Compact high-brightness X-ray sources for ultrafast probing of explosively driven solid-density materials by Travelling-Wave Thomson-Scattering

Klaus Steiniger

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[1] now at TOPTICA Photonics AG

What do we love about X-ray FELs?

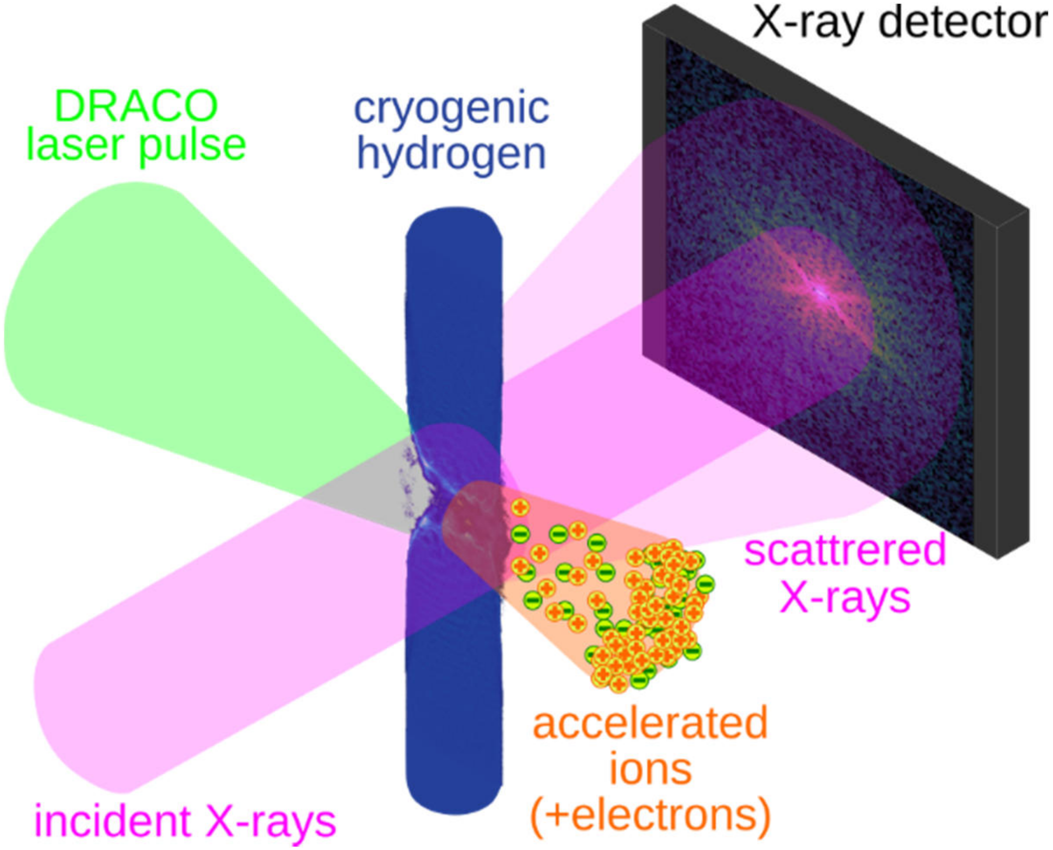
Radiation wavelength ~ 0.1nm
(Penetrate solid density plasmas, resolve density fluctuations)

Spatial coherence
(Form interference patterns)

High intensity
(Single-shot analysis)

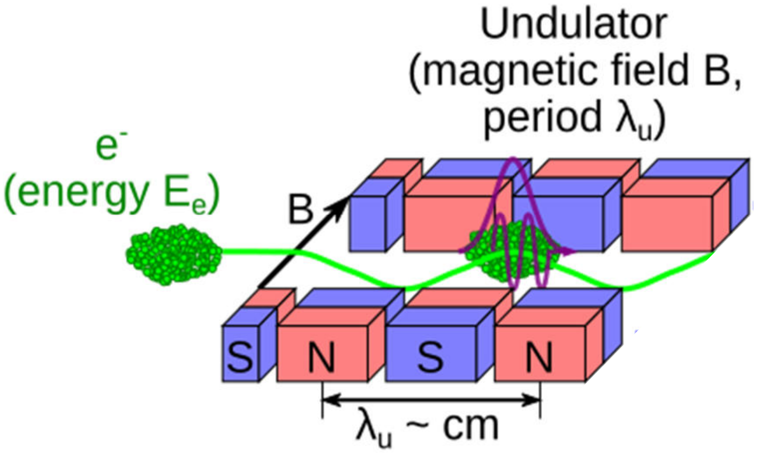
Pulse duration < 100fs
(resolve fast proceses)

Application of XFELs for HZDR research



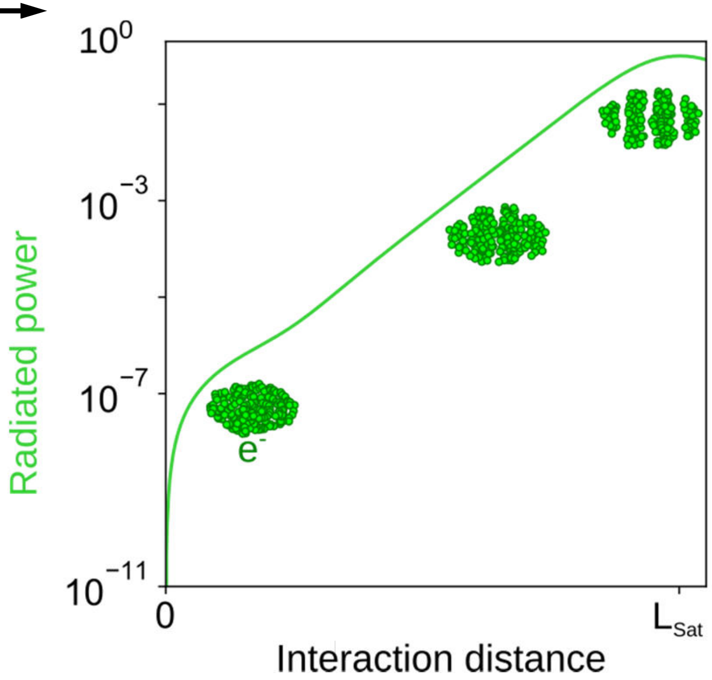
Kluge, Phys. Plasmas (2014), doi:10.1063/1.4869331
Obst, Sci. Rep. (2017), doi:10.1038/s41598-017-10589-3

(Very) Basic scheme of an FEL

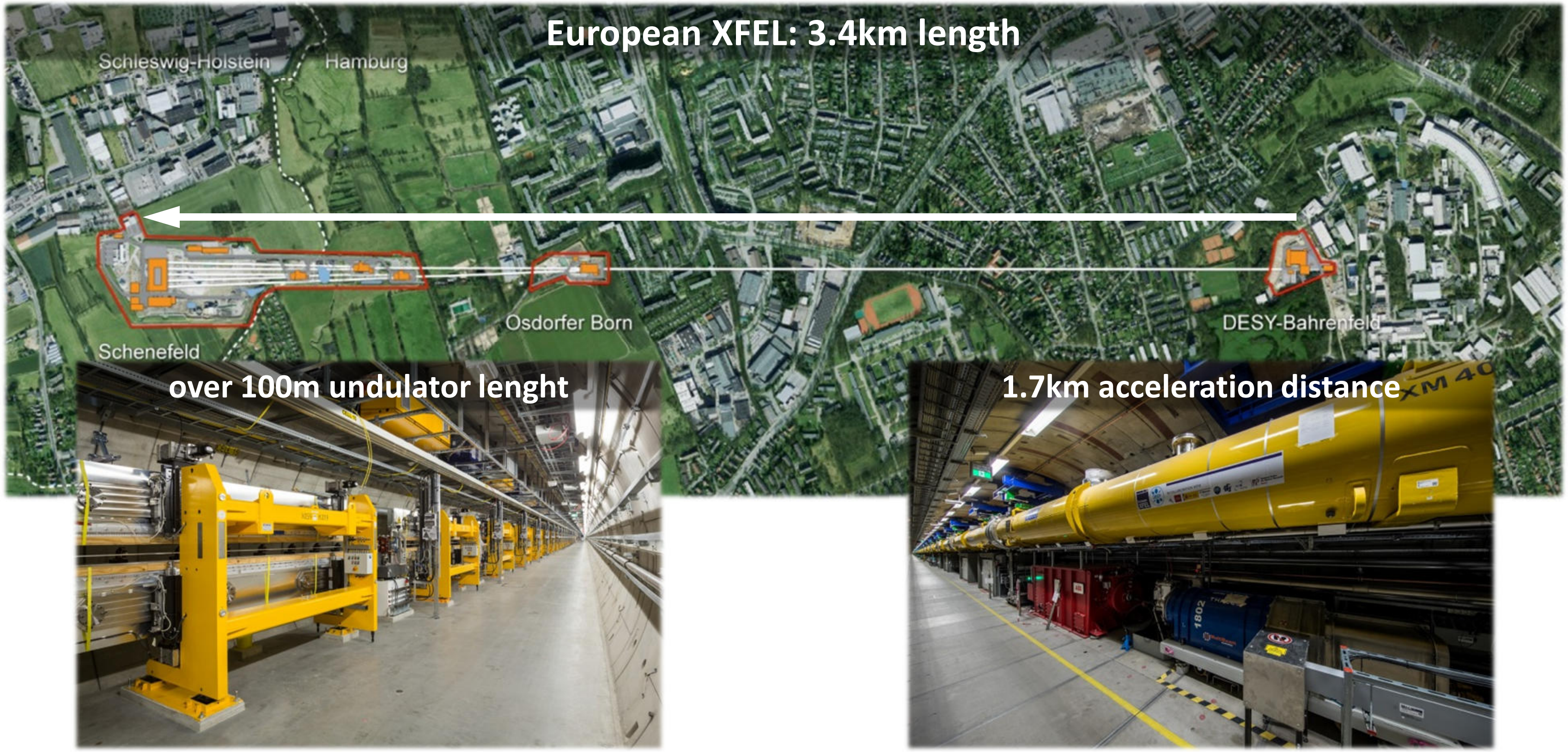


L_{int} ~ 100m

- Development of micro bunches due to radiation back reaction
- ➢ Coherent radiation amplification
- X-ray pulse length ~ Electron pulse length



