Control of FEL radiation properties by tailoring the seed pulses

Hamburg Alliance New Beams and Accelerators

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FEL control driven by seed laser

Importance of the control on the seed laser properties

Control on the seed laser phase permits to:

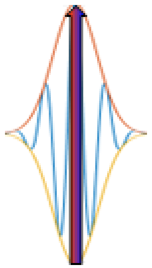
- Correct and control the FEL phase

$$\phi_{FEL}(t) = n\left(\phi_{seed}(t) + \phi_{electrons}(t)\right) + \phi_{fel}(t)$$

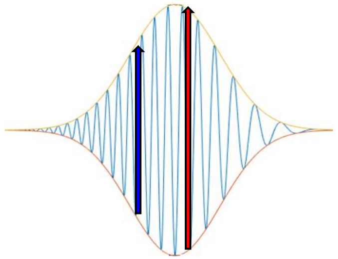
$$\phi_{seed}(t) = \phi_0 + \omega_0 t + \frac{1}{2}\boldsymbol{\alpha} t^2$$

$$\phi_{electrons}(t) \propto \frac{1}{\sigma_E} E(t)$$

$\boldsymbol{\alpha = 0}$



$\boldsymbol{\alpha \neq 0}$



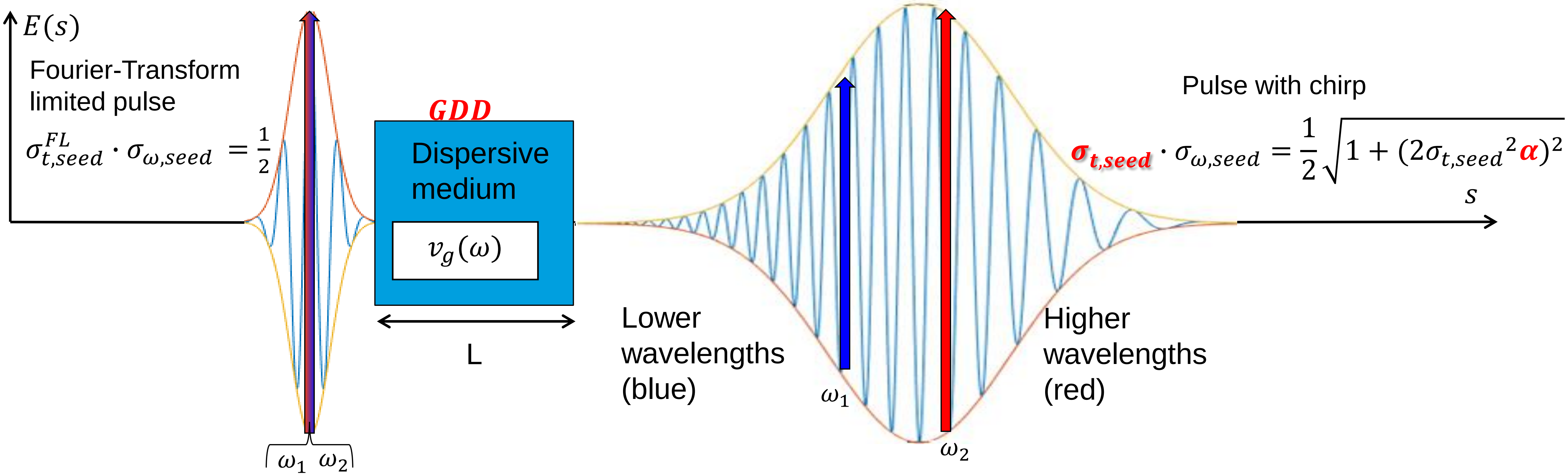
- Eventually FEL phase control enables CPA (chirped pulse amplification*) and phase sensitive experiments (four-wave mixing, attosecond coherent control[2]).

[1]**Chirped pulse amplification in an extreme-ultraviolet free-electron laser,** David Gauthier et al. *Nat. Comm.* **7**, 13688 (2016)

[2]**Coherent control with a short-wavelength free-electron laser,** *Nature Photonics* **volume 10**, pages 176–179 (2016) K. Prince et al.

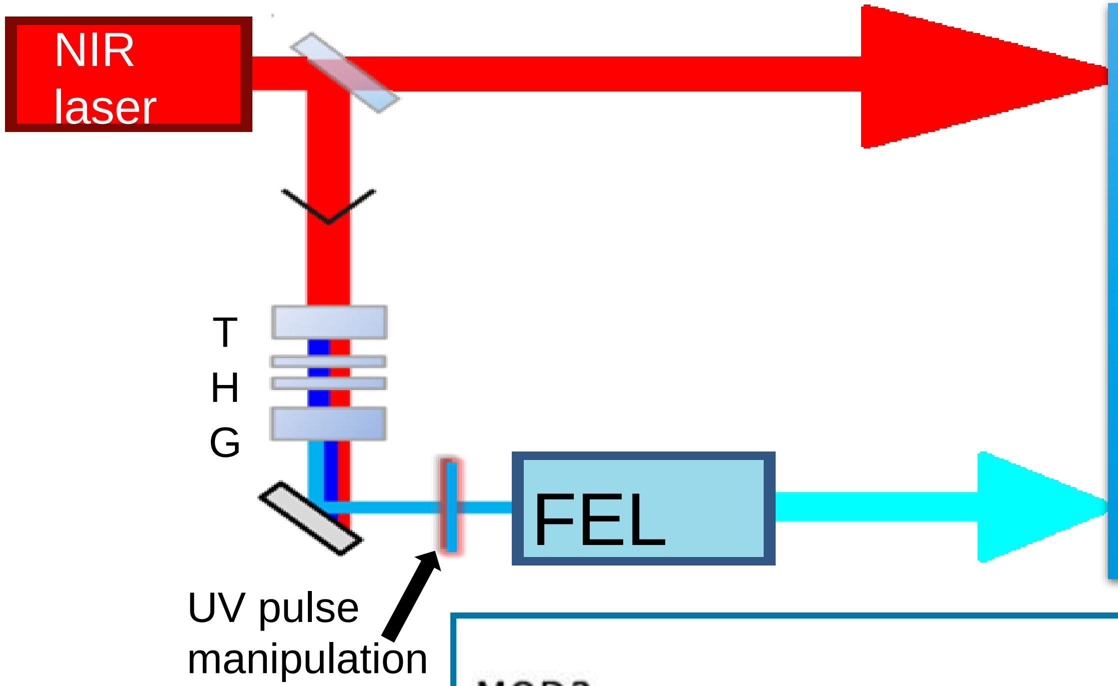
Ultra-short pulses passing through dispersive materials

Introducing Group Delay Dispersion (GDD)



