FERMI: EUV and Soft X-Ray FELs with HGHG

E. Allaria
on behalf of the FERMI commissioning team

Outline

- Elettra and the FERMI FEL project
  - FERMI parameters
- FEL-1 experimental results
  - FEL bandwidth and wavelength stability
  - FEL pulse control
- FEL-2 experimental results
  - First coherent photons
  - Double cascade results

FERMI at the ELETTRA LABORATORY

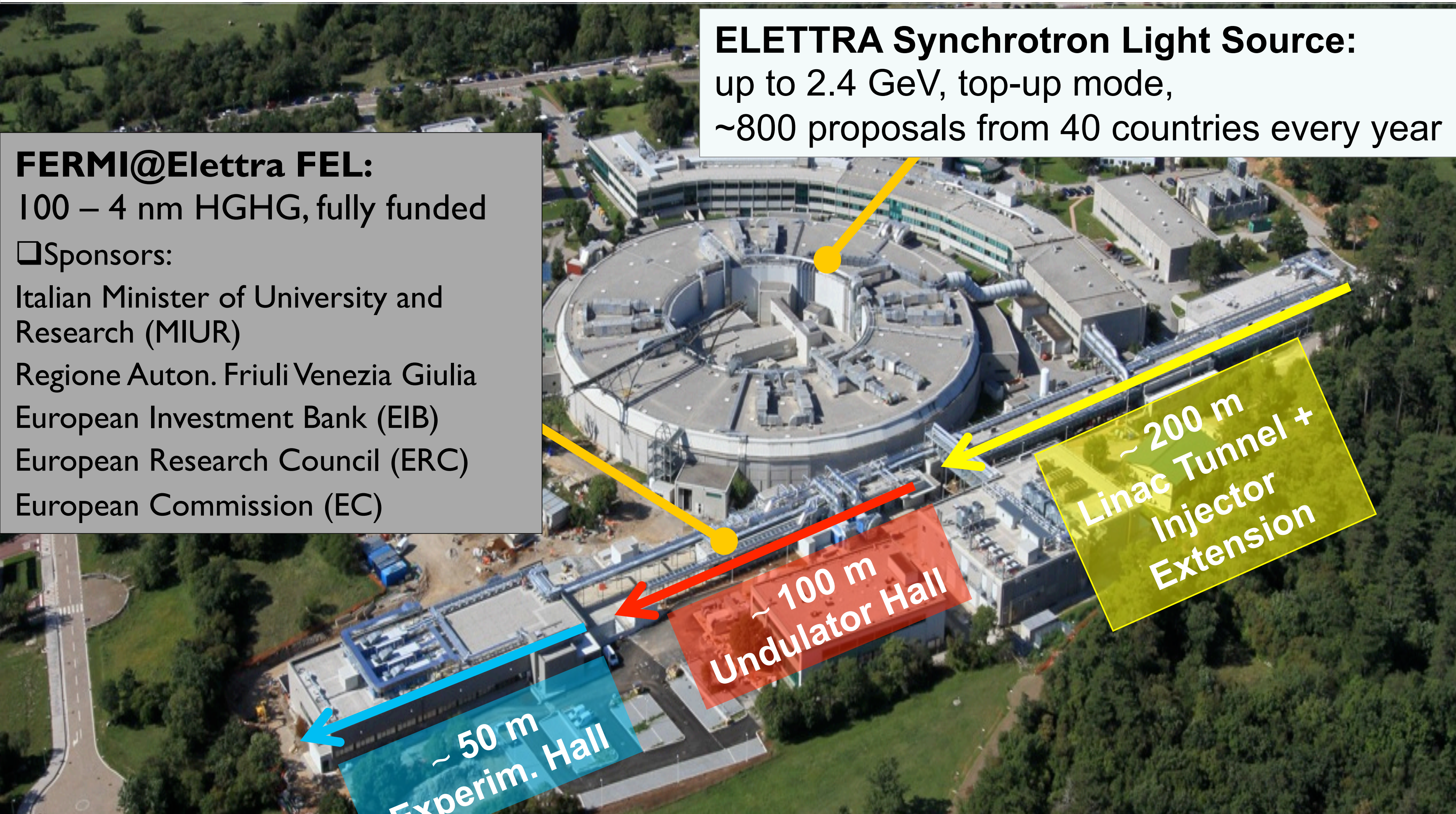
SINCROTRONE TRIESTE is a nonprofit shareholder company of national interest, established in 1987 to construct and manage synchrotron light sources as international facilities.

ELETTRA Synchrotron Light Source:
up to 2.4 GeV, top-up mode,
~800 proposals from 40 countries every year

FERMI@Elettra FEL:
100 – 4 nm HGHG, fully funded

- Sponsors:

Italian Minister of University and Research (MIUR)
Regione Auton. Friuli Venezia Giulia
European Investment Bank (EIB)
European Research Council (ERC)
European Commission (EC)



FERMI main features

FERMI@Elettra single-pass FEL user-facility.

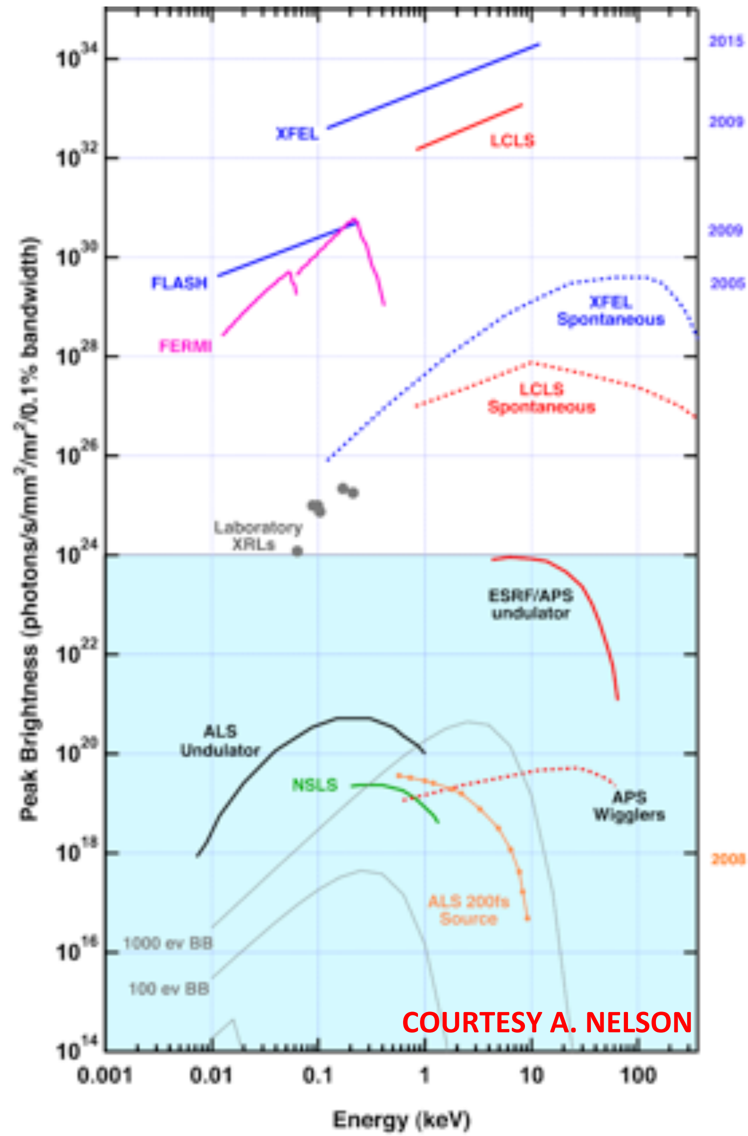
Two separate FEL amplifiers to cover the spectral range from 80 nm to 4 nm.

The two FEL's provide users with ~100fs photon pulses with unique characteristics.

❑ high peak power	0.3 – GW's range
❑ short temporal structure	sub-ps to 10 fs time scale
❑ tunable wavelength	APPLE II-type undulators
❑ variable polarization	horizontal/circular/vertical
❑ seeded harmonic cascade	longitud. and transv. coherence

This photons parameters are achieved using the coherent emission from high brightness and high energy electron beams. FERMI electron beam parameters are:

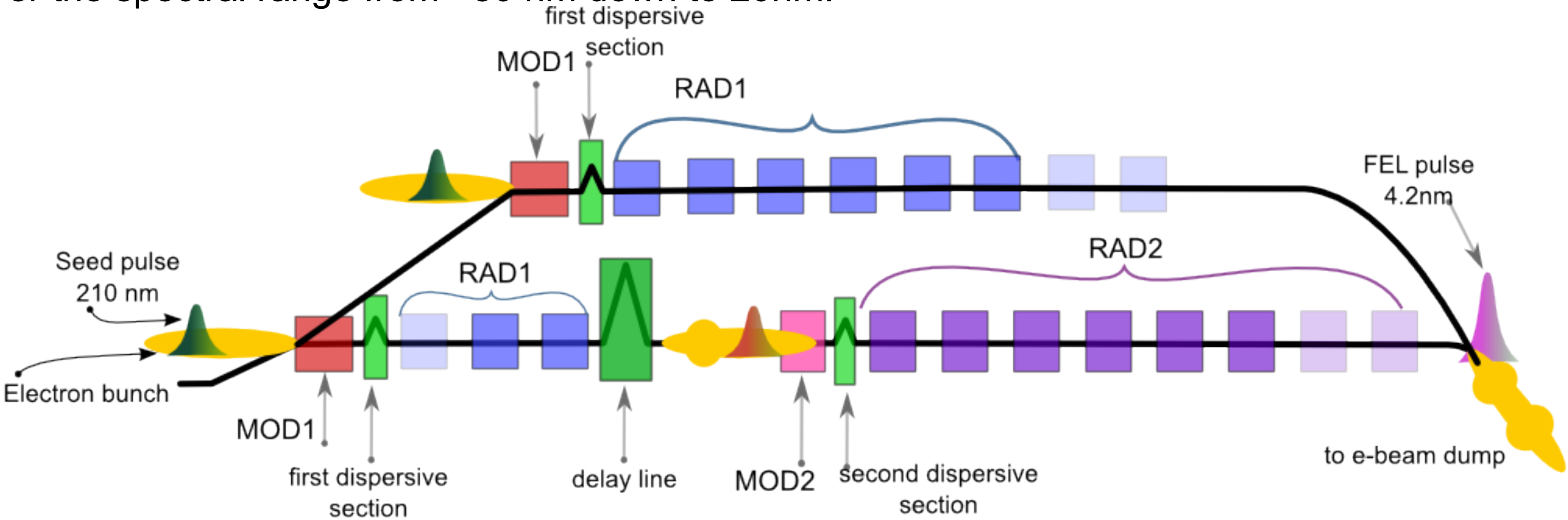
Charge	500 pC
Emittance	1 mm mrad
Energy	1.2-1.5 GeV



HGHG at FERMI: FEL-1 and FEL-2

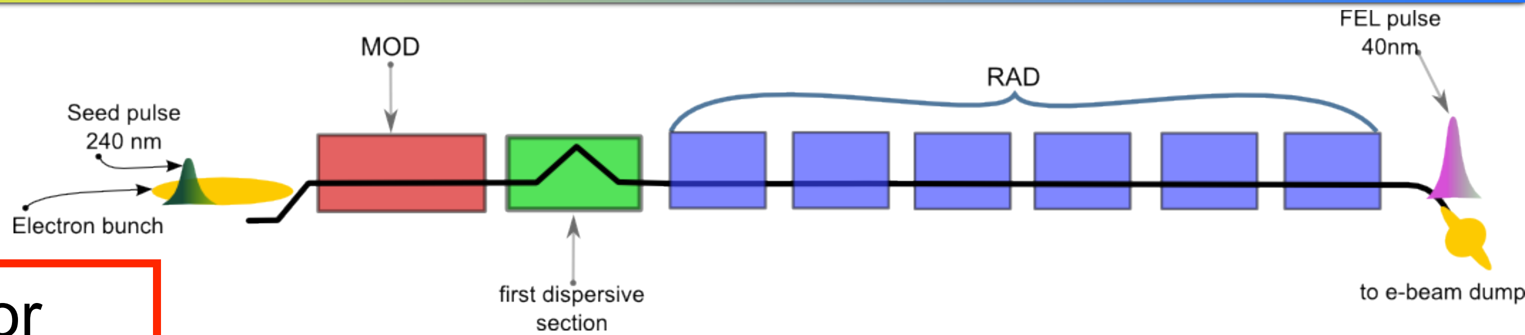
FERMI's two FELs cover different spectral regions.

