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Royal Holloway University of London, Egham, United Kingdom

Long optical undulators with Traveling-Wave Thomson Scattering

Towards tunable, high-yield sources in the hard X-ray range

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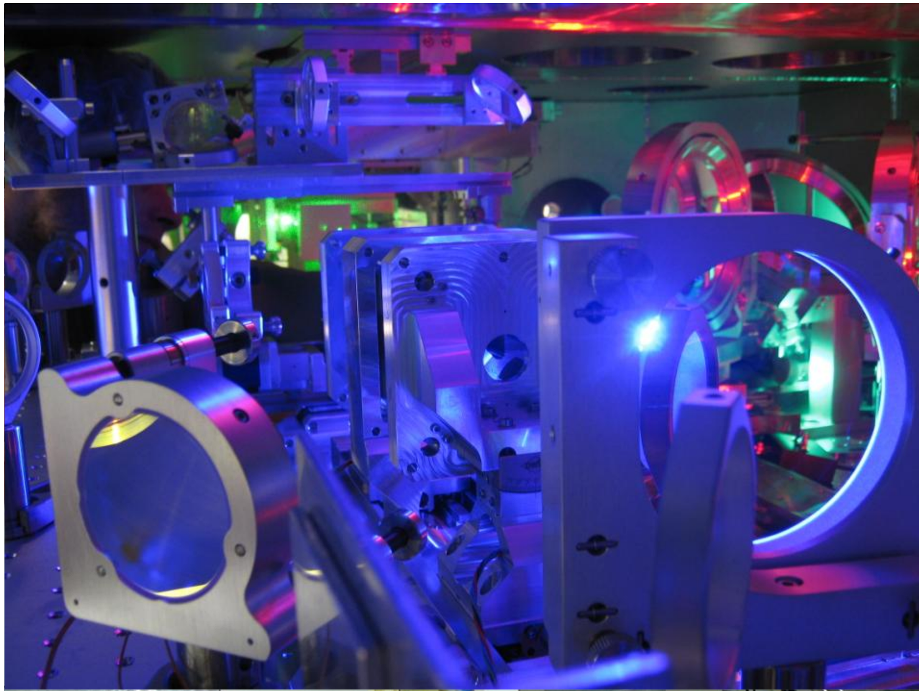
U. Schramm, T. E. Cowan, R. Sauerbrey and M. Bussmann

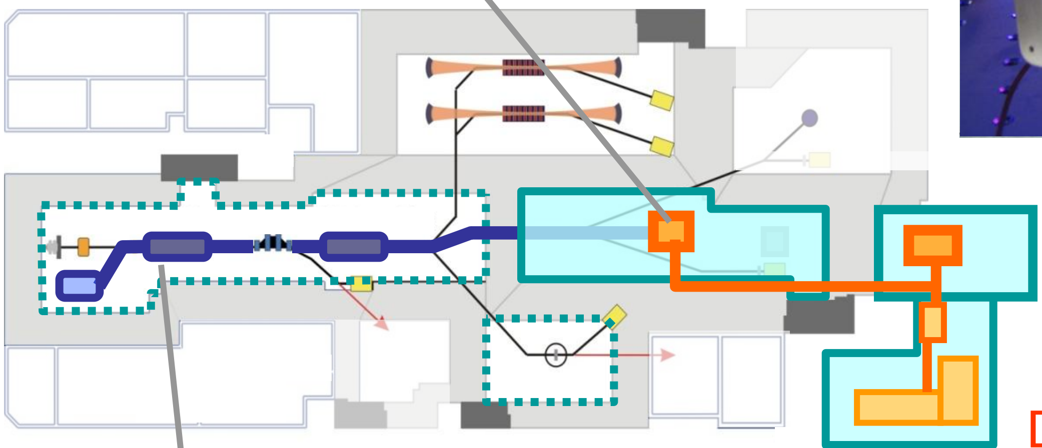
HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

At the ELBE facility the DRACO laser is used for head-on Thomson scattering



Target area at ELBE

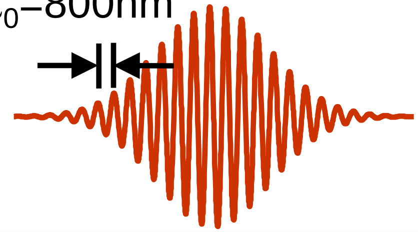
Thomson scattering
Laser-wakefield acceleration



ELBE LINAC
40 MeV

DRACO laser

λ_0=800nm

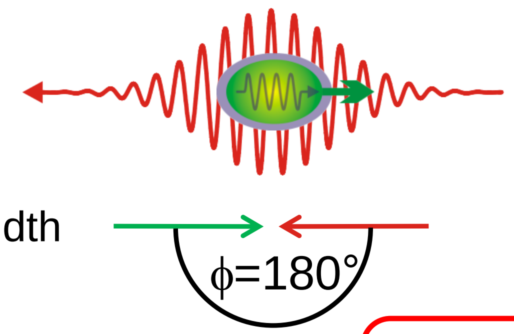


250 Terawatt
4 J / 25 fs
synchronized to electron beam

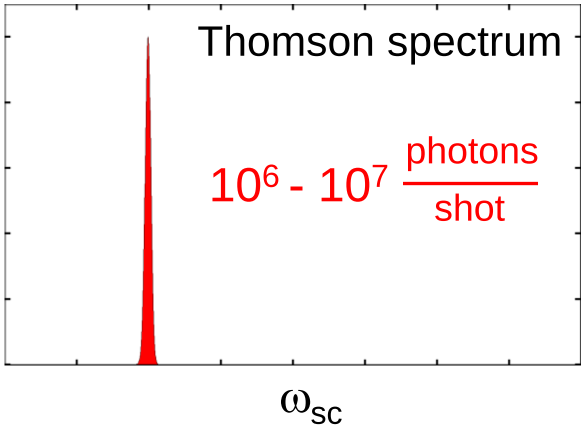
Alexander Debus

Head-on Thomson Scattering produces ultrashort X-ray pulses

electrons with X-ray pulse



- ultrashort
- small bandwidth
- hard x-rays



$$\omega_{\rm sc} = \frac{4\gamma^2 \cdot \omega_0}{1 + a_0^2/2 + \gamma^2\theta^2}$$

Most of the planned Thomson sources world-wide are aiming for high-repetition lasers combined with optical power enhancement cavities to achieve high-average powers.

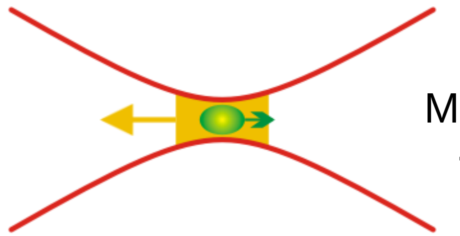
Many X-ray photons per shot are desired, but not pursued. Why?

So, what is wrong with ultrashort, high-power lasers for Thomson scattering?

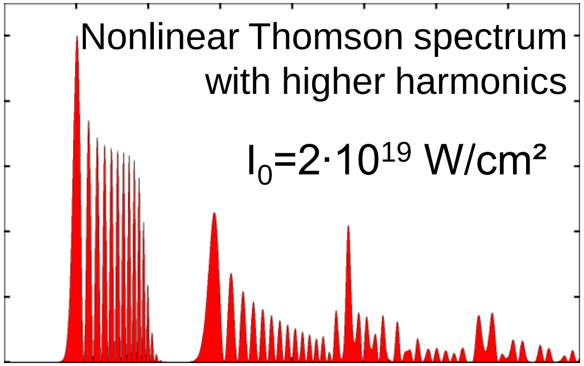
Why is it difficult to scale up the yield?

The photon yield can be improved by either increasing the intensity or the interaction duration.

① Increase the intensity !



Maximum intensity $< 2\cdot10^{18}$ W/cm²

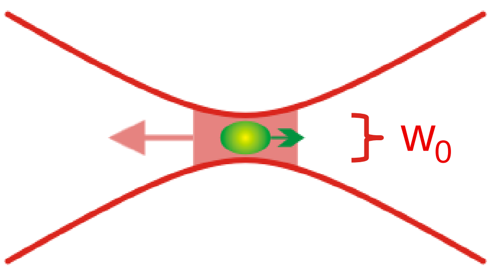


In the nonlinear Thomson regime the scattered laser energy is distributed among many higher harmonics instead only the fundamental.

Today's high-power lasers have intensities up into the 10^{21} W/cm² range.

② Increase the laser duration!

