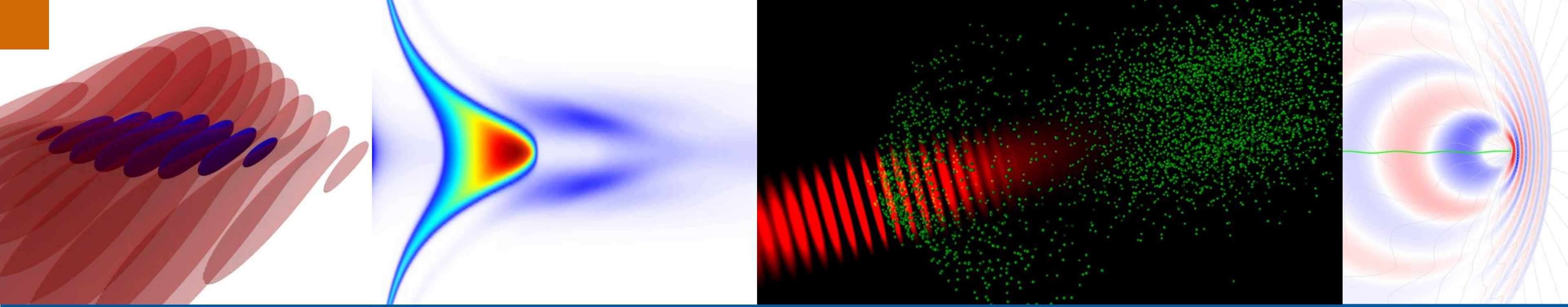
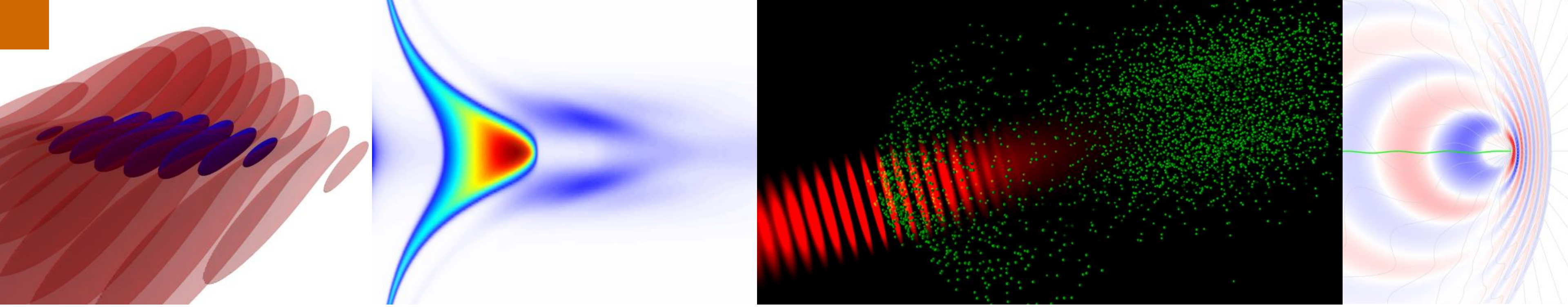


Ultra-compact all-optical FELs and Compton sources

Alexander Debus

Institute for Radiation Physics
Helmholtz - Zentrum Dresden – Rossendorf (HZDR)

EAAC, La Biodola, Isola d'Elba
September 13-19th, 2015



Optical free-electron lasers (OFELs)

- EUV to X-rays : **100eV - 10 keV**
- **Coherent** light source
- $10^{10} – 10^{12}$ photons per pulse at sub-% bandwidth
- Vision of a **compact (X-ray) FEL**, **no experimental realization yet**.

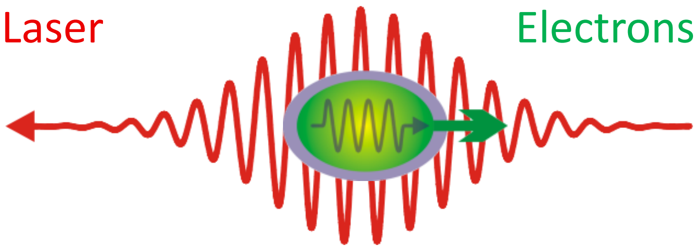
Compton sources

- Potentially most brilliant source at hard X-rays : **keV - MeV**
- **Incoherent** source
- Narrow bandwidth @ %-level, or broad bandwidth, tunable in wavelength
- **Experimental realizations** (linacs and LWFA) are available, but **more photons per shot desired.**

DRESDEN concept HZDR

Optical Free Electron Lasers

Optical free-electron laser (OFELs) – shorter FEL wavelengths while using less electron energy on table-top?

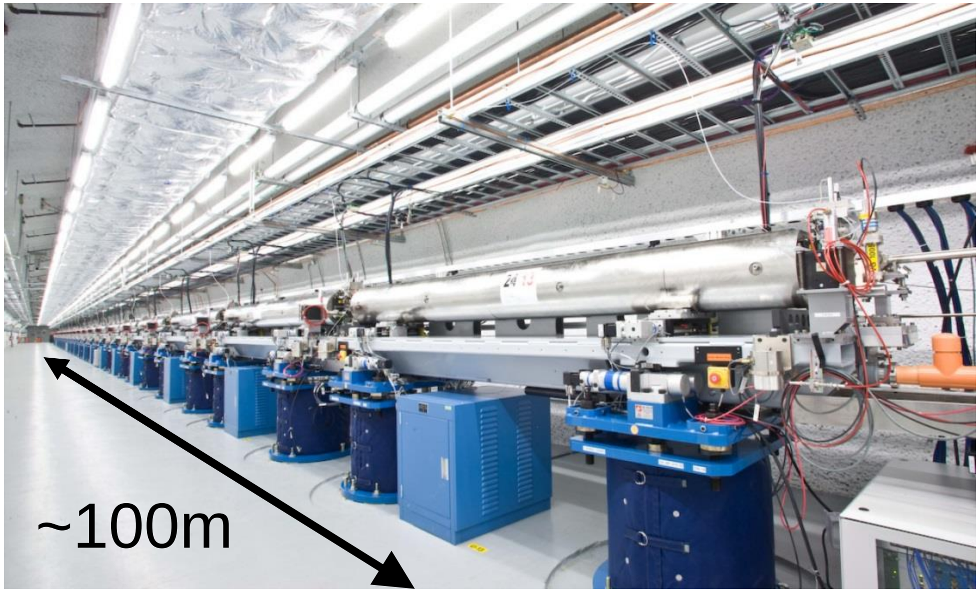


Even if GeV-scale LWFA accelerators are table-top, X-ray FEL undulators usually are not !

- **Optical undulators** provide µm-scale undulator lengths at high fields.

$$\lambda_{FEL} = \frac{\lambda_{laser}(1 + a^2/2)}{2\gamma^2}$$

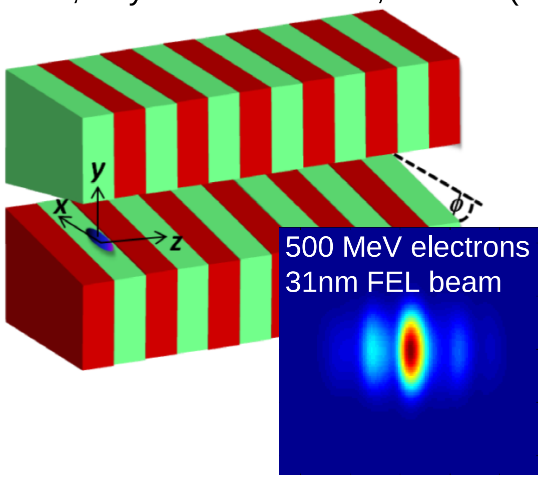
- **Optical free-electron lasers** additionally drive an electron beam instability and thus have to meet very different requirements.



