Advanced diagnostics for high-peak current electron beams

Unravelling the multiscale nature of LWFA longitudinal electron bunch characteristics

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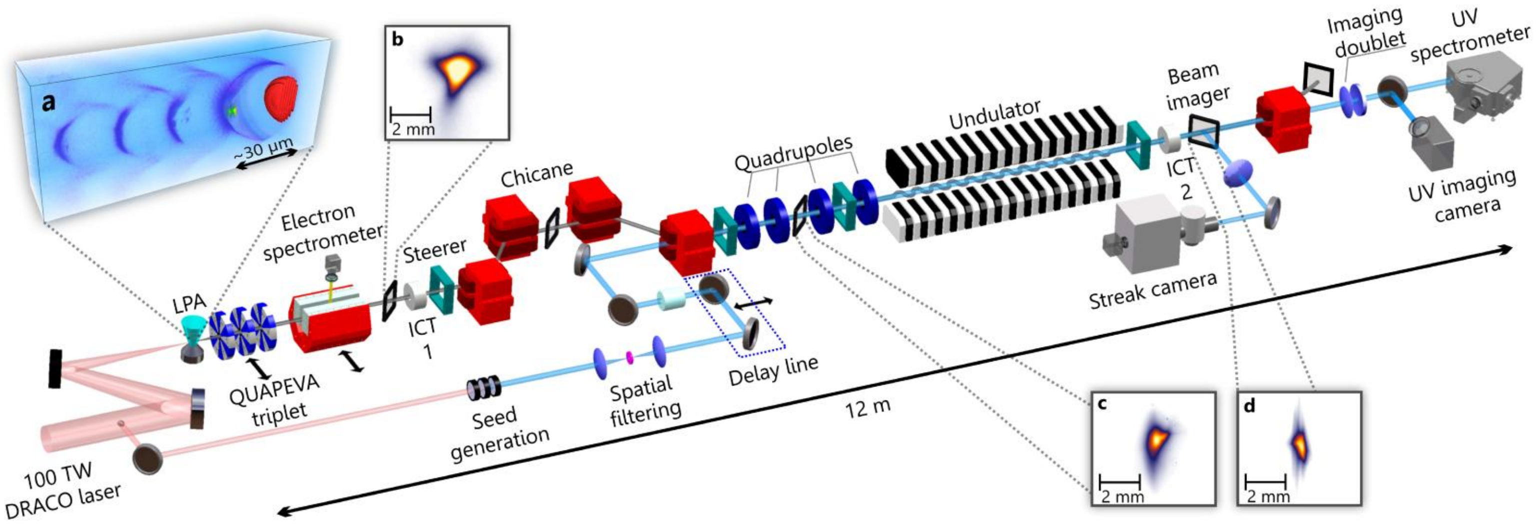
High brightness electron beams for future X-ray lasers

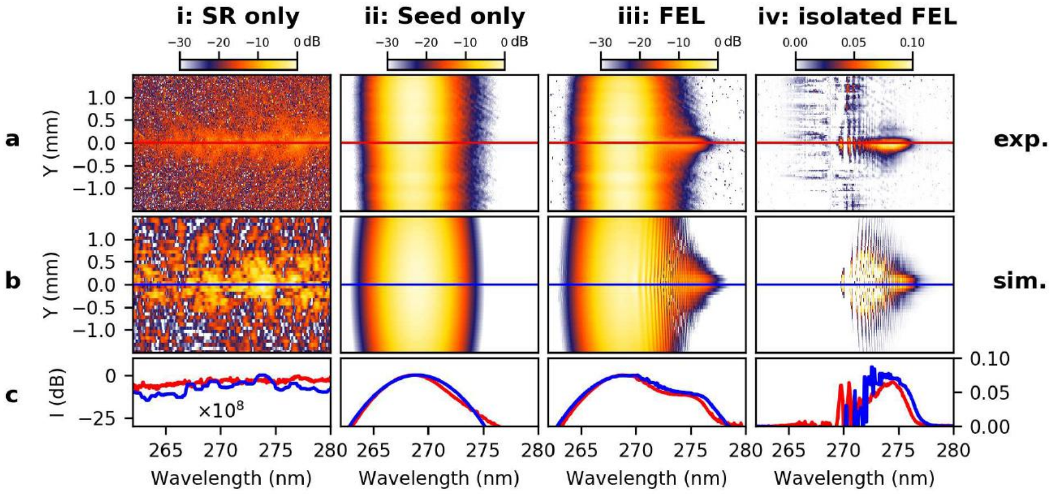


Marie Labat et al., *Nat. Photon.* **17**, 150–156 (2023)
COXINEL collaboration

First demonstration of a seeded FEL driven by a laser plasma accelerator at HZDR

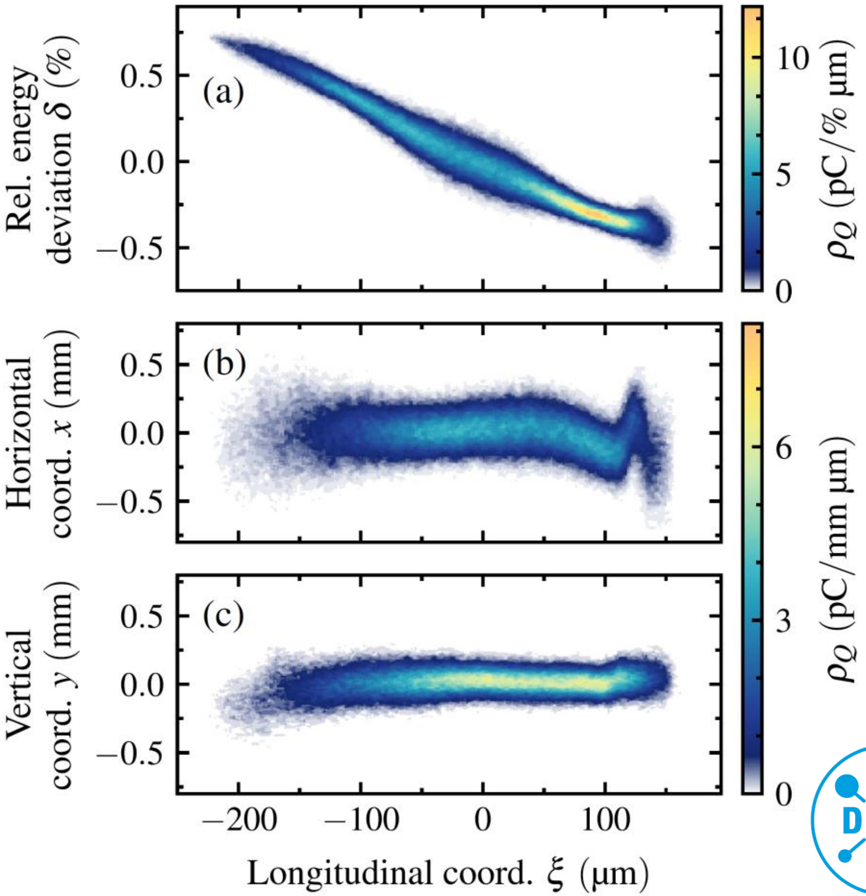
Motivation for measuring electron bunch profiles

- Measure, understand and control LPA beam dynamics.
- Micro-structures and pre-bunching are critical for designing FELs.
- Characterize chromaticity- and transverse-dynamics in subsequent beam transport.

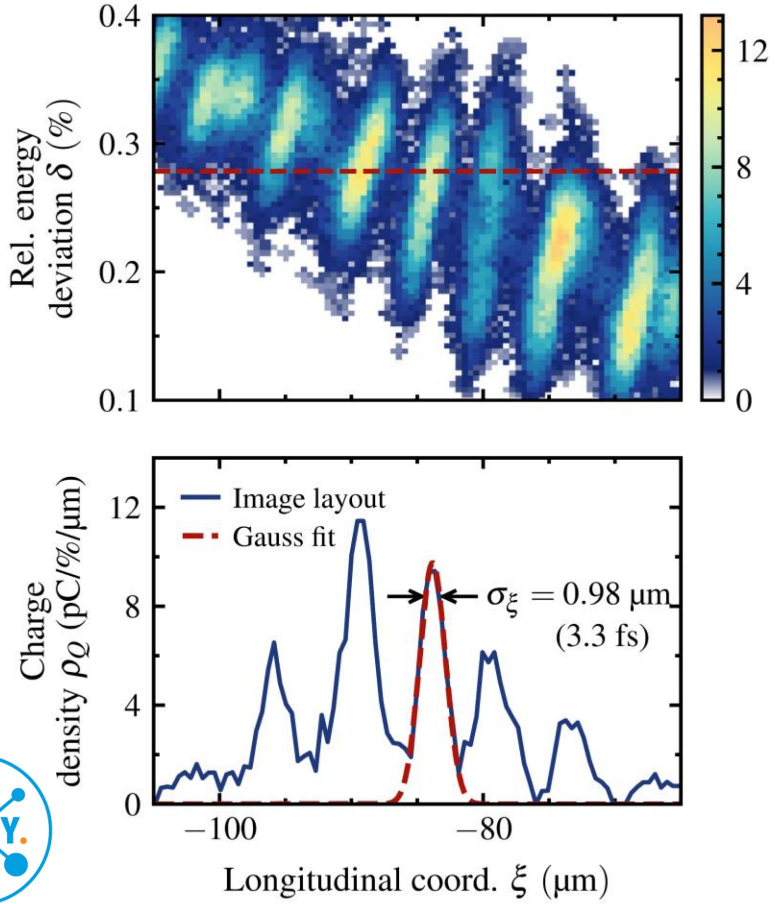


Longitudinal diagnostics in conventional accelerators leverage transverse deflecting rf-structures (TDS)

