

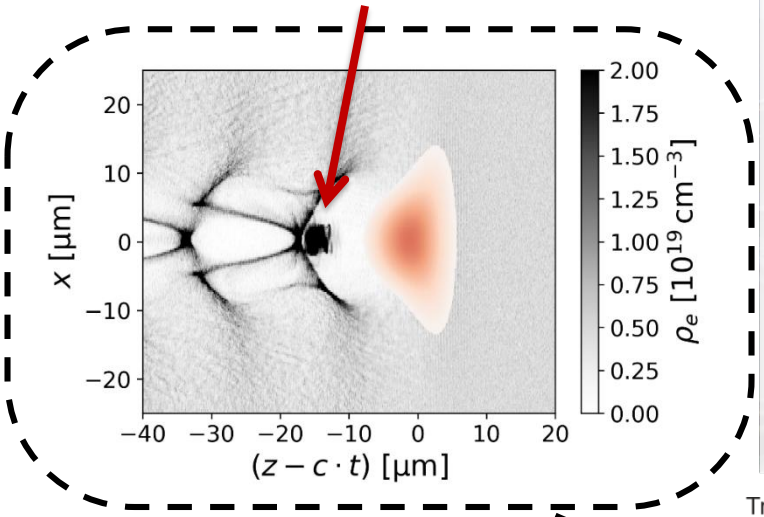
Determining the impact of LWFA injection schemes on electron bunch profiles and peak currents based on broadband, spectral CTR diagnostics at single shot

Alexander Debus[1], **Omid Zarini**[1,2], Maxwell LaBerge[1,3], Jurjen Couperus[1,2], Alexander Koehler[1,2], Thomas Kurz[1,2], Susanne Schoebel[1], Jakob Kraemer[1], Andrea Hannasch[1,3], Rafal Zgadzaj[1,3], Hauke Mewes[1,2], Heide Meissner[1], Michael Bussmann[1], Michael Downer[1,3], Ulrich Schramm[1], Arie Irman[1]

[1] Helmholtz-Zentrum Dresden – Rossendorf , [2] Technische Universität Dresden, [3] University of Texas at Austin

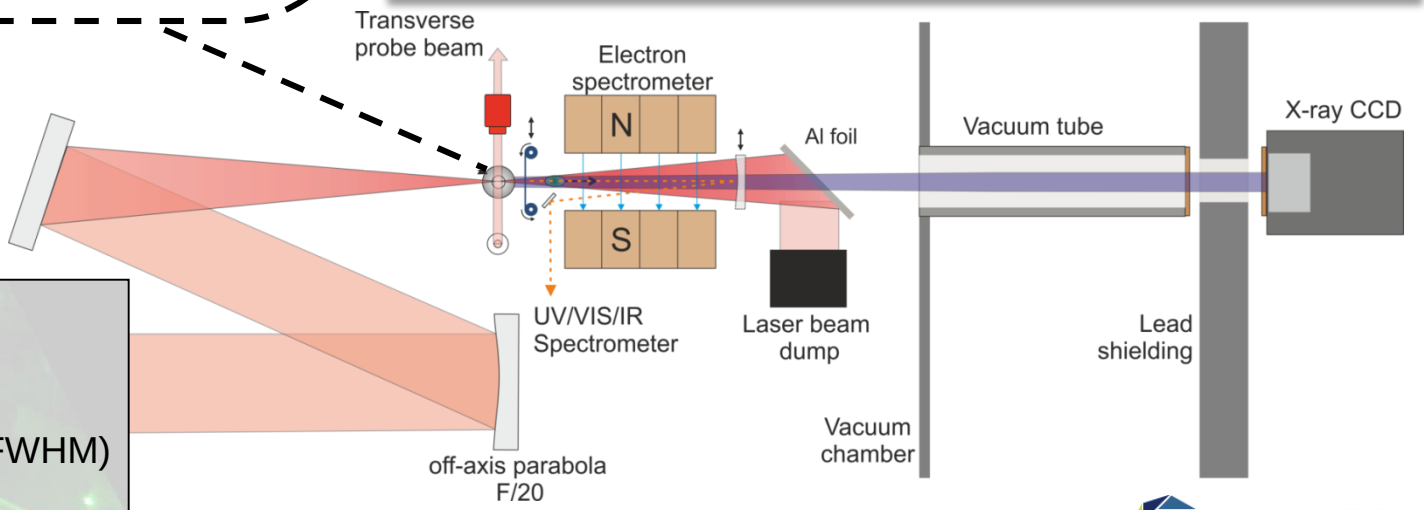
Short electron bunches in LWFA

Pulse duration?
Micro-structures?



- Knowledge on longitudinal electron bunch structures is key to bright radiation sources.
- Compact FELs require high peak currents for lasing

$$\rho = \frac{1}{2\gamma}\left(\frac{I}{I_A}\cdot\left(\frac{f_c \cdot K\lambda_u}{2\pi\sigma_b}\right)^2\right)^{1/3}$$



