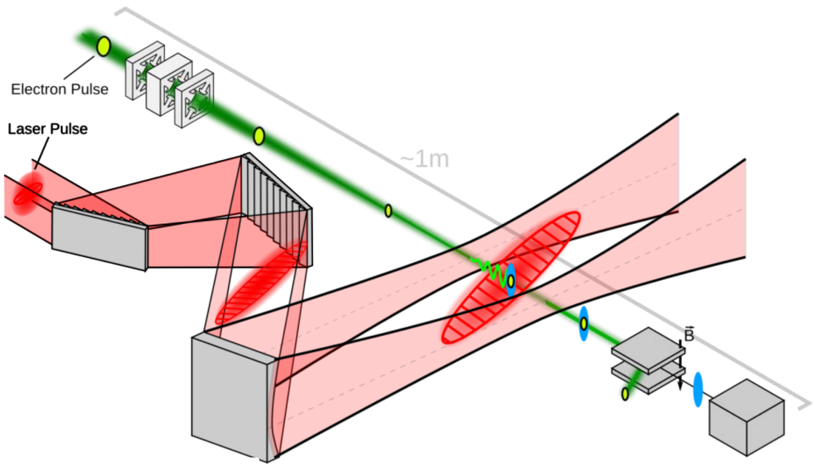
All-optical free-electron lasers – realizable with Traveling-wave Thomson scattering



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Thursday, WG 4

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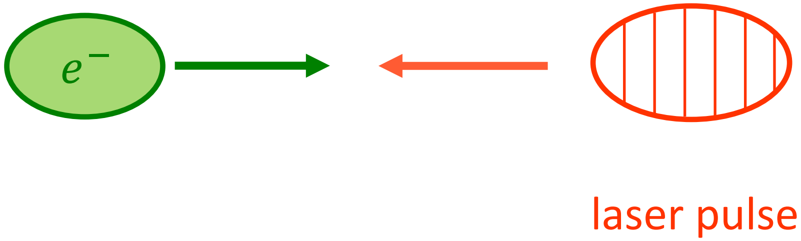
Traveling-**W**ave **T**homson-**S**cattering (TWTS) in a nutshell

Using pulse-front tilted petawatt lasers in side scattering geometries for arbitrarily long interaction distances

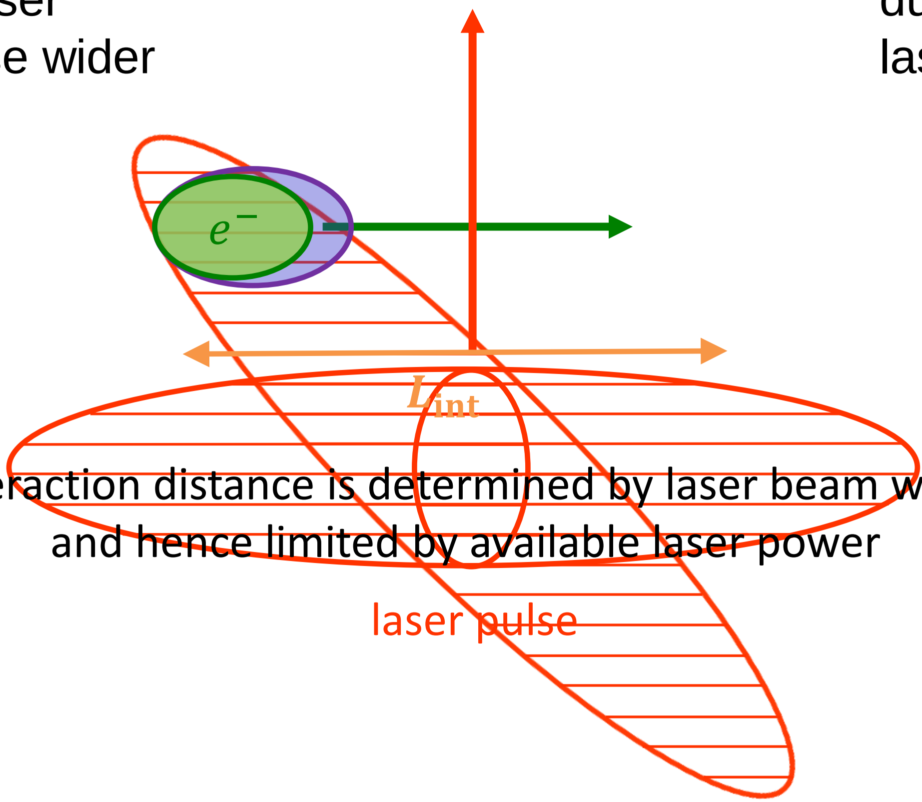


Traveling-Wave Thomson-Scattering (TWTS) in a nutshell

Using pulse-front tilted petawatt lasers in side scattering geometries for arbitrarily long interaction distances

1) Reduce the local intensity of a high power laser by making the pulse wider

2) Increase interaction duration by tilting the laser pulse front

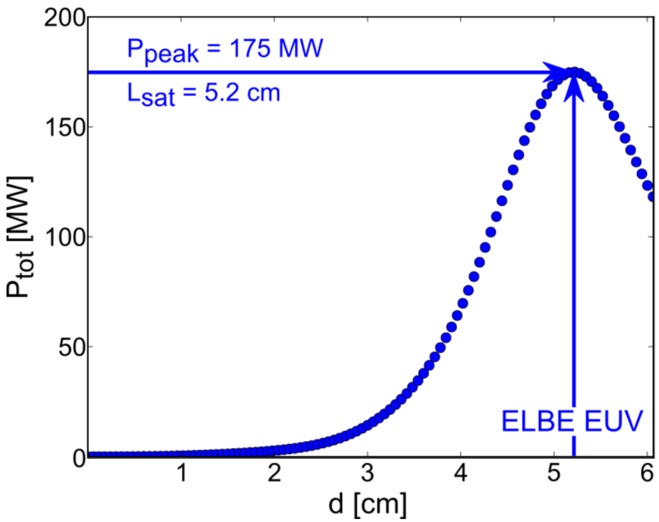


Interaction distance is determined by laser beam width and hence limited by available laser power

Design 1

13.5nm Flash-type TWTS OFEL at ELBE energy

Parameter	EUV TWTS OFEL ELBE@HZDR	FLASH conventional FEL
Scattered wavelength [nm]	13.5	13.5
Interaction angle [deg]	6.6	-
Undulator period [mm]	0.15	27.3
Electron energy [MeV]	40	700
Peak current [kA]	2.5	2.5
Norm. emittance [mm mrad]	1.0	1.45
Rel. energy spread	0.2%	0.2%
Undulator parameter a_0/K	0.5	1.2
Laser power [TW]	995	-
Gain length [cm]	0.35	250
Interaction distance [m]	0.052	27
Peak power [MW]	175	10000



Simulation of ELBE EUV TWTS OFEL based on analytic 1.5D TWTS OFEL equations

Traveling-wave Thomson Scattering (**TWTS**) OFELs can be realized with state-of-the-art accelerators and lasers.

