Spectro-temporal control and characterization of XUV pulses from a seeded free-electron laser

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on behalf of the FERMI Machine Physics Team

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Outline

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- MOTIVATION

Use the seed laser to control and shape the temporal pulse properties in a seeded FEL.
(+ some elements of theory)

- PULSE CONTROL and CHARACTERIZATION: 3 EXPERIMENTAL RESULTS on FERMI

(1) Spectro-temporal mapping and shaping of pulses

(2) Generation of time-delayed phase-locked pulses

(3) Spectral Phase Interferometry for Direct Electric-field Reconstruction (SPIDER): full temporal characterization of seeded FEL pulses.

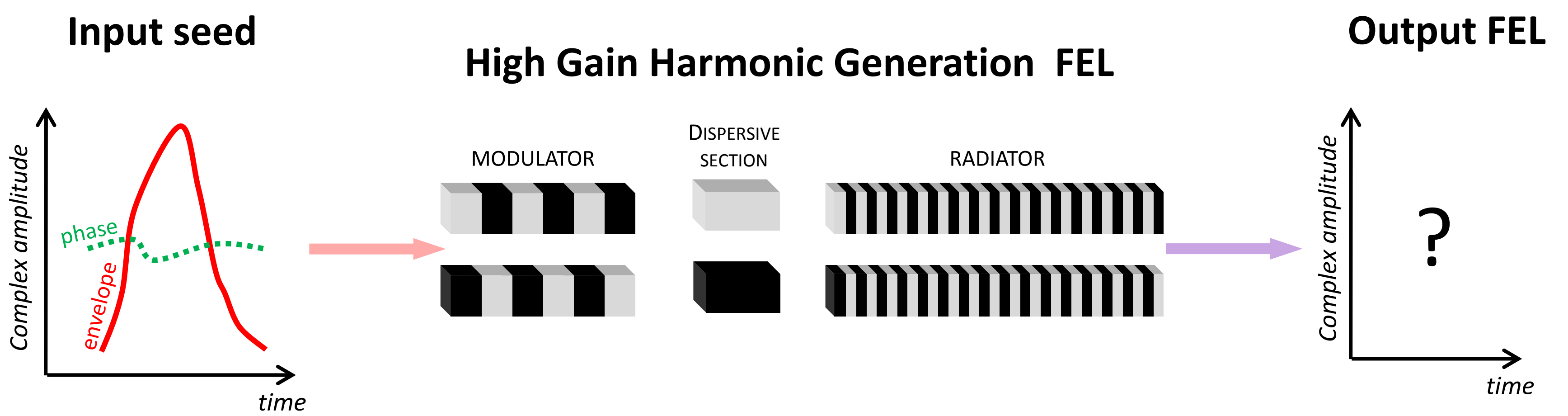
- CONCLUSION

Use of the seed to control the FEL pulse?

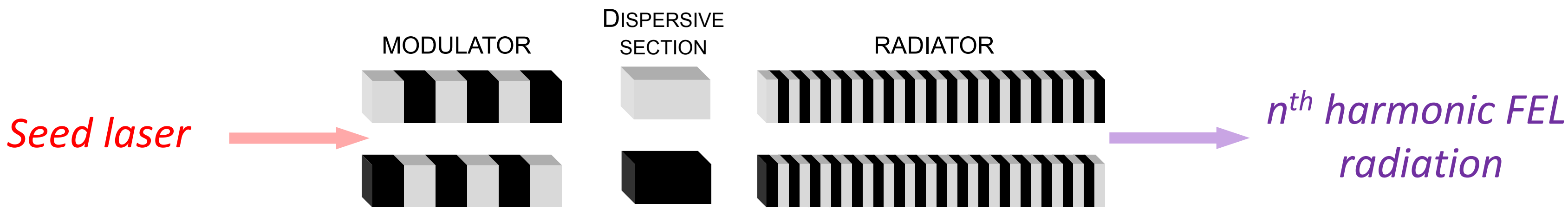
The seeded scheme was initially designed to improve the longitudinal coherence with respect to SASE.

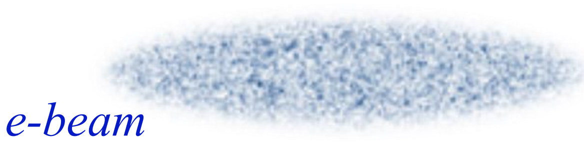
There is an interest to use the external seed laser to drive the characteristics of the generated light.

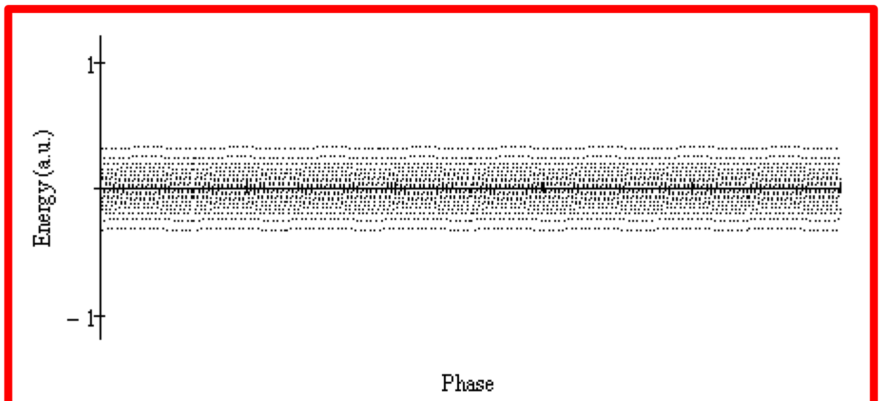
=> from coherence… to pulse control and shaping.