Major problem of conventional FELs is their size

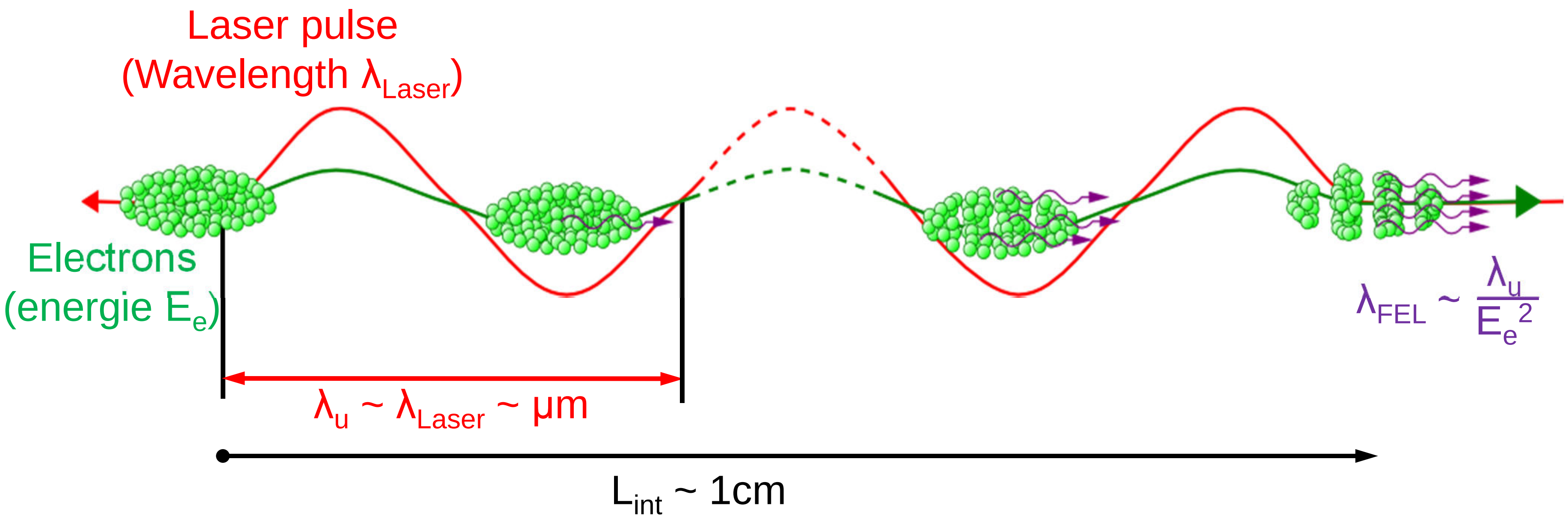


European XFEL (λ_{FEL}=0.05nm, 10^{12} photons/pulse, 27000 pulses/s):

- 1,22Mrd Eur construction cost
- 170Mil Eur yearly operating cost
- over 300 people personell
- of which 240 take care of accelerator

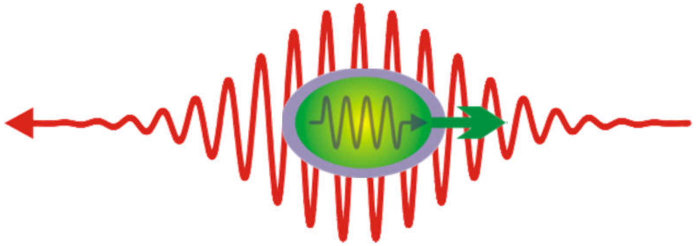
Quellen: www.xfel.eu, www.lightsources.org

Using laser pulses as compact, optical undulators



- Reduction of the undulator period:
  cm → µm
- Reduction of the electron enenergy:
  10 000 MeV→ 100 MeV
- Reduction of the interaction distance:
  100 m → 1 cm
- Reduction of the accelerator footprint:
  km → 10 m

Pitfalls of the head-on Optical FEL concept



incoherent sources using optical undulators:
PHOENIX@HZDR
MEGa-ray@LLNL

(Incomplete) Selection of show stoppers for optical FELs in head-on scattering setups:

1. Required electron beam energy spreads are not available.
2. Required electron beam emittance for transverse coherence is not available.
3. The photon emission recoil greatly reduces the gain.

Low electron energy of head-on OFELs is the problem

1. Electron beam energy spread
   scales with energy

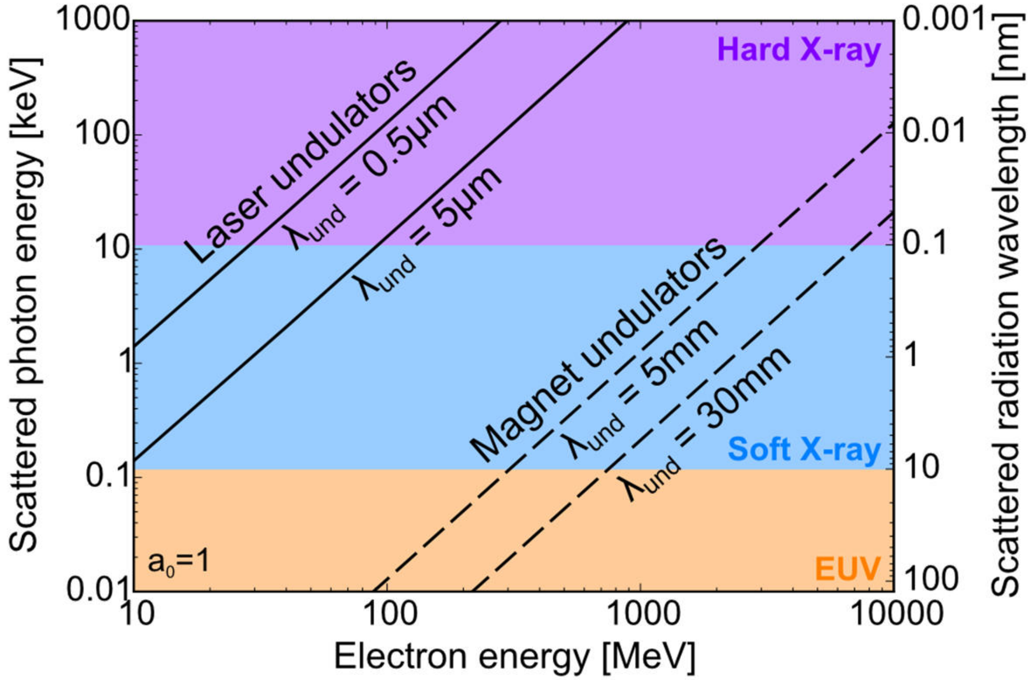
$$\frac{\Delta\gamma_0}{\gamma_0} \propto \gamma_0^{1/3}\lambda_{\mathrm{FEL}}^{2/3}$$

2. Electron beam emittance requirement
   scales with energy

$$\epsilon_{\mathrm{N}} \approx \frac{\gamma_0\lambda_{\mathrm{FEL}}}{2\pi}$$

3. Photon emission recoil requirements
   scales with energy

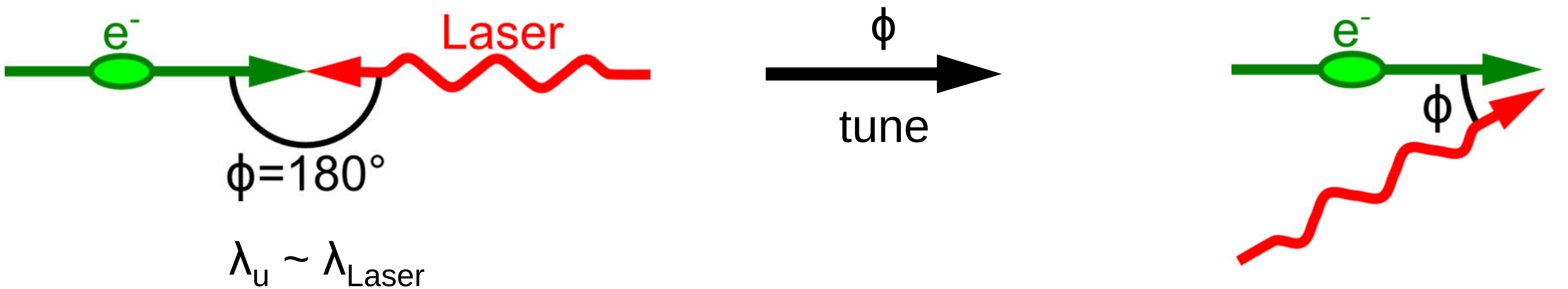
$$\frac{\text{allowed energy spread}}{\text{photon recoil}} \propto \gamma_0^{4/3}\lambda_{\mathrm{FEL}}^{5/3}$$



$E_e^2 \sim \lambda_{und}/\lambda_{FEL}$

Electron energies are small compared to conventional FELs (13GeV for 10keV photons @LCLS)

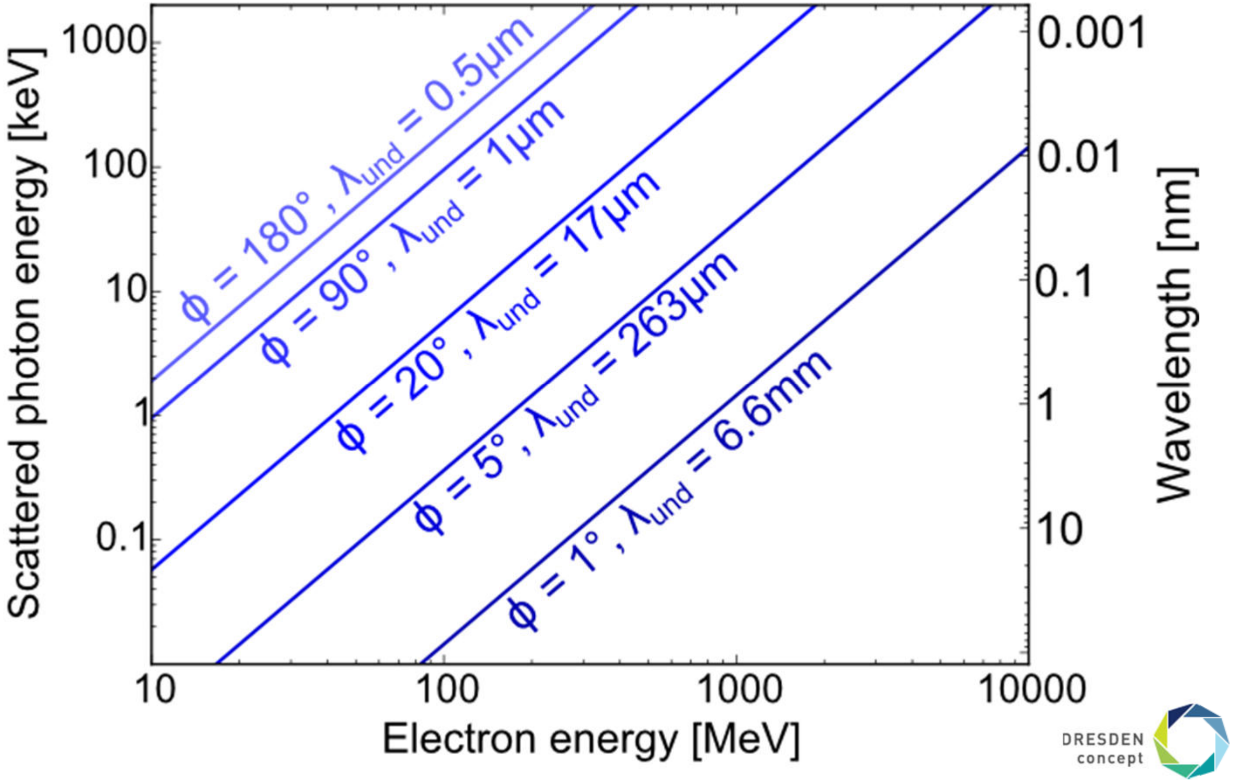
Controll over electron energy requirement by the interaction angle

