Compact and versatile infrared spectrometer for microbunching detection

LEDS 2023 - ENEA Frascati, Rome

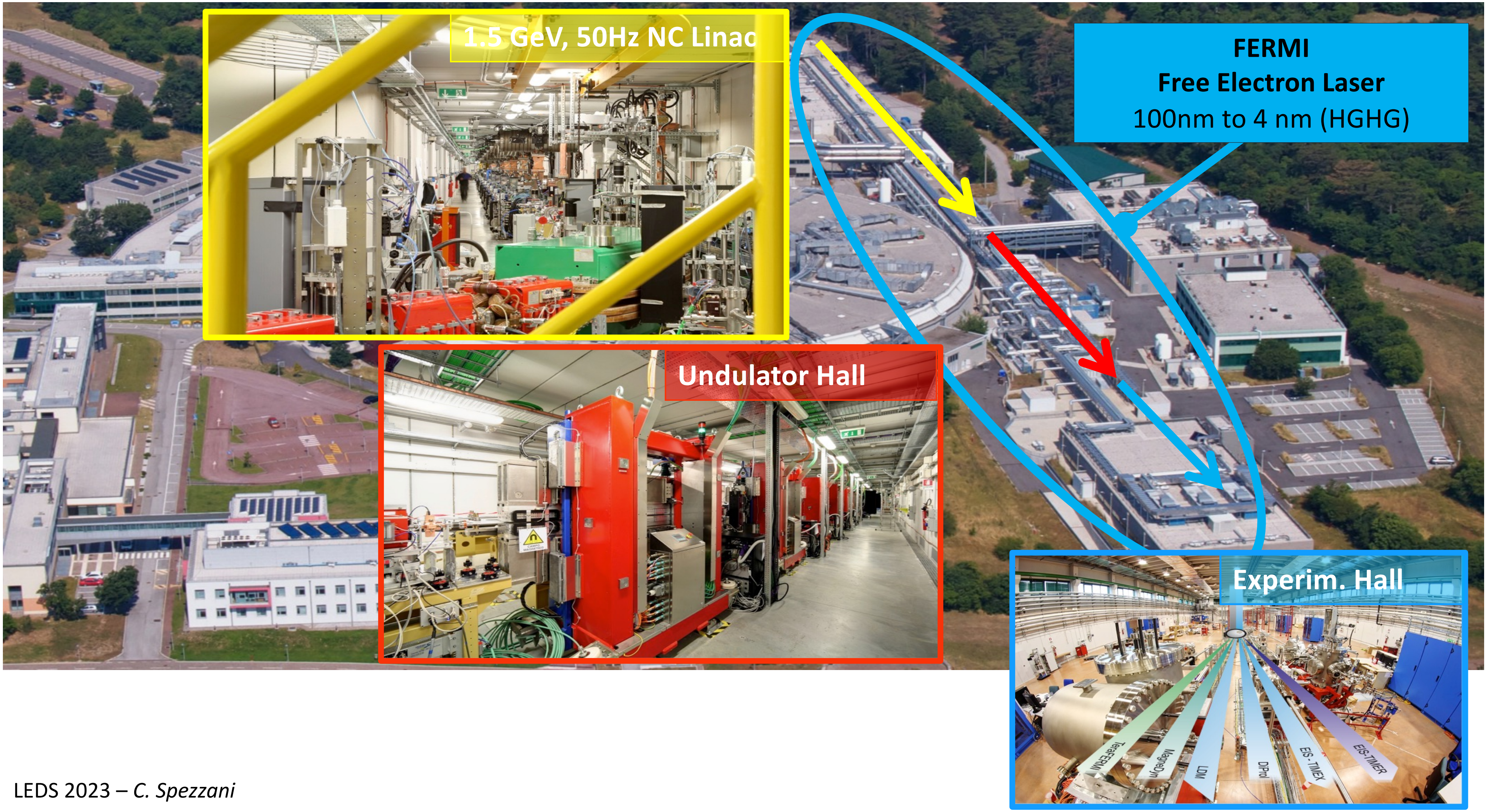
Carlo Spezzani

on behalf of

E. Allaria, A. Brynes, E. Ferrari, L. Giannessi, S. Di Mitri, G. Perosa, E. Roussel, S.Spampinati, M. Veronese

and the FERMI team

FERMI Free Electron Laser



FERMI
Free Electron Laser
100nm to 4 nm (HGHG)

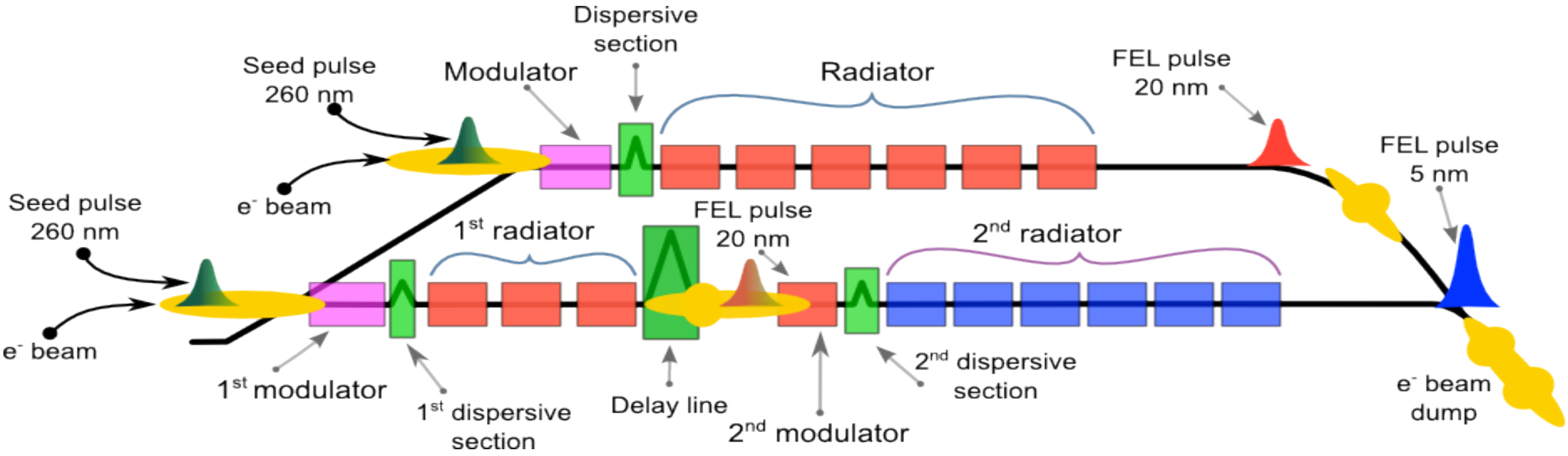
1.5 GeV, 50Hz NC Linac

Undulator Hall

Experim. Hall

FERMI seeded FELs

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	1x10^{-3} (FWHM)
Pulse length	<100 fs
Pulse energy	20-100 μJ

FEL-2 (Nat. Photon. **7**, 913 (2013), Jour.Synch.Rad 22 (2015))	
Tuning range	20-4 nm (60-300eV)
Relative bandwidth	1x10^{-3} (FWHM)
Pulse length	~50 fs
Pulse energy	10-70μJ

Single stage Seeded FEL amplifier - FEL1
High Gain Harmonic Generation (HGHG)

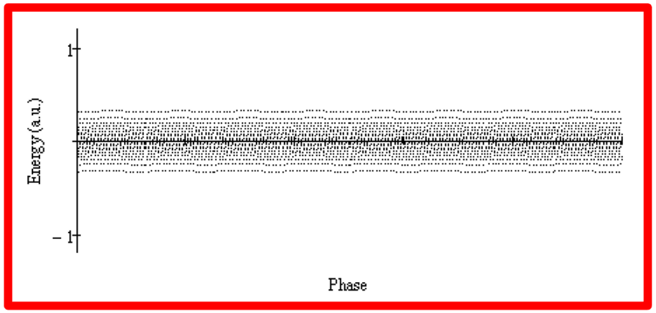
modulator

High gain radiator tuned at nth harmonic

Seed
THG or
tuneable OPA

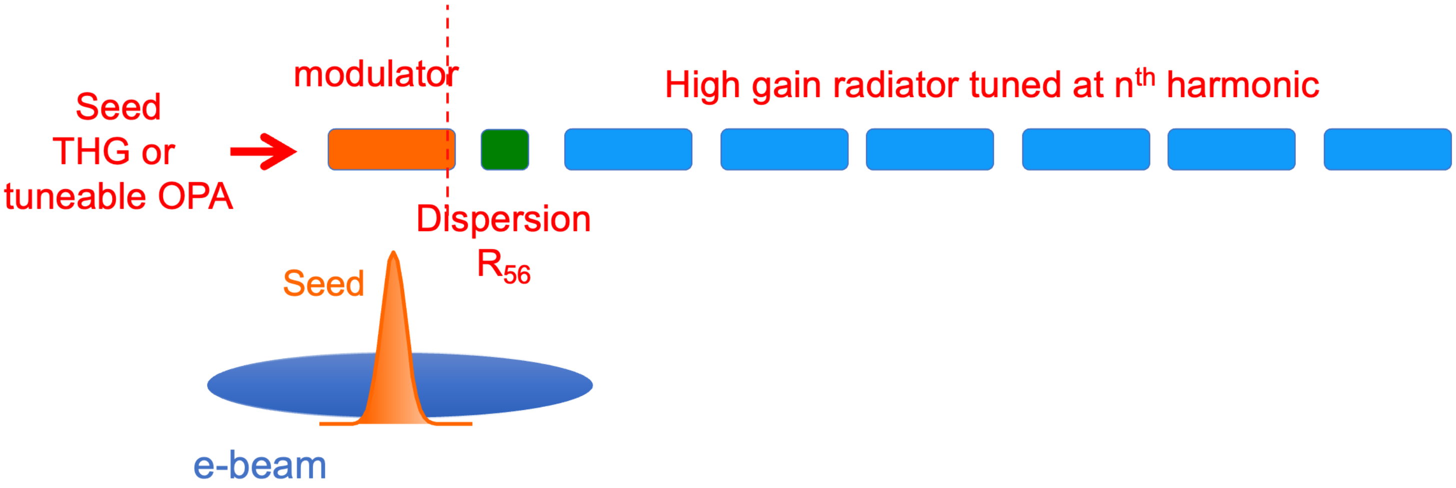
Dispersion
R_{56}

e-beam



Fresh beam

Single stage Seeded FEL amplifier - FEL1
High Gain Harmonic Generation (HGHG)