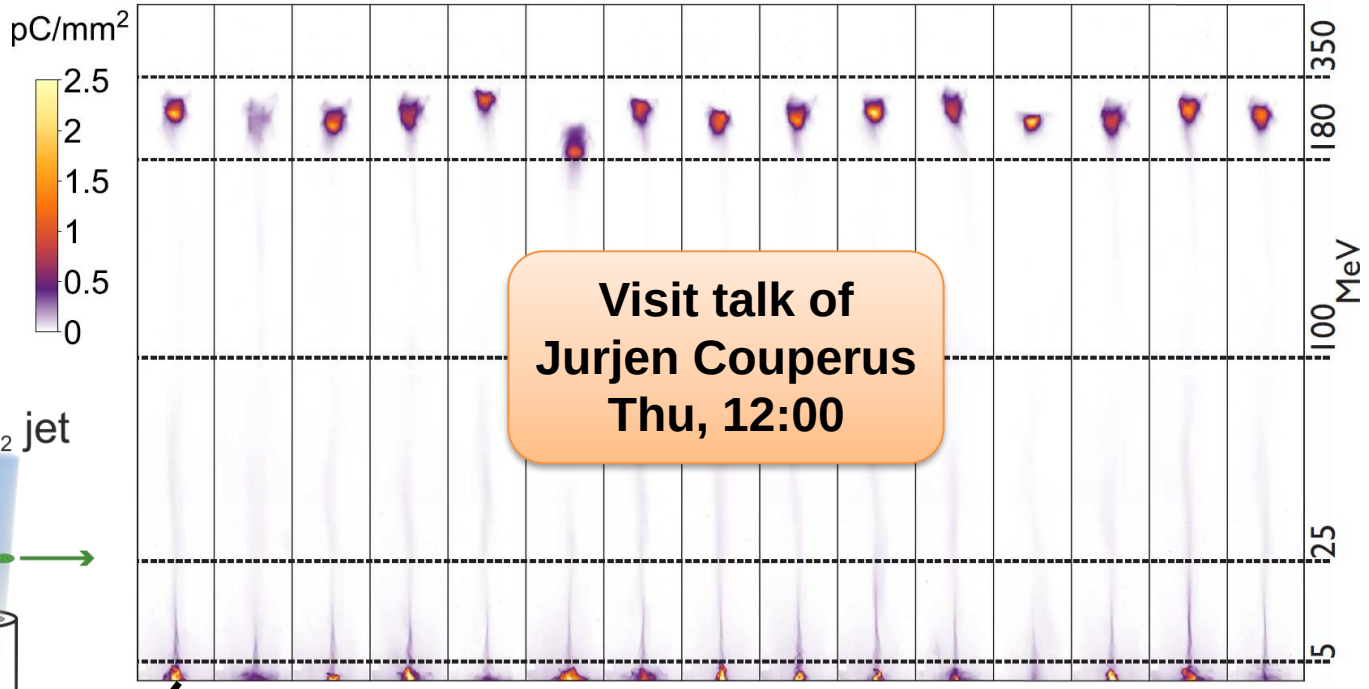
Ti:Sa Laser DRACO

- λ_0 = 800 nm
- up to 4 J on target
- 27 fs pulse width (FWHM)
- Strehl-ratio > 0.9
- 20 µm FWHM

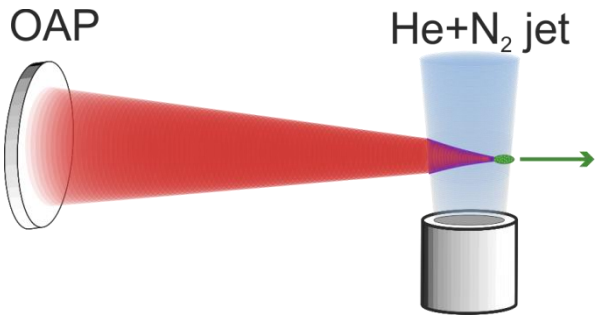
Self-truncated ionization injection regime of LWFA

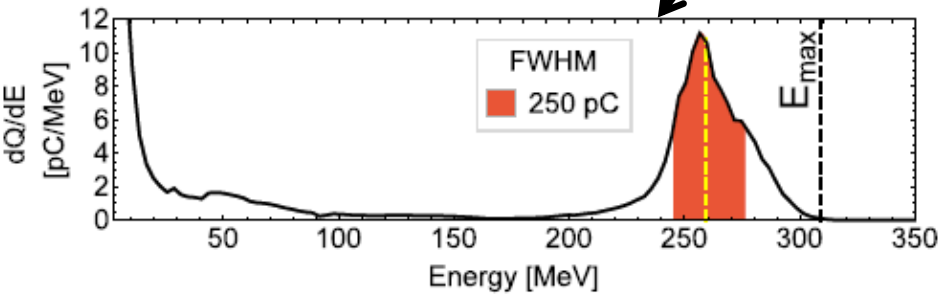
consecutive shots

high bunch charges at several 100pC



Visit talk of Jurjen Couperus Thu, 12:00





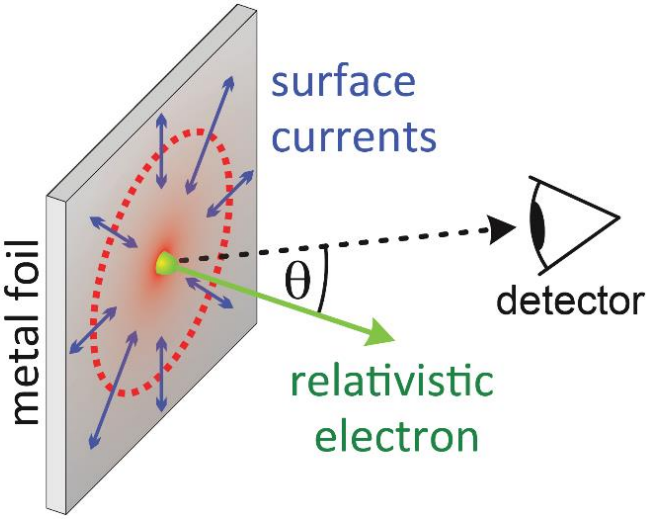
2.5 J, 30 fs, plasma density 3.1×10^{18} cm^{-3}, mixed He + 1% N_2 , 3 mm gas jet

Couperus *et al.* Nat. Commun. 8, 487 (2017)

Parameters	Mean ± Shot-to-shot jitter
Mean peak energy	250 MeV ± 22.5 MeV
Charge in FWHM	220 pC ± 40 pC
Abs. energy width	36 MeV ± 11 MeV
Divergence	7 mrad ± 1 mrad

A. Irman, J.P. Couperus *et al.*, Plasma Phys. Control. Fusion 60, 044015 (2018)

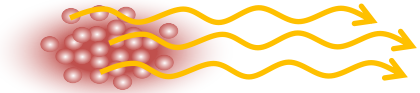
Coherent Transition Radiation in a nutshell



- Transition radiation (TR) is emitted when a relativistic charge passes through an interface between two dielectric media.

$$\frac{d^2 W_e}{d\omega d\Omega} = \frac{r_e m_e c}{\pi^2} \frac{\beta^2 \sin^2\theta}{(1-\beta^2\cos^2\theta)^2}$$

- Broadband radiation
- Radiation directional within 1/γ-cone
- TR-beam is radially polarized