Longitudinally resolved phase space



Resolution in femtosecond range



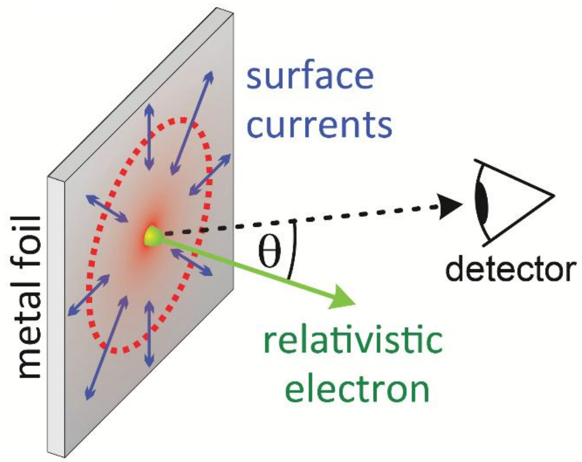
Challenging for Laser-plasma accelerators

- TDS require rf-accelerator infrastructure.
- Dedicated beam transport to TDS imposes limits on beam properties, p.ex. energy, energy spread and emittance.
- Although single-shot is possible, TDS results usually achieved by many-shots scans.
- **Temporal resolution is fundamentally limited by slice energy spread.**

Behrens and Gerth,DIPAC09 Proc. (JACoW, 2009), pp. 269–271

Gonzáles Caminal *et al.*, PRAB **27**, 032801 (2024)

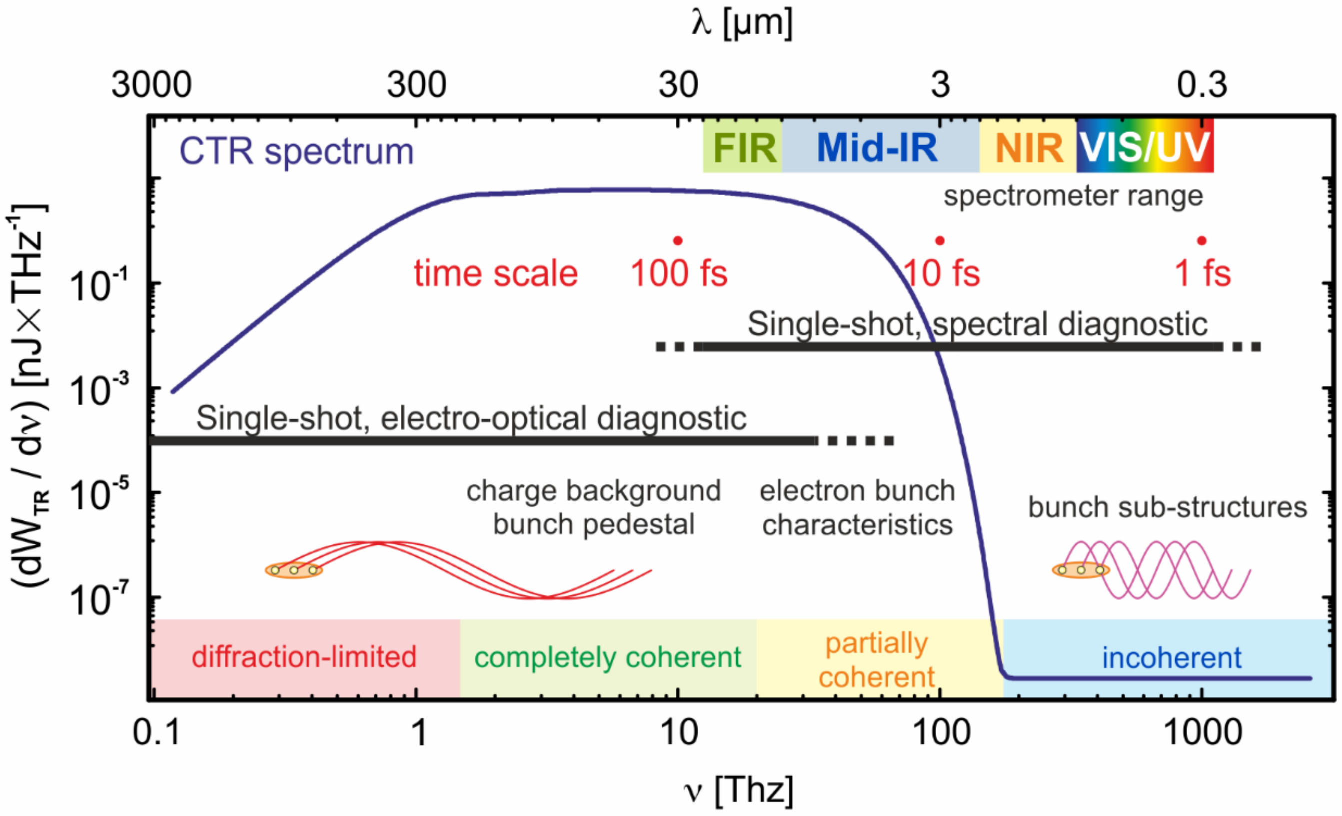
Coherent Transition Radiation diagnostics: A gateway to the fs-scale



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

$$\frac{d^2 W_{\mathrm{beam}}}{d\omega d\Omega} = \left(N_e + N_e^2 F(\omega,\theta)\right) \frac{d^2 W_e}{d\omega d\Omega}$$

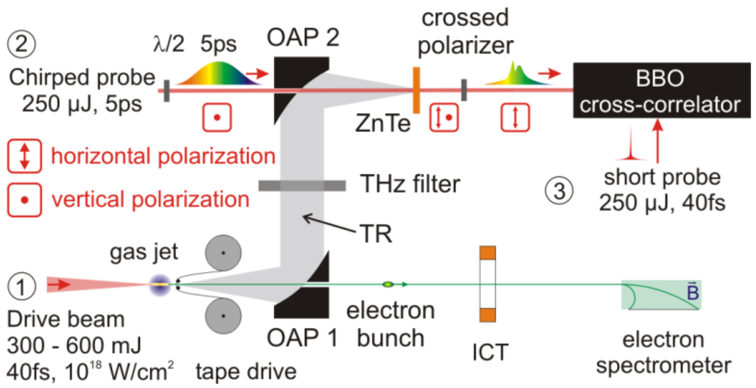
- Transition radiation (TR) is emitted when a relativistic charge passes through an interface between two dielectric media.
  - Broadband radiation
  - Radiation directional within 1/γ-cone
  - TR-beam is radially polarized
  - Very weak dependence on electron energy

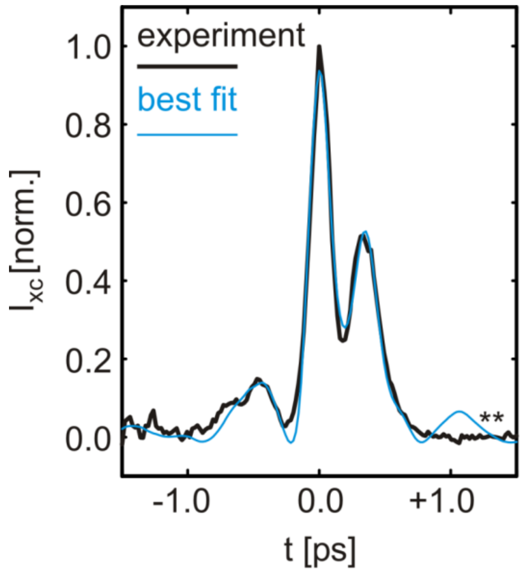


Diagnostics for plasma-based electron accelerators
M. C. Downer, R. Zgadzaj, A. Debus, U. Schramm, and M. C. Kaluza
Rev. Mod. Phys. **90**, 035002 (2018)