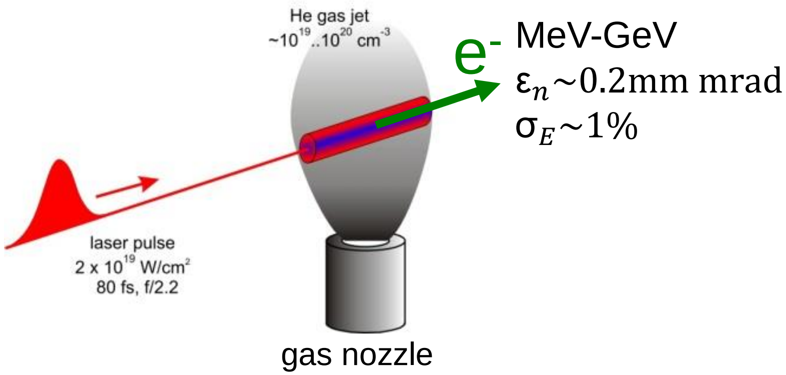
Design 2

Ultra compact TWTS OFEL using LWFA electrons

Parameter	EUV TWTS OFEL LWFA
Scattered wavelength [nm]	13.5
Interaction angle [deg]	3.0
Undulator period [mm]	0.578
Electron energy [MeV]	98
Peak current [kA]	5 (50pC/10fs)
Norm. emittance [mm mrad]	0.2
Rel. energy spread	1%
Undulator parameter a_0/K	1.2
Laser power [TW]	865
Gain length [cm]	0.27
Interaction distance [m]	0.043
Peak EUV power [MW]	4888

Use ultra-low emittance of LWFA electrons for tight focusing to 5µm (rms).

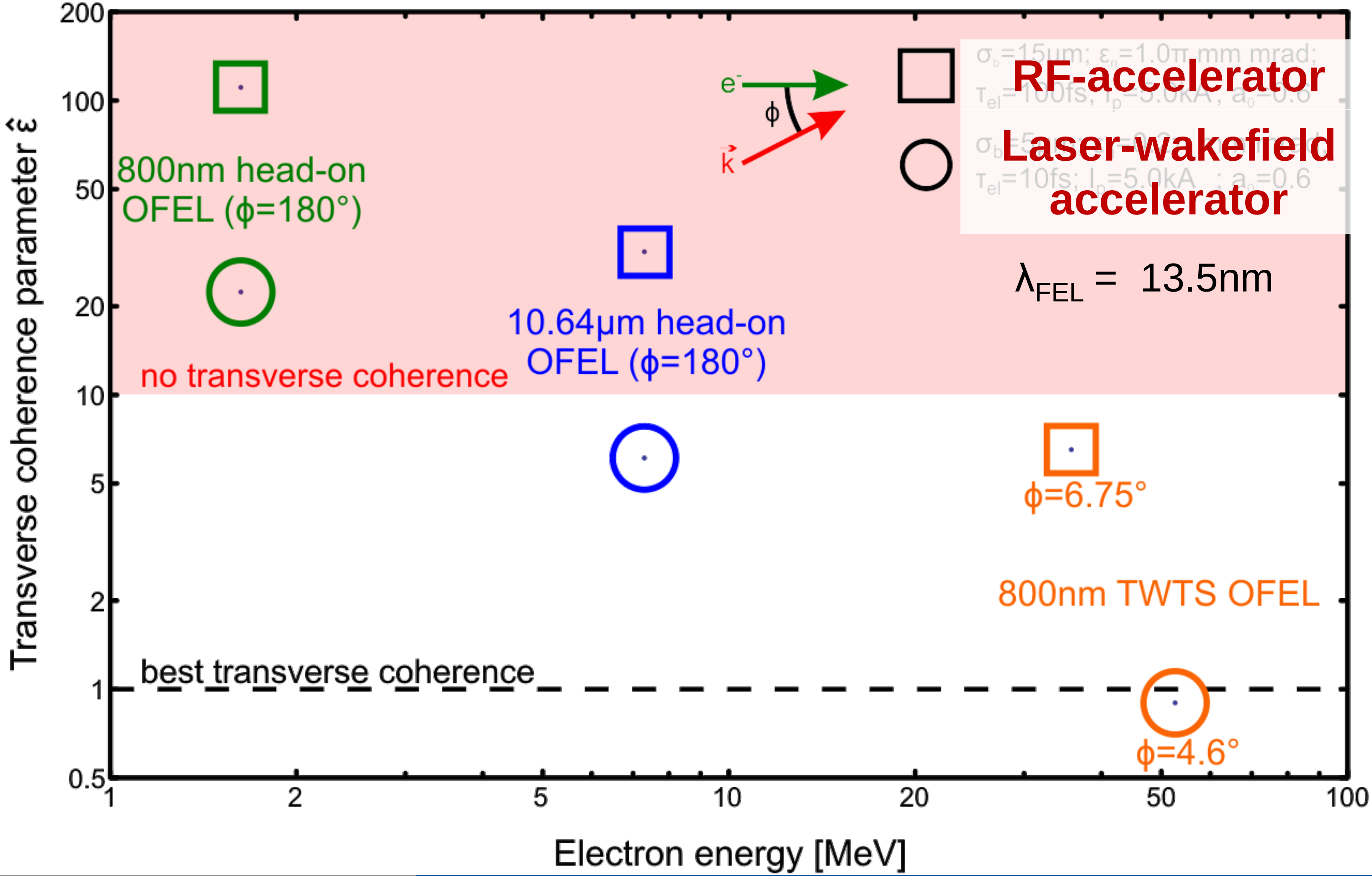
This maximizes radiation-electron coupling for LWFA electrons with 1% level energy spread.



- TWTS+LWFA offers inherent synchronization of laser and electrons.

