Spectral characterization of the FERMI pulses in the presence of electron-beam phase-space modulations

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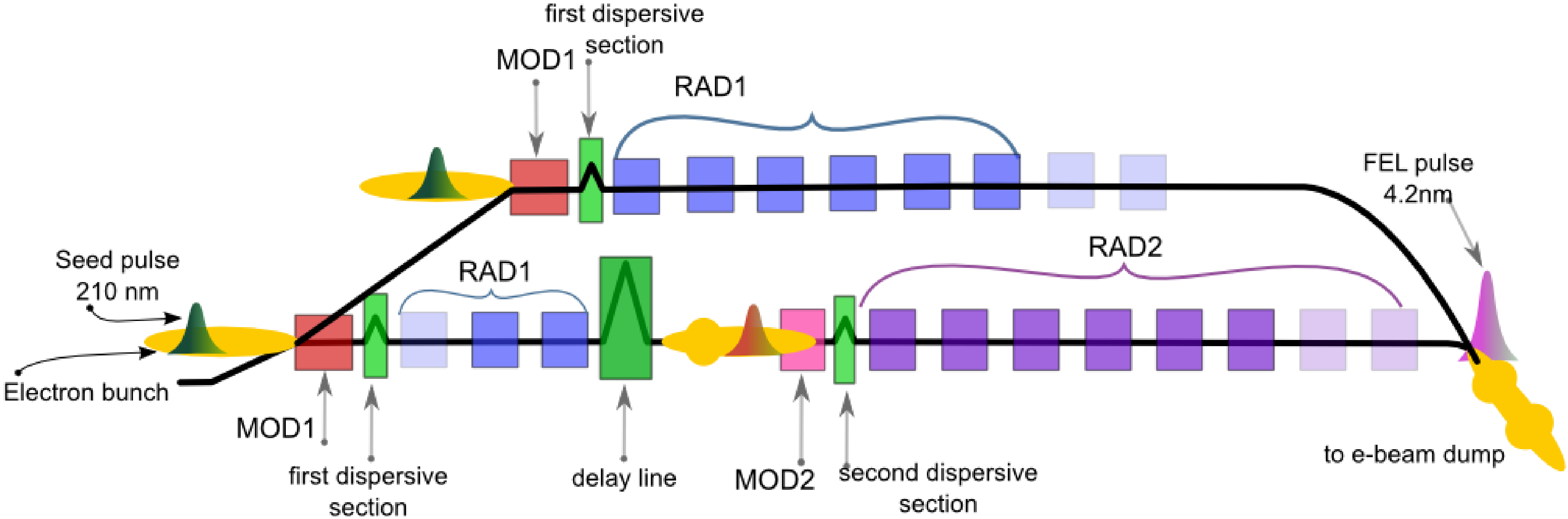
Outline

- HGHG FEL and FERMI FEL-1
- Effects of electron beam longitudinal phase space on the HGHG process
- Experimental FEL spectral measurements at FERMI
  - Linearly chirped electron beam
  - Microbunched electron beam
  - Quadratically chirped electron beam
- Conclusions

FERMI FELs

The two FERMI FELs cover different spectral regions; FEL-1 designed for 80-20 nm, FEL-2 for 20-4nm.



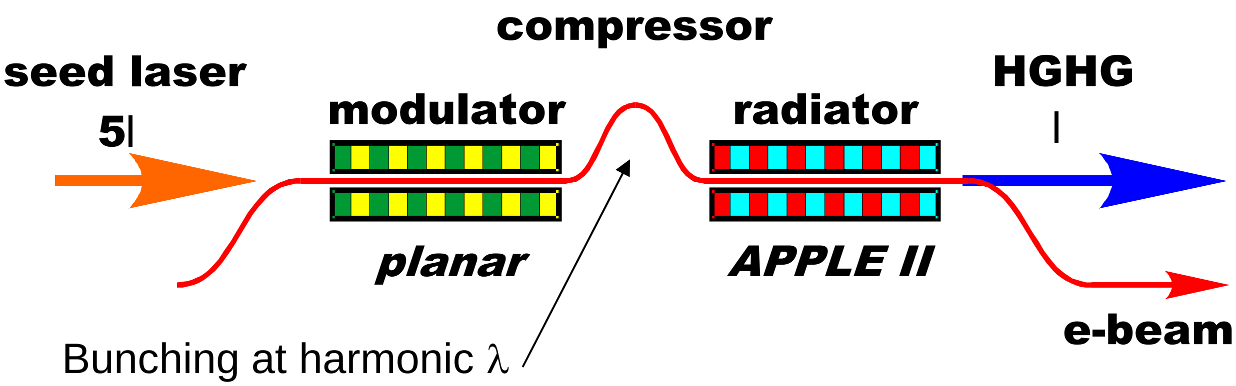
FEL-1 is in operation since December 2010. In the first year of operation (no x-band, laser heater) serveral tens of μJ have been produced. From May 2012 more than 200 μJ in the nominal spectral range have been produced.

FEL-2 have been already operated in the first stage and the second stage will be commissioned in October 2012.

TUPD01 FERMI@Elettra Progress Report	THOA02 L. Raimondi Photon Beam Transport Systems at FERMI@Elettra	THOEI03 C. Masciovecchio Four Wave Mixing at a Seeded FEL

High Gain Harmonic Generation - HGHG

HGHG scheme has been proposed as a way to partially solve the lack of seeding sources at short wavelengths.



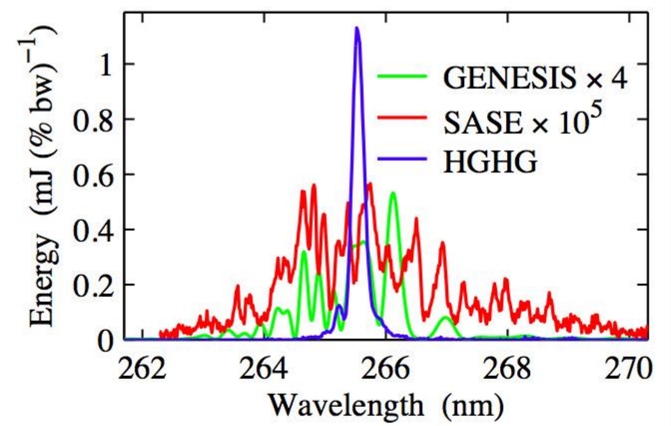


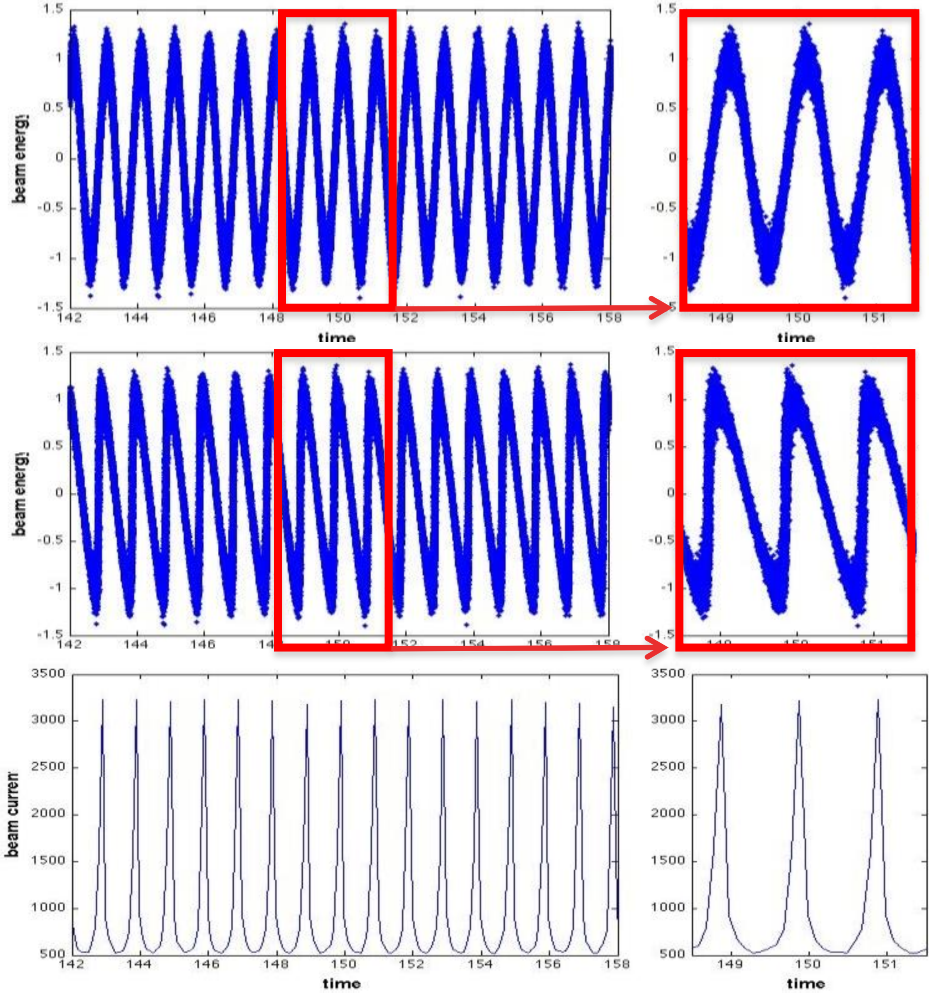
FIG. 4: Single shot HGHG spectrum for 30 MW seed (blue), single shot SASE spectrum measured by blocking the seed laser (red) and simulation the SASE spectrum after 20 m of NISUS structure (green). The average spacing between spikes in the SASE spectrum is used to estimate the pulse length.

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

Compared to SASE devices, generally more compact and nearly full temporally coherence output; many spectral parameters more easily controlled (e.g., pulse length, chirp).

After the initial HGHG demonstration experiment done at Brookhaven – BNL, **HGHG** and Coherent Harmonic Generation (GHG) have been demonstrated and explored in other facilities (UVSOR-II(JP), Elettra SR-FEL(IT), Max-Lab FEL (SE), SPARC(IT), SDUV-FEL(CN), SLAC(USA)).

HGHG with no e-beam chirp



Energy modulation of the phase space by the seed.

Energy modulation converted into spatial modulation.

Electron beam current strongly modulated at the seed wavelength, sharp spike indicate strong harmonic components.