Sim: 200 MeV, 20pC, 10 fs bunch length, 20 µm diameter

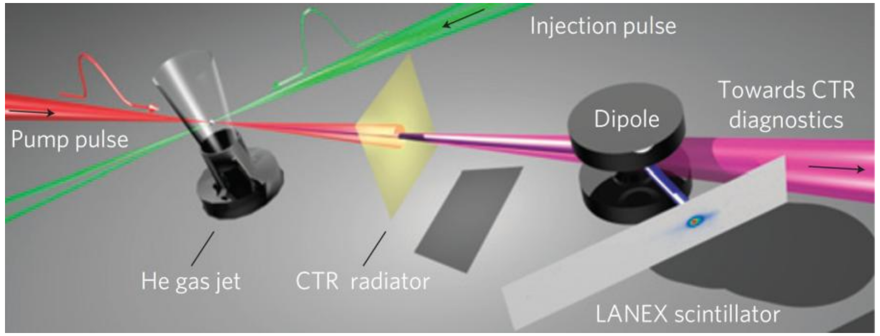
Early CTR time-domain electro-optics and CTR spectroscopy

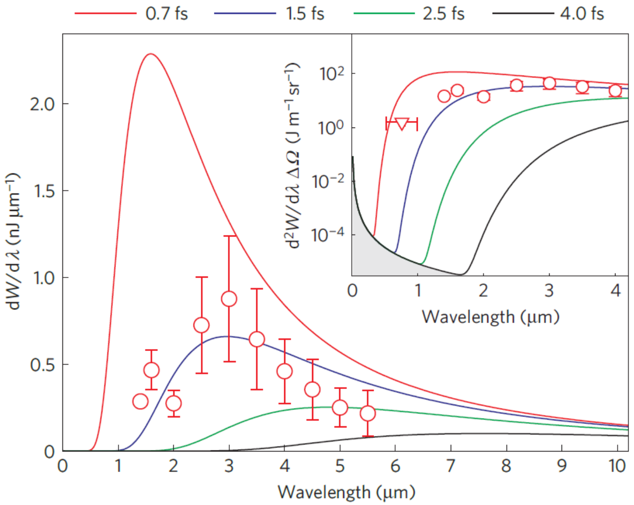




Debus *et al.* PRL **104**, 084802 (2010)

- Single-shot CTR diagnostic using ZnTe-based EO setup.
- Short bunch <38fs (FWHM) sitting on top of long background ~710 fs (FWHM). Exploited interference patterns.
- Limited in resolution by TO resonance of ZnTe crystal.





Lundh *et al.* Nat. Phys. **7**, pp. 219–222 (2011)

- Multi-shot CTR spectral diagnostic using monochromator, averaging 15 shots over for each wavelength.
- Mean bunch charge 15 pC.
- Inferred 1.4 –1.8 fs (rms) feature with 3 – 4 kA peak current.

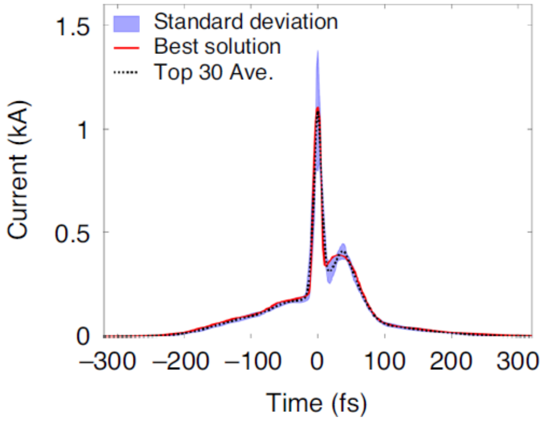
Towards 3D snapshots – Electro-optic sampling combined with optical CTR images

- GaP-based electro-optic setup and optical imaging of CTR foil.
- Bunch head <10fs, >1kA and transverse beam size <30µm
- Single-shot capability
- Combination of EO reconstruction from GaP signals yields impressive resolution.

Kansai Photon Science Institute

- Assuming separability, the 3D distribution is simply a product of the transverse and longitudinal beam distributions.

Reconstructed absolute longitudinal current profile



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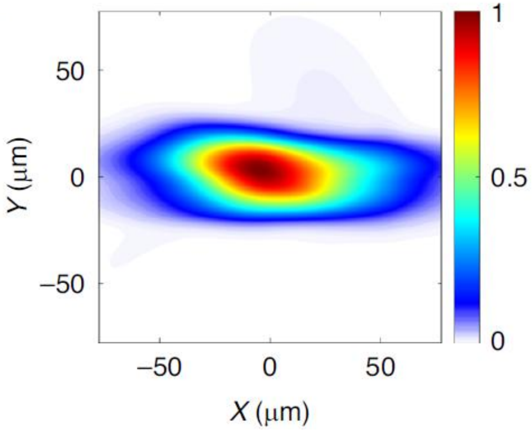
Reconstructed relative transverse beam profile



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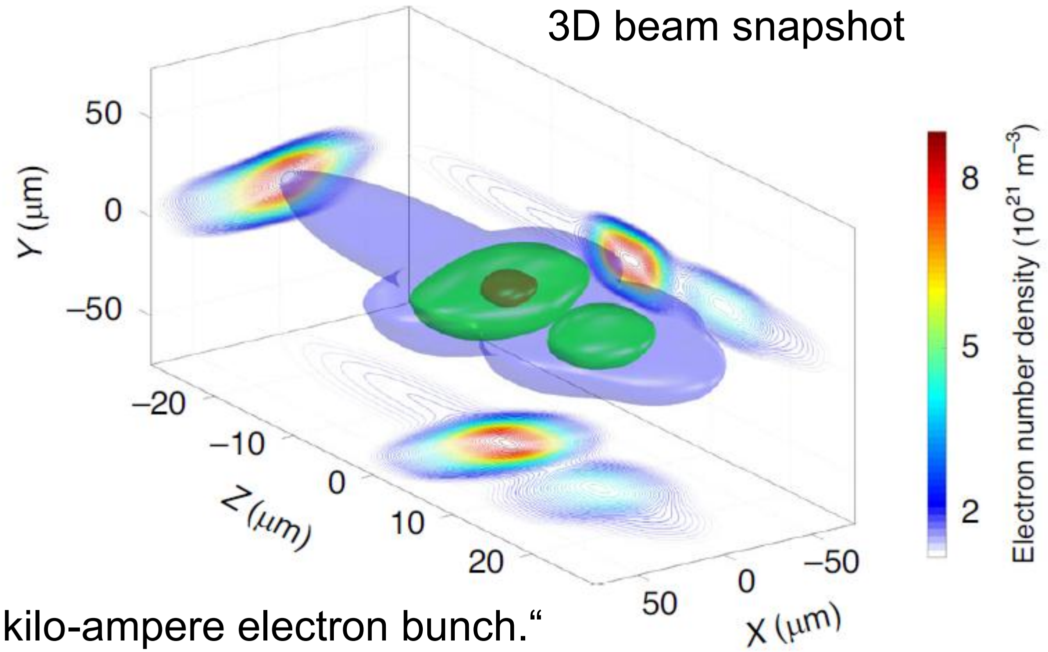
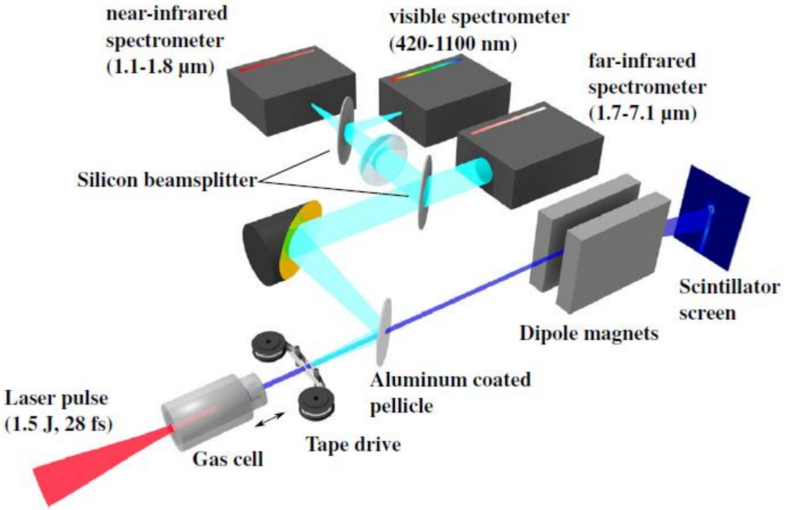
3D beam snapshot