Seed
THG or
tuneable OPA

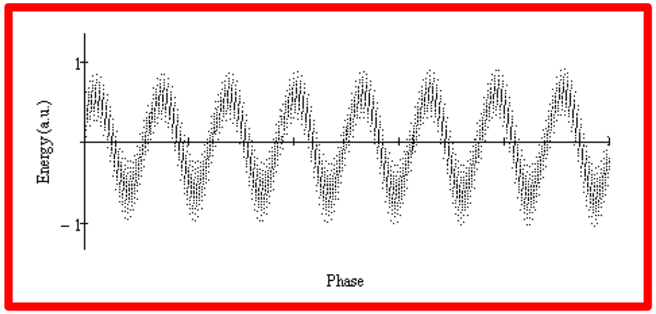
modulator

High gain radiator tuned at n^{th} harmonic

Dispersion
R_{56}

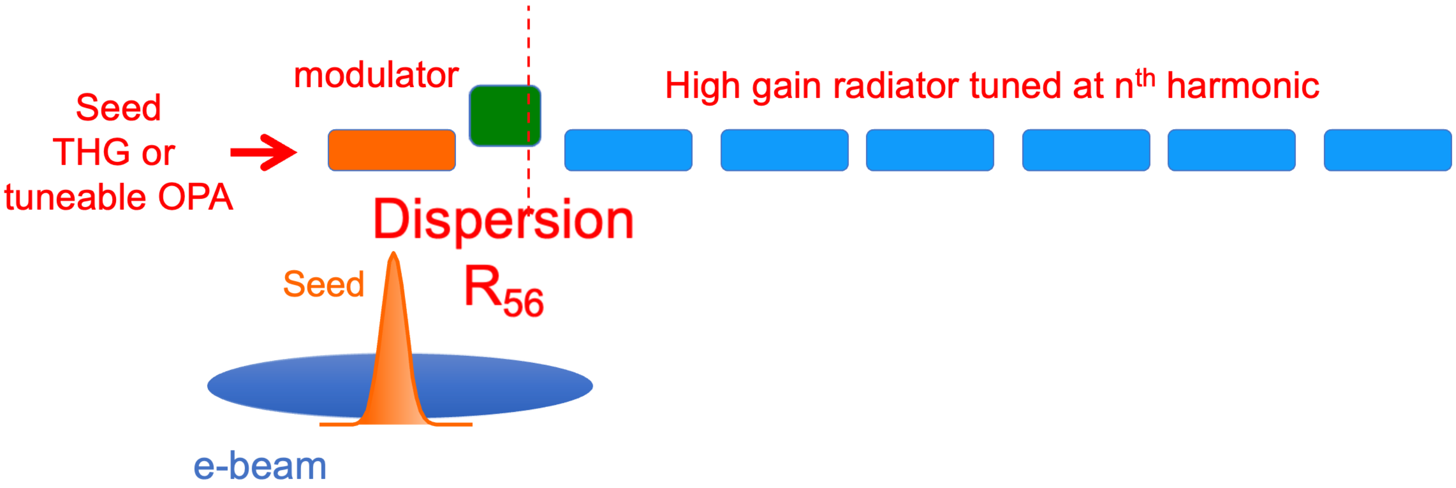
Seed

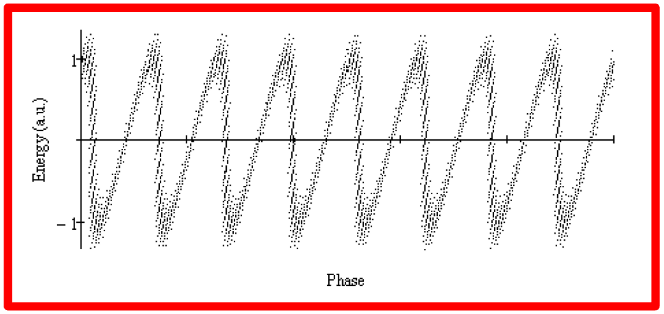
e-beam



Modulated beam

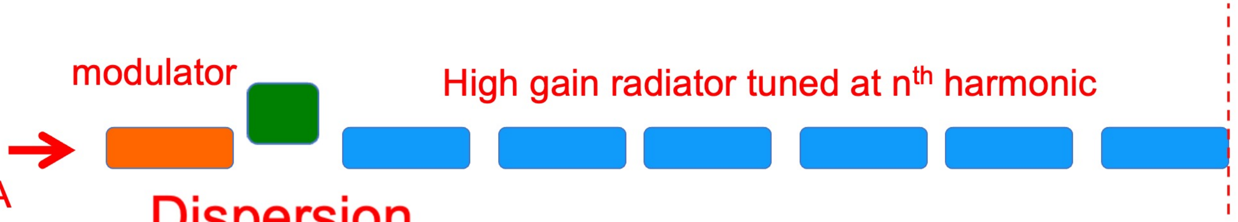
Single stage Seeded FEL amplifier - FEL1 High Gain Harmonic Generation (HGHG)





Bunched beam

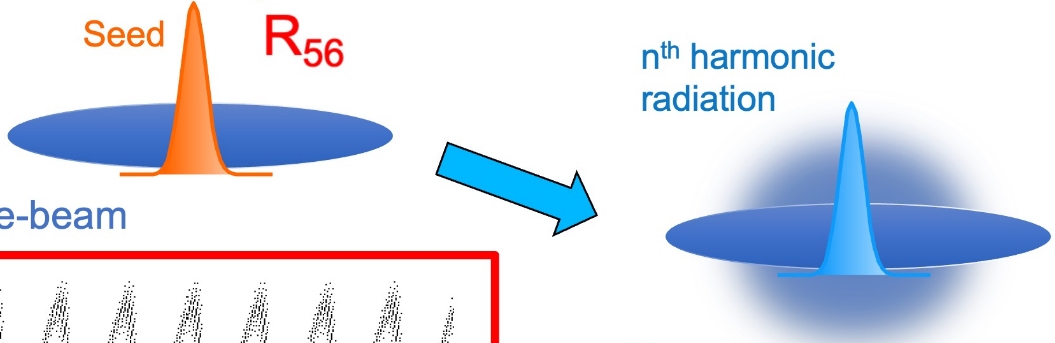
Single stage Seeded FEL amplifier - FEL1
High Gain Harmonic Generation (HGHG)


Seed
THG or
tuneable OPA

modulator

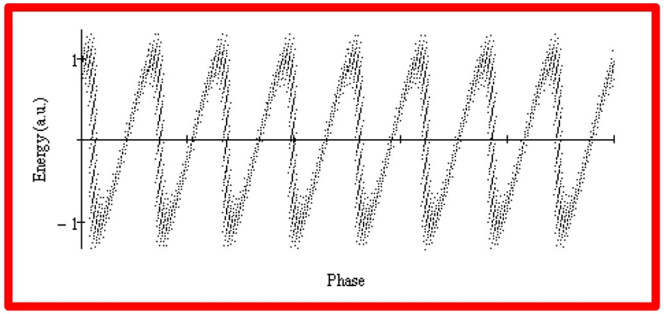
High gain radiator tuned at nth harmonic

Dispersion

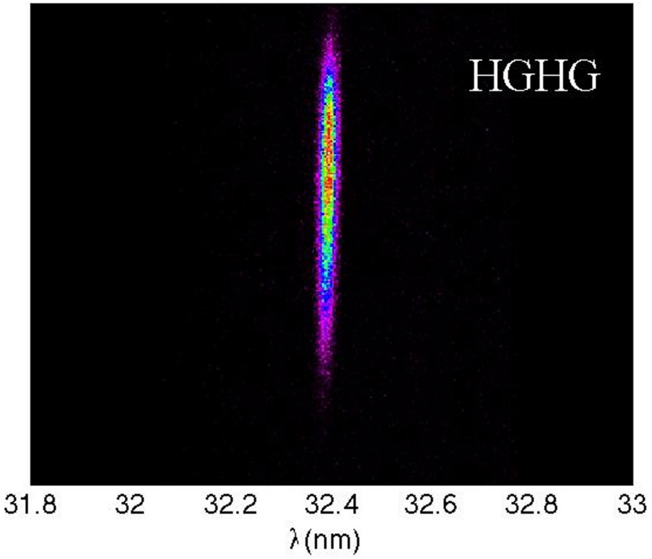


e-beam

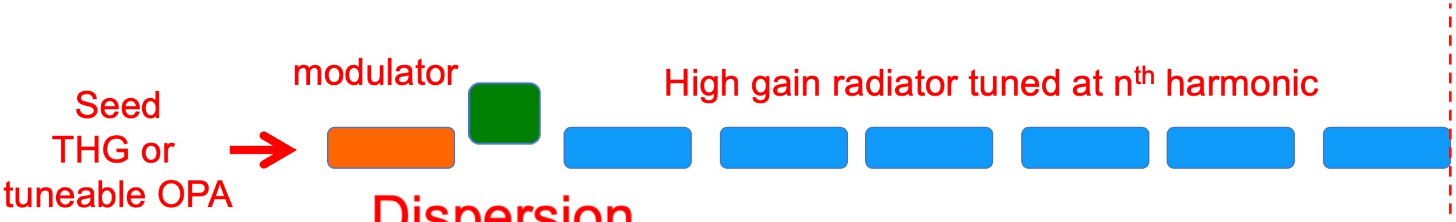
Charge density
modulated e-beam



Bunched beam



Single stage Seeded FEL amplifier - FEL1
High Gain Harmonic Generation (HGHG)

