FEL commissioning at FERMI@Elettra

E. Allaria
on behalf of the FERMI team

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Outline

- FERMI FEL project
  - FERMI parameters
  - FEL schemes

- Commissioning activities
  - FEL commissioning and results

- FEL experimental results at FERMI
  - Gain
  - Coherence properties
  - Spectral characterization

- Future plans

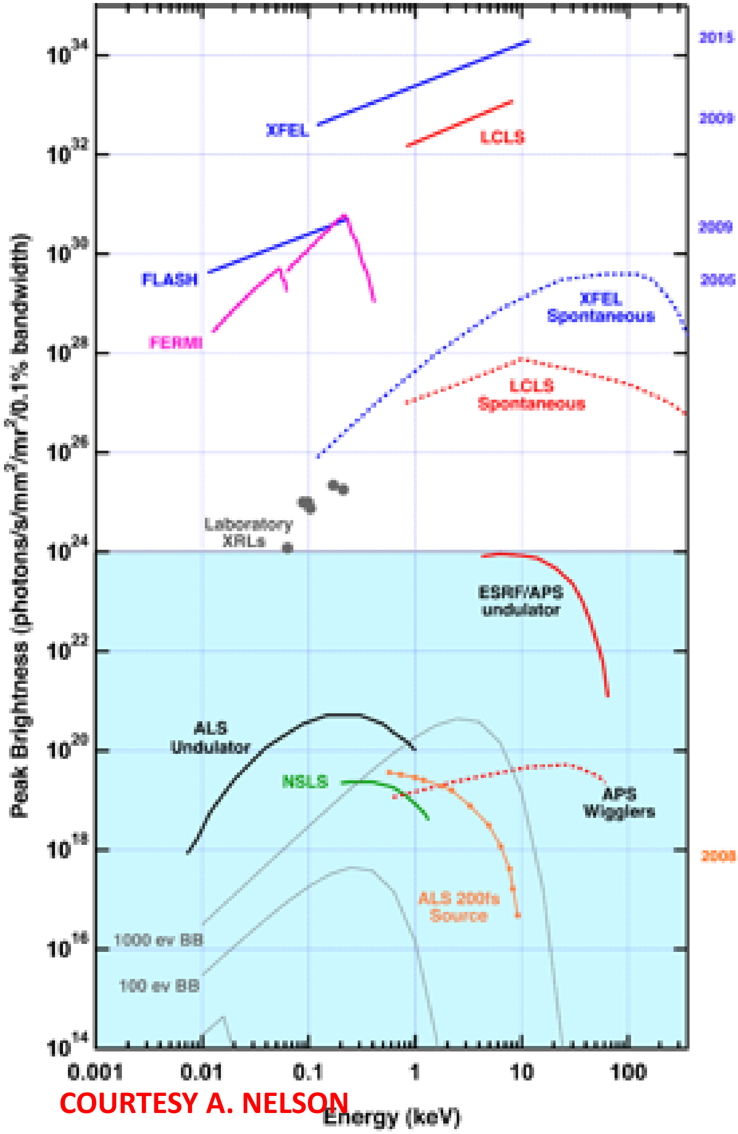
FERMI main features

FERMI@Elettra single-pass FEL user-facility*.

Two separate FEL amplifiers will cover the spectral range from 100 nm (12eV) to 4 nm (320 eV).

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

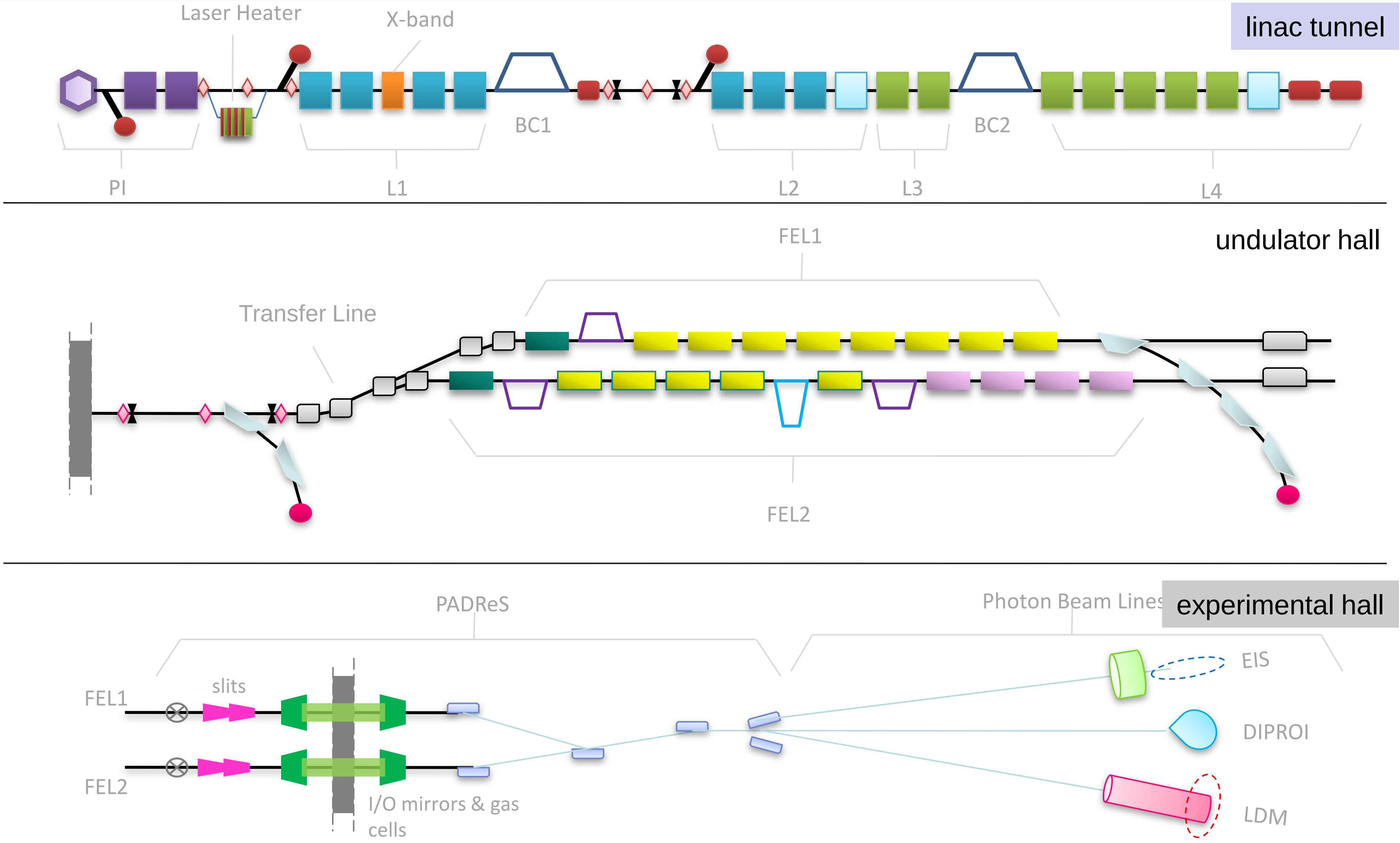
☐ high peak power	0.3 – GW's range
☐ short temporal structure	sub-ps to 10 fs time scale
☐ tunable wavelength	APPLE II-type undulators
☐ variable polarization	horizontal/circular/vertical
☐ seeded harmonic cascade	longitud. and transv. coherence



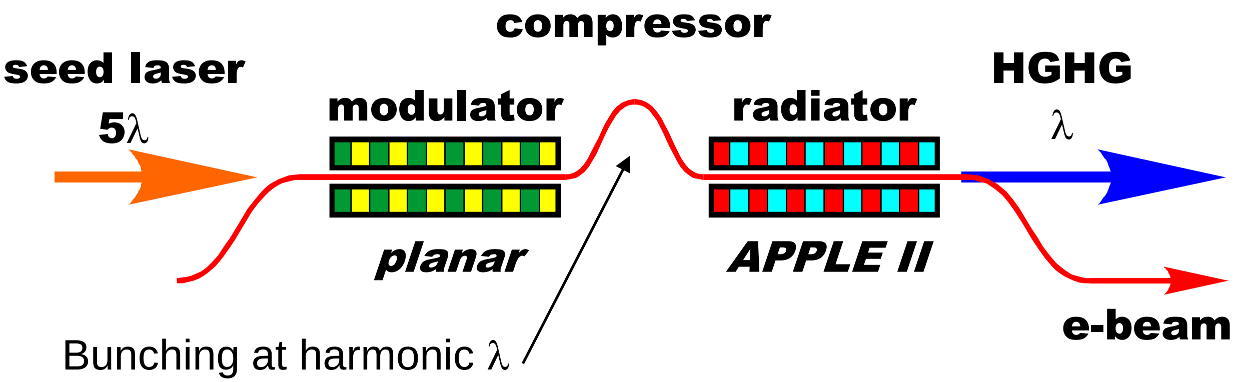
COURTESY A. NELSON

* **TUPB29** Status of the FERMI@Elettra Project

FERMI Layout



High Gain Harmonic Generation - HGHG



Bunching at harmonic λ

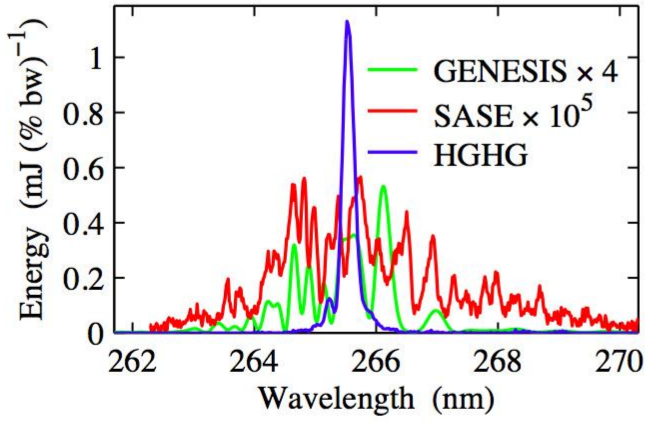


FIG. 4: Single shot HGHG spectrum for 30 MW seed (blue), single shot SASE spectrum measured by blocking the seed laser (red) and simulation the SASE spectrum after 20 m of NISUS structure (green). The average spacing between spikes in the SASE spectrum is used to estimate the pulse length.

