LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Technische Universität München

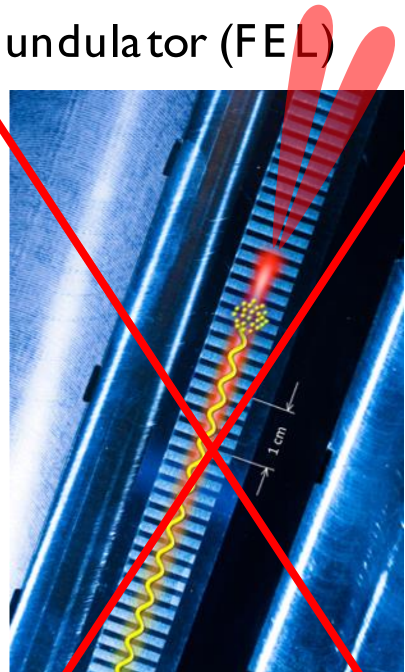
Center for Advanced Laser Applications

Towards Multi-Color Thomson X-ray sources

Stefan Karsch
Ludwig-Maximilians-Universität München/
MPI für Quantenoptik
Garching, Germany

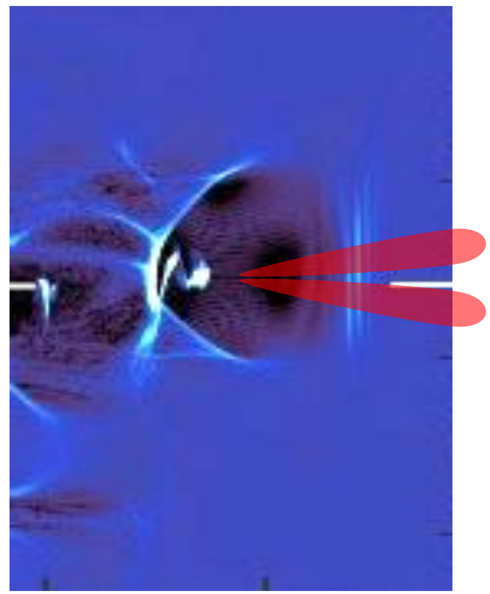
Free electron X-ray sources: Ingredients: relativistic electron beam +

undulator (FEL)



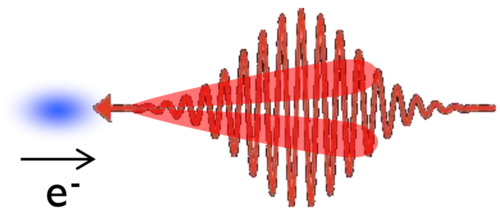
undulator radiation, FEL
100's eV - keV
$\lambda_u \approx$ 1 µm

plasma fields



Betatron radiation
keV – 10's keV
$\lambda_b \approx$ 500µm

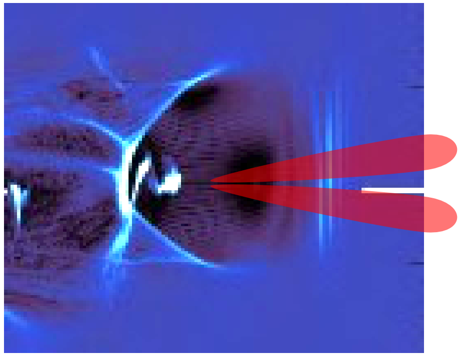
laser fields

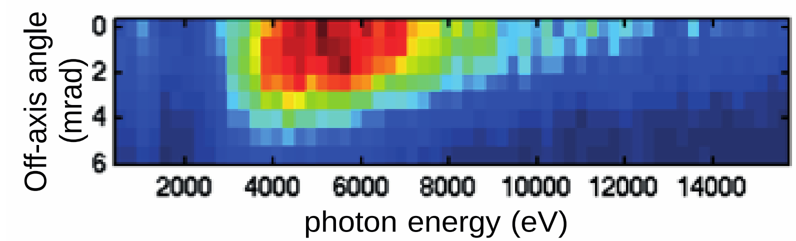


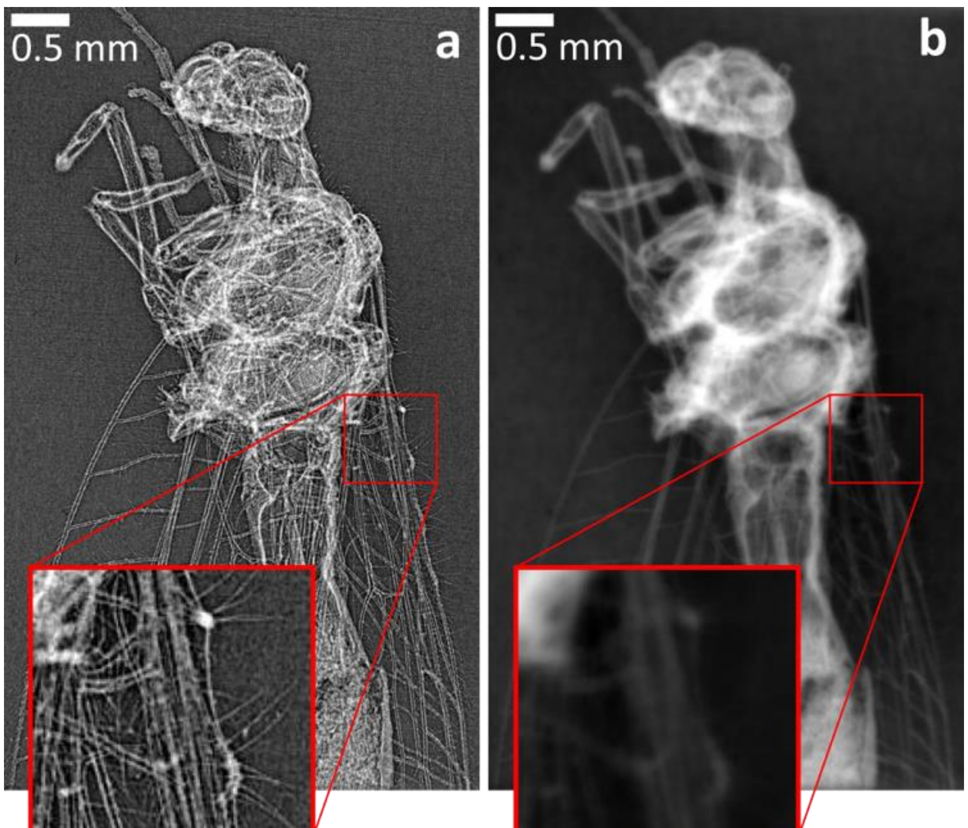
Thomson backscattering
10's keV - MeV
$\lambda_l \approx$ 1 µm

$$/_{x\text{-}ray} = \frac{/_{u,b,l}}{2(4)g^2}\left(1 + \frac{(K, a_0)^2}{2} + g^2 q^2\right)$$

Betatron X-ray tomography (5 keV) (2012)





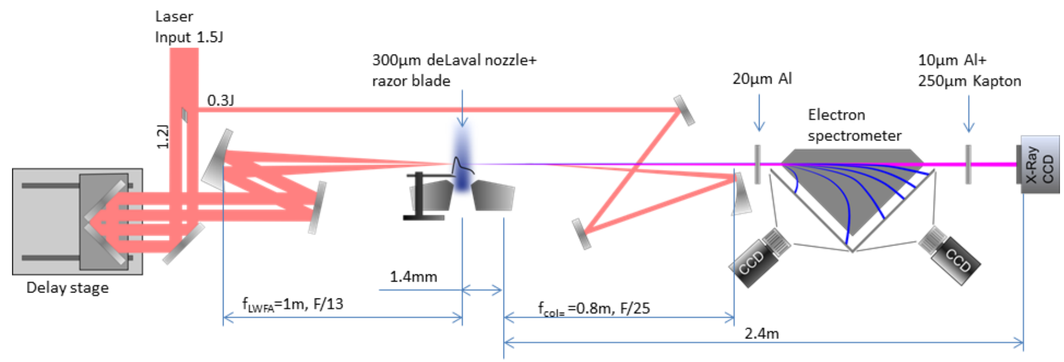


3600 exposures
360 angles

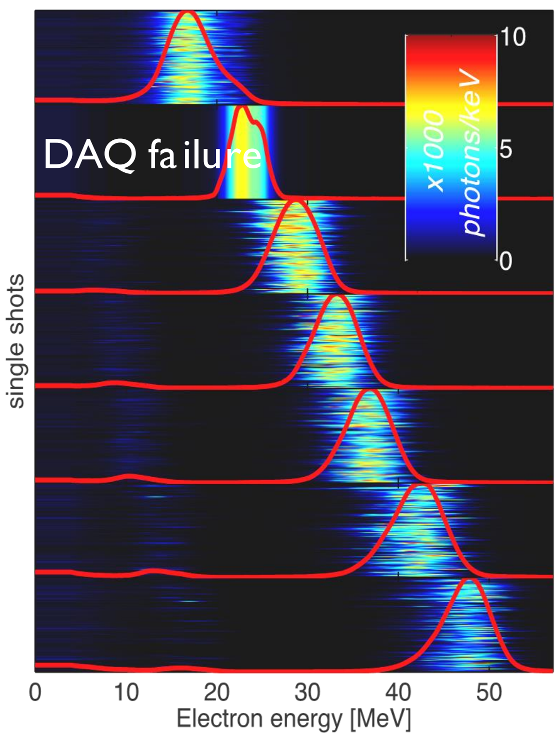
J. Wenz et al. Nature Communications (201

