2443-18

Winter College on Optics: Trends in Laser Development and Multidisciplinary Applications to Science and Industry

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Free Electron Lasers (FEL)

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Free Electron Lasers

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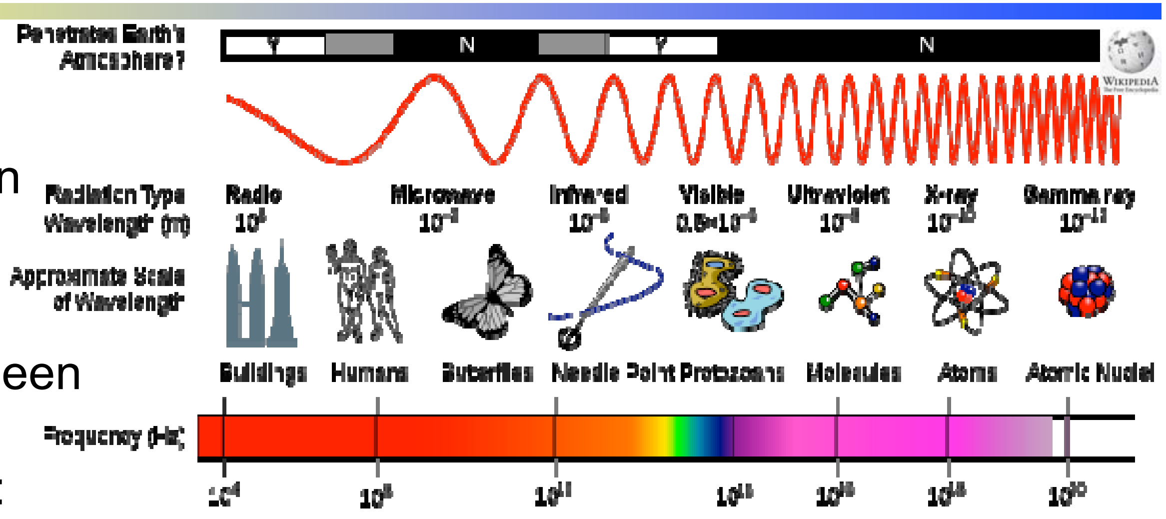
Outline

- **Why a free electron laser**
- **Basic concepts of light-electron interaction in a Free-Electron Laser**
  - How it works
- **Different schemes for FEL**
  - FEL oscillator
  - FEL amplifier
  - Self Amplified Spontaneous Emission FEL (SASE)
  - High Gain Harmonic Generation FEL (HGHG)
- **The FERMI free electron laser project at Elettra**
- **Recent experimental results FERMI**

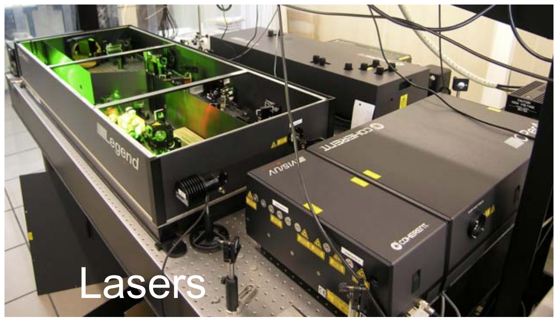
The need for light sources

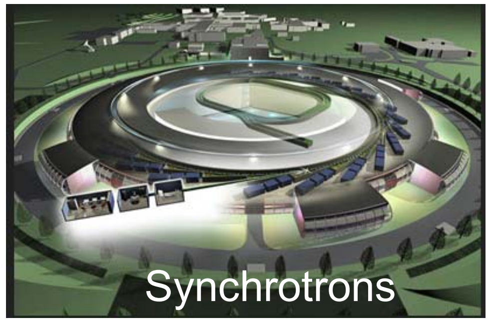
A significant part of our scientific progress has been driven by the use of the electromagnetic radiation and light.

In order to characterize the matter with always more accuracy it has been necessary to develop light sources that could satisfy the requirements: spectrum, brightens, coherence, … .



Depending on the experiment requirements it is possible to use, lamps, lasers, synchrotrons.
Each system has is own characteristics:
pulse duration, power, wavelength, coherence, … .



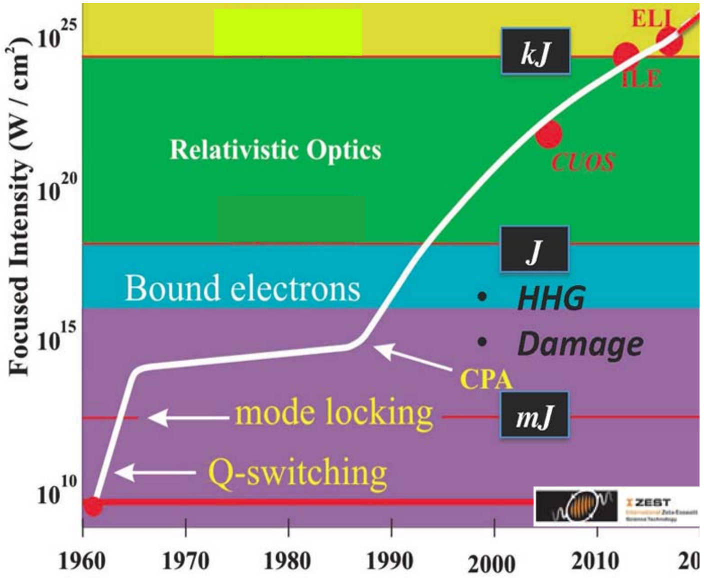


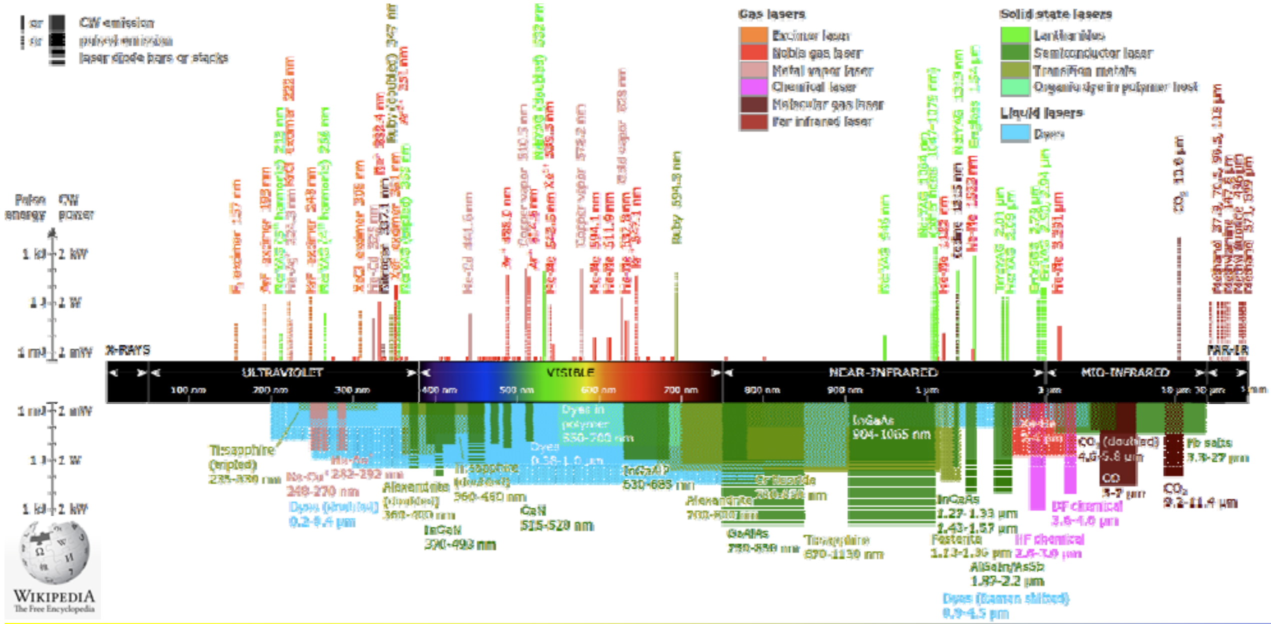
Light sources: lasers

From the discovery of lasers their performances constantly improved over the years.

As a light sources lasers offer many possibilities allowing:

- high coherence,
- peak power,
- short pulses,
- …..





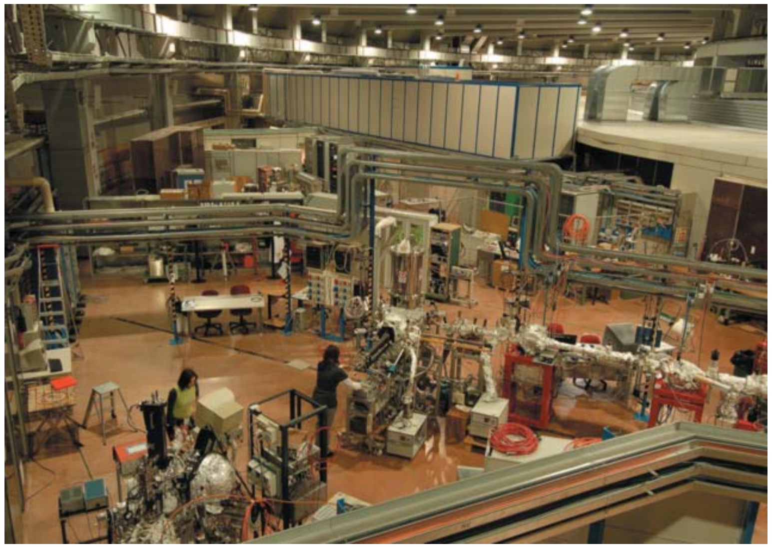
Main limitation for these systems is the tunability. Extension to the EUV and X-ray spectral range is related to secondary process.

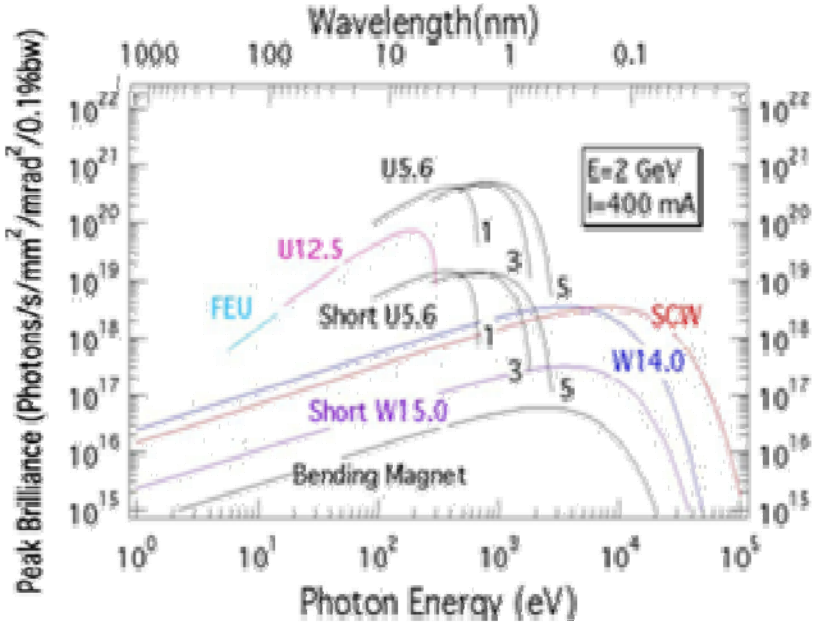
Light sources: synchrotrons

Synchrotron radiation sources use the emission produced by relativistic electron bunches.
These sources allow a full tunability of the radiation over a very broad spectrum from IR to hard X-ray.

Synchrotrons can produce high average power with a partial degree of coherence.

Their are limited in the peak power and the pulse length which can not be reduced below some tens of ps.





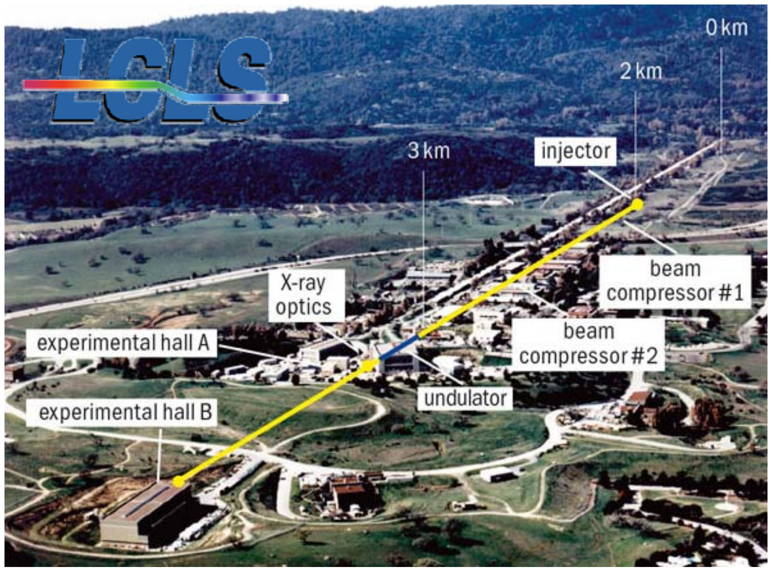
Light sources: Free Electron Lasers

Free Electron Lasers (**FEL**) can **combine** the properties of **lasers** with those of **synchrotron** sources.

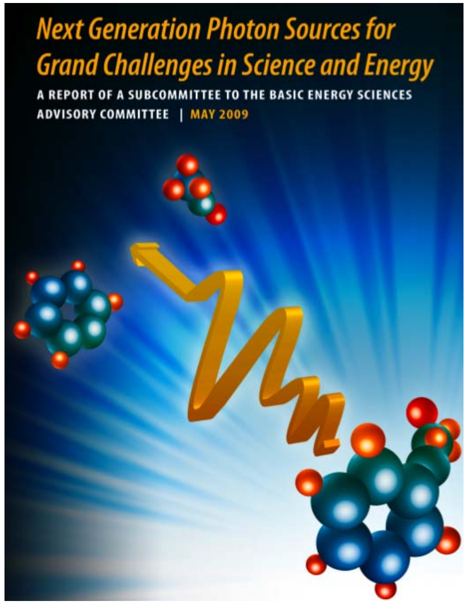
FEL can produce radiation in the **whole spectral range** from **IR** to **hard X-ray** with a high degree of coherence, **short pulses** (~ fs) and **high peak power** (~ TW).

Like synchrotrons, FELs use **relativistic electron beams** to generate the electromagnetic radiation. **Electron beam** has to satisfy very **stringent requirements** in order to allow the FEL process to occur.

Depending on the **FEL** characteristics, the whole system including the accelerator can be **very long** up to few kilometers.

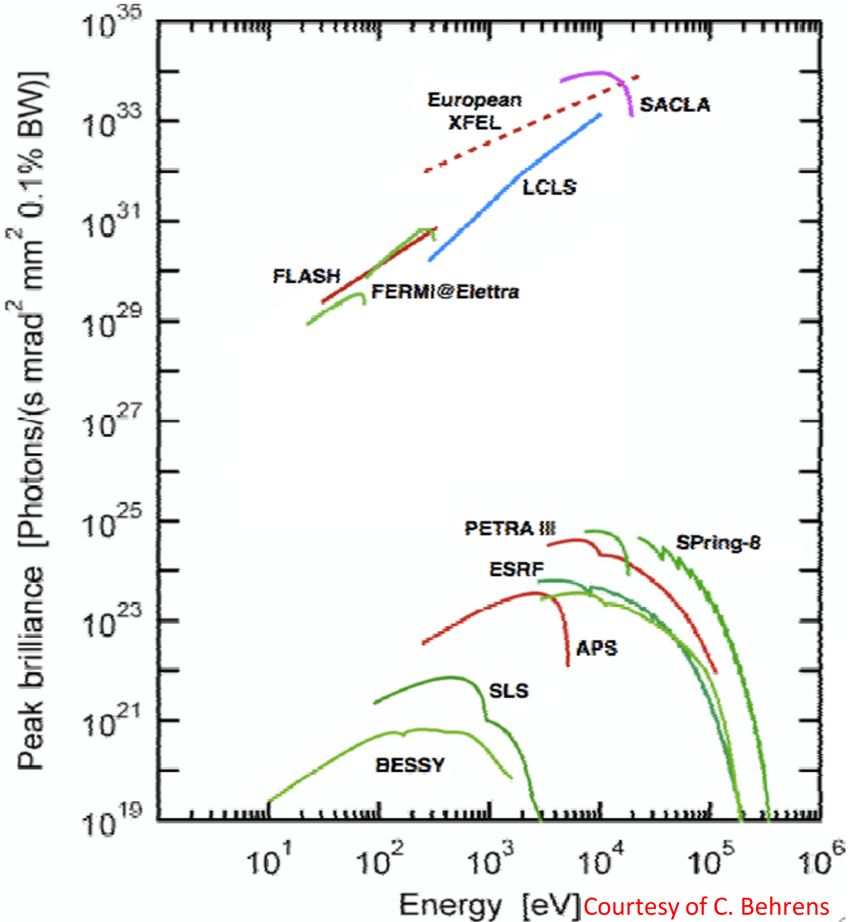


FELs as next generation light source



For their characteristics FELs have been recently recognized as the next generation light sources. First FEL user facilities start to be available around the world. More facilities are planned to appear in the near future.

