PhLAM Physique des Lasers Atomes et Molécules

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Microbunching Instability and Laser Heater Impact on Seeded Free Electron Lasers

Eléonore Roussel – Eugenio Ferrari

FEL2017 Prize Talk(s)

26.08.2019

European XFEL

DESY.

Outline

- Microbunching instability

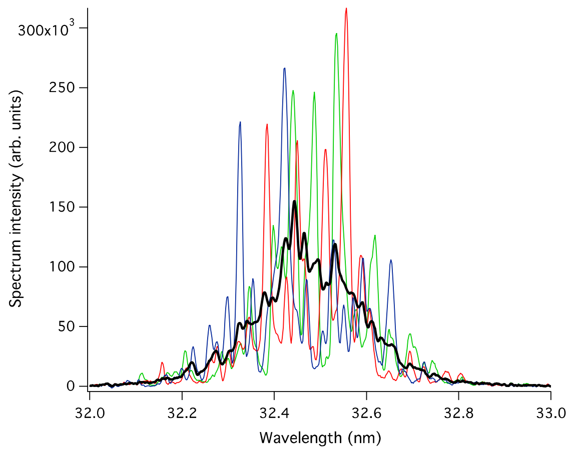
- Laser heater

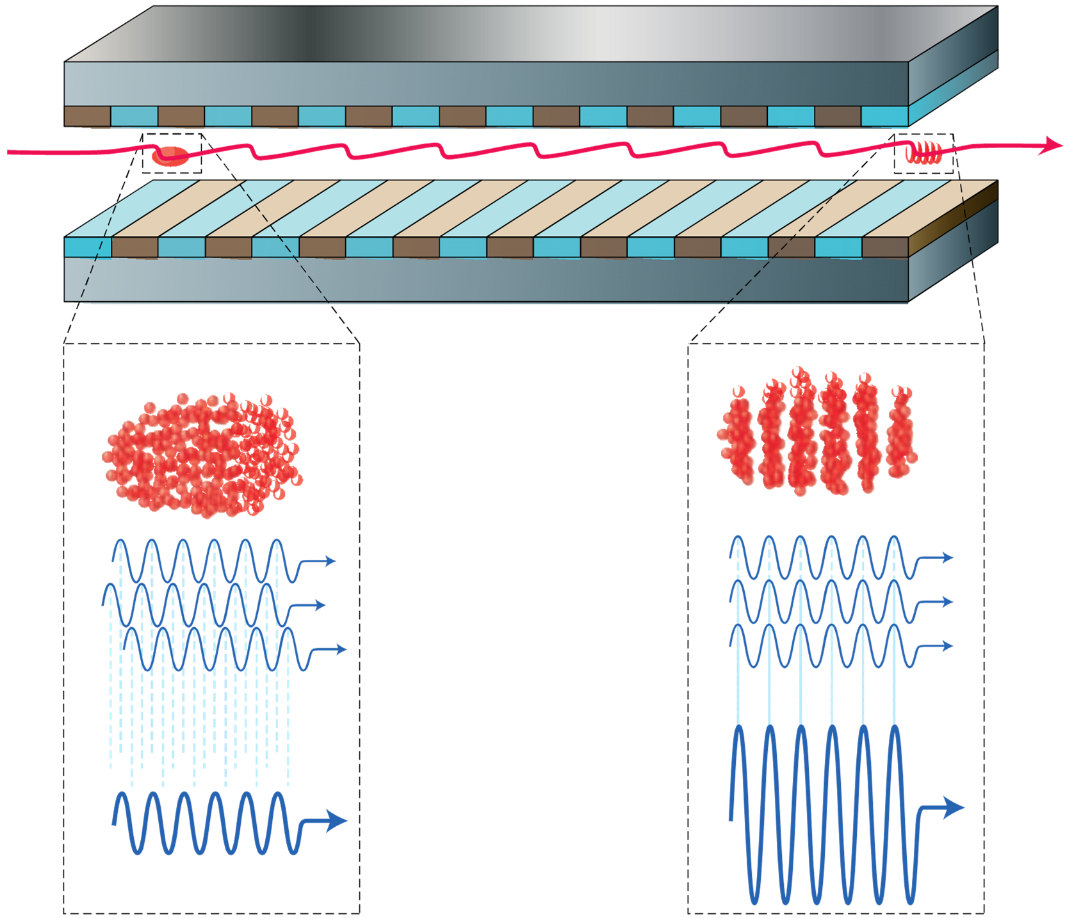
- Optimization and control of Seeded FELs with LH

• SASE Free Electron Laser

Self Amplified Spontaneous Emission (SASE)

- amplification, up to saturation, of the spontaneous emission produced by the e-beam entering in the undulator.
- requires high quality e-beam with very high peak current ~kA.
- typical bunch length in the 1 – 100 fs.
- usually poor longitudinal coherence (temporally and spectrally spiky emissions).





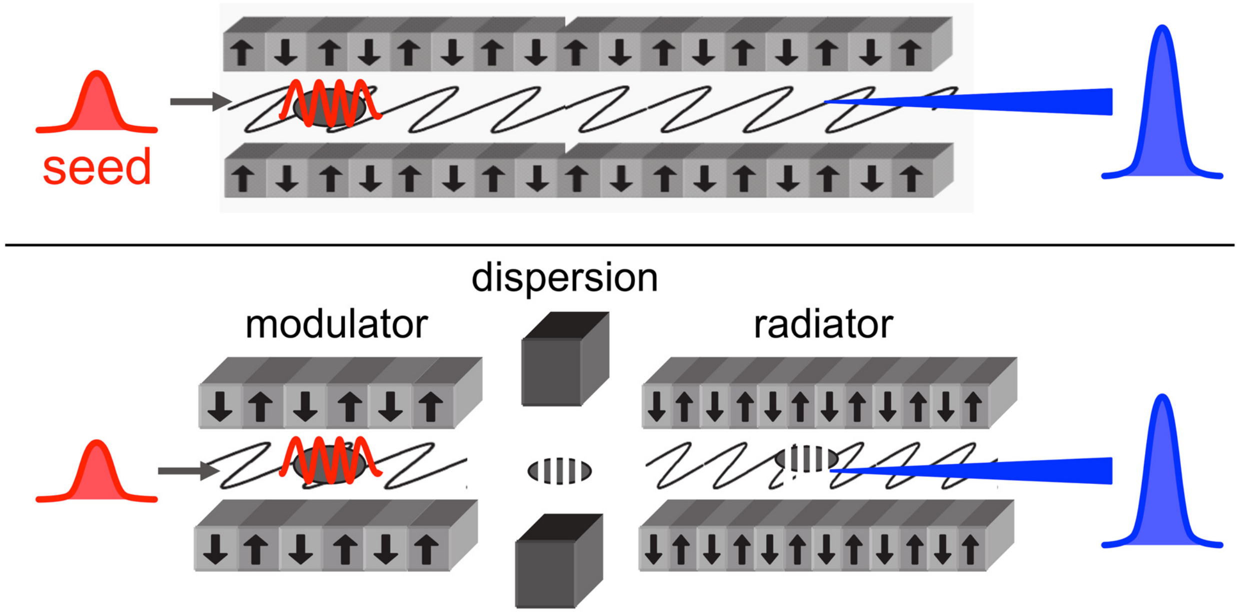
Incoherent emission: electrons randomly phased

Coherent emission: electrons bunched at radiation wavelength

[B.W.J. McNeil N.R. Thompson, Nat. Photon. 239 (2010)]

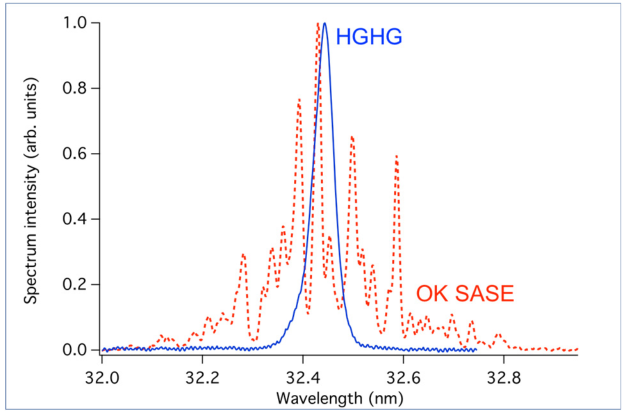
• Seeded FEL

Use of external *seed* laser to control the distribution of the electrons within the bunch



Benefits of a seeded FEL:

- final FEL pulses inherit properties of the seed
- improvement of **temporal coherence** of FEL pulses
- control of time duration and bandwidth
- low arrival time jitter
- reduction of undulator chain to reach saturation



Drawbacks:

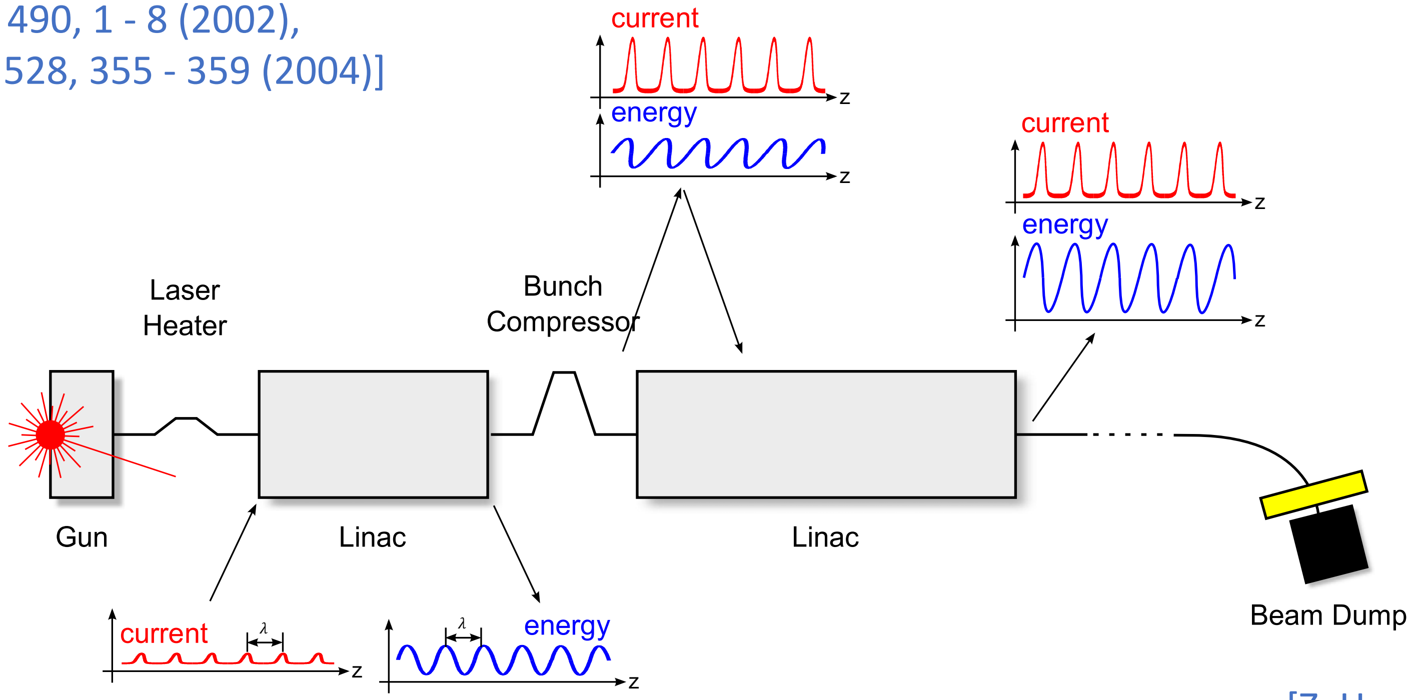
- no seeding sources at very short wavelength range
- spectral properties sensitive to the e-beam longitudinal phase-space

Microbunching instability in LINACs

Gain mechanism:
density modulation —linac→ energy modulation —bunch compression→ density modulation

Main ingredients:
LSC (Longitudinal Space Charge) & CSR (Coherent Synchrotron Radiation)

[Saldin et al., NIMA 490, 1 - 8 (2002),
Saldin et al., NIMA 528, 355 - 359 (2004)]

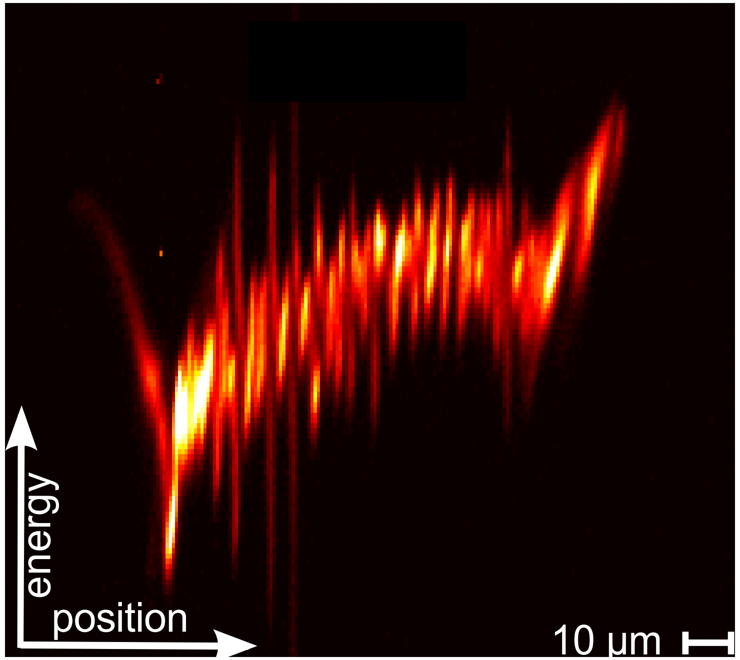


[Z. Huang et al., SLAC-PUB-11597 (2005)]

High quality e-beam for high-gain FELs?

