Elettra
Sincrotrone
Trieste

Advanced seeding techniques

L. Giannessi
FERMI data presented on behalf of the FERMI commissioning TEAM

Elettra Sincrotrone Trieste

Startup – Seeded FEL amplifier

FEL integral equation starting from a pre-modulated beam*

$$\frac{d}{d\tau}a(\tau) = -2\pi g_0 b_1 e^{-i\nu_0\tau} + i\pi g_0 b_2 e^{-2i\nu_0\tau}\int_0^\tau d\xi\,\xi e^{i\nu_0\xi}a^*(\tau-\xi) + i\pi g_0\int_0^\tau d\xi\,\xi e^{-i\nu_0\xi}a(\tau-\xi)$$

Shot noise, spontaneous emission (or emission from a pre bunched beam)

Negligible at startup (prop. to field a & b_2)

High gain growing roots

Comparing the first and third term we find an intensity level corresponding to e- shot noise

$$I_{sn} \approx 3\,\omega\,\gamma m_0 c^2 \rho_{fel}^2$$

ω resonant frequency
$\gamma m_0 c^2$ e-beam energy
ρ_{fel} FEL parameter

*G. Dattoli et al. Phys. Rev. E 49 (1994) a, ξ, ν coortinates in Colson's notation, b_1,b_2 1st & 2nd bunching coeffs

Direct seeding an amplifier: the seed power required to overcome the shot noise scale with the inverse of the wavelength

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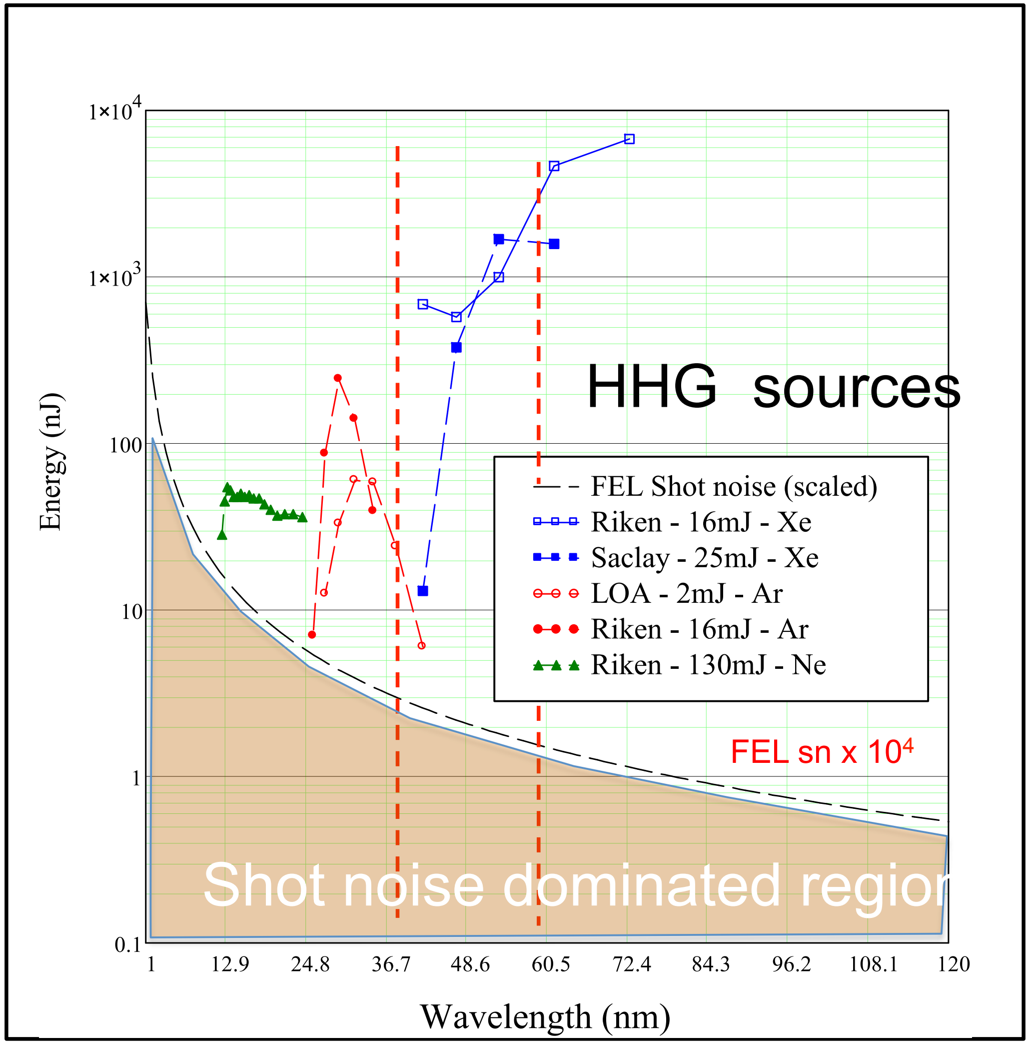


SCSS (2008) 160nm

LETTERS

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] AND M.-E. COUPRIE[3]

[1]Service des Photons, Atomes et Molécules, DSM/DRECAM, CEA-Saclay, 91191 Gif-sur-Yvette, France
[2]RIKEN SPring-8 Centre, Harima Institute, 1-1-1, Kouto, Sayo-cho, Sayo-gun, Hyogo 679-5148, Japan
[3]Groupe Magnétisme et Insertion, Synchrotron Soleil, L'Orme des Merisiers, Saint Aubin, 91192 Gif-sur-Yvette, France
[4]XFEL Project Head Office/RIKEN, 1-1-1, Kouto, Sayo-cho, Sayo-gun, Hyogo 679-5148, Japan
*e-mail: guillaume.lambert@synchrotron-soleil.fr

SPARC (2010) 160nm

TUPB18 Proceedings of FEL2010, Malmö, Sweden

FEL EXPERIMENTS AT SPARC: SEEDING WITH HARMONICS GENERATED IN GAS

L. Giannessi, A. Petralia, G. Dattoli, F. Ciocci, M. Del Franco, M. Quattromini, C. Ronsivalle, E. Sabia, I. Spassovsky, V. Surrenti ENEA C.R. Frascati, IT. D. Filippetto, G. Di Pirro, G. Gatti, M. Bellaveglia, D. Alesini, M. Castellano, E. Chiadroni, L. Cultrera, M. Ferrario, L. Ficcadenti, A. Gallo, A. Ghigo, E. Pace, B. Spataro, C. Vaccarezza, INFN-LNF, IT. A. Bacci, V. Petrillo, A.R. Rossi, L. Serafini INFN-MI, IT. M. Serluca, M. Moreno INFN-Roma I, IT. L. Poletto, F. Frassetto CNR-IFN, IT. J.V. Rau, V. Rossi Albertini ISM-CNR, IT. A. Cianchi, UN-Roma II TV, IT. A.Mostacci, M Migliorati, L. Palumbo, Università di Roma La Sapienza, IT. G. Marcus, P. Musumeci, J.Rosenzweig, UCLA, CA, USA., M. Labat, F. Briquez, M. E. Couprie, SOLEIL, FR. B. Carré, M.Bougeard, D. Garzella CEA Saclay, DSM/DRECAM, FR. G. Lambert LOA, FR. C.Vicario PSI, CH.

SCSS (2011) 61nm

Extreme ultraviolet free electron laser seeded with high-order harmonic of Ti:sapphire laser

Tadashi Togashi, Eiji J. Takahashi, Katsumi Midorikawa, Makoto Aoyama, Koichi Yamakawa, Takahiro Sato, Atsushi Iwasaki, Shigeki Owada, Tomoya Okino, Kaoru Yamanouchi, Fumihiko Kannari, Akira Yagishita, Hidetoshi Nakano, Marie E. Couprie, Kenji Fukami, Takaki Hatsui, Toru Hara, Takashi Kameshima, Hideo Kitamura, Noritaka Kumagai, Shinichi Matsubara, Mitsuru Nagasono, Haruhiko Ohashi, Takashi Ohshima, Yuji Otake, Tsumoru Shintake, Kenji Tamasaku, Hitoshi Tanaka, Takashi Tanaka, Kazuaki Togawa, Hiromitsu Tomizawa, Takahiro Watanabe, Makina Yabashi, and Tetsuya Ishikawa

3 January 2011 / Vol. 19, No. 1 / OPTICS EXPRESS 317

DESY (2012) 38nm

PRL 111, 114801 (2013) PHYSICAL REVIEW LETTERS week ending 13 SEPTEMBER 2013

Generation of Coherent 19- and 38-nm Radiation at a Free-Electron Laser Directly Seeded at 38 nm

S. Ackermann,[1,2] A. Azima,[1,5,6] S. Bajt,[2] J. Bödewadt,[1,5,*] F. Curbis,[1,†] H. Dachraoui,[2] H. Delsim-Hashemi,[2] M. Drescher,[1,5,6] S. Düsterer,[2] B. Faatz,[2] M. Felber,[2] J. Feldhaus,[2] E. Hass,[1] U. Hipp,[1] K. Honkavaara,[2] R. Ischebeck,[4] S. Khan,[3] T. Laarmann,[2,6] C. Lechner,[1] Th. Maltezopoulos,[1,5] V. Miltchev,[1] M. Mittenzwey,[1] M. Rehders,[1,5] J. Rönsch-Schulenburg,[1,5] J. Rossbach,[1,5] H. Schlarb,[2] S. Schreiber,[2] L. Schroedter,[2] M. Schulz,[1,2] S. Schulz,[2] R. Tarkeshian,[1,‡] M. Tischer,[2] V. Wacker,[1] and M. Wieland[1,5,6]

- *data from B. Carré, Colloque AEC - Slicing, Paris 2004*
- *Estimate includes transport and matching to e-beam – Seeded FELs Workshop, Frascati 10-12 (2008)*

The FEL as an "harmonic converter"

I.Boscolo, V. Stagno, Il Nuovo Cimento 58, 271 (1980)

- *R. Barbini e*
  Sag Harbor,
  52273 UC-4
  (1990)
- *R. Bonifacio*
- *L. H. Yu PR*
- *F. Ciocci et*