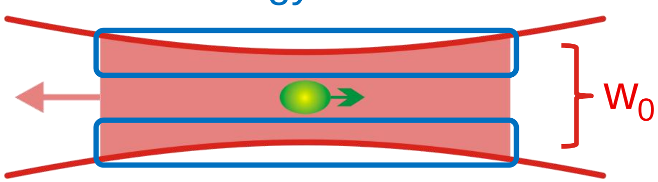
$$Z_0 = \frac{\pi w_0^2}{\lambda_0}$$



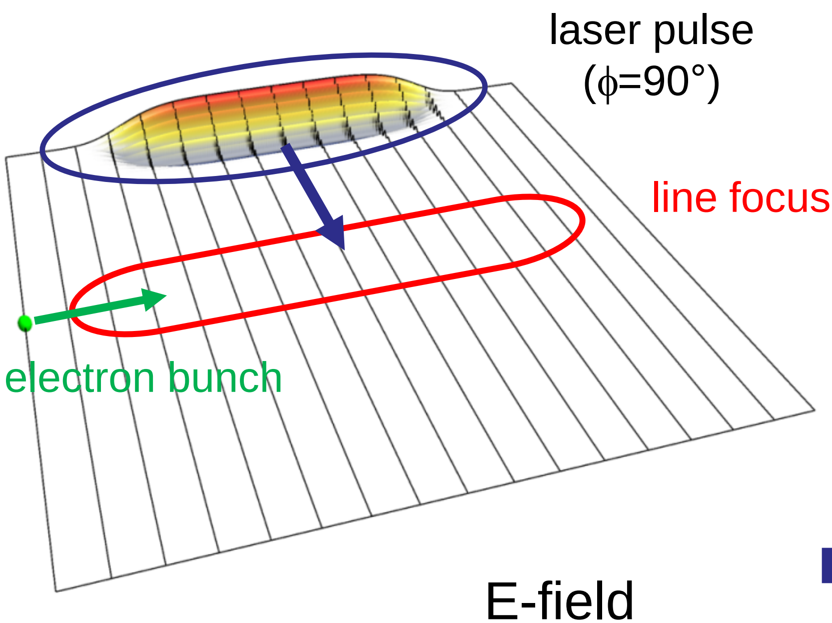
Increase laser waist

to extend Rayleigh length

wasted laser energy $\propto w_0^2$



Idea: In a side-scattering geometry the focus can be extendend to a line



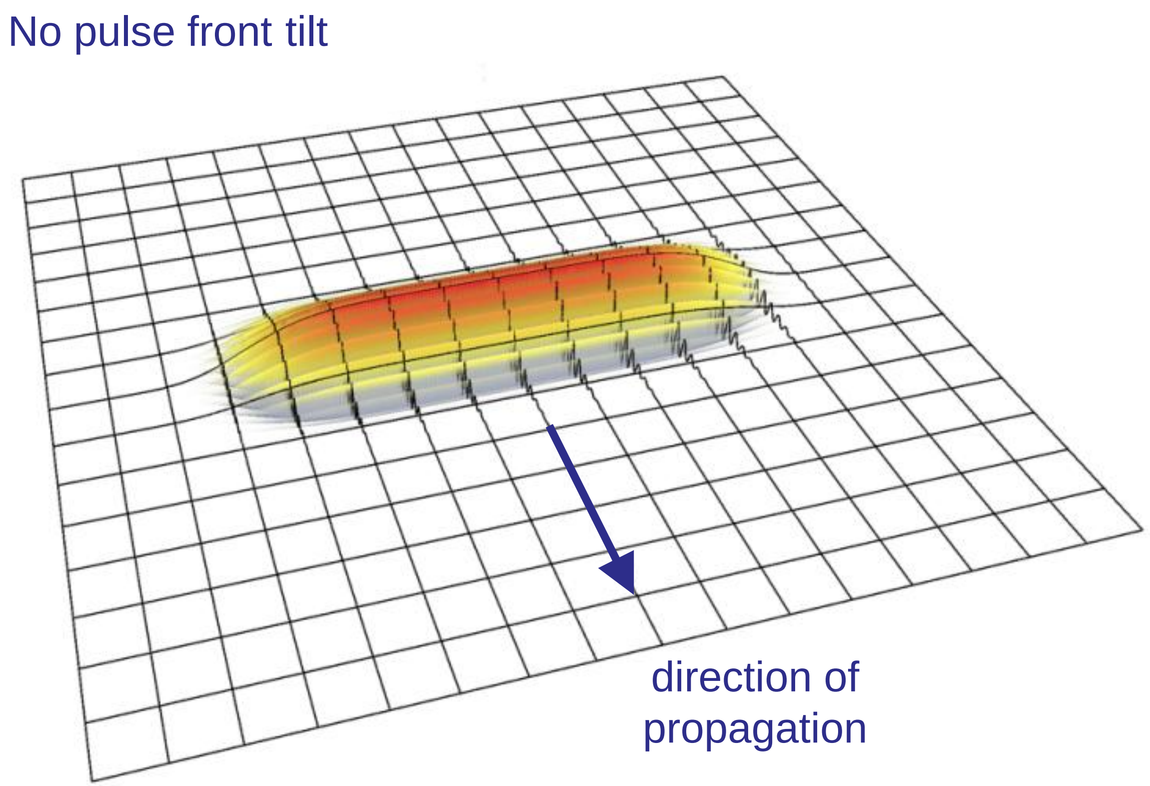
- A cylindrical mirror creates a line focus.
- Electrons propagate along this focal line. The length of that line is determined by the beam width rather than the focal properties.
- Side-scattering red-shifts the frequency of the scattered radiation.

$$\Rightarrow \quad \omega_{\mathrm{sc}} = 2(1 - \beta_0 \cos\phi)\gamma^2 \cdot \omega_0$$

- Electrons remain in the focal region, but temporal overlap becomes an issue.
- Can we adjust the pulse such that all parts of the laser beam interact with the electron bunch?

DRESDEN concept HZDR

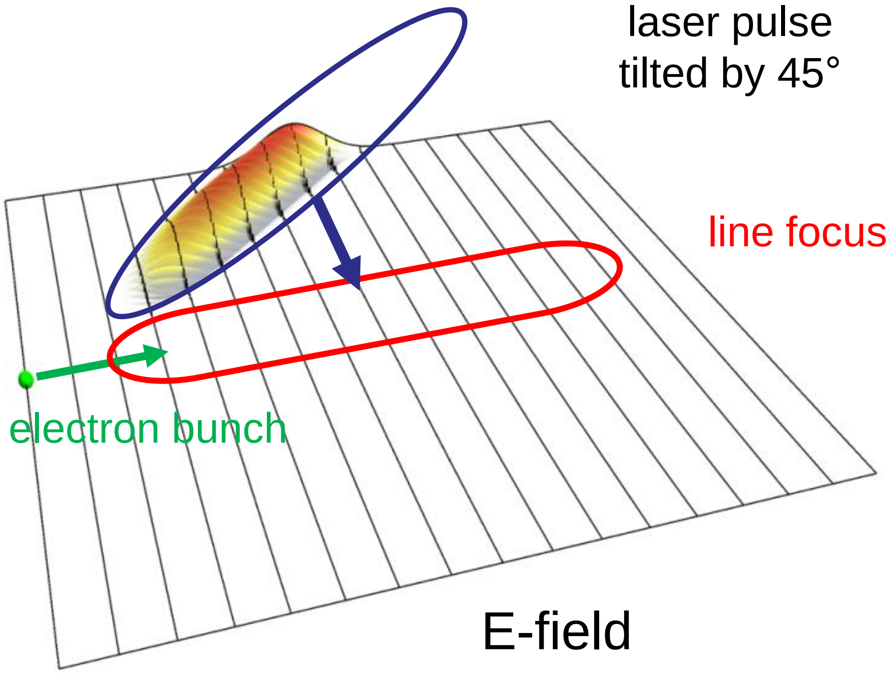
Tilt the laser pulse front to optimize temporal overlap with electrons



- Pulse front tilts do not affect the phase fronts.
  Instead, the laser envelope is shifted with respect to its carrier frequency.

- At scattering angle ϕ, one needs a pulse front tilt of $\phi/2$.

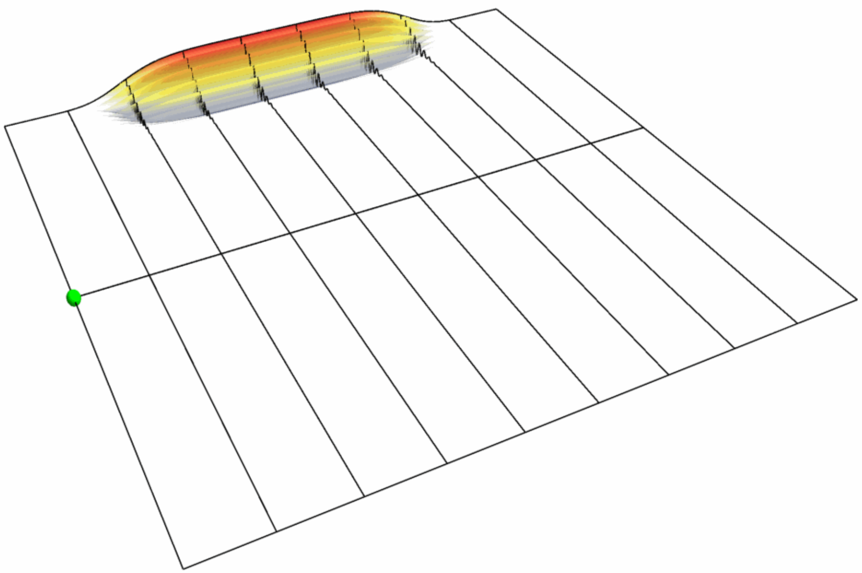
Travelling-wave Thomson scattering (TWTS) provides continuous overlap with electrons



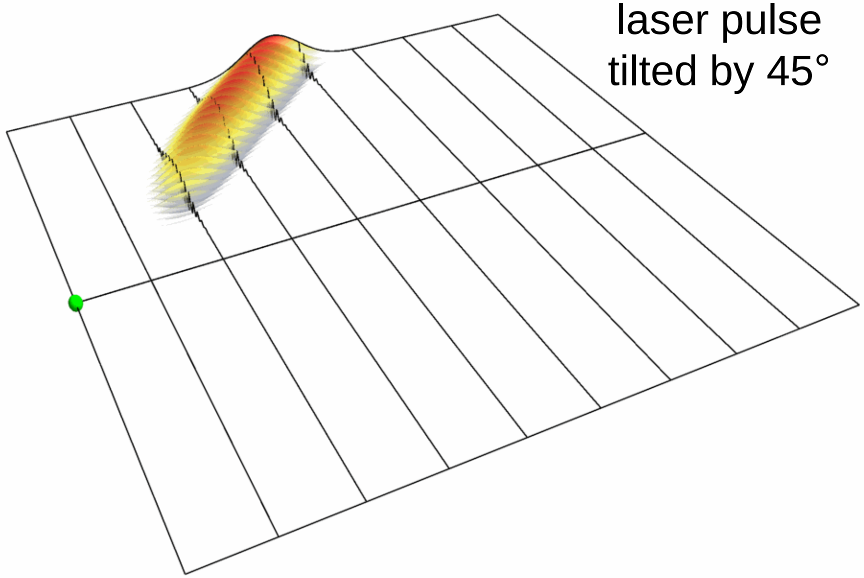
- In an extended overlap laser energy is continuously transferred into the x-ray pulse
- Both electrons and laser travel over distances much longer than the Rayleigh length.
- Electrons oscillate with the carrier frequency $\omega_0 \cdot (1 - \cos\phi)$.
- Effective intensity envelope extends over the entire laser beam width.