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

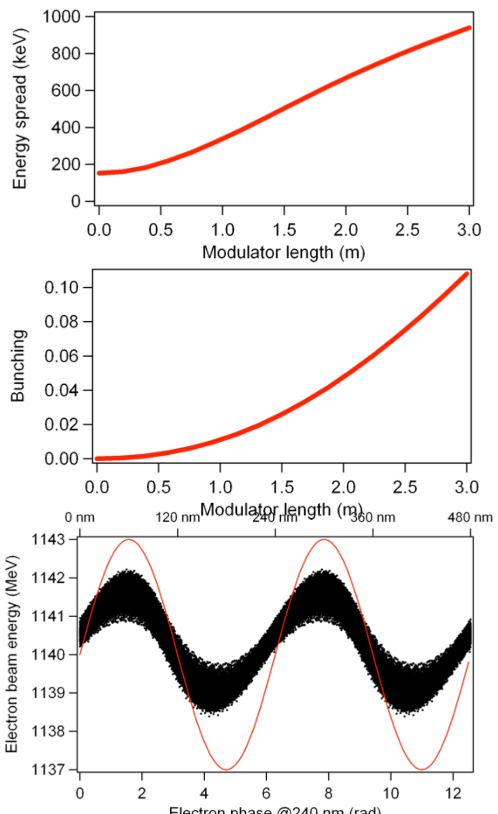


FEL-2, in order to be able to reach the wavelength range from 20 to ~4 nm starting from a seed laser in the UV, is based on a double cascade of high gain harmonic generation. The nominal layout uses a magnetic electron delay line in order to improve the FEL performance by using the fresh bunch technique.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

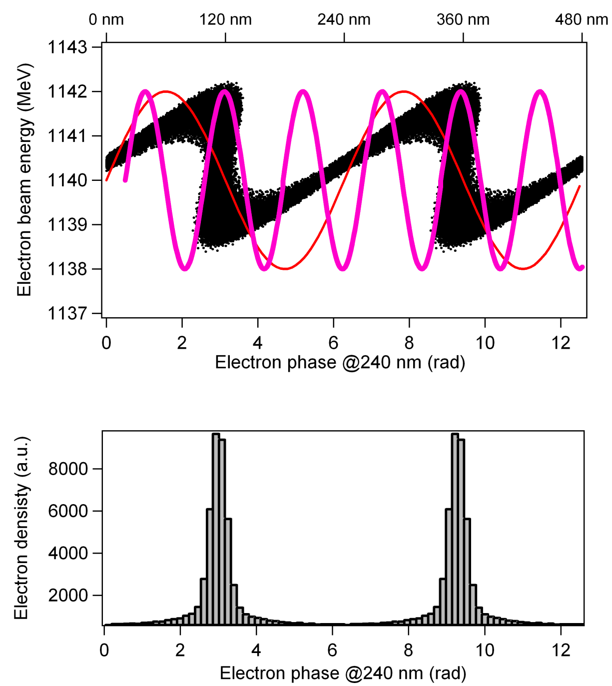
HGHG: FEL-1



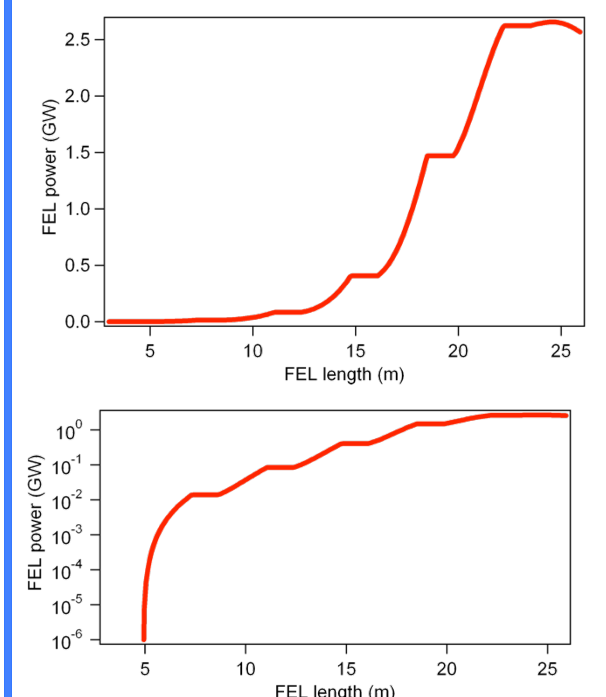
Modulator



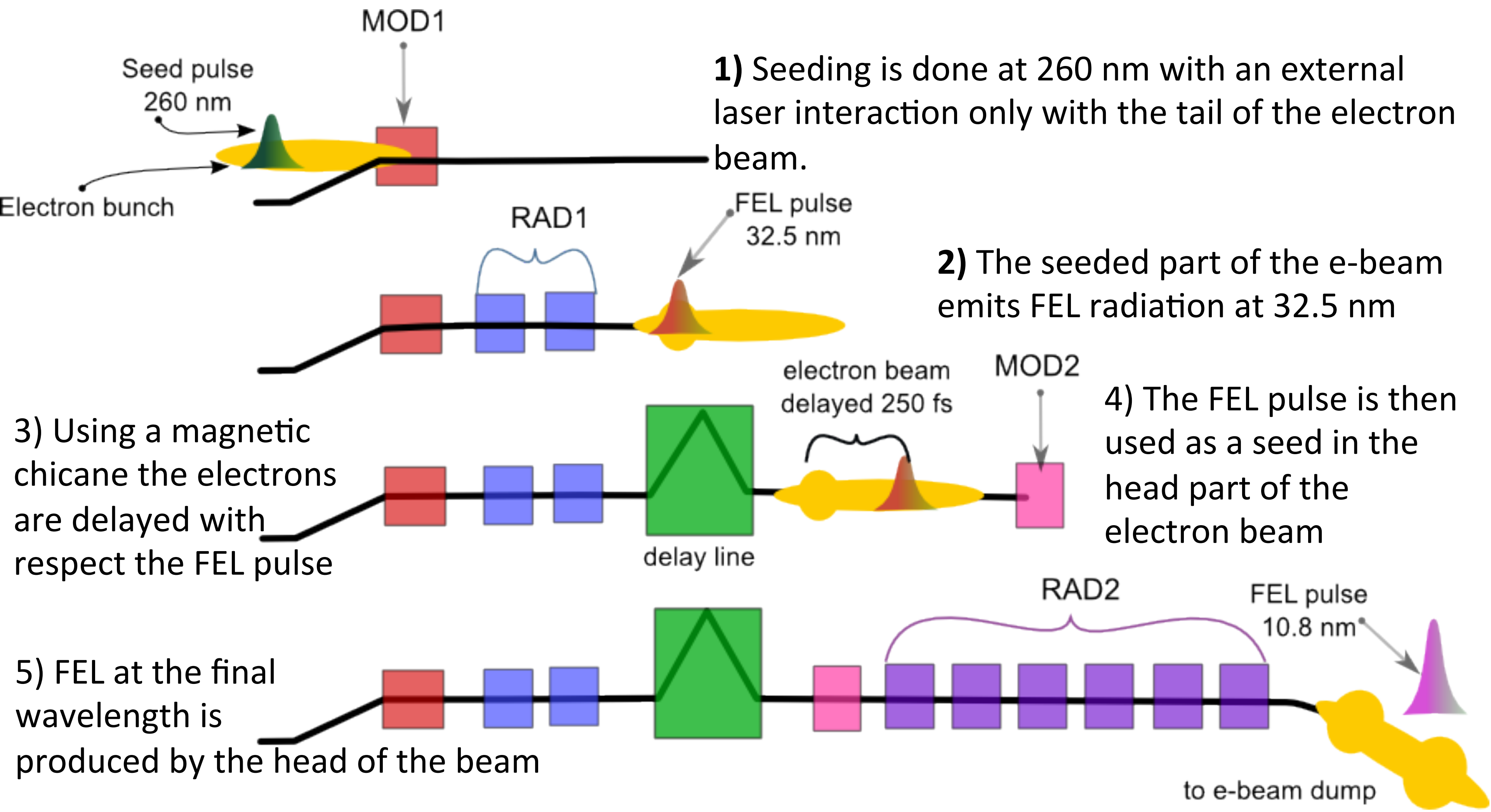
Dispersive section



Radiator



Fresh Bunch HGHG cascade: FEL-2



1) Seeding is done at 260 nm with an external laser interaction only with the tail of the electron beam.

2) The seeded part of the e-beam emits FEL radiation at 32.5 nm

3) Using a magnetic chicane the electrons are delayed with respect the FEL pulse

4) The FEL pulse is then used as a seed in the head part of the electron beam

5) FEL at the final wavelength is produced by the head of the beam

Critical issues for HGHG

In order to efficiently use HGHG to generate high quality EUV and soft X-ray FEL pulses starting from a laser pulse in the UV a lot of effort has to be done to optimize various components.

In addition to the usual requirements for a **high brightness beam**, HGHG also requires for:

- A well controlled electron beam lo**ngitudinal phase space**;
- Very good e-beam **energy stability**;
- A stable and controlled **tunable seed laser**;
- A very **low timing jitter**.

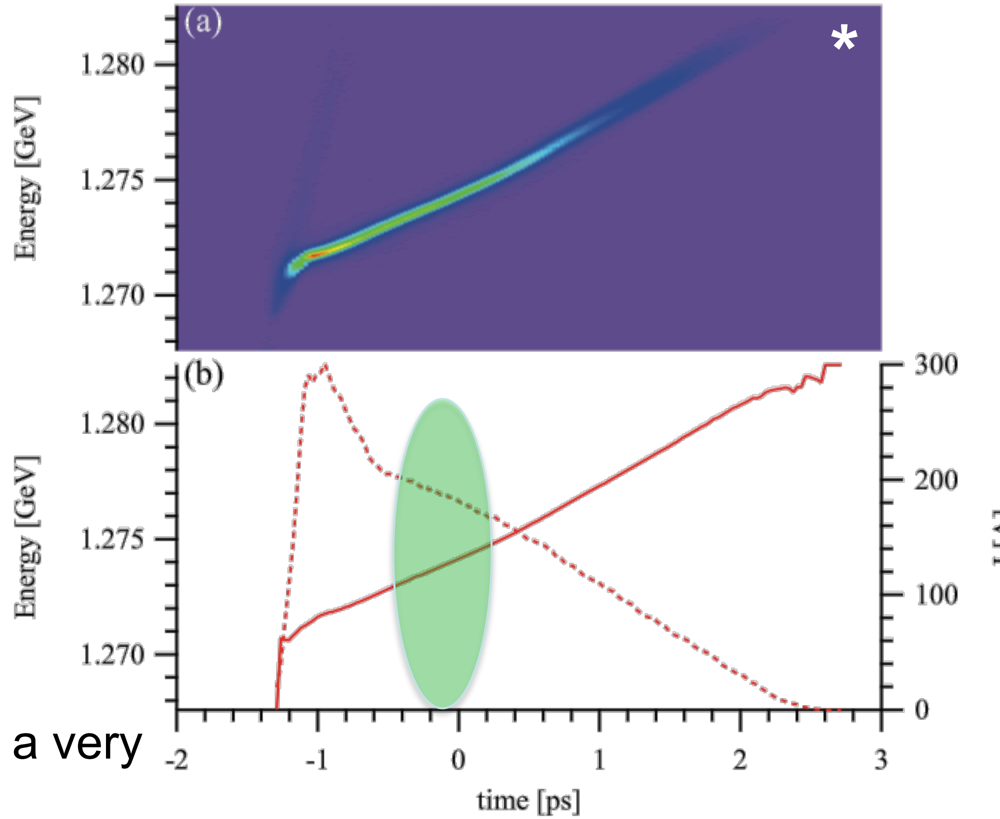
No X-band, chirped beam

First FEL operations started with an electron beam that was compressed without the X-band. Since current **spike** is **not useful for HGHG**, FEL operations started with a low compression.

Current profile is characterized by a **ramped** shape and a longitudinal phase space with **linear chirp** in the region useful for the seeding.

As a consequence of the **ramped current** profile, the **timing jitter** between the laser and the electron beam **induces FEL power fluctuations**.