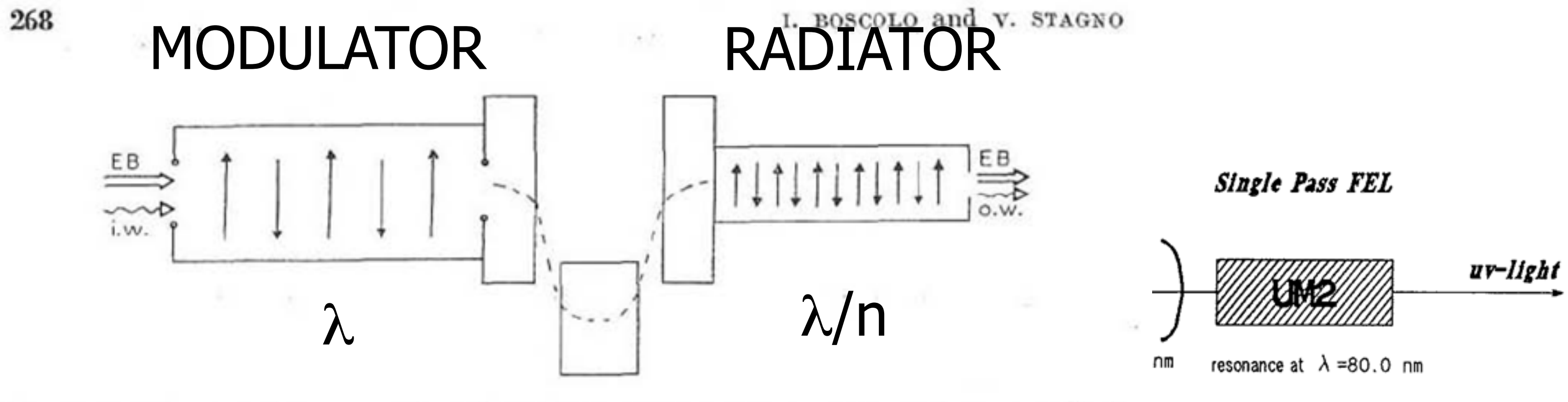
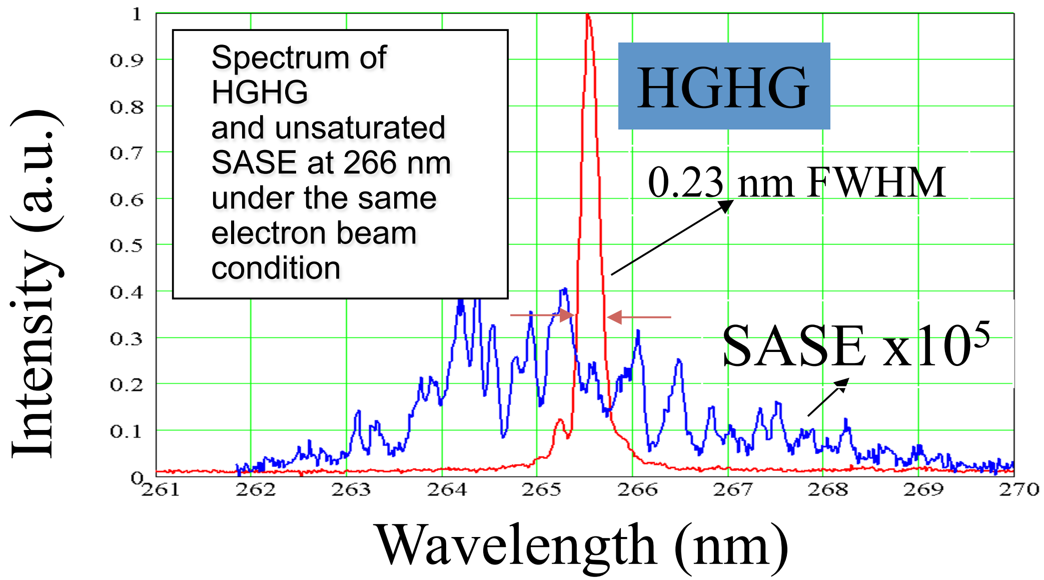


Fig. 1. – Scheme of the converter: EB electron beam, i.w. input wave, o.w. output wave.