Travelling-wave Thomson scattering (TWTS) provides continuous overlap with electrons

Partial overlap with laser

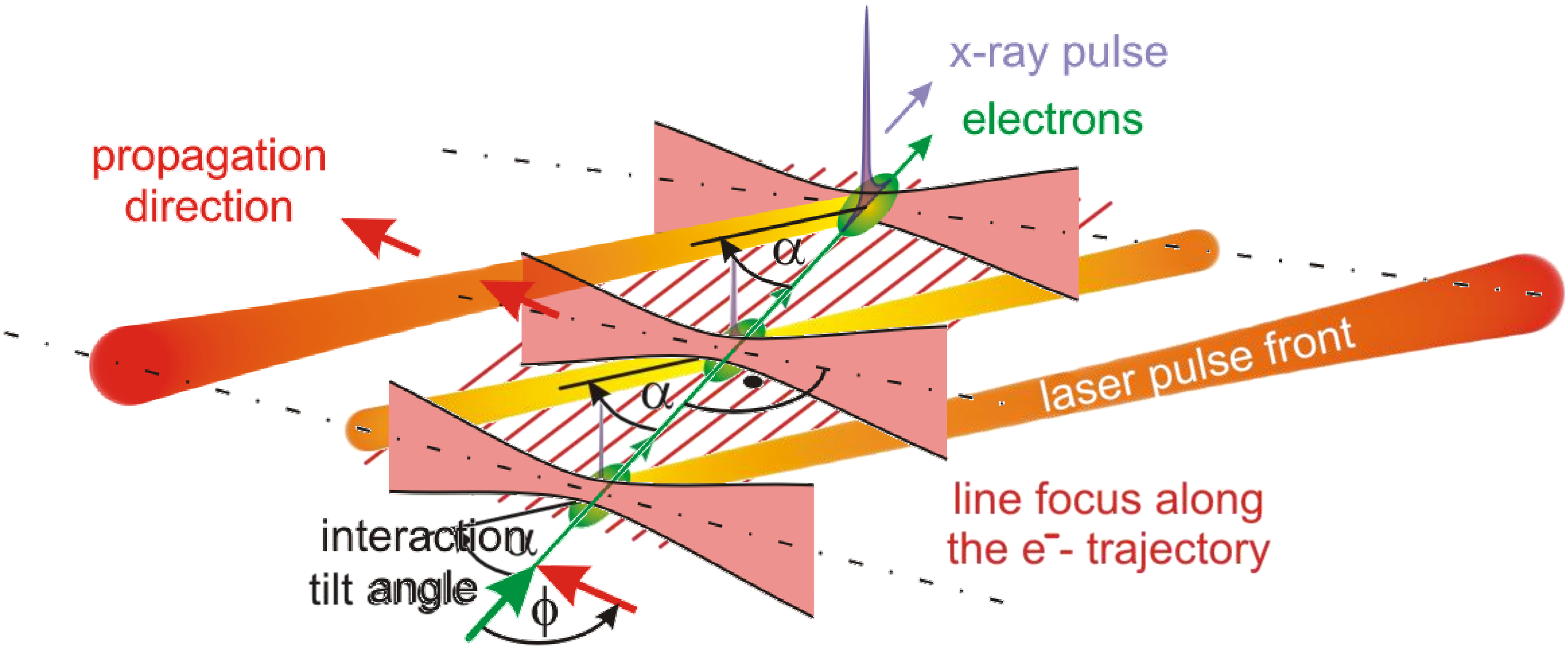


Electrons in a comoving overlap



The „Traveling-wave recipe“

[illegible]

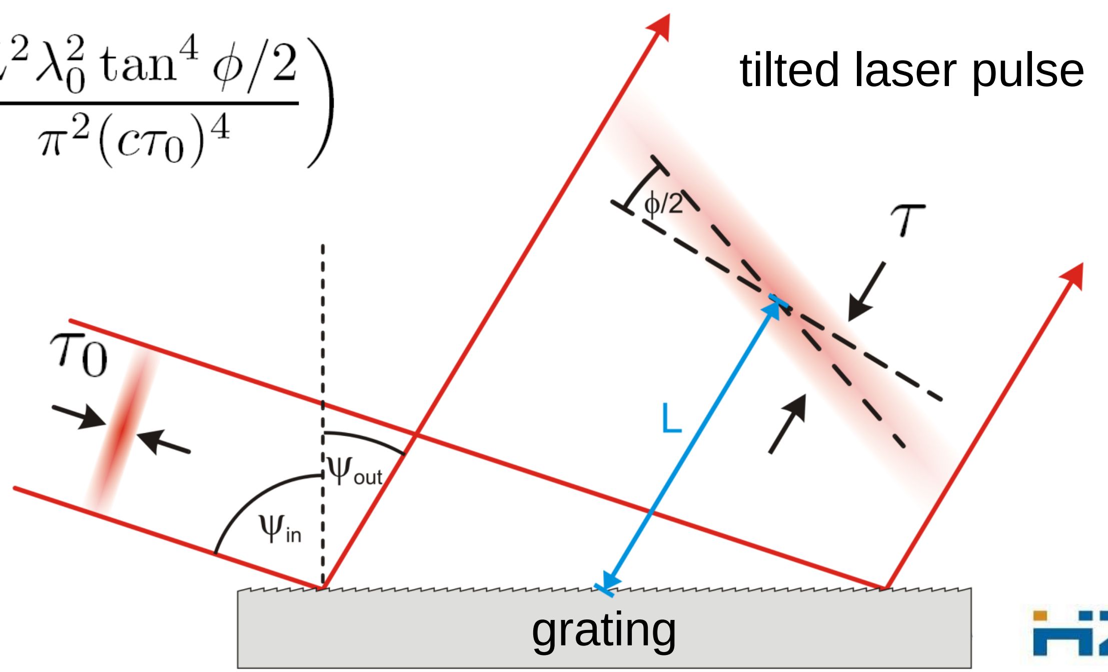


Pulse front tilts are experimentally realized using reflective gratings

pulse front tilts $\phi/2$ are connected to angular dispersion $$\tan\phi/2 = \omega_0 \left|\frac{\mathrm{d}\theta_{\mathrm{out}}}{\mathrm{d}\Omega}\right|_{\Omega=\omega_0}$$

group delay dispersion increases pulse duration

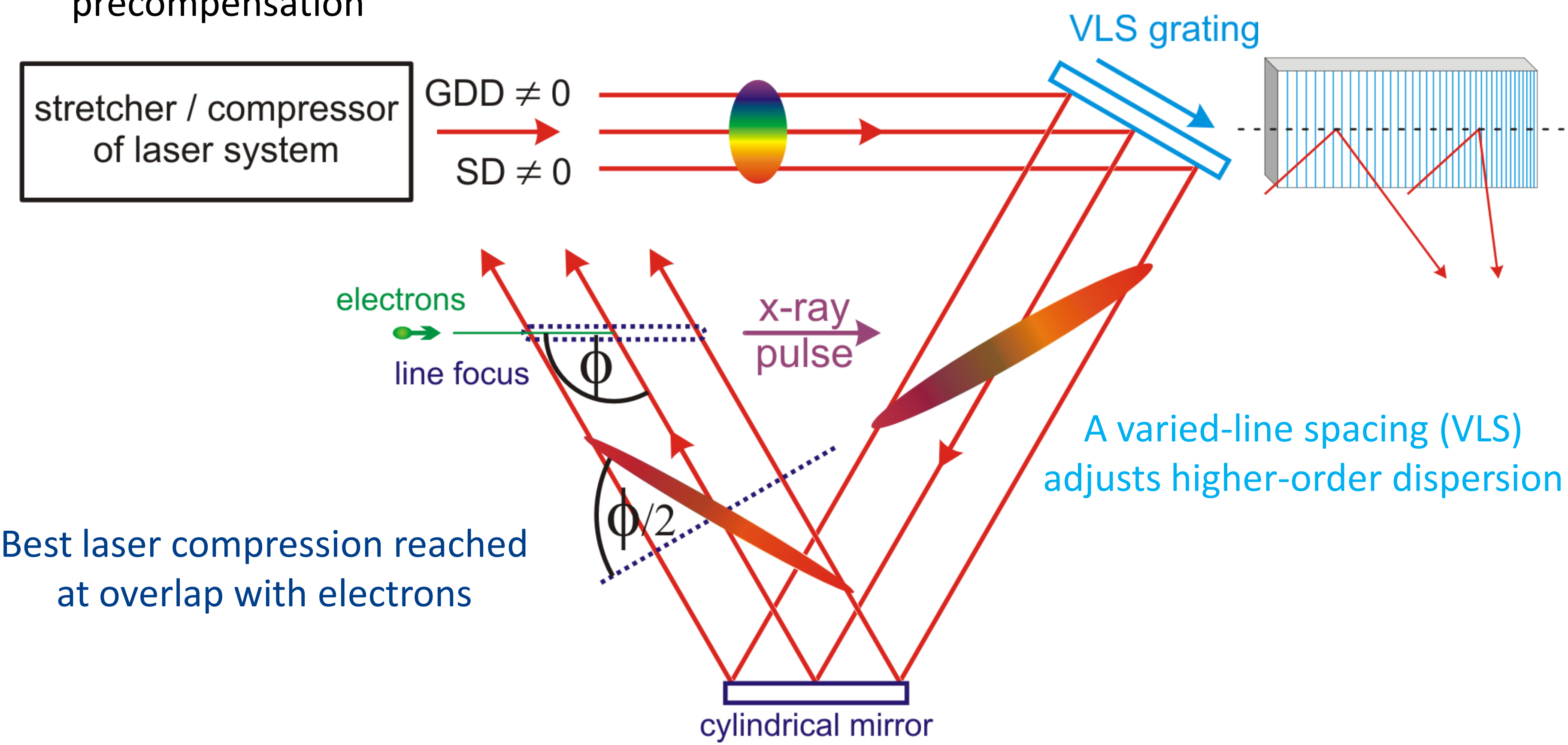
$$\tau^2 = \tau_0^2\left(1 + \frac{L^2\lambda_0^2\tan^4\phi/2}{\pi^2(c\tau_0)^4}\right)$$



How does a travelling-wave Thomson scattering experiment look like?

