Elettra Sincrotrone Trieste

ipam

Beam Dynamics workshop
January 23 - 27, 2017

Need for high quality electron beams for seeded FEL

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on behalf of the FERMI team

Outline

- **Free-Electron Laser and seeded FELs**

- **FEL properties control with seeding**
  - Wavelength and spectral control
  - Pulse properties control
  - Coherent control

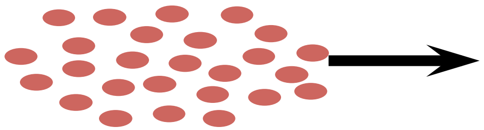
- **Impact of e-beam quality**
  - Microbunching instability

- **Conclusions**

FEL basic ingredients

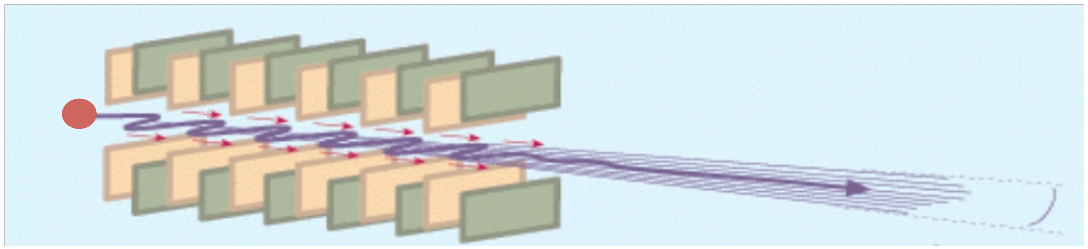
A **Free-Electron Laser** exploits the induced coherent emission of a relativistic electron beam "guided" by the periodic and static magnetic field of an undulator.

1) Relativistic **electron beam**



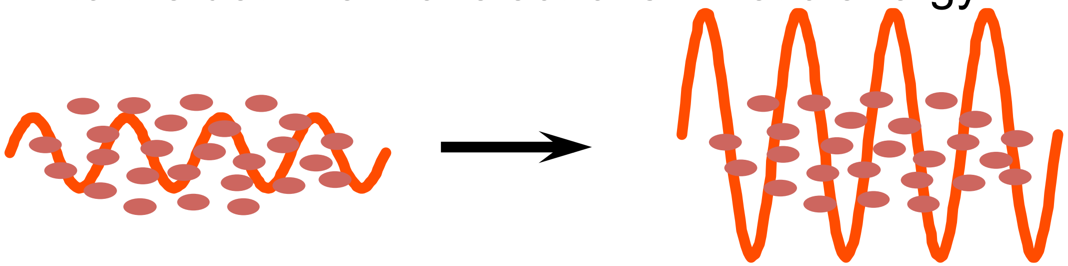
Energy (γ)
Current (I)
Emittance (ε)
Energy spread ($\delta\gamma$)
Dimensions (σ)

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)

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Free Electron Laser

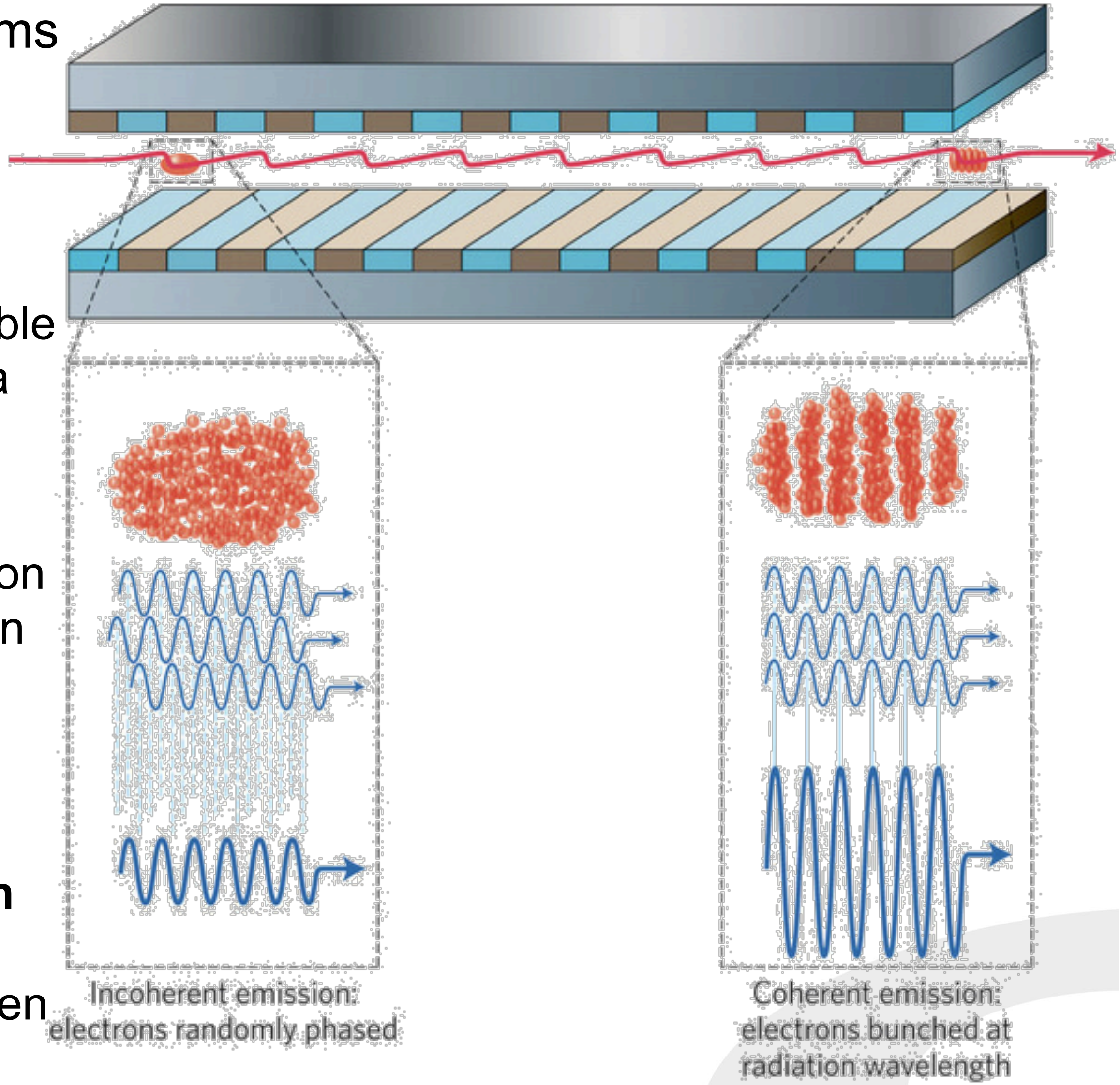
Free electron lasers are systems that **allow** an **electron beam** to emit **coherent synchrotron radiation.**

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

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

Bunching process **requires** 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)



Collective effects of free electron laser

FEL is the result of a collective effect similar to other cases present in nature.

The interaction of an high density electron beam with a common medium is at the origin of an instability.

Oscillations start from the initial noise due to the granularity of the system.

It is also possible to inject into the systems specific frequencies by a proper control of the initial conditions (seeding).

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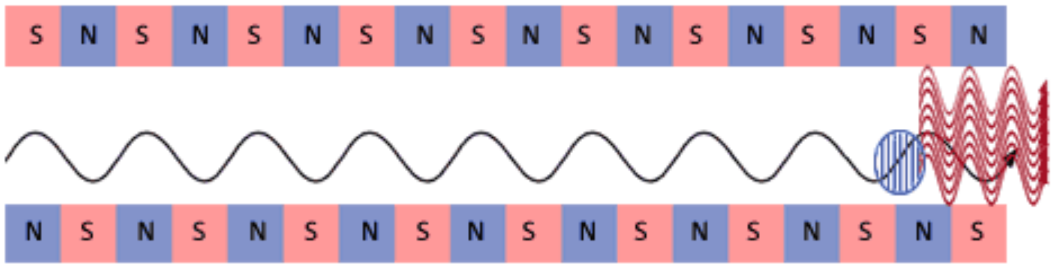
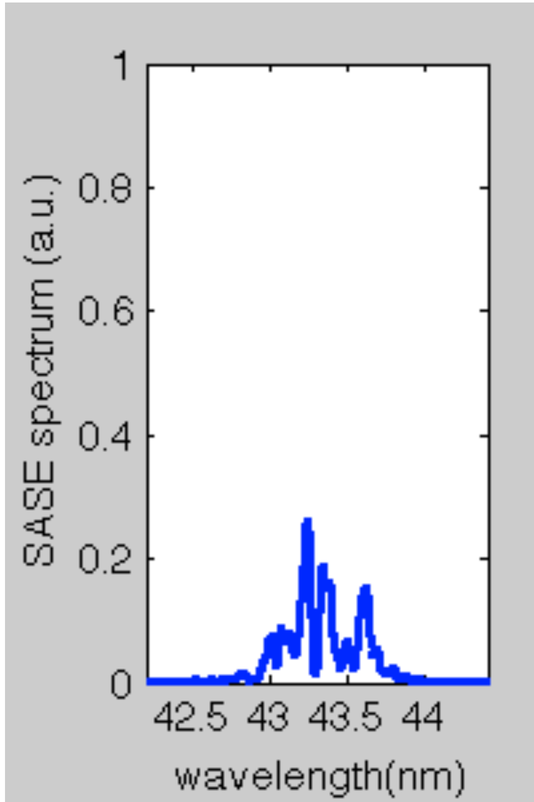
SASE FEL

In **high gain** FEL, Self Amplified Spontaneous Emission (SASE) is possible.

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**.

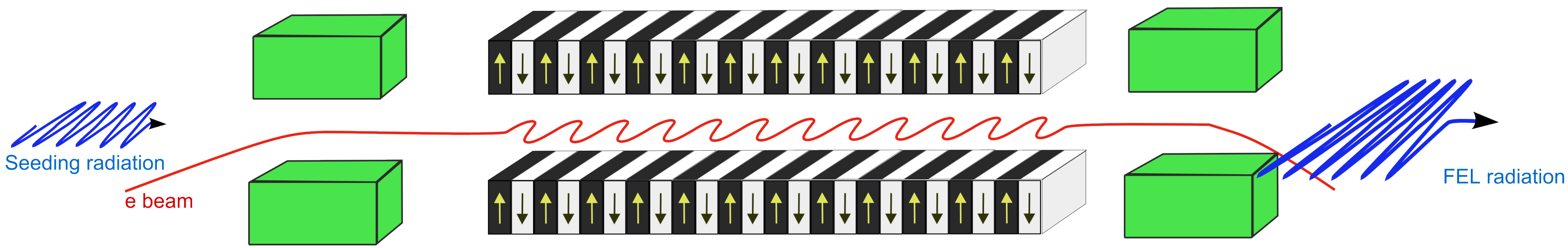
Pictures from: www-ssrl.slac.stanford.edu/lcls/glossary.html

Benefits of a Seeded FEL

An external “seed” laser allows to control the distribution of electrons within a bunch. FEL output pulses inherit properties from the seed.

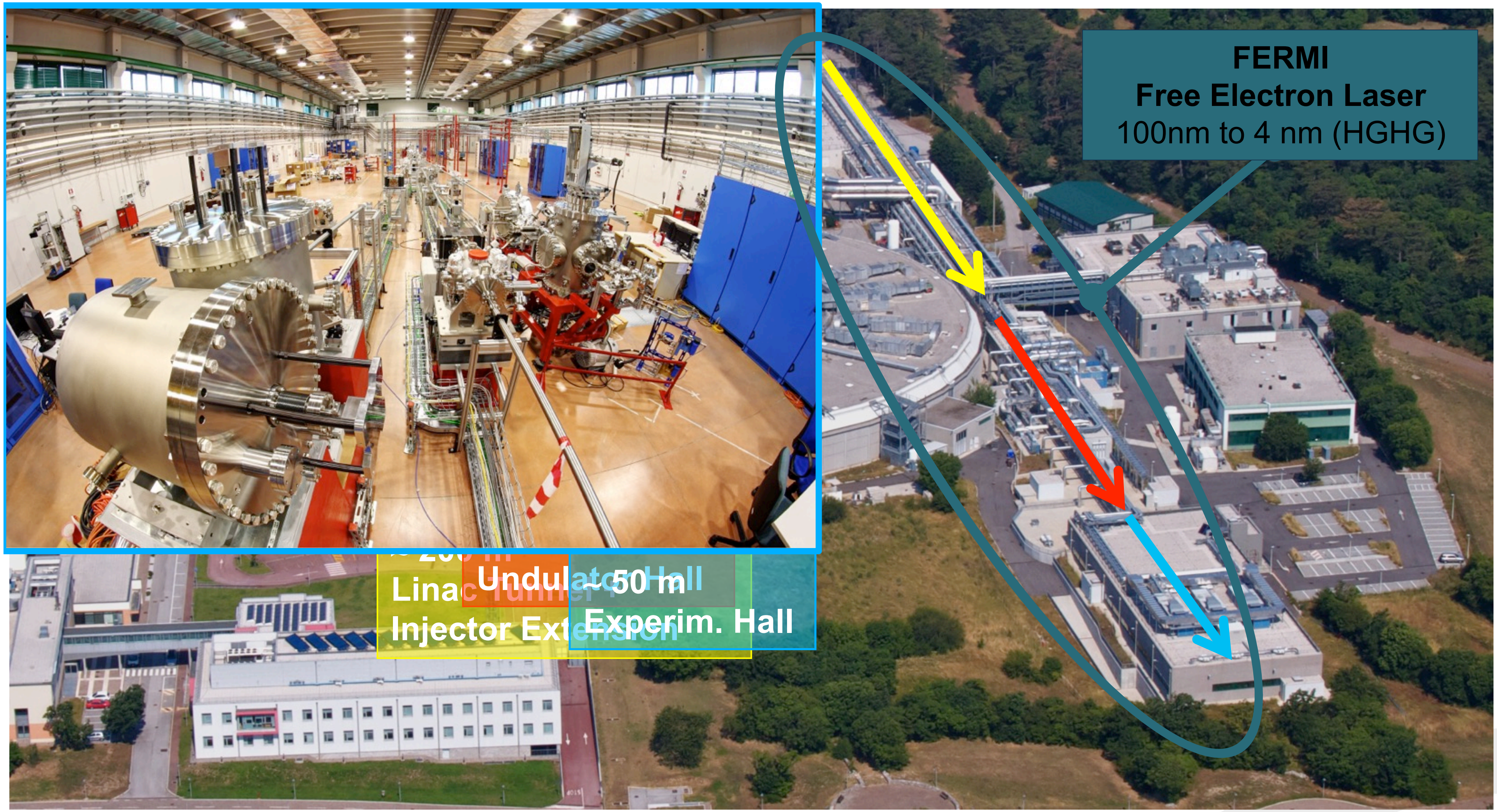
Seeding allows improving:

- 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.