The 0.1nm FEL at SLAC (http://lcls.slac.stanford.edu)

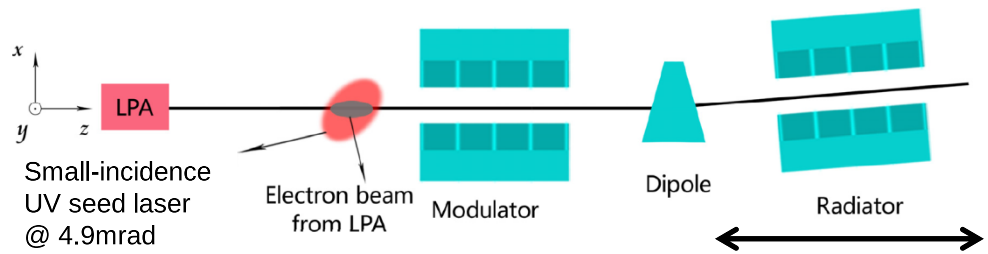
Laser-plasma driven free-electron lasers using magnetic undulators can be compact at EUV to soft x-rays.

SASE FEL using transverse-gradient undulators
Huang *et. al.*, Phys. Rev. Lett. **109**, 204801 (2012)



← undulator length 5m →

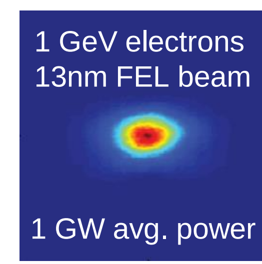
Coherent harmonic generation
Chao Feng et. al., Opt. Express **23**, 14993-15002 (June 2015)



seed laser (260nm, 5GW, 30fs)

radiator length 1.5m

- Introduce **angular modulation** onto LPA beam and transform to **density modulation**
- Not sensitive to energy spread
- Good transverse coherence

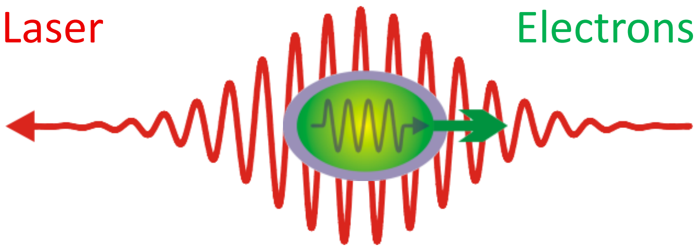


When scaling to sub-nm wavelengths magnetic undulators cease to be compact!

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

$$\rho \propto \gamma^{-1} \lambda_u^{2/3}$$

Optical free-electron laser (OFELs) – shorter FEL wavelengths while using less electron energy on table-top?



- Optical lasers provide µm-scale undulator lengths at high fields.
- However, yields of existing Compton sources

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

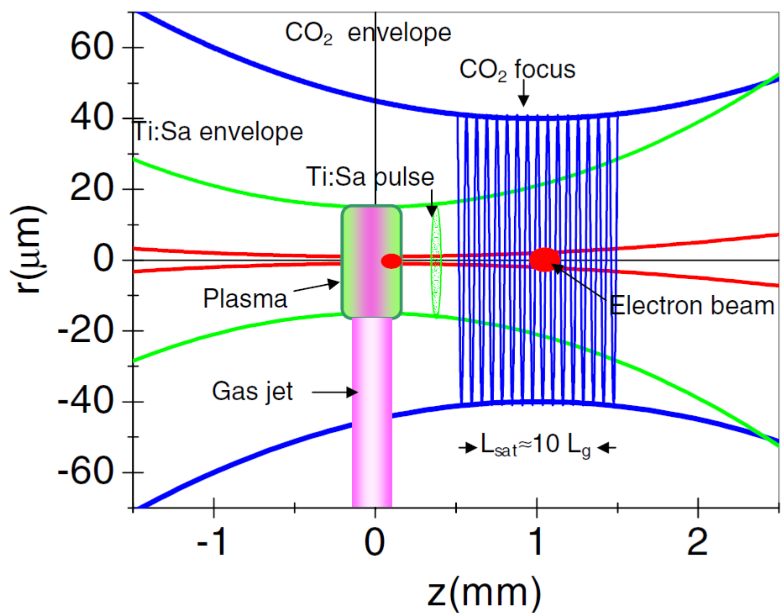
indicate difficulties in realization.

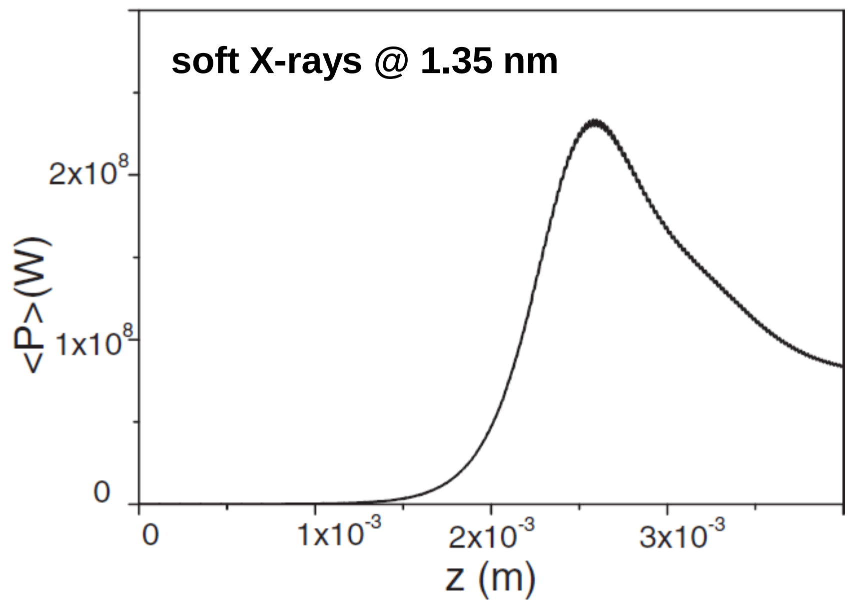
Challenges for OFELs

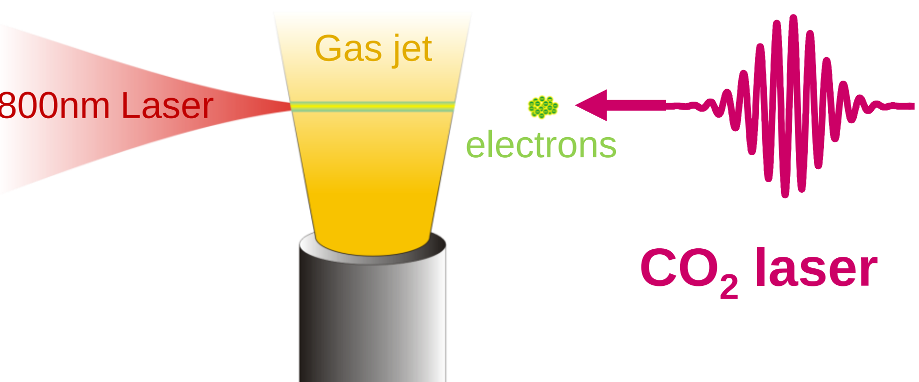
- **Interaction distances needs to be long**
  Else the FEL instability cannot develop.
- **High energy efficiency**
  Else too much (laser) energy required.
- **Avoid ultra-high intensities a_0>>1**
  Else impractical for real-world lasers.
- **One needs**: An optical undulator, which is both long and narrow.