Conversion 800nm -> 266nm



Milestones

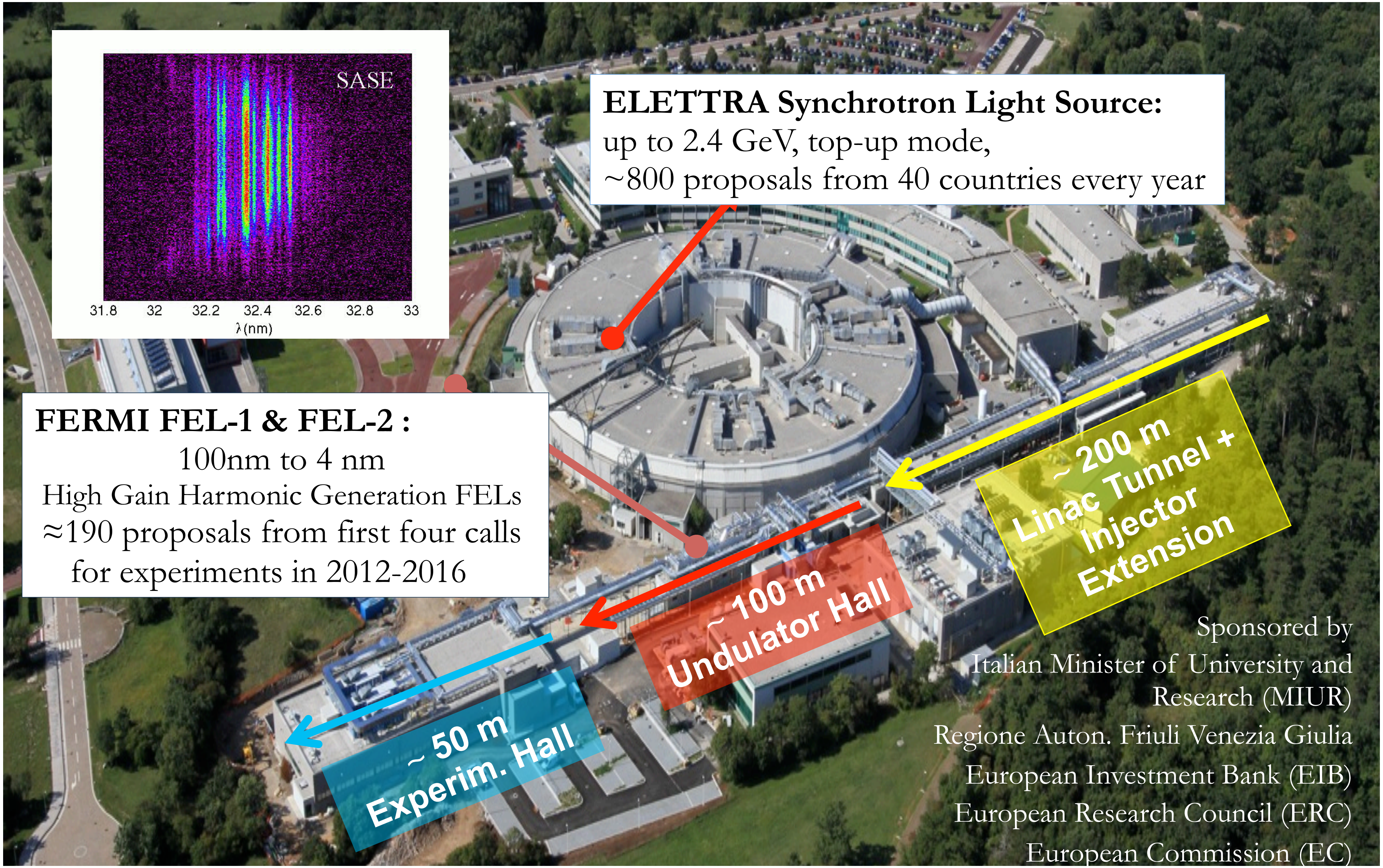
HGHG Experiment

L. H. Yu et al. Science 289 (2000)

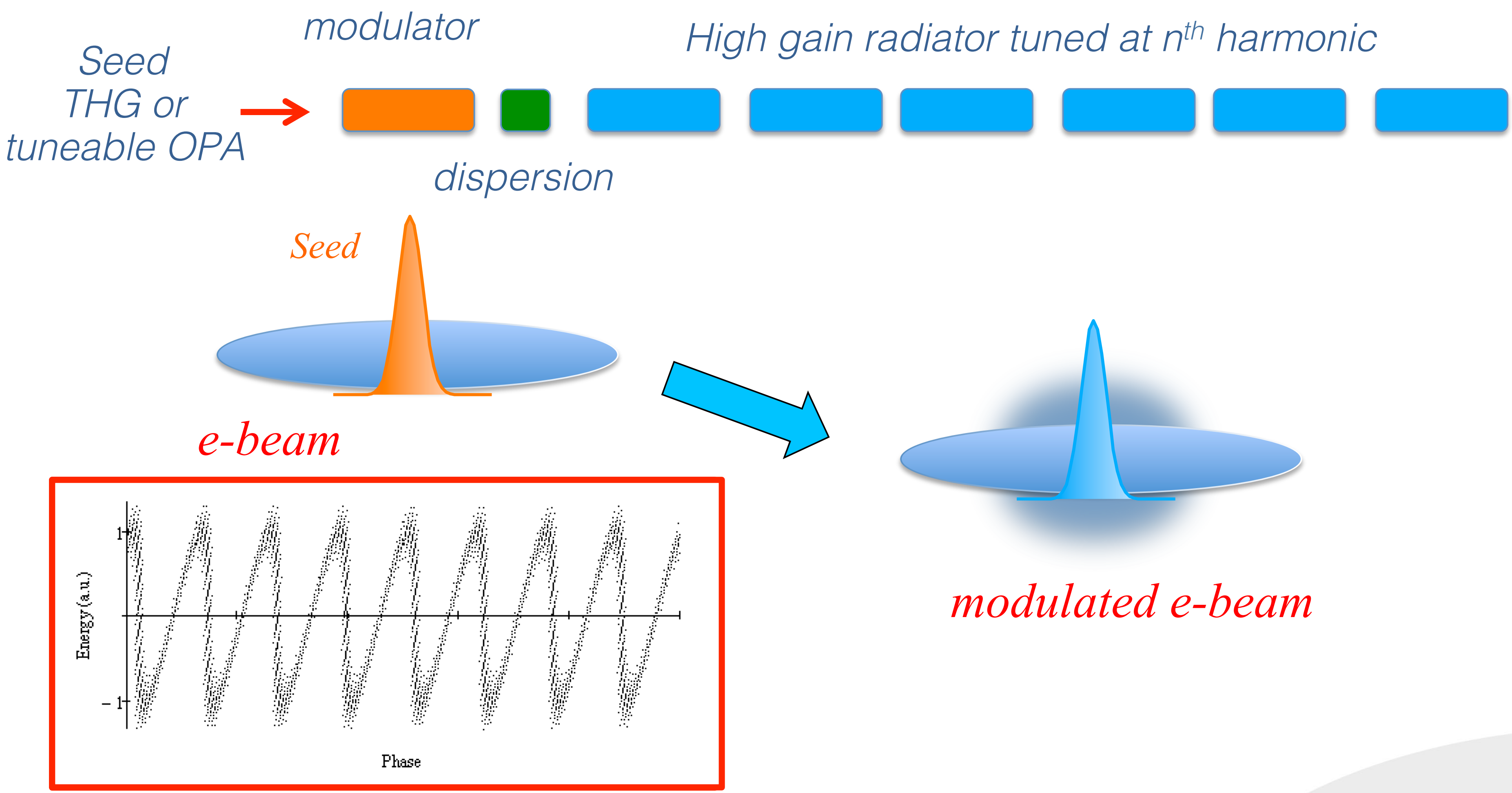
UV HGHG Experiment

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

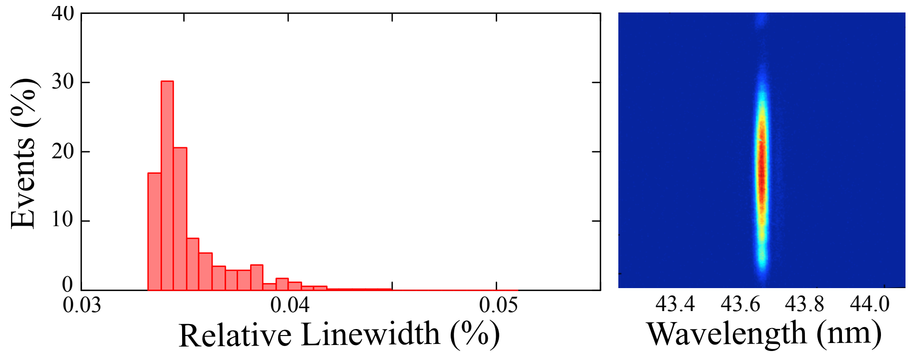
FERMI and Elettra

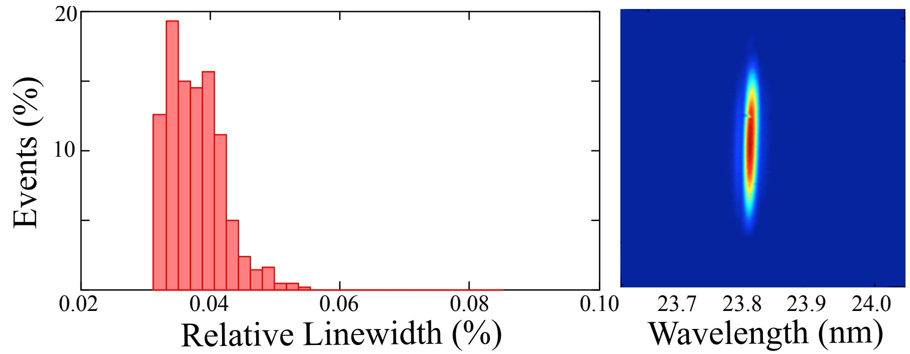


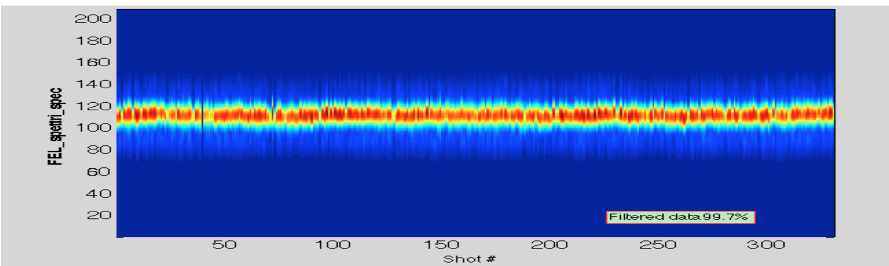
FEL-1 – HGHG FEL at work …



FEL-1 Spectral properties



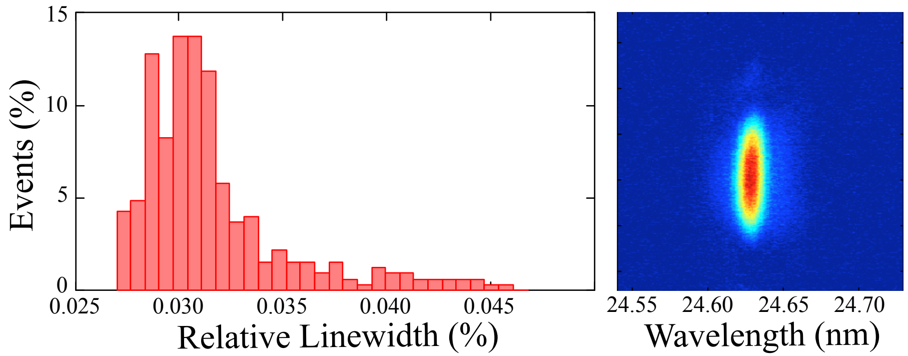




Seeded by the OPA laser at 245nm, the h14 delivers more than 10 uJ with good spectral properties.

The spectral properties can be preserved up to h13-h15 (h6 and h11 are shown in the pictures)

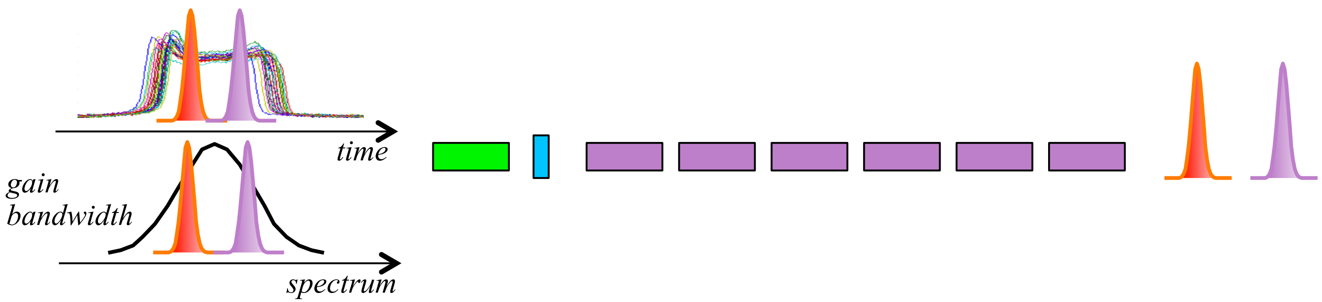
These sequences were acquired with the THG seed laser setup



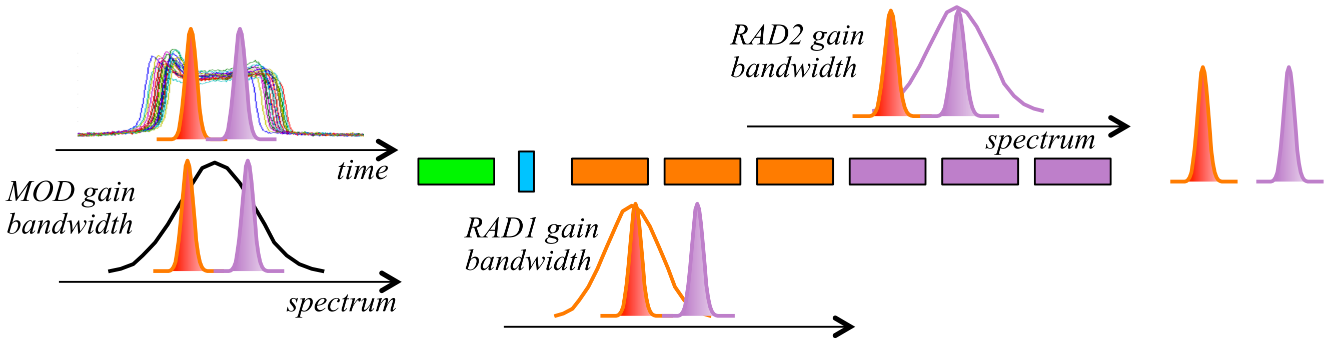
With the OPA laser system similar spectral quality can be obtained, with limitations mainly depending on the optical properties of the mirrors transporting the seed to the undulator

FEL-1 – Multiple colour operation

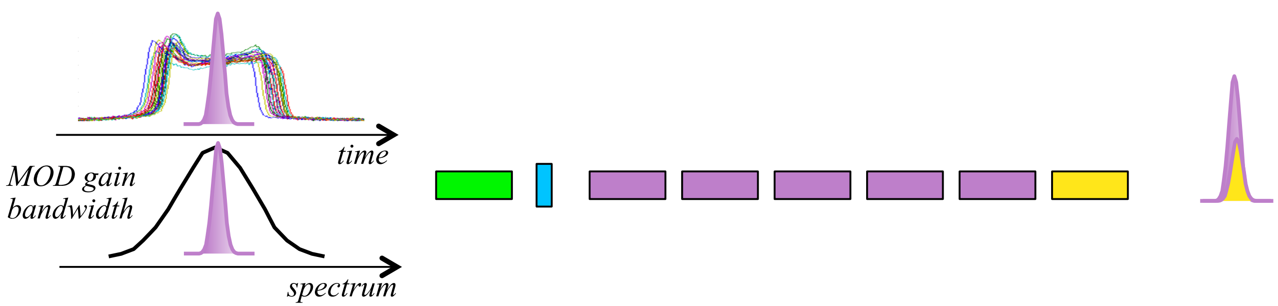
Multiple pulses can be generated by **double pulse seeding** in different ways, depending on the requirements on the output radiation. Temporal **separation between 250-300 and 700-800 fs**. Shorter separations are accessible via FEL pulse splitting*. Larger separations require the split & delay line.



Spectral separation 0.4-0.7%
Allaria et al., Nat. Comm., 2013



Spectral separation 2-3% or much larger if the two radiators are tuned at different harmonics
Ferrari et al., Nat. Comm, 2016



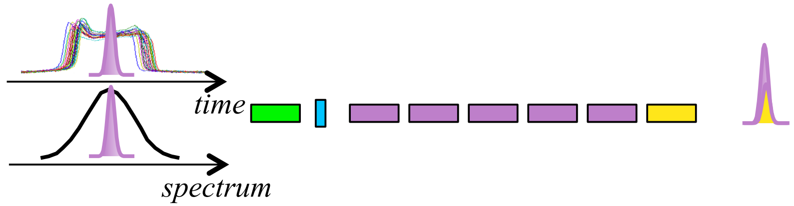
Two (almost) temporally superimposed pulses at harmonic wavelengths of the seed. The two pulses are correlated in phase and the phase can be controlled with the phase shifter. **K. Prince et al. Nat. Phot., 2016**

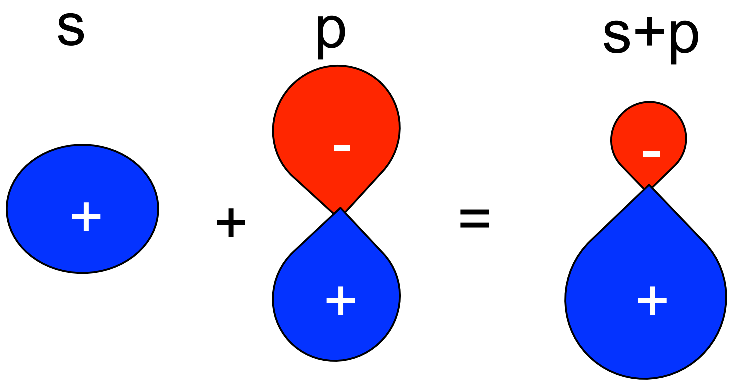
** See e.g. Mahieu et al. Optics Express 21, 22728 (2013)*

FEL-1 - Multiple pulse configurations

K. Prince exp. Ne, noble gas,has high first ionization potential. FERMI can be tuned below this threshold so the first harmonic does not ionize with a single photon. The second harmonic does. Ionization by two photons at FEL wavelength 63 nm ($2p^5 4s$ resonance), and single photon at 31.5 nm
The two channels have different parity:

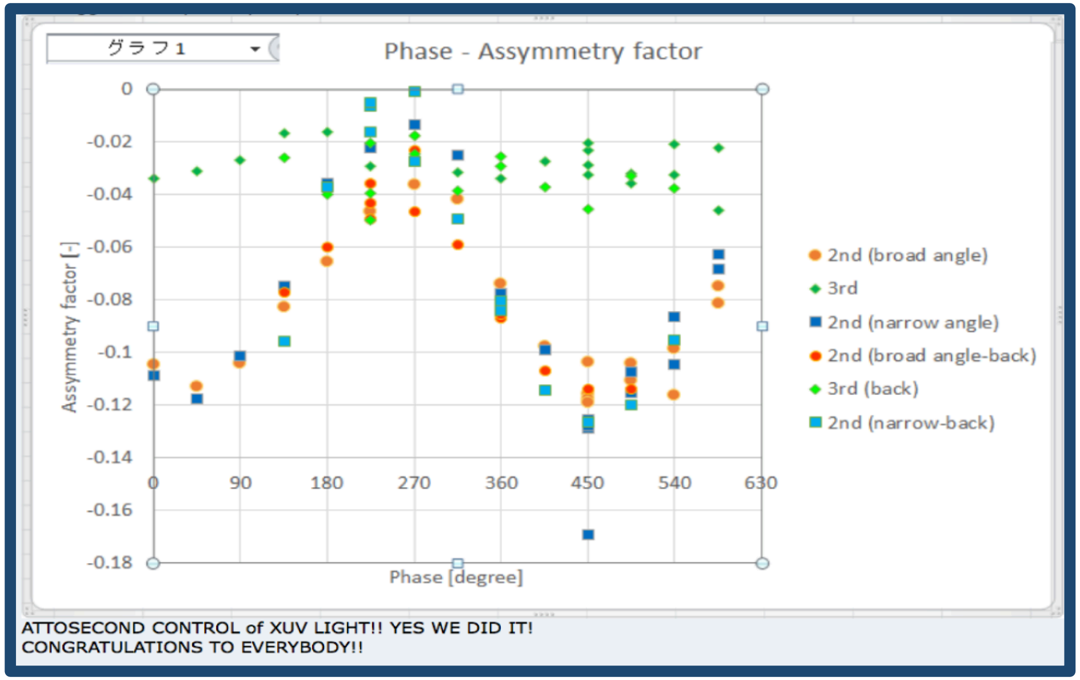
Velocity Map Imaging spectrometer installed on the Low Density Matter end-station





Interference = asymmetry

The asymmetry strongly depends on the relative phase between the two components of the fields.