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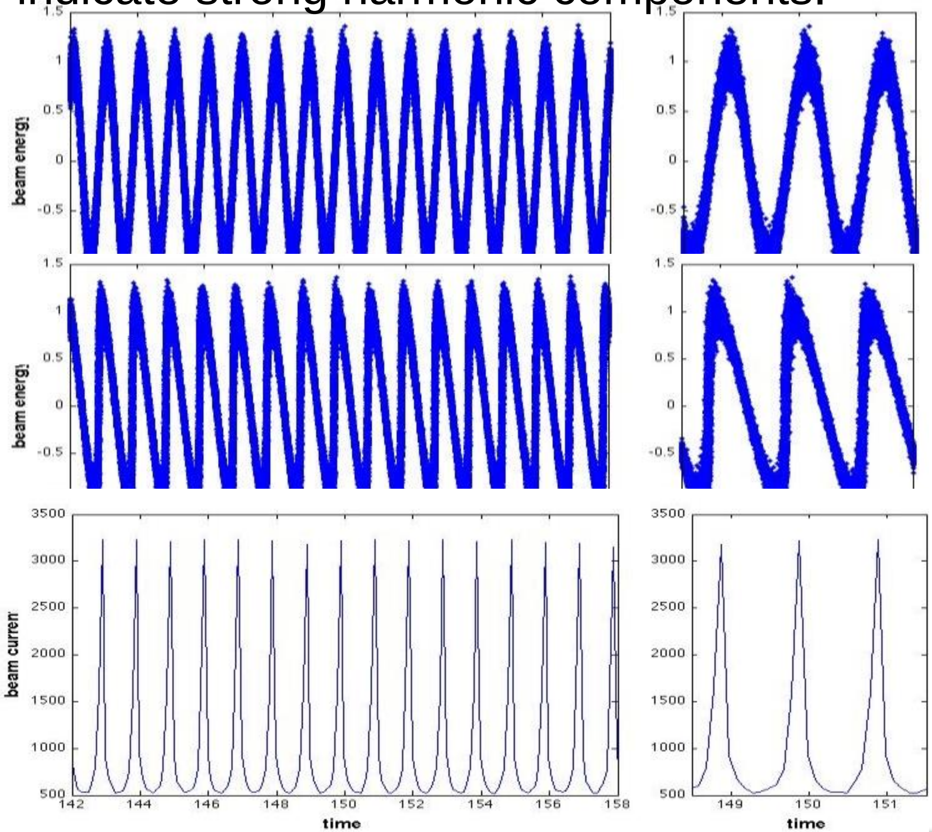
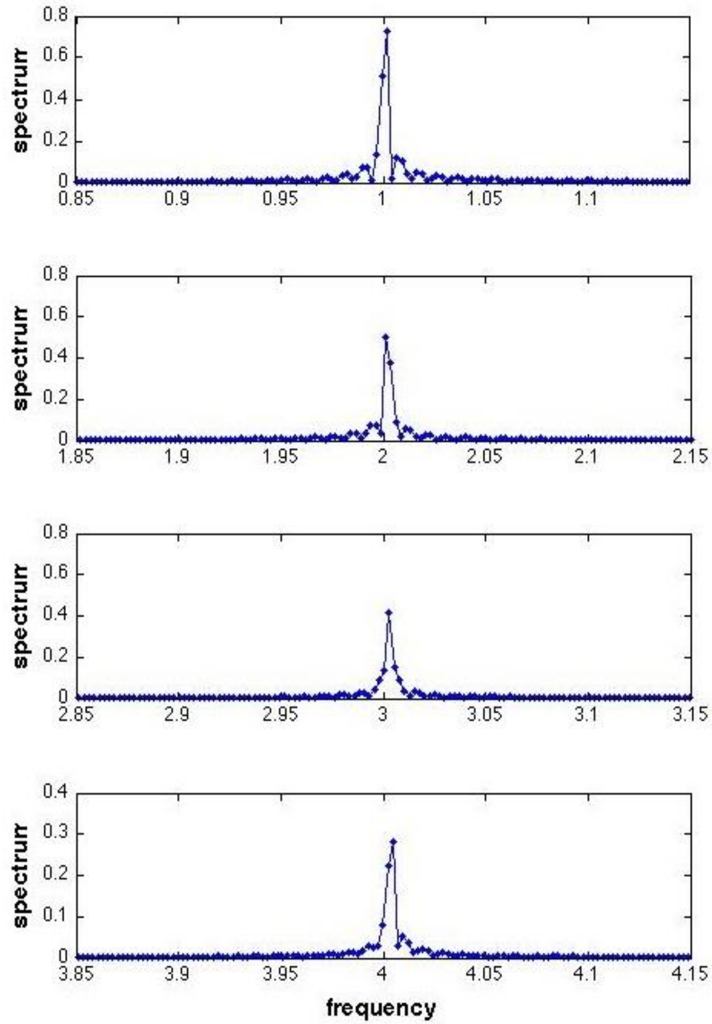
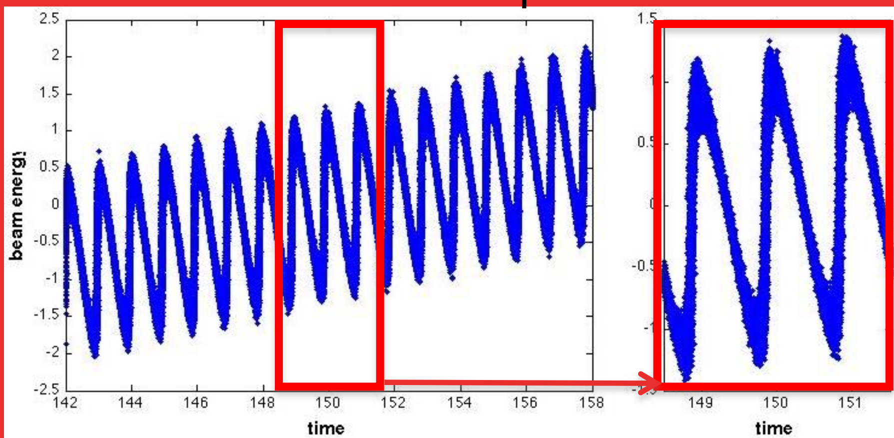




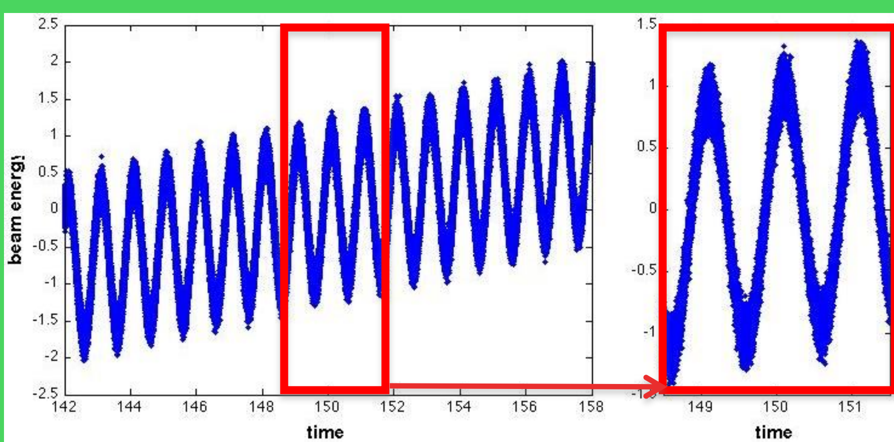
Spectral analysis of the bunching show strong harmonic components.

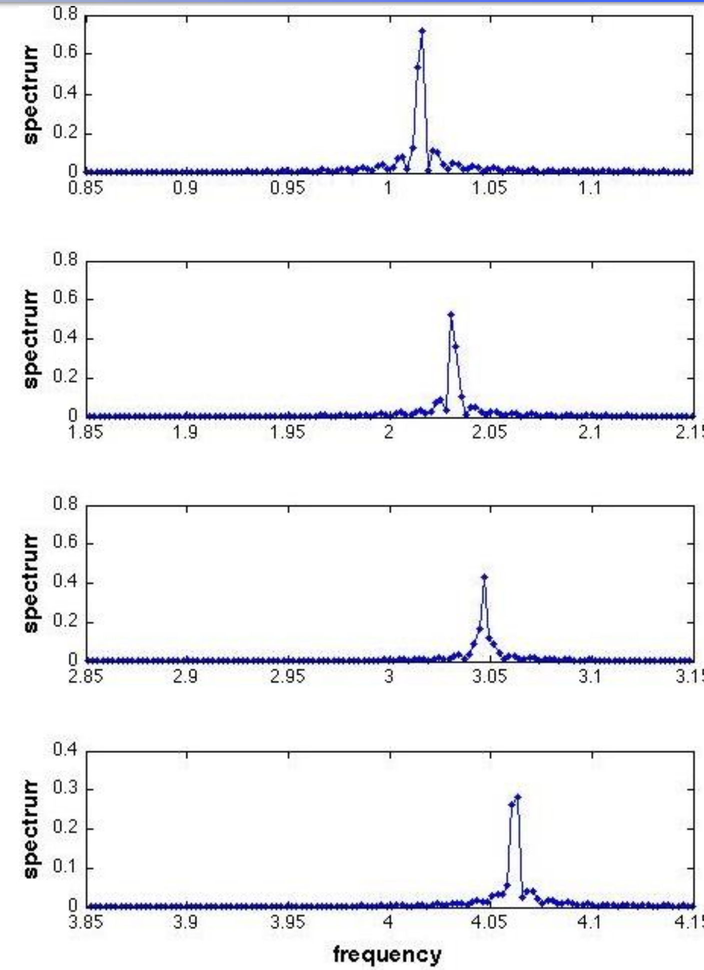
HGHG with linear e-beam chirp

After the modulator e-beam has energy modulation and linear chirp



After the dispersive section, e-beam compression and density modulation

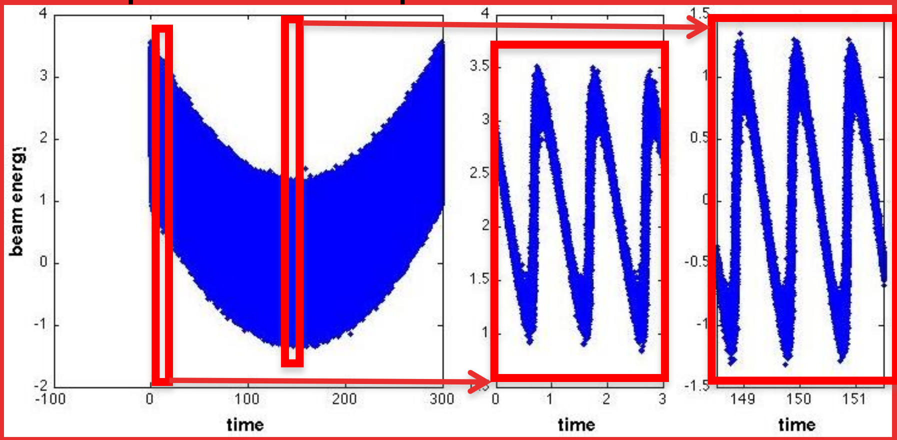




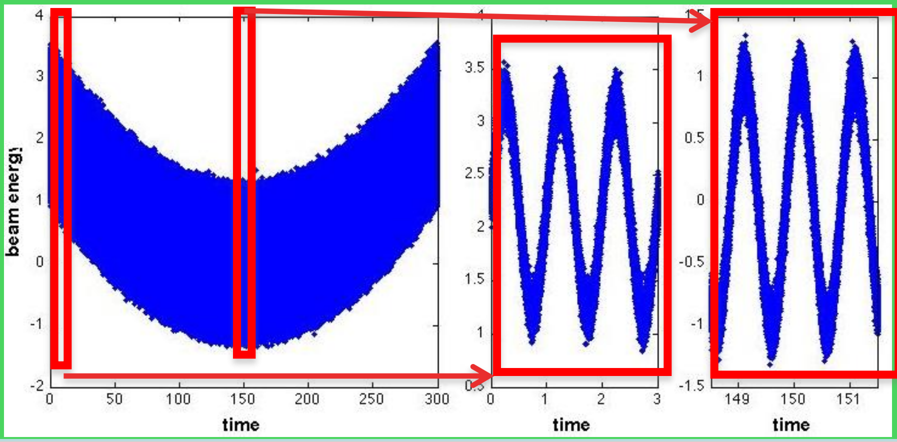
As a consequence of the beam compression the wavelength of the bunching produced by the seeding are shifted.