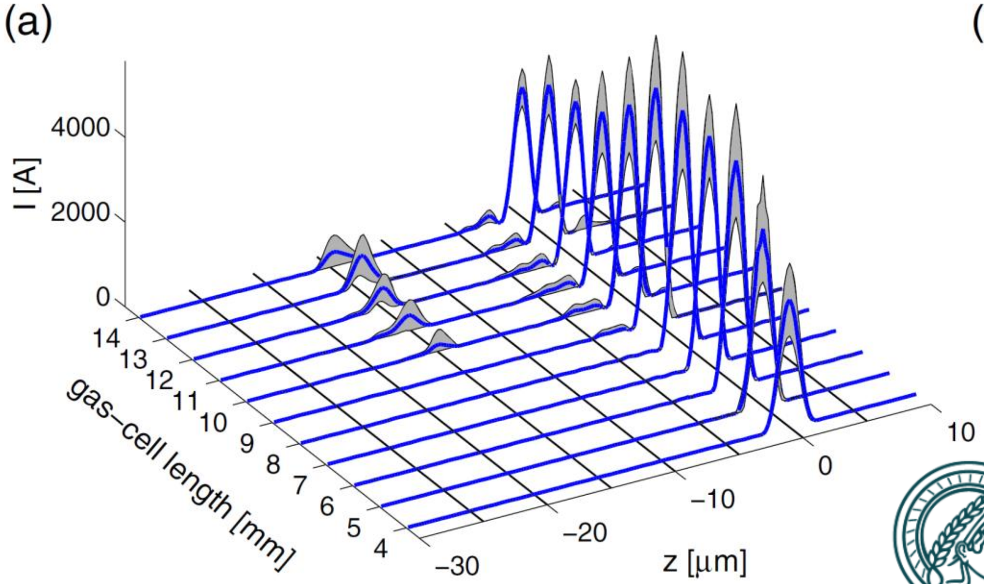


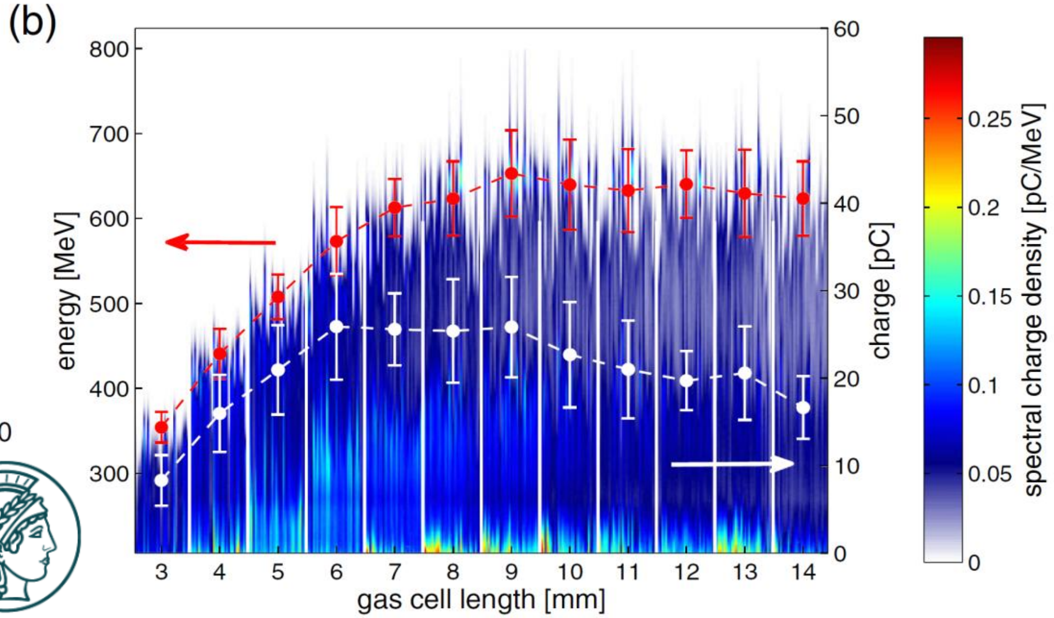
Kai Huang et al. "Electro-optic 3D snapshot of a laser wakefield accelerated kilo-ampere electron bunch.“ Light: Science & Applications (2024) 13:84.

CTR spectroscopy probes the short time scale

- Single-shot spectrometer (420nm – 7.1 µm)
- Bunch duration: 5.1 ± 0.2 fs (FWHM)
- Peak current: 5.5 ± 1.2 kA
- Used 30-shot average for systematic analysis
- Observed change to double bunch structure when reaching pump depletion length.



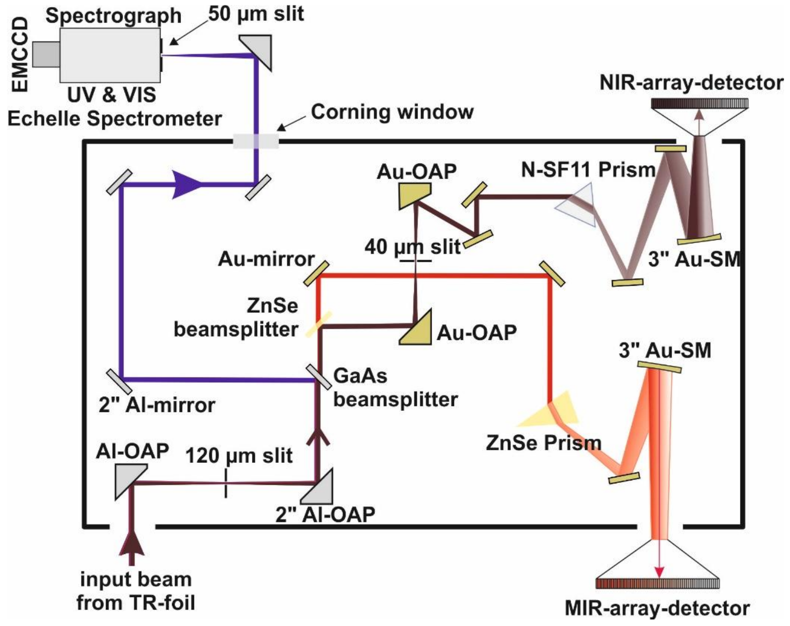




Heigoldt *et al.* PRAB **18**, 121302 (2015).

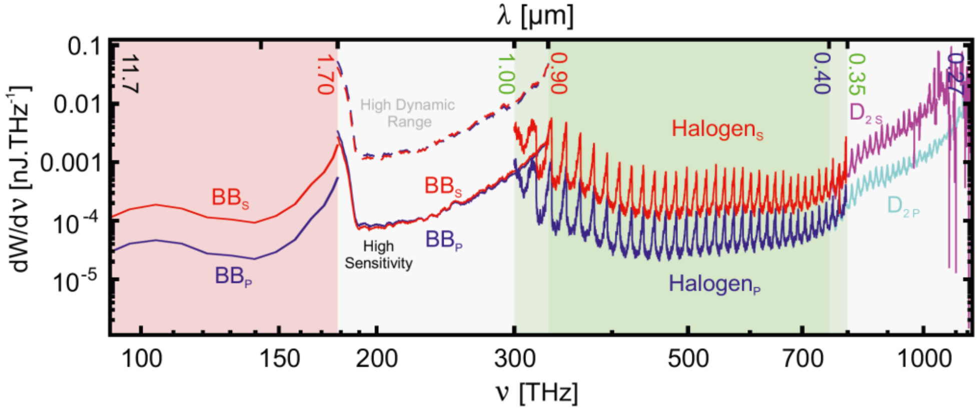
Bajlekov *et al.* PRAB **16**, 040701 (2013).

Ultrabroadband UV to mid-IR spectrometer at single shot



- **single-shot capability**
- 5.5 octaves frequency range
- **250 nm (UV) – 11.35 μm (MIR)**
- high spectral resolution
- high-dynamic range
- detection limit ~ 50 fJ of CTR

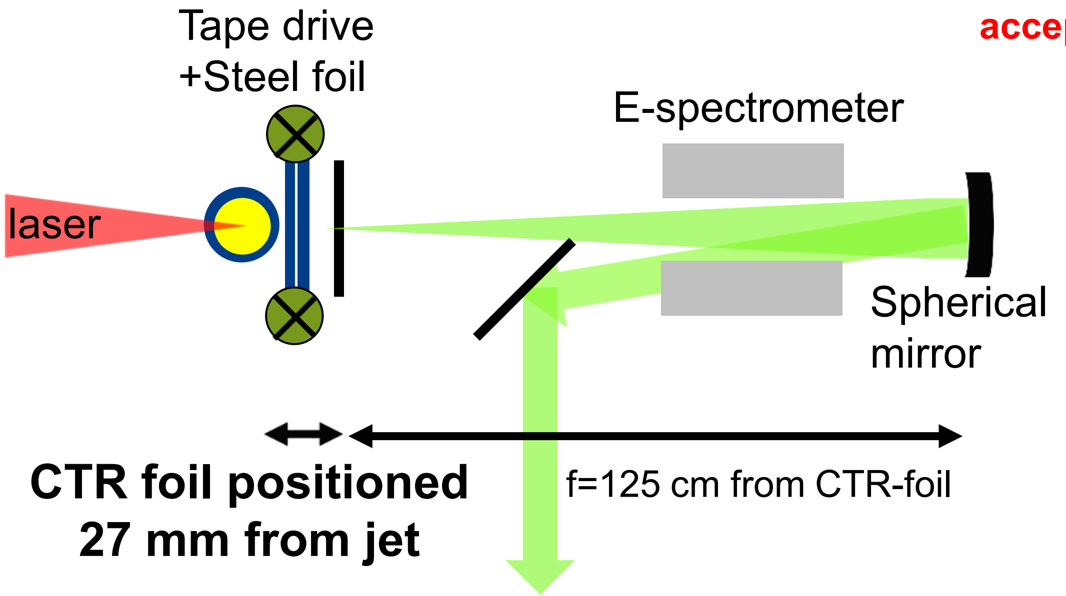
Detection threshold curve



Omid Zarini, *et. al.*, PRAB 25, 012801, (2022)
DOI: 10.1103/PhysRevAccelBeams.25.012801