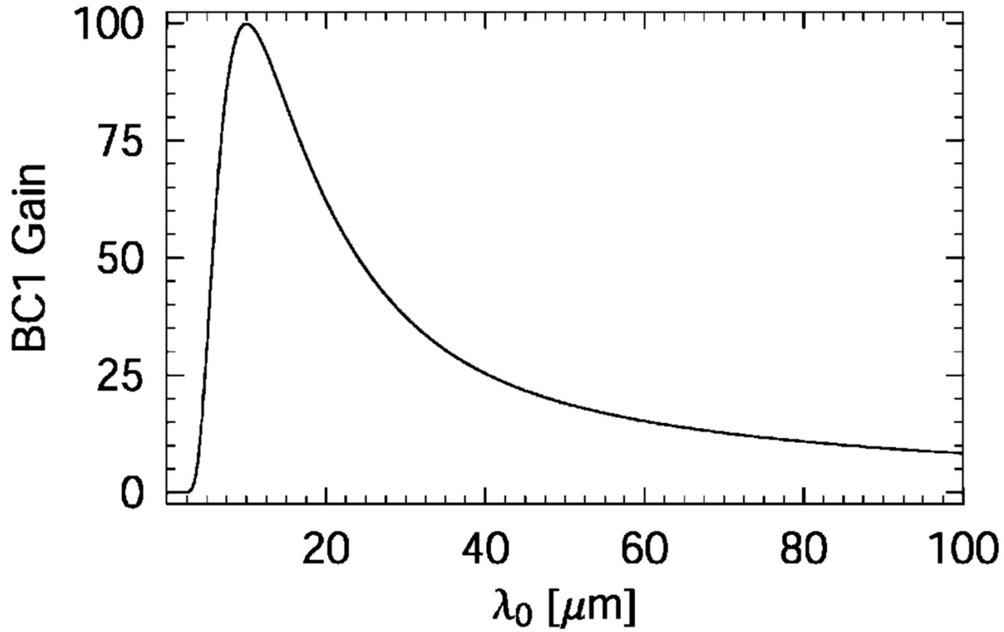
- Broadband µBI with maximum gain around few µm.
- Longitudinal phase-space modulated in energy and/or density through µBI.
- Increase of energy spread comparable to the FEL parameter.

→ suppression of SASE gain.



[Ratner et al., PRSTAB **18**, 030704 (2015)]

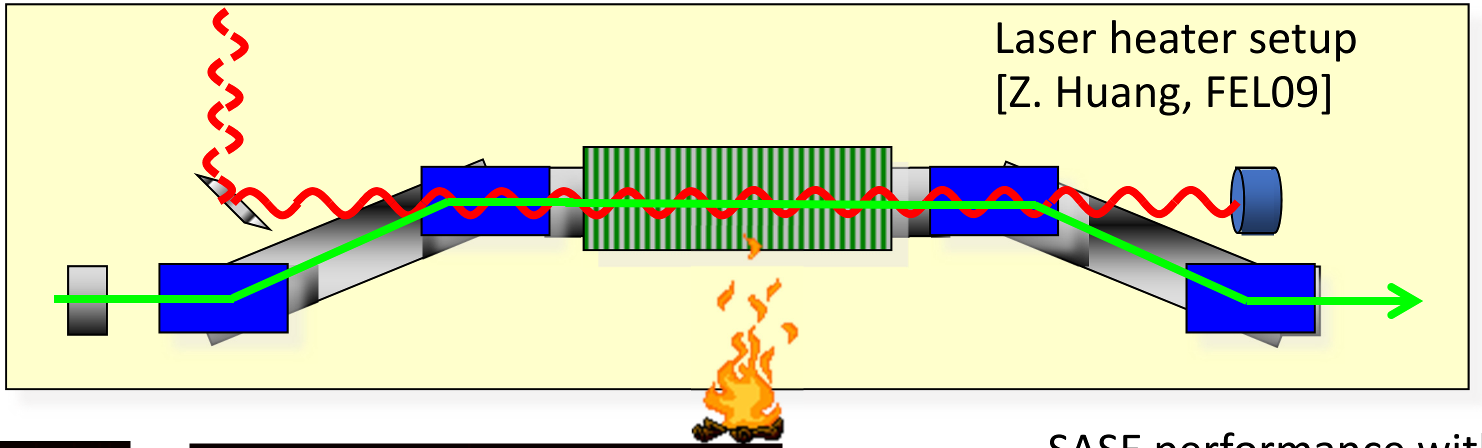
[Z. Huang et al., PRSTAB **7**, 074401 (2004)]



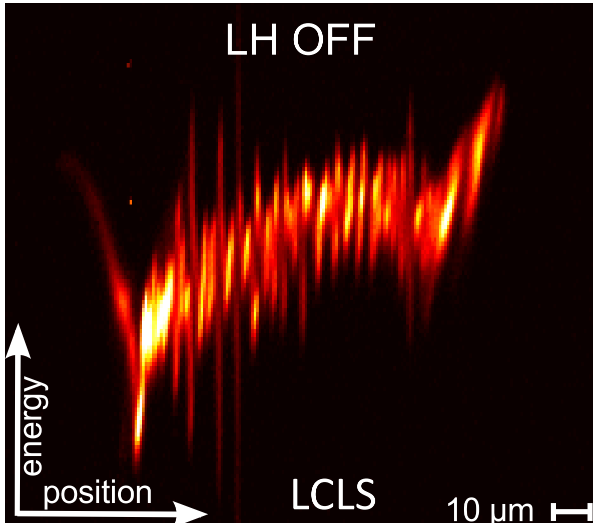
Laser heater

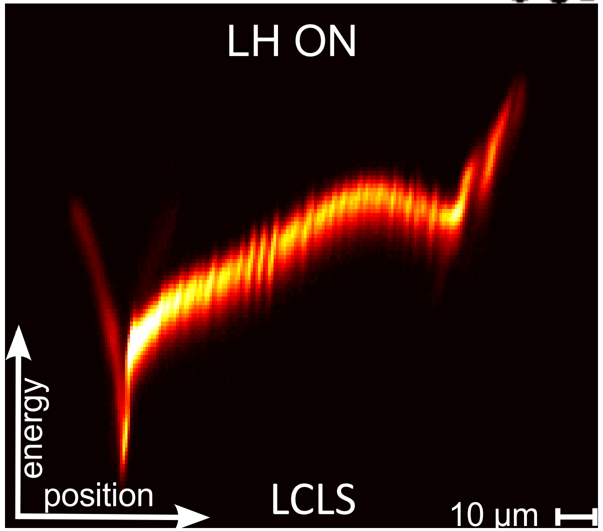
Induce a controllable increase of the **uncorrelated energy spread** to Landau damp µBI.

[Saldin et al., NIMA 528, 355 - 359 (2004)]



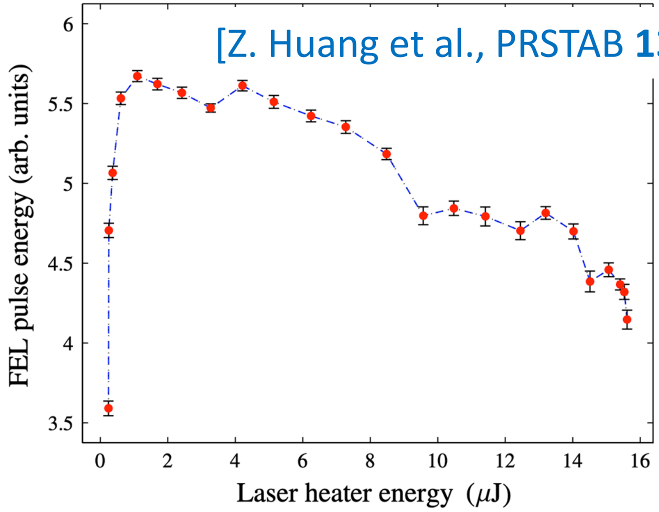
Longitudinal phase space





SASE performance with LH @ 1.5 Å

[Z. Huang et al., PRSTAB **13**, 020703 (2010)]

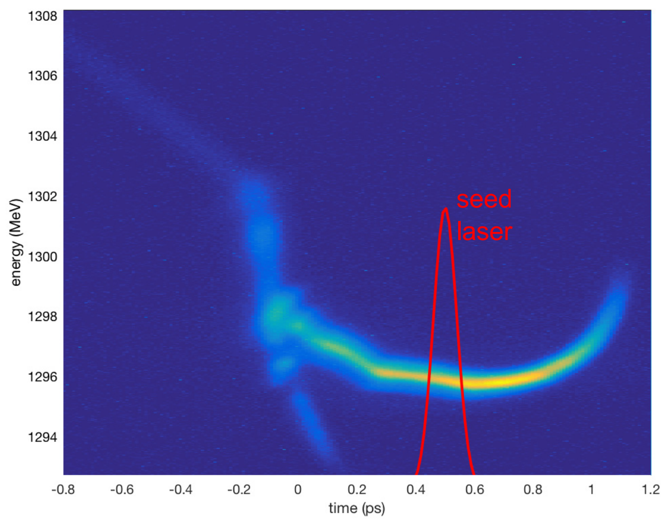


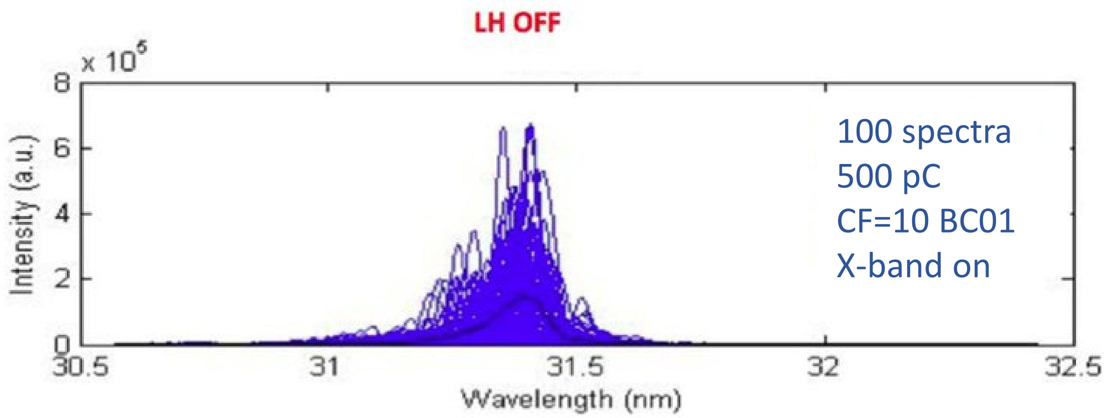
• Microbunching Instability and seeded FELs

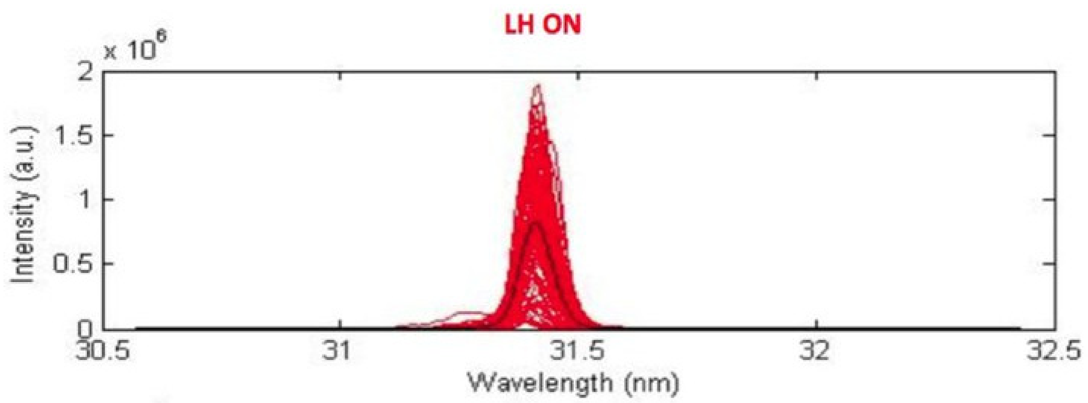
A seeded FEL is more sensitive to e-beam phase-space properties.

Small imperfections on the phase-space degrade the FEL spectrum.

