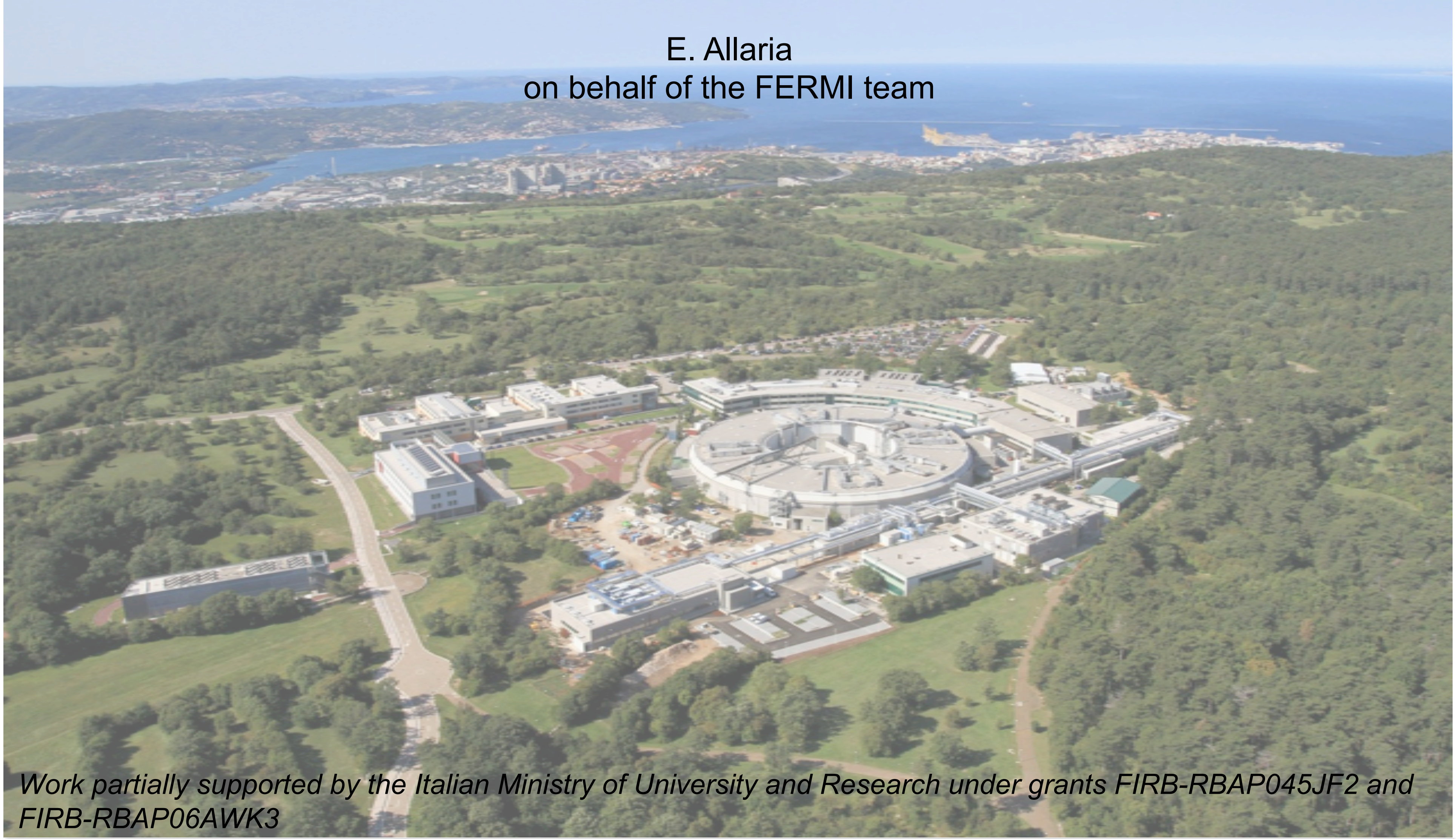
FERMI, a seeded Free Electron Laser source for experiments



E. Allaria
on behalf of the FERMI team

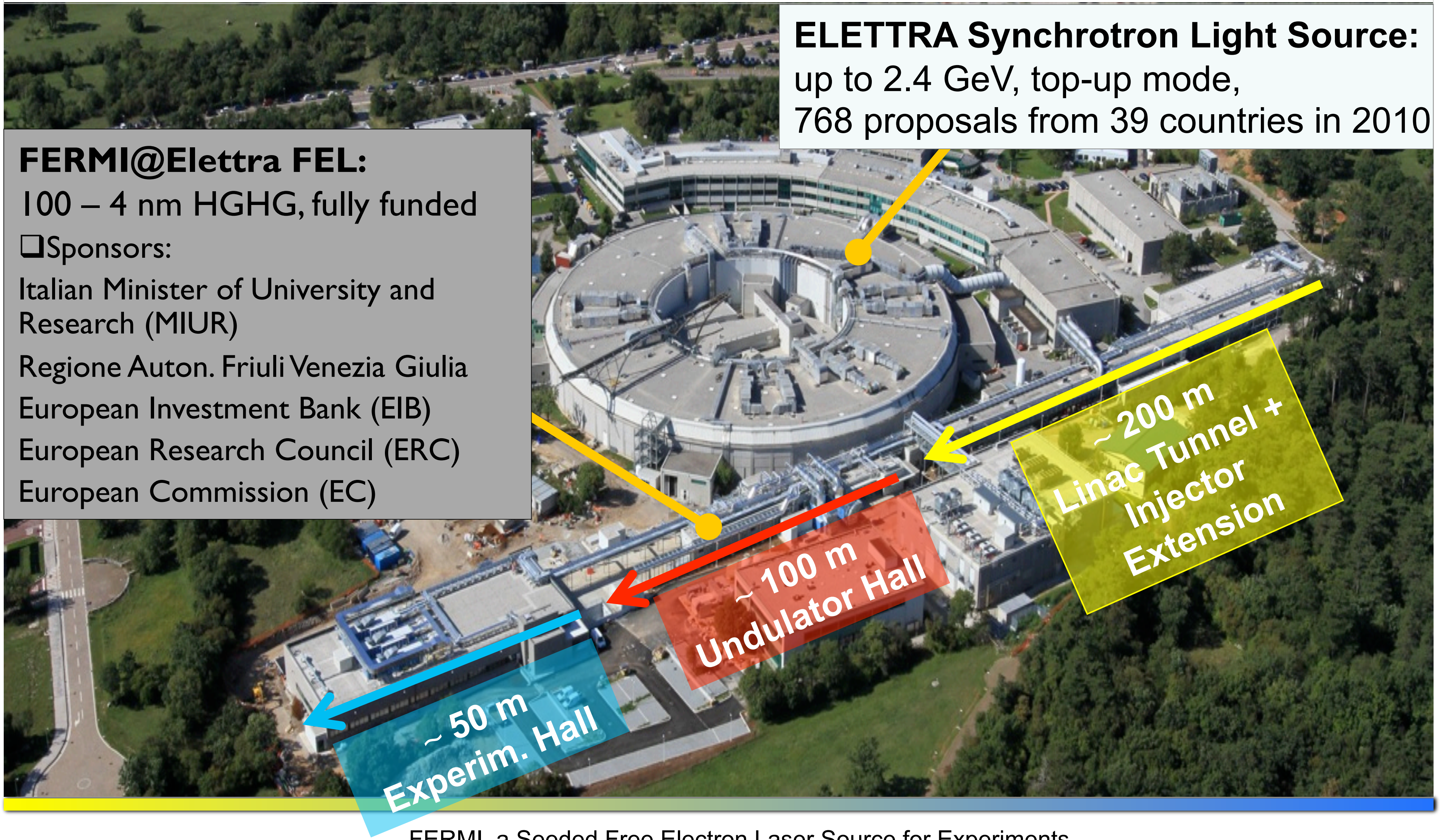
Work partially supported by the Italian Ministry of University and Research under grants FIRB-RBAP045JF2 and FIRB-RBAP06AWK3

Outline

- Elettra and the FERMI FEL project
  - FERMI parameters
- FEL mechanisms
  - Self Amplified Spontaneous Emission
  - High Gain Harmonic Generation
- Commissioning activities
  - FEL commissioning and results
- FEL experimental results at FERMI
  - Coherence properties
  - Spectral characterization
- Future plans

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,
768 proposals from 39 countries in 2010

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)

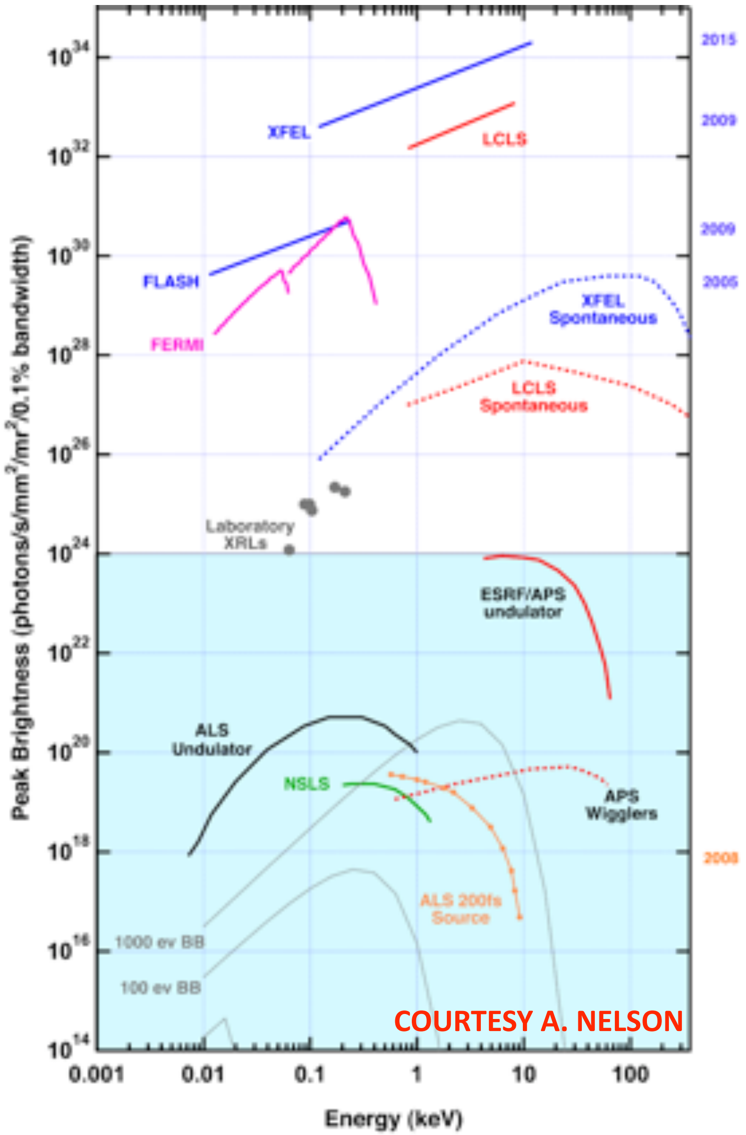
FERMI main features

FERMI@Elettra single-pass FEL user-facility.

Two separate FEL amplifiers 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

SCIENCE CASE

F. Parmigiani (Head of Scientific Programs)

- **Low Density Matter** (*coord. C. Callegari*):
  - structure of nano-clusters .... *brightness*
  - high resolution spectroscopy .... *narrow bw, λ-tunability*
  - magnetism in nano-particles .... *circular polarization*
  - catalysis in nano-materials .... *fs pulse and stability*

- **Elastic and Inelastic Scattering** (*coord. C. Masciovecchio*):
  - Transient Grating Spectroscopy (collective dynamics at the nano-scale) .... *bw Fourier Tansform Limit*
  - Pump & Probe Spectroscopy (meta-stable states of matter) .... *brightness, λ-tunability*

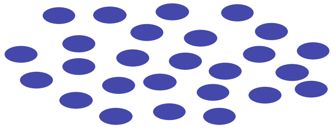
- **Diffraction and Projection Imaging** (*coord. M. Kiskinova*): Single-shot & Resonant Transverse Coherent Diffraction Imaging
  - morfology and internal structure at the nm scale
  - chemical and magnetic imaging .... *brightness*

Free Electron Laser components

High brightness light sources in VUV - X-ray spectral range defined as 4th Generation Light sources are based on the high gain Free Electron Laser mechanism.

Free-Electron Lasers exploite the spontaneous and/or induced emission of a relativistic electron beam “guided” by the periodic and static magnetic field generated by an undulator

1) Relativistic **electron beam**

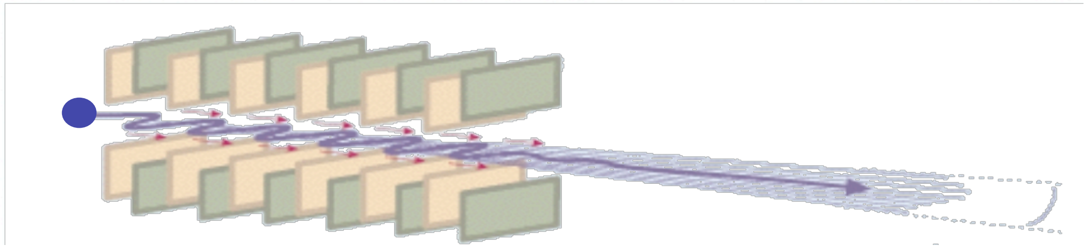


Energy (γ)
Current (I)
Emittance (ε)
Energy spread ($\delta\gamma$)
Dimensions (σ)

Resonance condition

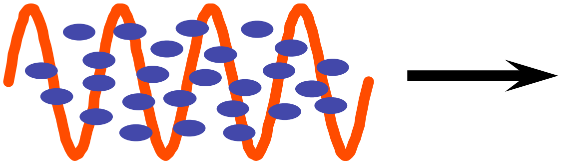
$$\boxed{\lambda = \frac{\lambda_w}{2\gamma^2}\left(1+K^2\right)}$$

2) **Undulator**



Magnetic period (λ_w)
Magnetic strength (K)
Undulator length (L)

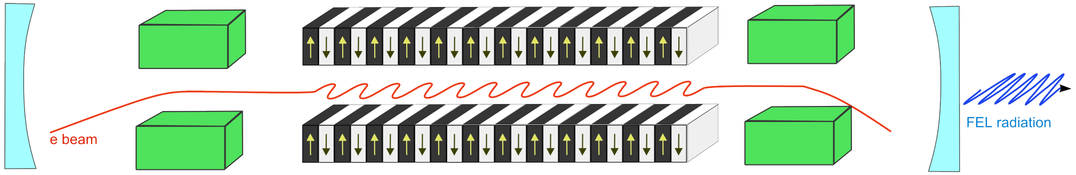
3) **Electromagnetic field** co-propagating with the electron beam and **getting amplified** to the detriment of electrons’ kinetic energy



Wavelength (λ)
Power (P)

FEL Types: Oscillator, Seeded FEL, SASE

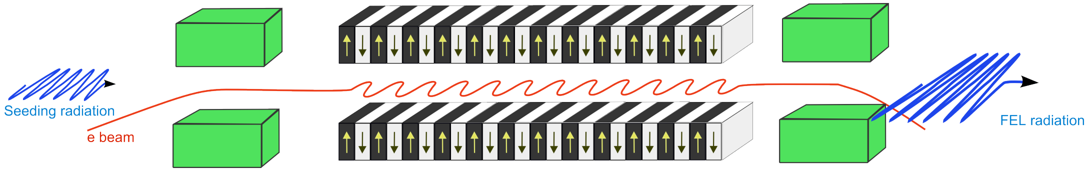
Oscillator FEL



The tunability toward short wavelengths is limited by the availability of high quality mirrors.

Very good spectral quality (mirrors act as a filter).

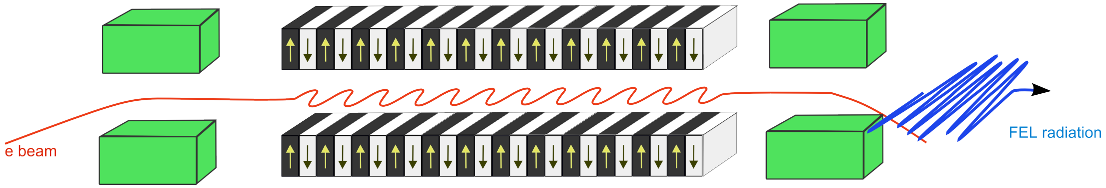
Amplifier FEL



The tunability toward short wavelengths is limited by the availability of the seed wavelength.

Spectral quality limited by the quality of the electron beam.

SASE FEL



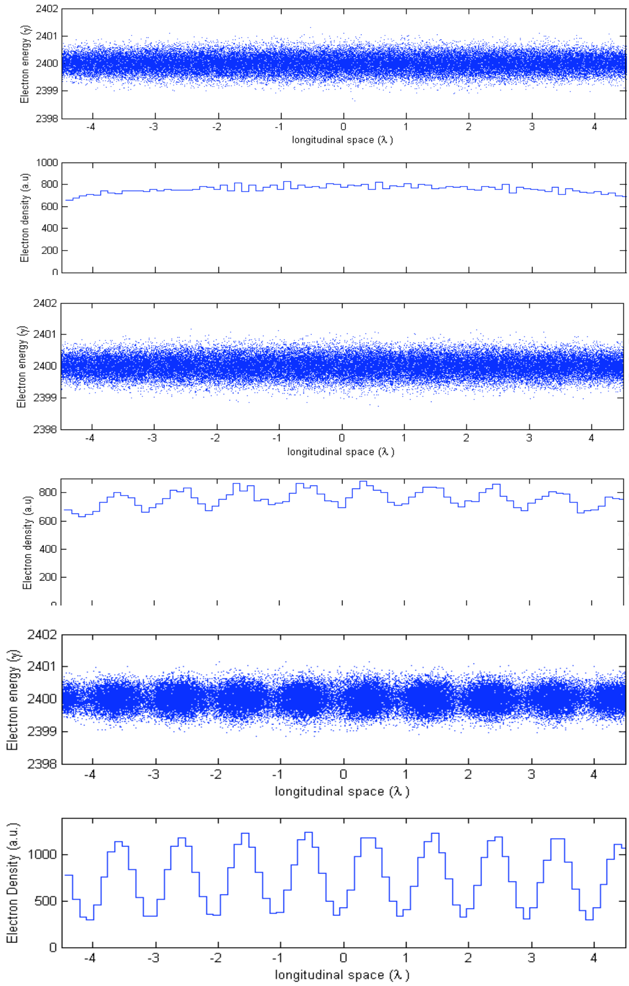
Potentially completely tunable, FEL wavelengths only depend on the resonance condition.