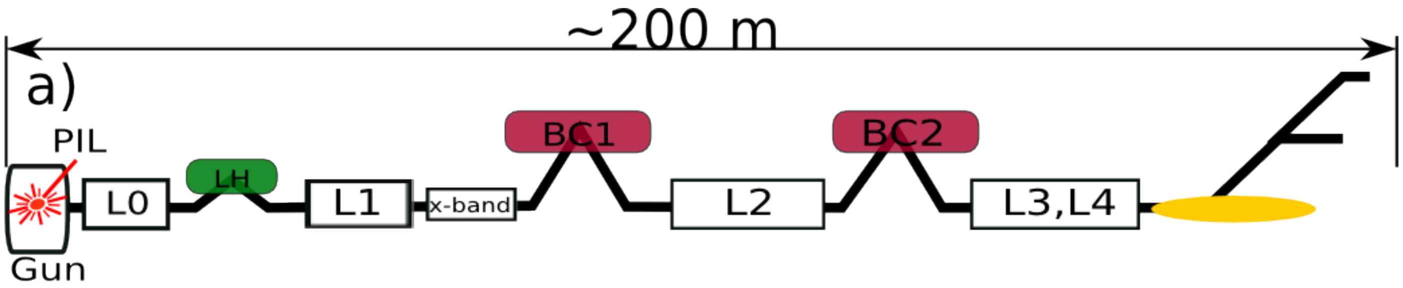
The problem with seeding is that there are not sources available for direct seeding at the very short wavelength range (<1nm).

FERMI Free Electron Laser



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

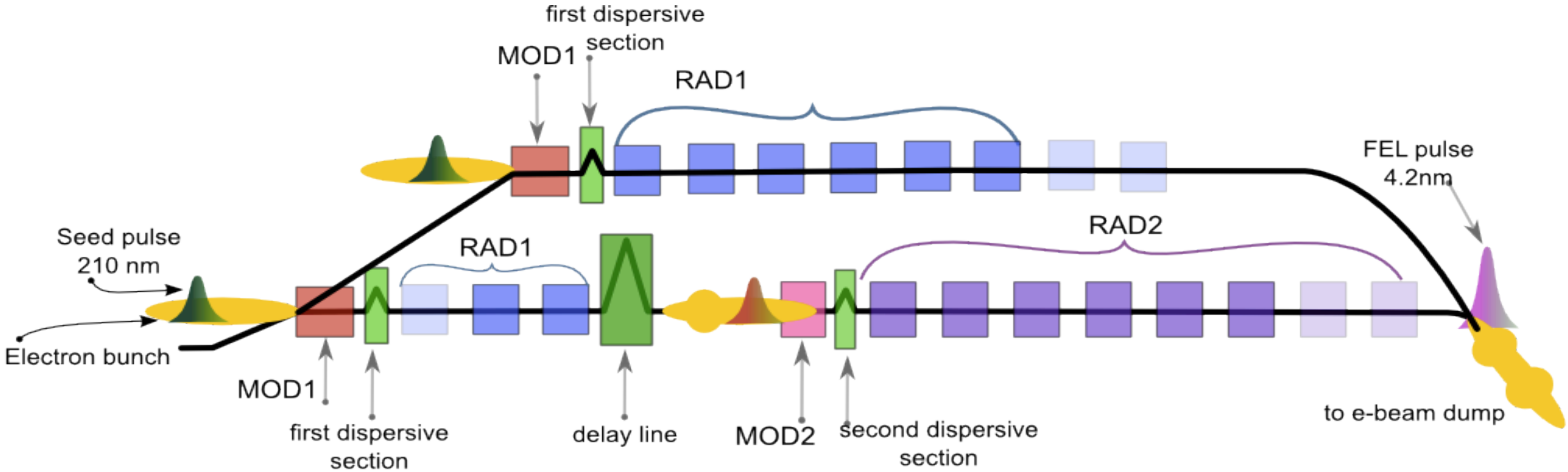
FERMI layout



Linear accelerator:
Rep rate 50Hz
Beam charge 700pC
Beam energy up to 1.5GeV
Peak current ~700A.

FERMI FELs: FEL-1 & FEL-2

FEL-1: **single** stage **HGHG** seeded by a **UV laser**, covers the range **100** nm – **20** nm.



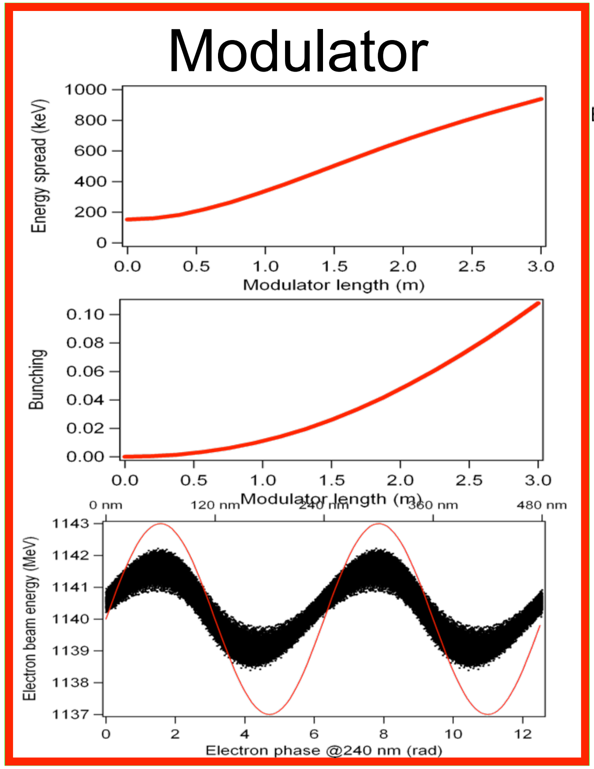
FEL-2: **double** cascade HGHG to reach the wavelength **20** nm – **4** nm.

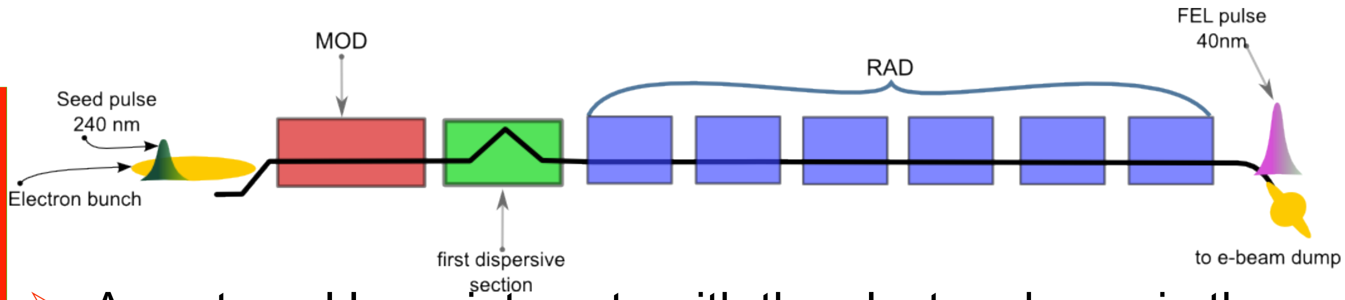
FEL-1 (Nat. Photon. **6**, 699 (2012))	
Tuning range	100-20 nm (12-60eV)
Relative bandwidth	1×10^{-3} (FWHM)
Pulse length	<100 fs
Pulse energy	20-100 μJ

FEL-2 (Nat. Photon. **7**, 913 (2013), Journal of Synchrotron Radiation 22 (2015))	
Tuning range	20-4 nm (60-300eV)
Relative bandwidth	1×10^{-3} (FWHM)
Pulse length	~50 fs
Pulse energy	10-70μJ

Both FELs have APPLE-II undulators in the final radiator allowing polarization control.

FEL-1: High Gain Harmonic Generation





- An external laser interacts with the electron beam in the modulator inducing a periodic modulation of the electron beam energy.

- In a dispersive region, energy modulation is converted into density modulation with significant harmonic content. Beam current modulation inherits coherence properties from the input laser.

- Coherent bunching produces coherent emission in the radiator at the desired harmonic that is then amplified.

FERMI electron beam

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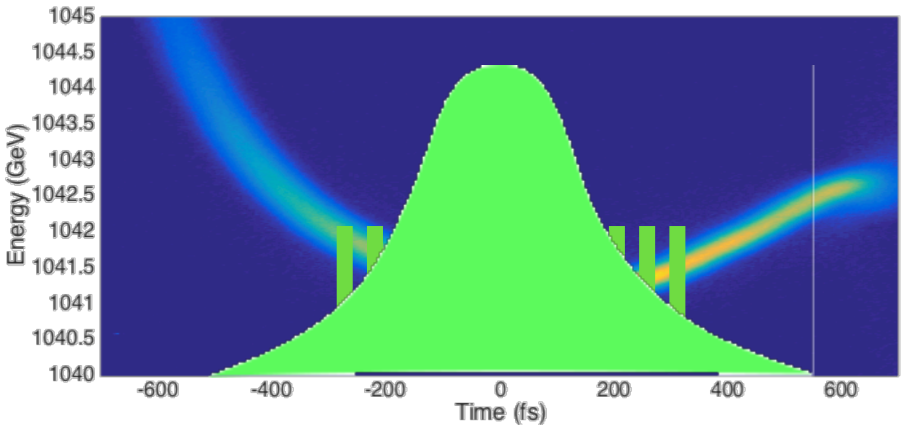
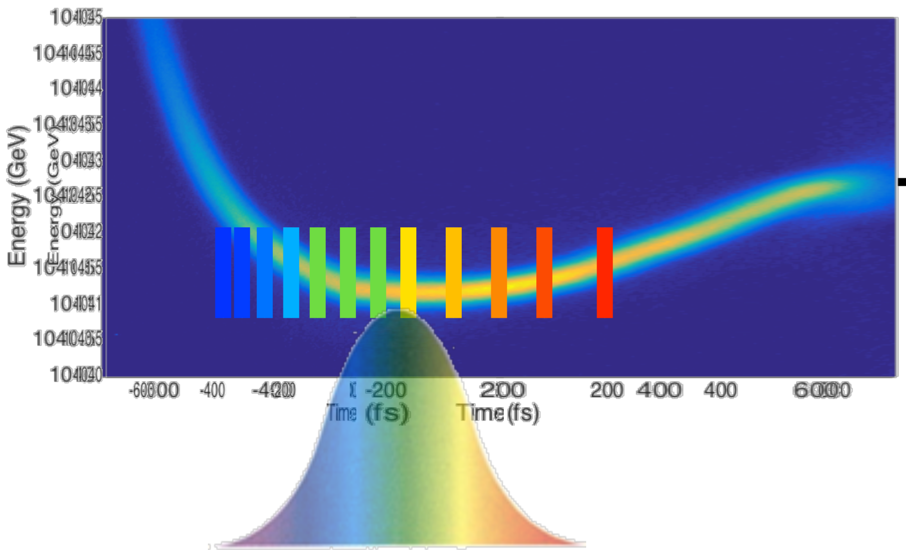
- Current **spikes** are **not suitable** for seeded FELs.
- **Low energy spread** and **flat phase space** are required for seeding.
- Electron beam **optimization** is **different** than for a **SASE** FEL.