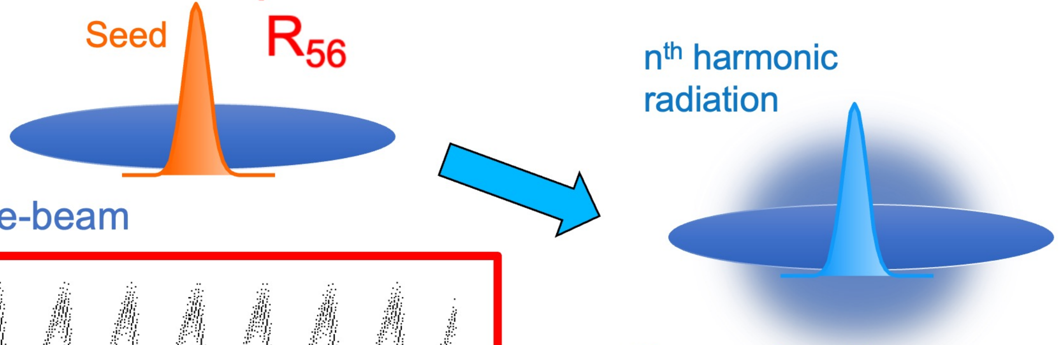


Seed
THG or
tuneable OPA

modulator

High gain radiator tuned at nth harmonic

Dispersion



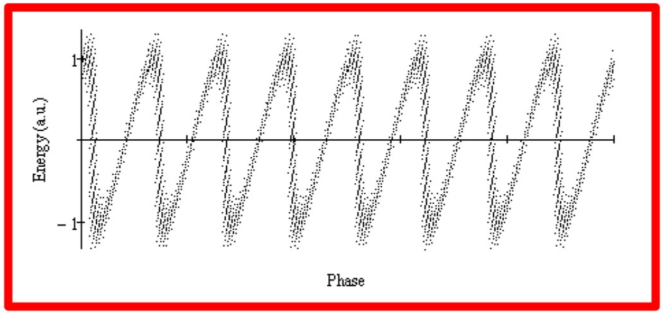
Seed

R_{56}

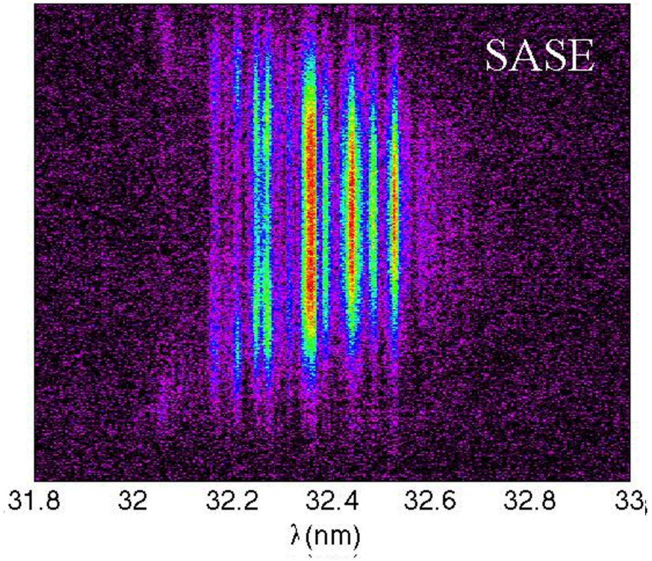
e-beam

nth harmonic
radiation

Charge density
modulated e-beam



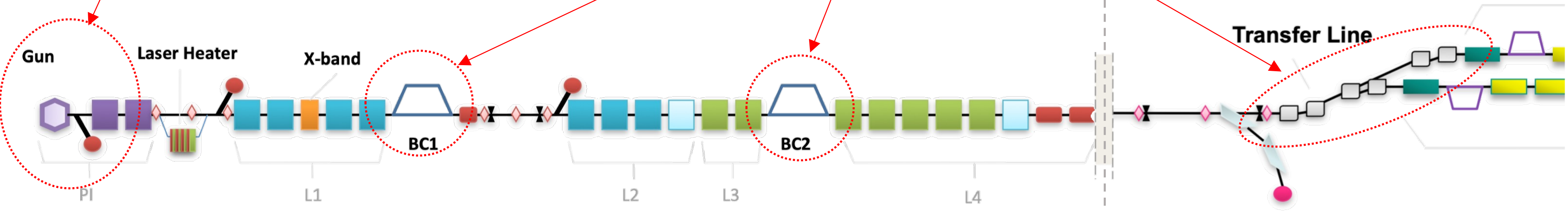
Bunched beam



Sources of Micro-Bunching Instability at FERMI

- Longitudinal space charge (LSC)
- Bunch imperfections

- Coherent Synchrotron Radiation (CSR)



- Longitudinal Wake fields

Linear Accelerator

Undulator Hall

Methods to mitigate MBI

- Laser Heater: increases the uncorrelated energy spread
- Linear optics control to dump MBI gain

More details in A.D. Brynes' talk
Thu 5/10, 10:10 A.M.

Sources of Micro-Bunching Instability at FERMI

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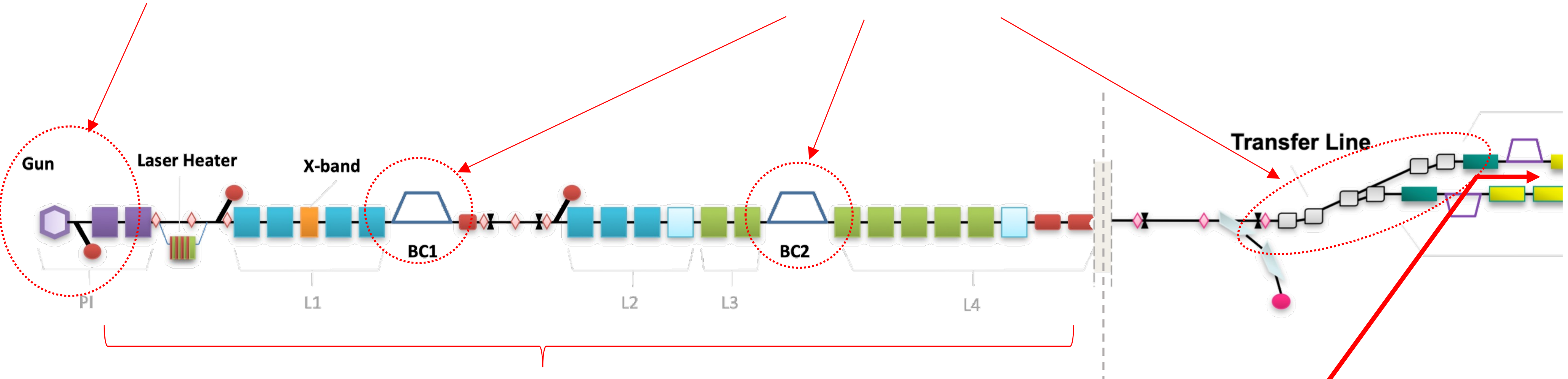


- Longitudinal Wake fields

Prediction models indicate 1 – 10 µm as a ROI for MBI at FERMI FELs

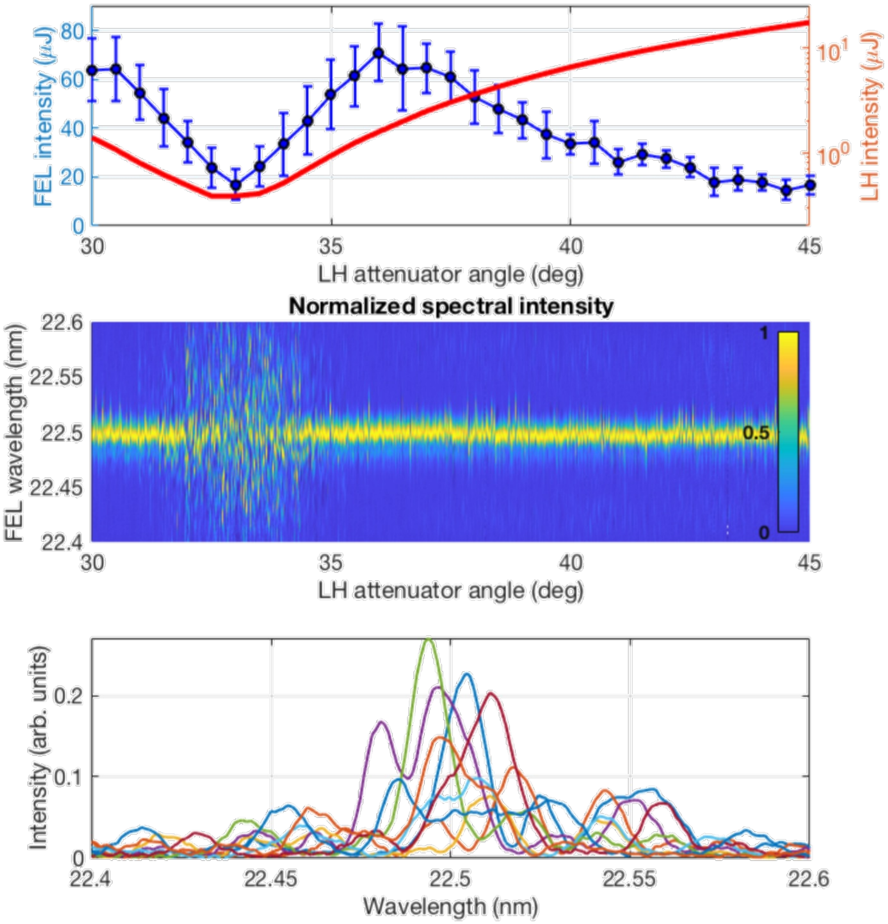
Methods to mi

- Laser Heater: increases the uncorrelated energy spread
- Linear optics control to dump MBI gain

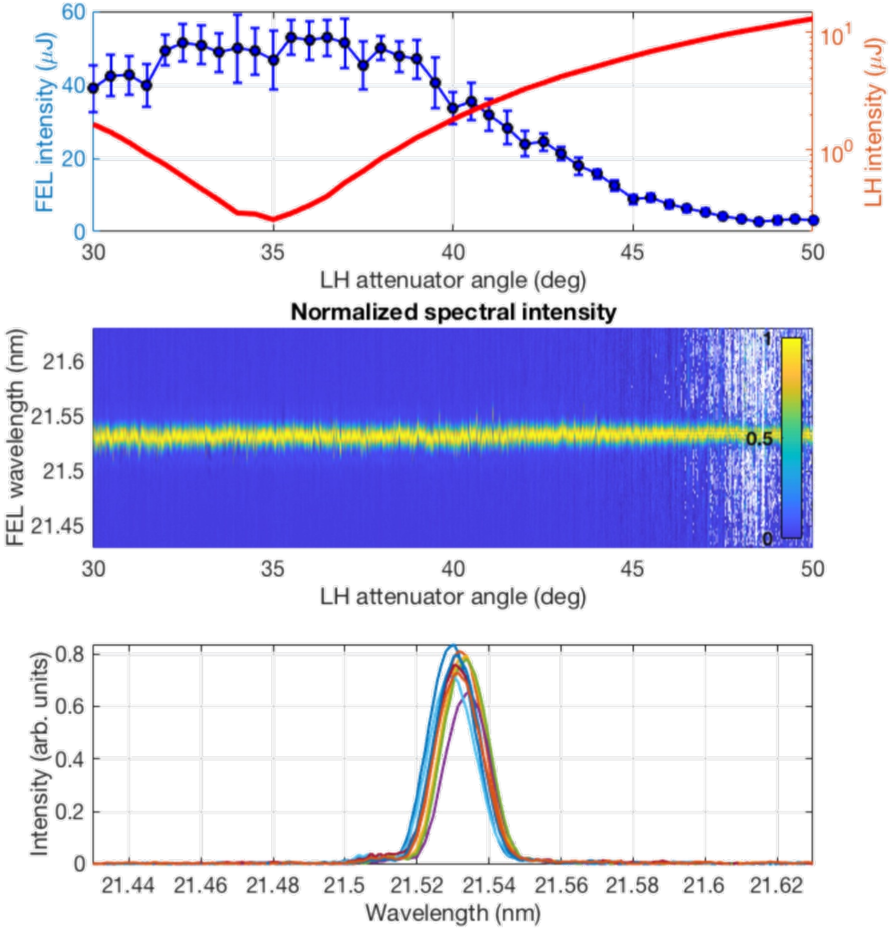
More details in A.D. Brynes' talk
Thu 5/10, 10:10 A.M.