Early „head-on“ OFEL designs show undulator wavelengths beyond optical wavelengths

Petrillo *et. al.*, PRSTAB **11**, 070703 (2008)







undulator laser

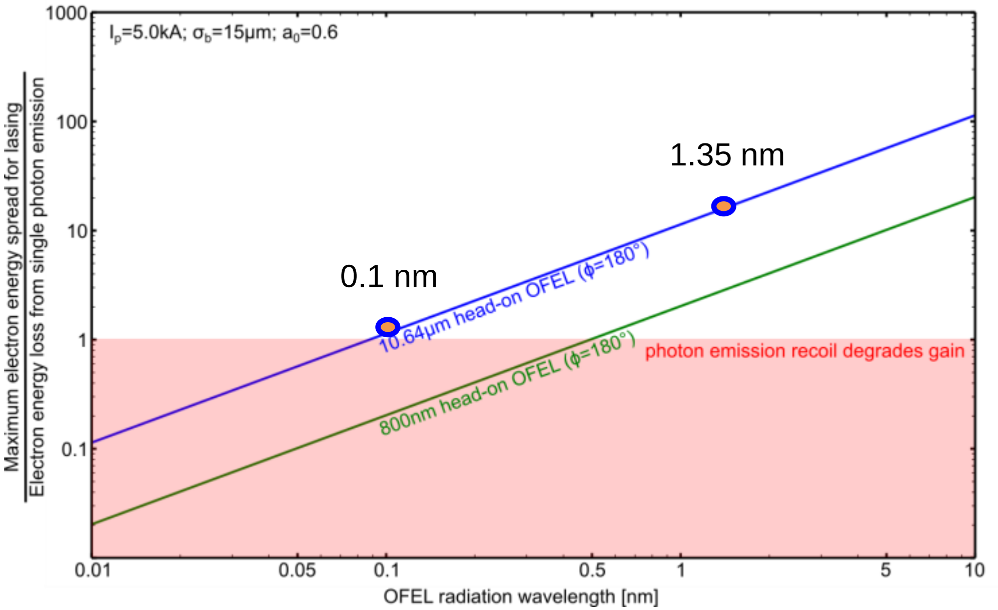
CO_2 laser, λ=10µm, ~18.7ps, ~17J, 40µm spot size, a_0=0.8

electrons

28 MeV ; >20 kA LWFA bunch ; 0.4% energy spread

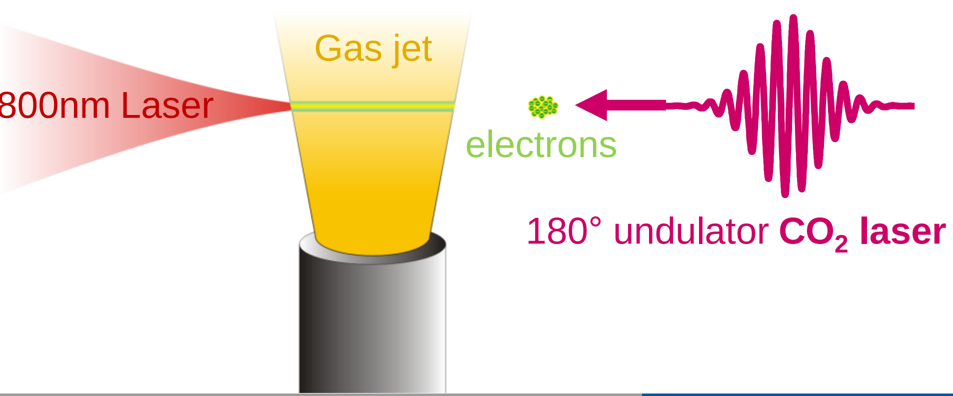
~10fs duration ; <0.3 mm mrad transverse emittance slices

„Head-on“ OFELs do not scale to the hard X-ray range



- High-power, flattop CO_2 laser on ps-scale at <1.2% field stability is challenging.
- High photon emission recoil instantly kicks electrons out of FEL resonance.

➢ **Going to sub-nm X-rays not possible for „head-on“ designs.**



Petrillo *et. al.*, PRSTAB **11**, 070703 (2008)

240 MW soft X-rays @ 1.35 nm

undulator laser

CO_2 laser, λ=10μm, ~18.7ps, ~17J, 40μm spot size, a_0=0.8

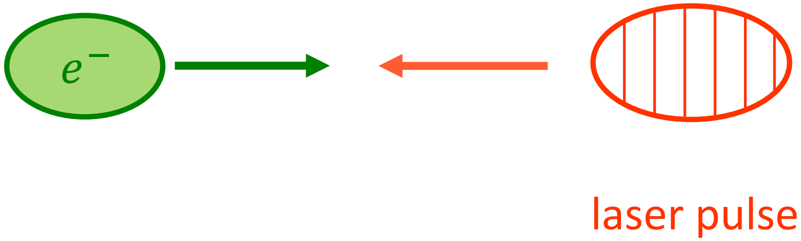
electrons

28 MeV ; >20 kA LWFA bunch ; 0.4% energy spread

~10fs duration ; <0.3 mm mrad transverse emittance slices

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

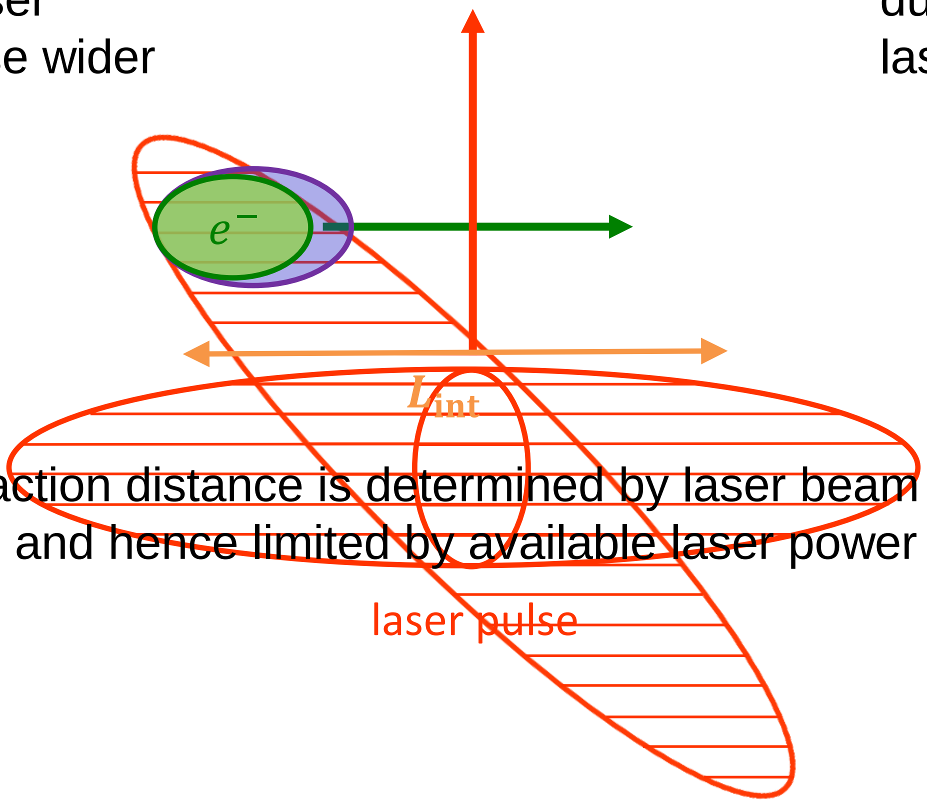


Traveling-**W**ave **T**homson-**S**cattering (TWTS) in a nutshell

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

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

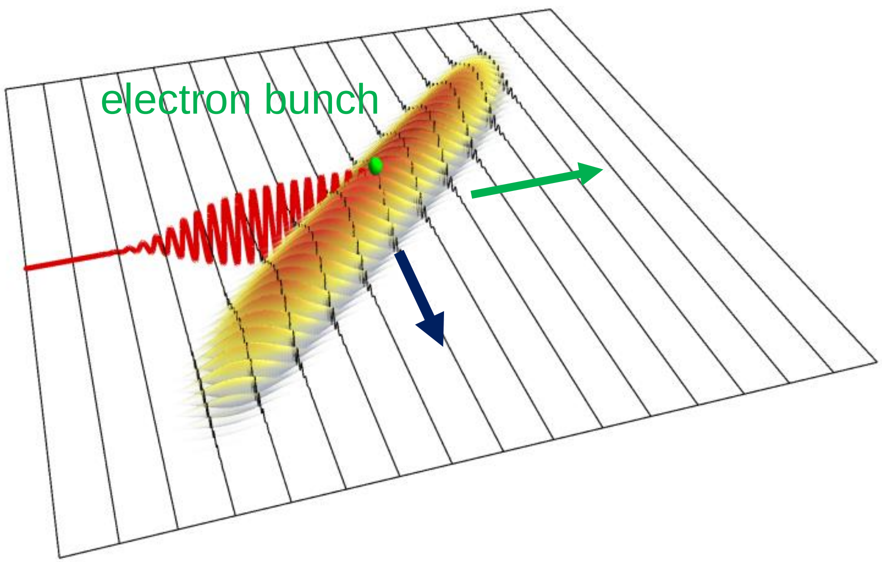
2) Increase interaction duration by tilting the laser pulse front