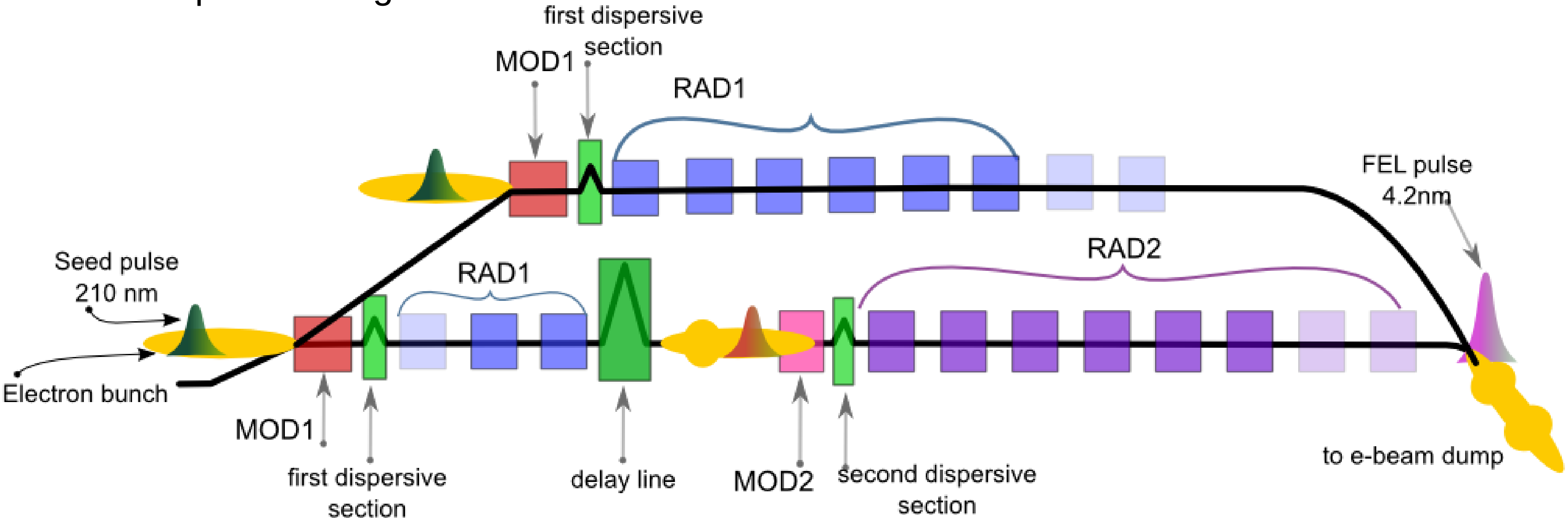
Compared to SASE devices, generally more compact and nearly full temporally coherence output; many spectral parameters more easily controlled (e.g., pulse length, chirp).

L.H. Yu et al.
Phys. Rev. Lett. 91, 074801 (2003)

FEL-1 and FEL-2

FERMI’s two FELs will cover different spectral regions.

FEL-1, based on a single stage high gain harmonic generations scheme initialized by a UV laser will cover the spectral range from ~100 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, will be 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).

FERMI, measured photon flux

December 2010 (*250pC*):
Compressed e-beam 43nm with photodiode: ~**6 nJ**;~1*10^{9}
Compressed e-beam 43nm with spectrometer: ~3 nJ;~5*10^{8}
Compressed e-beam down to 17 nm: clear evidence of coherent signal

March 2011 (*250pC*):
Uncompressed e-beam 65 nm with the DESY gas detector: ~0.3μJ, ~1*10^{11}, ~2MW
Compressed e-beam 65 nm with the calibrated FERMI gas detector: ~**3 μJ** , ~1*10^{12}, ~20MW

April 2011 (*350pC*):
Compressed e-beam 65 nm with spectrometer (average): ~2 μJ, ~6*10^{11}, ~12MW
Compressed e-beam 43 nm with spectrometer (average): ~**5 μJ**, ~1*10^{12}, ~30MW
Down to ~24 nm ~0.3 μJ, ~4*10^{10}, ~2MW

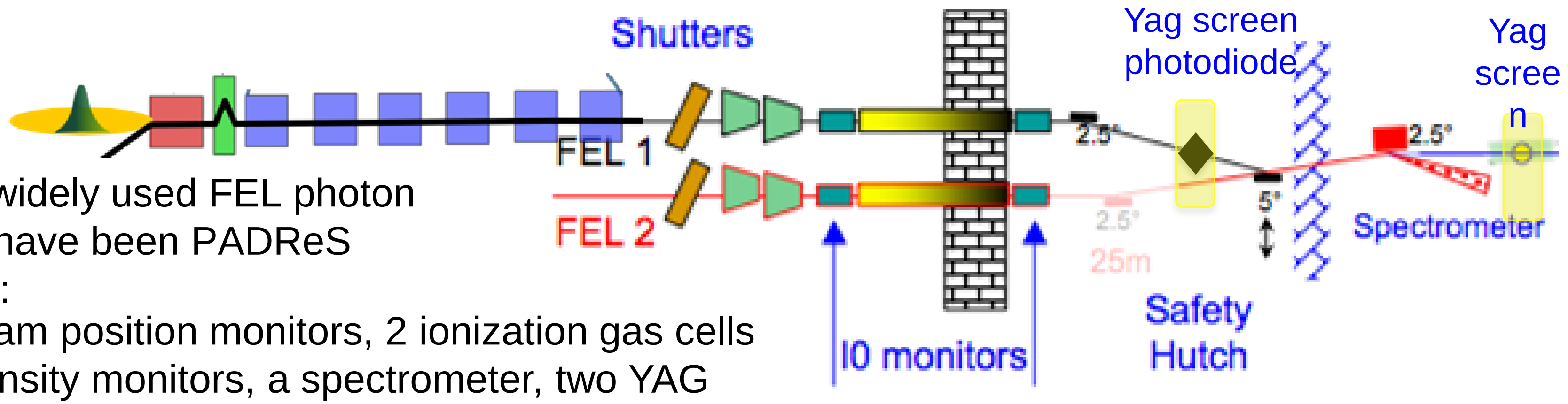
***Experimental stations**:*
Timex 65 nm with Al filter (March 25th): ~135nJ (peak), 70-80nJ (average).
LDM 65 and 52 nm: estimated from PADReS measurements

June-July 2011:
350pC-450pC
*** Photodiode calibration to be confirmed**
Compressed e-beam 52nm with calibrated***** photodiode: ~30μJ, ~1*10^{13} [VERY PRELIMINARY]
Compressed e-beam 43nm with calibrated***** photodiode: ~45μJ, ~1*10^{13} [VERY PRELIMINARY]
Compressed e-beam 32.5nm with calibrated***** photodiode: ~**100μJ**, ~1*10^{13} [VERY PRELIMINARY]
Compressed e-beam 20nm with calibrated***** photodiode: ~40μJ, ~1*10^{12} [VERY PRELIMINARY]

***Experimental stations**:*
LDM 52 nm: ~---
Timex 52nm: ~*20*μJ at the sample
DIPROI 32nm: ~ *2*μJ in the chamber with ~*4*μJ at the photodiode

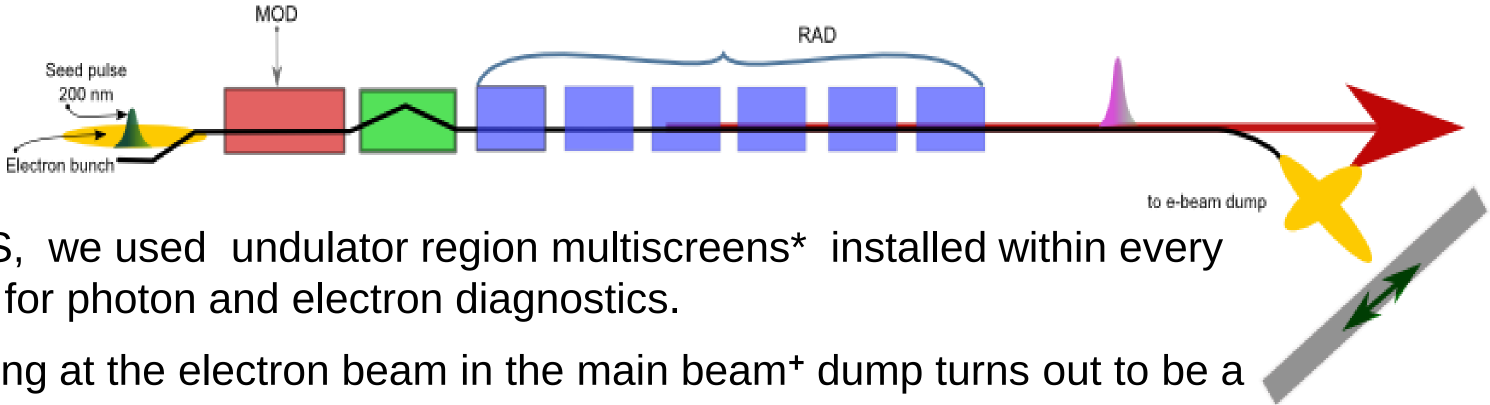
Diagnostics used for FEL Measurements

Photon diagnostic PADReS[#] (Photon Analysis Delivery and Reduction System)



The mostly widely used FEL photon diagnostics have been PADReS components:
2 photon beam position monitors, 2 ionization gas cells used as intensity monitors, a spectrometer, two YAG screens and a calibrated photodiode.