TWTS OFELs enable transverse coherence

$$\hat{\varepsilon} = \frac{2\pi\varepsilon_{\mathrm{n}}}{\gamma\lambda_{\mathrm{FEL}}}$$



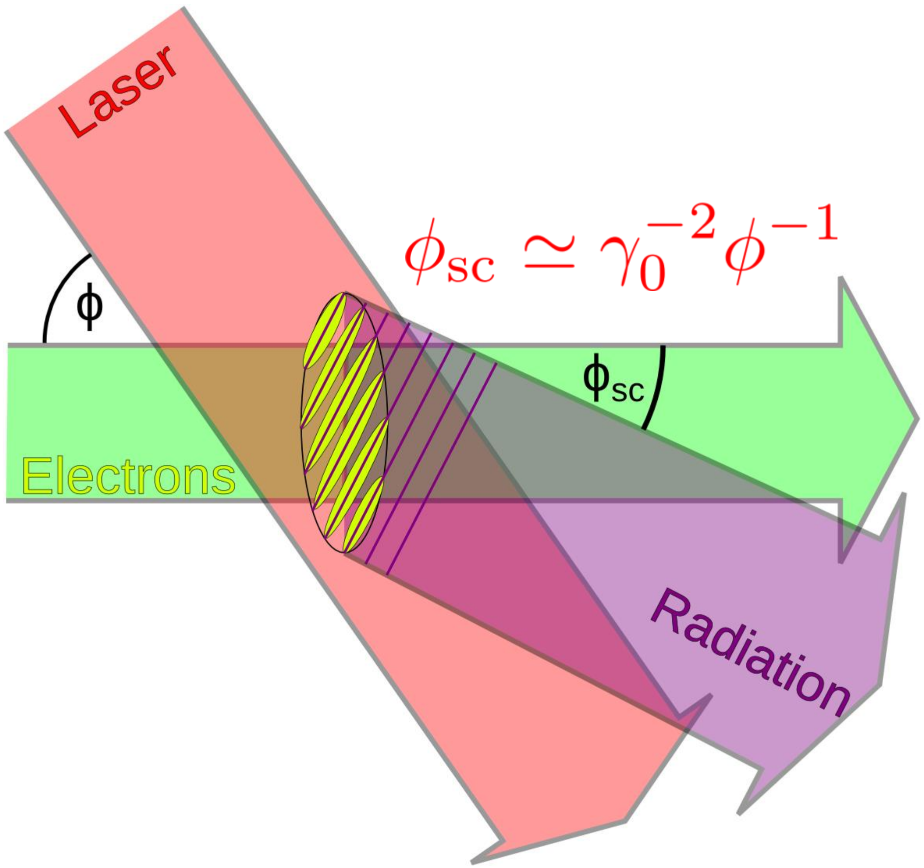
Formally TWTS-OFELs are fully equivalent to conventional FELs.

$$\omega_n = n\omega_0 \cdot \frac{2\gamma_0^2(1-\beta_0\cos\phi)}{(1+a_0^2/2+\gamma_0^2\phi_{\rm sc}^2)}$$

(resonance frequency)

$$\rho = \left[\frac{a_0^2 f_{\rm B}^2 \Omega_{\rm p}^2}{32\gamma_0^3 c^2 k_0^2 (1-\beta_0\cos\phi)^2}\right]^{1/3}$$

(FEL coupling parameter)



$$L_{\rm G} = \frac{\lambda_0}{4\pi\sqrt{3}(1-\beta_0\cos\phi)\rho}$$

(FEL power gain length)

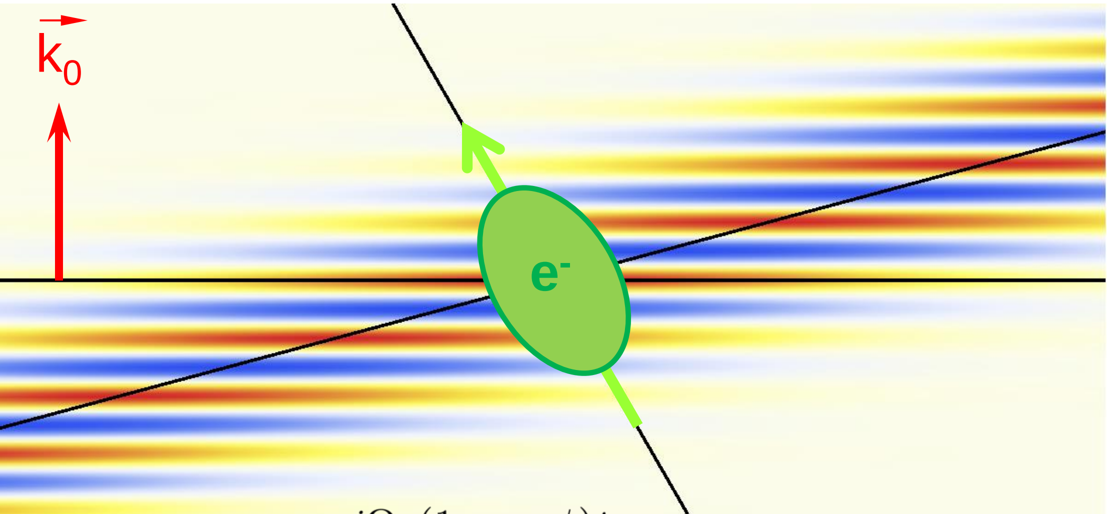
$$\frac{d\theta_j}{d\bar{t}} = p_j$$
$$\frac{dp_j}{d\bar{t}} = 2\alpha\cos(\theta_j+\Upsilon)$$
$$\frac{d\alpha}{d\bar{t}} = \langle\cos(\theta_j+\Upsilon)\rangle$$
$$\frac{d\Upsilon}{d\bar{t}} = -\frac{1}{\alpha}\langle\sin(\theta_j+\Upsilon)\rangle$$

(FEL equations)

