Elettra Sincrotrone Trieste

# Advanced Concepts for Seeded FELs

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# What is seeding?

Single-pass Free Electron Lasers (FELs) can amplify the noise present in the electron beam density profile obtaining powerful SASE radiation.

Using instead an “external” electro-magnetic field (a seed) it is possible to initiate the FEL process in a deterministic way.

The properties of the output FEL radiation are inherited and determined by the seed itself.

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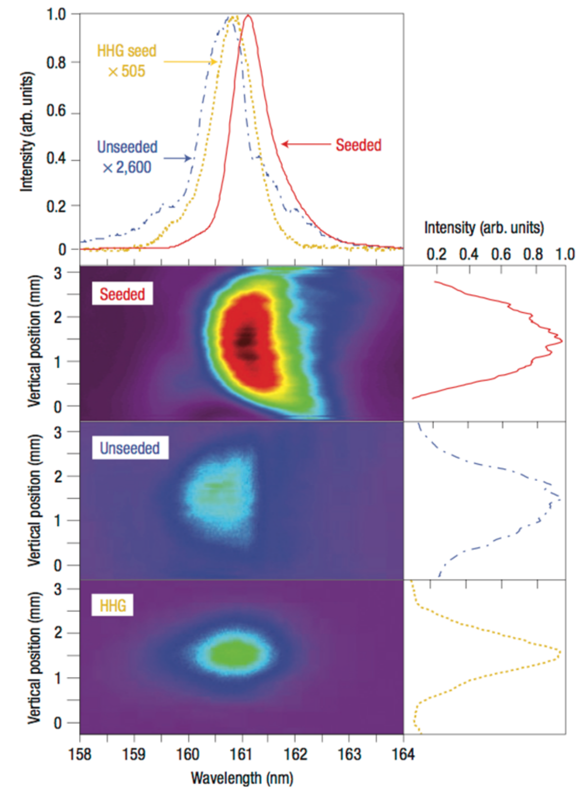
# The seed

## The "external" seed can be:

## High order harmonics generated in gas (HHG)

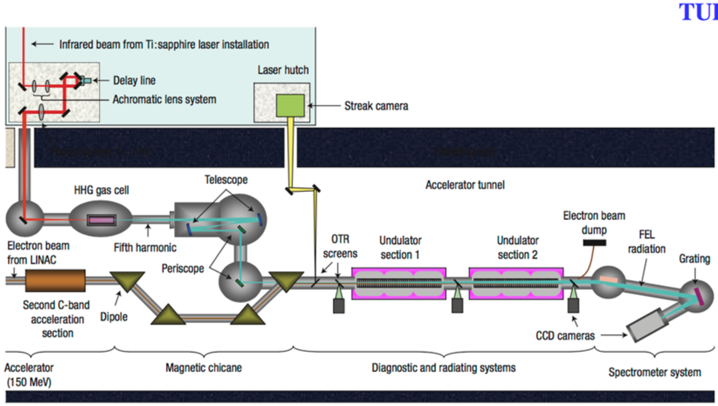



nature physics

*Nature Physics* **4**, 296 - 300 (2008)
Published online: 9 March 2008 | doi:10.1038/nphys889

### Injection of harmonics generated in gas in a free-electron laser providing intense and coherent extreme-ultraviolet light

G. Lambert[1,2,3], T. Hara[2,4], D. Garzella[1], T. Tanikawa[2], M. Labat[1,3], B. Carre[1], H. Kitamura[2,4], T. Shintake[2,4], M. Bougeard[1], S. Inoue[4], Y. Tanaka[2,4], P. Salieres[1], H. Merdji[1], O. Chubar[3], O. Gobert[1], K. Tahara[2] & M.-E. Couprie[3]




TUPA04 Proceedings of FEL2011, Shanghai, China

### sFLASH - PRESENT STATUS AND COMMISSIONING RESULTS*

S. Ackermann, A. Azima, J. Bödewadt, F. Curbis, M. Drescher, E. Hass,
M. Mittenzwey, T. Maltezopoulos, V. Miltchev†, J. Rönsch-Schulenburg,
J. Rossbach, R. Tarkeshian, Hamburg University, Hamburg, Germany
H. Delsim-Hashemi, K. Honkavaara, T. Laarmann, H. Schlarb,
S. Schreiber, M. Tischer, DESY, Hamburg, Germany
R. Ischebeck, PSI, Villigen, Switzerland

# The seed

*Journal of Modern Optics*
Vol. 58, No. 16, 20 September 2011, 1391–1403

**A novel self-seeding scheme for hard X-ray FELs**

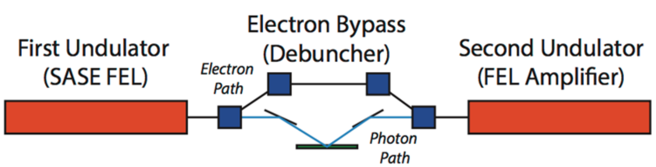
Gianluca Geloni[a]*, Vitali Kocharyan[b] and Evgeni Saldin[b]
[a]*European XFEL GmbH, Hamburg, Germany;* [b]*Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany*
*(Received 17 December 2010; final version received 29 April 2011)*

The "external" seed can be:
- Another FEL
- Monochromatised SASE (self-seeding) or multiple stages

nature photonics ARTICLES
PUBLISHED ONLINE: 12 AUGUST 2012 | DOI: 10.1038/NPHOTON.2012.180

## Demonstration of self-seeding in a hard-X-ray free-electron laser

J. Amann[1], W. Berg[2], V. Blank[3], F.-J. Decker[1], Y. Ding[1], P. Emma[4]*, Y. Feng[1], J. Frisch[1], D. Fritz[1], J. Hastings[1], Z. Huang[1], J. Krzywinski[1], R. Lindberg[2], H. Loos[1], A. Lutman[1], H.-D. Nuhn[1], D. Ratner[1], J. Rzepiela[1], D. Shu[2], Yu. Shvyd'ko[2], S. Spampinati[1], S. Stoupin[2], S. Terentyev[3], E. Trakhtenberg[2], D. Walz[1], J. Welch[1], J. Wu[1], A. Zholents[2] and D. Zhu[1]




PRL **114,** 054801 (2015) PHYSICAL REVIEW LETTERS week ending 6 FEBRUARY 2015

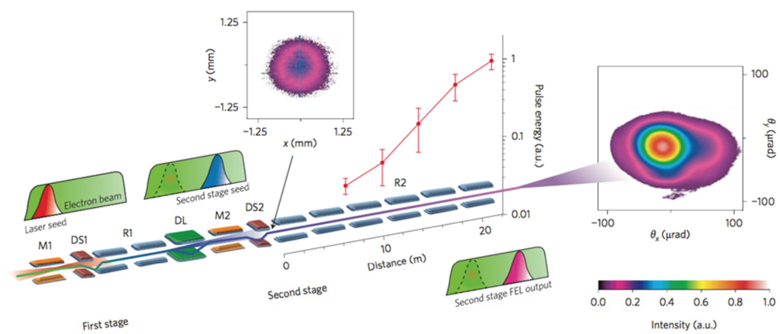
**Experimental Demonstration of a Soft X-Ray Self-Seeded Free-Electron Laser**

D. Ratner,[1,*] R. Abela,[2] J. Amann,[1] C. Behrens,[1] D. Bohler,[1] G. Bouchard,[1] C. Bostedt,[1] M. Boyes,[1] K. Chow,[3] D. Cocco,[1] F. J. Decker,[1] Y. Ding,[1] C. Eckman,[1] P. Emma,[1] D. Fairley,[1] Y. Feng,[1] C. Field,[1] U. Flechsig,[2] G. Gassner,[1] J. Hastings,[1] P. Heimann,[1] Z. Huang,[1] N. Kelez,[1] J. Krzywinski,[1] H. Loos,[1] A. Lutman,[1] A. Marinelli,[1] G. Marcus,[1] T. Maxwell,[1] P. Montanez,[1] S. Moeller,[1] D. Morton,[1] H. D. Nuhn,[1] N. Rodes,[3] W. Schlotter,[1] S. Serkez,[4] T. Stevens,[3] J. Turner,[1] D. Walz,[1] J. Welch,[1] and J. Wu[1]
[1]*SLAC National Accelerator Laboratory, Menlo Park, California 94720, USA*
[2]*Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland*
[3]*Lawrence Berkeley National Laboratory (LBNL), 1 Cyclotron Road, Berkeley, California 94720, USA*
[4]*Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, D-22607 Hamburg, Germany*
(Received 3 October 2014; published 6 February 2015)

nature photonics ARTICLES
PUBLISHED ONLINE: 20 OCTOBER 2013 | DOI: 10.1038/NPHOTON.2013.277

## Two-stage seeded soft-X-ray free-electron laser

E. Allaria[1], D. Castronovo[1], P. Cinquegrana[1], P. Craievich[1†], M. Dal Forno[1,2], M. B. Danailov[1], G. D'Auria[1], A. Demidovich[1], G. De Ninno[1,3], S. Di Mitri[1], B. Diviacco[1], W. M. Fawley[1]*, M. Ferianis[1], E. Ferrari[1], L. Froehlich[1], G. Gaio[1], D. Gauthier[1,3], L. Giannessi[1,4]*, R. Ivanov[1], B. Mahieu[1,5], N. Mahne[1], I. Nikolov[1], F. Parmigiani[1,2], G. Penco[1], L. Raimondi[1], C. Scafuri[1], C. Serpico[1], P. Sigalotti[1], S. Spampinati[1,3], C. Spezzani[1], M. Svandrlik[1], C. Svetina[1,2], M. Trovo[1], M. Veronese[1], D. Zangrando[1] and M. Zangrando[1,6]



# The seed

The "external" seed can be*:

A conventional laser

PHYSICAL REVIEW A VOLUME 44, NUMBER 8 15 OCTOBER 1991

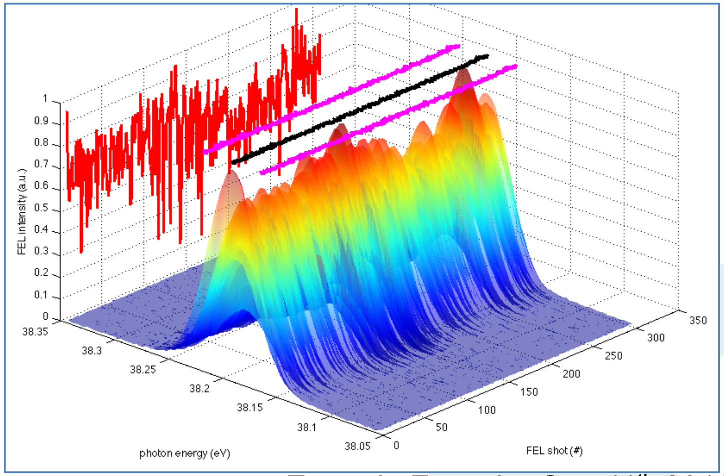
**Generation of intense uv radiation by subharmonically seeded single-pass free-electron lasers**

L. H. Yu
*National Synchrotron Light Source, Brookhaven National Laboratory, Upton, New York 11973*
(Received 1 April 1991)

nature photonics ARTICLES
PUBLISHED ONLINE: 23 SEPTEMBER 2012 | DOI: 10.1038/NPHOTON.2012.233

**Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet**

E. Allaria *et al.**






*And many others…

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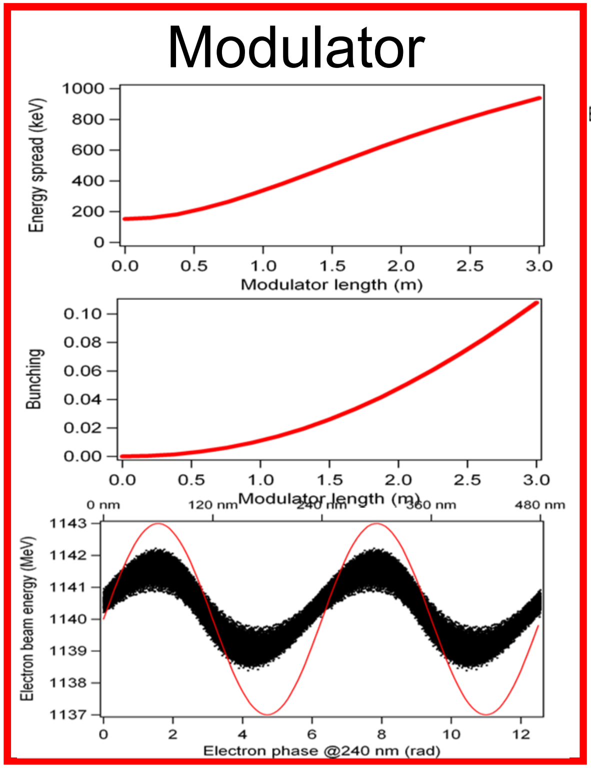
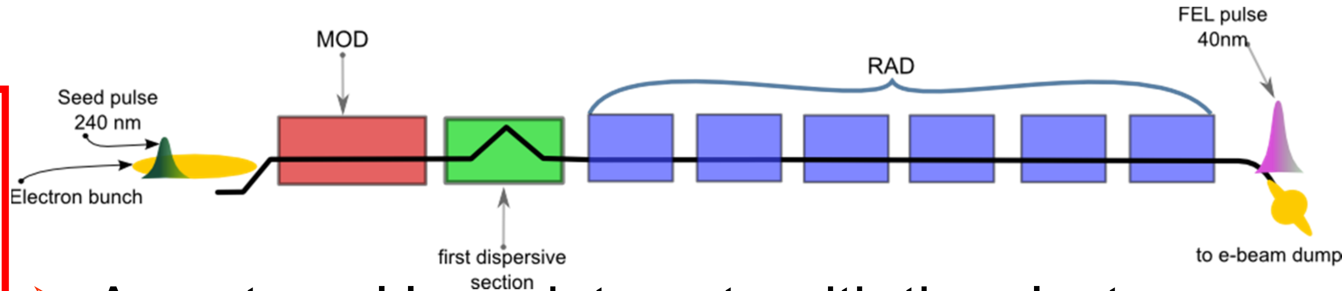
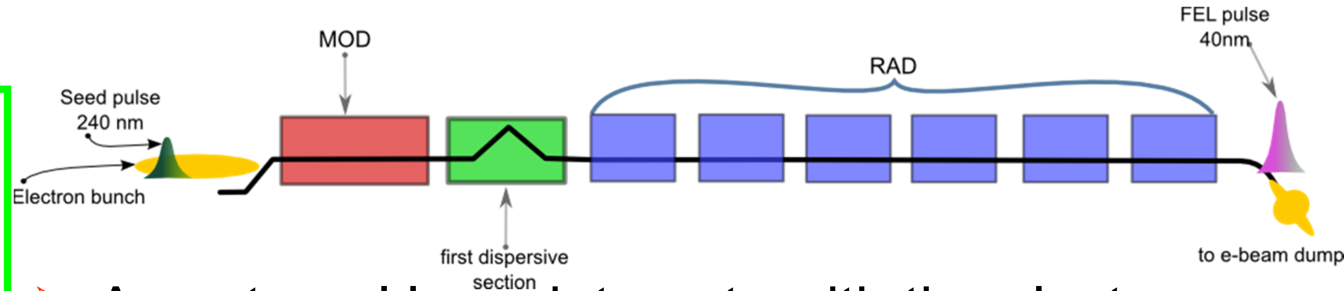
# High Gain Harmonic Generation (HGHG)



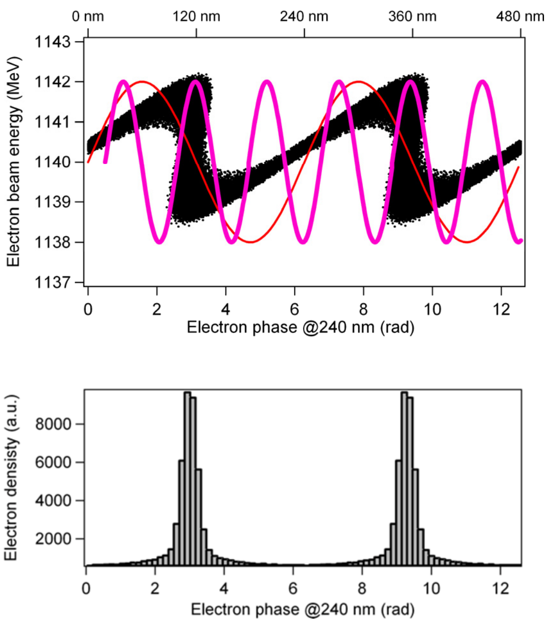




- An external laser interacts with the electron beam in the modulator inducing a periodic modulation of the electron beam energy.
- In a dispersive region, energy modulation is converted into density modulation with significant harmonic content. Beam current modulation inherits coherence properties from the input laser.
- Coherent bunching produces coherent emission in the radiator at the desired harmonic that is then amplified.