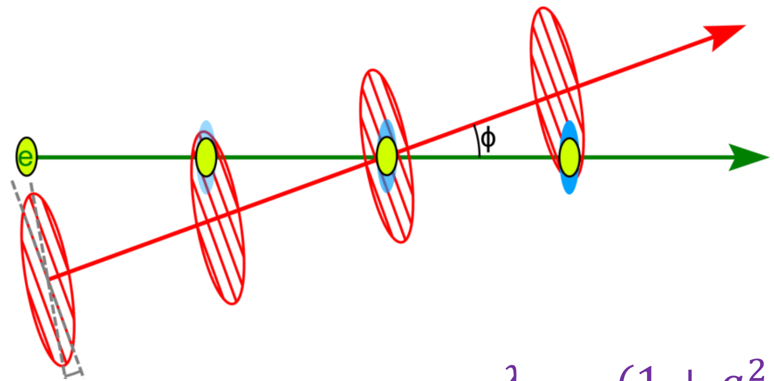


Interaction distance is determined by laser beam width and hence limited by available laser power

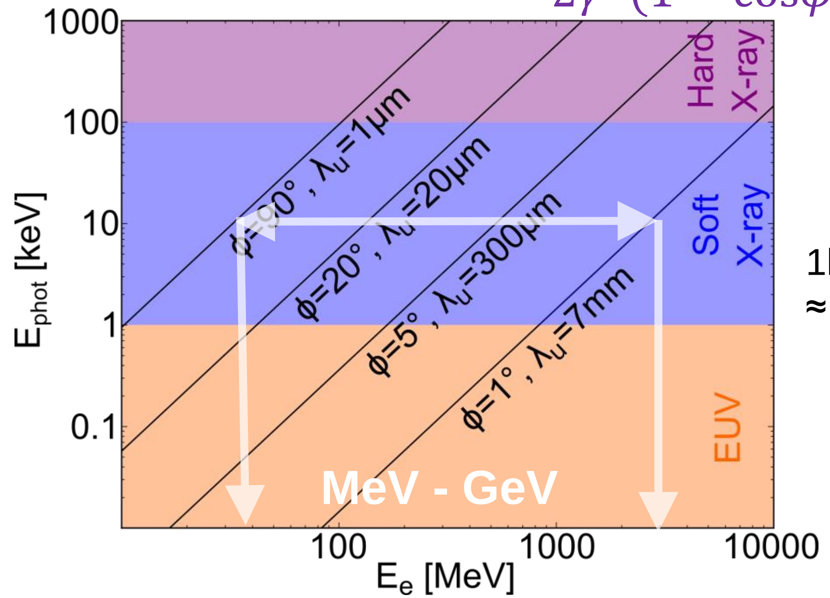
The undulator wavelength of a TWTS OFEL is scalable

Pulse front tilt of half the interaction angle ensures continuous overlap independent of interaction angle.





$$\alpha_{tilt} = \phi/2 \qquad \lambda_{FEL} = \frac{\lambda_{laser}(1 + a^2/2)}{2\gamma^2(1 - \cos\phi)}$$



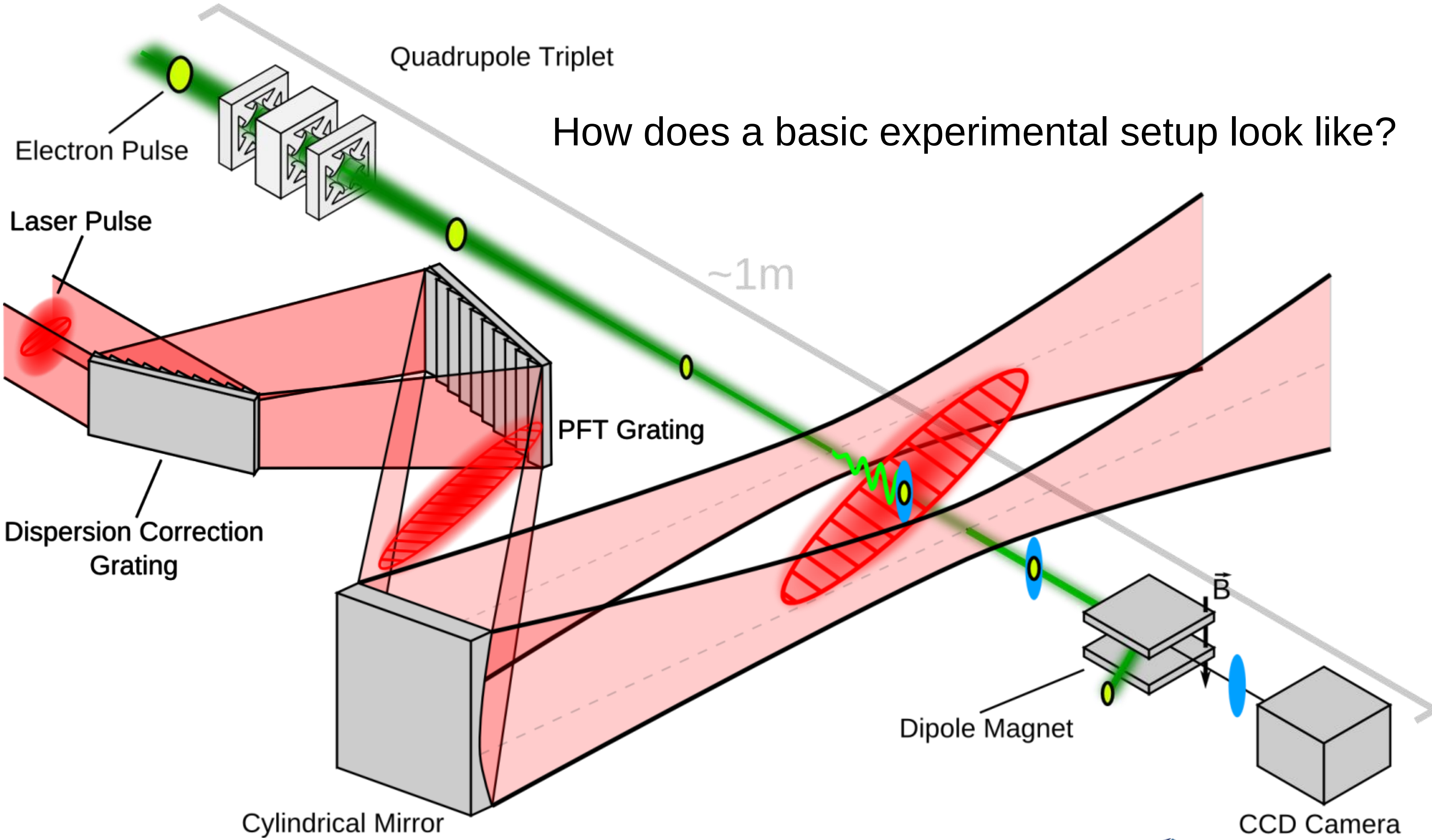
1keV ≈1nm

Note

The number of laser periods seens by an electron exceeds the periods of the laser pulse duration.

Traveling Wave-Thomson Scattering OFEL in experiment

How does a basic experimental setup look like?