In terms of peak brilliance FELs increase the performance with respect to synchrotrons by several order of magnitude



Courtesy of C. Behrens

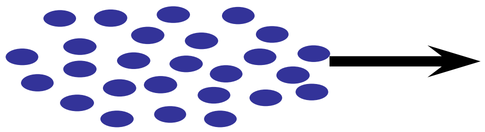
Existing and *planned* FEL facilities

- **FLASH, Germany**
- **Linac Coherent Light Source (LCLS), USA**
- **FERMI@Elettra, Italy**
- **SACLA (SPring-8 Angstrom Compact Free Electron Laser), Japan**
- *European XFEL, Germany*
- *PAL-XFEL, Korea*
- *SwissFEL, Switzerland*
- *SINAP XFEL, China*
- *Next Generation Light Source (NGLS), USA*

FEL basic ingredients

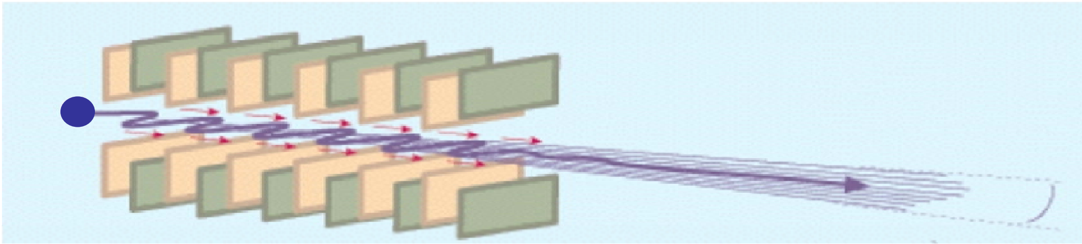
A **Free-Electron Laser** is a light source exploiting the induced coherent emission of a relativistic electron beam "guided" by the periodic and static magnetic field generated by an undulator.

1) Relativistic **electron beam**



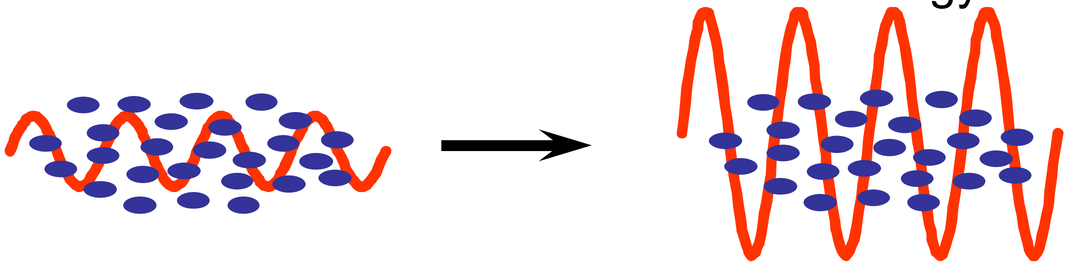
Energy (γ)
Current (I)
Emittance (ε)
Energy spread ($\delta\gamma$)
Dimensions (σ)

2) Undulator



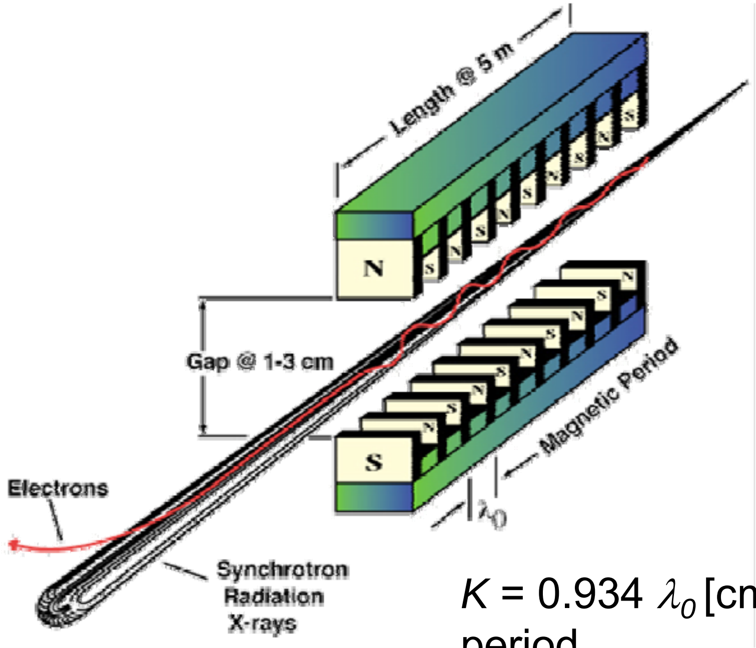
Magnetic period (λ_w)
Magnetic strength (K)
Undulator length (L)

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



Wavelength (λ)
Power (P)

Synchrotron radiation



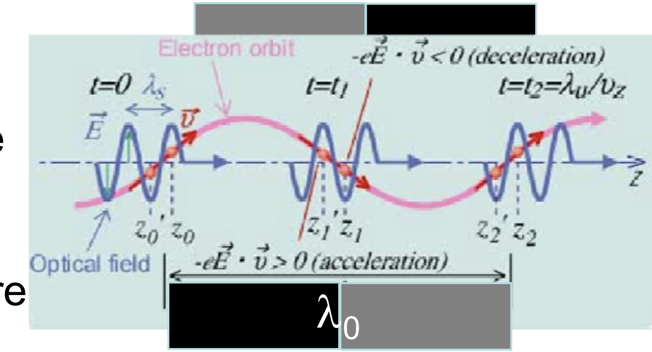
A **relativistic electron beam** passing in the **periodic magnetic field** of an undulator **oscillates** transversally.

As a consequence of these oscillations the electrons **produce an electromagnetic field**.

The wavelength of the radiation produced by electron oscillations is function of the electron **beam energy,** and **period** and **strength** of the **magnetic field**.

$$\lambda_{rad} = \frac{\lambda_o}{2\gamma^2}\left(1+K^2/2\right) \qquad 1)$$

$K = 0.934\ \lambda_0$ [cm] B_{max} [T]; γ is the electron beam energy; λ_0 is the undulator period.

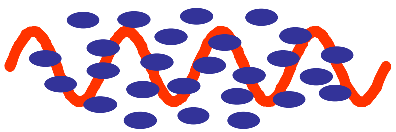


The "resonance" condition given be the equation 1) imposes that the electron beam oscillation in the magnetic field has the same phase with respect to the produced electromagnetic radiation after each undulator period.

Other characteristic of synchrotron radiation from undulator are

Bandwidth: $\frac{\Delta\lambda}{\lambda} \approx \frac{1}{N_{per}}$; Divergence $\theta \approx \frac{1}{\gamma}$

Coherent synchrotron radiation



Electron bunches contains many electrons that on the length scale of the radiation are randomly distributed.

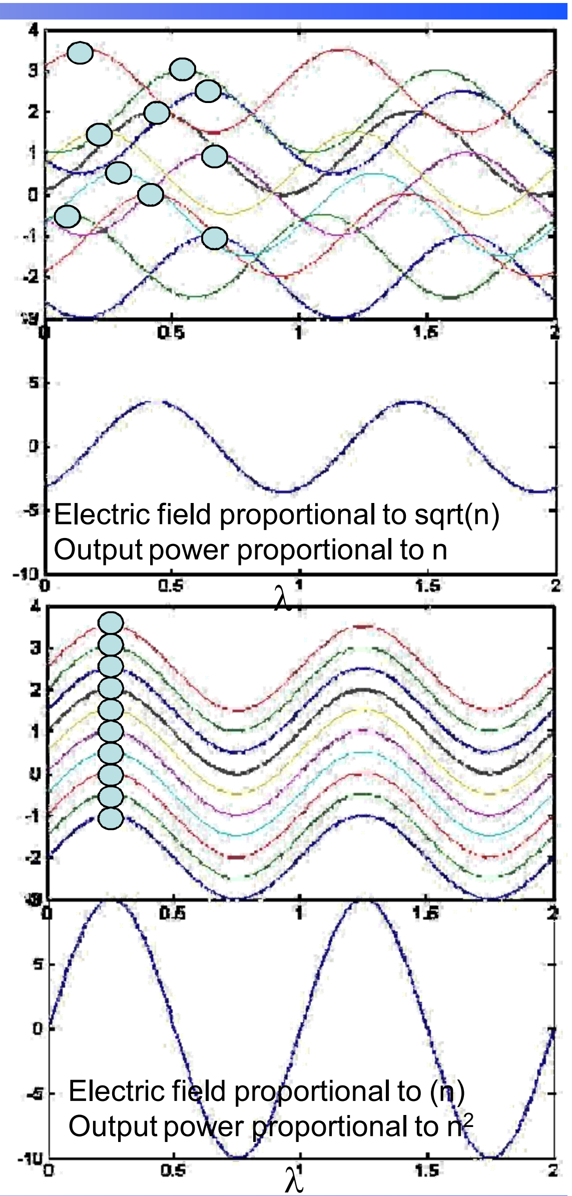
Because there is no correlation between the electron positions, the fields emitted by single electrons are also uncorrelated.

As a results the field produced by the entire bunch of electrons is expressed by $E_{rad} \propto \sqrt{n}$, where *n* is the number of emitting electrons.

If we are able to control the electron beam in order to force each electron to be in phase with the others we can significantly improve the quality and intensity of the produced radiation.

Being all electrons in phase the fields produced by each electron sum coherently, as a consequence the produced field can be expressed by $E_{rad} \propto n$.

Typical electron bunches have a charge of about 100pC-1nC, *n* is of the order of 10^9.



Free Electron Laser

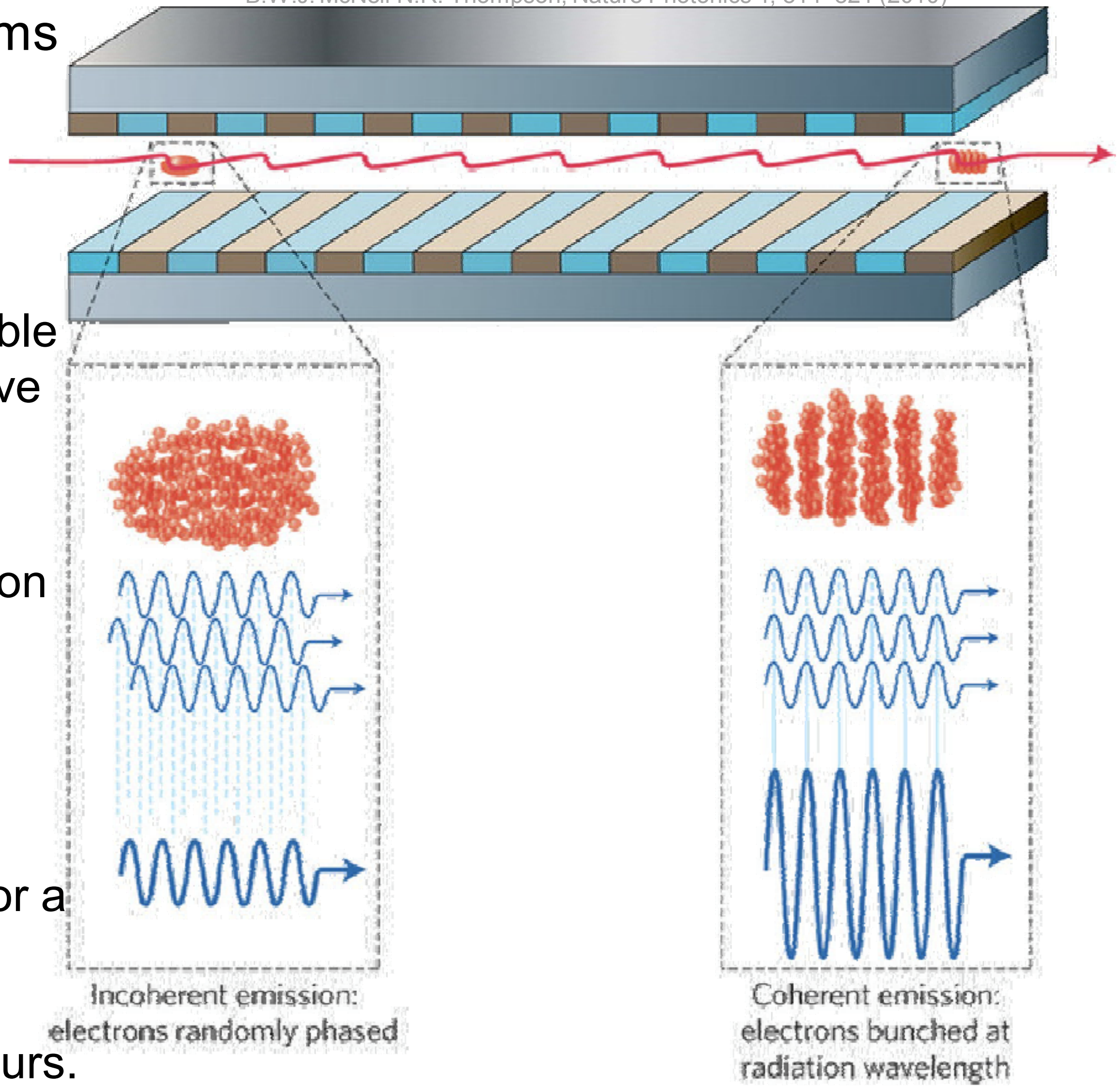
Free electron lasers are systems that **allow** an **electron beam** to emit **coherent synchrotron radiation.**

For short wavelength it is not possible to prepare the electron beam to have a coherent structure at the desired wavelengths.

FELs are able to **modify** the electron **beam distribution** and induce an electron **density modulation** (**bunching**) at the wavelength of interest.

This **bunching** process **requires** for a **high quality electron beam** and a **long undulator** where interaction between radiation and electron occurs.

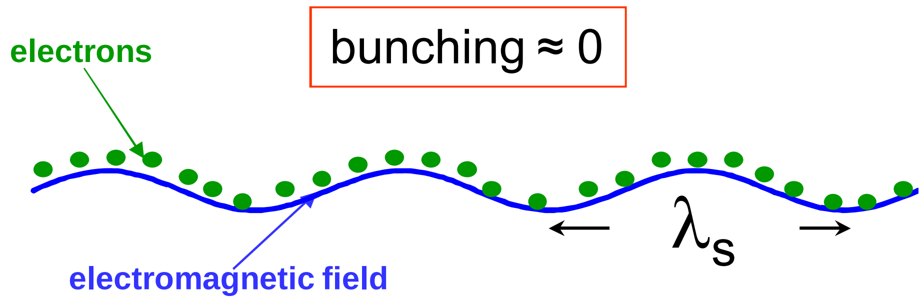
B.W.J. McNeil N.R. Thompson, Nature Photonics 4, 814–821 (2010)



Bunching creation

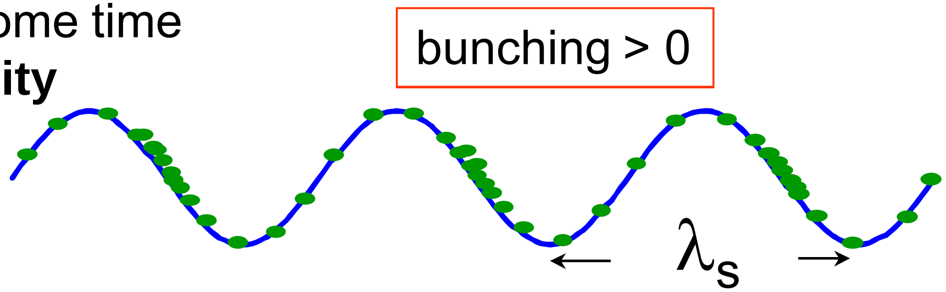
Bunching is created in the electron beam thanks to an instability.

At the **undulator entrance** the **uniformly** distributed electrons interact (through the magnetic field of the undulator) with a **weak electromagnetic** field.



As a consequence of this interaction some **electrons gain energy** and **others lose energy**.

Because in the undulator **high energy electrons** move **faster** than low energy electron after some time **electrons become bunched** with a **periodicity** equal to the one of the electromagnetic field.



Bunched electrons can **emit coherently** and **amplify** the electromagnetic field. This instability induces an **exponential growth** of the radiation along the undulator.

The origin of the co-propagating wave

An initial “seed” is necessary for initiating the amplification process.

This can be provided by:

- **The spontaneous emission**

  → The **spontaneous emission** can be **stored in an optical cavity** and amplified by means of several **consecutive interactions** with a “fresh” or re-circulated electron beam (**Oscillator** configuration)

  → The **spontaneous emission** is **amplified** during a **single interaction** with the electron beam (Self Amplified Spontaneous Emission (**SASE**))

- **An external signal (e.g. a laser)**

  → The **external coherent** signal is **amplified** by the FEL (direct seeding)

  → The **external coherent signal** is used to create **harmonic bunching** and thus **generate coherent radiation** to a **harmonic** of the original seeding wavelength (Coherent Harmonic Generation (CHG))

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).

SASE FEL

Potentially completely tunable, FEL wavelengths only depend on the resonance condition.
Tighter requirements for the electron beam parameters
Spectral properties are be affected by the random startup

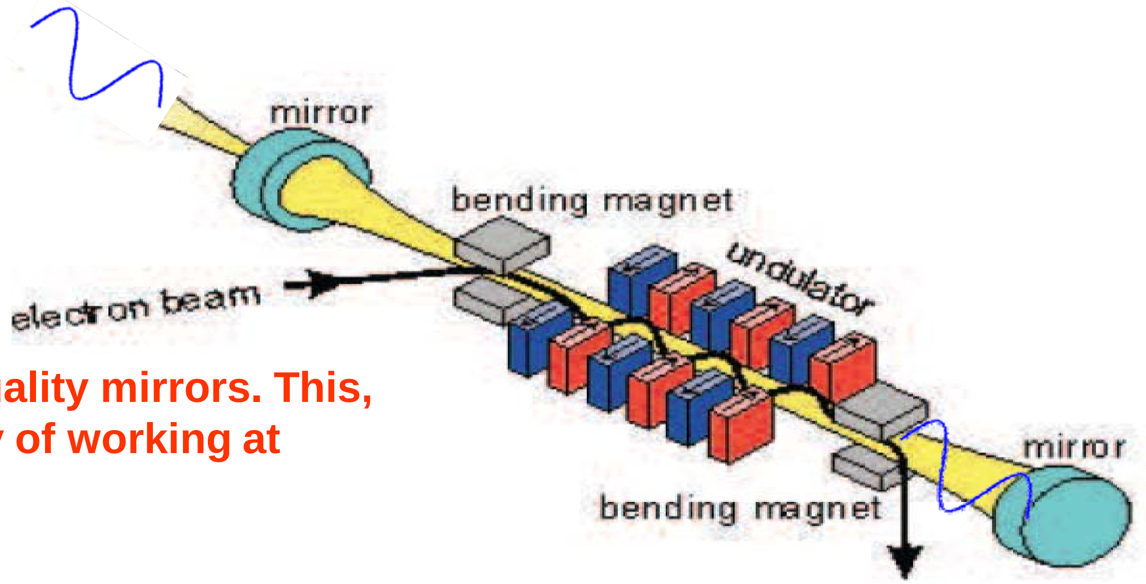
Amplifier FEL

The tunability toward short wavelengths is limited by the availability of the seed wavelength.
Spectral quality limited by the quality of the electron beam.