- **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 positioning & shielding close to source for full transverse coherence



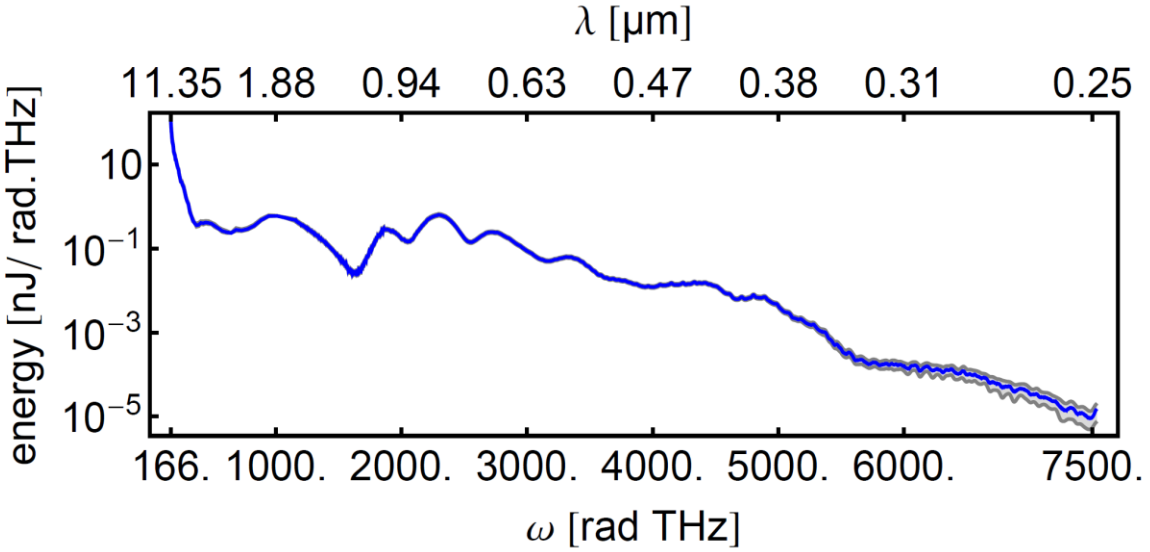
CTR foil positioned 27 mm from jet

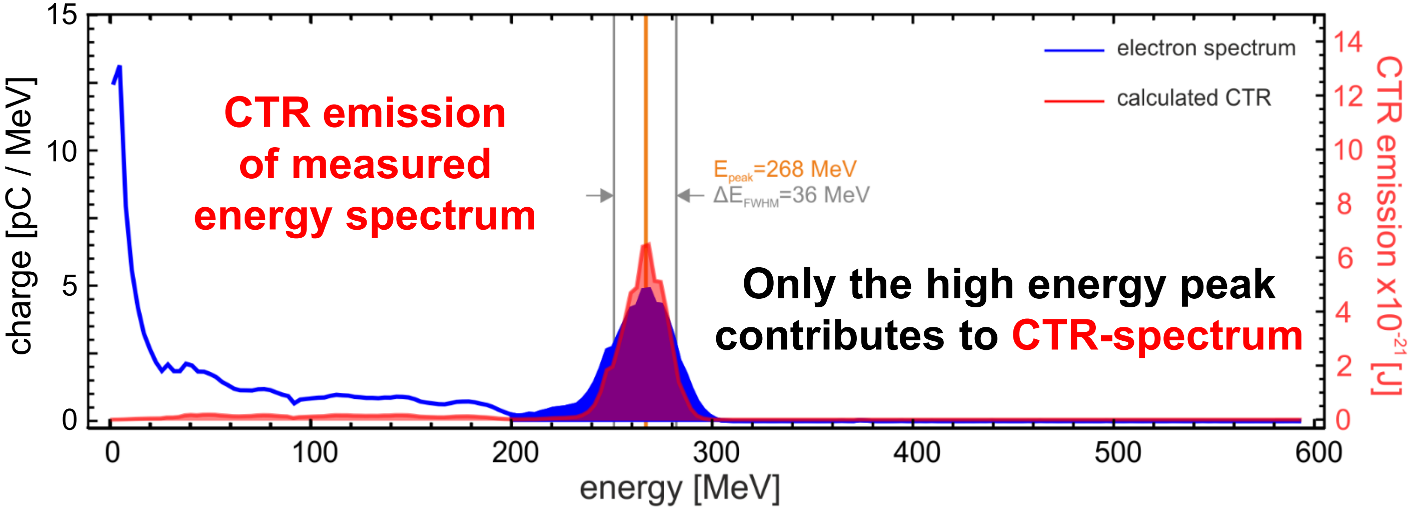
CTR spectrometer

Use electron spectra with divergence information to calculate formfactor spectrum normalization of measured CTR spectrum

Exclude shots with “insufficient” electron spectra

CTR-spectrometer acceptance angle θ ~ 16 mrad
$\gamma = 1/\theta \rightarrow E_{min} \sim 30$ MeV





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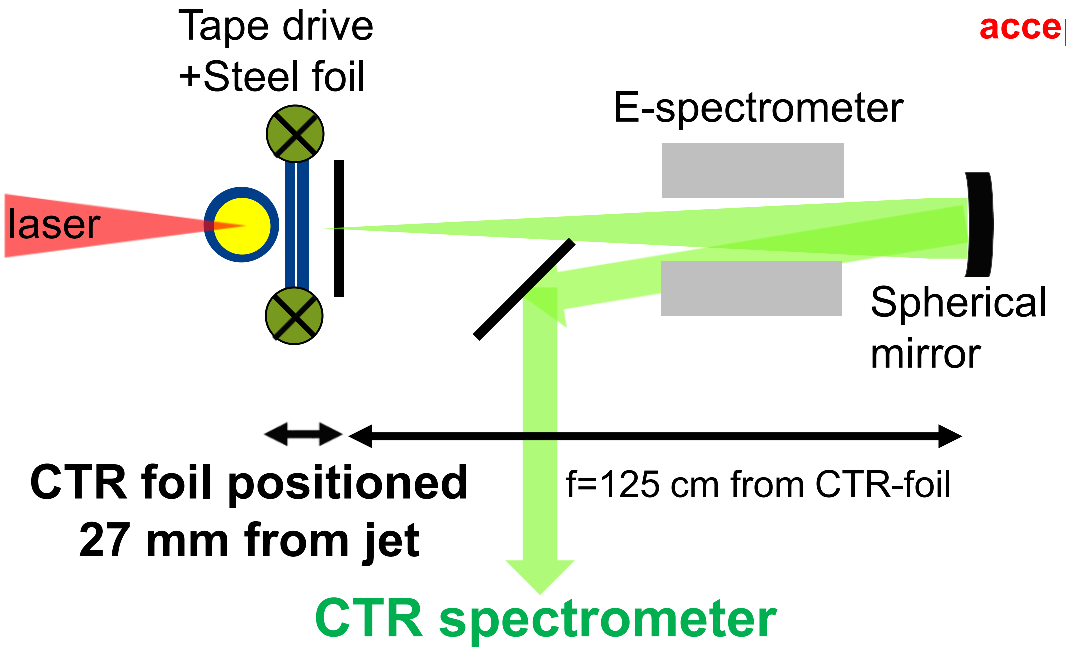