HGHG with quadratic e-beam chirp

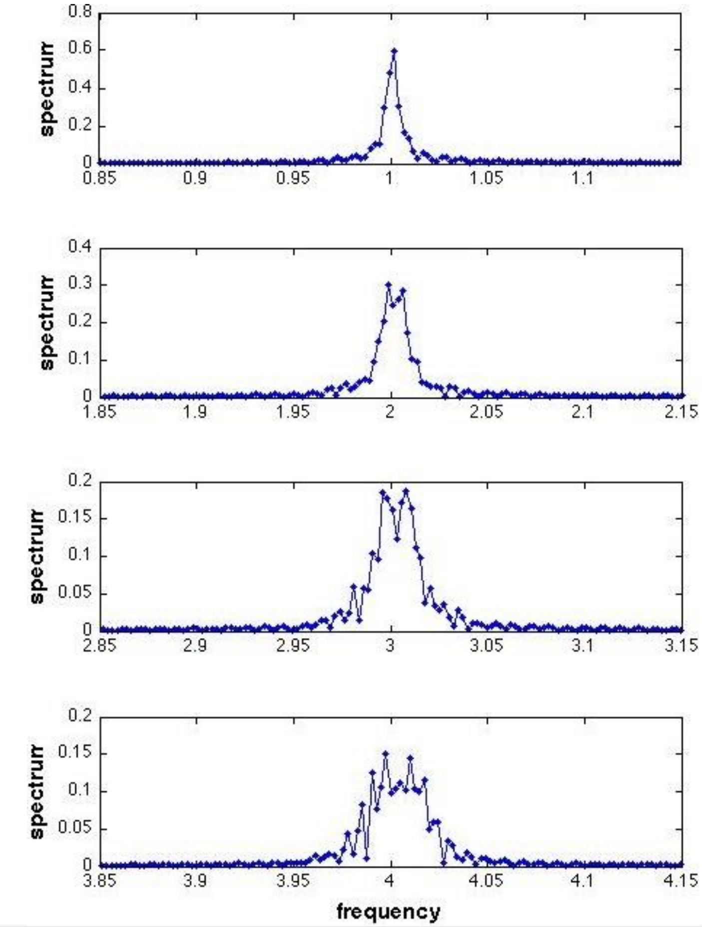
In the modulator energy modulation is added to the quadratic chirp



After the chicane beam compression varies along the bunch due to the nonlinear chirp



Due to the nonlinear chirp different part of the beam suffer different compressions and wavelength shifts. As a results the spectrum of the bunching has a broadening.



Different operating modes

Since the beginning of the commissioning of FEL-1 in 2010 several improvement of the LINAC lead to changes of the electron beam parameters.

- First experiments where done without the lineariser (x-band) and with 350 pC.
- In a second period the charge has been increased to 450pC.
- Since may 2012 laser heater and x-band become available and have been used toghether with a 500pC electron beam.

Every configuration has different effects on the beam that also affect the FEL.

- No X-band
- No LH
- Low charge

- No X-band
- No LH
- Medium charge

- X-band
- LH
- Normal compression

- X-band
- LH
- High compression

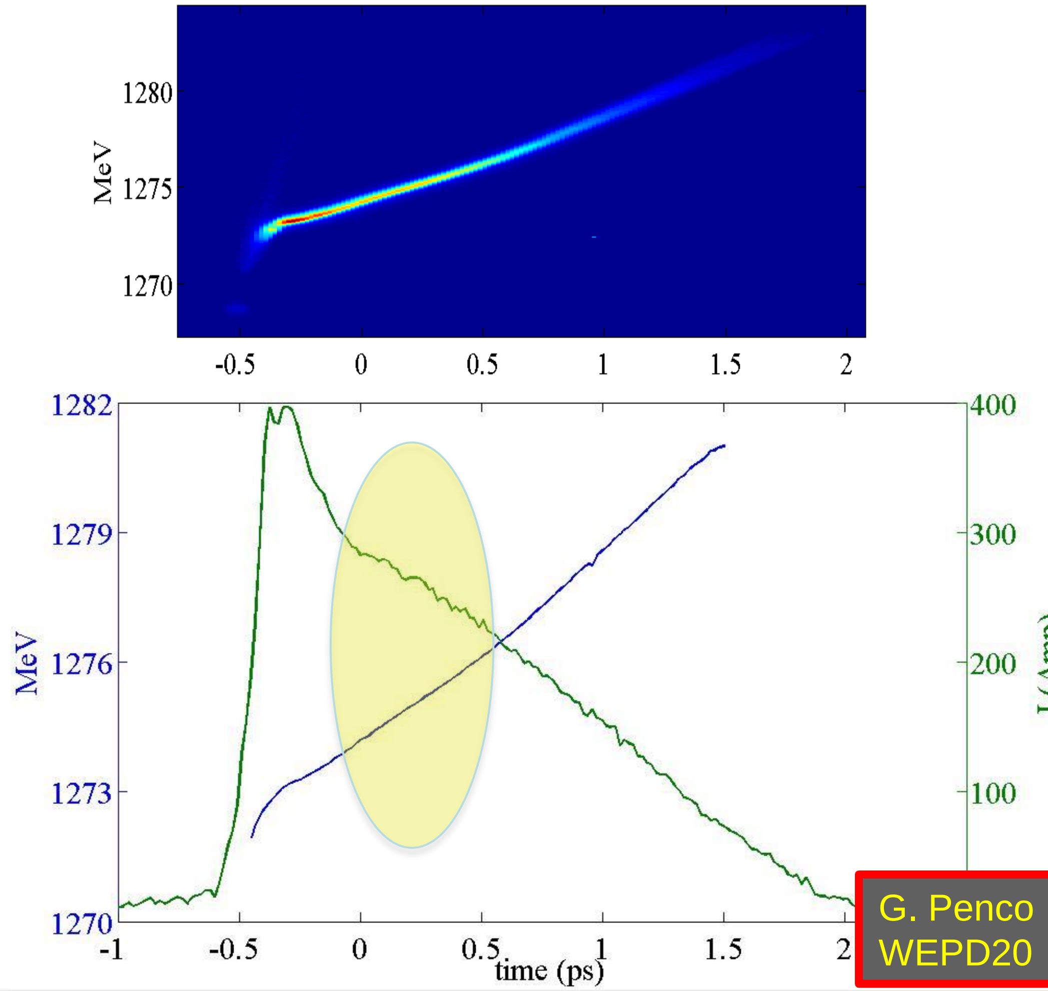
Low compression, ramped beam

Both laser heater and X-band where not available from the beginning of the FEL commissioning. Since current spike is not useful for HGHG, FEL operations started with a slightly compressed beam.

Current profile has a ramped shape and longitudinal phase space shows a 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 converts into FEL power fluctuations.

The nice longitudinal phase space allows a very good control of the FEL bandwidth.



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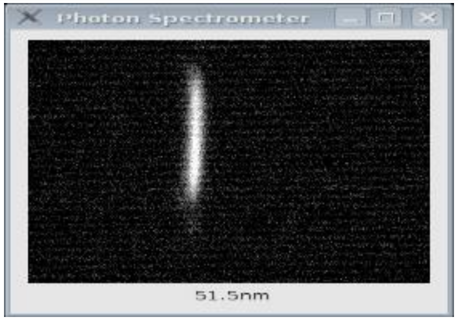
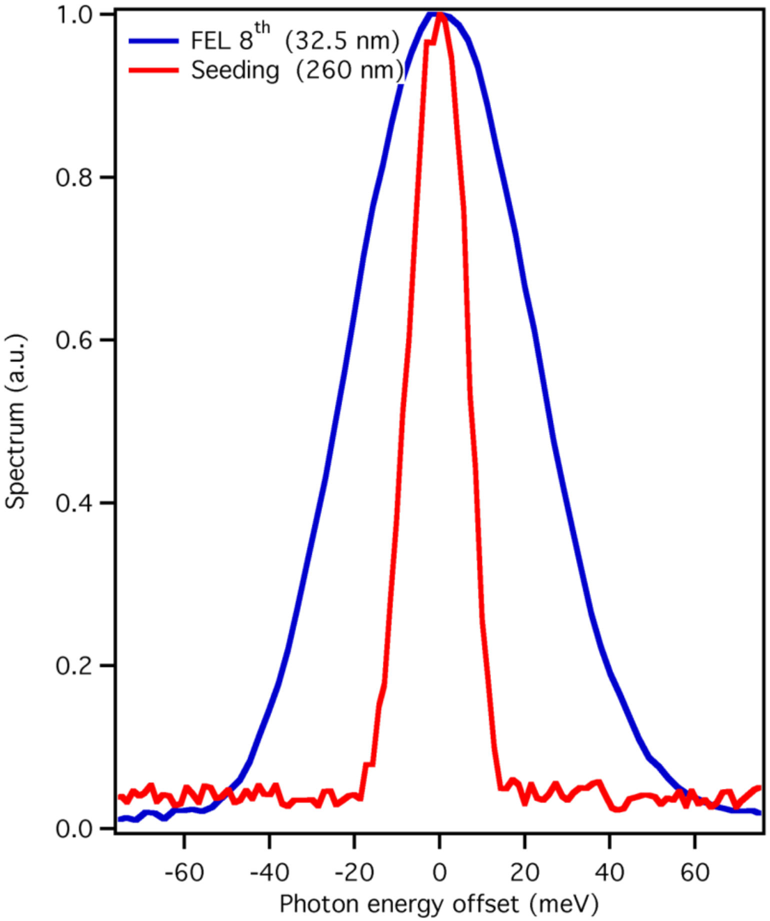
WEPD20

FEL bandwidth (eV)

Relative bandwidth of the FEL is **smaller** than the bandwidth of the **seed laser**. In the **frequency** (energy) domain the **FEL spectrum is larger** than the one of the seed laser.