$\lambda < L_{bunch}$ → incoherent



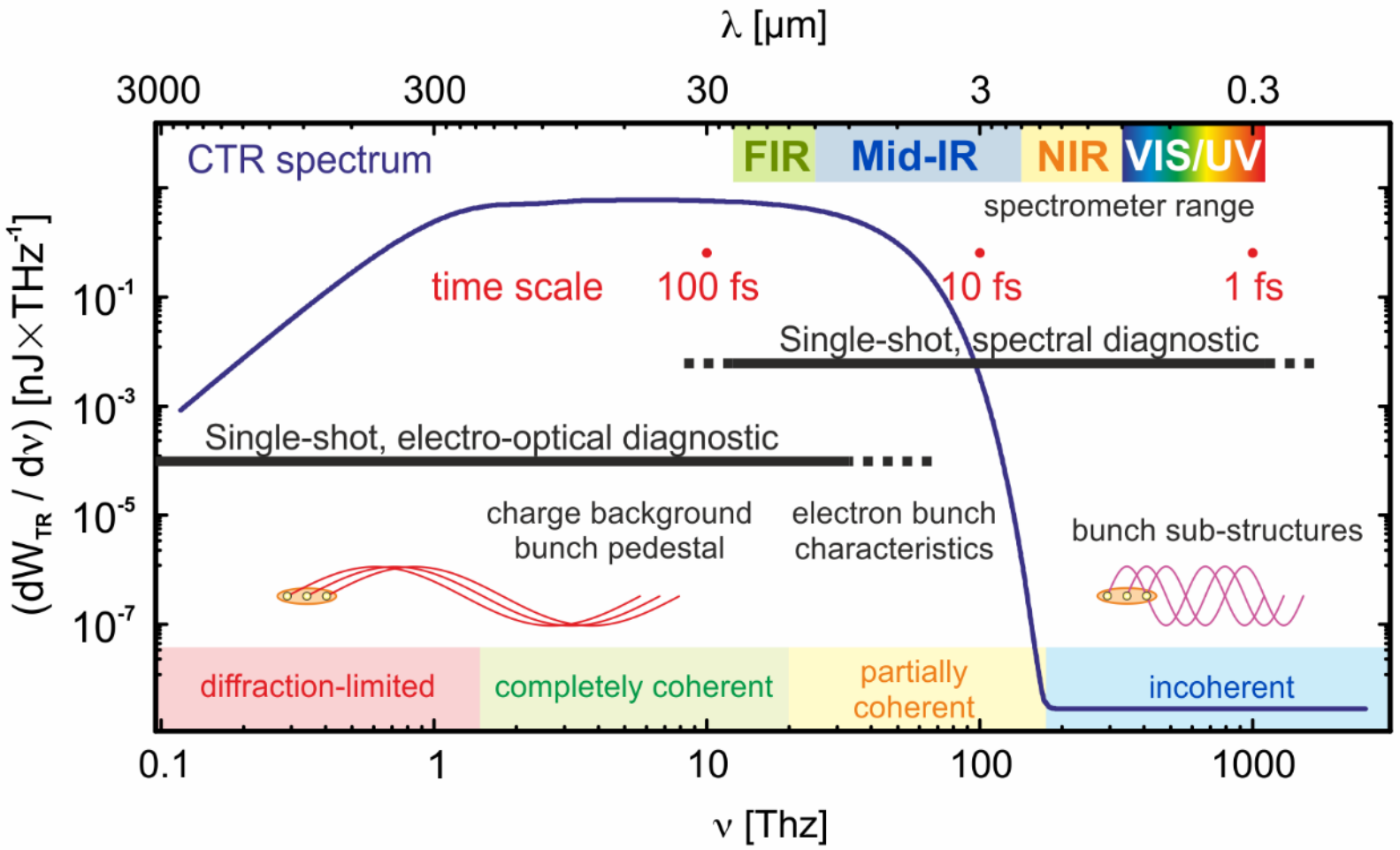
$\lambda > L_{bunch}$ → coherent

Useful for many (beam) diagnostics beyond pulse duration measurement

Diagnostics for plasma-based electron accelerators
M. C. Downer, R. Zgadzaj, A. Debus, U. Schramm, and M. C. Kaluza
Rev. Mod. Phys. **90**, 035002 (2018)

Spectral CTR diagnostics:

A gateway to the fs-scale



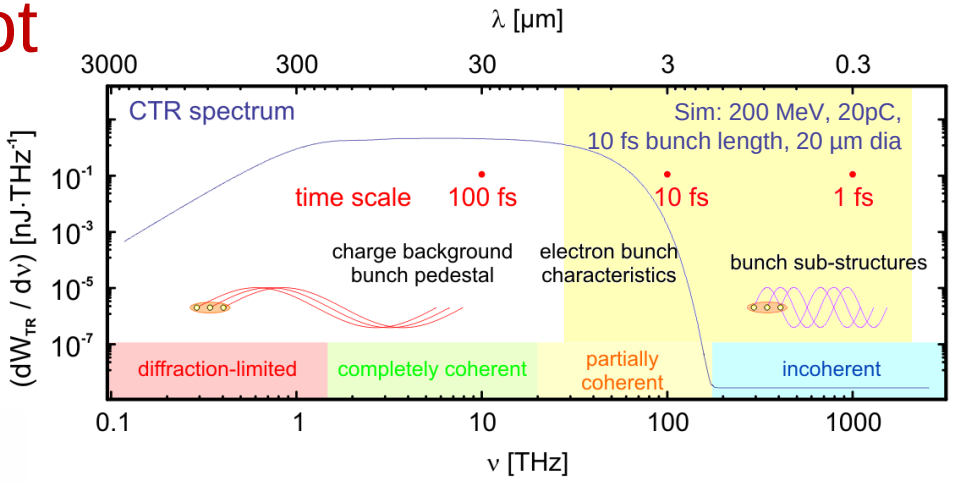
O. Lundh, *et al.,* Nat. Phys. **7**, 219 (2011).

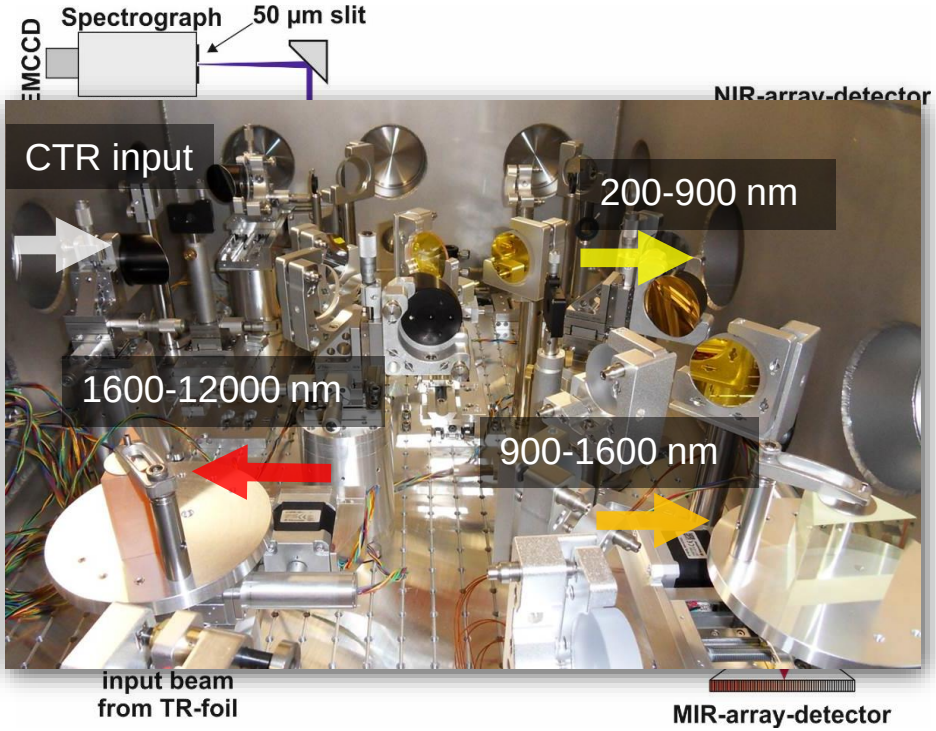
O. Lundh, *et al.*, PRL **110**, 065005 (2013).