Laser provides dispersion precompensation

The grating introduces a pulse front tilt



A varied-line spacing (VLS) adjusts higher-order dispersion

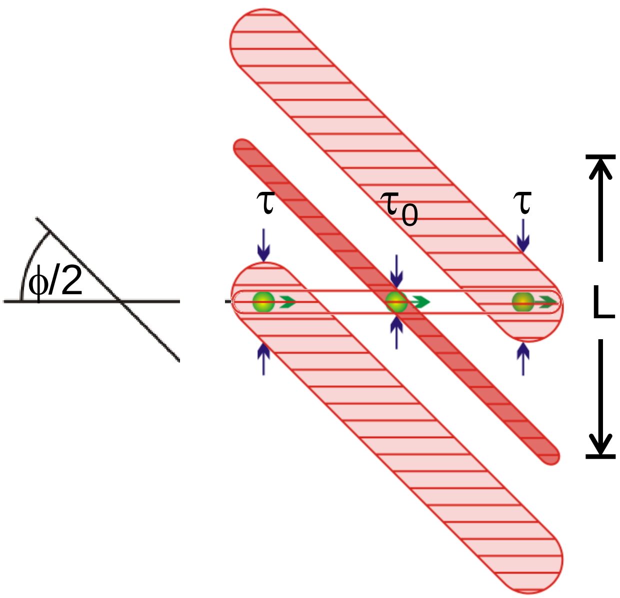
Best laser compression reached at overlap with electrons

The cylindrical mirror focuses perpendicular to the plane of projection and creates a line focus.

Varied line-spacing gratings are essential to compensate for group delay dispersion

Best pulse compression at only one point in time.

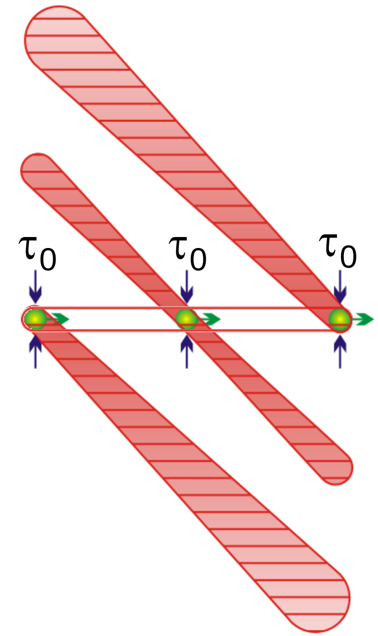
Spatially varying dispersion compensation across the beam.



GDD accumulated during interaction becomes relevant for large tilt angles ϕ/2>10°

$$\tau^2 = \tau_0^2 \left(1 + \frac{L^2 \lambda_0^2 \tan^4 \phi/2}{\pi^2 (c\tau_0)^4}\right)$$

>1



standard gratings

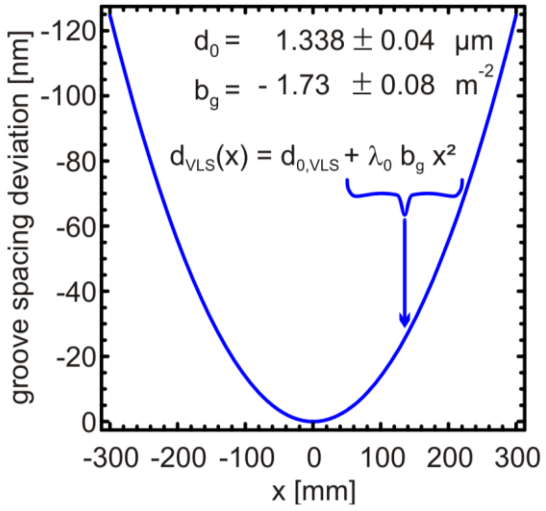
chirped grating (VLS)

How do the Varied-line spacing (VLS) gratings look like?

- Requirements along the line of interaction

1.) Group delay dispersion (GDD) vanishes
2.) Spatial dispersion (SD) vanishes
3.) Pulse front tilt (PFT) does not bend

- Optical setup modeled in a Raytracing framework relative to a central ray using position, angle, frequency and time delay coordinates.



__Result:__

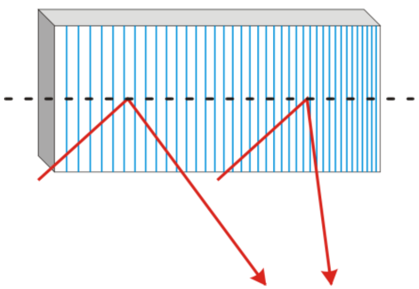
quadratic line-spacing function introduces linear variation of angular dispersion (AD)

$$d(s) = d_0 + b_g \lambda_0 s^2$$

$$b_g = -\frac{\cos\psi_{\text{out}} \cdot (\tan(\pi/2 - \phi) + \tan\phi/2)}{2L_0^2 \tan^2\phi/2}$$

$$\text{AD}(x) = \text{AD}_0 + \text{SD}_0 C_1 \cdot x$$

A weak, nonlinear focusing term, combined with spatial dispersion leads to a position dependent angular dispersion.



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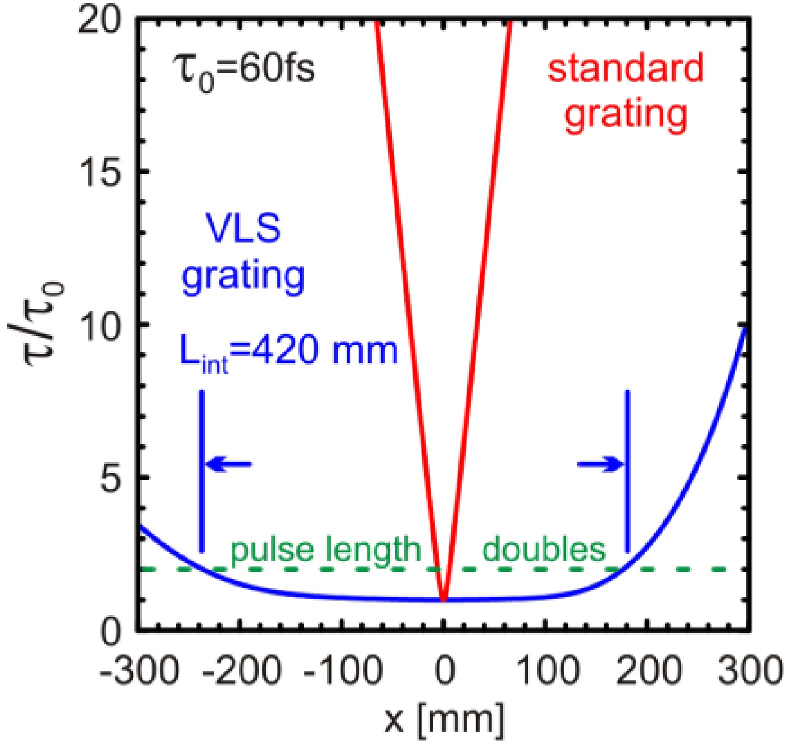
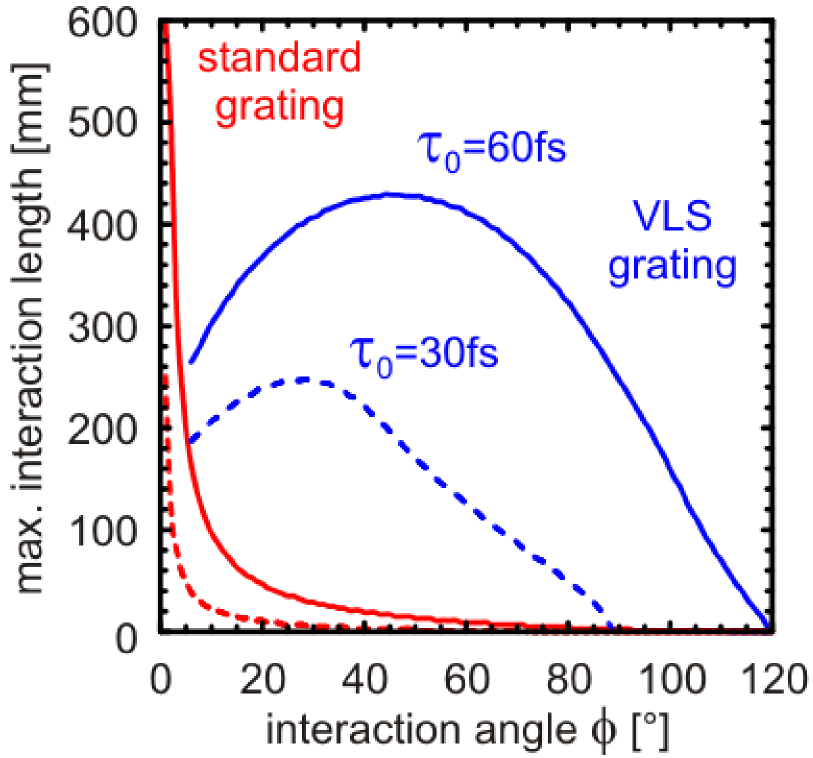
With VLS gratings long interaction lengths become possible

Calculation at ϕ=60°
standard vs. VLS grating



Maximum interaction lengths



The VLS gratings precompensate
for dispersion during the interaction !

