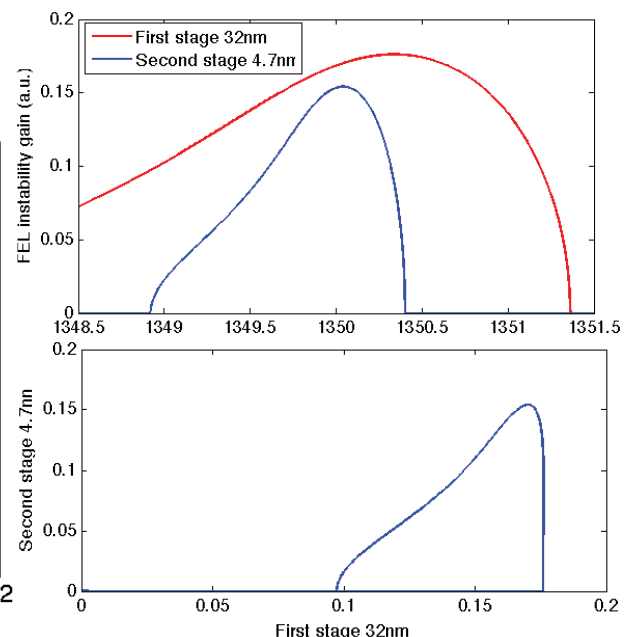


Also in case of a quite **stable** FEL from the **first stage** the **second stage** can show **large fluctuations**.



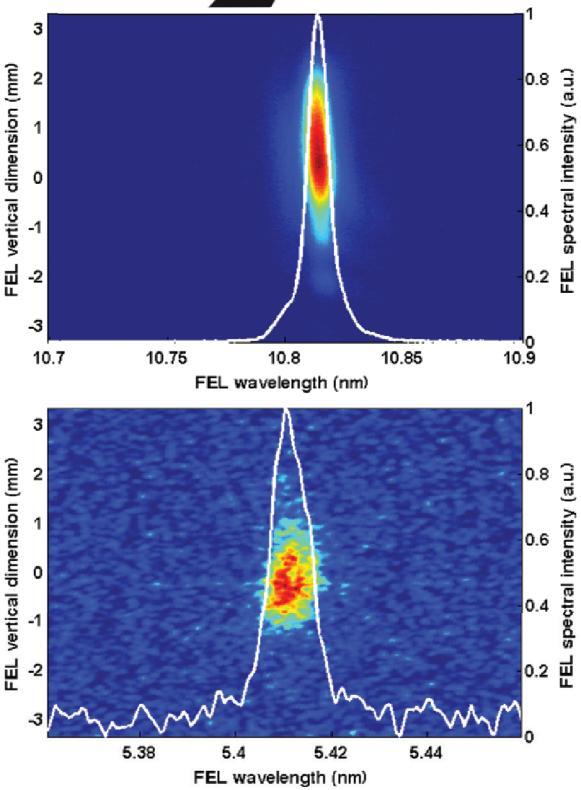
First stage shows a linear but small correlation with the electron beam position in final spectrometer. Second stage dependence is stronger and non linear.
This suggests that electron beam energy is at the origin of FEL fluctuations.

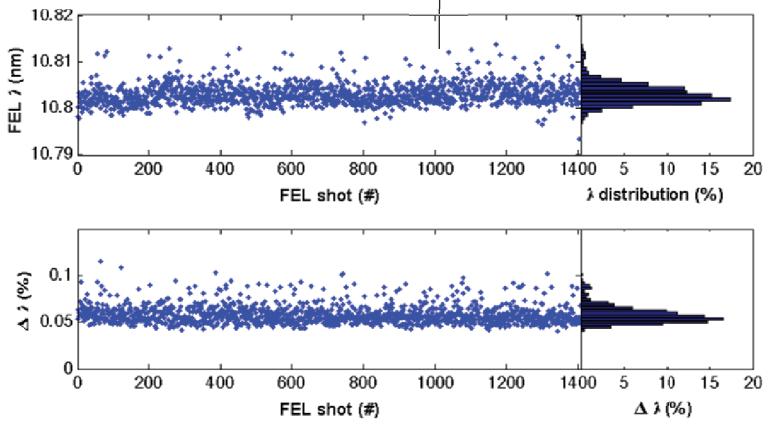


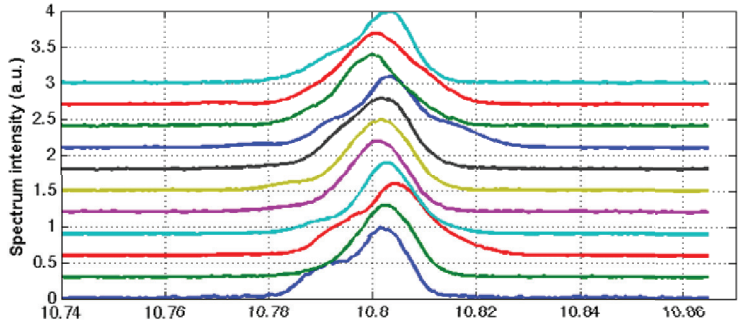


Obtained results can be qualitatively reproduced if one consider the different gains for the first and second stage associated to the different ρ (2e-3, 8e-4) and undulator k parameter (2.5,1).