M. Heigoldt, *et al.*, PRSTAB **18**, 121302 (2015).

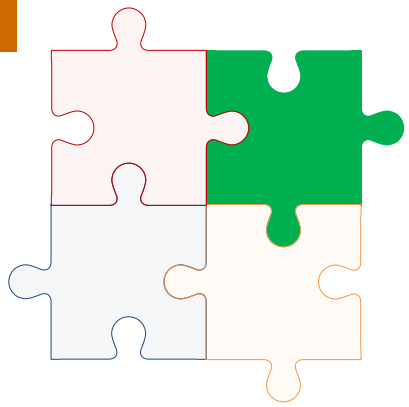
B. Schmidt, *et al.*, arXiv: 1803.00608 (2019)

Ultra-broadband UV-VIS spectrometer at single-shot



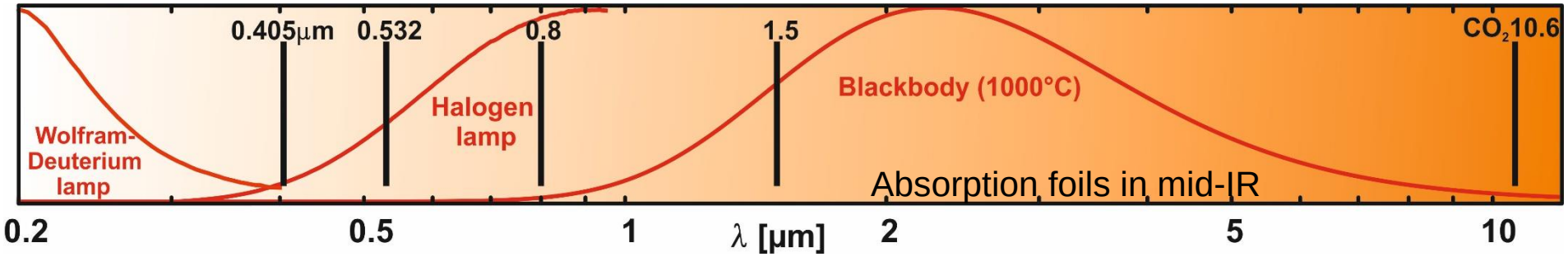


- **single-shot capability**
- 5.9 octaves frequency range
- **200 nm (UV) – 12 µm (MIR)**
- high spectral resolution
- high-dynamic range
- detection limit ~ 50 fJ of CTR

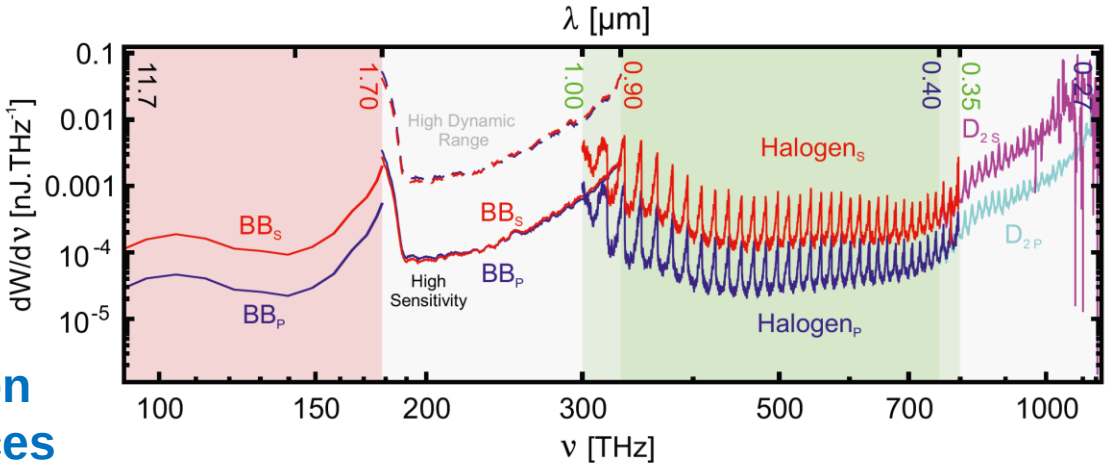


Photometric calibration
over the full spectrum for both polarizations

Absolute polarization dependent spectral calibration over 5.9 octaves needs lots of calibration sources!