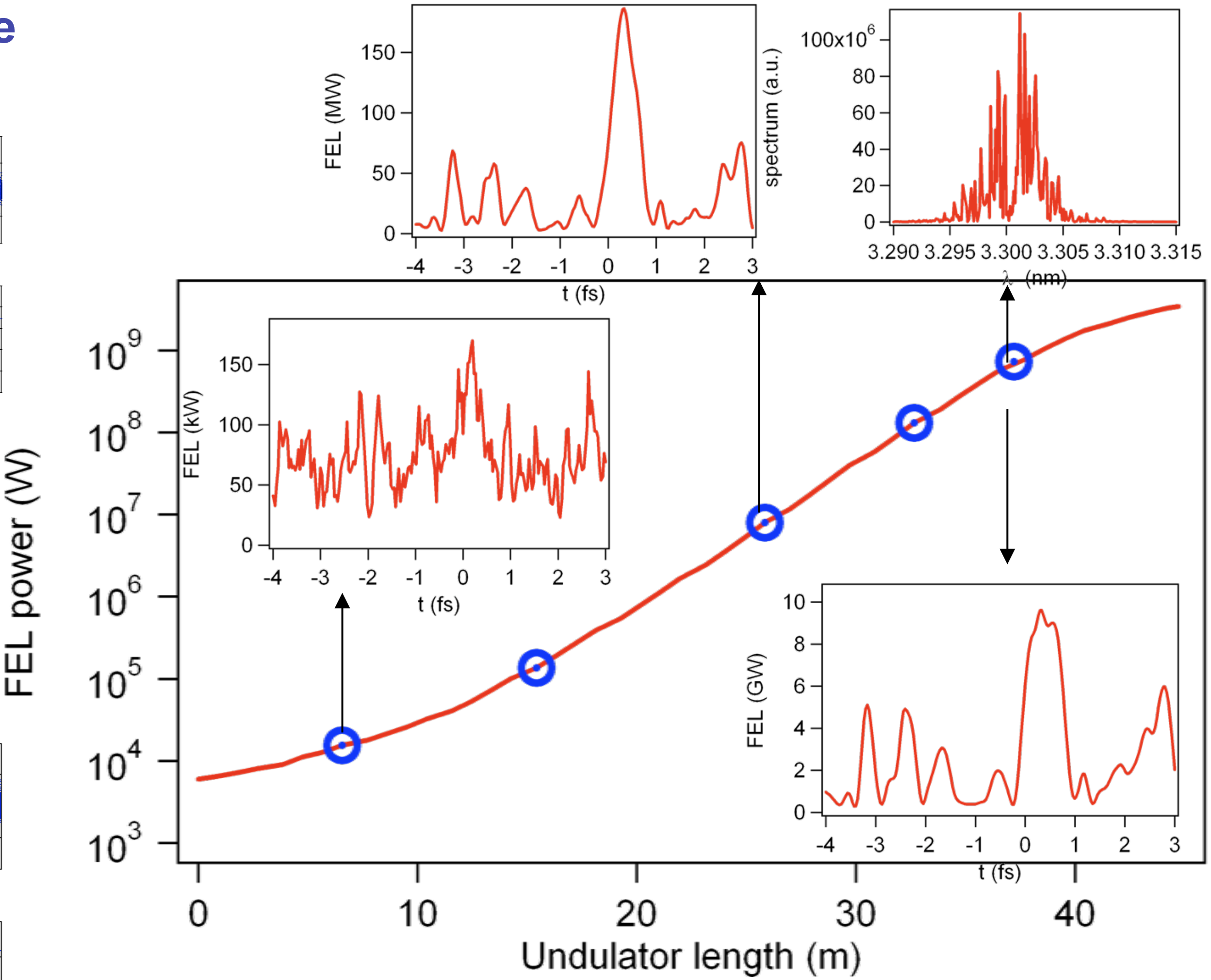
Tighter requirements for the electron beam parameters

Spectral properties are affected by the random startup

Self-Amplified Spontaneous Emission (SASE)

Electron beam phase space





SASE limitations

- SASE FELs are the most suitable for X-ray FELs (FLASH, LCLS, SACLA, …)
- As it has been shown by the LCLS and SACLA, SASE can be succesfully operated at wavelength below 1nm.

However:

- Desired power is reached only with long undulators
- Spectral properties are affected by the startup from noise

For the soft X-ray spectral range other facilities are looking for a seeded configuration.
The FERMI@Elettra has considered from the beginning the seeded option in order to produce high quality FEL pulses.
The seeding is also under investigation now at FLASH and recently studies started for a seeded FEL configuration at LCLS.

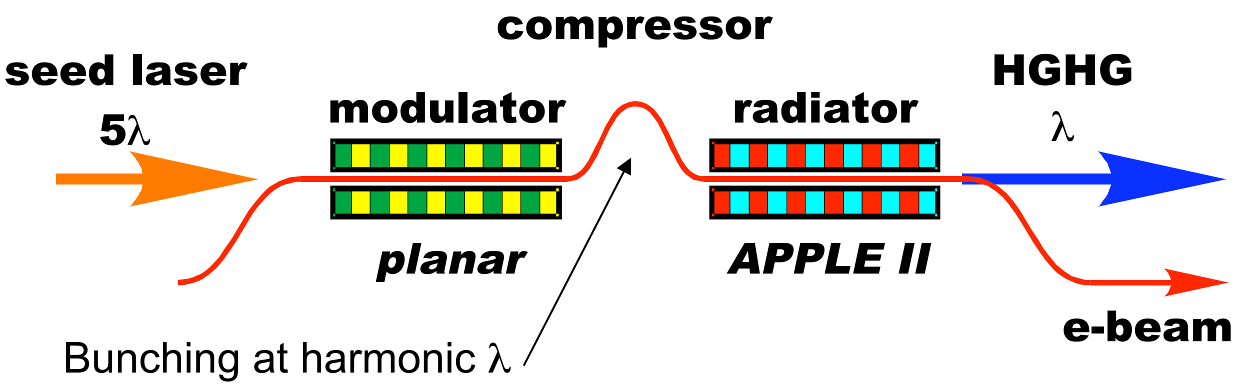
Benefits of a Seeded FEL

A “seed” laser controls the distribution of electrons within a bunch:

- Very high peak flux and brightness (comparable to SASE FELs)
- Temporal coherence of the FEL output pulse
- Control of the time duration, wavelength and bandwidth of the coherent FEL pulse
- Close to transform-limit pulse provides excellent resolving power without monochromators
- Perfect synchronization of the FEL pulse to the seed laser
- Reduction in undulator length needed to achieve saturation.

The problem with seeding is that there are not sources available for direct seeding in the very short wavelength range (few nanometers).

High Gain Harmonic Generation - HGHG



compressor

seed laser
5λ

modulator

planar

radiator

APPLE II

HGHG
λ

e-beam

Bunching at harmonic λ

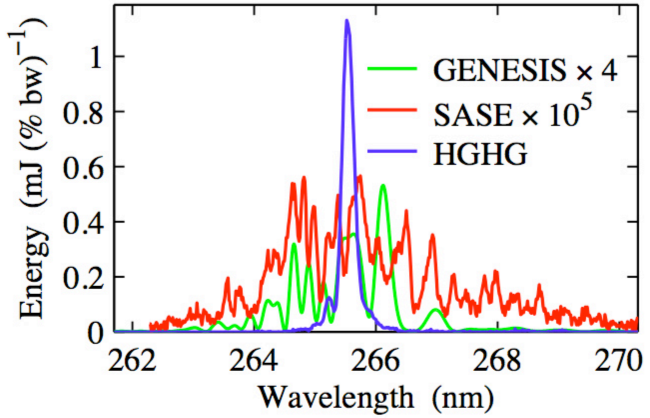
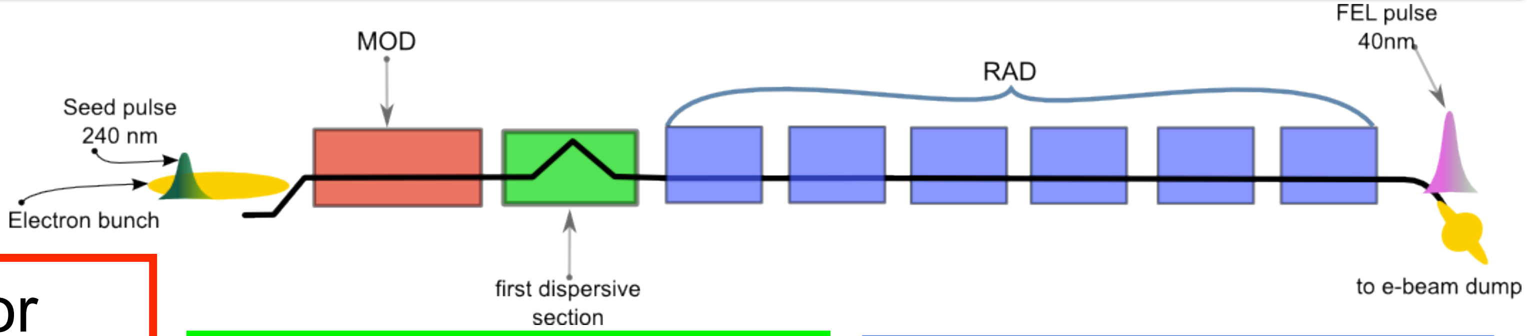


FIG. 4: Single shot HGHG spectrum for 30 MW seed (blue), single shot SASE spectrum measured by blocking the seed laser (red) and simulation the SASE spectrum after 20 m of NISUS structure (green). The average spacing between spikes in the SASE spectrum is used to estimate the pulse length.

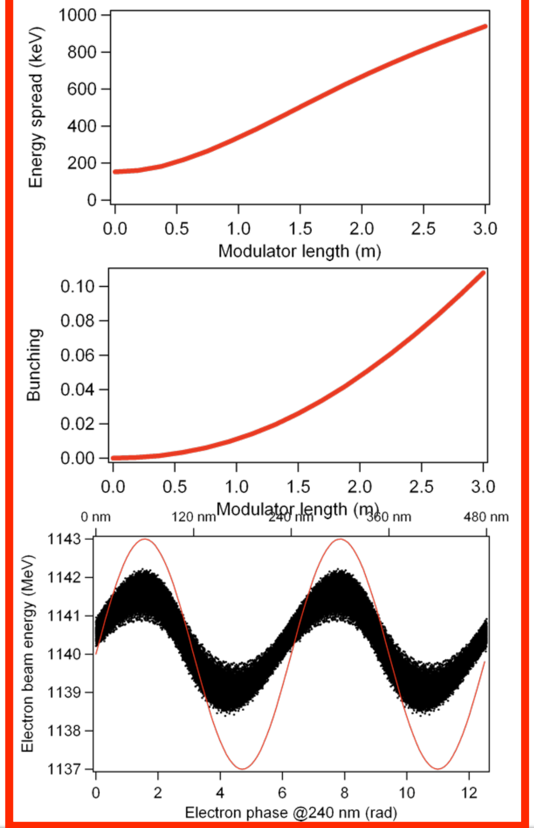
Compared to SASE devices, generally more compact and nearly full temporally coherence output; many spectral parameters more easily controlled (e.g., pulse length, chirp).

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

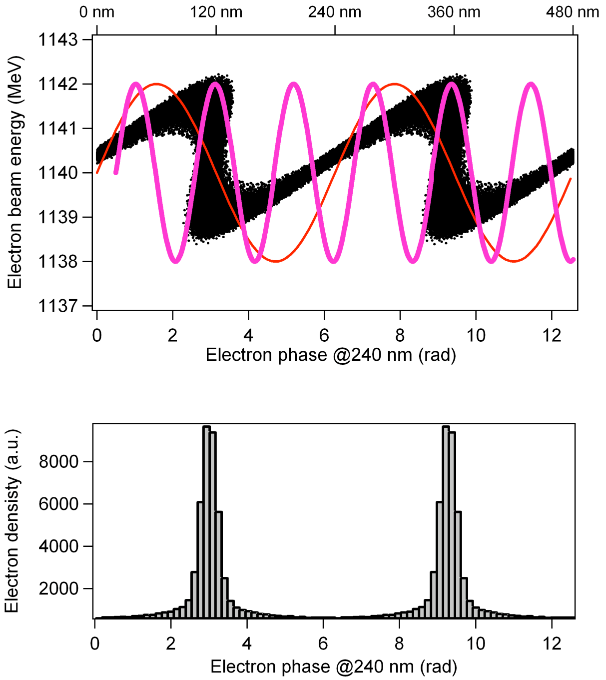
HGHG scheme in FEL-1



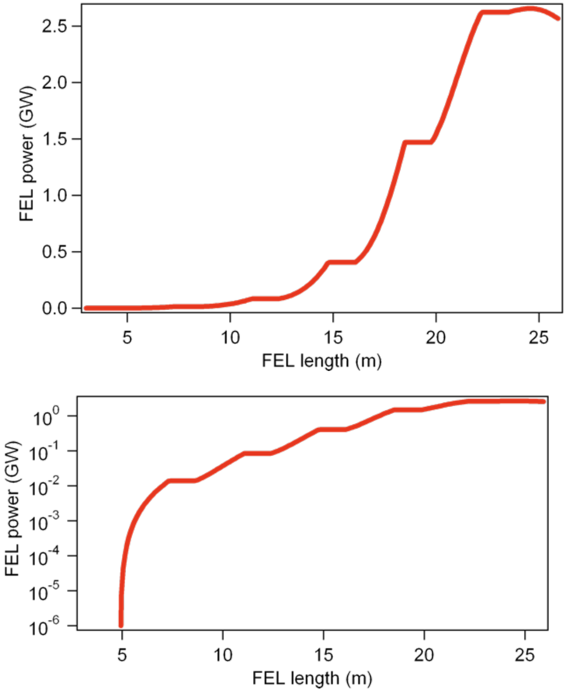
Modulator



Dispersive section



Radiator

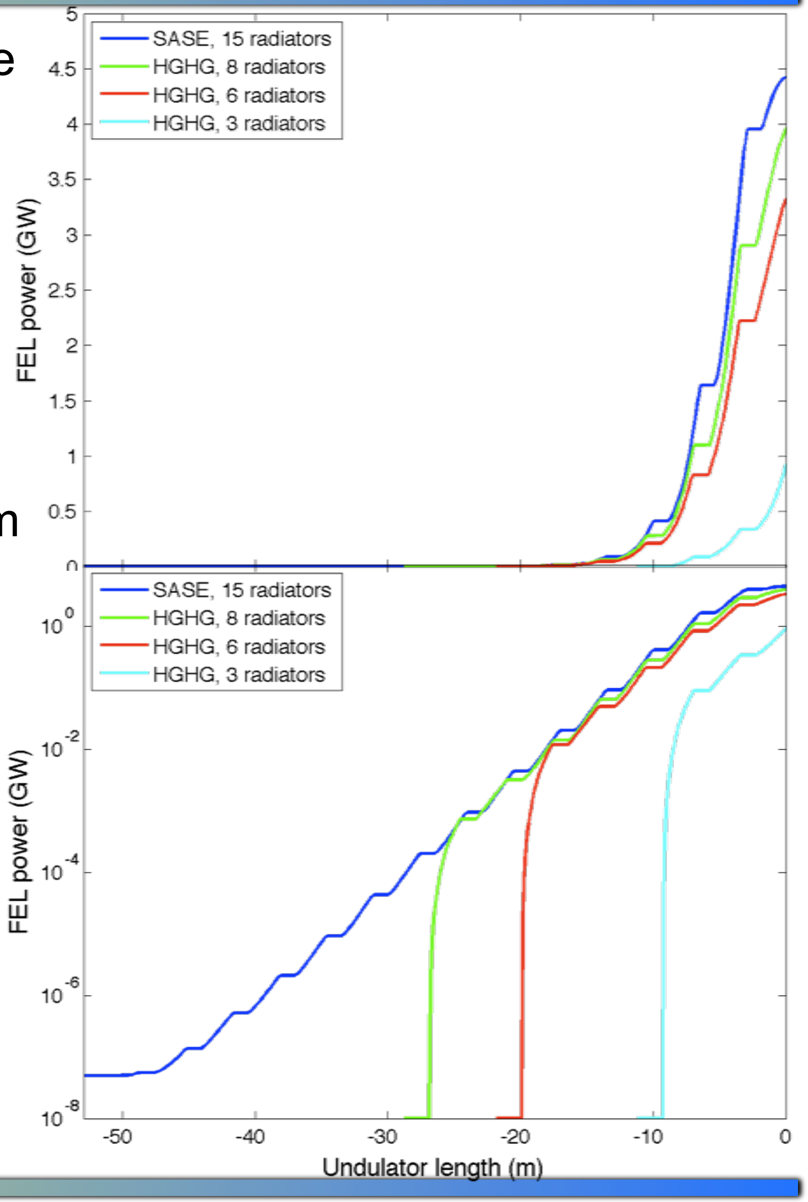


HGHG configuration

The HGHG FEL can be configured depending on the desired FEL performance and available undulator length.

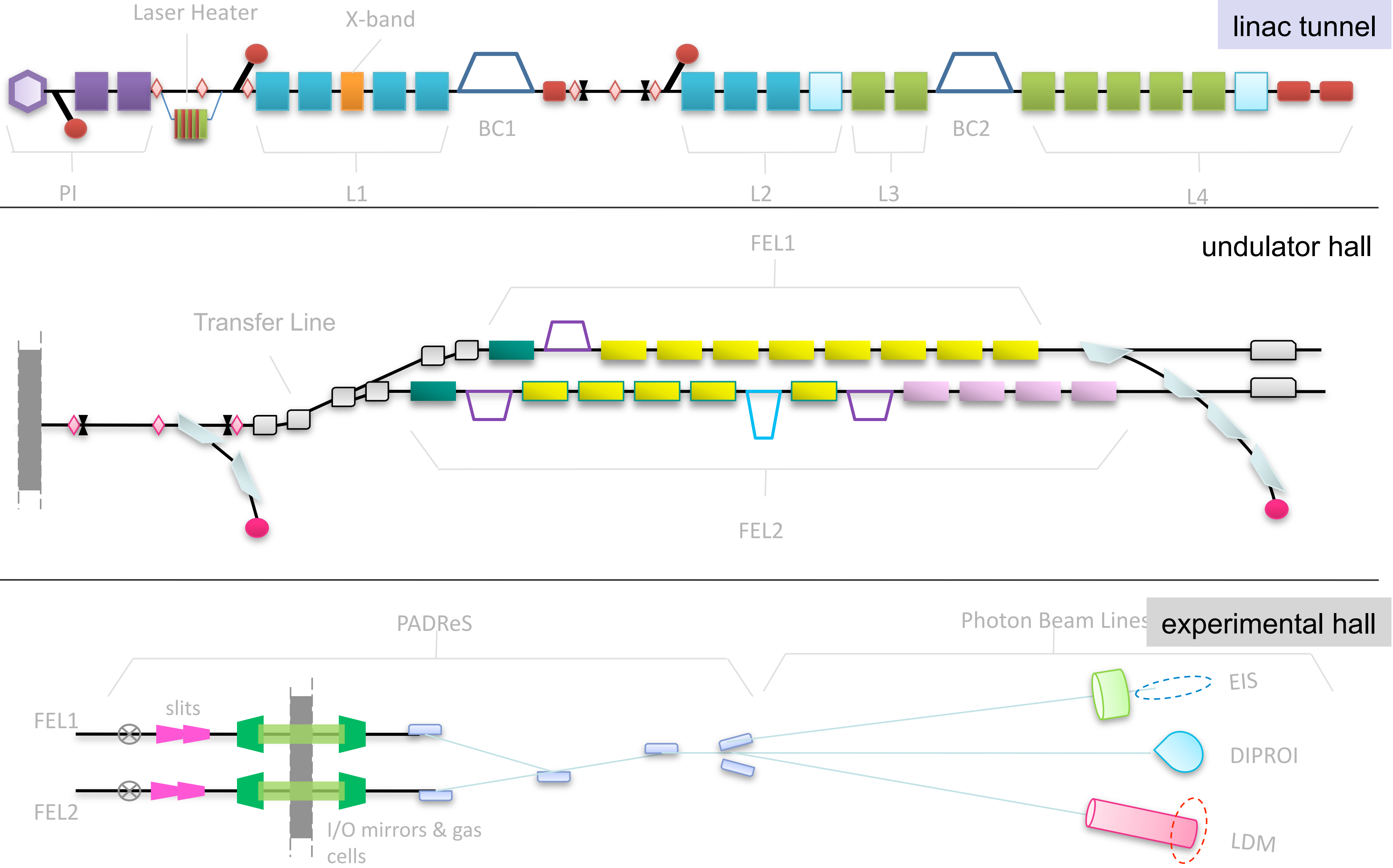
An output power comparable to the one achievable from the SASE FEL can be produced using a radiator which is about half the length needed for SASE. In the case of a very short radiator only coherent emission from a prebunched electron beam is generated and no exponential gain is expected in the final radiator.

The maximum power from the FEL only slightly decreases with the undulator length.



Reported simulation results are for a FERMI FEL with the parameters similar to FERMI:
Energy: 1.2GeV, peak current: 1kA, emit: 1 mm mrad, energy spread: 150keV, wavelength: 20nm, … .