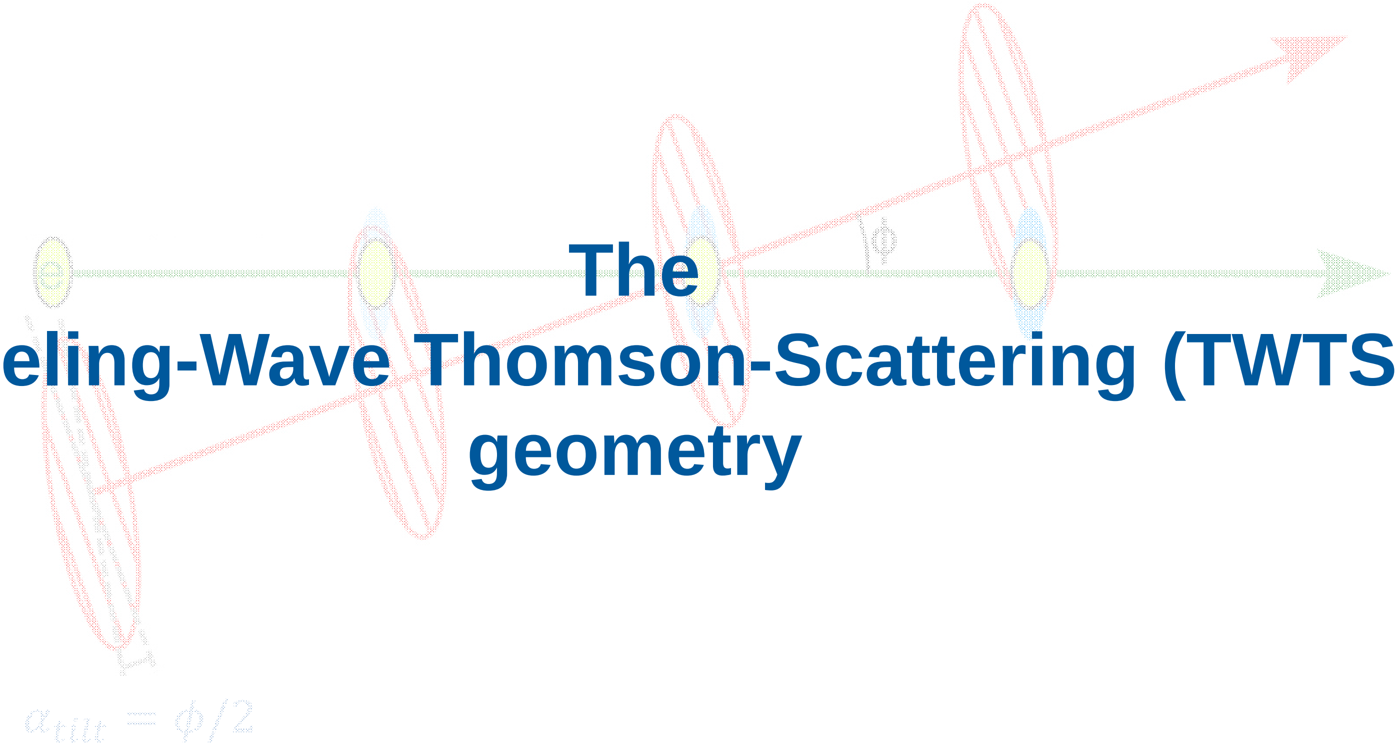


$\lambda_u \sim \lambda_{Laser}$

$\lambda_u = \lambda_{Laser} / (1 - \cos \phi)$

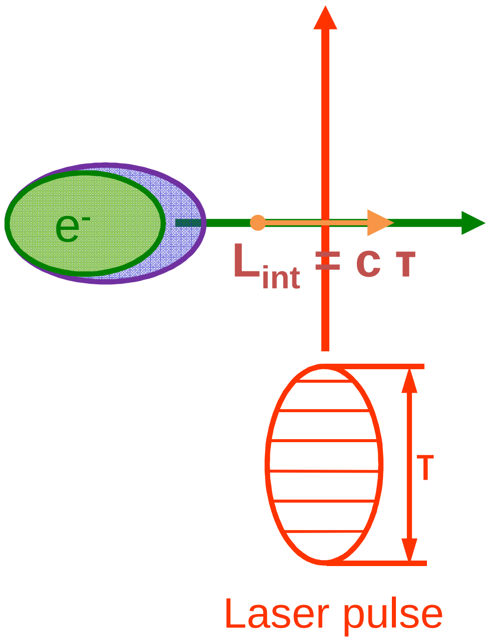
$\lambda_{FEL} \sim \lambda_u / E_e^2$





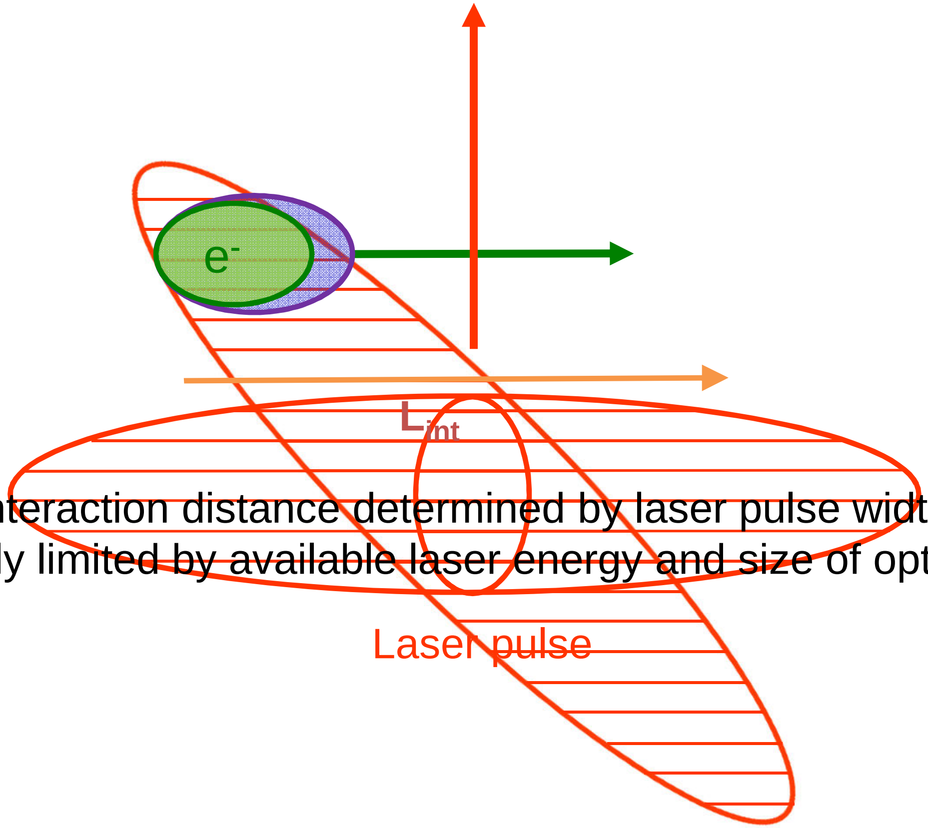
The
Traveling-Wave Thomson-Scattering (TWTS)
geometry

Laser pulse duration limits interaction distance



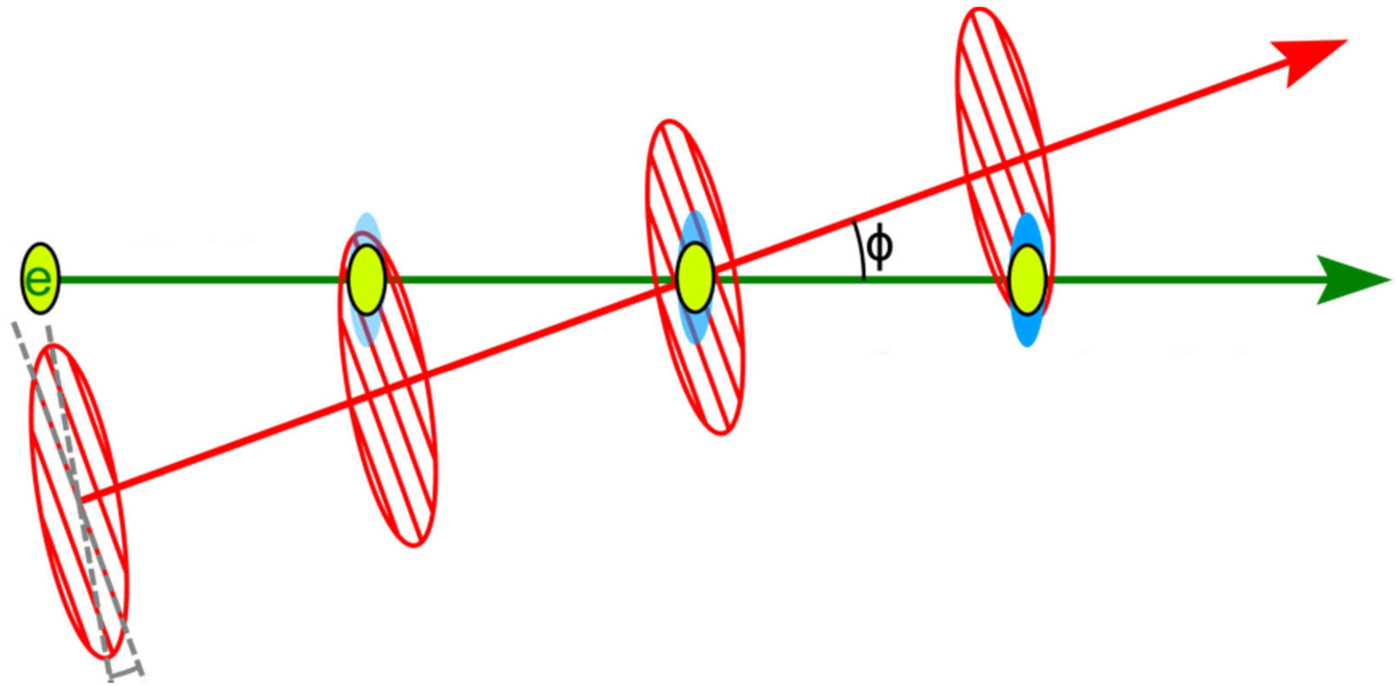
Long interaction distances by Traveling-Wave Thomson-Scattering (TWTS)

TWTS:
Wide laser pulses
+
Pulse-front tilt
=
Long interaction



Interaction distance determined by laser pulse width.
Only limited by available laser energy and size of optics.