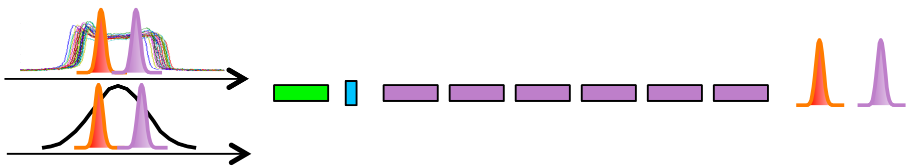


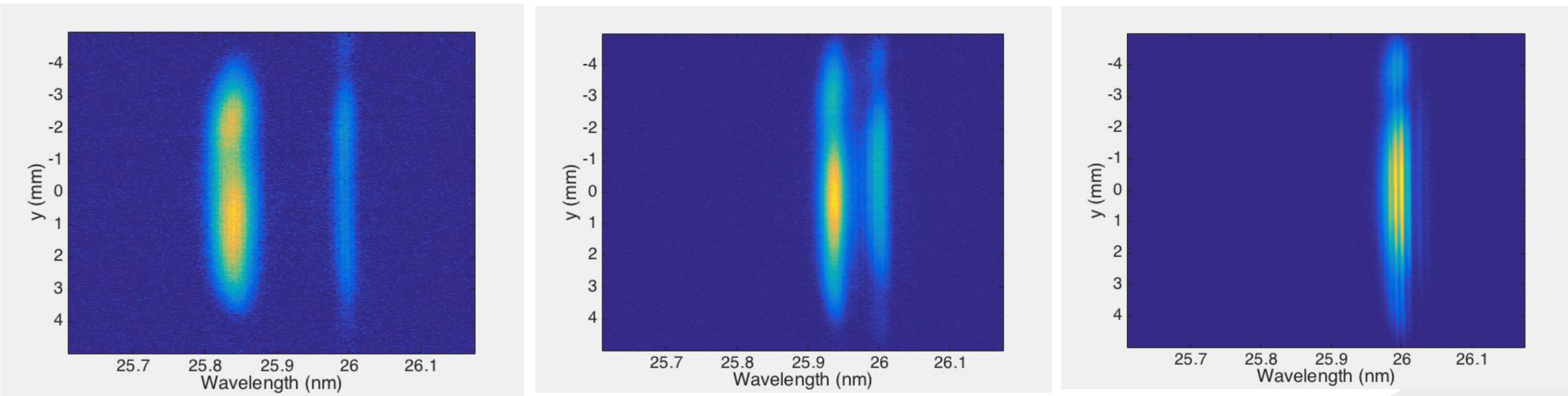
(3.1 as rms resolution) Prince et al., Nat. Phot., submitted

Double pulse operation

- ✓ Double pulse double color operation toward a standard condition of FEL operation. Laser system reliability and control improved.

- ✓ **FEL-based coherent anti-Stokes Raman scattering spectroscopy** - *EUV transient gratings (TG) & First FEL-stimulated coherent anti-Stokes Raman scattering (CARS) experiment (*BENCIVENGA)



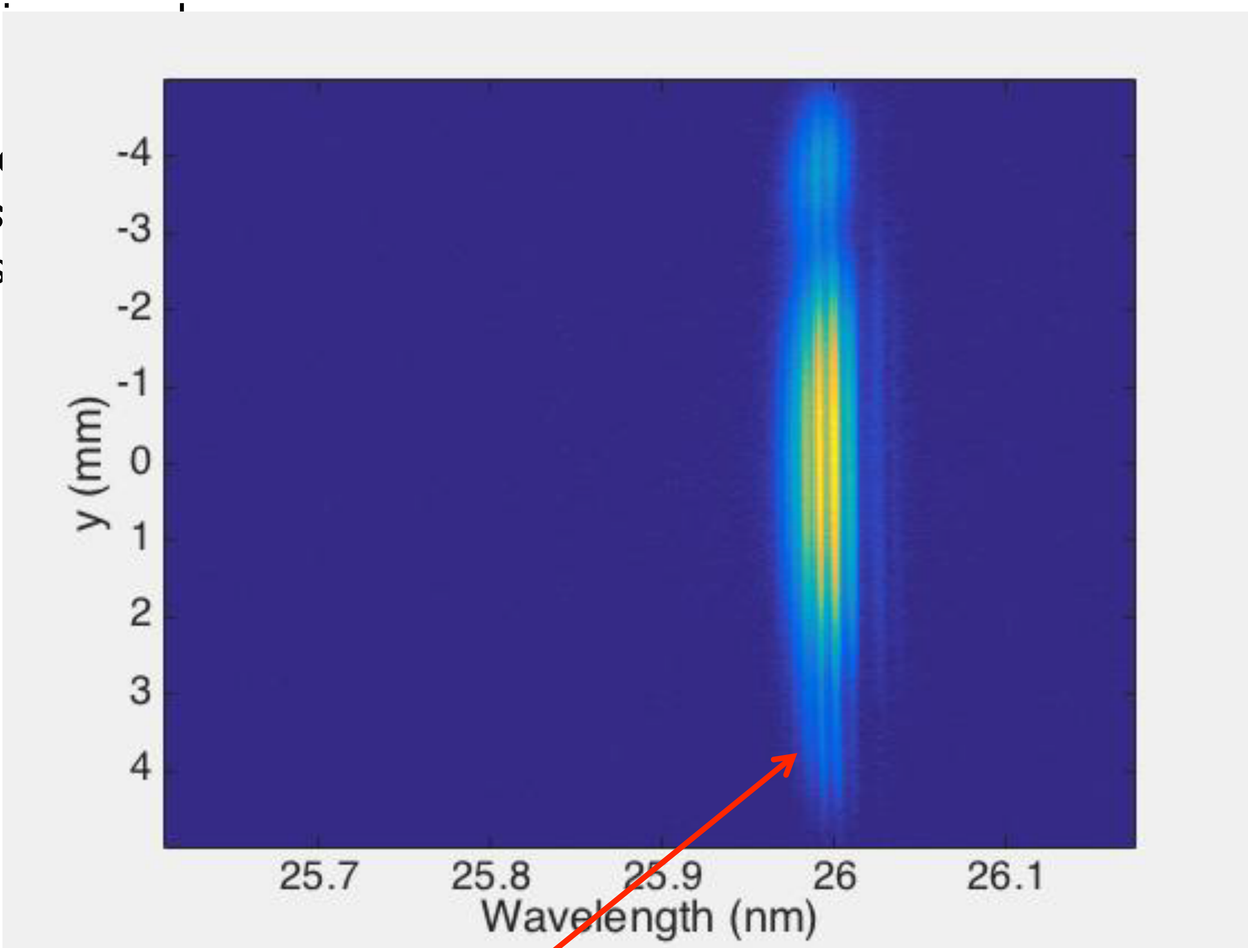


The two pulses 285 ± 5 fs constant temporal separation

Double pulse operation

- ✓ Double pulse double color operation toward a standard condition of FEL operation. Laser system reliability and control i

- ✓ BENCIVENGA **FEL-based c**
  transient gratings (TG) & Firs *S)*
  experiment (details in C. Mas



The two pulses 285 ± 5 fs constant temporal separation

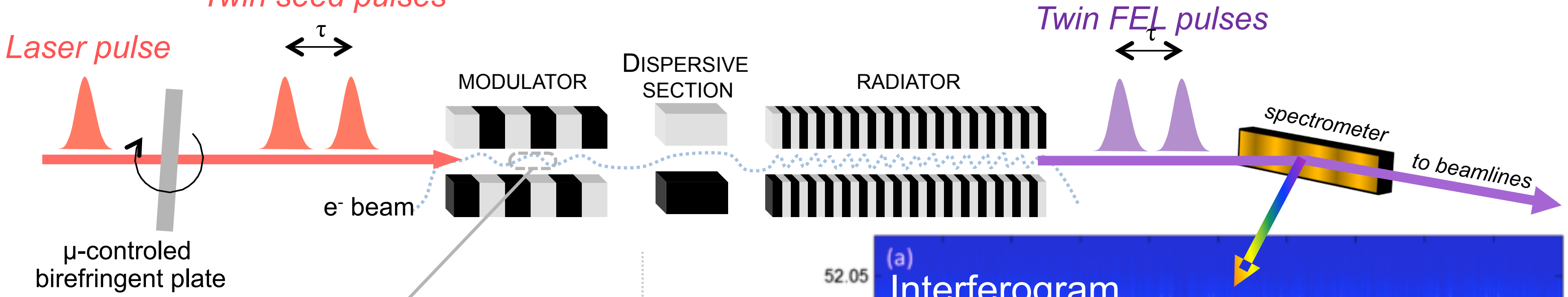
No phase locking (OPA+THG seed).

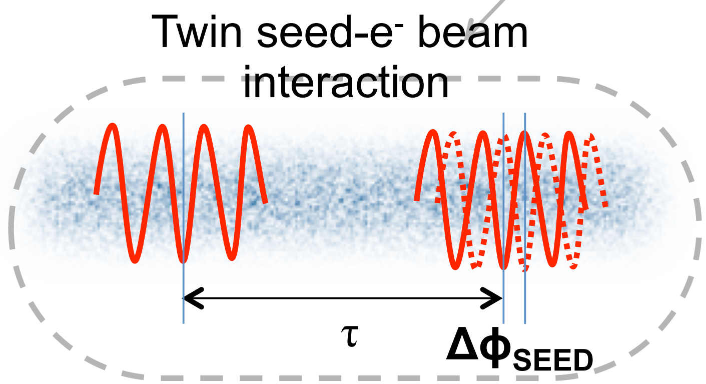
Phase-locked pulses

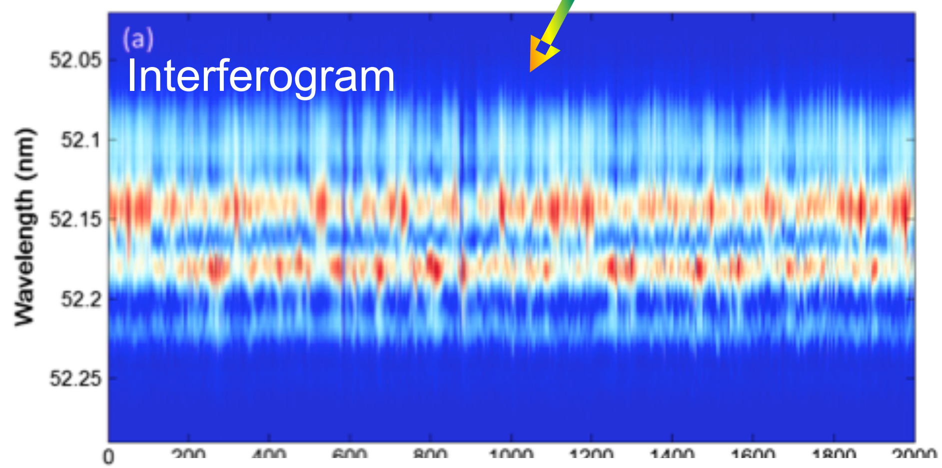
D. Gauthier et al., PRL 2016

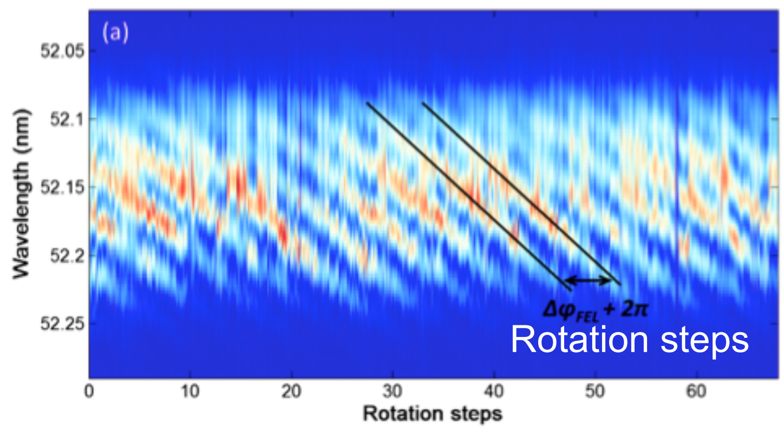
Elettra Sincrotrone Trieste

Two phase-locked seed pulses create two FEL pulses locked in phase. The relative phase control and stability between the two FEL pulses is demonstrated with the evolution and stability of the spectral phase









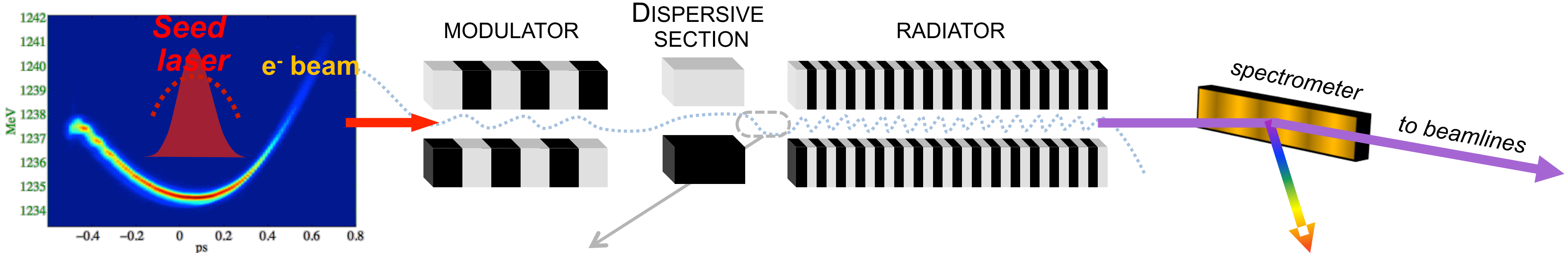
τ = 290fs and duration of the individual FEL pulse is about 70-80fs.