The nice longitudinal phase space allows a very **good control** of the **FEL bandwidth**. As demonstrated by first operation of FERMI FEL-1

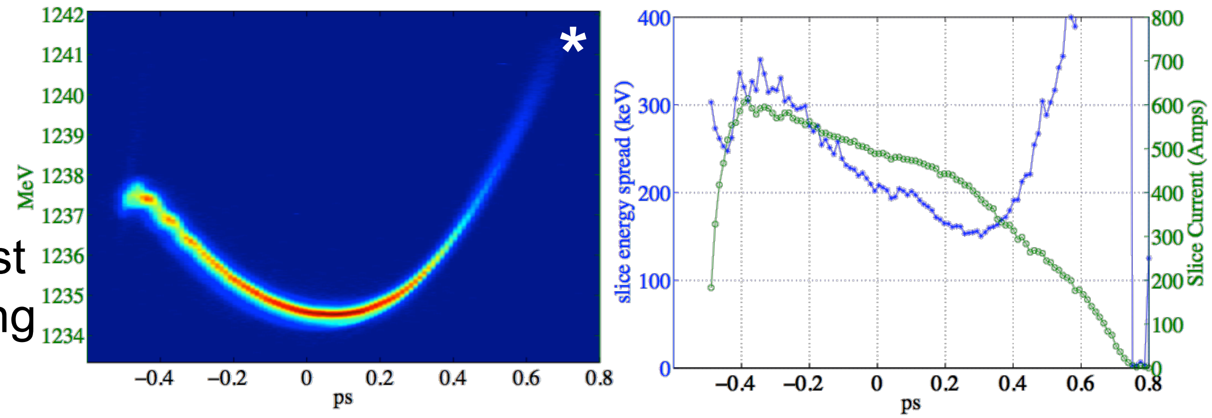


* C. Callegari et al. "Tunability experiments at the FERMI@Elettra free-electron laser", New Journal of Physics, **14** (2012).

Highly compressed beam with X-band

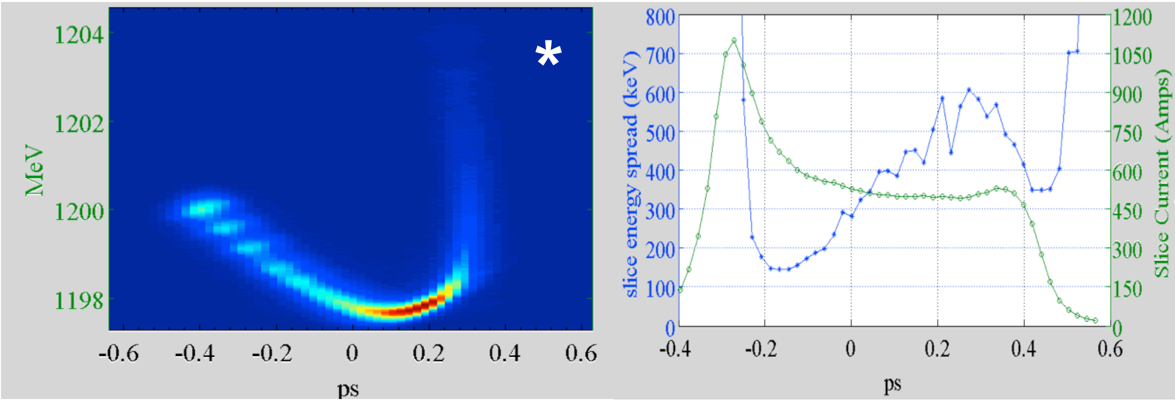
With the use of **X-band** to linearize the phase space at the **bunch compressor** it is possible to produce a **flatter electron** beam current profile. In these conditions easily one can be generate beams with about **500A** of peak current over a region of of the order of **400 fs**.

For such a high current beams it becomes very **important** the control of the **phase space**. Indeed, the **wakefields** in the last part of the linac produces a strong **quadratic chirp**.



By properly tuning the X-band and the RF phase of the last part of the linac it is possible to mitigate the effect of wakefield and reduce the quadratic chirp.

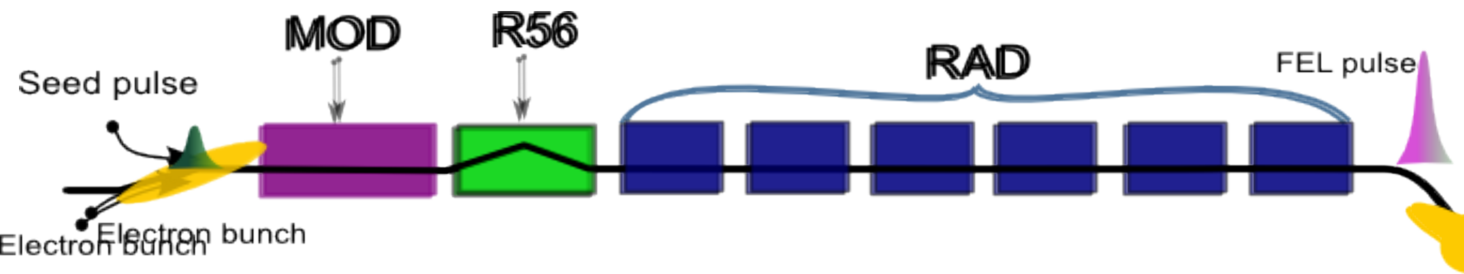
A **flatter electron** beam phase space could be achieved by using a **ramped current** profile at the **gun** and will be tested in the near **future**.

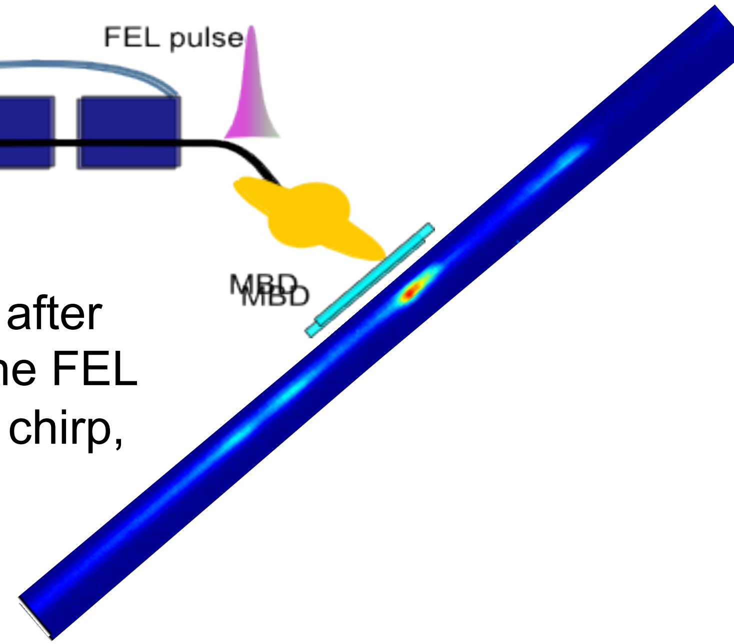


* G. Penco

Measurements of e-beam – seed timing jitter

FEL process is initiated by the seed laser interacting with the electron beam. The timing between the two is critical for having a stable FEL.





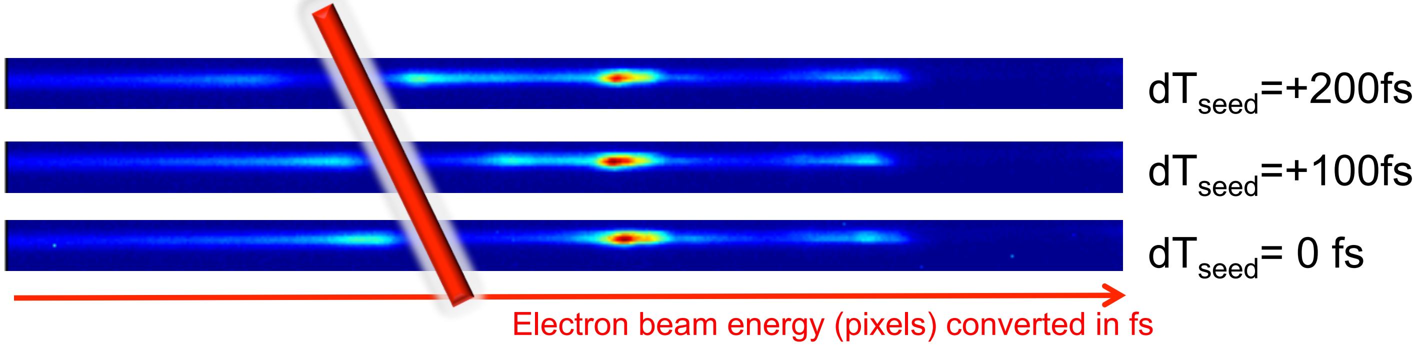
The YAG screen in beam dump electron spectrometer after the undulators can be used to look at the beam after the FEL interaction. When the e-beam has a linear longitudinal chirp, the energy in the YAG is correlated with time.

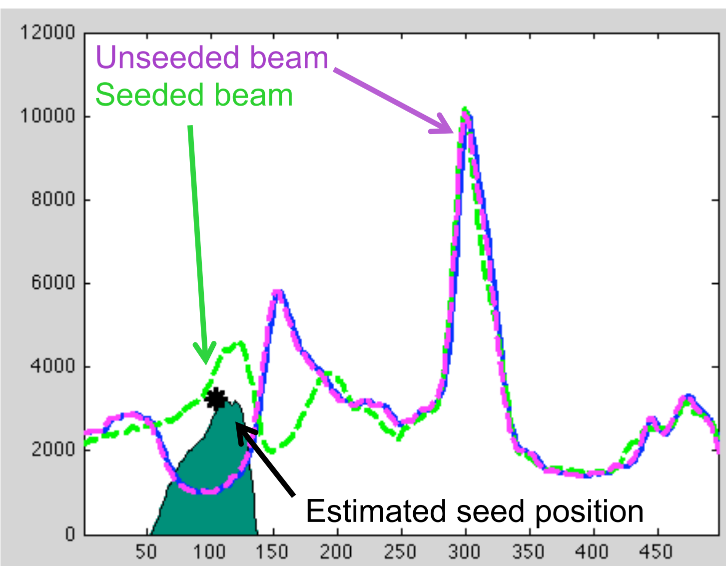
When the seeding is acting on the beam the energy distribution is modified in the interaction region.

We have demonstrated that using this signature of the seed on the beam it is possible to measure directly the timing jitter between the two.

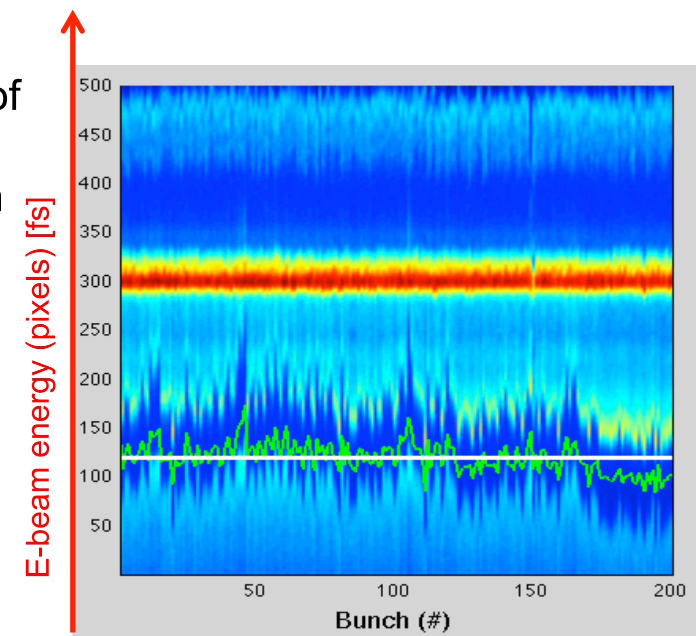
Calibration of the YAG screen

By measuring the position of the "seed signature" on the e-beam spectra changing the seed delay we can calibrate the system.