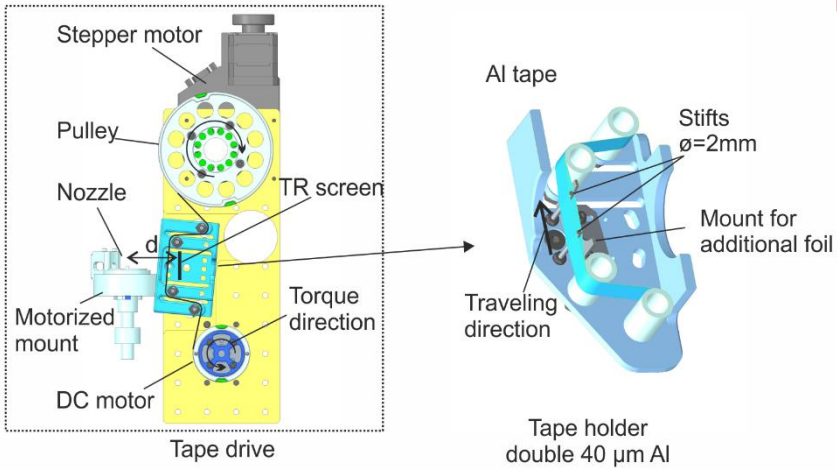


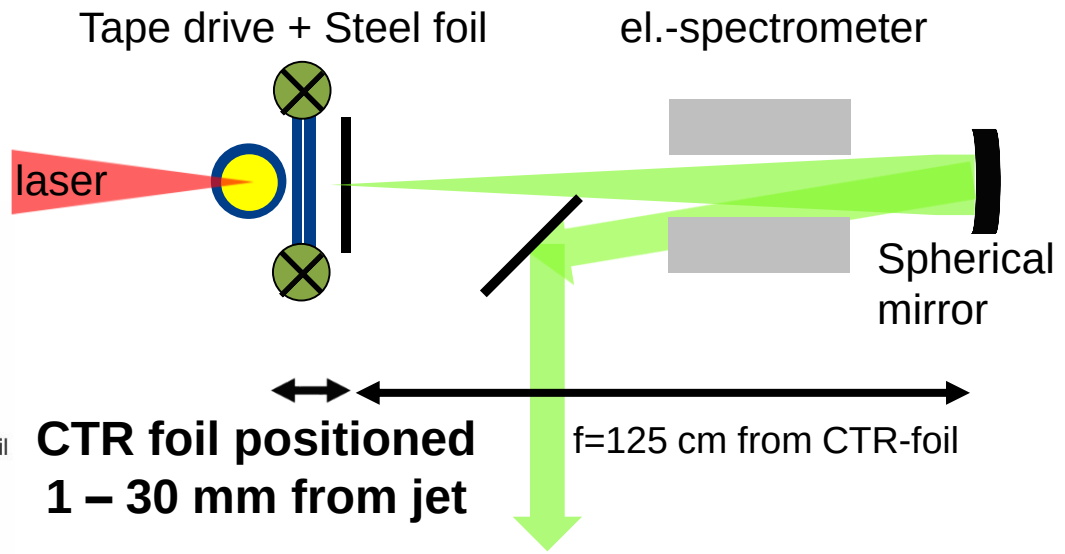
- **Wavelength calibration**
  Mercury-Argon lamp, Argon lamp, absorption lines of Teflon foils
- **Relative response calibration**
  Halogen and Deuterium lamps, blackbody radiator
- **Absolute photometric calibration based on a range of laser sources**
  400nm, 532 nm, 800 nm, 1.5µm and 10.6µm

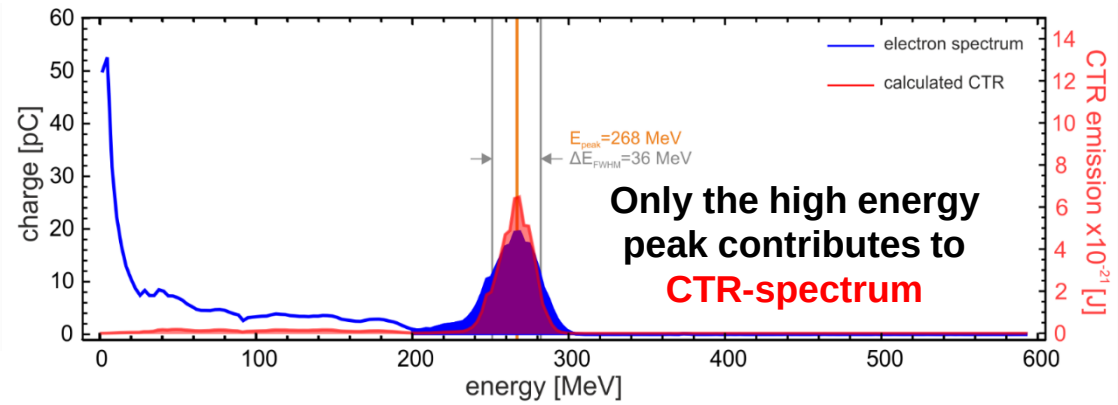


CTR foil target positioning & shielding

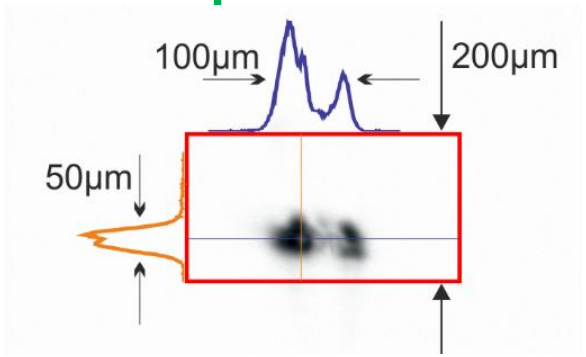
close to source for full coherence







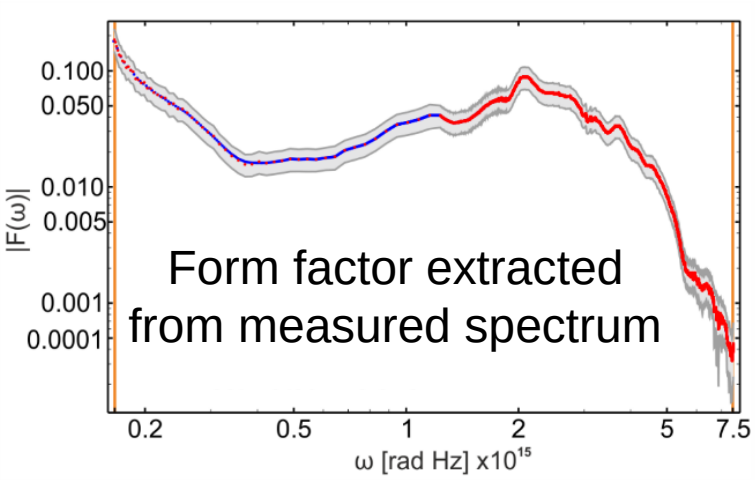
CTR spectrometer



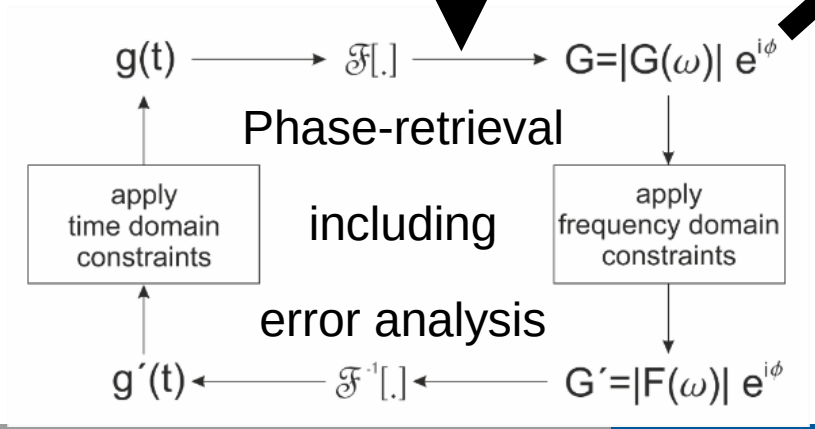
Only select shots that make it through the CTR spectrometer aperture without clipping.