Oscillator FEL

The use of an optical cavity allows to trap the radiation. Radiation is then amplified as a consequence of multiple interaction with the electron bunches

- **The system is tunable with good spectral properties**
- **The repetition rate can be high allowing high average power**



- **The system require very good quality mirrors. This, currently prevents the possibility of working at wavelength shorter than 170nm.**

Similarly to standard lasers oscillators, the system requires the **gain** to be **larger than** cavity **losses**. **High quality mirrors** are needed to reduce the losses, and high quality electron with **high peak current** is required to increase the gain.

Typical electron bunches that can support FEL oscillators are between 1 ps and few tens of ps long. The repetition rate of the electron bunches has to match the cavity round trip(~300 ns). The FEL is then naturally pulsed (~ps) and high repetition rate (~MHz).

FEL oscillators

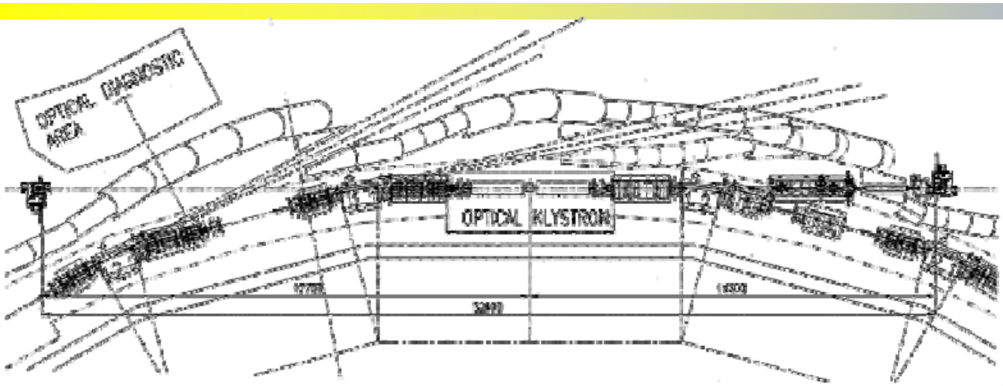
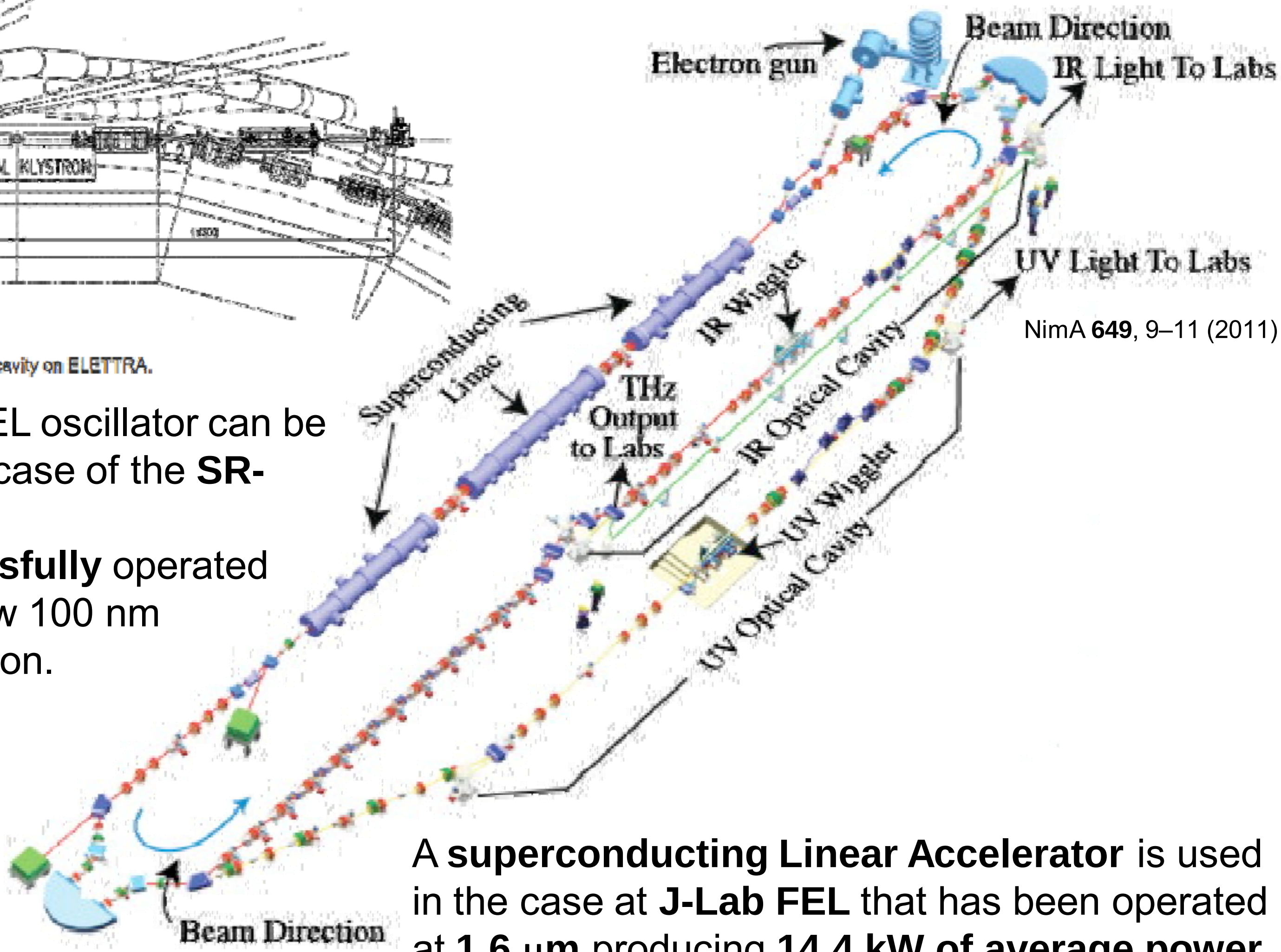


Fig. 1. Layout of the undulator (optical klystron) and optical cavity on ELETTRA.

Electron sources for an FEL oscillator can be a **storage ring** like in the case of the **SR-FEL** at **Elettra**.

SR-FEL has been **successfully** operated down to **170 nm** and below 100 nm using the harmonic emission.

SR-FEL require special operation mode of the storage ring.



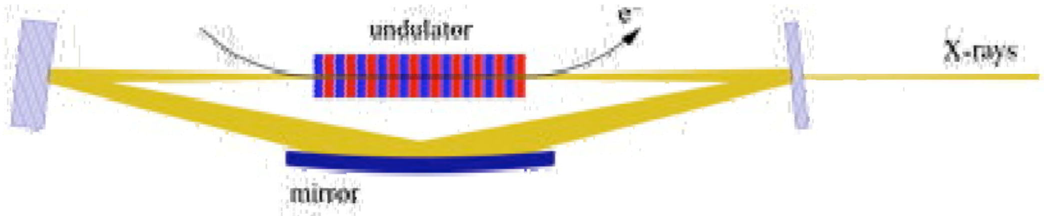
NimA **649**, 9–11 (2011)

A **superconducting Linear Accelerator** is used in the case at **J-Lab FEL** that has been operated at **1.6 μm** producing **14.4 kW of average power**. The same accelerator has been used for a UV FEL.

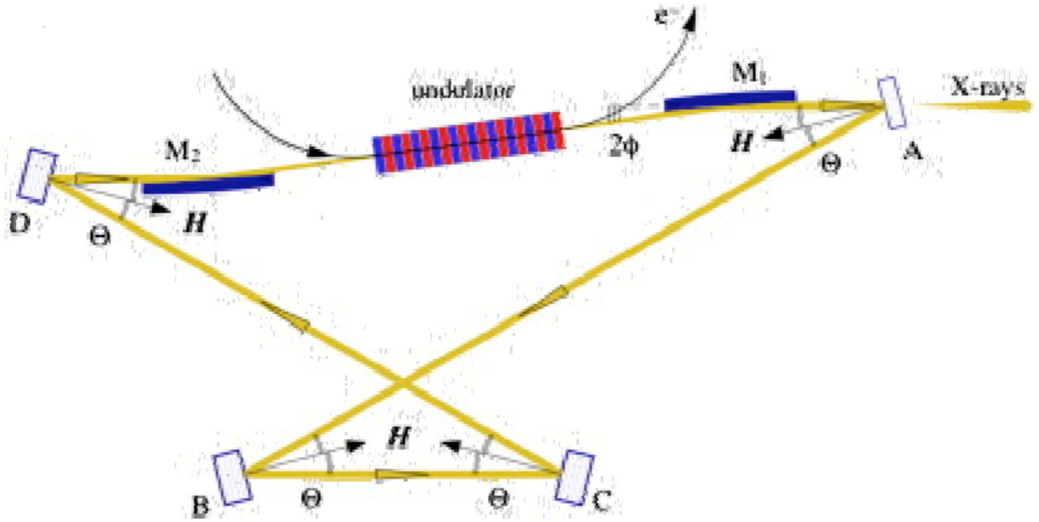
Extending to X-rays

Recently, schemes have been proposed to extend the capability of oscillators FEL to hard x-rays.

These schemes uses very high quality electron beams in combination with cavities based on Bragg diffracting crystals. Bragg crystals acts both as a filter and mirror.



At the moment there are not designed machines able to support this operational mode but people is working on possible solutions.



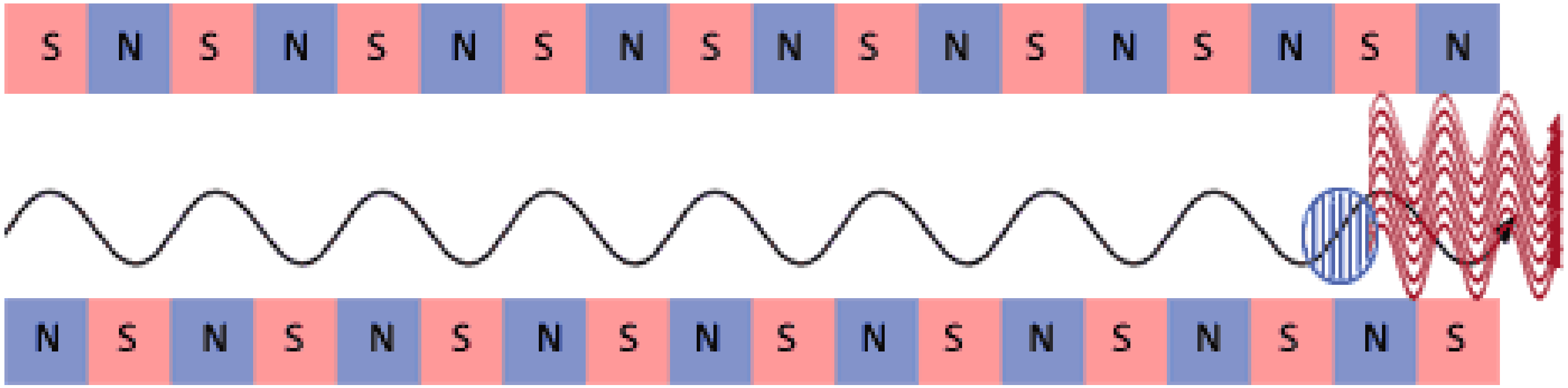
Phys. Rev. Lett. **100**, 244802 (2008). NimA 618, 69–96 (2010).

SASE FEL

In the case of a **high gain** FEL, a possible scheme is the Self Amplified Spontaneous Emission (SASE).

In this kind of FEL the gain is so high that the **spontaneous emission** produced by the electron beam **entering in the undulator** can be **amplified** up to the saturation within the **single passage** of the electron beam in the undulator.

There is **no need of mirrors** and external seed sources.



For this FEL the electron beam has to be extremely good with a very **high peak current** (kA), typical **bunch length** is in the range **1-100 fs**. Repetition rate is between 10 and 100 Hz with the possibility to have bursts.

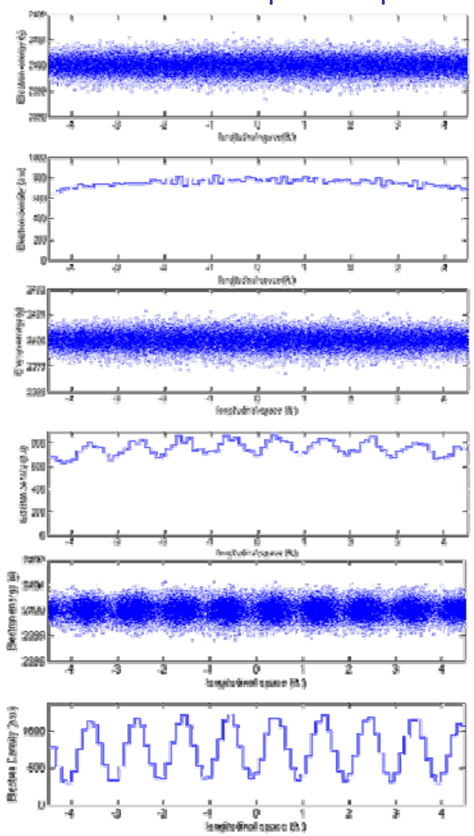
Pictures from: www-ssrl.slac.stanford.edu/lcls/glossary.html

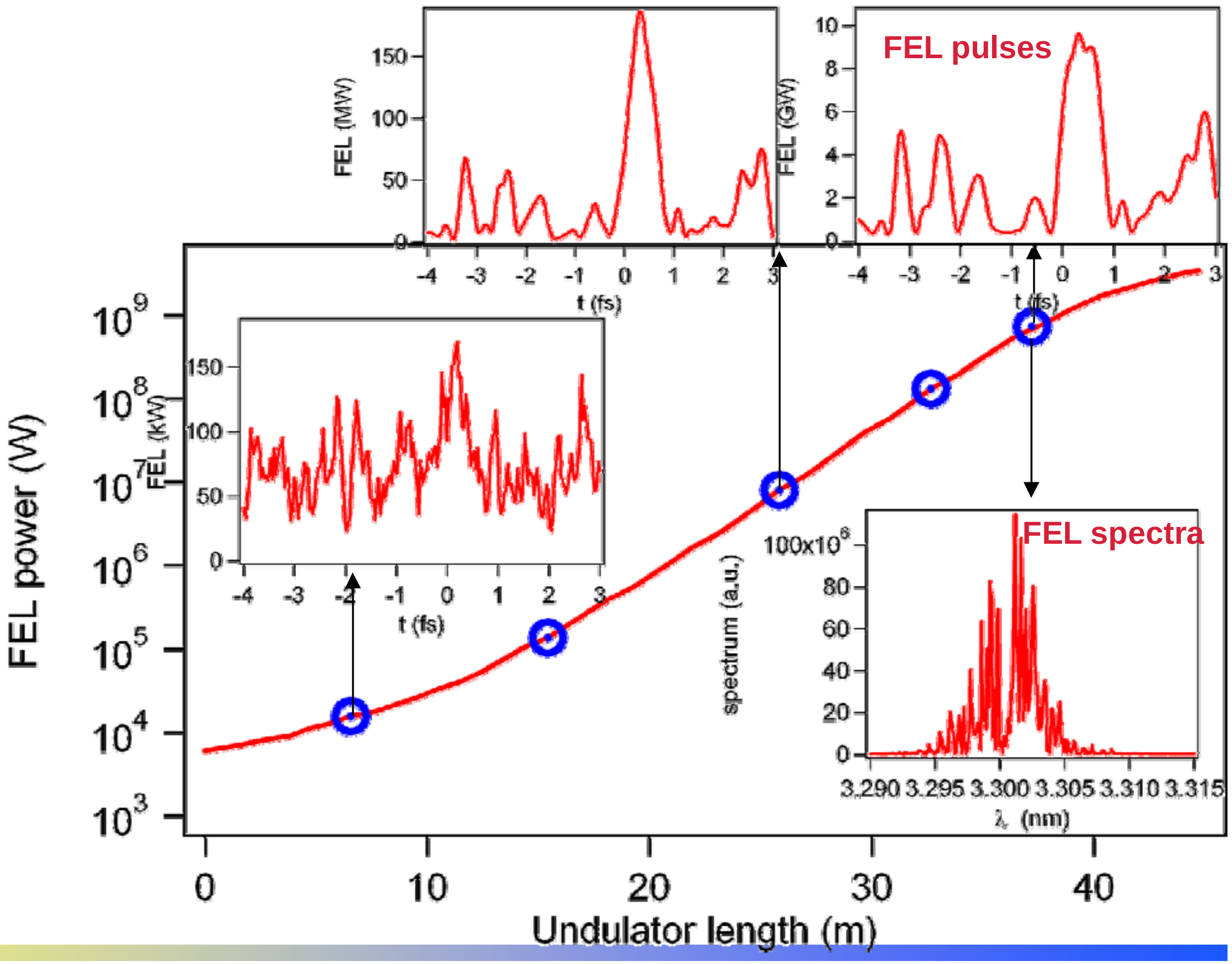
SASE FEL properties

Main limitation for SASE is related to the origin of the radiation that initiate the process. Because the initial spontaneous emission is a stochastic process there is no control on the spectral and temporal properties of this radiation.

Signal can be partially cleaned by the FEL process but the output FEL pulses can not be completely coherent.