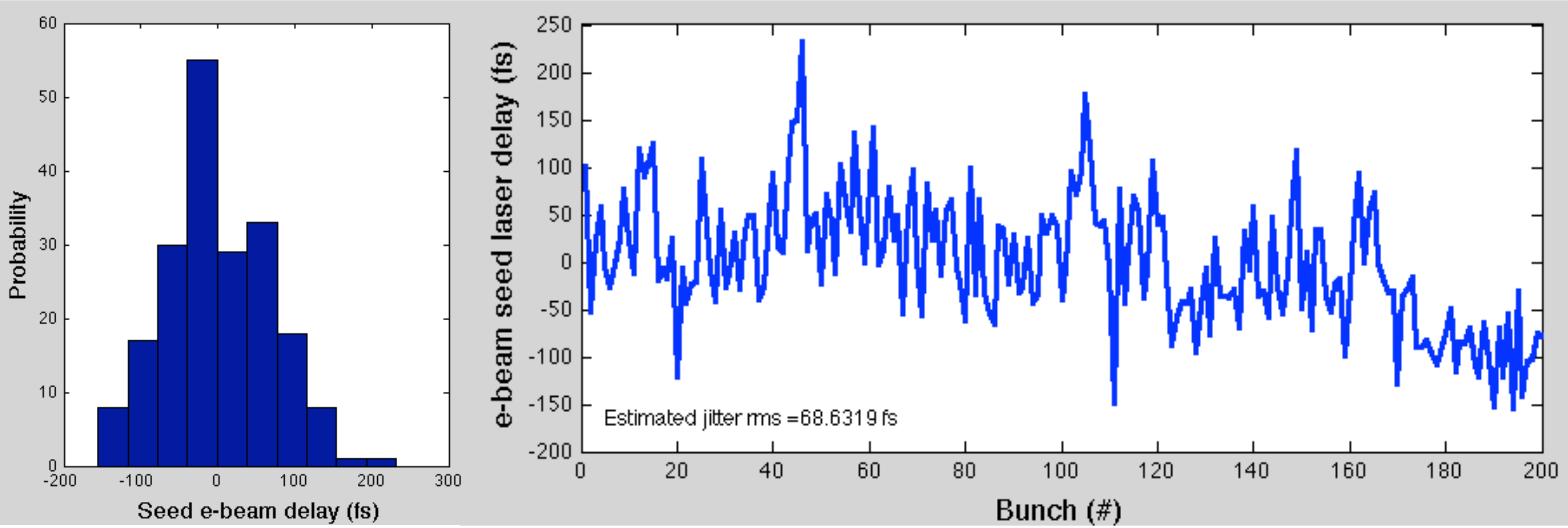
From a sequence of spectra we can follow the evolution of e-beam – laser timing.



A procedure has been implemented to detect the position of the seed laser from the difference between seeded and unseeded e-beam spectra

Direct measurement of e-beam – seed laser timing jitter

With this technique the a jitter below 70 fs has beam measured at FERMI in RUN12. This account for both the electron beam and seed laser jitters.



In RUN13 an optical locking system of the seed laser has been installed. The obtained improvement in the FEL stability suggests a reduced timing jitter that has not yet been measured with such a technique.
In case of a non chirped beam, similar measurements could be done using a deflecting cavity installed after the undulators.

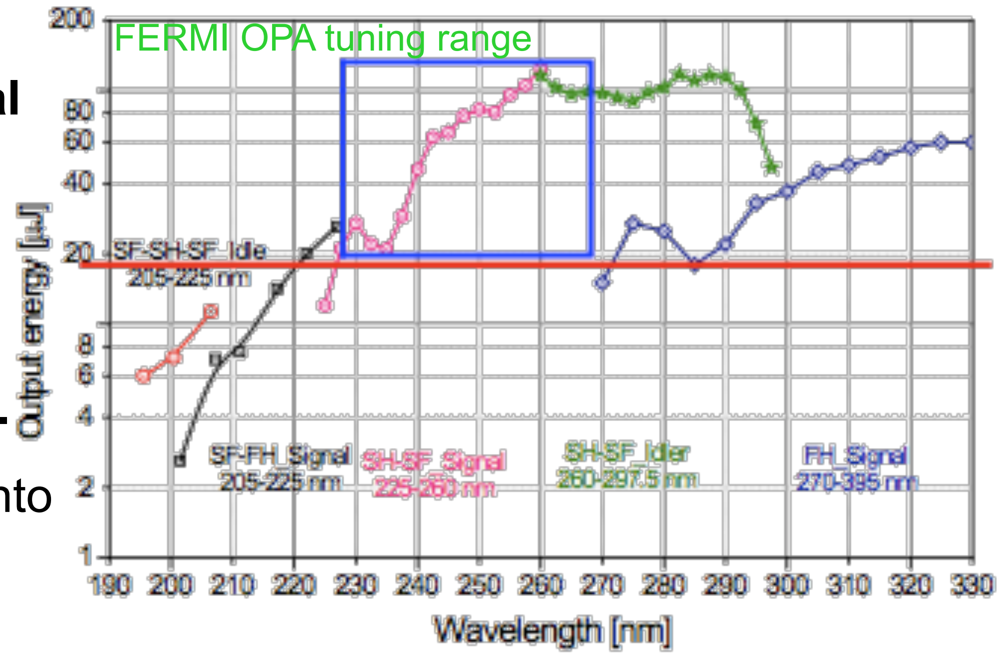
Seed laser

Tuning the FEL in **HGHG** configuration requires a **tunable seed laser**.
For **FERMI** the required tuning range is obtained using an **optical parametric amplifier**.

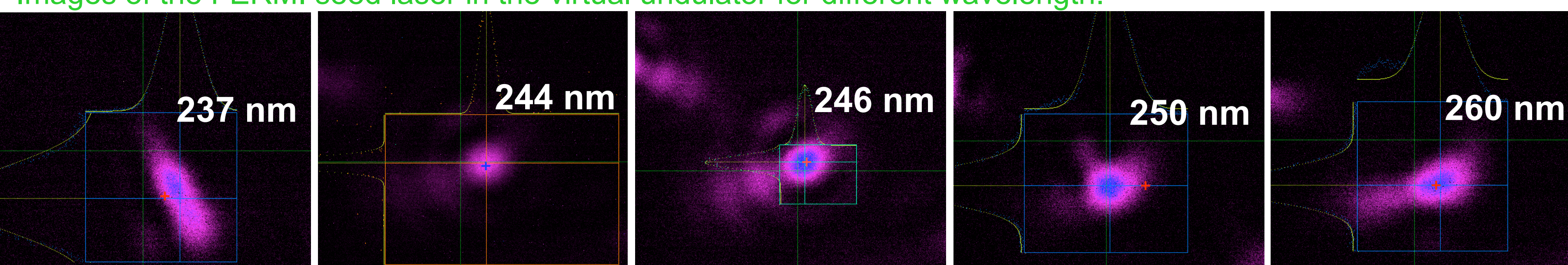
The difficulty of a tunable laser is not only related to the source but also to the **optical transport system** from the laser to the undulators that usually account several optical elements.

In the present version the FERMI **seed laser** can be used **from 230nm to 260nm.**

A good control of the seed beam arriving into the undulator in the whole tuning range is required.



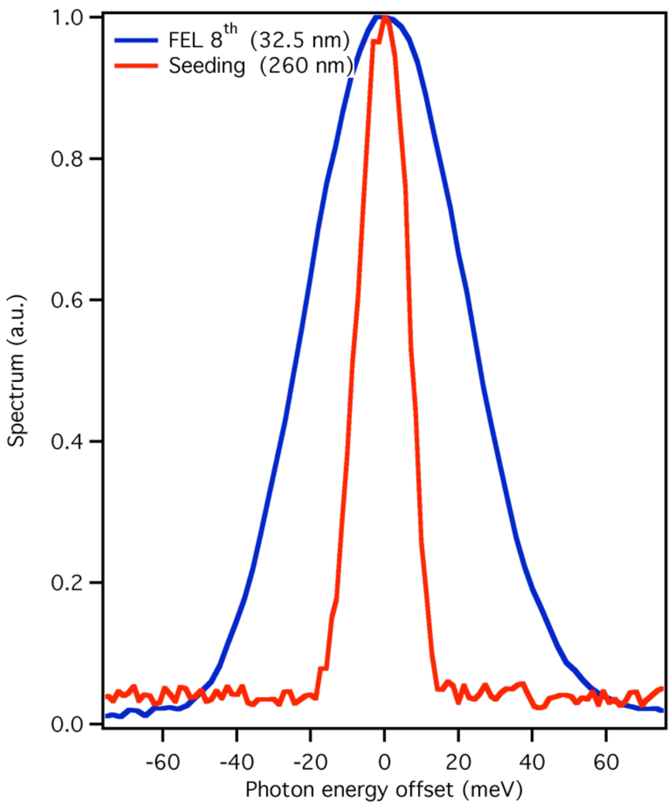
Images of the FERMI seed laser in the virtual undulator for different wavelength.



FEL-1 results: spectral properties

Direct benefit of starting the process from an external laser is that the bandiwdth of the FEL is mainly determined by the one of the laser.

Measured **relative bandwidth** of the FEL is **smaller** than the one of the **seed laser**. In the **frequency** the **FEL spectrum is** slightly **larger** than the one of the seed laser.



$$\sigma_{rms}^{SEED} = 4.7meV(0.098\%)$$

$$\sigma_{rms}^{FEL} = 14meV(0.038\%)$$

Since we expect the **FEL pulse** to be **shorter** than the seed laser the spectrum broadening does not necessary implies a degradation of the **longitudinal coherence of the FEL pulse**.

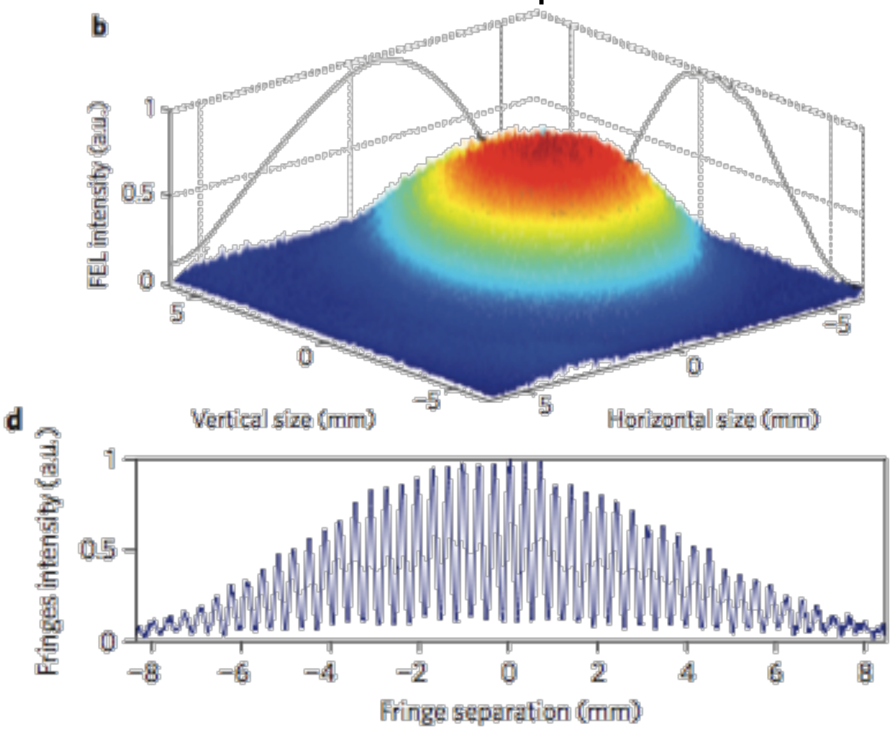
Considering the **pulse shortening** predicted by theory for the 8th harmonic we can estimate tat FERMI FEL pulses are **close to the Fourier limit** and have a good longitudinal coherence.