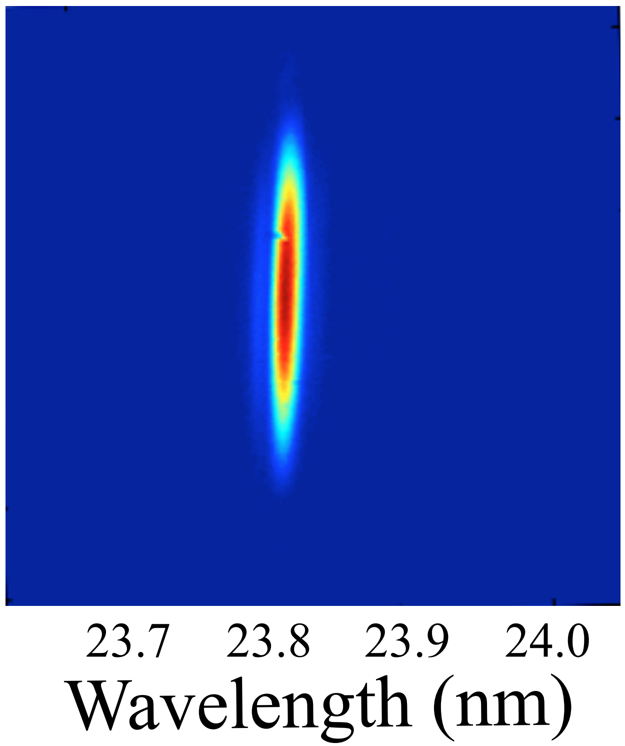
Electron beam parameters

Charge	700	pC
Peak current	~700	A
Energy	1 – 1.5	GeV
Energy spread	~150	keV
Energy chirp	~3	MeV
Emittance	1	mm mrad
Size (rms)	~100	μm

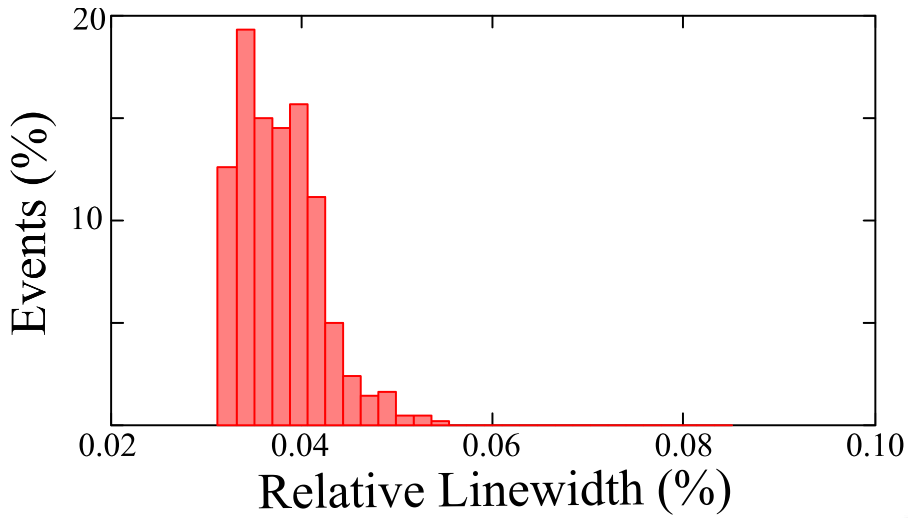
→ Only electrons interacting with the laser participate to the FEL emission.
Phase space nonlinearities may counteract the benefits of the seed.

FEL bandwidth control

FEL pulses inherit the **coherence** from the **external seed** laser.
The use of **seed pulses** close to the **Fourier limit**, allows the production of **FEL pulses** that are also **close** to the **Fourier limit**.



- Seed pulses of **120 fs** long with **0.9 nm** spectral width produce **FEL pulses** characterized by **single mode spectra** with **narrow linewidth**



- **FEL spectra** fit **Gaussian** curves and both **wavelength** and **bandwidth** are **stable**.
- Calculated Fourier-limited pulse length is close to theoretical predictions suggesting a **very high** longitudinal **coherence**.

Advanced (coherent) control schemes

The use of an **external laser** can be efficiently **used** to match **specific requirements** for the FEL.

Advanced configurations can be implemented

- Two pulses;
- Two color.

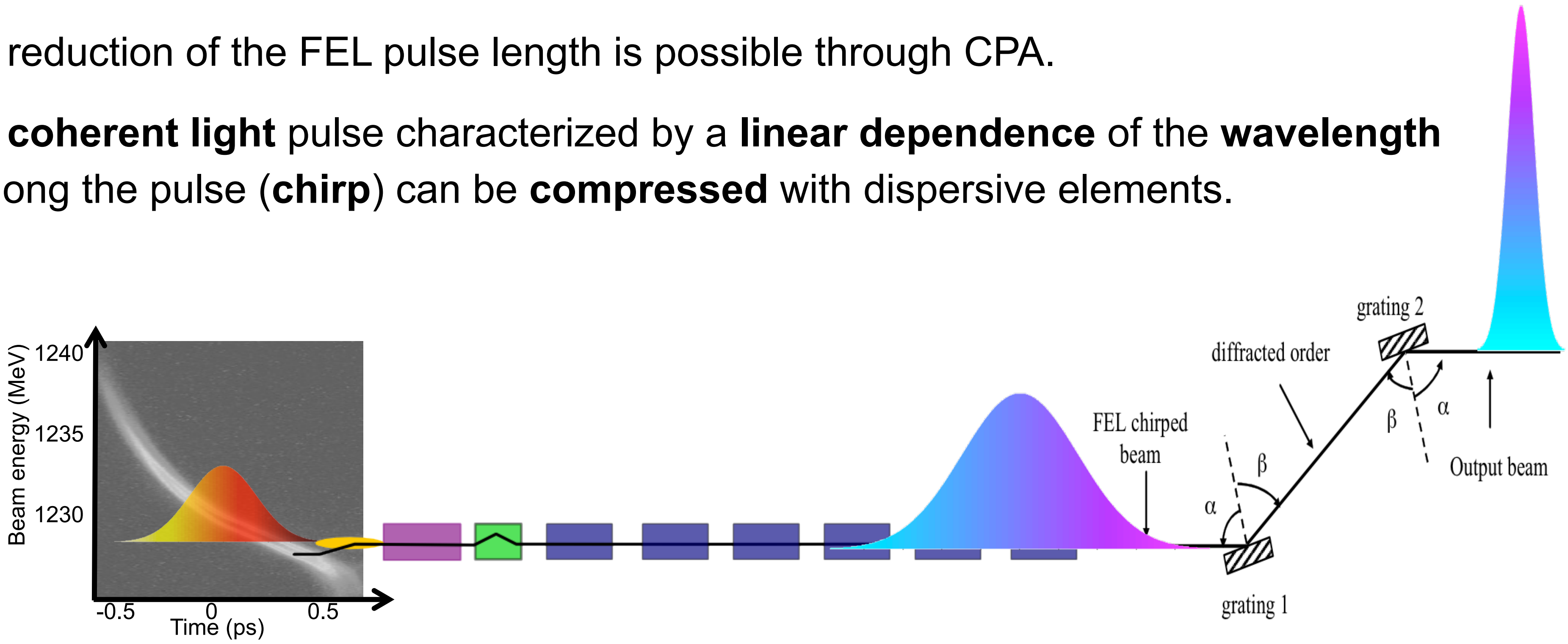
Schemes taking **advantage** of the **high degree** of longitudinal **coherence** become available

- Chirped Pulsed Amplification;
- Phase locked pulses;
- Coherent control.

Chirped pulsed amplification (CPA)

A reduction of the FEL pulse length is possible through CPA.

A **coherent light** pulse characterized by a **linear dependence** of the **wavelength** along the pulse (**chirp**) can be **compressed** with dispersive elements.

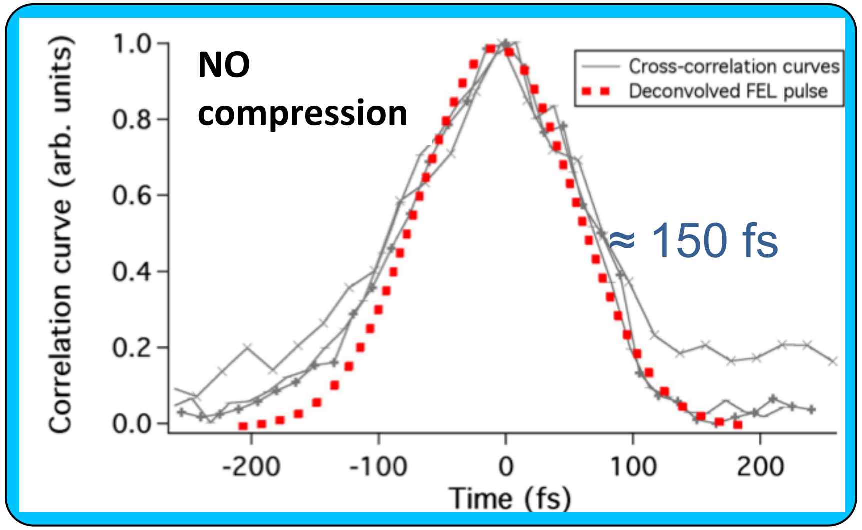


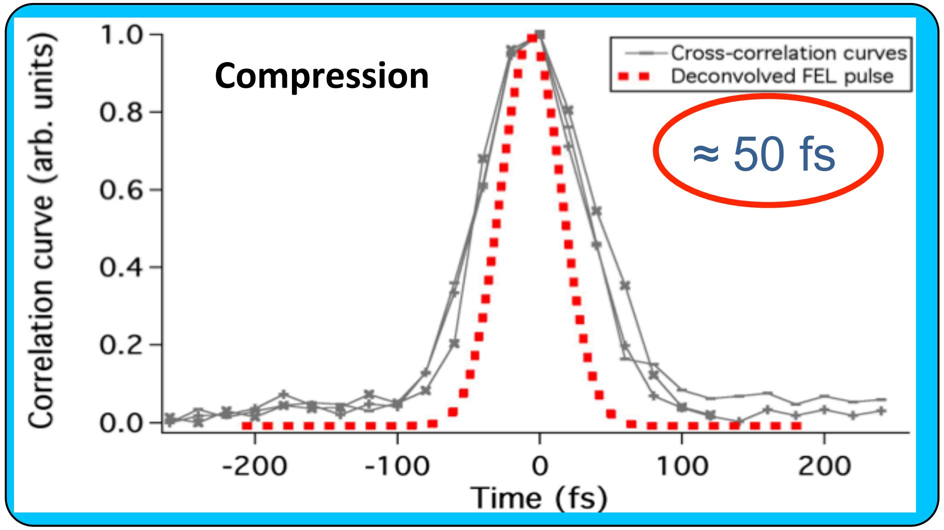
- A **chirped e-beam** is used in combination with a **chirped seed laser** to create **FEL** pulses with **time-wavelength dependence**.
- **Chirped FEL** pulses are sent to a **compressor** based on **double grating**.

CPA in FEL, first demonstration

The standard FERMI **seed laser** has been **stretched** to **290 fs** (FWHM). With the **nominal** seed laser **bandwidth** (0.9nmFWHM) this seed has a **significant chirp** and is about **a factor 3** far from the **Fourier limit**.

FEL **pulse length** has been **measured** for different **settings** of the optical **compressor**.