TWTS improves per shot photon yields by orders of magnitudes

	MHz head-on (ϕ=180°)	kHz head-on (ϕ=180°)	PW-TWTS (ϕ=120°)	PW-TWTS (LWFA) (ϕ=120°)
rep. rate [Hz]	10^6	10^3	1	1
wavelength [µm]	1	0.5	1	1
W_{pulse} [mJ]	0.2	200	200 x 10^3	200 x 10^3
avg. laser power [W]	200	200	200	200
I_0 [W/cm²]	7.9 x 10^{13}	7.9 x 10^{16}	5.5 x 10^{16}	5.7 x 10^{16}
L_{int} [mm]	0.3	1.5	57.6	200
photon energy [keV]	31	62	23	3500
$N_{phot,5\%}$ per pulse	2.5 x 10^5	1.2 x 10^8	4.9 x 10^{10}	3.4 x 10^{10}

ELBE electrons (MHz head-on, kHz head-on, PW-TWTS)

LWFA electrons are more efficient (PW-TWTS (LWFA))

Electrons:

ELBE electrons: 40 MeV, 1nC, 2 π mm mrad (norm. trans. emittance)

LWFA electrons: 500 MeV, 200 pC,
0.1 π mm mrad (norm. trans. emittance)

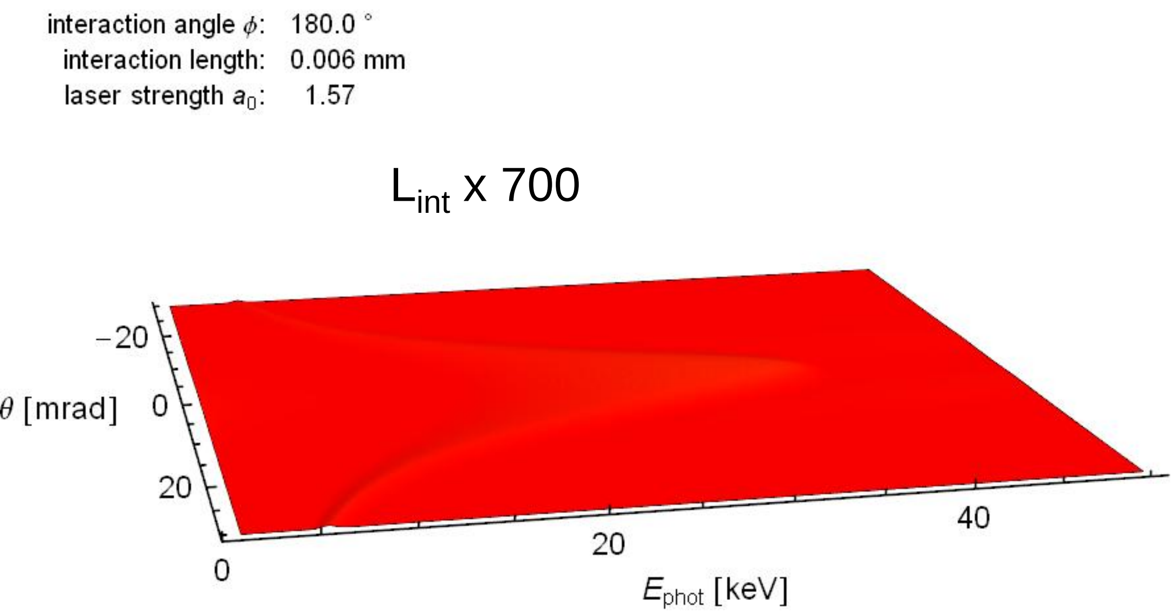
DRESDEN concept HZDR

TWTS concentrates photons into the 1st harmonic

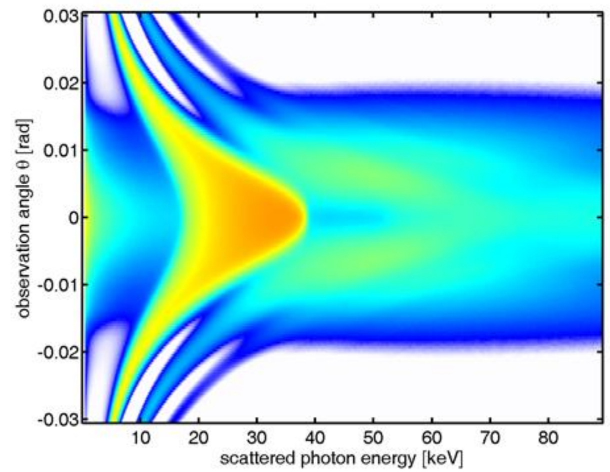
- increase interaction length
- local a_0 (intensity) is reduced

- change interaction angle
- adjust laser pulse front

$$\omega_{sc} = \frac{2(1-\beta_0 \cos\phi)\gamma^2 \cdot \omega_0}{1 + a_0^2/2}$$



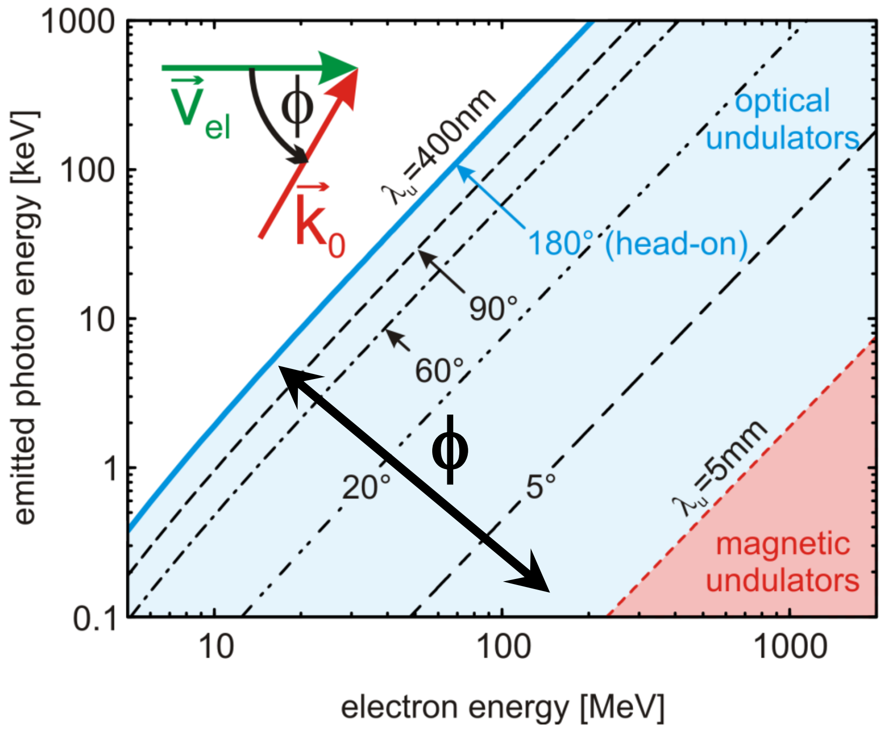
Scattering of DRACO laser at ELBE electrons



Log-scale to visualize harmonics

Calculations from Liénert-Wiechert solver CLARA and GPT

TWTS provides control over scattered photon energy and bandwidth



photon energy

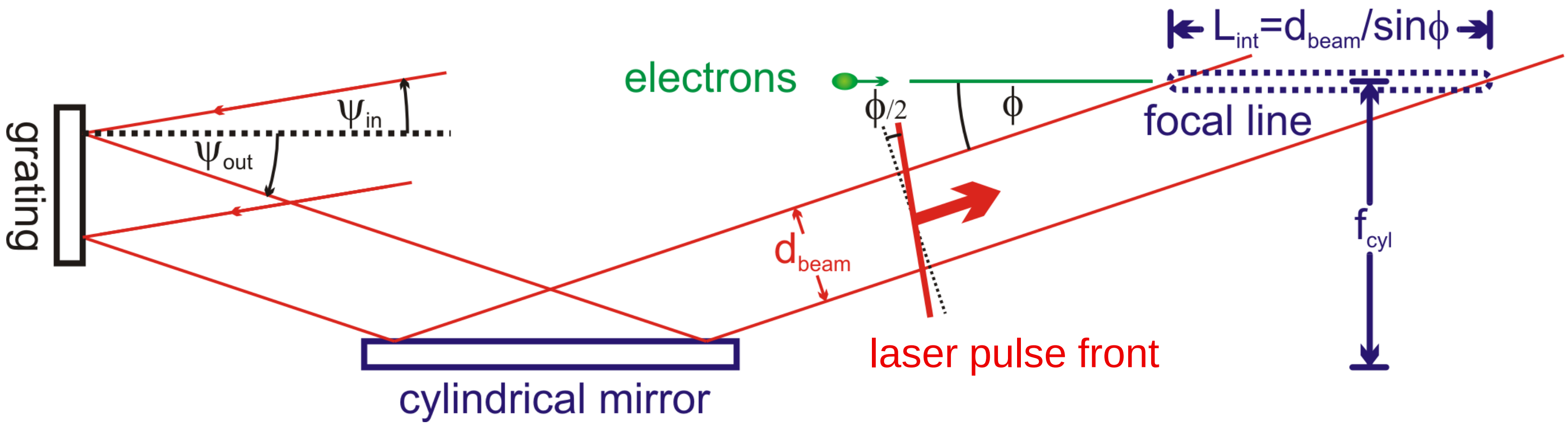
$$\omega_{sc} = 2\gamma_0^2 \omega_0 \cdot (1 - \beta_0 \cos\phi)$$

photon bandwidth

$$\Delta\omega_{sc}/\omega_{sc} \simeq \frac{\lambda_0}{(1-\beta_0\cos\phi)L_{int}} = \frac{\lambda_0}{d_{laser}\sin\phi\tan(\phi/2)}$$

L_{int} ... interaction length

For small interaction angles ϕ<10° angular dispersion becomes neglible, so standard gratings are fine!



λ_0=800nm, d_{beam}=10cm, ϕ=7° ➔ L_{int}= 82 cm and 3.5° pulse front tilt

Effective undulator period λ_{eff} = 0.1 mm

Using existing multi-100 TW lasers it is possible to create such line foci with a_0=0.01-0.1 .

Could this lead to a TWTS-FEL?

Could TWTS be an optical free-electron laser?

effective undulator wavelength & resonant wavelength

$$\lambda_u = \lambda_0/(1-\beta_0\cos\phi)$$

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}$$

Lasers provide short „undulator“ wavelengths, so XUV/X-Ray wavelengths can be achieved at moderate energies.