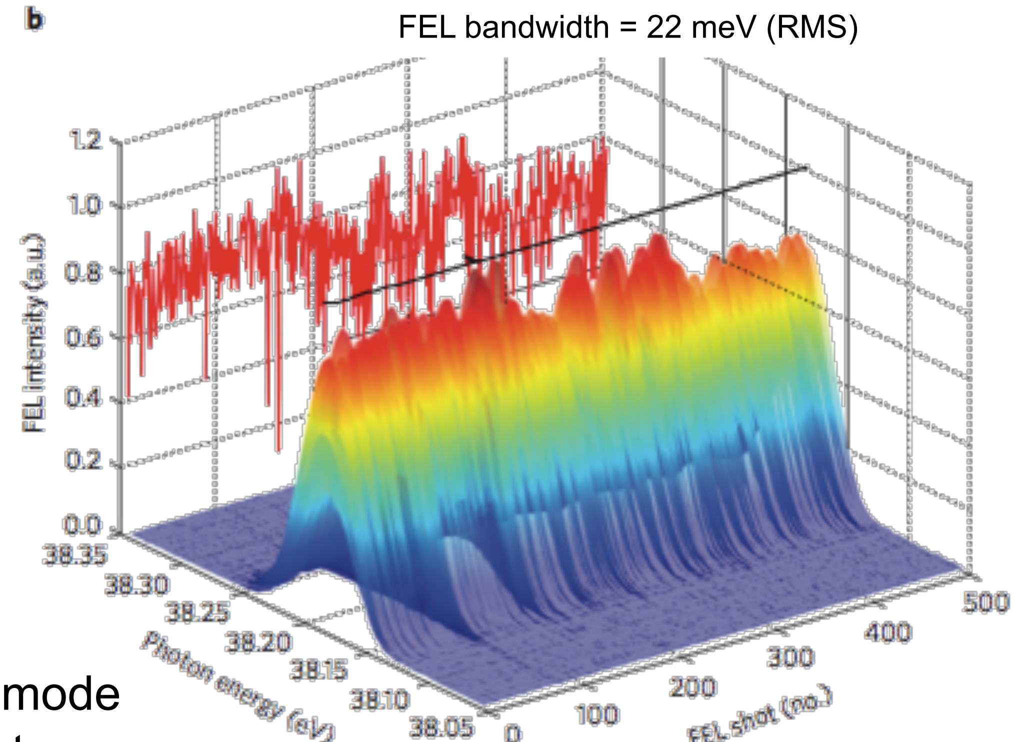
Spectral stability and mode quality

In addition to the narrow spectrum FERMI pulses are characterized by excellent spectral stability. Both short and long term measurements show that the spectral peak can be stable within less than 1 part in 10^4.

FEL photon energy ~ 38.19eV
fluctuations = 1.1meV (RMS)
fluctuations = 3e-5 (RMS)

FEL bandwidth = 22 meV (RMS)

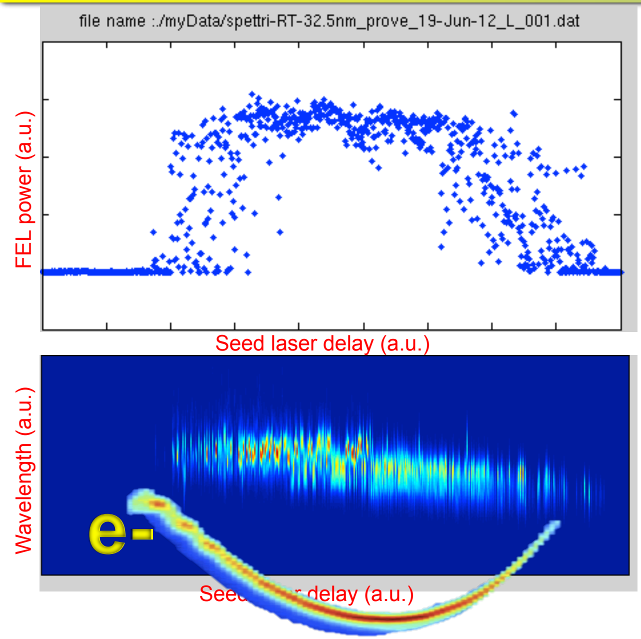




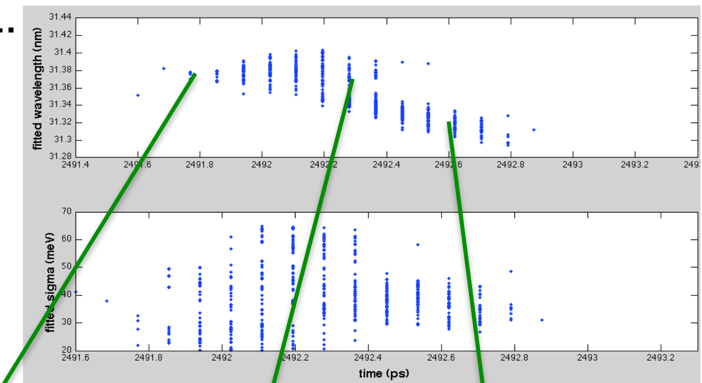
The **transverse** spatial **mode** has been measured to be very close to the **TEM00** mode and also coherence measurements indicate a very **high degree of transverse coherence**.

"Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet", E. Allaria et al., Nature Photonics **6**, (2012)

Spectral properties affected by e-beam phase space



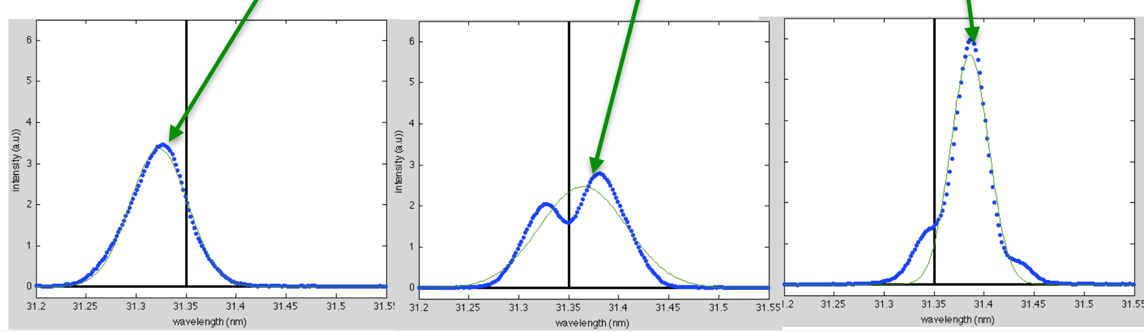
By measuring the **FEL spectra** as a function of the seed **laser delay** we can look at the **effects** of the **e- beam phase space** into the FEL.



For this kind of e- beam, compressed with the x-band) we started to see more clearly the FEL **wavelength shift** and **bandwidth increase**.

When the seeding is placed on the minimum of the of the electron beam energy the tail and the head of the seed see a different electron beam chirp and the FEL spectrum is splitted.

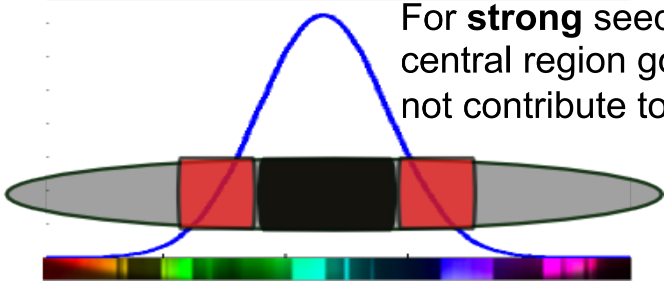
When a nonlinear chirp is present in the beam it is necessary that FEL optimization is done by carefully looking at spectra and not only at FEL power.

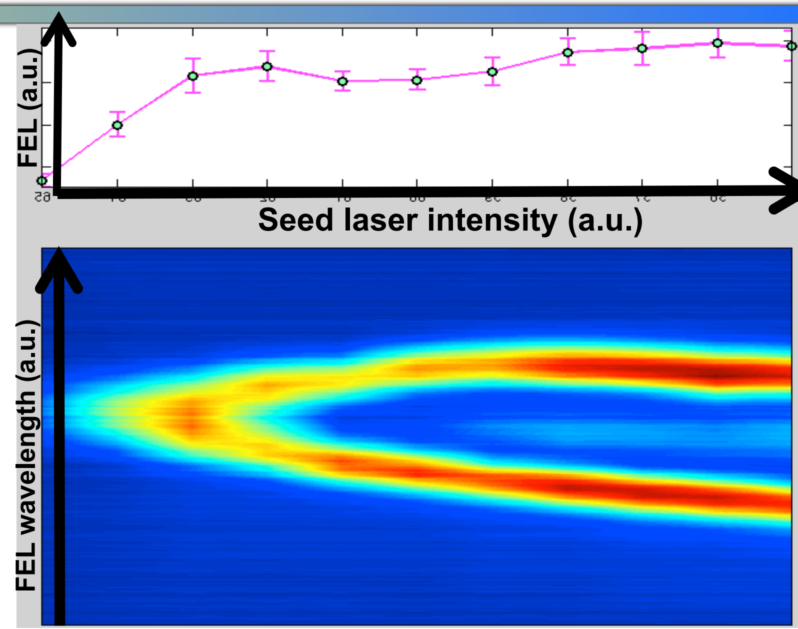


FEL pulse control

In HGHG only electrons that see **optimal seed intensity** contribute to FEL

For **strong** seeding, electrons in the central region go in **overbunching** and do not contribute to amplified FEL radiation*.



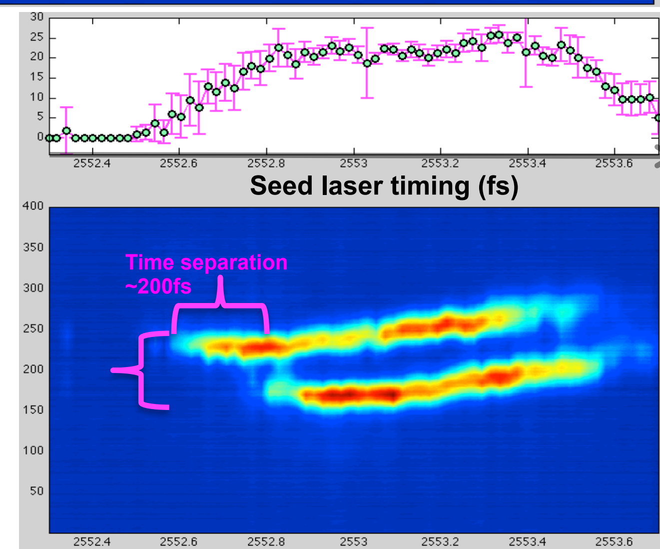


Seeding with a **chirped laser** allows to produce two **FEL pulses separated in time and spectrum**. Time and frequency separation can be controlled acting on the seed laser and on FEL parameters**.

Recently the combined spectral and temporal separation of the two pulses has been **experimentally demonstrated at FERMI**.

Limitation for this scheme is the temporal separation that can not be much longer than the seed pulse length.

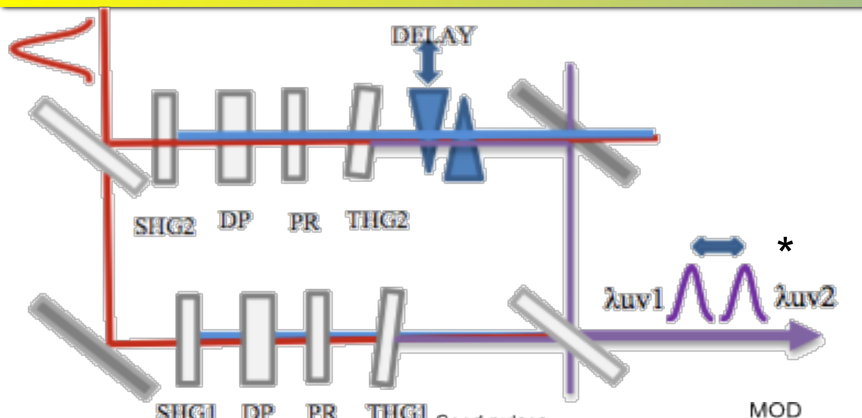
A different approach is to seed the electron beam directly with two FEL pulses. This has been successfully implemented at FERMI.

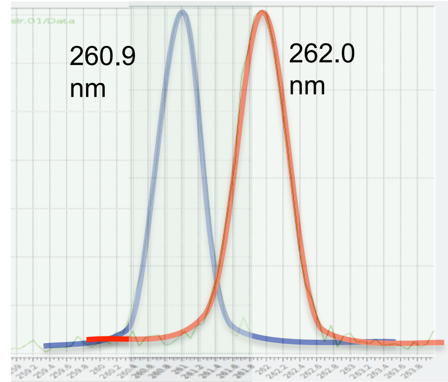


(*) "Pulse Splitting in Short Wavelength Seeded Free Electron Lasers", M. Labat et al., Phys. Rev. Lett. 103, 264801 (2009).