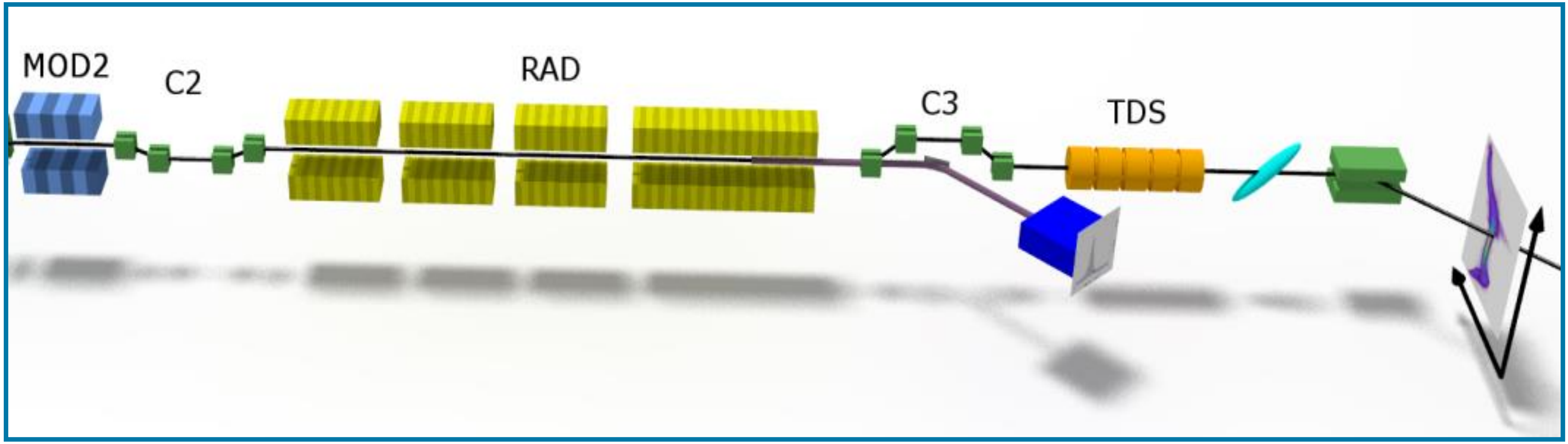
- GDD depends on the **material**, on the **distance travelled** by the light in the material and the **bandwidth** of the considered light pulse
- GDD quantifies the amount of chirp $\boldsymbol{\alpha}$ held from a light pulse ($\phi_{seed}(t) = \phi_0 + \omega_0 t + \frac{1}{2}\alpha t^2$)

Controlling the chirp

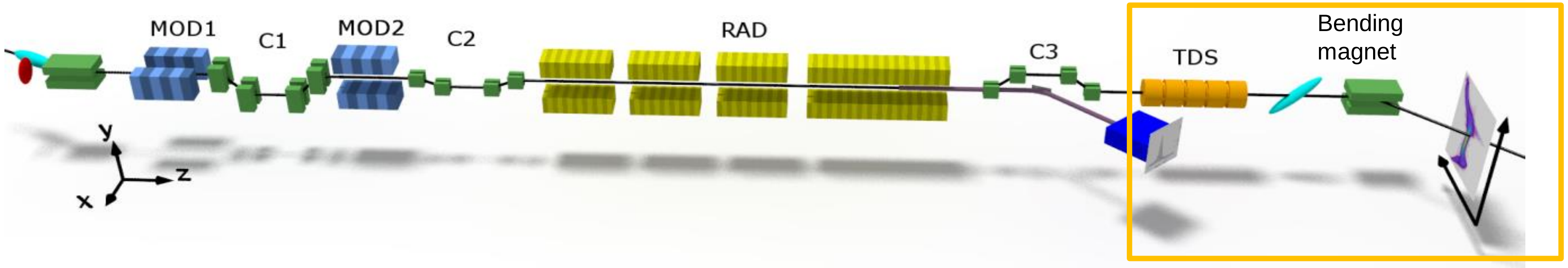


Photon Diag. Laboratory

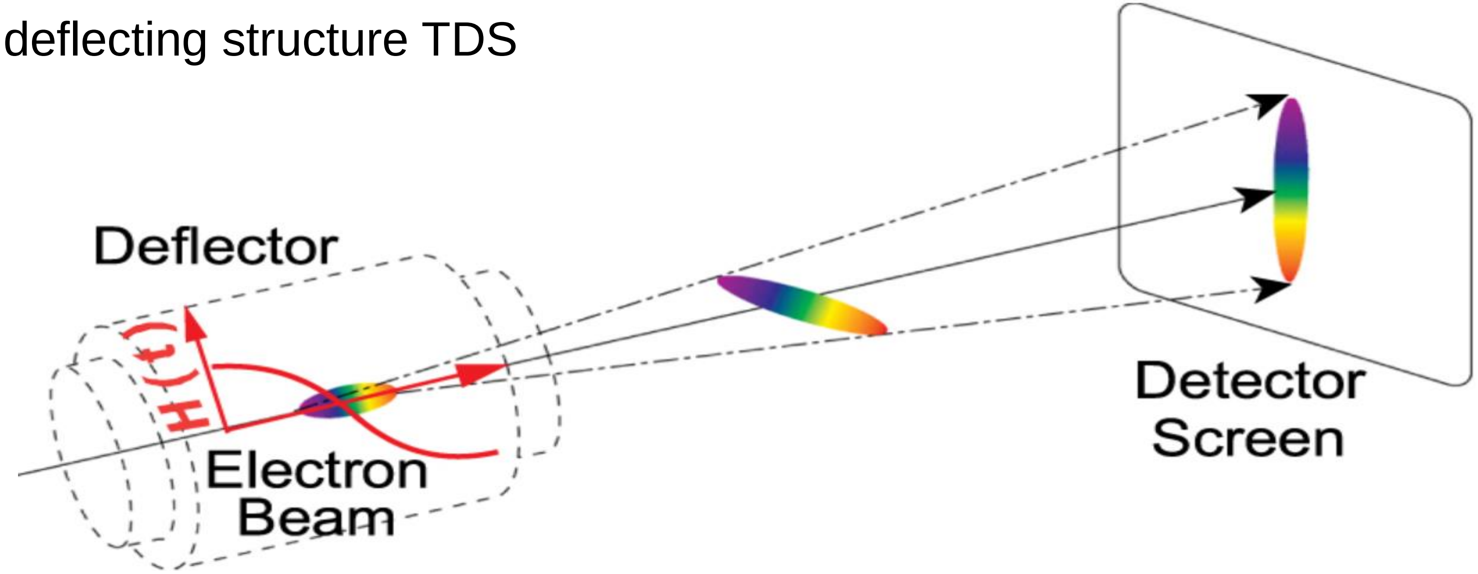
THz experiment
→ temporal profile of the FEL pulse
→ enables derivation of the seed laser chirp at the interaction point in MOD2



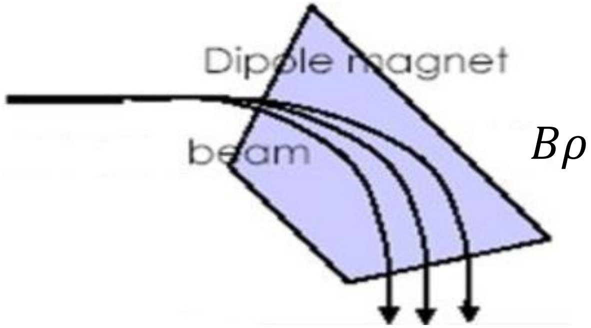
Longitudinal phase space distribution measured with TDS