Data analysis

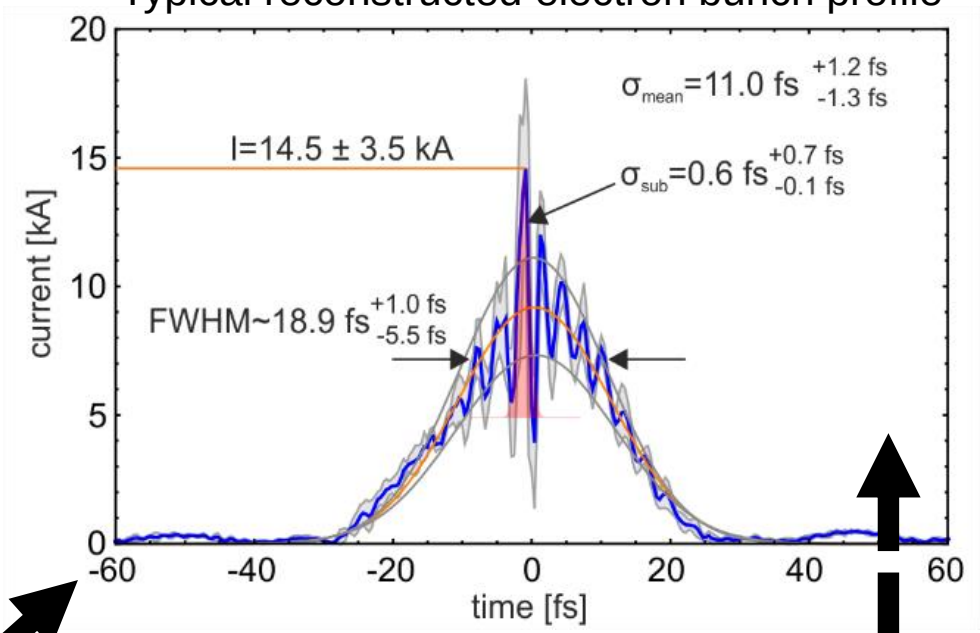
From the spectral to the time-domain



Form factor extracted from measured spectrum



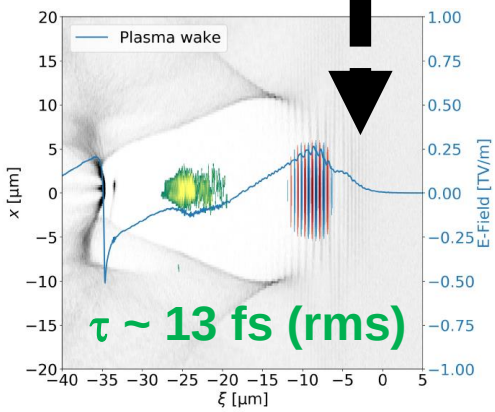
Typical reconstructed electron bunch profile