Electron beam phase space

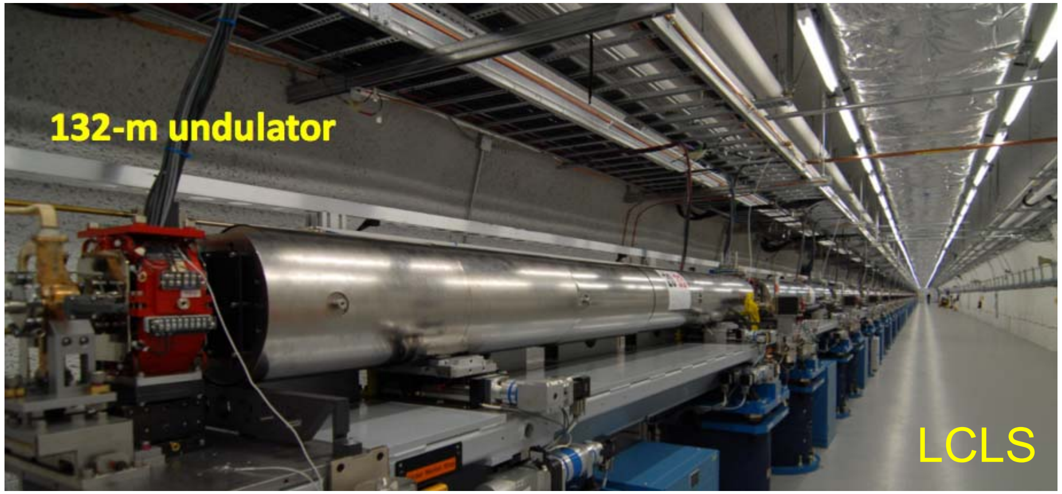




SASE FELs

SASE has been used for existing hard x-ray facilities indeed SASE is:

- **completely tunable**
- **can reach very high peak power**

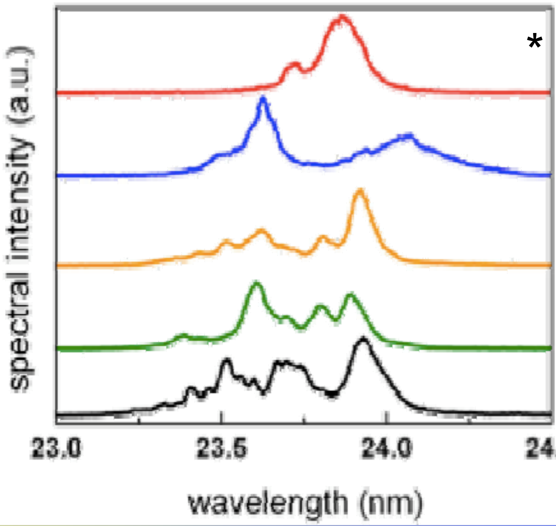


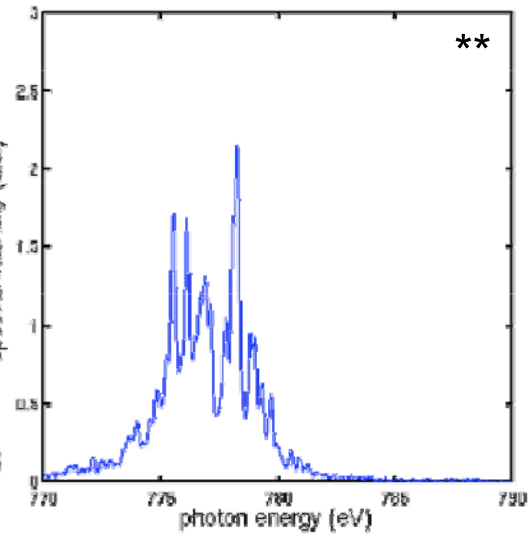
The mechanism is simple but come with some limitations.

The process is initiated by shot noise:

- **a very long undulator is required**
- **both temporal and spectral properties are affected**
- **no control on the FEL pulse**

Operation of SASE have been demonstrated below 1 **Å** at SACLA, several tens of GW are currently produced at LCLS in the hard x-ray. Possible schemes to solve SASE limitations have been proposed and experiments are ongoing.





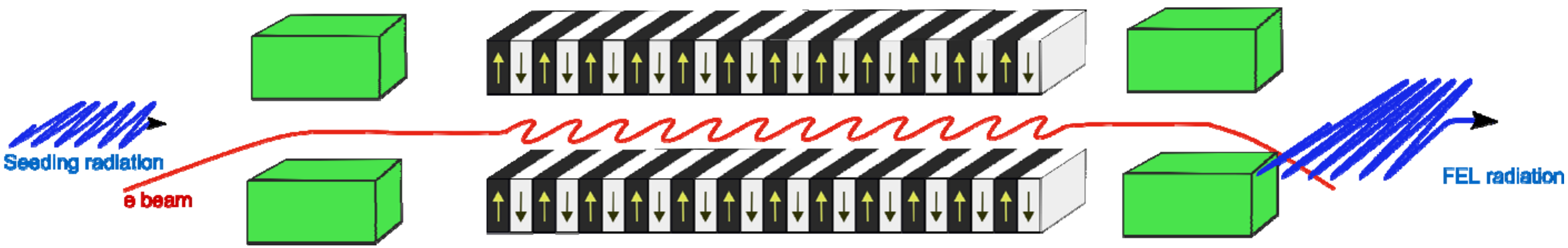
*Opt Express 16, 19909 (2008)
**FEL Spectral Measurements at LCLS, FEL2011

Benefits of a Seeded FEL

An external "seed" laser allow to control the distribution of electrons within a bunch. FEL output pulses will inherit properties from the seed.

Seeding allow to improve:

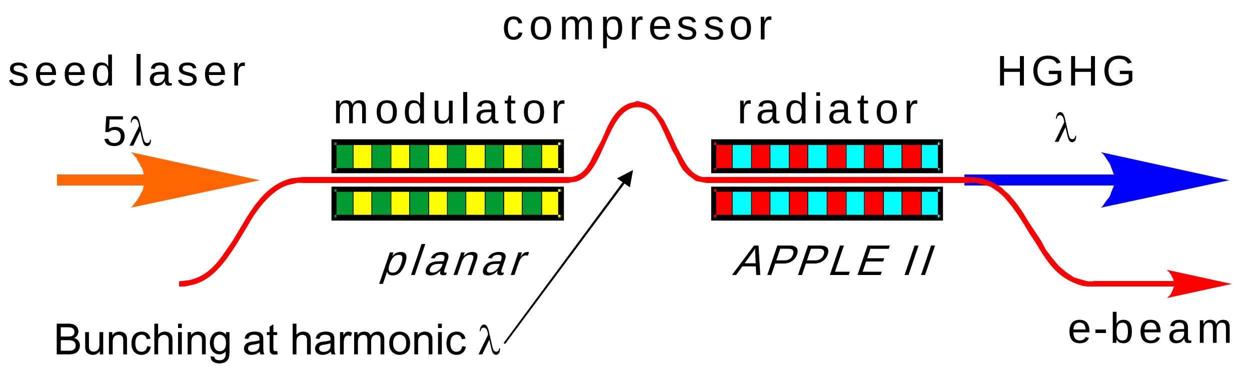
- temporal coherence of the FEL output pulse;
- control of the time duration and bandwidth of the coherent FEL pulse;
- synchronization of the FEL pulse to a pump laser;
- reduction of undulator length needed to achieve saturation.



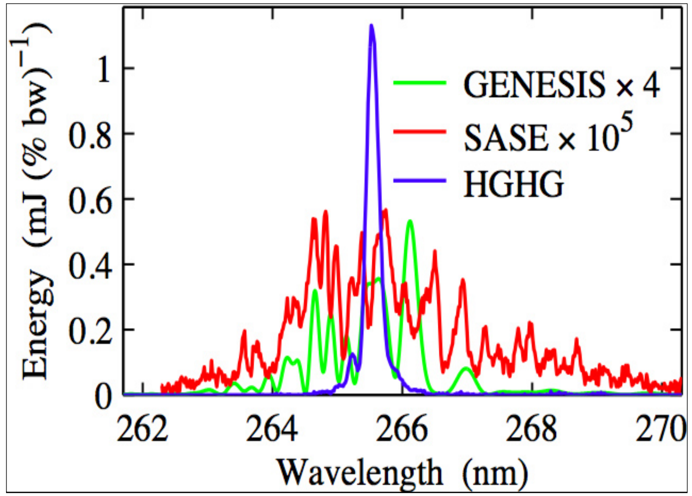
The problem with seeding is that there are not sources available for direct seeding in the very short wavelength range (<1nm).

High Gain Harmonic Generation (HGHG)

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



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

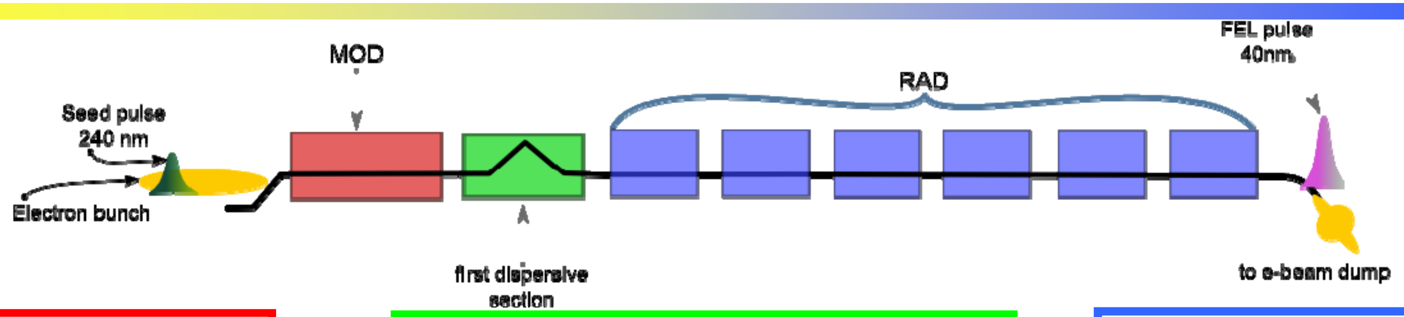


L.H. Yu et al. PRL 91, 074801 (2003)

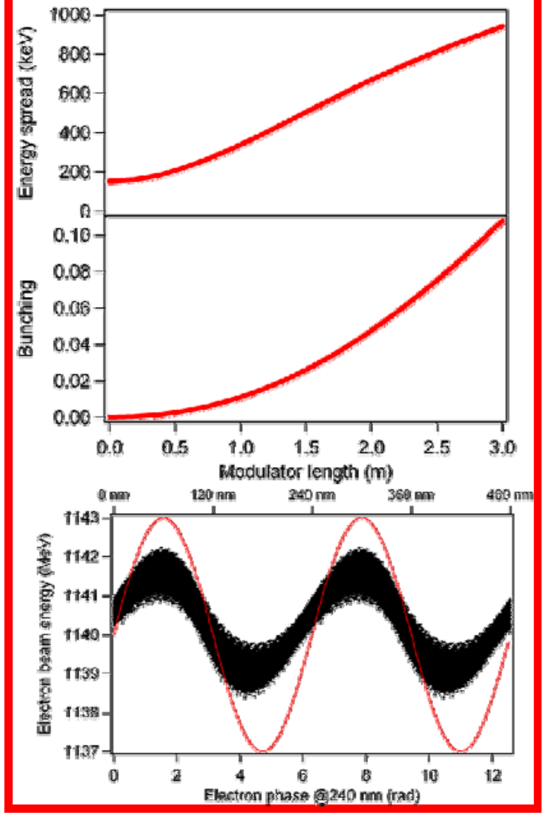
After the initial HGHG demonstration experiment done at Brookhaven – BNL, **HGHG** has been demonstrated and explored in other test facilities (UVSOR-II(JP), Elettra SR-FEL(IT), Max-Lab FEL (SE), SPARC(IT), SDUV-FEL(CN), SLAC(USA)).

The design of FERMI FELs is based on HGHG.

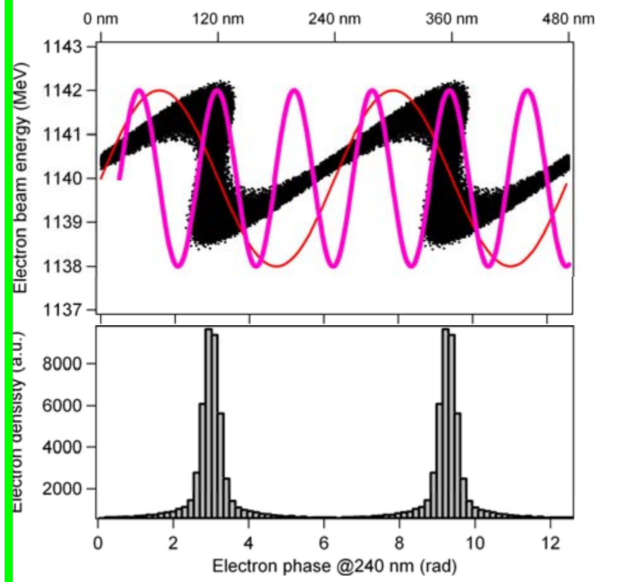
HGHG mechanism



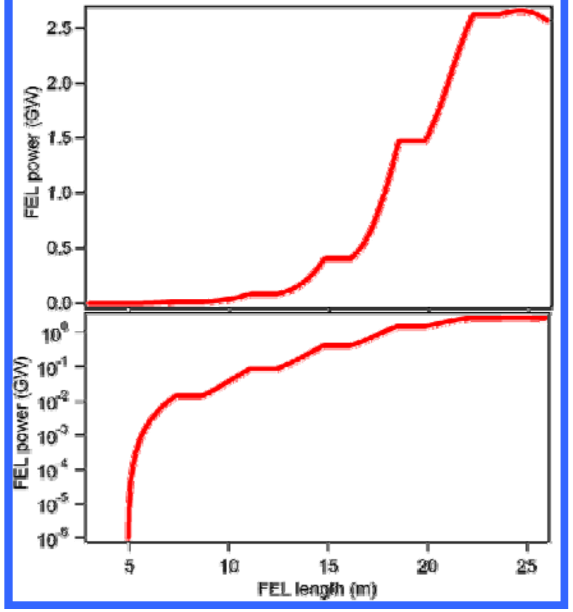
Modulator



Dispersive section



Radiator



Interaction with the seed laser in the modulator produces bunching also at the harmonics. Bunching at the desired harmonic is enhanced in the dispersive section. In the radiator the FEL process is initiated by the coherent emission from the bunched electrons.

FERMI@ELETTRA

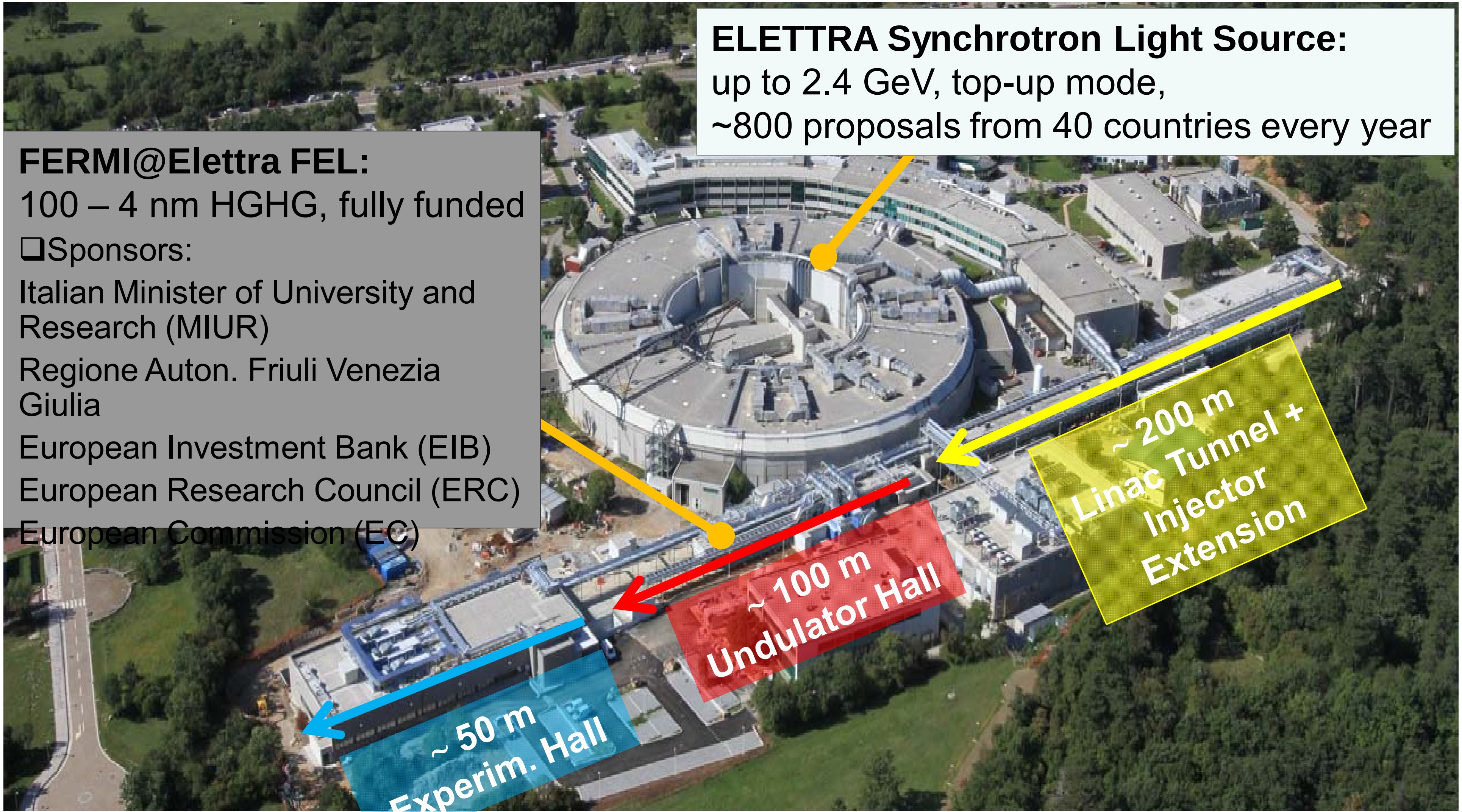
SINCROTRONE TRIESTE is a nonprofit shareholder company of national interest, established in 1987 to construct and manage Italian synchrotron light sources as international facilities.