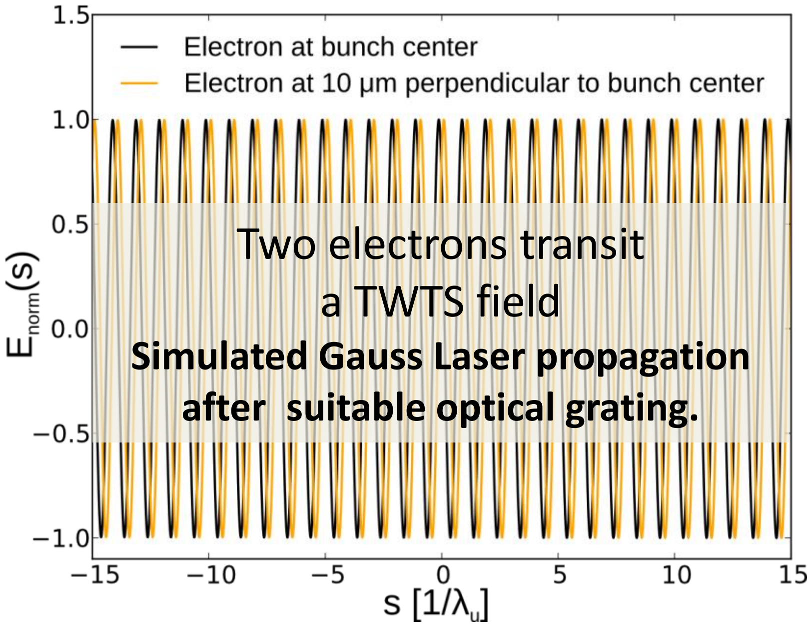
TWTS-OFELs features a walk-off, but $\Phi_{\rm sc}$ is always smaller than $1/\gamma_0$!

DRESDEN concept HZDR

Individual electrons in an electron bunch experience the TWTS-field as a plane wave



$$E_{\mathrm{traj}}(t) = E_0 \mathrm{e}^{i\Omega_0(1-\cos\phi)t}$$

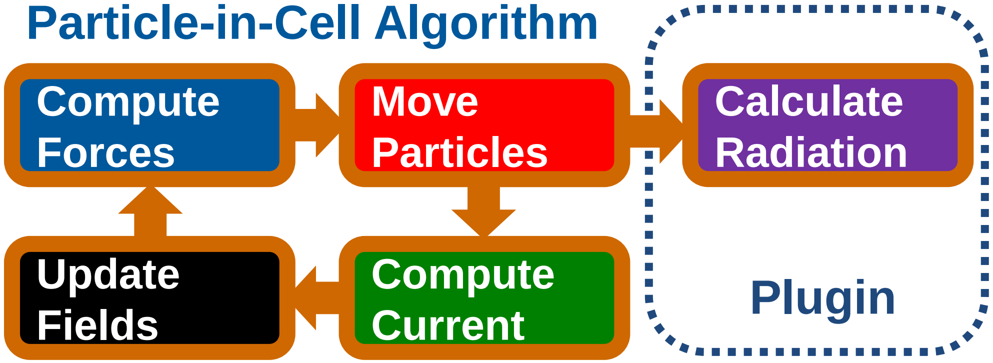


$$E(0, s_\perp, t) = E_{\mathrm{traj}}(t) \exp\left(-\frac{(s_\perp \tan(\phi/2))^2}{(c\tau)^2}\right) \exp(-ik_0 s_\perp \sin\phi)\,; \left(\frac{s_\perp}{c\tau}\right)^2 \ll (\Omega_0 \tau)^2$$

$$E(s_\parallel, 0, t) = E_{\mathrm{traj}}(t) \exp\left(-\frac{s_\parallel^2}{(c\tau)^2}\right) \exp(ik_0 s_\parallel \cos\phi)$$

Liénard-Wiechert far field code integrated in PIConGPU.

Particle-in-Cell Algorithm



Far-field radiation spectra from all billions of particles in a simulation.

Includes phase, coherence and polarization properties.

Spectra from IR to X-ray wavelengths in arbitrary directions.

TWTS type laser pulses now also included!

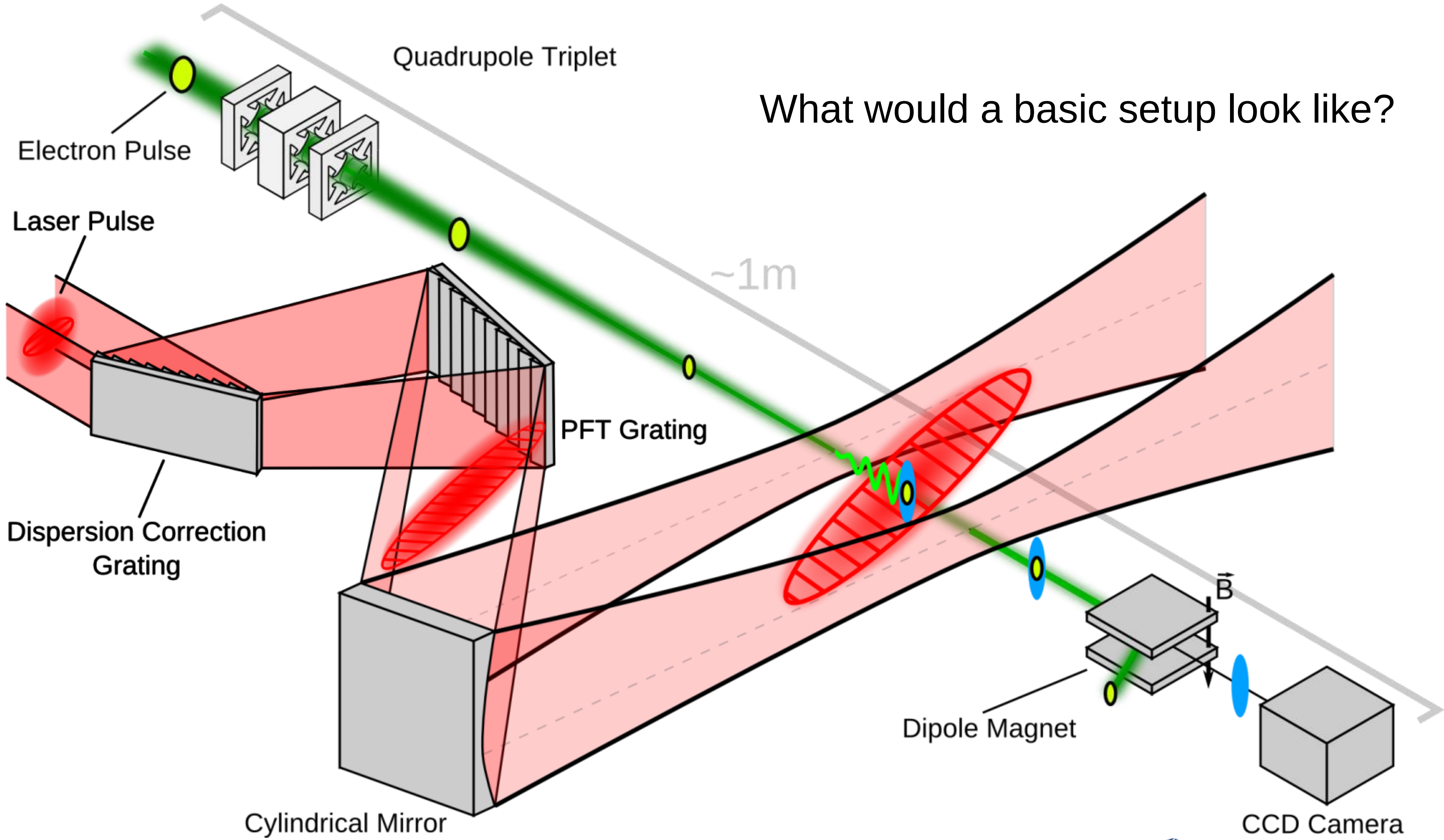
GPLv3 Free Software — Free as in Freedom