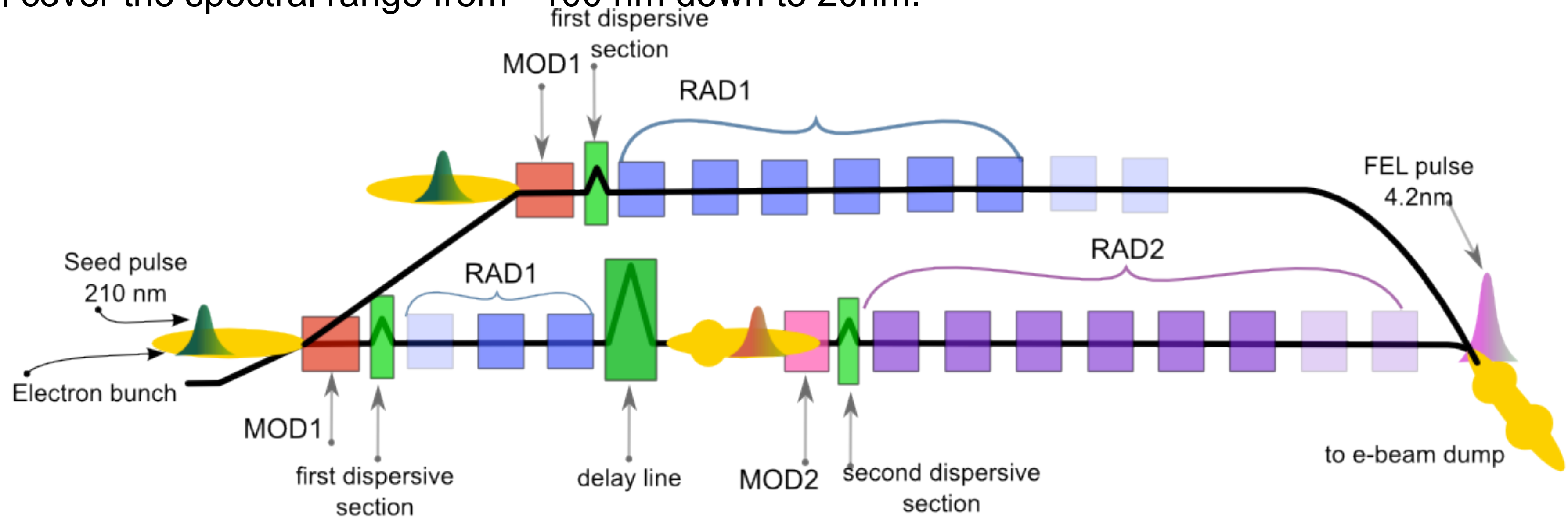
FERMI Layout



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.

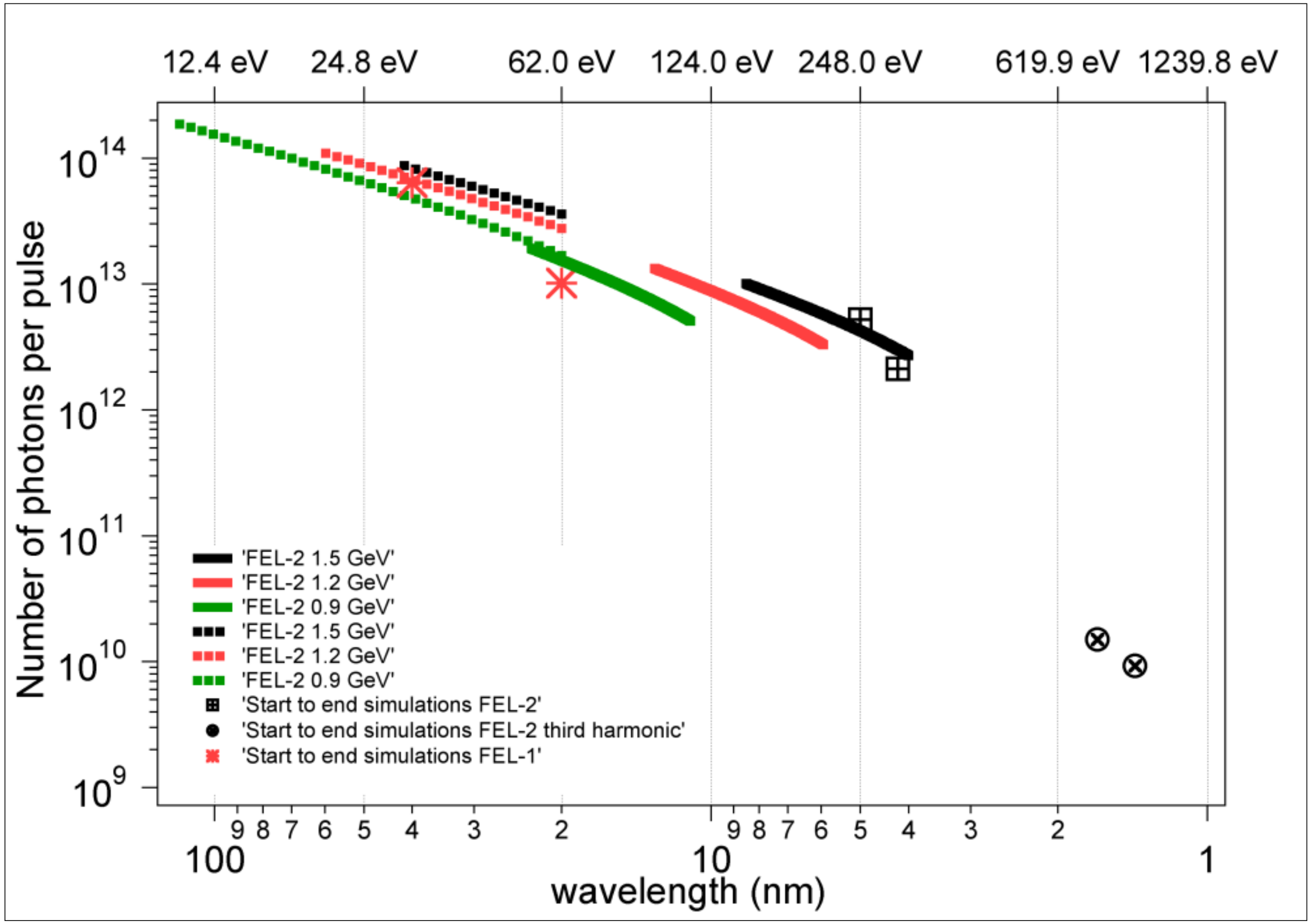


FEL-2, in order to be able to reach the wavelength range from 20 to ~4 nm starting from a seed laser in the UV, will be based on a double cascade of high gain harmonic generation. The nominal layout uses a magnetic electron delay line in order to improve the FEL performance by using the fresh bunch technique.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

FEL1 and FEL2 Output Power vs λ

Using the expected values for the electron beam parameters for FERMI we can predict the FEL performance.

Parameter	*Value*	*Units*
Energy	**0.9-1.5**	**GeV**
Peak current	**>750**	**A**
Emittance	**<1.0**	**mm mrad**
Energy spread	**<150**	**keV**



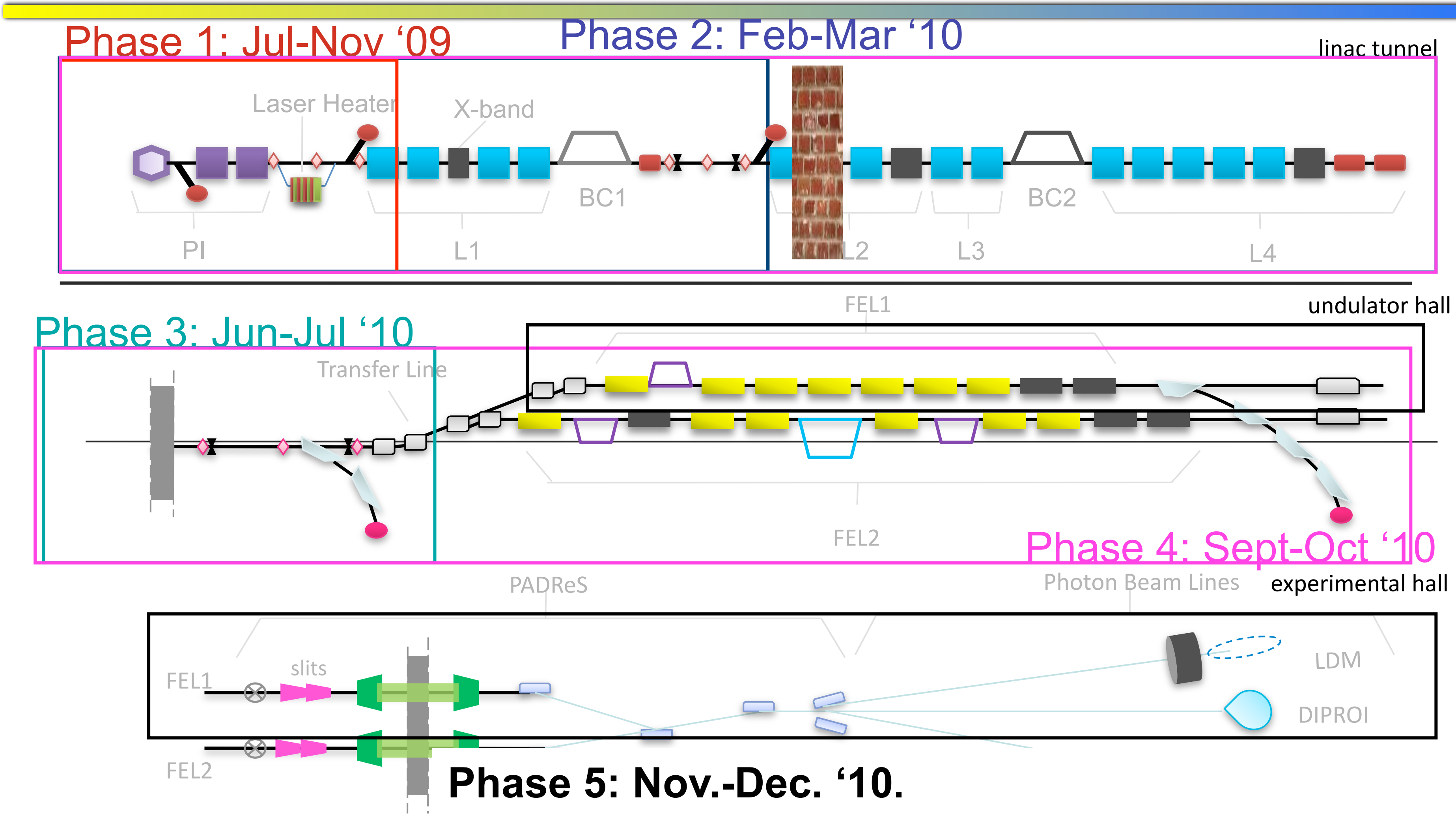
Lines predicted using M.Xie formulae for expected FERMI parameters assuming 40fs pulse length

Points Ginger and Genesis simulations for S2E files

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} [PRELIMINARY]
Compressed e-beam 43nm with calibrated* photodiode:	~45μJ, ~1*10^{13} [PRELIMINARY]
Compressed e-beam 32.5nm with calibrated* photodiode:	**~100μJ**, ~1*10^{13} [PRELIMINARY]
Compressed e-beam 20nm with calibrated* photodiode:	~40μJ, ~1*10^{12} [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

FERMI commissioning phases



Phase 1: Jul-Nov '09

Phase 2: Feb-Mar '10

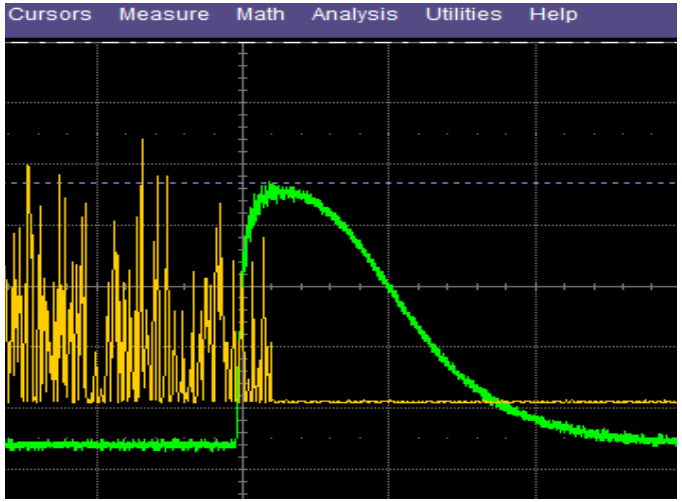
Phase 3: Jun-Jul '10

Phase 4: Sept-Oct '10

Phase 5: Nov.-Dec. '10.
Seeded FEL1: single stage HGHG scheme

Commissioning progress

- PI Laser, Gun & Injector commissioned: Sept. 2009 **– 2.5 months.**
- Linac & First Bunch Length Compressor: 2010 **– 3.5 months.**
- Transfer Line to Main Beam Dump: 2010 **– 1.5 month.**
  - FELI Undulators installed in 3 weeks.
- FIRST LASING at 43 nm: 2010 **– 1.5 months.** (Dec.13, first try!)



- X-ray Transport & Diagnostics: 2011 **– 2 months.**
  - Tests with Beam Lines *LDM* and *TIMEX*: 3 weeks.
- Exponential Gain, Stability, Polariz. & Tunability: 2011 **– 1.5 months.**
- 65 – 32.5 nm to *LDM*, *TIMEX* & *DIPROI* Lines: 2011 **– 3 weeks.**

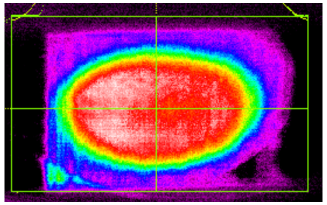


Photo-Injector GUN

The photo-injector gun has been used for about 2 years without major problems. Beam charge of 800pC have been extracted and measured. Operations have been mainly using 350 or 200pC.

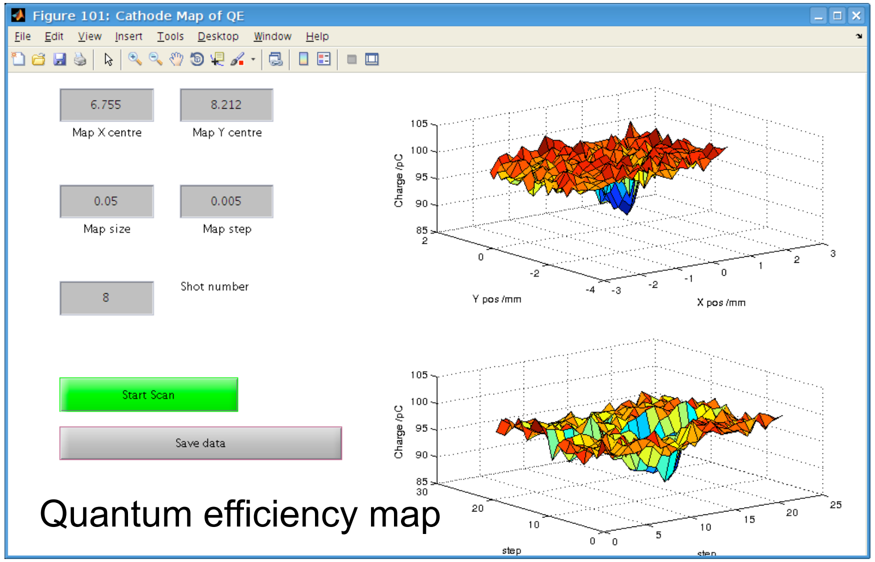
Degradation of the quantum efficiency has been experience but every run has been successfully re-establishes with an ozone cleaning procedure. The copper cathode has not yet been changed.

Gun is operated at 100MV/m filed with a fault rate smaller than 3e-3.

Bright electron beams (5 ps, 50 A, 1 mm mrad) space-charge repulsion forces are balanced by acceleration and magnetic focusing trough a solenoid.

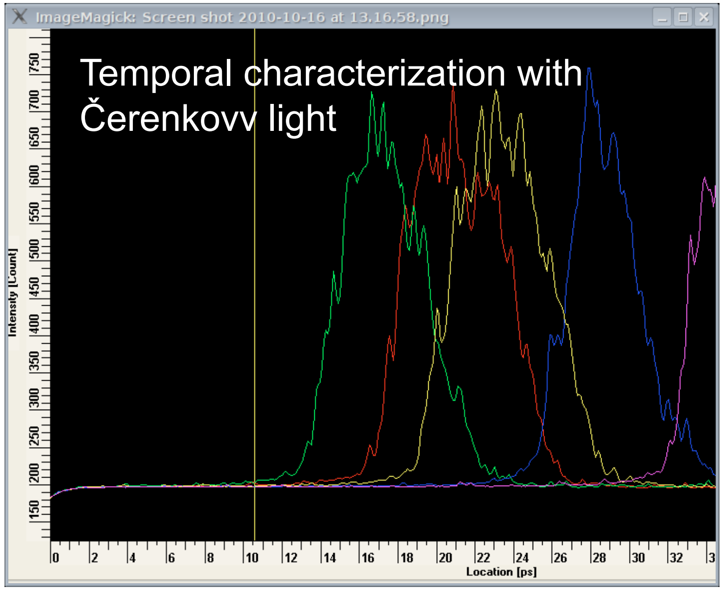
Round e-beam at the GUN exit

position X: -0.901 [mm]
position Y: -1.264 [mm]
max value: 71
px max val: 1
Spot Area: 41.154 [mm2]
Intensity: 2301196
Sigma H: 1.527 [mm]
Sigma V: 1.571 [mm]
Phase: 0.02 [deg]
pos X relative: 0.000 [mm]
pos Y relative: 0.000 [mm]



Map X centre: 6.755
Map Y centre: 8.212
Map size: 0.05
Map step: 0.005
Shot number: 8

Quantum efficiency map

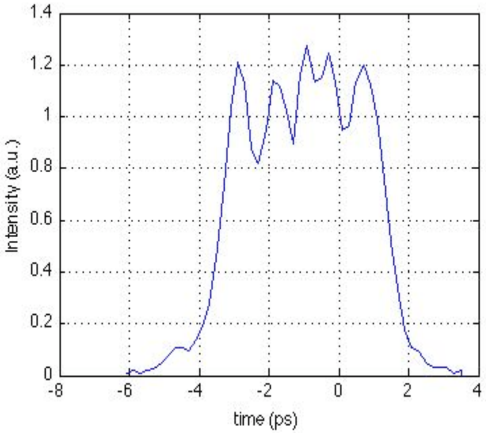


Temporal characterization with Čerenkovv light

M. Trovo', L. Badano, C. Spezzani

Emittance Studies

Laser: FWHM=5ps, ϕ= 1.3mm

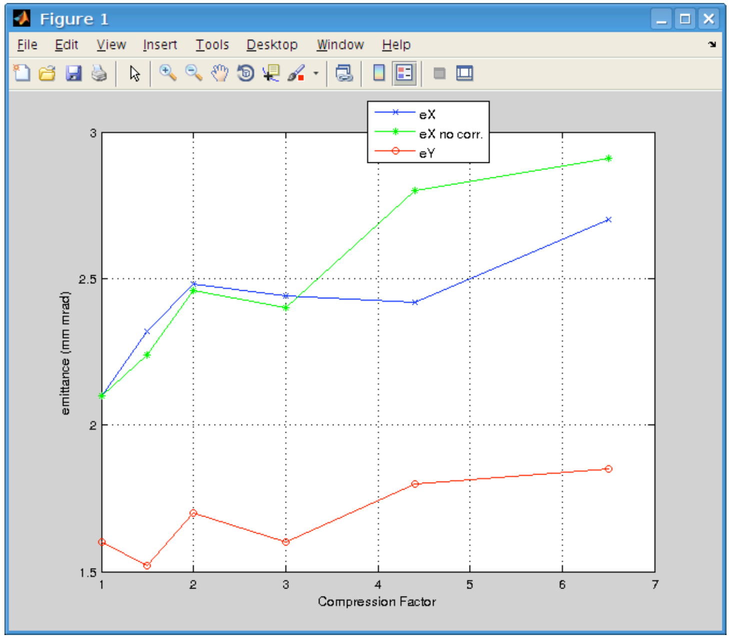


Most of the **emittance studies** have been focused on a **350pC** generated by a 5ps laser pulse. Typical values for the **projected emittance** in the laser heater region (100MeV) are below 1 mm mrad. The best measured values **0.8 mm mrad**. We experience a **critical dependence** of the emittance on the **optics and trajectory** while propagating the beam.