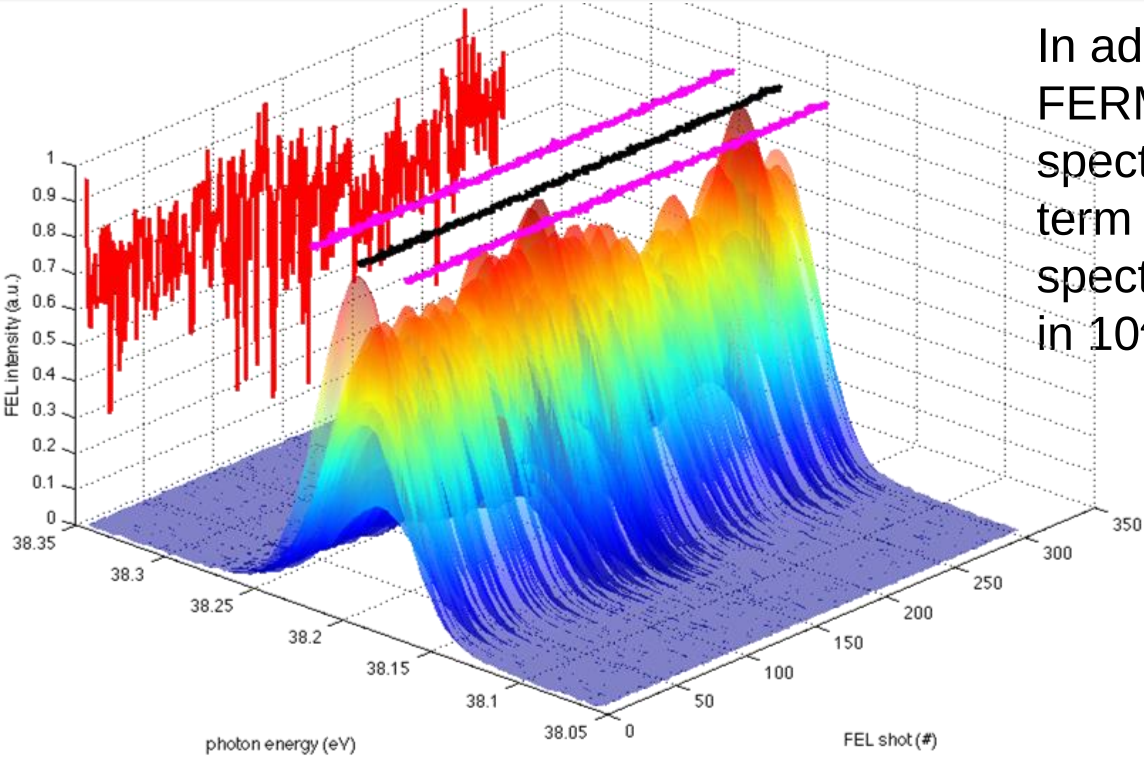
$$s_{rms}^{SEED} = 4.7 meV (0.098\%)$$

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

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 8^{th} harmonic we can estimate tat FERMI FEL pulses are **close to the Fourier limit** and have a good longitudinal coherence.

Wavelength stability



In addition to the very narrow spectrum FERMI is characterized by excellent spectral stability. Both short and long term measurements show that the spectral peak jitters of less than 1 part in 10^4.

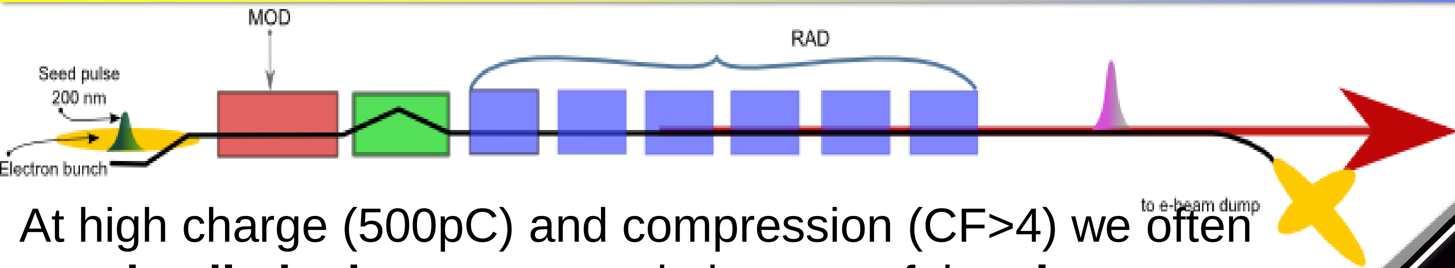
Reported data refer to an electron beam of 350pC at 1.24GeV compressed about a factor 3. The 6 radiators are tuned to 32.5nm.

FEL photon energy	~ 38.19eV
fluctuations	= 1.1meV (RMS)
fluctuations	= 3e-5 (RMS)
FEL bandwidth	= 22.5meV (RMS)
fluctuations	= 5.9e-4 (RMS)
fluctuations	= 3% (RMS)

Increasing peak current

- To increase the FEL power we pushed to higher compression factors and/or higher e-beam charge.
- Without x-band we are limited by the nonlinear compression that mainly enhance the spike while the tail (used for seeding) remain at relatively low current.
- With the increase of the charge density we started to see effects of microbunching also on the FEL emission.

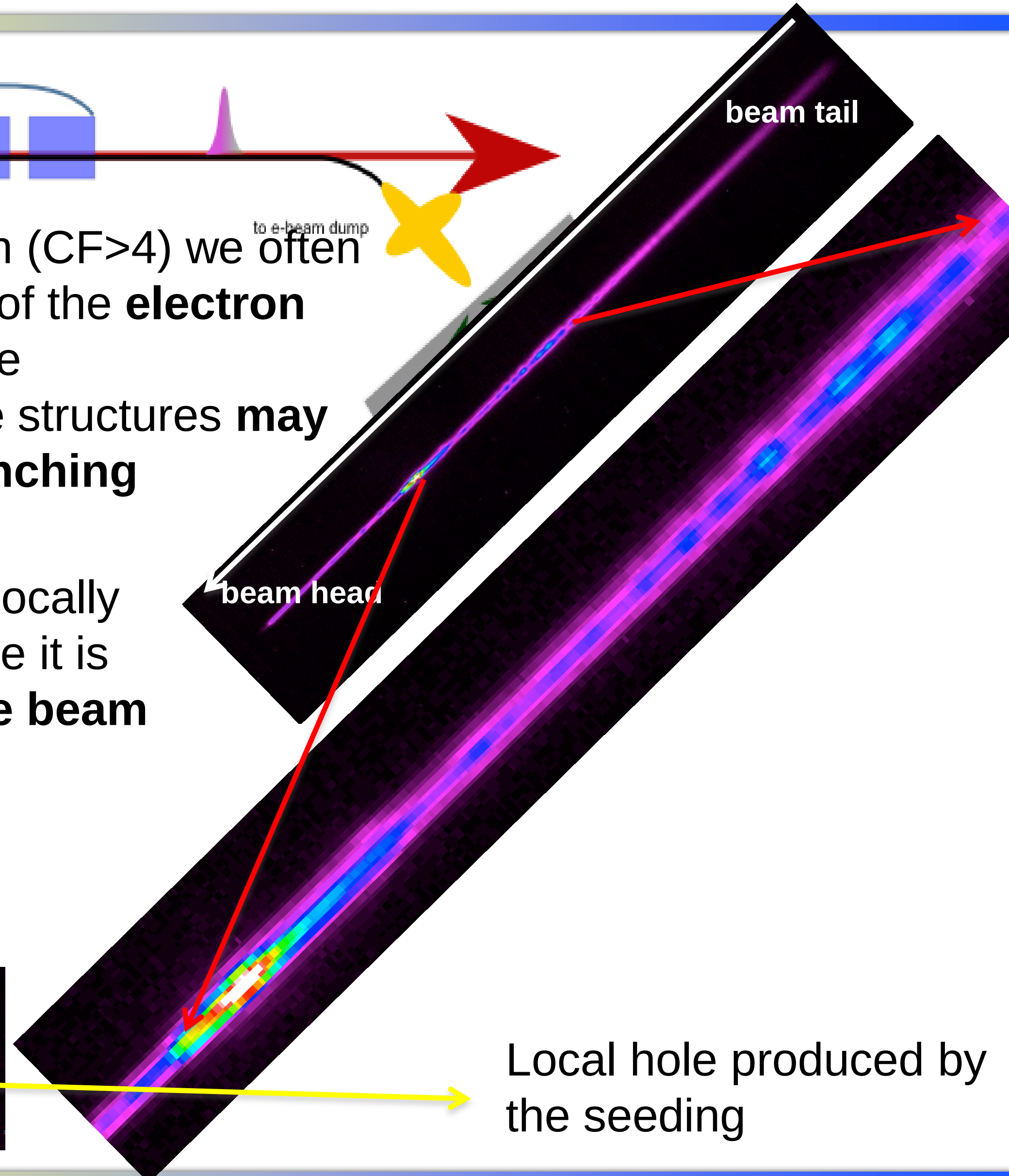
E-beam microstructures in beam dump

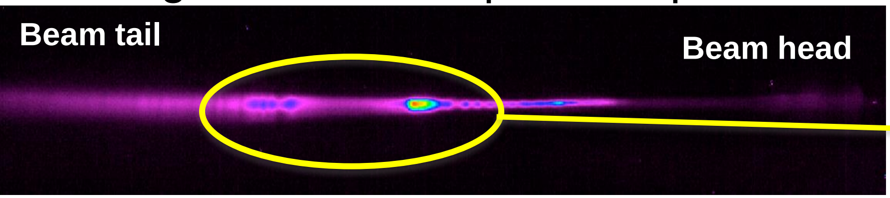


At high charge (500pC) and compression (CF>4) we often see **detailed microstructure** in images of the **electron beam energy spectrum** measured in the Main Beam Dump (after the FEL). These structures **may** suggest the presence of some **microbunching** developing in the LINAC and spreader.

Since the seeding and FEL process are locally modifying the electron beam phase space it is possible to **recognize the portion of the beam** that is **contributing** to the **FEL**.