MBI at FERMI

FEL1 HGHG at H11 of 247.5 nm seed



Hot beam



Cold beam

MBI at FERMI

FEL1 HGHG at H11 of 247.5 nm seed

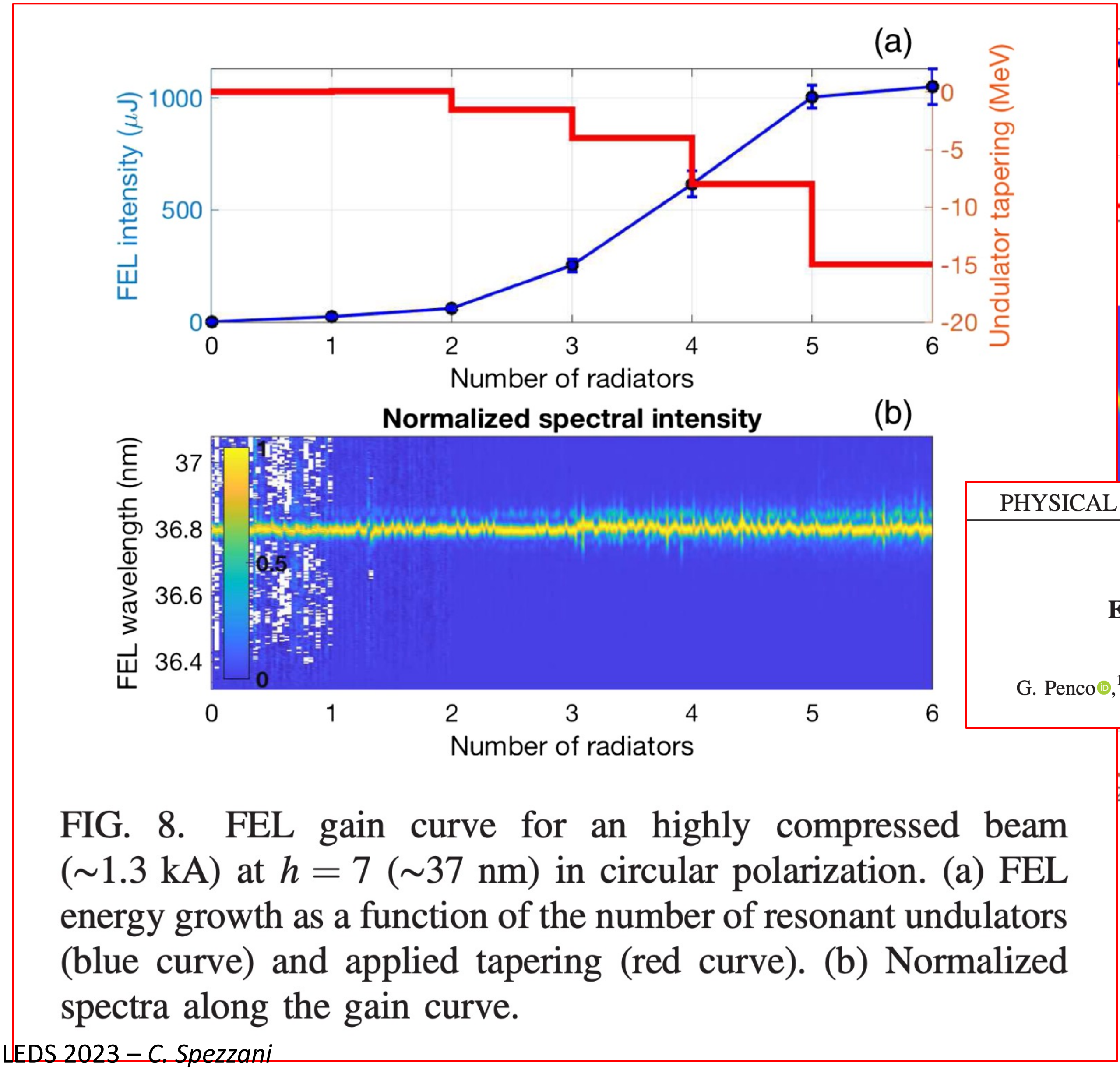
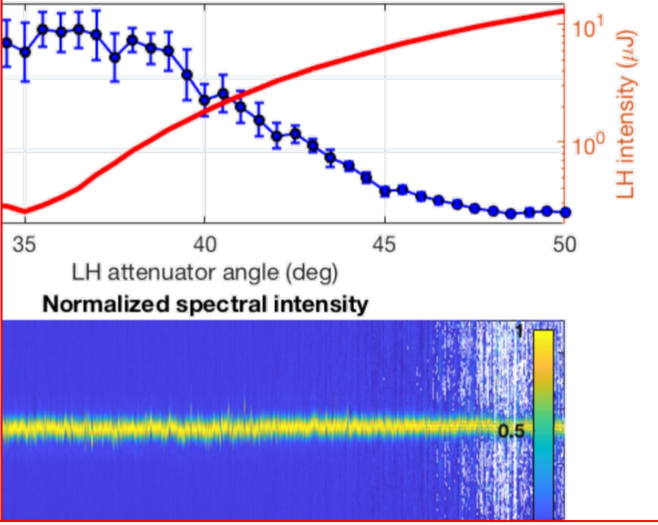
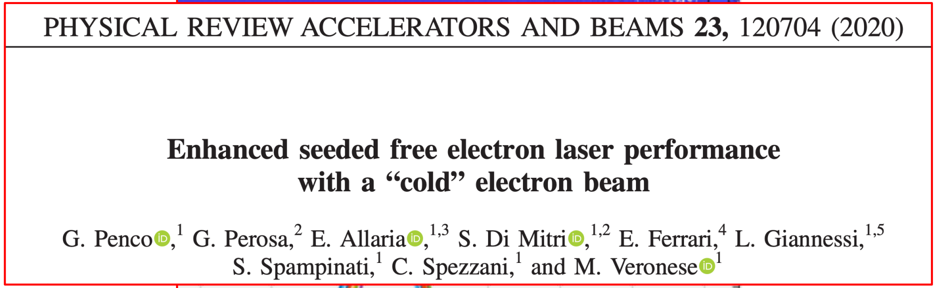


FIG. 8. FEL gain curve for an highly compressed beam (~1.3 kA) at $h = 7$ (~37 nm) in circular polarization. (a) FEL energy growth as a function of the number of resonant undulators (blue curve) and applied tapering (red curve). (b) Normalized spectra along the gain curve.

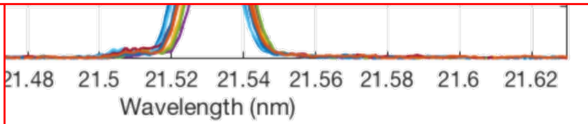




PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 120704 (2020)

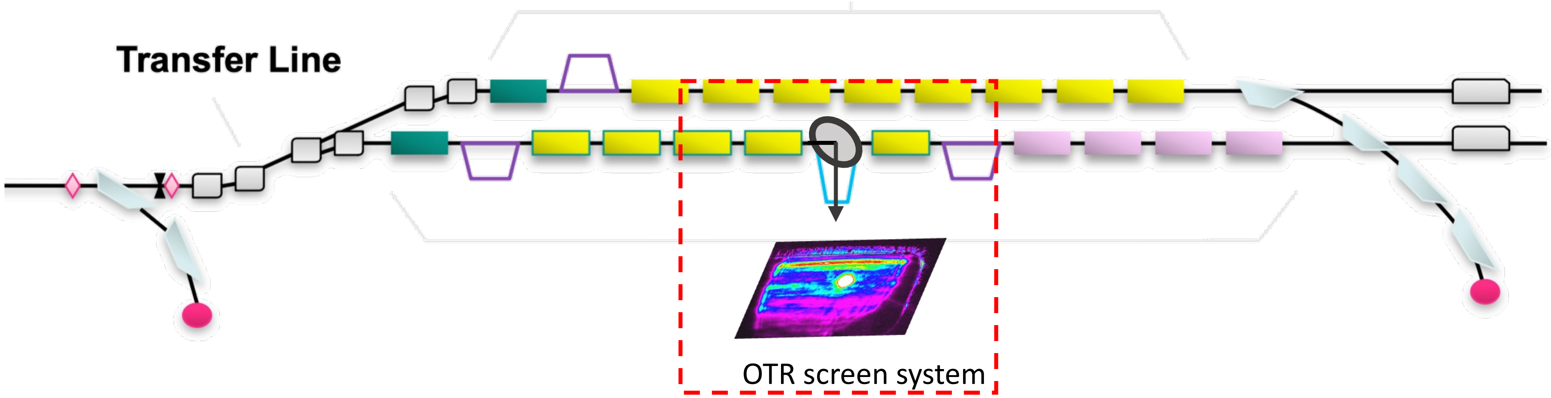
Enhanced seeded free electron laser performance with a “cold” electron beam

G. Penco,[1] G. Perosa,[2] E. Allaria,[1,3] S. Di Mitri,[1,2] E. Ferrari,[4] L. Giannessi,[1,5] S. Spampinati,[1] C. Spezzani,[1] and M. Veronese[1]



Cold beam

Direct access to MBI via COTR spectral energy density measurement



arXiv > physics > arXiv:1803.00608v1

Physics > Accelerator Physics

[Submitted on 1 Mar 2018]

Longitudinal Bunch Diagnostics using Coherent Transition Radiation Spectroscopy

Bernhard Schmidt, Stephan Wesch, Toke Kövener, Christopher Behrens, Eugen Hass, Sara Casalbuoni, Peter Schmüser