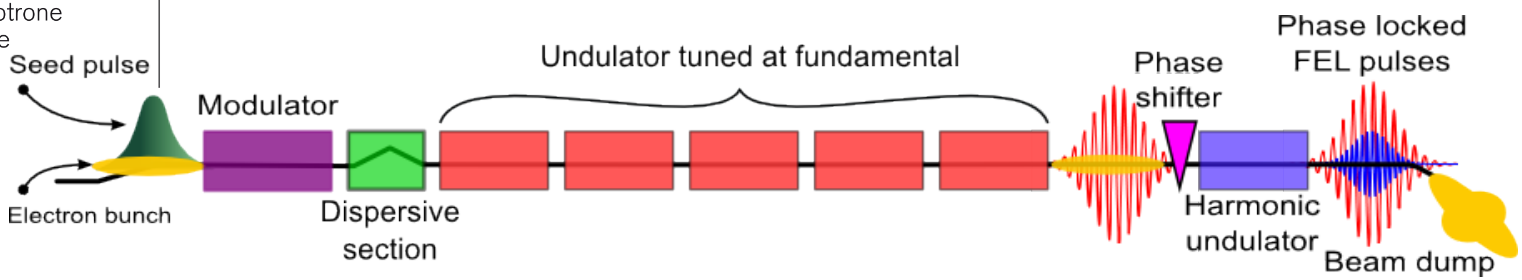




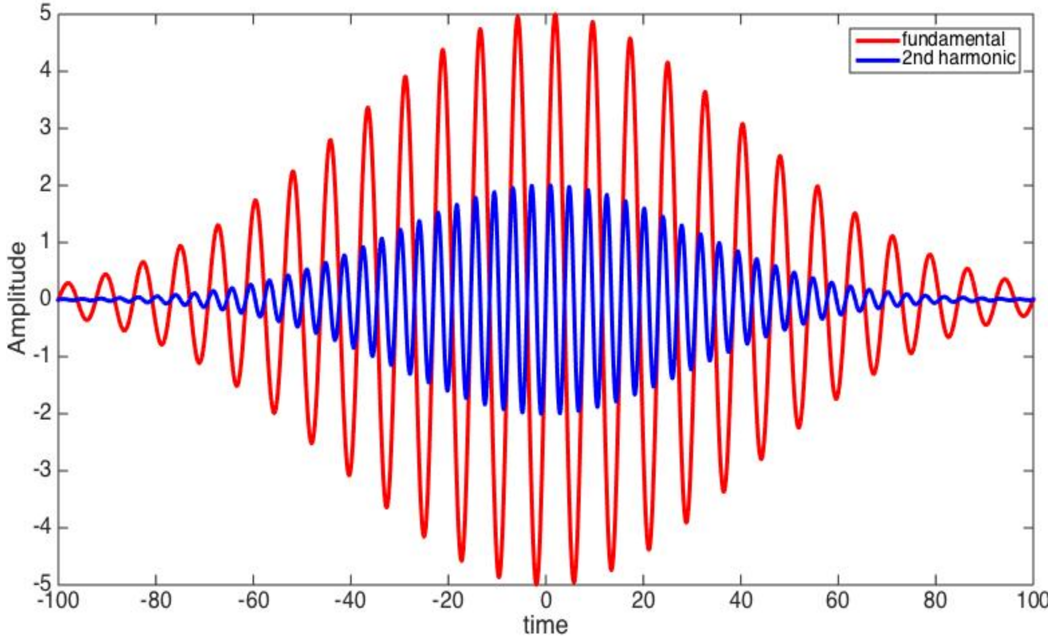
The demonstrated **compression** of FEL pulses is an **indication** of the **high degree** of coherence of the FERMI FEL pulses and open the way to new possibilities for very short pulses.

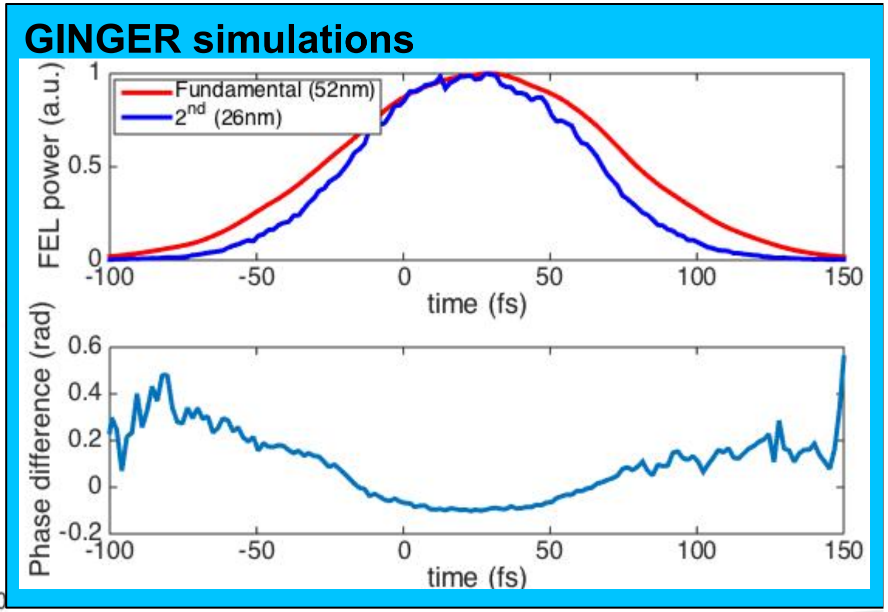
D. Gauthier et al. Nat. Commun. 7, Article 13688 (2016)

Coherent control: harmonic phase locking



Good longitudinal coherence of the pulse gives the possibility of producing pulses with a controlled phase difference.



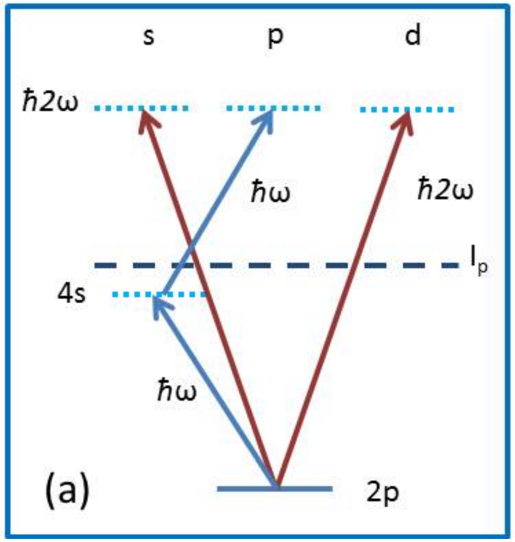


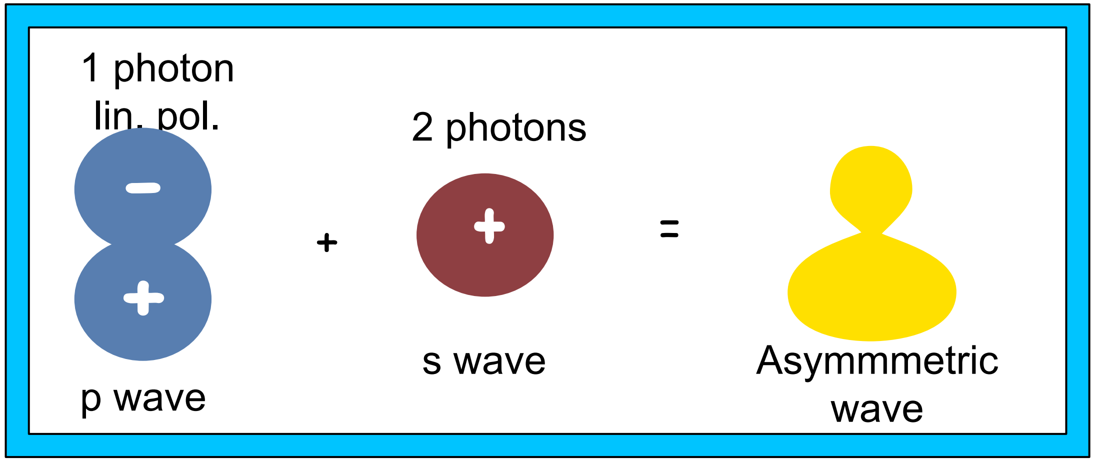
The simplest possibility relies on the generation of a second harmonic pulse phase locked to the main pulse.

Phase control experiment: physical phenomena

The photoelectron distribution generated by two coherent fields (λ_1, $\lambda_1/2$) shows an interference that may depend on the **relative phase between** λ_1 and $\lambda_1/2$.

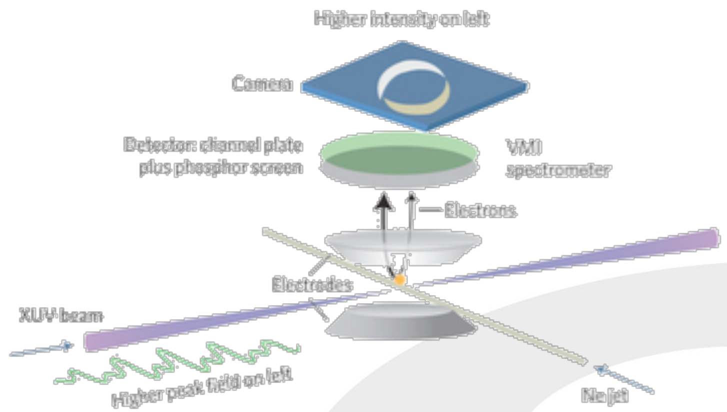
The experiment is done in Neon that can be ionized with a two photon process (19.67 eV - 63 nm) or single photon process (39.34 eV - 31.5 nm) showing different electron distributions.





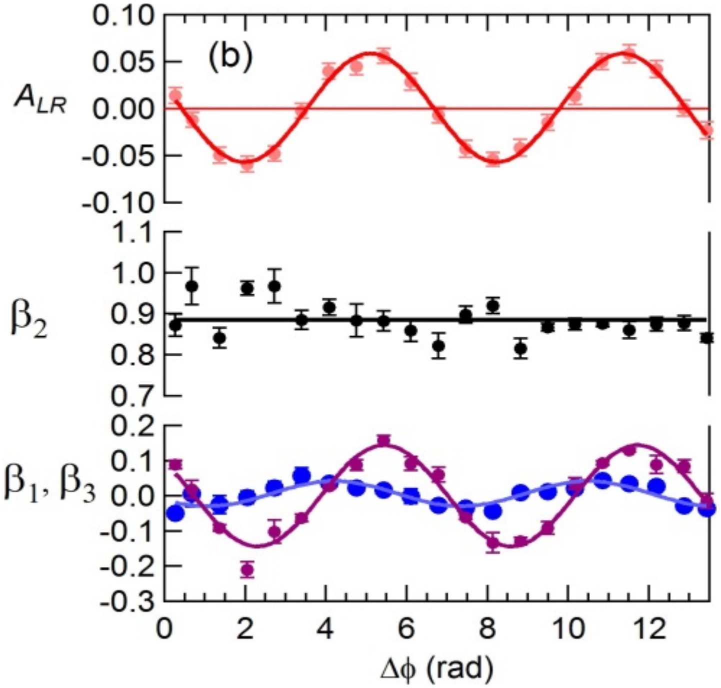
$2s^2 2p^5(^2P^\circ_{3/2})4s$ resonance of **Ne**

a



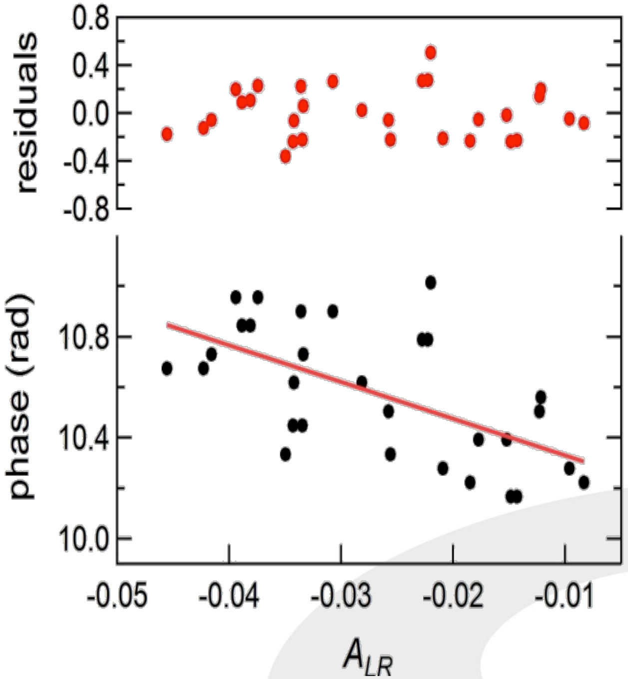
K. Prince, et al. Nature Photon. 10, 176–179 (2016)

Phase control : results



The experiment consist in characterizing the asymmetry A_{LR} of the electron distribution as a function of the phase difference between the two fields.

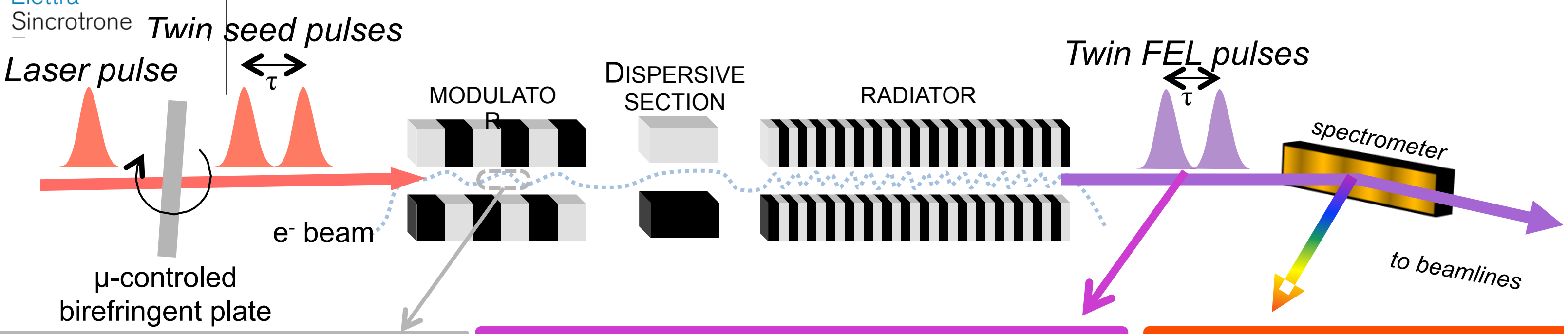
Clear oscillations are present, with a period 2π rad or 105 as.