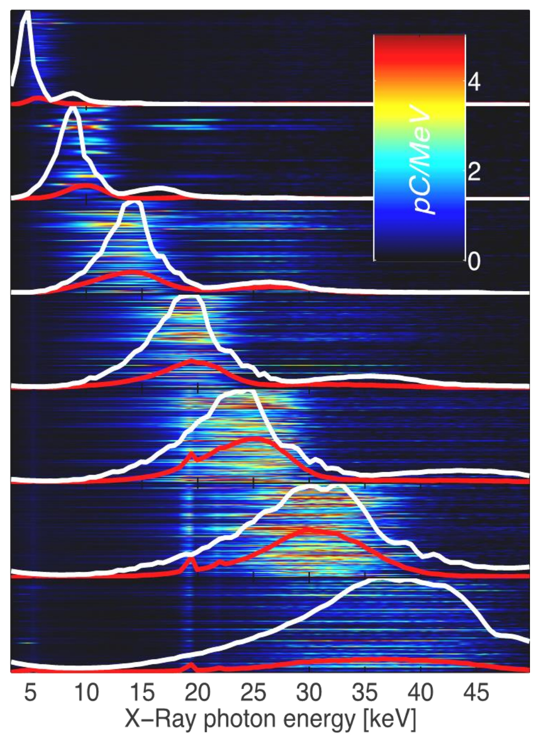
Nonlinear Thomson backscattering (a_0=0.9) (2012)

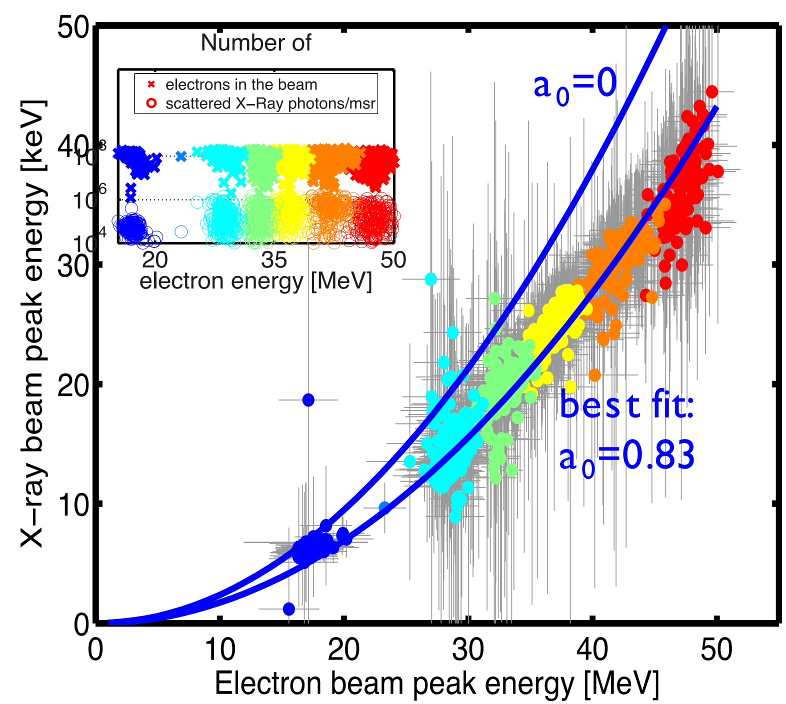
Khrennikov et al., PRL 114, 195003 (2015)



Shock-front injected e-beams: X-ray energy
Electron energy (red – averaged) (red – averaged; white – expected)







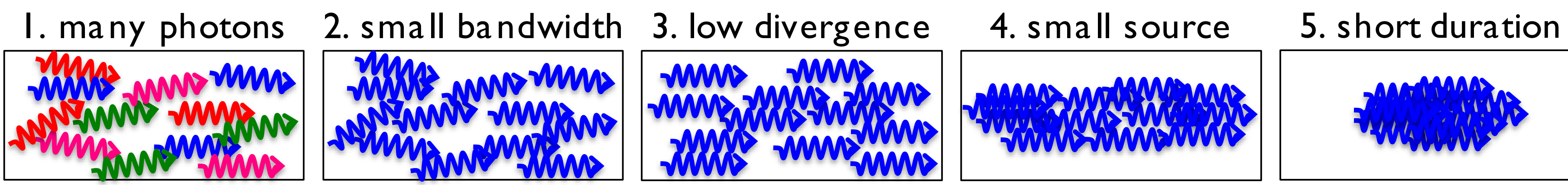
Quality scale for x-rays ...

their brilliance:

$$\text{Brilliance} = \frac{\text{photons}}{\text{mm}^2 \times \text{mrad}^2 \times \text{s} \times 0.1\%\ \text{bandwidth}}$$

transv. emittance (=phase space area)