Rotation step: $\Delta\phi_{SEED}$ **= λ_{SEED} /28.33** => $\Delta\phi_{FEL}$ **= λ_{FEL}/ 5.67** (harmonic 5) - Full range of 68 steps => **12** time λ_{FEL}
Each step correspond to 20 consecutive single-shot spectra.

Analysis of fringes gives rms phase stability of $\lambda_{FEL}/10$

FEL pulse characterization & control
Spectro-temporal shaping

These beautiful pictures are prepared by
D. Gauthier



Spectral profile of the FEL pulse

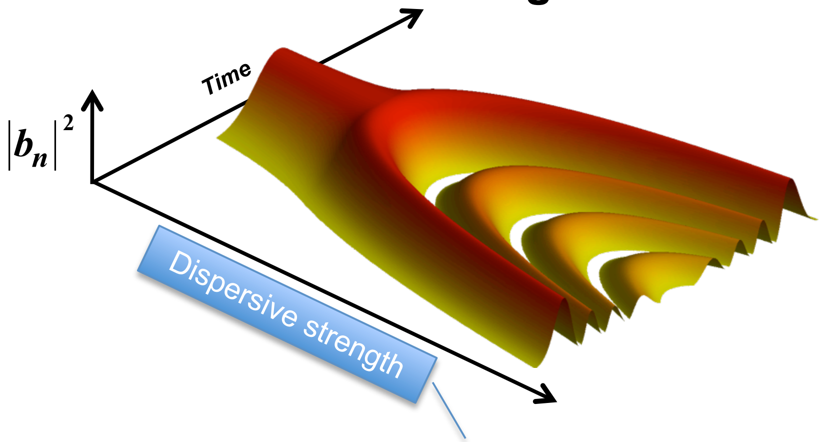
$$b_n(t) = e^{-n^2B^2/2}J_n[-nBA(t)]e^{in[\phi_s(t)+\phi_e(t)]}$$

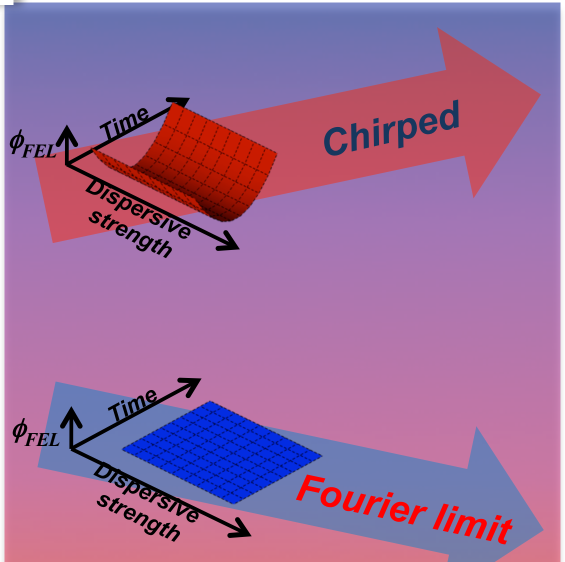
seed envelope

seed slowly varying phase

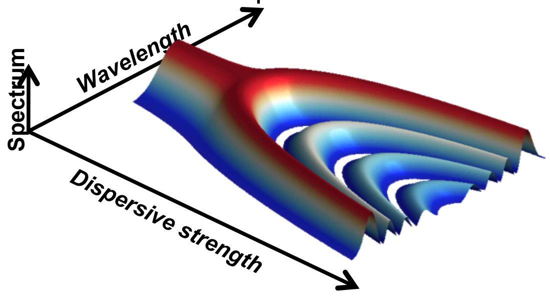
e- beam phase from time-dependent energy profile

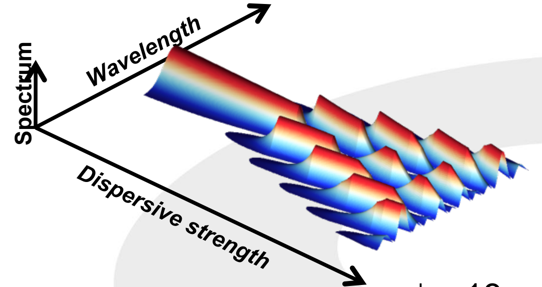
Temporal profile of the microbunching





Temporal profile of the phase:
contribution of the microbunching + FEL amplification





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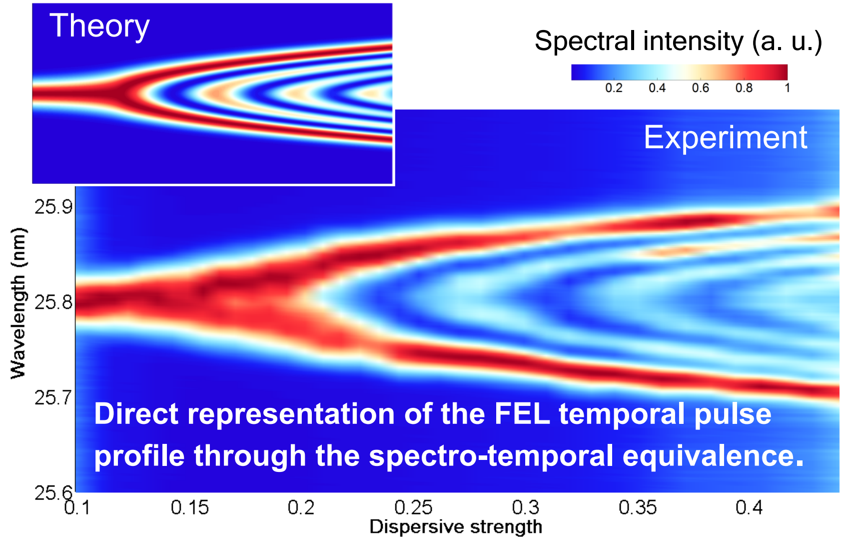
Featured in Physics

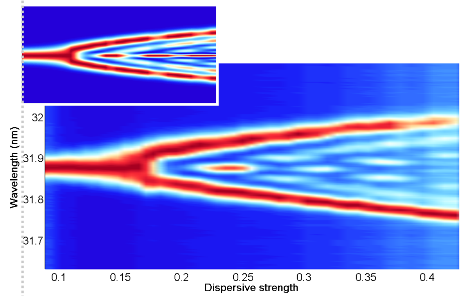
Spectrotemporal Shaping of Seeded Free-Electron Laser Pulses

David Gauthier, Primož Rebernik Ribič, Giovanni De Ninno, Enrico Allaria, Paolo Cinquegrana, Miltcho Bojanov Danailov, Alexander Demidovich, Eugenio Ferrari, Luca Giannessi, Benoît Mahieu, and Giuseppe Penco

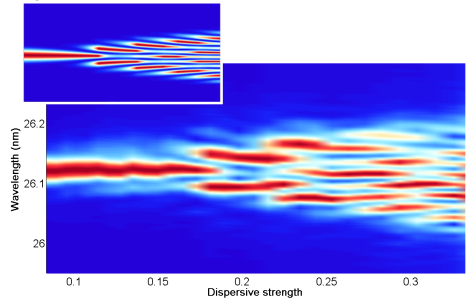
Phys. Rev. Lett. **115**, 114801 (2015) – Published 8 September 2015

Case 1: seed with strong linear frequency chirp
=> strong chirp on the FEL pulse

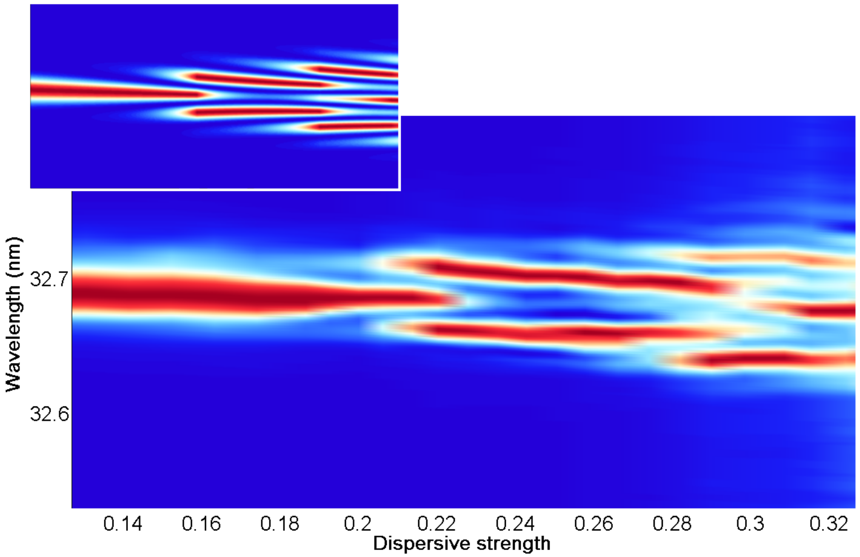




Case 2: intermediate positive chirp on the seed



Case 3: intermediate negative chirp on the seed

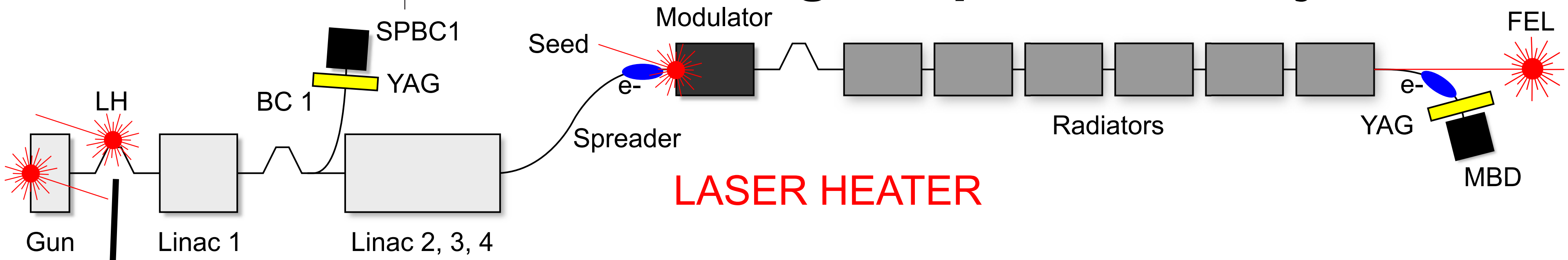


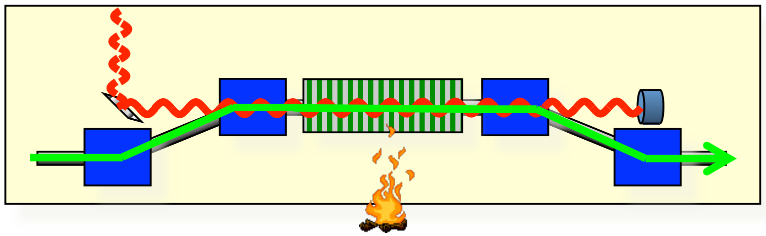
Case 4: moderate negative chirp on the seed
<=> chirp compensation

Possibility to compensate chirps from e-beam distribution and seed laser to generate Fourier transform limited pulses.