A good LINAC configuration allow to propagate to BC1 (350 MeV) a beam with about 50% emittance increase ($e_{x,y}$=1.3 mm mrad) before compression.

Effects of the **compression** on the emittance are not easy to avoid, generally an **increase** close to **a factor 2** is measured in the **horizontal plane**. An accurate tune of the LINAC optics can reduce the emittance growth to another 50%.

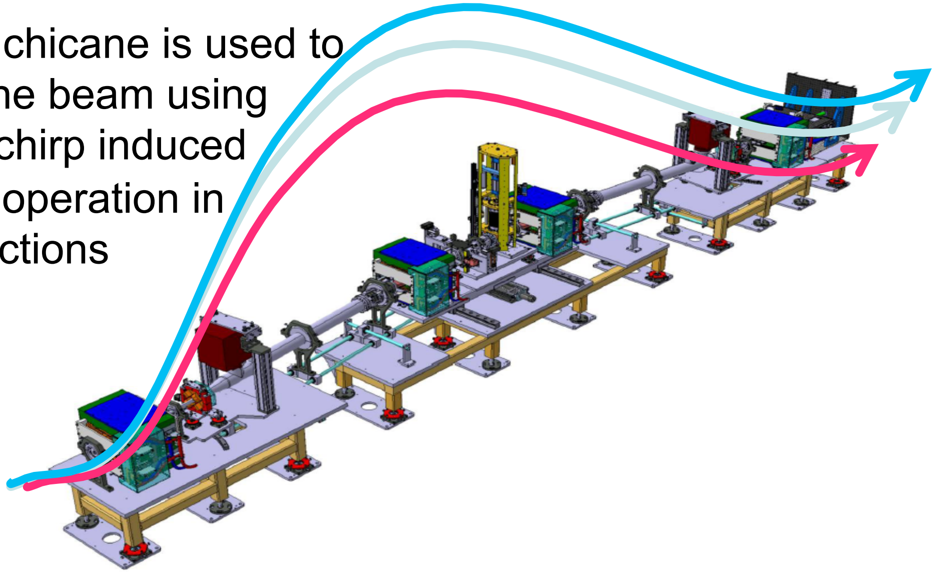
	ε_x	ε_y
BC1 Off	1.1	1.0
BC1 Off, with L01 at +25deg	1.7	1.3
BC1 On, CF=1	1.3-1.6	1.3-1.5
BC1 On, CF=6.5 (L01 at +25deg)	1.9	1.4



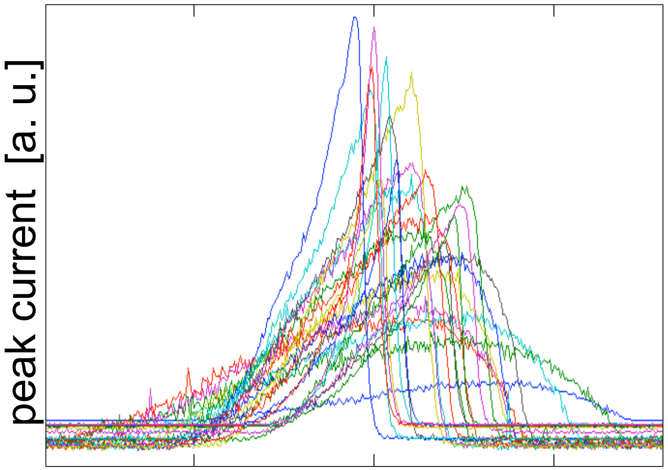
Ref. Di Mitri, Penco

Bunch Compressor

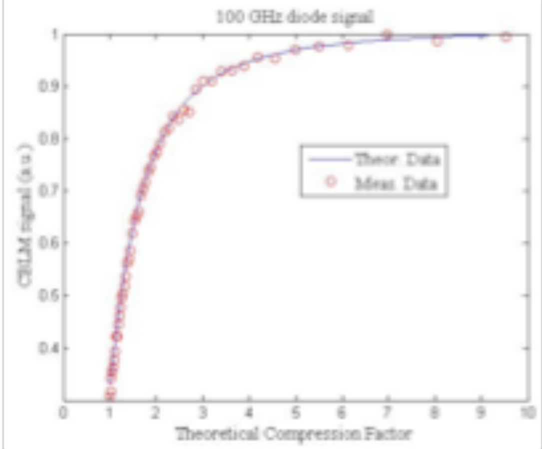
A magnetic chicane is used to compress the beam using the energy chirp induced by off-crest operation in previous sections

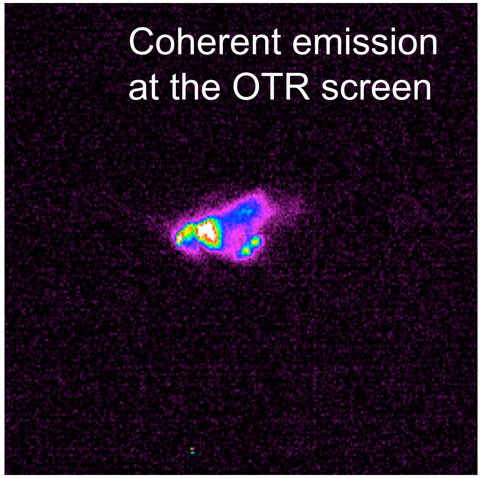


Bunch are compressed from 6 ps to about 0.7 ps



Measurements from the new diagnostic using the coherent signal of the bunch are in agreement with the theoretical predictions



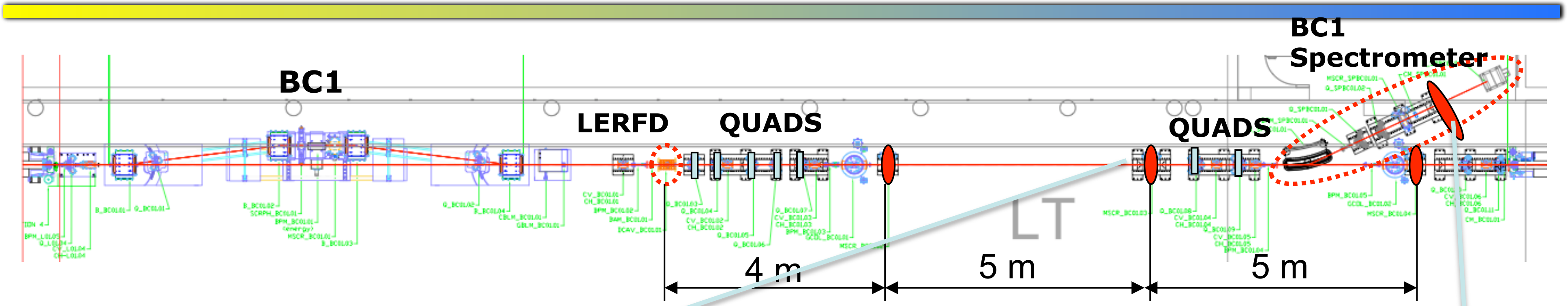

Coherent emission at the OTR screen

A **high peak current** (500 A over 0.7 ps FWHM) is generated by compressing the bunch length.

When the beam is compressed OTR screen after BC1 are affected by COTR, usually YAG screens can be used.

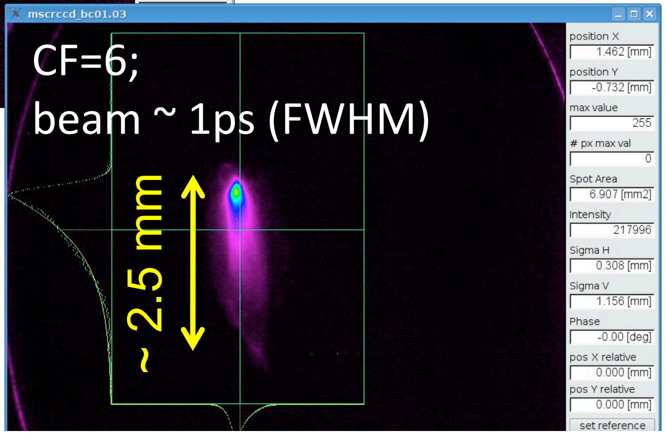
M. Veronese, R. Appio, P. Craievich, S. Di Mitri, G. Penco, D. La Civita

RF deflecting cavity



Uncompressed
~ 6ps (FWHM)

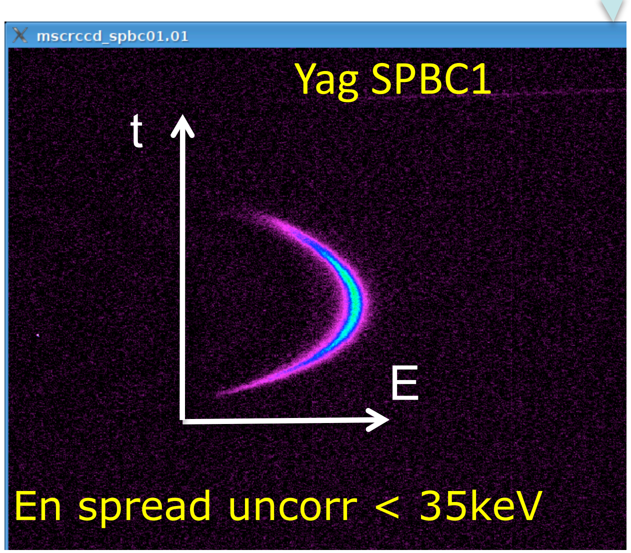
position X 2.466 [mm]
position Y 0.444 [mm]
max value 88
px max val 0
Spot Area 18.815 [mm2]
Intensity 579468
Sigma H 0.183 [mm]
Sigma V 3.911 [mm]
Phase



CF=6;
beam ~ 1ps (FWHM)

position X 1.462 [mm]
position Y -0.732 [mm]
max value 255
px max val 0
Spot Area 6.907 [mm2]
Intensity 217996
Sigma H 0.308 [mm]
Sigma V 1.156 [mm]
Phase -0.00 [deg]
pos X relative 0.000 [mm]
pos Y relative 0.000 [mm]

Deflecting cavity is now routinely used for bunch length measurements.



En spread uncorr < 35keV

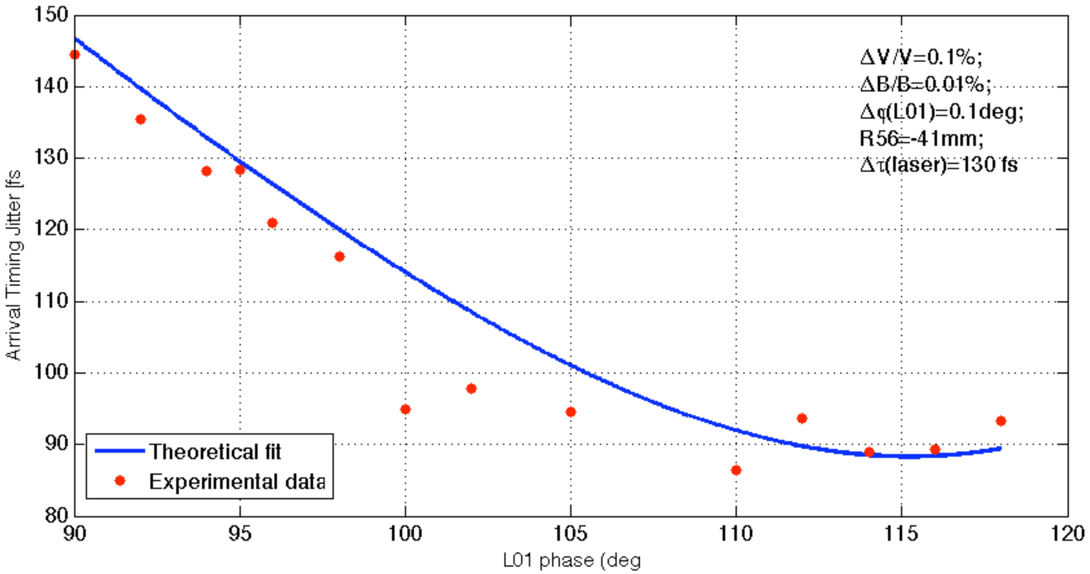
Combined with the spectrometer allow to reconstruct the phase space and can be also used for slice parameters.

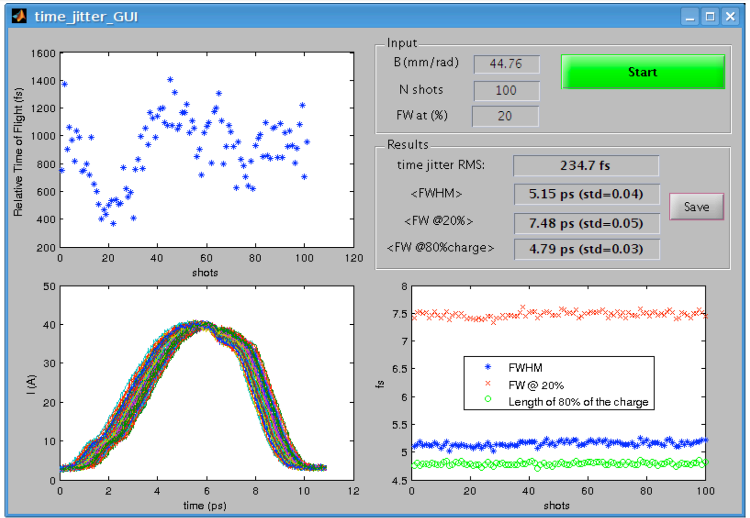
P.Craievich, M. Petronio, A. Lutman, G. Penco

BC1 timing jitter studies

A crucial parameter for the seeded FEL is the timing jitter of the electron beam.
A dedicated diagnostic (Bunch Arrival Monitor) is under commissioning, BAM jitter measurements are confirmed by measurements with deflecting cavity.

A significant increase of the timing jitter as we start compressing the beam was experienced for not optimized Low Level RF system. Optimizing the LLRF system allow to decrease the timing jitter from about 300fs to about 100fs.





Input

B(mm/rad) 44.76

N shots 100

FW at (%) 20

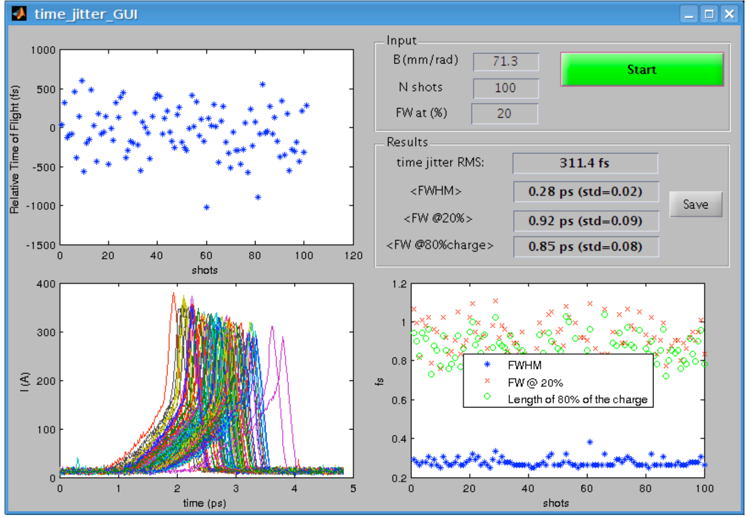
Results

time jitter RMS: 234.7 fs

<FWHM> 5.15 ps (std=0.04)

<FW @20%> 7.48 ps (std=0.05)

<FW @80%charge> 4.79 ps (std=0.03)



Input

B(mm/rad) 71.3

N shots 100

FW at (%) 20

Results

time jitter RMS: 311.4 fs

<FWHM> 0.28 ps (std=0.02)

<FW @20%> 0.92 ps (std=0.09)

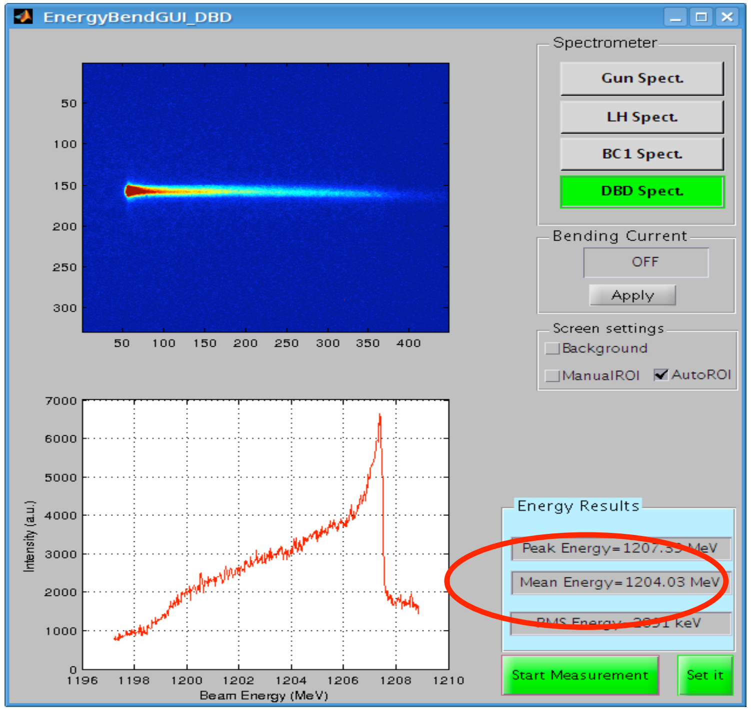
<FW @80%charge> 0.85 ps (std=0.08)

G. Penco, P. Craievich

Main Linear Accelerator

The goal energy of 1.2 GeV at the end of the linac has been achieved. Shot to shot energy stability is usually smaller than 1e-3.

An emittance growth is measured from BC1 to LINAC end, probably due to residual dispersion in LINAC the problem is under investigation.



Peak Energy=1207.33 MeV

Mean Energy=1204.03 MeV

RMS Energy=2091 keV

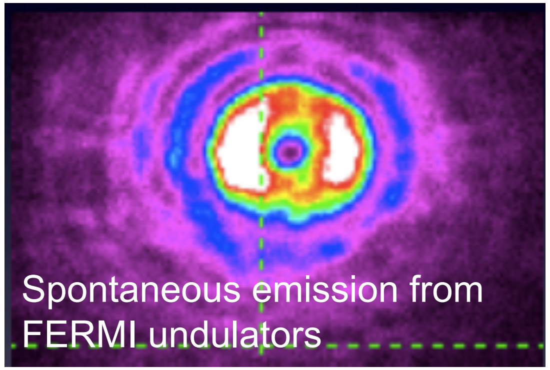
MAIN LINAC – I
100 – 300 MeV

MAIN LINAC – II
300 – 1200 MeV

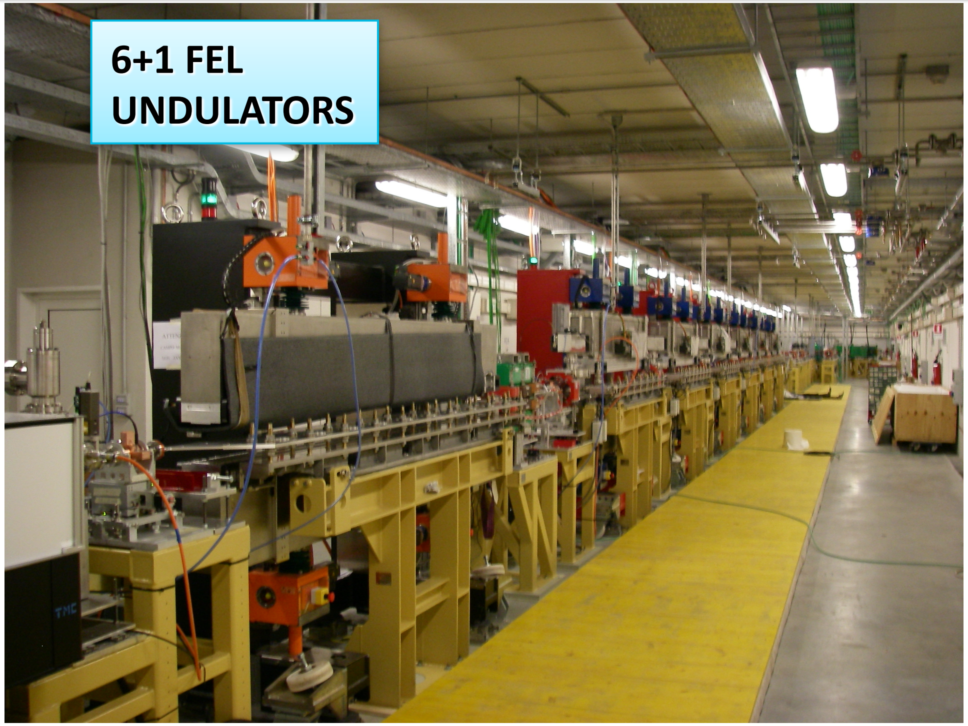
By using the phase reversal modulation on the sled cavities 1.3GeV is easily achieved with the present linac.