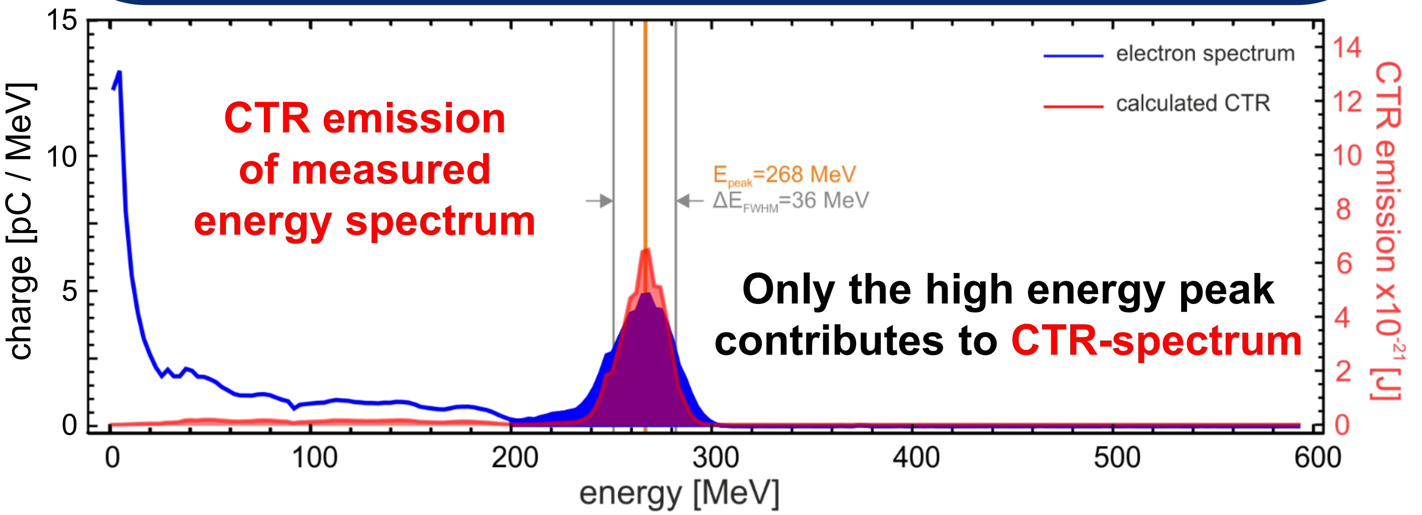
CTR-spectrometer acceptance angle $\theta \sim 16$ mrad
$\gamma = 1/\theta \rightarrow E_{min} \sim 30$ MeV

Small collection angle θ and proximity to LPA ensures

- **Full transverse coherence down to the UV range, decoupling longitudinal from transverse properties.**
- **Supressing CTR signal from low-energy electrons, thus enhancing bunch to (long) background contrast.**

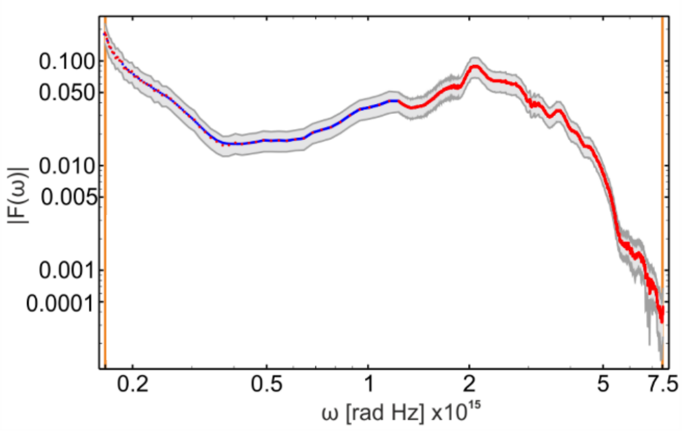
Use electron spectra with divergence information to calculate formfactor spectrum normalization of measured CTR spectrum

Exclude shots with "insufficient" electron spectra

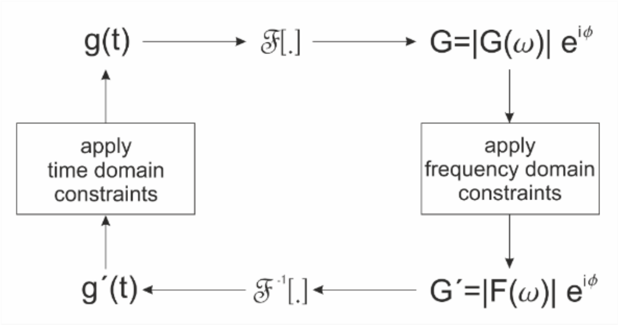


Data analysis: From the spectral to the time-domain

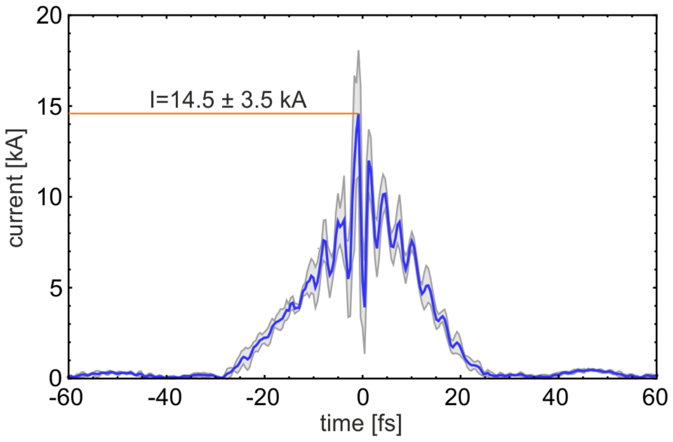
Form factor extracted from measured spectrum



Phase-retrieval including error analysis



Reconstructed electron bunch profile



Generate 50 - 150 reconstruction candidates for each shot based on variant of GS-phase retrieval algorithm

Remove reconstructions with insufficient quality-of-fit

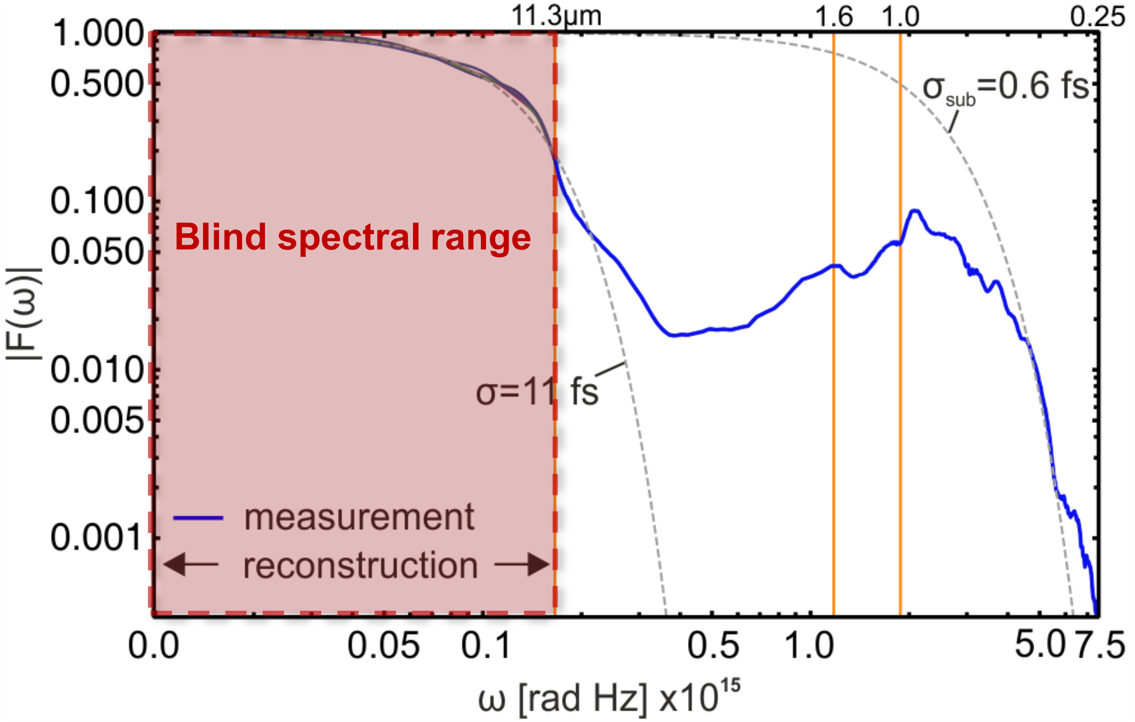
Define metric within acquivalent candidate solutions
Correlate all candidates with one another, accounting for mirror and translational ambiguity and identify differences between solution candidates (sum of diff-squared).

Apply clustering algorithm to detect ambiguous reconstruction data (multiple clusters!) and remove outliers.