Seeded FEL –> Seeded "LINAC"

seeding the μB instability



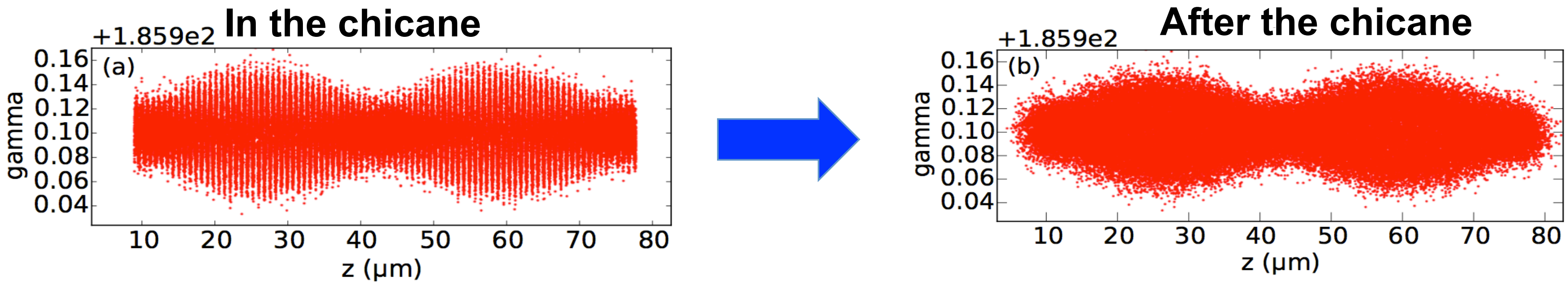


LASER HEATER

- Induces a controllable increase of the **uncorrelated energy spread** to damp the microbunching instability (MBI).
- The chicane "washes out" the modulation at the laser wavelength

Smearing condition for LH chicane: $2\pi\,|R_{52}\,\sigma_{x'}| >> \lambda_{rad}$

For FERMI LH parameters $2\pi\,|R_{52}\,\sigma_{x'}| = 4\ \mu m$



Frequency beating at LH

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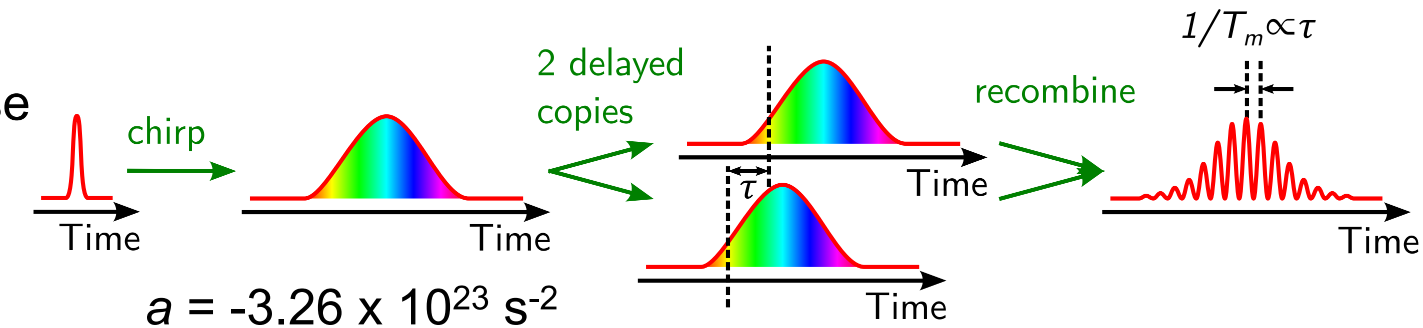
Double chirped pulse at the laser heater:

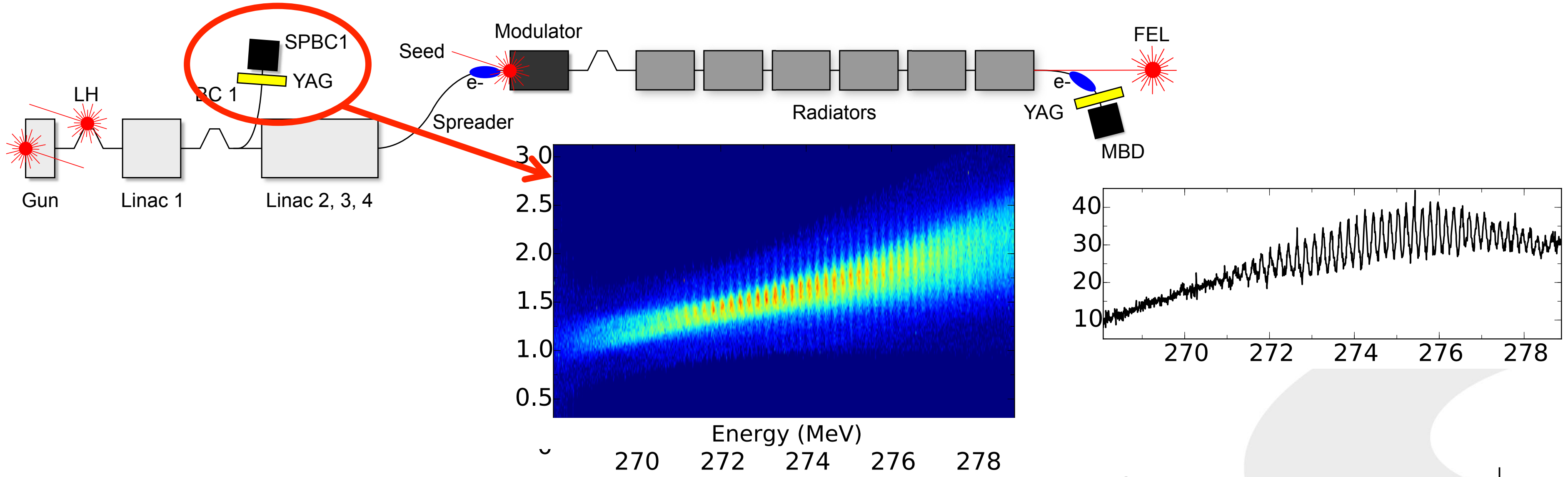


Laser linear chirp a = -3.26 x 10^{23} s^{-2}

Measured time separation τ = 28.2 ps

Beating frequency: 9.2 THz **Beating wavelength λ_B = 32.6 μm**

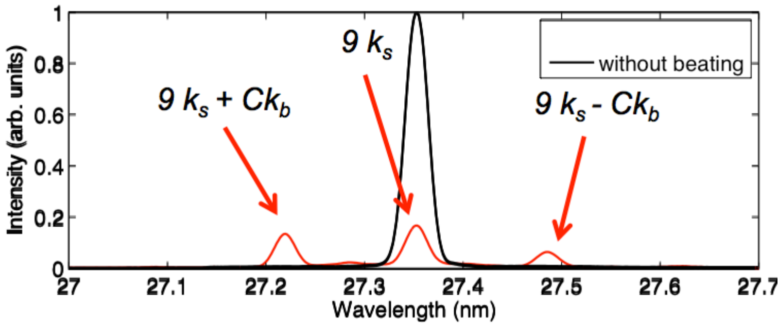
$\lambda_B >> \lambda_{cut\text{-}off}$ **The beating can propagate downstream of the LH chicane**



Seeded FEL with pre-modulated beam

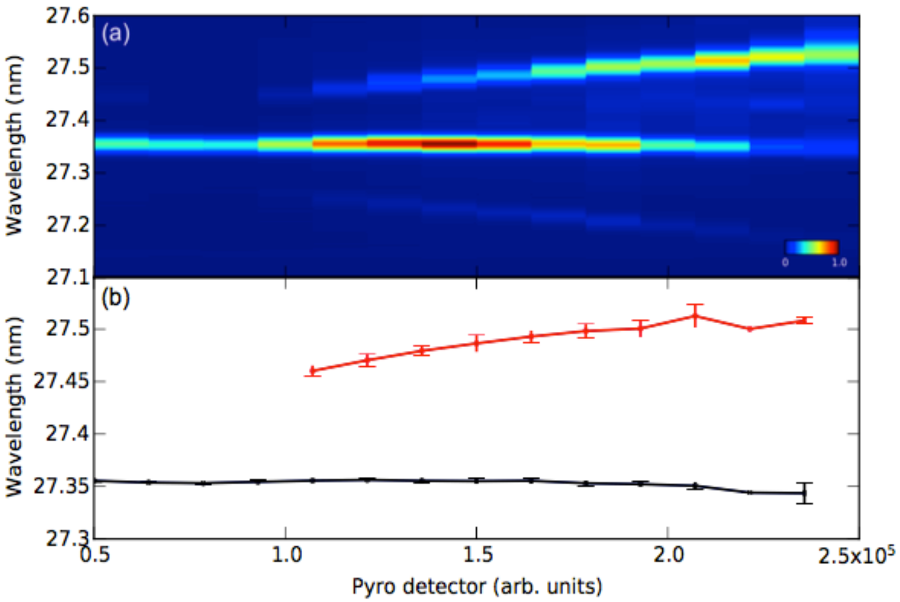
E. Ferrari et al. PRL 2015

After modulation the beam will have bunching content at $k = nCk_B + mk_S$



n, m	integers
C	compression factor
k_B	beating wavenumber
k_s	seed wavenumber

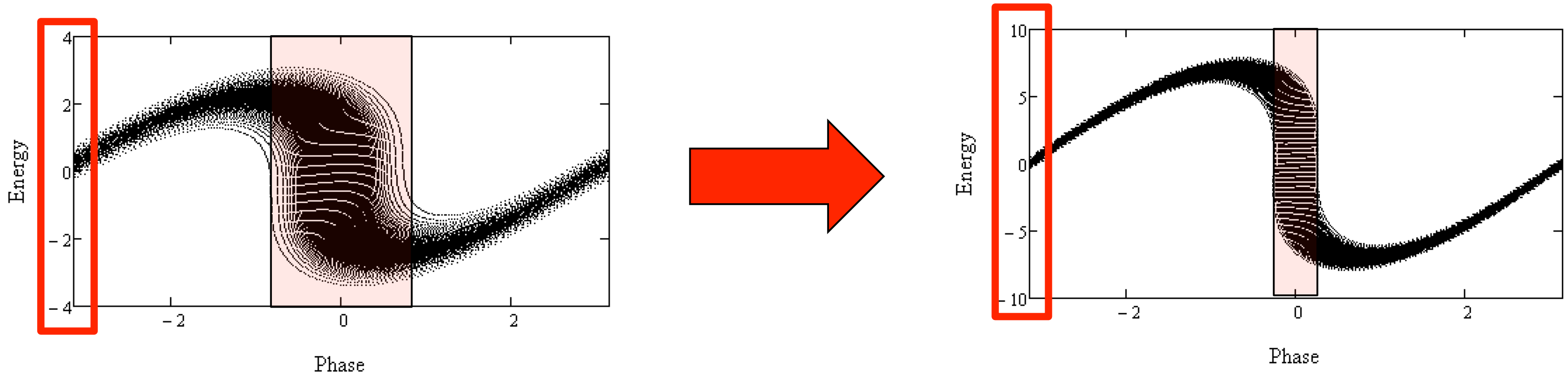
Measured spectrum: presence of sidebands



- ✓ Two color FEL pulses
- ✓ Wavelength tuning via compression factor or laser heater beating frequency
- ✓ Wavelength which are not integer harmonics of the seed can be generated

High harmonic conversion and the energy spread budget

Virtually any harmonic order can be obtained by increasing the seed power … at a cost of an increased energy spread