long. emittance

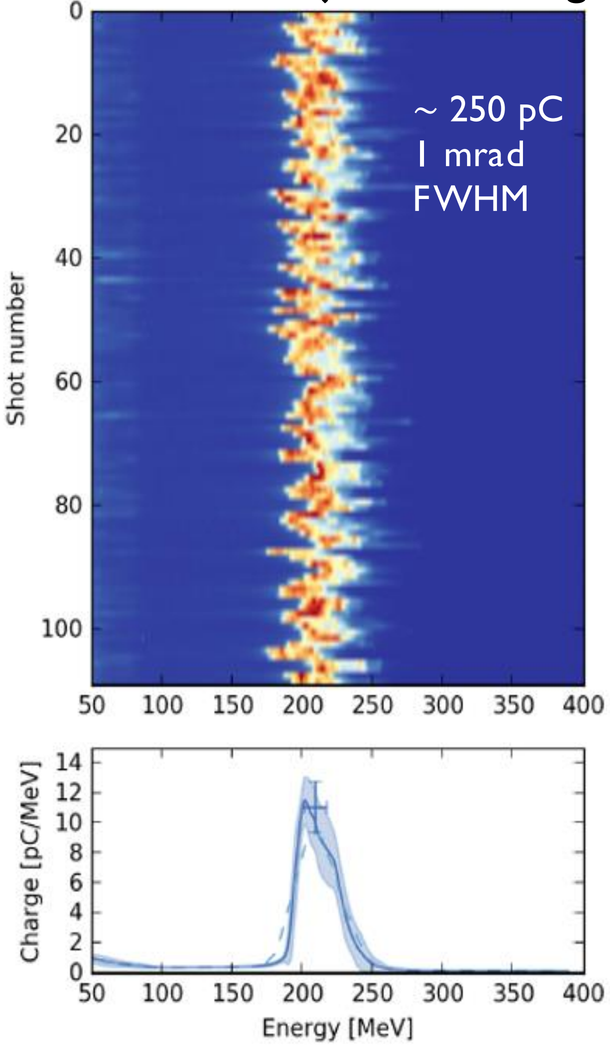


That's where LWFA sources excel

Electrons – spectrum, stability and tunability

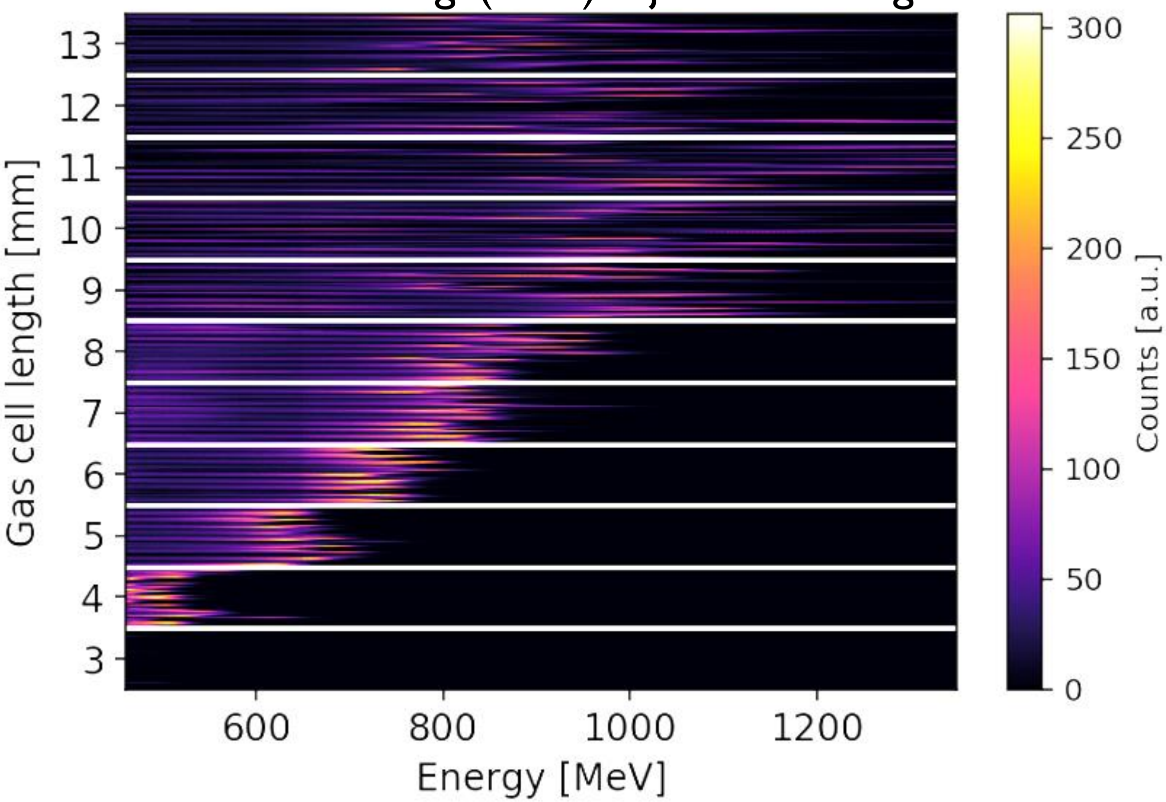
Electrons with 60-100 TW

shock-front injection in a gas jet

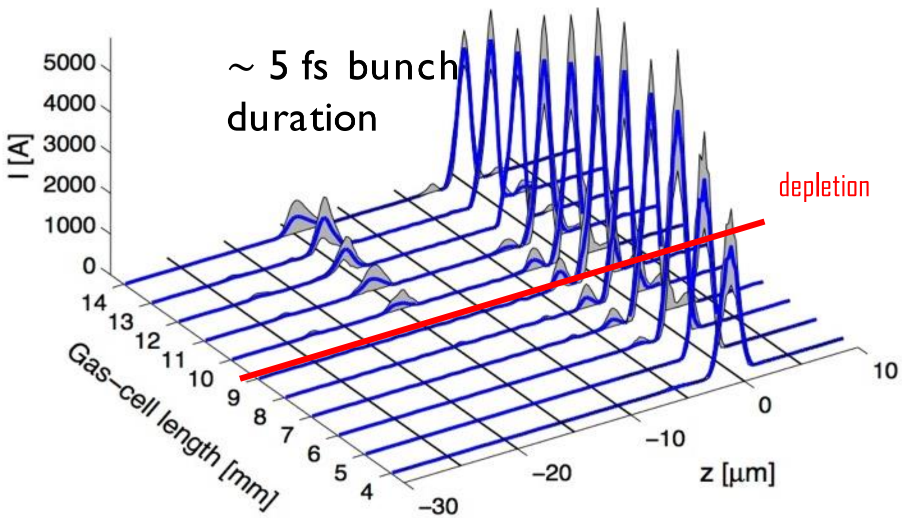


- tuneable, stable, nC-class electron bunches
- ultrahigh-current (multi-kA)

wavebreaking (self-) injection in a gas cell

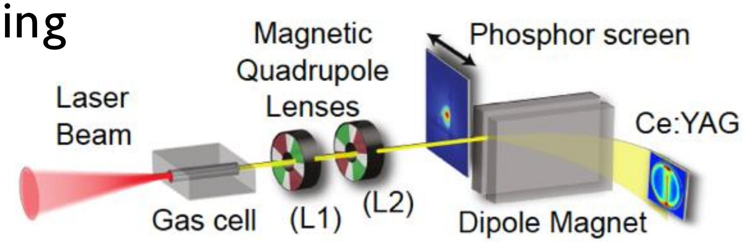


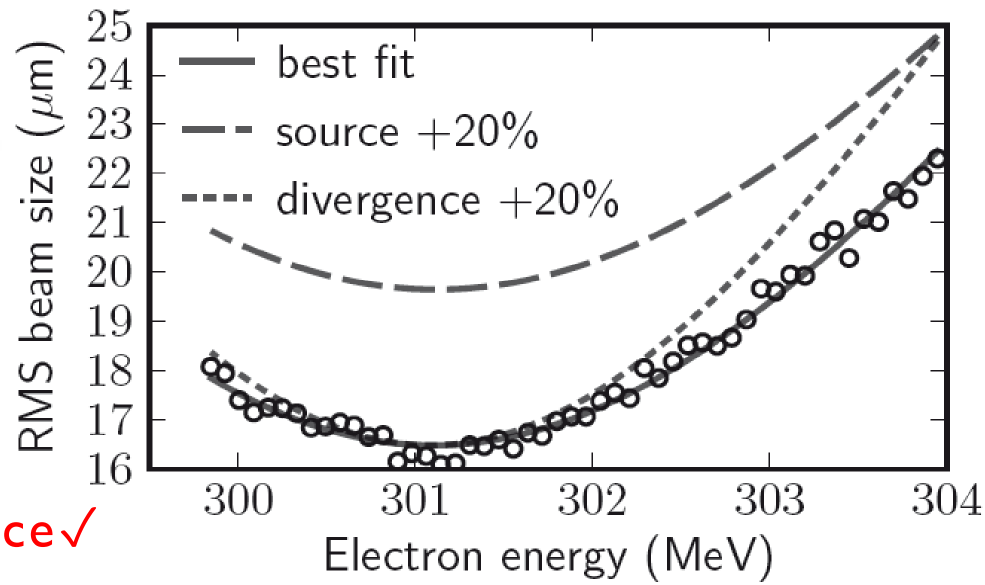
Temporal characterization with CTR spectroscopy



Heigoldt et al., Phys. Rev STAB 18, 121302 (2015)
Bajlekov et al., Phys. Rev STAB 16, 040701 (2013)

Transverse emittance: Chromatic imaging





Normalized emittance: 0.14 π mm mrad

Weingartner et al., Physi. Rev STAB 14, 052801 (2

Bunch duration & transverse emittance✓

however....
so far only done with self-injected beams
⇒ integrate CTR & quadrupole setup

Thomson X-ray spectra

Wiggling wavelength

Instantaneous field amplitude

$$\lambda_{x-ray} = \frac{\lambda_l}{4\gamma^2}\left(1 + \frac{a_0^2}{2} + \gamma^2\theta^2\right)$$

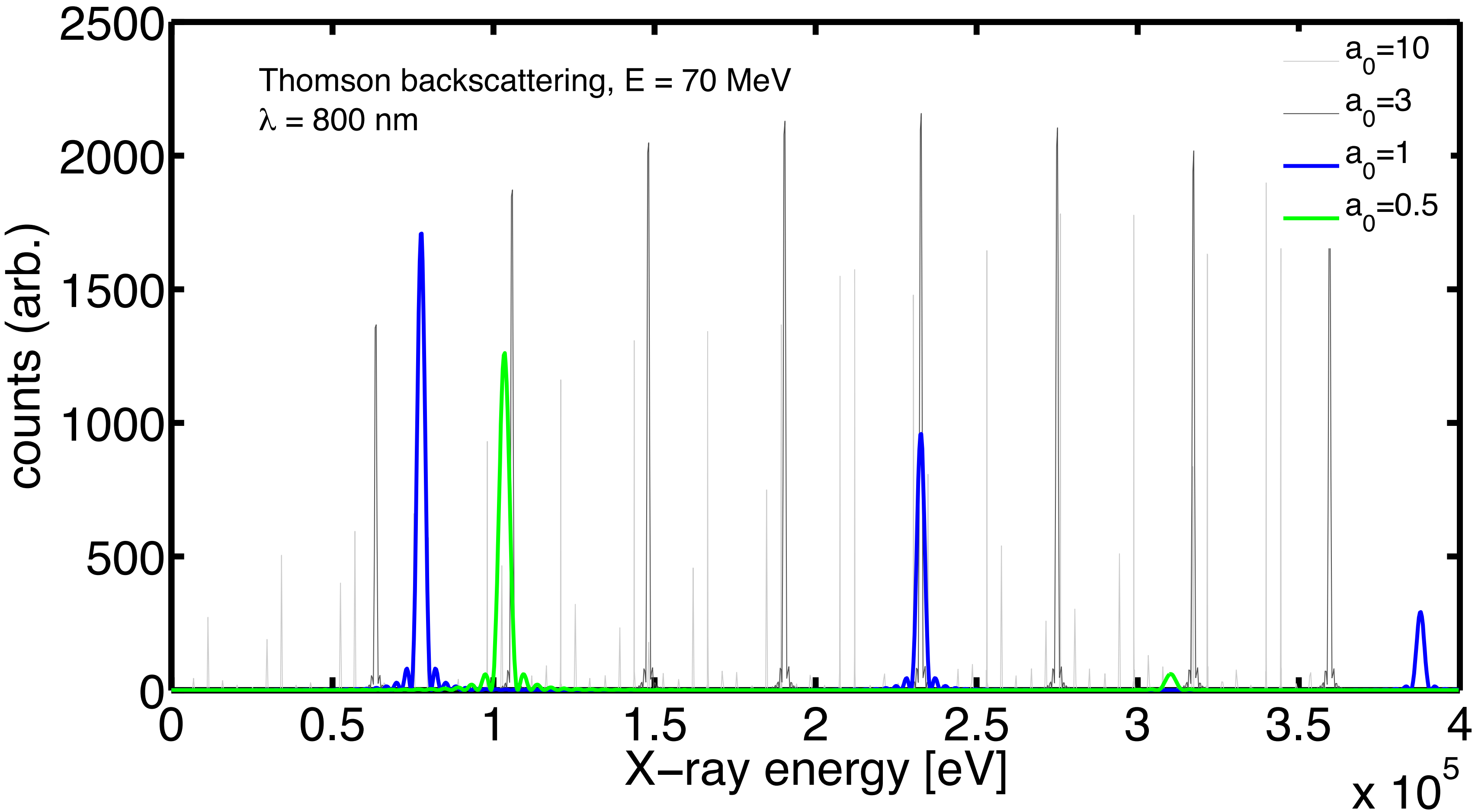
Electron gamma factor

Observation angle range

X-ray spectrum is influenced by:

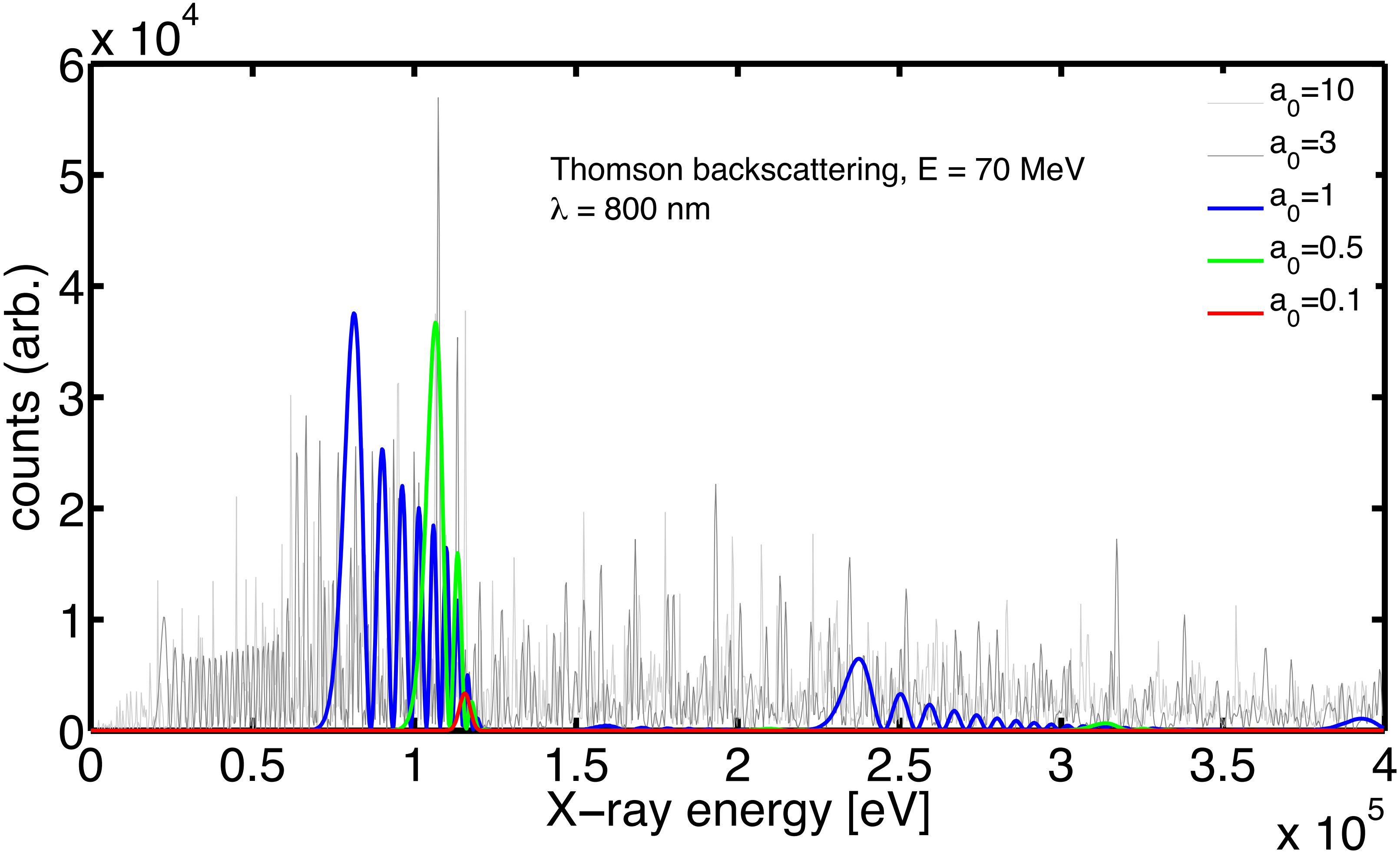
- Electron energy, bandwidth and emittance
- Wiggling field strength and number of oscillations
- Observation direction and solid angle
- Wiggling period

Simulation with SPECTRA 10.0[1] (and verified with RDTX[2])

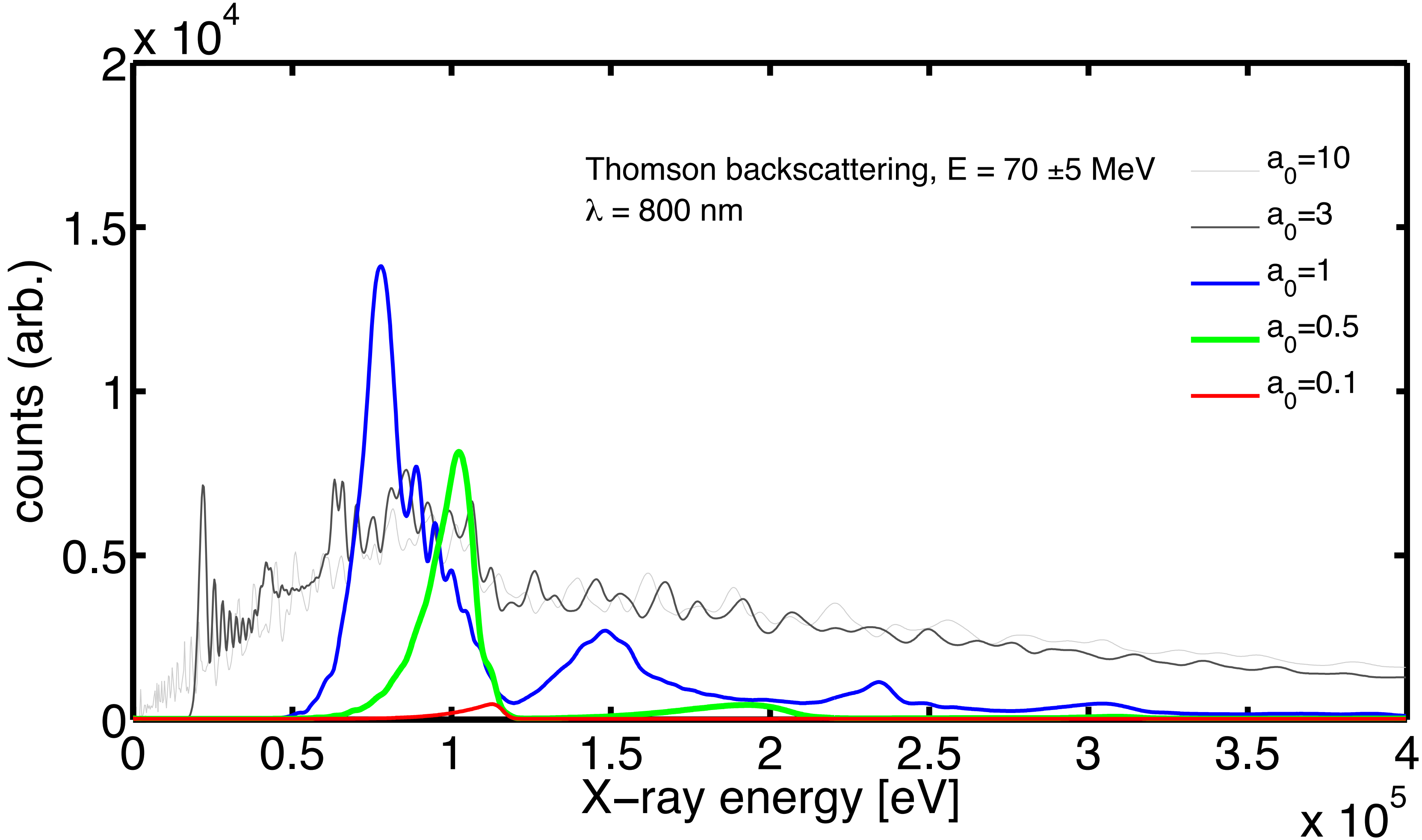


Collimated, monochromatic e-beam, 25 period, flat-top optical undulator

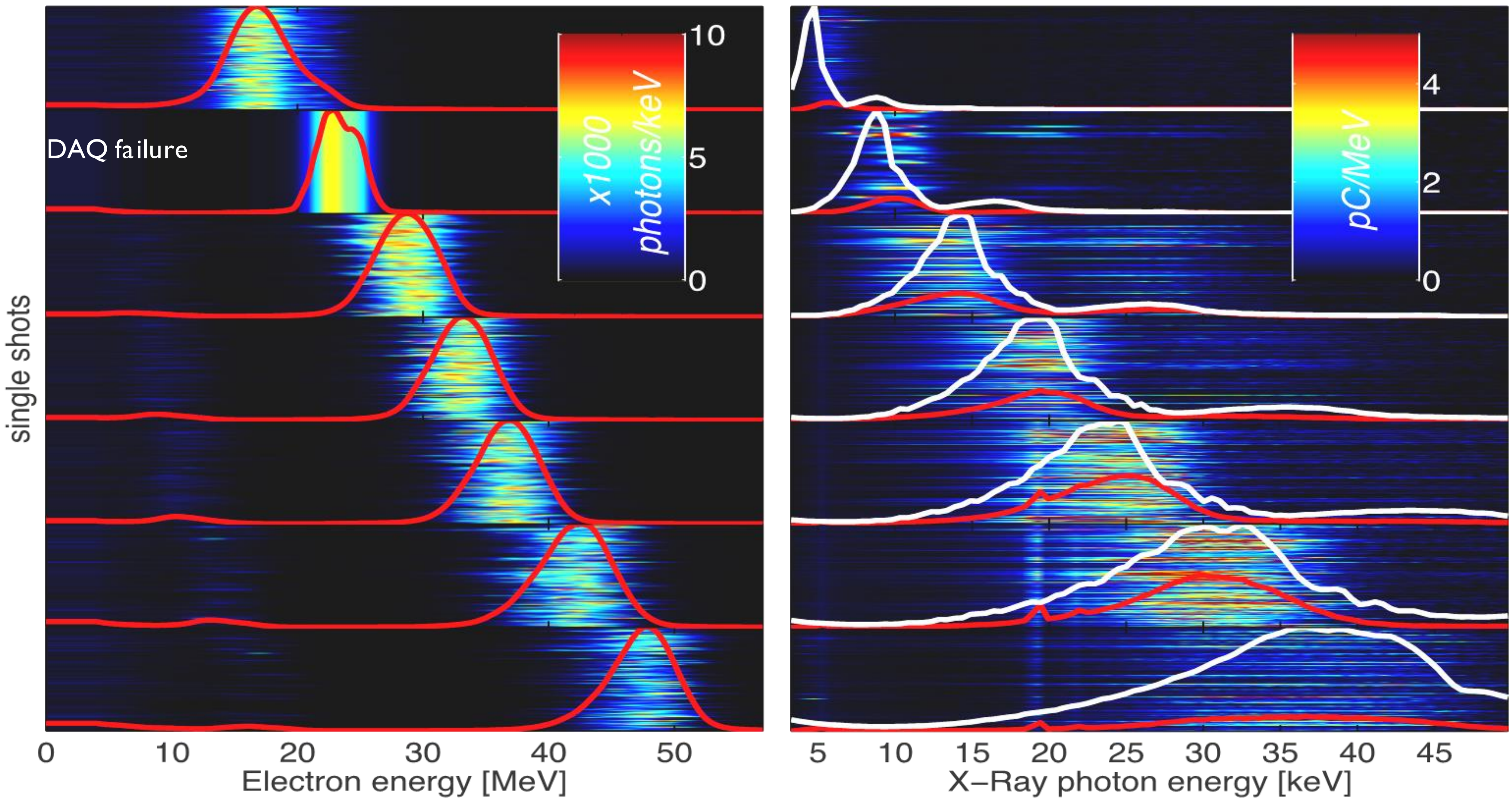
[1]T. Tanaka and H. Kitamura, J. Synchrotron Radiation, 8 (2001) 1221
[2]A.G.R. Thomas, PRS TAB 13, 020702 (2010)