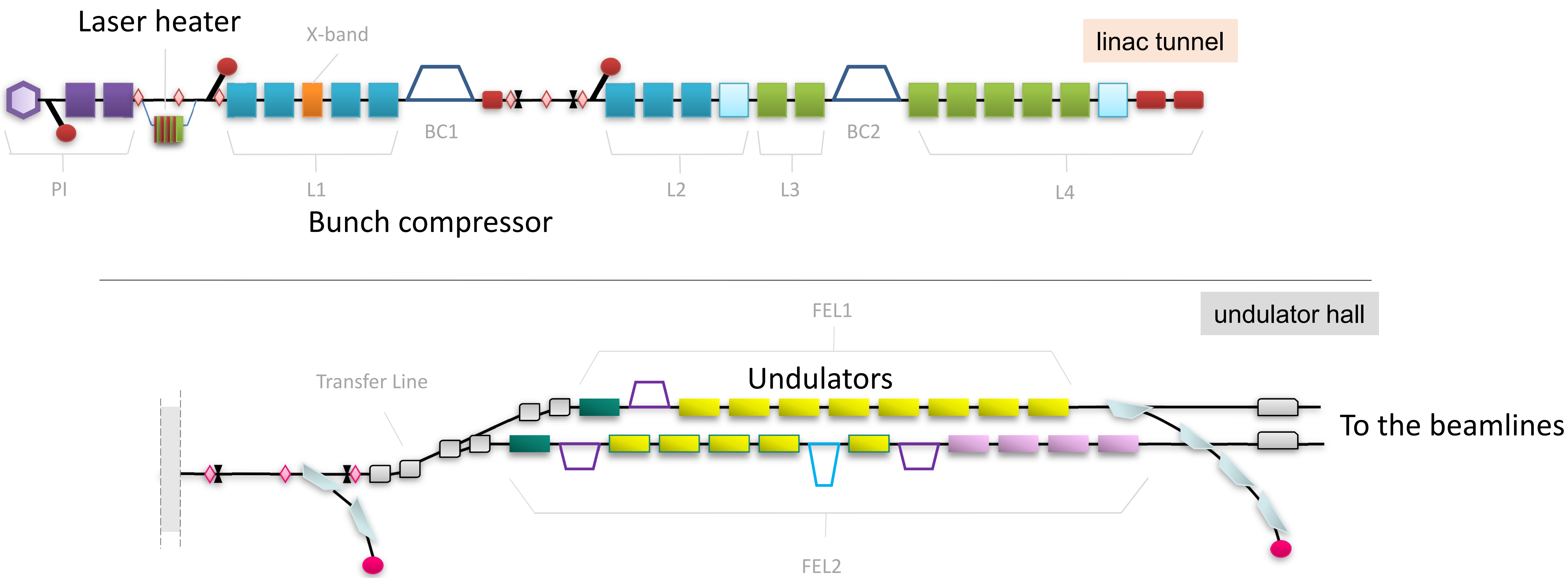
Stochastic effect on the FEL spectrum
[Z. Zhang et al., PRAB 19, 050701 (2016)]







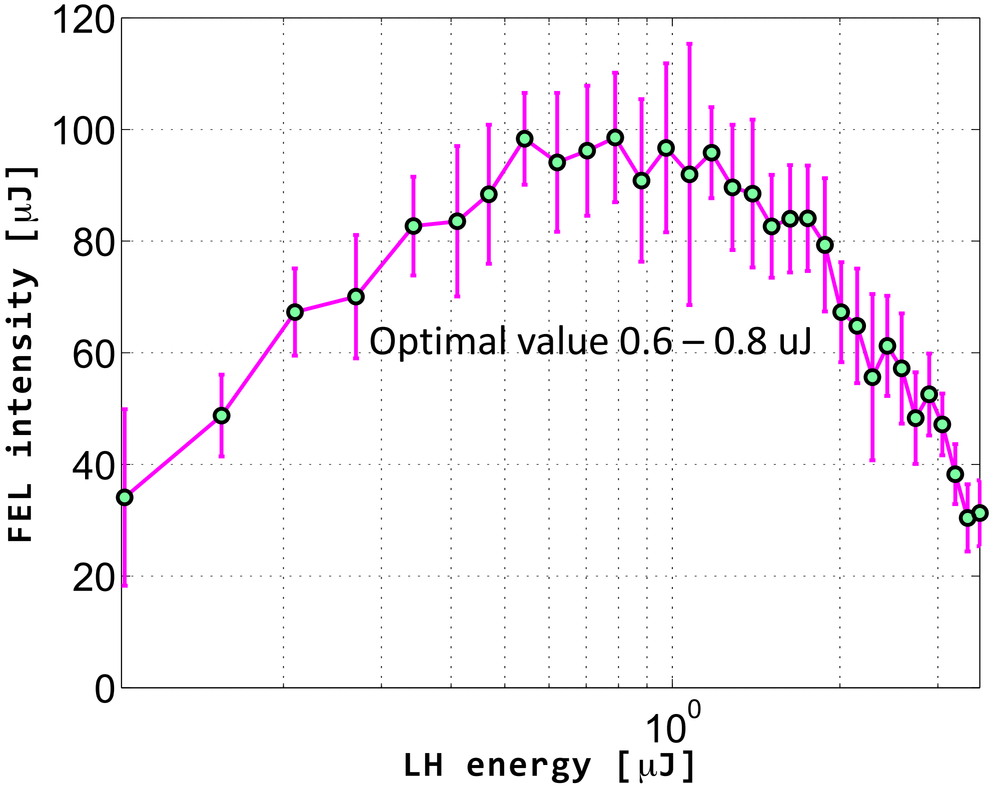
• FERMI seeded FEL

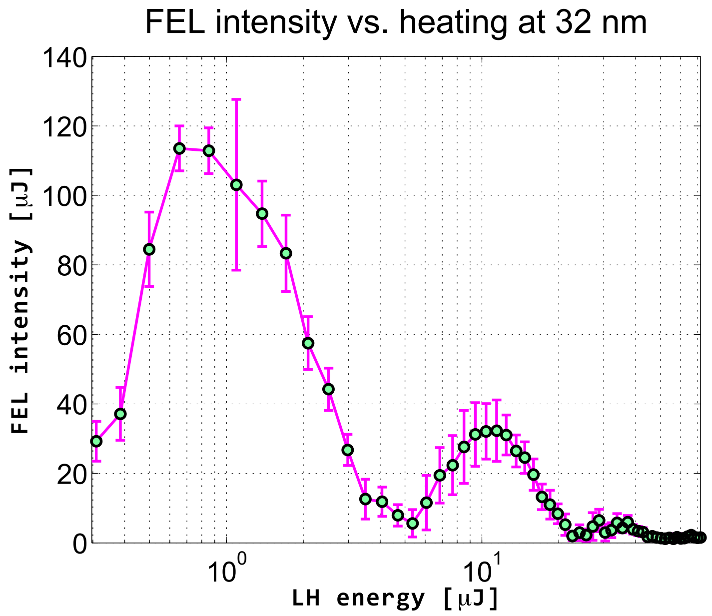


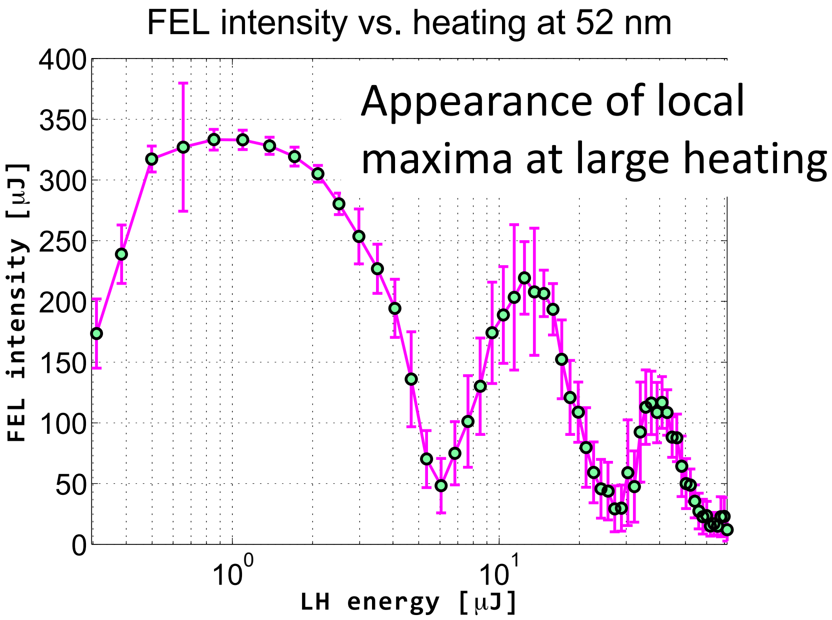
The results in the following refer to FERMI

• Performance of FERMI LH

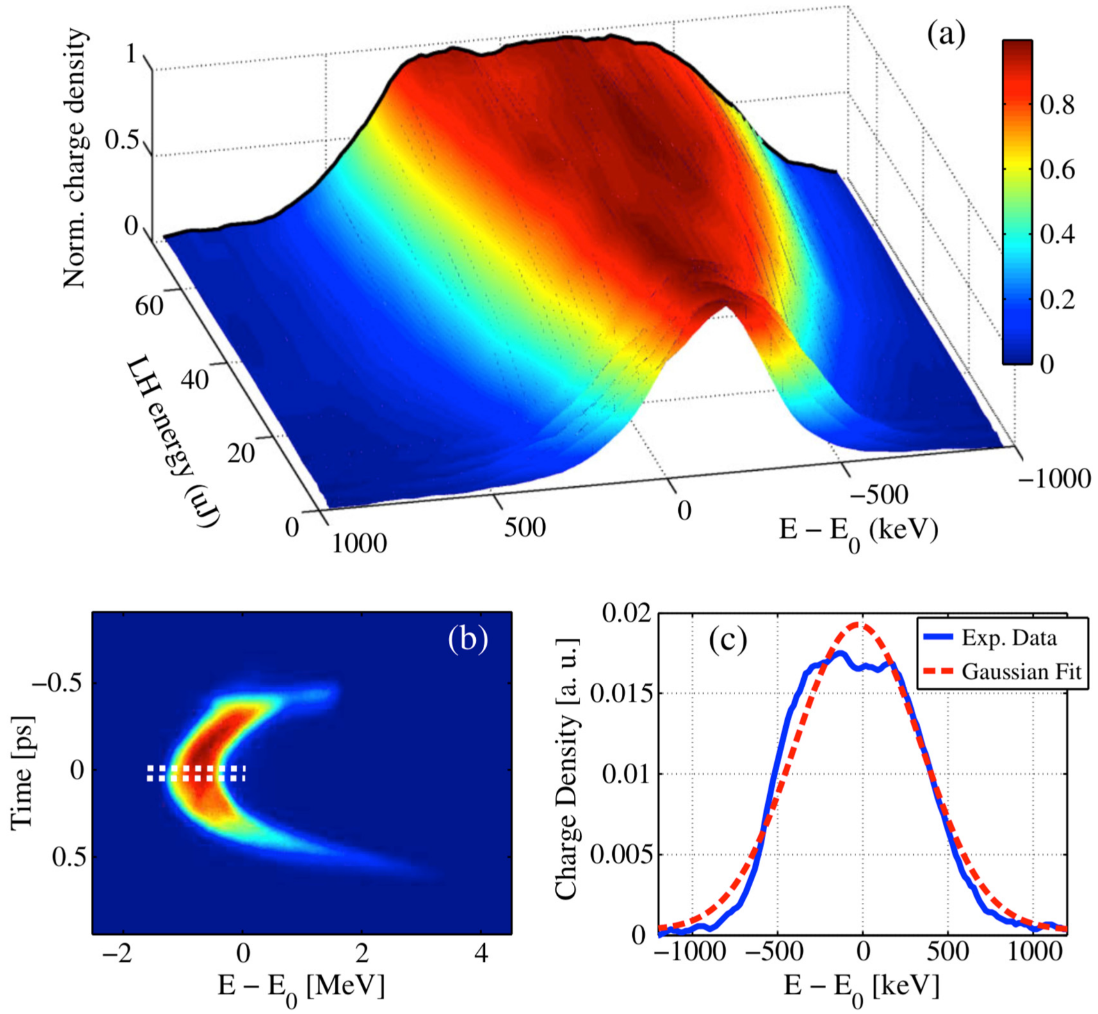
Only very small LH power required
Improvement of x2 in the output power







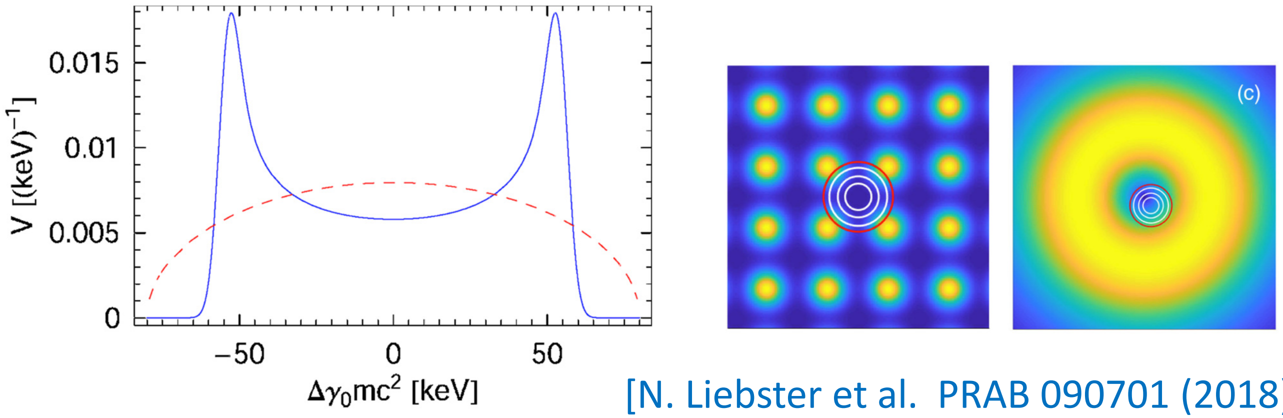
Energy distribution induced by LH



Most of FEL predictions are based on Gaussian distributions for e-beam parameters.

The shape of the laser heater induced energy distribution depends on the relative transverse size between the e-beam and the laser.