[#]D. Cocco, C. Svetina, M. Zangrando



In addition to PADReS, we used undulator region multiscreens* installed within every undulator break, both for photon and electron diagnostics.

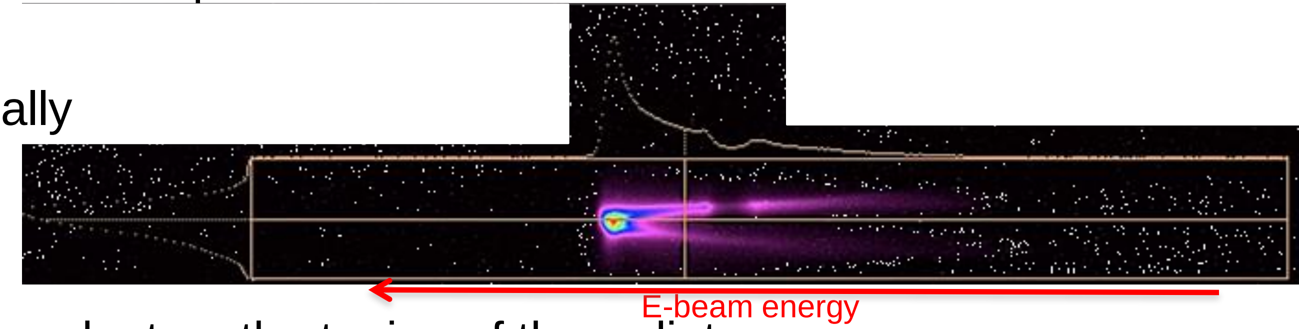
The YAG screen looking at the electron beam in the main beam[+] dump turns out to be a pivotal diagnostic system for FEL optimization.

***M. Veronese**
[+]L. Badano

Optimize the seeding process

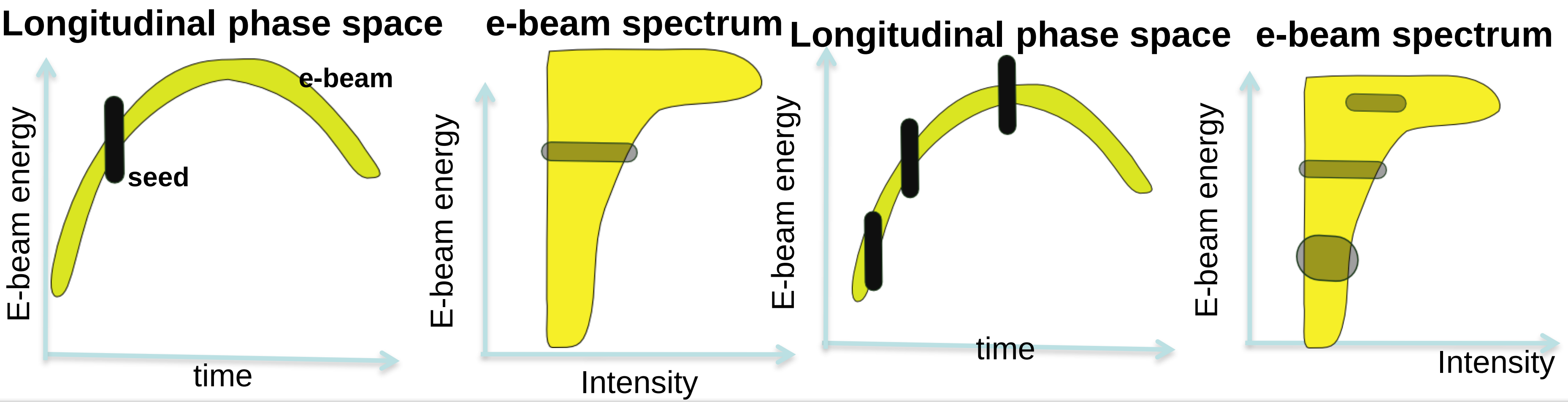
A useful diagnostic for detecting the occurrence of the seeding is provided by the MBD spectrum of the electron beam.

When the seed laser temporally overlaps the electron beam, a dark "shadow" appears on the MBD image.



The effect is only slightly dependent on the tuning of the radiators, and the dispersive sections R56.

We used this effect several times to confirm proper overlap since it (often) was more reliable than FEL intensity diagnostics.



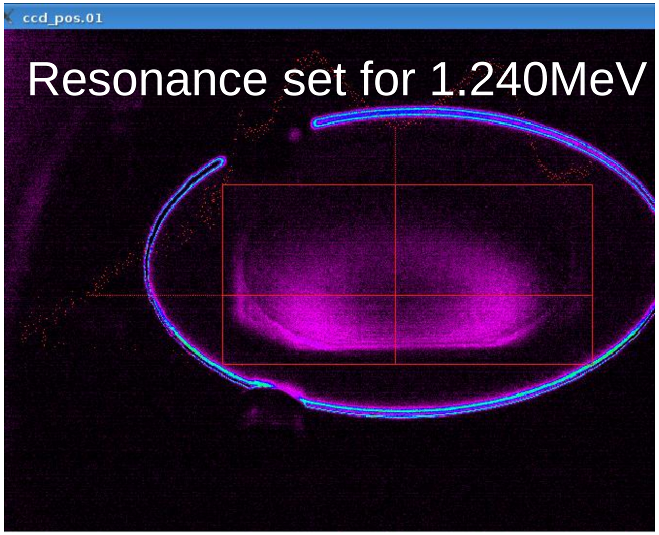
FEL, critical optimization

Optimizing the undulator tuning (both in K and electron beam position) is done by examining the far-field FEL spot size. This has been very critical for FERMI since the signal detected by the I0 monitor is sensitive to the FEL spatial mode.

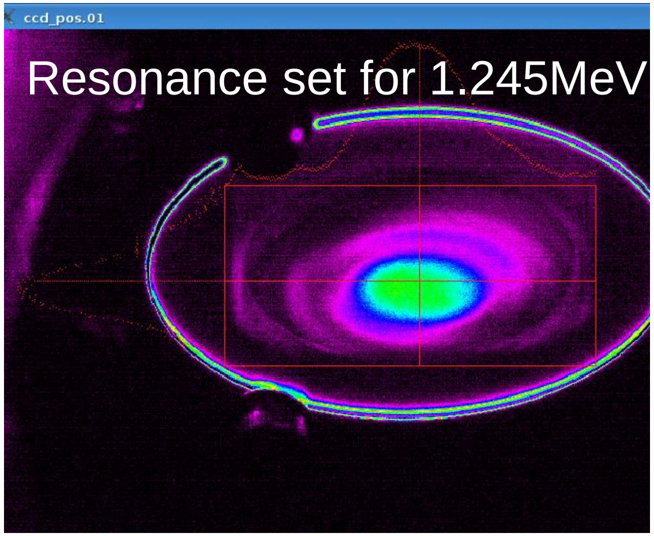
A small undulator mismatch (of the order of ΔK~0.1%) can produce a "doughnut" transverse mode with resonance moved to the outer portions of the electron beam.

The image of the FEL radiation on the PADReS YAG screen has become a critical diagnostic for FEL optimization, allowing us to increase the overall power by a factor 10 or greater.

The images to the right correspond to 43nm with 6 radiators tuned to resonance.