HGHG FEL



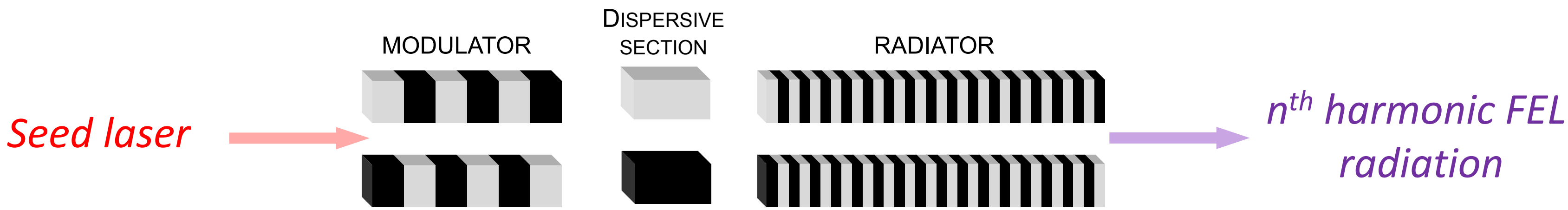


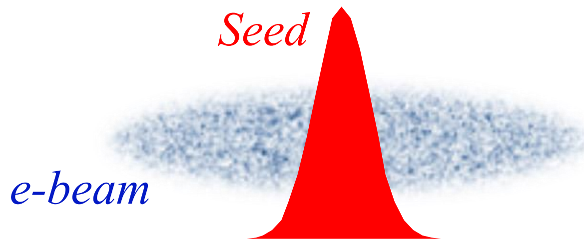


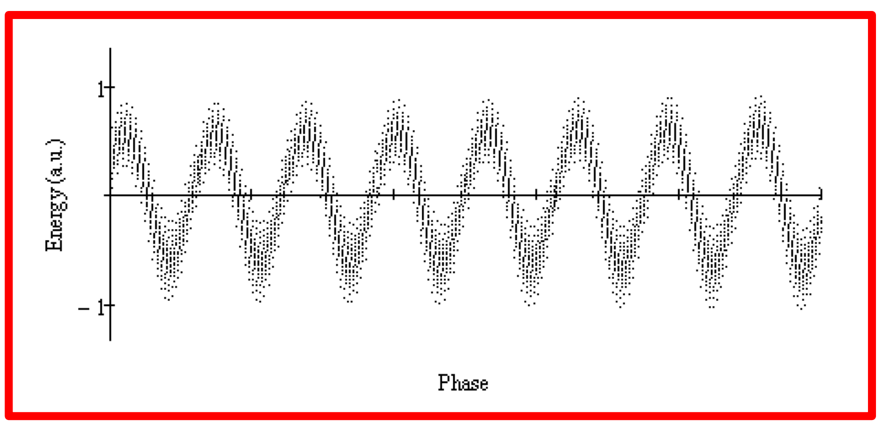
Fresh beam

Courtesy of Luca Giannessi

HGHG FEL



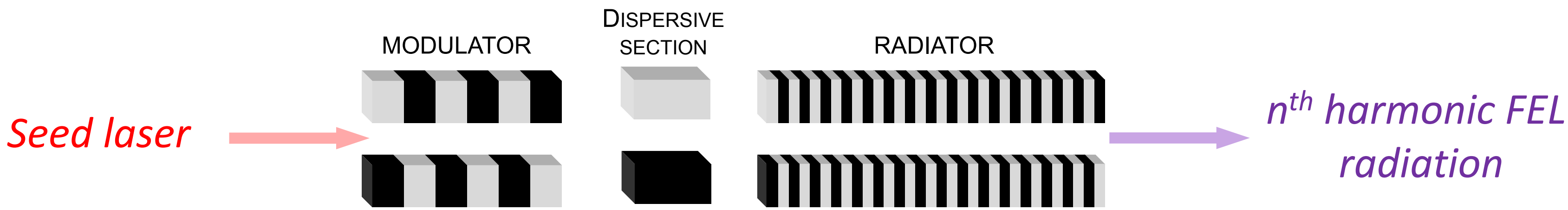


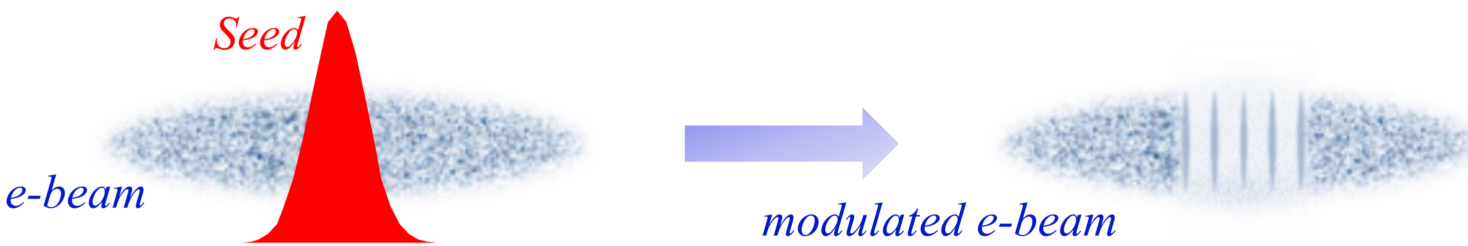


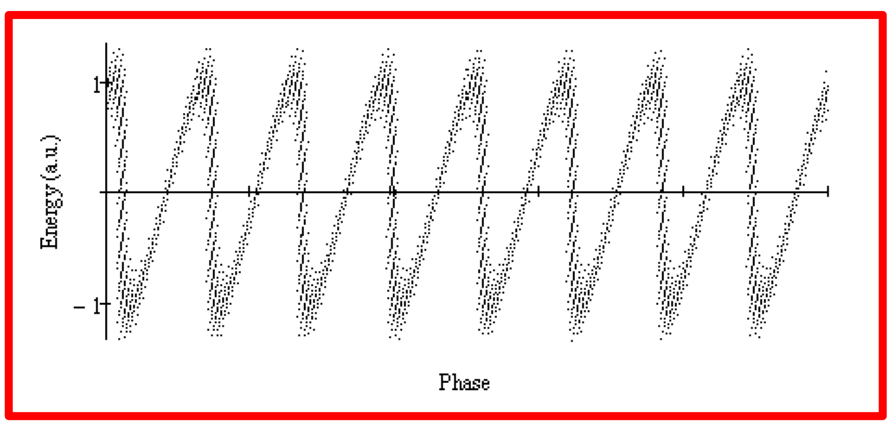
Modulated beam

Courtesy of Luca Giannessi

HGHG FEL



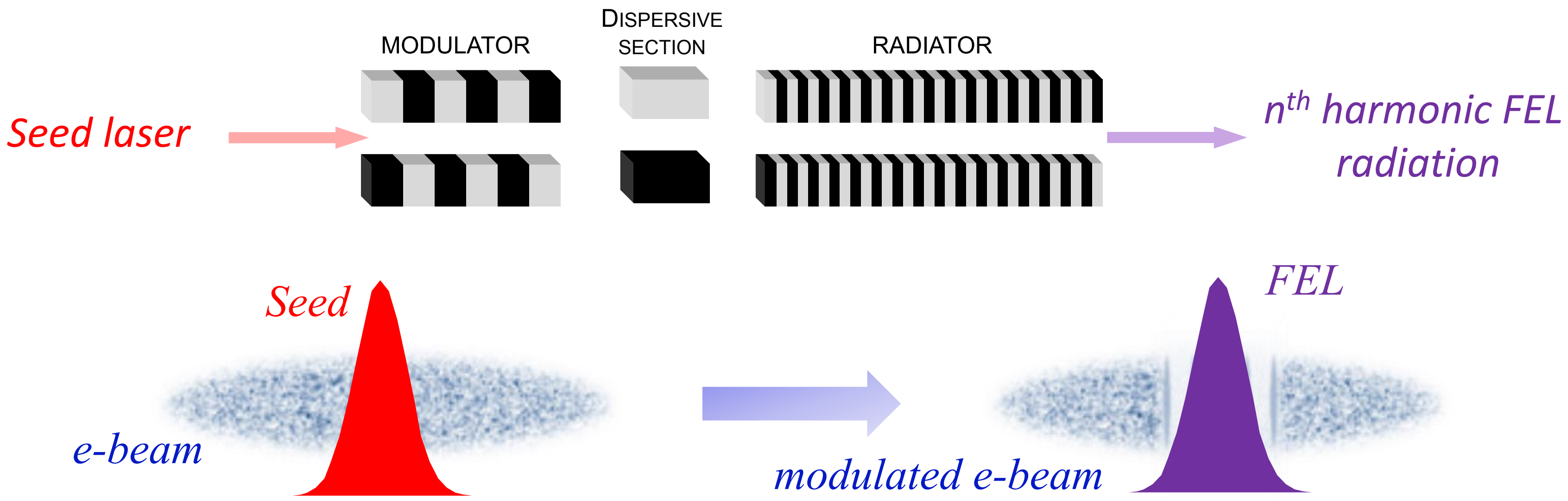


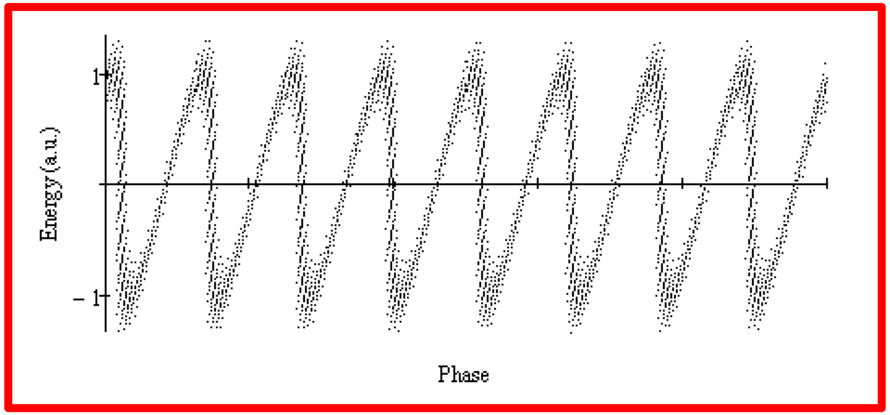


Bunched beam

Courtesy of Luca Giannessi

HGHG FEL





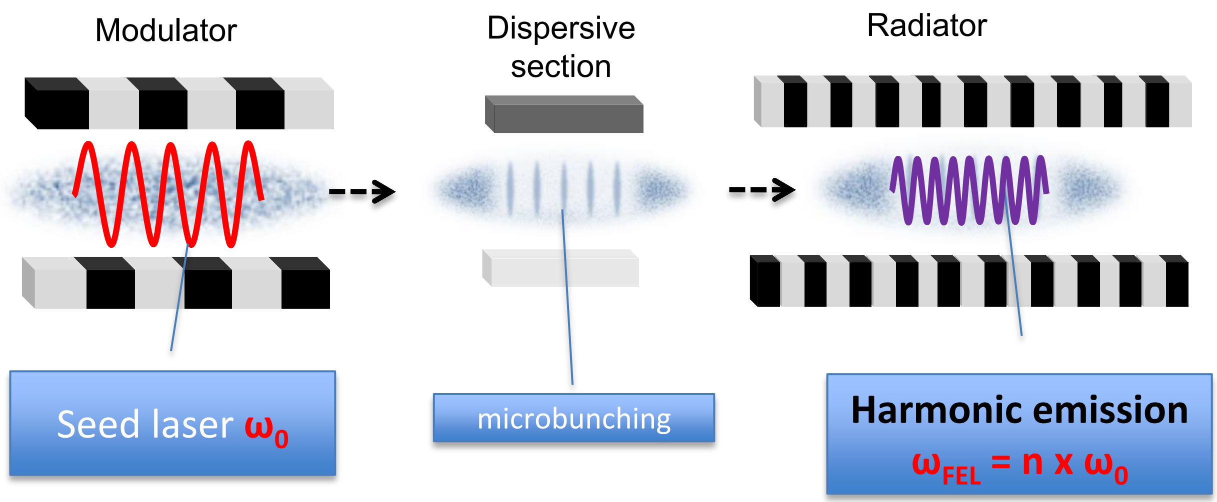
Bunched beam

Courtesy of Luca Giannessi

Microbunching driven by the seed carrier wave

Flat phase seed:

With ω_0 the seed carrier frequency

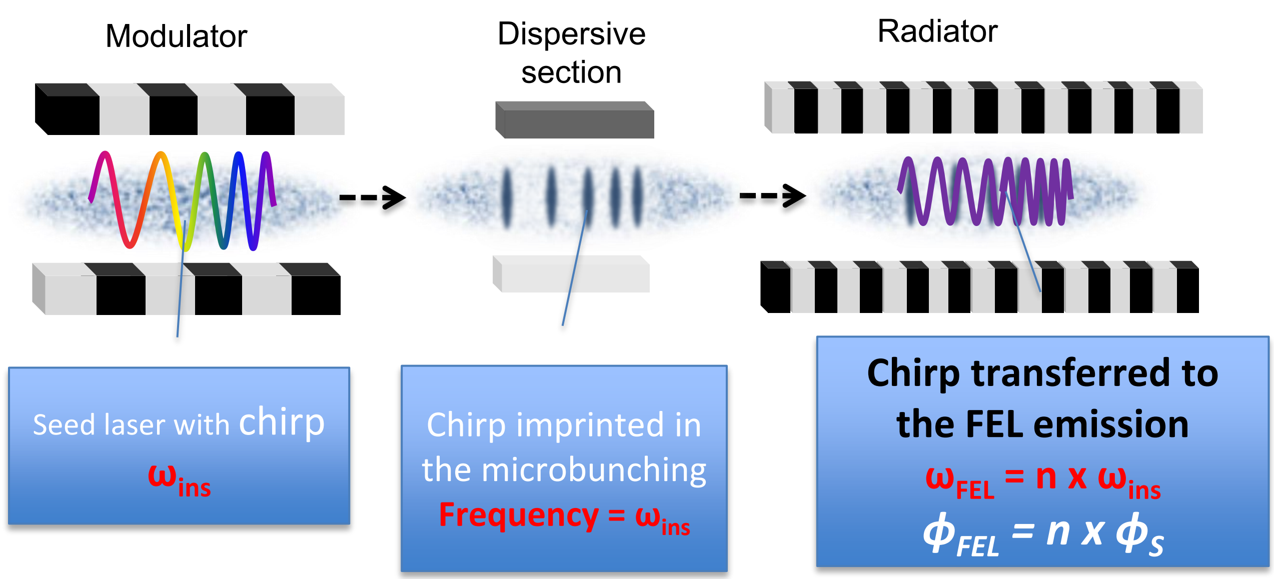


With a chirped seed:

Instantaneous frequency:

$$\omega_{ins}(t) = \frac{d\phi_s(t)}{dt} + \omega_0$$

With ϕ_s the slow varying phase of the seed



Effect of a chirped electron beam

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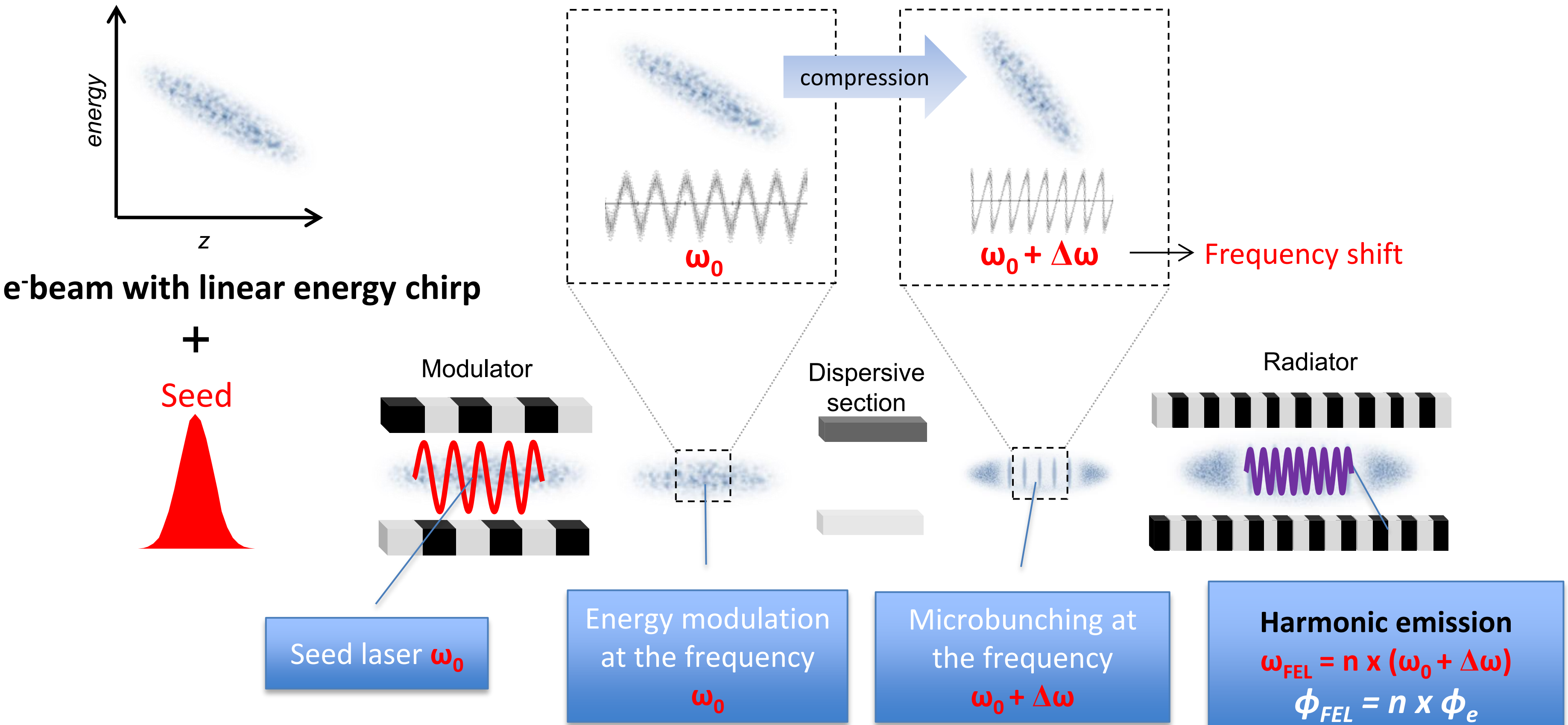
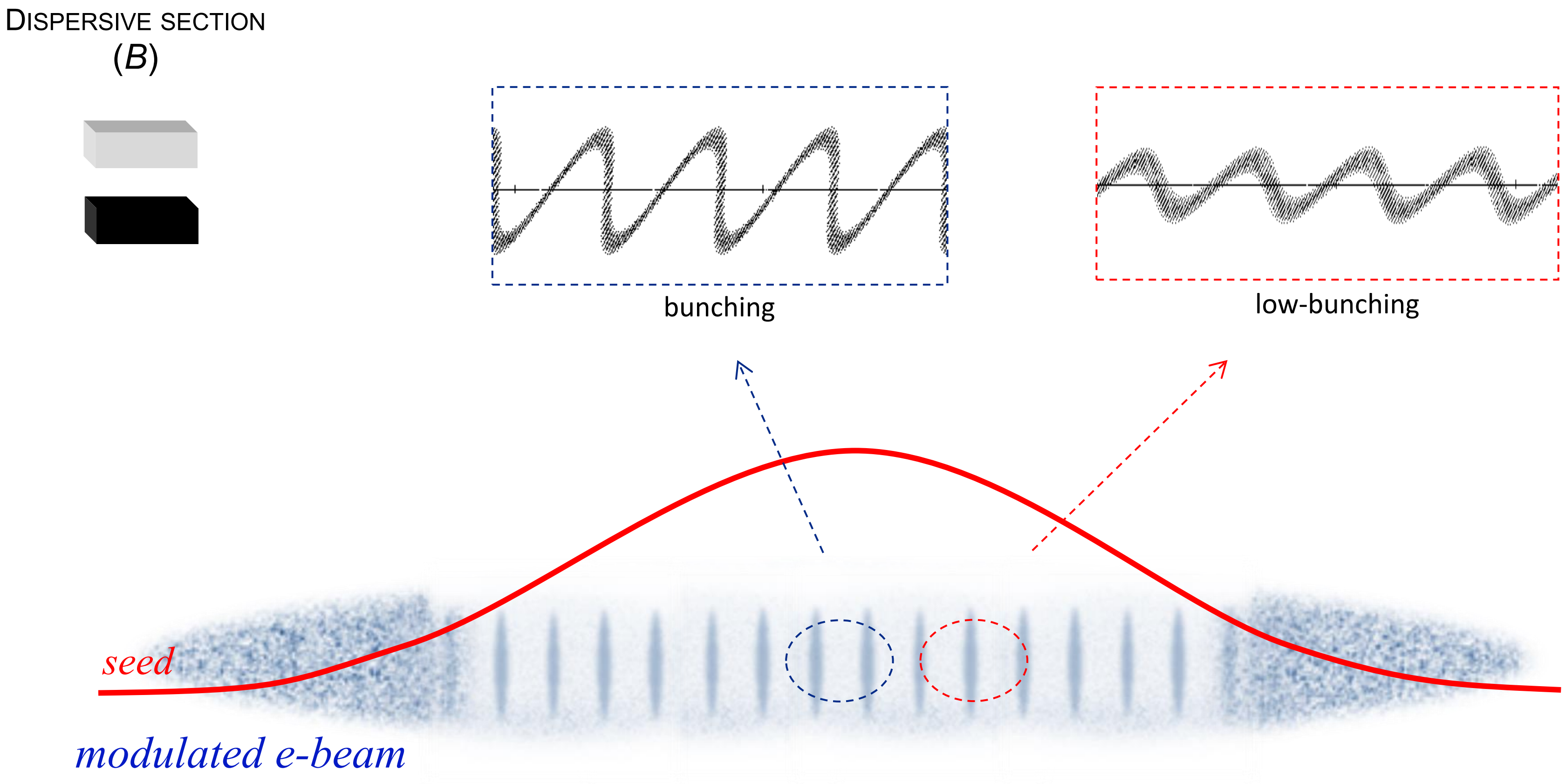