[Z. Huang et al., PRSTAB **7**, 074401 (2004)]

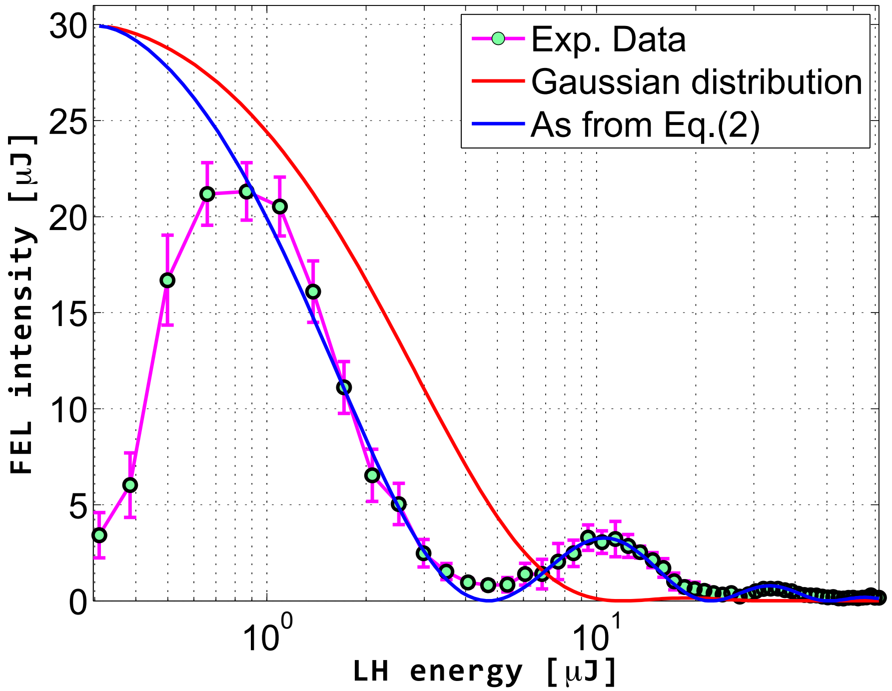


[N. Liebster et al. PRAB 090701 (2018)]
and poster THP034

- # Impact of LH energy spread distribution

Without gain, the FEL intensity is almost proportional to the square of the bunching b_m

FEL intensity vs. heating (no gain, 32 nm)



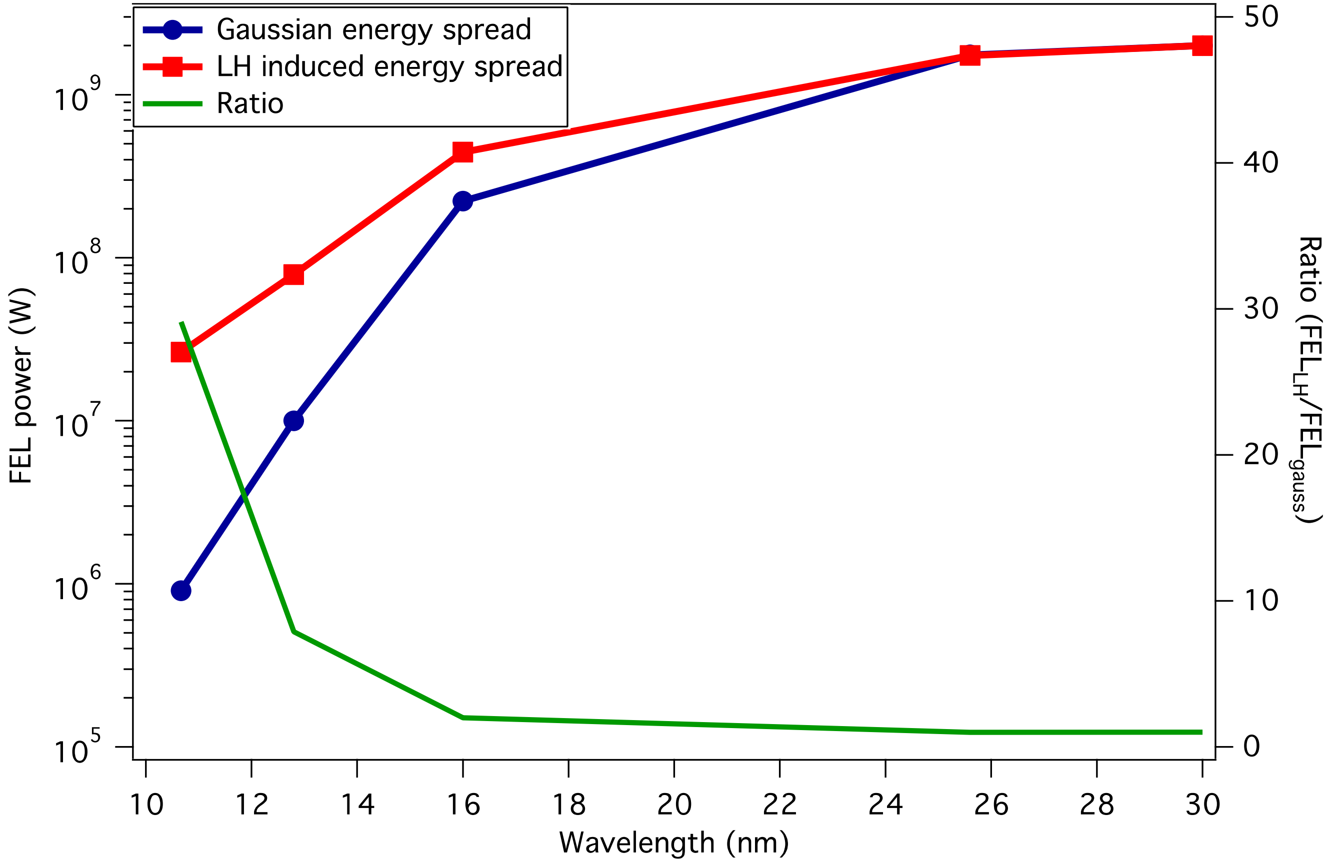
$$(2)\quad \mathbf{b_m} = \exp(-\frac{1}{2}\mathbf{m}^2\mathbf{D}^2\sigma_\gamma^2)\mathbf{J_m}(\mathbf{mD}\boldsymbol{\Delta}\gamma)\boxed{\mathbf{S_L}(\mathbf{mD}\boldsymbol{\Delta}\gamma, \frac{\sigma_\mathbf{r}}{\sigma_\mathbf{x}})}$$

$$\mathbf{S_L}(\mathbf{A}, \mathbf{B}) = \int \mathbf{RdR} \exp\left(-\frac{\mathbf{R}^2}{2}\right) \mathbf{J_0}\left[\mathbf{A} \exp\left(-\frac{\mathbf{R}^2}{4\mathbf{B}^2}\right)\right]$$

[E. Ferrari et al., Phys. Rev. Lett. 112, 114802 (2014)]

• Impact on HGHG performance

Increase of a factor x30 at high harmonics of HGHG

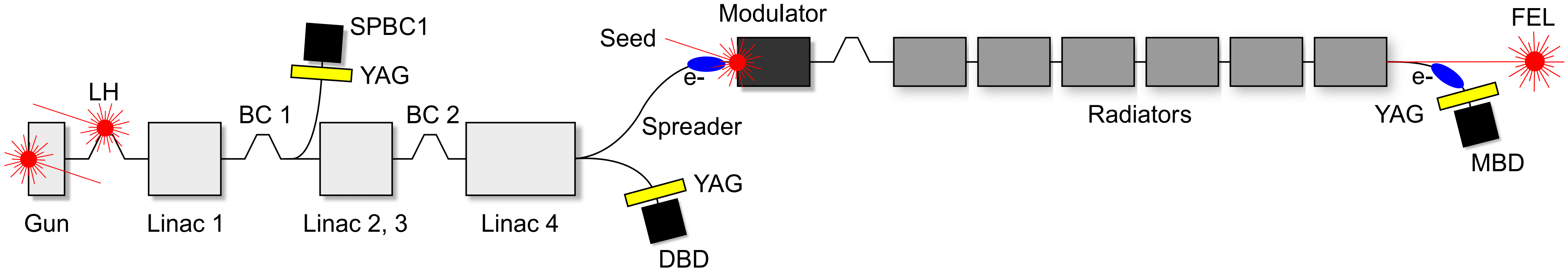


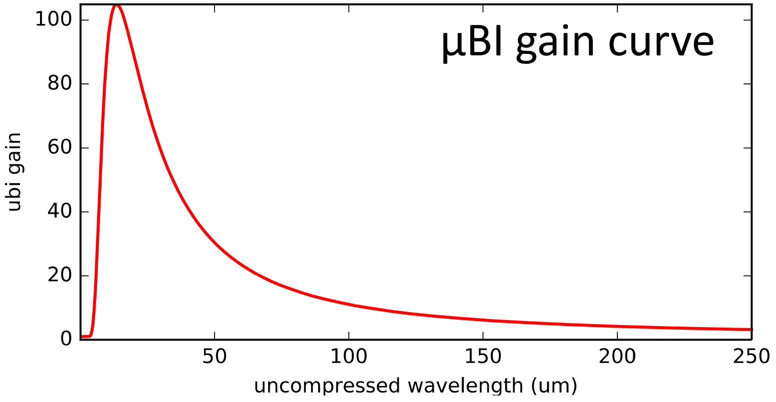
• Seeded linac

Take advantage of the microbunching instability gain to imprint a coherent modulation onto the e-beam.

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

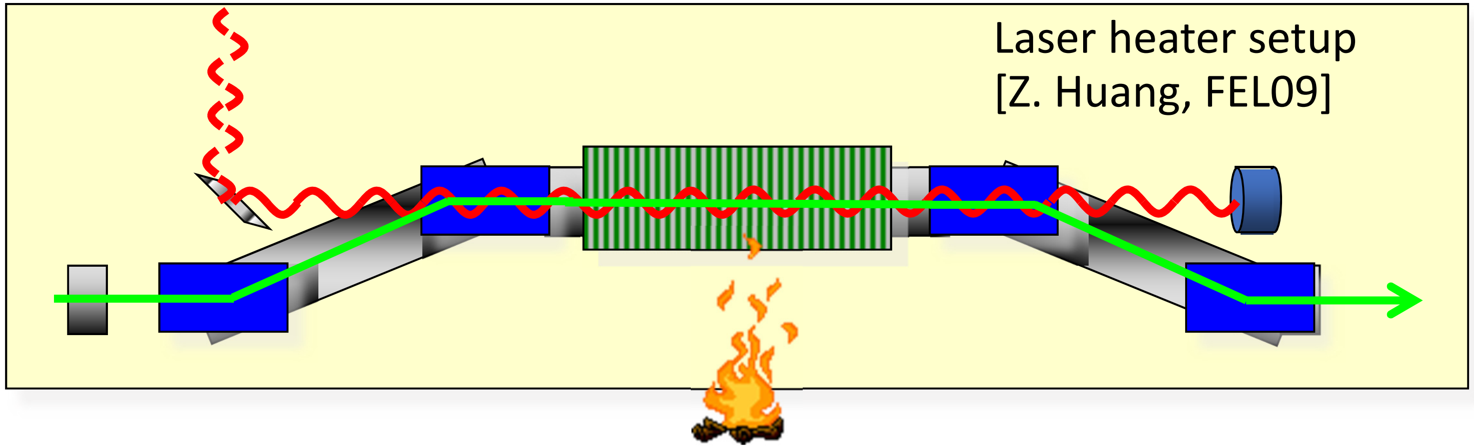
Achieved using a dedicated laser heater pulse shaping.

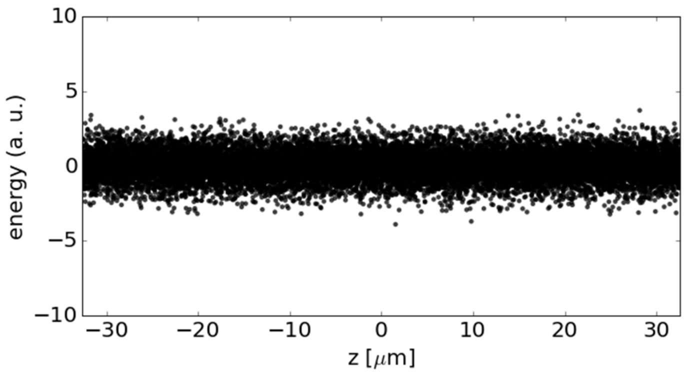


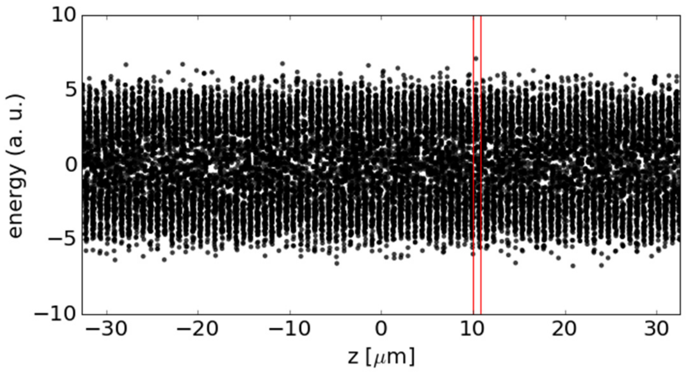


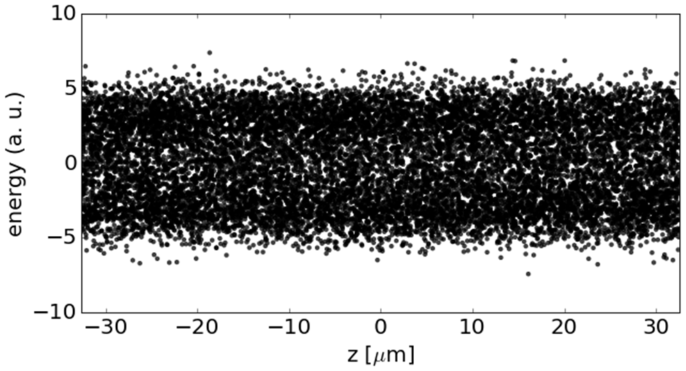
• Laser heater principle

Optical wavelength washed out at the exit of the chicane.