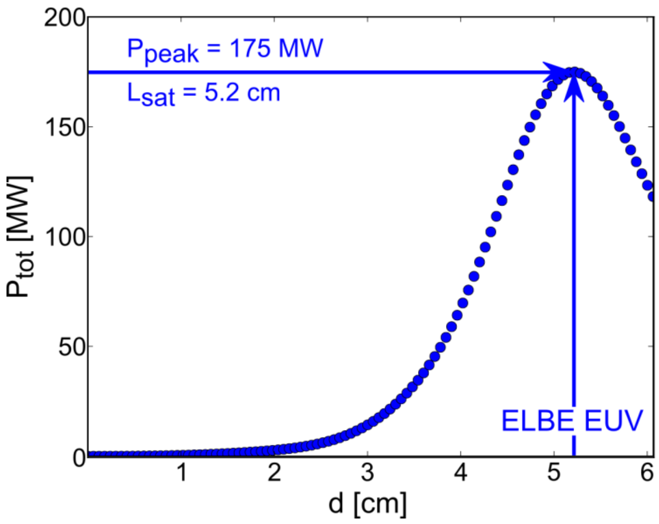


Steiniger, Debus *et. al*., J. Phys. B **47** (2014) 234011

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.

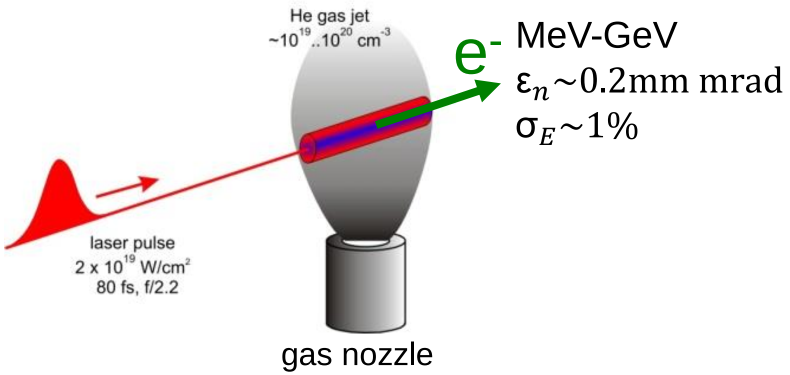
Design 2

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

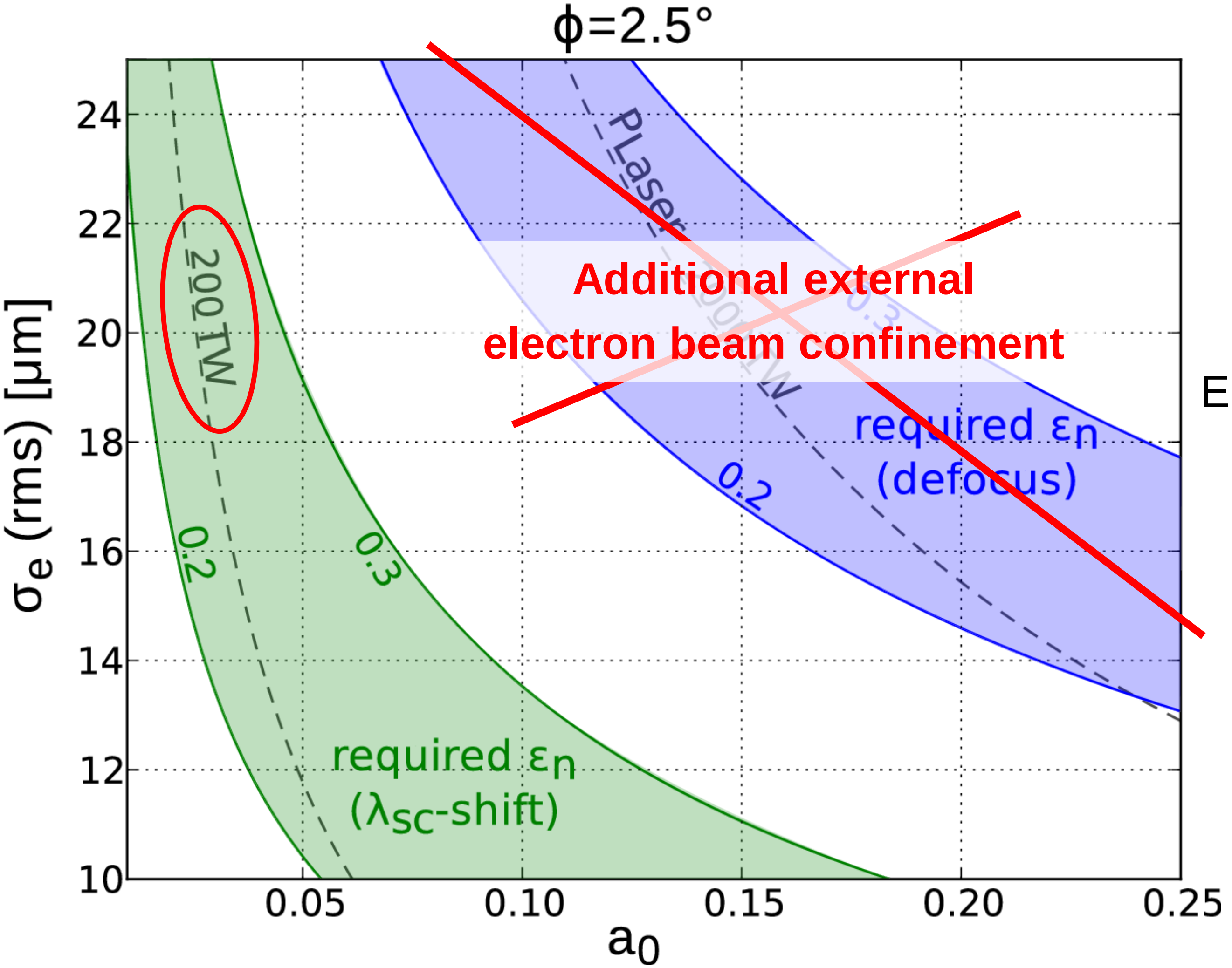
Use ultra-low emittance of LWFA electrons for tight focusing to 5μm (rms).