T. Shaftan and L. H. Yu, Phys. Rev. E 71, 046501 (2005)

Generalization to a multi-order time-dependent electron-beam energy profile: $E(t) = E_0 + \chi_1 t + \chi_2 t^2 + \chi_3 t^3 + \cdots$

Instantaneous frequency shift: $\Delta\omega(t) \approx \frac{B}{\sigma_E}\frac{dE(t)}{dt}$ and The slow varying phase from the chirped e⁻ beam: $\phi_e(t) \approx \frac{B}{\sigma_E} E(t)$

Time-dependent microbunching amplitude



M. Labat et al., Phys. Rev. Lett. 103, 264801 (2009)
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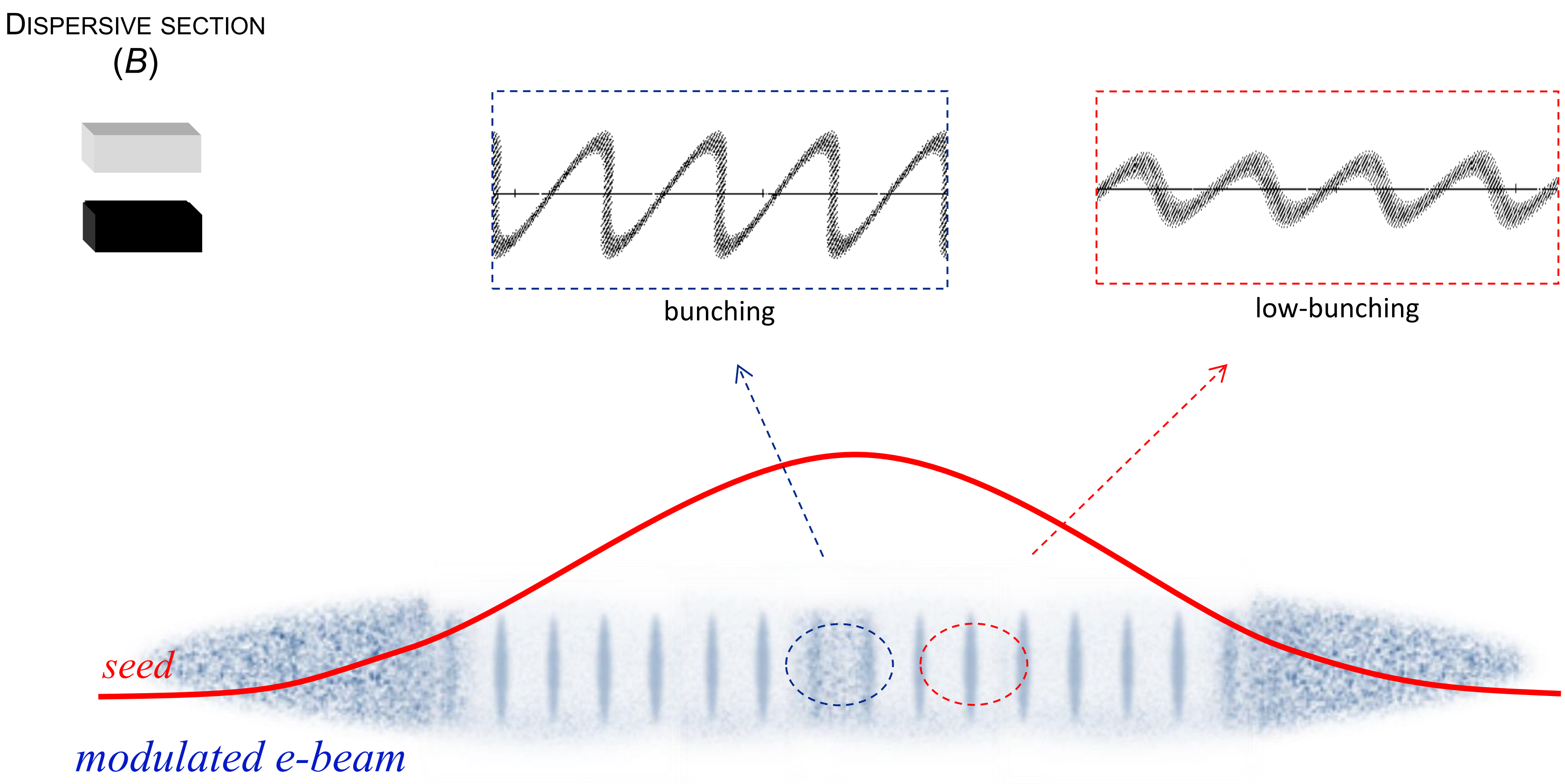

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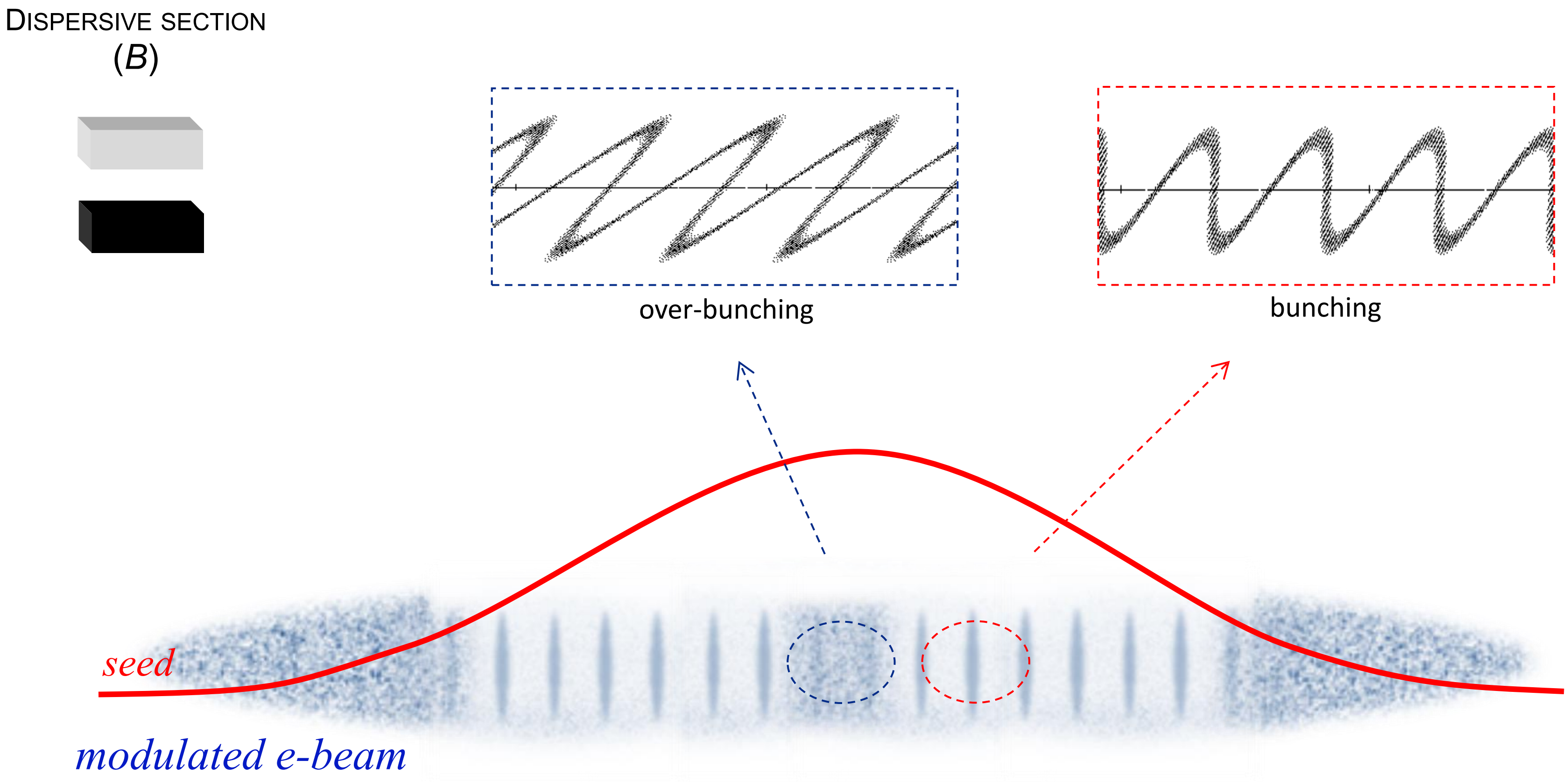

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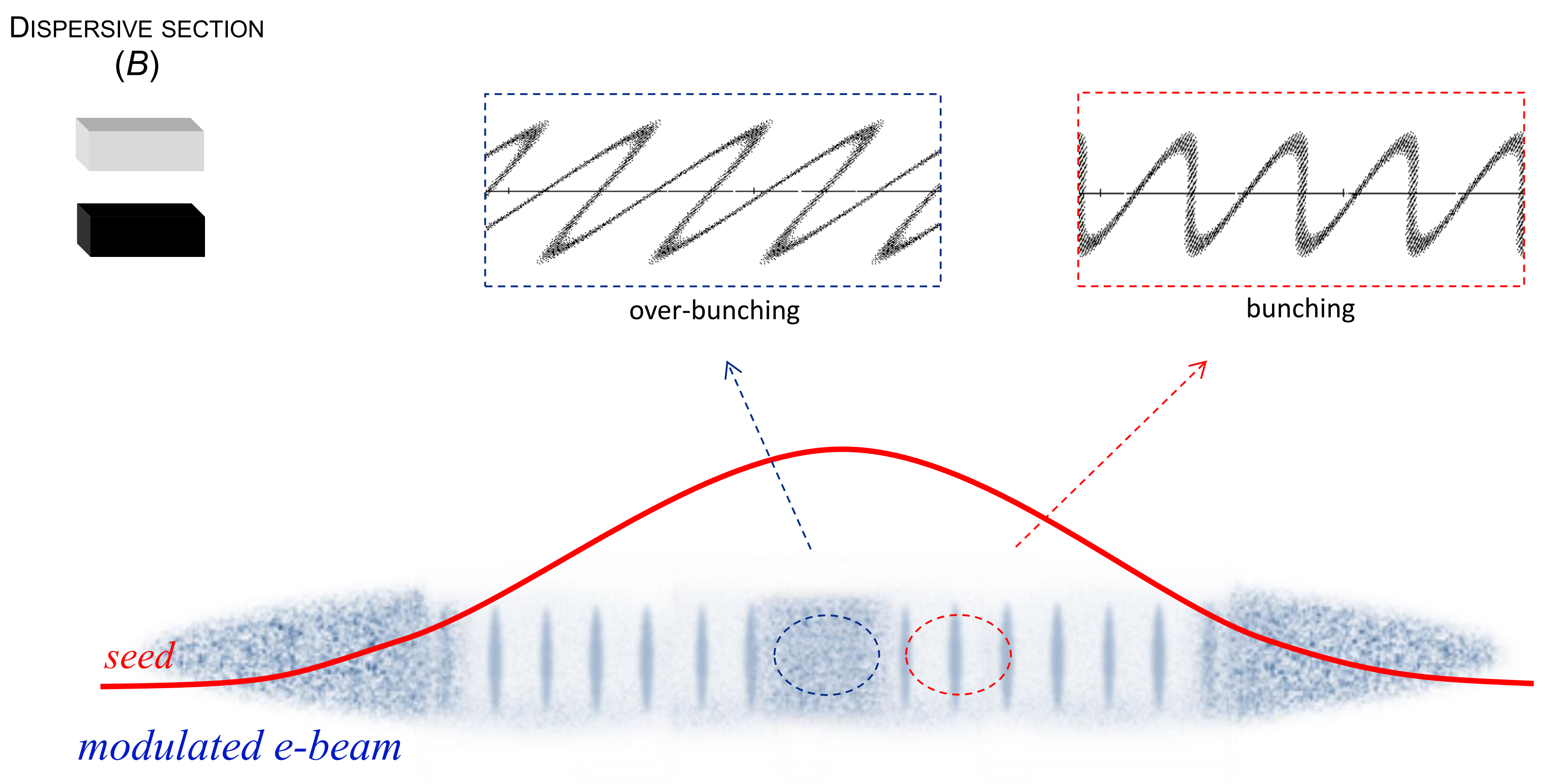