Transverse deflecting structure TDS

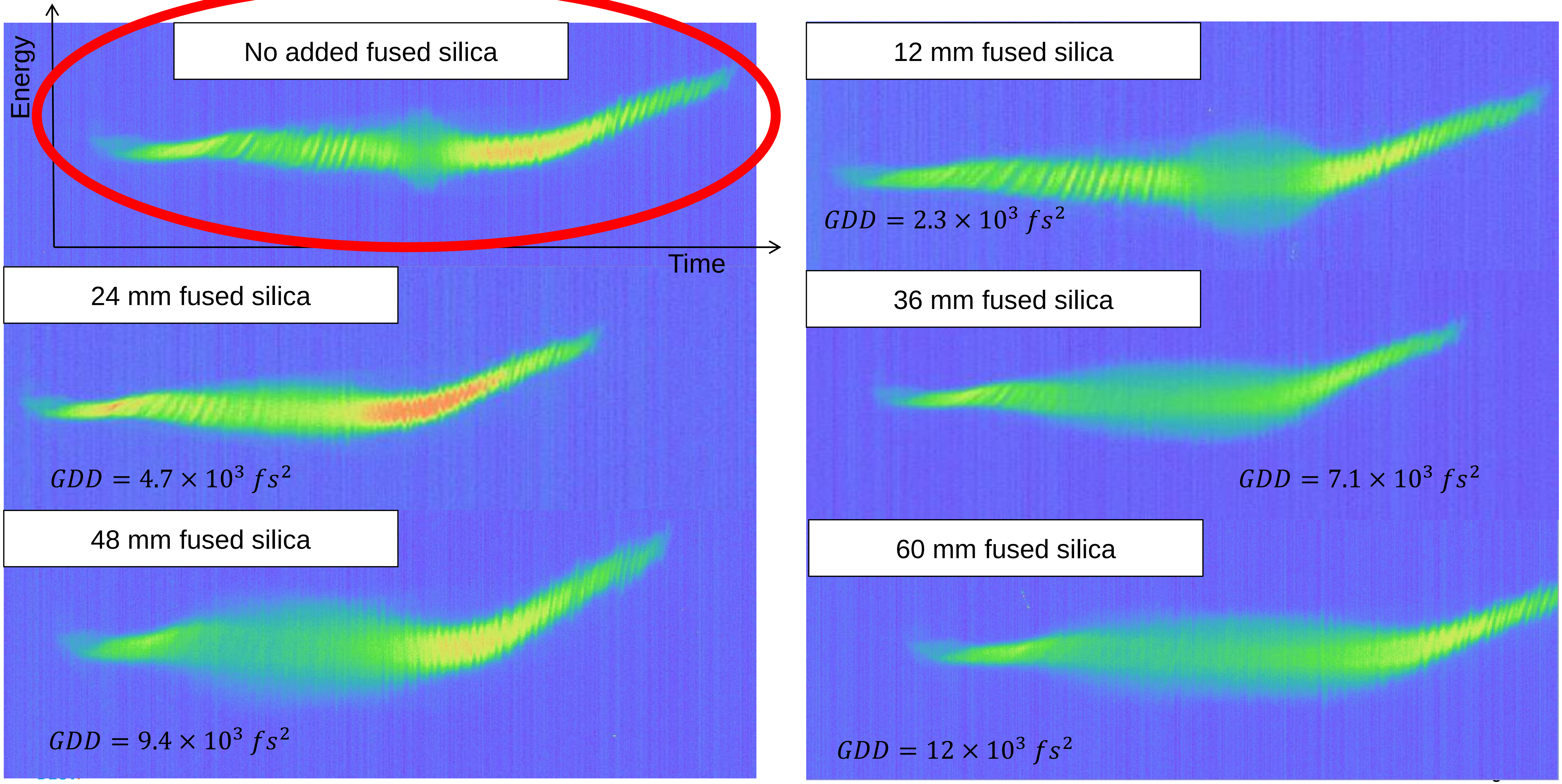


Bending magnet



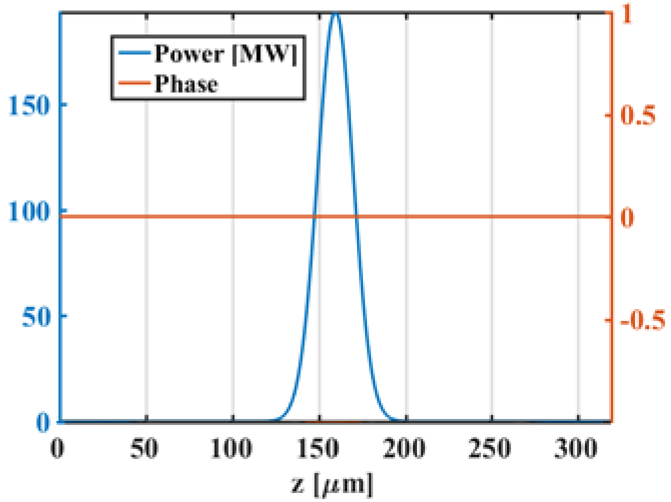
$B\rho \sim m_e \beta c$

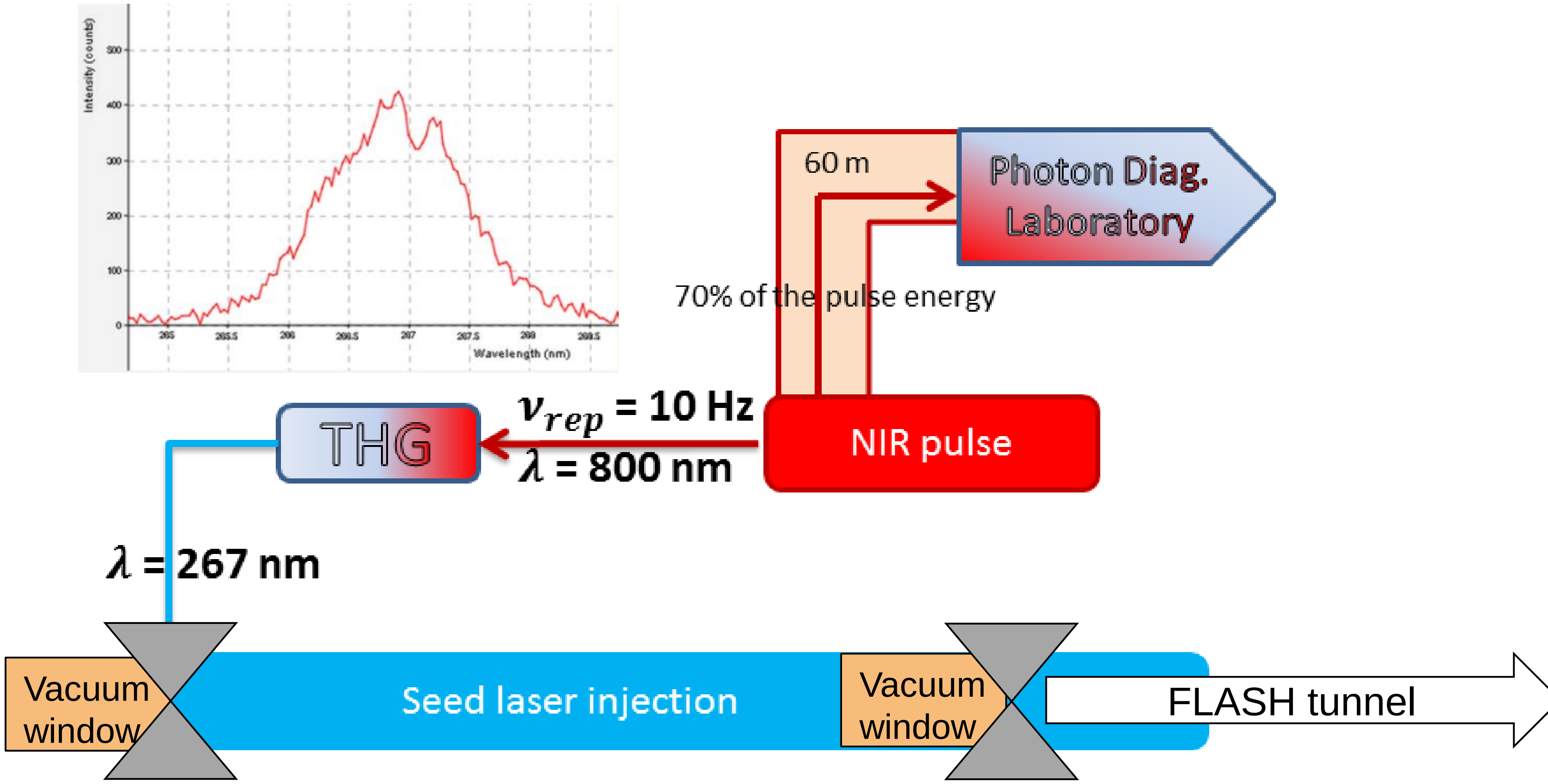
Impact of fused silica on energy modulation