# High Gain Harmonic Generation (HGHG)




## Dispersive section

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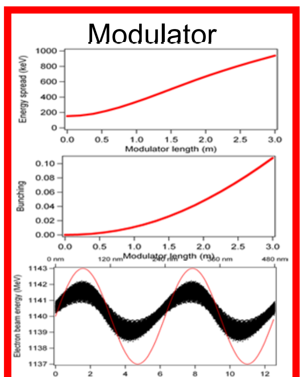

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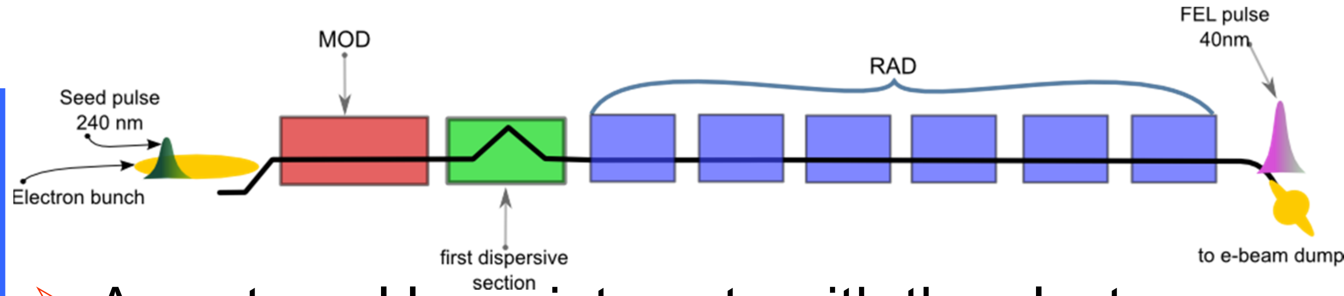


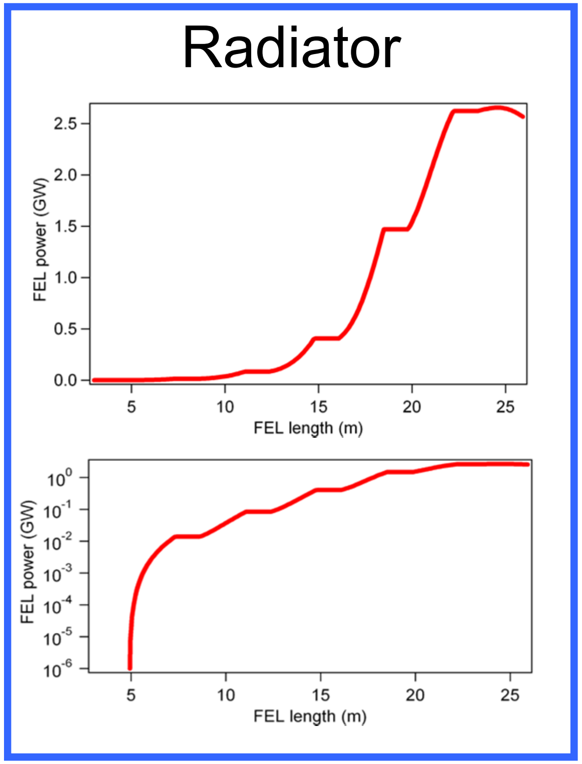


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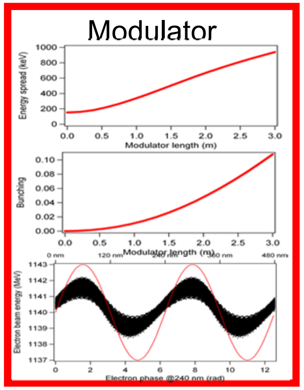
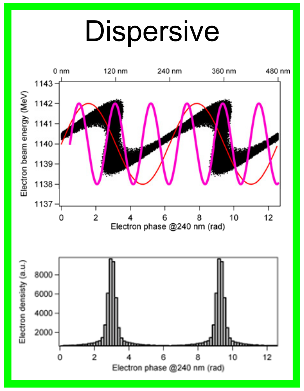
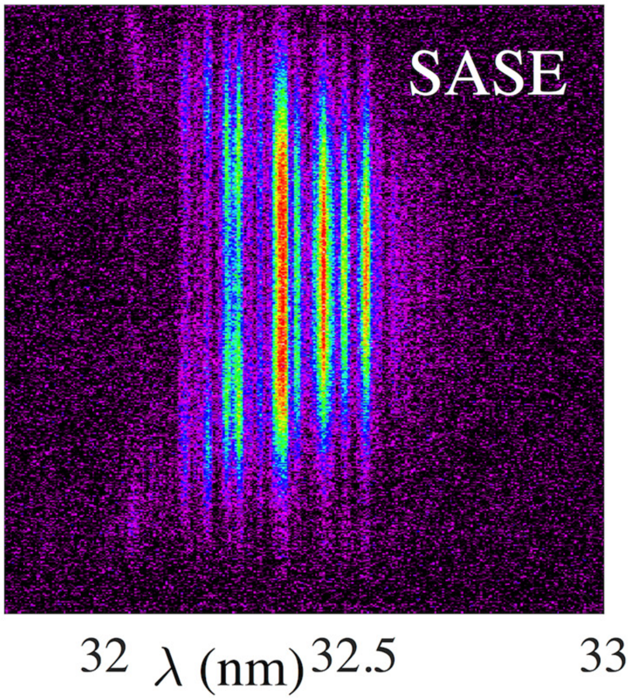


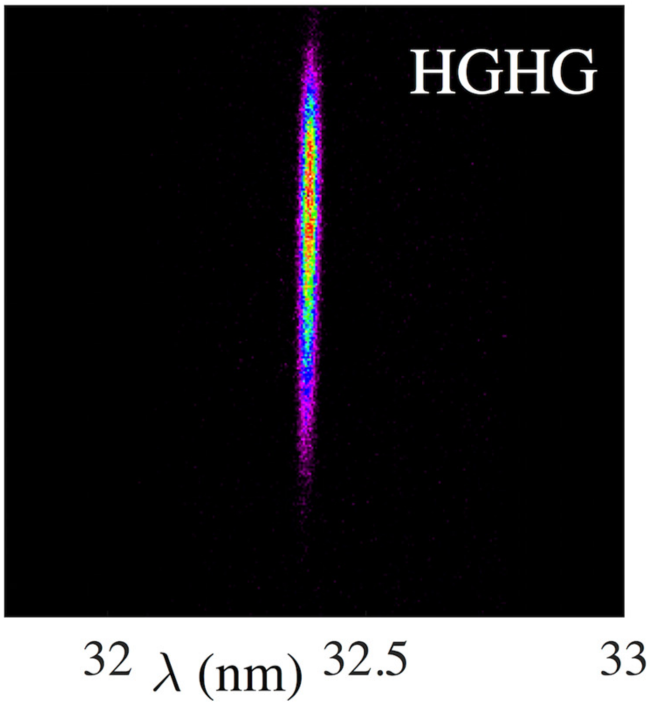




- Coherent bunching produces coherent emission in the radiator at the desired harmonic that is then amplified.

# Self-Amplified Spontaneous Emission

Comparison between SASE and seeded spectra



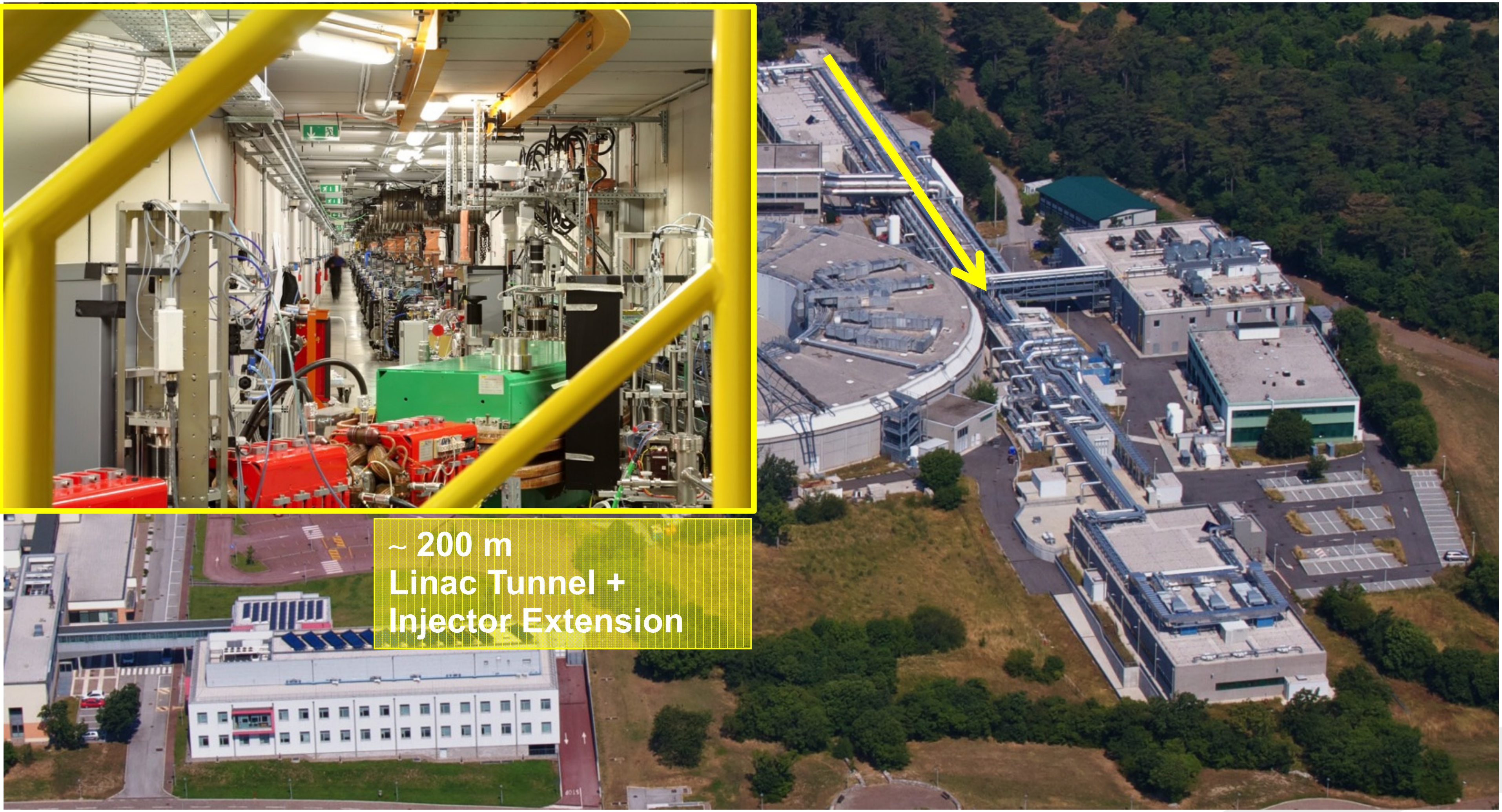




**That's why you need a seed!**

# 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 Free Electron Laser

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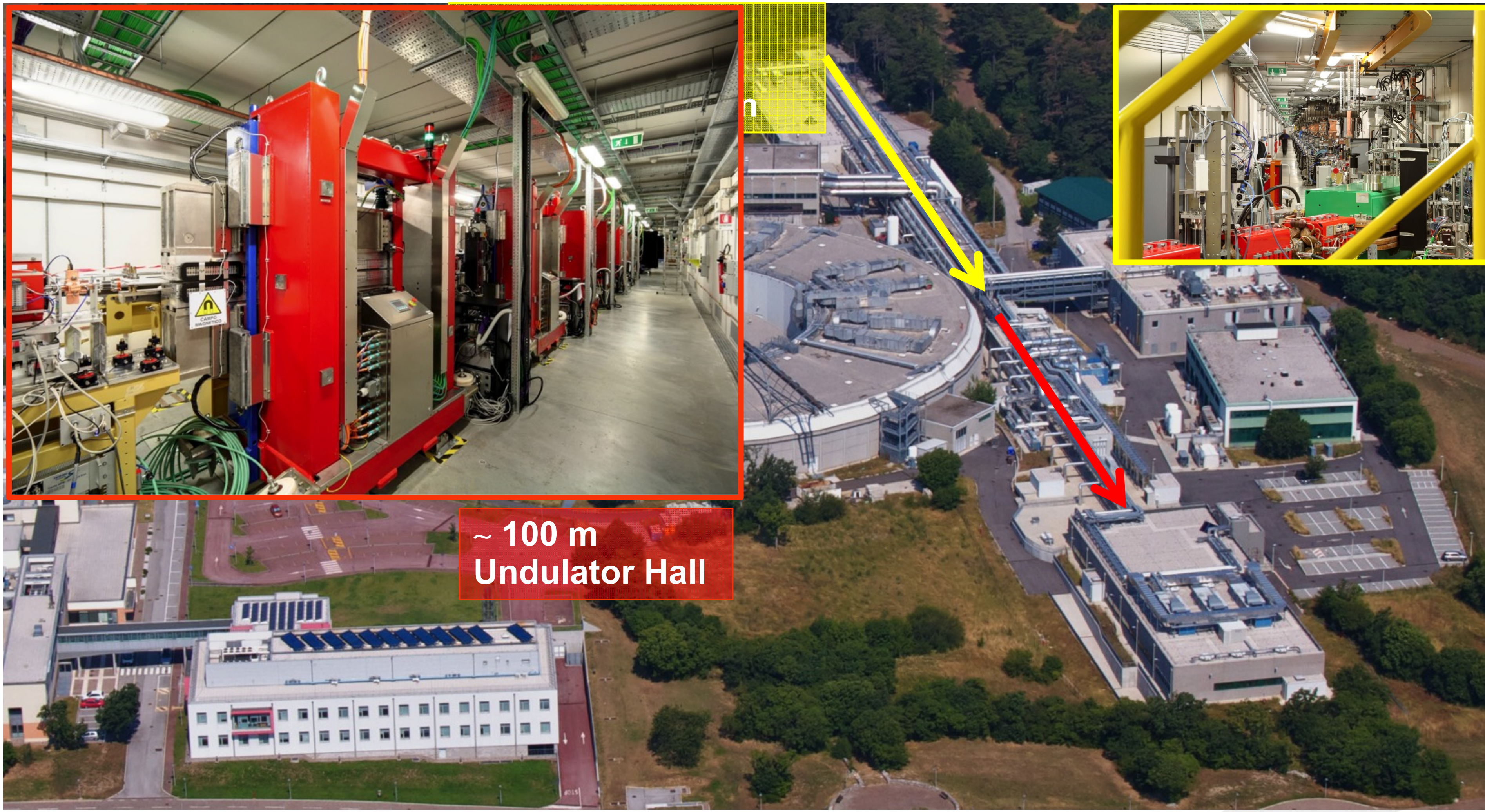