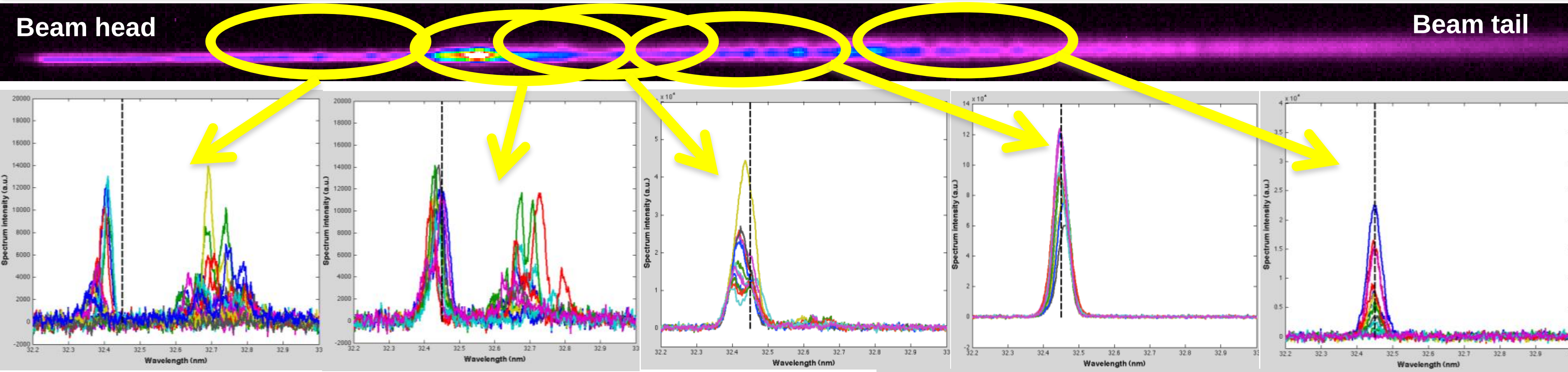
In the reported case, representative of RUN10, the FEL was typically optimized seeding close to the spectrum peak.





Local hole produced by the seeding

FEL spectrum changes

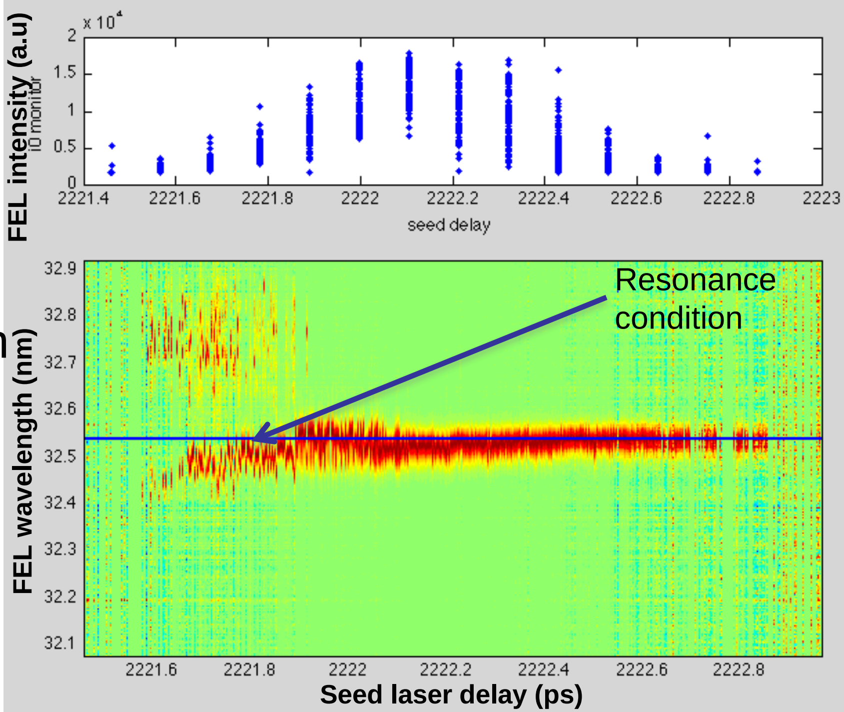


At the usual working point the FEL has good stability, high intensity and a clean spectrum.

Moving toward the tail the FEL intensity decreases without affecting the spectrum.

Moving the seeding toward the head of the bunch we see first a degradation of the spectrum and a small wavelength shift.

More toward the head, the spectrum splits in two with a new emission band that has a very different wavelength (red shifted) and noisy.



Needs for x-band and LH

- Results suggested that further improvement of the FEL would necessarily require the x-band and the laser heater.

- In may 2012 x-band become operational and commissioning of LH and X-band started.

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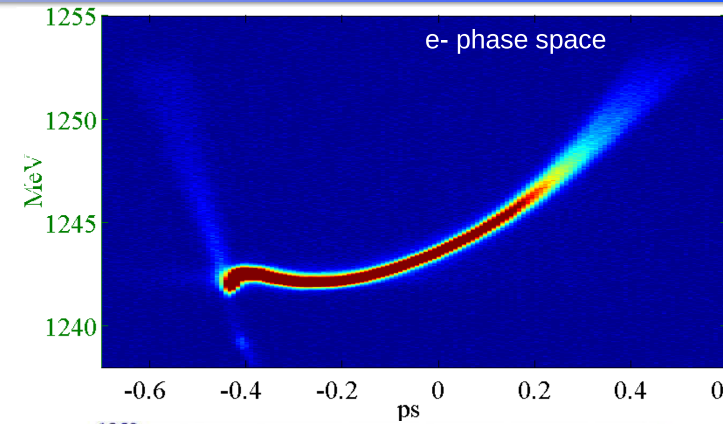
Linearized compression

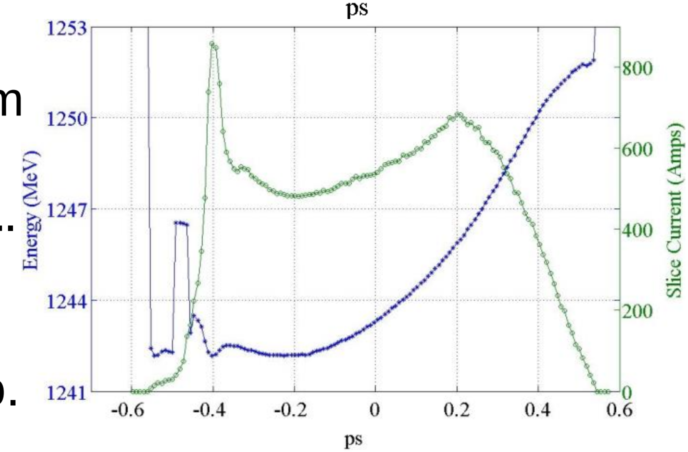
With the **X-band** the electron beam can be **efficiently compressed** for HGHG operations with a **good part** of the beam characterized by **high current** (~**500A**).

Typically we operate with in **L1** at ~28° degree from the crest (**118°**) and the **X-band** at the negative crest (**-90°**).



Since some of the plants, including the x-band, suffer from **small drifts** the phase of the x-band may vary by some degrees and his **final optimization** is done **with the FEL.**

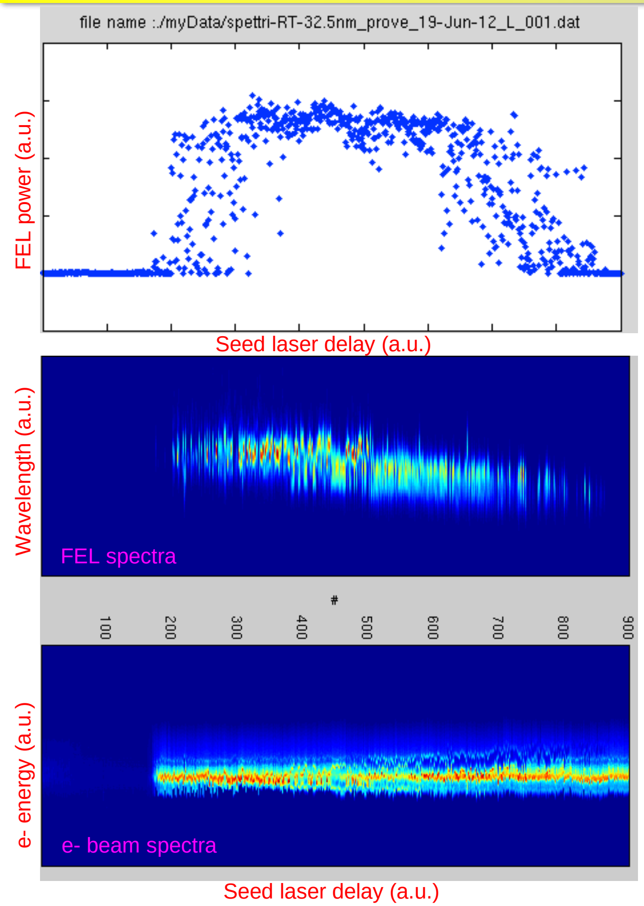
Current profile is **flat** but with such a short pulse the electron beam has a **significant nonlinear energy chirp**.



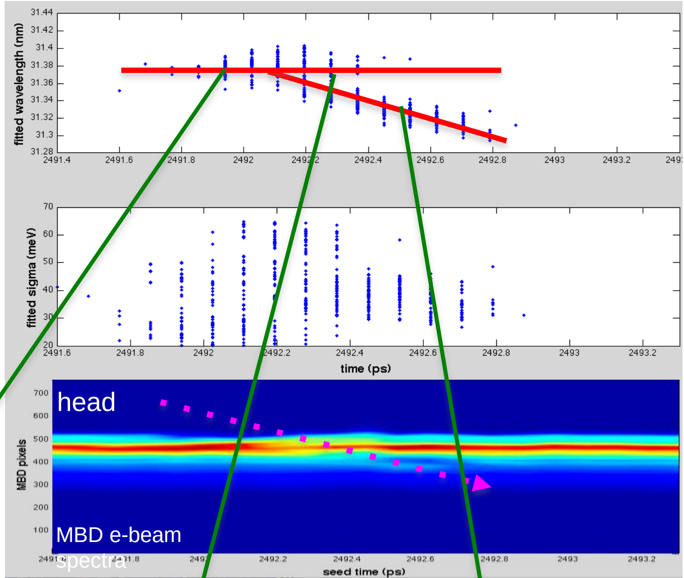
Various compression configurations have been studied trying to reduce the chirp but at the moment we are not able to completely remove it.
The design of FERMI included a ramped current profile at the injector in order to cure such a non-linear phase space.