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)



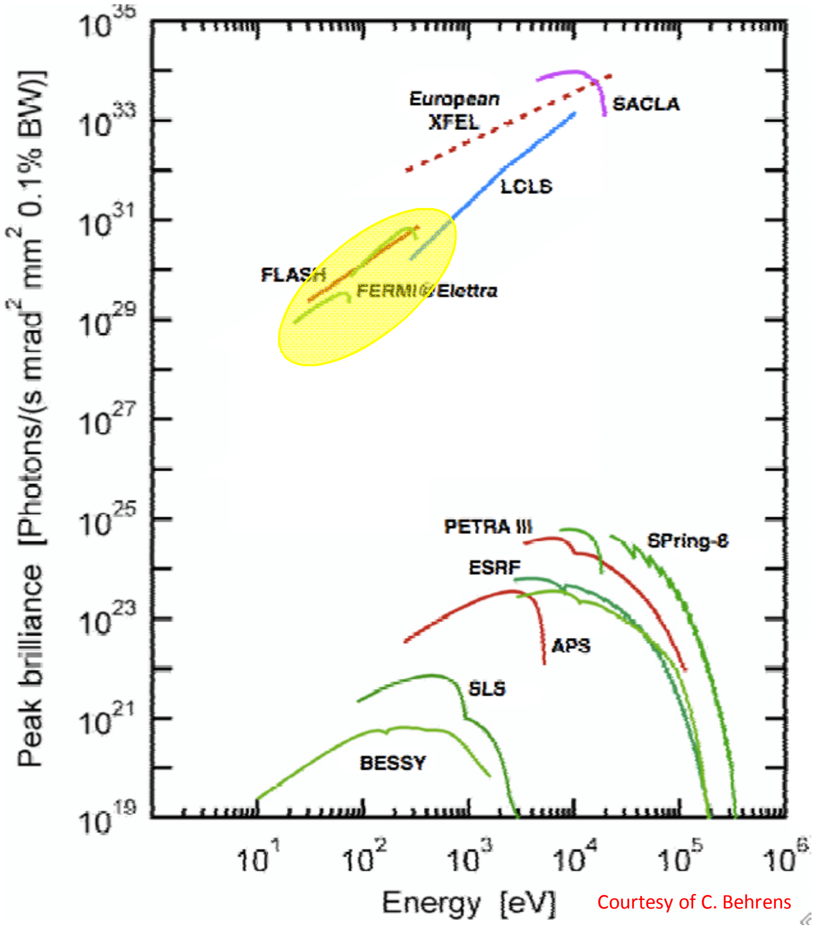
FERMI main features

FERMI@Elettra is a 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.

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



Courtesy of C. Behrens

SCIENCE CASE

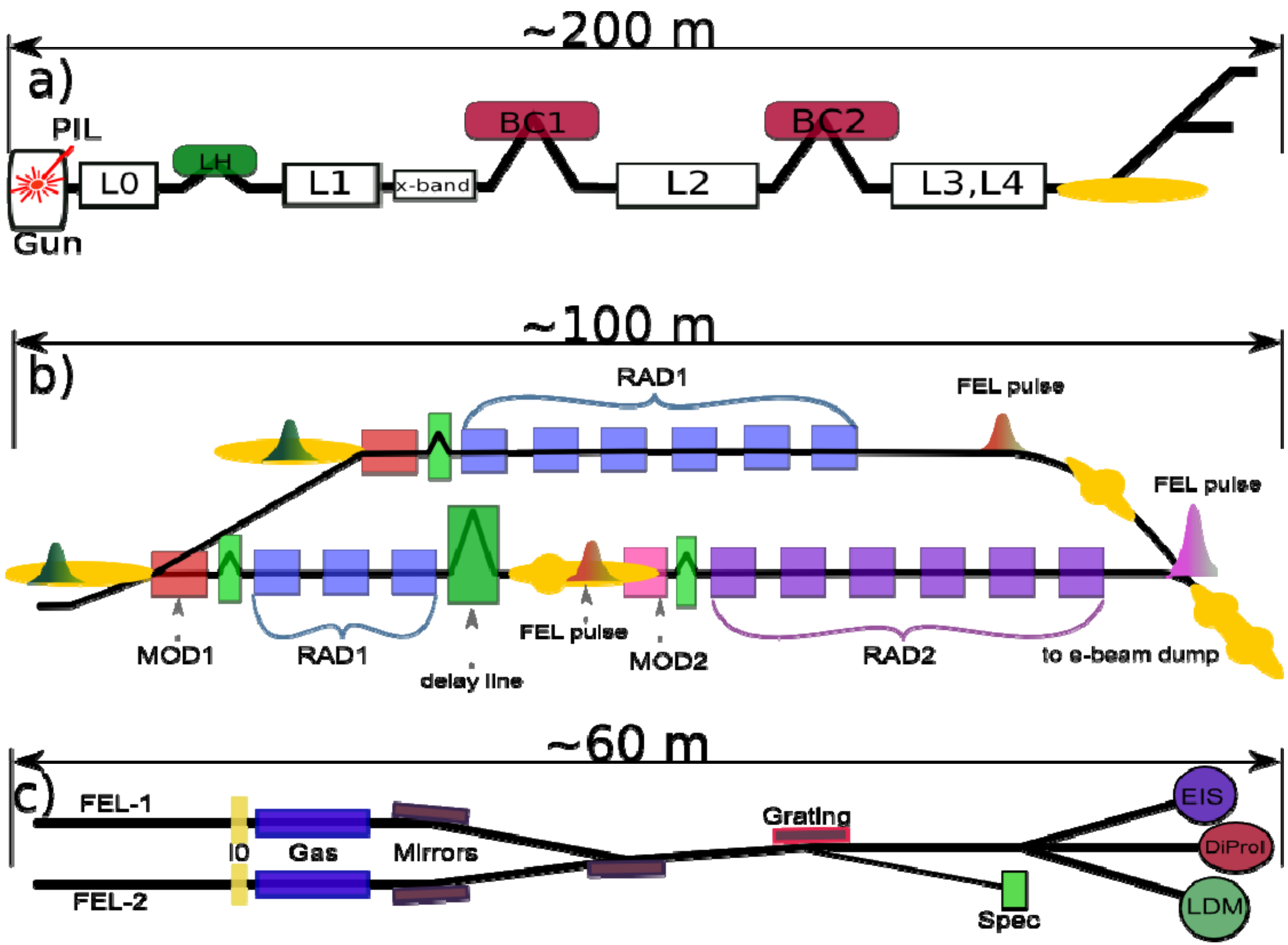
F. Parmigiani (Head of Scientific Programs)

- **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*

FERMI layout



Linear accelerator:
Rep rate 50Hz,
Beam charge 500pC,
Beam energy 1.5GeV,
Peak current 500A.

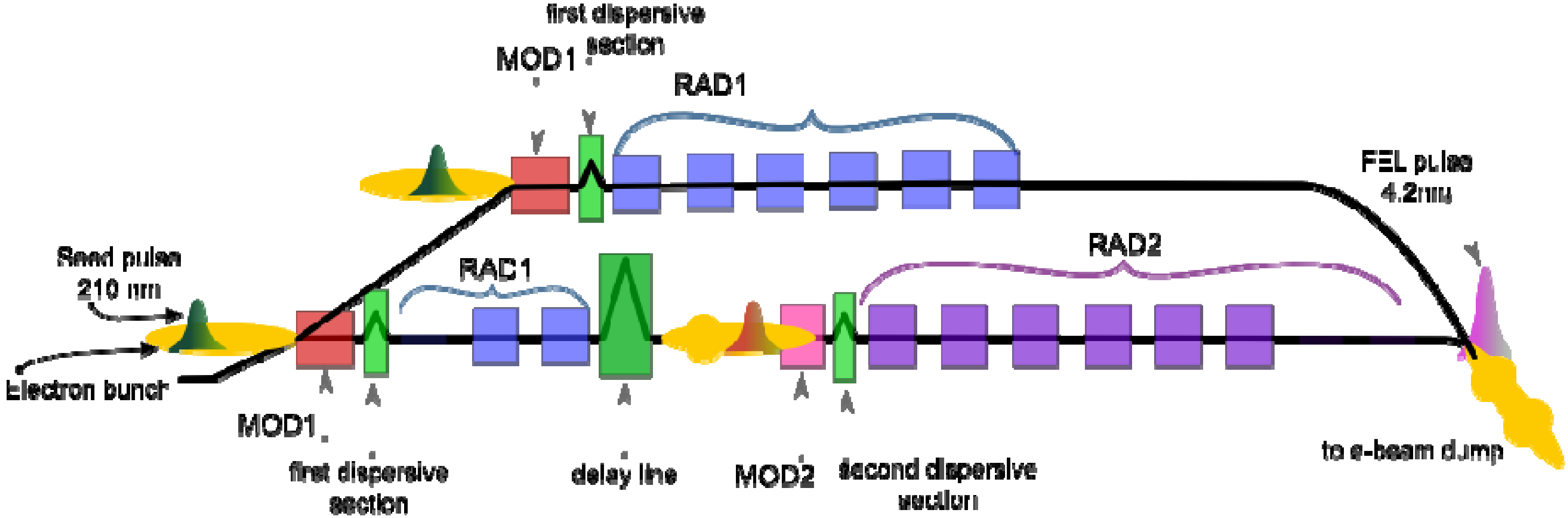
The **two undulator** lines uses APPLE-II undulators.
Both FELs are seeded by an UV laser.

FEL pulses are **analyzed** and **delivered** to the three **experimental stations**.

HGHG at FERMI: FEL-1 and FEL-2

FERMI's two FELs will cover different spectral regions.

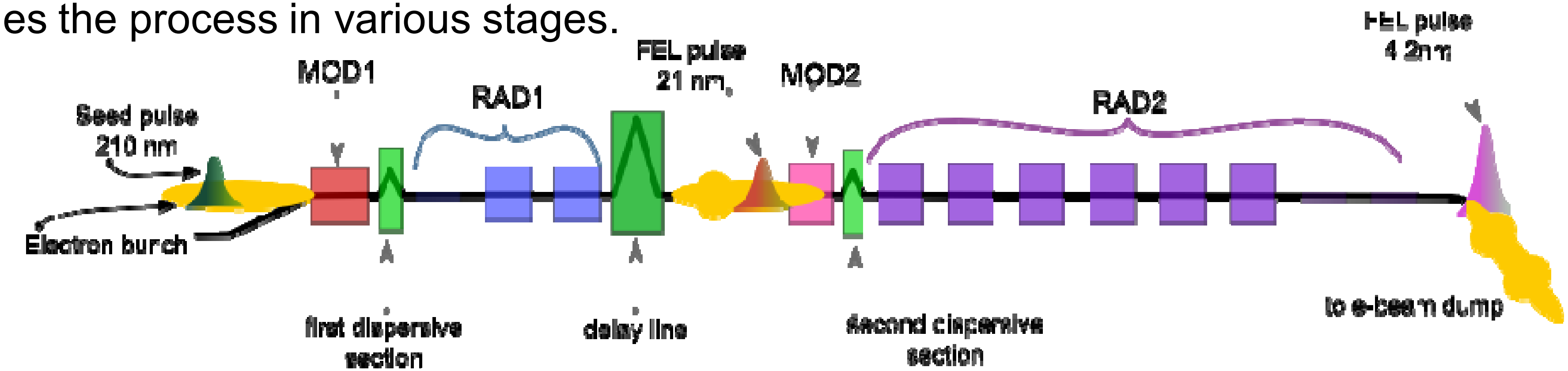
FEL-1, based on a single stage high gain harmonic generation scheme initialized by a UV laser will cover the spectral range from ~100 nm down to 20nm.



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).

FEL-2: HGHG cascade

A way to **really extend the HGHG** to **higher harmonics** (50^{th}-100^{th}) is to **repeat** several times the process in various stages.



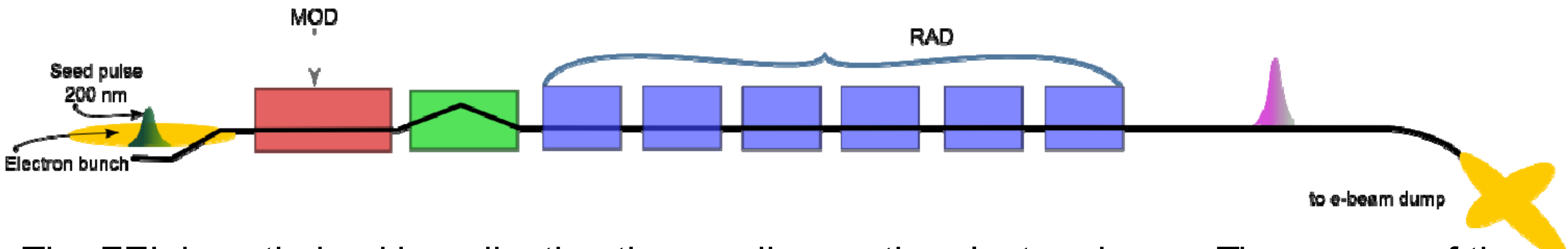
In a **two stages HGHG cascade FEL**, the **first stage** can allow to generate a FEL pulse at about **20nm** starting with a seed laser at 200nm.

The produced **FEL pulse at 20nm** is then used as a **seed in a second HGHG** stage allowing to **create bunching** and have the FEL operating at about **4 nm**.

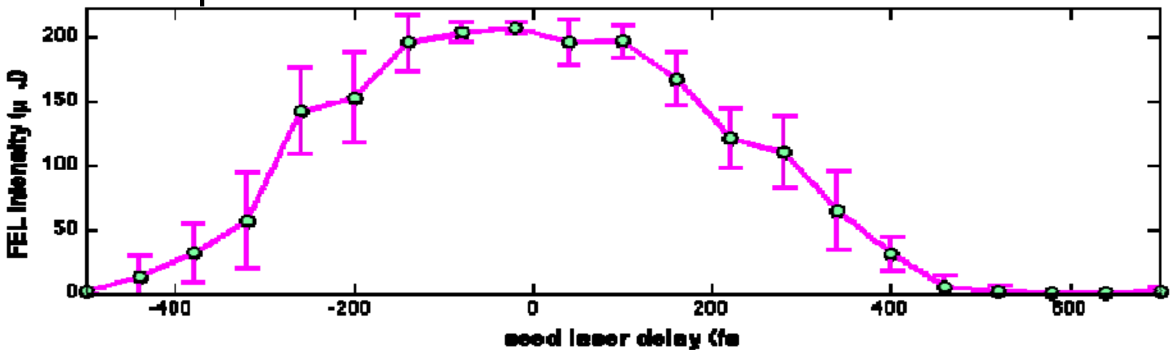
The "fresh bunch" technique is used to have the seeding always occurring in a part of the electron beam that has not been spoiled by previous FEL interaction.

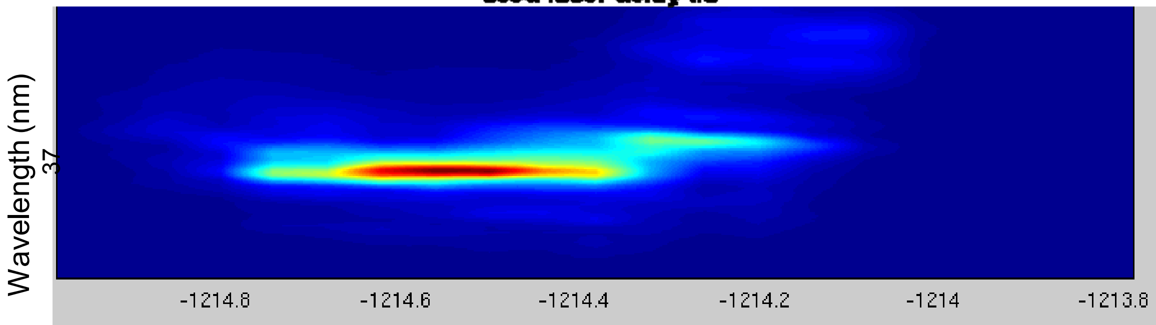
The double stage HGHG cascade with "fresh bunch" has been recently demonstrated at FERMI.

FEL1: seeding



The FEL is optimized by adjusting the seeding on the electron beam. Time scans of the delay between the electron beam and the seed lasers shows that only the seeded electrons produce FEL radiation.





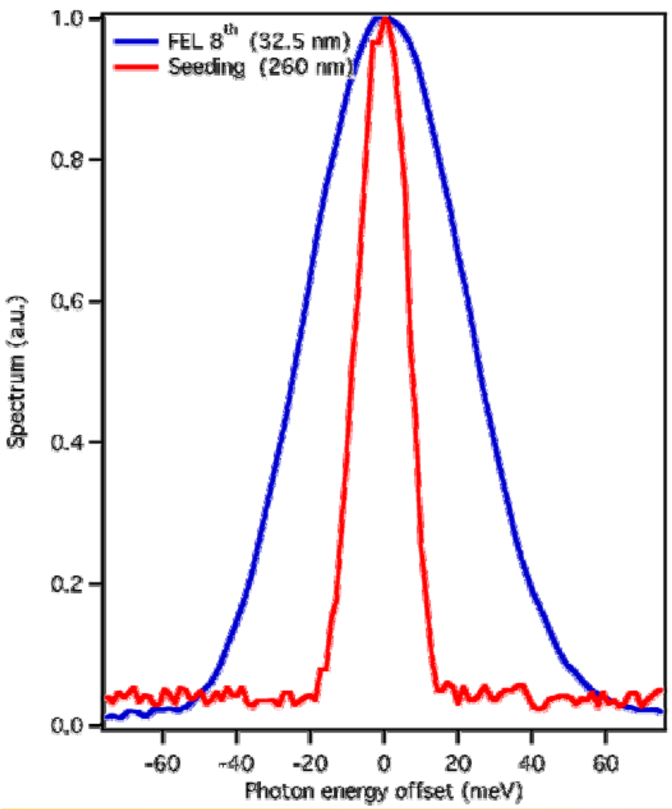
The output spectral properties of the FEL may depend on which part of the beam is producing FEL radiation.