Undulators

APPLE-II type undulators allow **high brilliance** FEL with **variable polarization** and **tunable wavelength**

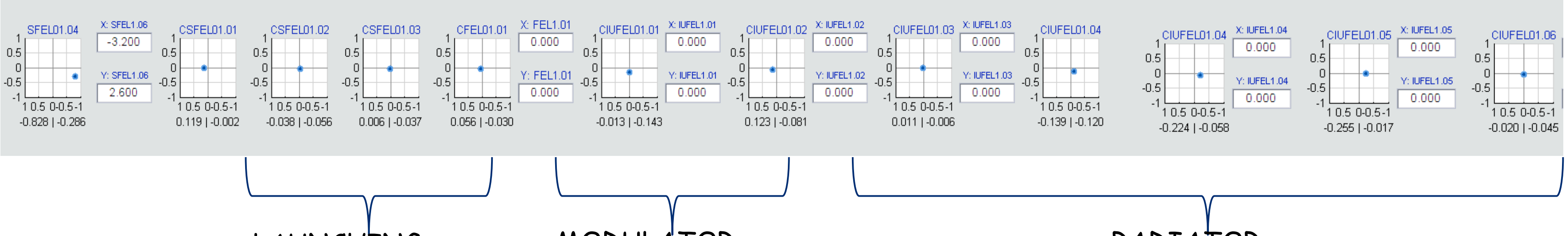


Spontaneous emission from FERMI undulators



6+1 FEL UNDULATORS

Beam-based straight line defined in the undulator: quadrupoles (x,y) and undulators (y only) moved to mimimize beam steering. All C-BPMs set to zero. All correctors turned off.

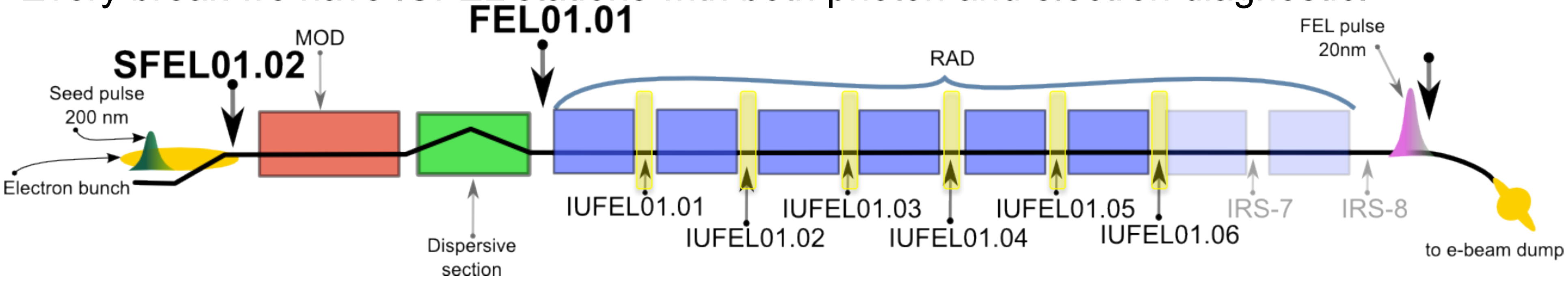


SFEL01.04: -0.828 | -0.286
X: SFEL1.06 -3.200
Y: SFEL1.06 2.600
CSFEL01.01: 0.119 | -0.002
CSFEL01.02: -0.038 | -0.056
CSFEL01.03: 0.006 | -0.037
CFEL01.01: 0.056 | -0.030
X: FEL1.01 0.000
Y: FEL1.01 0.000
CIUFEL01.01: -0.013 | -0.143
X: IUFEL1.01 0.000
Y: IUFEL1.01 0.000
CIUFEL01.02: 0.123 | -0.081
X: IUFEL1.02 0.000
Y: IUFEL1.02 0.000
CIUFEL01.03: 0.011 | -0.006
X: IUFEL1.03 0.000
Y: IUFEL1.03 0.000
CIUFEL01.04: -0.139 | -0.120
CIUFEL01.04: -0.224 | -0.058
X: IUFEL1.04 0.000
Y: IUFEL1.04 0.000
CIUFEL01.05: -0.255 | -0.017
X: IUFEL1.05 0.000
Y: IUFEL1.05 0.000
CIUFEL01.06: -0.020 | -0.045

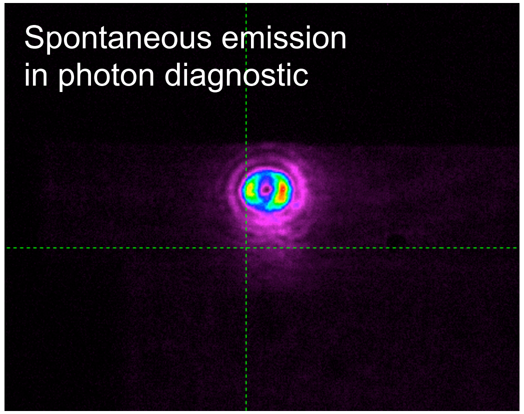
S. Di Mitri, L. Froelich, B. Diviacco

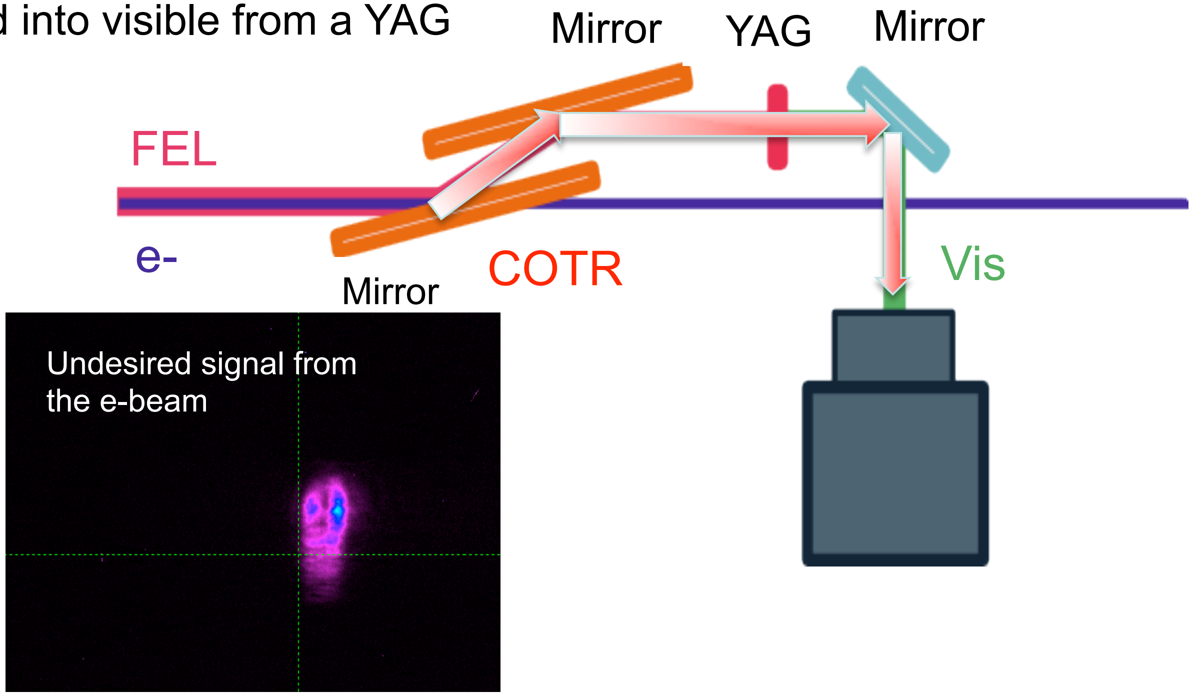
Intra Undulator FEL screens: photons

Every break we have IUFEL stations with both photon and electron diagnostic.



Photon diagnostic use a copper mirror to separate FEL from electrons. VUV light is then converted into visible from a YAG and detected by a CCD camera.

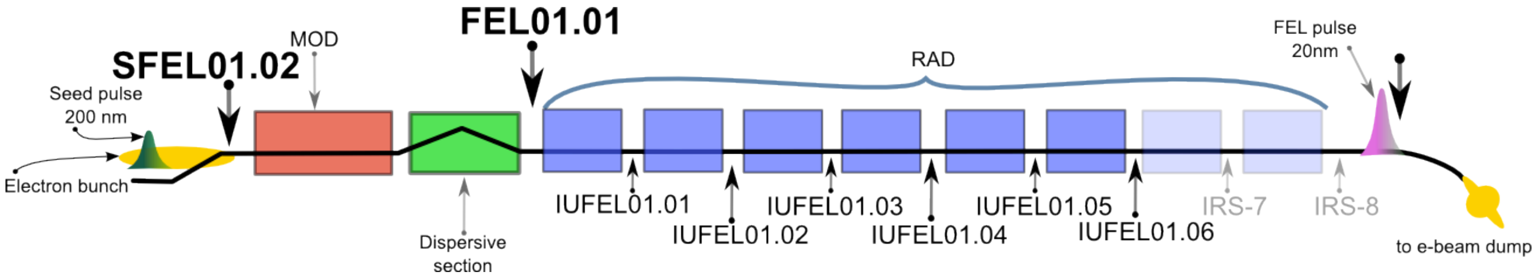

Spontaneous emission
in photon diagnostic



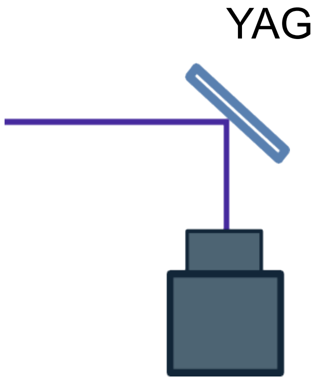
Undesired signal from
the e-beam

Depending on the electron alignment the measure is affected by OTR emission on the first mirror.

IUFEL screens: electrons



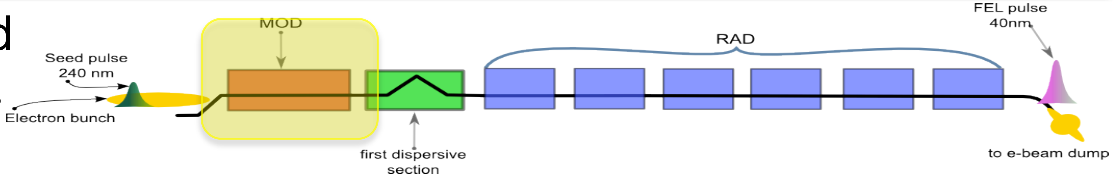
Most of IUFEL stations have a simple YAG to detect electrons.
Also photons from the seed can be seen on this screen.



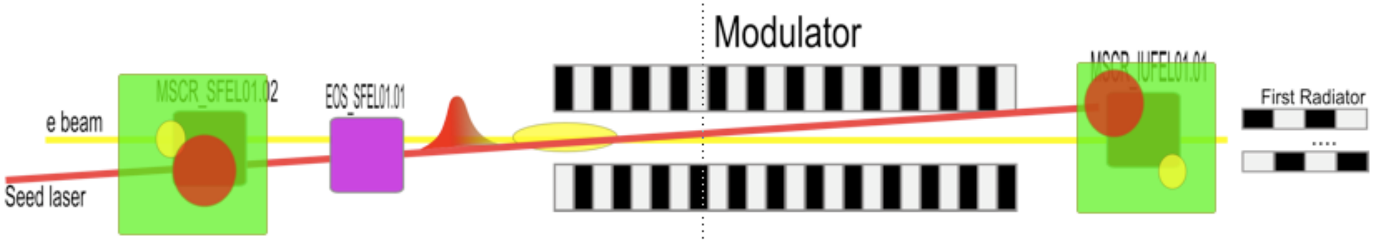
Original designed uses OTR in this position but for the moment it has not been possible to used them a we will continue using the YAG

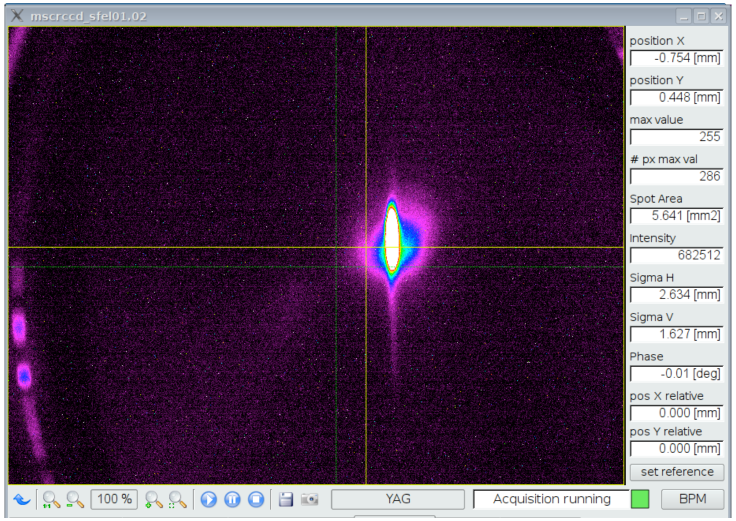
Spatial seed-electron overlap

Spatial **overlap** of the **seed laser** and the **electron beam** in **modulator** has been tested using two YAG screens around the modulator.

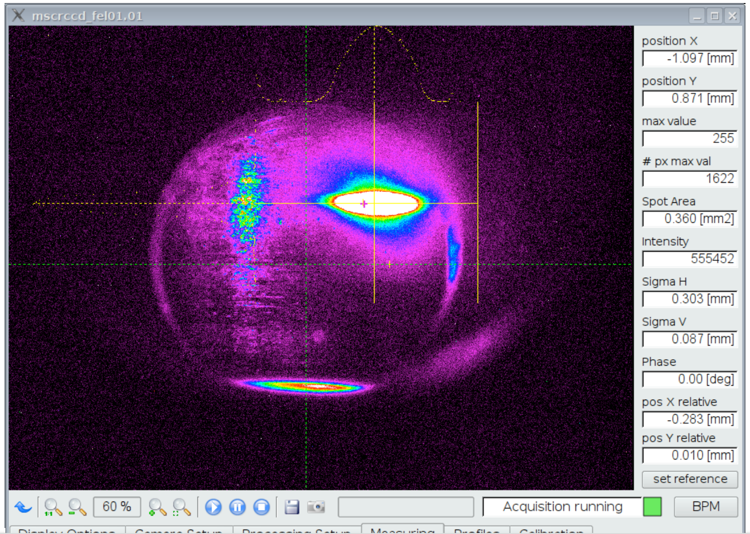


Using the seed laser steering mirror it is possible to superpose the two beams.





position X: -0.754 [mm]
position Y: 0.448 [mm]
max value: 255
px max val: 286
Spot Area: 5.641 [mm2]
Intensity: 682512
Sigma H: 2.634 [mm]
Sigma V: 1.627 [mm]
Phase: -0.01 [deg]
pos X relative: 0.000 [mm]
pos Y relative: 0.000 [mm]
YAG
Acquisition running

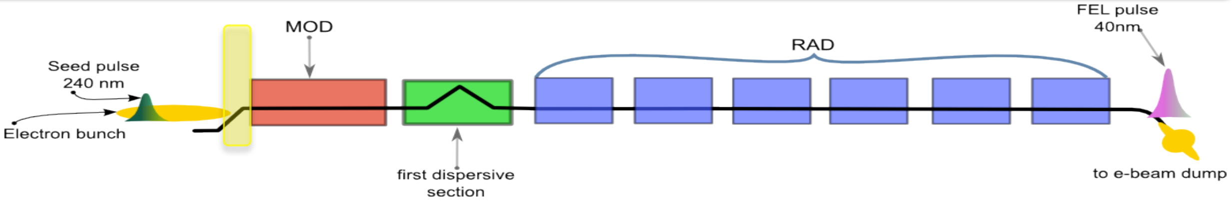


position X: -1.097 [mm]
position Y: 0.871 [mm]
max value: 255
px max val: 1622
Spot Area: 0.360 [mm2]
Intensity: 555452
Sigma H: 0.303 [mm]
Sigma V: 0.087 [mm]
Phase: 0.00 [deg]
pos X relative: -0.283 [mm]
pos Y relative: 0.010 [mm]
Acquisition running

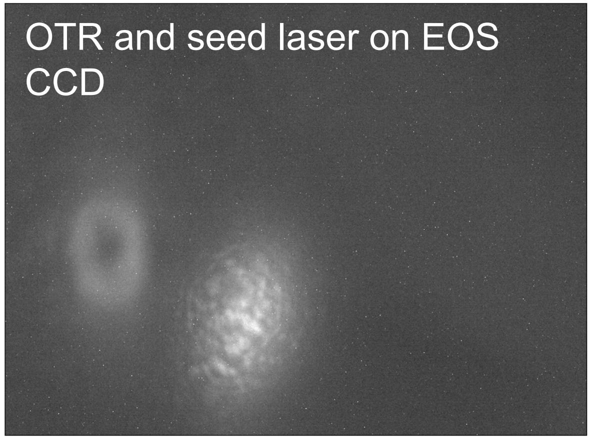
C. Spezzani, M. Veronese, P. Sigalotti, S. Demidovich, …

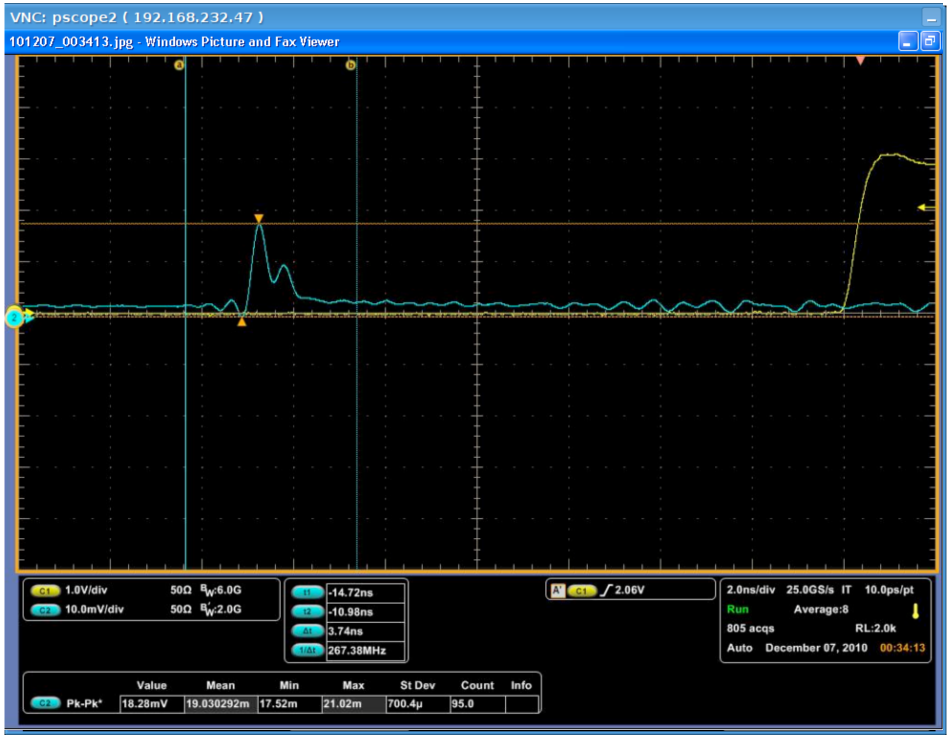
Seed-electron timing alignment

The seed laser and the electron beam are detected on a photodiode installed in the Electron Optical Sapling chamber.