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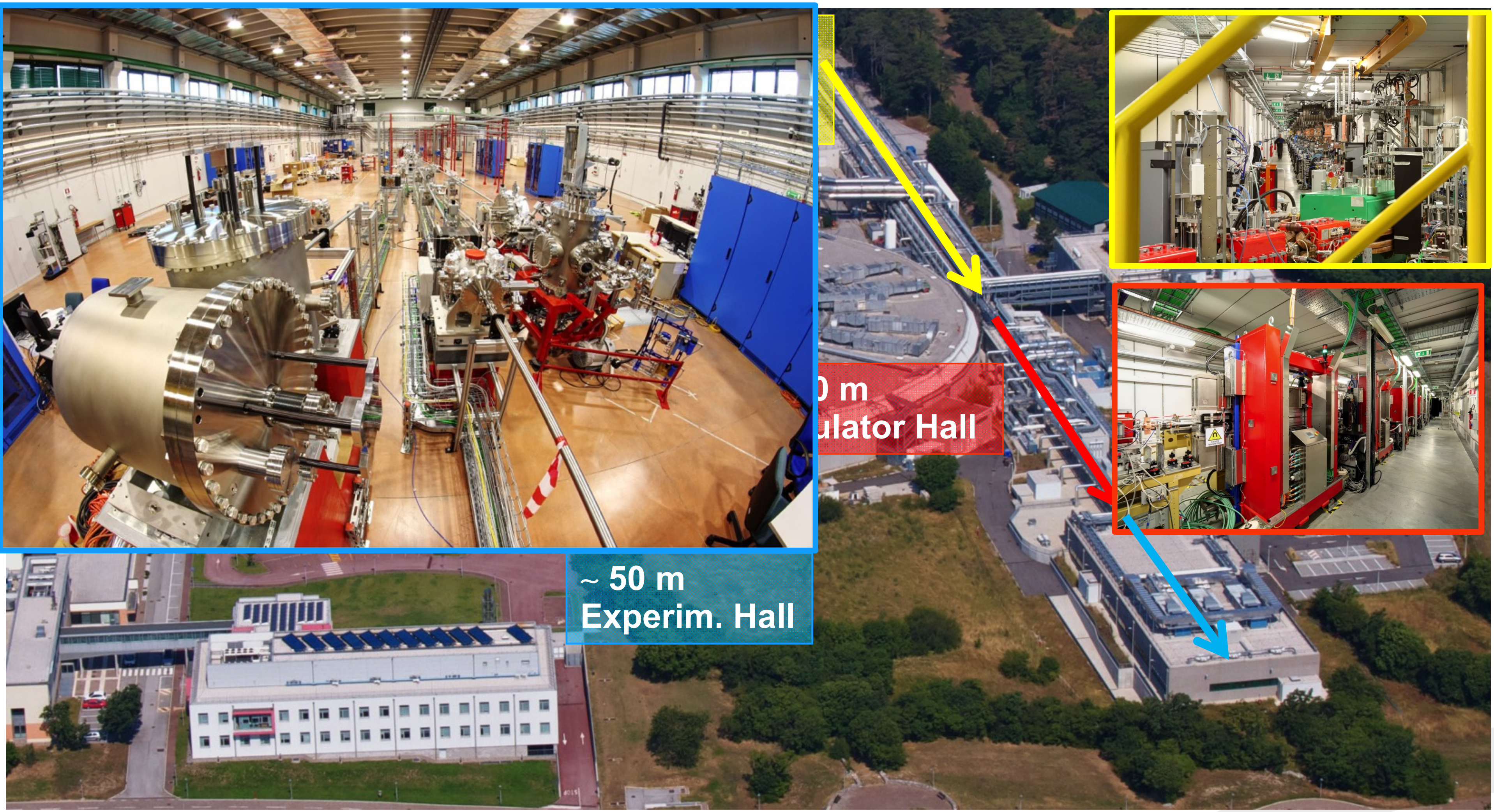
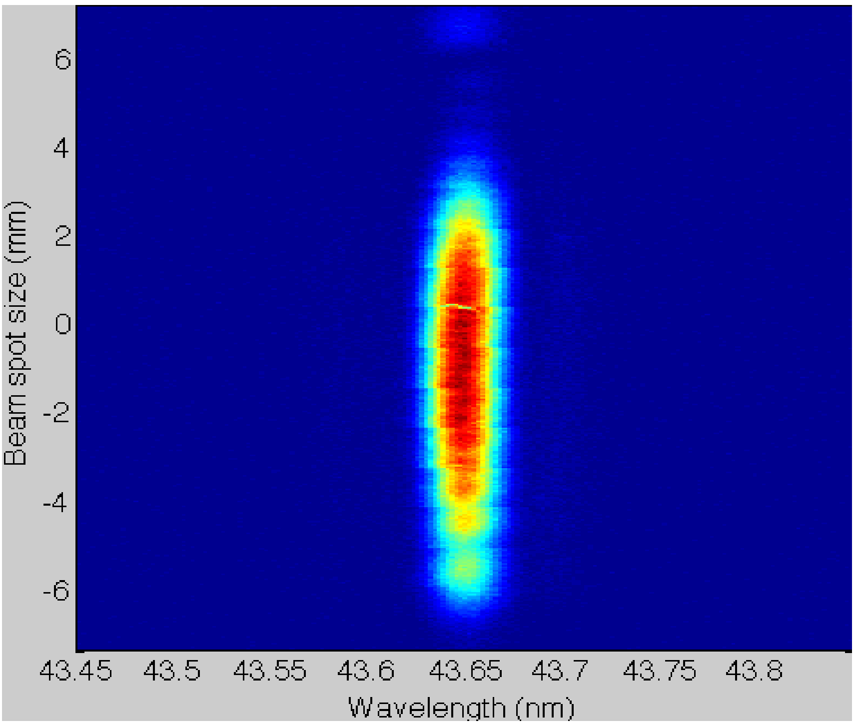



Sponsored by: Italian Minister of University and Research (MIUR), Regione Auton. Friuli Venezia Giulia, European Investment Bank (EIB), European Research Council (ERC), European Commission (EC)

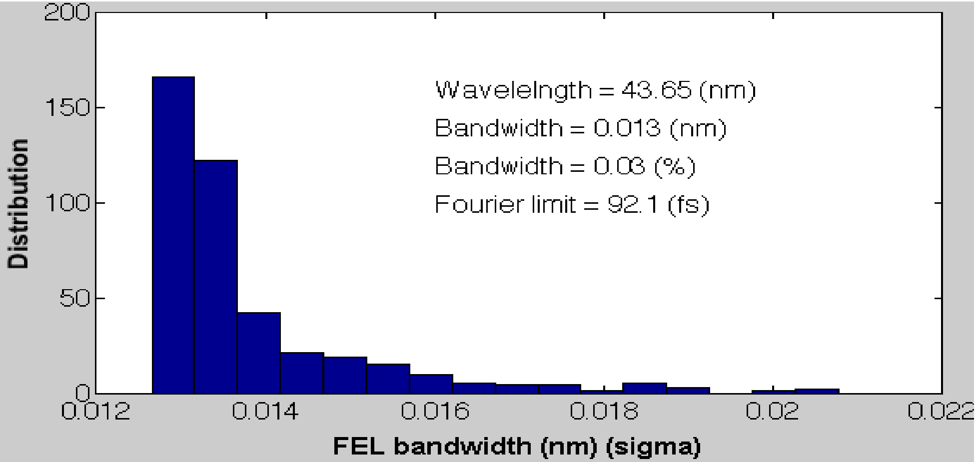
# FEL bandwidth control

**FEL pulses** inherit the **coherence** from the **external seed** laser.

The use of **seed pulses** close to the **Fourier limit**, allow the production of **FEL pulses** that are also **close** to the **Fourier limit**.




- Typical seed pulses are **120 fs** long with **0.9 nm** spectral width.
- **FEL pulses** are 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 matches theoretical predictions suggesting a **very high** longitudinal **coherence**.

# Seed laser chirp

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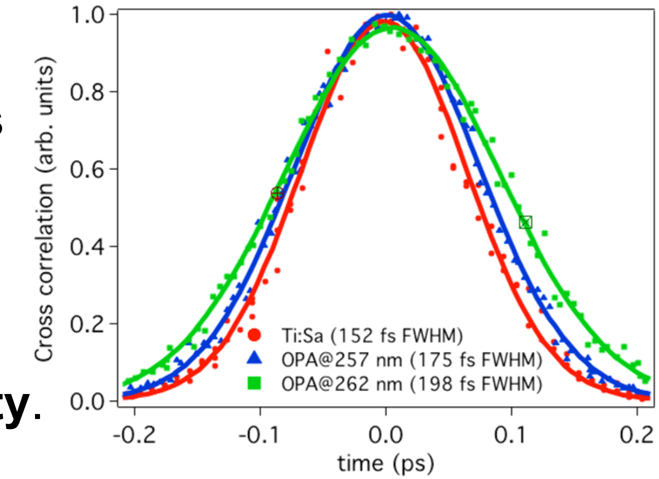
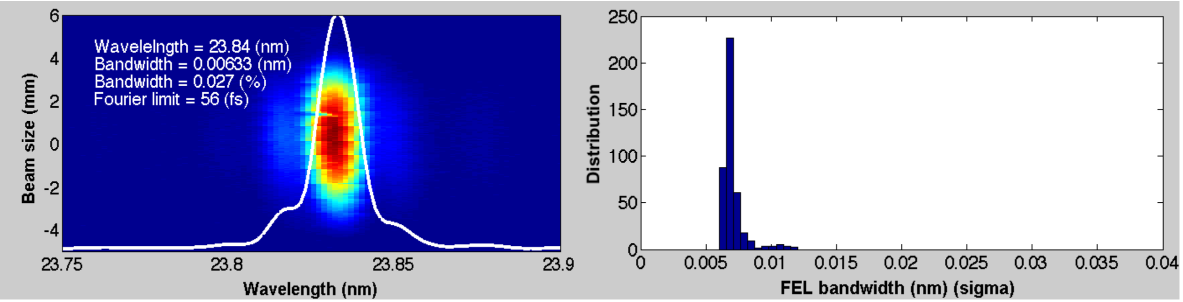
Fine **tuning** of the **FEL wavelength** requires **changes** of the **seed laser wavelength** and it implies the use of an Optical Parametric Amplifier **(OPA)** laser.

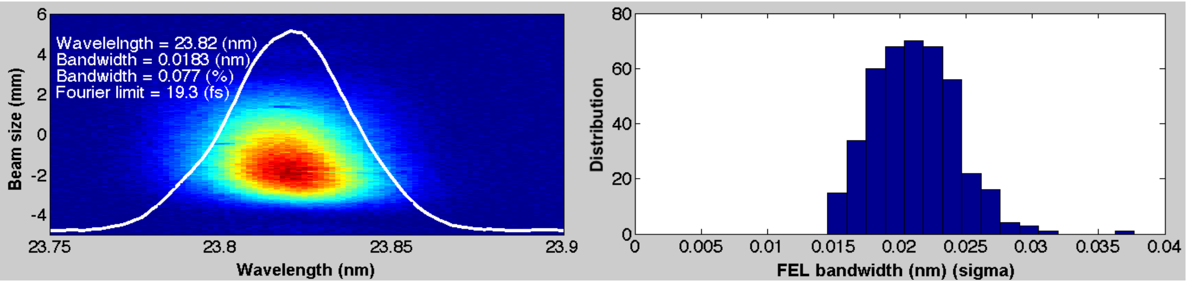
Due to his complexity and to the effects of the multilayers mirrors, with **OPA** we have **less control** on the seed laser **chirp**. At some specific wavelengths **seed pulses** can be **longer** with stronger **chirp**.




This has a **significant impact** in the FEL **spectral quality**.