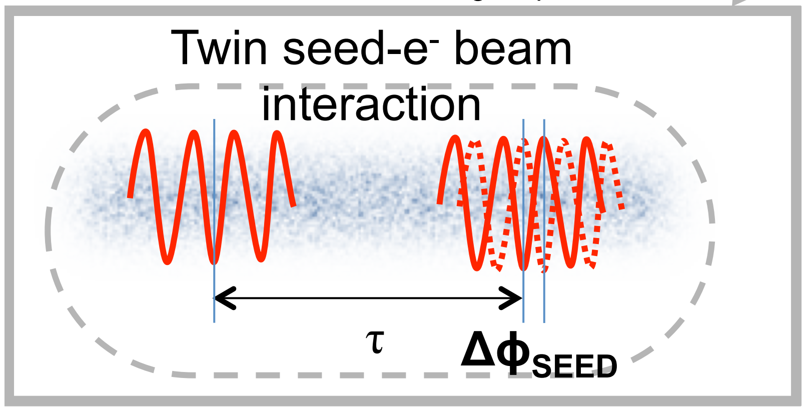


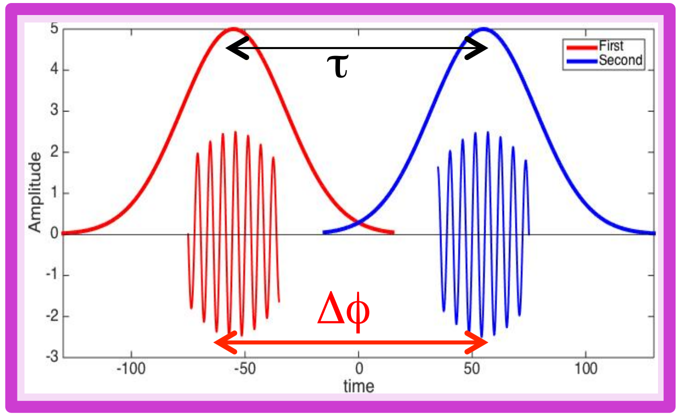
At the maximum sensitivity position results indicates a resolution of 3.1 as

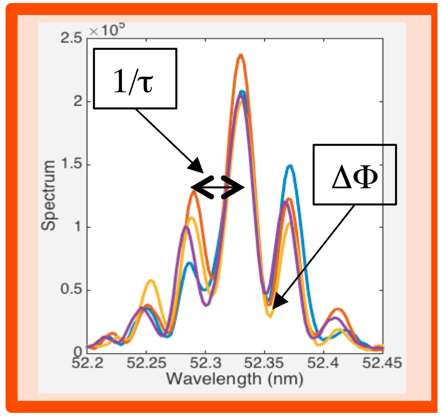
K. Prince, et al. Nature Photon. 10, 176–179 (2016)

Phase-locked FEL pulses



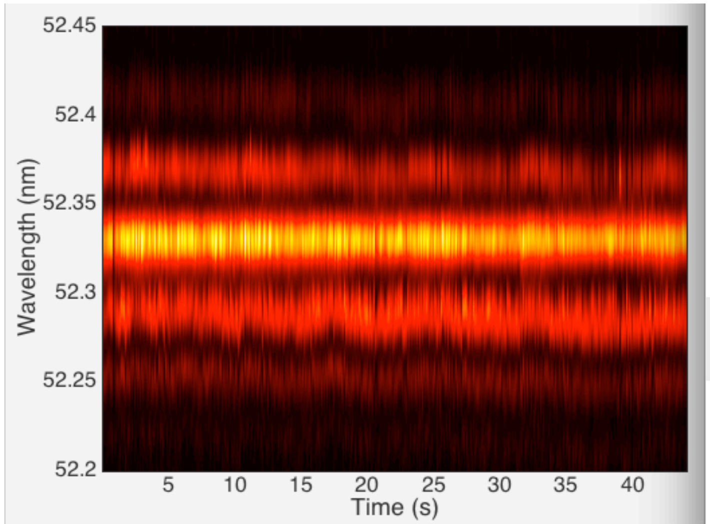






With two seed lasers one can control and change the **relative time** between **two FEL** pulses. For coherent pulses, a fine tuning allows to **control** the **relative phase** between the two **FEL pulses**.

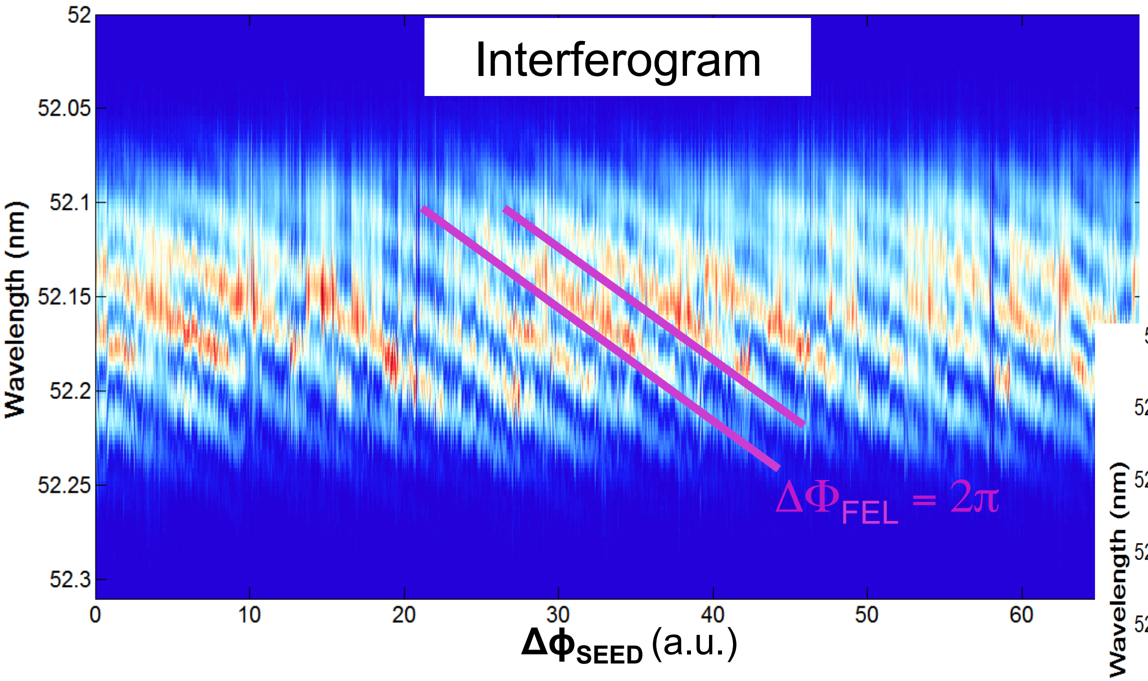
Interference between two **coherent** and **phase-locked** pulses is evident in the spectral domain.



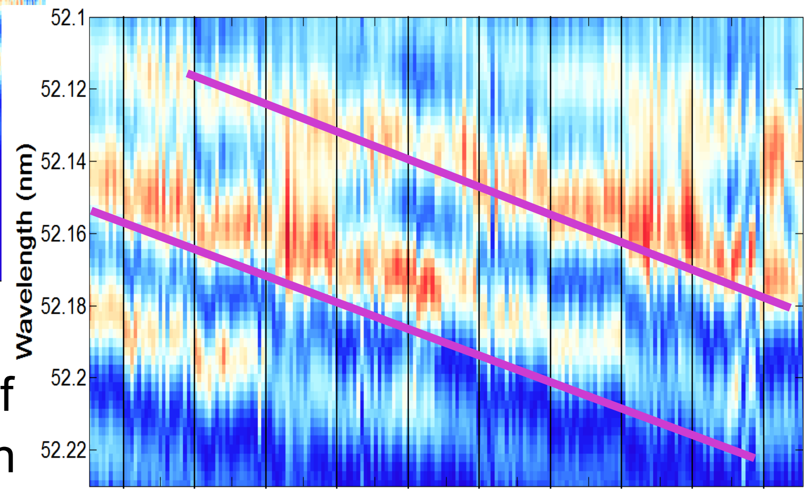
D. Gauthier et al., Phys. Rev. Lett. **116**, 024801 (2016)

FEL phase-locking control

Relative **phase** between the **seed pulses** with changed with **$\Delta\phi_{seed}$ ~ 12°@260nm** corresponding to changes of the **phase** between **FEL pulses** by **$\Delta\phi_{FEL}$ ~ 60°@52nm**



This correspond to **a control with ~ 30 as** resolution.



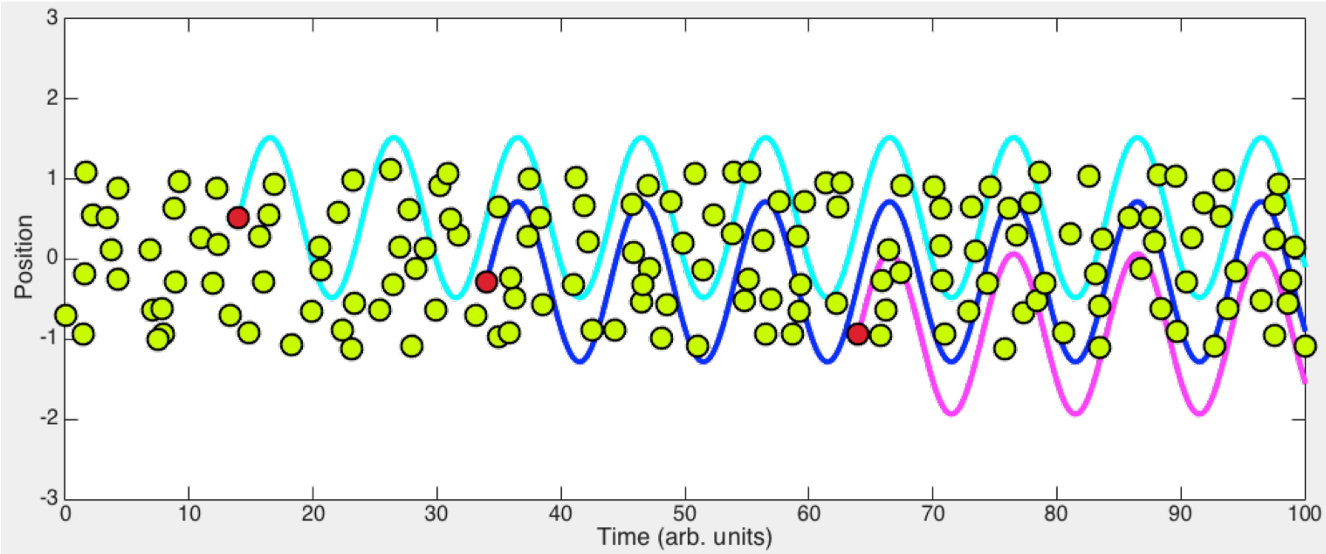
Zoom of the central part

Fringe instability is associated to wavelength jitter of the spectral envelope and is correlated with electron bunch compression monitor.

Higher resolution to ~ **as** requires a **better control** of the **electron** beam **phase space**.

Coherence preservation

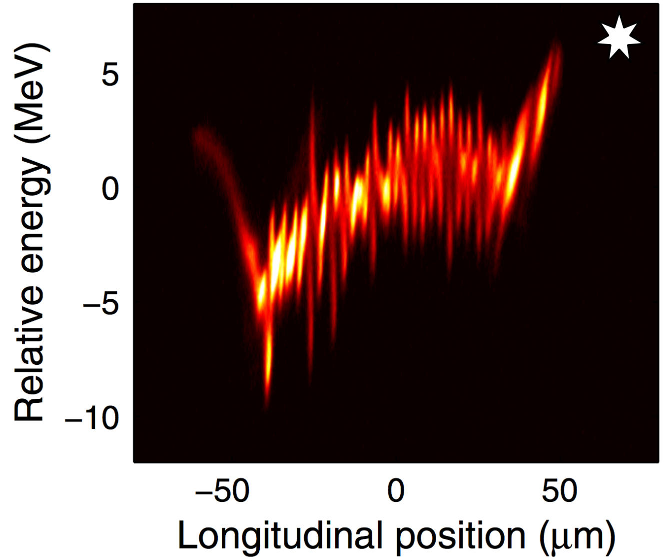
- ✓ Most advanced **schemes** taking **advantage** of seeding use the high **degree** of **longitudinal coherence**.
- ✓ **Coherence lengths >100 μm** can be generated because the **seed** set a **common phase** for all **electrons** participating to the FEL emission.