Free choice of the interaction angle ϕ

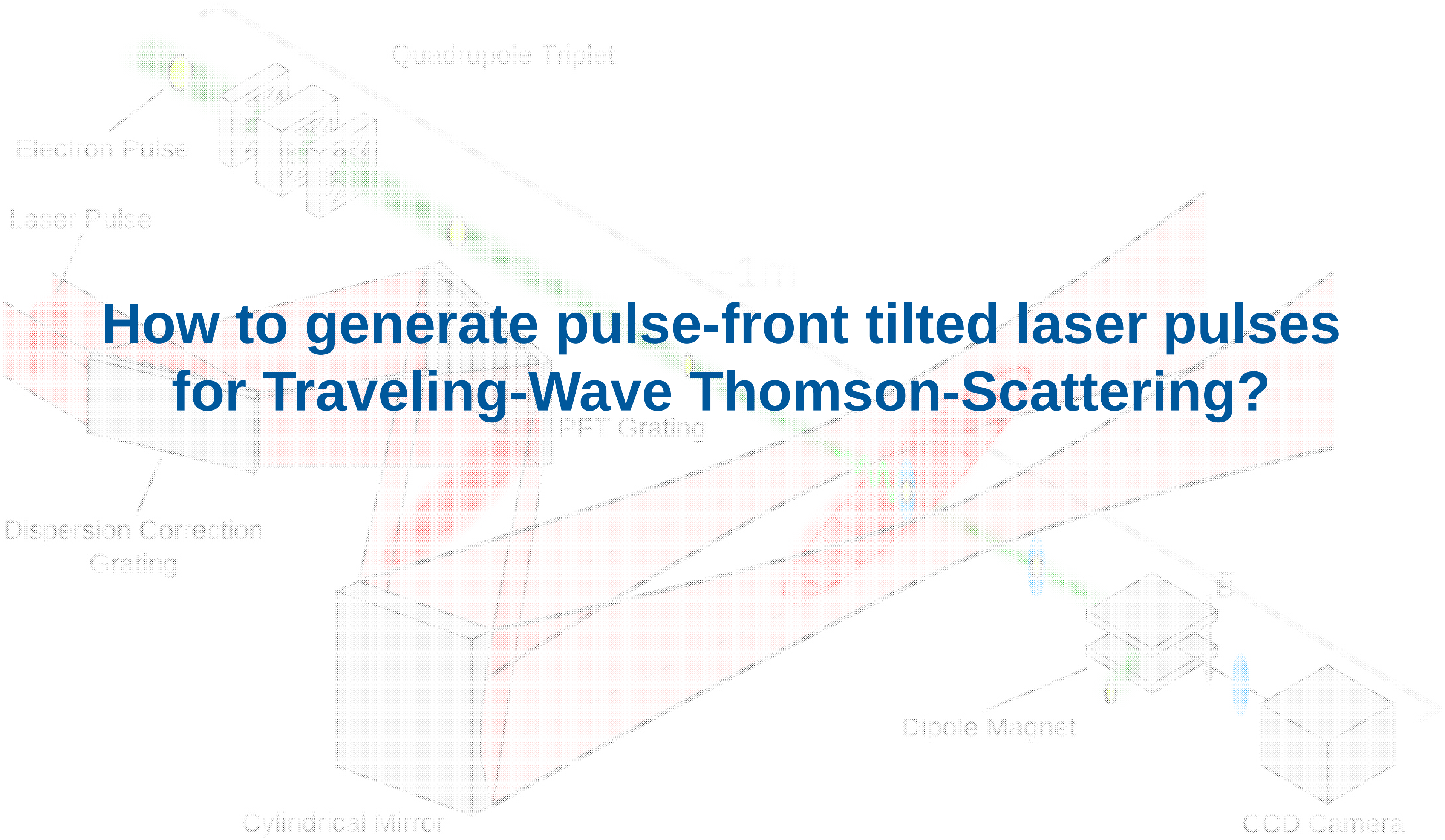


$\alpha_{tilt} = \phi/2$

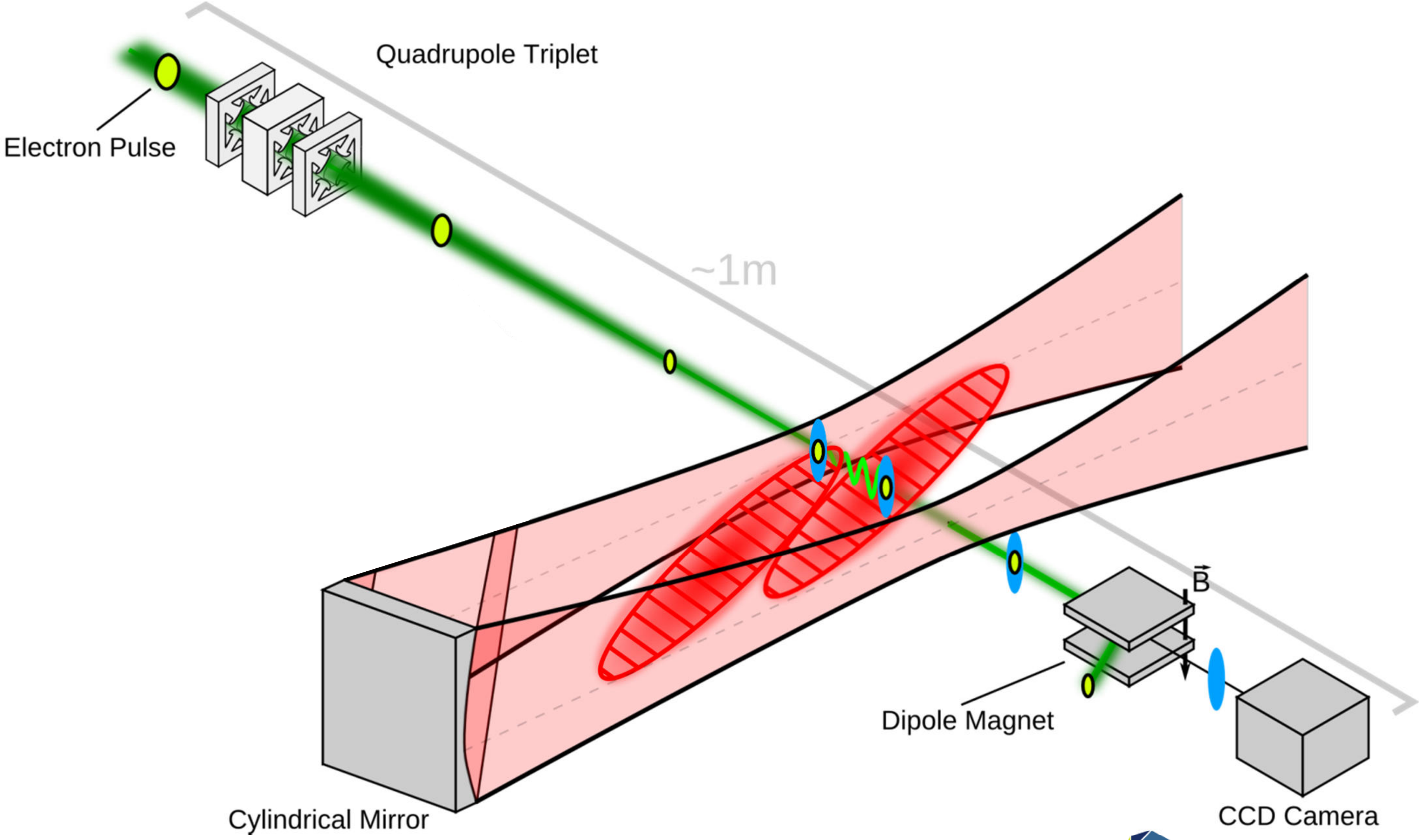
Pulse front tilt angle $\alpha_{tilt} = \phi/2$ for continuous overlap

A. Debus et al, *Appl. Phys. B* 100 (2010)

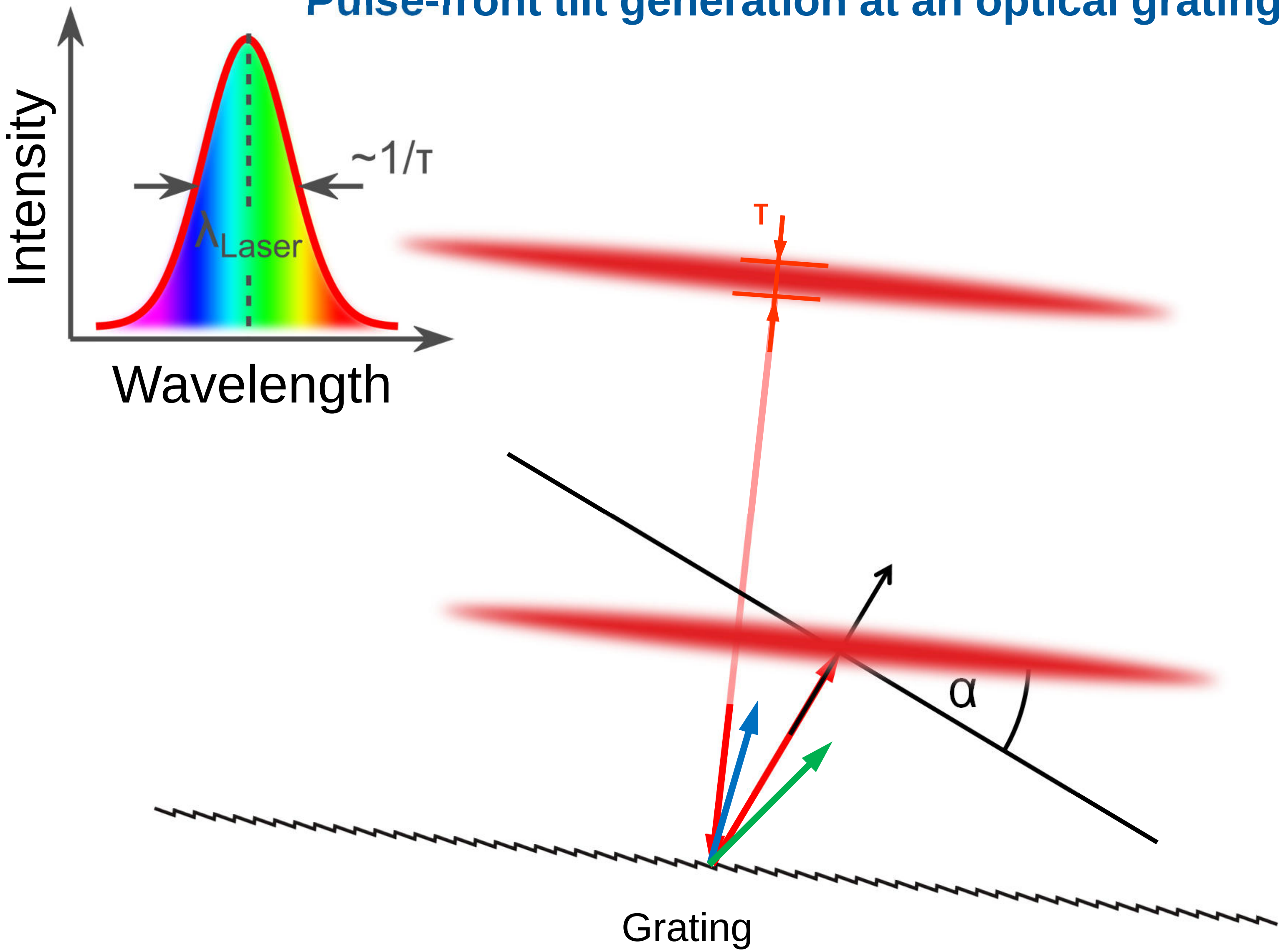
How to generate pulse-front tilted laser pulses for Traveling-Wave Thomson-Scattering?