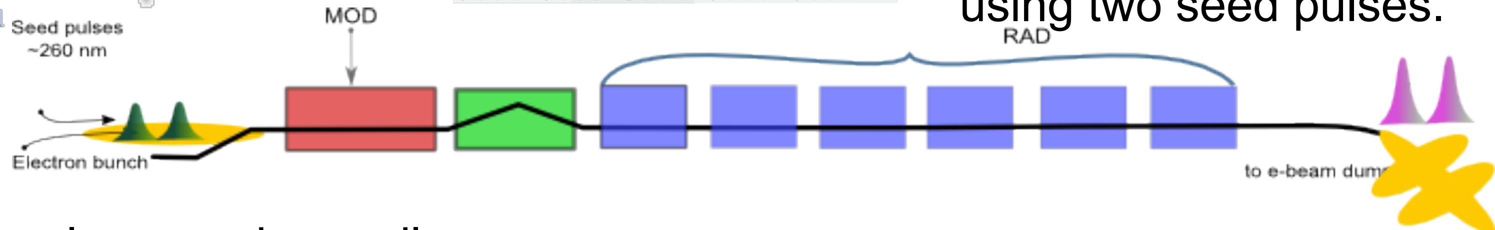
(**) "Chirped seeded free-electron lasers: self-standing light sources for two-colour pump-probe experiments" G.De Ninno et al. sub to Phys. Rev. Lett.

Double seeding



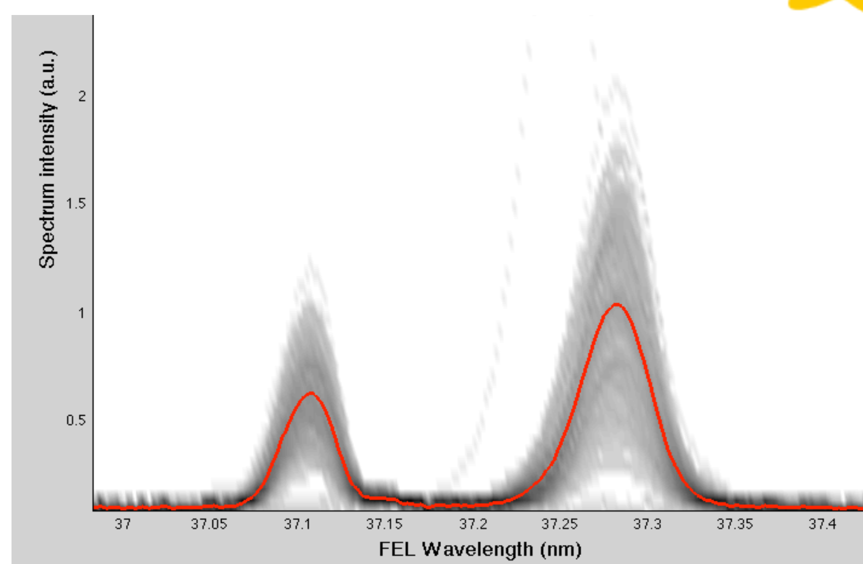


In order to allow a wider temporal separation between the two pulse required by one of the FERMI user we also implemented a scheme using two seed pulses.



Delay between two pulses can be easily controlled and also the two wavelengths can be slightly different.

Pump laser at 37.3 nm, proble laser at 37.1. Relative FEL intensities can be controlled by FEL tuning



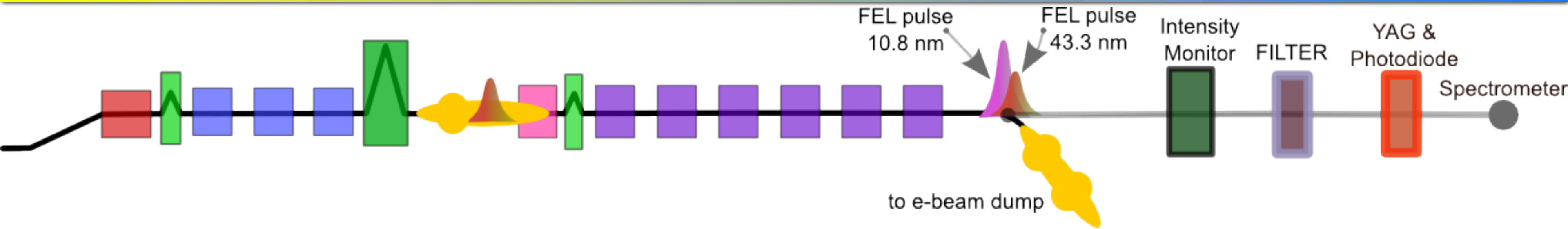
* M. Danailov

FEL-2

- First photons from first stage, May 2012;
- Attempt to operate the second stage, October 2012;
- Evidence of HGHG double stage at 1GeV with fresh bunch;
- Optimization of second stage at 14 nm and 10.8nm;
- Shortest wavelength require higher electron beam energy.

1st Stage (n)	2nd Stage (m)	Final λ (nm)	
x6	x3	14.4	Initial configuration
x6	x4	10.8	Main studies
x8	x3	10.8	Main studies
x12	x2	10.8	Dem. of high order in 1st stage
x4	x6	10.8	Dem. of high order in 2nd stage

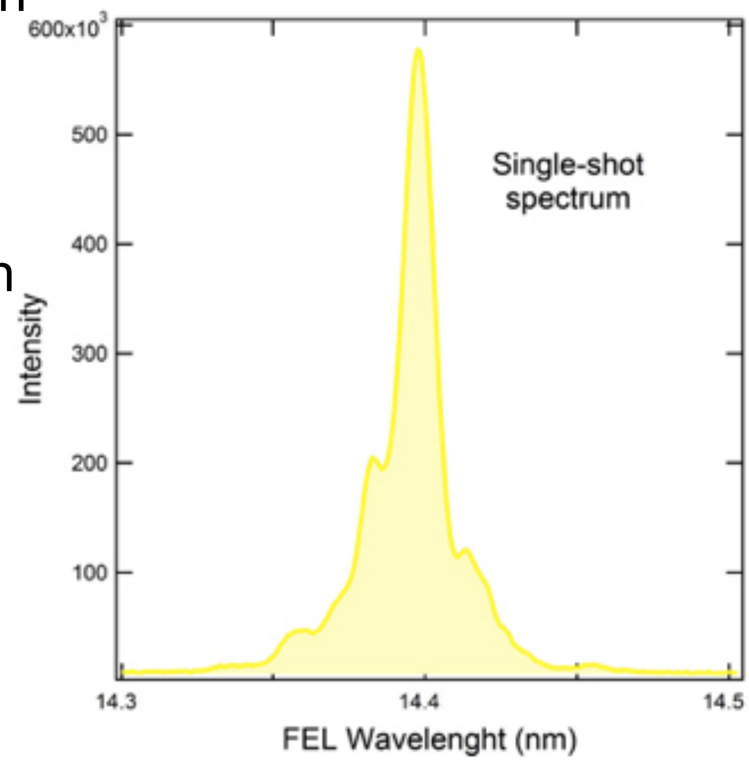
FEL fresh bunch operation



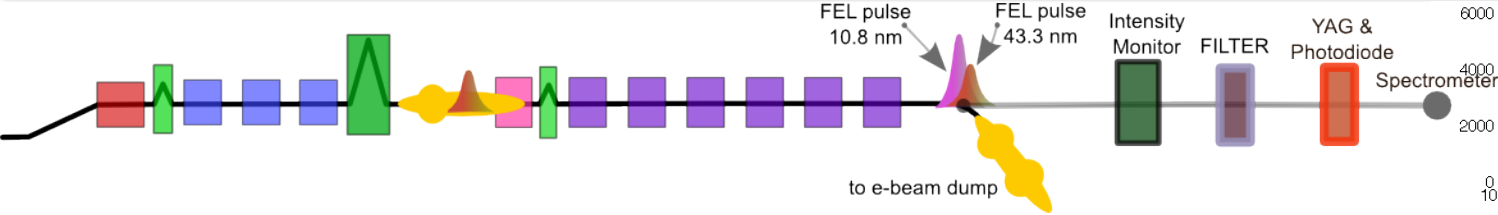
Optimized the electron beam and aligned the FEL and diagnostic looking at the first stage radiation at 43 nm.

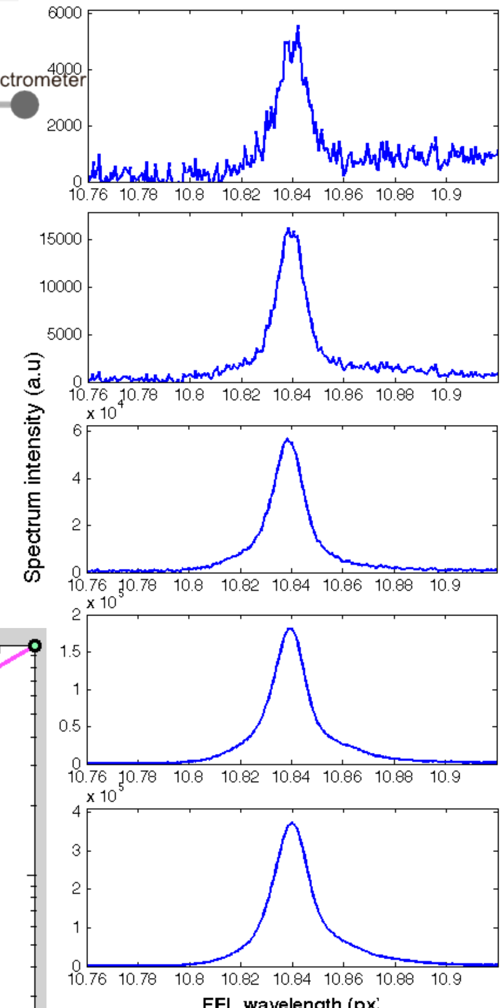
Operate the second stage radiator at 14 nm in single stage and two stage cascade HGHG with fresh bunch.

After some optimization we have been able to measure single shot spectra at 14 nm and few days after at 10 nm.



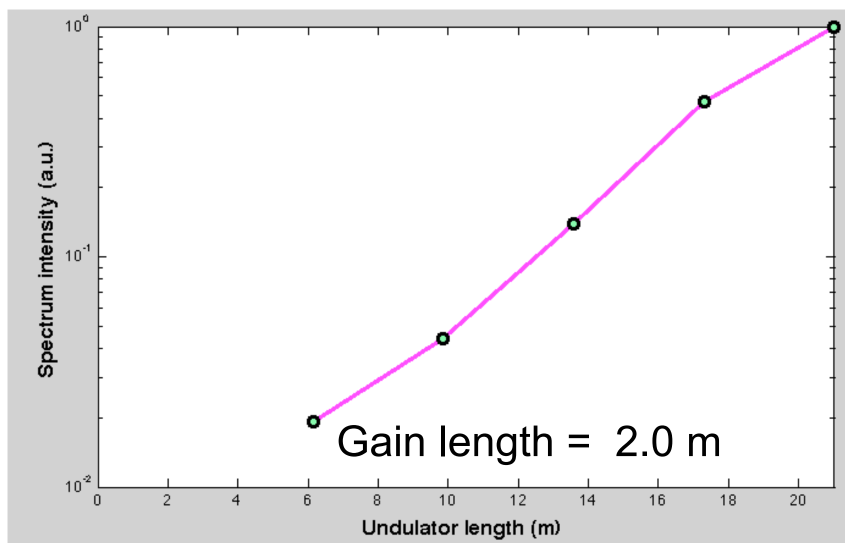
Exponential gain in second stage



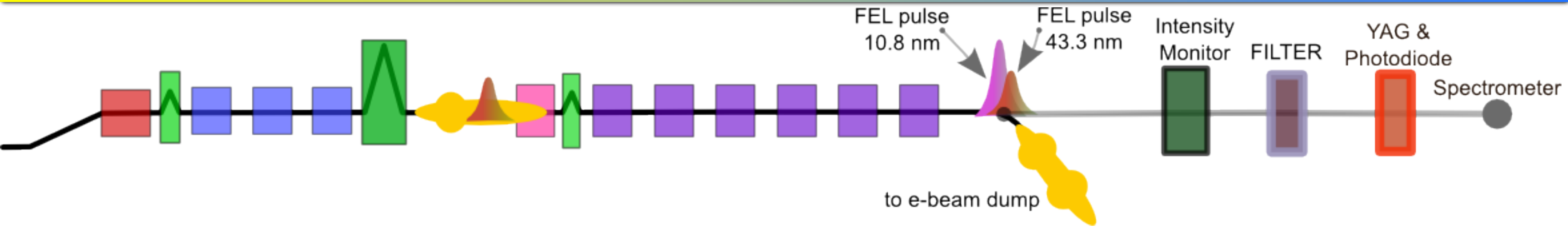


The exponential growth of the power on the second radiator has been measured both looking at a YAG after a filter that stops the first stage radiation and at the spectrum intensity.