Resonance set for 1.240MeV



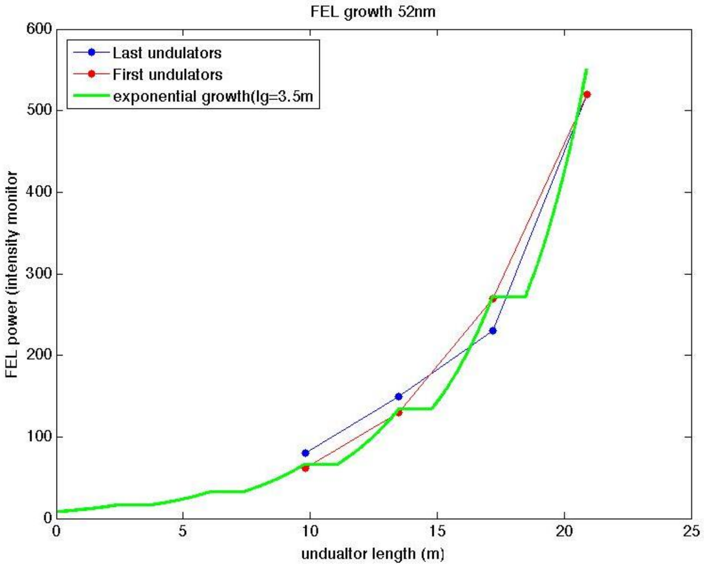
Resonance set for 1.245MeV

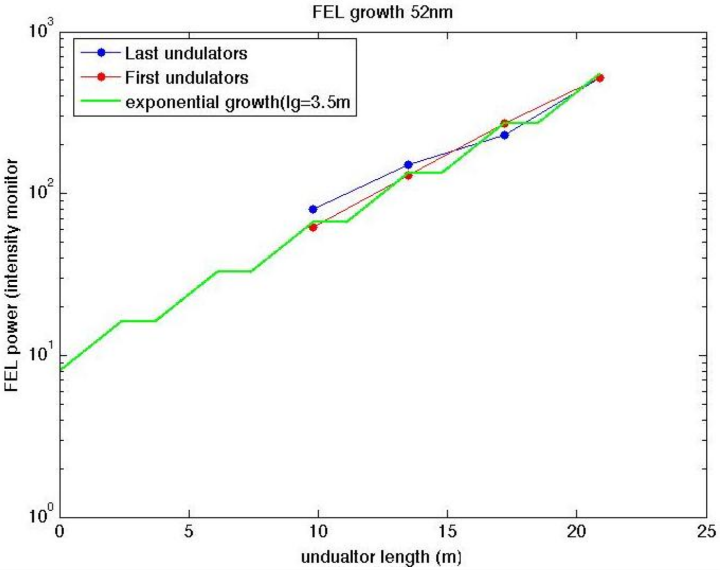
FEL gain

Once the FEL is optimized to produce an on-axis, TEM00 mode, there is a clear evidence of FEL gain with increasing undulator number.

Data reported here refer to the measured FEL power with the calibrated photodiode. Experimental conditions were:
350pC beam at 1.24GeV, electron beam compressed about a factor 3, seeding at 260nm, undulators tuned at 52nm (h=5).
Maximum measured FEL energy ~20μJ

Measured data fit well with the exponential growth predicted for a 200A beam with 4 mm mrad emittance and 600keV energy spread in the radiator. Although 4 mm mrad is the typical emittance measured in the FEL region, the slice emittance could be better than this but also the electron beam matching could be worse. A more careful beam characterization is needed.


FEL growth 52nm


FEL growth 52nm

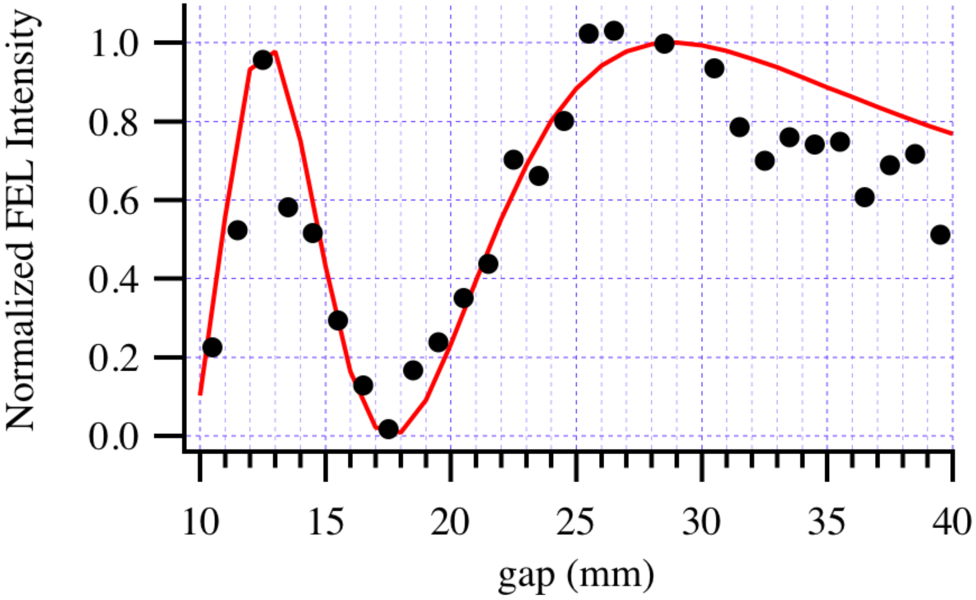
Phase shifter: utility and calibration

The radiation’s longitudinal coherence is confirmed by the clear effect of the phase shifter.

Using the phase shifter it is possible to coherently sum or subtract the emission from two consecutive undulators tuned to the same harmonic of the seed laser.

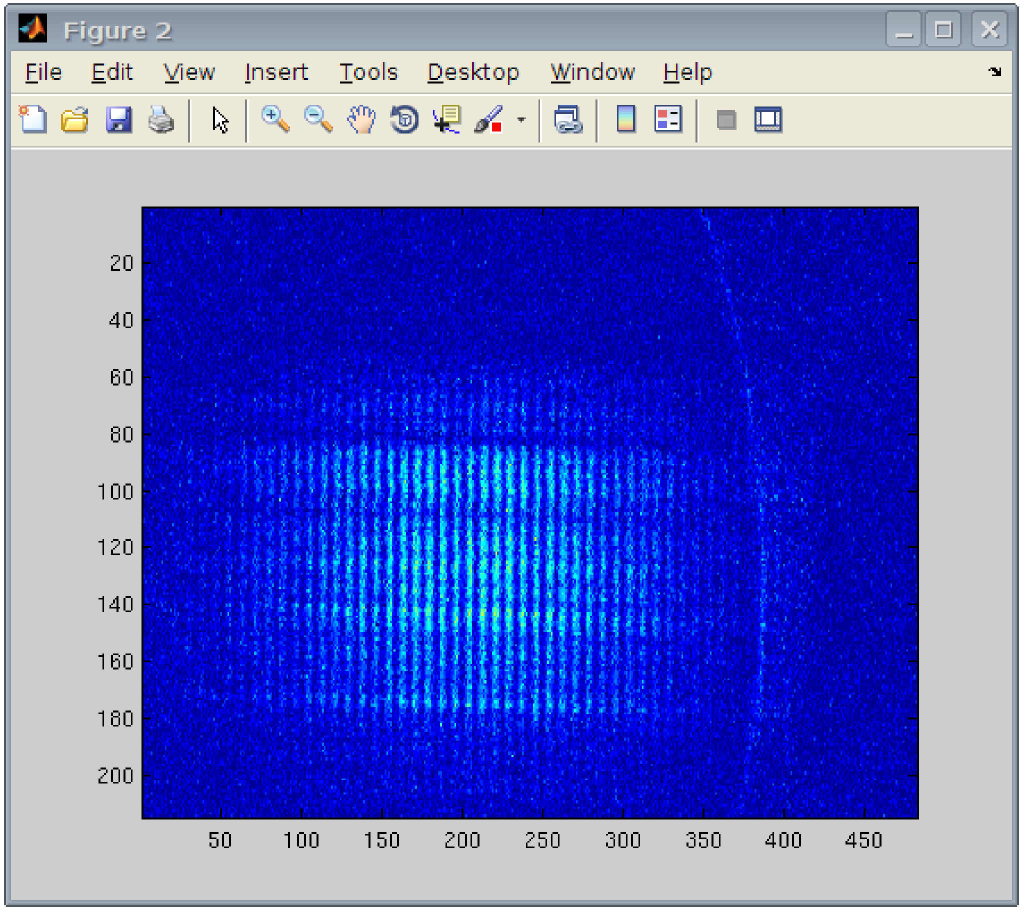
Data here reported refer to the case of a 350pC beam compressed by abut a factor 3. The beam is seeded at 260nm and passes through two consecutive radiators tuned to 52 nm.

The measured FEL intensity (dots) as a function of the phase shifter gap is compared with a simple interference model of the phase shifter (solid line) based on the measured magnetic field.



Transverse coherence (1/2)

Once the FEL output been optimized to a Gaussian TEM00 mode, measuring the spatial coherence(*) has been straightforward.



Several images have been acquired for different wavelength and slits conditions. Preliminary analysis indicate a very good degree of spatial coherence. Further quantitative analysis is ongoing.

Image of interference fringes of 52-nm FEL light produced by a double slit. Images taken with 9 second of acquisition (i.e., 90 pulses).

(*) Young slit experiments on FERMI proposed by F. Parmigiani and setup implemented by C. Svetina.