An aluminum foil is used to reflect the laser out of the chamber and to produce OTR. The two signals can be detected with a CCD and a fast photodiode


OTR and seed laser on EOS CCD


VNC: pscope2 (192.168.232.47)

101207_003413.jpg - Windows Picture and Fax Viewer

C1 1.0V/div 50Ω BW:6.0G
C2 10.0mV/div 50Ω BW:2.0G

t1 -14.72ns
t2 -10.98ns
Δt 3.74ns
1/Δt 267.38MHz

A' C1 ∫ 2.06V

2.0ns/div 25.0GS/s IT 10.0ps/pt
Run Average:8
805 acqs RL:2.0k
Auto December 07, 2010 00:34:13

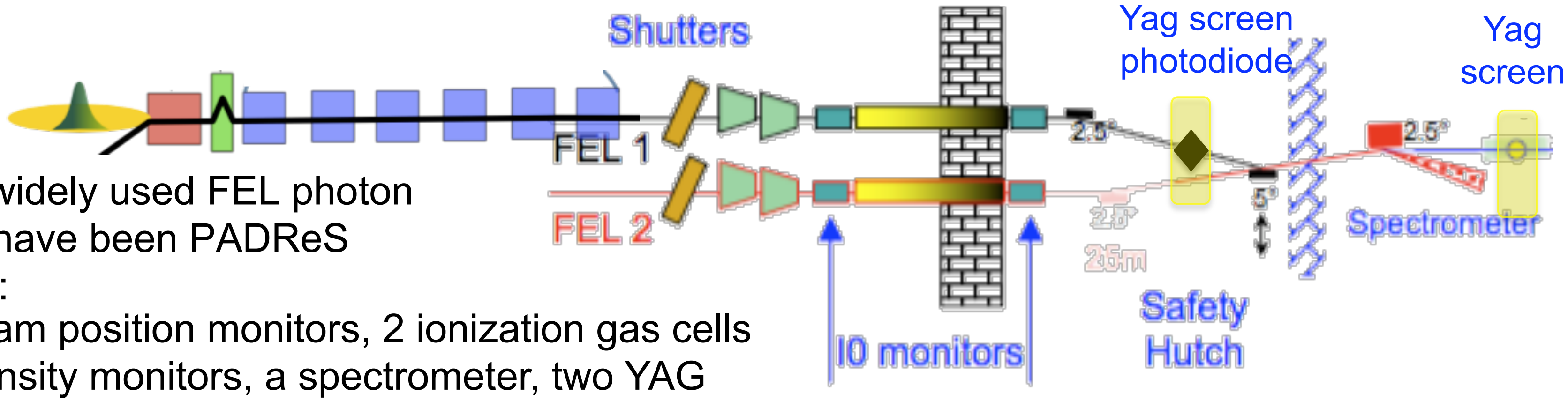
	Value	Mean	Min	Max	St Dev	Count	Info
C2 Pk-Pk*	18.28mV	19.030292m	17.52m	21.02m	700.4µ	95.0	

After the signal optimization using a CCD it has been possible to obtain the timing parameters that allow to overlap in time e-beam and seed laser within +-50 ps

M. Veronese, C. Spezzani, P. Sigalotti, R. Ivanov, …

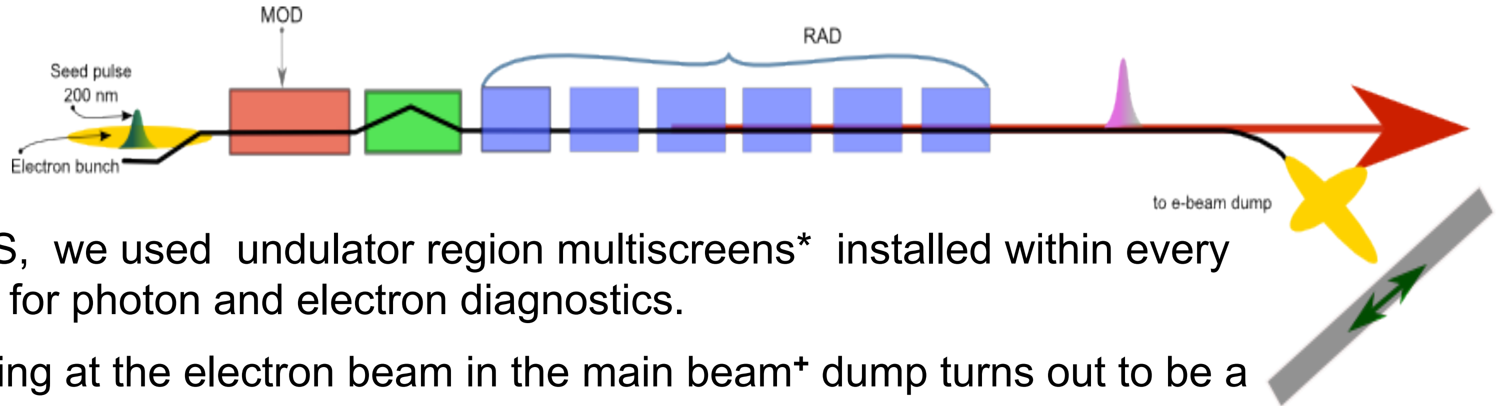
Diagnostics used for FEL Measurements

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.

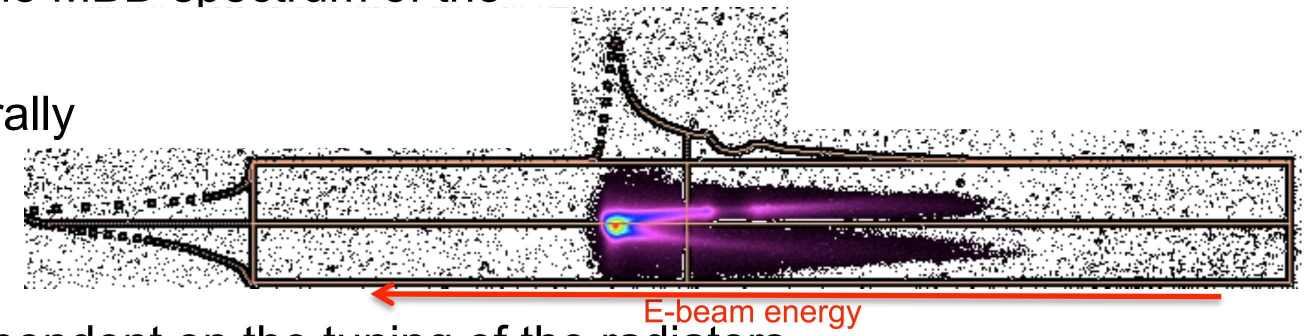
The YAG screen looking at the electron beam in the main beam⁺ dump turns out to be a pivotal diagnostic system for FEL optimization.

***M. Veronese**
⁺L. Badano

Optimize the seeding process

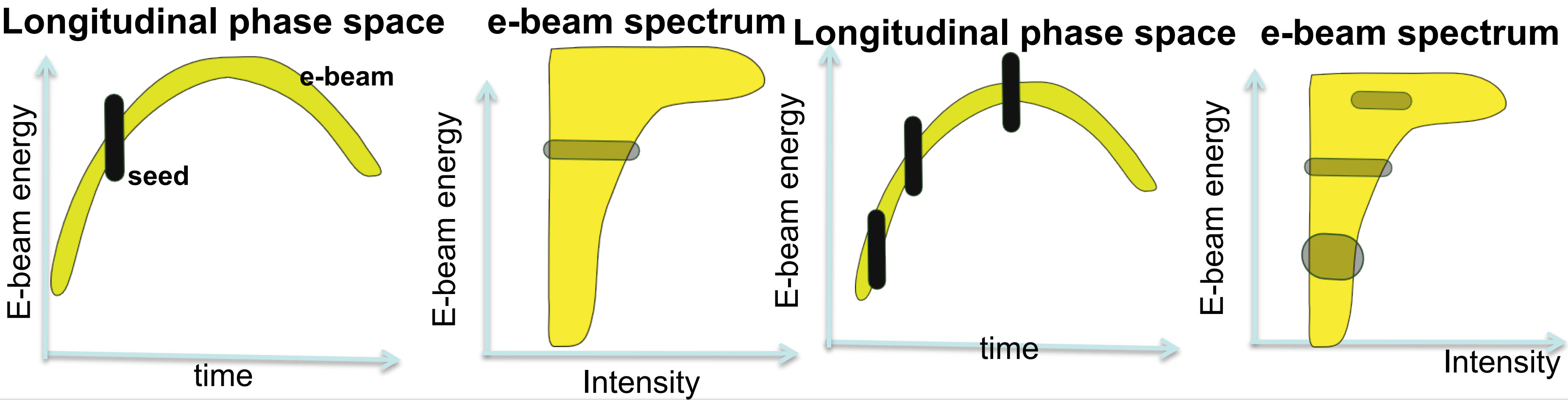
A useful diagnostic for detecting the occurrence of the seeding is provided by the MBD spectrum of the electron beam.

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



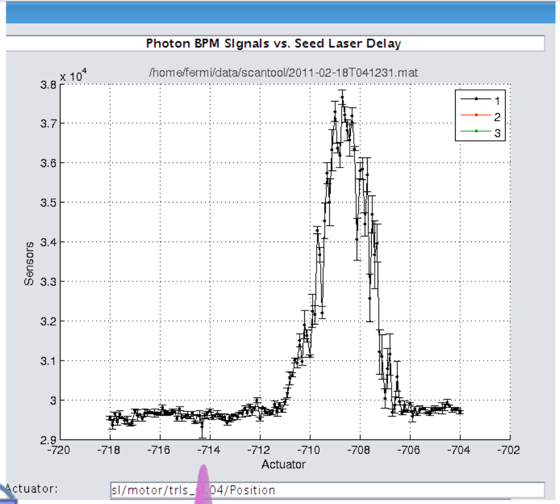
The effect is only slightly dependent on the tuning of the radiators, and the dispersive sections R56.

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



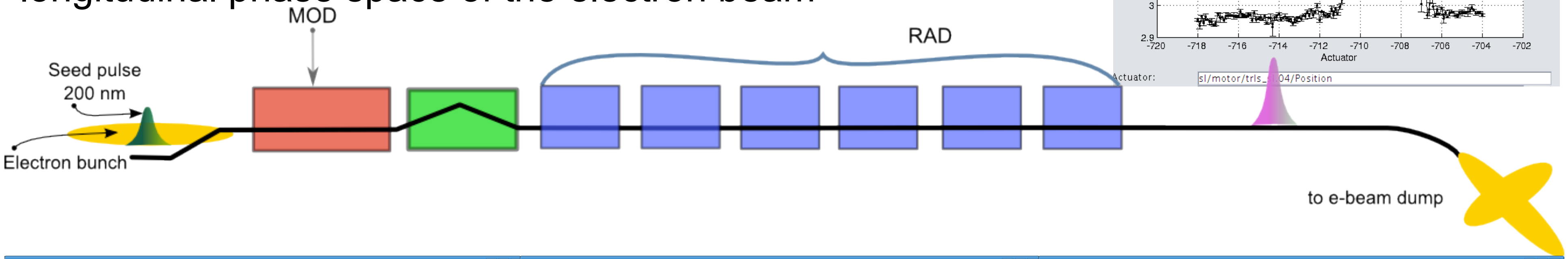
FEL tuning

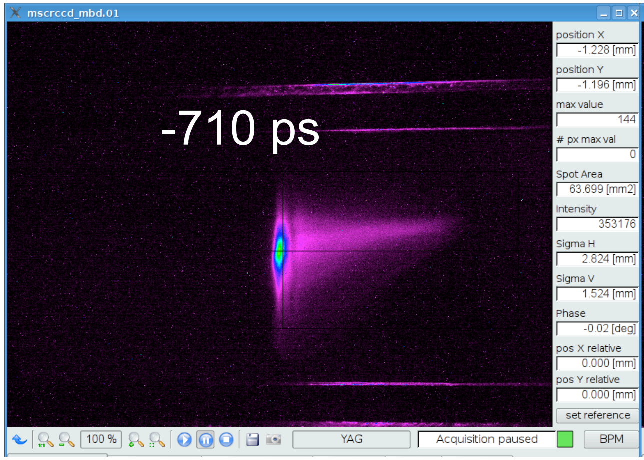
After the seed alignment procedure the FEL easily ON.



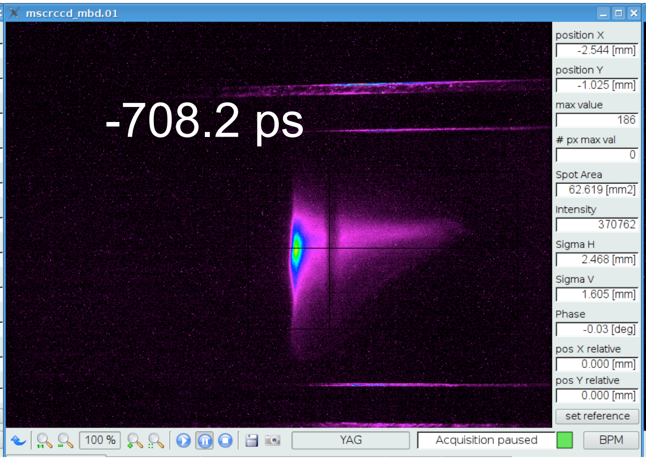
Evidence of a band in the e-beam spectrometer in Main Bean Dump as a result of the seeding.

The seeding can provide information on the longitudinal phase space of the electron beam

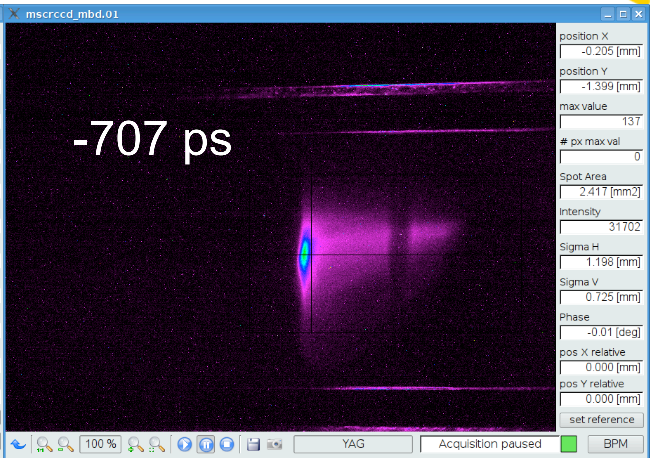




position X -1.228 [mm]
position Y -1.196 [mm]
max value 144
px max val 0
Spot Area 63.699 [mm2]
Intensity 353176
Sigma H 2.824 [mm]
Sigma V 1.524 [mm]
Phase -0.02 [deg]
pos X relative 0.000 [mm]
pos Y relative 0.000 [mm]



position X -2.544 [mm]
position Y -1.025 [mm]
max value 186
px max val 0
Spot Area 62.619 [mm2]
Intensity 370762
Sigma H 2.468 [mm]
Sigma V 1.605 [mm]
Phase -0.03 [deg]
pos X relative 0.000 [mm]
pos Y relative 0.000 [mm]



position X -0.205 [mm]
position Y -1.399 [mm]
max value 137
px max val 0
Spot Area 2.417 [mm2]
Intensity 31702
Sigma H 1.198 [mm]
Sigma V 0.725 [mm]
Phase -0.01 [deg]
pos X relative 0.000 [mm]
pos Y relative 0.000 [mm]

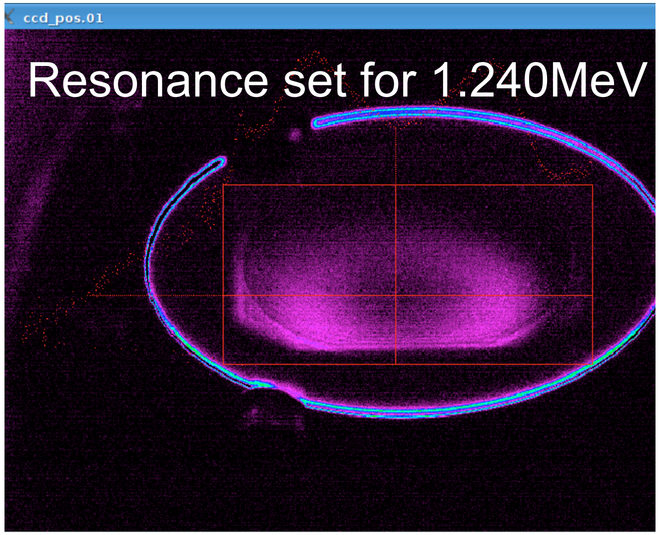
FEL, critical optimization

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.

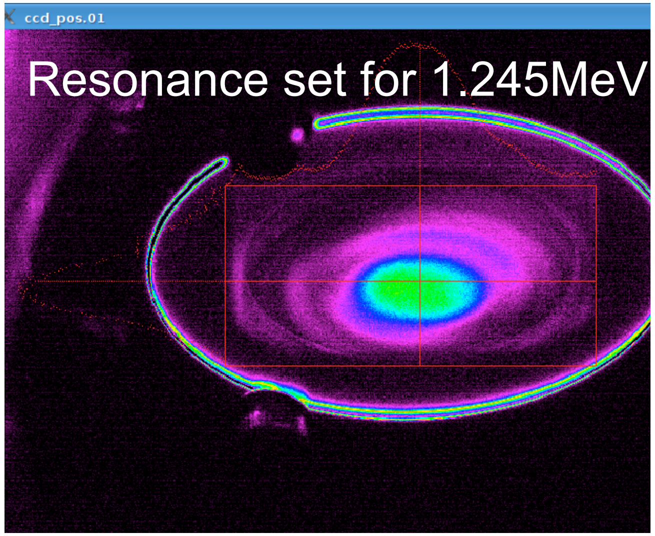
A small undulator mismatch (of the order of ΔK~0.1%) can produce a “doughnut” transverse mode with resonance moved to the outer portions of the electron beam.