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



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

Electron beam trapping could drastically reduce laser power requirements

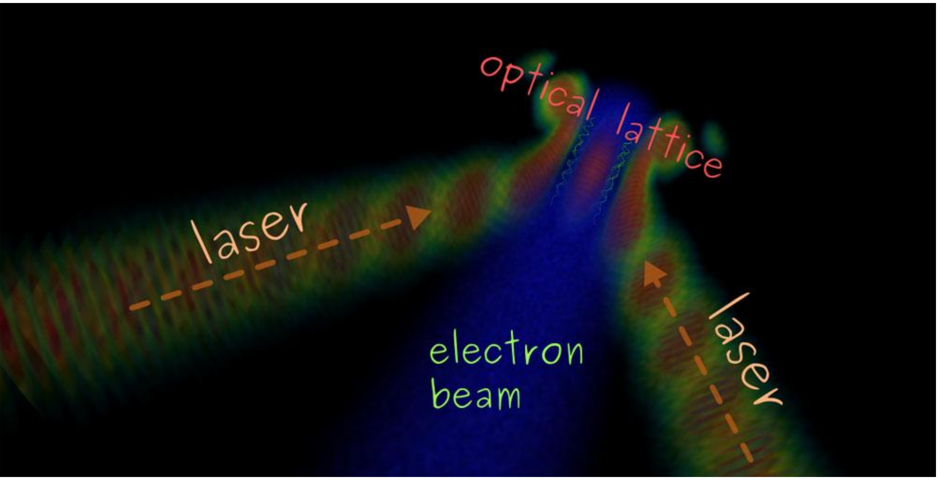


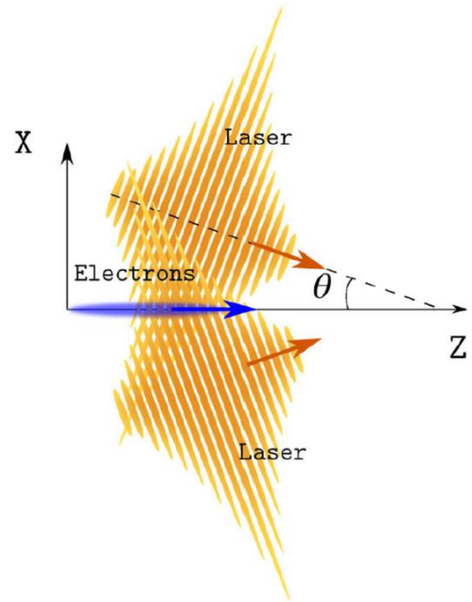
ε_n for FEL instability

ε_n for maintaining focus

Emittance and laser power landscape for an 0.15nm X-ray OFEL

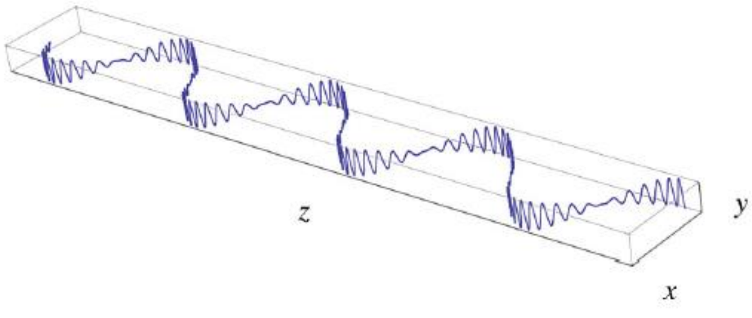
Optical lattices provide electron beam trapping





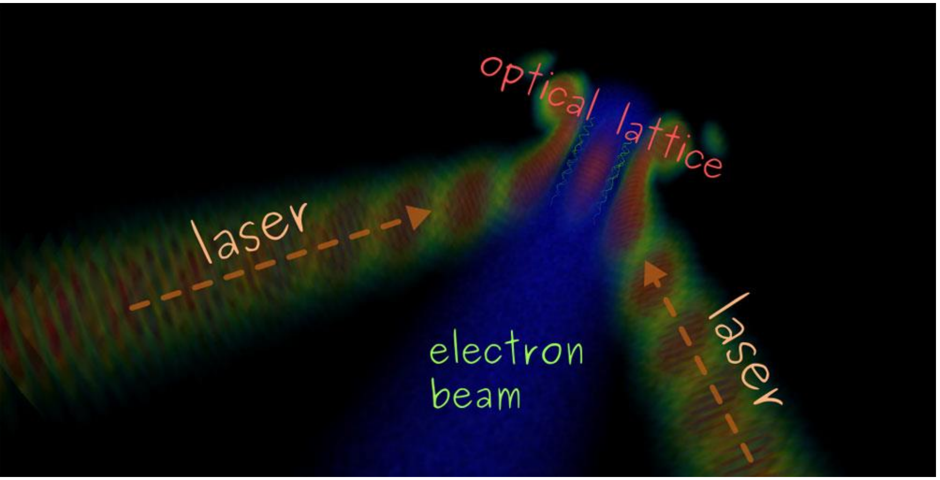
- Two counter propagating TWTS laser beams provide an optical lattice.
- Electrons experience
  - fast laser oscillation
  - slow ponderomotive oscillation in the optical lattice potential

Elliptical trajectory alters FEL dynamics

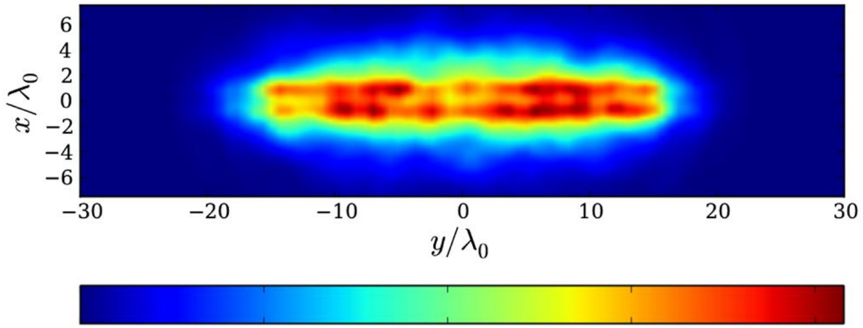


Andriyash *et. al.*, PRSTAB **18**, 050704 (2015)

Optical lattices provide electron beam trapping



seeded FEL, transverse mode



laser

800nm; $2\cdot10^{16}$ W/cm² (a_0=0.1); ~300mJ

θ=10° → λ_u=52µm

electron beam

40 MeV; 100pC; 10fs; 1µm diameter
1mrad (x) and 0.36mrad (y) divergence

x-ray beam

4.4nm; 200MW; 2cm saturation length; $\rho=4.4\cdot10^{-3}$

- Electron beam trapping in one dimension

Andriyash *et. al.*, PRSTAB **18**, 050704 (2015)

Andriyash *et. al.*, PRSTAB **16**, 100703 (2013)

Andriyash *et. al.*, PRL **109**, 244802 (2012)

Compton sources

RF accelerator-driven Compton source

PHOENIX source @ HZDR

Fresh results from last week

See **Axel Jochmann**'s talk on the **PHOENIX source** at WG4 – **today 17:00**

measured spectrum photondensity over energy & observation angle in log. scale

Removed unpublished data in Web-version.

ELBE RF accelerator (thermionic gun)
23.5 MeV ; 3ps; 80pC ; 0.4% energy spread
norm. transverse emittance   11 mm mrad

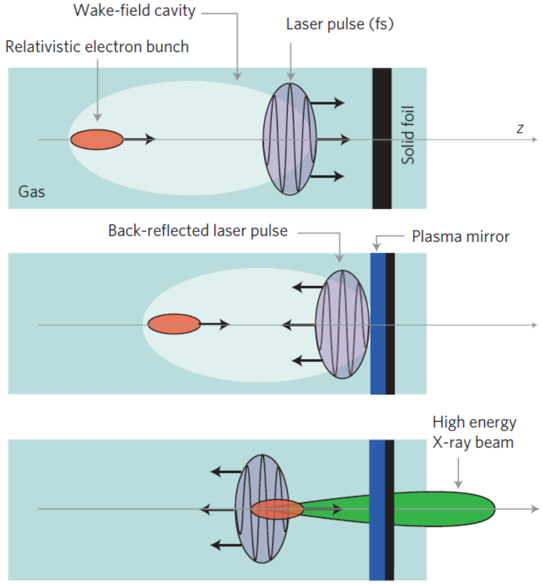
X-ray beam
$5.5 \cdot 10^5$ photons/shot   total yield
30% BW @ 11.7 keV

scattering DRACO laser
2J ; 27fs ; a_0=1.5 ; 35µm spot size

Peak brilliance
$1.5 \cdot 10^{17}$ s^{-1} mm^{-2} $mrad^{-2}$ [0.1% BW]

State-of-the-art LWFA Compton sources provide either **broadband high photon yield** or **low-bandwidth**