Omid Zarini, et. al., *IEEE AAC* 2018, pp. 1-5, (2018), DOI: 10.1109/AAC.2018.8659388

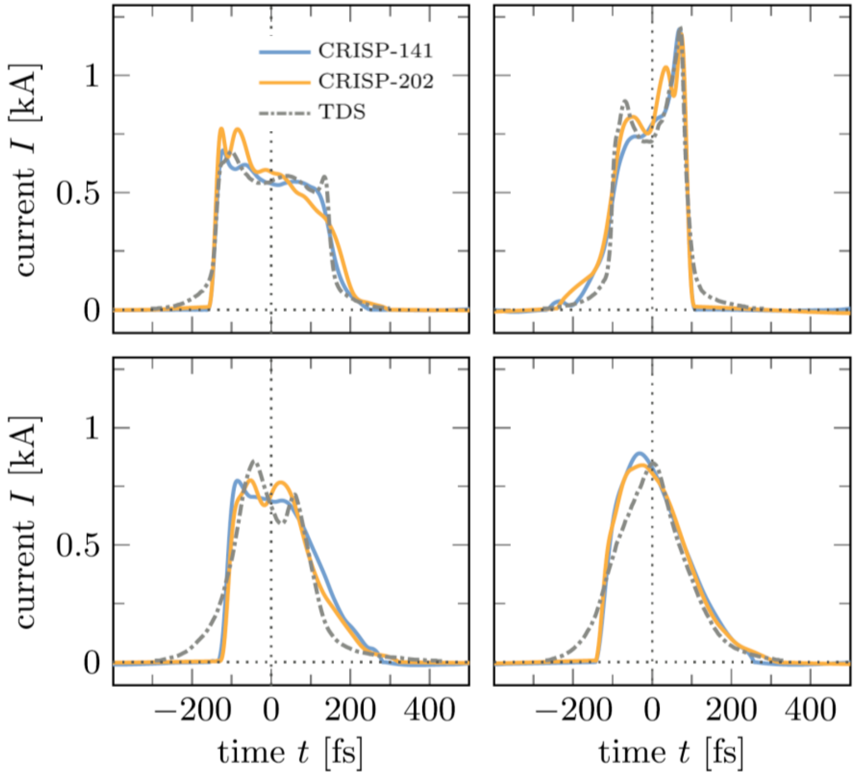
Typical electron bunch profiles extend over multiple time scales

Measured & reconstructed form factor spectrum



- Pulse pedastal: 11 fs (rms)
- Micro-structure 0.6 fs (rms)
- Actual pulse profile and duration is in between.

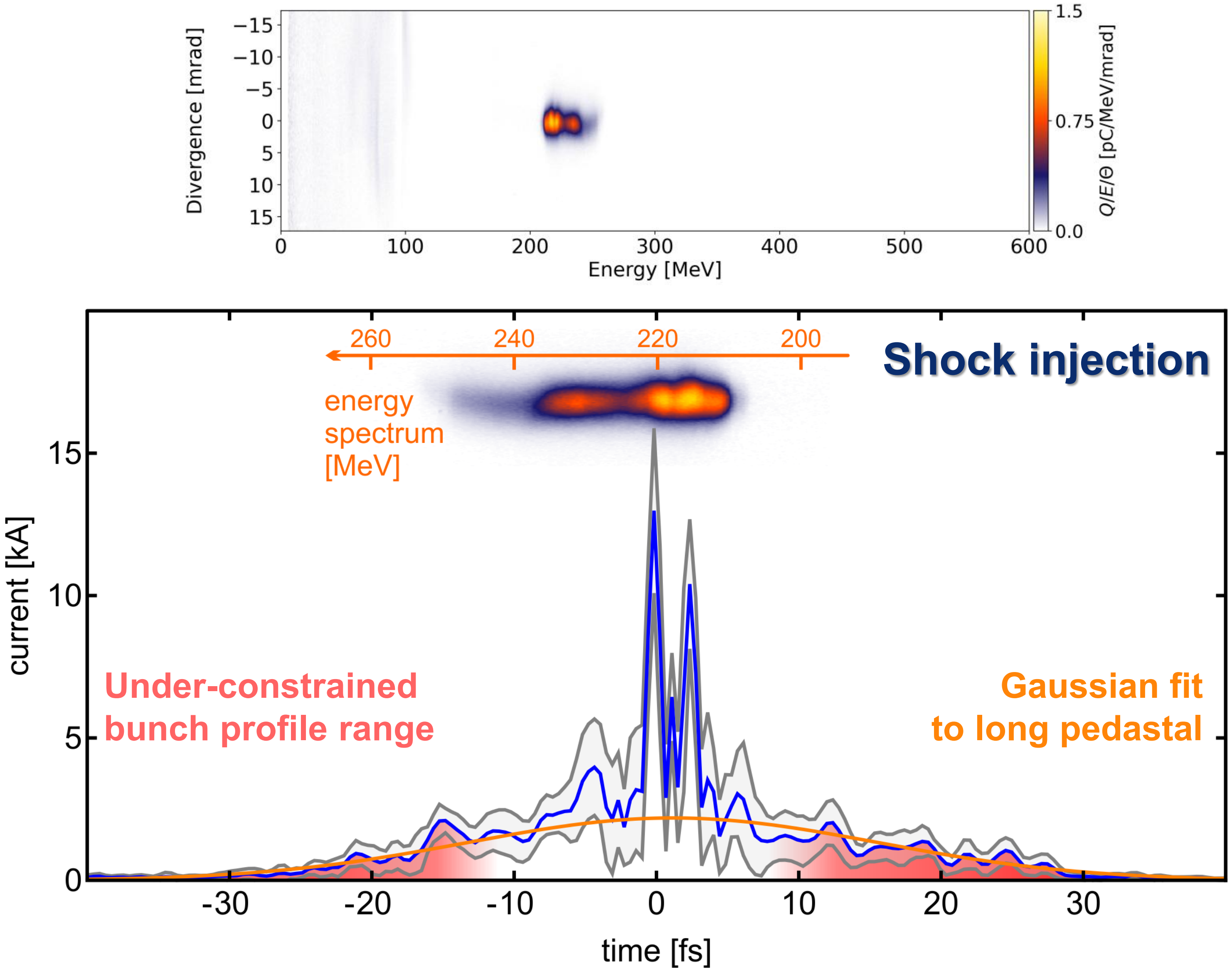
Extending CTR spectrum to the far IR would help



- Far-IR pyroelectric detector spectrometer **5µm – 433 µm**.
- Successfully benchmarked CTR spectroscopy against TDS measurements.

Bernhard Schmidt *et al.*
PRAB **23**, 062801 (2020)

Understanding the multiscale structure of LWFA bunch profiles



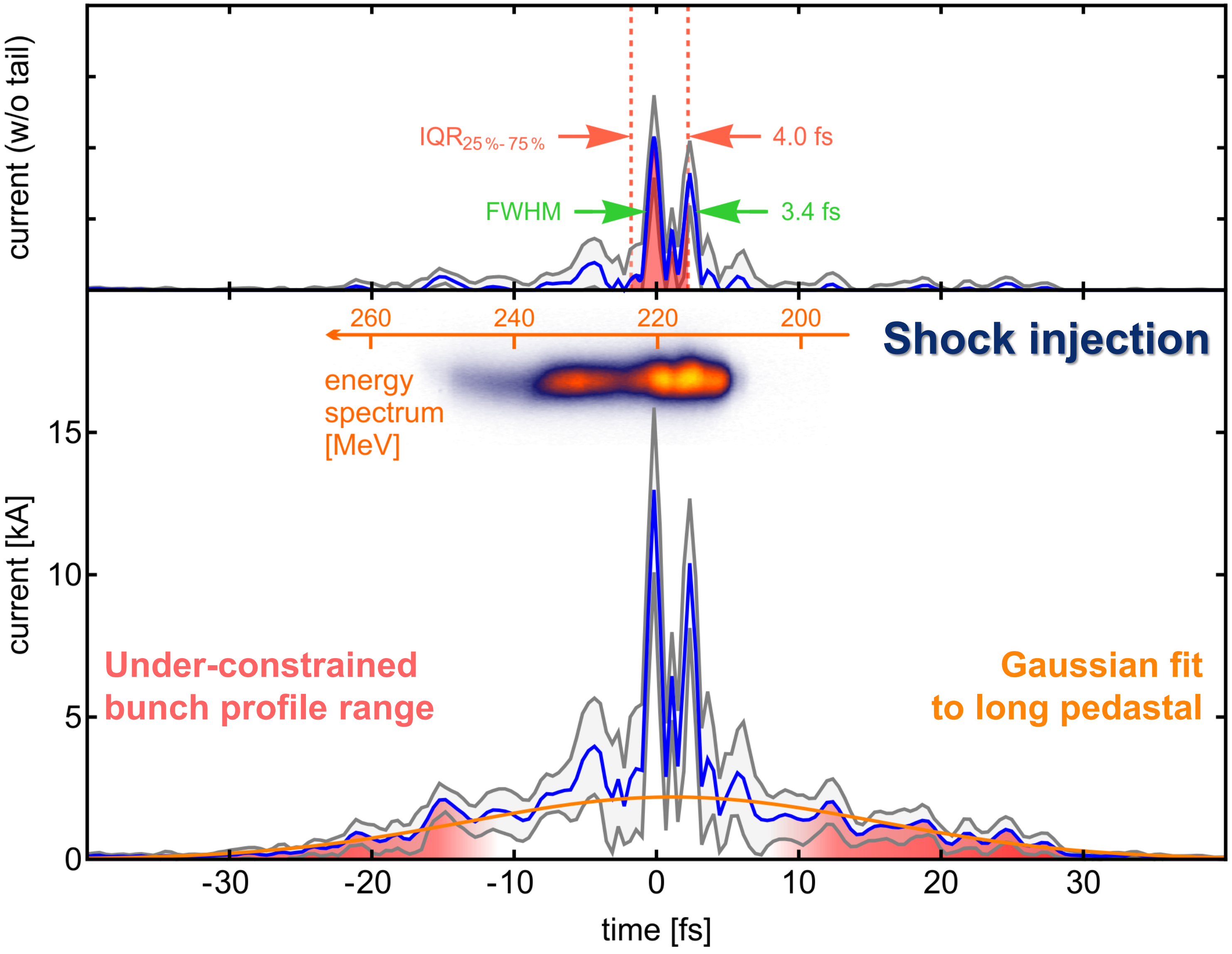
- **Long time-scale**
  Only well-constrained, where short-scale structure is available.