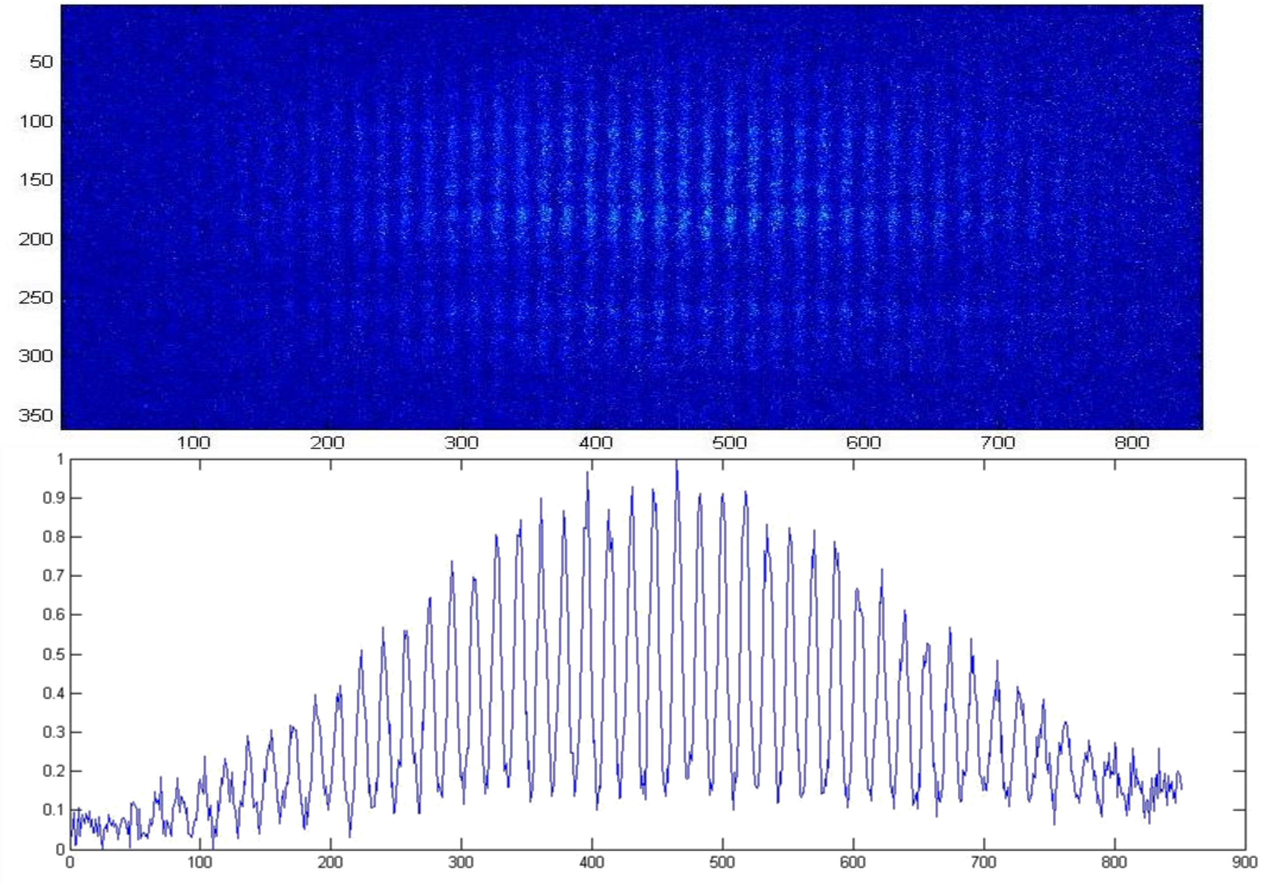
Transverse coherence (2/2)

Double slit experiments were repeated at 32.5 nm, also showing very good transverse coherence.

Fringe visibility is very high along the entire FEL pulse and also for relative large slits separation, indicating a very high degree of transverse coherence.

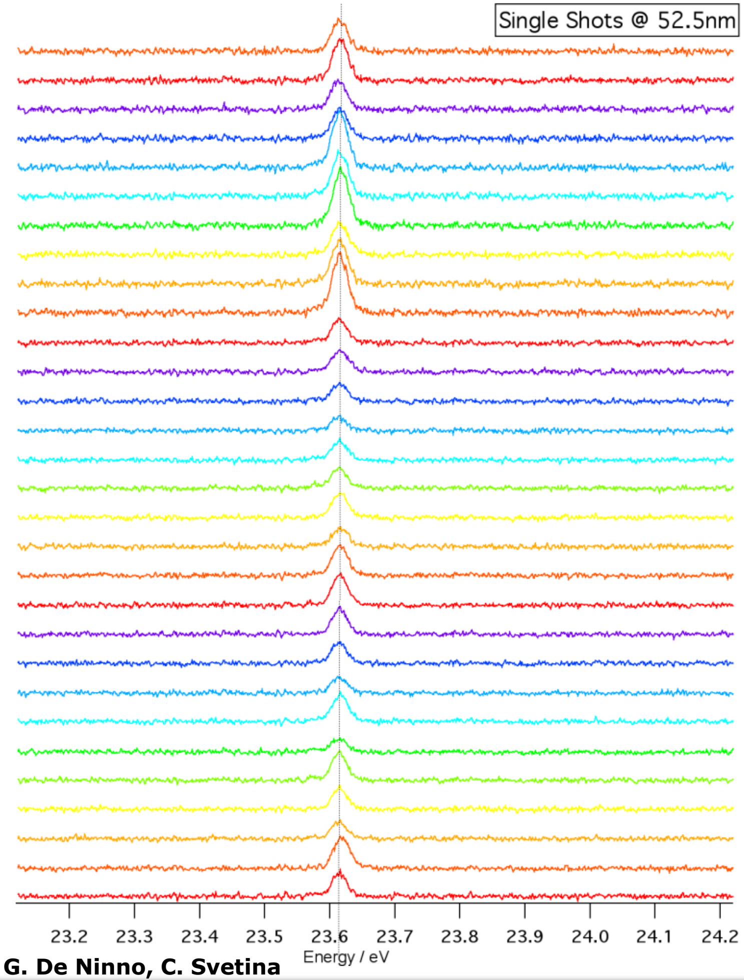
Quantitative analysis is ongoing.

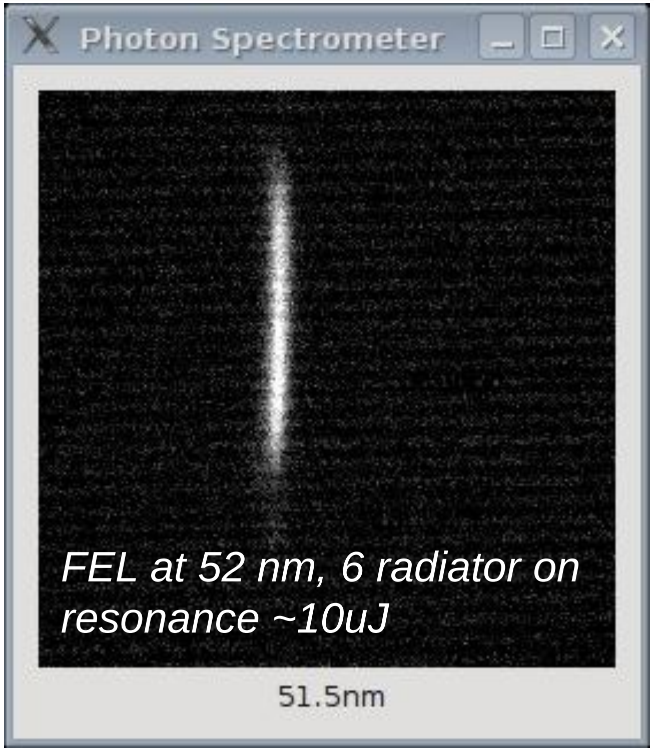
FEL at 32.5 nm, 6 radiators, 450pC, compression ~3. Slit separation = 0.8 mm, width = 20 μm



FEL bandwidth

From the first day of FEL operation there has been clear benefits from using the external seeding in terms of bandwidth and photon energy stability.



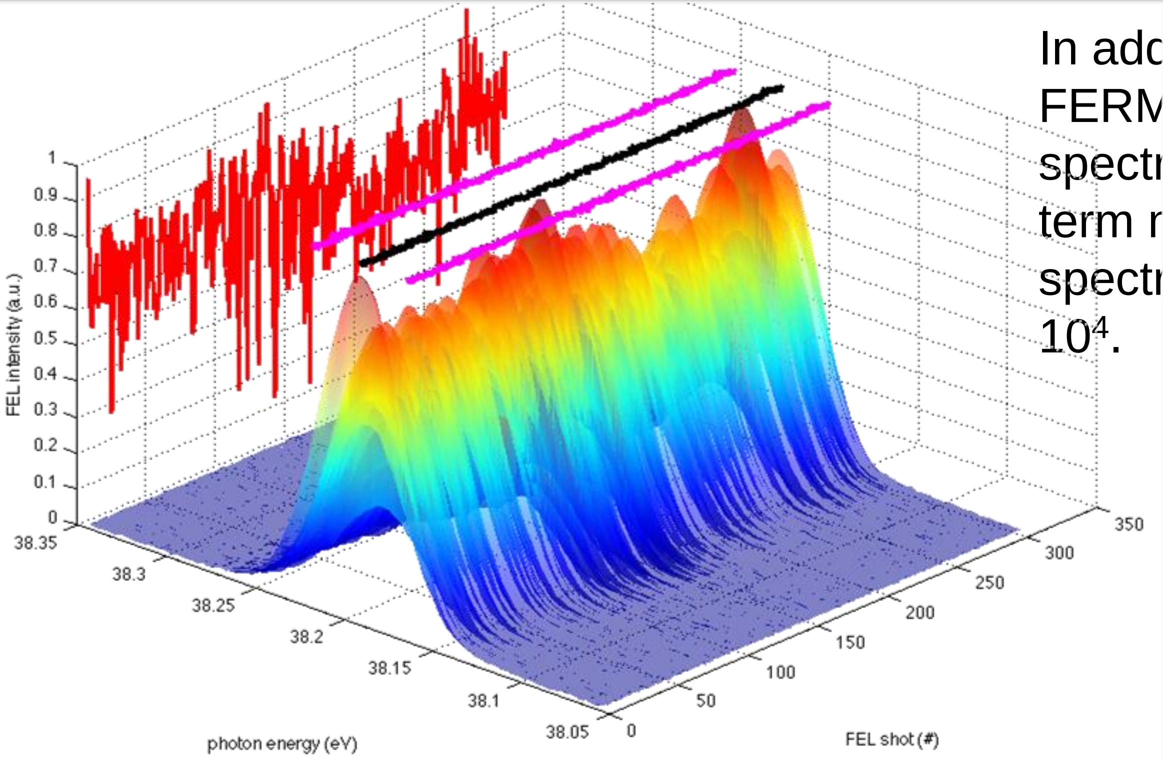


FEL at 52 nm, 6 radiator on resonance ~10uJ

Single shot measurements at 52nm show a bandwidth of 28meV (~0.1%)