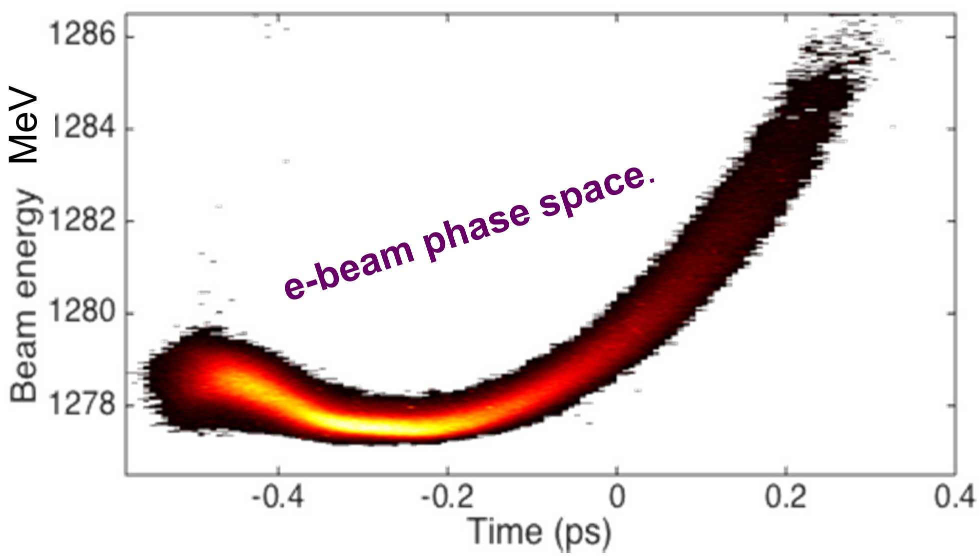

In some cases, **by switching** the seed laser from **Ti:Sa** to **OPA,** the FEL **bandwidth** can **increase** by a **factor ~3.**




If coherence and chirp are preserved, **larger bandwidth** can be used for compressing the pulse (**CPA**).

# FERMI electron beam

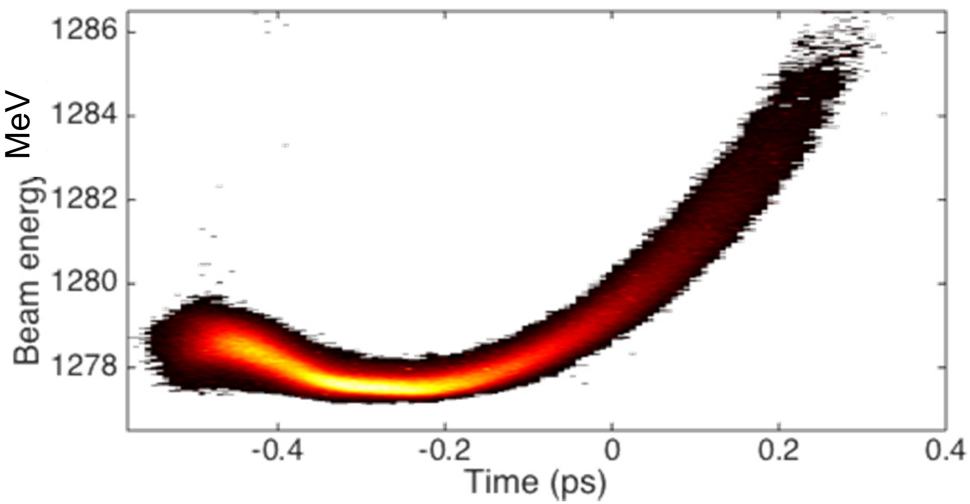
- Current **spikes** are **not suitable** for seeded FELs.
- **Low energy spread** and **flat longitudinal phase space** are required for seeding.
- Electron beam **optimization** is **different** than for a **SASE** FEL.
- Moderate compression is used.
- Phase space nonlinearities may counteract the benefits of the seed.
- Only electrons interacting with the laser participate to the FEL emission.




| | | |
|---|---|---|
| Charge | 700 | pC |
| Peak current | ~800 | A |
| Energy | 1 – 1.5 | GeV |
| Energy spread | ~150 | keV |
| Energy chirp | ~3 | MeV |
| Emittance | 1 | mm mrad |
| Size (rms) | ~100 | µm |

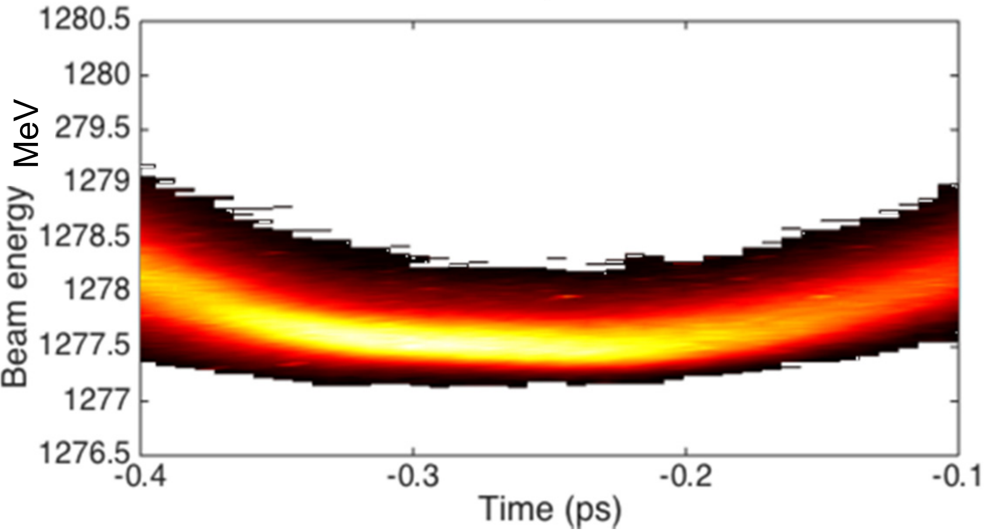
**Electron beam parameters**

# Seeded electron beam




**Head** and **tail** parts of the beam can **deteriorate** FEL properties.

# Seeded electron beam



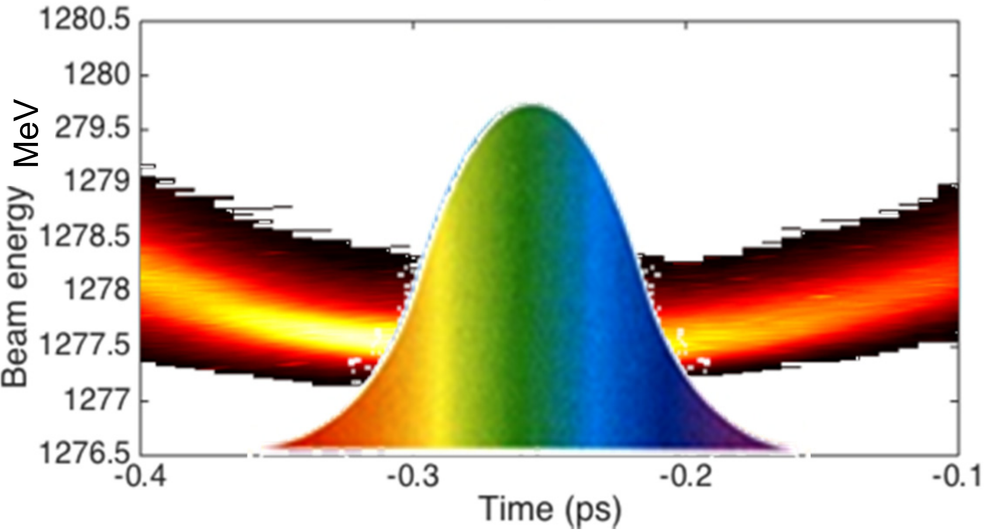

**Head** and **tail** parts of the beam can **deteriorate** FEL properties.

**Seed laser** pulse is **shorter** than the electron beam.

This allow to properly select the **best** part of the **electron for FEL**.

Because the final radiator is short the **unseeded part** does **not produce** any significant **radiation**.

# Seeded electron beam

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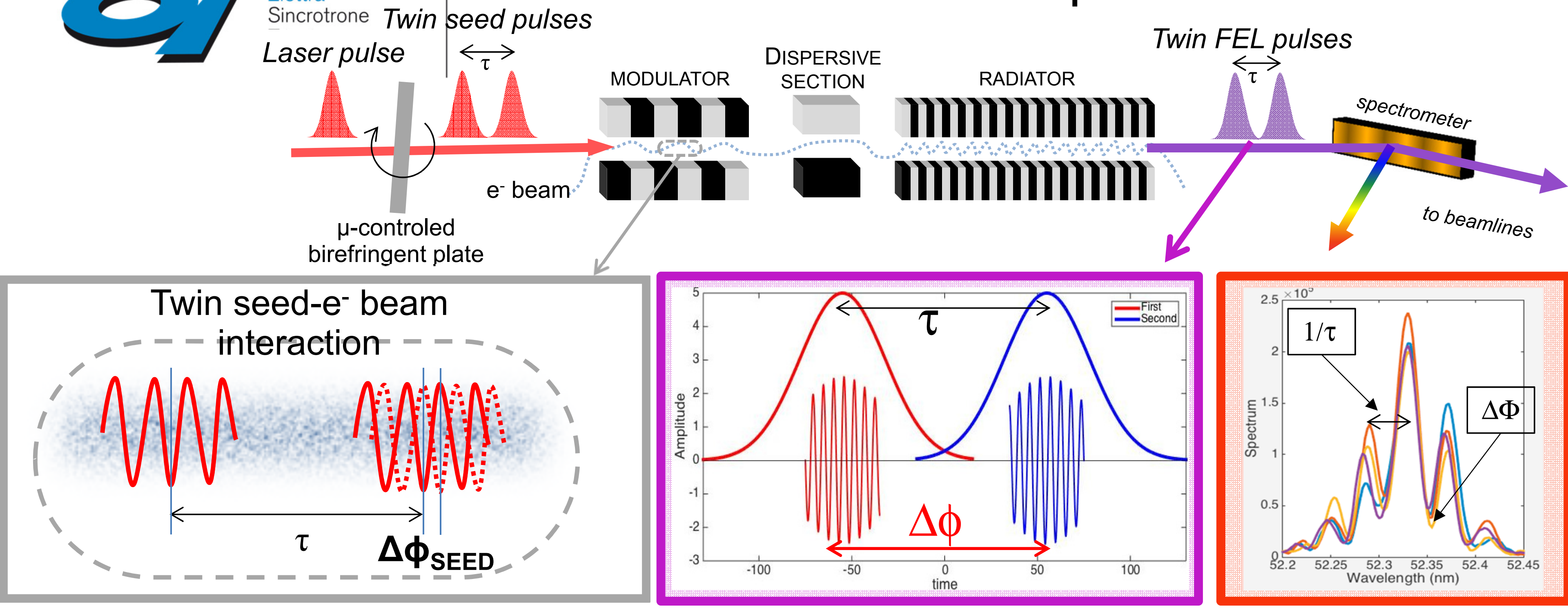
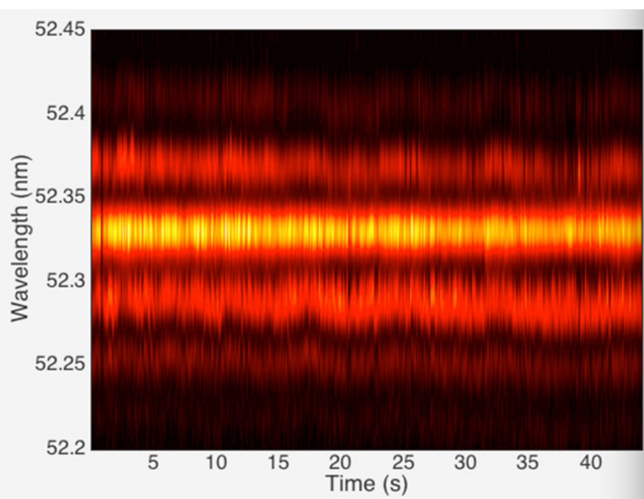
If the **electron beam** is **not uniform** the FEL properties may depend on seed timing.

# 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**.

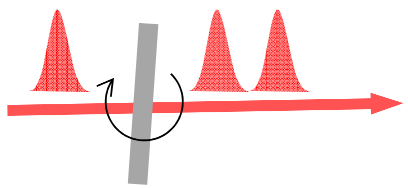
**Interference** between two **coherent** and **phase-locked** pulses is evident in the spectral domain.



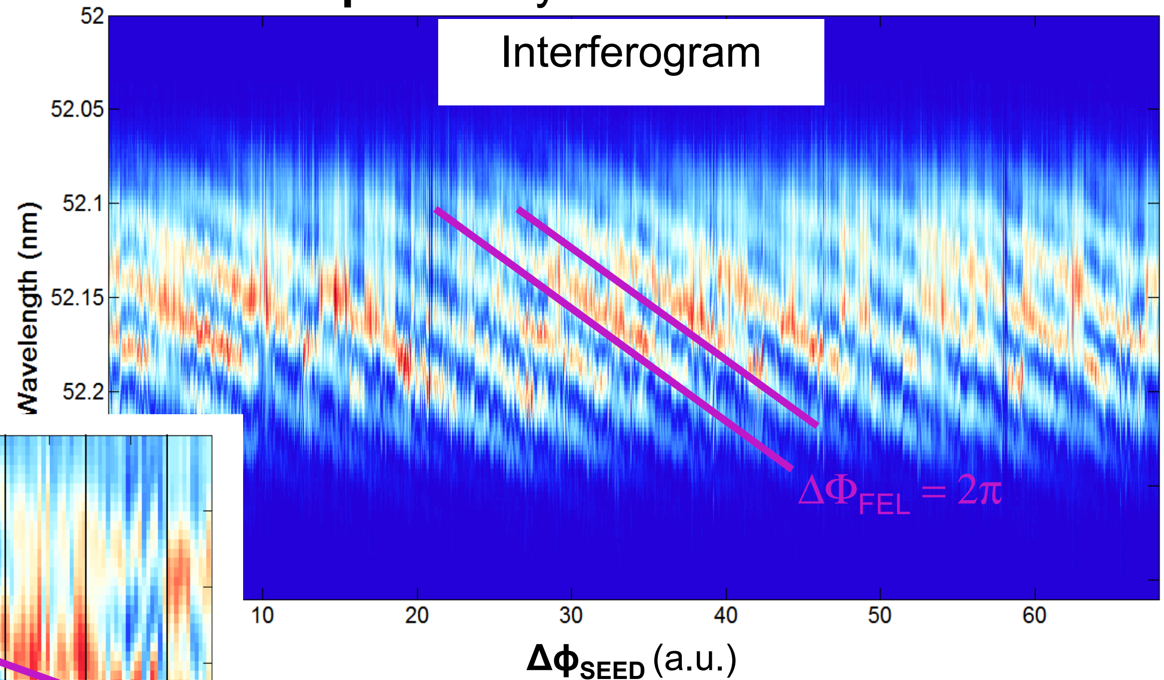

D. Gauthier et al., PRL **116**, 024801 (2016)

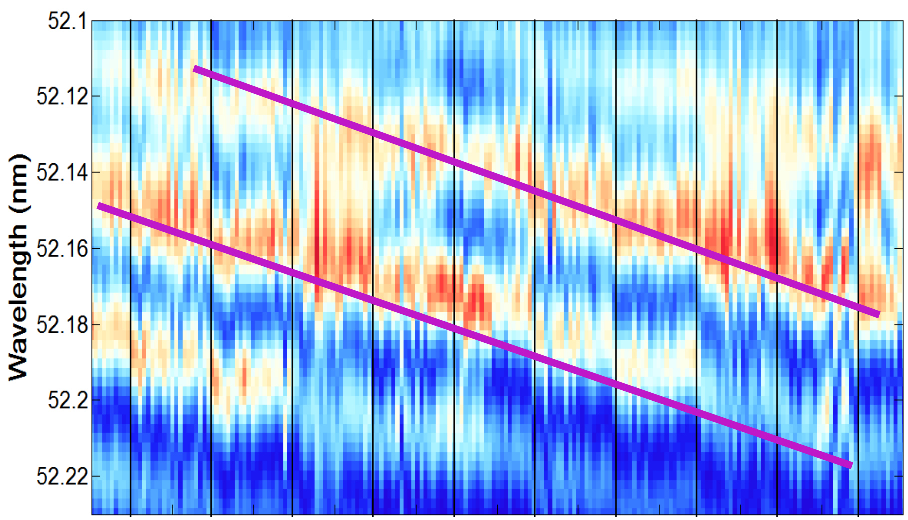
# FEL phase-locking control

An accurate **control** of the relative **phase** between the **seed pulses** with steps
**$\Delta\phi_{seed}$ ~ 12°@260nm**
Allow to change the **phase** between the **FEL pulses** by
**$\Delta\phi_{FEL}$ ~ 60°@52nm**