Required energy spread in order to bunch at the nth harmonic (Liouville's theorem)

$$\sigma_{induced} \approx 2n\sigma_{initial}$$

Condition to ensure high gain growth in final radiator

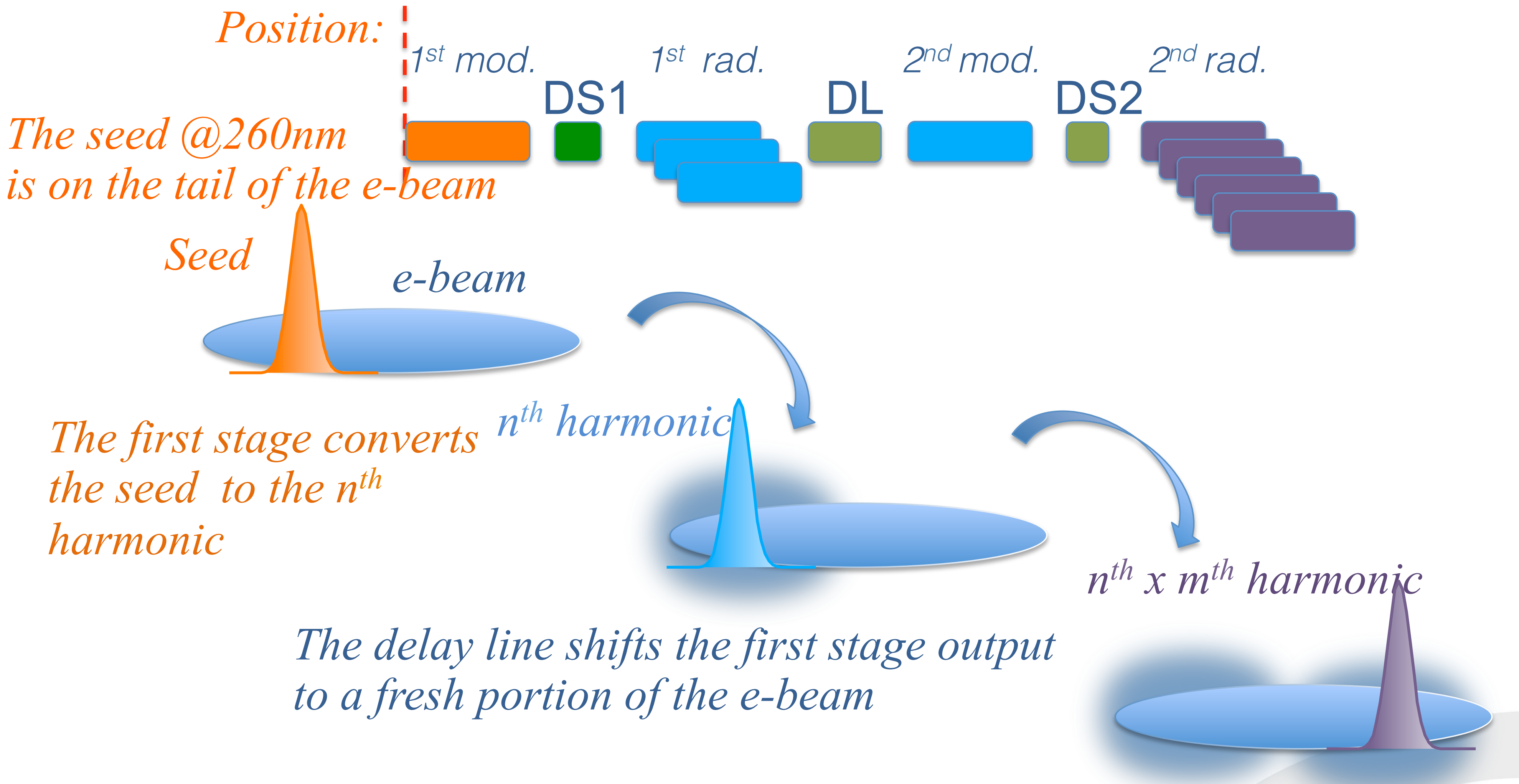
$$n < \frac{rho}{\sigma}$$

Ideas:

- Fresh bunch injection technique, *L. H. Yu, I. Ben-Zvi, NIM 1993*
- Echo Enabled harmonic generation, *G. Stupakov, PRL, 2009*
- Non Gaussian energy spread distrib., *E. Ferrari et al., PRL, 2014*
- Energy spread removal by space charge, *E. Hemsing et al., PRL 2014*
- Phase merging in TGU undulator, *H. Deng and C. Feng PRL (2013)*
- ....

FEL-2 in Fresh Bunch Inj. Technique

double stage cascade *E. Allaria et al. Nat. Phot. 2013*



The second stage converts the first stage to the n^{th} x m^{th} harmonic of the seed

**L. H. Yu, I. Ben-Zvi, Nim 1993*

FEL-2 - spectra vs wavelength

E. Allaria et al. J. of Synch. Rad. 22, p.485 (2015)

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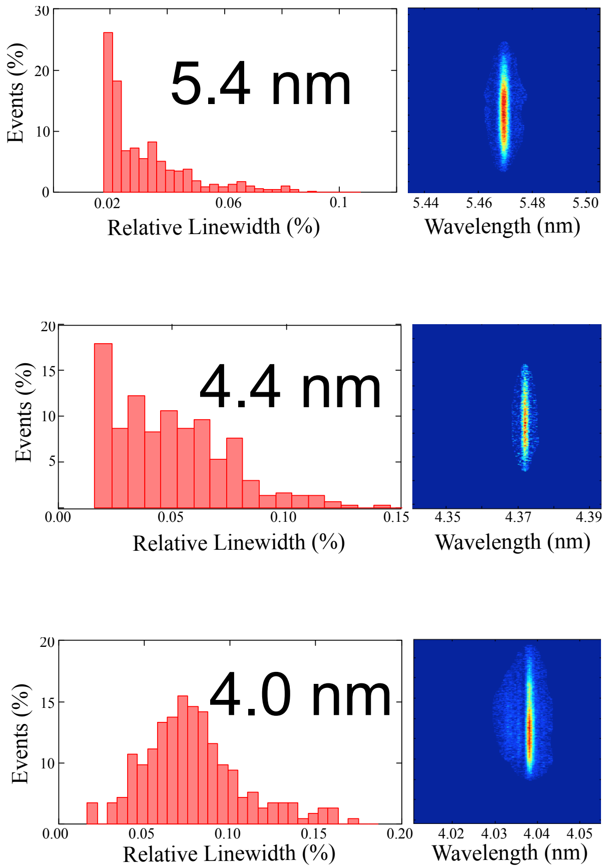
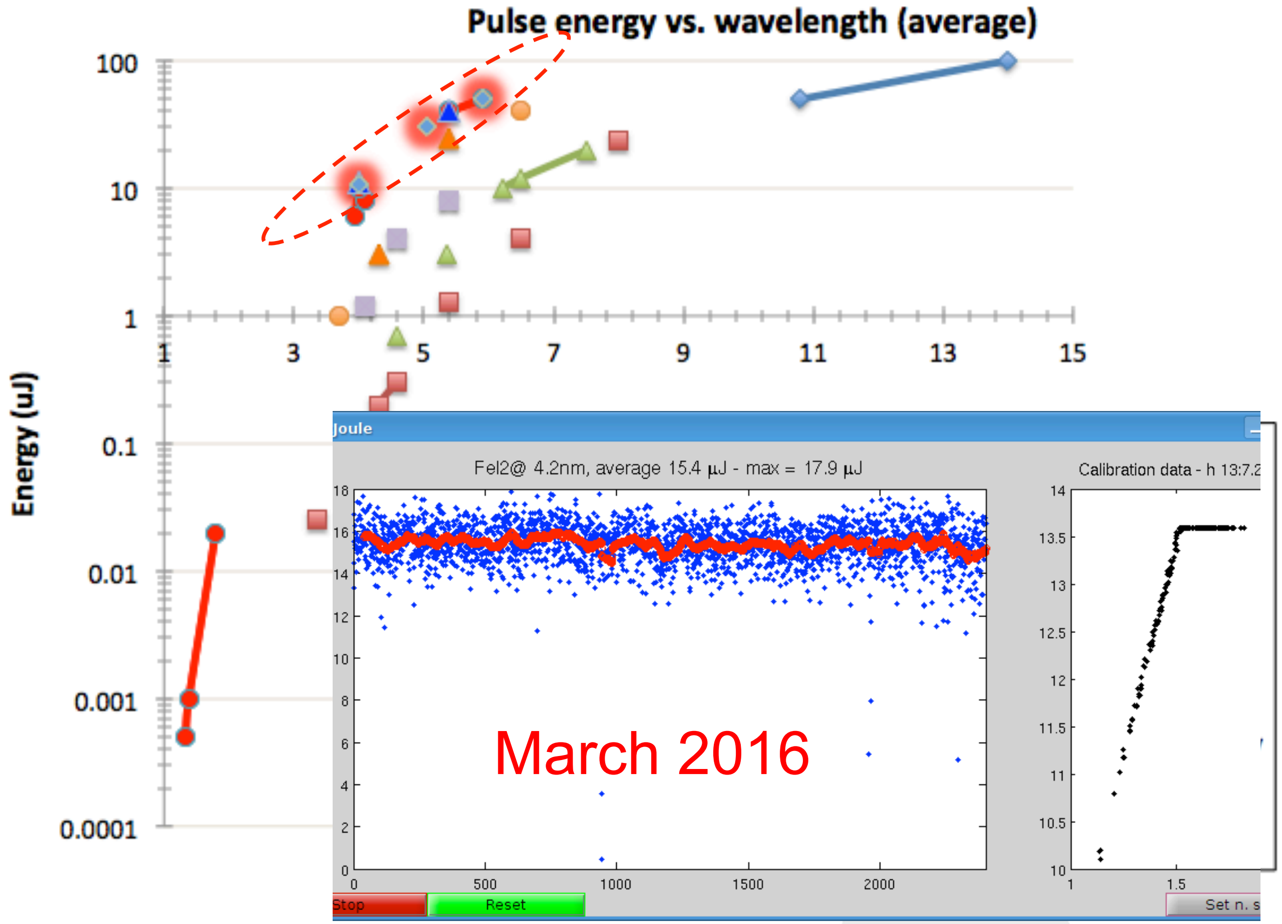
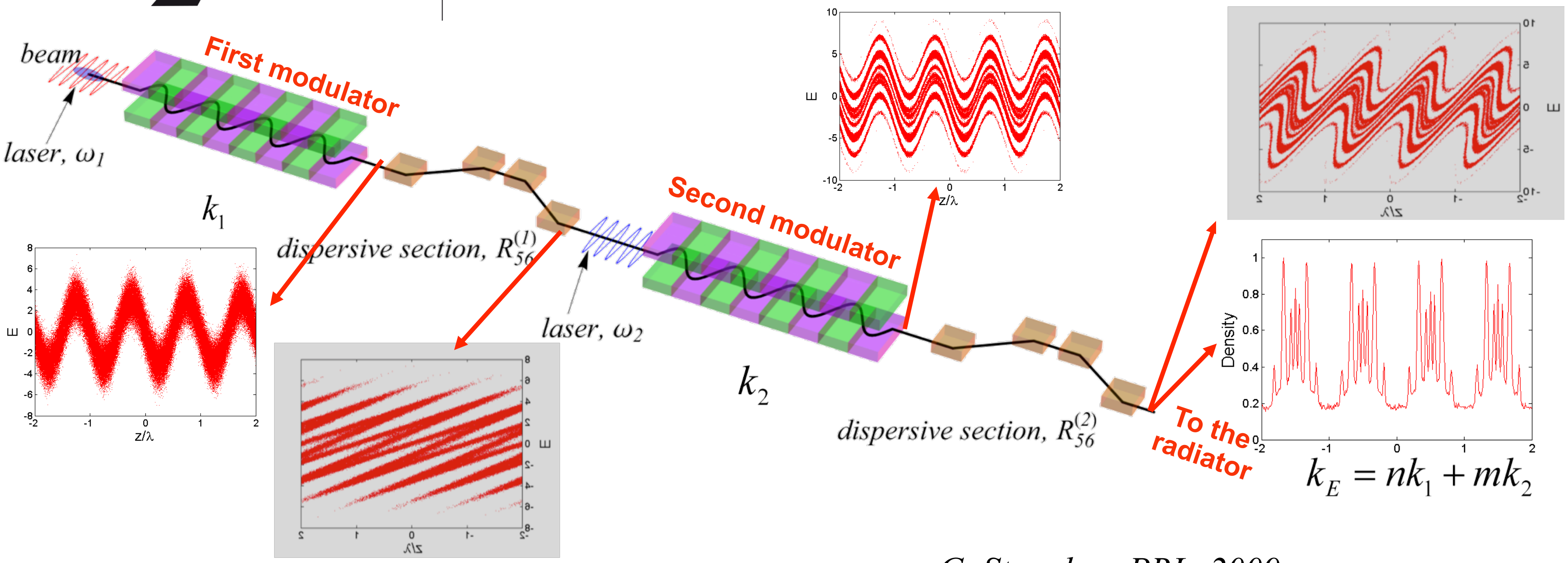
Single shot **spectra** measured down to **4 nm** and show **narrow linewidth** with an **energy** per pulse at shorter wavelengths larger than **10 μJ**

(pictures from run 21 – Energy figures confirmed in 3/2015, run 23)





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 "energy" structures in the longitudinal phase space.
- A second laser imprints energy modulation.
- The second chicane converts energy modulation into harmonic density modulation.