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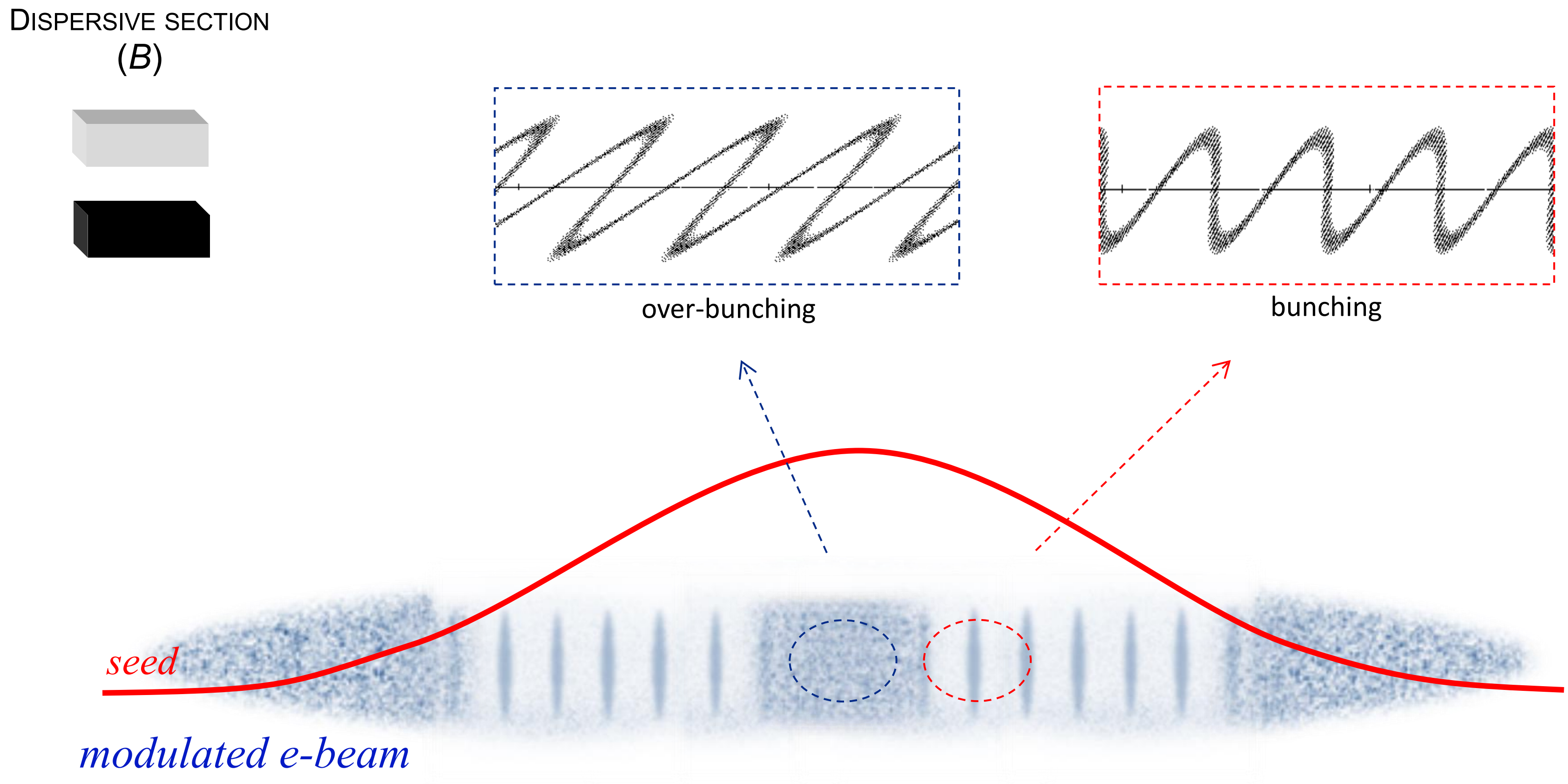

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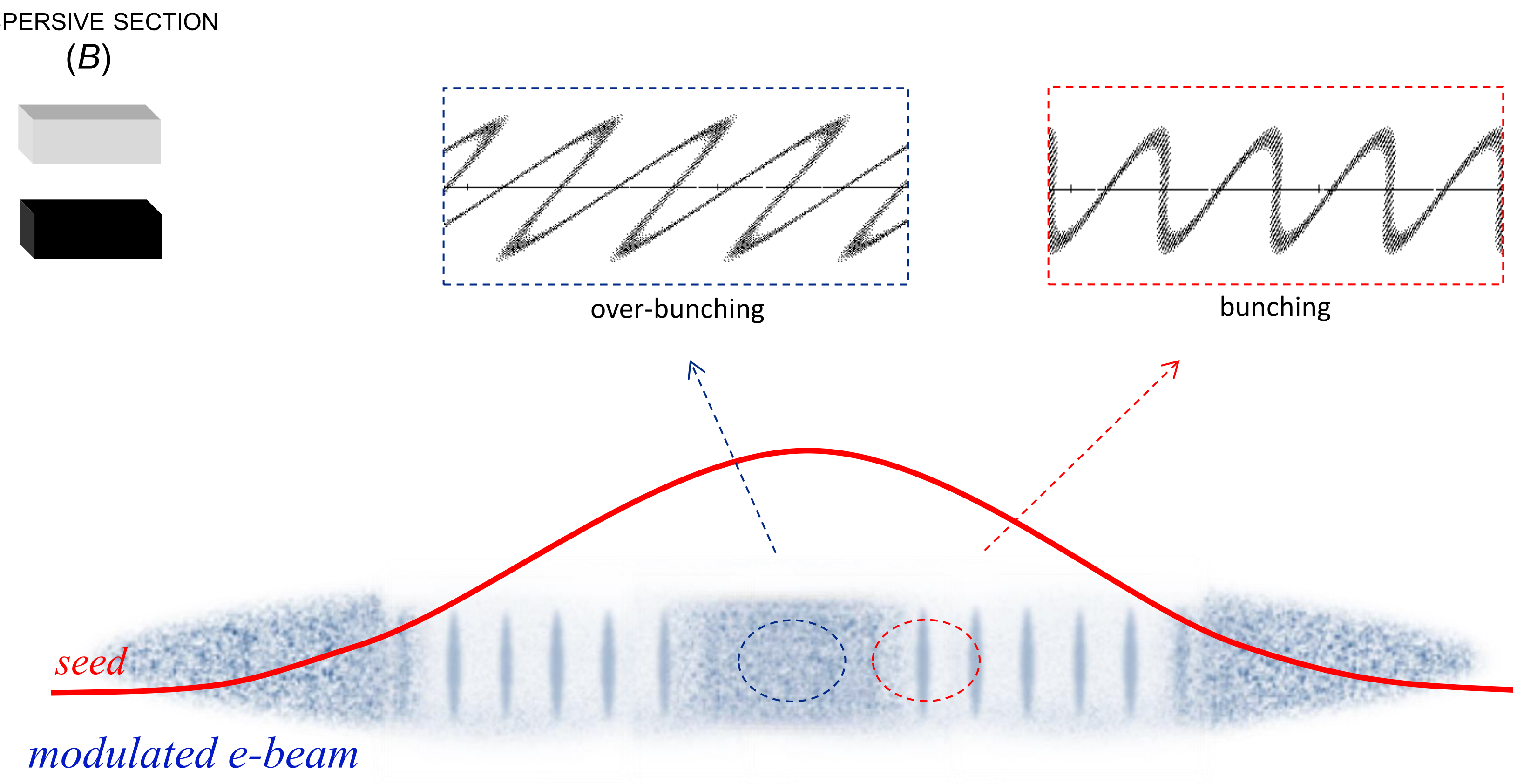

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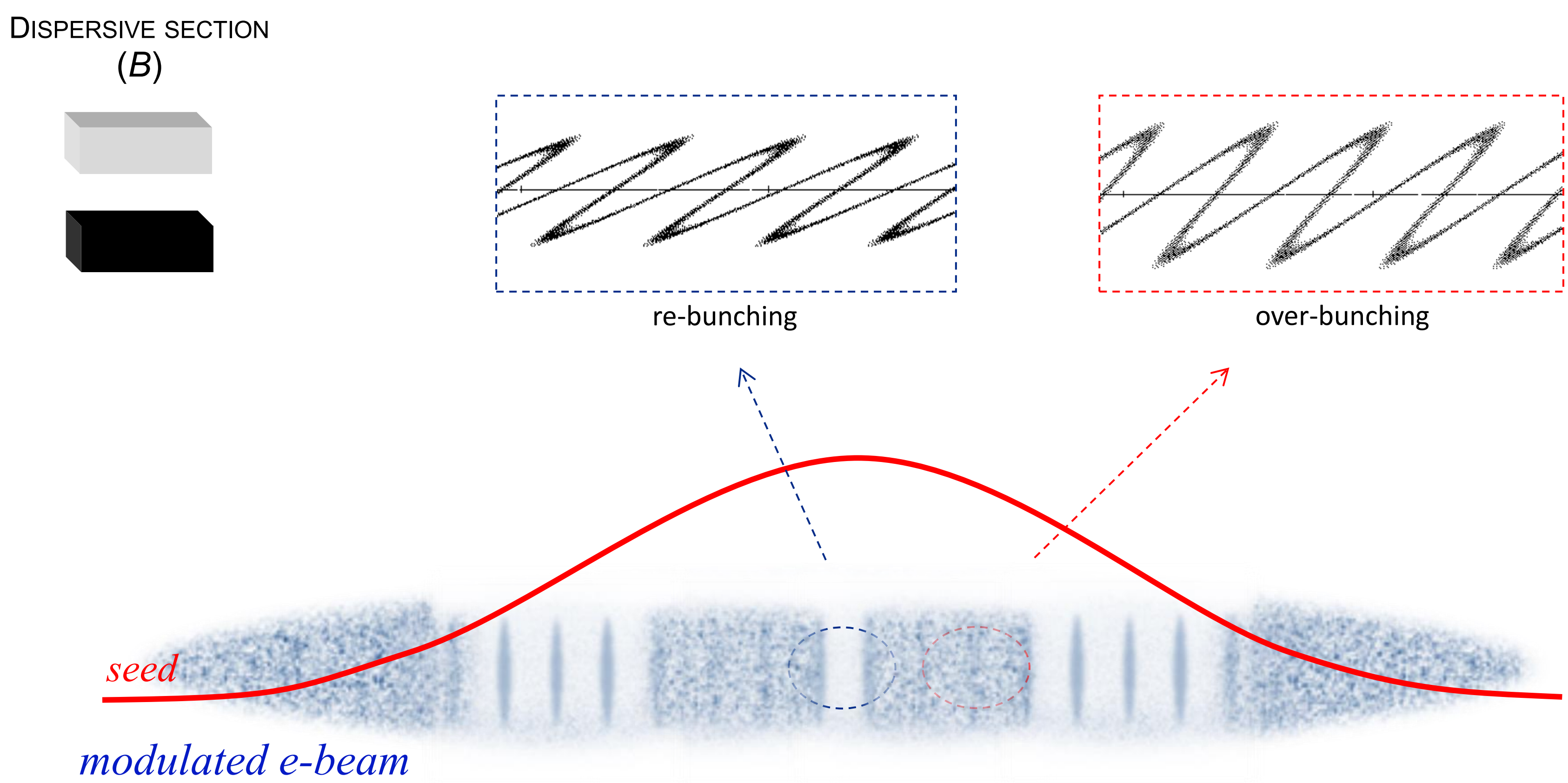

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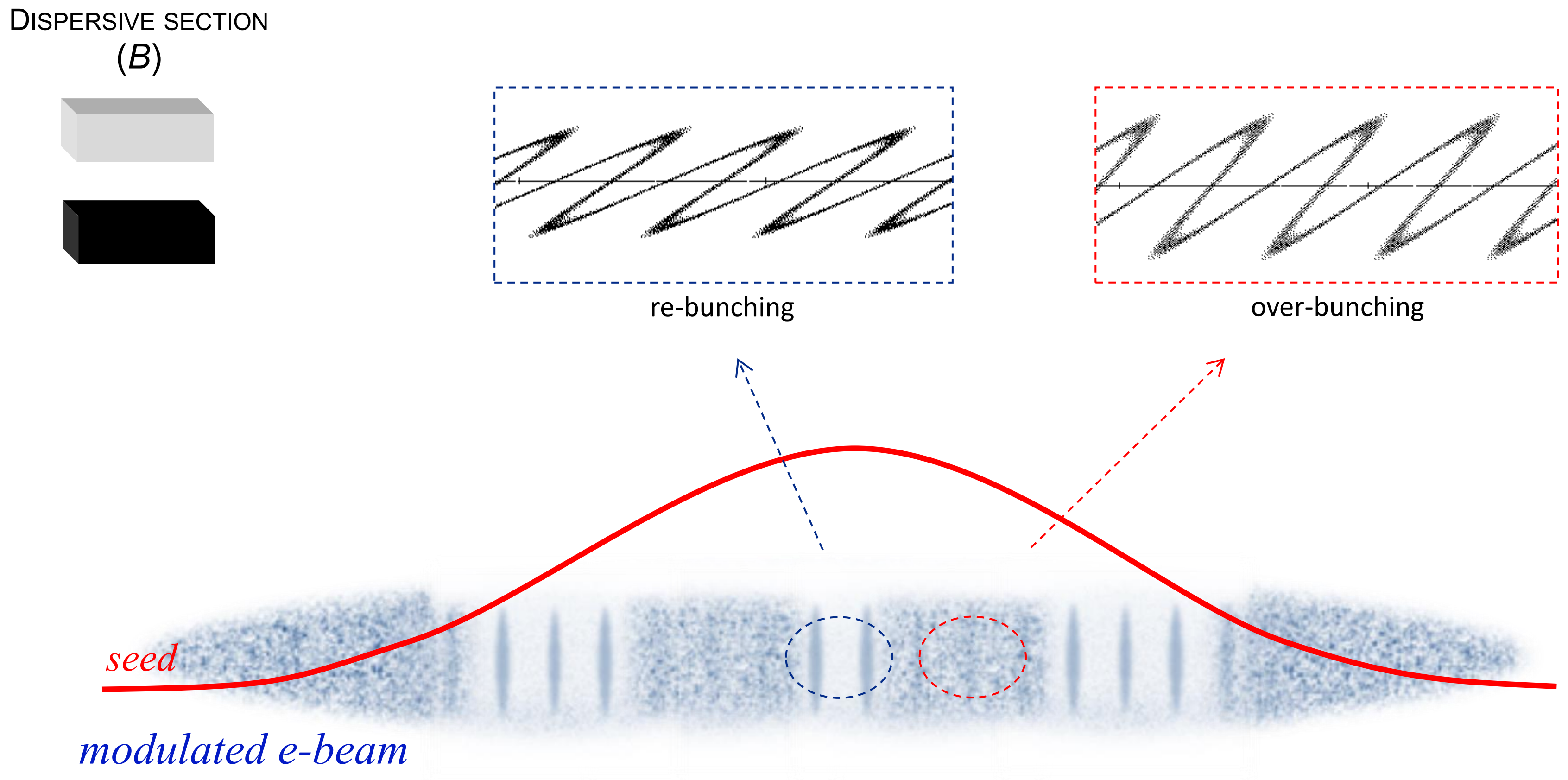