Characterization of seed laser chirp

Chirp gained by passing through seed laser beamline w/o any additional material

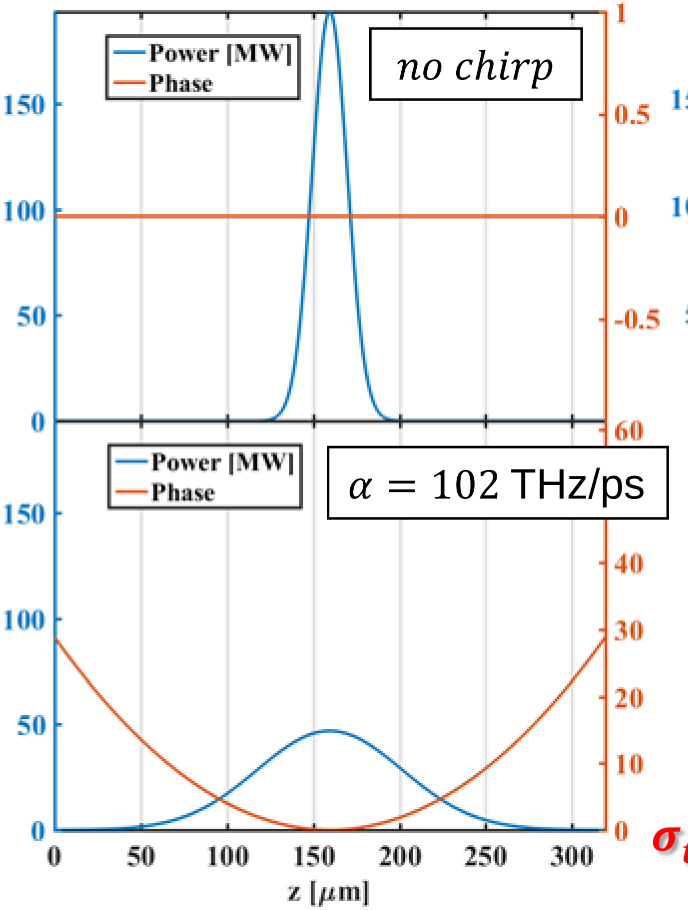


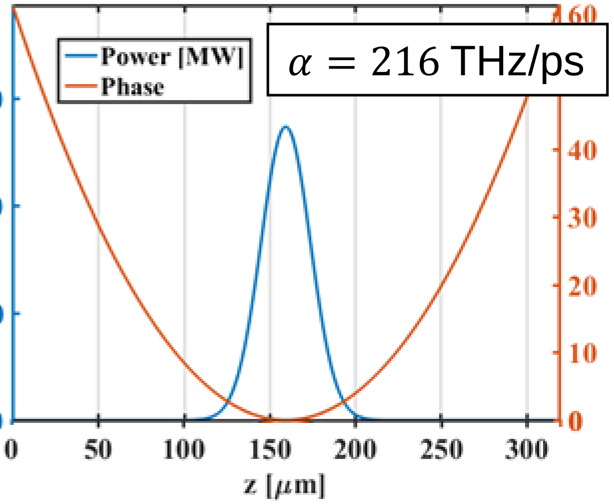


$\sigma_{\omega,seed} = 14.7\ \text{THz}$ ⇨ $\sigma_{t,seed}^{FL} \cdot \sigma_{\omega,seed} = \frac{1}{2}$ ⇨ $\sigma_{t,seed}^{FL} = 34\ \text{fs}$

Simulated working points

Seed laser pulses at the modulator entrance



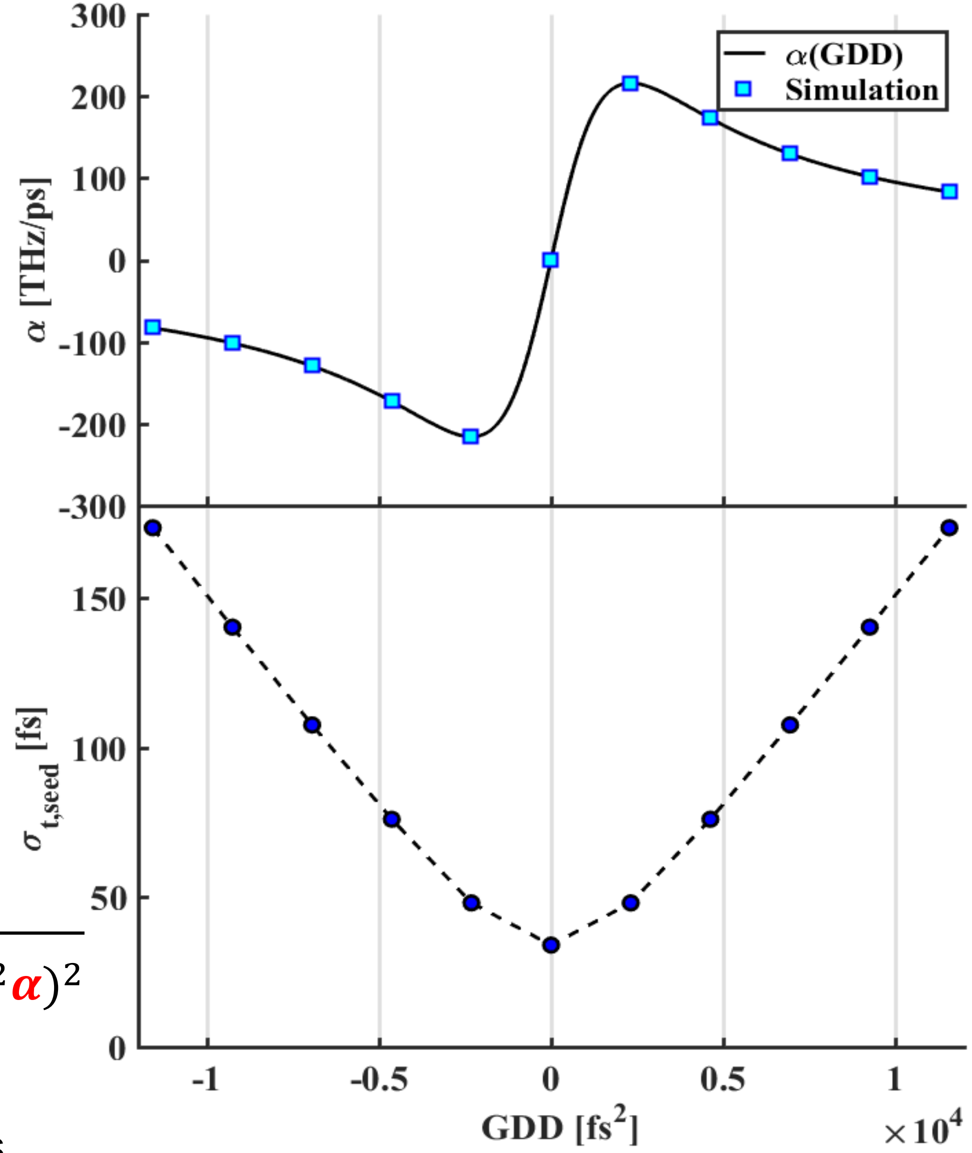


$$\phi_{seed}(t) = \phi_0 + \omega_0 t + \frac{1}{2}\boldsymbol{\alpha} t^2$$

$$\boldsymbol{\sigma_{t,seed}} \cdot \sigma_{\omega,seed} = \frac{1}{2}\sqrt{1 + (2{\sigma_{t,seed}}^2 \boldsymbol{\alpha})^2}$$

Seed laser energy and $\sigma_{\omega,seed}$ is identical for all the simulated pulses.