FEL spectra become worst close to the head and tail of the electron beam.

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.



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

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

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**.

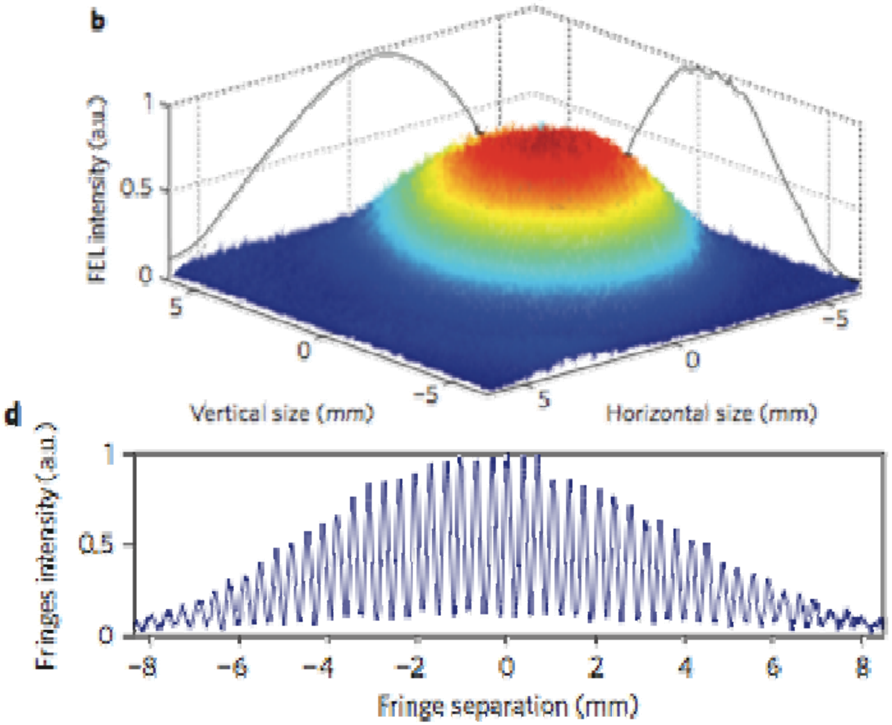
Considering the **pulse shortening** predicted by theory for the 8^{th} harmonic we can estimate tat FERMI FEL pulses are **close to the Fourier limit** and have a good longitudinal coherence.

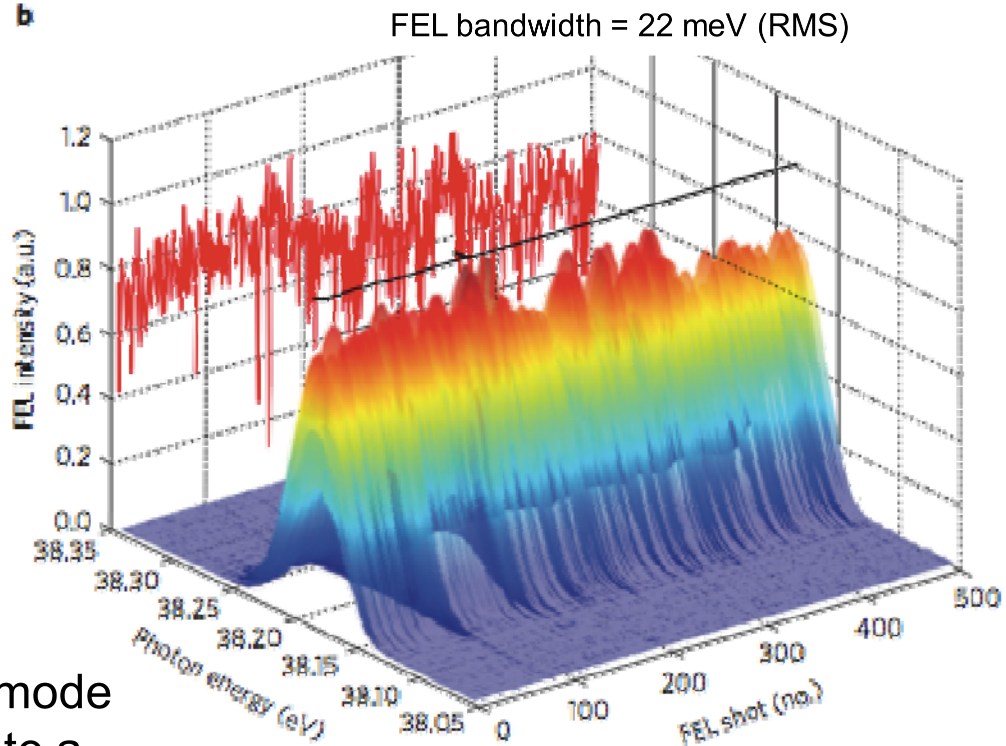
Spectral stability and mode quality

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)



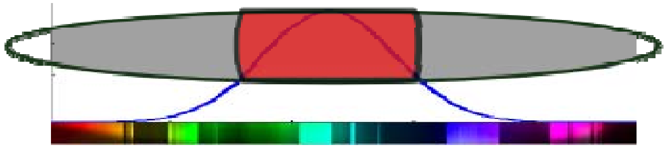


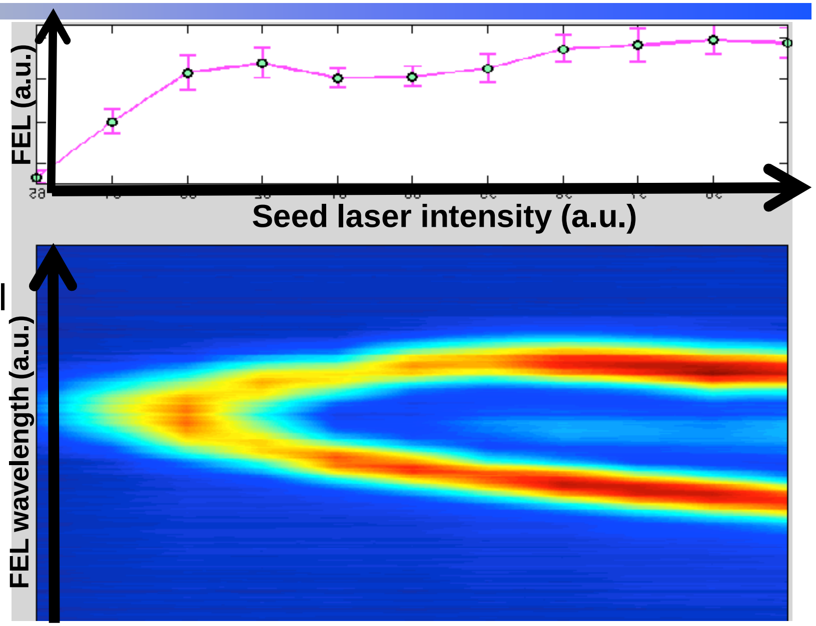
The **transverse** spatial **mode** has been measured to be very close to the **TEM00** mode and also coherence measurements indicate a very **high degree of transverse coherence**.

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

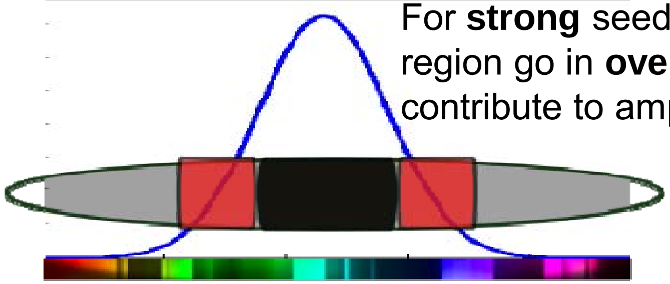
FEL pulse control

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



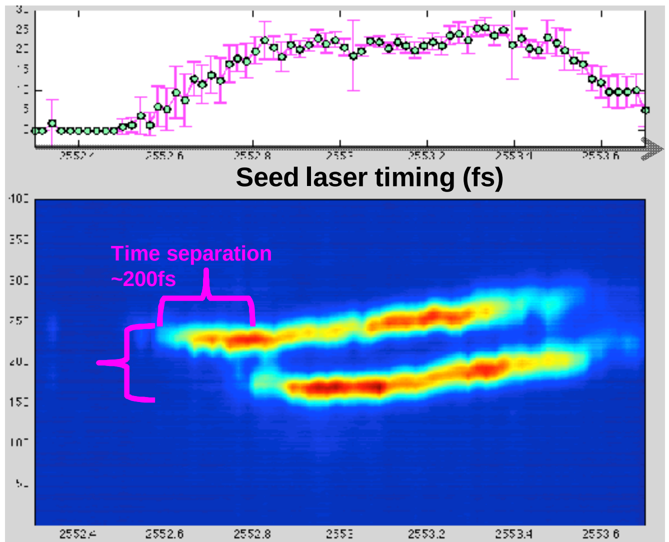


For **strong** seeding, electrons in the central region go in **overbunching** and do not contribute to amplified FEL radiation*.



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**.



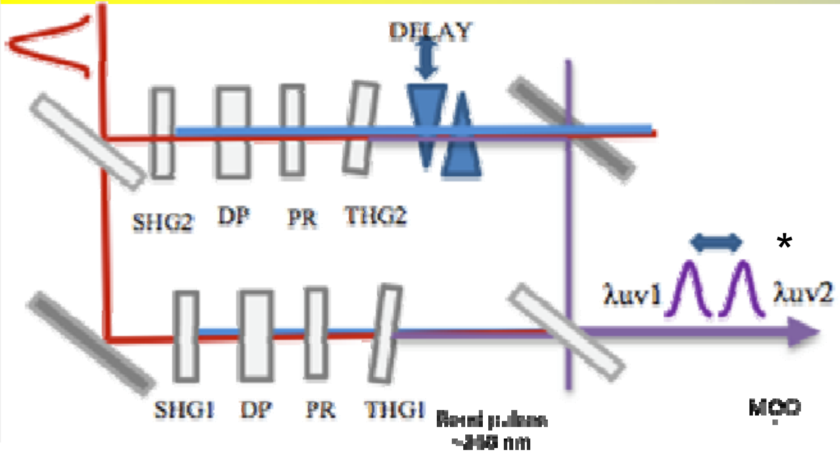
Limitation for this scheme is the temporal separation that can not be much longer than the seed pulse length.

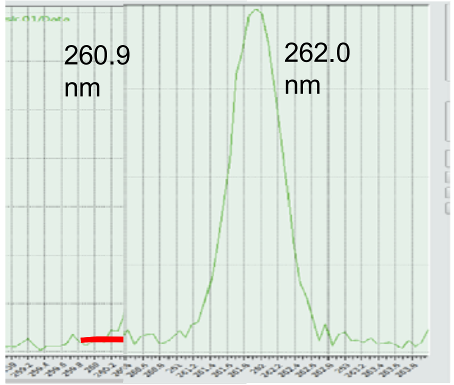
A different approach is to seed the electron beam directly with two FEL pulses. This has been successfully implemented at FERMI.

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

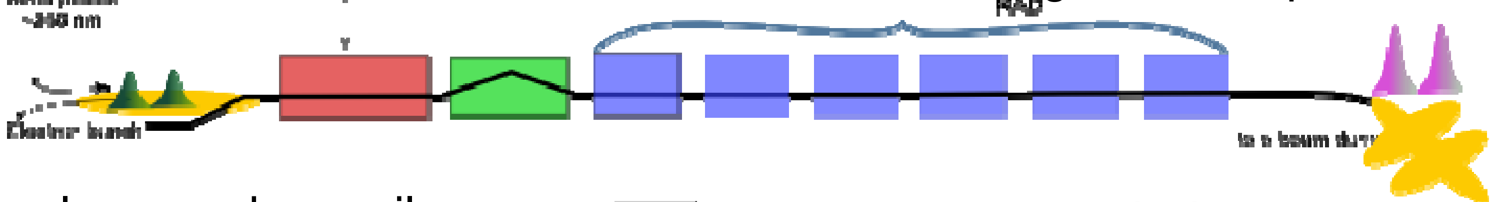
(**) "Chirped seeded free-electron lasers: self-standing light sources for two-colour pump-probe experiments" G.De Ninno et al. sub to Phys. Rev. Lett.

Two FEL pulses: double seeding



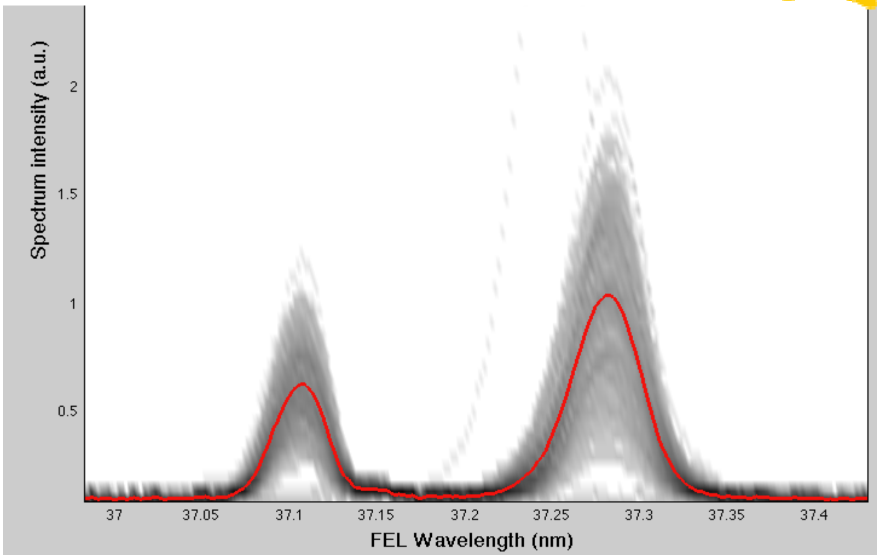


In order to allow a wider temporal separation between the two pulse required by one of the FERMI user we also implemented a scheme using two seed pulses.



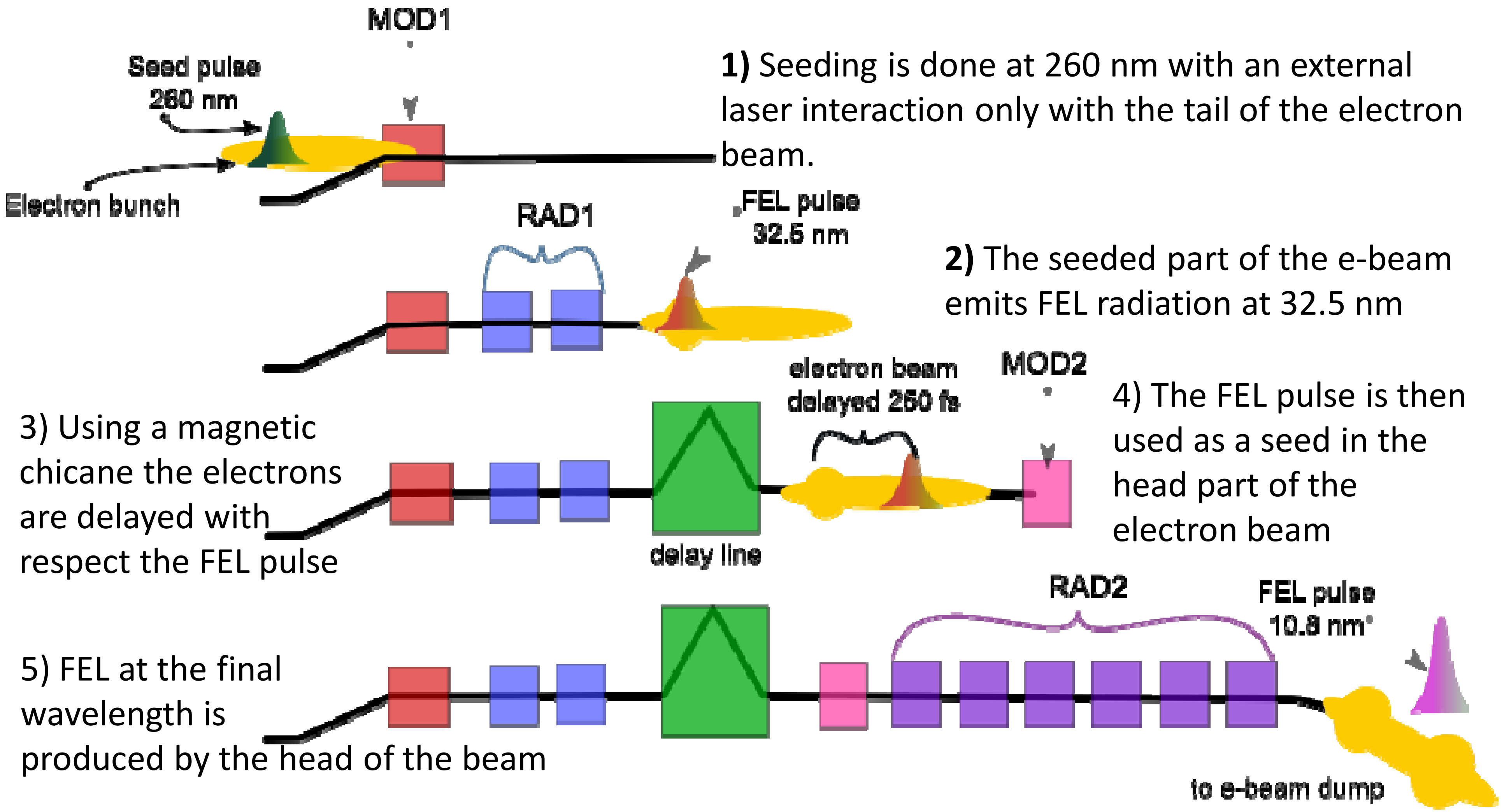
Delay between two pulses can be easily controlled and also the two wavelengths can be slightly different.