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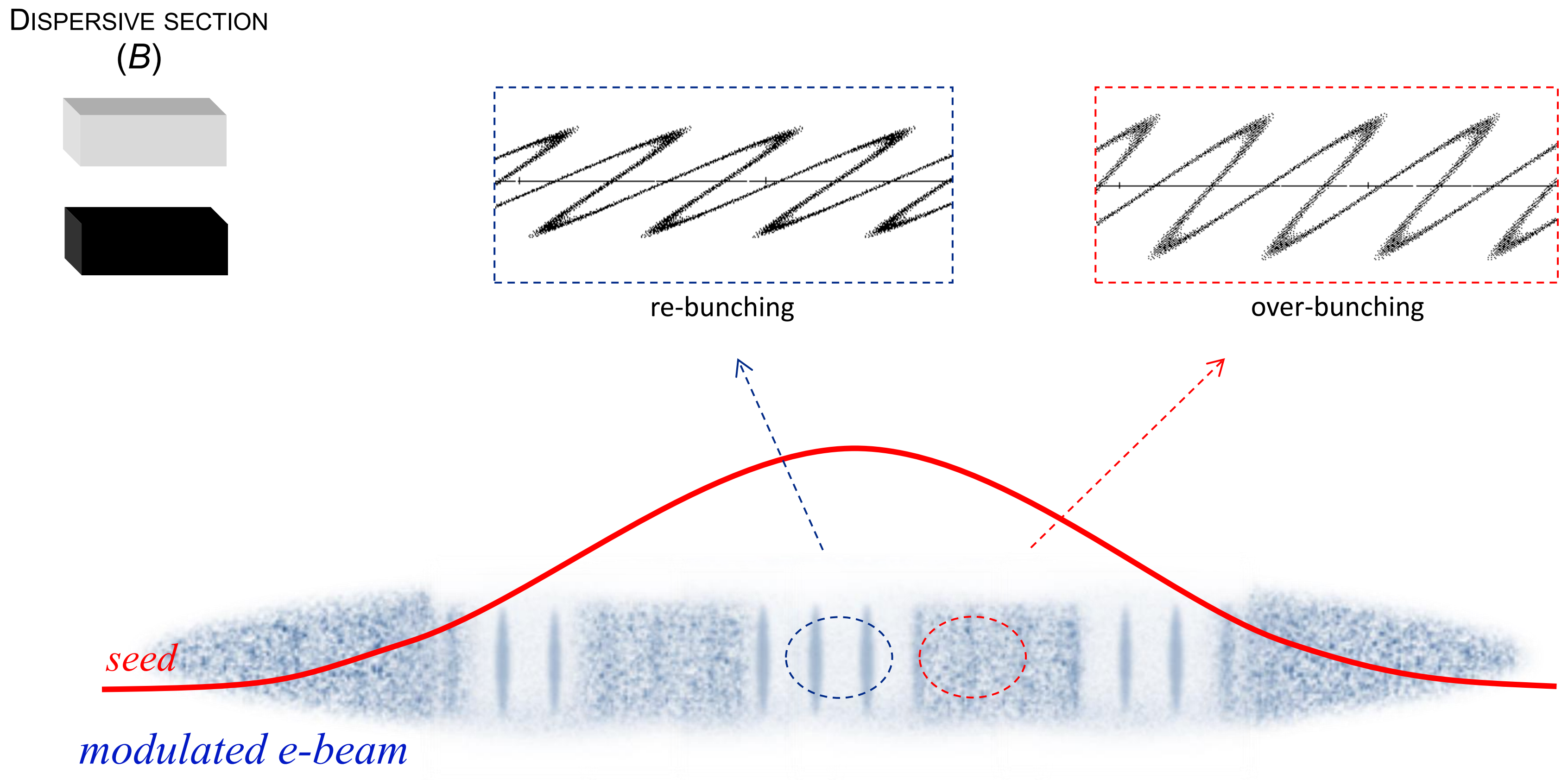

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Time-dependent complex bunching factor

envelope | phase

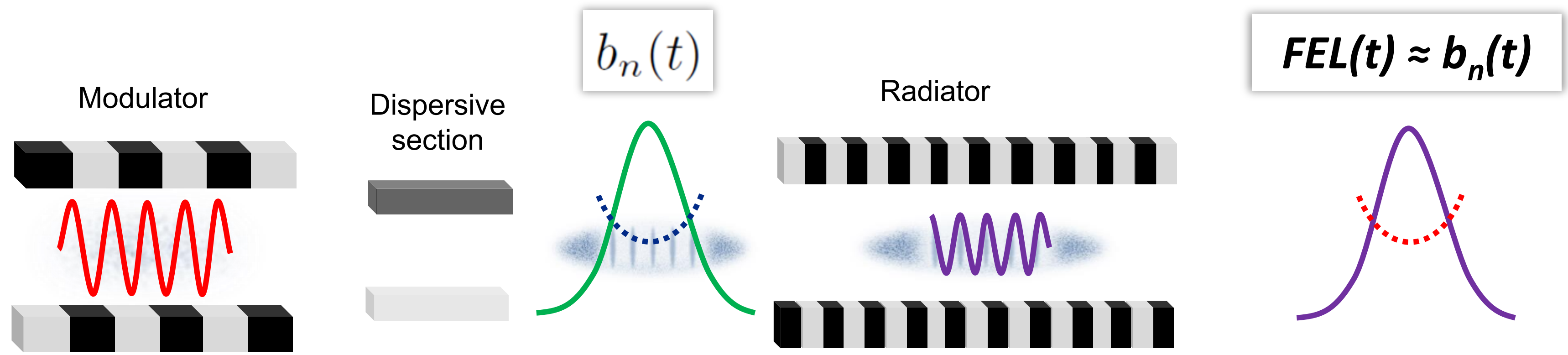
$$b_n(t) = e^{-n^2B^2/2} J_n[-nBA(t)] e^{in[\phi_s(t)+\phi_e(t)]}$$

- Bunching at the harmonic n
- Dispersive strength
- seed envelope
- seed slowly varying phase
- e- beam phase from time-dependent energy profile

G. Stupakov, *SLAC-PUB-14639 (2011)*

About the complex amplitude of the FEL pulse…

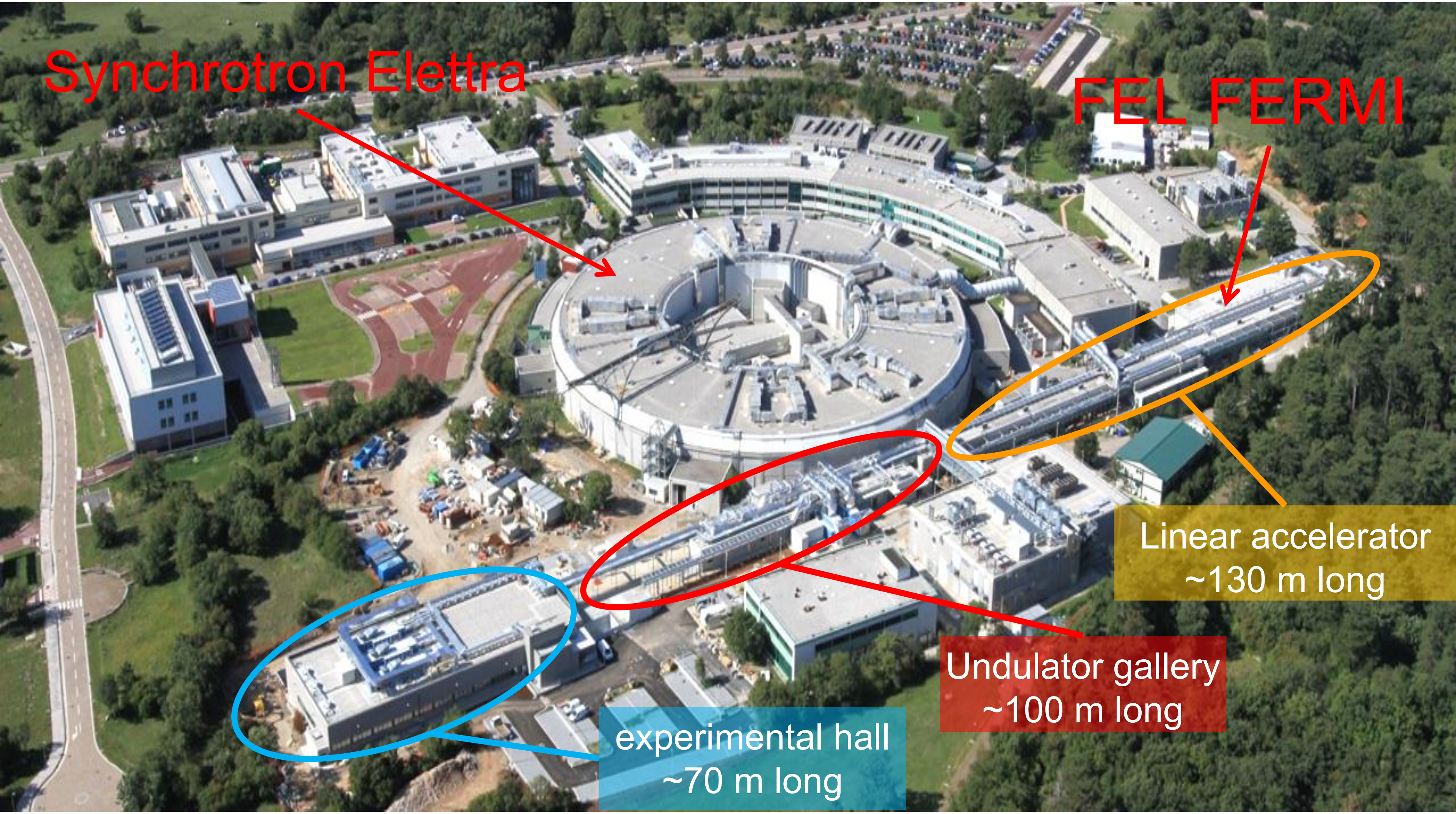
Hypothesis: in the linear regime before saturation, the FEL pulse is expected to mimic the bunching distribution + small additional phase during amplification.



Measurement of the FEL pulse characteristics…

The FERMI free-electron laser in Trieste (Italy)

Elettra Sincrotrone Trieste



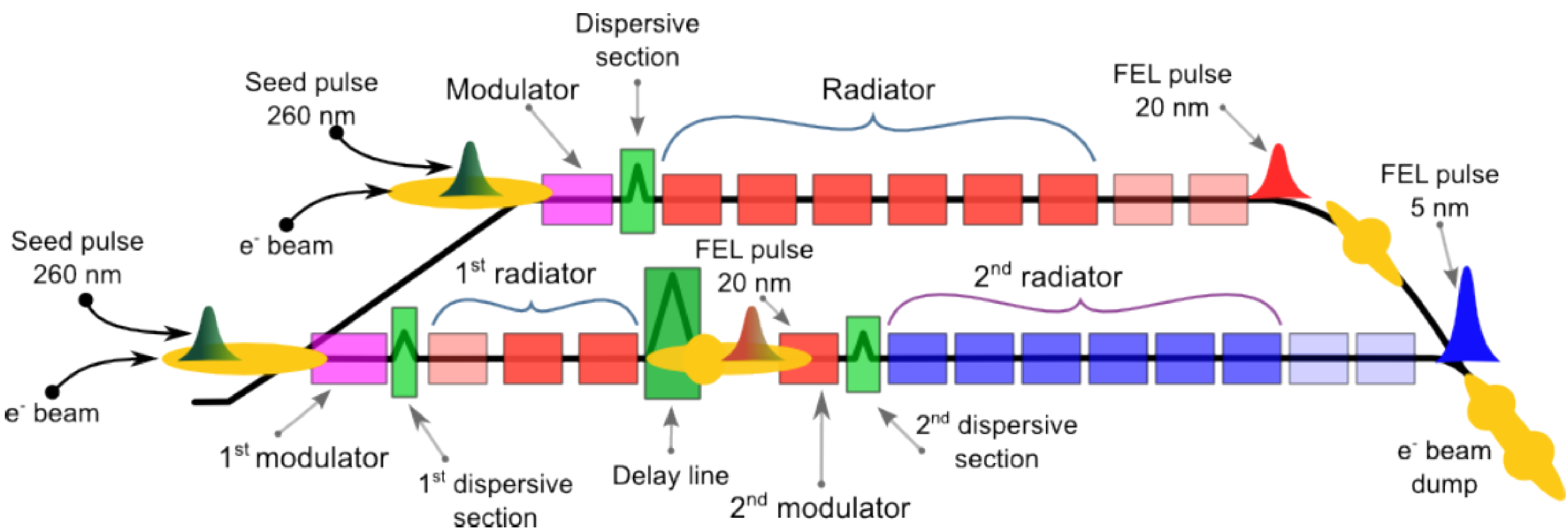
Overview of FERMI

Elettra Sincrotrone Trieste

Linear accelerator:
Rep rate 10Hz
Beam charge ~700pC
Beam energy 0.9 - 1.5 GeV
Peak current ~700A.