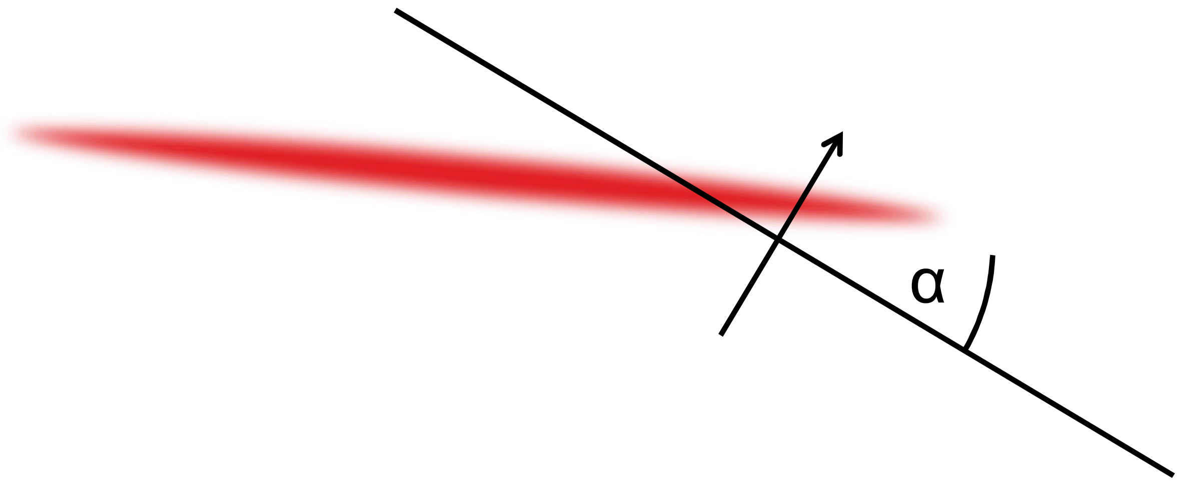
Aufbau eines TWTS OFEL



Pulse-front tilt generation at an optical grating

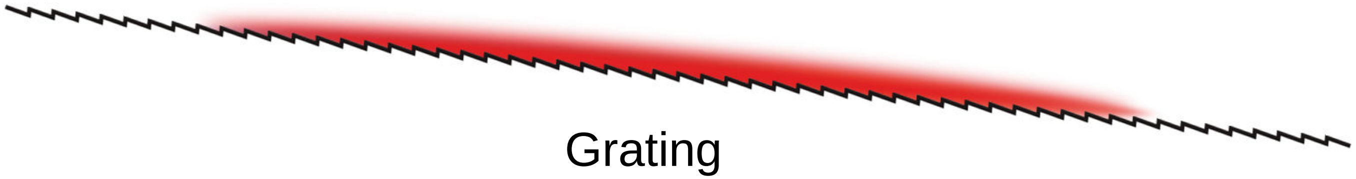


Diffraction at a grating induces dispersion

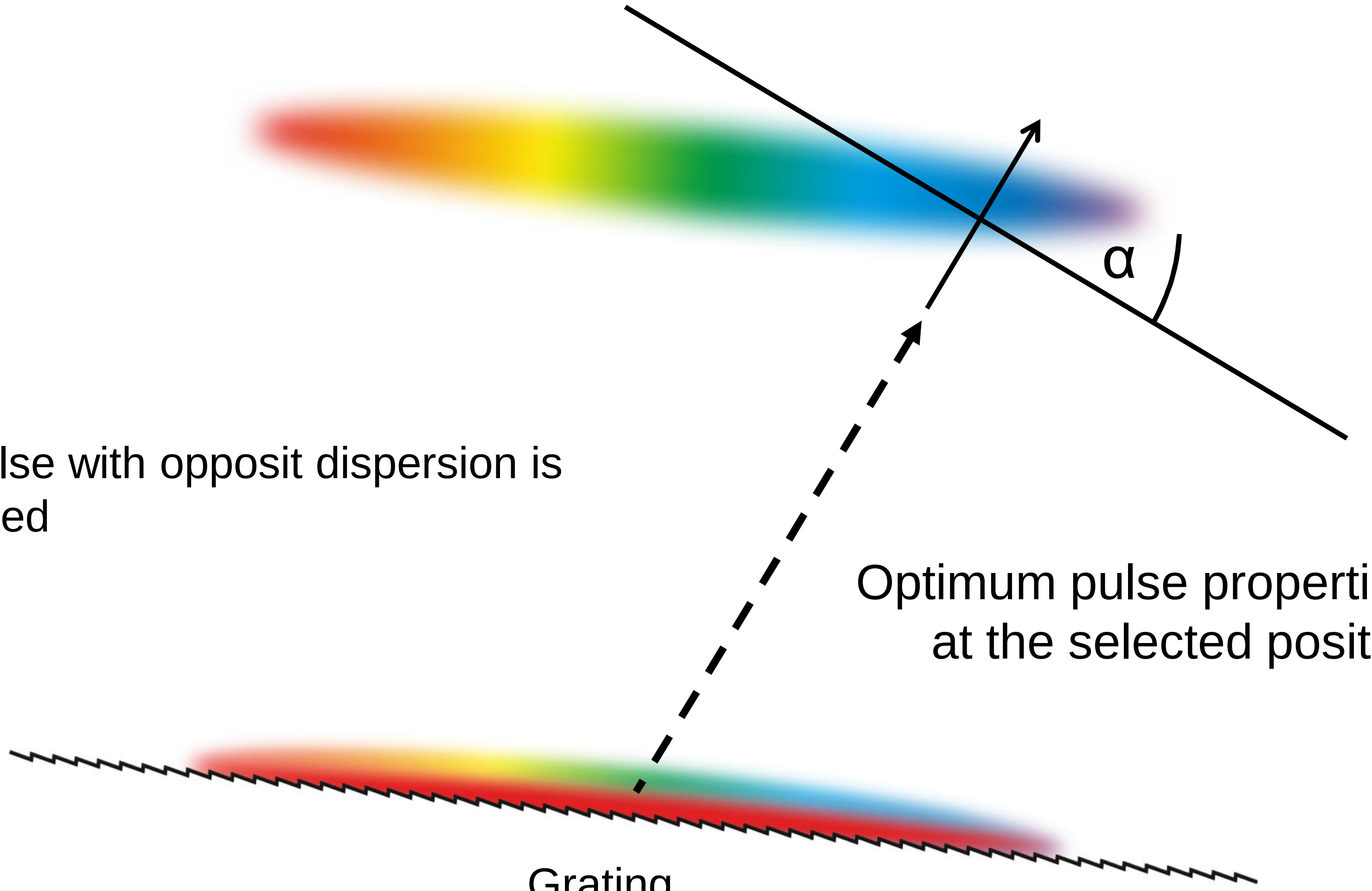


Dispersion broadens the radiation spectrum and reduces the interaction distance.

Instead of diffracting a dispersion free pulse at the grating…



Dispersion control: (1) Precompensation



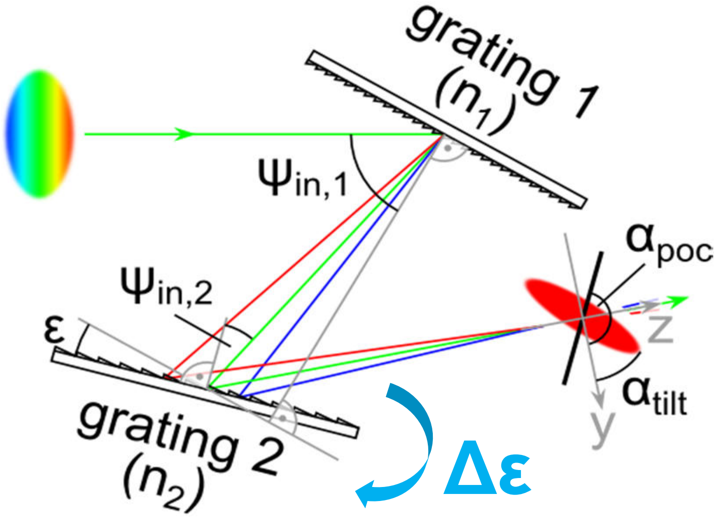
…a pulse with opposit dispersion is diffracted

Optimum pulse properties only at the selected position!

Grating

Dispersion control: (2) local compensation by grating pair

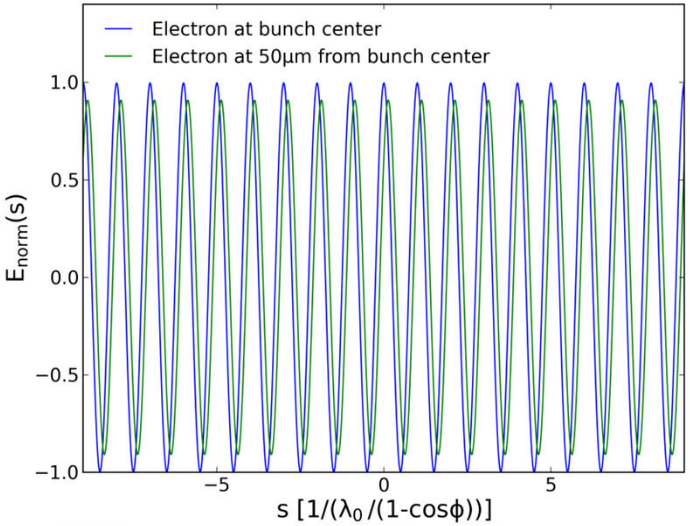
Two-grating setup grant control over local 1st and 2nd order dispersion properties



Required alignment precission is available today

typically required: Δε ~10µrad
(e.g. PEnELOPE compressor: Δε ~ 1µrad)

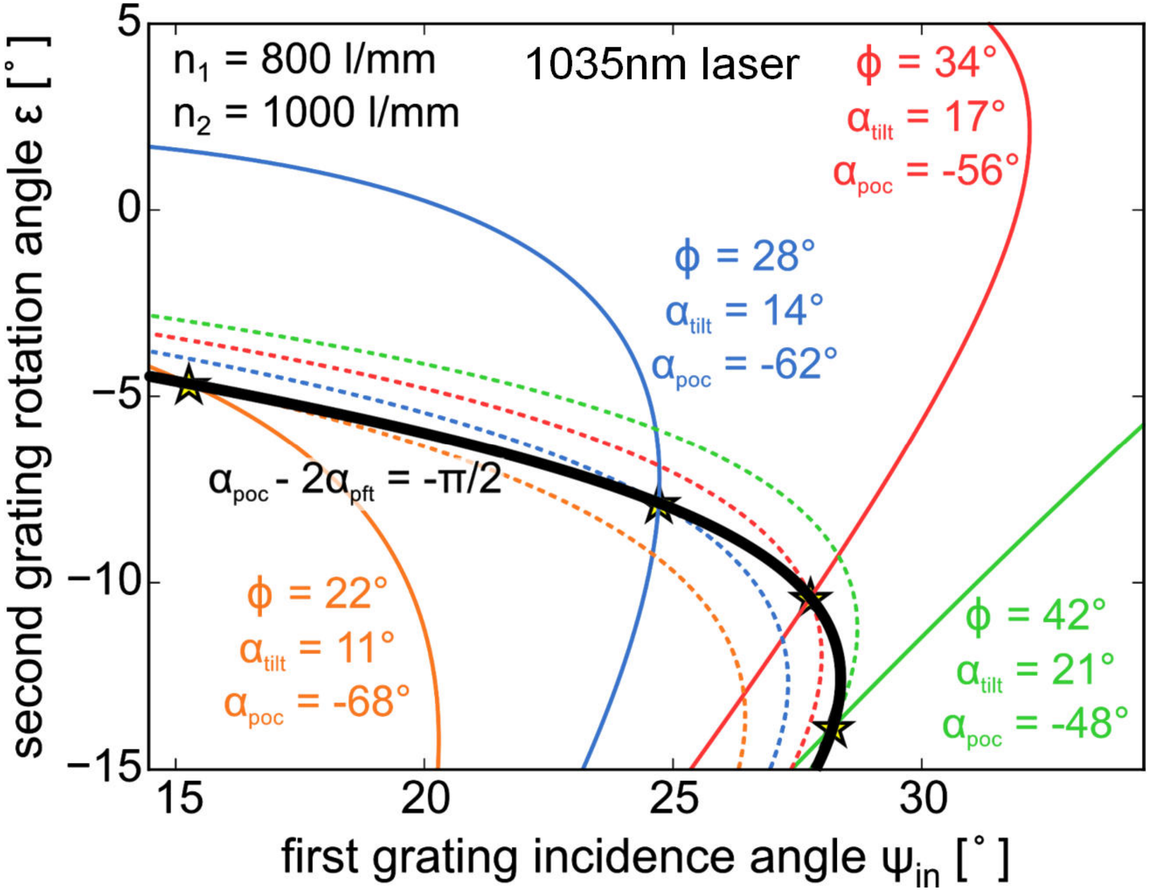
Dispersion vanishes along the electron trajectory for proper angles ($\psi_{in,1}$, $\psi_{in,2}$) and gratings (n_1,n_2)



Plane wave field as in a magnetic undulator

Amplitude of the electric field along the electron trajectory.
1µm, 120fs laser pulse at 25° interaction angle