Chirp of the seed laser α



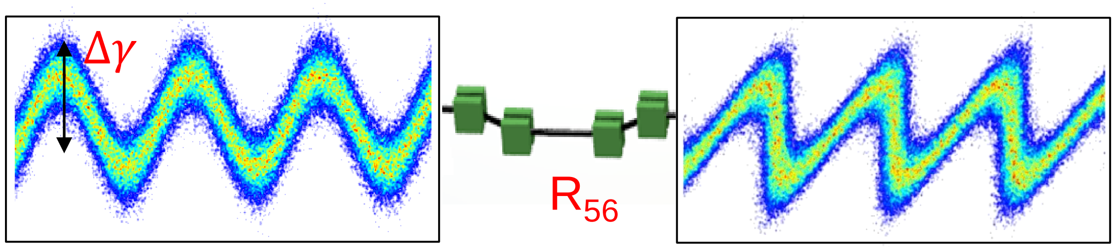
$\sigma_{t,seed}$ **respect to the GDD of the seed laser**

Initial GDD of the seed laser

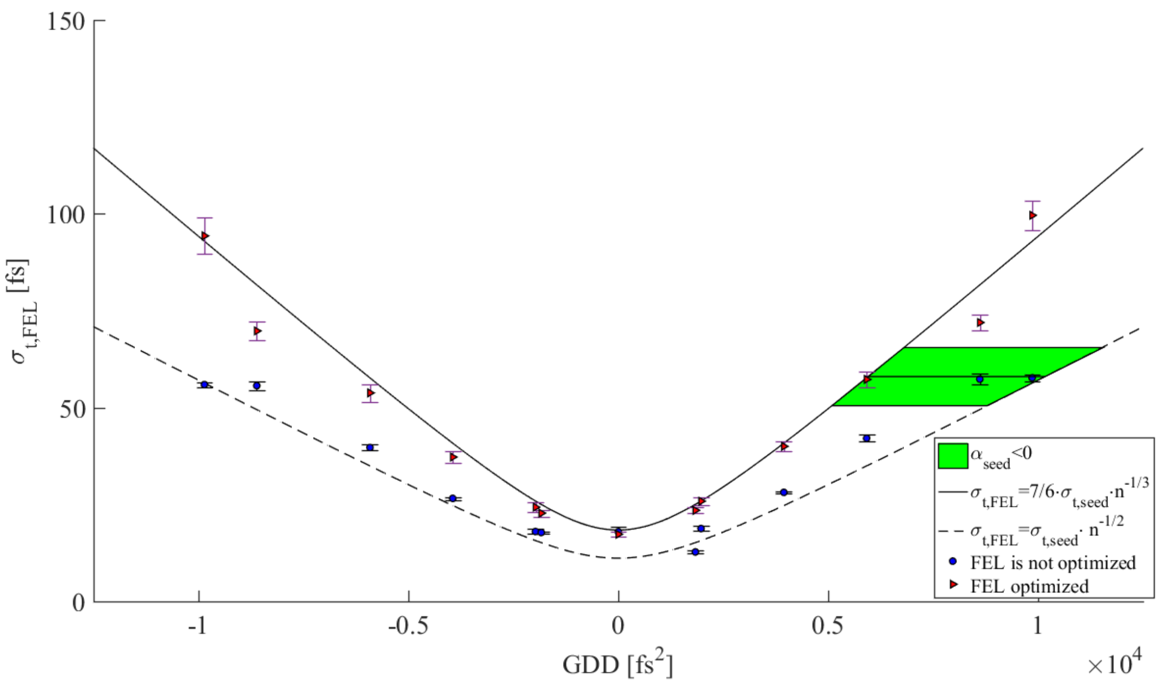
Simulation results are compared with THz streaking measurement

Seeded FEL pulse depends on FEL optimization:

- Seed laser power → energy modulation of the electron beam $\Delta\gamma$
- Strength of dispersion R_{56}



$$\frac{\sigma_{t,seed}}{\sqrt{n}} < \sigma_{t,FEL} < \frac{7}{6}\frac{\sigma_{t,seed}}{n^{1/3}}$$



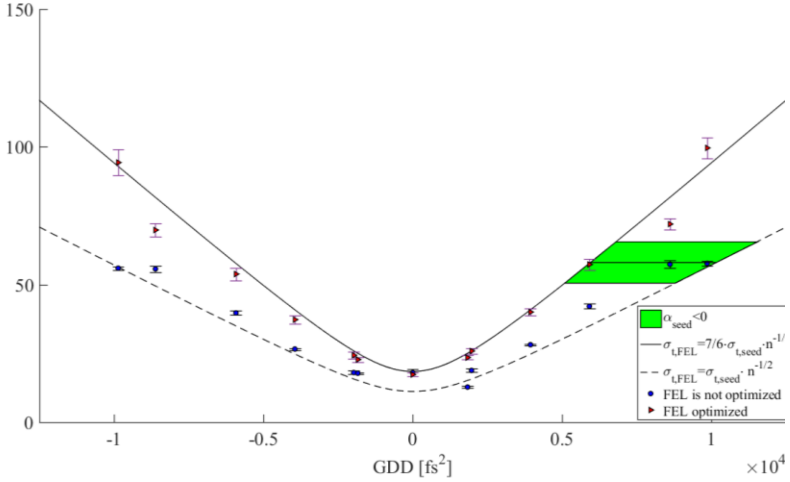
THz streaking measurement: $\sigma_{t,FEL} = (58 \pm 7.5)$ fs

Seed laser GDD in the modulator $GDD = (8.3 \pm 3.2) \cdot 10^3$ fs^2
This GDD corresponds to the amount of chirp that a pulse gains passing through (42 ± 16) mm of fused silica.

Summary and Outlook

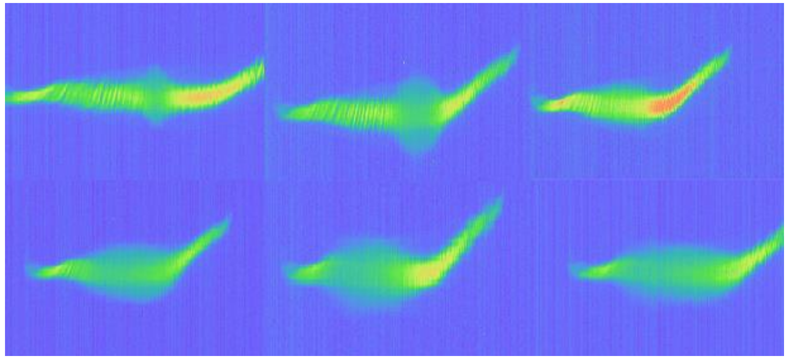
Summary

- Setup of the sFLASH experiment used to characterize the seed laser chirp
- GENESIS simulation of seeded FEL for different chirp of the seed laser
- THz streaking reveals chirp and duration of the seeded FEL pulse
- Combination of simulation outcome with the THz streaking experiment results enables the estimation of the GDD of the seed laser in front of the modulator



Outlook

- Study the seeded FEL for different amounts of chirp on the seed laser.
- First step towards FEL pulse tailoring driven by seed laser manipulation