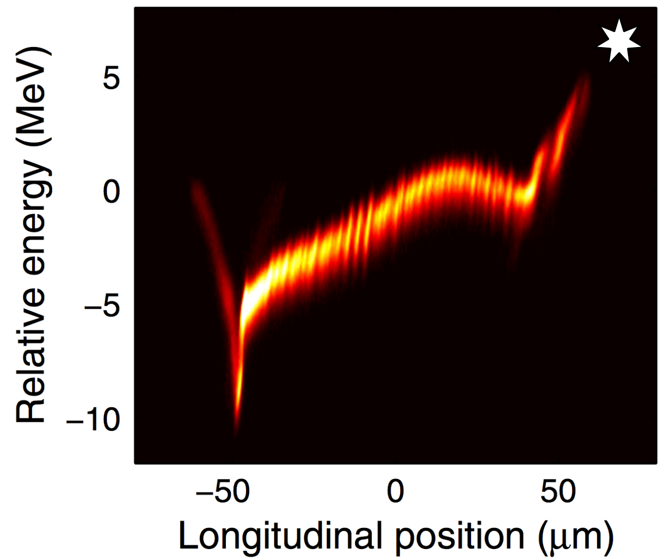


- ✓ **Coherent** emission requires that **all electrons** have **same** properties.
- ✓ However e-beam **properties varying** over the seed **pulse length** can **deteriorate** the coherence of the final **FEL** pulse.

Microbunching deterioration

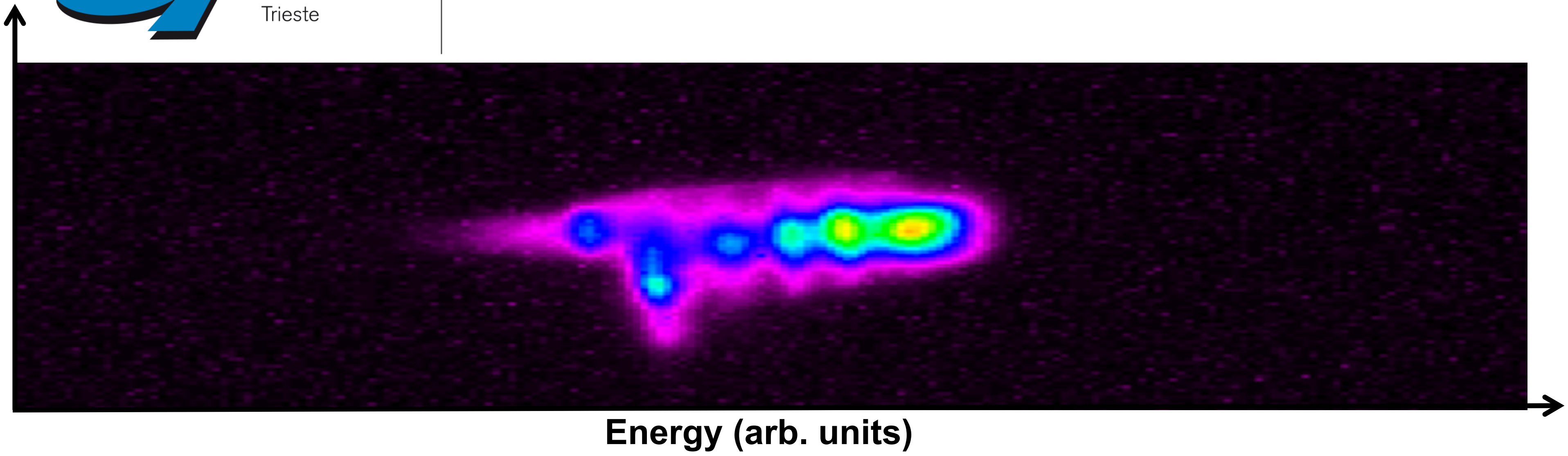
- ✓ Few μm is the length at which the micro-bunching instability has its maximum gain.
- ✓ μB changes the e-beam phase space creating modulations of the electron beam energy and/or density.
- ✓ Large μB modulation is detrimental for SASE since it increases the average energy spread that can become comparable with the FEL ρ parameter and suppress the gain.
- ✓ Methods to control and suppress μB are available.
- ✓ For SASE the reduction of the final δγ is sufficient to maximize the FEL power and optimally operate the FEL.





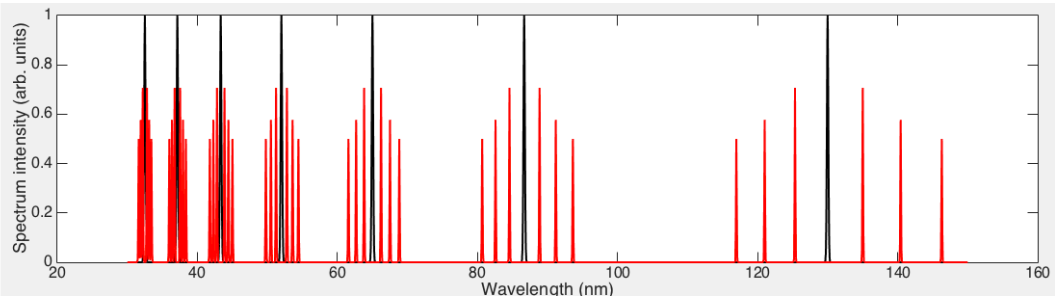
✸ **D. Ratner et al. PhysRevSTAB 18 30704 (2015)**

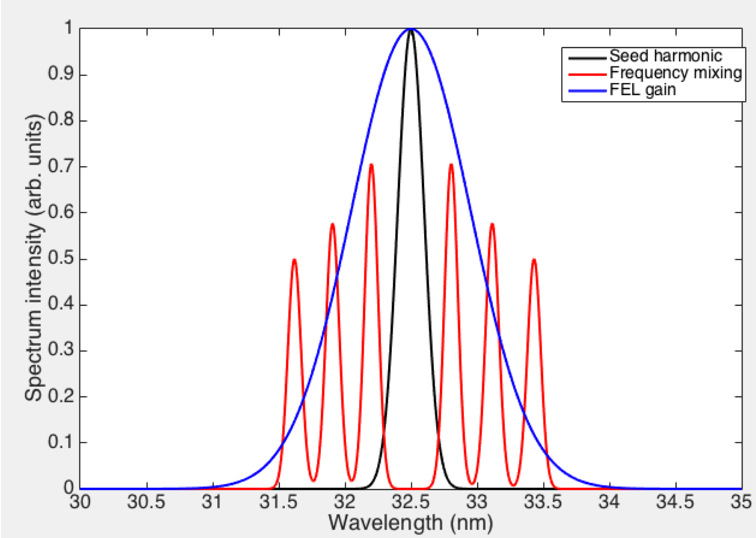
Seeding and μB



Seed laser modulation at λ_s (ω_s) superposed to μB modulations ($\lambda_{\mu B}$)

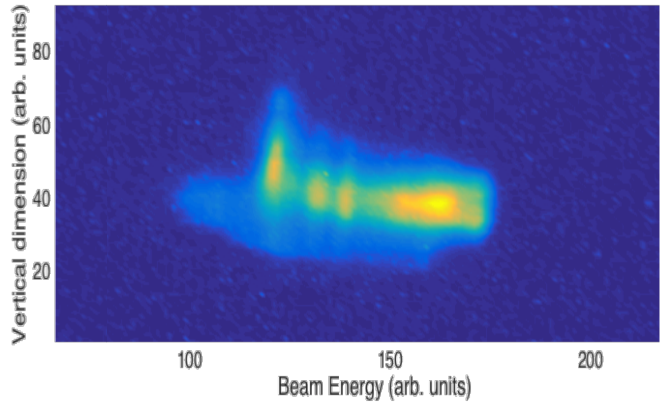
Frequency mixing $\omega_{FEL} = N_H \bullet \omega_s \pm M \bullet \omega_{\mu B}$



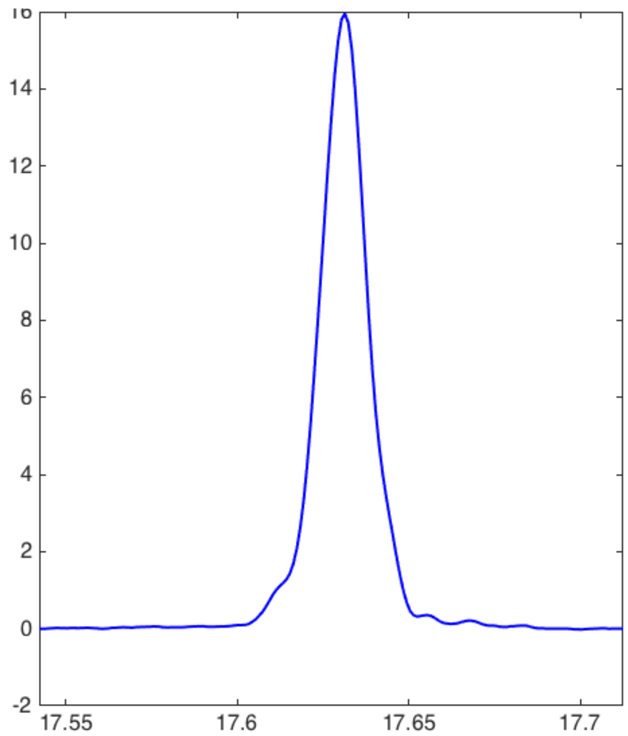


μB effects in seeded FEL

- ✓ In the case of a seeded FEL however, even small residual modulations affect the FEL interfering with the coherence created by the seed.



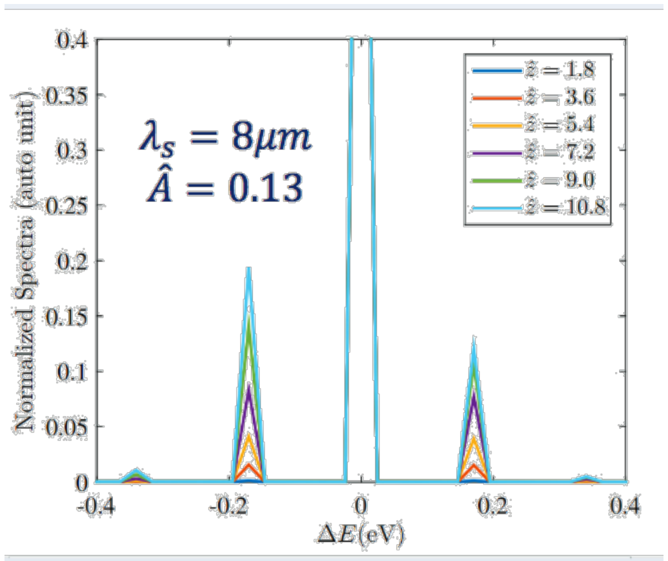
- ✓ The seed frequency is added to the already existing μB modulation frequency. As a result a frequency mixing signals are produced that generate FEL pulses with several frequencies components.

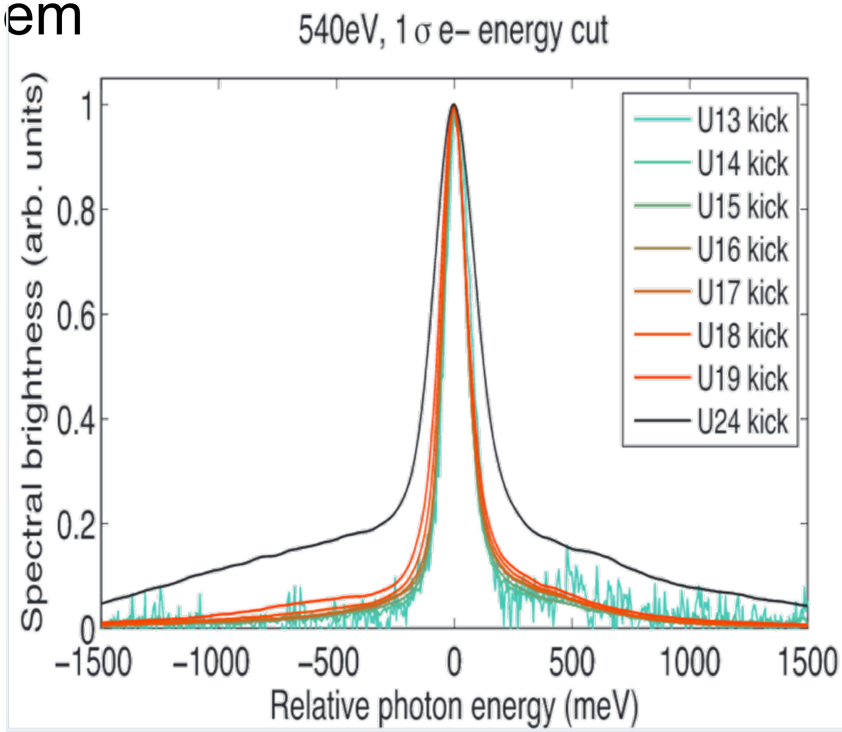


- ✓ Since the μB modulation is stochastic, the effect on the FEL is also stochastic.

μB and self seeding

✓ It is not only a problem of externally seeded FELs, also in the case of a self-seeding one has the same problem





The stochastic sidebands produced by the μB in combination with self seeding has been recognized as the source of the pedestal that contaminates the final FEL spectrum at LCLS*.