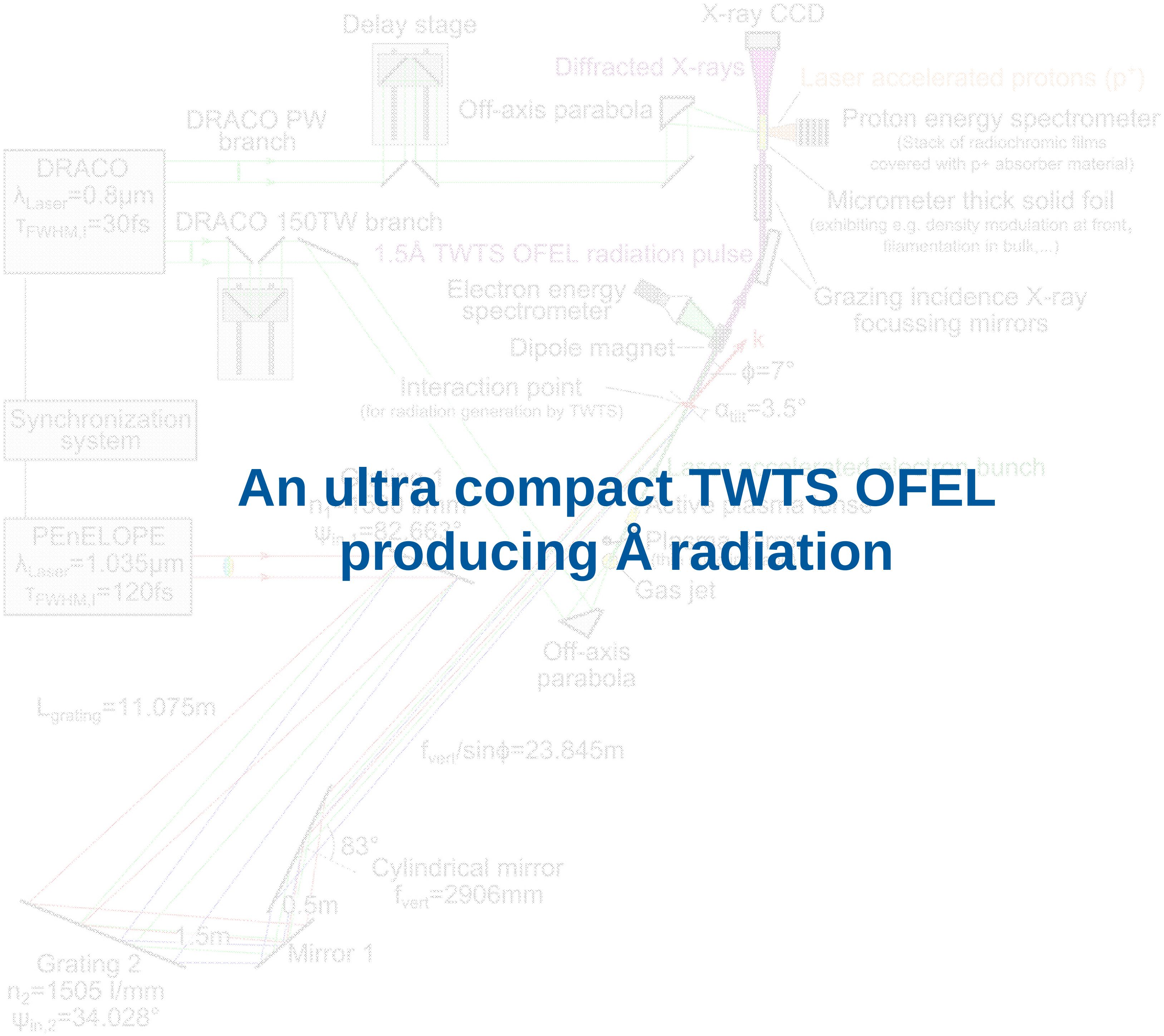
A single grating pair is useable for many TWTS OFELs



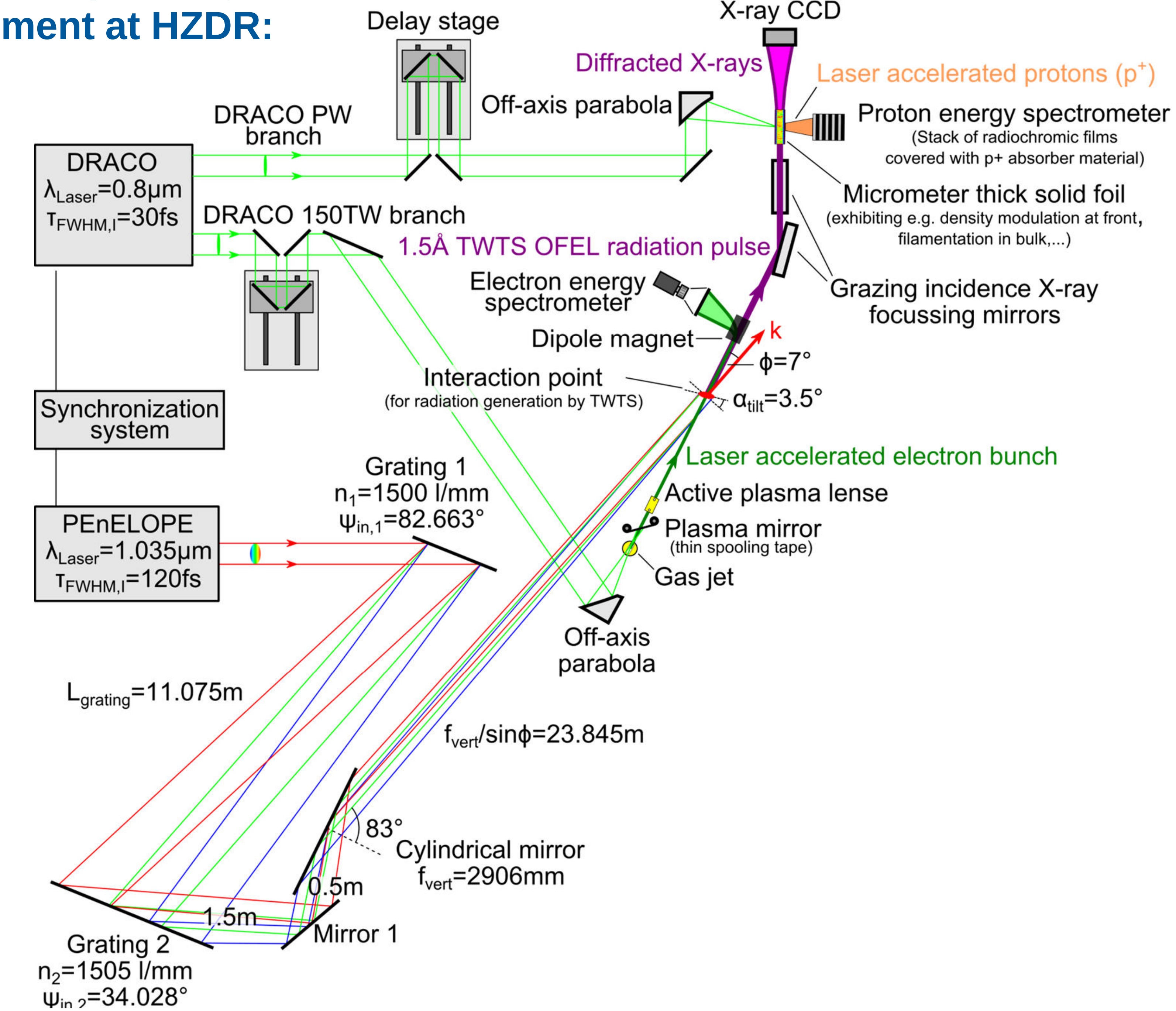
Colored continuous lines: constant orientation of plane of optimum compression

Colored dashed lines: constant orientation of pulse-front tilt

An ultra compact TWTS OFEL producing Å radiation

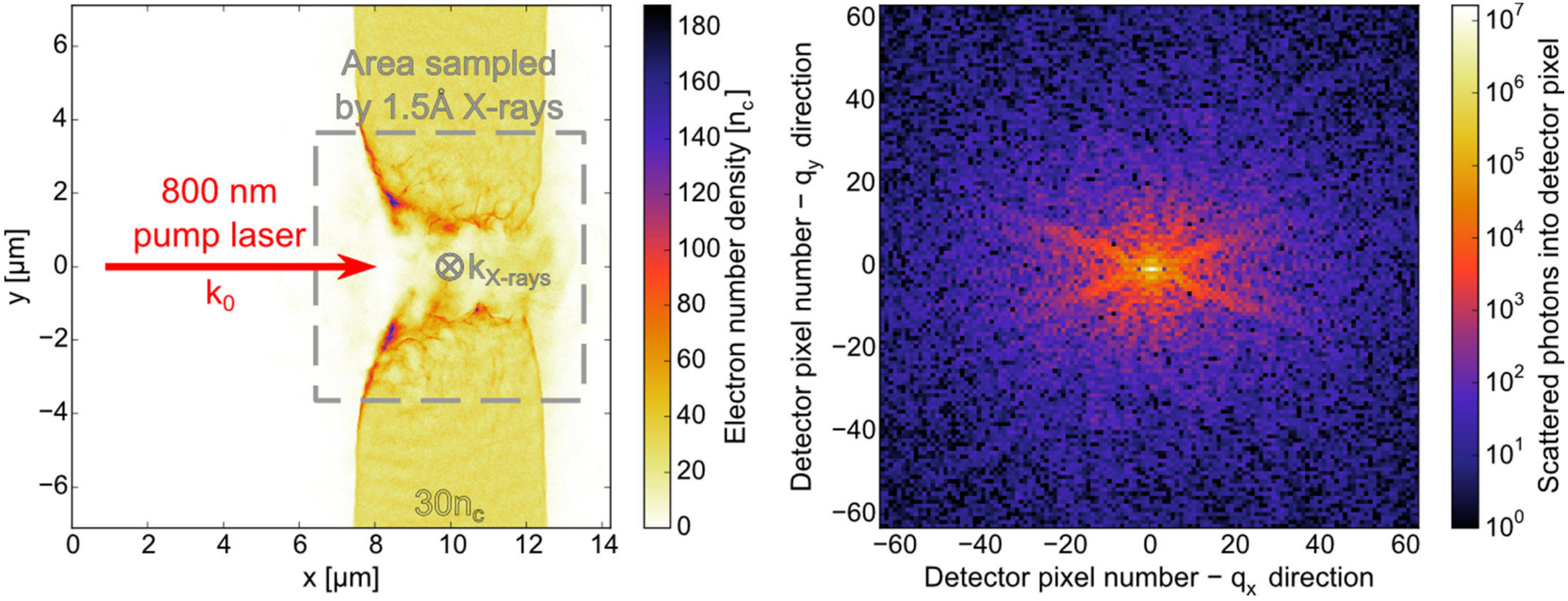


An (almost) complete layout of an experiment at HZDR:



Imaging plasma dynamics in explosively driven solid-density materials with an Å TWTS OFEL (e.g. laser ion acceleration, compression experiments)

Ex.: Imaging electron density in a cryogenic hydrogen jet during laser proton acceleration via small-angle X-ray scattering (SAXS)



Scattered photon number for the scattering image is about **1000 photons/pixel per shot** from the Å TWTS OFEL