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



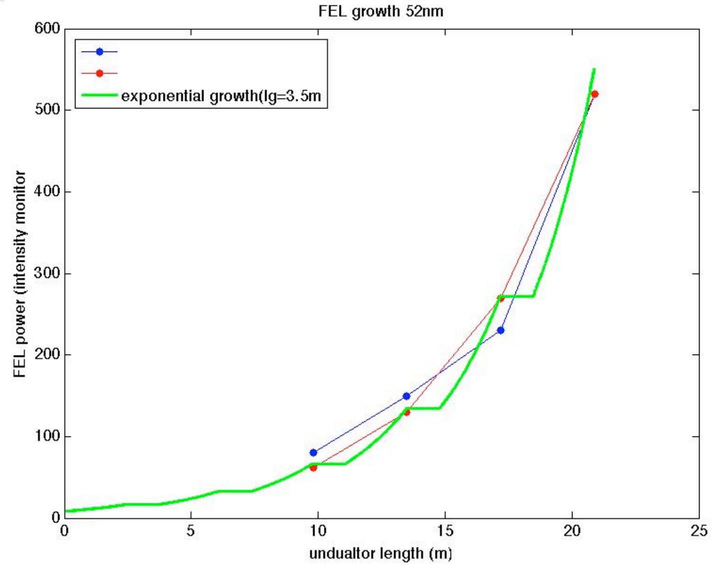
Resonance set for 1.245MeV

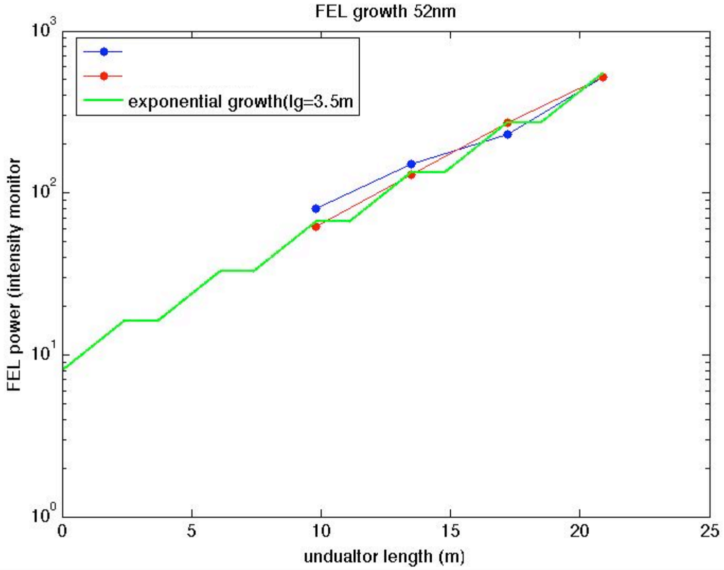
FEL gain

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.





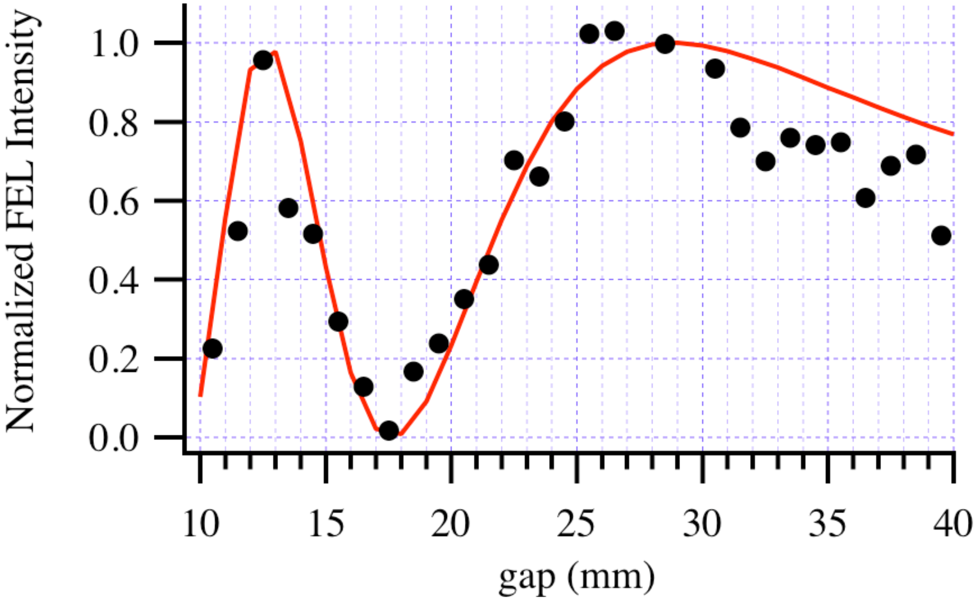
Phase shifter: utility and calibration

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.

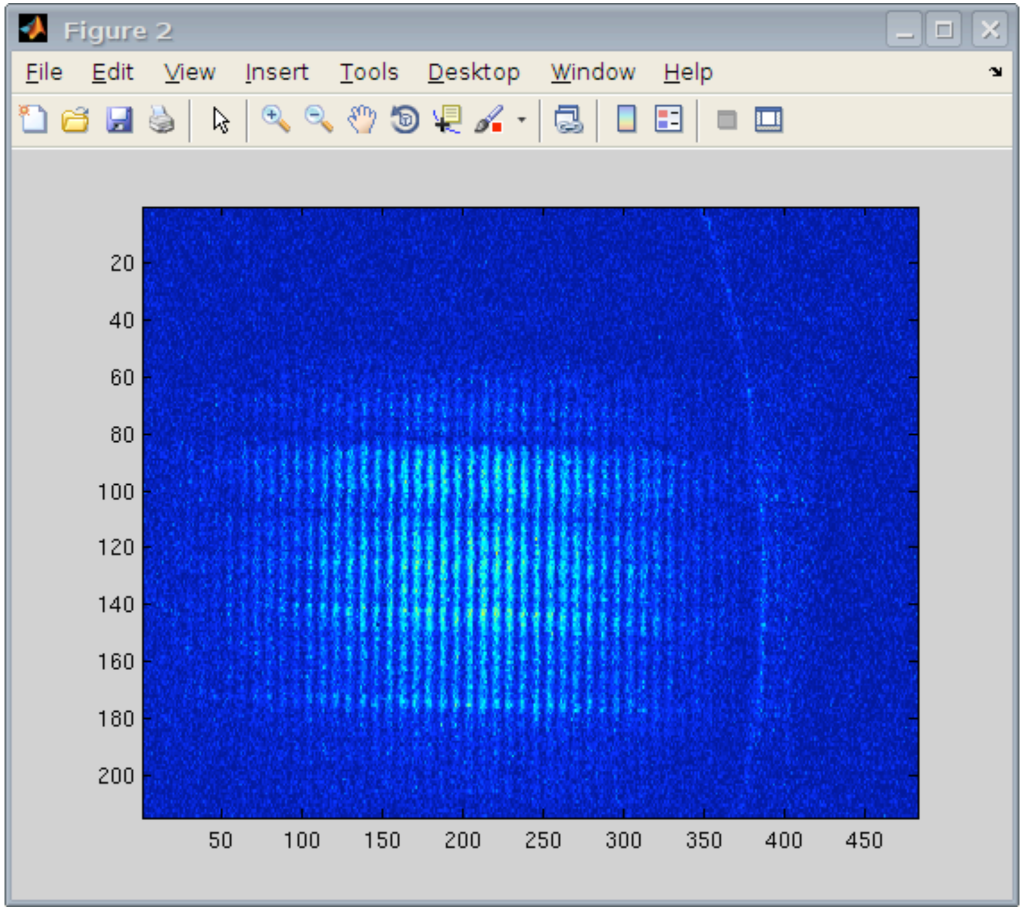
Data here reported refer to the case of a 350pC beam compressed by abut a factor 3. The beam is seeded at 260nm and passes through two consecutive radiators tuned to 52 nm.

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.

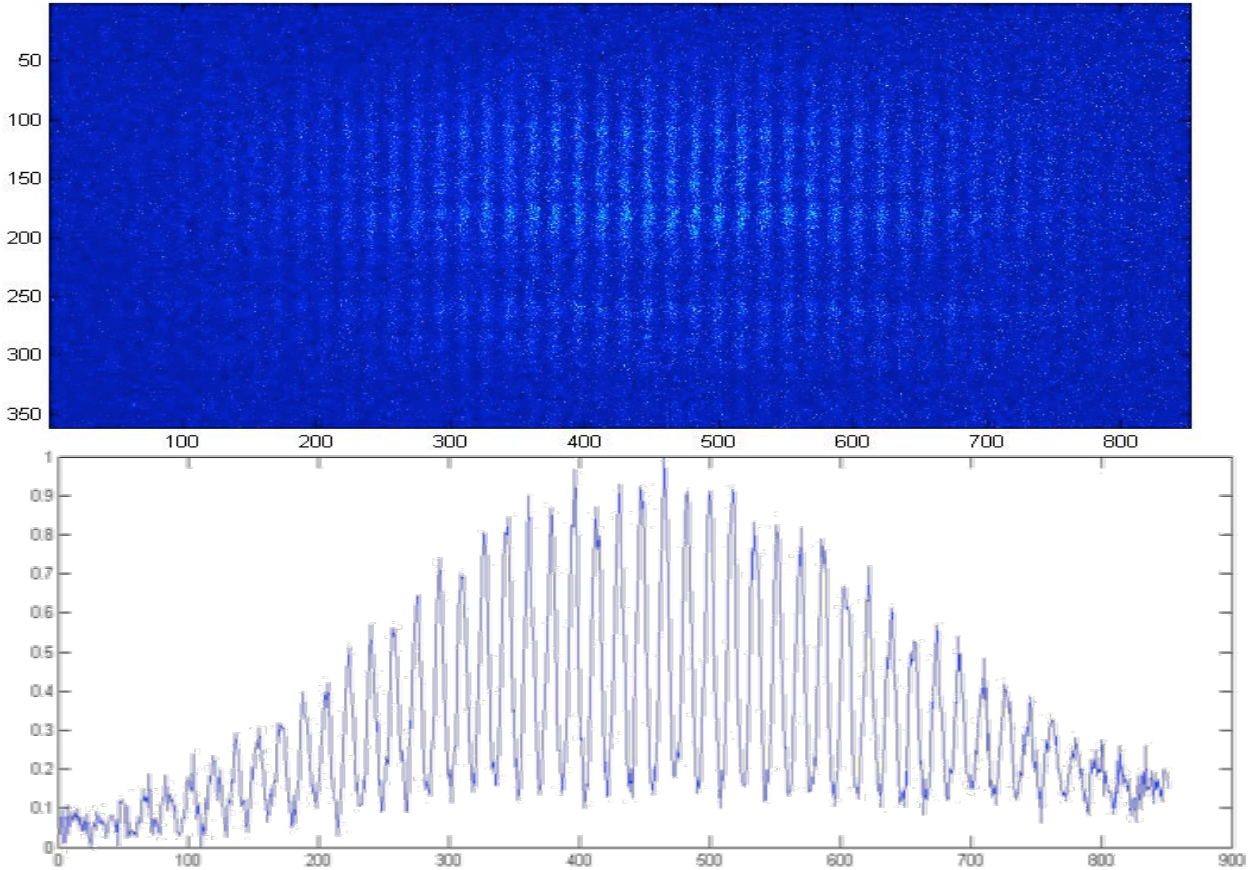
Transverse coherence (2/2)

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.

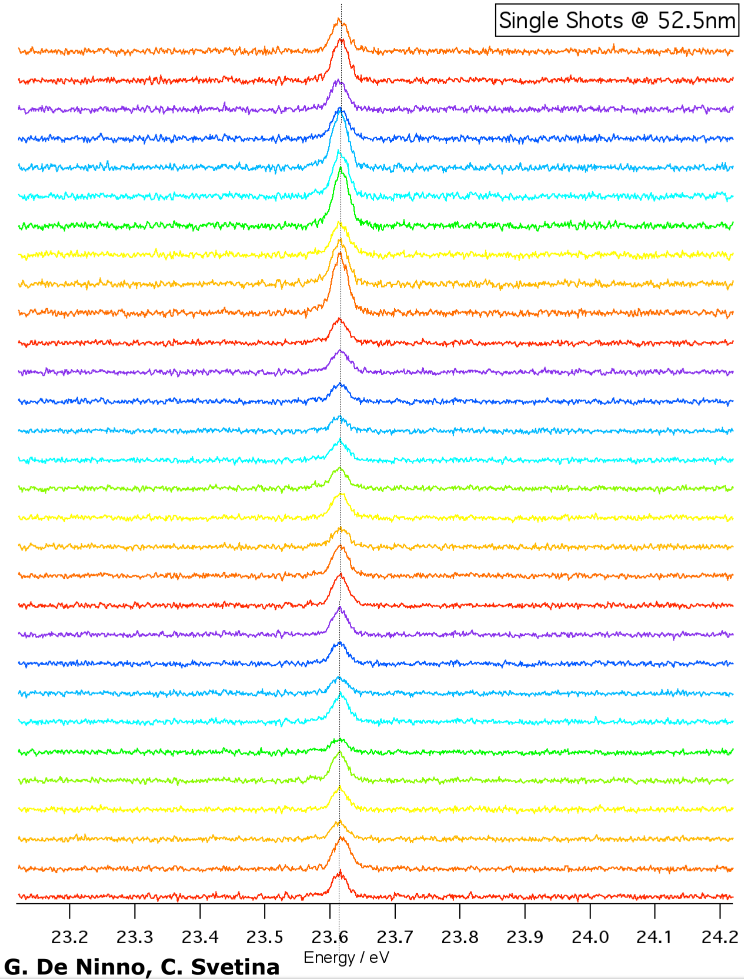
Quantitative analysis is ongoing.

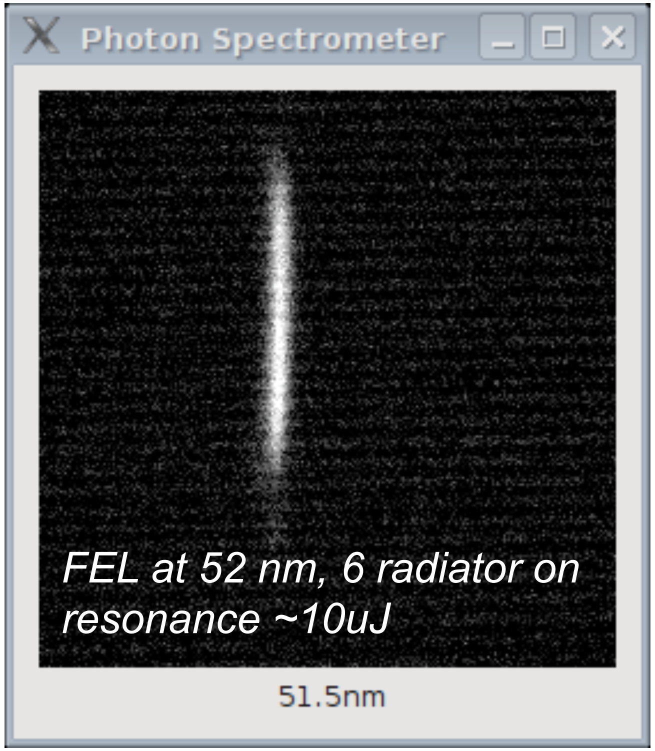
FEL at 32.5 nm, 6 radiators, 450pC, compression ~3.
Slit separation = 0.8 mm, width = 20 μm



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.



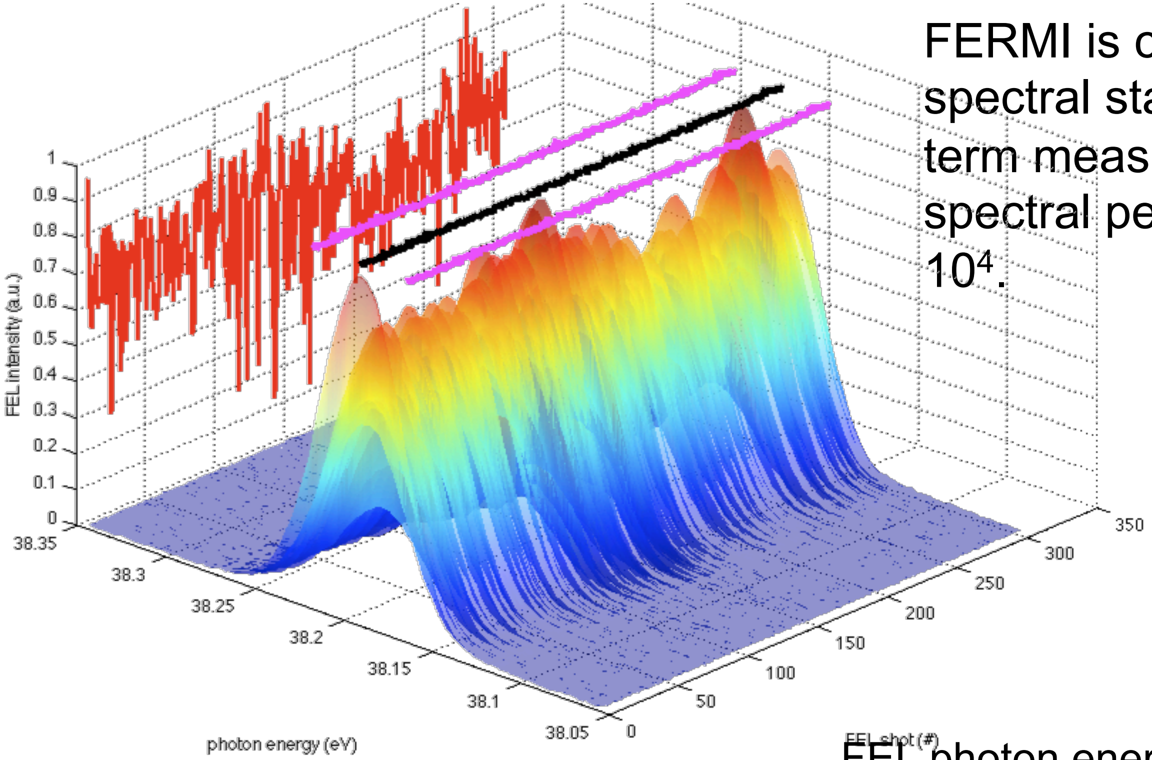


FEL at 52 nm, 6 radiator on resonance ~10uJ

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



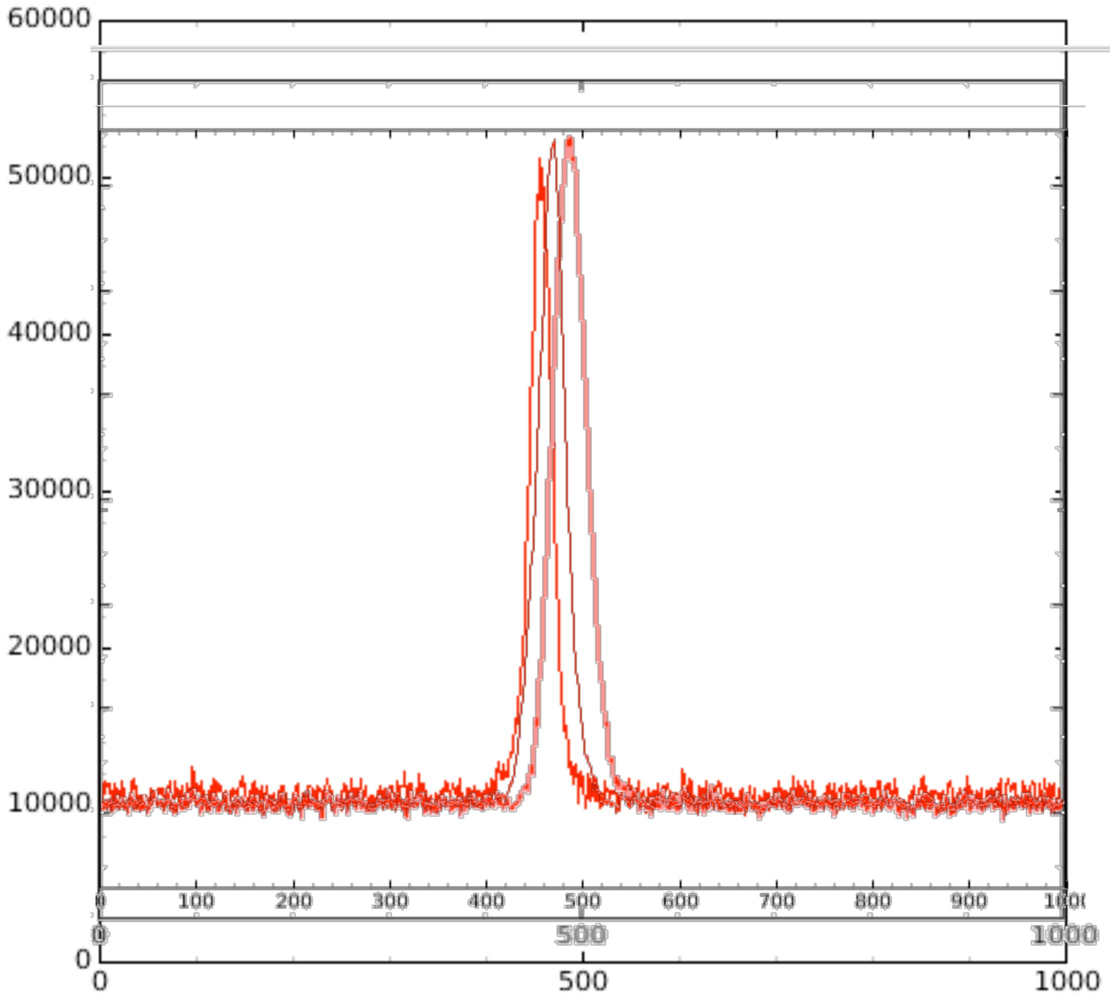
In addition to the very narrow spectrum FERMI is characterized by excellent spectral stability. Both short and long term measurements show that the spectral peak jitter of less than 1 part in 10^4.