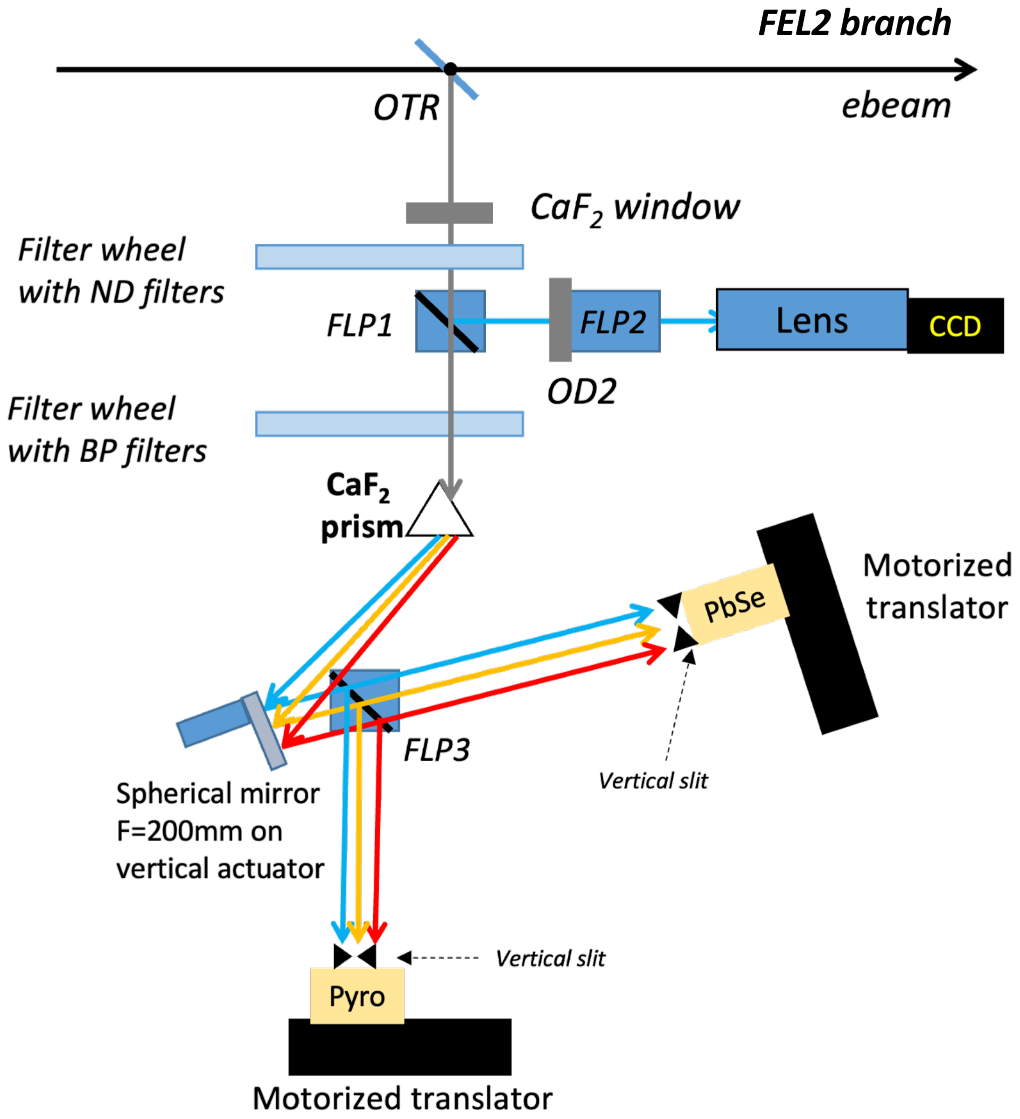
$$\left[\frac{d^2U}{d\omega d\Omega}\right]_{\mathrm{coh}} = N^2 \left[\frac{d^2U}{d\omega d\Omega}\right]_1 |\tilde{F}_{\mathrm{3D}}(\boldsymbol{k})|^2.$$

$$\tilde{F}_{\mathrm{3D}}(\boldsymbol{k}) = \tilde{F}_{\mathrm{trans}}(k_x, k_y)\, \underline{\tilde{F}_{\mathrm{long}}(k_z)}\,.$$

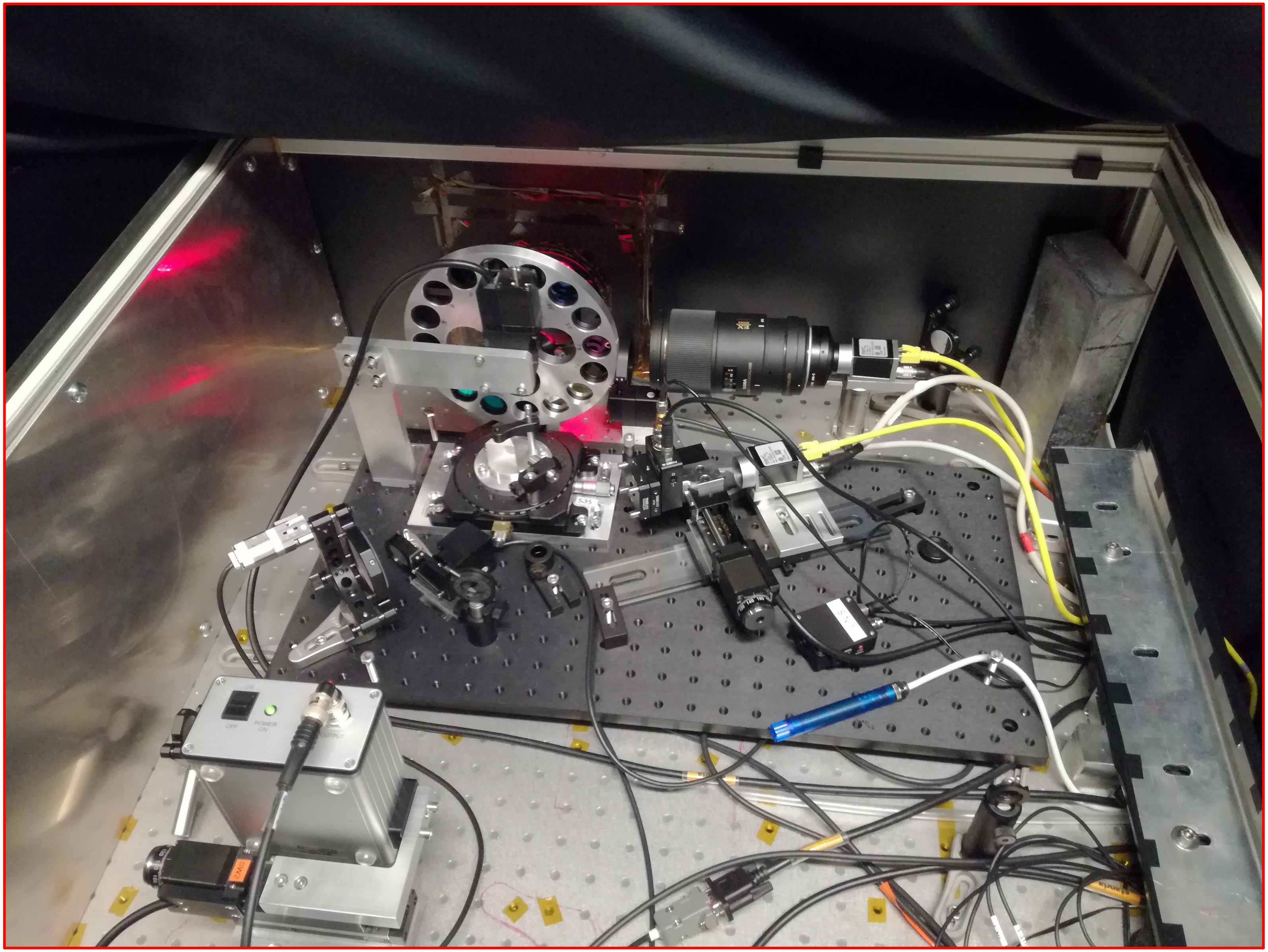
Working hypothesis
i.e. slice emittance and other
params are constant along the bunch

$$\mathcal{F}(\omega) = \int_{-\infty}^{\infty} \rho(t) \exp(i\,\omega\, t) dt\,, \qquad \mathcal{F}(\omega) = \tilde{F}_{\mathrm{long}}(\omega/c)$$