Available for download.
It‘s open source!

Key challenges for actual realization of an TWTS OFEL

Traveling Wave-Thomson Scattering OFEL in experiment

What would a basic setup look like?



Experimental challenges for TWTS OFELs

FEL beam emittance
$\Delta\lambda/\lambda < 2\,\rho$

Electron energy spread
$\Delta\gamma/\gamma < \rho$

Electron beam transport

Centimeter-scale gain lengths

FEL beam Diffraction

Space-charge

Challenges inherited from „conventional" FEL physics

TWTS laser dispersion

Uniformity in (transverse) laser profile

Beam synchronization

Low a_0 and cm-scale gain lengths

Optical beam transport and damage thresholds

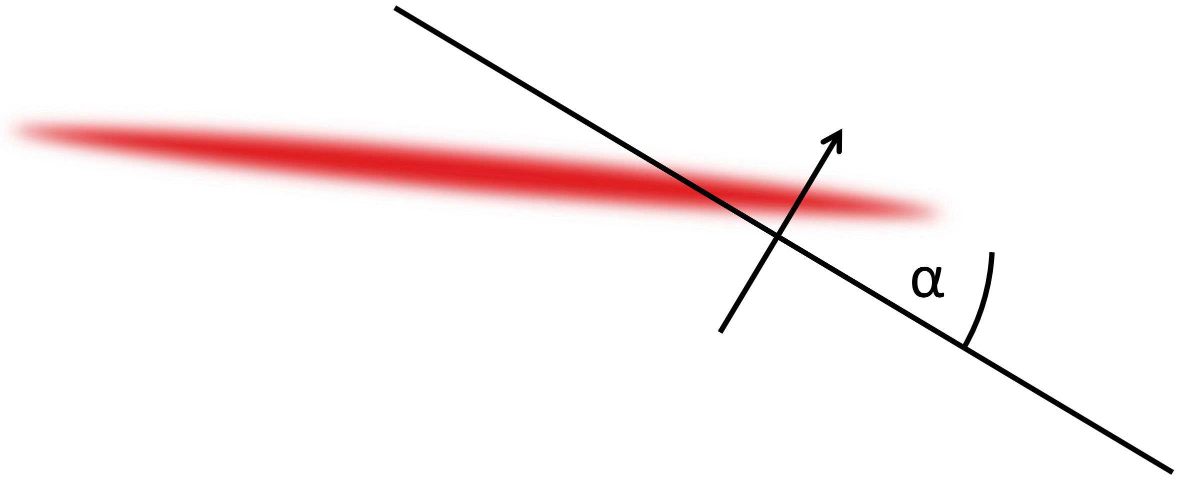
Laser Ponderomotive Force

FEL beam walk-off

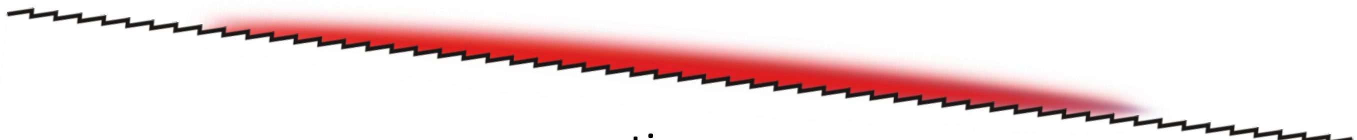
New challenges due to TWTS-OFEL