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



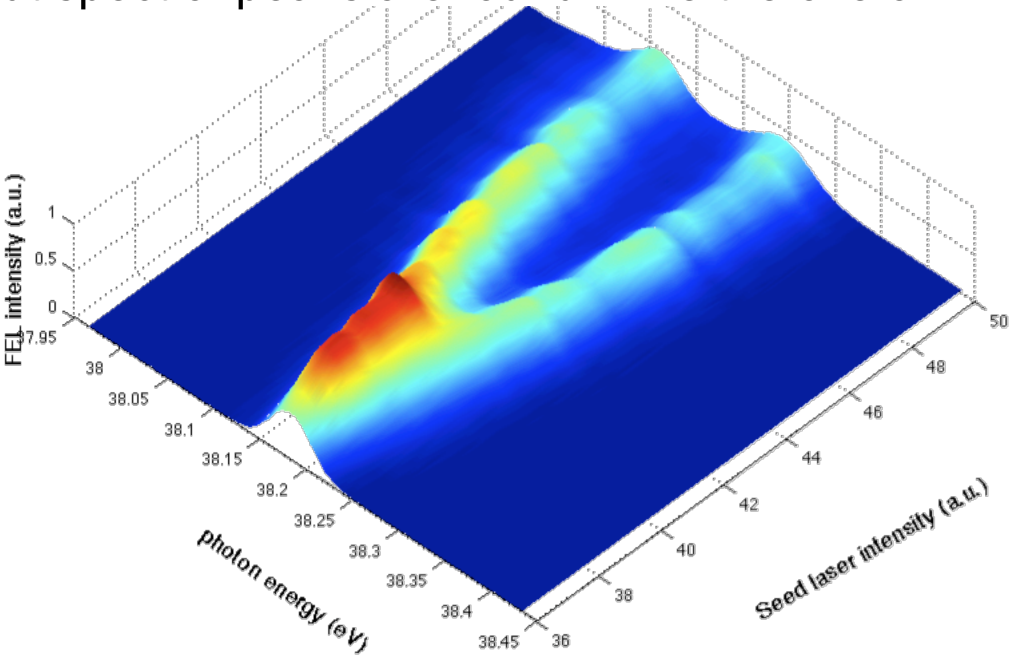
A small FEL tuning range around 52nm has been achieved by changing the seed laser wavelength of 1 nm (0.4%).

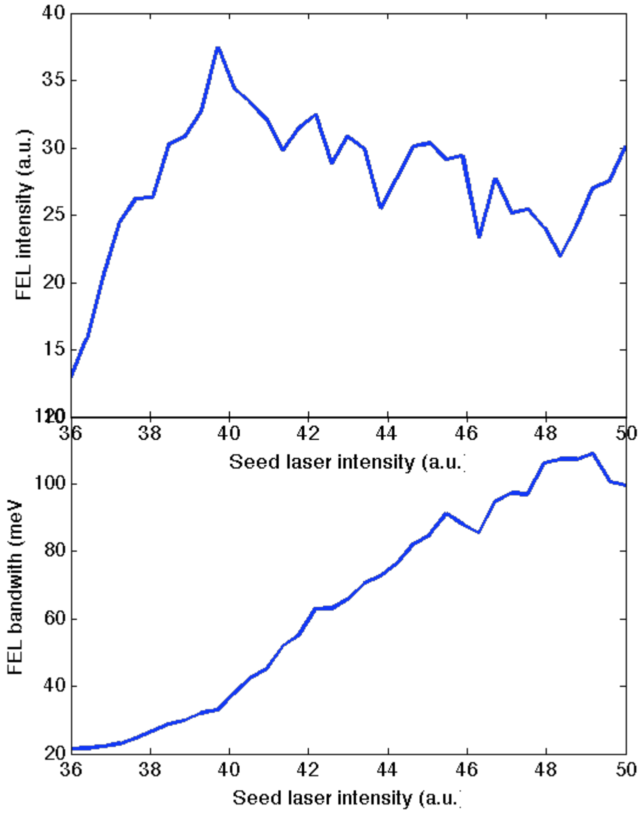
After tuning of the seed laser wavelength, the undulator resonance is changed accordingly to maximize the FEL power.

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.



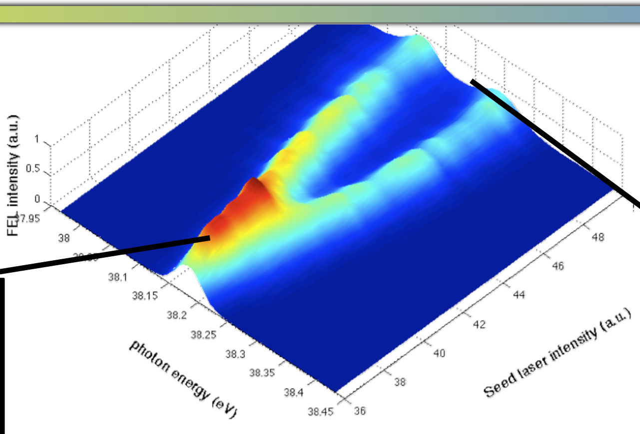


Both RMS and FWHM fits to the FEL bandwidth show an increase up to a factor 5 .

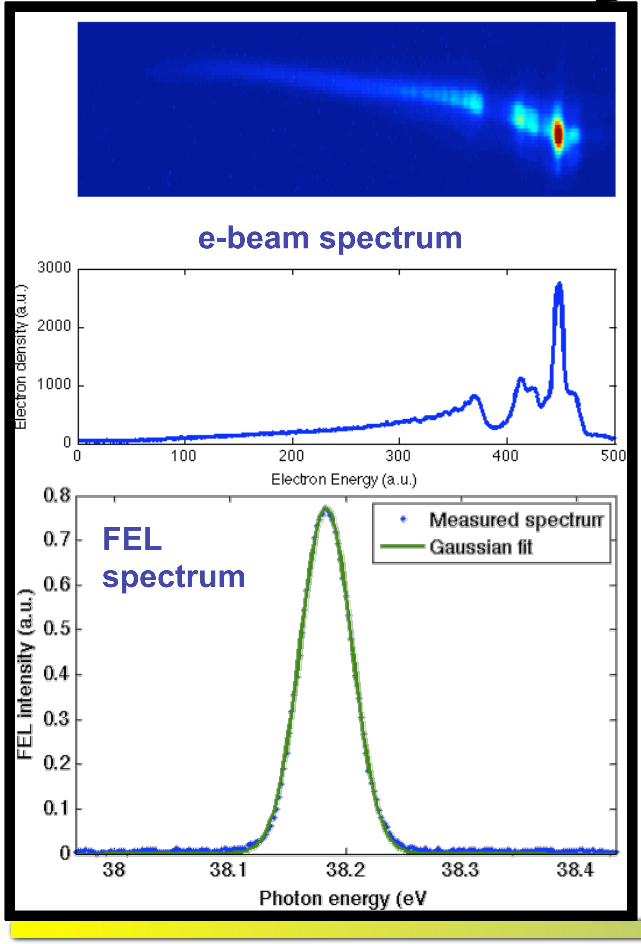
Data refers to a 350pC beam compressed ~3 at 1.24GeV. R56~16μm and the 6 radiators tuned at 32.5nm in circular polarization.

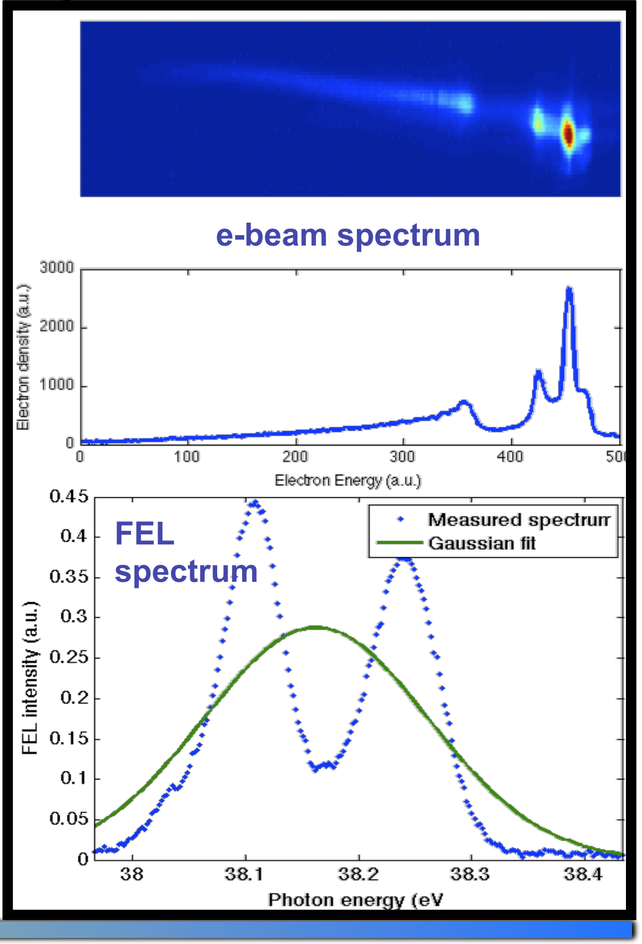
FEL bandwidth control (2/3)

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

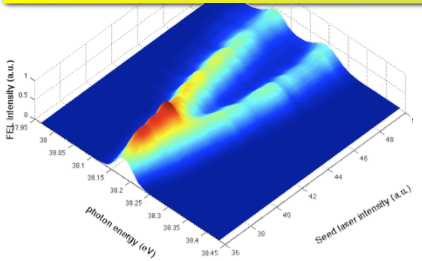


The double peak in the FEL spectrum is associated with a larger “hole” in the e-beam spectrum.



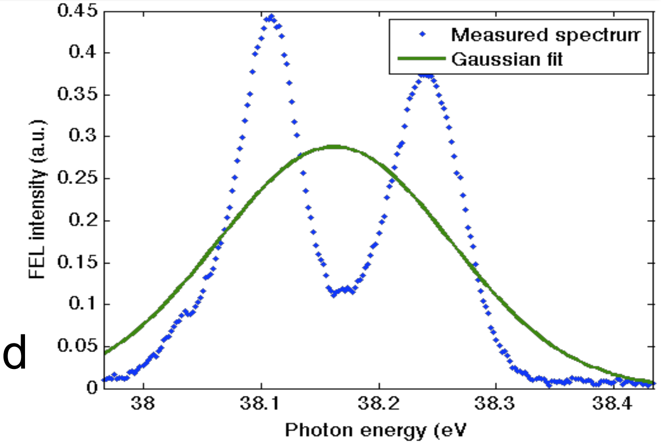


FEL bandwidth control (3/3)



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.

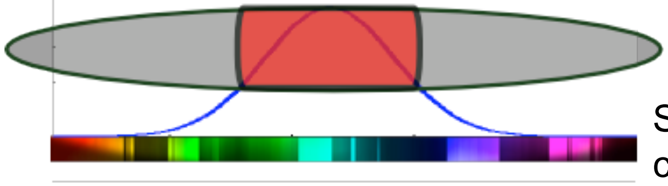


Single Gaussian fit

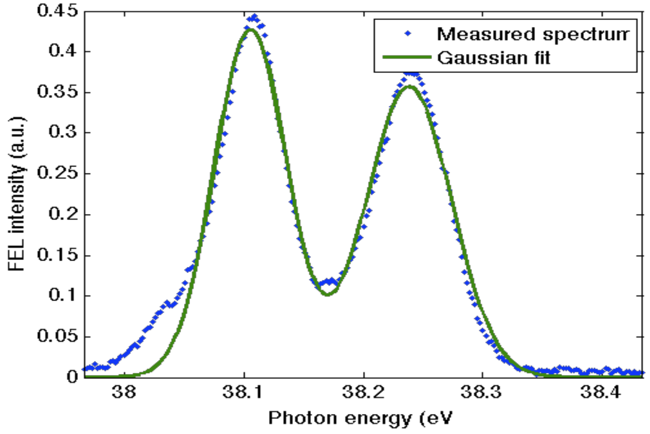
photon energy = 38.16

bandwidth = 100 meV

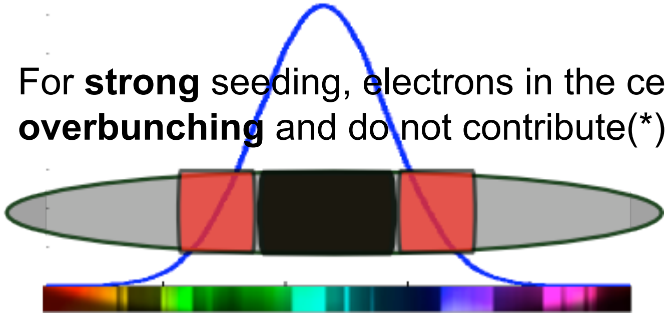
Only electrons that see **optimal seed intensity** contribute to FEL



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(*)



First peak

Intensity = 1

photon energy = 38.11

bandwith = 30

Second peak

Intensity = 0.8 (a.u.)

photon energy = 38.24eV

bandwith = 36meV

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

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

FEL has been operated also with the fully tunable, Optical Parametric Amplified 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.

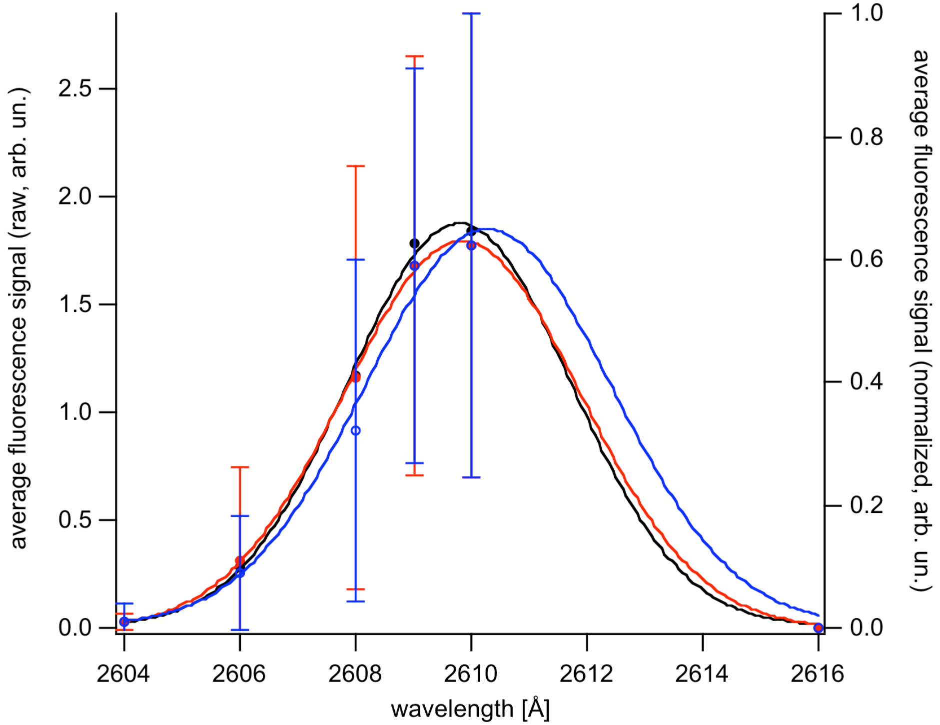
We have evidence of coherent transition radiation from the bunched electron beam at 130 nm or shorter wavelength.

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.

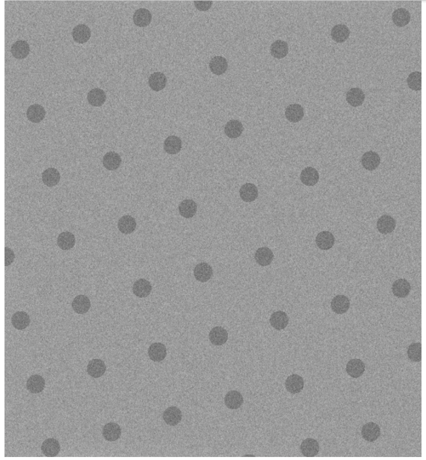
The atomic resonance is much narrower than the FEL linewidth, so measurement of the output spectrum by the LDM group allows independent determination of the input FEL spectrum.

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

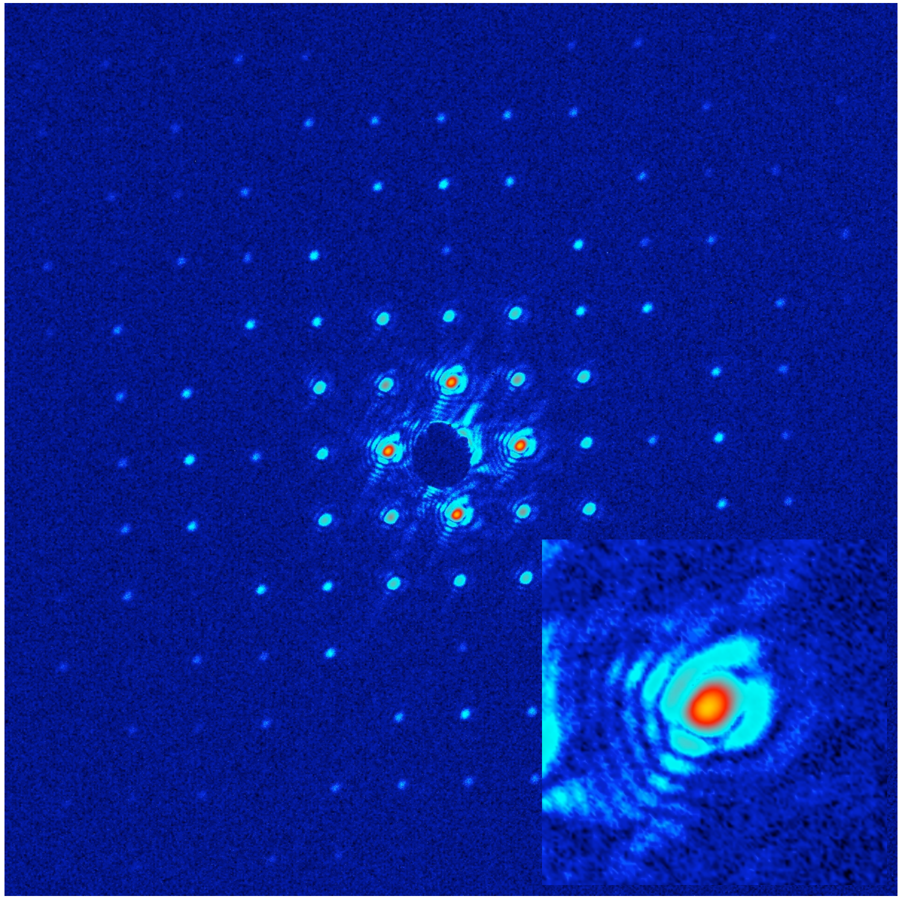


(*) C. Callegari, V. Feyer, G. Cautero, A. Moise, K. Prince, R. Richter, R. Sergo (Sincrotrone Trieste) V. Lyamayev, M. Mudrich, F. Stienkemeier, U. Person (University of Freiburg) L. Avaldi, P. Bolognesi, M. Coreno, P. O' Keeffe (CNR-IMIP, Montelibretti) M. Alagia, M. de Simone, A. Kivimäki, (CNR-IOM, 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 (2013 and beyond).
- 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.

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:
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