G. Penco
WEPD20

e- phase-space effects on FEL

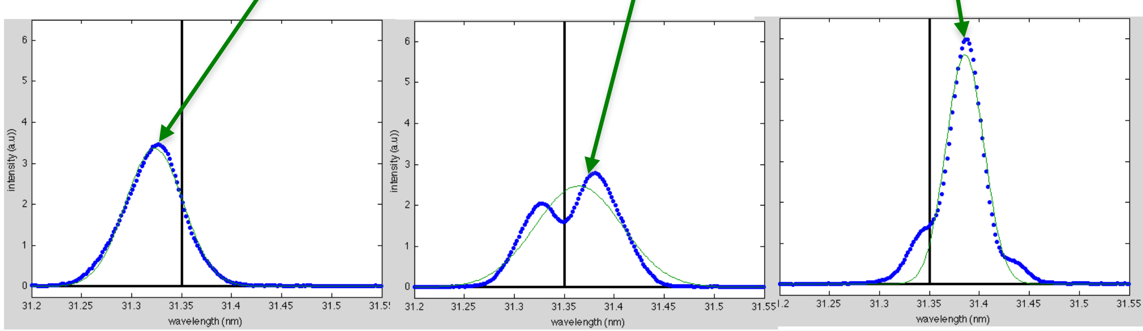


By measuring the **FEL spectra** as a function of the seed **laser delay** we can look at the **effects** of the **e- beam phase space** into the FEL.



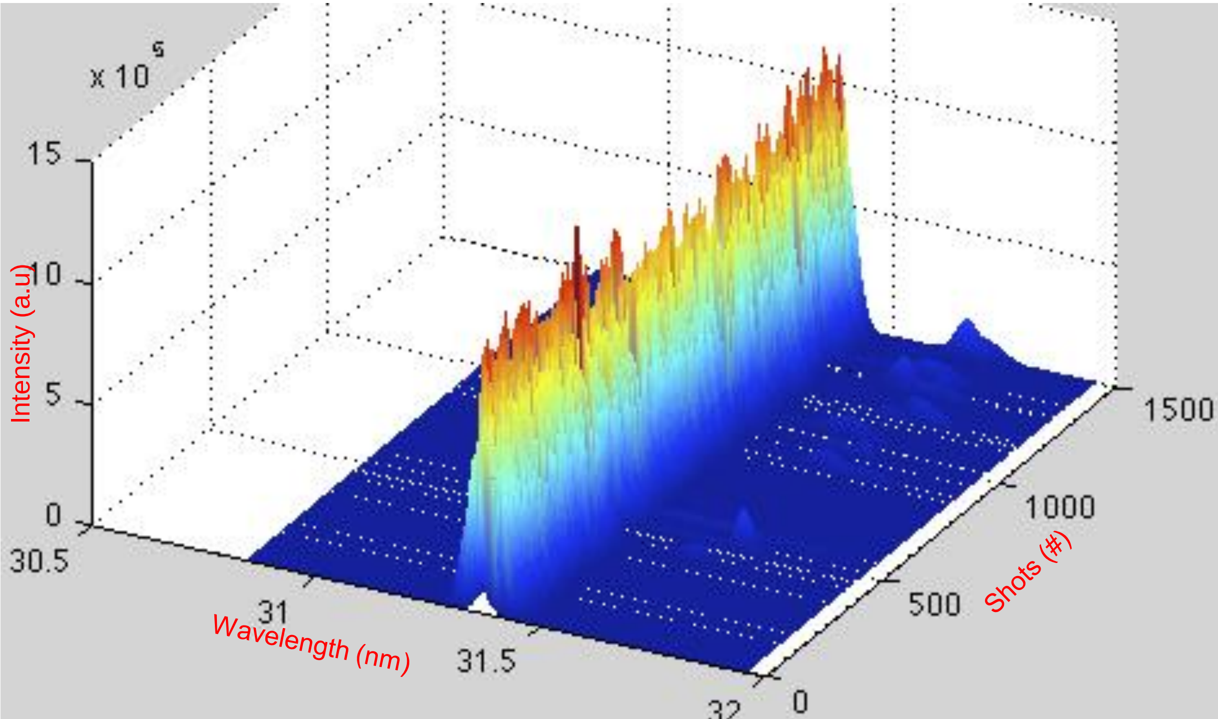
For this kind of e- beam, compressed with the x-band) we started to see more clearly the FEL **wavelength shift** and **bandwidth increase**.

Timing jitter make things worst.



This requires that FEL optimization should carefully look at spectra and not only at FEL power.

Statistical analysis



Wavelength =	31.38 nm
Photon energy =	39.58 eV
Lambda jitter =	0.04 nm
	0.13 (%)
Bandwidth(rms) =	29 meV
	7.3e-04
Bandwidth jitter =	0.013 (nm)
	57 (%)

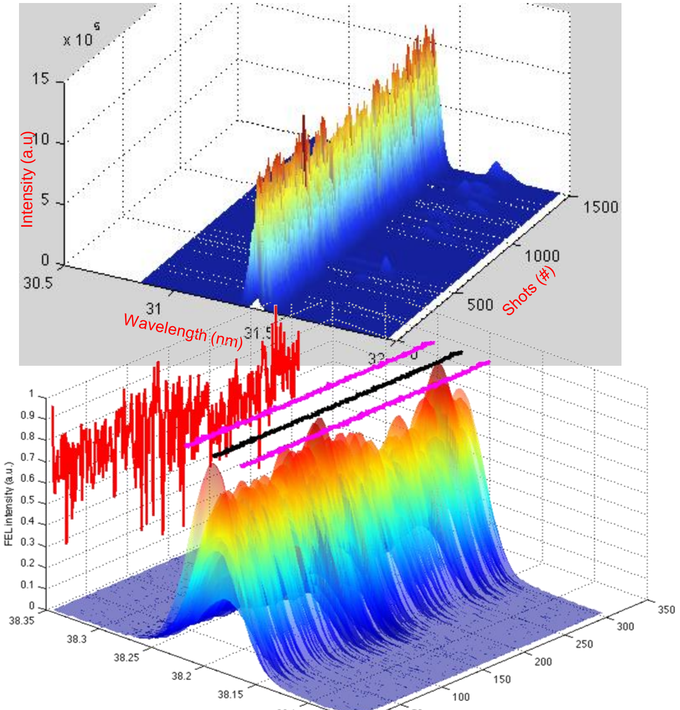
To compare FEL spectra from this configuration with previous we analyze a long sequence of spectra.

With respect to what obtained in the case without x-band the bandwidth is slightly larger but more important **wavelength fluctuations** are **a factor 20 larger**.

Optimizing the FEL "specifically" for reducing the wavelength fluctuations allow us to reduce this fluctuations to about 5e-4, still larger than in the past but is reasonable for the users.

SERIE_spettri-RT-BUNGAP_1238_R56_62A_seed_65.1_LH_38.0_Xband_ON_24-Jun-12_M_001.mat

Statistical analysis



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June 24 2012

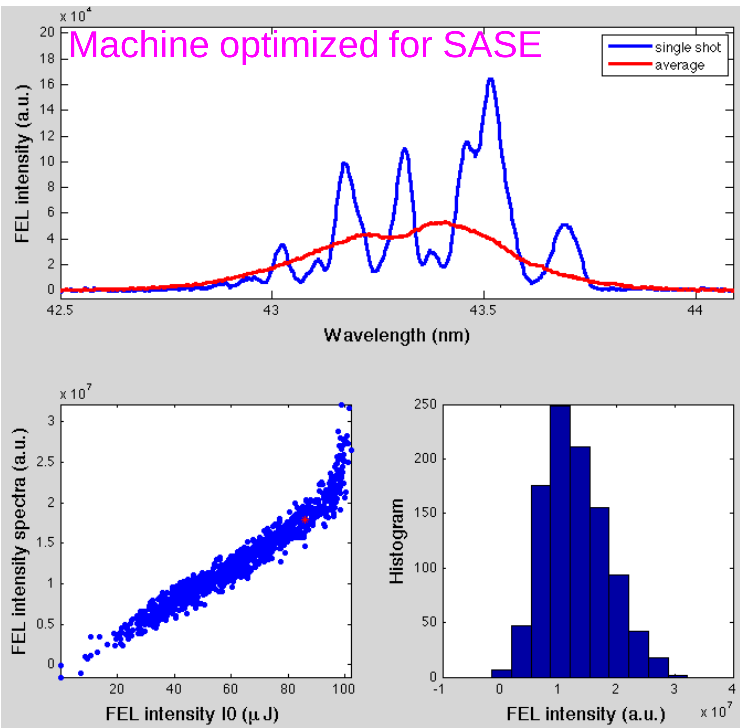
High compressions

In order to push for higher photon flux we increased the compression factor.

This, together with a good matching and alignment, leads to the first clear evidence of SASE at FERMI.

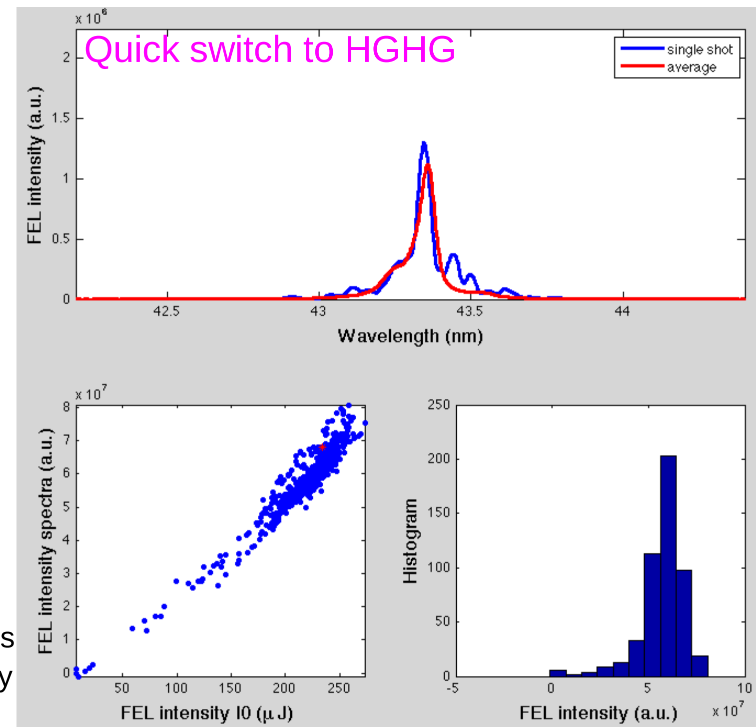
SASE(*) operation mode has been used to optimize the FEL.

If not undulator are not properly optimize the SASE background(**) appear also in HGHG configuration.