*Z. Zhang PRAB **19** 050701 (2016)

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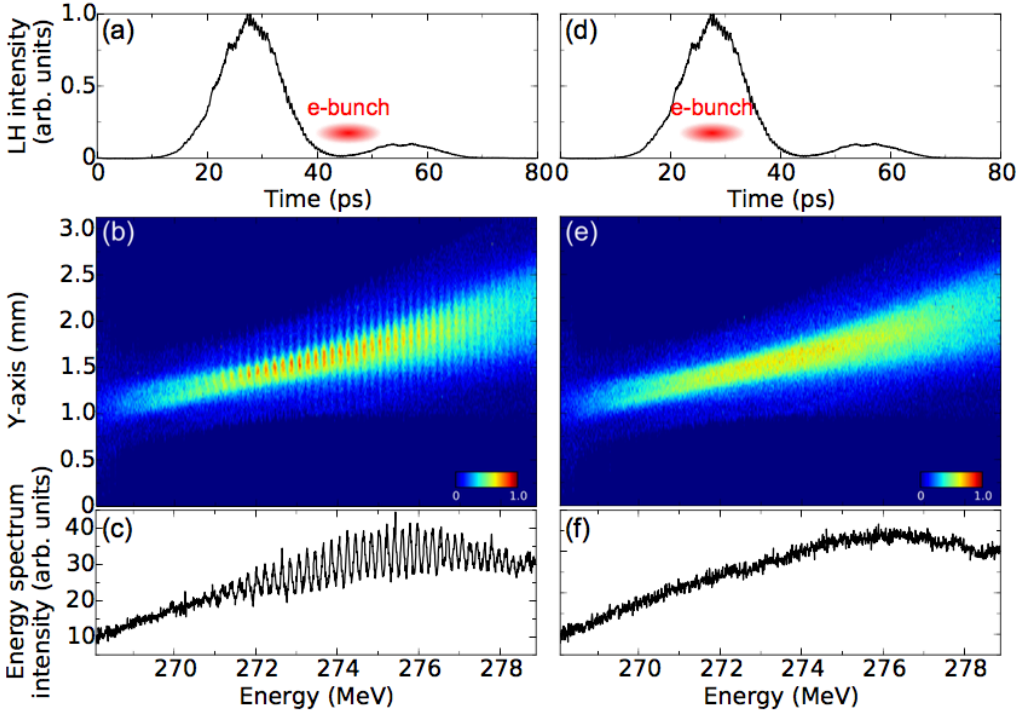
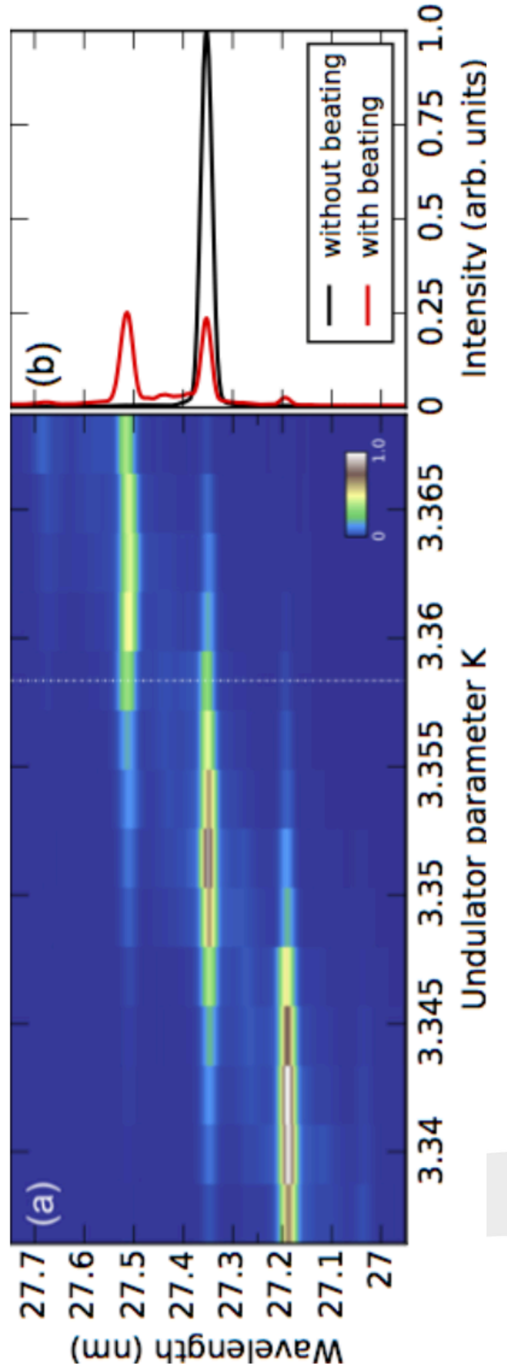
Control of μB

An external signal in LH can control the μB and create pure periodic modulation in the e-beam.



Periodic modulation with few μm period interferes with the seed and creates sidebands that are now under control.

*E. Roussel, PRL **115** 214801 (2015)



Removal of μB

- Short wavelength goal enhances requirements on μBI/CSR growth and temporal smoothness of general e-beam envelope properties at undulator entrance
  - ~ 1 to 10 μm wavelength energy modulations of greatest concern
  - Pedestal content < 25% of fundamental output requires

$$\langle\langle \Delta E^2 \rangle\rangle^{1/2} \leq 25\,\mathrm{keV} \times \left(\frac{R_{56}}{45\,\mu\mathrm{m}}\right)^{-1} \left(\frac{\lambda_R}{3\,\mathrm{nm}}\right) \left(\frac{E_0}{1800\,\mathrm{MeV}}\right)$$

  - Scaling is nasty ➡ pedestal fraction scales as $\langle\langle \Delta E^2 \rangle\rangle$

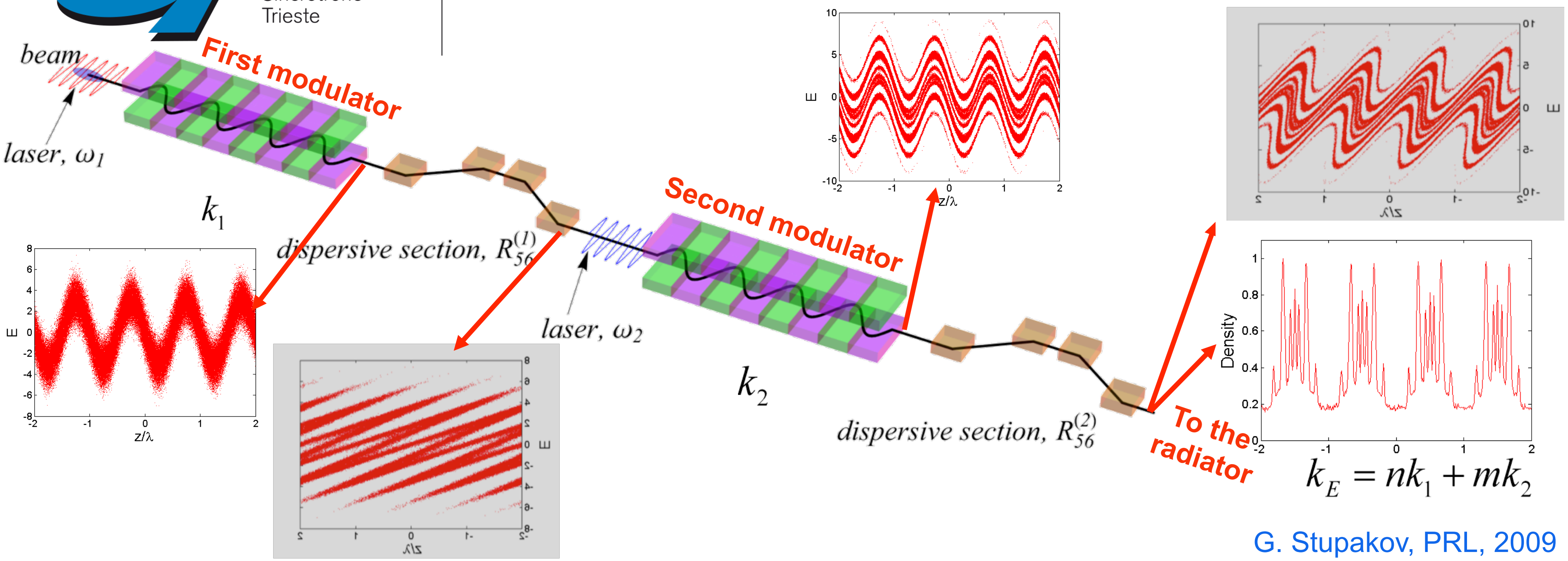
At short wavelength μB modulations of tens of keV can be detrimental for coherence.

Such a level of smoothness may not be easy to achieve and measure.

Seeding methods have been proposed that are expected to be less affected by μB

W. Fawley, FERMI MAC-SAC meeting Dec 2016

Echo Enabled Harmonic Generation



G. Stupakov, PRL, 2009

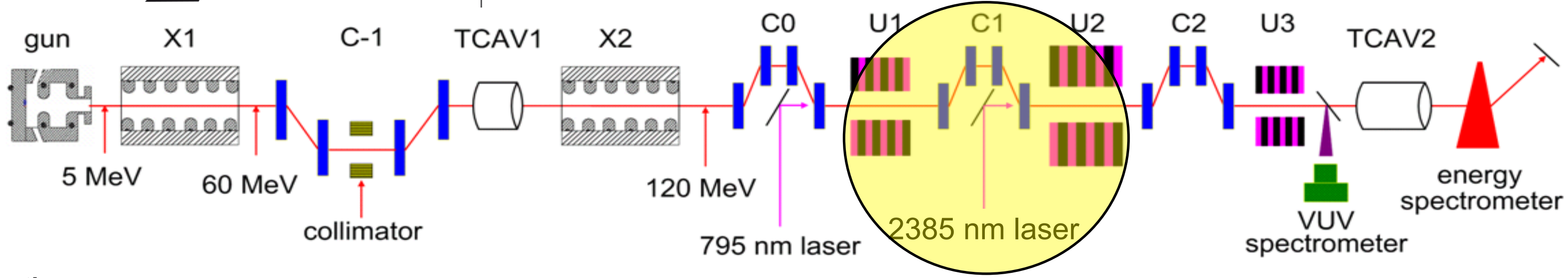
D. Xiang, G. Stupakov, PRST-AB, 2009

- A first laser generates energy modulation in electron beam.
- A strong chicane creates stripes in the longitudinal phase space.
- A second laser imprints energy modulation.
- The second chicane converts energy modulation into harmonic density modulation.

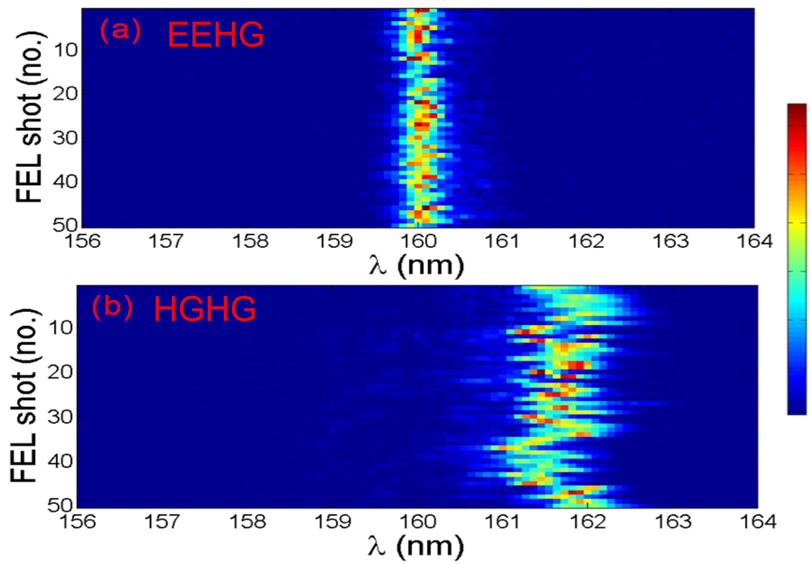
NLCTA : EEHG experiments

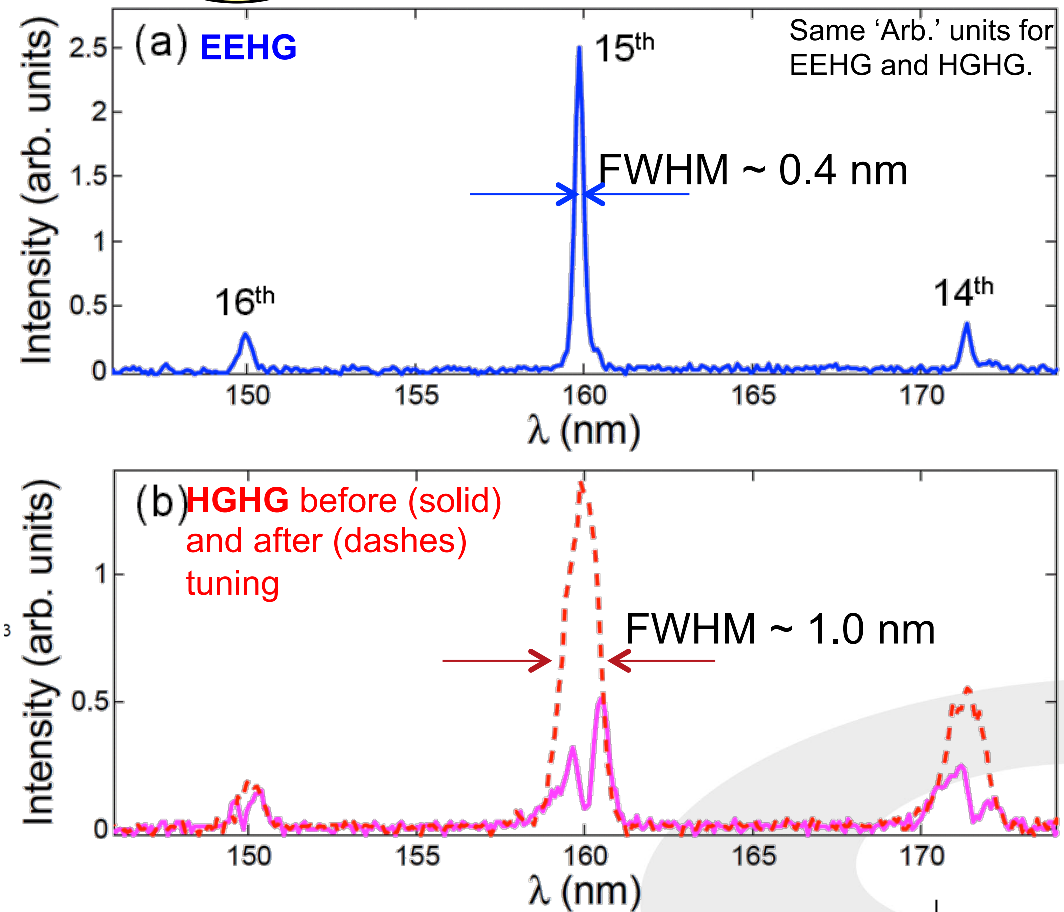
Courtesy of T. Raubenheimer and ECHO team

Elettra Sincrotrone Trieste



15th harmonic accessible using a longer wavelength seed. Recently **75th** harmonic.