Acknowledgement

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* former team member

Thank you for the attention

Contact

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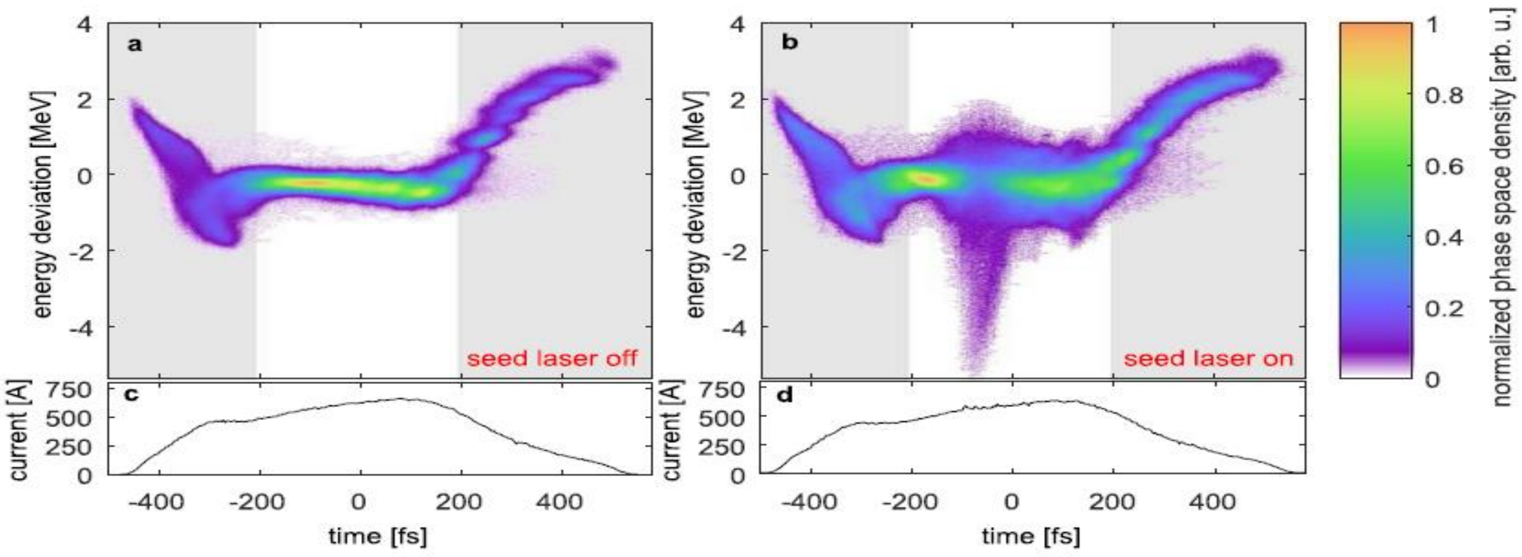
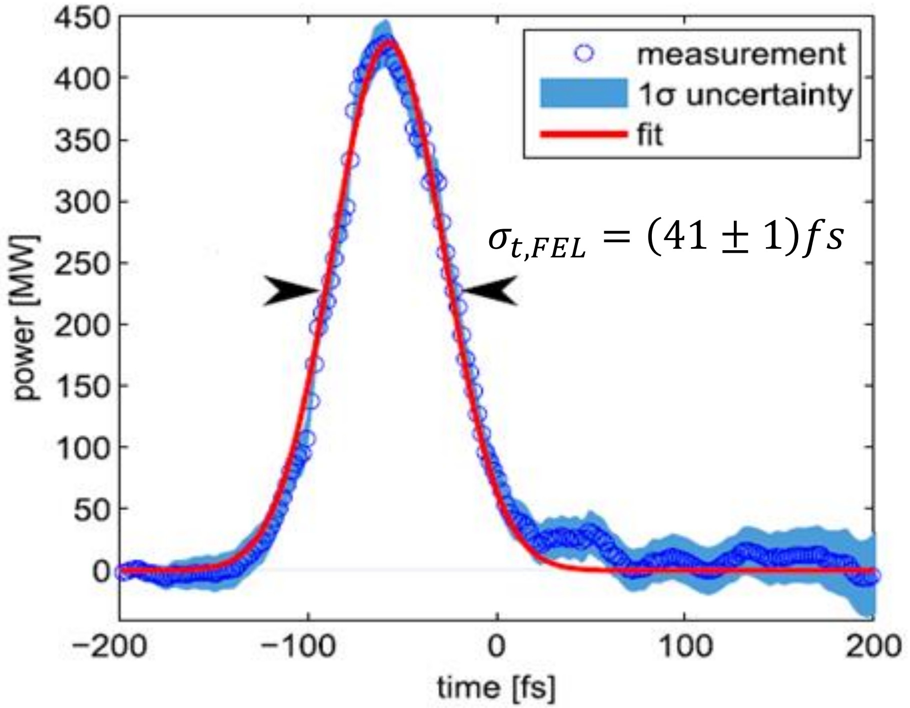
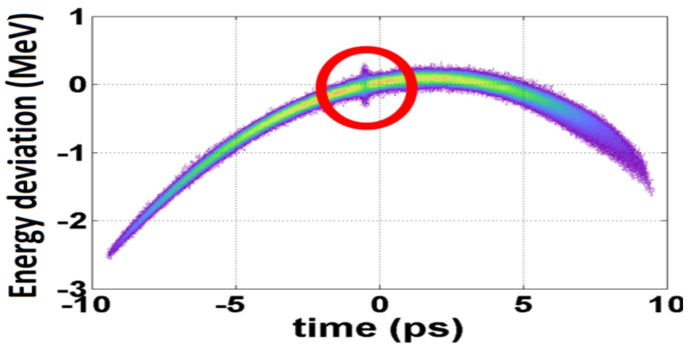
Backup

Characterization of the temporal profile of the FEL pulse





$\sigma_{t,FEL} = (41 \pm 1) fs$



$$\Delta E_i(t_i) = E_r(t_i) - E_s(t_i)$$

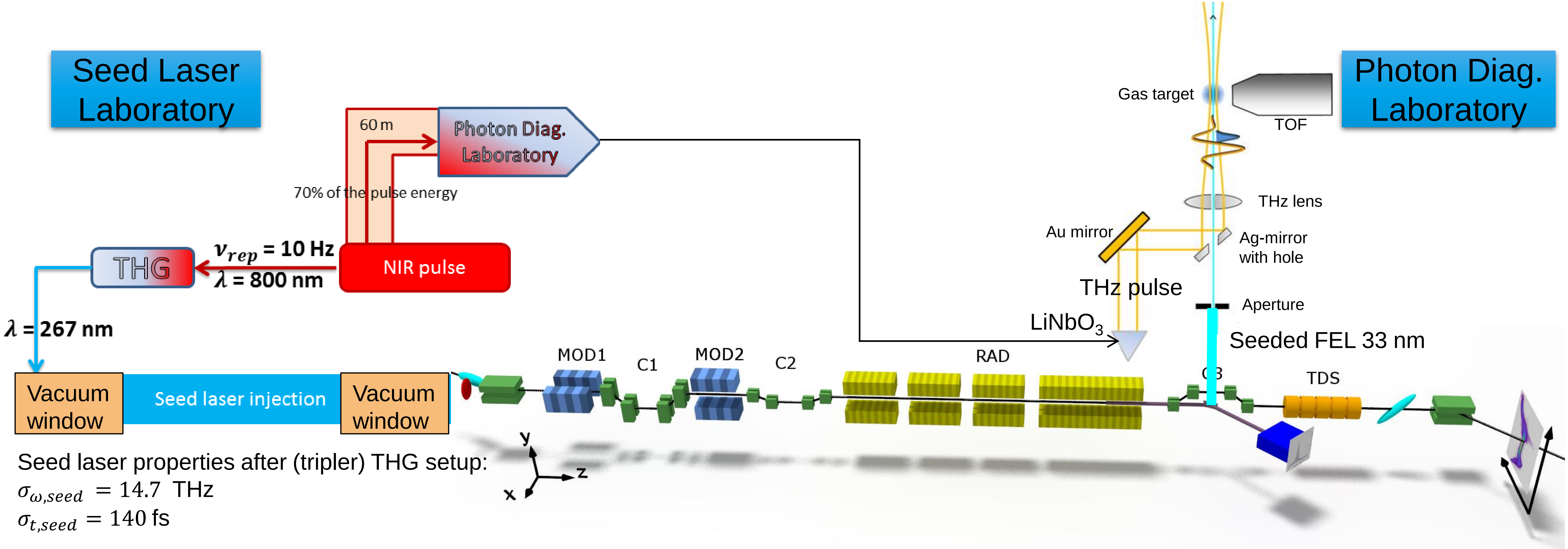
$$P_{FEL}(t_i) = \Delta E\ (t_i)\frac{\mathrm{I}(t_i)}{e}$$