Collimated, monochromatic e-beam, 30 fs laser pulse



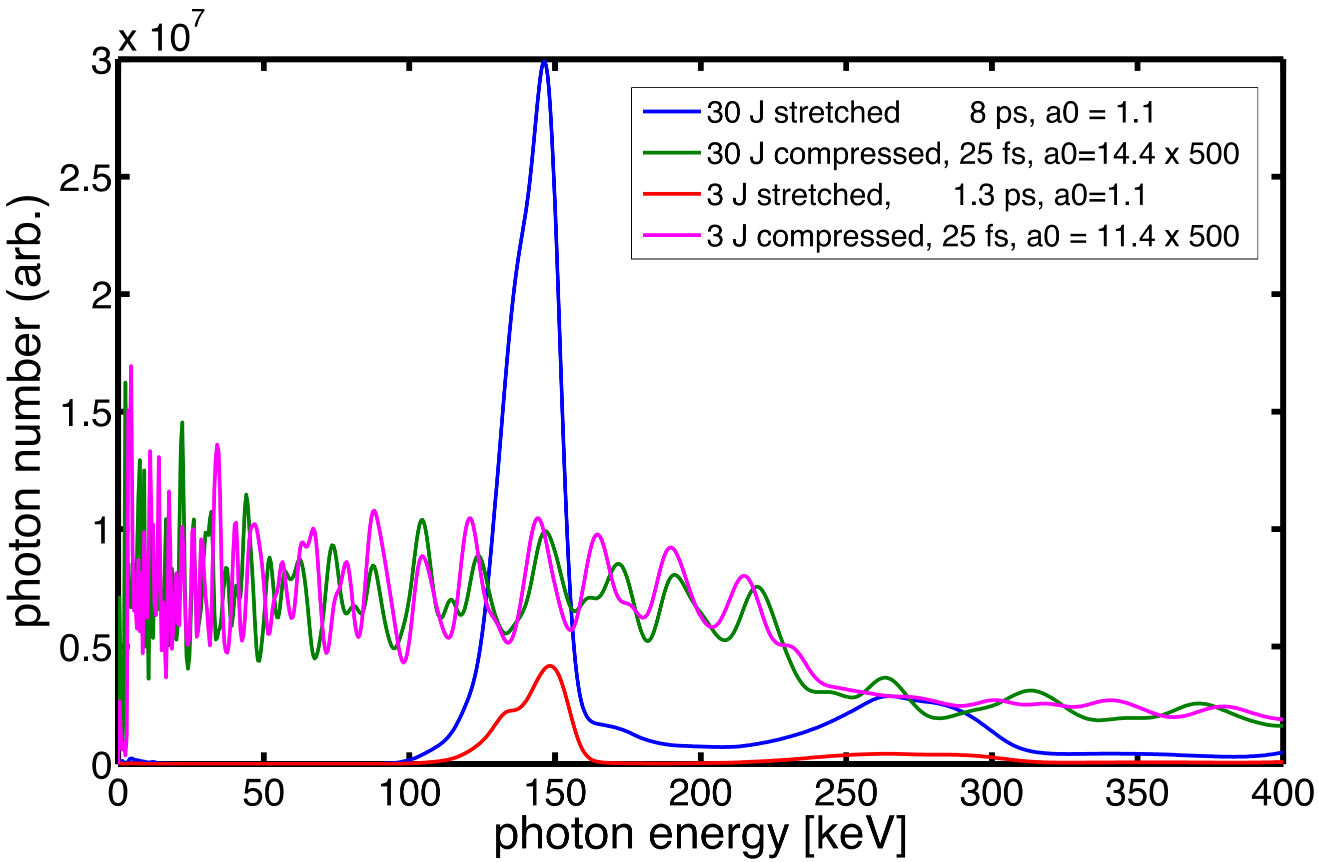
Divergent, 5 MeV bandwidth e-beam, 30 fs laser pulse


DAQ failure
x1000 photons/keV
10
5
0
single shots
0 10 20 30 40 50
Electron energy [MeV]
pC/MeV
4
2
0
5 10 15 20 25 30 35 40 45
X−Ray photon energy [keV]

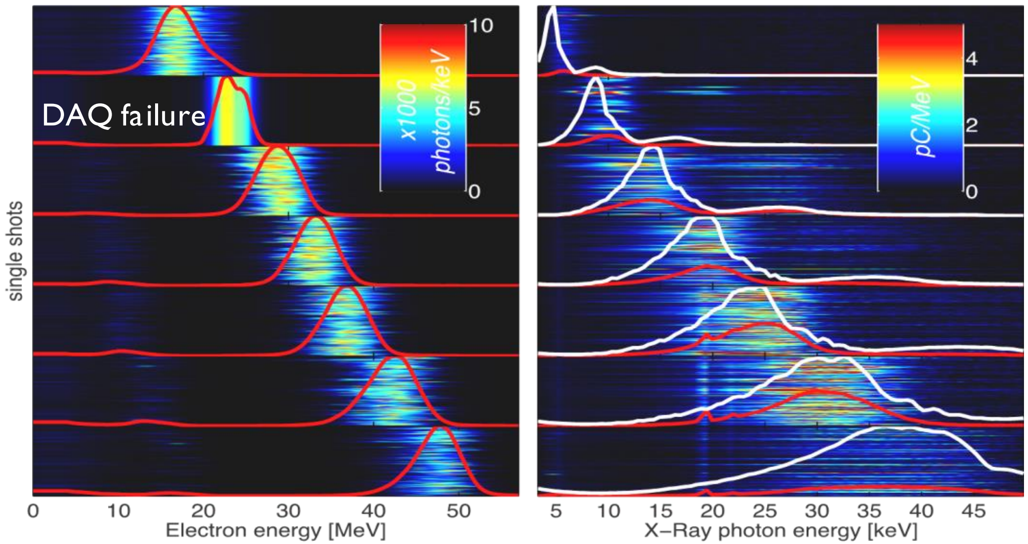
Scalability?

Increase in colliding pulse energy, $a_0 > 1$: high-harmonic generation, redshift

Scaling requires collision pulse shaping to keep narrow bandwidth: $\lambda_{x-ray}\left(=const\right)=\frac{\lambda_L(t)}{4\gamma^2}\left(1+\frac{a_0^2(t)}{2}\right)$ if $a_0(t)=\sqrt{\frac{8\gamma^2\lambda_{x-ray}}{\lambda_L(t)}-2}$



Thomson scattering



Khrennikov et al., PRL 114, 195003 (2015)

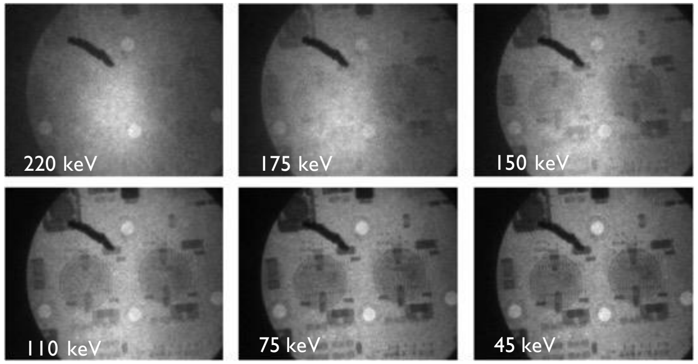
Nonlinear Thomson scattering with 1.2J, 26 fs driver and 0.3J, 26 fs collider.