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



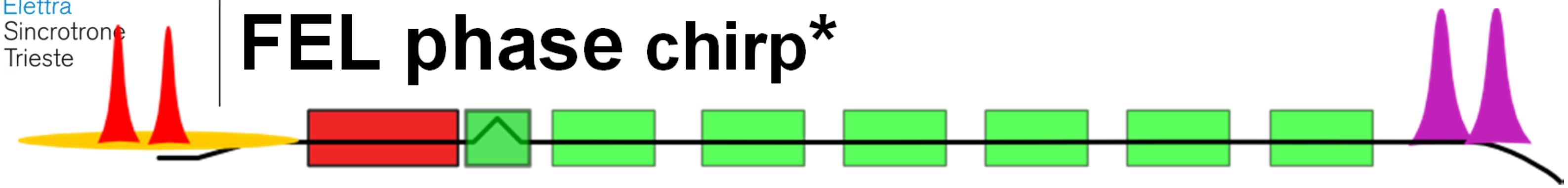




Zoom of the central part

D. Gauthier et al., PRL **116**, 024801 (2016)

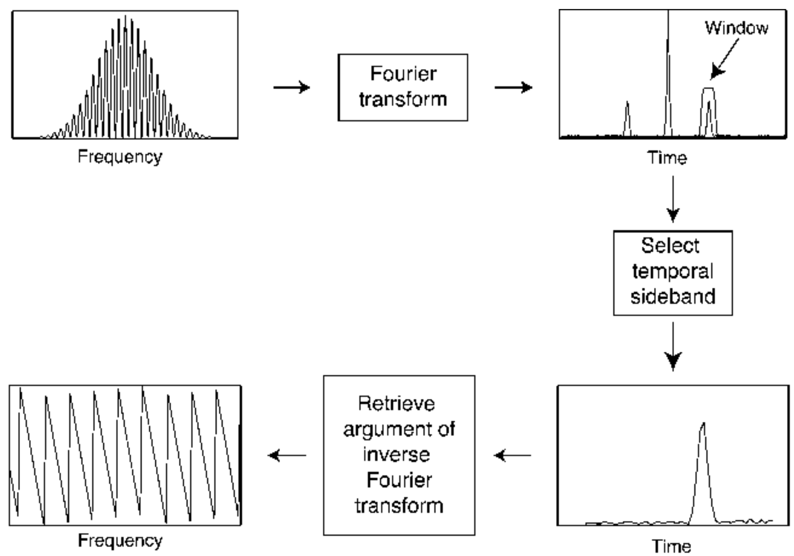
Residual fringe instability is associated to to shifts of the central wavelength of the spectral envelope and has strong correlation with the electron beam bunch compression monitor.

# Measurements and control of the FEL phase chirp*

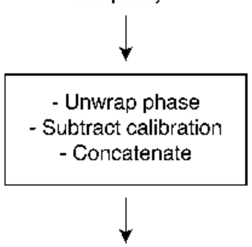


The **phase locked FEL pulses are** suitable for **SPIDER** [§] measurement **(amplitude and phase)**.

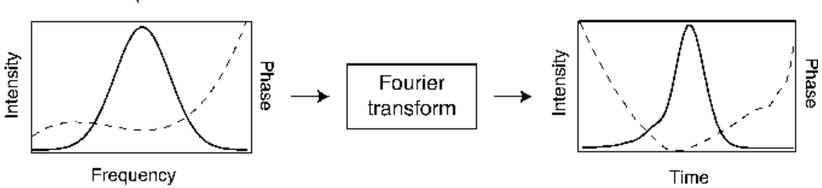
[§] "Spectral Phase Interferometry for Direct Electric-field Reconstruction …" . OPTICS LETTERS **23**, 792 1998




From a **single measurement** of the **interference spectrogram** of two **identical pulses** (with slightly different wavelength) the **SPIDER** algorithm **reconstructs** the **intensity and phase profiles** in the temporal and spectral domain.




A critical point in the SPIDER reconstruction is that the **two pulses** have to be **identical** with a small wavelength offset.




| FEL wavelength | 52.3 nm |
|---|---|
| seed wavelength/harmonic number | 261.5/5 |
| seed pulse duration | 126 fs/180 fs (FWHM) |
| Peak current | ≈ 600 A |
| temporal delay between seed pulse replicas ($\tau$) | 231 fs |
| spectral shear between pulse replicas ($\Omega$) | $1.7\times10^{13}$ Hz |

G.De Ninno et al.,Nat.Commun.6,9075(2015)

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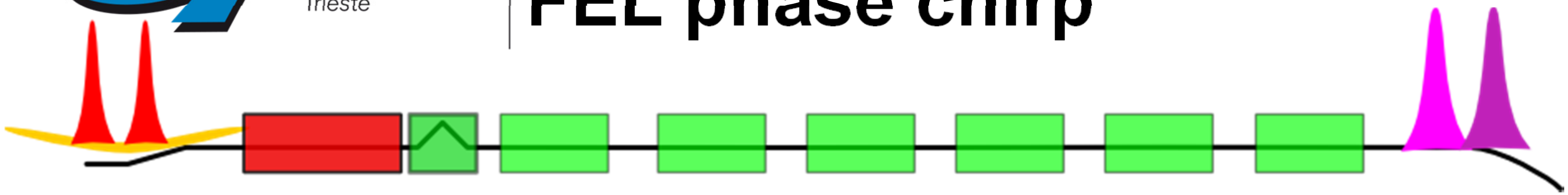
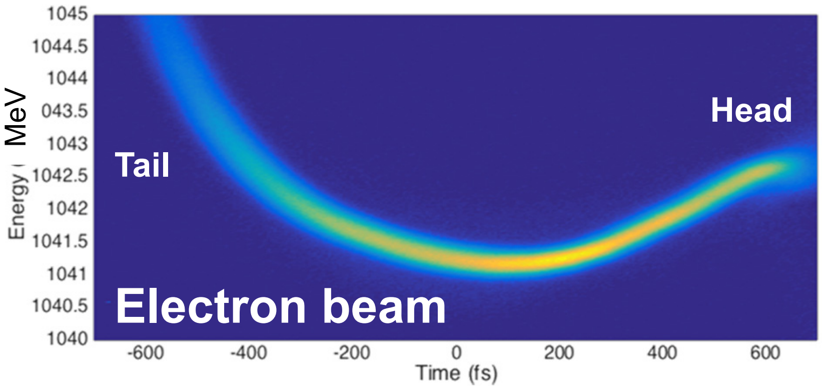
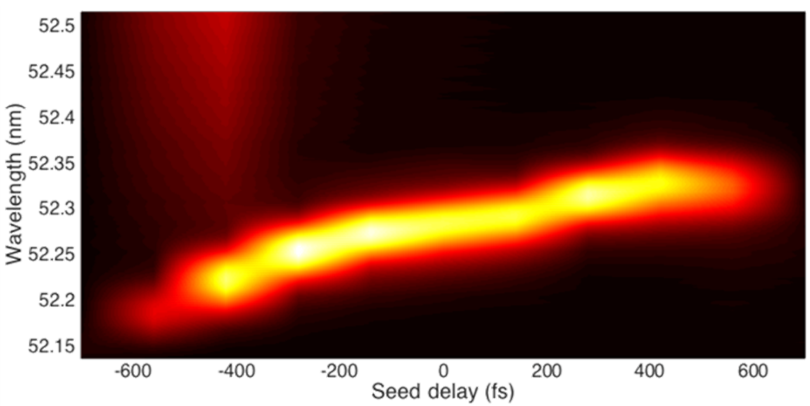
# Measurements and control of the FEL phase chirp

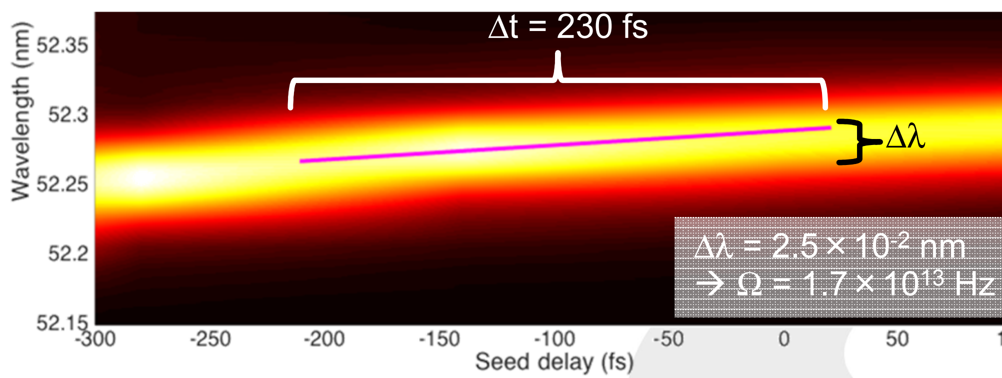





A simple **solution** at FERMI is to seed with **two identical pulses** and to allow the **electron** beam **phase-space** to slightly **detune** the FEL **wavelengths**.

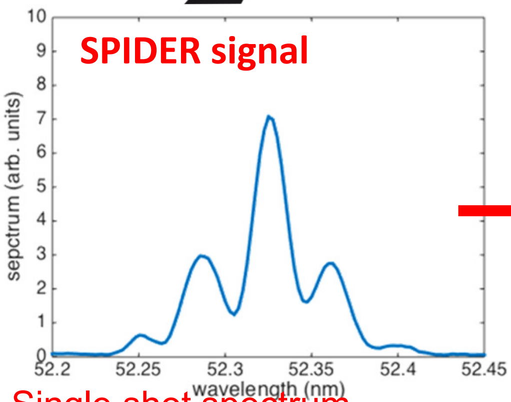



Spectral **measurements** at **different** seed laser **delay** give the **wavelength separation**.

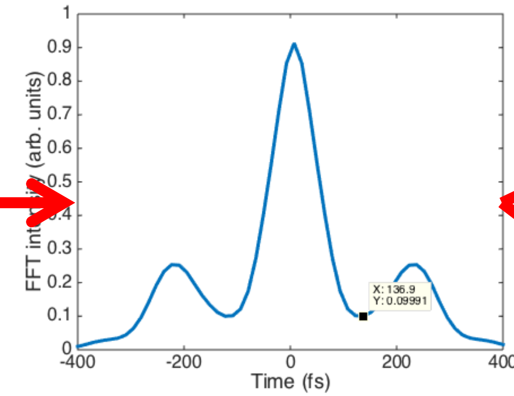


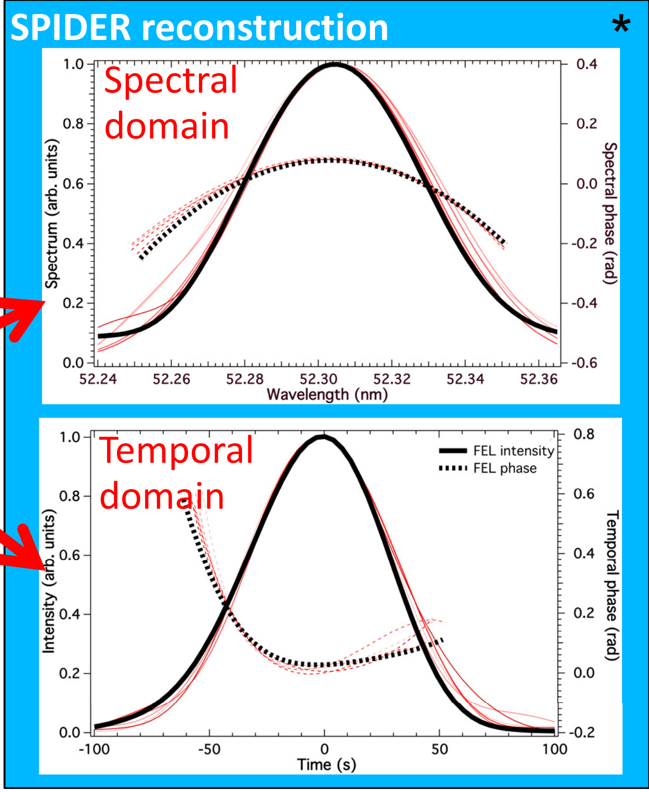

The frequency separation Ω is **used** in the **SPIDER** reconstruction.

# SPIDER reconstruction

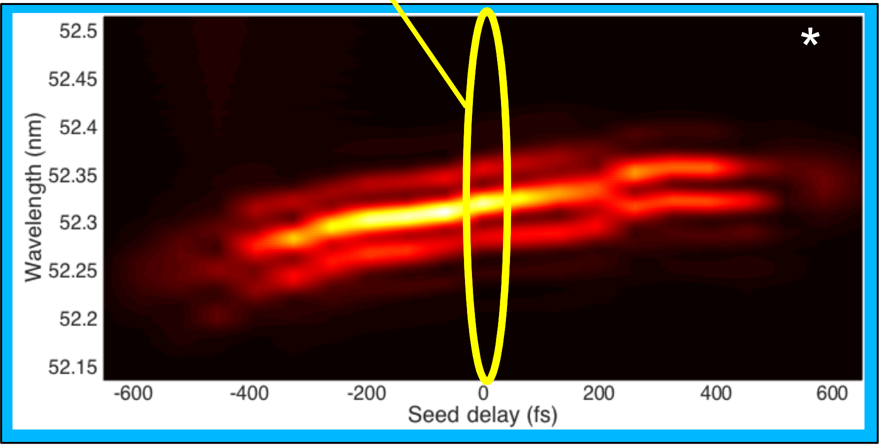



FFT




Single shot spectrum for a fixed seed position.