1. Dispersion compensation

Pulse front-tilts are introduced by optical gratings

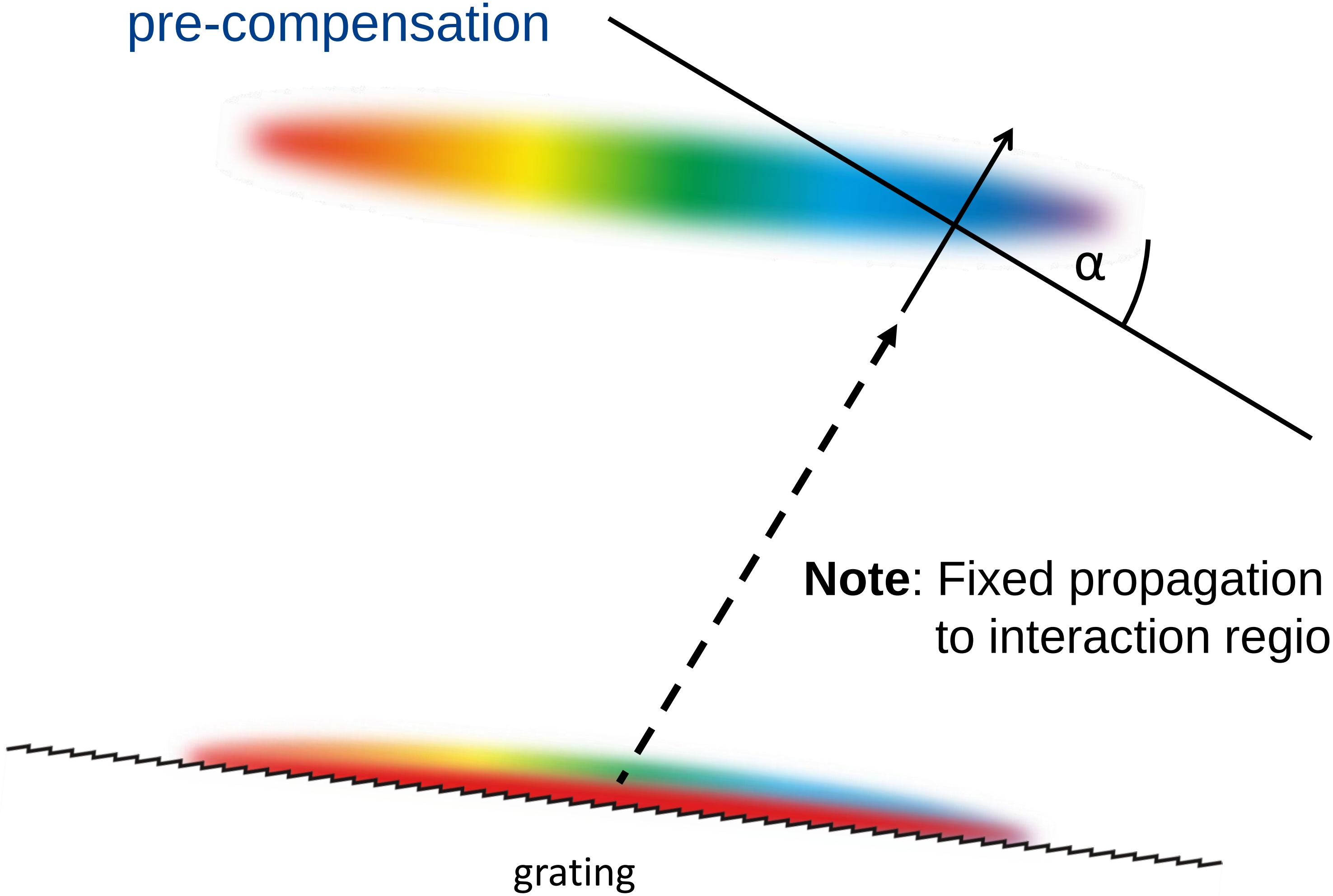


However, **angular dispersion** of a propagating laser pulse with pulse-front tilt gives rise to **group delay** and **spatial dispersion**.



1. Dispersion compensation

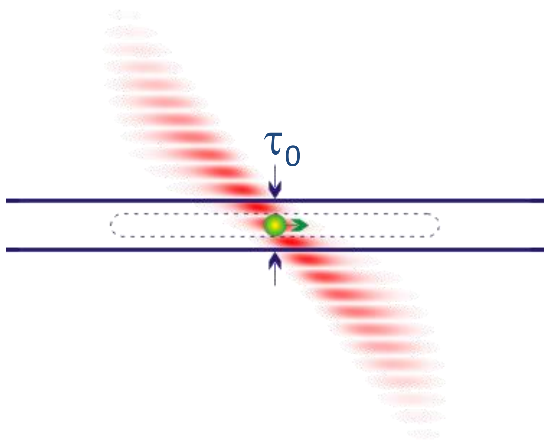
Goal: Optimal pulse compression during interaction by pulse pre-compensation



Note: Fixed propagation distance to interaction region !

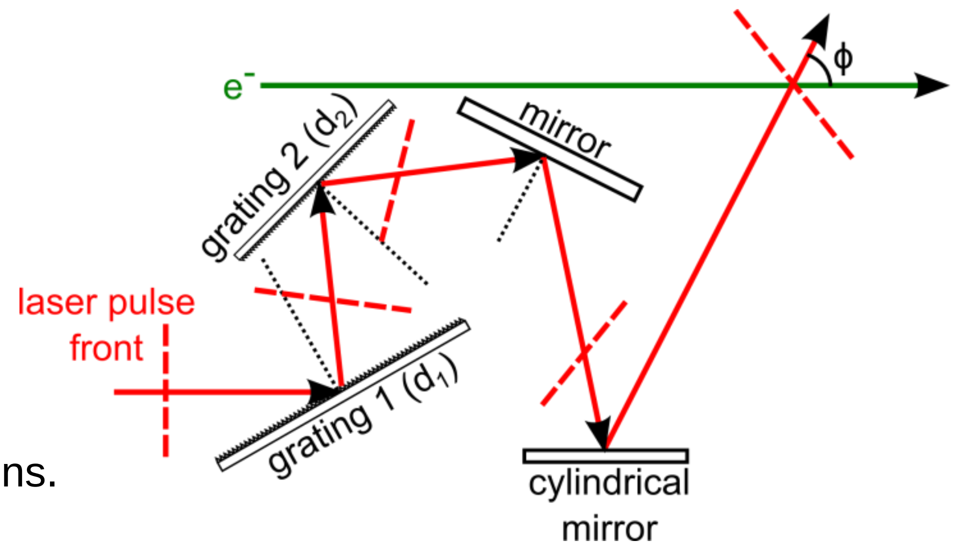
1. Dispersion compensation

Two grating setup for synthesizing the TWTS field



Two gratings pre-compensate

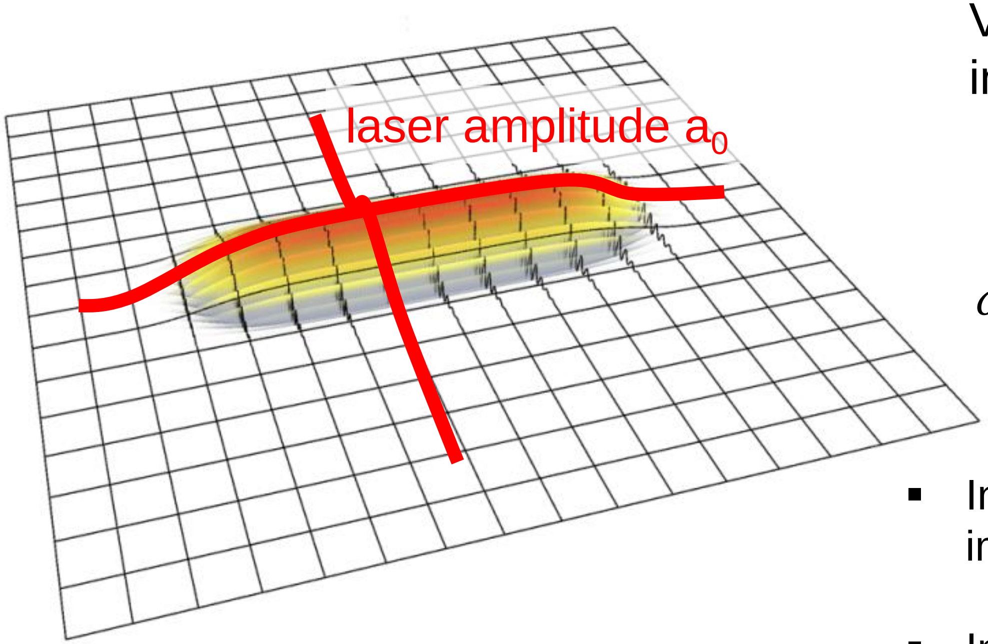
- Group delay and spatial dispersion at the center of interaction region.
- Group delay dispersion along the line focus.