* SASE signal comparable to HGHG is found for special arrangement of the undulators

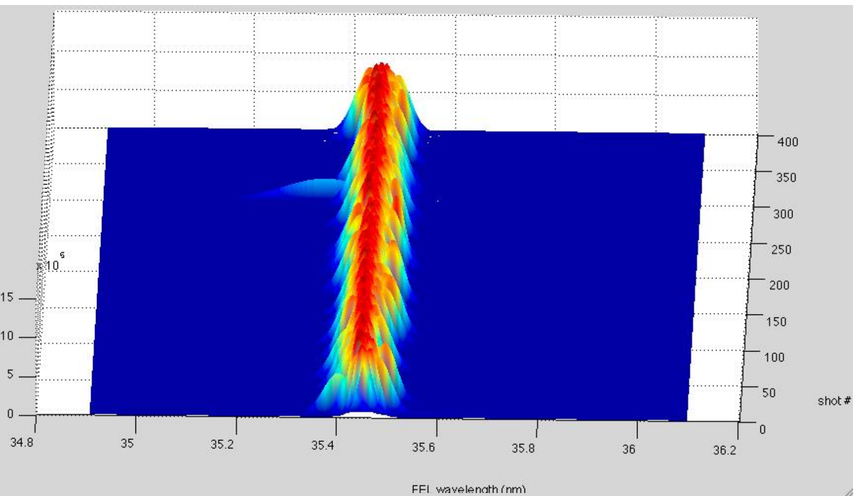
** Background is enhanced by seeding



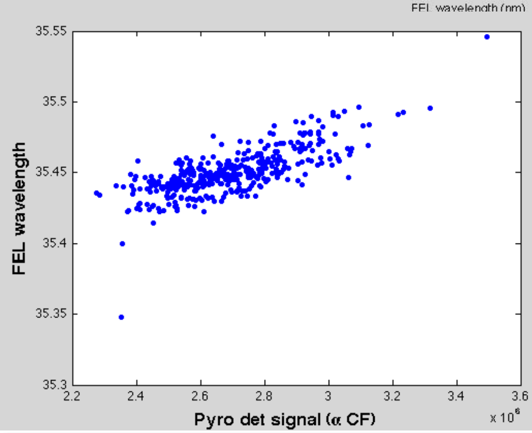
Wavelength stability

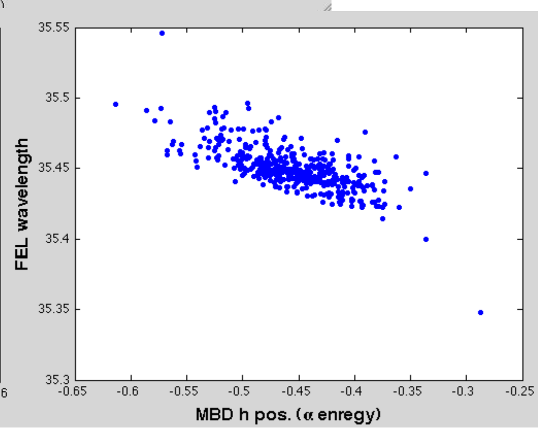
With this configuration during users operations we have provided about 200 μJ. With proper optimization both the bandwidth and the wavelength are kept under control and satisfy users requests.

Wavelength=	35.4 nm
Photon energy=	35.0 eV
Lambda jitter =	0.016 nm 0.046 (%)
Bandwidth(rms) =	0.022 (nm) 22.0 meV 6.2e-04
Bandwidth jitter =	0.0065 (nm) 29 (%)



Studies on the possibility to further improve wavelength stability and bandwidth are ongoing.





Measurements during users operations indicate that wavelength fluctuations are strongly correlated with the beam properties fluctuations in BC1 (compression) and in main beam dump (energy) .

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Conclusions

- Spectral measurements at FERMI show very good longitudinal coherence.
- Effects of electron beam phase space on the HGHG process have been studied at FERMI
- The use of x-band and laser heater allow us to reach with FEL-1 few hundreds of μJ in the 65–20 nm spectral range
  - Spectrum control operating FEL with such highly compressed beams is more critical.
  - Further studies on the optimal LINAC setting for high power and high spectral quality are ongoing.