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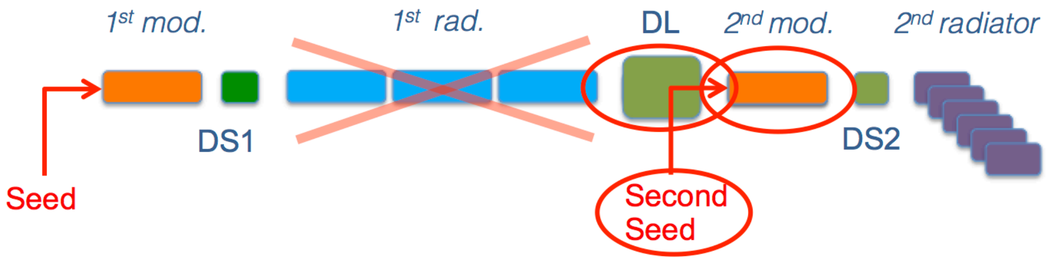
EEHG at FERMI

<u>Enrico Allaria</u> is coordinating an effort to implement an EEHG configuration at FERMI FEL-2

Preliminary studies on EEHG possibilities at FERMI were done during the design of FERMI in 2009, showing GW power levels at 4 nm.

E. Allaria, G. De Ninno and D. Xiang, "Feasibility studies for single stage Echo-Enabled Harmonic in FERMI FEL-2", Proceedings of FEL09 MOPC02 (2009)

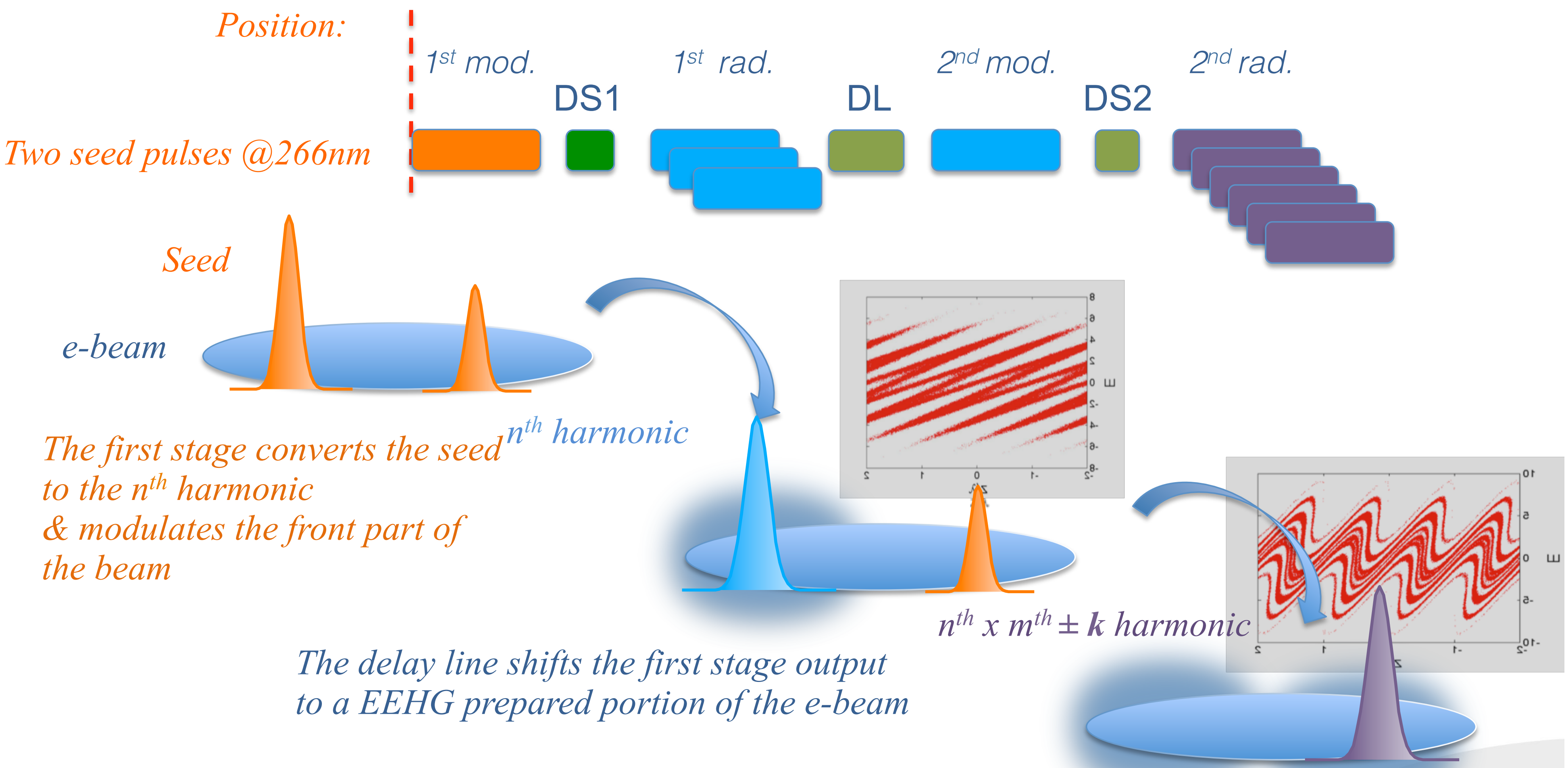
Small changes in the layout of FEL-2 allow to implement an EEHG configuration.



Advantages:

1. EEHG single stage more stable than Double stage configuration
2. Less Sensitivity to energy spread and beam quality in the second stage
3. Less constraints on the maximum current available
4. Easier control of the pulse duration
5. Two color configurations as on FEL-1 possible

FEL-2 in ECHO-Fresh double stage cascade*



The first stage converts the seed to the n^{th} harmonic & modulates the front part of the beam

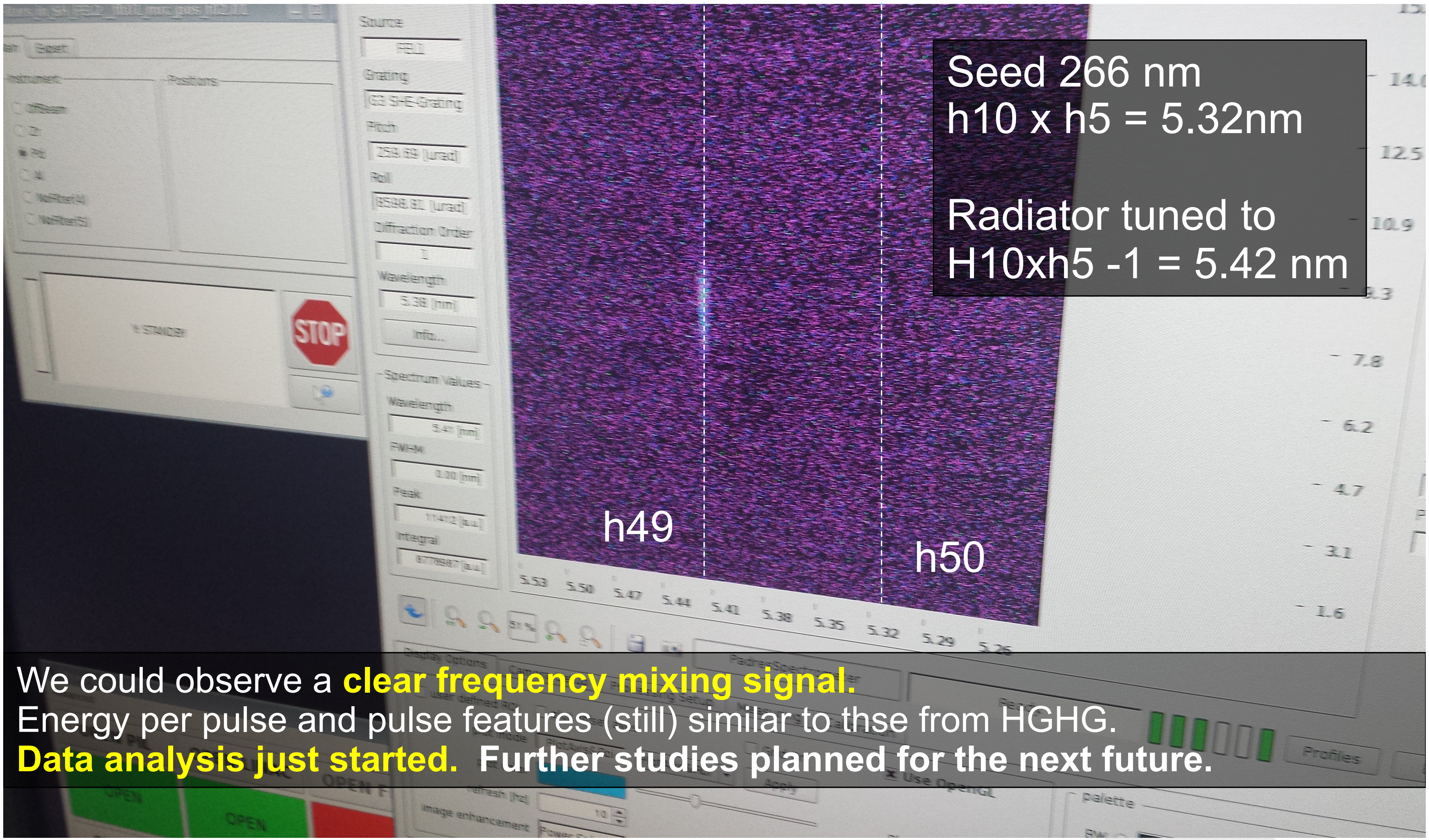
The delay line shifts the first stage output to a EEHG prepared portion of the e-beam

The second stage converts the first stage to the n^{th} x m^{th} – k harmonic of the seed

** by B. Fawley*

First test last week

ECHO-FRESH – first testlast week



Seed 266 nm
h10 x h5 = 5.32nm

Radiator tuned to
H10xh5 -1 = 5.42 nm

We could observe a **clear frequency mixing signal.**
Energy per pulse and pulse features (still) similar to thse from HGHG.
Data analysis just started. Further studies planned for the next future.

Conclusions

- ✓ "Seeding" was first introduced to shorten the gain length and improve longitudinal coherence of FEL amplifiers.
- ✓ A "seeded" FEL realizes a marriage between the accelerator and laser scientific communities, with methods typical of investigation of high intensity ultrashort pulses lasers applied to characterize and control the coherent FEL light
- ✓ The simple request of a "clean" spectrum is only the first step of the process. Now the possibility to control pulse shape/ phase/amplitude, generate multiple pulses with multiple colors is pushing to a higher level the expectations for a seeded FEL.
- ✓ The fertilization due to the close interaction with a strong user community is the key for the introduction of these new concepts.
- ✓ **This is what is happening at FERMI.**

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