Seed laser:
THG of Ti:Sa @261 nm or OPA in the range 230 to 260 nm
Variable linear frequency chirp and duration

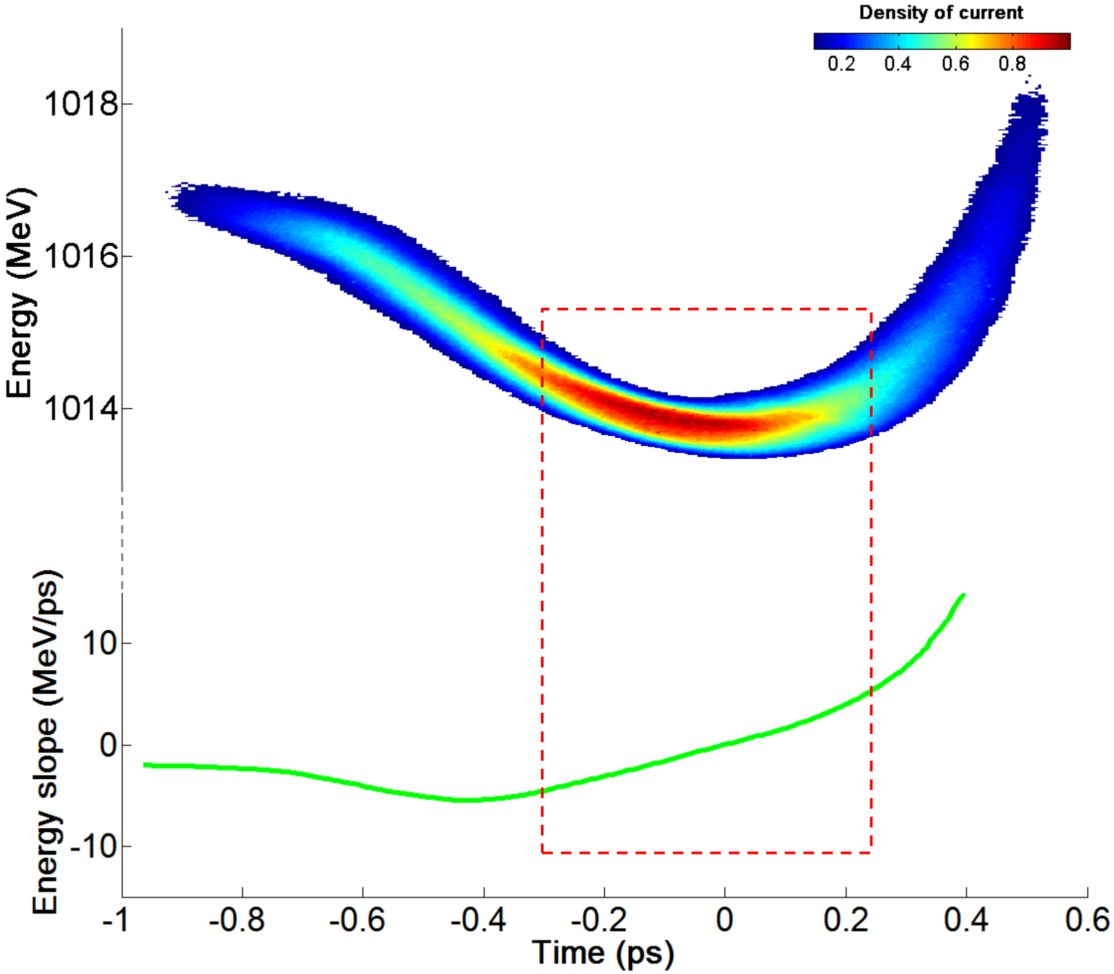
FEL undulator lines:
FEL-1: modulator + 6 radiators
FEL-2: two stages, 1 mod + 2 radiators followed by 1 mod + 6 radiators



Courtesy of Enrico Allaria

Electron beam time-dependent profile

Example of electron beam time-dependent profile on FERMI



Dominant quadratic chirp

$$E(t) = E_0 + \chi_1 t + \chi_2 t^2 + \chi_3 t^3 + \cdots$$

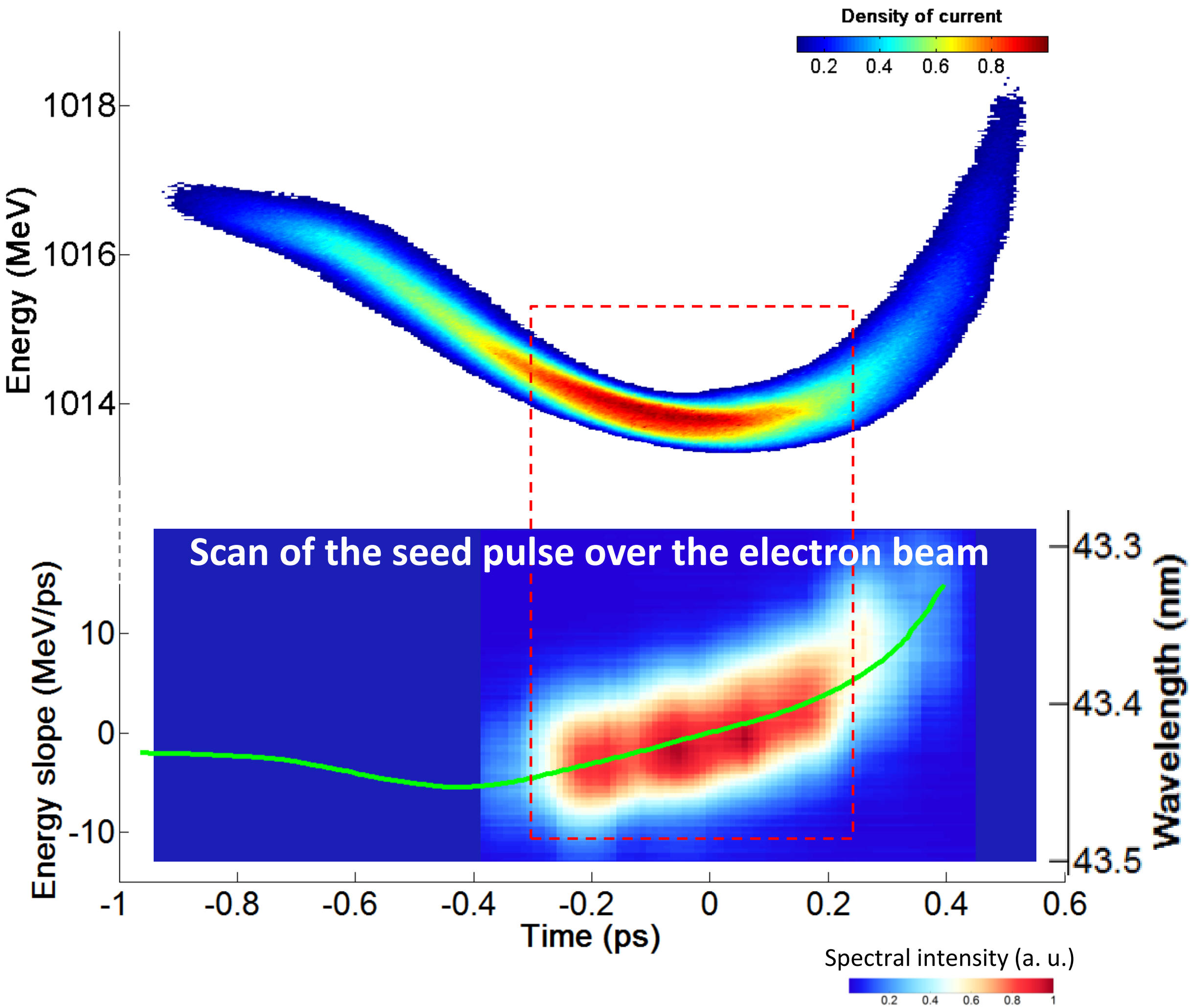
$$\chi_2 \sim 10\ MeV/ps^2$$

Linear energy slope:

Electron beam time-dependent profile

Elettra Sincrotrone Trieste

Example of electron beam time-dependent profile on FERMI



Dominant quadratic chirp

$$E(t) = E_0 + \chi_1 t + \chi_2 t^2 + \chi_3 t^3 + \cdots$$

$$\chi_2 \sim 10\ MeV/ps^2$$

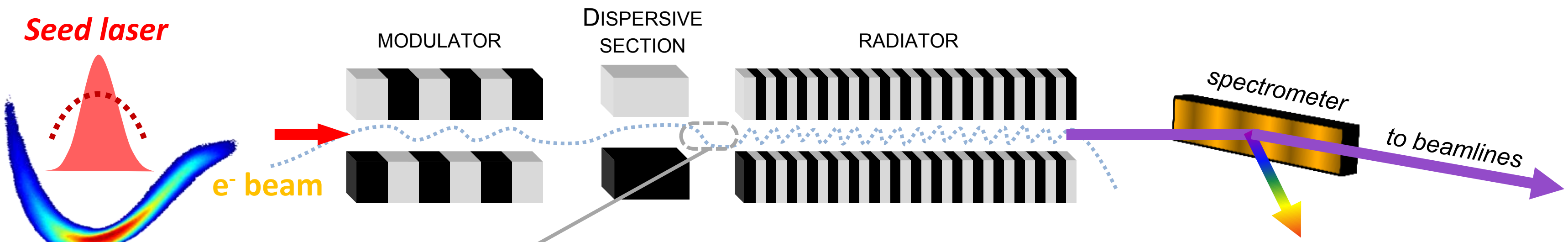
Linear energy slope:

=> Linear frequency shift

when changing the delay between the seed and the electron beam

=> linear frequency chirp

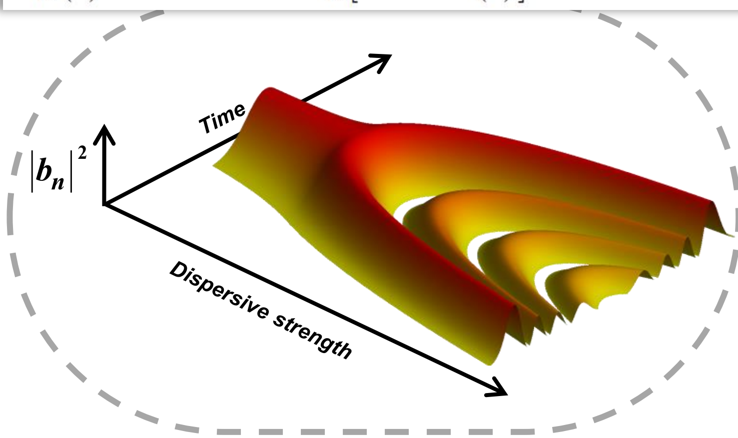
(1) Pulse shaping and spectral responses

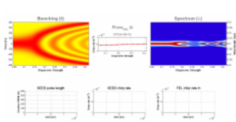


Spectral profile of the FEL pulse

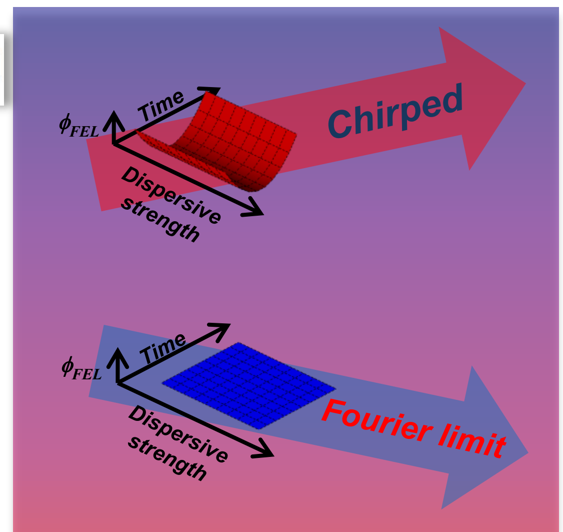
Temporal profile of the microbunching

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



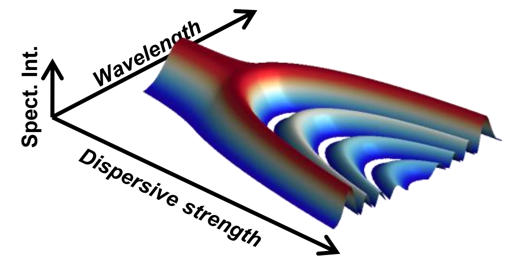


movie

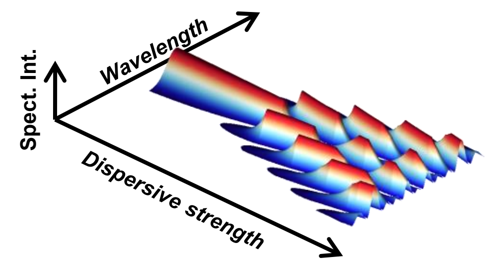


Temporal profile of the phase:

contribution of the microbunching
+ FEL amplification

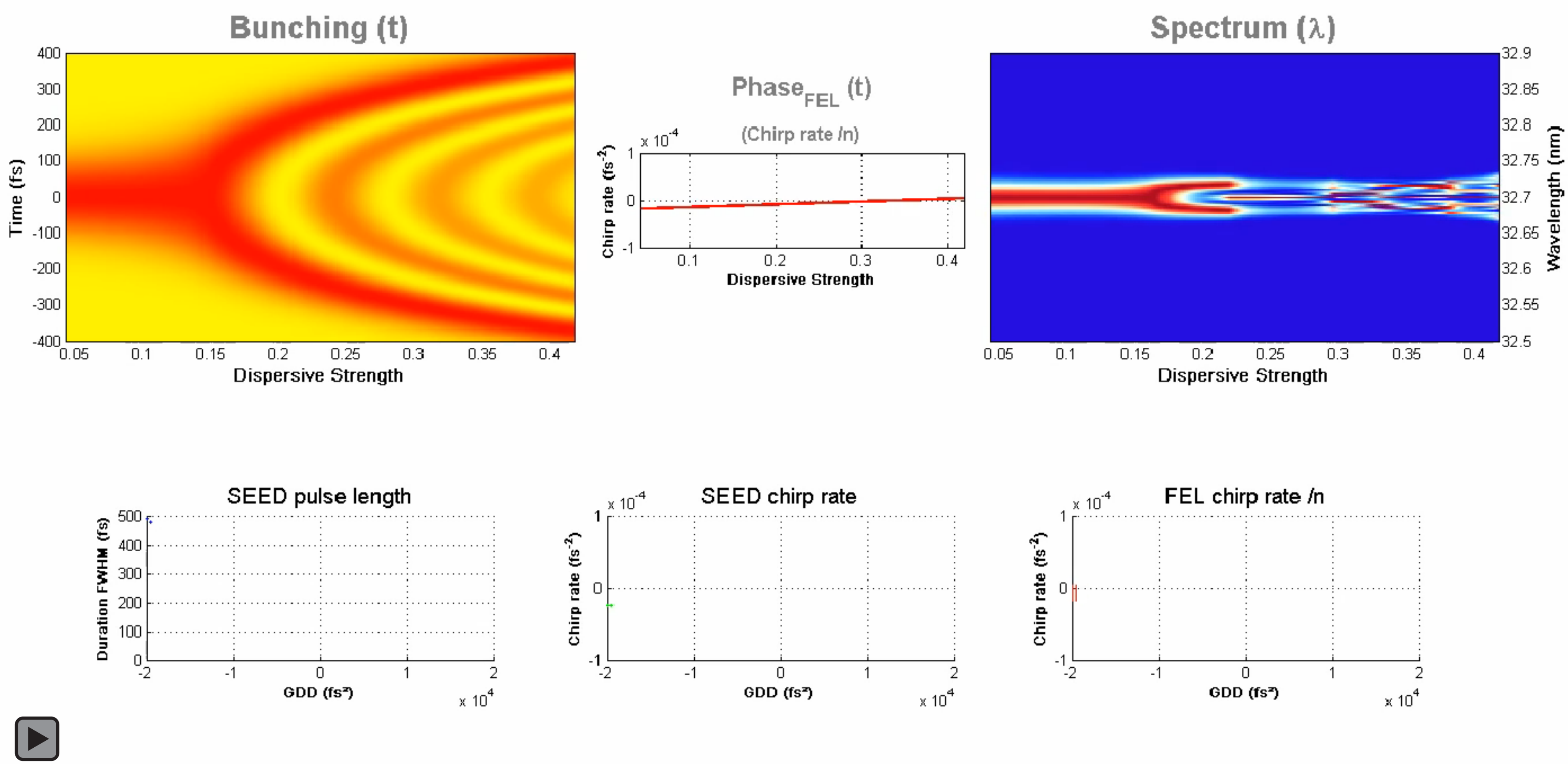


Time-frequency mapping



Specific spectral signature

(1) Pulse shaping and spectral responses



movie

(1) Spectral mapping of the pulse profile

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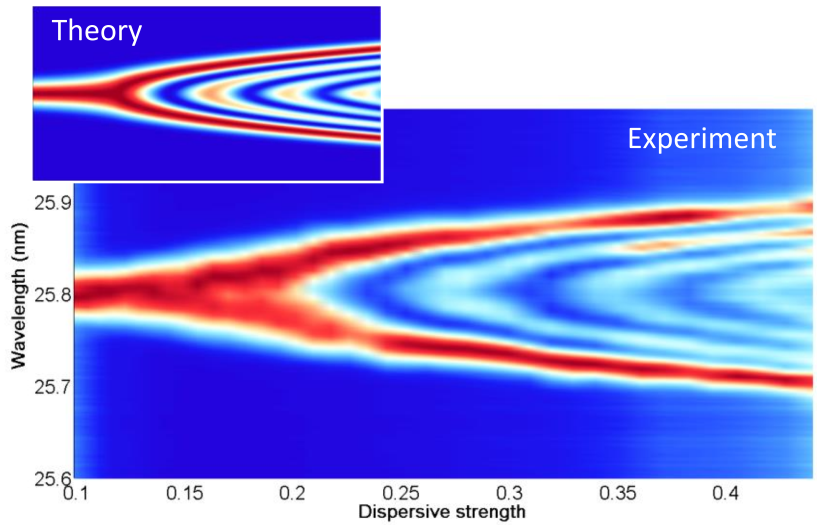
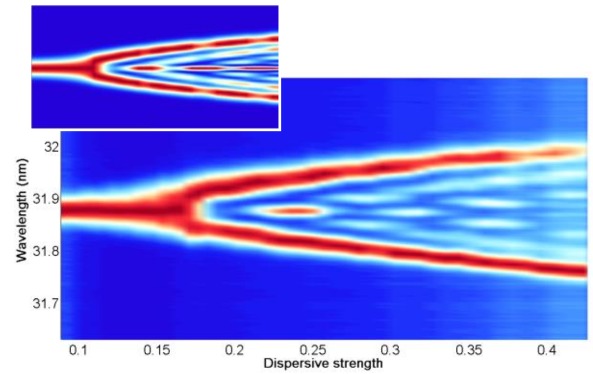
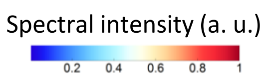
Case 1: seed with strong linear frequency chirp
=> strong chirp on the FEL pulse



Direct representation of the FEL temporal pulse profile through the time-frequency mapping.

Case 2: reduced positive chirp on the seed





Conclusions:
1) The seed-induced microbunching strongly drives the FEL pulse profile.
2) In the linear regime (before saturation) the field envelope is preserved despite amplification in the radiator.

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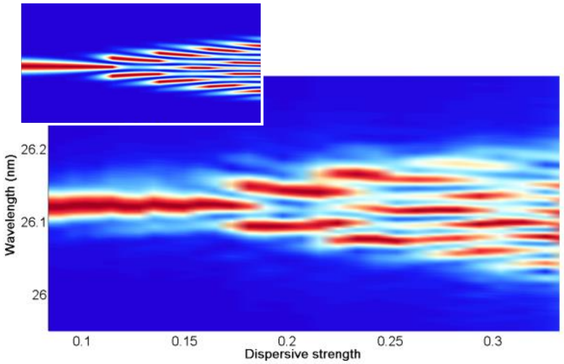
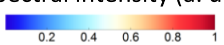
Case 3: negative chirp on the seed



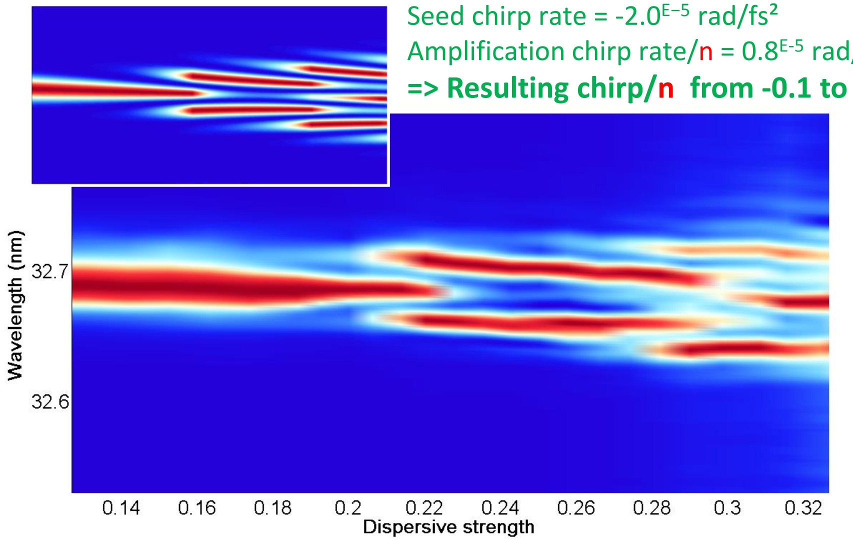
Demonstration of temporal coherence through the spectral modulations which result from interference between the multipeaked temporal structure.

Spectral intensity (a. u.)



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

Quadratic profile e- beam = 12 MeV/ps²
Seed chirp rate = -2.0^{E-5} rad/fs²
Amplification chirp rate/n = 0.8^{E-5} rad/fs²
=> Resulting chirp/n from -0.1 to 1.1^{E-5} rad/fs²



Spectral signature of the chirp compensation
=> Fourier limited pulse

Conclusions:

3) Possibility to cancel the FEL pulse chirp and generate Fourier limited pulses.

4) Proof of principle of the pulse control and shaping in a seeded FEL.

Spectrotemporal Shaping of Seeded Free-Electron Laser Pulses, PRL in press

(2) Generation of phase-locked pulses

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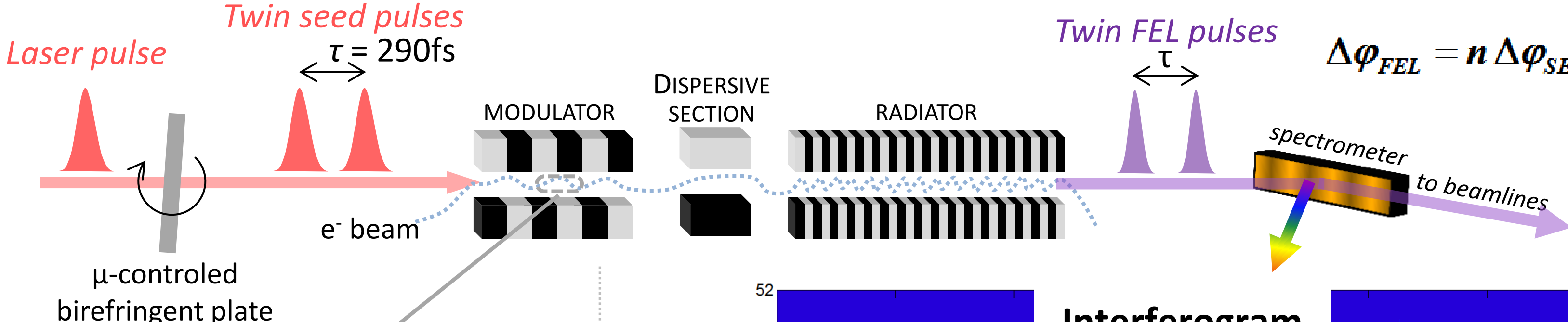
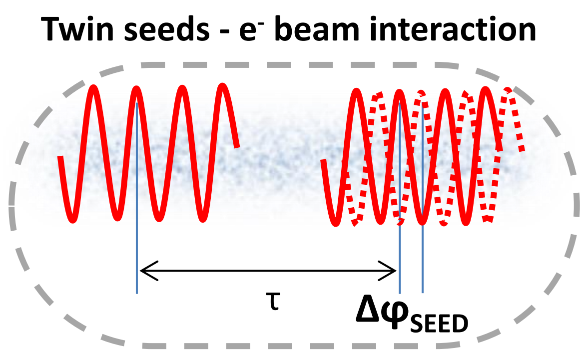
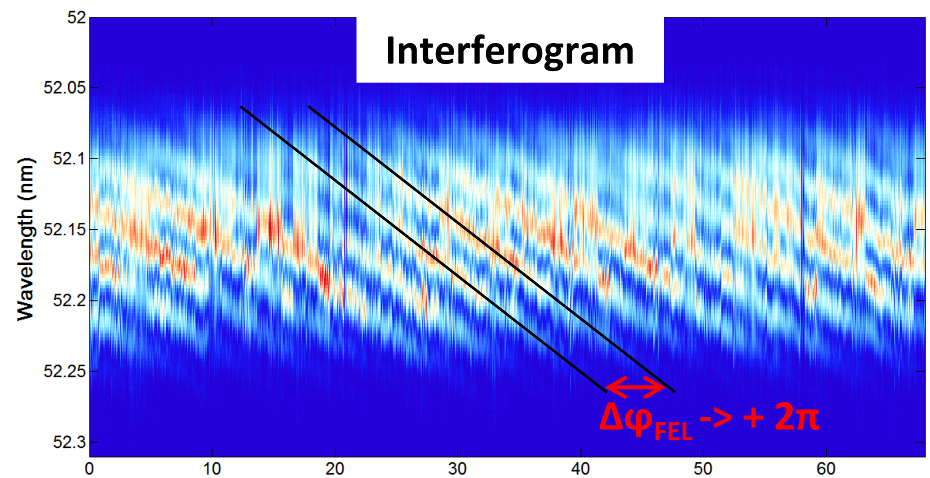
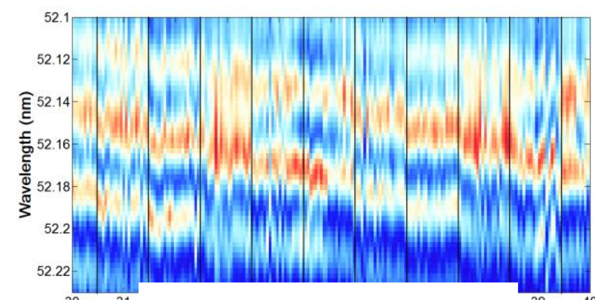
$$\Delta\varphi_{FEL} = n\,\Delta\varphi_{SEED} + C$$







Rotation steps => $\Delta\varphi_{FEL} = \lambda_{FEL}/5.67$



Zoom of the central part

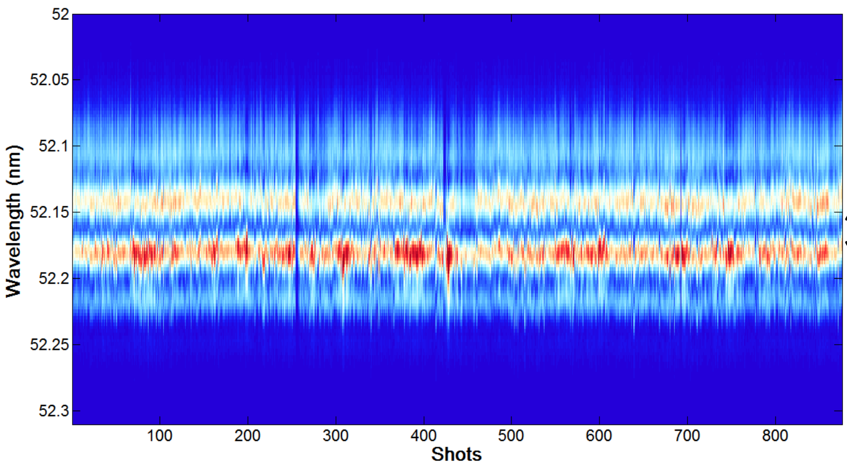
Phase locking and control between the **carrier envelope phases** of two time-delayed FEL pulses demonstrated by **frequency-domain interferometry**.

(2) Relative phase stability

Elettra Sincrotrone Trieste

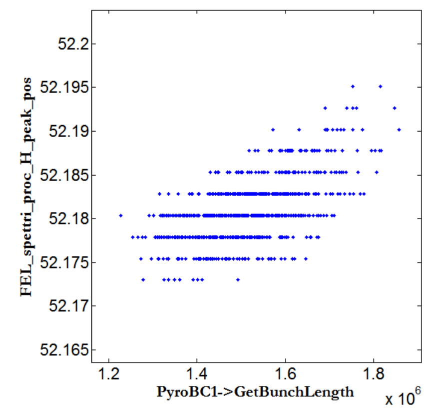
Statistical analysis looking at the brightest fringe:

Sequence of single shot spectra

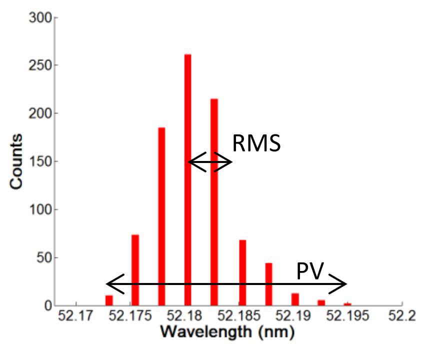


= 0.0383nm
≡ 2π (one wavelength)

Correlation of the fringe vs. bunch length monitor



Position of the brightest fringe



Phase stability from the fringes statistic:

Peak-to-valley = ***π rad*** ($\lambda_{FEL}/2$)

RMS = ***π/5 rad*** ($\lambda_{FEL}/10$) => locking in phase better than 20 attoseconds between the carrier-waves of the two consecutive FEL pulses.