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



* M. Danailov

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.

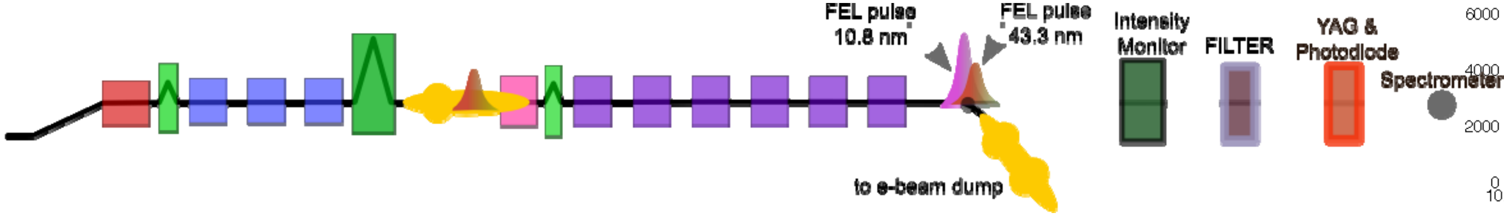
2) The seeded part of the e-beam emits FEL radiation at 32.5 nm

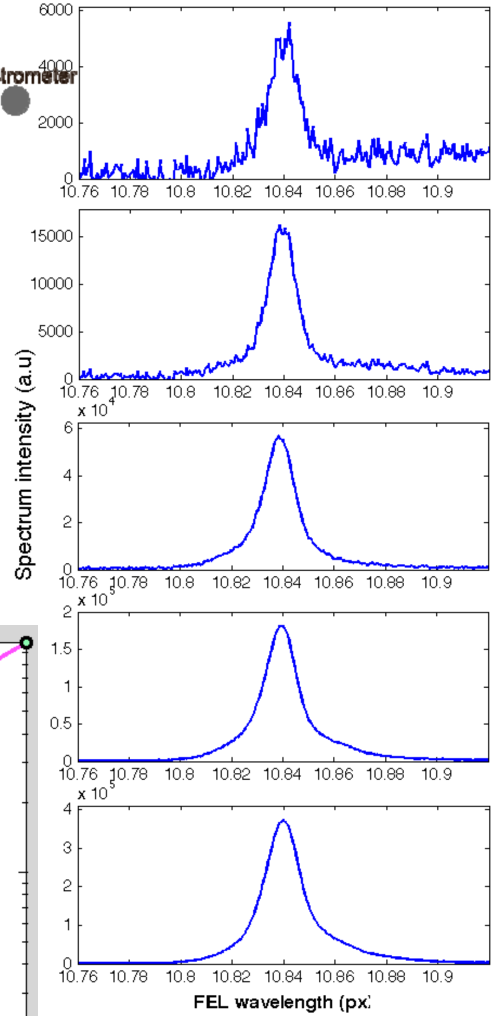
3) Using a magnetic chicane the electrons are delayed with respect the FEL pulse

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

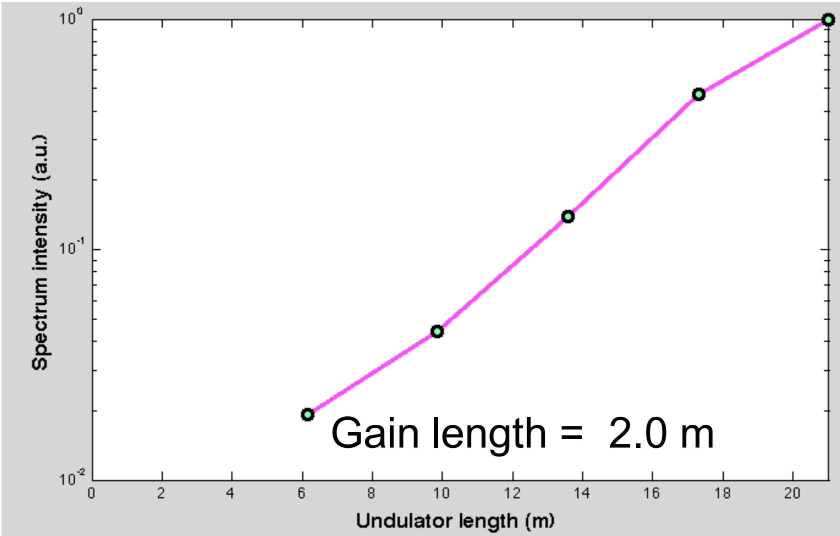
Exponential gain in second stage



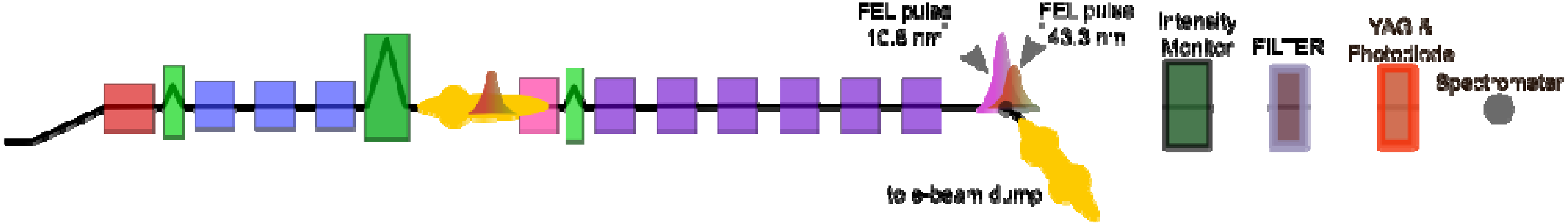


The exponential growth of the power on the second radiator has been measured both looking at a YAG after a filter that stops the first stage radiation and at the spectrum intensity.

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



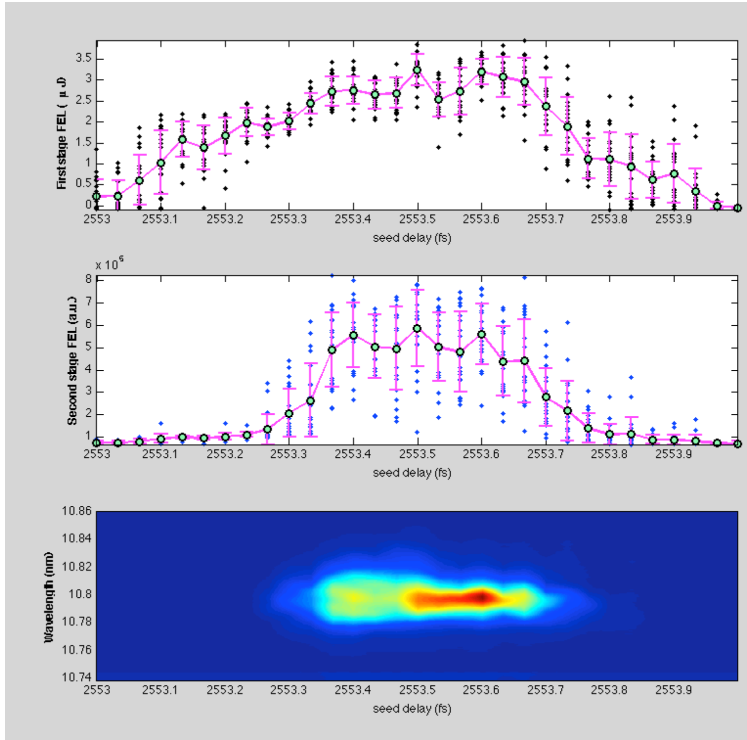
First stage and second stage lasing



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.

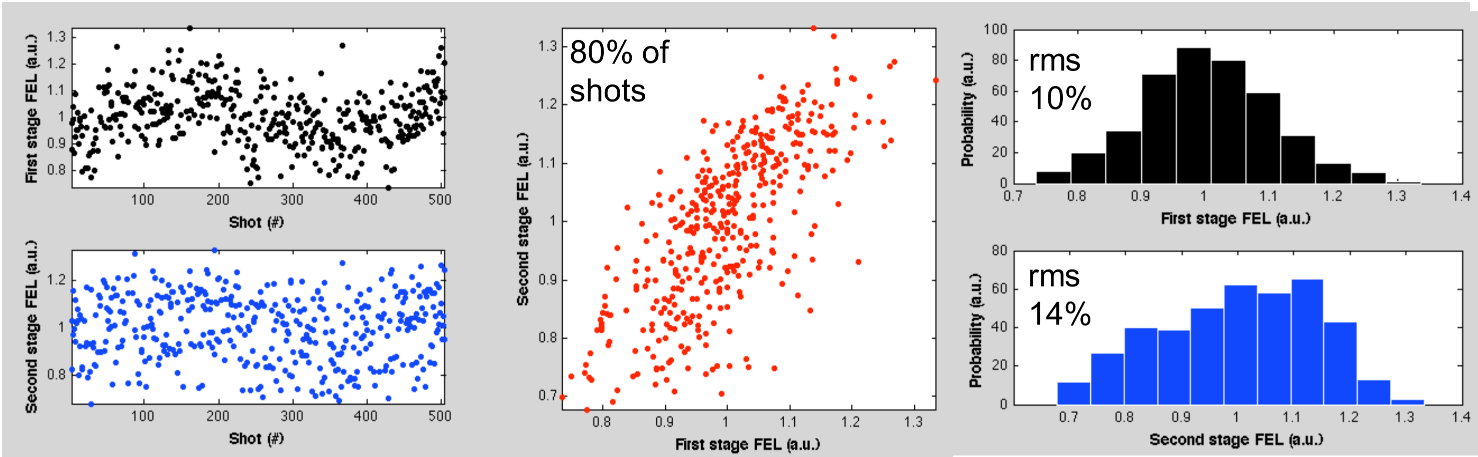


FEL-2 stability

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.

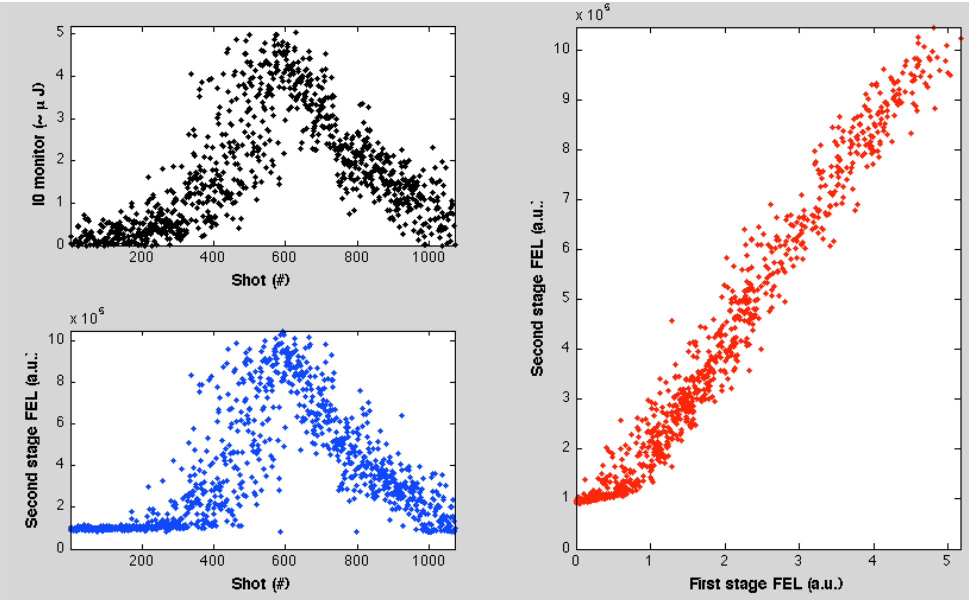
Filtering out the worst 20% of the shots the correlation is more clear and also the amount of jitter in the output power is similar for both the first and the second stage.

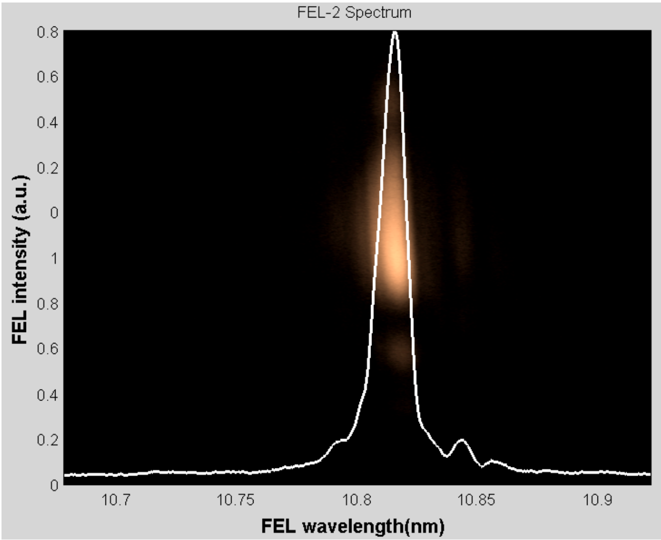


These data refer to the case of 260 → 43 →10.8 nm. In this configuration the power from the first stage is more than enough for seeding and it is generally needed to keep it down to maximize the power from the second stage.

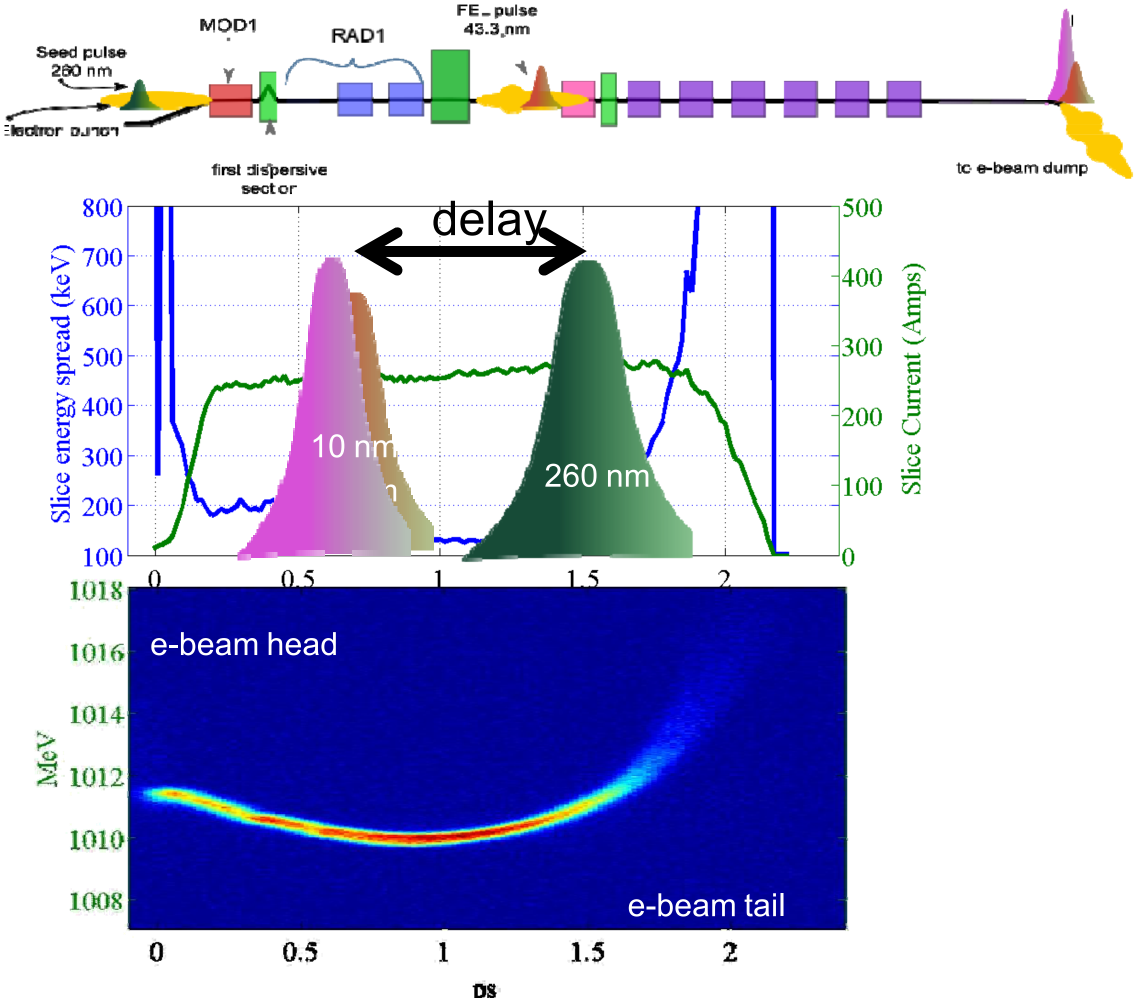
260nm →21.7nm →10.8nm

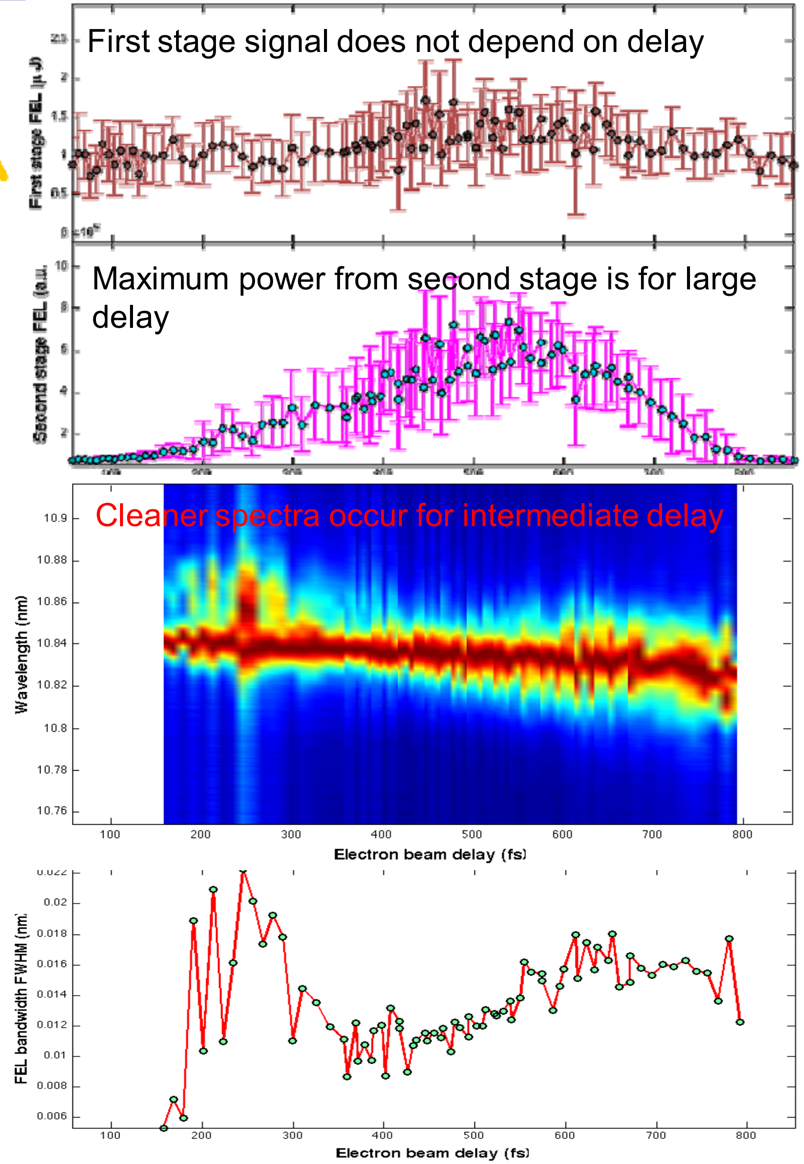
We have been able to operate the second stage at 10.8 nm also pushing the first stage to very high harmonics (12).
In this configuration most of the harmonic conversion is done on the first stage that become more critical.
The seed delay scan here show a stronger correlation indicating that it could 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