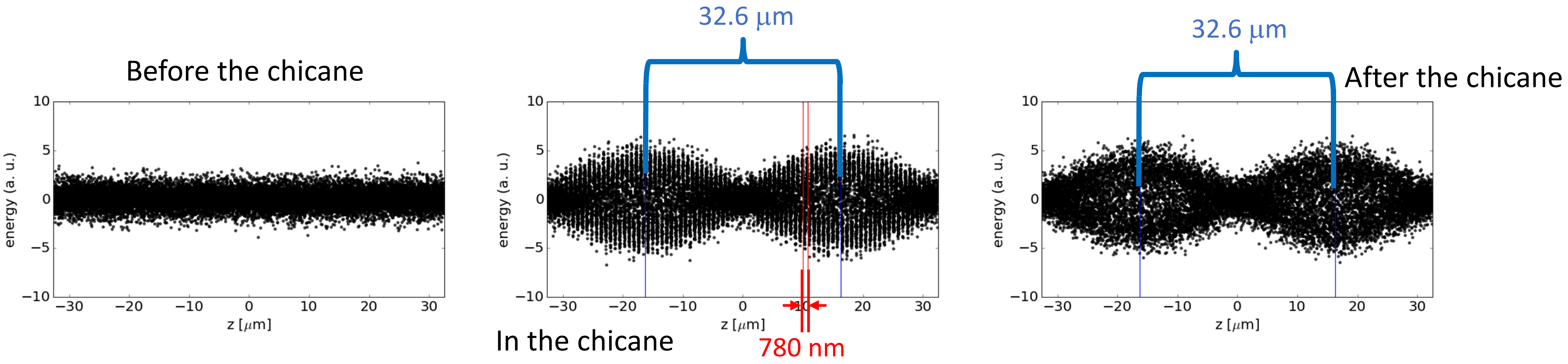


• Long wavelength modulation in LH

Smearing condition for LH chicane: $\lambda << 2\pi\ |R_{52}\ \sigma_{x'}|$ [Z. Huang et al., PRSTAB **7**, 074401 (2004)]

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

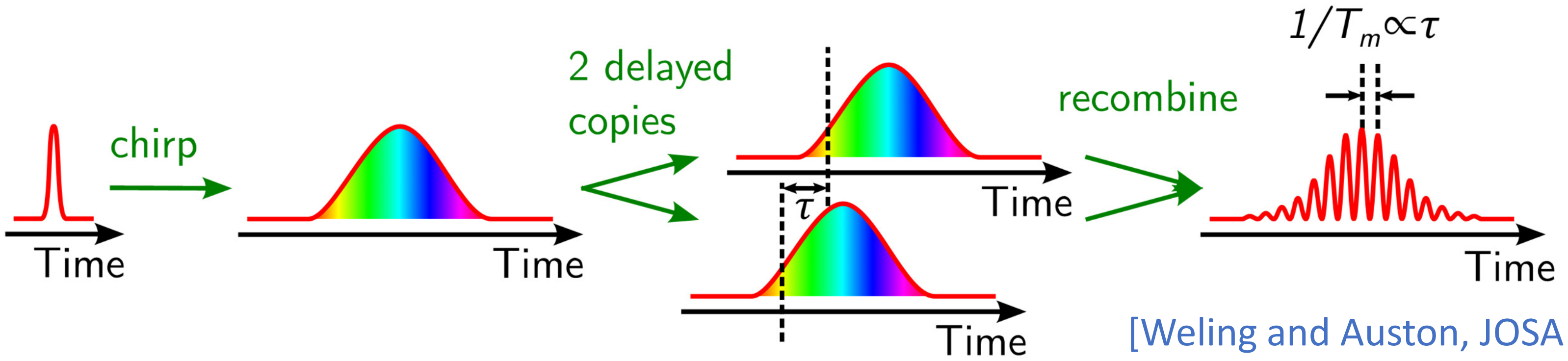
$\lambda_{LH} = 780\ nm$ $\lambda_B = 32.6\ \mu m$



A long wavelength modulation can propagate downstream the LH chicane

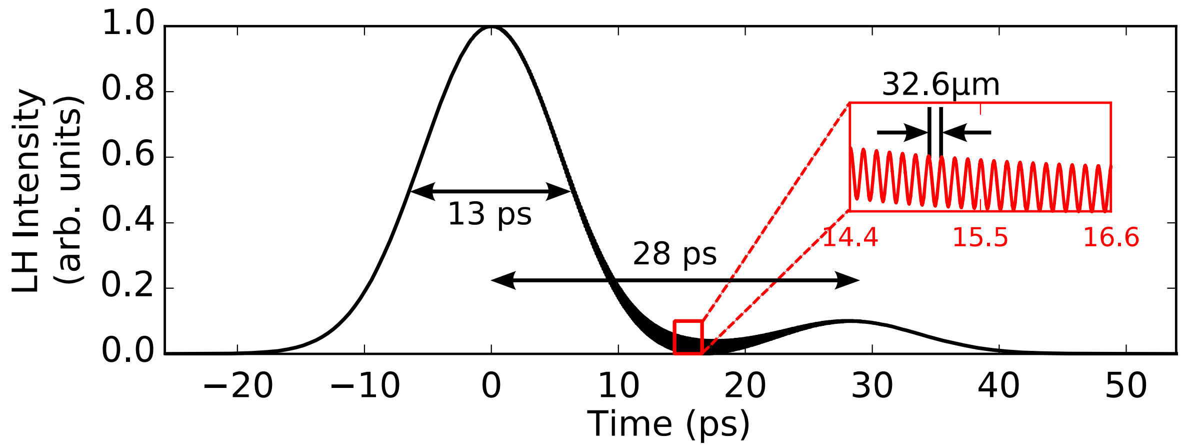
• LH pulse shaping

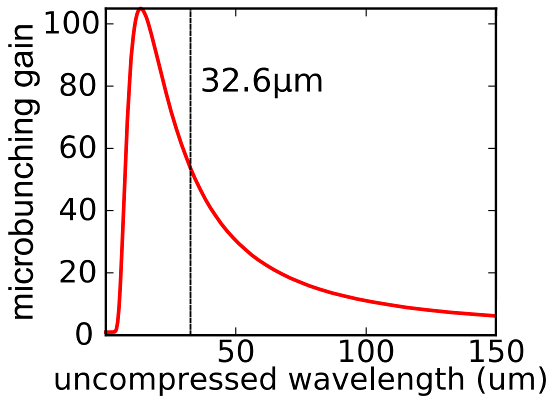
Generation of a modulated laser pulse using chirped pulse beating technique



[Weling and Auston, JOSA B 13, 2783 (1996)]

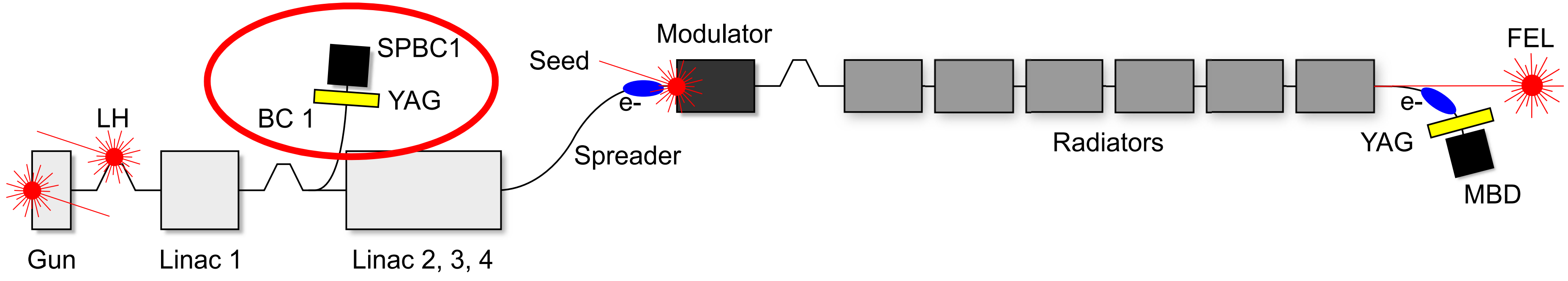
LH intensity profile with beating frequency inside the gain curve of μBI



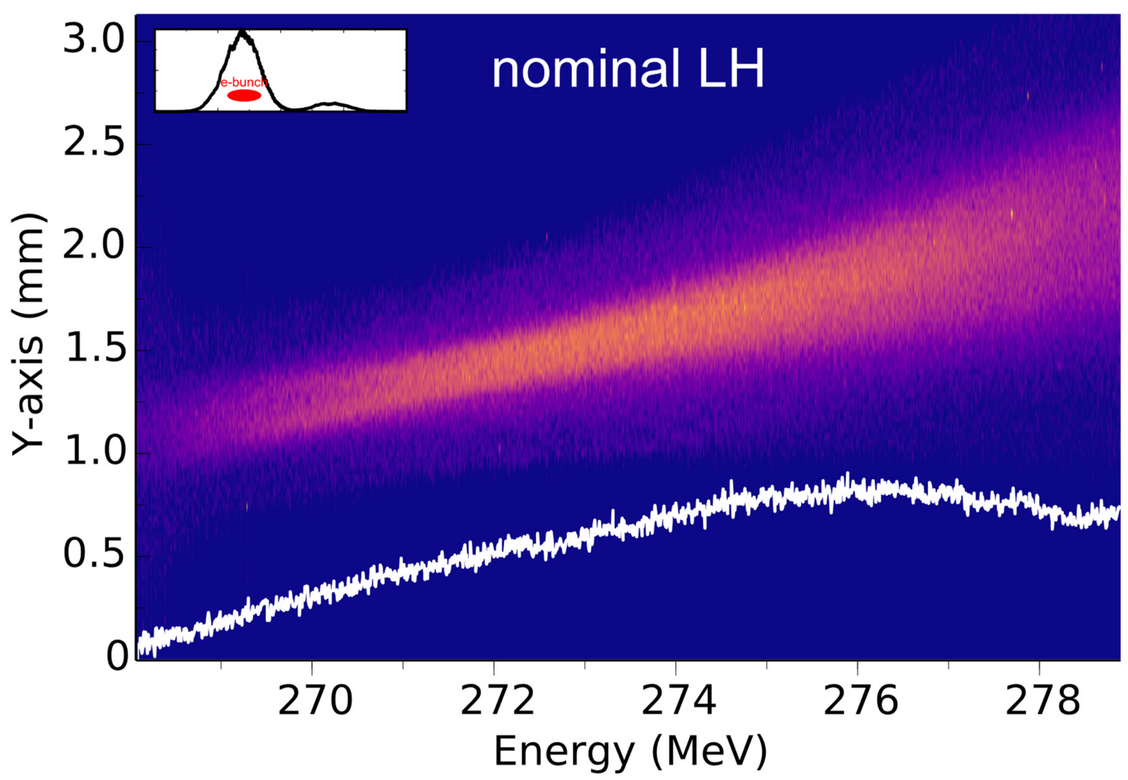


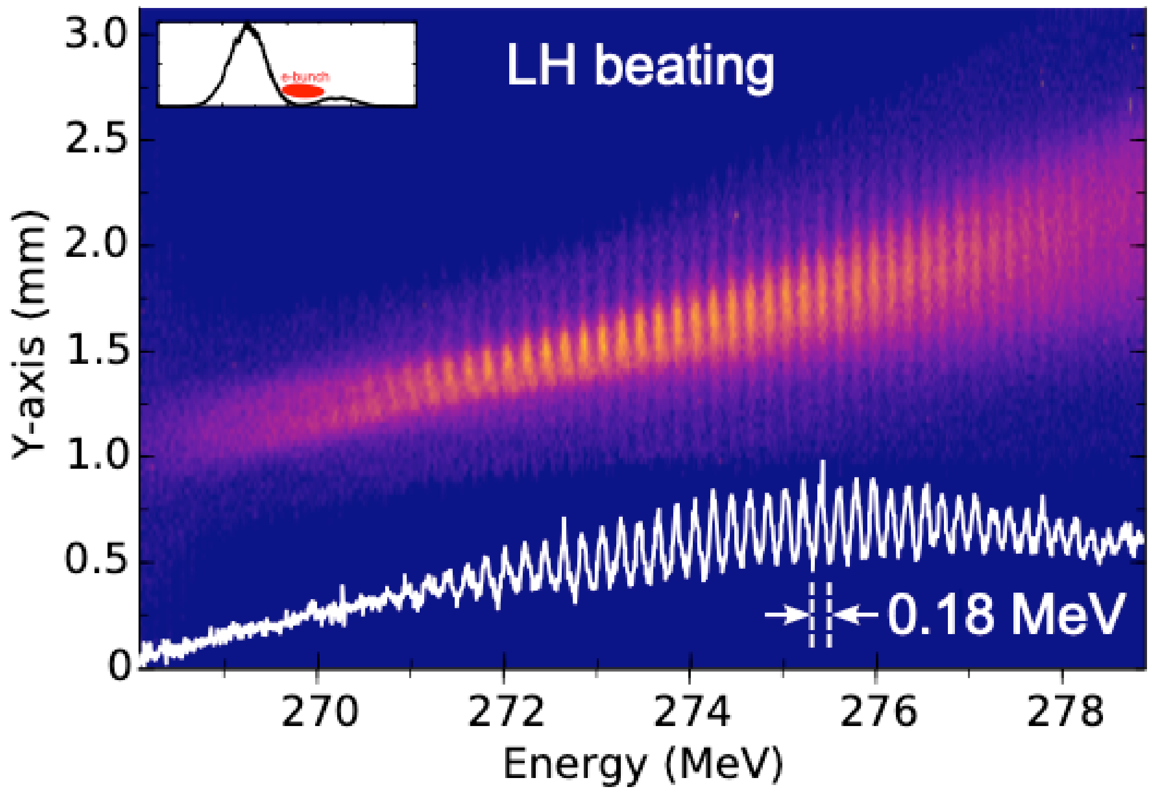
- Measurement of the modulation

Electron spectrometer station after the bunch compressor.