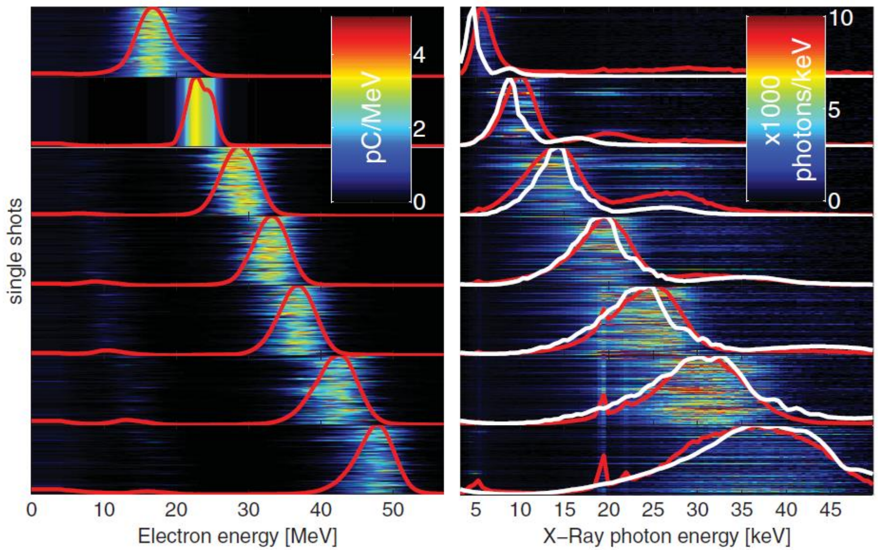
Ta Phuoc *et. al.*, PRL **114**, 195003 (2015)



tight overlap, but high intensity; a_0~1.5
17µm laser spot size

Broadband Compton spectra

K. Khrennikov *et. al.*, PRL **113**, 224801 (2014)

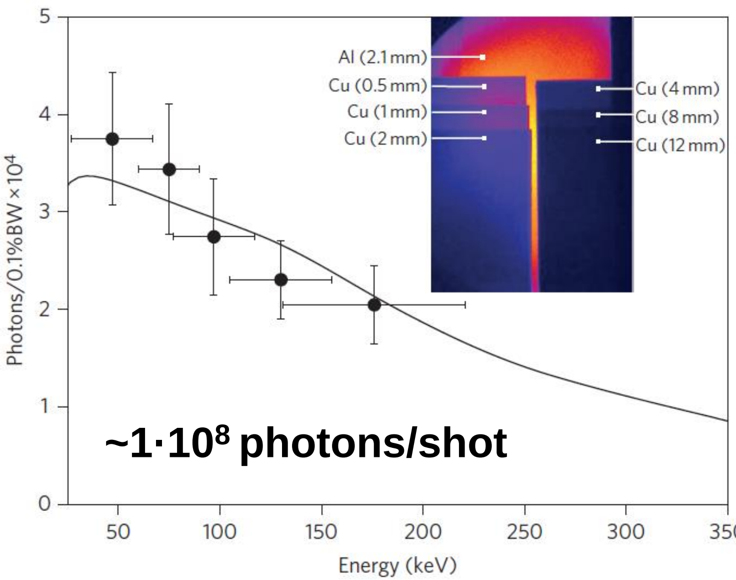


25µm laser spot size
max. ~40000 photons detectable

Tunable narrowband Compton spectra

State-of-the-art LWFA Compton sources provide either **broadband high photon yield** or **low-bandwidth**

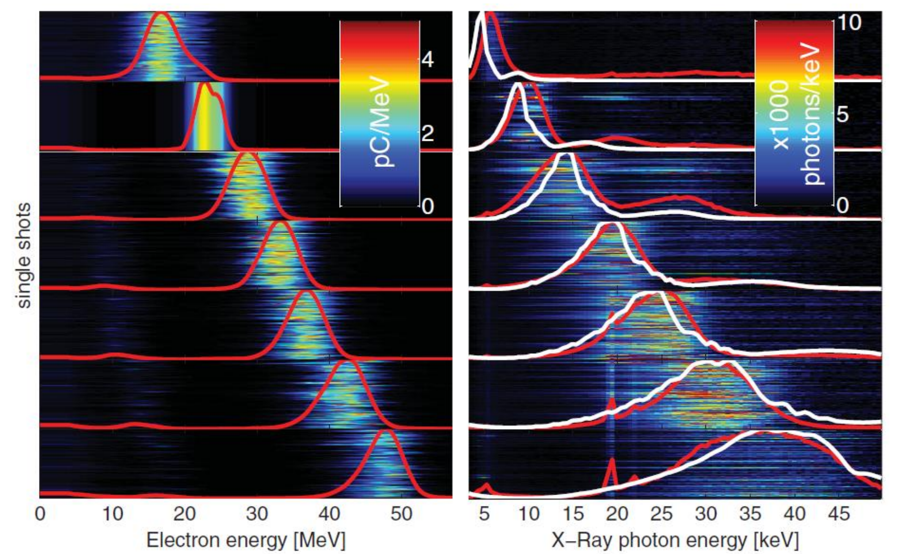
Ta Phuoc *et. al.*, PRL **114**, 195003 (2015)



scattering laser
Ti:Sa, 1J, 35 fs, a_0=1.5

peak brilliance
$1{\cdot}10^{21}$ s^{-1} mm^{-2} $mrad^{-2}$ [0.1% BW]

K. Khrennikov *et. al.*, PRL **113**, 224801 (2014)



scattering laser
Ti:Sa, 300mJ, 28 fs, a_0=0.9

peak brilliance
$0.2..15{\cdot}10^{18}$ s^{-1} mm^{-2} $mrad^{-2}$ [0.1% BW]

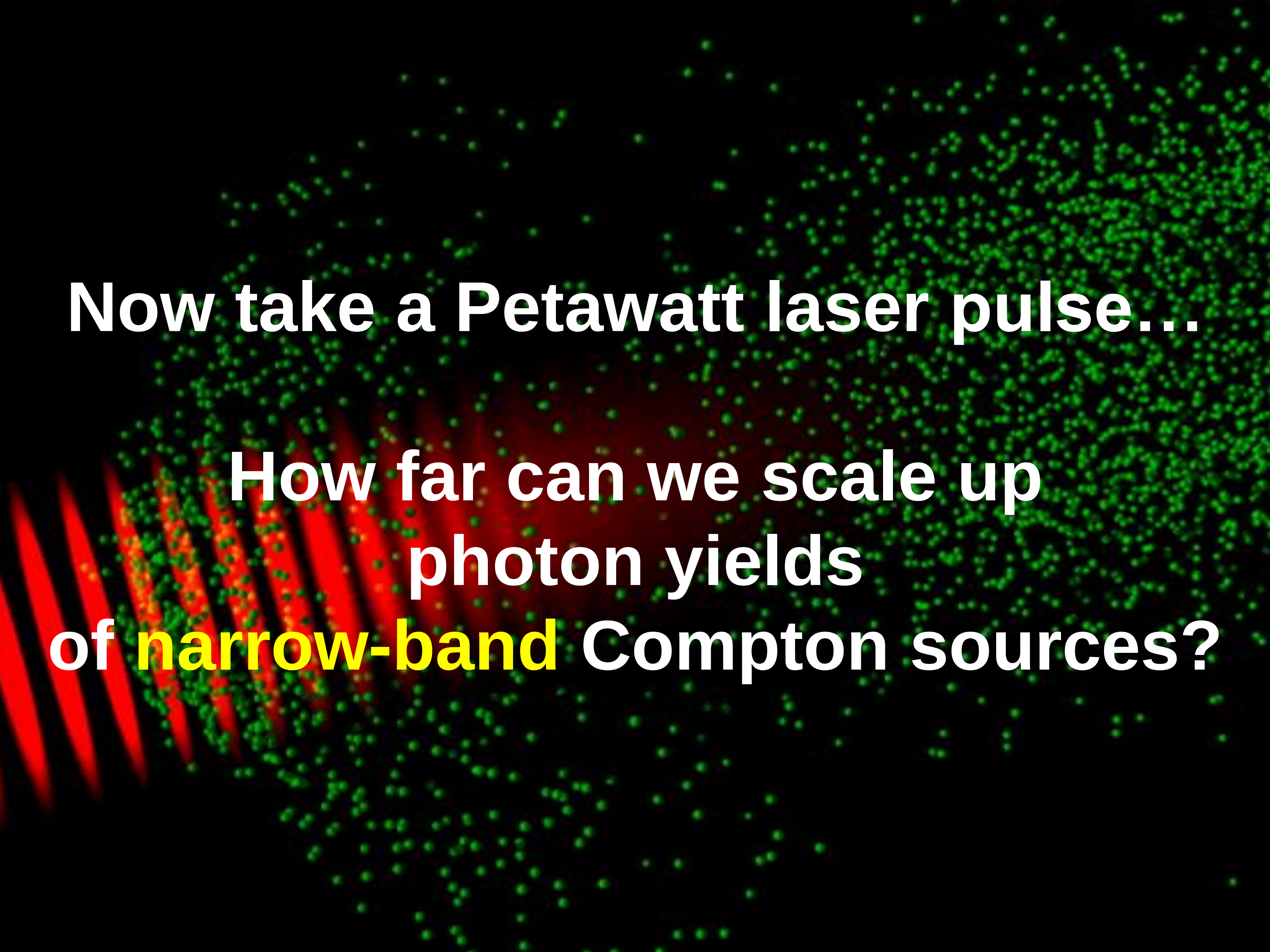
max. ~40000 photons detectable

Sarri *et. al.*, PRL **114**, 195003 (2015)

peak brilliance
$1.8{\cdot}10^{20}$ s^{-1} mm^{-2} $mrad^{-2}$ [0.1% BW] @ 6-18 MeV