FEL parameter

$$\rho = \frac{1}{2\gamma}\left(\frac{I}{I_A}\left(\frac{\lambda_u a_0}{2\sqrt{2}\pi\sigma}\right)^2\right)^{1/3}$$

The resulting small γ allows for FEL operation with small undulator wavelengths λ_u and laser strengths a_0.

gain length

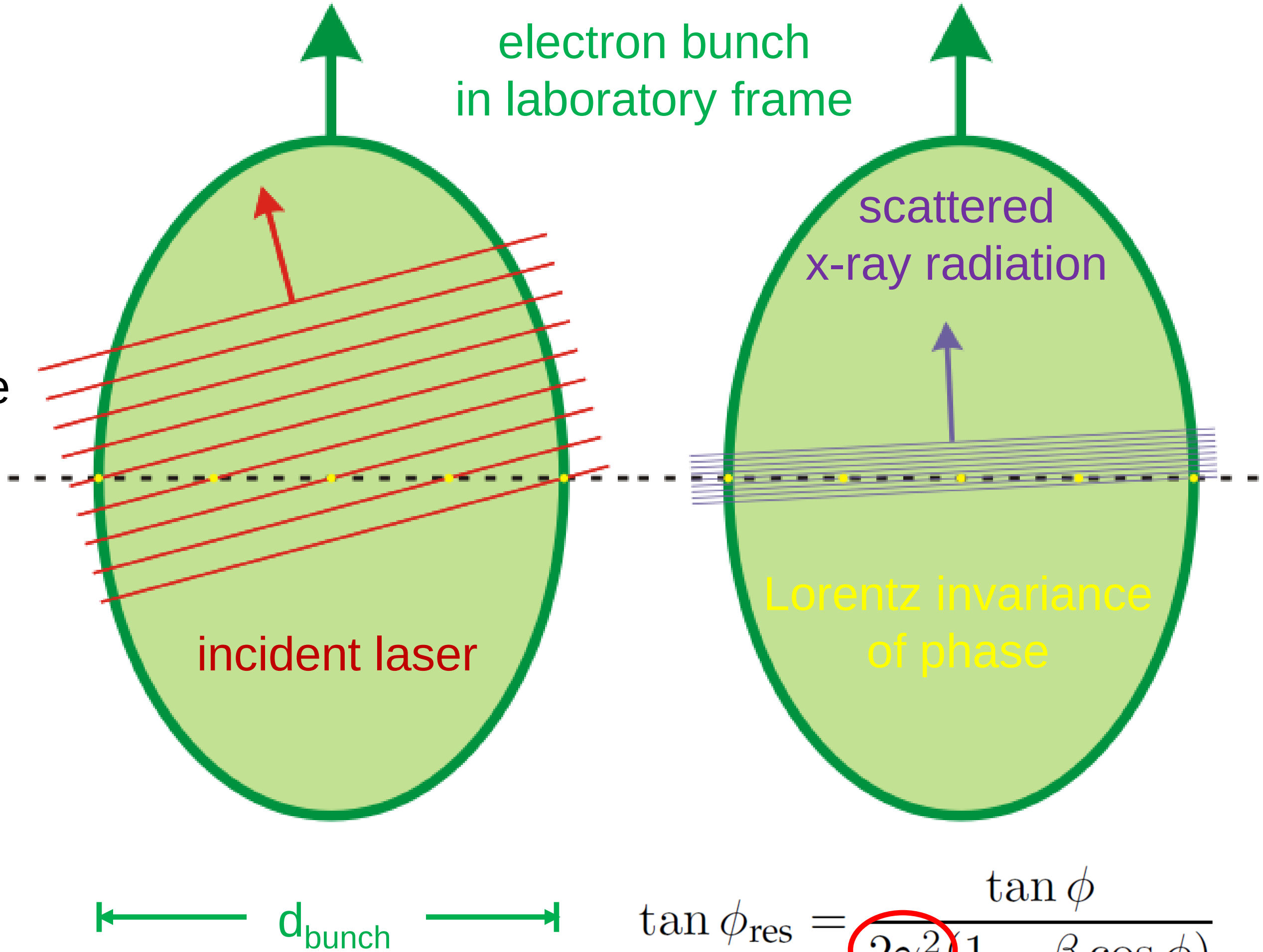
$$L_{\text{gain}} = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

λ_u in the sub-mm range and ρ from 10^{-4} to 10^{-3} lead to cm-scale gain lengths.

- Compact FEL - could fit into a laboratory.
- TWTS enables the interaction distances required to enter the FEL regime.
- No issues with field errors or wall wakefields.

What is the effect of side scattering in a TWTS-FEL?

- Each electron emits in propagation direction.
- Plane waves, when electrons emit coherently.
- For TWTS the plane wave propagates at an angle.
- Condition against radiation „leaking“ out of the interaction area



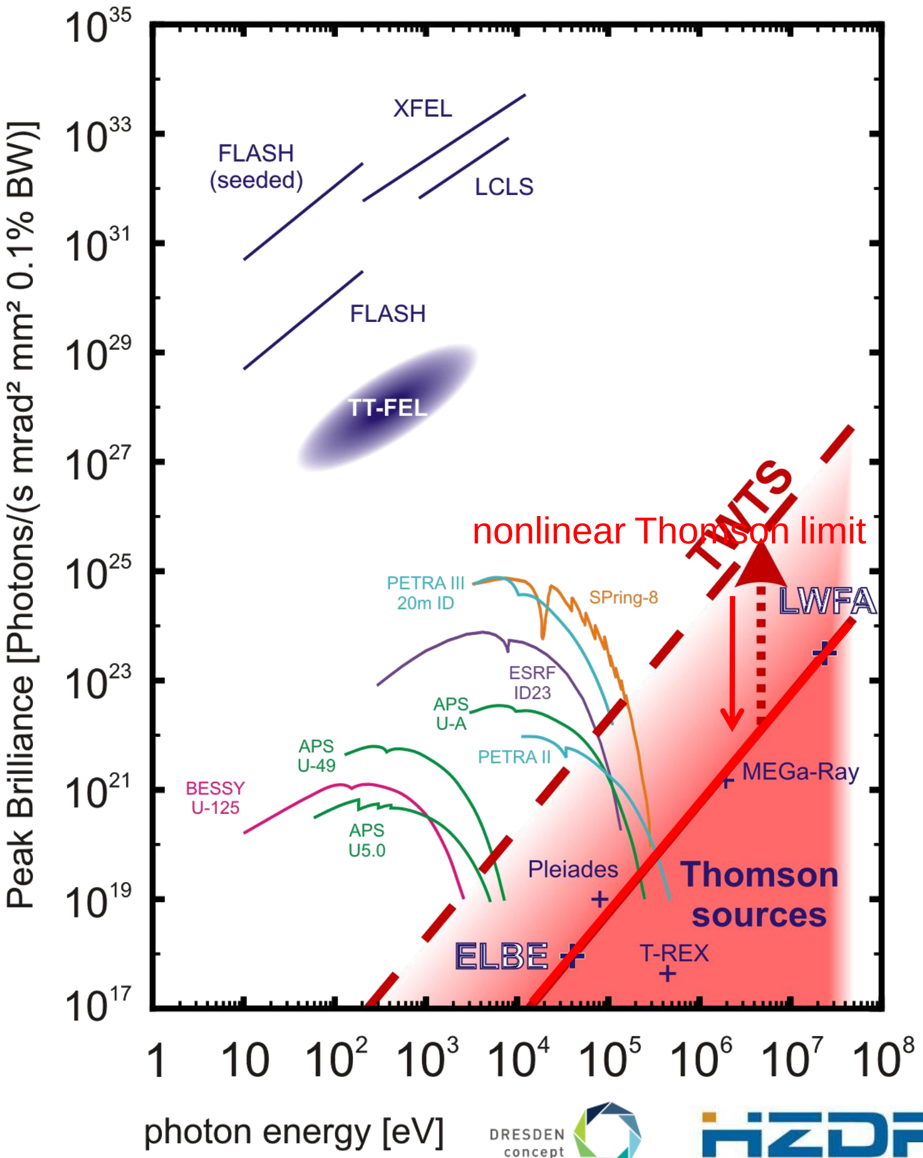
$$\tan\phi_{\mathrm{res}} \cdot L_{\mathrm{gain}} \ll d_{\mathrm{bunch}}$$

$$\tan\phi_{\mathrm{res}} = \frac{\tan\phi}{2\gamma^2(1-\beta\cos\phi)}$$

TWTS opens a path towards brilliant X-ray sources

- „Head-on“ Thomson sources are limited in peak brilliance by nonlinear Thomson scattering.
- TWTS sources can increase peak brilliances in the X-ray range by 2-3 orders of magnitudes.
- The brilliance limit using TWTS is purely technical.

  It arises from electron divergence, size of optics and available laser power.