When the **two** identical **seed lasers** are used clear interference **fringes** are visible.

**Fringes shape** is **constant** when **scanning** the **seed** lasers over a good range of the beam (**~400 fs**).

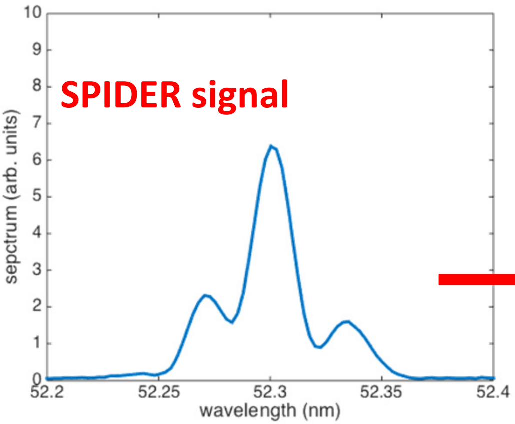
Under the assumption that the two FEL pulses have similar characteristics the SPIDER algorithm allows reconstruction of the temporal pulse profile (positive chirp).

**A pulse length of 70 fs is measured.**

# FEL phase chirp control

Elettra Sincrotrone Trieste

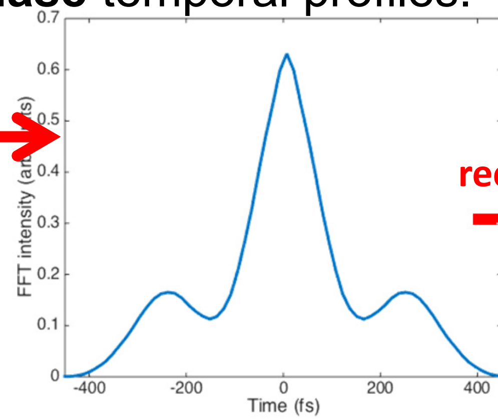
**When changing** the seed **laser chirp** from **positive** to **negative**, the **shape** of the interference **fringes changes** significantly.



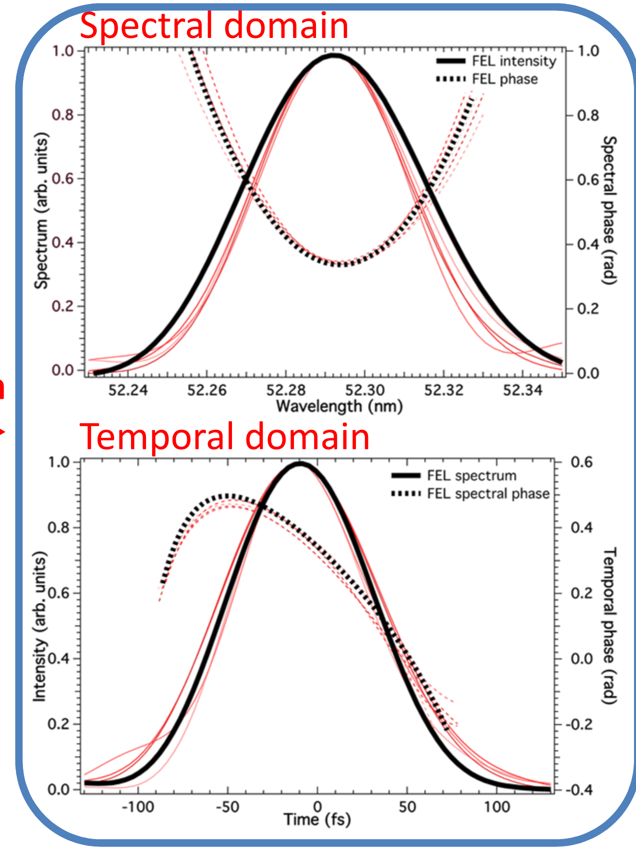

Single shot spectrum for a fixed seed position.

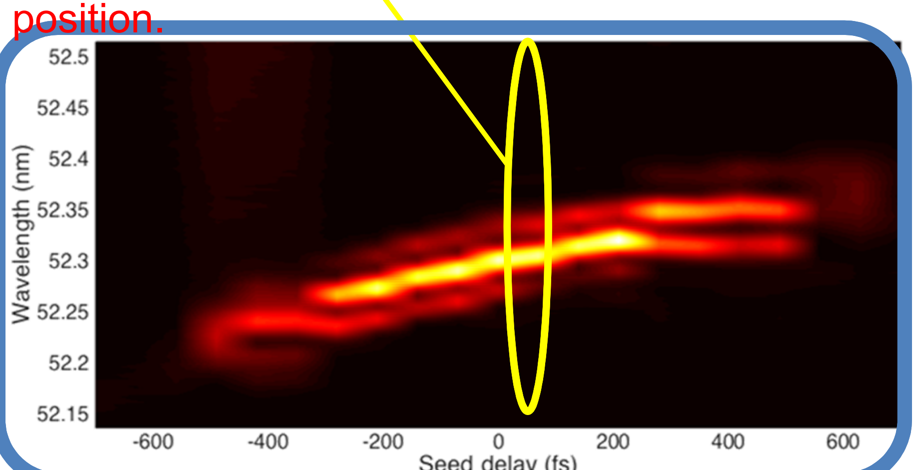
FFT

Evident difference in the **reconstructed intensity** and **phase** temporal profiles.




**SPIDER reconstruction**



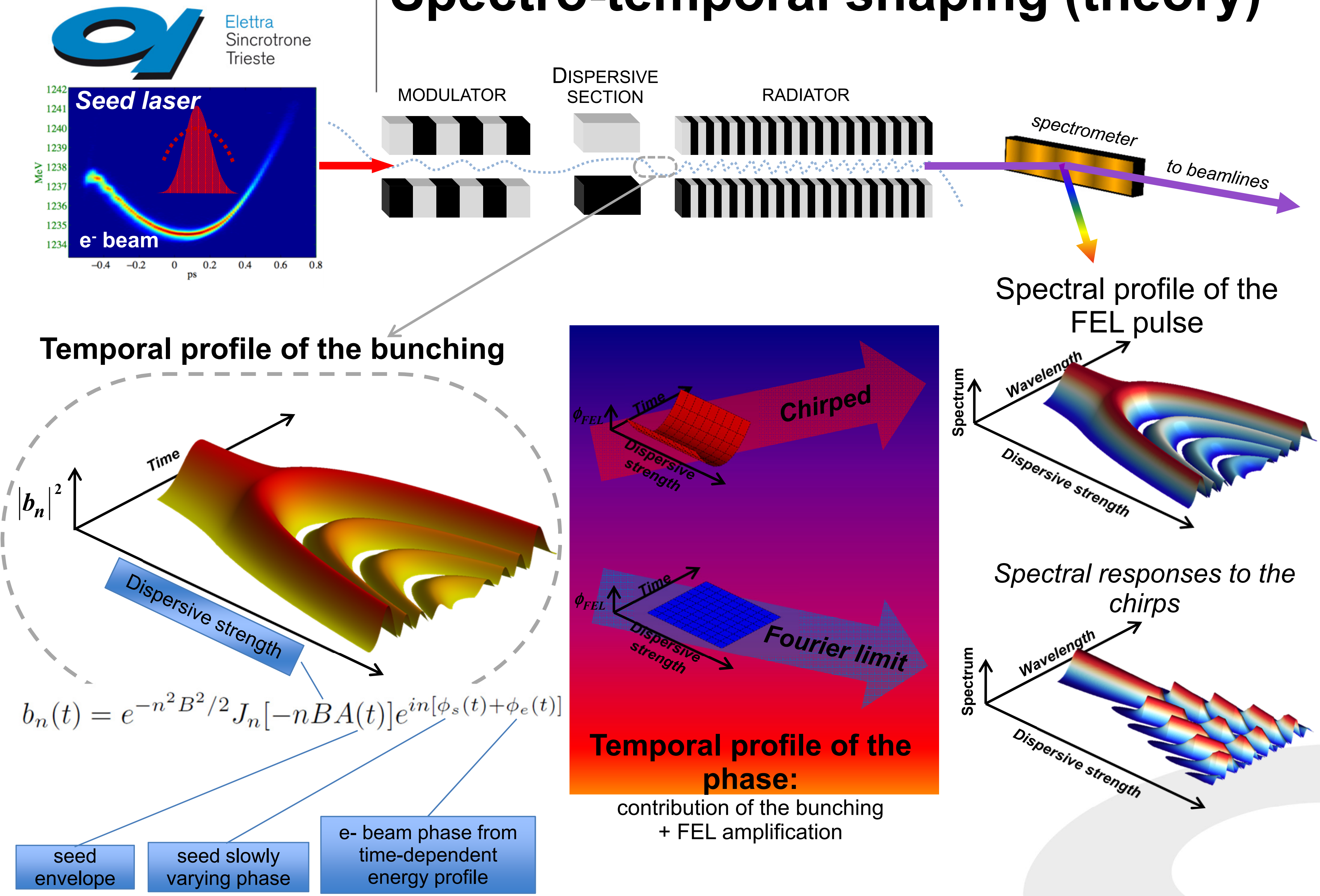




**Experiments** with a **controlled chirp** along the **FEL pulse** may become **possible**.



G.De Ninno et al.,Nat.Commun.6,9075(2015)

# Spectro-temporal shaping (theory)

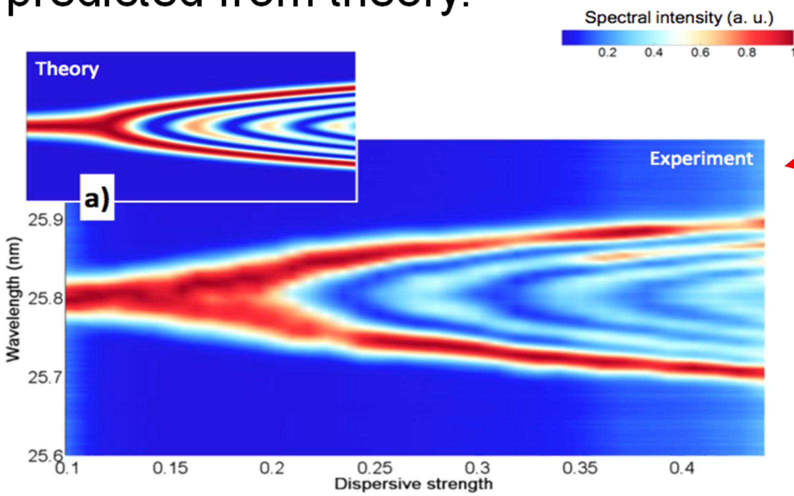



$$b_n(t) = e^{-n^2B^2/2}J_n[-nBA(t)]e^{in[\phi_s(t)+\phi_e(t)]}$$

D.Gauthier et al., PRL115,114801(2015).

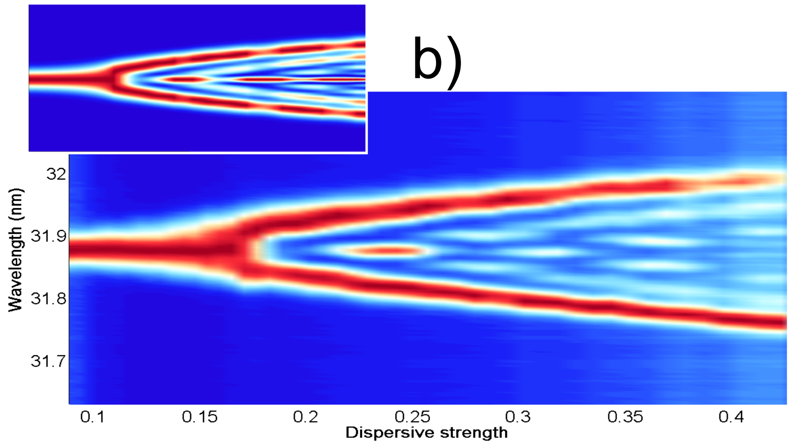
# Spectro-temporal shaping (results)

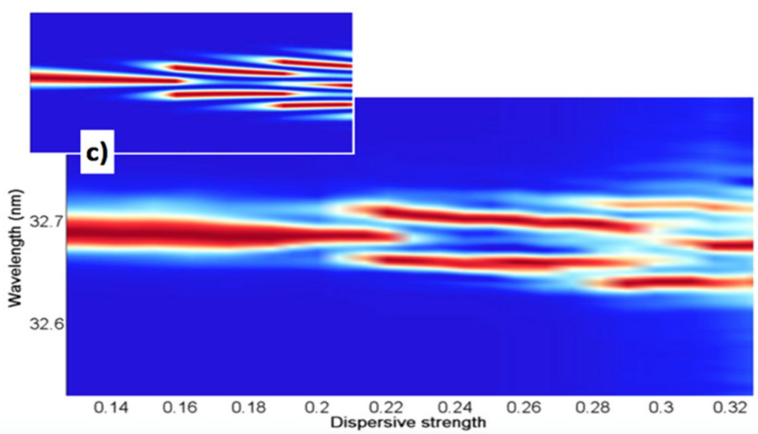
Properties of spectra modulation are strongly dependent on the FEL chirp and can predicted from theory.




With a significant **positive chirp** the **temporal-spectral** mapping allows to **see** the **bunching modulation**.