Electron bunch length agrees with 3D-PIC simulations

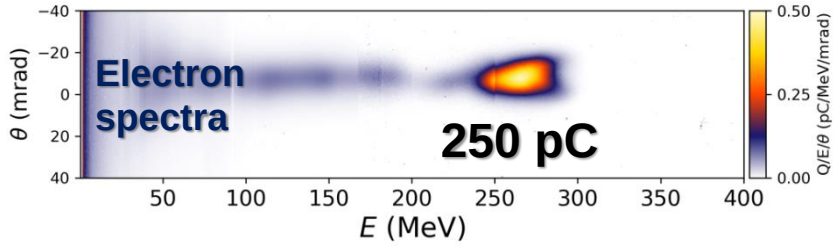
PIConGPU

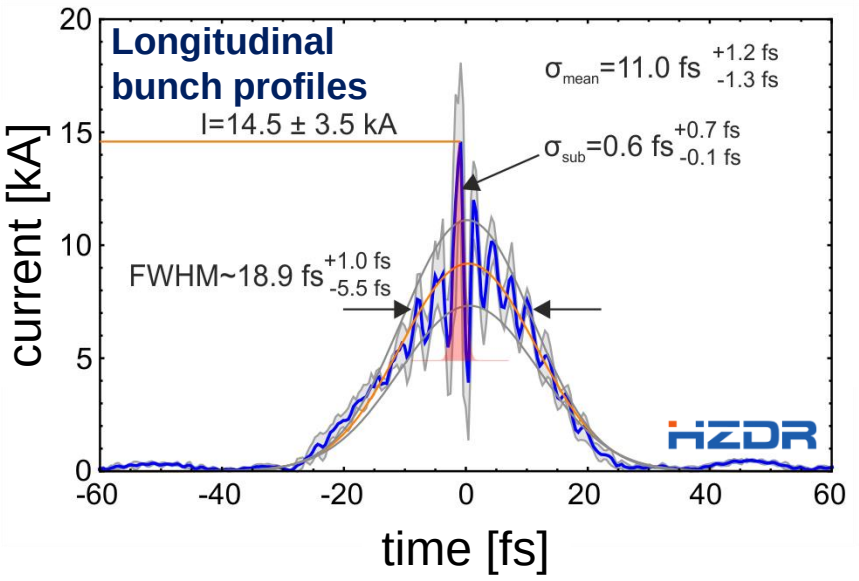
picongpu.hzdr.de



Longitudinal bunch profiles at sub-fs resolution

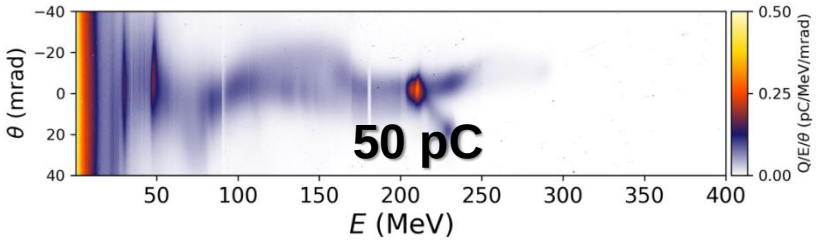
Ionization injection

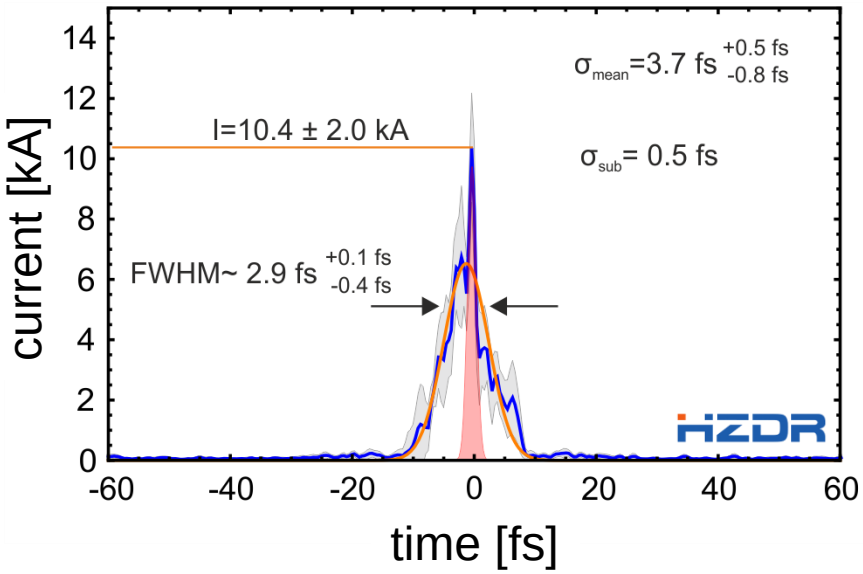




210MeV energy @ 5% energy spread

Self-injection





260MeV @ 15% energy spread

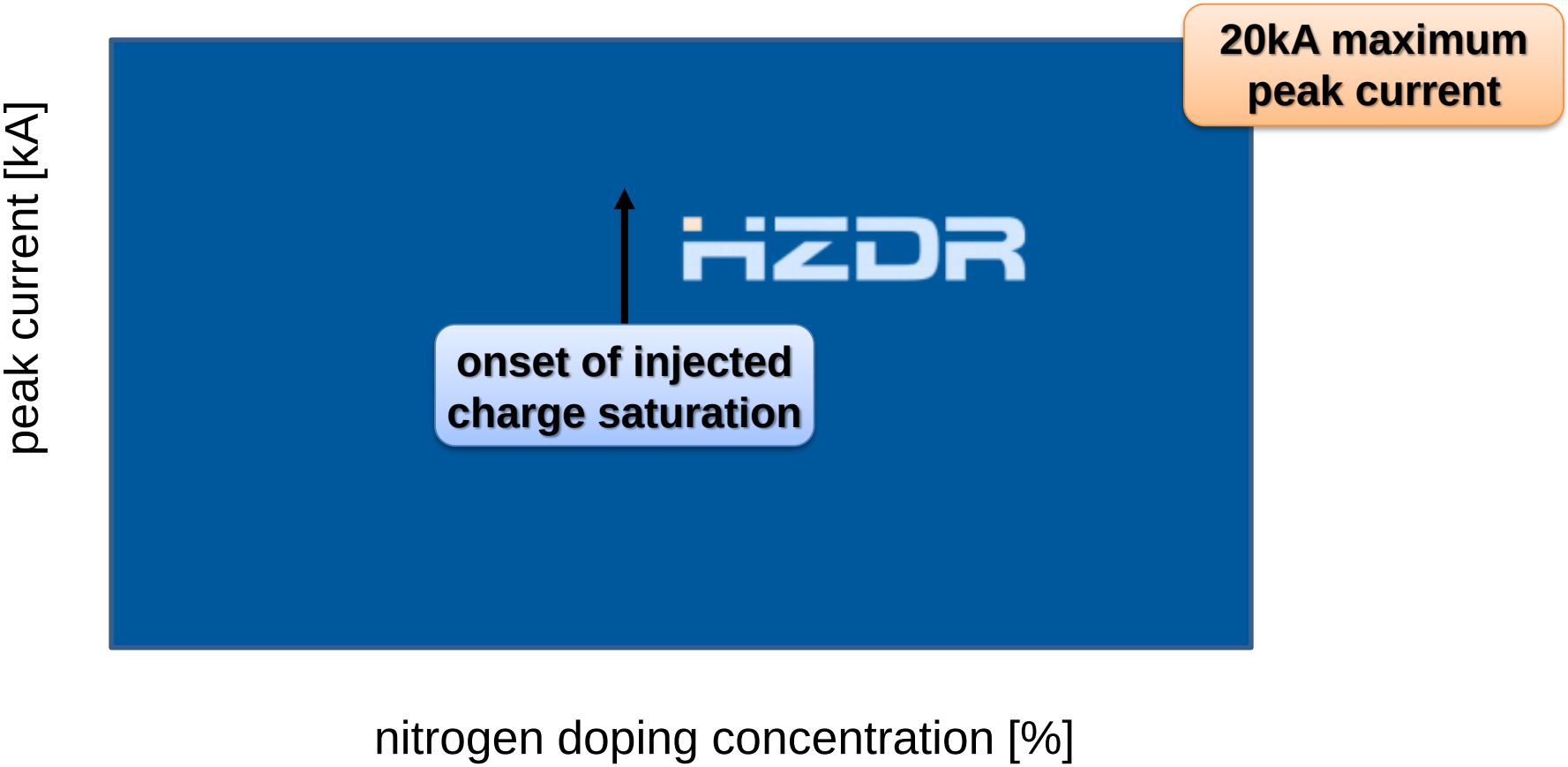
Bunch duration

15 – 20 fs (FWHM)
+ distinct sub-fs substructure

~3fs (FWHM)
+ less pronounced substructure

Systematical benchmarks of peak current
in laser-wakefield accelerator experiments

Injection scheme: self-truncated ionization

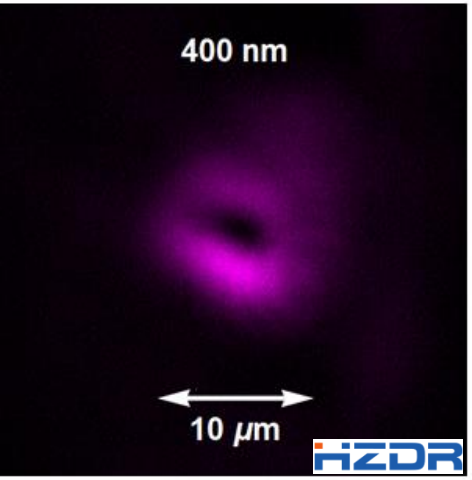


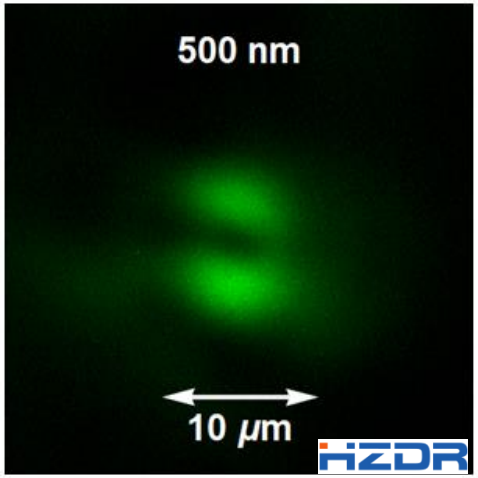
Each data point denotes the statistics of 15 – 25 shots.