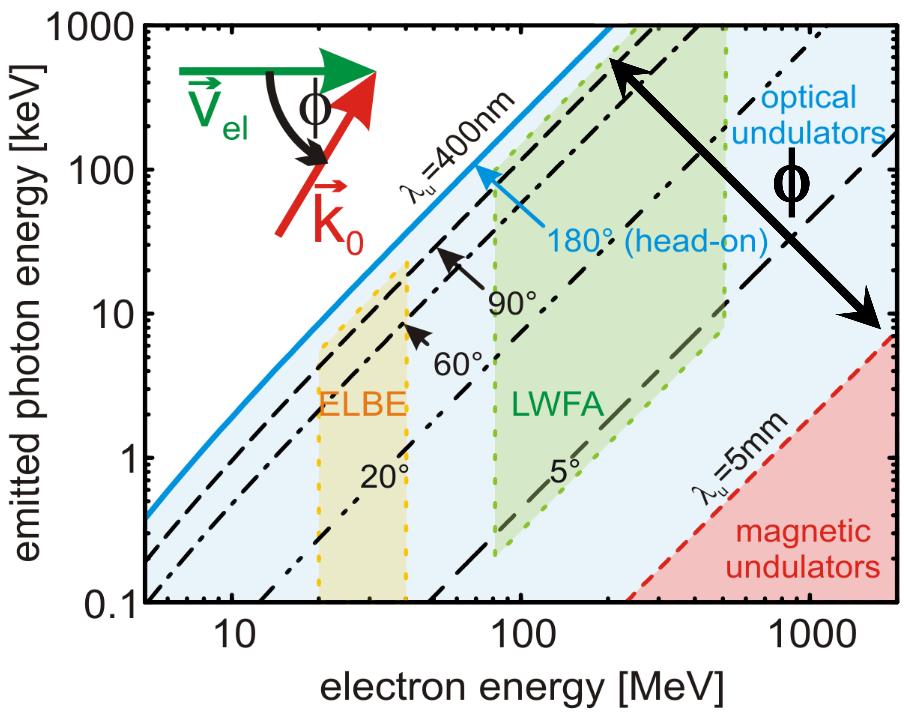


Conclusions

- Travelling-wave Thomson scattering circumvents the Rayleigh limit for both small interaction diameters and long interaction distances.
- Flexibility of interaction angle between laser and electron beams enables adjustments in the effective optical undulator periodicity without negatively impacting beam overlap.
- TWTS surpasses existing Thomson scattering designs by several orders of magnitude and could bring high-yield sources ($\sim 10^{10}$ photons/pulse) to the keV and MeV energy range.
- The scattering setup itself is quite general and is interesting for many other applications.

A.D. Debus, M. Bussmann, M. Siebold, A. Jochmann, U. Schramm, T.E. Cowan, and R. Sauerbrey
"Traveling-wave Thomson scattering and optical undulators for high-yield EUV and X-ray sources"
Applied Physics B **100**, 61-76 (2010)

TWTS provides control over scattered photon energy and bandwidth



photon energy

$$\omega_{sc} = 2\gamma_0^2 \omega_0 \cdot (1 - \beta_0 \cos\phi)$$

photon bandwidth

$$\Delta\omega_{sc}/\omega_{sc} \simeq \frac{\lambda_0}{(1-\beta_0\cos\phi)L_{int}} = \frac{\lambda_0}{d_{laser}\sin\phi\tan(\phi/2)}$$

L_{int} ... interaction length

The Rayleigh-Sommerfeld diffraction integral yields a wave optical description of the laser pulse behind a VLS grating

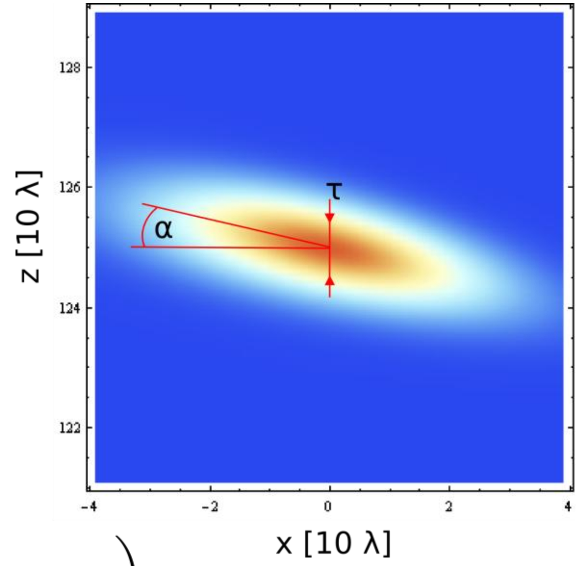
$$E_{\rm out}(x,y,z,t)|_{\xi_k>0} = \sum_{k=1}^{l} i\frac{{\rm e}^{-i\frac{1}{4}\pi}}{\sqrt{2\pi}}\frac{d_0}{\sqrt{c}}\times$$

$$\times \frac{{\rm e}^{-\frac{(\xi_k\cos\psi_{\rm in})^2}{w_0'^2}}}{\sqrt{\Omega_0\tau'^2+\frac{4SD}{w_0^2}\xi_k\cos\psi_{\rm in}}}{\rm e}^{i\frac{\Omega_0^2}{c}AD\xi_k\cos\psi_{\rm in}}\times$$

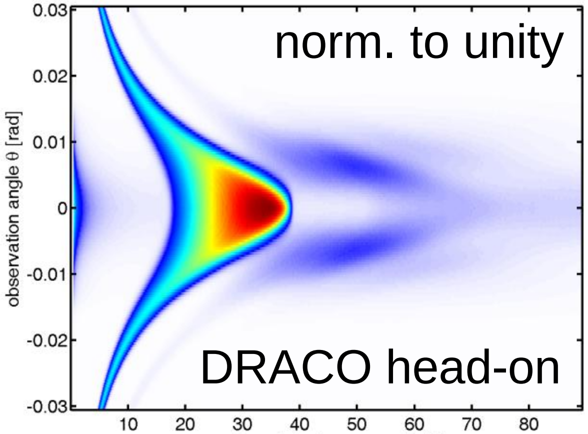
$$\times\sqrt{\frac{w_{y,0}}{w_y(z-z_{\rm F})}}{\rm e}^{i\zeta_y(z-z_{\rm F})/2}{\rm e}^{-\frac{y^2}{w_y(z-z_{\rm F})^2}}\times$$

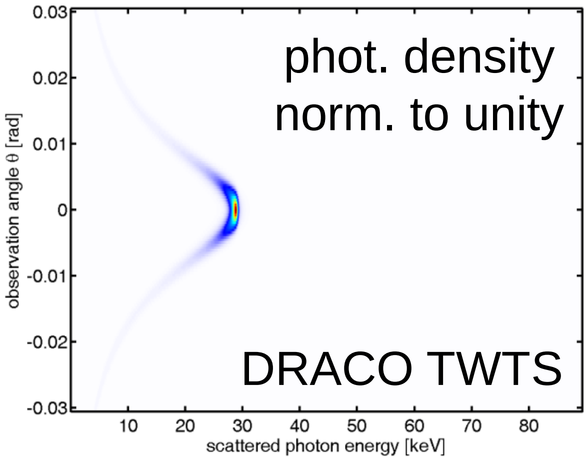
$$\times\, z\cdot{\rm e}^{-\frac{G_k^2}{\tau'^2}}\frac{{\rm e}^{-i\left(\Omega_0\tau'^2+\frac{4SD}{w_0^2}\xi_k\cos\psi_{\rm in}\right)\frac{G_k}{\tau'^2}}}{(z^2+(x-\xi_k)^2)^{3/4}}\left(\Omega_0\tau'^2+\frac{4SD}{w_0^2}\xi_k\cos\psi_{\rm in}-iG_k\right)$$

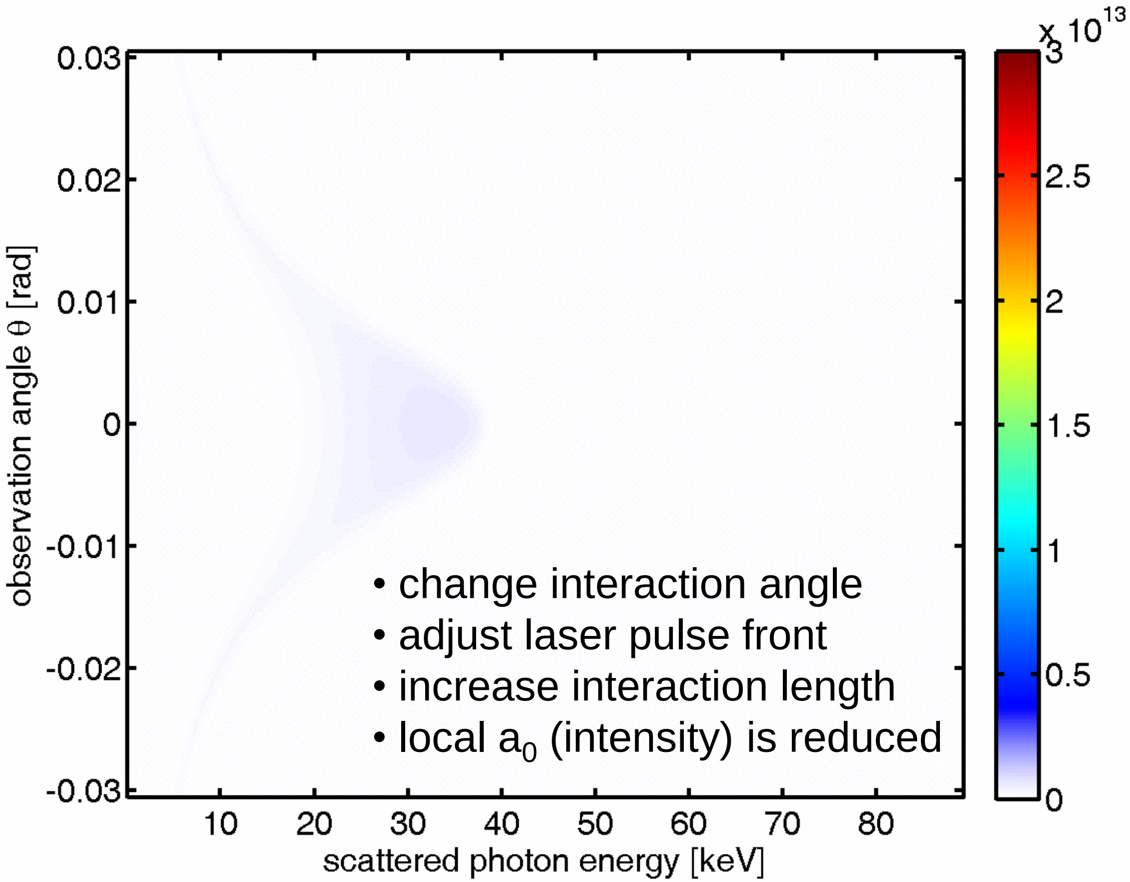
$$G_k = G_k(x,z,y,t) = \frac{1}{c}\left\{\left[z^2+(x-\xi_k)^2\right]^{1/2}-\xi_k\sin\psi_{\rm in}+z_0 + \frac{y^2}{2R_y(z-z_{\rm F})}+\Omega_0AD\xi_k\cos\psi_{\rm in}-ct\right\}$$