Modulated energy profile



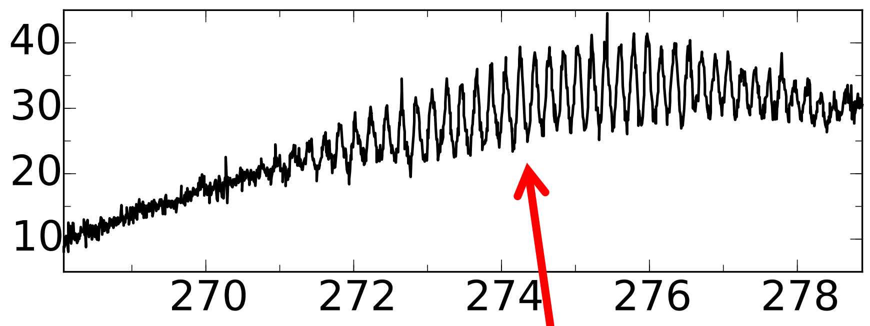


Linear energy chirp (h = -20.2 m^{-1}) --- longitudinal position mapped to energy.
0.18 MeV => 32.4 µm modulation wavelength

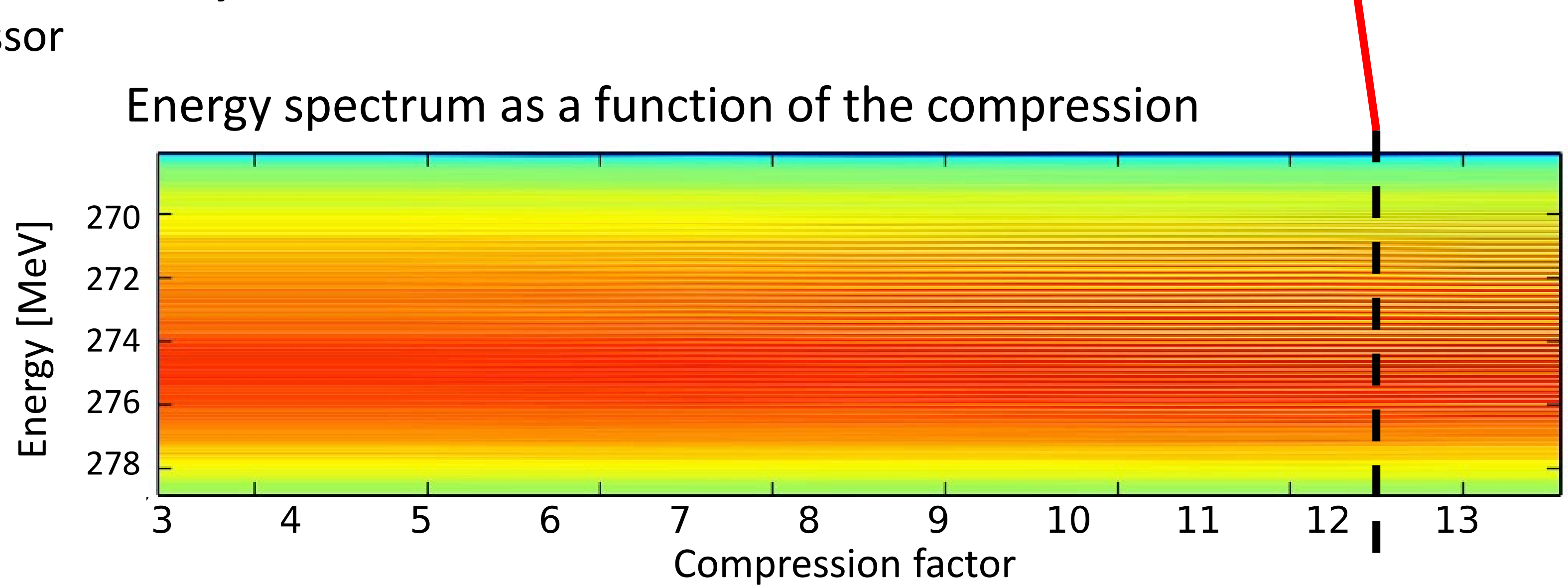
• Microbunching amplification

At the LH exit, the modulation is mainly an **energy spread modulation** (at the beating wavelength)

It can be amplified by the μBI gain and **converted** into **energy and/or density modulation** at the bunch compressor



Energy spectrum as a function of the compression



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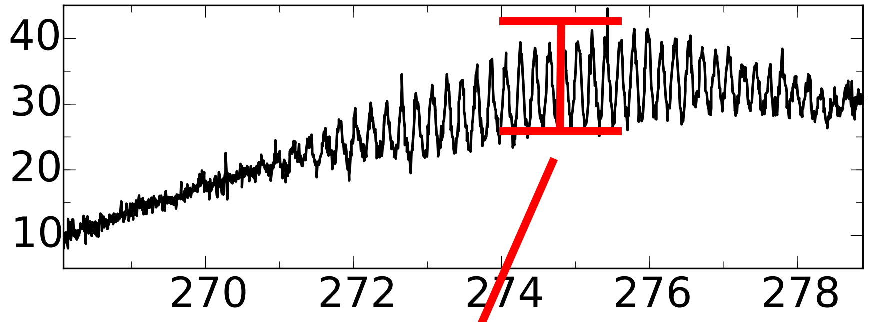
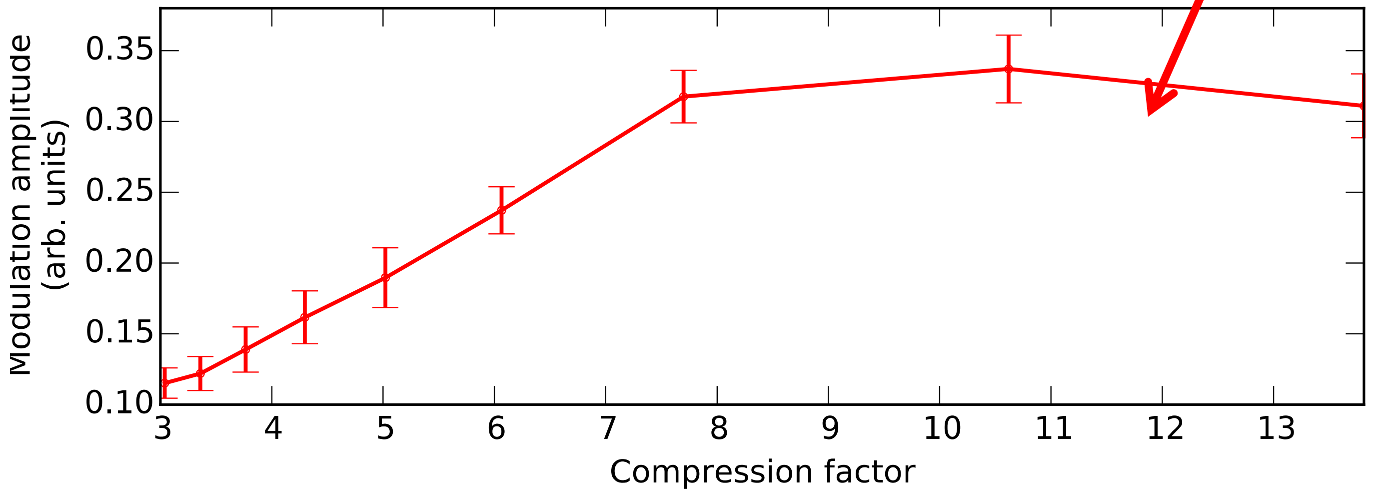
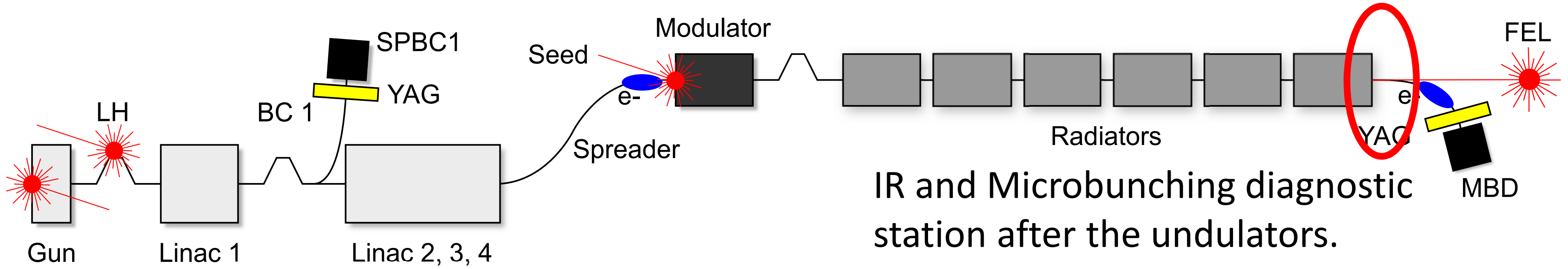