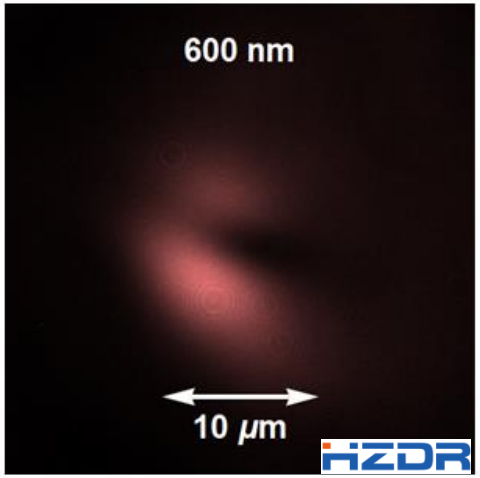
Coherent Optical Transition Radiation (COTR) imaging @ UV-NIR

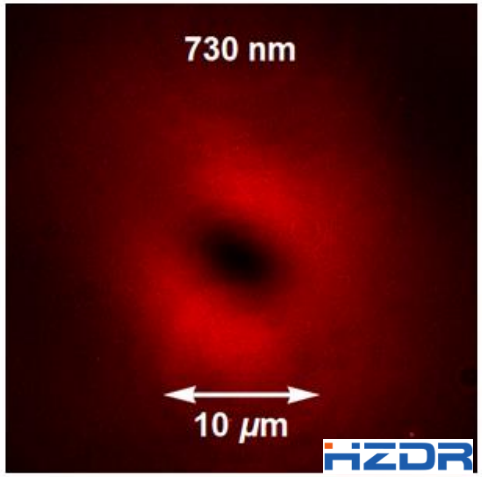
- High-resolution, transverse CTR data aquired at 1mm behind the gas jet
- Observation of annular Point Spread Function
  - source size sub microns
  - hints at sub-structures
- Coherence observed at various wavelengths
  - bunch sub-structures
  - sub-fs length
- CTR (Wartski) Interferometry can analyze bunch sub-structure properties (e.g. emittance)

Visit talk of Mike Downer Wed, 18:00





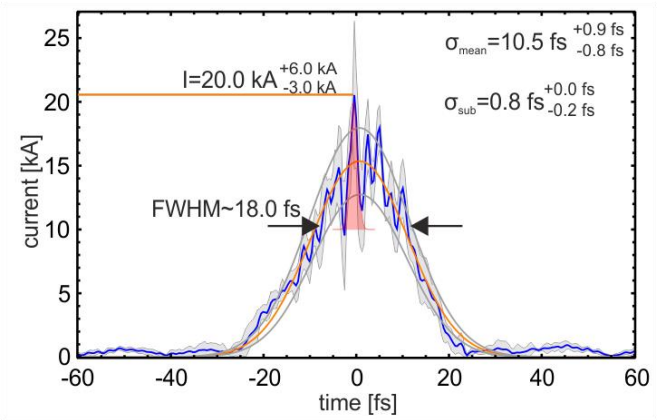




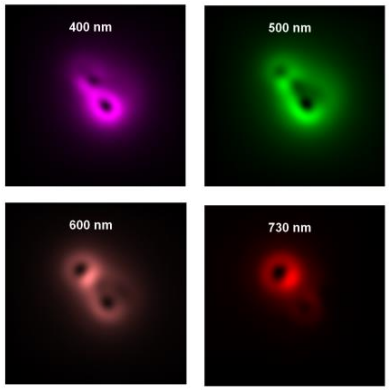
Outlook – 3D bunch profile diagnostics

- CTR spectra and images are complementary diagnostics of longitudinal and transverse electron beam distribution.
- All spectral and imaging measurements are simultaneously aquired at single shot.
- Our goal is to combine the analysis diagnose the 3D bunch profile at µm and fs-resolution.

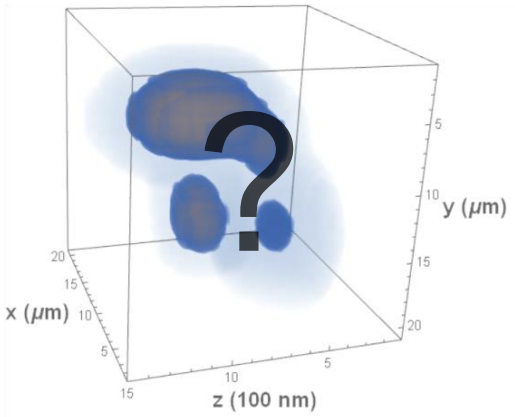
Reconstructed bunch profile



CTR images aquired at several wavelengths



3D Reconstruction



Conclusions

- **Single-shot, sub-fs** resolution, energy independent spectral-domain bunch profile diagnostics for electron bunches **down to the sub-pC charge scale**.

- **Enables characterizing** longitudinal bunch profiles for different **Laser-wakefield acceleration injection schemes**, such as self-injection, self-truncated ionization injection,… .

- **CTR spectra and imaging are complementary** techniques, promising for 3D electron bunch reconstructions.

Self-Truncated Ionization injection

- Typical bunch duration **11fs (rms), 19 fs (FWHM)**
- Typical bunch sub-structure duration **0.6 fs (rms)**
- Typical peak current **15 kA**
- Maximum peak currents of **20kA** reproducibly attained using steep gas profiles and nitrogen doping concentrations of 1.5%.

Self-injection

- Typical bunch duration **3.7fs (rms), 2.9 fs (FWHM)**
- Weak sub-structure with **~0.5 fs (rms)** duration
- Typical peak current **10 kA**