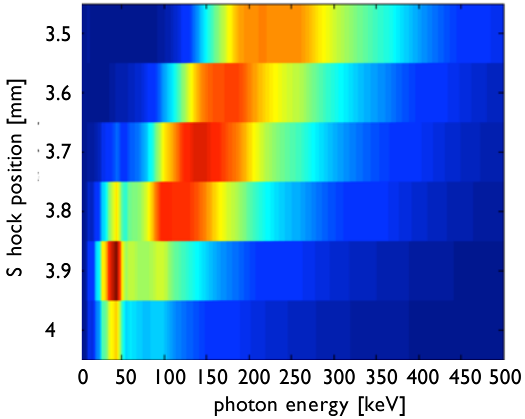
measured X-ray spectra correspond very well to those predicted from electron spectra

electrons allow to predict X-ray spectrum

Nonlinear Thomson scattering with 2.5J, 28 fs driver, reflected of a tape for collision

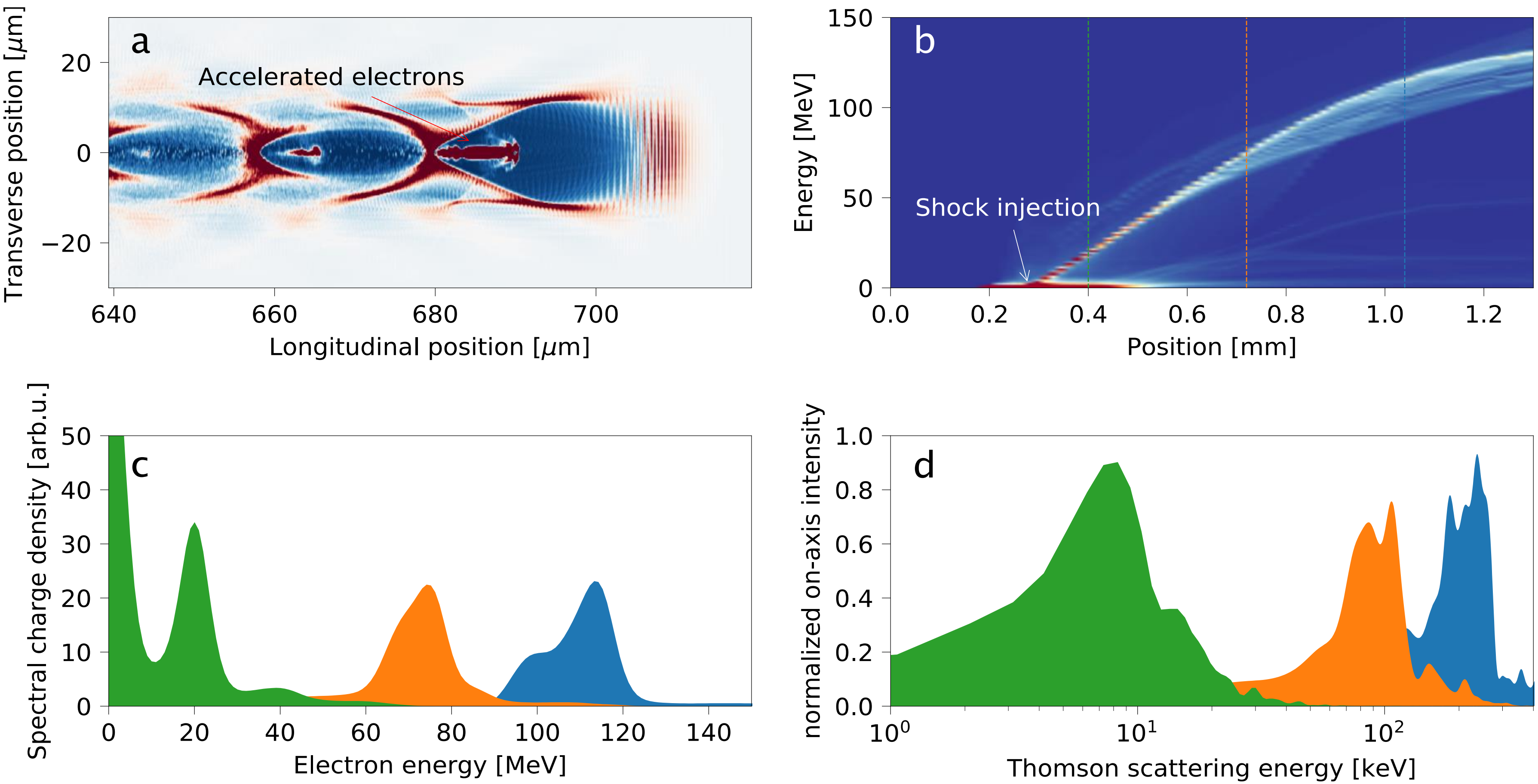
different absorption contrast for different photon energies



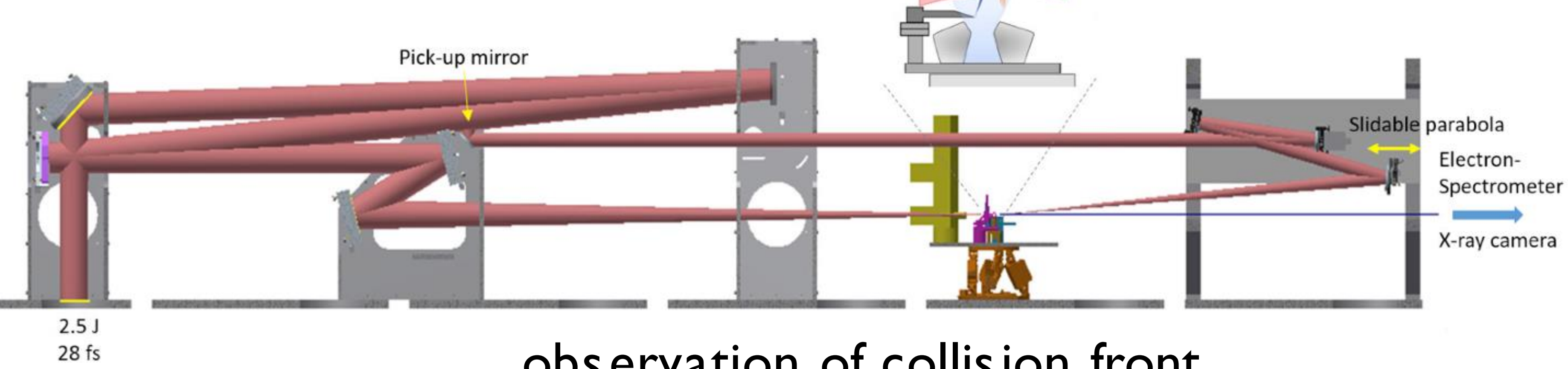


Alternative control of photon energy:

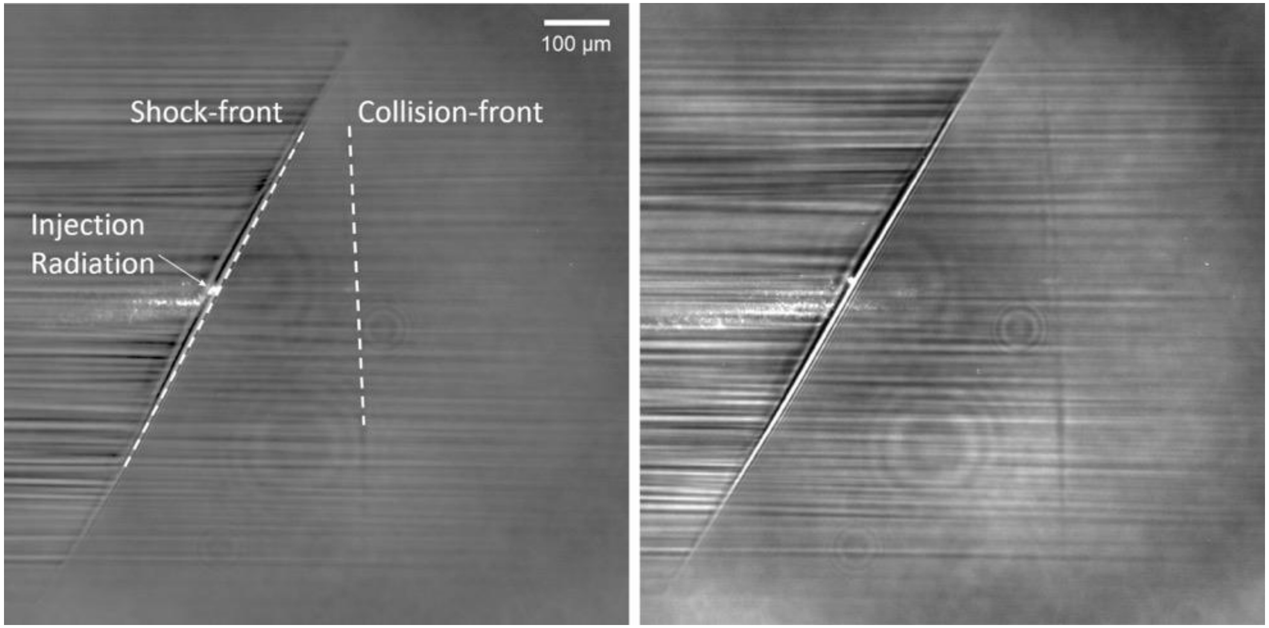
Collision inside wakefield accelerator



Setup



observation of collision front

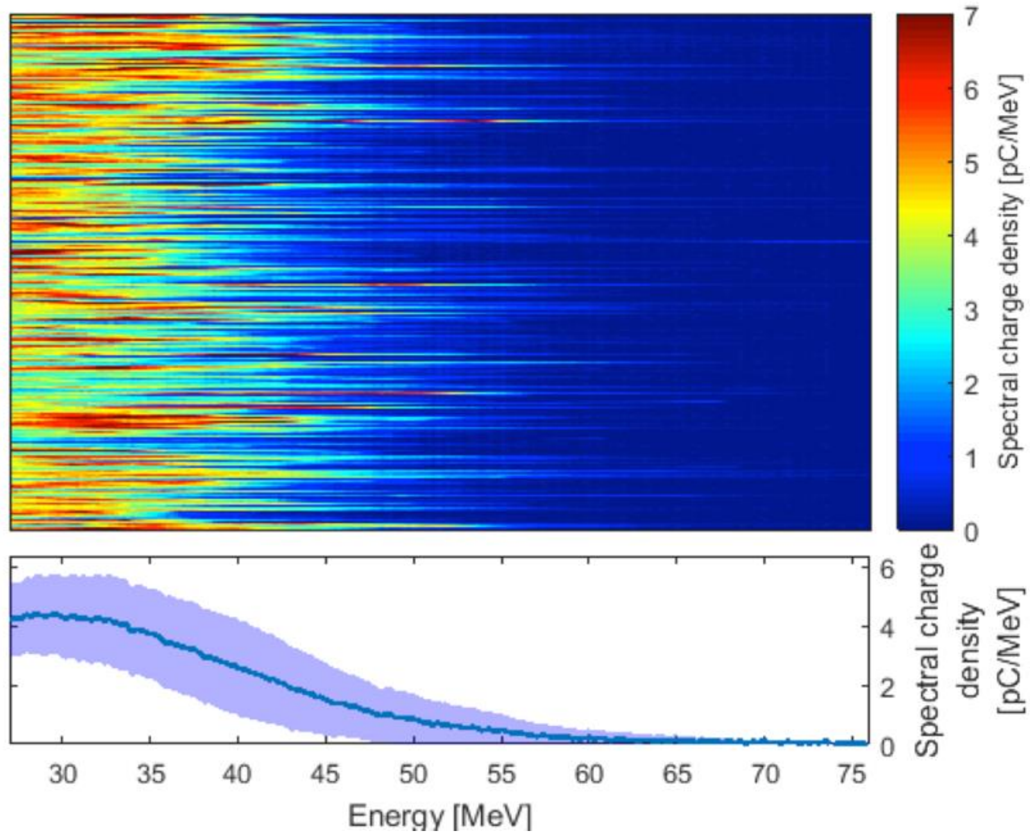


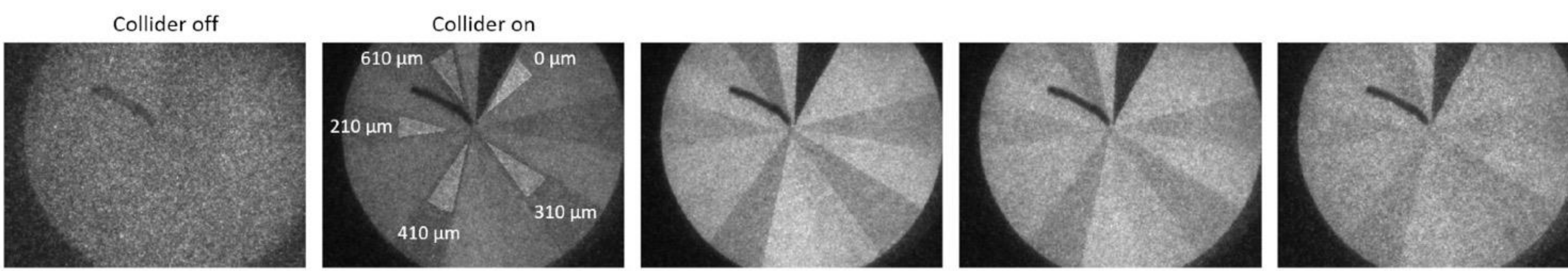
Electrons ⇒

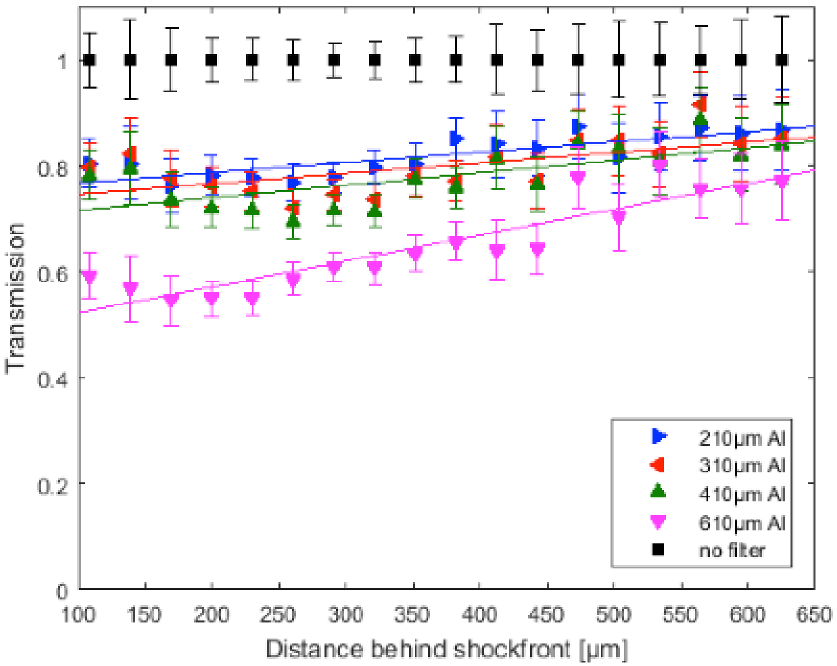
and

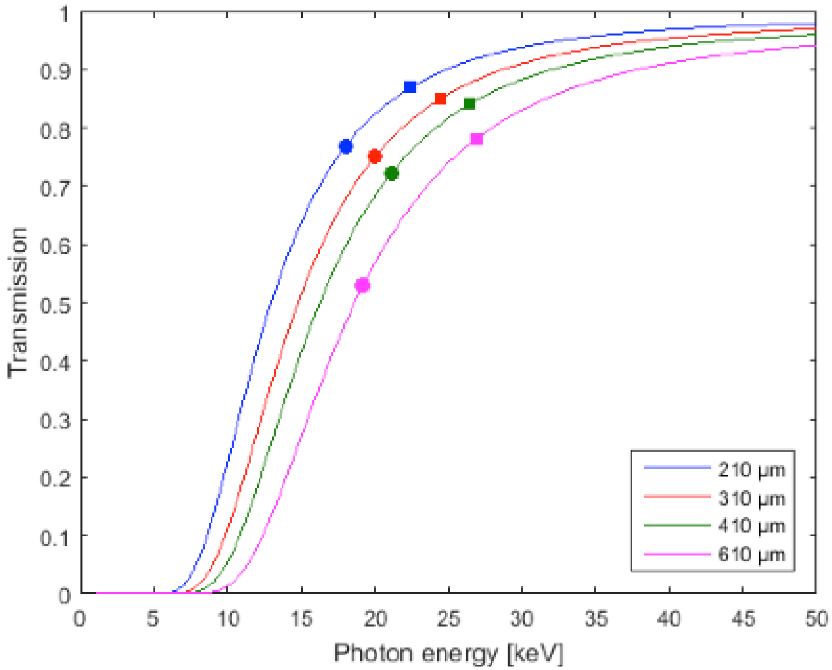
X-rays

⇓



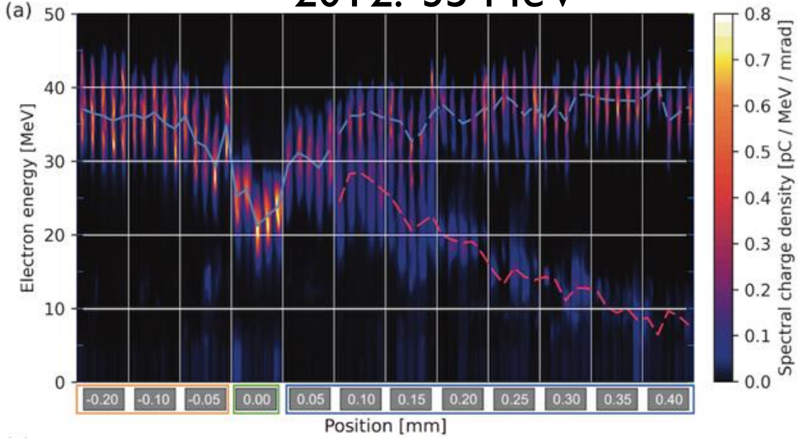



Transmission
Distance behind shockfront [µm]
210µm Al
310µm Al
410µm Al
610µm Al
no filter

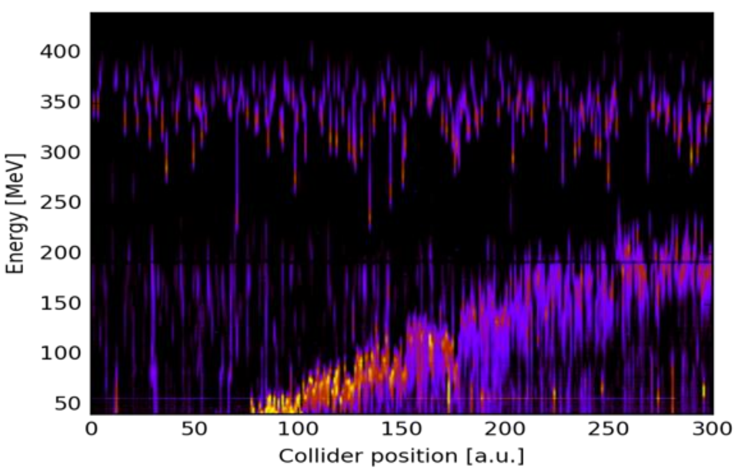

Transmission
Photon energy [keV]
210 µm
310 µm
410 µm
610 µm

Tunable dual-energy electron bunches from a single laser shot for dual energy X-ray sou