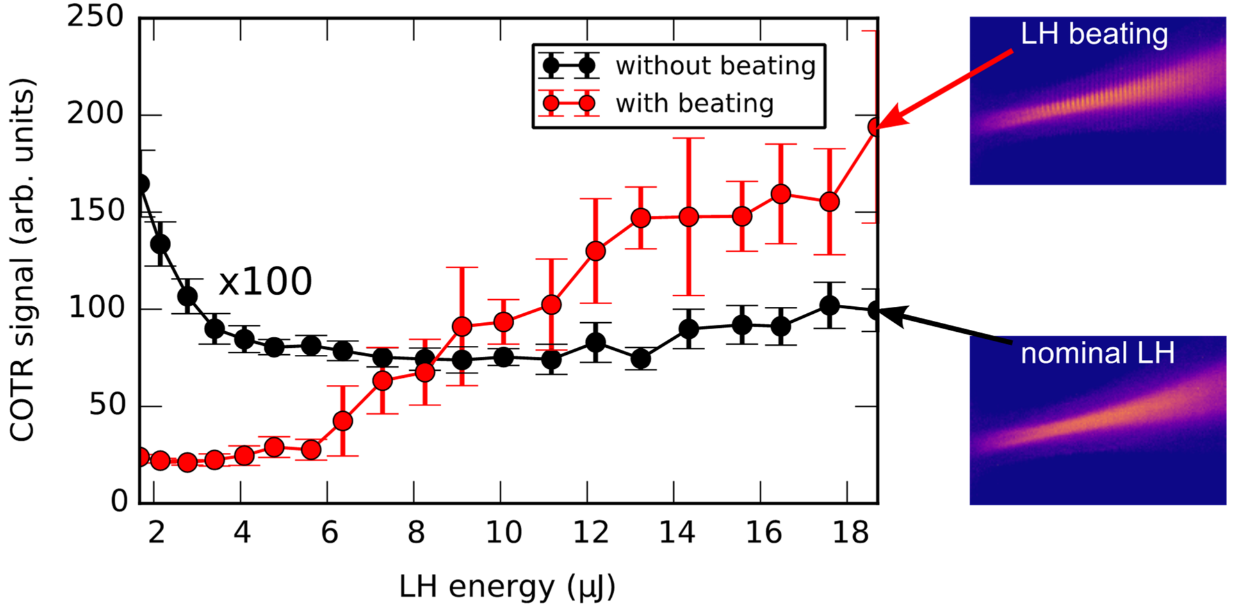


The amplitude of the modulation is amplified by the compression

• Microbunched electron beam in undulators

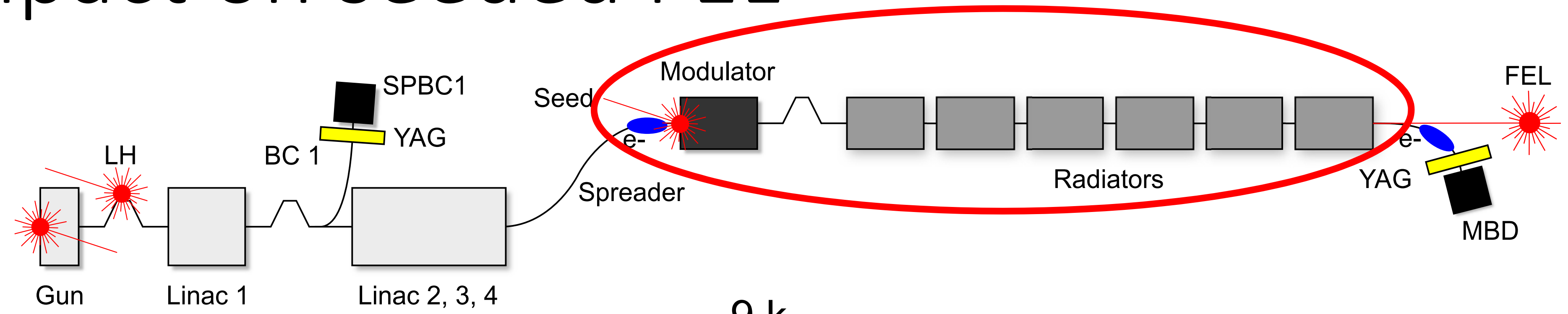


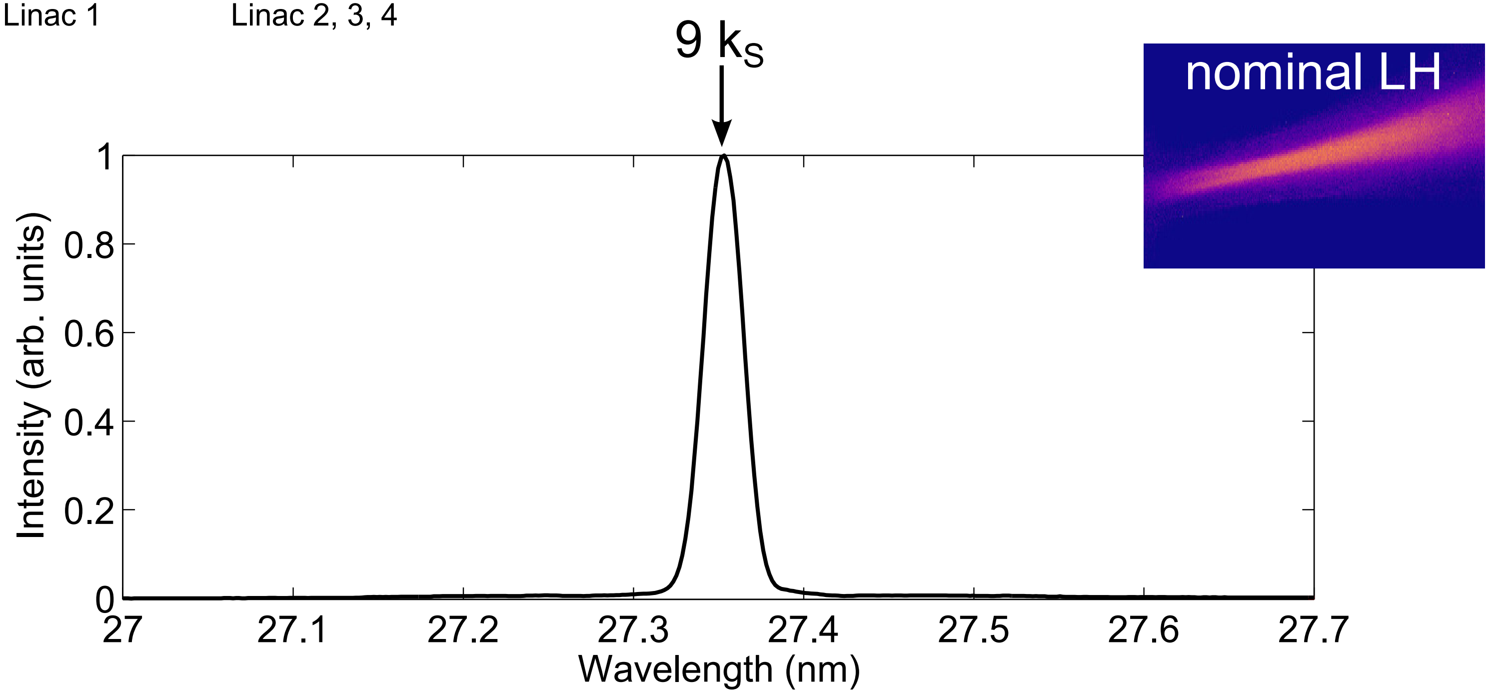
IR and Microbunching diagnostic station after the undulators.



Observation of strong coherent transition radiation (COTR) in the IR domain at the exit of the undulators in case of microbunched e-beam.

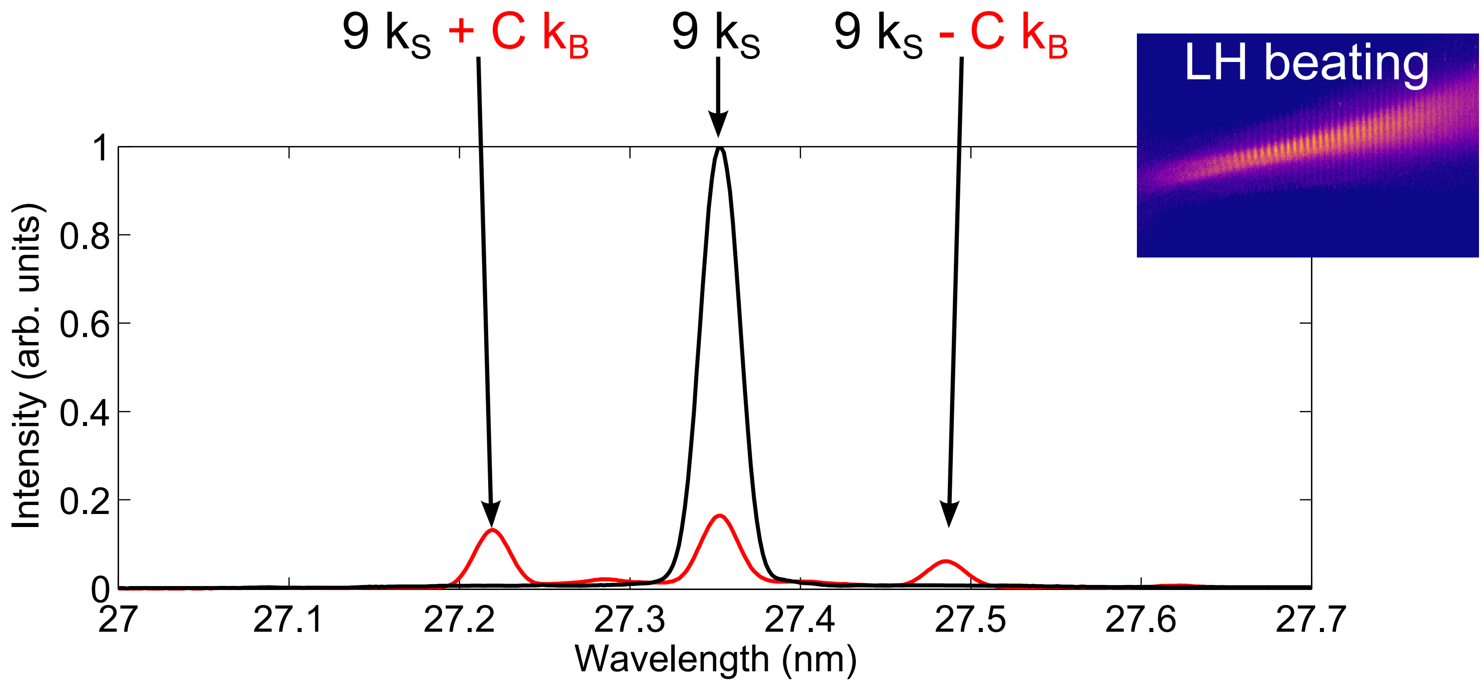
- Impact on seeded FEL





- Impact on seeded FEL

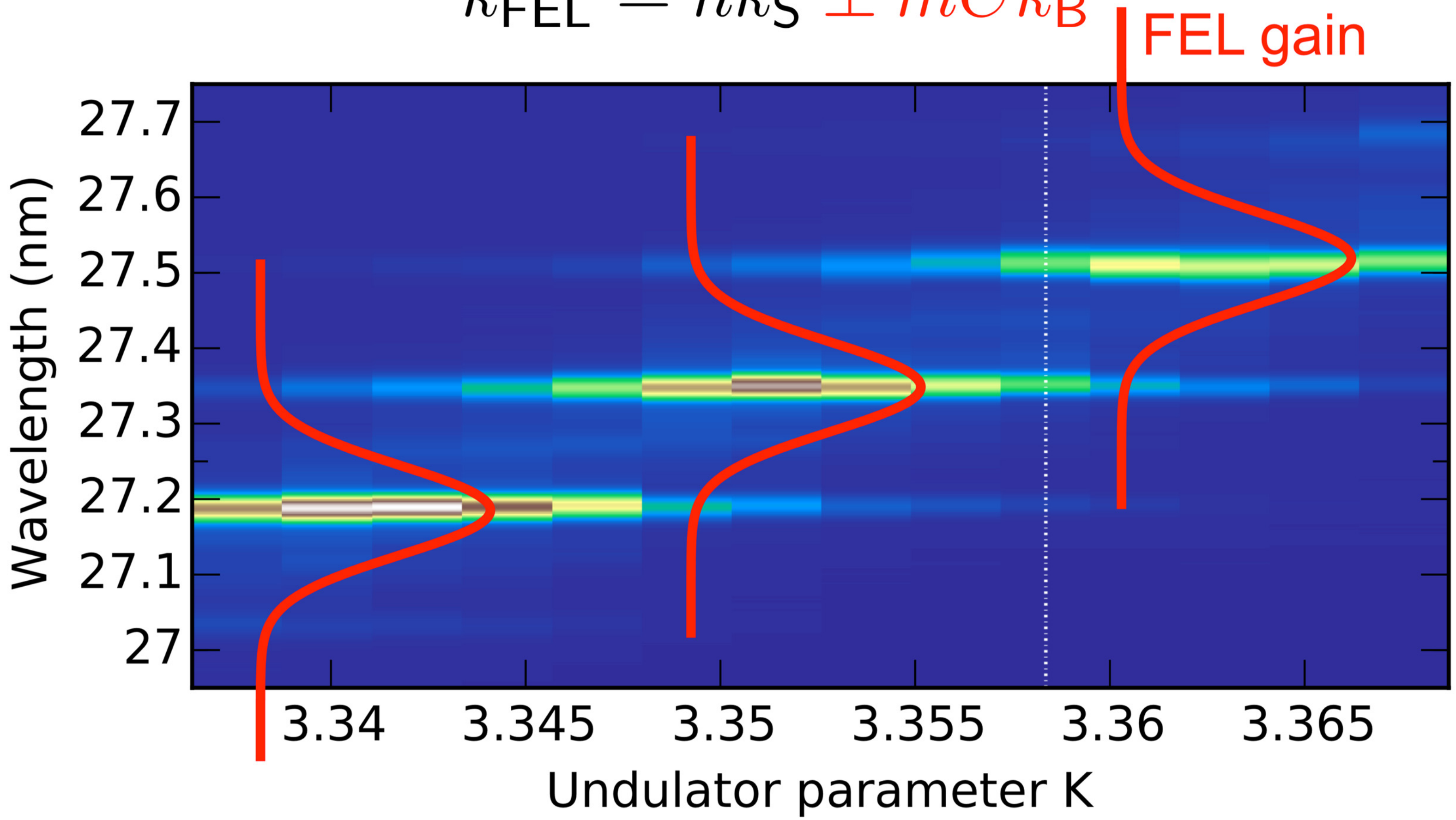
$$k_{\mathrm{FEL}} = hk_{\mathrm{S}} \pm mCk_{\mathrm{B}}$$



Observation of sidebands coming from a frequency mixing between the seed wavelength and the beating wavelength (scaled by the compression factor C).

- FEL sidebands selection

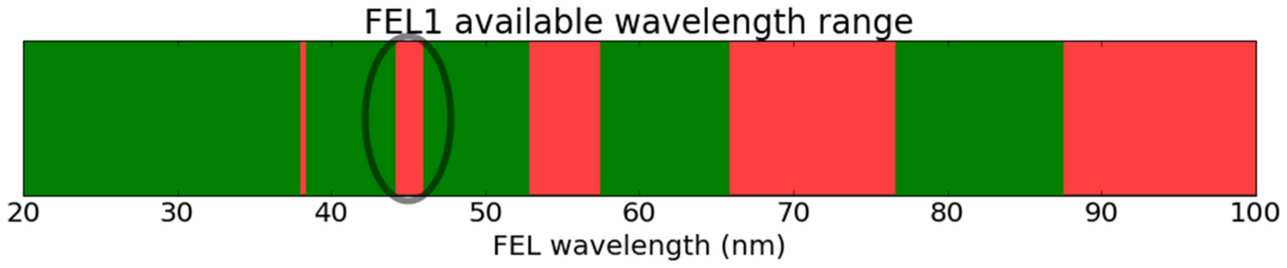
$$k_{\mathrm{FEL}} = hk_{\mathrm{S}} \pm mCk_{\mathrm{B}}$$



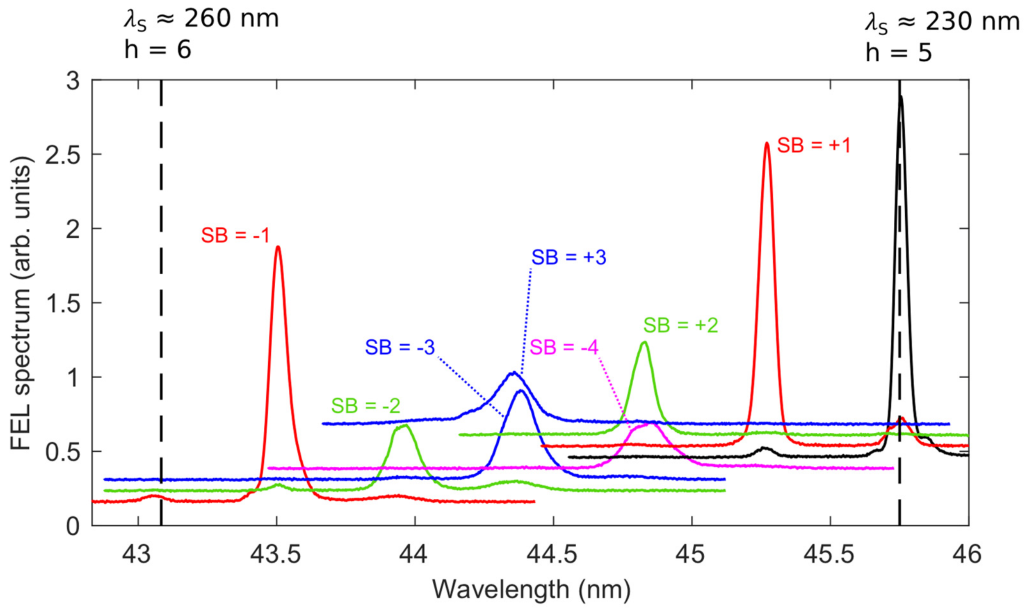
Selection and FEL amplification of one sideband by tuning the radiator resonance condition.