Measured gain length can vary significantly depending on the optimization of the FEL configuration.



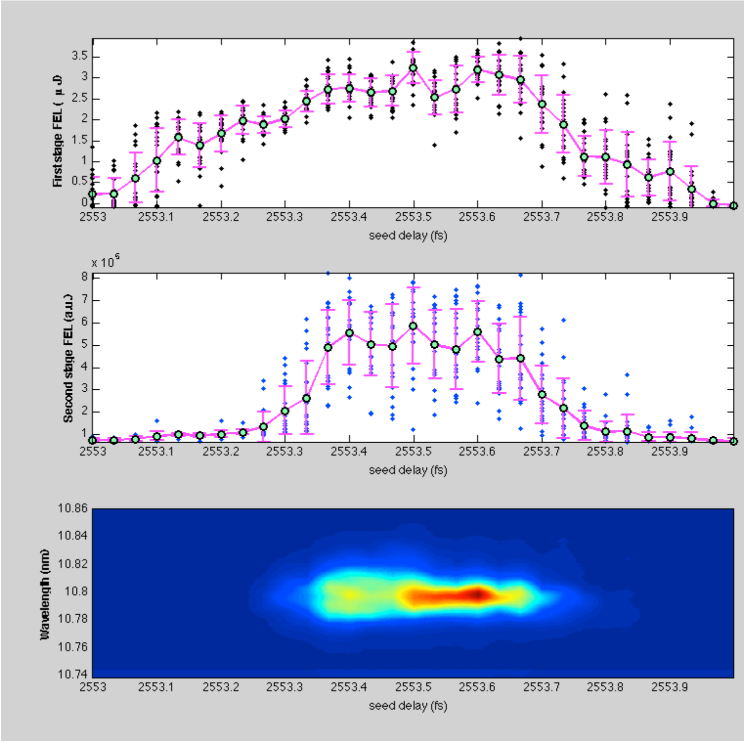
First stage and second stage lasing



Using intensity monitor and the photodiode after the filter it is possible to measure simultaneously the power from the first and the second stage.

By measuring the two signal as a function of the delay we recognize features of the fresh bunch.

The delay scan show a large range for the first stage while emission from the second stage is limited to a narrower region.

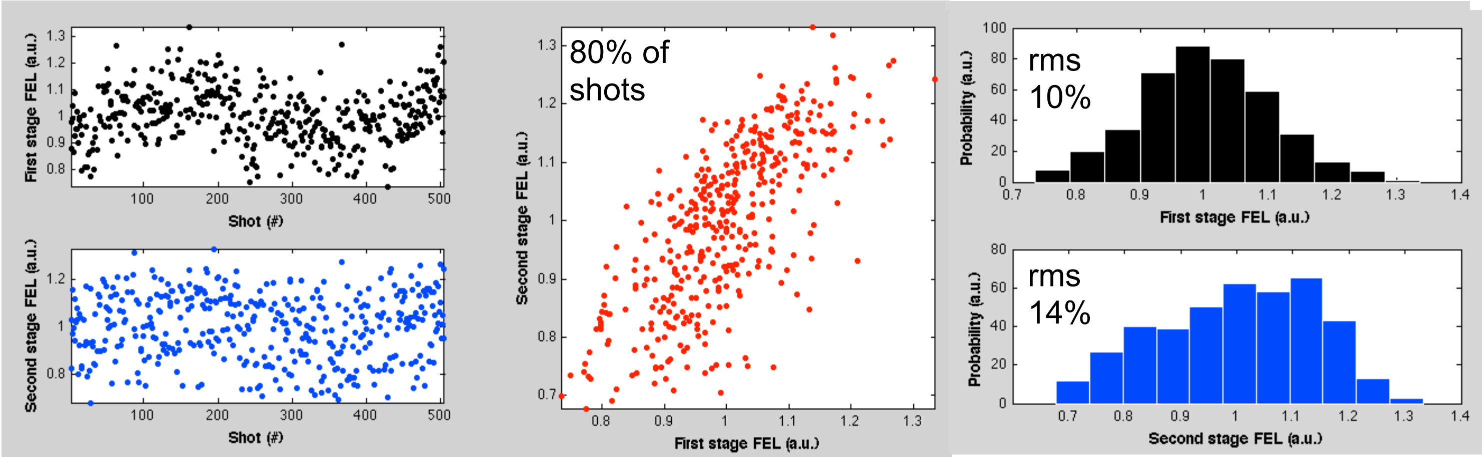


FEL-2 stability

Using the FEL diagnostic we can measure at the same time the radiation produced by the first stage at 43 nm and the one produced by the second stage 10.8nm.

Data show a sort of linear correlation between the first and second stage FEL intensities.

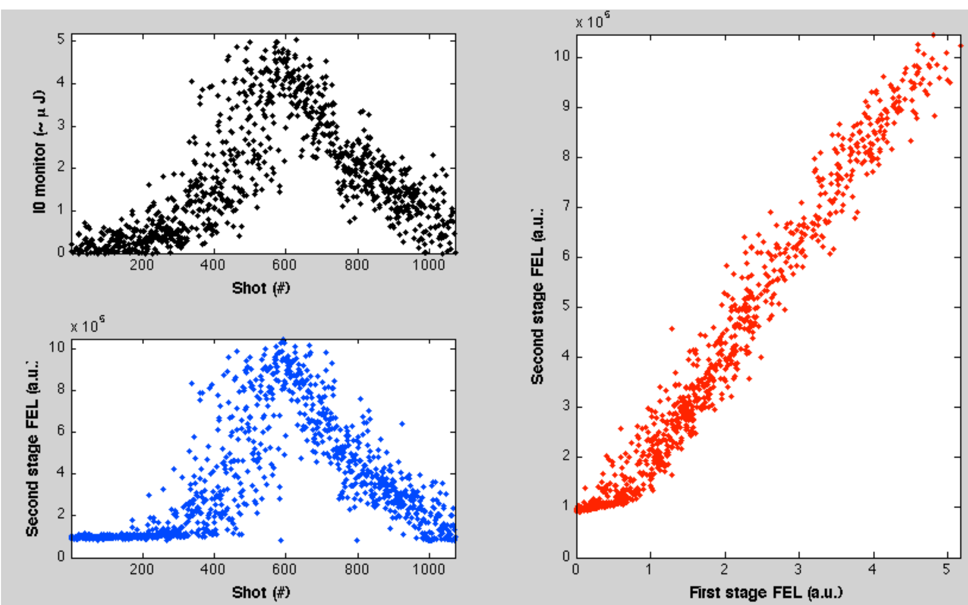
Filtering out the worst 20% of the shots the correlation is more clear and also the amount of jitter in the output power is similar for both the first and the second stage.

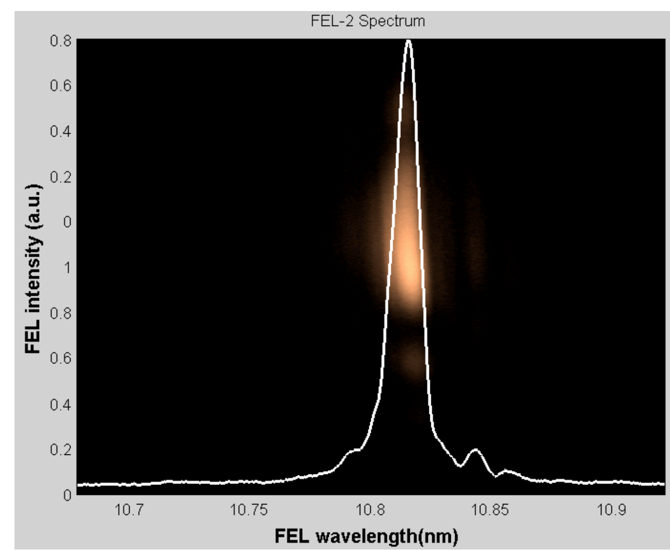


These data refer to the case of 260 → 43 →10.8 nm. In this configuration the power from the first stage is more than enough for seeding and it is generally needed to keep it down to maximize the power from the second stage.

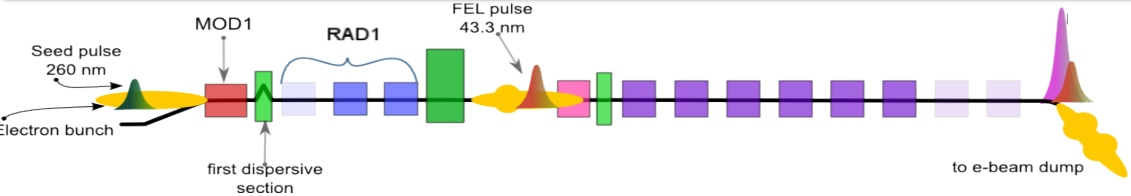
260nm →21.7nm →10.8nm

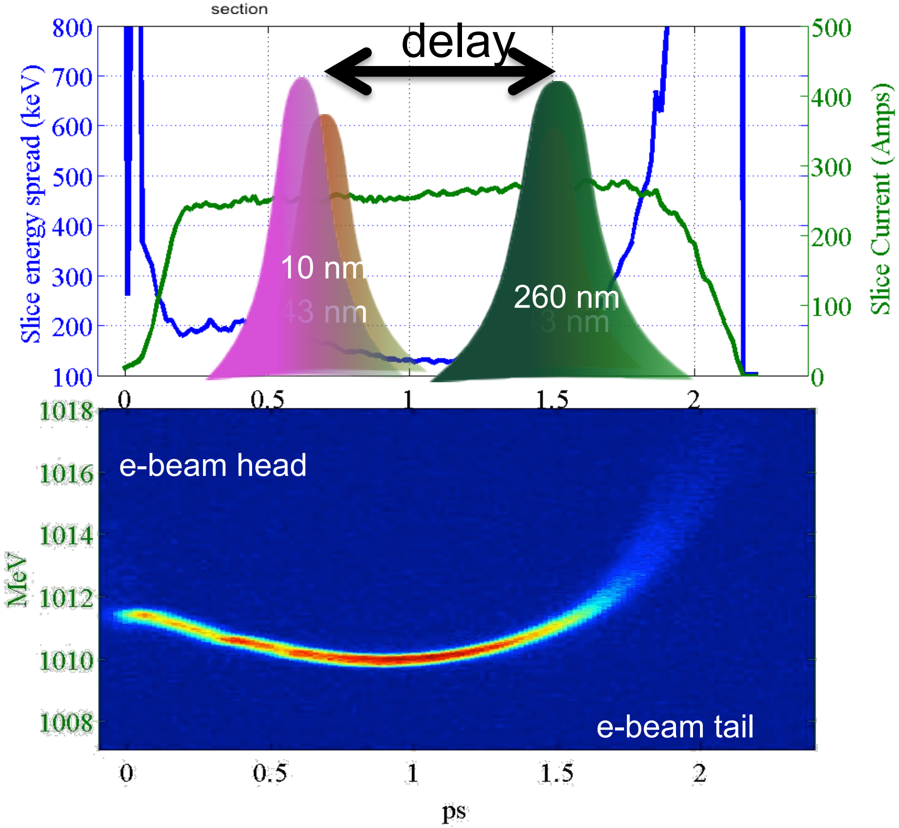
We have been able to operate the second stage at 10.8 nm also pushing the first stage to very high harmonics (12).
In this configuration most of the harmonic conversion is done on the first stage that become more critical.
The seed delay scan here show a stronger correlation indicating that it could be possible to improve the second stage performance by having a longer radiator in the first stage.
Nevertheless we have measured signal at the level of tens of μJ also in this configurations with a good spectra.