- Grating setup can be set up and tested with a low power laser and without electrons.
- Diagnostics need to be developed for laser pulse dispersion characteristics in line focus

Grating angular stability: $\Delta\varepsilon$ <10μrad (PEnELOPE compressor: $\Delta\varepsilon$ <1μrad)

2. Minimum laser profile uniformity of TWTS OFELs



Variations in laser intensity increase scattered bandwidth.

$$\omega_{sc} = \frac{2\gamma^2(1-\cos\phi)\omega_{Laser}}{(1+{a_0}^2/2)}$$

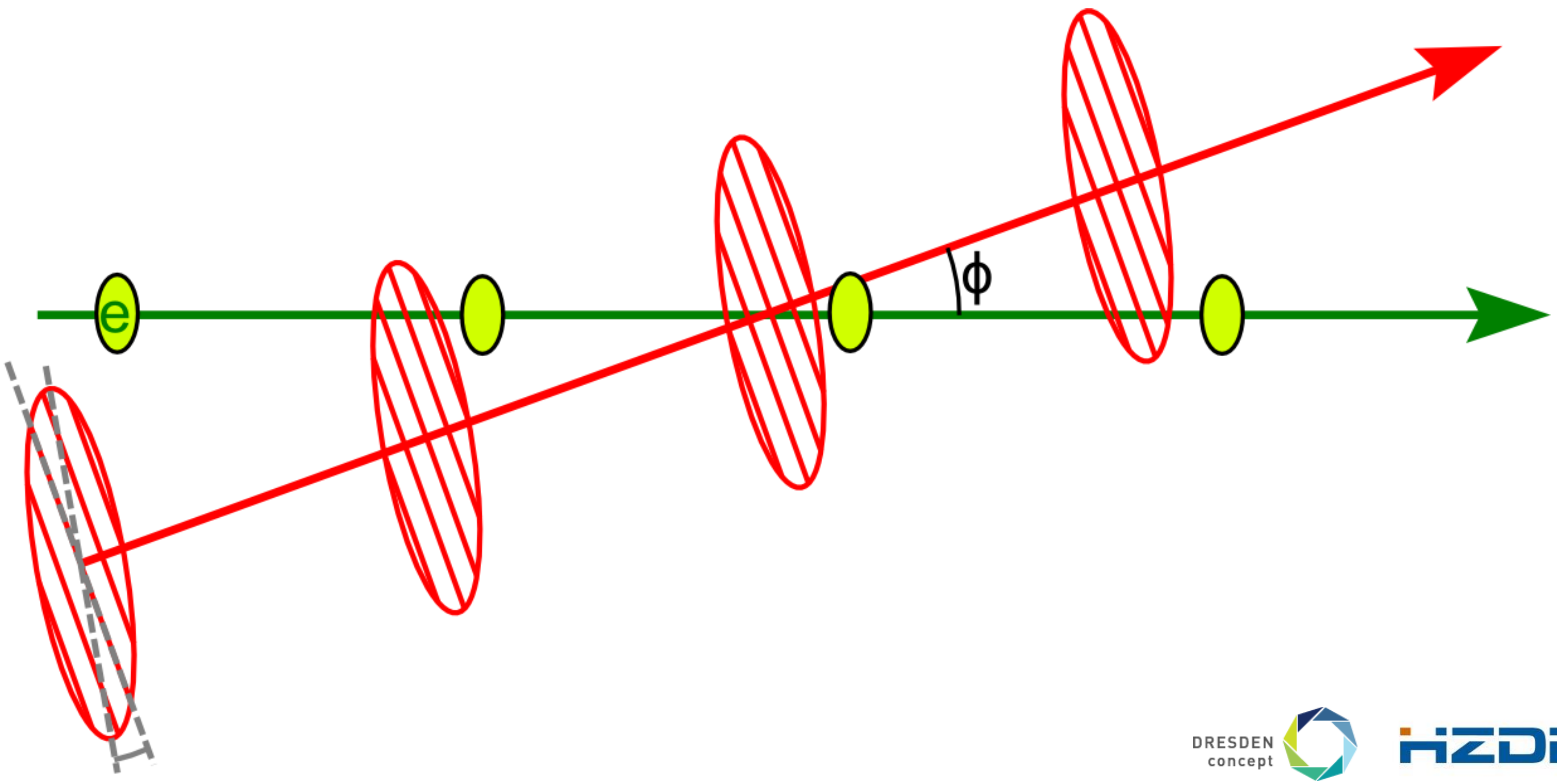
- Intensity variations in **transverse profile** impact the **FEL instability**.
- Intensity variations in **longitudinal profil**e impact **transverse coherence**.

Better radiation-electron beam coupling of TWTS OFELs leads to larger acceptable intensity variations