T. Plath et al., Scientific Reports, 7, *2431*

Uncompressed electron beam and opened radiator

Characterization of seeded laser pulses at sFLASH

Experiment overview



Seed laser properties after (tripler) THG setup:

$\sigma_{\omega,seed} = 14.7$ THz

$\sigma_{t,seed} = 140$ fs

THz streaking

→ temporal profile of the FEL pulse

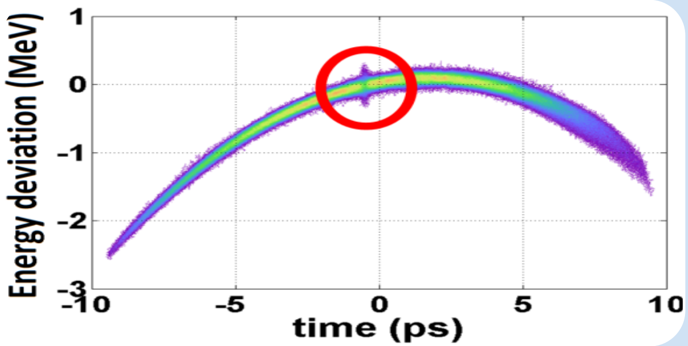
→ enables derivation of the seed laser chirp at the interaction point in MOD2

*A. Azima et al. "Direct measurement of the pulse duration and frequency chirp of seeded XUV free electron laser pulses"

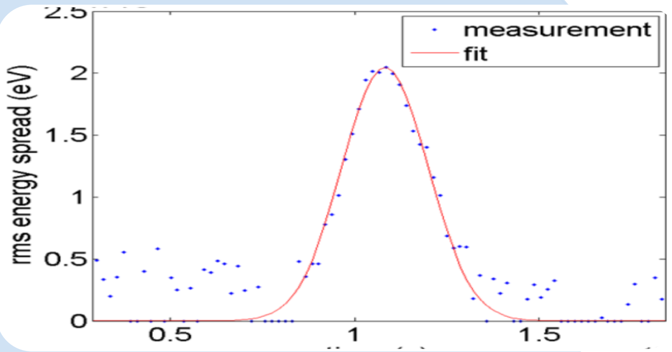
TDS based longitudinal overlap

- Used to adjust the longitudinal overlap between the e-beam and the seed laser pulse when they have been already coarsely overlapped: they are in a temporal window of 200 ps
- Setup: modulator closed to resonance condition, radiator open, e-beam decompressed