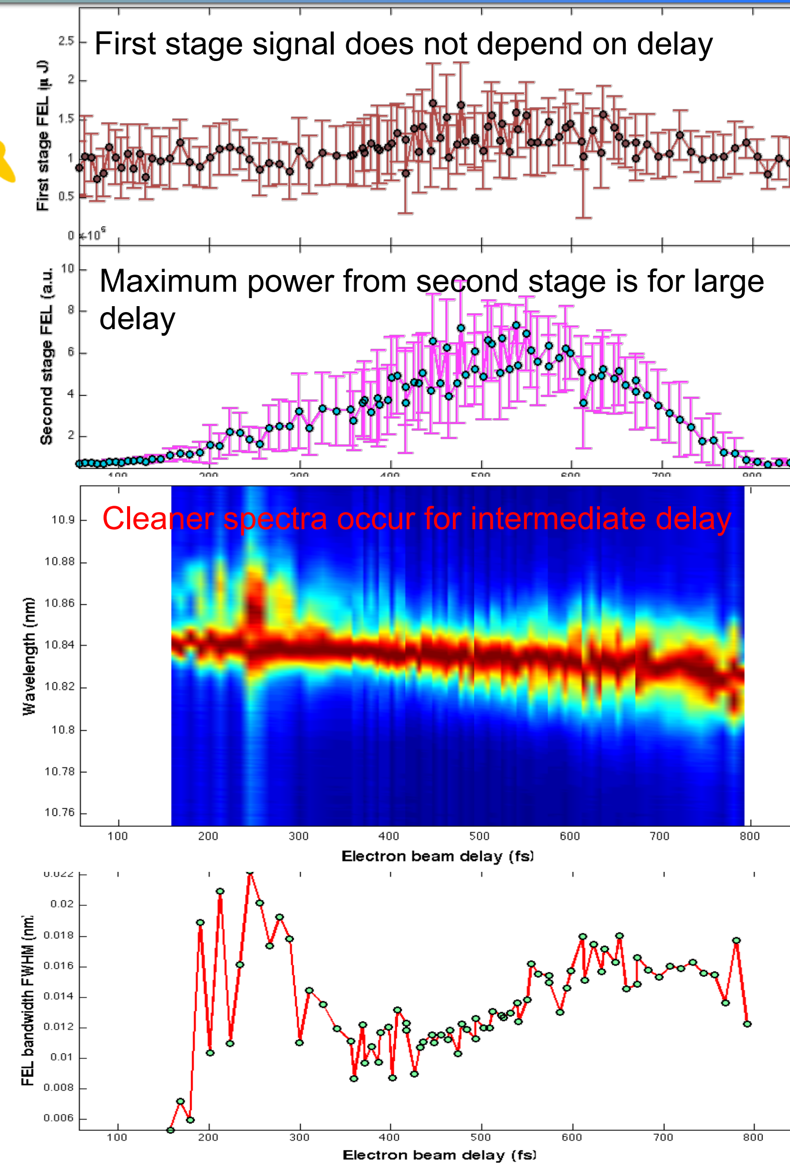




Effect of fresh bunch delay





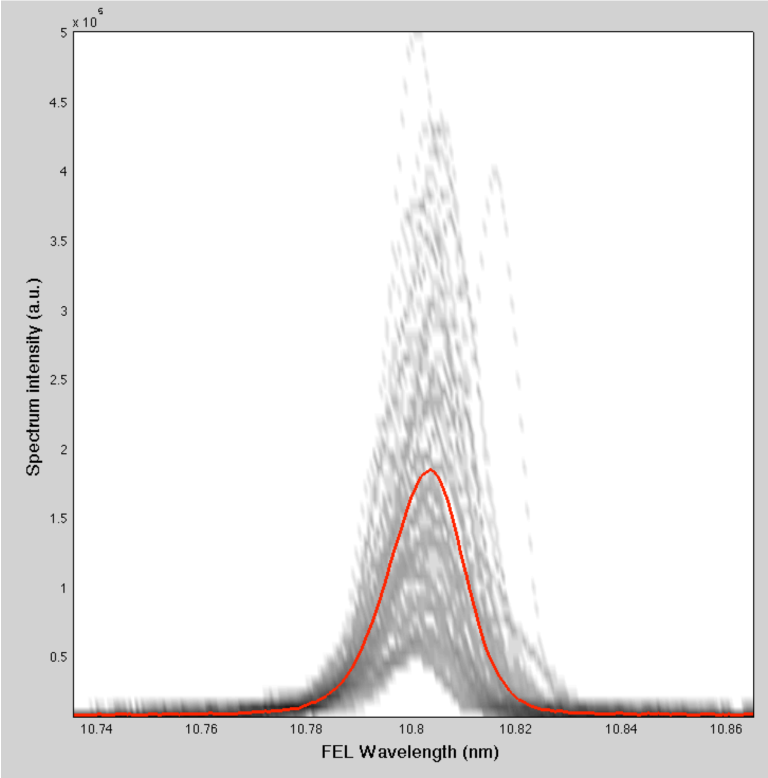


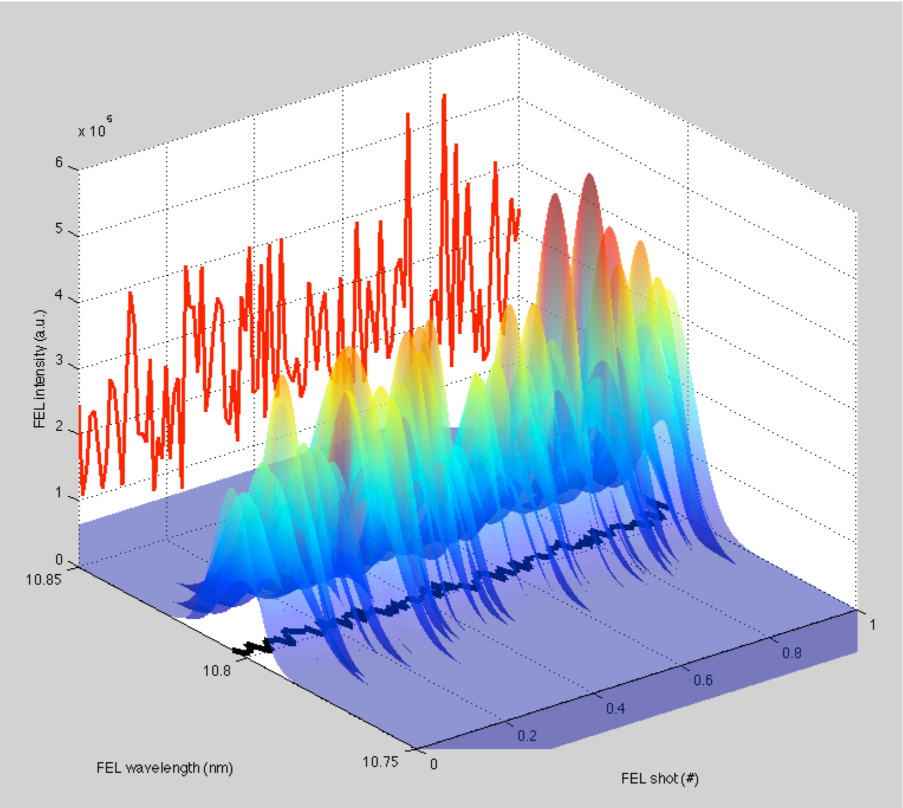
- Seed laser is placed as much as possible toward the tail of the bunch.
- For short delay the e beam is still affected by the process occurred in the first stage (low signal bad spectrum)

FEL-2 spectral stability

Spectral stability of second stage can depend on the FEL setting. In good conditions we have measured pulses with stable and good spectra.

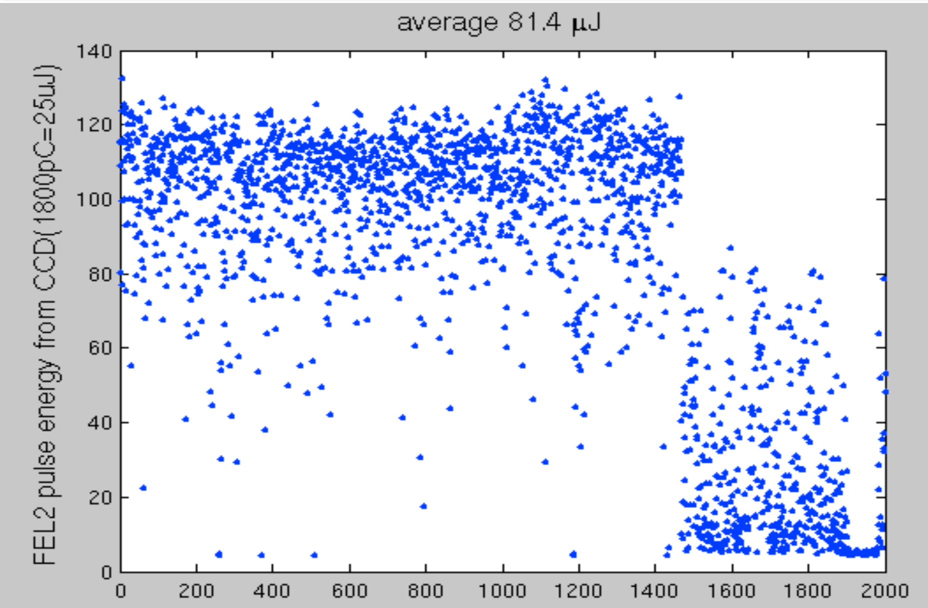
In these conditions the measured FWHM bandwidth is about 150 meV at 10nm (1.5e-3). Fluctuations are smaller than the bandwidth (6.4e-4).

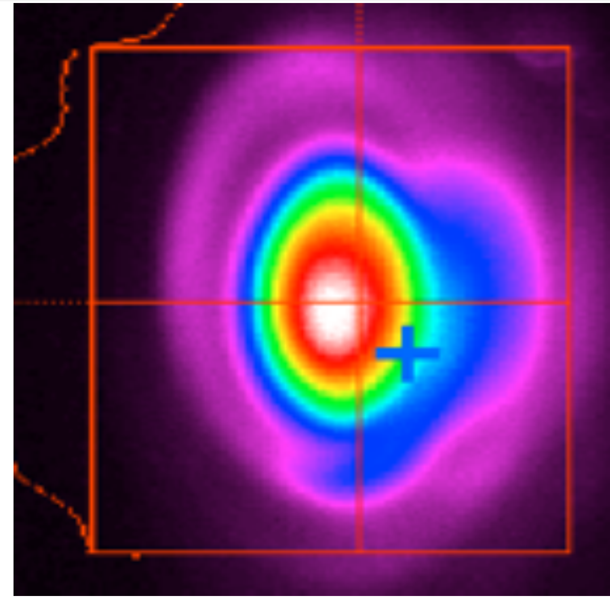




Further improvements for the wavelength stabilization requires an improvement of the longitudinal phase space of the electron beam.

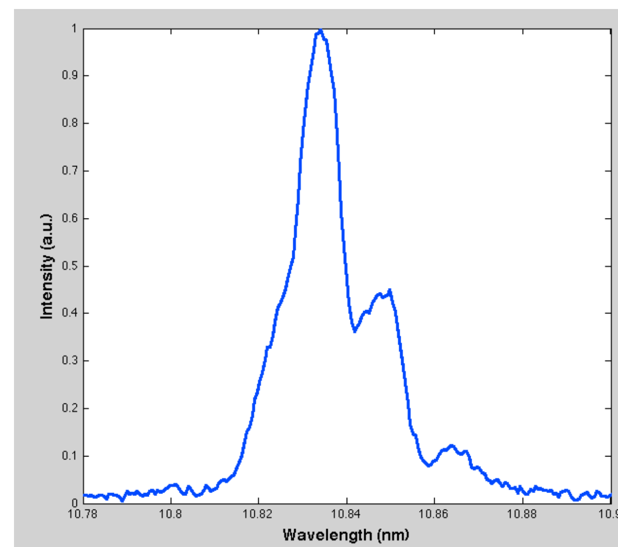
Increasing the FEL-2 power





By optimizing the FEL for maximum power and not looking at keeping the spectrum single mode it has been possible to increase the output power at 10 nm up to more than 100 µJ.

Although this configuration has a larger spectrum that the transvers mode is still very good and could be a possible configuration for experiments that are more interested to the photon flux than to the longitudinal coherence.



Conclusions

- Both FERMI FELs have been operated showing the capability of HGHG to produce high quality FEL pulse.
- Single stage HGHG has been efficiently operated down to ~20 nm.
- Double stage HGHG has been demonstrated to be able to extend the tuning range down to 10 nm and further extension is expected when higher electron beam energy will be available.