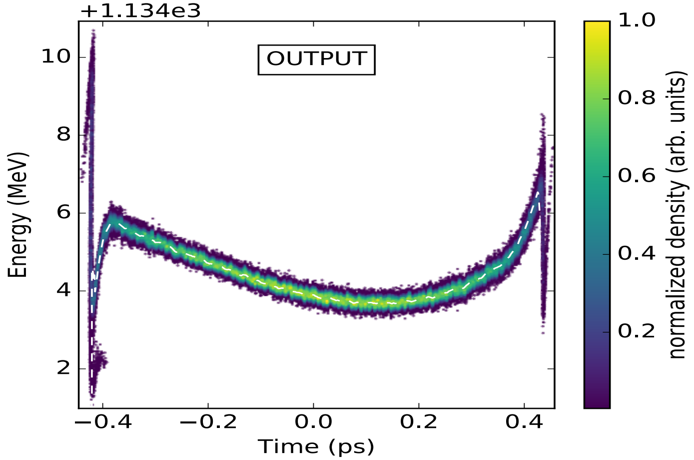


Measured **better spectral** properties with **EEHG**.

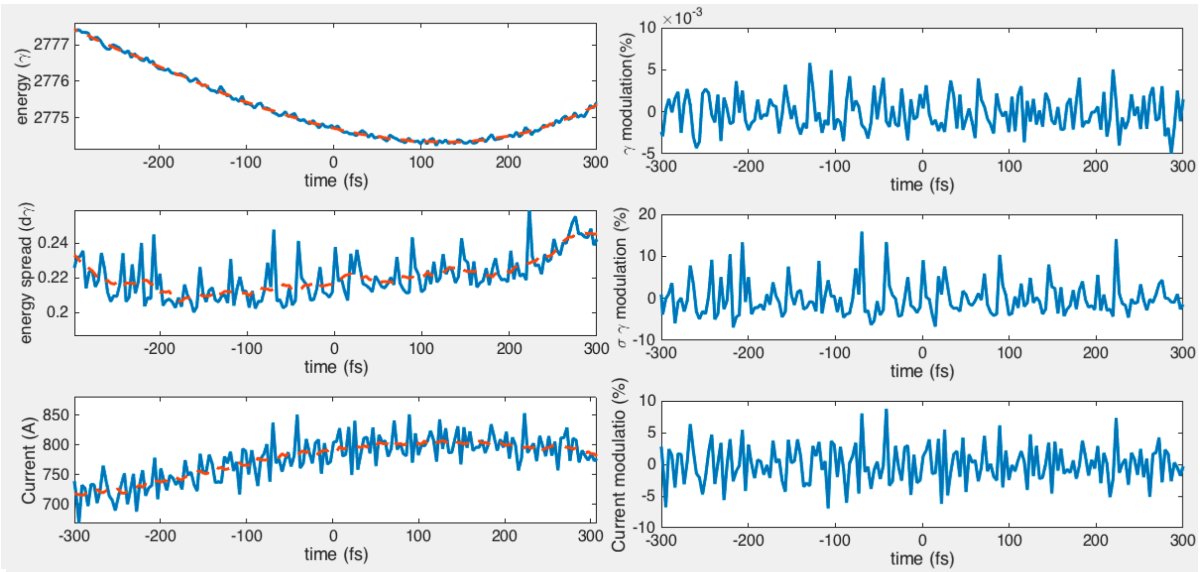
E. Hemsing, et al PRST-AB **17**, 070702 (2014)
E. Hemsing, et al Nat. Photon. **10**, 512–515 (2016)

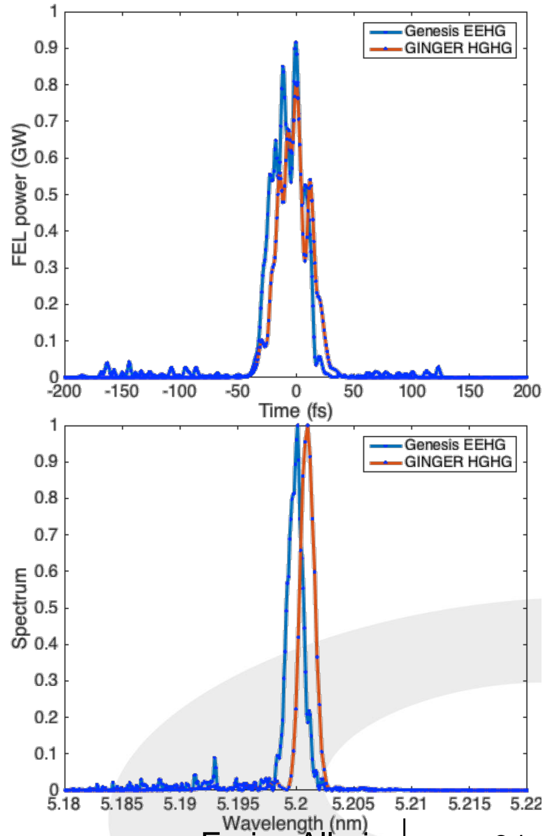
Elettra
Sincrotrone
Trieste

Comparison of HGHG and EEHG



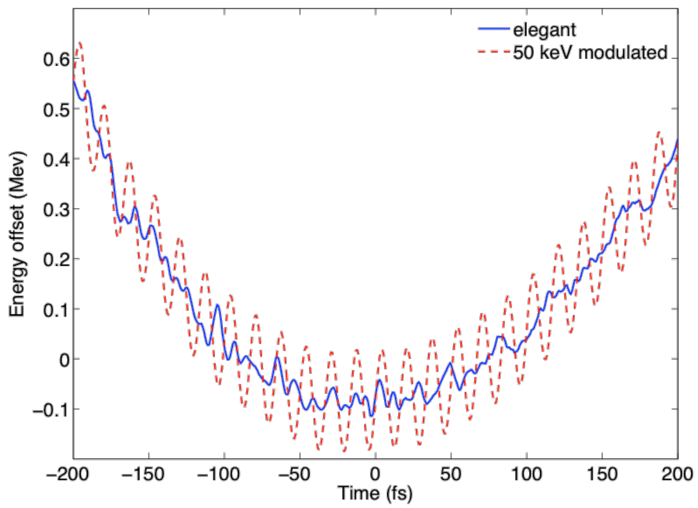
- Start to end simulations of FERMI linac
- Focus on the longitudinal phase space
- Evidence of noisy energy modulation



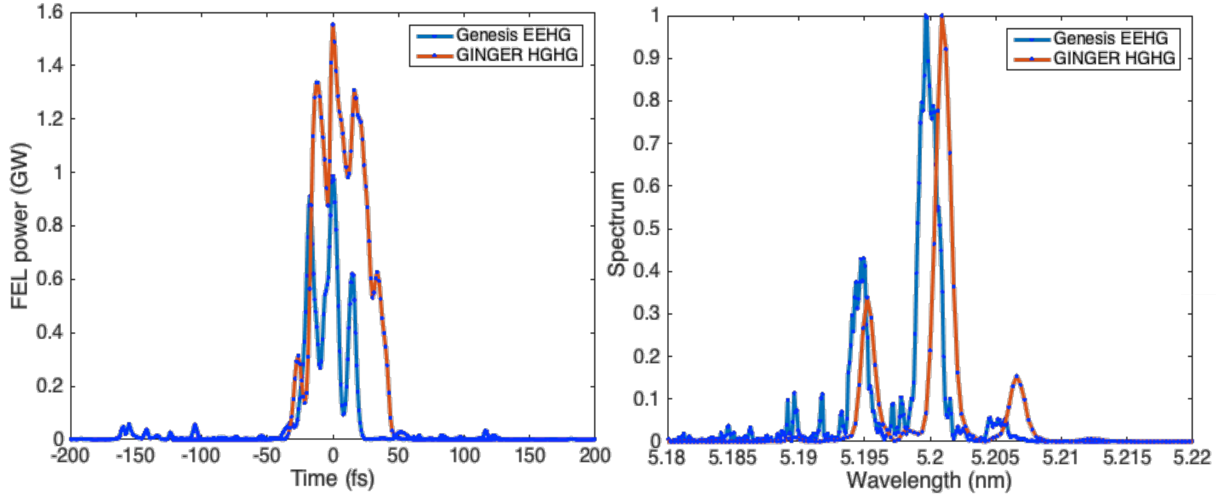


Periodic modulation

For a quantitative comparison of HGHG and EEHG sensitivity on the energy modulation a periodic modulation is used.

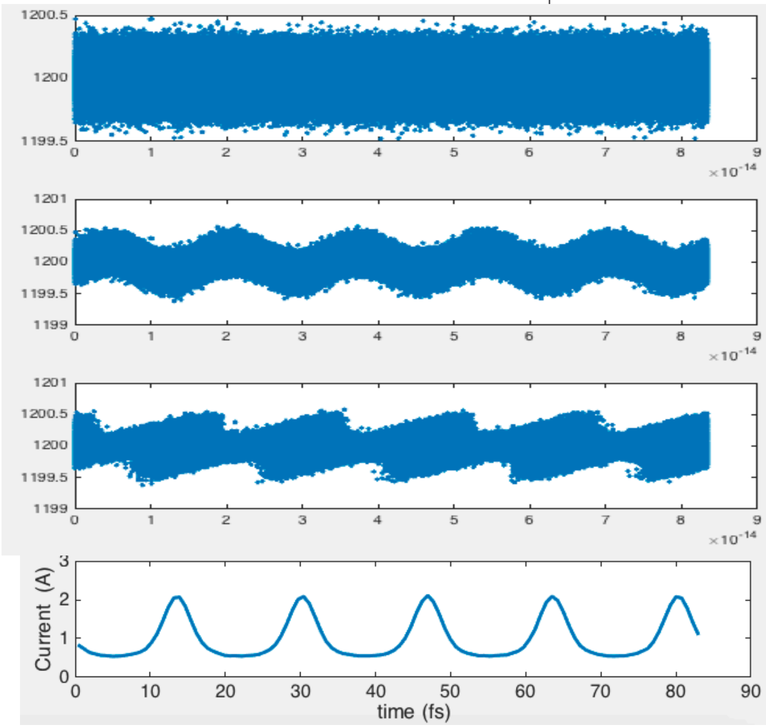


With used parameters HGHG and EEHG show similar behavior on phase space distortion.



Sidebands in EEHG are associated to the current modulation produced by the beam passing through the large R56.

Current modulation



EEHG sensitivity on μB is due to the conversion of energy modulation into density modulation occurring in the large chicane.

Current modulation is maximized by: $R_{56} = \frac{\lambda_{\text{mod}}}{4} \frac{\gamma}{\Delta\gamma_{\text{mod}}}$

R56 should be chosen to avoid maximum bunching.

- EEHG benefits in bandwidth control depend on μB wavelength.
- Prediction of amplitude and shape of μB at the position of FEL undulator is essential.

Conclusions

- ✓ Seeding allows to generate FEL pulses with a high degree of longitudinal coherence.
- ✓ Fully coherent pulses open the door to new coherent control experiments in the x-ray.

- ✓ Success of seeding strongly relies on the quality of the electron beam.
- ✓ Control of the microbunching instability is crucial.
- ✓ Reliable **predictions of μB** are **necessary** for properly **design** FEL and minimize the effect on the FEL quality.