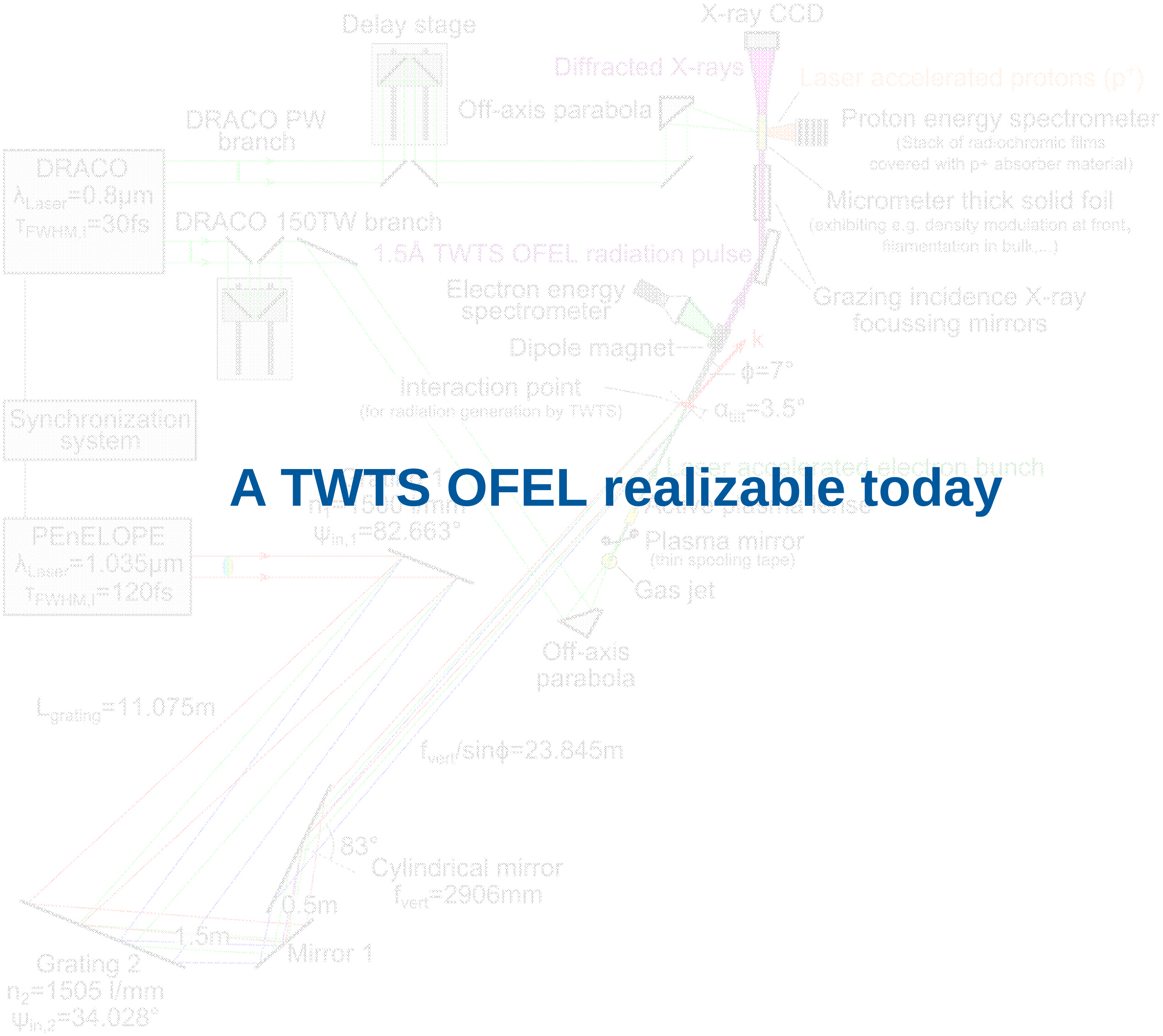
Electron density data in laser-driven solid hydrogen is obtained from PICLS simulation performed by J. Branco

What about electron and laser requirements?

Parameter	ÅTWTS OFEL	LCLS@ SLAC
Radiation wavelength [nm]	0.1	0.1
Interaction angle [deg]	7.0	-
Undulator period [mm]	0.14	30
Electron energy [MeV]	349	16900
Peak current [kA]	5.0	4.0
Norm. transv. emittance [mm mrad]	0.2	0.2
Rel. energy spread	0.02%	0.1%
Laser peak power [PW]	576	-
Interaction distance [cm]	5.1	$13.2\cdot10^2$
X-ray photons/pulse	$2\cdot10^{10}$	$2.4\cdot10^{12}$

Size reduction by orders of magnitude (Fits into this building rather than kilometer long tunnels)

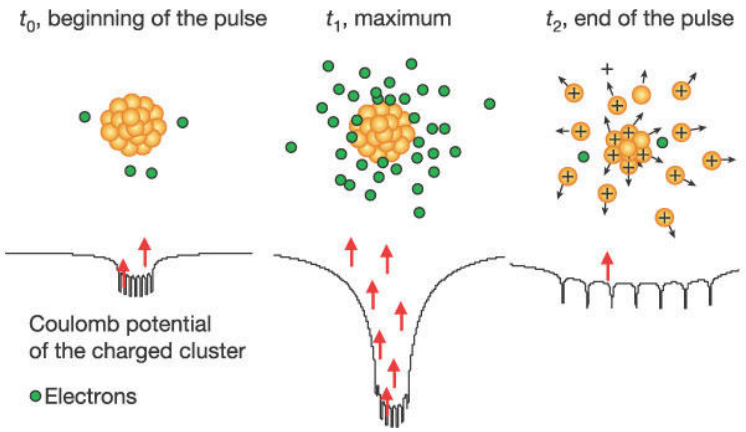
A TWTS OFEL realizable today



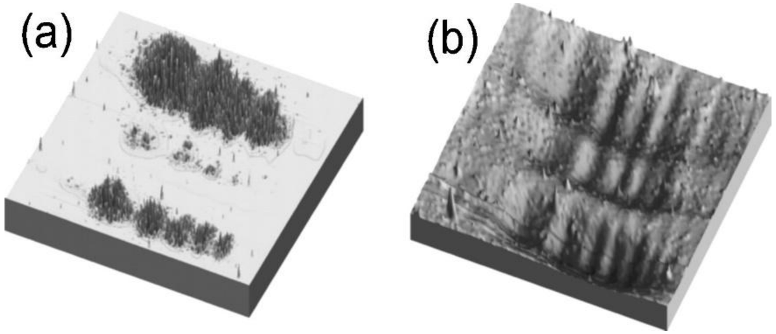
Example setup: 100nm TWTS OFEL

Applications include temporal studies of e.g.

- reaction kinetics at surfaces
- cluster ionization dynamics
- laser ablation for micromachining or damage induction



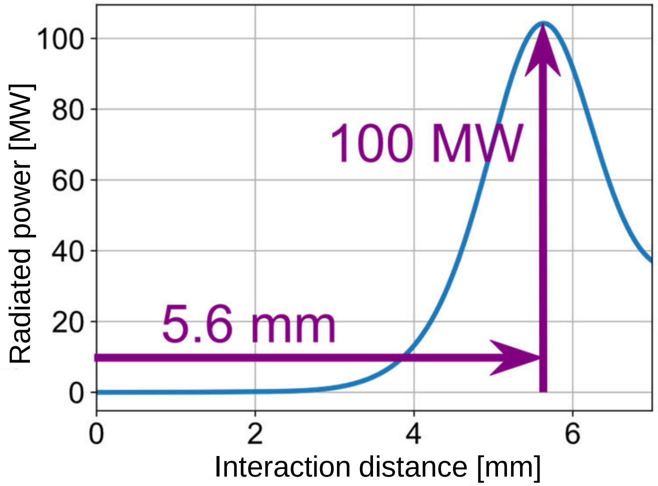
Wabnitz, Nature (2002), doi:10.1038/nature01197



Krzywinski, J. Appl. Phys. (2007), doi:10.1063/1.2434989

What about electron and laser requirements?

Parameter	TWTS OFEL	FLASH@ DESY(2000)
Radiation wavelength [nm]	99.5	109
Interaction angle [deg]	10.1	-
Undulator period [mm]	0.065	27.3
Electron energy [MeV]	15	240
Peak current [kA]	0.8	1.5
Norm. transv. emittance [mm mrad]	0.5	6
Rel. energy spread	0.8%	0.1%
Laser peak power [PW]	1	-
Interaction distance [mm]	5.6	$13.5 \cdot 10^3$
VUV photons/pulse	$23 \cdot 10^{12}$	$52 \cdot 10^{12}$



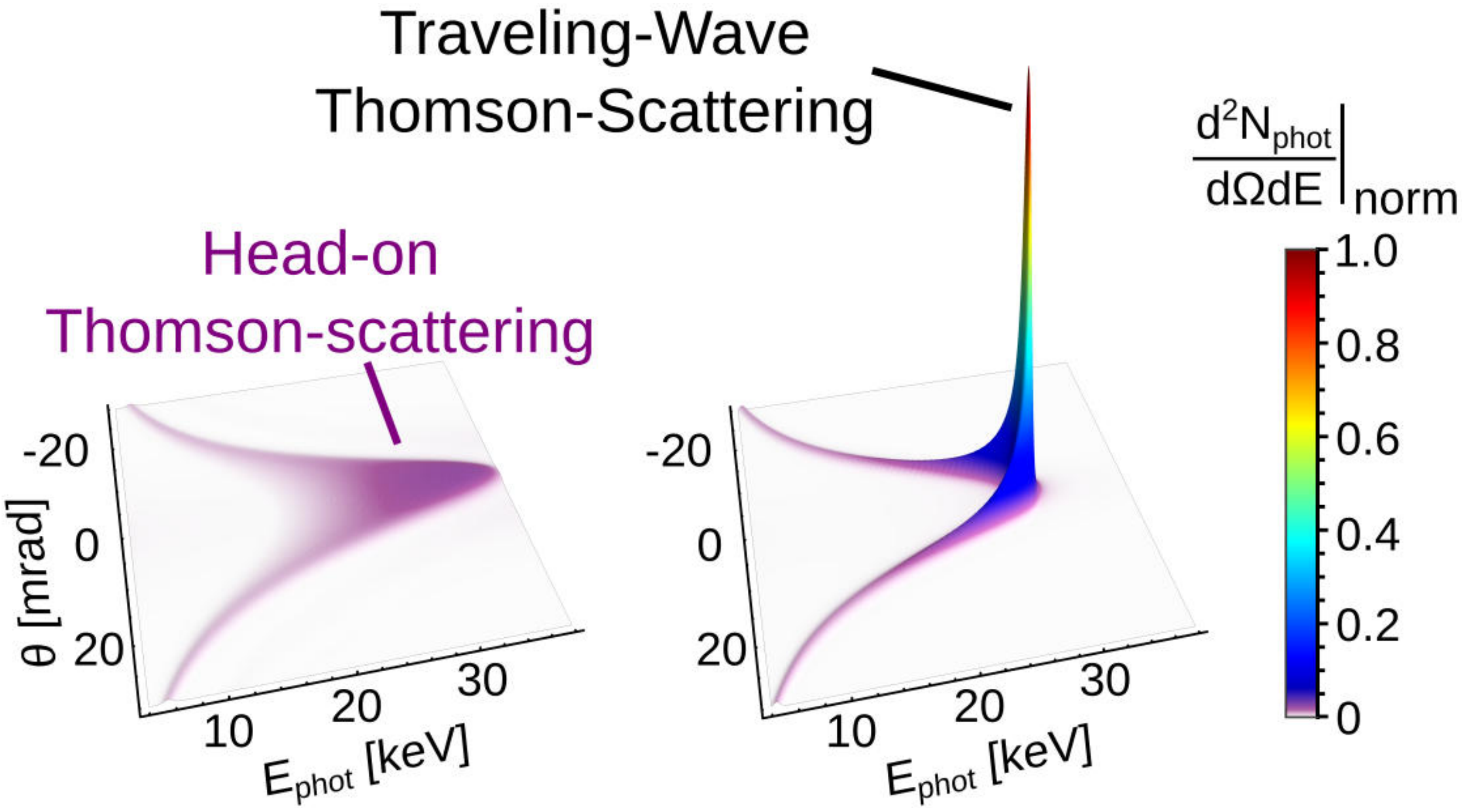
Realizable with state-of-the-art accelerator and laser systems!