TWTS puts all photons into a single harmonic







- change interaction angle
- adjust laser pulse front
- increase interaction length
- local a_0 (intensity) is reduced

Laser driven SASE-FEL using ELBE electrons

	FLASH	TWTS
FEL wavelength [nm]	13.0	13.0
peak current [kA]	2.5	10.0
bunch duration [fs]	393	100
a_0	1.2	0.02
electron energy [MeV]	1000	40
und. period [mm]	27.3	0.16
gain length [m]	2.55	0.074
interaction length [m]	27	0.8
FEL parameter	9.8×10^{-4}	2.0×10^{-4}
peak power [MW]	2.5×10^{3}	80

Scalings according to 1D-theory

→ 8.7×10^{14} W/cm² in a focal line of 80 cm

A free-electron laser made more compact !

yield: $5.2 \cdot 10^{11}$ photons

TWTS parameters: λ_0=800 nm ; P_{laser}=84 TW ; d_{beam}=120µm (FWHM) ; τ_{laser}=100fs ; ϕ=5.69°

Scaling Laws

- Interaction angle
- radiated photon energy
- Tilted pulse front
- Interaction length defines minimum attainable bandwidth
- Pulse duration determined by electron bunch

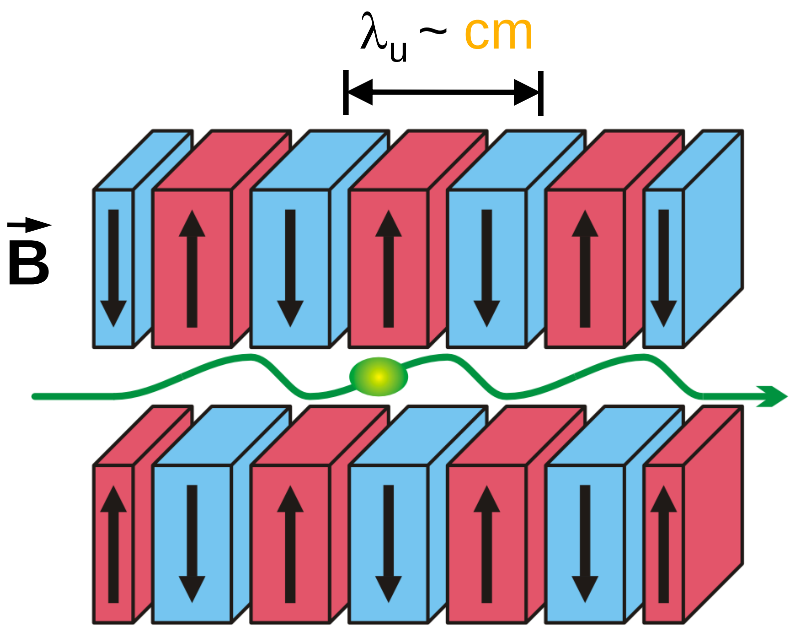
- FEL resonance for sidescattering

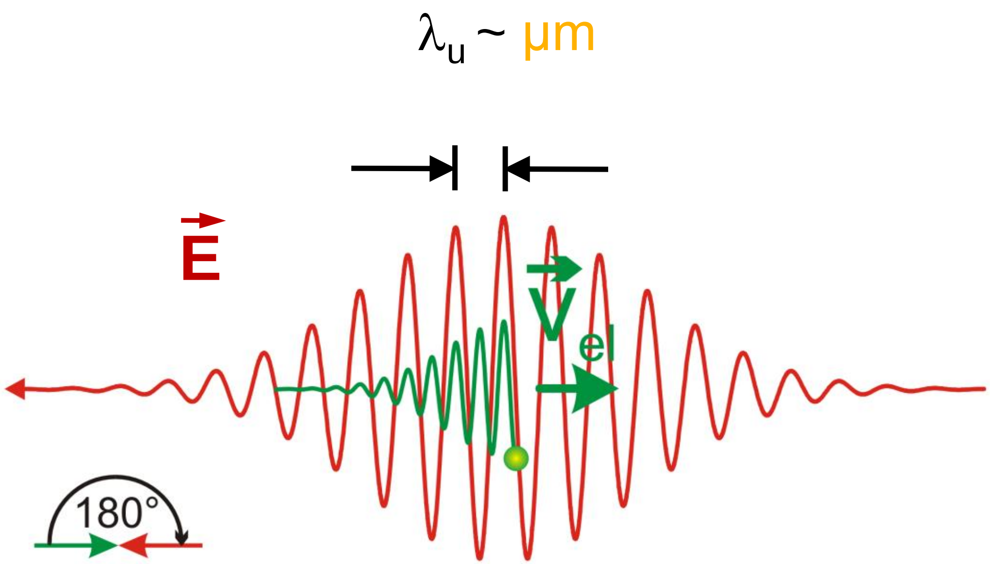
$$\lambda_r = \frac{\lambda_0}{2\gamma^2 \cdot (1 - \beta \cos \phi)} \cdot \left(1 + \frac{1}{\gamma^2 \phi^2}\right)$$

- Lasers need to fulfill to intensity conditions

$$\frac{1}{1 + a_0^2/2}(a_0 \cdot \delta a + \delta a^2/2) \ll 2\rho$$

Magnetic undulators and optical undulators are (almost) the same





undulator parameter K ⟺ laser strength parameter a_0

$$K = 0.93\lambda_u[\mathrm{cm}]B_0[\mathrm{T}]$$

$$a_0 = 0.85 \cdot 10^{-9}\lambda_0[\mu\mathrm{m}]I_0^{1/2}[\mathrm{W/cm^2}]$$

$I_0 \sim 10^{20}$ W / cm²

How do the Varied-line spacing (VLS) gratings look like?

- Requirements along the line of interaction
  1.) Group delay dispersion (GDD) vanishes
  2.) Spatial dispersion (SD) vanishes
  3.) Pulse front tilt (PFT) does not bend

- Optical setup modeled in a Raytracing framework relative to a central ray using position, angle, frequency and time delay coordinates.

- Standard gratings
  ➔ Kostenbauder matrix formalism (cite it)

- VLS gratings
  ➔ nonlinear formalism required
  ➔ extended Kostenbauder to higher orders using operators instead of matrices
  ➔ Rather technical and „messy".

See paper for details.

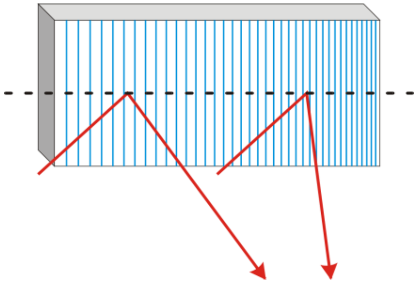
Result:

quadratic line-spacing function introduces linear variation of angular dispersion (AD)

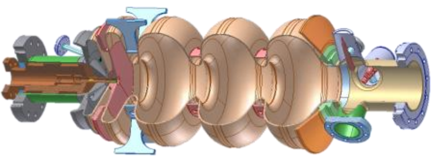
$$d(s) = d_0 + b_g \lambda_0 s^2$$

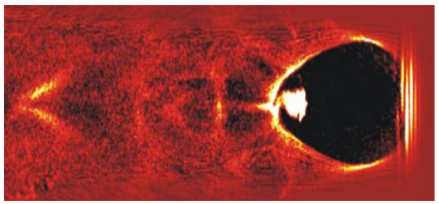
$$b_g = -\frac{\cos\psi_{\mathrm{out}} \cdot (\tan(\pi/2 - \phi) + \tan\phi/2)}{2L_0^2 \tan^2\phi/2}$$

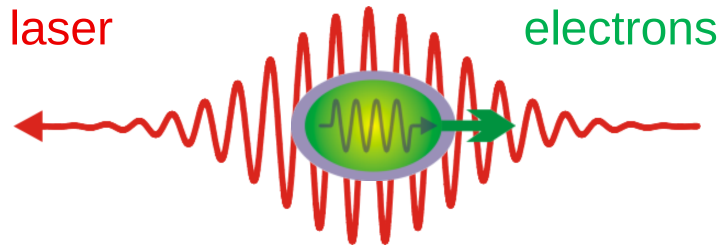
$$\mathrm{AD}(x) = \mathrm{AD}_0 + \mathrm{SD}_0 C_1 \cdot x$$

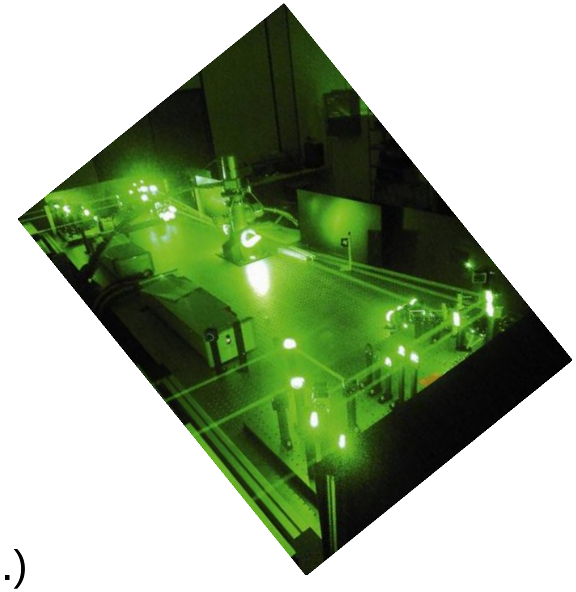


DRESDEN concept HZDR









- Thomson Scattering Facilities (T-REX, NewSUBARU, COBALD, ...)

photon energy	~ 10 keV – 10 MeV	pulse duration	~ 100fs – 10ps
photon yield	~ 10^5 - 10^6 photons / pulse	spectral width	~ 10^{-2}

Most Thomson sources worldwide aim for high repetition rates
to maximize average photon flux.

Laser-wakefield accelerated electrons are ultrashort <10 fs
and have small emittances below $\varepsilon_{n,rms}$=1.0 π mm mrad.

Head-on Thomson Scattering produces ultrashort X-ray pulses