Typical seed laser parameters:
Pulse length ~150fs FWHM with a measured bandwidth at 260nm of 0.8nm (15meV)

FEL wavelength stability

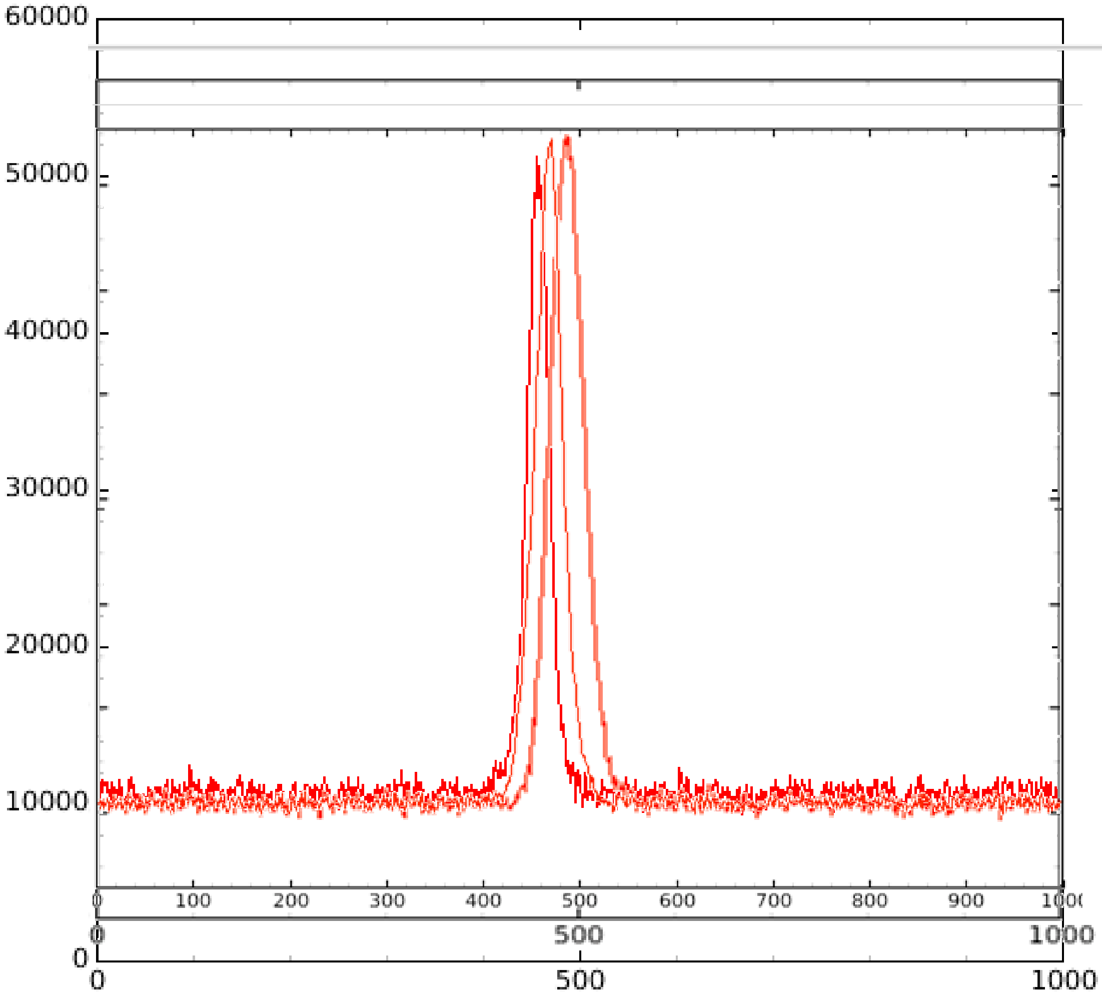


In addition to the very narrow spectrum FERMI is characterized by excellent spectral stability. Both short and long term measurements show that the spectral peak jitter of less than 1 part in 10^4.

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)

FEL tuning



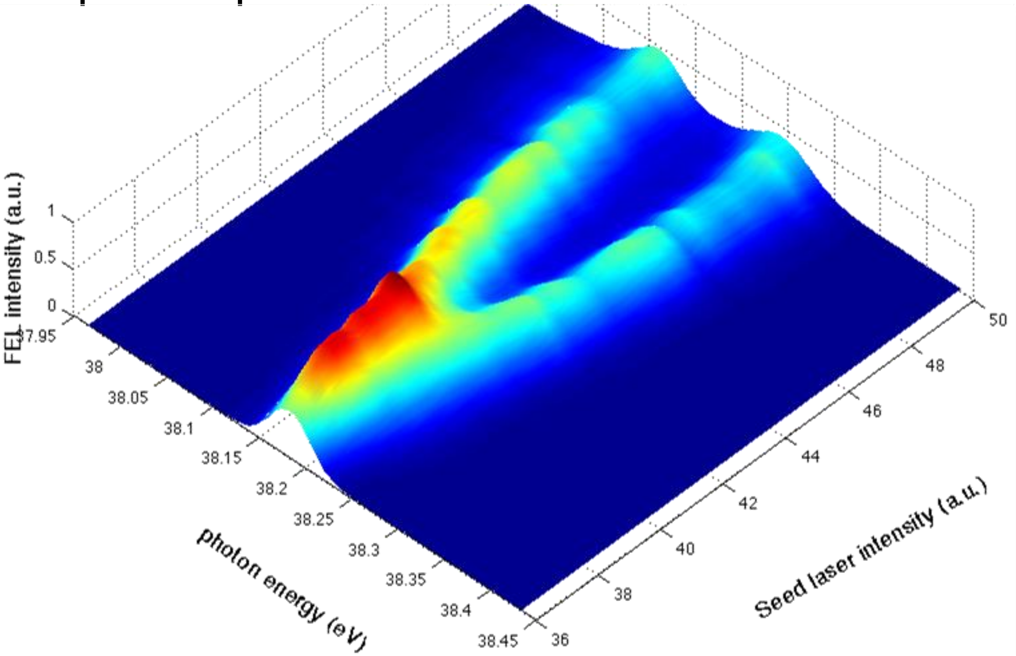
A small FEL tuning range around 52nm has been achieved by changing the seed laser wavelength of 1 nm (0.4%).

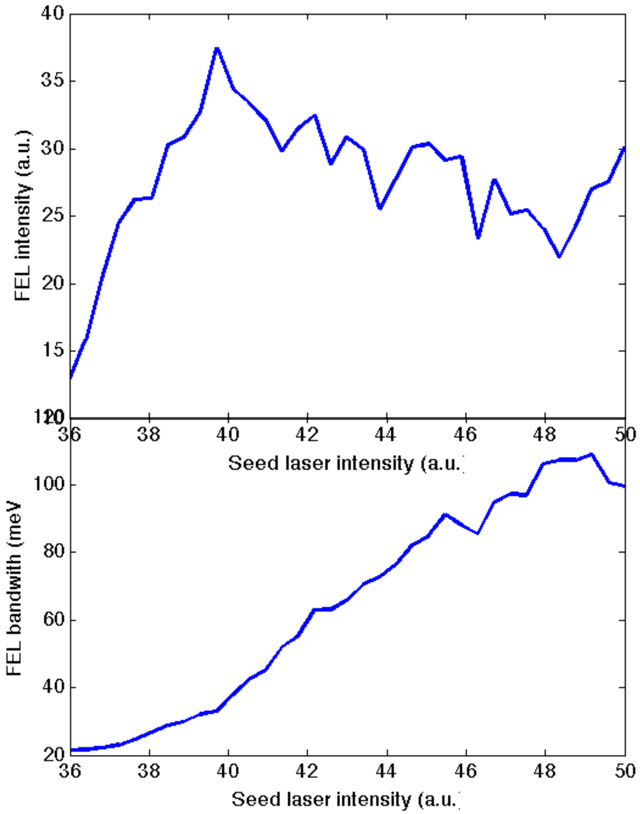
After tuning of the seed laser wavelength, the undulator resonance is changed accordingly to maximize the FEL power.

In the future, we larger tuning ranges will be possible using the tunability of the seed laser based on the Optical Parametric Amplifier.

FEL bandwidth control (1/3)

The measured FEL bandwidth depends critically on the FEL optimization.
By controlling the seeding process (seed intensity and/or R56 strength) it is possible to control the FEL bandwidth. In case of a very strong seed (overbunching regime) two output spectral peaks are found while the overall FEL intensity is only slightly affected.