**Reducing** the **positive** chirp changes the spectral properties.



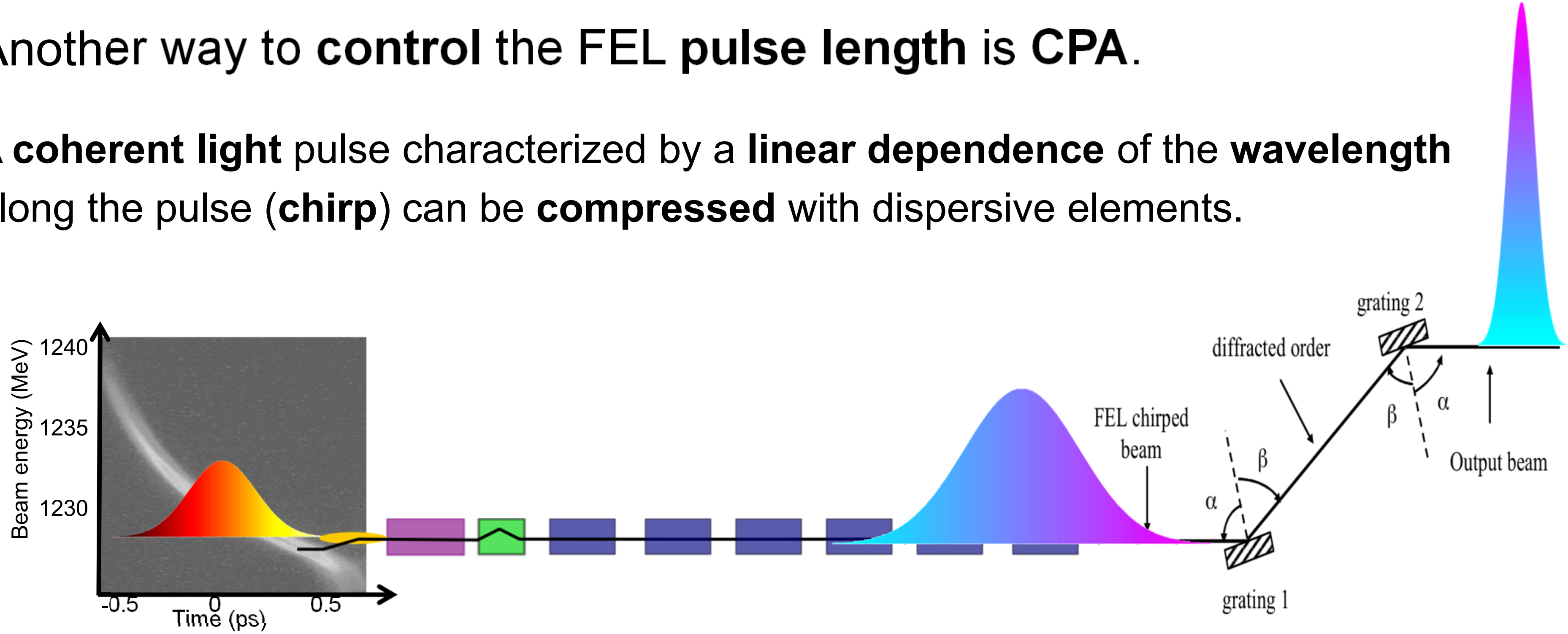

With slightly **negative** chirp of the seed (compensating the e-beam chirp) the FEL response is completely different and one can identify **signatures** of **Fourier limit FEL** pulses.

D.Gauthier et al., PRL115,114801(2015).

# Chirped pulsed amplification (CPA)

Another way to **control** the FEL **pulse length** is **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** and higher intensity as the number of electrons participating to the FEL process increases.
- **Chirped FEL** pulses are sent to a **compressor** based on **double grating**.

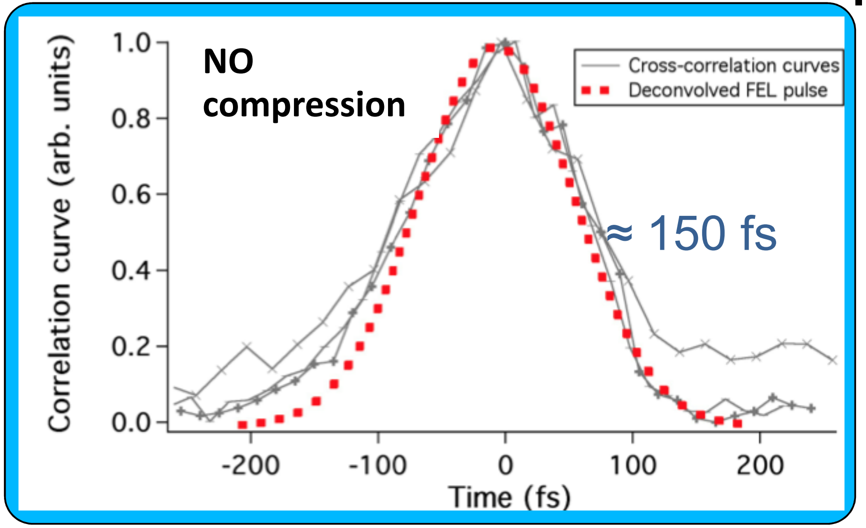
# CPA in FEL, first demonstration

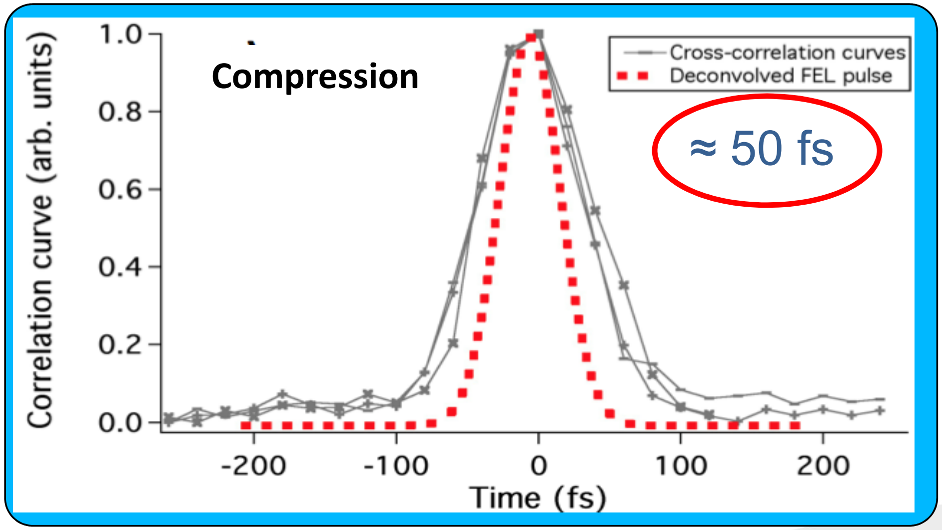
Elettra Sincrotrone Trieste

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

FERMI FEL-1 has been operated at **37 nm** corresponding to one of the **good wavelength** for the **available compressor**.

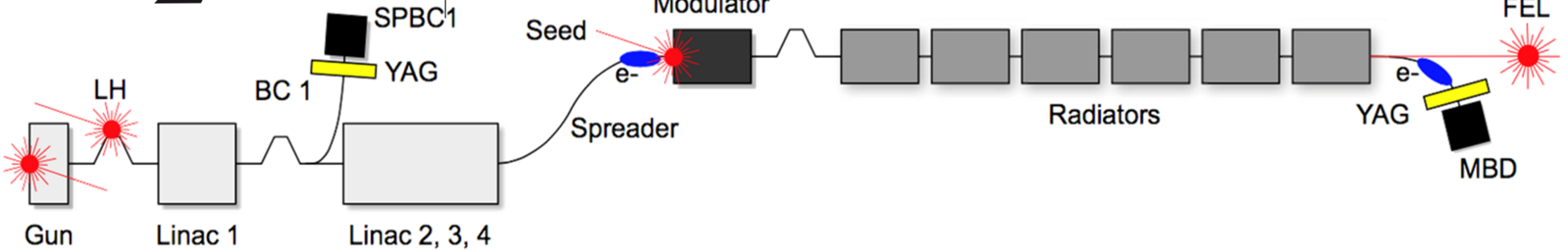
FEL **pulse length** has been **measured** for different **settings** of the optical **compressor**.




The demonstrated capability of **compressing** 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.

# Two frequencies seeding



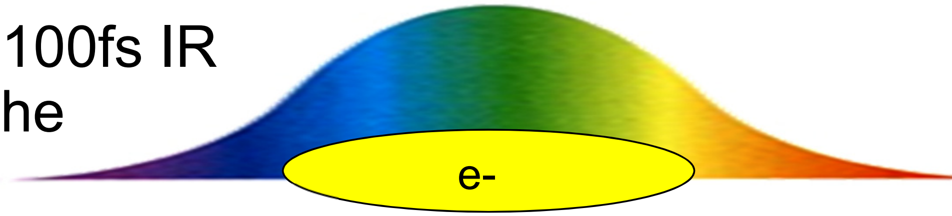

Instead of seeding with two wavelengths at the end of the accelerator we can seed the beam at different locations along the accelerator.

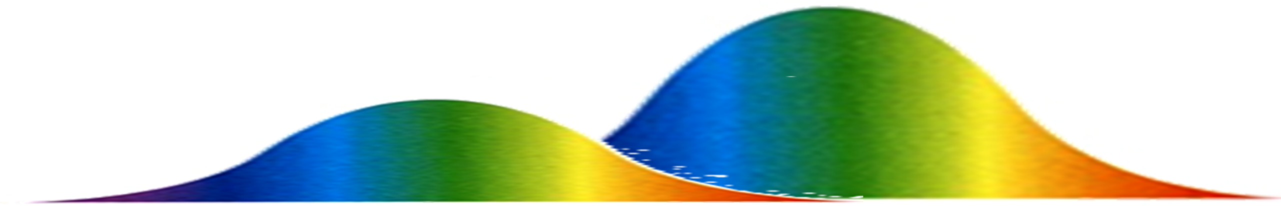
Most FELs already have a second seeding section in the low energy part (laser heater), but induced modulation is washed out.

Using the chirped pulse beating technique one can seed in LH a modulation wavelength that survives or is amplified in the accelerator and is then interfering with the final seeding.

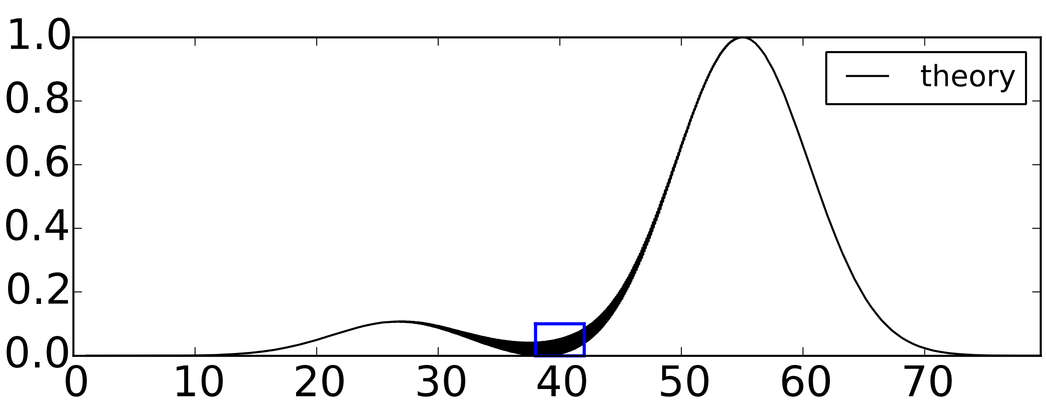
# Laser heater beating

LH laser pulses are produced from 100fs IR pulses that are stretched to match the electron beam pulse length ~10ps.



From the **superposition** of **two** laser **pulses** with a small **delay** we can **create** a **beating** of the **laser amplitude** due to the **superposition** of **two fields** with slightly **different wavelength**.




In our configuration, **beating** wavelength is **~30μm** and can be **controlled** by acting on the laser **chirp** or pulse **separation**.

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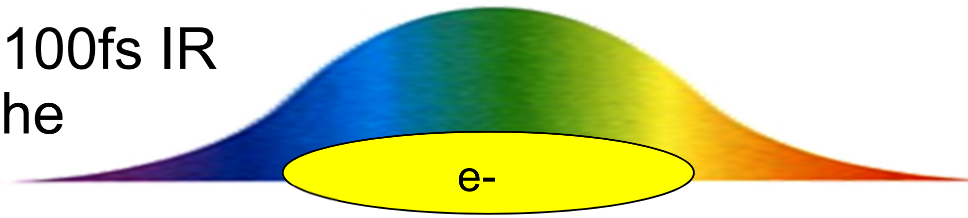


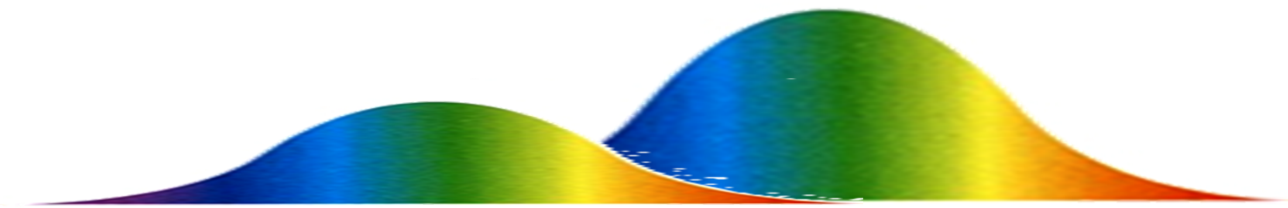

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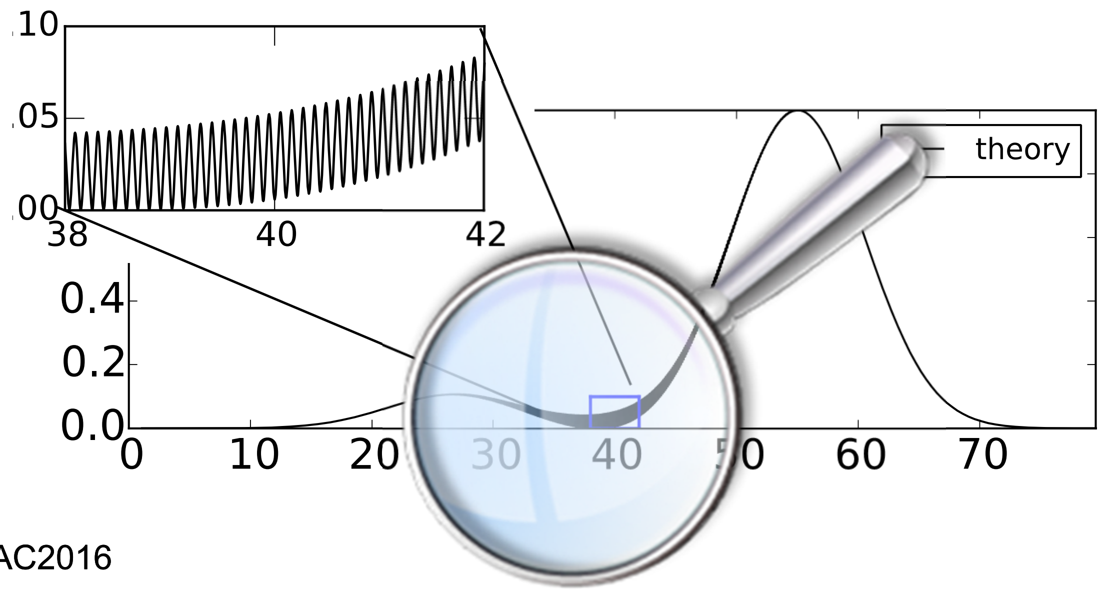