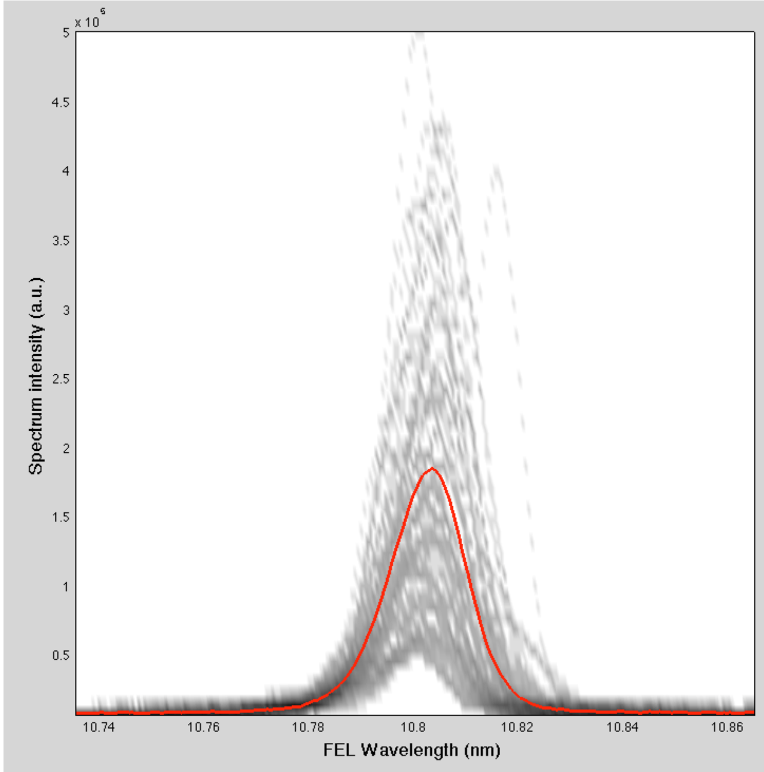




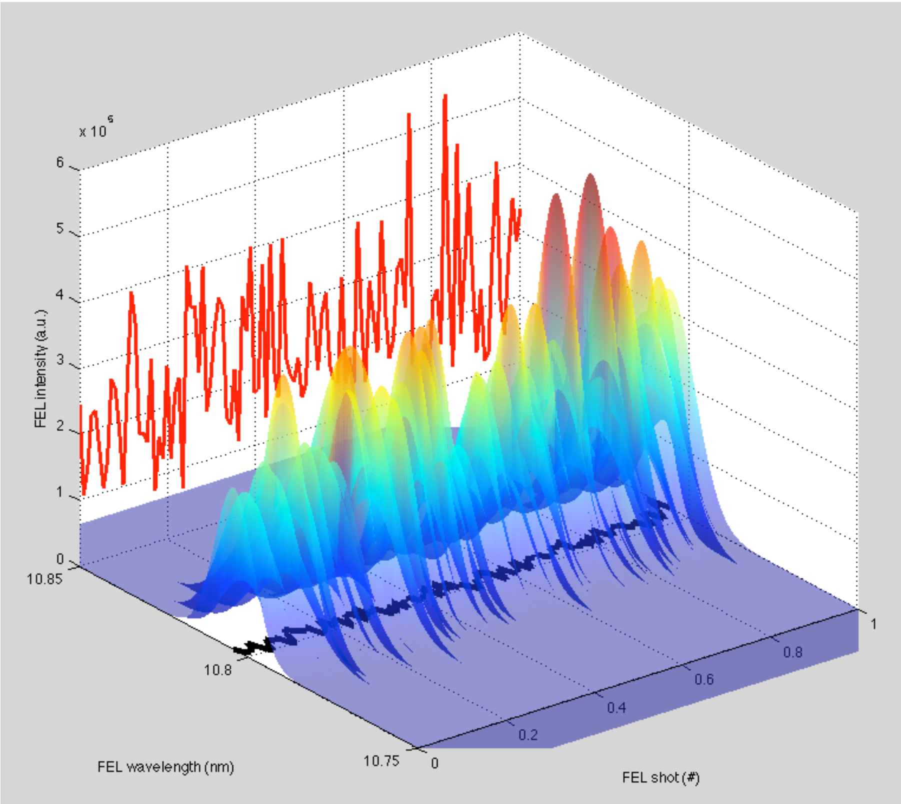
- Seed laser is placed as much as possible toward the tail of the bunch.
- For short delay the e beam is still affected by the process occurred in the first stage (low signal bad spectrum)

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.

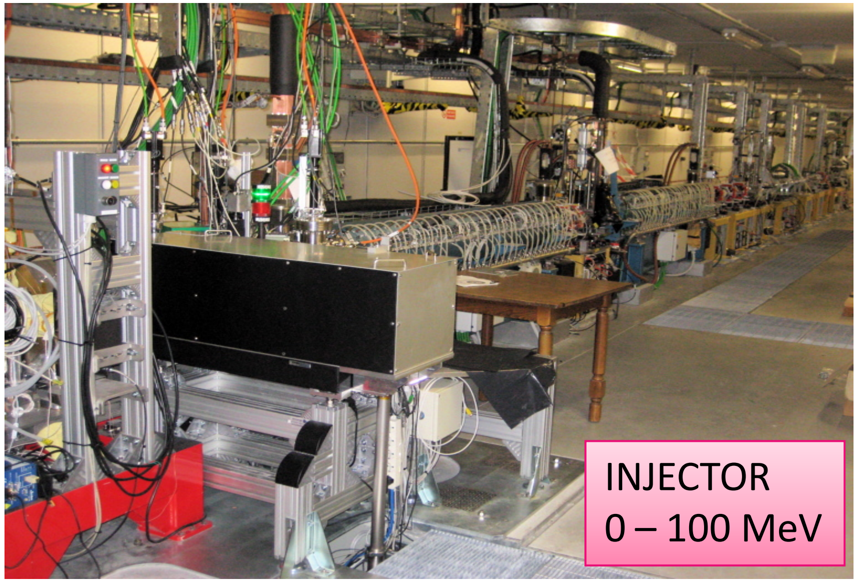


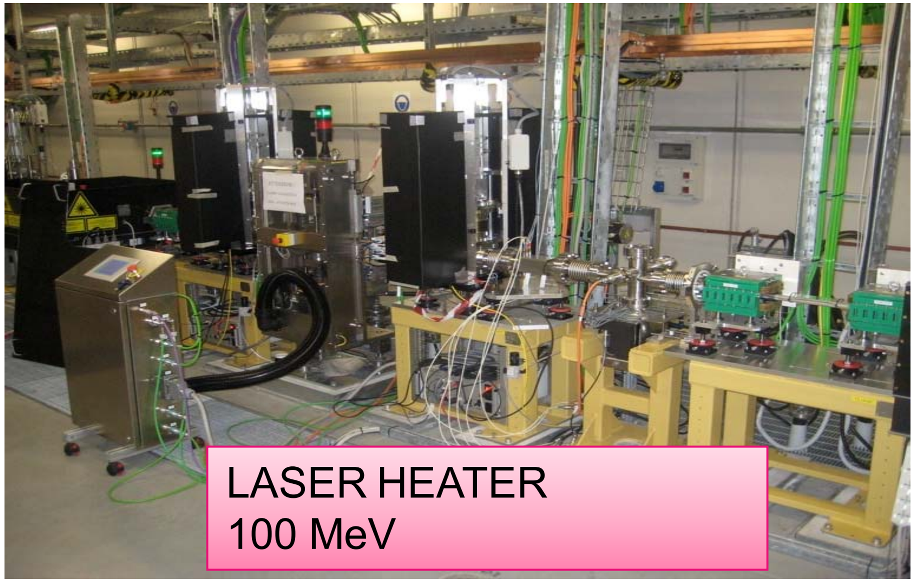
In these conditions the measured FWHM bandwidth is about 150 meV at 10nm (1.5e-3). Fluctuations are smaller than the bandwidth (6.4e-4).

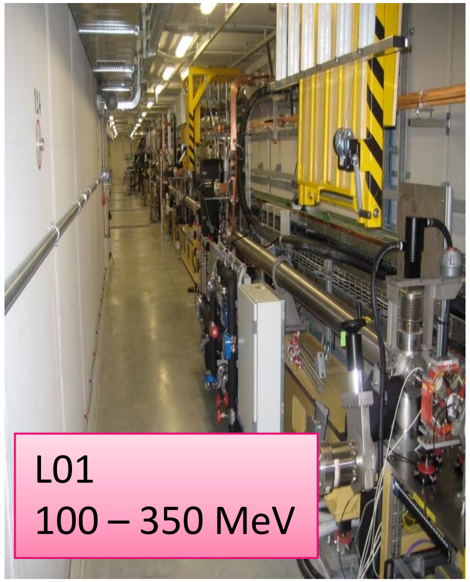


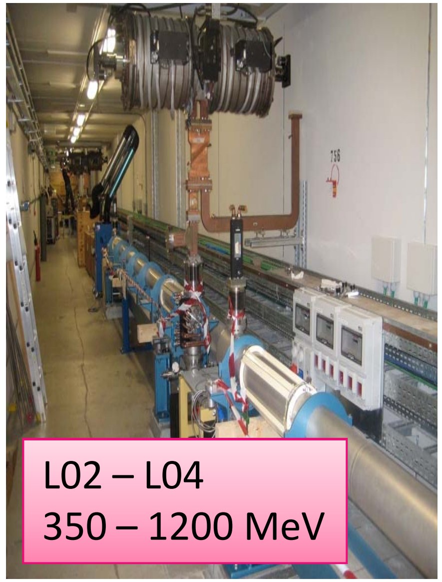
Further improvements for the wavelength stabilization requires an improvement of the longitudinal phase space of the electron beam.

Linac Tunnel

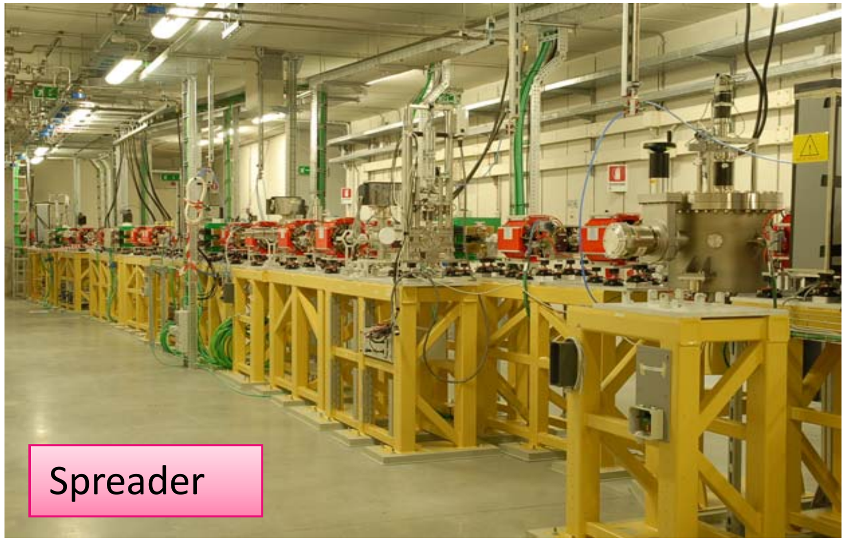


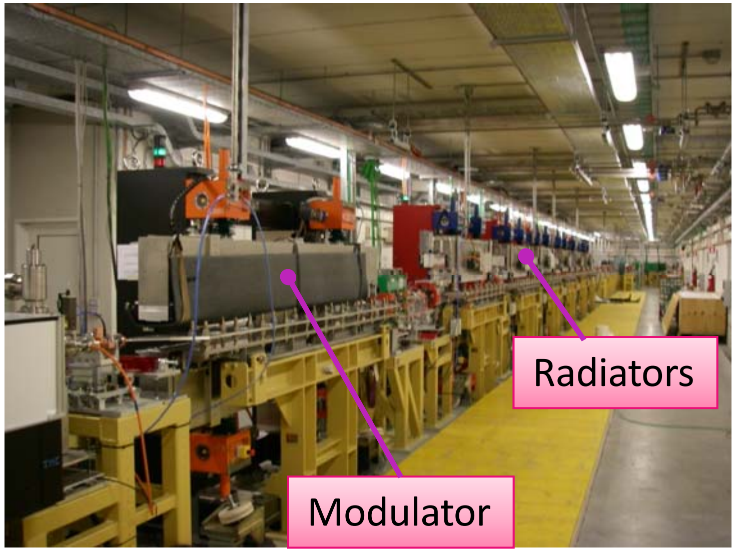


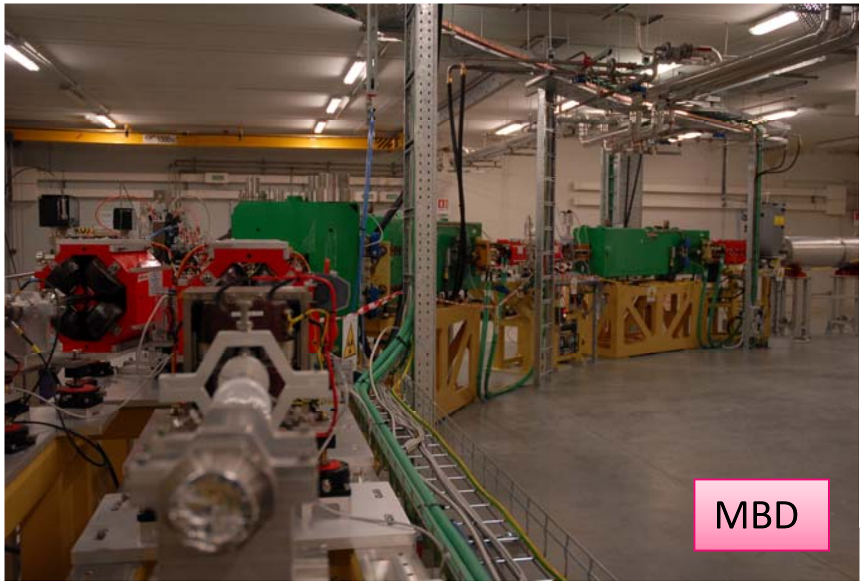


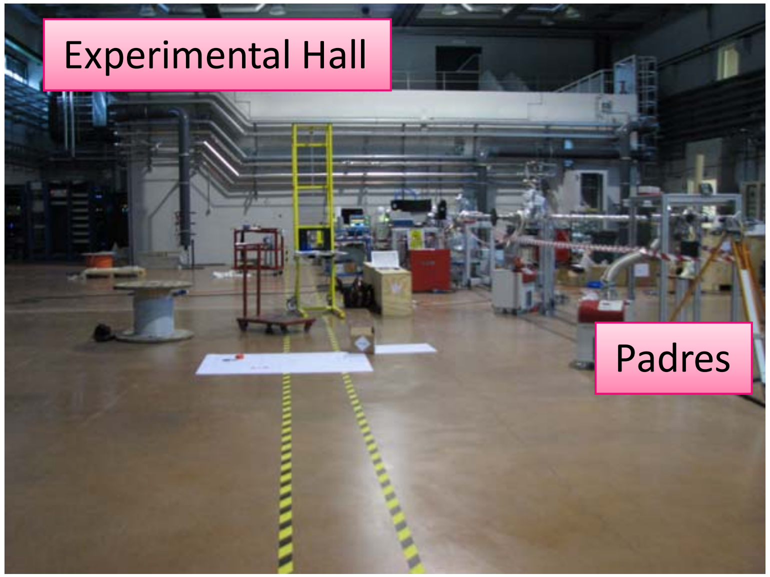


Spreader - Fel 1 – MBD – Exp.









Thank you

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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