FEL spectral stability

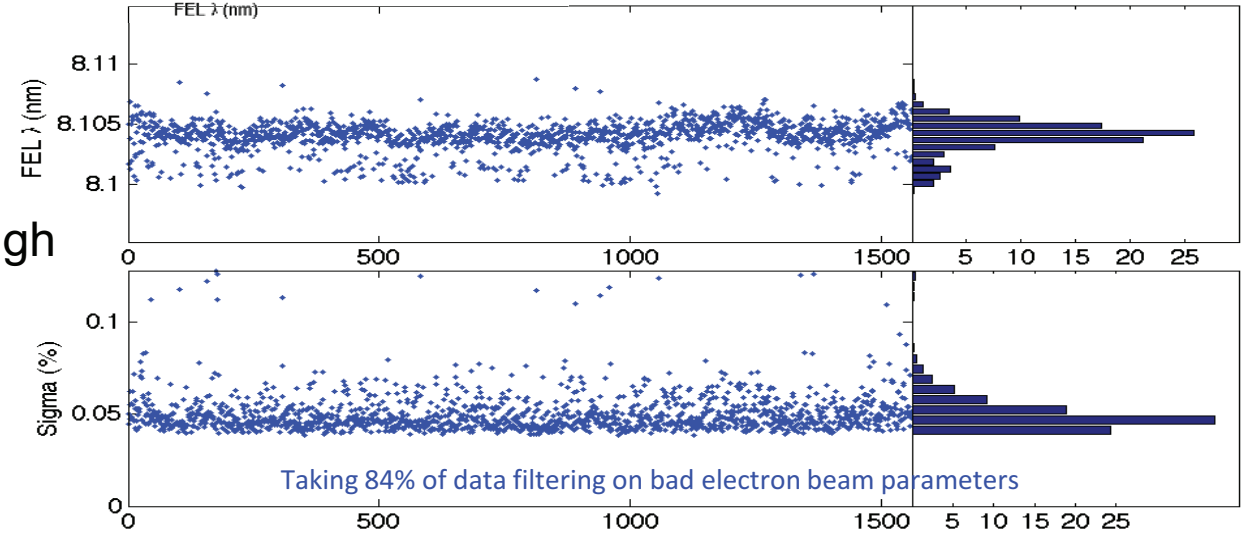




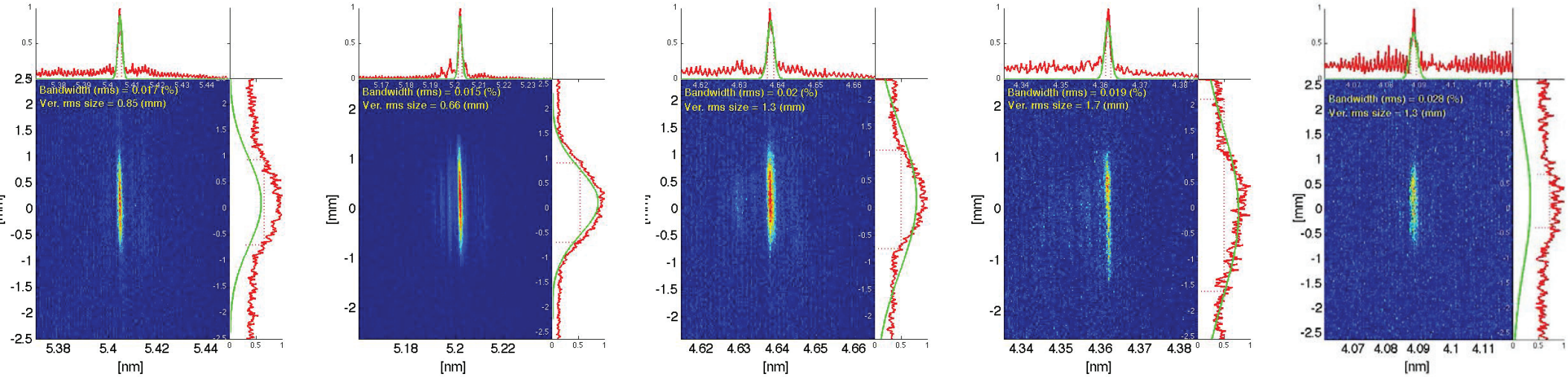


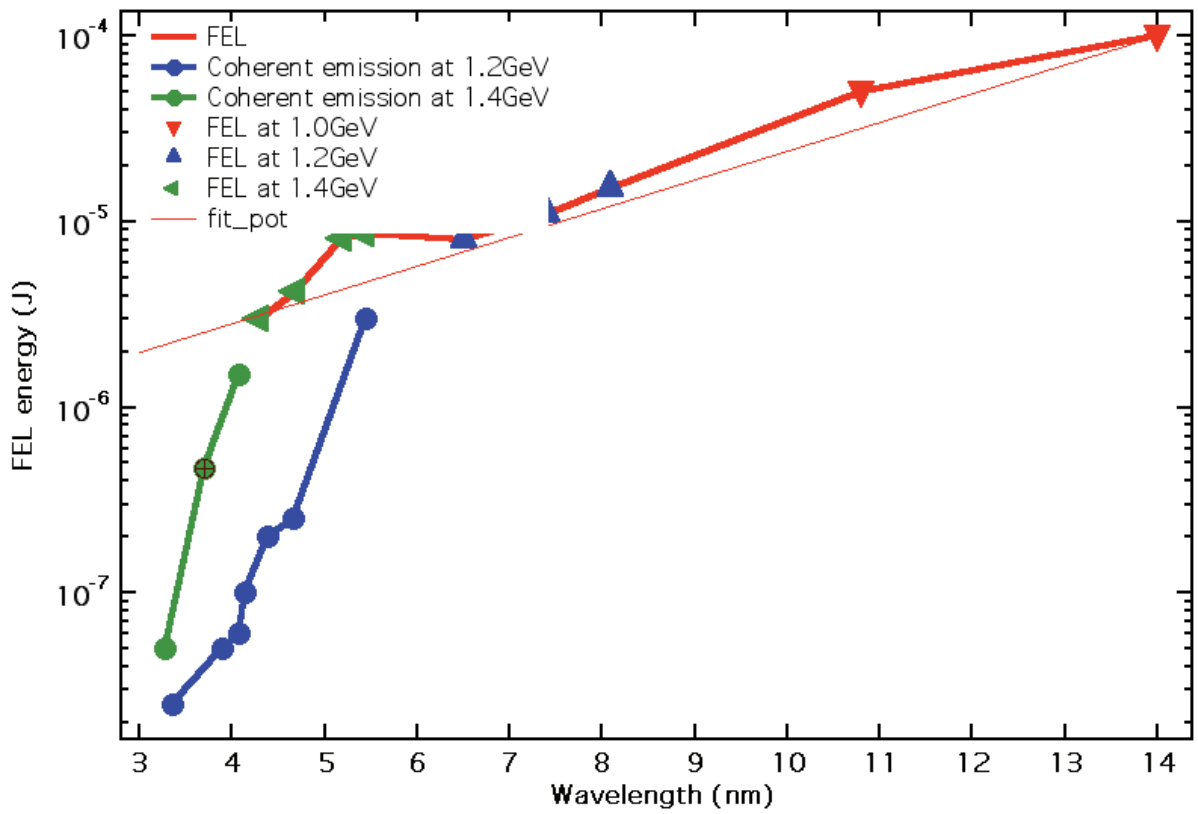
As with FEL-1, **FEL-2 spectra** can be **very narrow**, clean and **stable**. In the displayed data (10nm), after filtering out bad data points (based on electron beam parameters) we have a wavelength **stability** of **$2*10^{-4}$** with an average FEL **bandwidth** of **$6*10^{-4}$** (sigma).

Similar results have been obtained at 8nm. At shorter wavelength, not enough single shot data have been collected yet.



Coherent emission at shorter wavelengths





Coherent emission with FEL-2 has been obtained down to about **3 nm**.

Although very week single shot **spectra** have beam measured up to **4 nm** and the good ones show narrow line ($\sigma\lambda/\lambda \sim 10^{-4}$).

Real **FEL gain** is at the moment limited to about **4 nm** due to the electron beam energy limit.

Larger energy per pulse would be accessible with brighter electron beam (higher peak current)

Conclusions

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Achieved results

A two stage harmonic generation FEL has been successfully operated with the fresh bunch technique up to a final harmonic upshift ratio exceeding 50.

FEL output pulse energies of ~10 μJ or greater has been achieved down to 5.2 nm.

Coherent emission levels of 1 μJ down to 4.0 nm has been generated in the cascade configuration.

Near term plan

- Increase e-beam energy and brightness to improve performances at shorter wavelengths
- Improve output energy stability by:
  - Decrease shot-to-shot jitter in electron energy and compression;
  - Improve matching in undulator;
  - Improve transverse phase space by reducing CSR and microbunching effects and residual dispersion in transport optics

Long term plan

FEL-2 user's operation will start in 2015.

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Thank you!

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