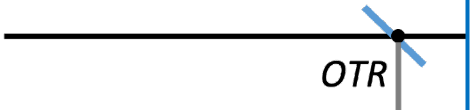
IR Spectrometer design



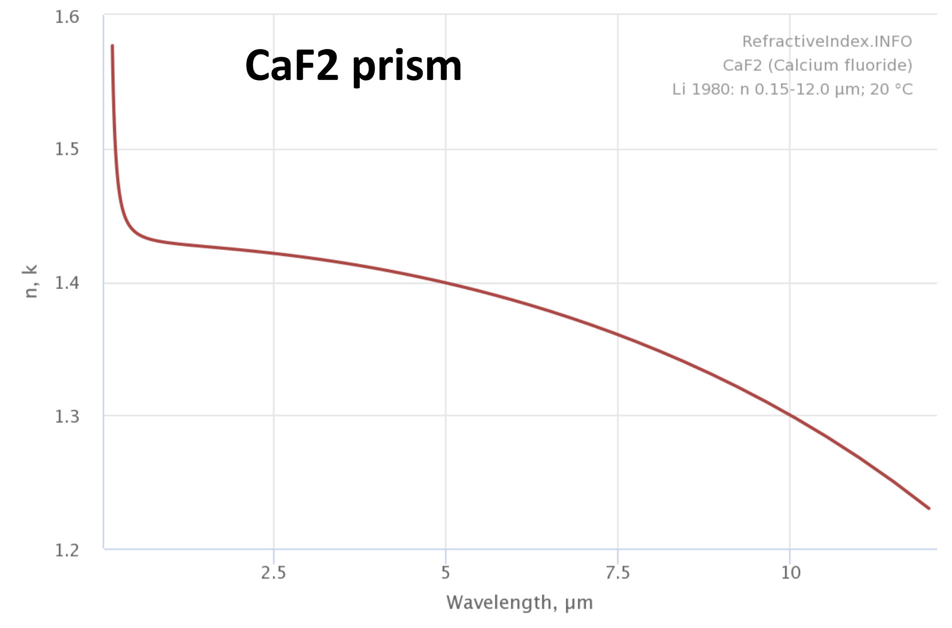
IR Spectrometer design



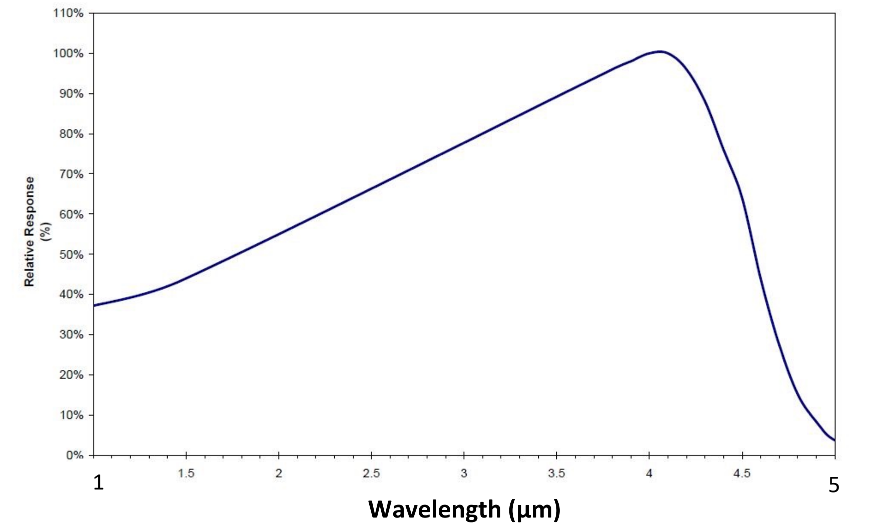
IR Spectrometer design



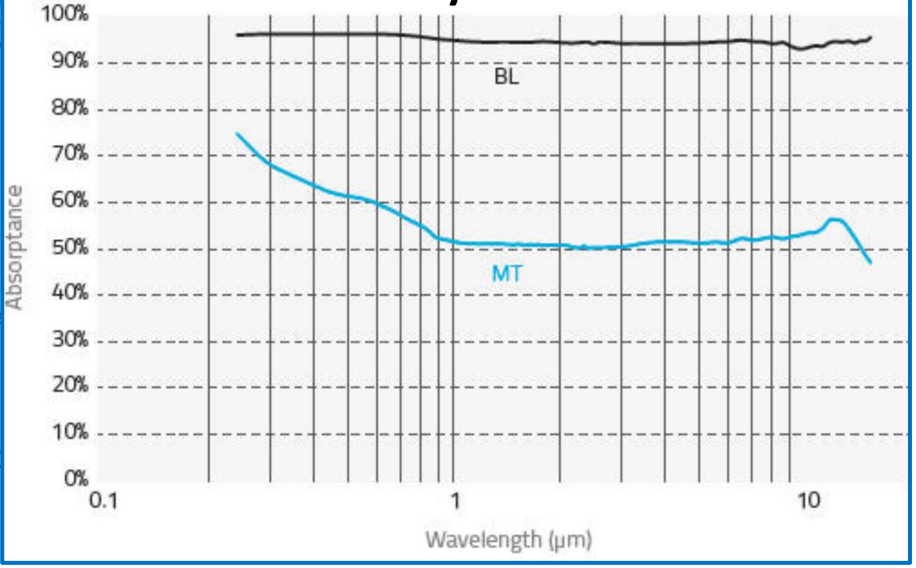
CaF2 prism

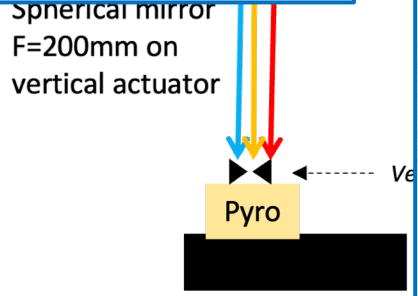


Thorlabs PbSe detector



Gentec Pyro detector



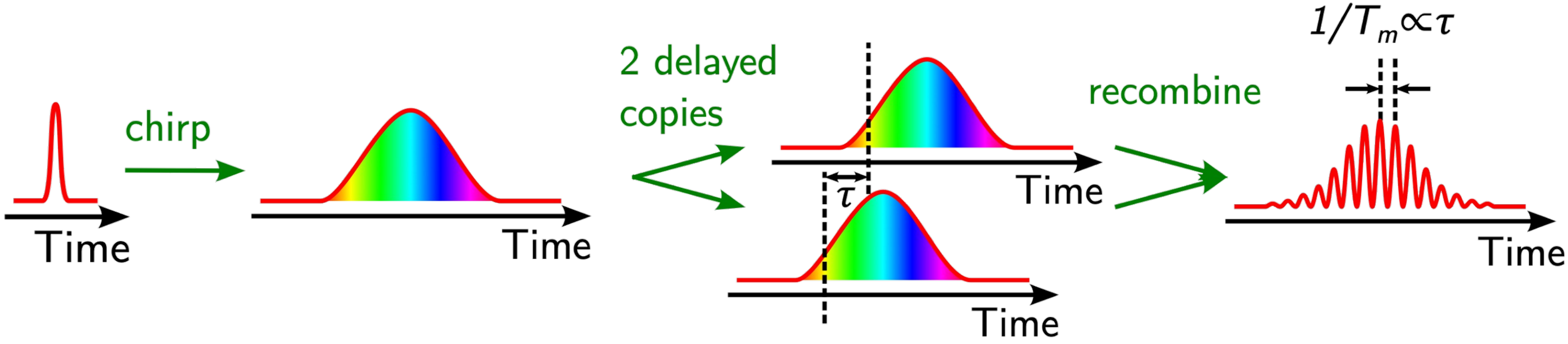


Spherical mirror
F=200mm on
vertical actuator

Pyro

Motorized translat

Frequency beating with LH



$$E(t) = A(t)\exp\left[i\left(\omega_0 t + \pi a t^2\right)\right]$$

$$I(t,\tau) = A(t)^2 + A(t+\tau)^2 + 2A(t)\,A(t+\tau)\cos\left(\omega_0\tau + 2\pi a\tau t + \pi a\tau^2\right)$$

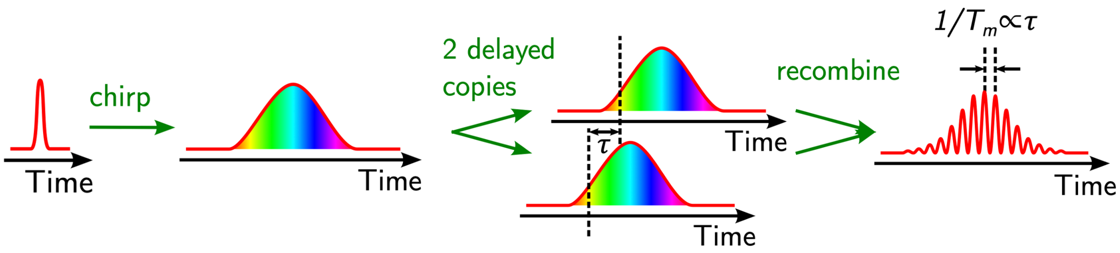
The envelope of the recombined laser pulse is modulated at a **frequency proportional to the delay**.

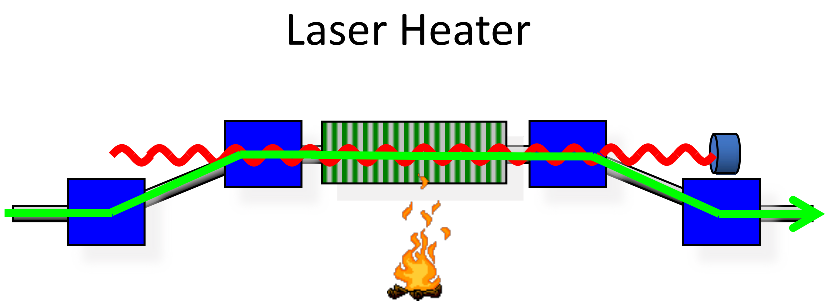
Laser linear chirp $a = -2.7 \times 10^{23}\ \mathrm{s}^{-2}$

Time separation $\tau = 28$ ps

➔ **Beating wavelength λ_B = 38.4 μm**

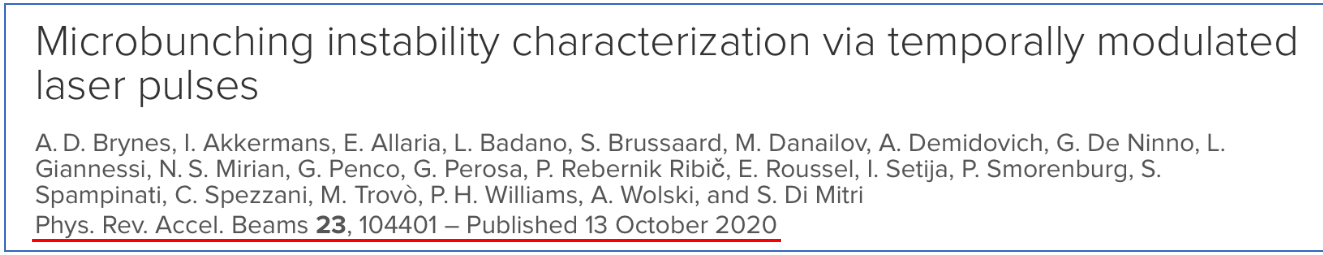
Artificial modulation introduced by means of Frequency beating with LH





Multicolor High-Gain Free-Electron Laser Driven by Seeded Microbunching Instability

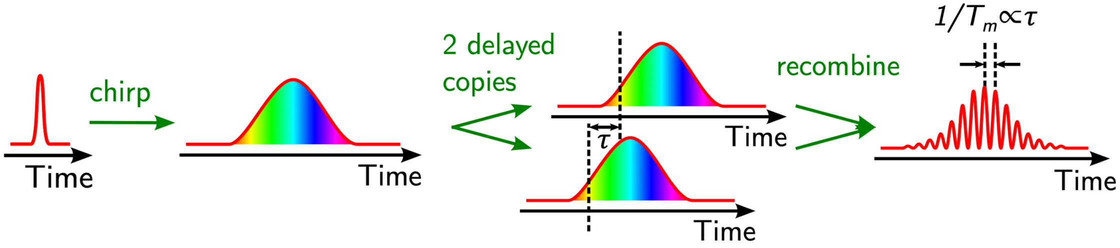
E. Roussel, E. Ferrari, E. Allaria, G. Penco, S. Di Mitri, M. Veronese, M. Danailov, D. Gauthier, and L. Giannessi
Phys. Rev. Lett. **115**, 214801 – Published 20 November 2015