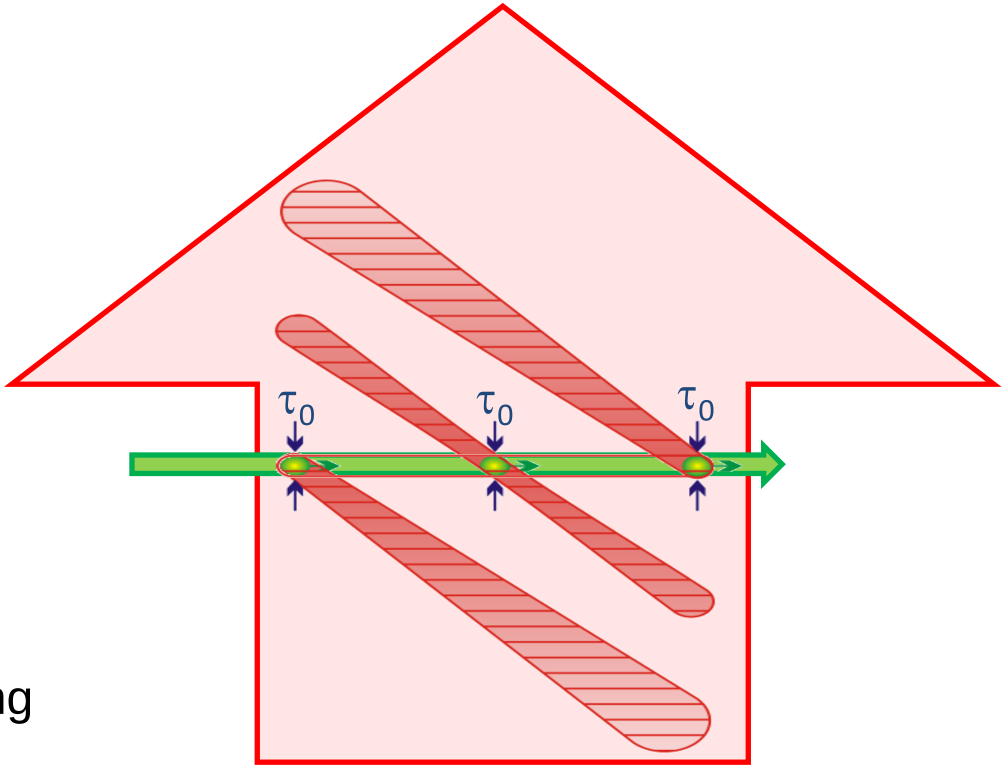
‰ (head-on) → % (TWTS)

3. Synchronization of TWTS pulses to electrons

- Synchronization accuracy needs to be a fraction of the laser pulse duration (<100fs).
- Technically equivalent problem in pump-probe experiments or external seeding of X-ray FELs.
- Facility-wide, all-optical system has been implemented at FLASH@DESY



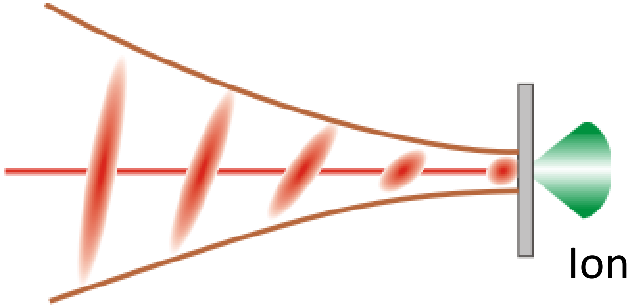
4. Diagnostics development for TWTS pulse analysis



How to measure the pulse duration and pulse dispersion in the plane of optimum laser compression?

Equivalent problem in experiments using high power laser pulses as a pump

(e.g. ion acceleration from foils)



Find measurement methods that provide laser pulse information in focus

First application on the way to TWTS OFEL lasing

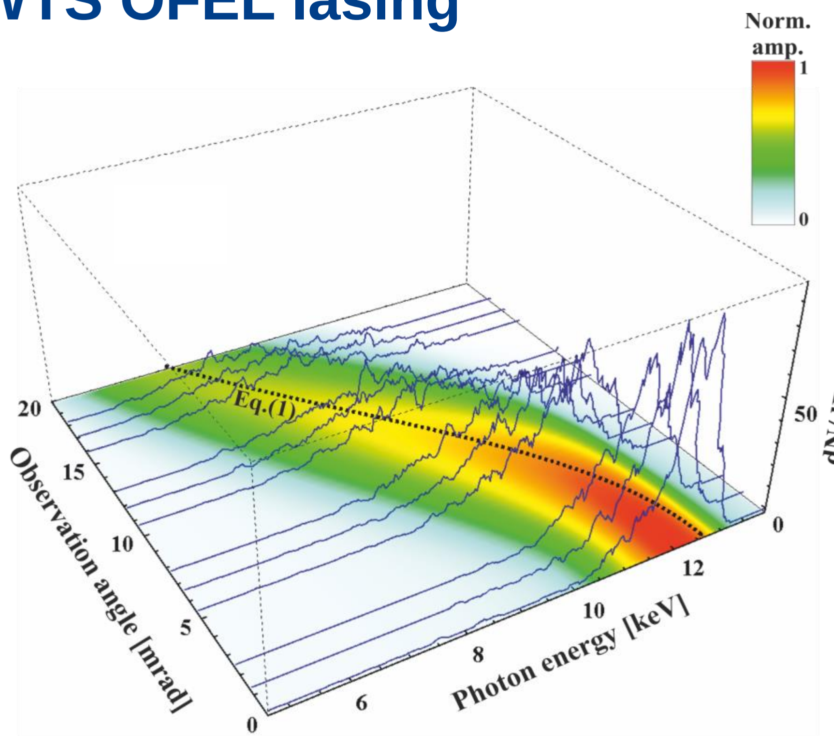
Enhance PHOENIX photon yield

With super-conducting RF photo gun at ELBE

$$Q = 1\ nC$$

$$\epsilon_N = 1\pi\ \mathrm{mm\ mrad}$$

and DRACO laser (30 J, 30fs)



standard colliding beam PHOENIX source

$10^7 - 10^8\ \frac{\text{photons}}{\text{shot}}$

TWTS - enhanced PHOENIX source

$10^{10} - 10^{11}\ \frac{\text{photons}}{\text{shot}}$

@ 5% spectral bandwidth

Note:
Different photon energies!

Coming up next **Axel Jochmann**'s talk on the **PHOENIX source** – stay tuned!

Summary

- TWTS is the most promising OFEL scheme that can be realized with state-of-the-art electron sources and laser systems
- TWTS is scalable, provides transverse coherence and does not suffer from photon emission recoil in contrast to head-on OFEL schemes
- The technical challenges are equivalent to those in the construction and application of Petawatt laser systems

Thank you for your attention!

All of this has been published and more will follow…

- Fully analytic theory of TWTS OFELs including TWTS laser field

Optical Free-Electron Lasers with Traveling-Wave Thomson-Scattering

Journal of Physics B 47(2014)23, 234011

- Taming transverse coherence and photon recoil with TWTS for high brightness TWTS OFELs

Brilliant and efficient optical free-electron lasers with Traveling-Wave Thomson-Scattering

AAC 2014 Proceedings

- We can build TWTS OFELs with state-of-the-art technology

to be submitted

- Simulating TWTS OFELs using the Particle In Cell algorithm

the next step