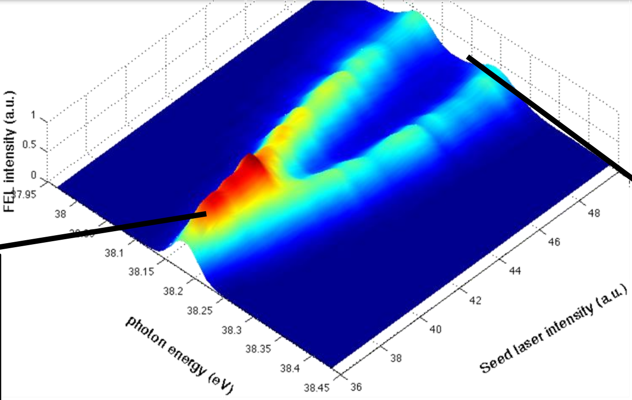


Both RMS and FWHM fits to the FEL bandwidth show an increase up to a factor 5 .

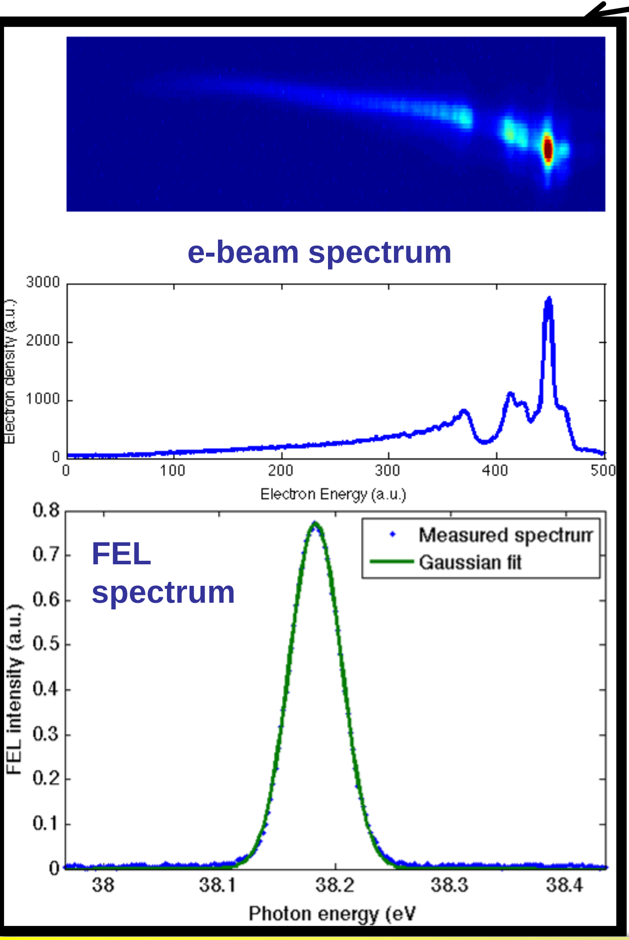
Data refers to a 350pC beam compressed ~3 at 1.24GeV. R56~16μm and the 6 radiators tuned at 32.5nm in circular polarization.

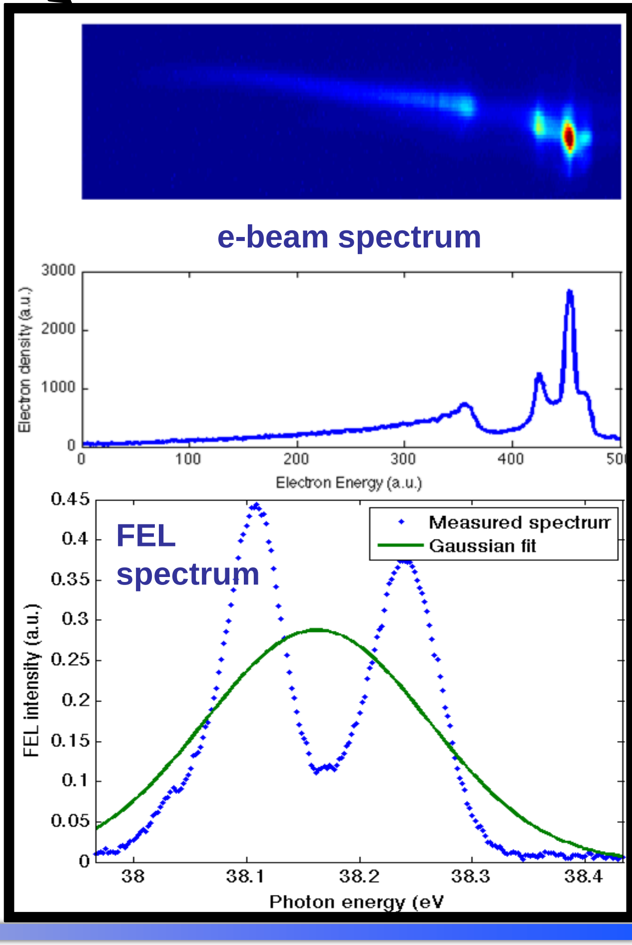
FEL bandwidth control (2/3)

The effect of a stronger seeding process is clearly visible also in the e-beam spectrometer.

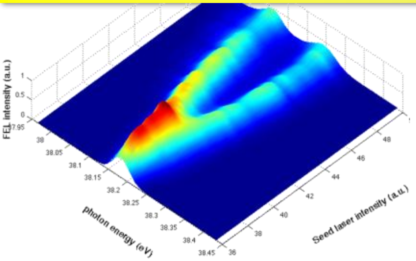


The double peak in the FEL spectrum is associated with a larger “hole” in the e-beam spectrum.





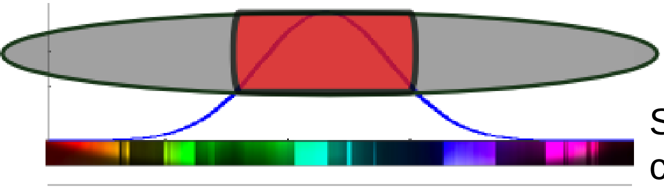
FEL bandwidth control (3/3)



The two spectral peaks individually have a bandwidth only slightly larger than that of lower seed power, single peak FEL emission (~30meV).

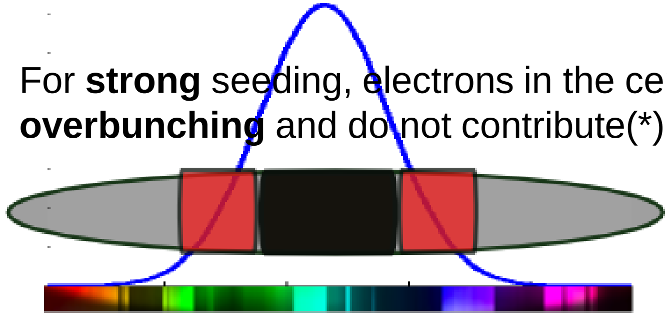
A possible interpretation of the phenomenon is that in the case of overbunching, only the head and the tail of the seed are producing an effective bunching used in the radiator and they are at different wavelength due to a residual chirp in the seed laser.

Only electrons that see **optimal seed intensity** contribute to FEL

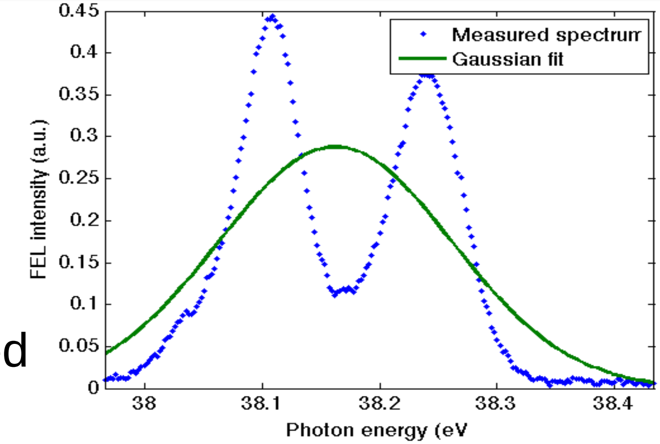


Seed laser with a residual chirp on the head and tail.

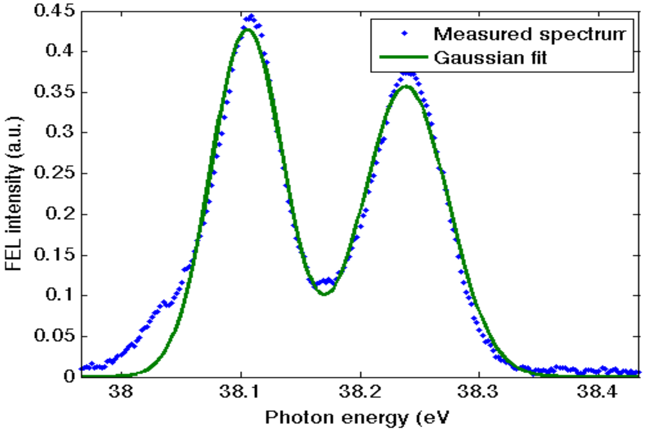
For **strong** seeding, electrons in the central region go in **overbunching** and do not contribute(*)



(*) M. Labat, et al. Phys. Rev. Lett. 103, 264801 (2009)



Single Gaussian fit
photon energy = 38.16
bandwidth = 100 meV



First peak
Intensity = 1
photon energy = 38.11
bandwith = 30

Second peak
Intensity = 0.8 (a.u.)
photon energy = 38.24eV
bandwith = 36meV

Additional studies

The effect of a chirped seed pulse has been studied as a possible means to increase the overall number of photons per pulse.