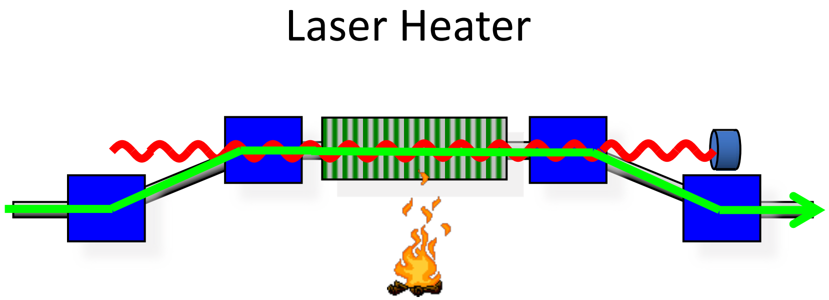


Microbunching instability characterization via temporally modulated laser pulses

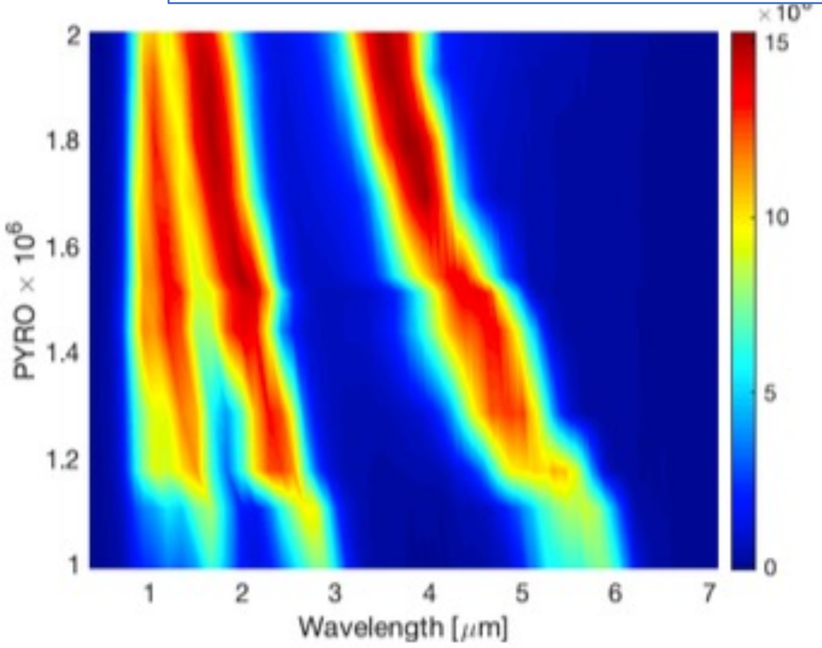
A. D. Brynes, I. Akkermans, E. Allaria, L. Badano, S. Brussaard, M. Danailov, A. Demidovich, G. De Ninno, L. Giannessi, N. S. Mirian, G. Penco, G. Perosa, P. Rebernik Ribič, E. Roussel, I. Setija, P. Smorenburg, S. Spampinati, C. Spezzani, M. Trovò, P. H. Williams, A. Wolski, and S. Di Mitri
Phys. Rev. Accel. Beams **23**, 104401 – Published 13 October 2020

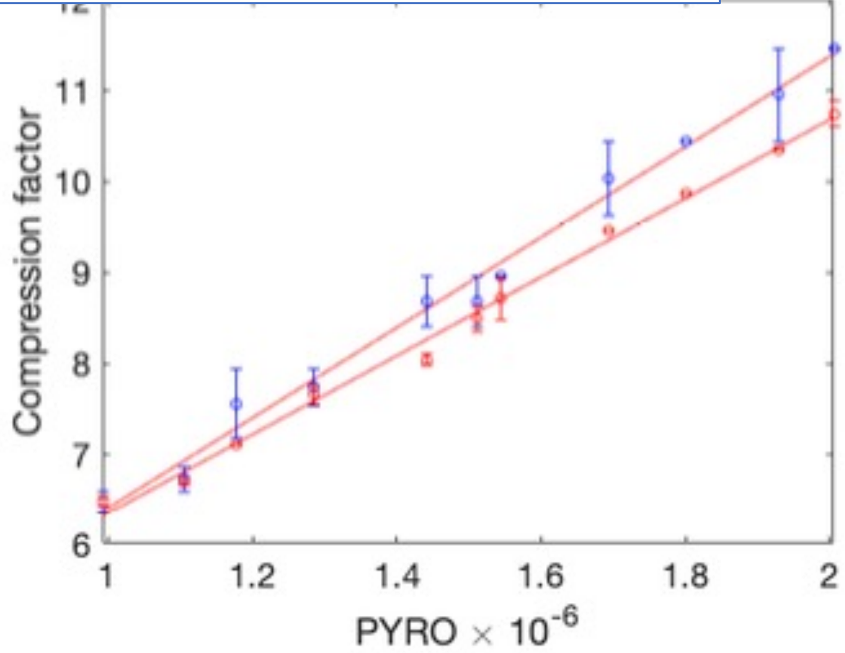
Artificial modulation introduced by means of Frequency beating with LH



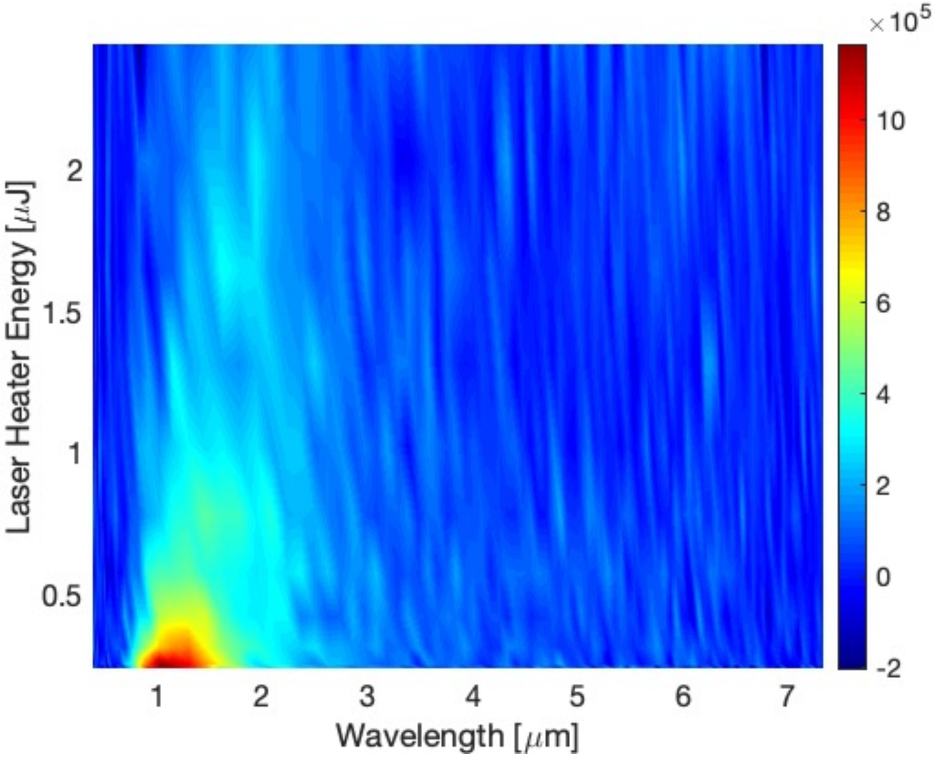


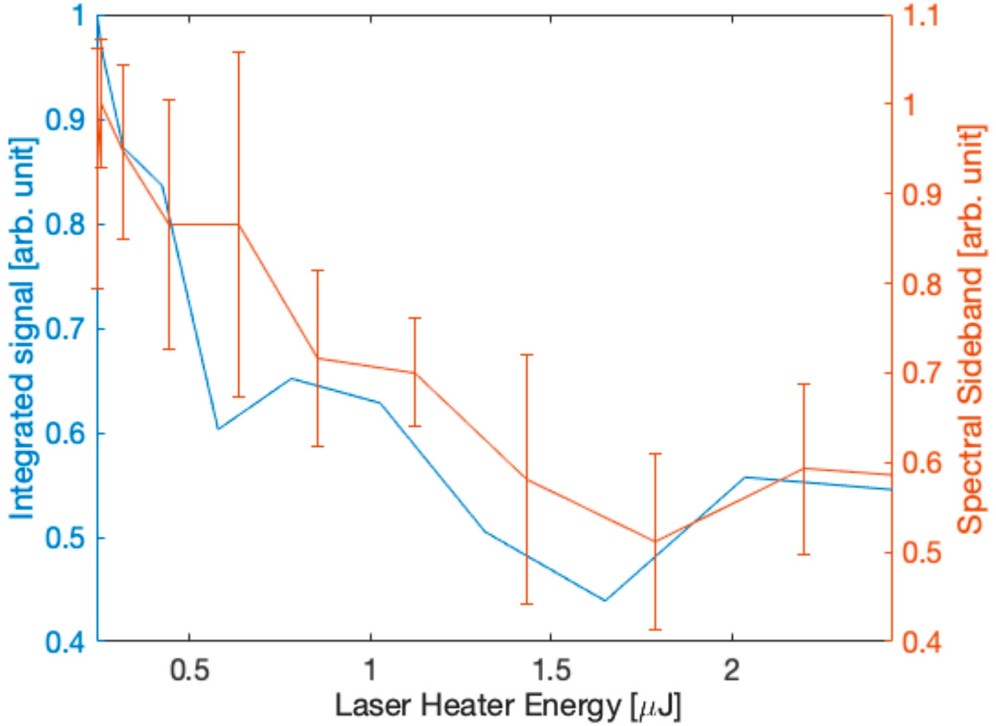
Modulation signature in IR spectrum scale with compression as expected