• The dark side of a seeded FEL

FEL-1 range for the ”nominal” FERMI seed laser operation (230 – 260 nm)

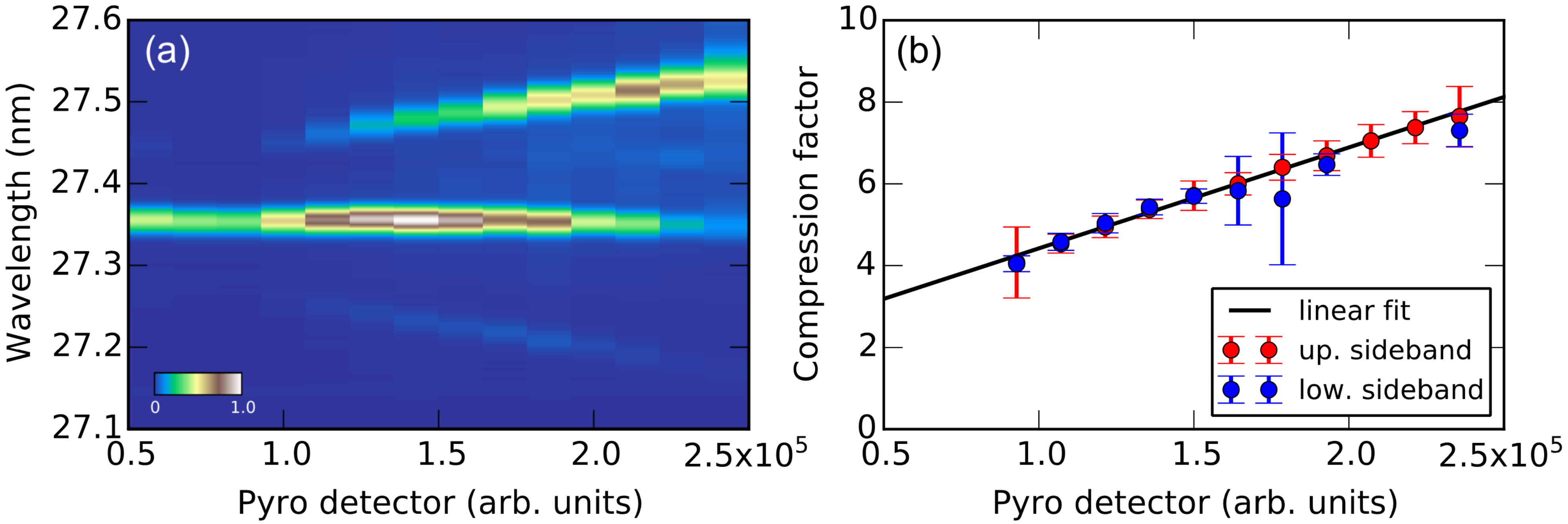


Increased tunability via LH beating-induced sidebands



- Tunability of FEL spectrum

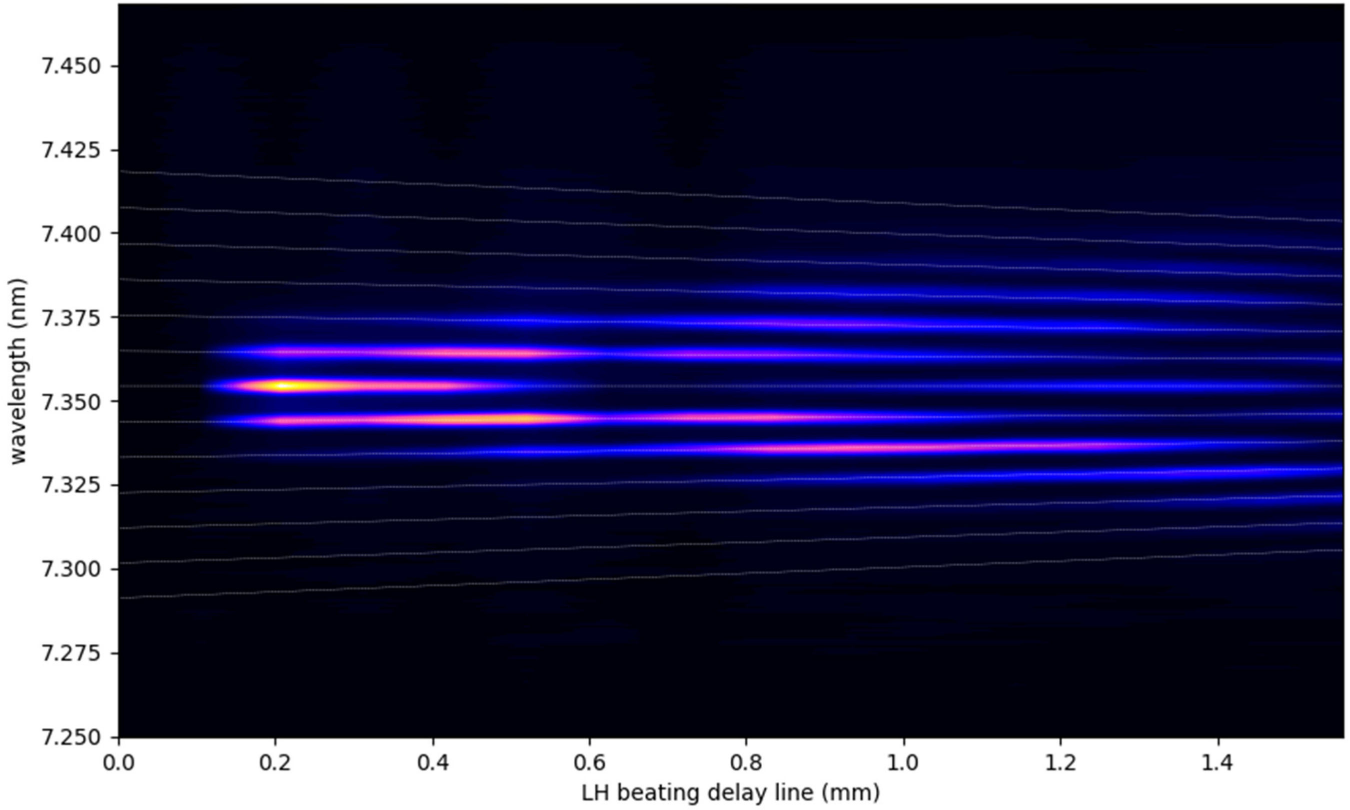
$$k_{\mathsf{FEL}} = h k_{\mathsf{S}} \pm m C k_{\mathsf{B}}$$



Tuning of the sideband position by changing the compression factor C.

• Also works with EEHG/ECHO

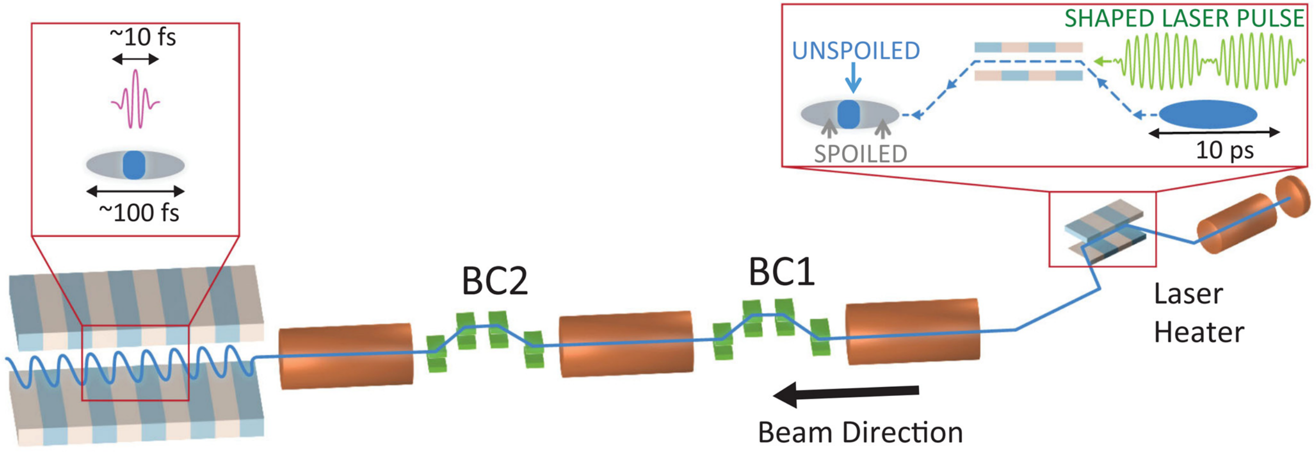
Tuning of the sideband position by changing the beating wavelength k_B.



EEHG spectrum as a function of the modulation wavelength:

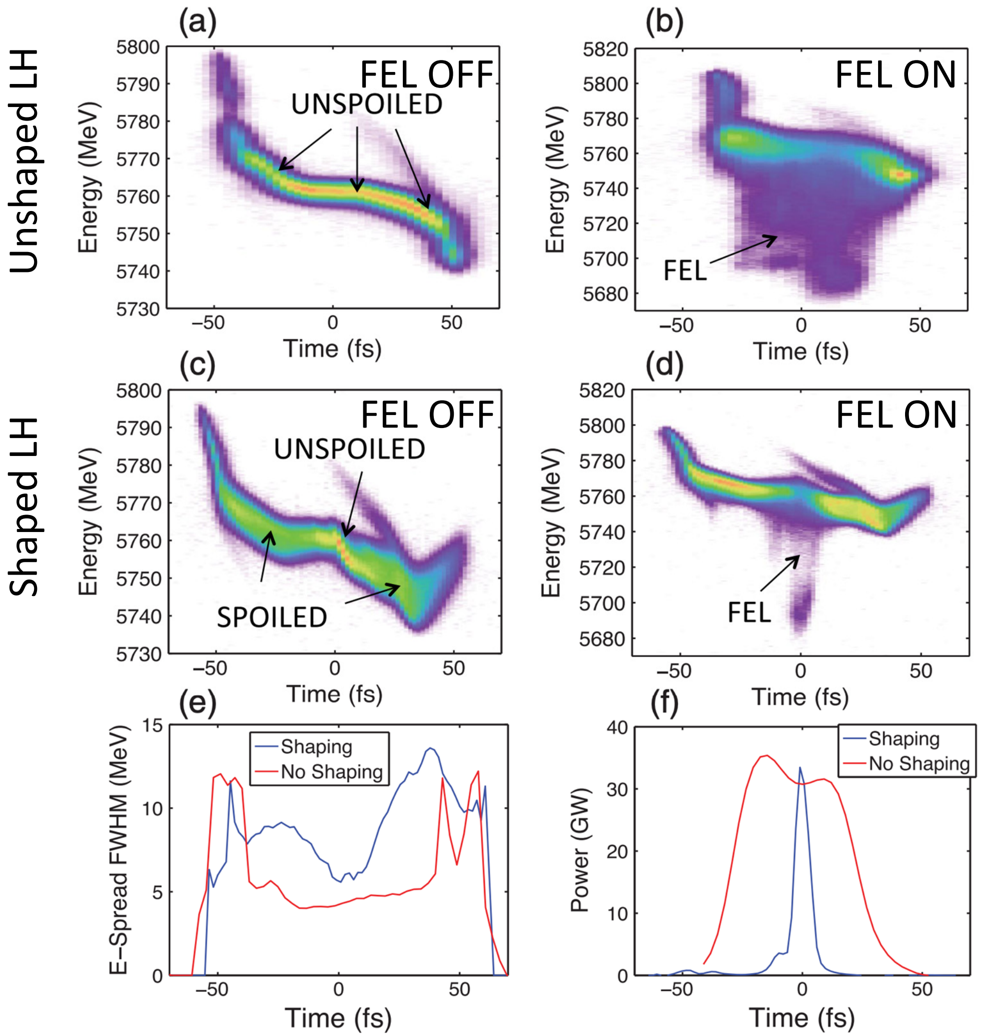
- multiple sidebands are visible.
- FEL gain bandwidth is too large to select only one line.

• Optical shaping of x-ray SASE FEL



[A. Marinelli et al., PRL 116, 254801 (2016)]

- LH pulse shaping technique to tailor the temporal profile of XFEL pulses at the fs-scale.
- Reduction of pulse duration, from 50 fs to 11 fs FWHM.
- The method is directly applicable to high average power machines.



Conclusions

- LH: a powerful tool to control the FEL spectro-temporal properties.
  - Generation of tunable, incommensurate, multicolor FEL pulses.
  - Non-gaussian e-beam heating for higher harmonic frequency conversion.
  - LH pulse shaping for FEL pulse duration control.
    [A. Marinelli et al., PRL 116, 254801 (2016), V. Grattoni, IPAC17, WEPAB034]

- LH pulse shaping: an alternative method to probe and investigate the microbunching instability.

- The laser heater continues to be a **surprising device**, with extremely rich and interesting physics.

Thank you

Thank you one more time to the FEL2017 prize award committee.

A special thank you to the FERMI, PhLAM, Synchrotron SOLEIL, COXINEL and SwissFEL teams, and to all the colleagues we had the honor and pleasure to work with in these years.