TWTS for high yield incoherent X-ray sources

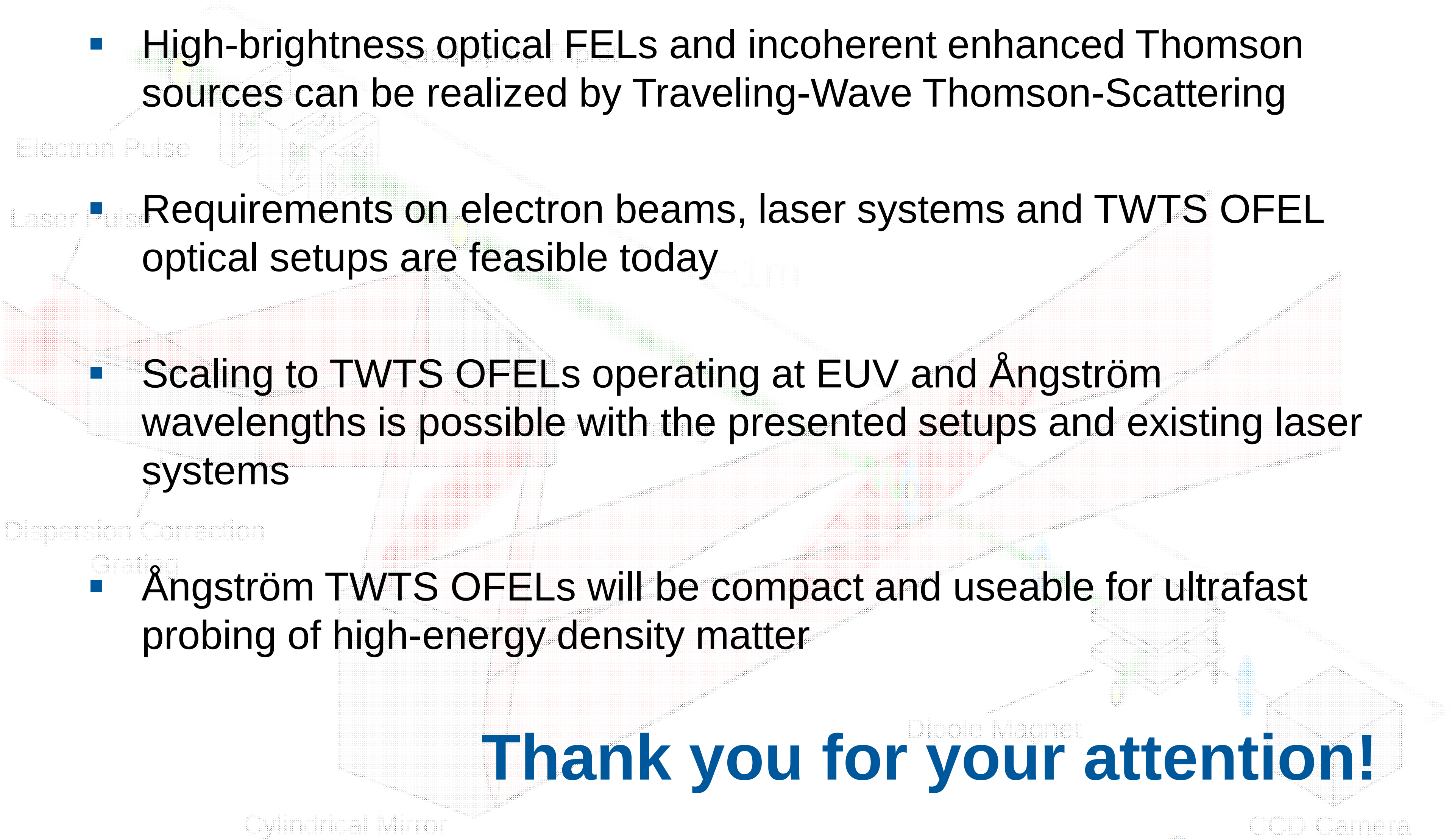
High yield through long interaction distances in TWTS geometries

Orders of magnitude increase in spectral photon density with TWTS using the same laser and electrons

(Yet the photon energy is slightly reduced)



Electrons: 40MeV, 2mm mrad; Laser: 1J, 25fs, 800nm; Geometry: ϕ=120°, L_{int}=42mm, by A. Debus

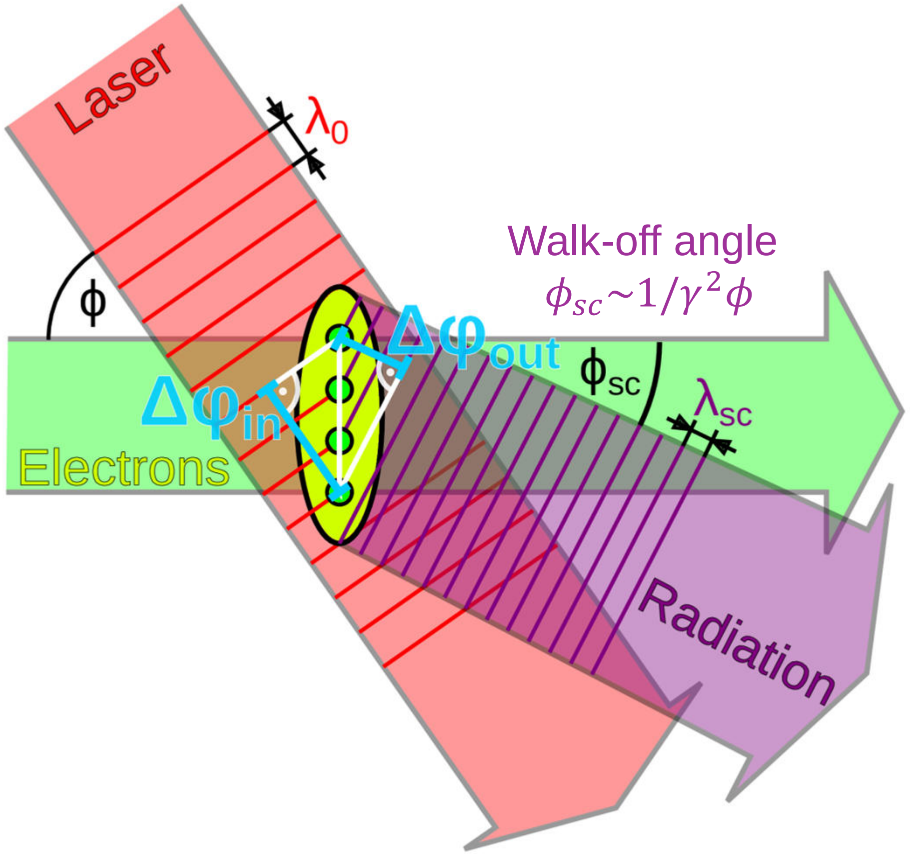


- High-brightness optical FELs and incoherent enhanced Thomson sources can be realized by Traveling-Wave Thomson-Scattering
- Requirements on electron beams, laser systems and TWTS OFEL optical setups are feasible today
- Scaling to TWTS OFELs operating at EUV and Ångström wavelengths is possible with the presented setups and existing laser systems
- Ångström TWTS OFELs will be compact and useable for ultrafast probing of high-energy density matter

Thank you for your attention!

Aufgrund der Seitenstreuungsgeometrie wird Strahlung unter einem Winkel emittiert

- Elektronen oszillieren in unterschiedlichen Phasen aufgrund des schrägen Lasereinfalls
- Sie emittieren Strahlung mit der gleichen Phasendifferenz
- Ausgehende Strahlung wird unter dem Winkel ϕ_{sc} emittiert
- Ist die Strahlungswellenlänge viel kürzer als die Laserwellenlänge gilt $\phi_{sc} \ll \phi$

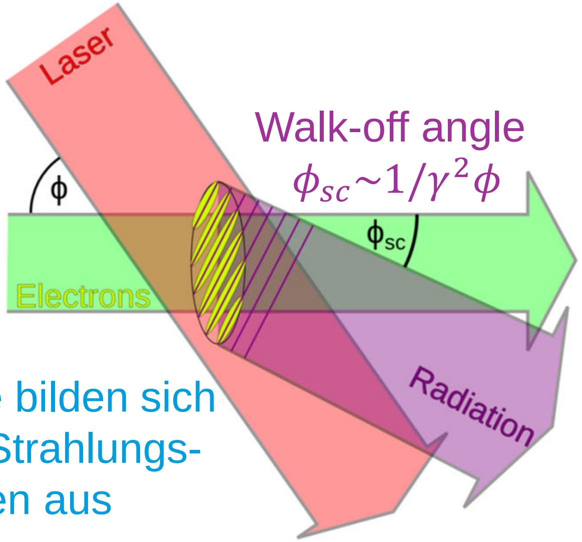


Entwicklung einer neuen 1.5D Theorie zur Beschreibung der TWTS OFELs!

Zeitliche Entwicklung der Elektronenpuls- und Strahlungsfeldparameter ist äquivalent zur Entwicklung in standard FELs

1.5D Theorie von TWTS OFELS:

- Elektronen wechselwirken mit dem elektrischen und magnetischen Feld des Lasers
- Elektronen- und Laserflugrichtung schließen den Winkel ϕ ein
- Strahlung wird unter dem Winkel ϕ_{sc} emittiert



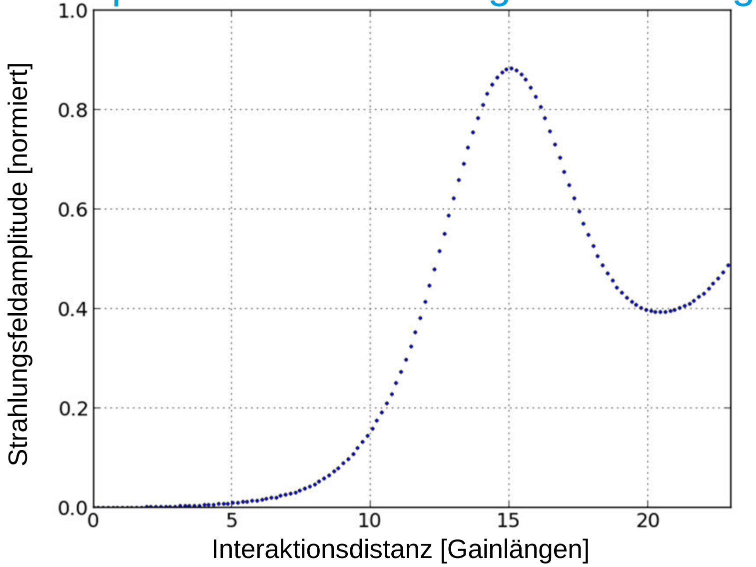
Walk-off angle
$\phi_{sc} \sim 1/\gamma^2 \phi$

Microbunche bilden sich entlang der Strahlungsphasenfronten aus

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

TWTS OFEL Bewegungsgleichungen sind in ihrer Form äquivalent zu denen herkömmlicher FEL

Exponentielle Strahlungsverstärkung



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    - Slide 1.2
    - Slide 1.3

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