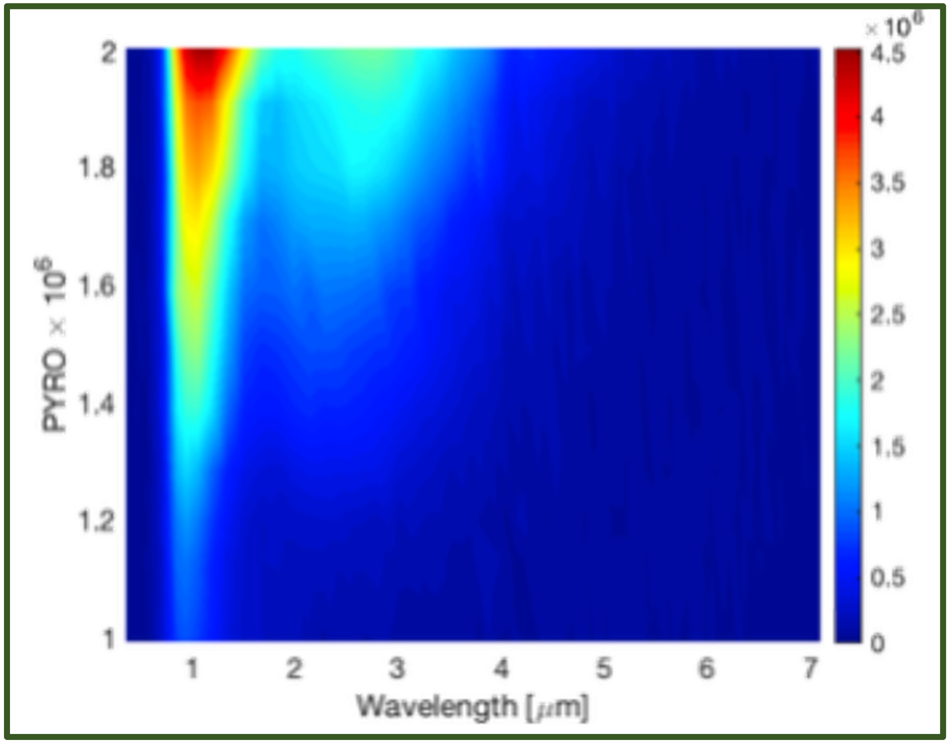
COTR spectrum of FERMI e-beam

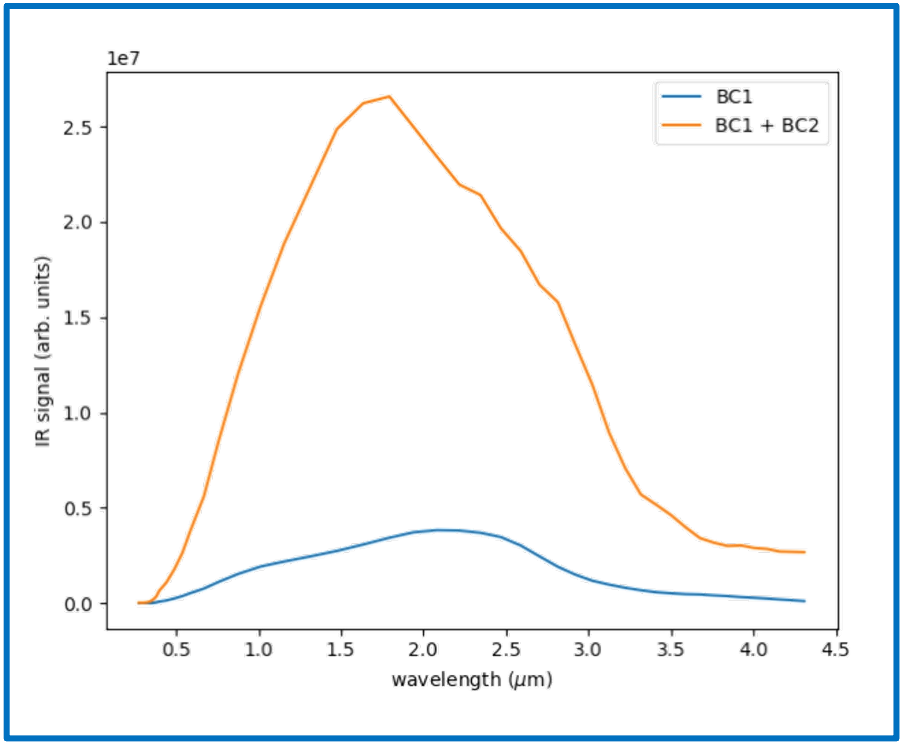




- FERMI *e*-beam COTR spectrum typically shows a dominant component at λ ∼ 1.5 μm that is quickly suppressed with few hundreds nJ of LH. The same trend is observed on the sideband amplitude of the FEL spectrum

COTR spectrum of FERMI e-beam

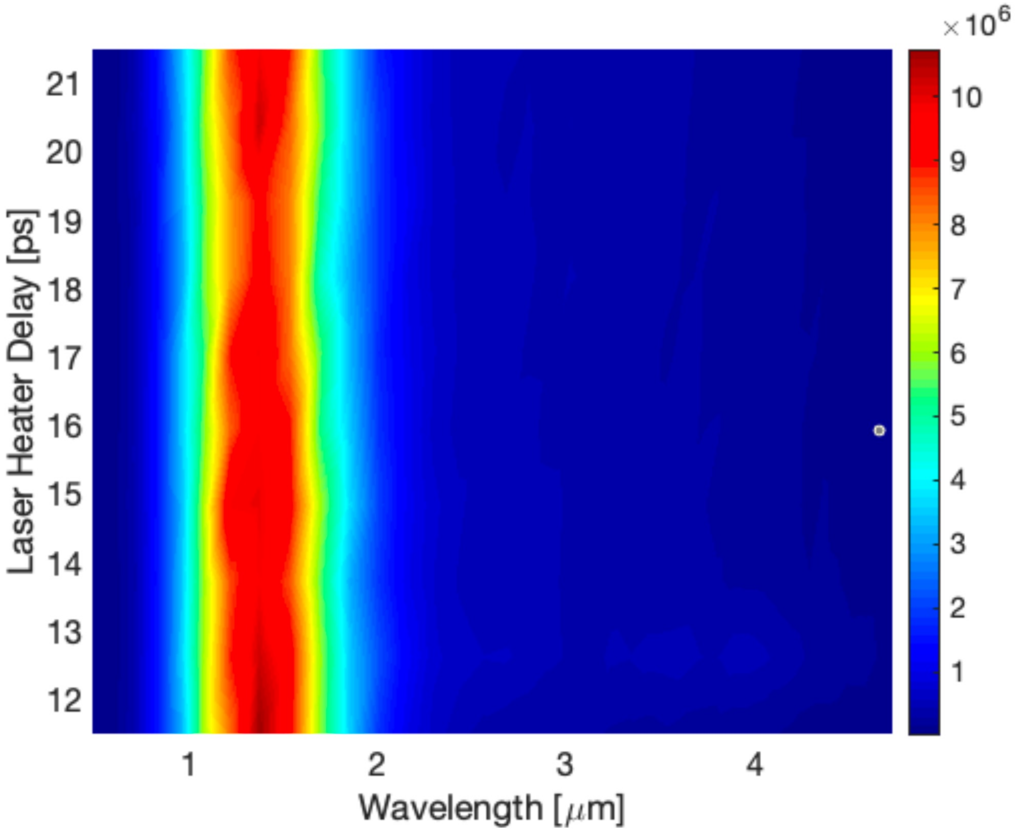


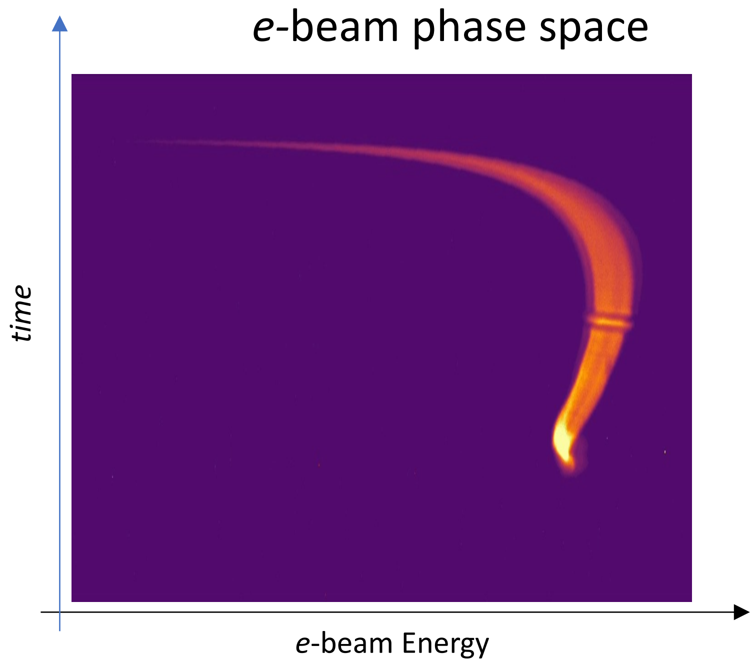


- 1.5 μm component increases with the *e*-beam compression and other components appear for higher compression
- the observed structures doesn't scale with compression indicating that they originate (or gain amplitude) after BC1

- BC1 + BC2 compression scheme shows a dramatic increase of the IR signal

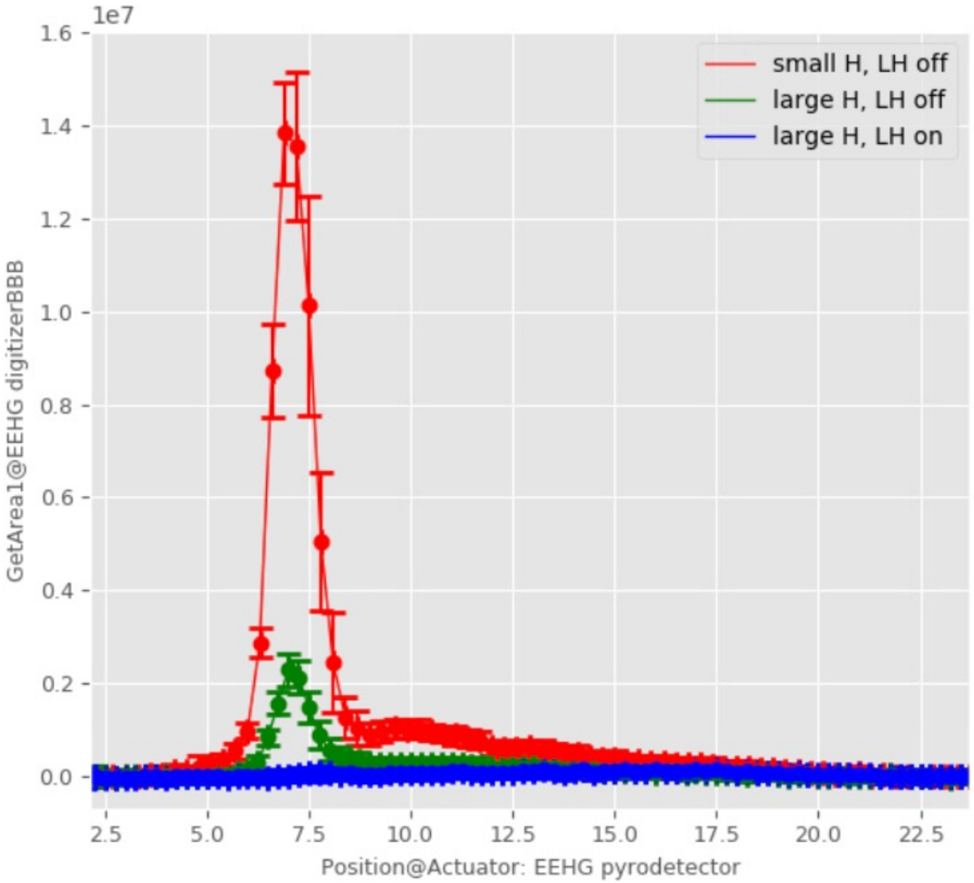
COTR spectrum of FERMI e-beam





We used short LH pulses to probe the longitudinal distribution of MBI

COTR spectrum of FERMI e-beam



Tuning of spreader optics may reduce MBI gain

Conclusions

- a new IR spectrometer has been developed at FERMI to give direct access to MBI via analysis of the spectral energy density of COTR measured on the FEL2 amplifier
- simple design based on prism refraction
- use of LH beating demonstrate the sensitivity of COTR spectral analysis to periodic modulation of the *e*-beam
- use of LH with short pulses shows that MBI is not longitudinally localized
- role of compression scheme and linear optics need further exploration
- the use of a single channel detector, together with the limited amount of time available for machine studies at a user facility, is a big limit for this instrument. Upgrading to array pyro detector for single shot IR spectrum acquisition will drastically shorten acquisition time

Thank you!

Marco Veronese	Elettra ST
Alexander Brynes	
Simone Di Mitri	
Enrico Allaria	
Luca Giannessi	ENEA/Elettra ST
Giovanni Perosa	Uppsala University
Eugenio Ferrari	DESY
Eléonore Roussel	CNRS/Université de Lille
Simone Spampinati	INFN