Acknowledgements

FERMI team

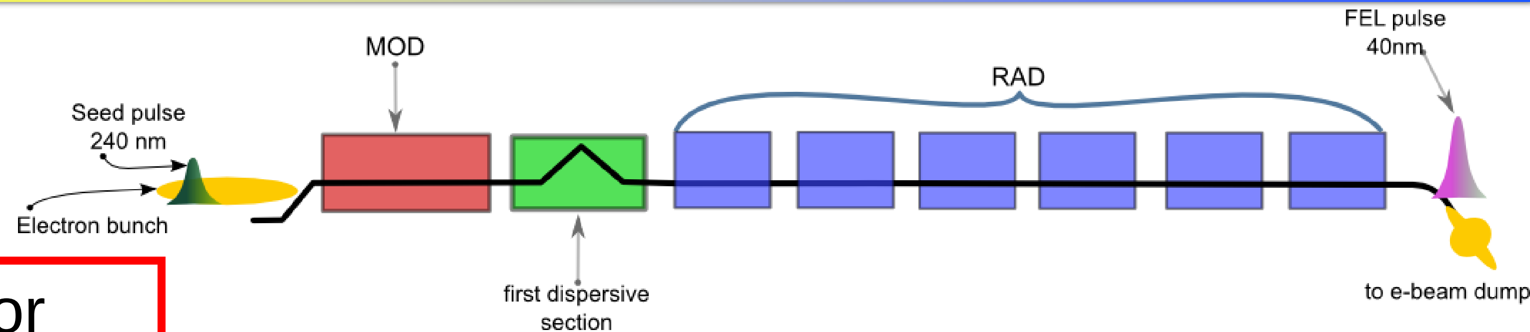
FERMI shift people and guests

FERMI Commissioning team

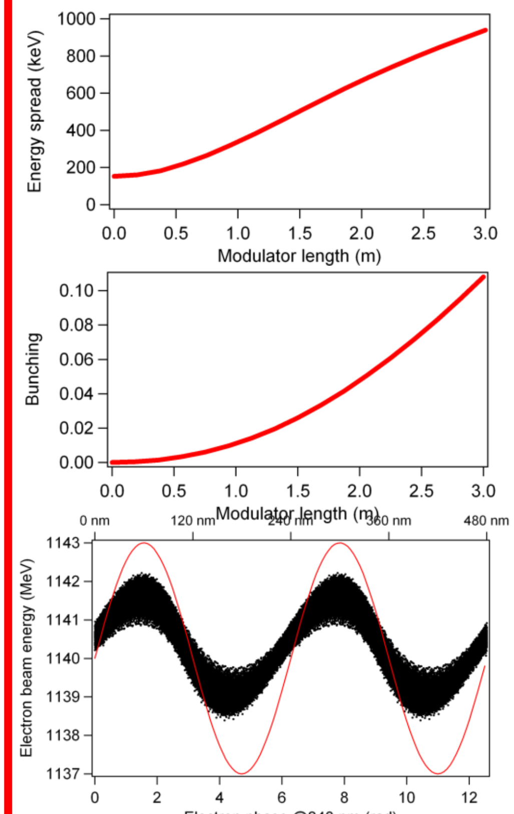
Thank you

http://www.elettra.trieste.it/SSSFEL12/

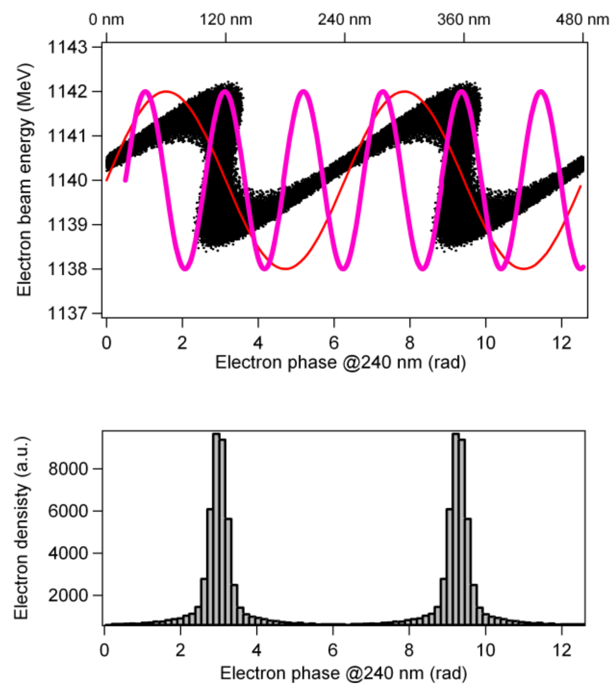
HGHG mechanism



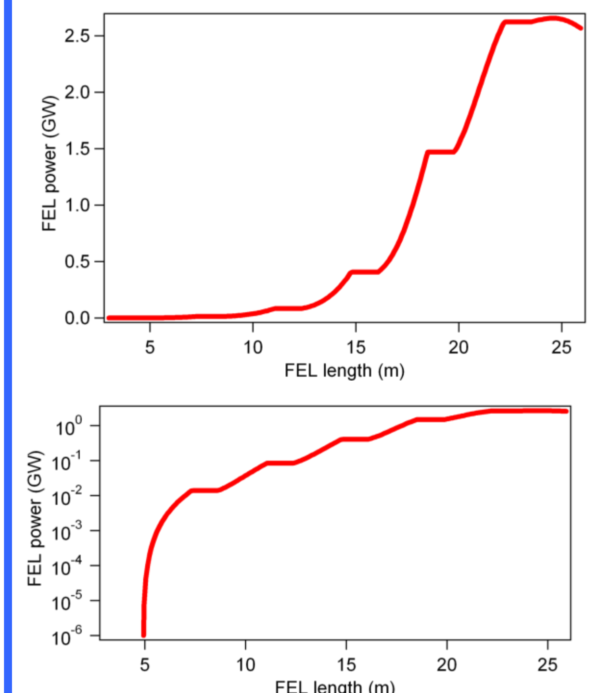
Modulator



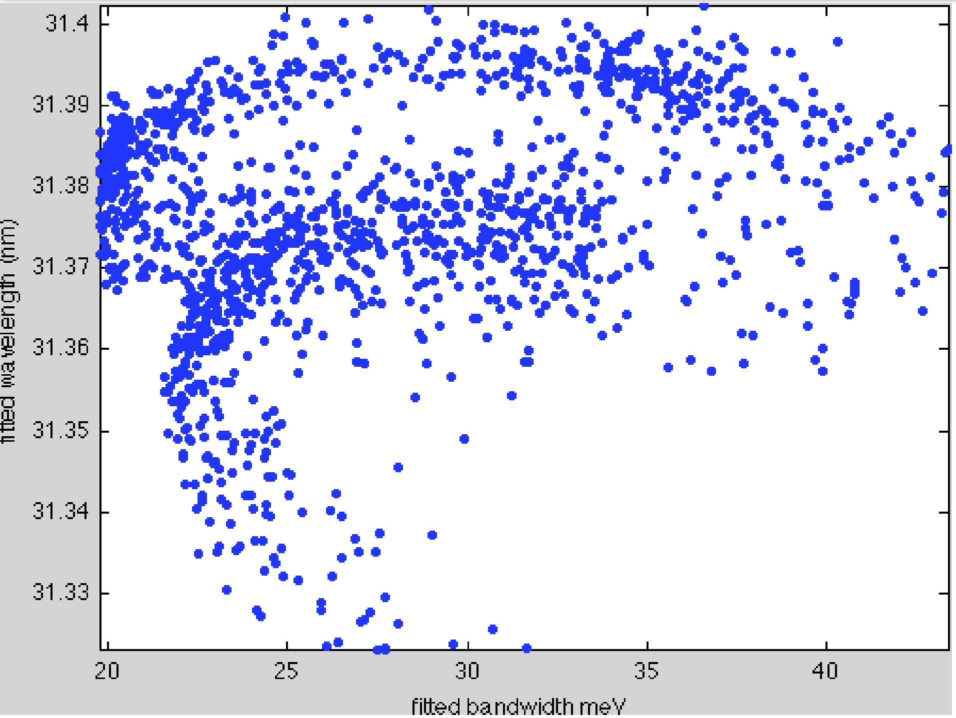
Dispersive section



Radiator

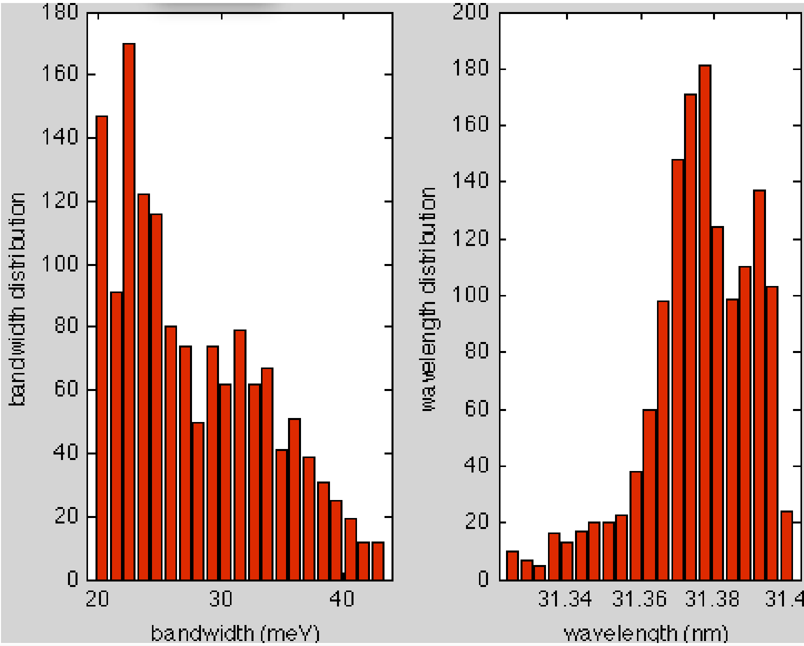


Correlation between wavelength and bandwidth and distributions



By plotting the **central wavelength** as a function of the **bandwidth** we find strong **correlations.** This suggests that **fluctuations** are related to electron **beam phase space** and **timing jitter**.

FEL bandwidth has an asymmetric distribution with a peak at 20meV that is close to the one measured in previous cases that is presumably close to the Fourier limit FEL bandwidth (20meV → 40fs FWHM).



SERIE_spettri-RT-BUNGAP_1238_R56_62A_seed_65.1_LH_38.0_Xband_ON_24-Jun-12_M_001.mat

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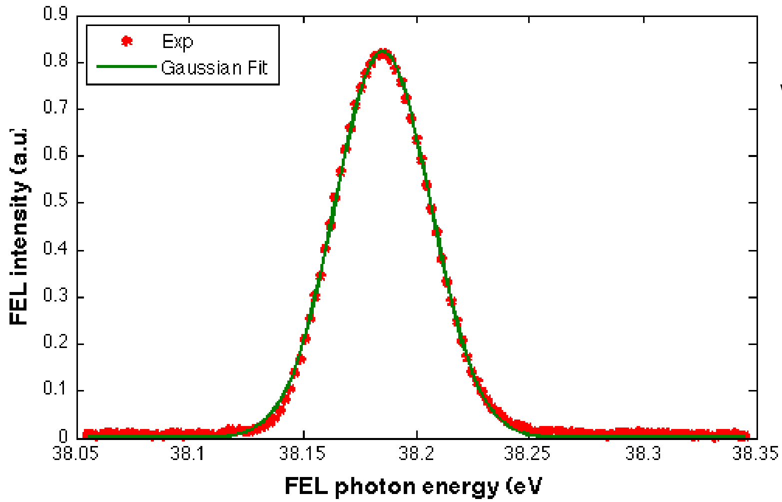
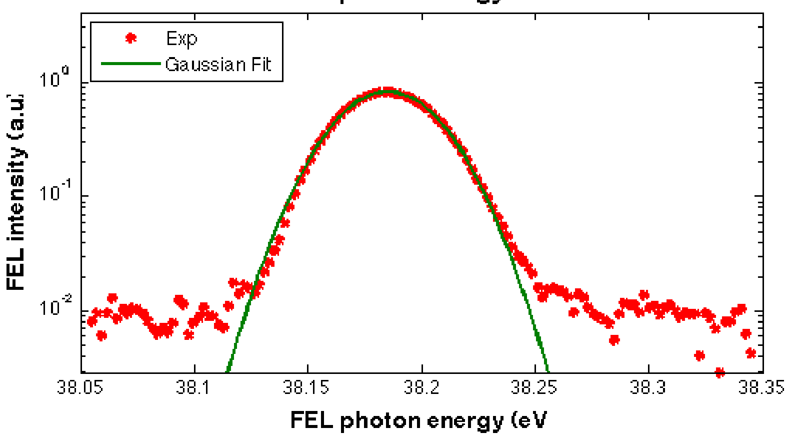
Gaussian single mode spectra





In this configuration the FEL spectra are well fitted with a single Gaussian curve except a very small discrepancy toward the red.

Spectra have been cross-calibrated using He absorption*.

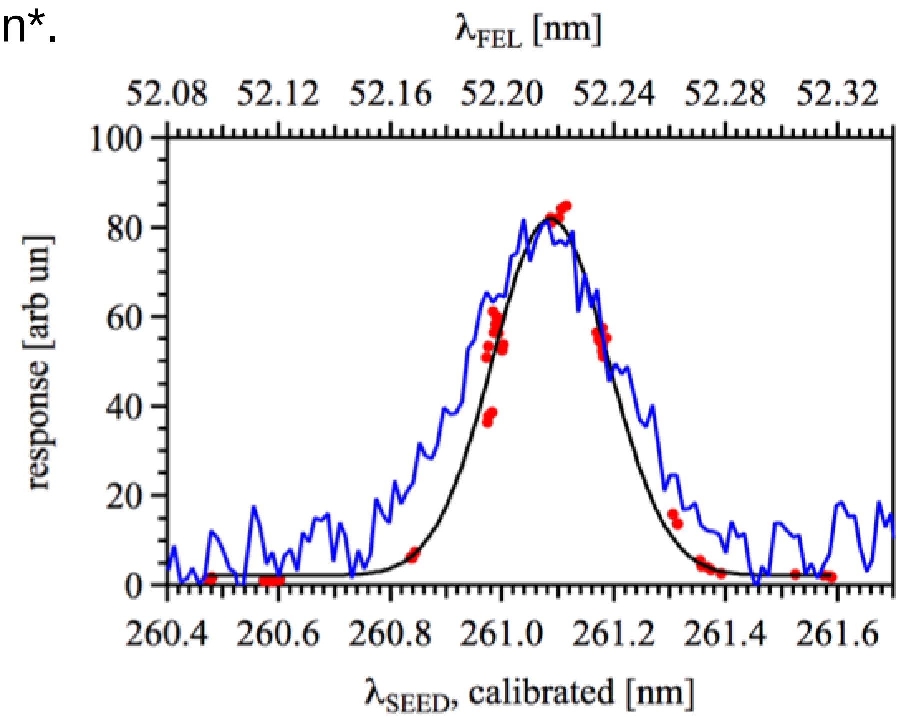
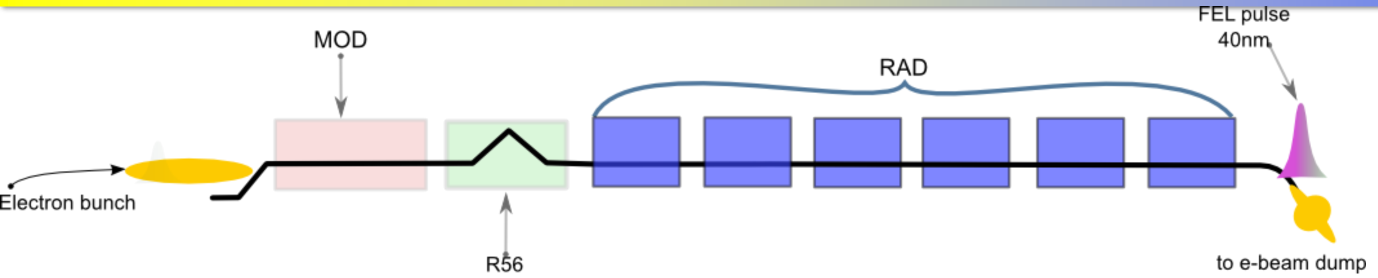


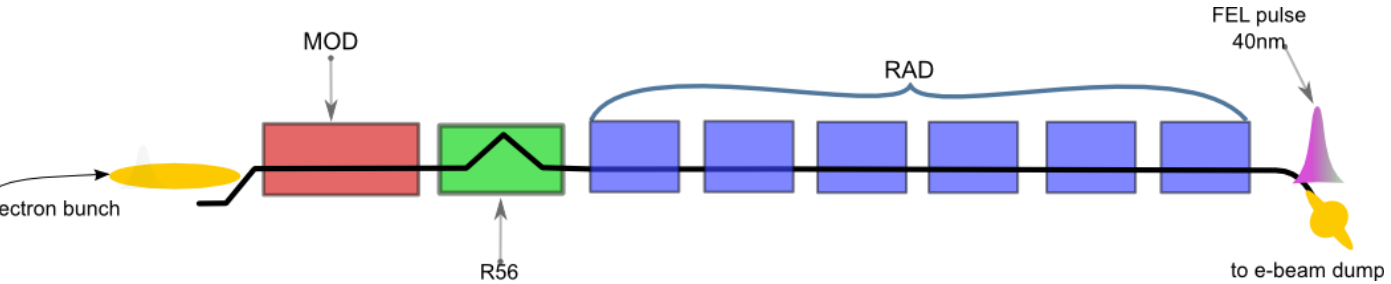
Figure 10. Reconstructed He absorption profile (red dots: PMT response vs calibrated wavelength; black line: gaussian fit), and comparison with Padres spectrometer trace (blue line). Note $\lambda_{FEL} = \lambda_{SEED}/5$.

(*) LDM team

SASE



Highly compressed beam with 6 undulators tuned at ~40nm in circular polarization



SASE signal is strongly enhanced by using the optical klystron configuration, with modulator tuned at the same wavelength and small dispersion in R56.