$$\Delta\gamma_{seed} = (350 \pm 50)\ keV$$

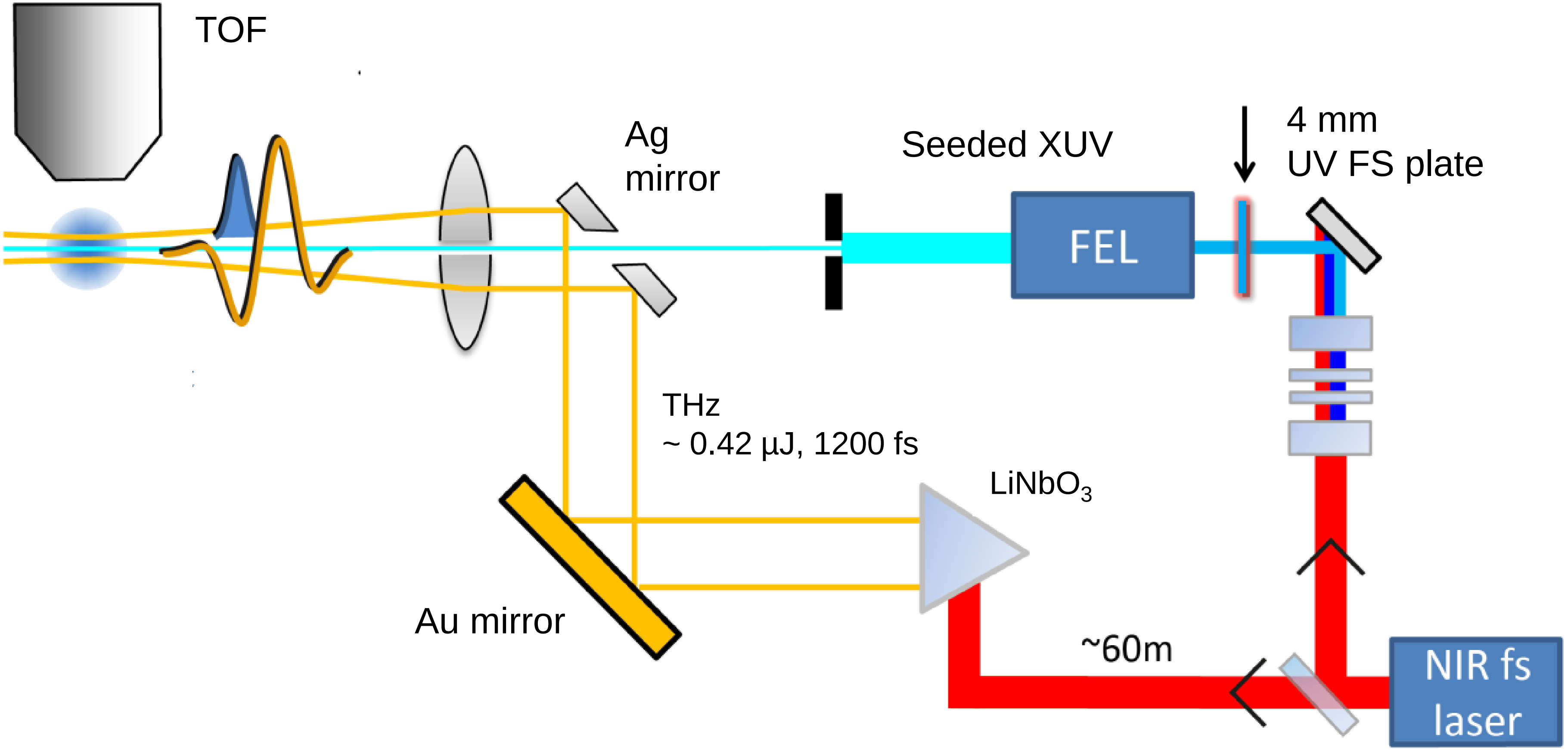


Uncompressed electron beam and opened radiator



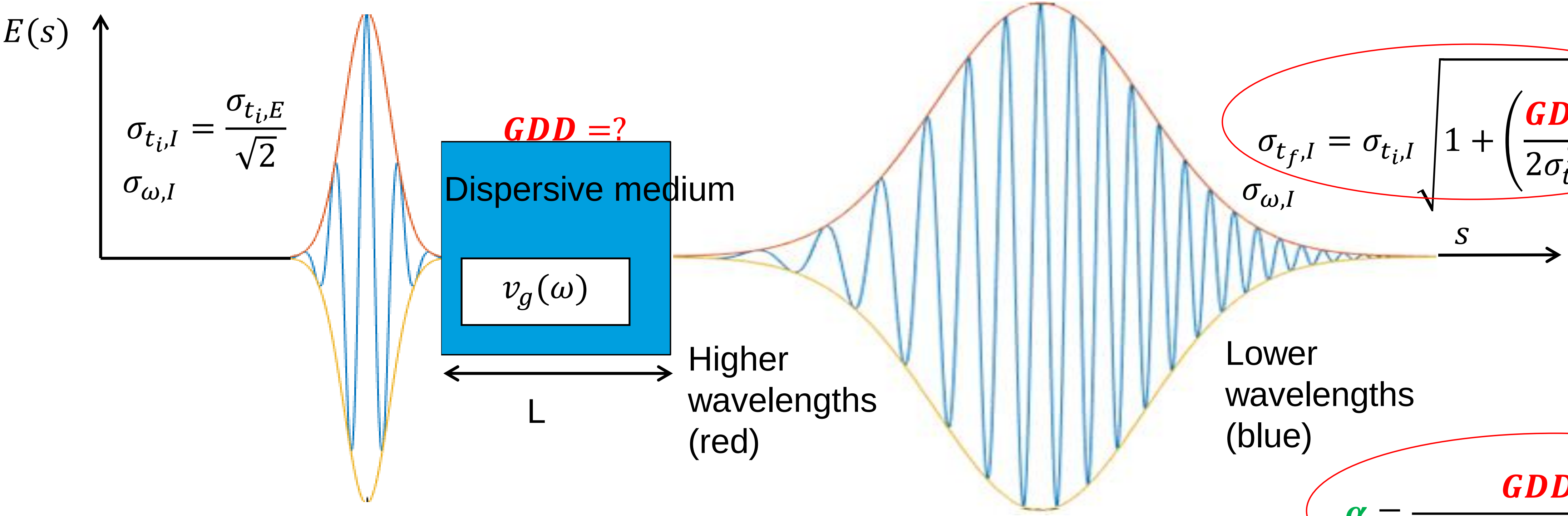
Energy modulation resulting from seed laser interaction

Controlling the chirp



Tailoring electromagnetic pulses

- Case of positive dispersion (GDD>0) $\boldsymbol{GDD} = \frac{d}{d\omega}\left(\frac{1}{v_g(\omega)}\right)$



$$\sigma_{t_f,I} = \sigma_{t_i,I}\sqrt{1 + \left(\frac{\boldsymbol{GDD}}{2\sigma_{t_i,I}^2}\right)^2}$$

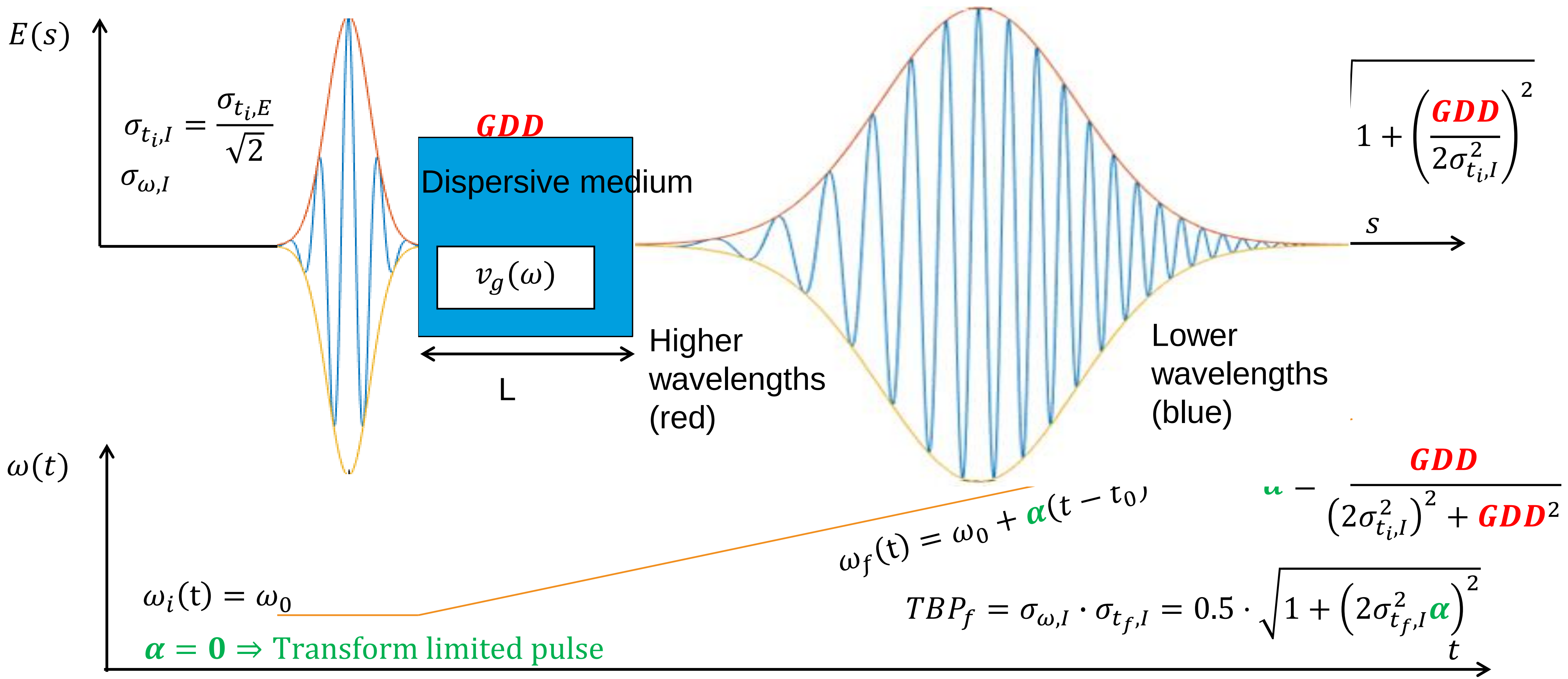
$$\boldsymbol{\alpha} = \frac{\boldsymbol{GDD}}{\left(2\sigma_{t_i,I}^2\right)^2 + \boldsymbol{GDD}^2}$$

$$\boldsymbol{GDD_{seed}} \cdot \sigma_{\omega,I}^2 = \boldsymbol{\alpha_{seed}} \cdot \sigma_{t_f,I}^2$$

$$TBP_f = \sigma_{\omega,I} \cdot \sigma_{t_f,I} = 0.5 \cdot \sqrt{1 + \left(2\sigma_{t_f,I}^2 \boldsymbol{\alpha}\right)^2}$$

Tailoring electromagnetic pulses

- Group delay dispersion (case: GDD>0) $\boldsymbol{GDD} = \frac{d}{d\omega}\left(\frac{1}{v_g(\omega)}\right)$



$TBP_i = \sigma_{\omega,I} \cdot \sigma_{t_i,I} = 0.5$