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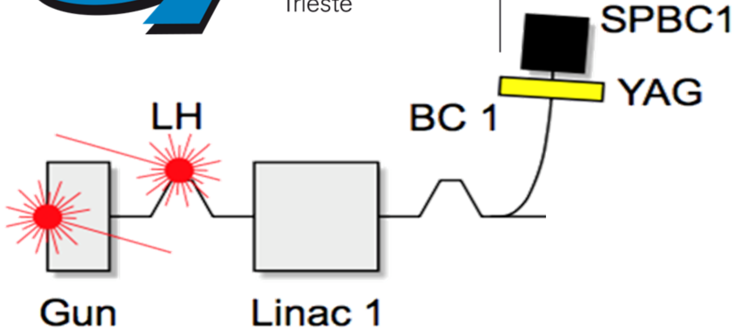
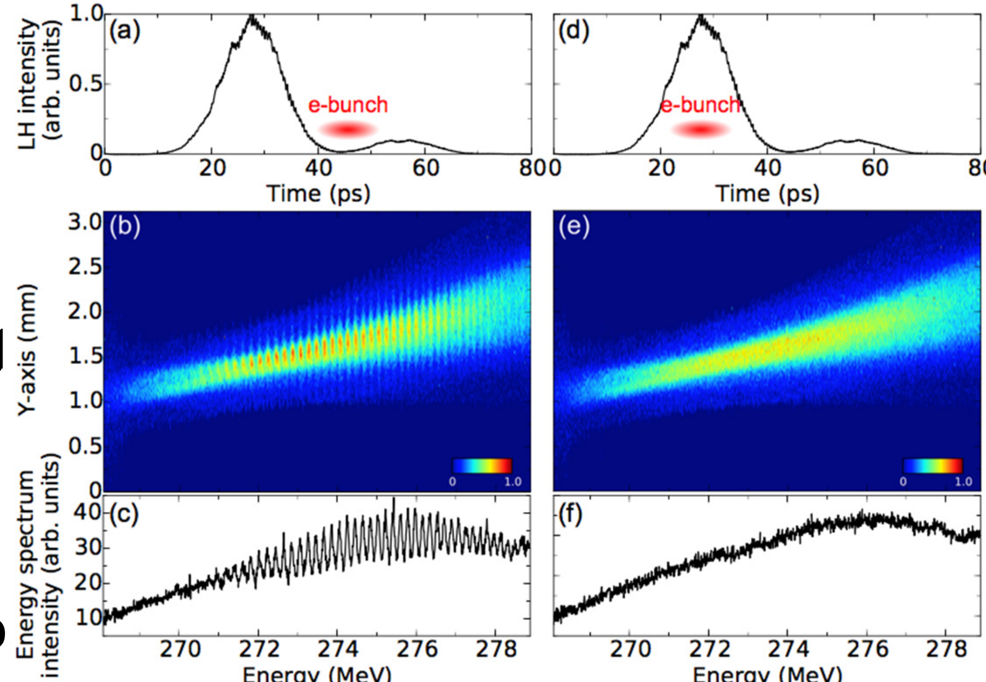
# Beating induced modulation to e-beam

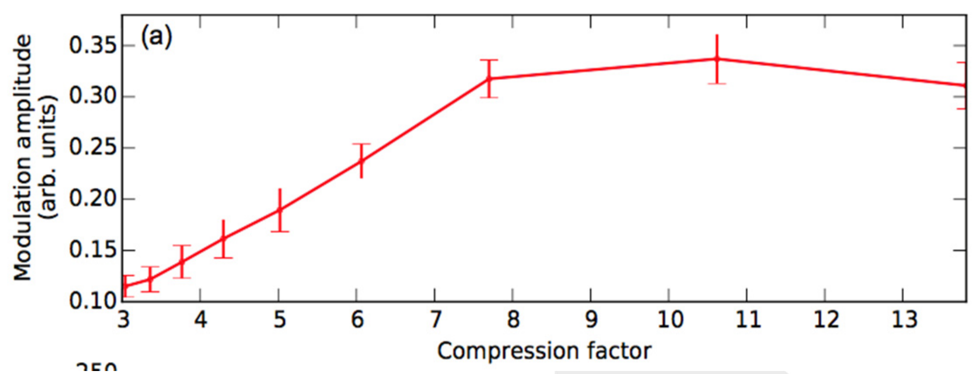



Placing the e-beam in the **beating** region creates **energy spread modulation**.

In the accelerator energy spread modulation can be **converted** into **energy and/or density modulation**.

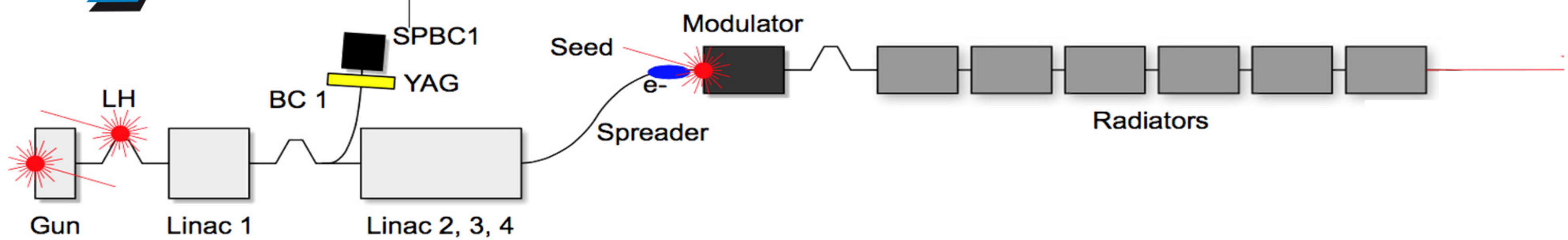
**Modulation** amplitude **depends** on the **compression** suggesting that **μB instability** is playing a role and amplifies the initial modulation.





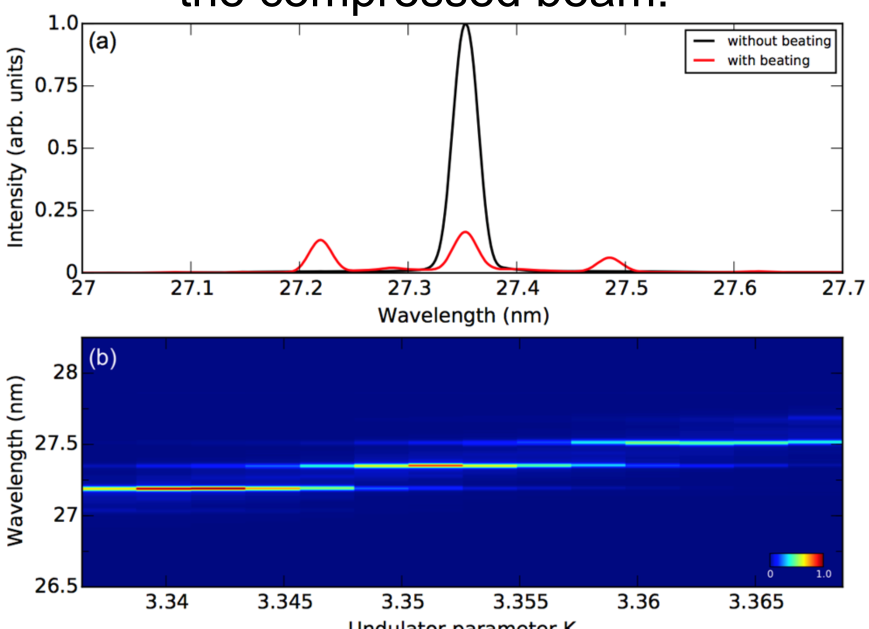

*E. Roussel et al., PRL **115**, 214801 (2015).

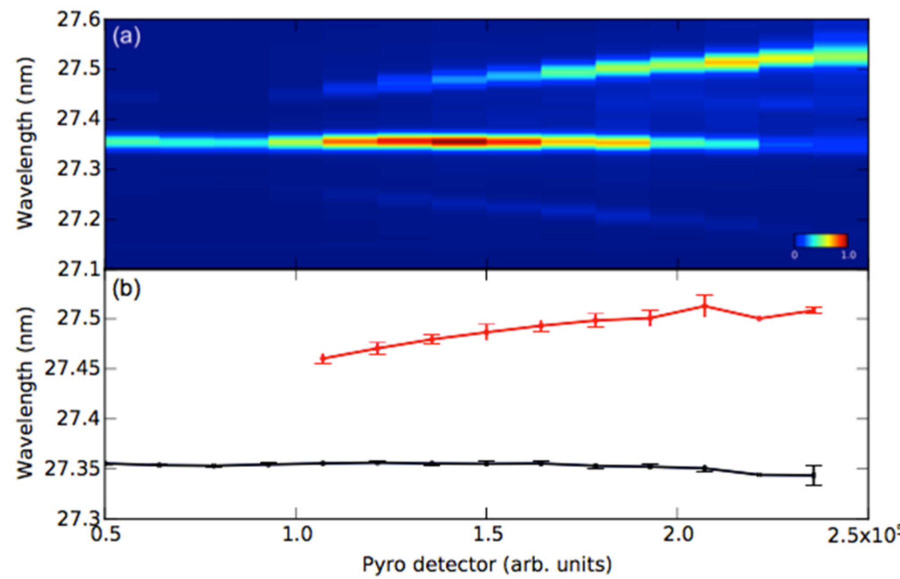
# Beating induced modulation to e-beam




Also the seeded **FEL spectra** show **signatures** of coherent **modulation** in the **e-beam**. Sidebands distance matches the estimated periodicity for the compressed beam.

The sideband central wavelength changes with the compression (i.e., the periodicity of the modulation): **Tunable FEL source** without tunable seed laser



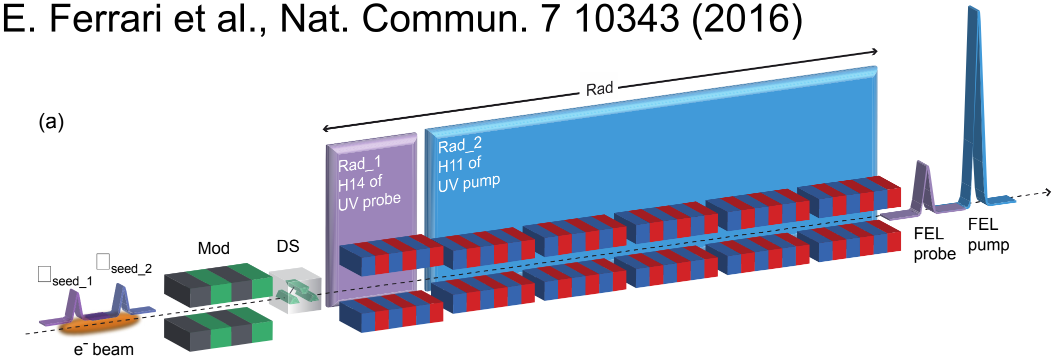



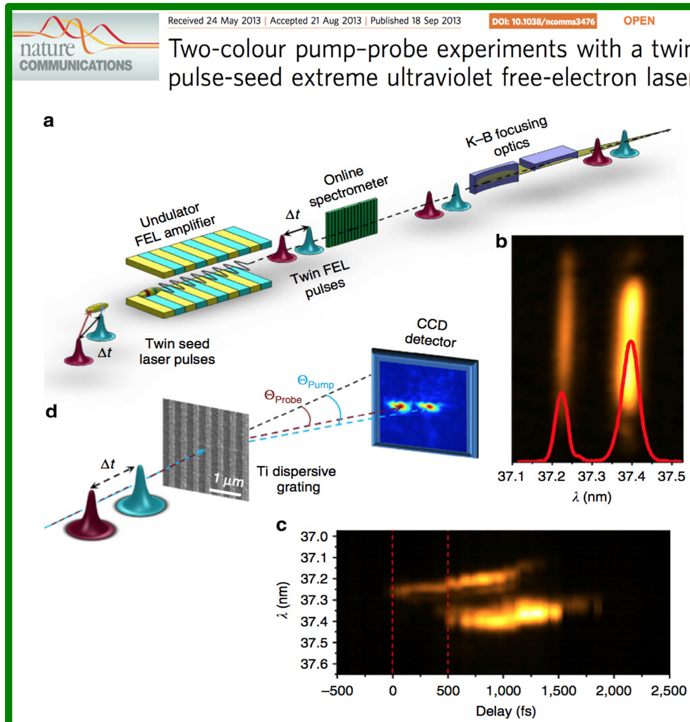

*E. Roussel et al., PRL **115**, 214801 (2015).

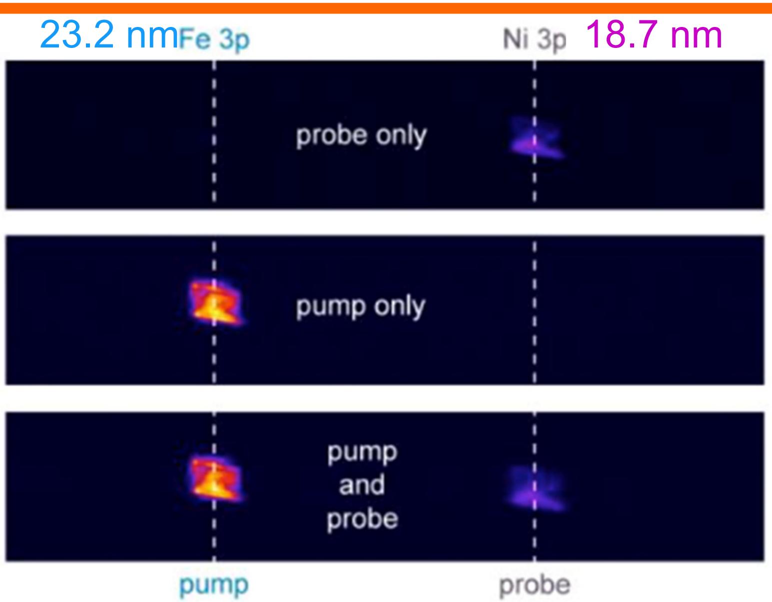
# Two color seeded FEL

Various **schemes** for **two color FEL** pulses have been **implemented** and provided to the users.

E. Ferrari et al., Nat. Commun. 7 10343 (2016)




FEL pump - FEL probe experiments

- Different **diffraction angles** to have distinguishable signals
- **Selectively** excite a **resonance** in an atom and resonantly probe another atom bound to the excited one

# Conclusions

- ✓ The seeded FEL radiation inherits the coherence properties of the seed laser, mediated by the electron beam.
- ✓ The use of the external seed allows control of critical FEL properties:
  - ➢ Wavelength, bandwidth;
  - ➢ Pulse length and pulse separation;
  - ➢ Phase and chirp;
  - ➢ …
- ✓ The high degree of coherence and control capabilities open the possibility of "engineer" the FEL pulses specifically for the experiment one wants to perform (it's a laser!!!)

Elettra Sincrotrone Trieste

# Acknowledgements

- ✓ FERMI commissioning, laser and PADReS teams.
- ✓ FERMI beamline scientists (LDM, DiProI, TIMEX-TIMER) and their users.

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Sincrotrone
Trieste

# Thank you!

www.elettra.eu