FEL in circular polarization has been produced (**TUPA05:** Polarization Tunability at FERMI@Elettra. First Tests and Perspectives)

FEL has been operated also with the fully tunable, Optical Parametric Amplified seed laser. (**TUOC4**: Design and First Experience with the *FERMI* Seed Laser)

Coherent Harmonic Generation has been extended efficiently down to the 13th harmonic (20nm) with an estimated FEL power of tens of μJ.

Clear evidence of coherent emission has been demonstrated down to 17nm (15th harmonic). Studies are ongoing to better optimize the FEL and quantify the produced intensity.

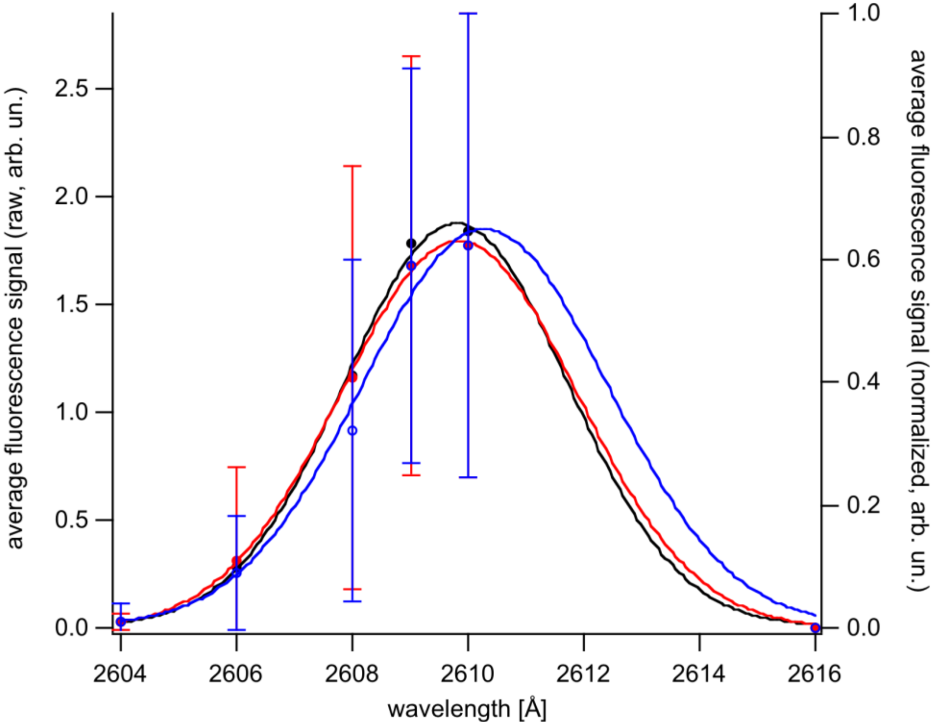
We have evidence of coherent transition radiation from the bunched electron beam at 130 nm or shorter wavelength (**WEPB23:** Coherent Ultraviolet Transition Radiation for Seeded FEL Bunching Optimization).

First use of FEL light in experimental chambers (1/2)

During the last run, the Low Density Matter team(*) used the FEL tunability to scan the photon energy and measure the signal at an absorption resonance around the He 1s-4p
.
The experiment immediately showed the dependence of the fluorescence signal on the FEL wavelength.

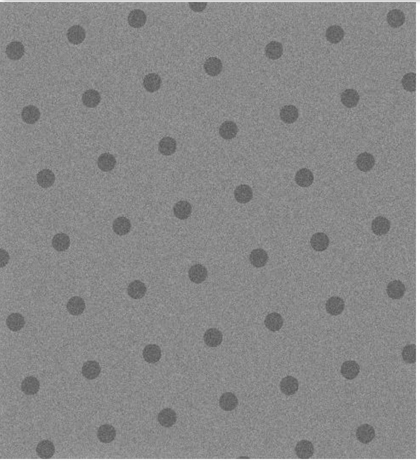
The atomic resonance is much narrower than the FEL linewidth, so measurement of the output spectrum by the LDM group allows independent determination of the input FEL spectrum.

A more detailed data analysis of other collected data is ongoing, to study the effect of FEL intensity on the ionization process.

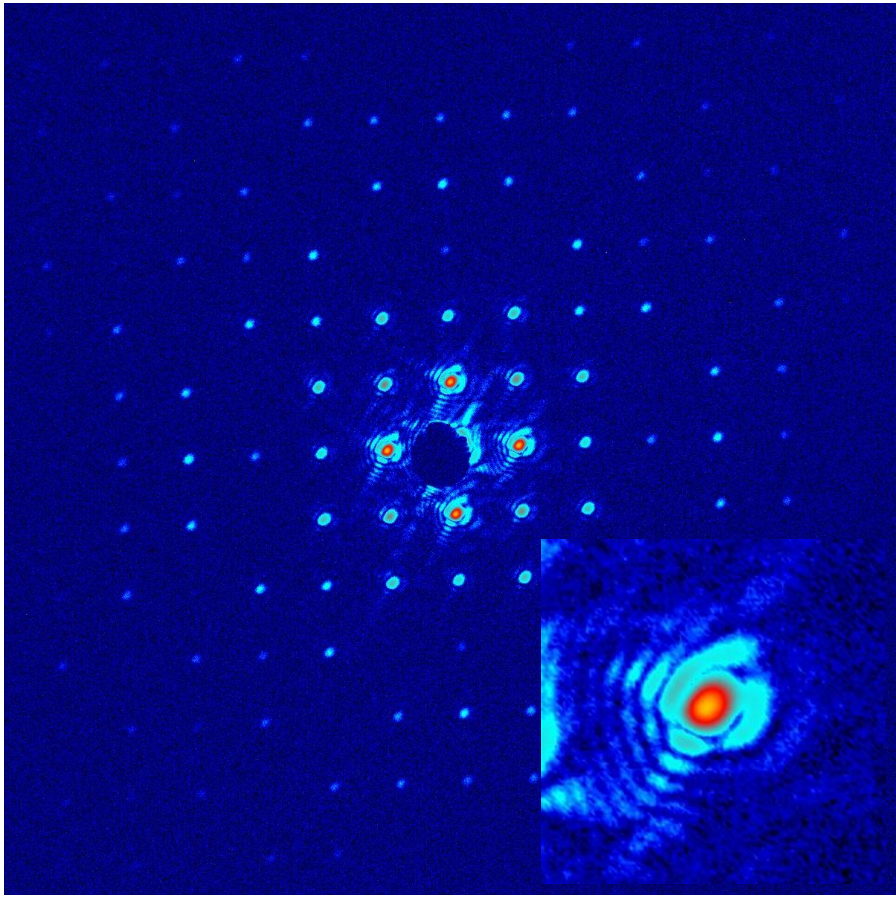


(*) C. Callegari, V. Feyer, G. Cautero, A. Moise, K. Prince, R. Richter, R. Sergo (Sincrotrone Trieste) V. Lyamayev, M. Mudrich, F. Stienkemeier, U. Person (University of Freiburg) L. Avaldi, P. Bolognesi, M. Coreno, P. O' Keeffe (CNR-IMIP, Montelibretti) M. Alagia, M. de Simone, A. Kivimäki, (CNR-IOM, TASC, Trieste) M. Devetta, P. Milani, P. Piseri, T. Mazza (University of Milan) S. Stranges (University "La Sapienza", Rome) T. Möller, Y. Ovcharenko (TU Berlin) M. Drabbels (EPFL Lausanne).

First use of FEL light in experimental chambers (2/2)



FEL radiation at 32.5 nm was used to start commissioning of DiProI experimental chamber. The FEL signal was filtered by using two Al filters (400 and 800 nm) which reduces the pulse intensity by more than an order of magnitude



Due to problems with the K-B focusing mirror the FEL spot was produced using a 20 μm pin-hole in front of the specimen.

Under these conditions coherent scattering images were recorded from a periodic array by integrating the signal for 10-100 seconds. This supposes that single shot CDI will be possible removing the filters and using the focusing K-B mirror

F. Capotondi, E. Pedersoli, R.H. Menk, M. Kiskinova and
H. Chapman et al. (CFEL-DESY), J. Hajdu et al. (Uppsala), M. Bogan et al. (SLAC), M. Pivovaroff, A. Nelson et al. (LLNL)

Future FERMI FEL Plans

- FEL-1
  - FEL-1 optimization is expected to be concluded in 2011.
  - Two projects are already underway to implement HHG sources as a possible seeds for FERMI at λ~30nm and more long term below 10 nm
  - When FEL-2 comes online FEL-1 could be temporarily configured for HHG tests (*end 2012?*).
- FEL-2
  - FEL-2 has been already shown to be very compatible with the ECHO scheme. A possible temporary modification could be done (if agreeable with users) for testing ECHO at the 50th or higher harmonic (late *2013?*).

Acknowledgments

Success at FERMI has been the result of a concerted and unified effort by the entire FERMI team and the support staff at Sincrotrone Trieste.
The physics commissioning team thanks all the people involved in the project (including consultants, guests and advisory committee members) that contributed to the design, construction and commissioning of FERMI over the the past 6 years.

My special thanks goes to the following people that contributed to FERMI's success by working on most of the commissioning shifts over the past two years:
P. Craievich, S. Di Mitri, W. Fawley, L. Froehlich, G. De Ninno, G. Penco, S. Spampinati, C. Spezzani, M. Trovo'

Thank you