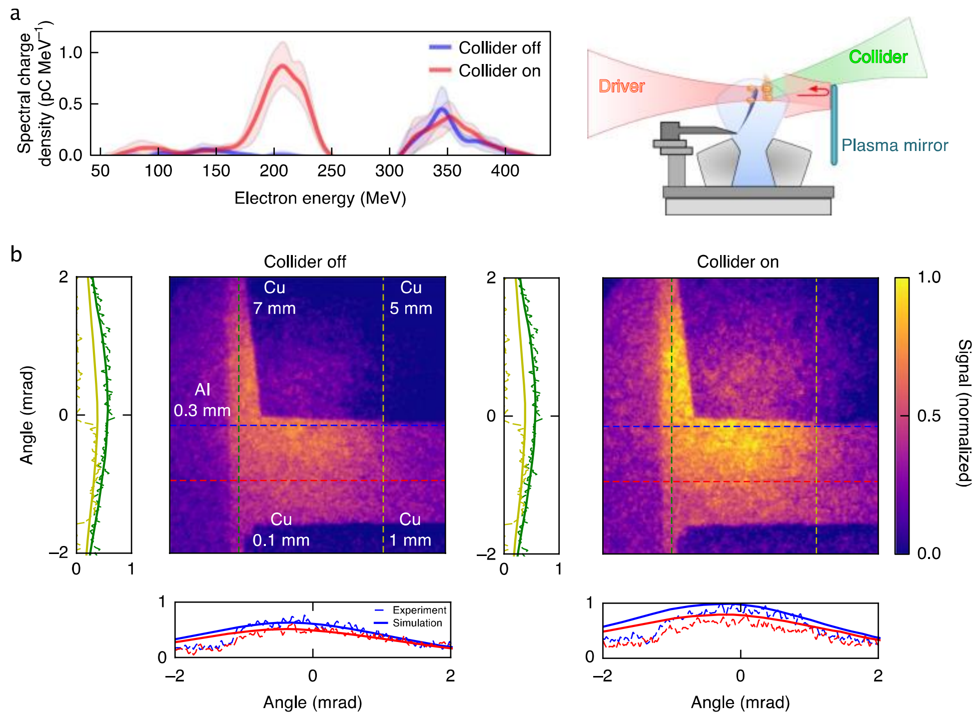
2012: 35 MeV



2016: 350 MeV



Collider tunable over 50-200 MeV, while shock injection at 350 MeV

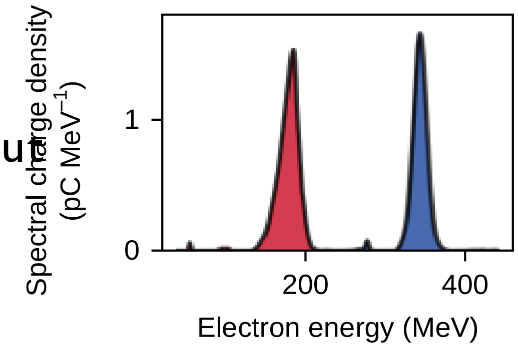


Bottom: Thomson source without (left) and with (right) dual beams

Wenz et al., Nature Photonics, DOI: 10.1038/s41566-019-0356-z (

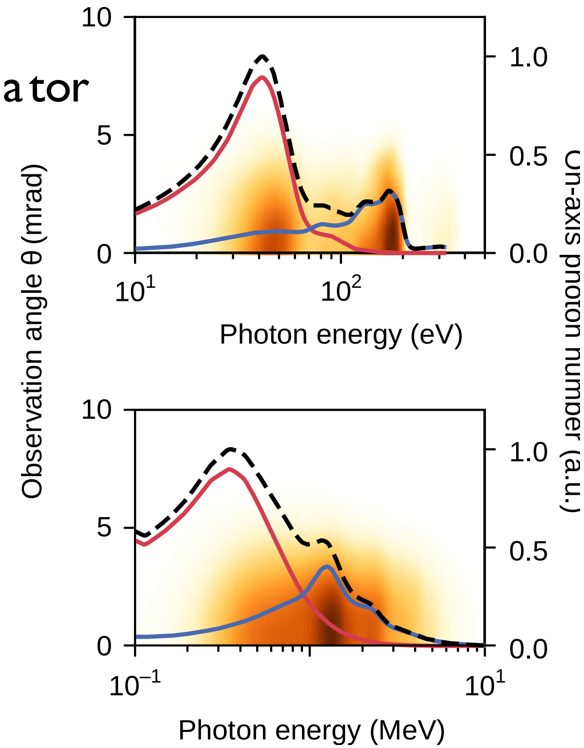
Theoretical x-ray spectra

measured electron spectrum used as simulation input

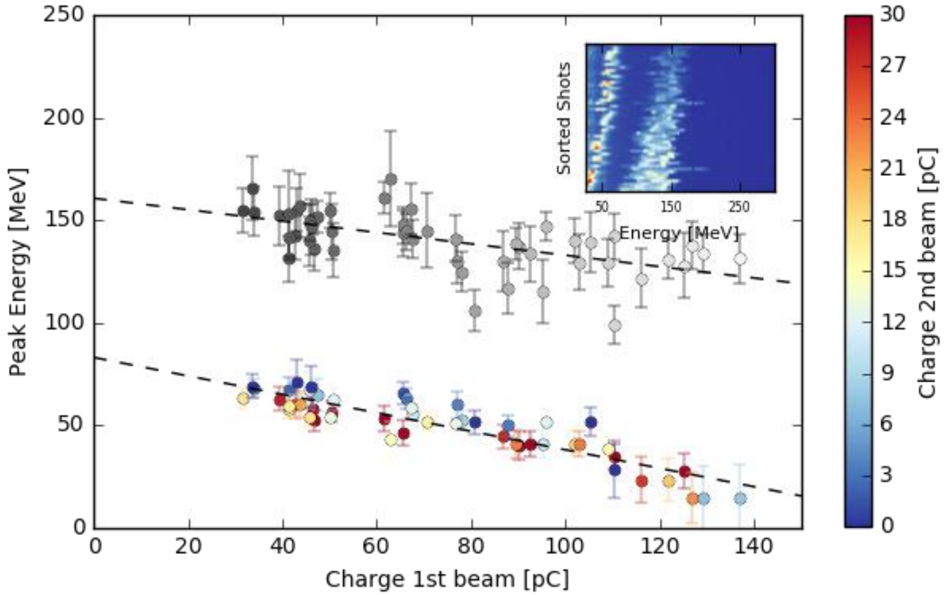


angle-resolved VUV spectrum from a magnetic undulator ($K=0.55$, $\lambda_u=5$mm, $N_{period} = 60$)

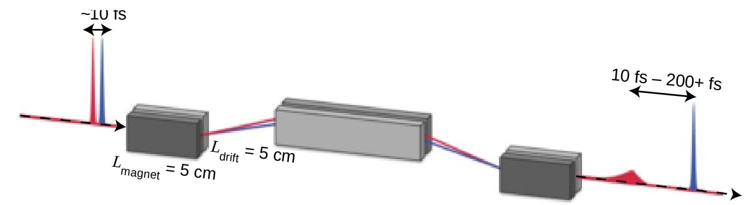
angle-resolved x-ray spectrum from Compton-backscattering ($a_0=1.5$, $\lambda=800$ nm, $\Delta t = 30$fs)

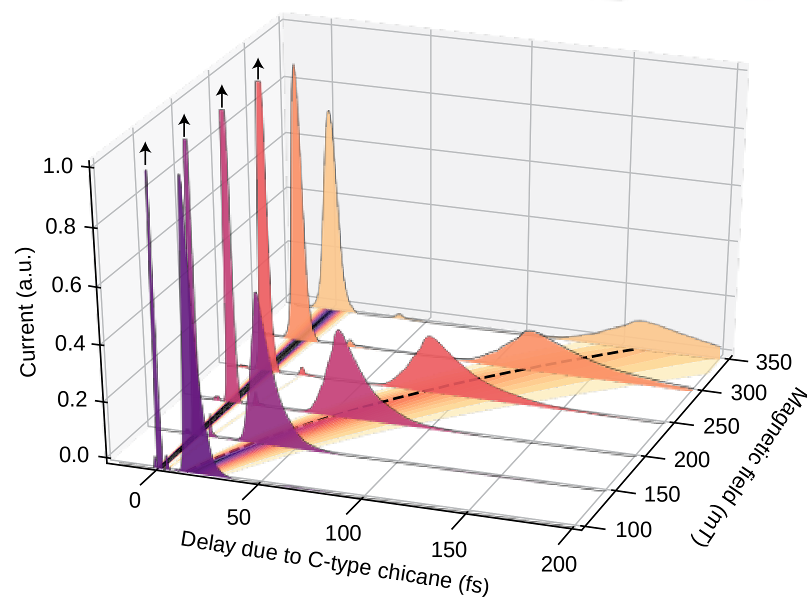


Prospects for multi-colour, controllable delay x-ray pulses ("x-ray pump, x-ray probe")



- Clear correlation between charge of 1st beam and energy of 2nd beam: both beams sit in the same bubble
- Pulse delay given by dephasing between both injection points (down to a few fs!) - obviously coupled to 2nd bunch energy
- Very difficult for conventional accelerators!





Thomson scattering or undulator after chicane would allow setting delay

Credits:

WG Karsch:
Postdoc:
A. Döpp
PHD candidates:
- J. Wenz
- M. Heigoldt
- K. Khrennikov
- M. Gilljohann
- H. Ding
- S. Schindler
- J. Götzfried
- M. Foerster

Master students:
- C. Lin
- T. Hager

Engineers:
- G. Schilling
- A. Münzer

WG Veisz:
PHD candidates:
- A. Buck
- S.W. Chou
- J. Xu

S. Hooker, U Oxford:
- S. Bajlekov
- N. Bourgeois
- G. Cheung

M. Kirchen, Uni Hamburg

F. Pfeiffer, TU München
- S. Schleede
- M. Bech
- P. Thibault

and HYBRID collaboration:
U. Schramm, A. Irman et al. (HZDR)
S. Corde (LOA)
A. Martinez de la Ossa (UHH)
B. Hidding (Strathclyde)