Powers *et. al.*, Nat. Phot. **8**, 28-31 (2014)

peak brilliance
$1{\cdot}10^{21}$ s^{-1} mm^{-2} $mrad^{-2}$ [0.1% BW] @ 70-100 keV



Now take a Petawatt laser pulse…

How far can we scale up photon yields of narrow-band Compton sources?

Traveling-wave Thomson scattering improves photons yield per shot by 2-3 orders of magnitudes

	PW-TWTS (ϕ=120°)	PW-TWTS (LWFA) (ϕ=120°)
wavelength [µm]	1	1
W_{pulse} [J]	200	200
pulse length [fs]	150	150
I_0 [W/cm²]	5.5×10^{16}	5.7×10^{16}
L_{int} [mm]	57.6	200
photon energy [keV]	23	3500
$N_{phot,5\%}$ per pulse	4.9×10^{10}	3.4×10^{10}

@ 5% bandwidth

Debus *et. al*.
Appl. Phys. B (2010) **100**(1) 61-76

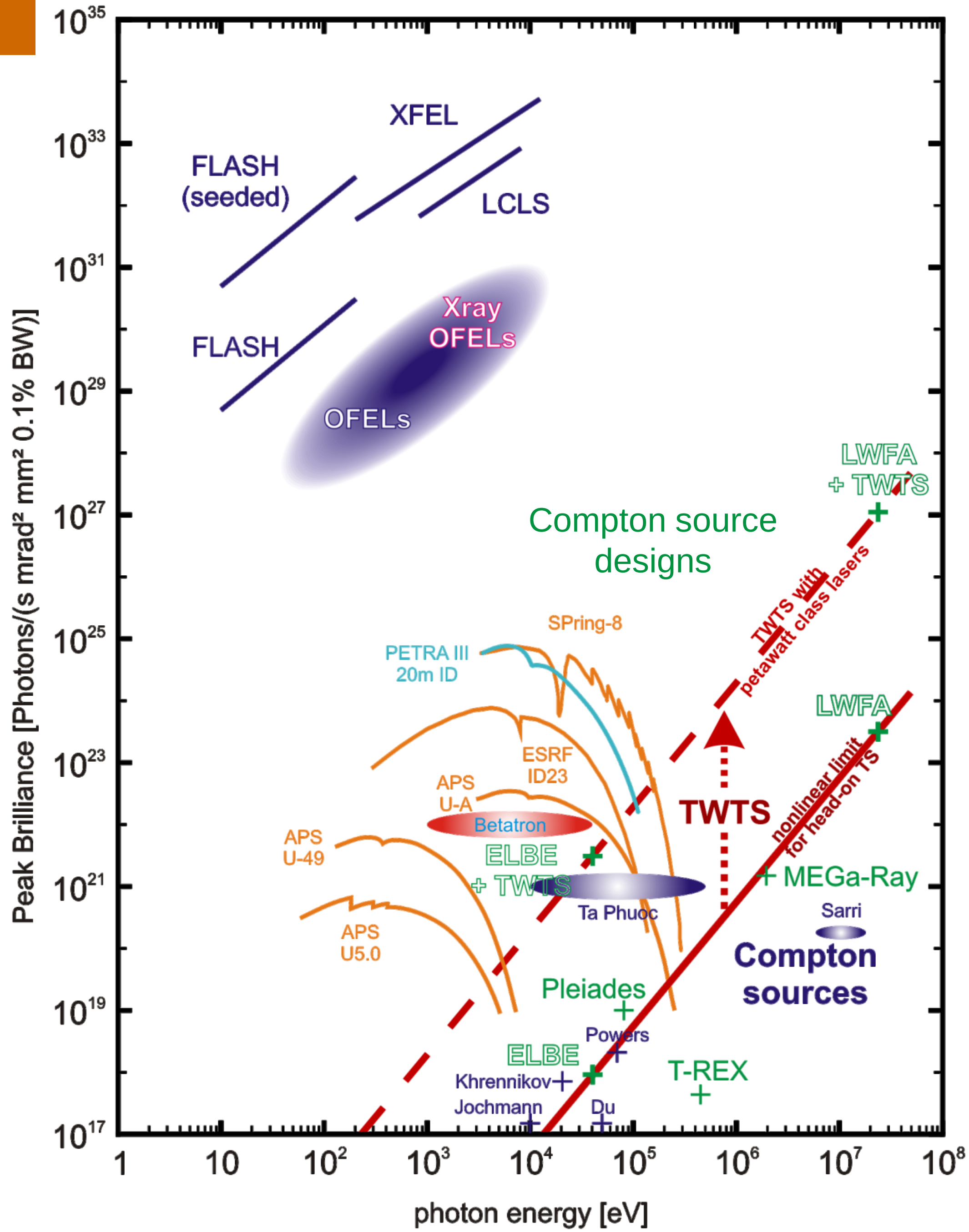
ELBE electrons | low-emittance LWFA electrons

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)

Towards brilliant Compton sources



- „Head-on“ Compton 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.

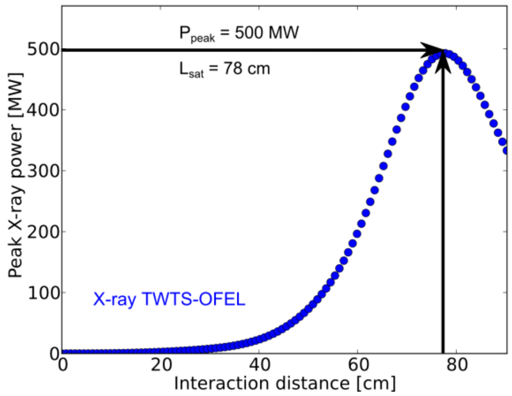
  It arises from electron divergence, size of optics and available laser power.

Outlook

How would a LCLS-type TWTS-OFEL at 1.5Å look like?

Parameter	TWTS	LCLS
scattered wavelength [Å]	1.5	1.5
electron energy [GeV]	0.46	13.6
peak current [kA]	5	3.5
norm. emittance [mm mrad]	0.24	0.5
rel. energy spread	0.02 %	0.01 %
undulator parameter (a_0 or K)	0.2	3.5
laser power [PW]	1.1	-
interaction angle [°]	5	-
saturation length [m]	0.8	132
peak power [GW]	0.5	40

3800 undulator periods



Required laser intensity uniformity within one gain length → 2.4%

Conclusions

- Optical Free-Electron Lasers (OFELs) can be realized with existing electron sources and laser systems.
- In contrast to head-on OFEL designs, TWTS OFELs have favorable properties with regard to *transverse coherence, space charge* and *photon recoil*.
- TWTS OFELs are scalable to higher photon energies. An X-ray TWTS OFEL would remain compact.
- Narrowband, peak-brilliance Compton sources scale beyond 10^{10} photons per shot @ 5% bandwidth.

Thank you for your attention!

Acknowledgements

Klaus Steiniger, Richard Pausch, Michael Bussmann

Jakob Krämer, Axel Jochmann, Arie Irman