Main sources of instability:

Bunch length compressor -> evolution of the e^- beam profile (again).

Generation of phase-locked pulses from a seeded free-electron laser, in preparation

(3) SPIDER
(Spectral-phase Interferometry for Direct Electric-field Reconstruction)

Idea:
Measurement of the spectral phase φ(ω)

Principle:
Spectral phase interferometry between two time-delayed (as previously) spectrally sheared pulses.

Main steps:
Step 1) recording of the interferogram. The fringes distribution contains the information on the differential of the spectral phase :

$$\cos\left[\varphi(\omega)-\varphi(\omega+\Omega)+\omega\tau\right]$$

Interferometric term

Step 2) reconstruction of the spectral phase φ(ω) by concatenation of the phase difference.

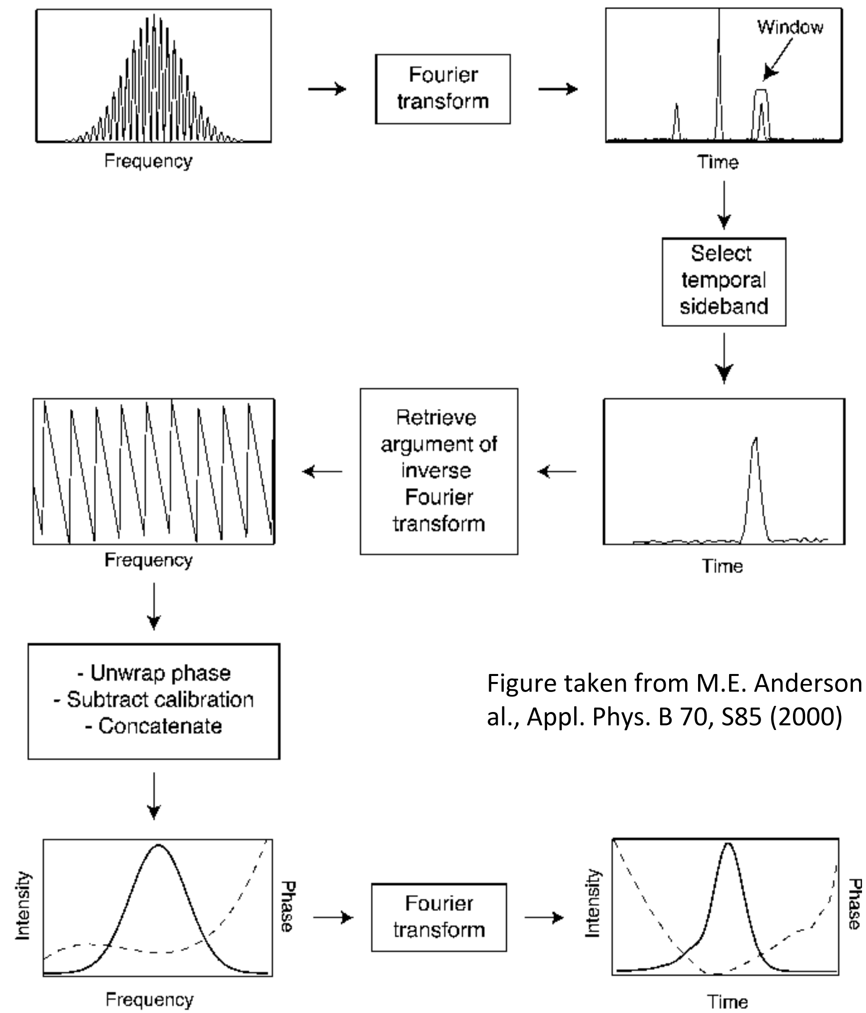


Figure taken from M.E. Anderson et al., Appl. Phys. B 70, S85 (2000)

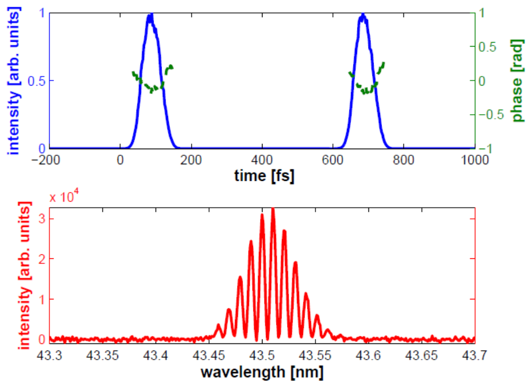
⇒ Full reconstruction of the pulse electric field, phase and envelope.

Acquisition in single shot/no iterative algorithm, feasible in real time

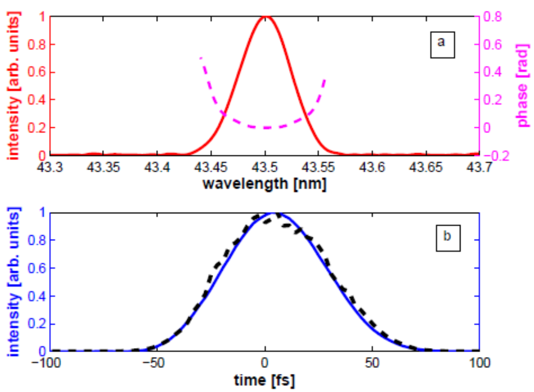
(3) Spectrally sheared identical pulses on FERMI

1) Seed a flat electron beam with two spectrally sheared pulses

Output pulses simulated with FERMI parameters:



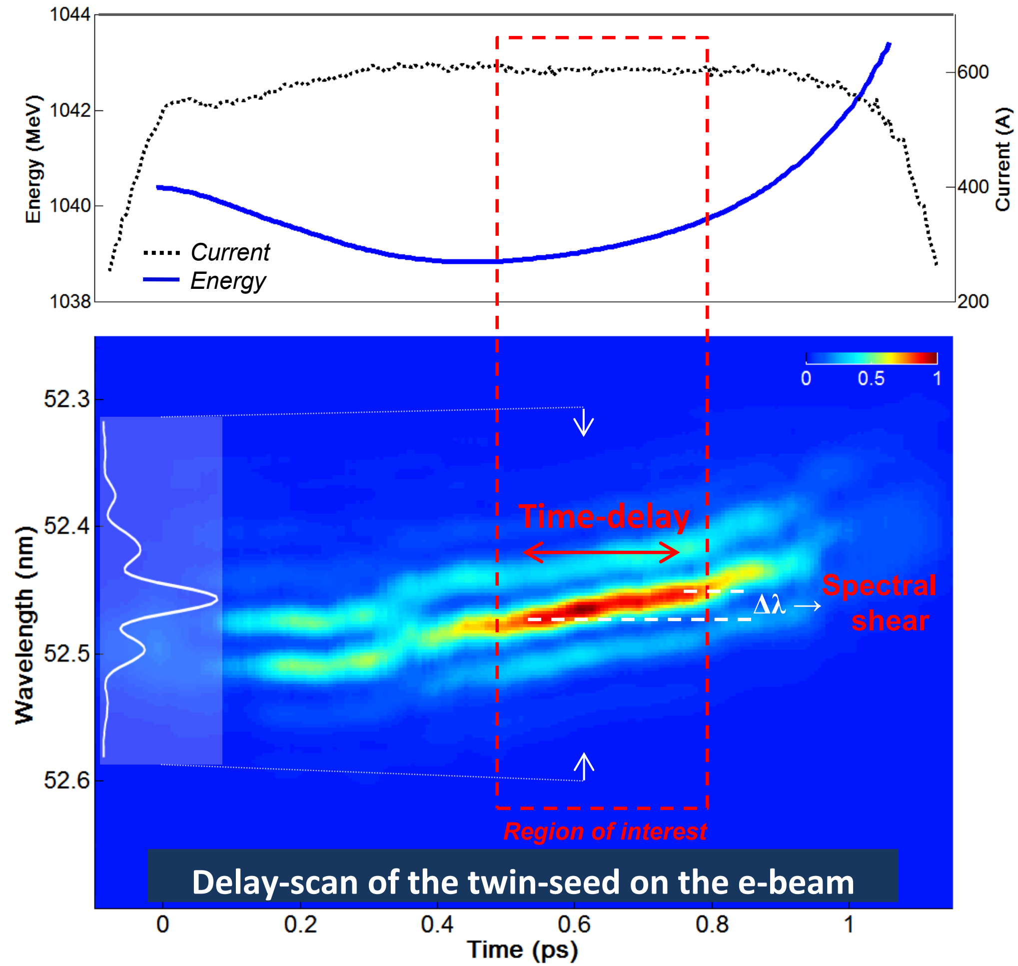
Reconstruction with SPIDER algorithm:



Spectral-phase interferometry for direct electric-field reconstruction applied to seeded extreme-ultraviolet free-electron lasers, Optics Express

or

2) Use the quadratic chirp of the electron beam



⇒ **Spectral shear from the e- beam frequency shift**

⇒ **homogeneity that ensure the phase similarities**

(3) SPIDER results

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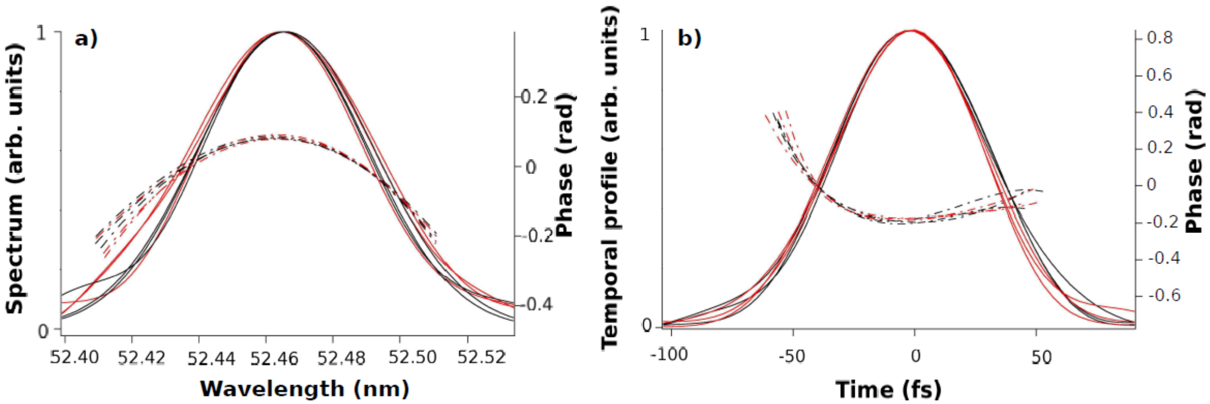
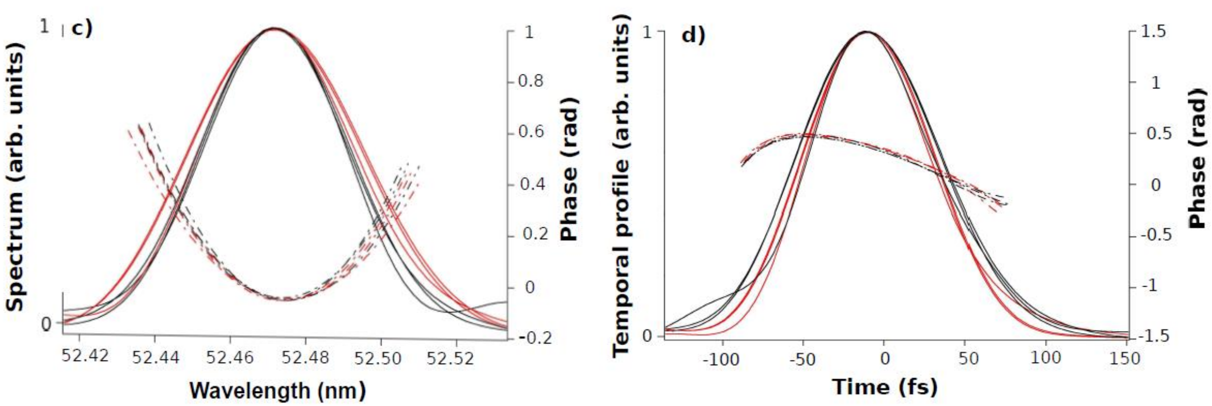
First seed condition: duration = 125fs (FWHM), chirp rate = 0.9 x 10–5 rad/fs²



FEL pulse duration ~ 70 fs
temporal chirp ~ 12^{E-5} rad/fs²

Second seed condition: duration = 180fs (FWHM), chirp rate = -4.5 x 10–5 rad/fs²



FEL pulse duration ~ 100 fs
temporal chirp ~ -16^{E-5} rad/fs²

Reconstructions for 3 consecutive FEL shots (lines of the same color) for two different delays (red and black lines).

⇒ Full single-shot measurement of the FEL pulse envelope and phase.

Single-shot spectro-temporal characterization of XUV pulses from a seeded free-electron laser, Nature Communication in press

Conclusion

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We demonstrated:

1) The control and shaping of the pulse properties in a seeded (HGHG) FEL
2) The indirect and direct full characterization (+ confirmation of coherence)

Finally, we demonstrated the full laser-driven characteristic of a seeded FEL. We have proposed and demonstrated the implementation of flexible tools opening new perspectives in ultrafast matter-light interaction with UV to X-ray light pulses.

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Thank you!

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