- **Short time-scale**
  Any measure of bunch duration needs to be robust with respect to bunchlets and microstructures.

Recipe for separating the time scales

1. Substract long symmetric, Gaussian pedestal to isolate short-scale structure.
2. For extracting the characteristic bunch duration, determine positive-definite interquartile range (IQR) on short structures.
3. Extract mean current within IQR.

Understanding the multiscale structure of LWFA bunch profiles



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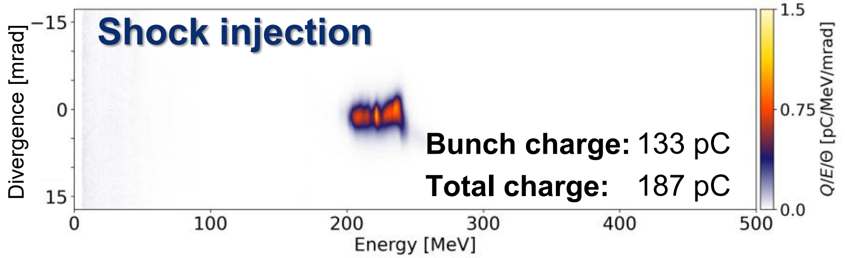
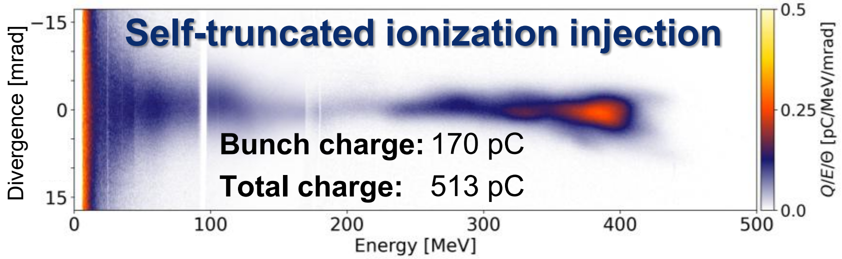
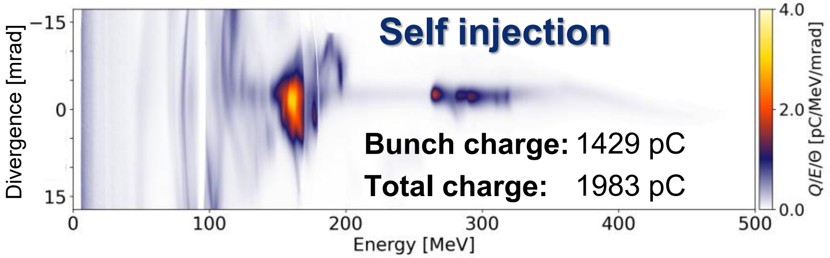
Typical bunch profile characteristics



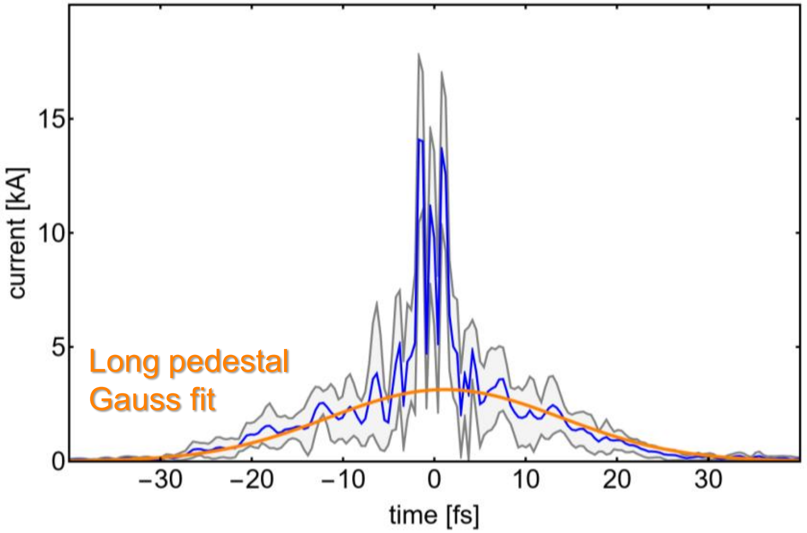


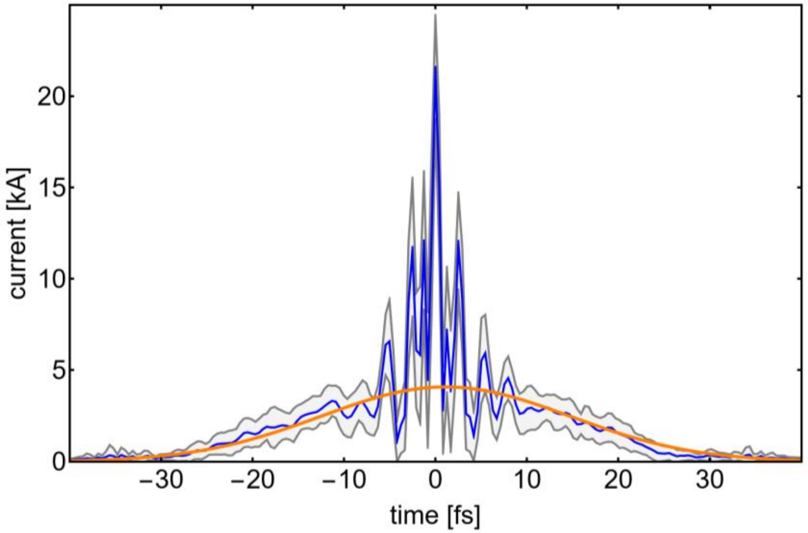


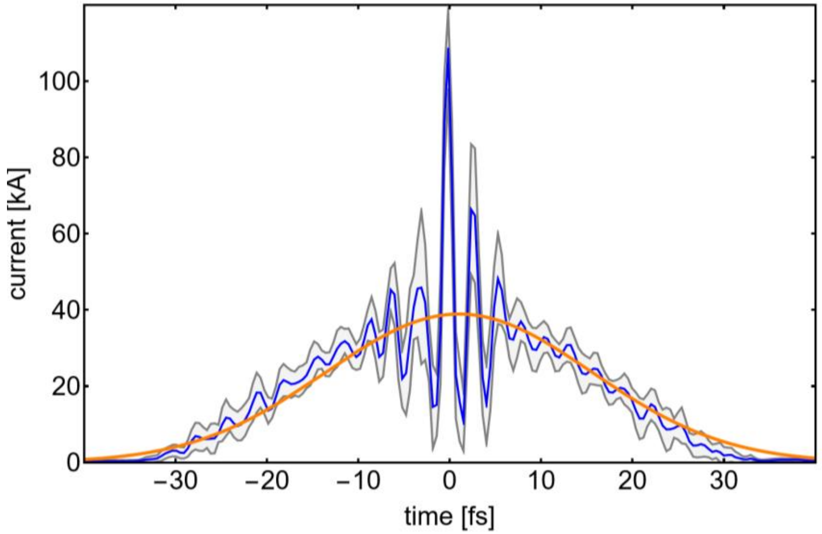
- Short bunches
- bunchlets
- minimal low-energy electron background
- micro-structure

- Short bunches
- broad electron spectra
- managable electron background
- micro-structure

- Longer bunches
- high charges and currents
- hard to diagnose → large pedestal
- micro-structure







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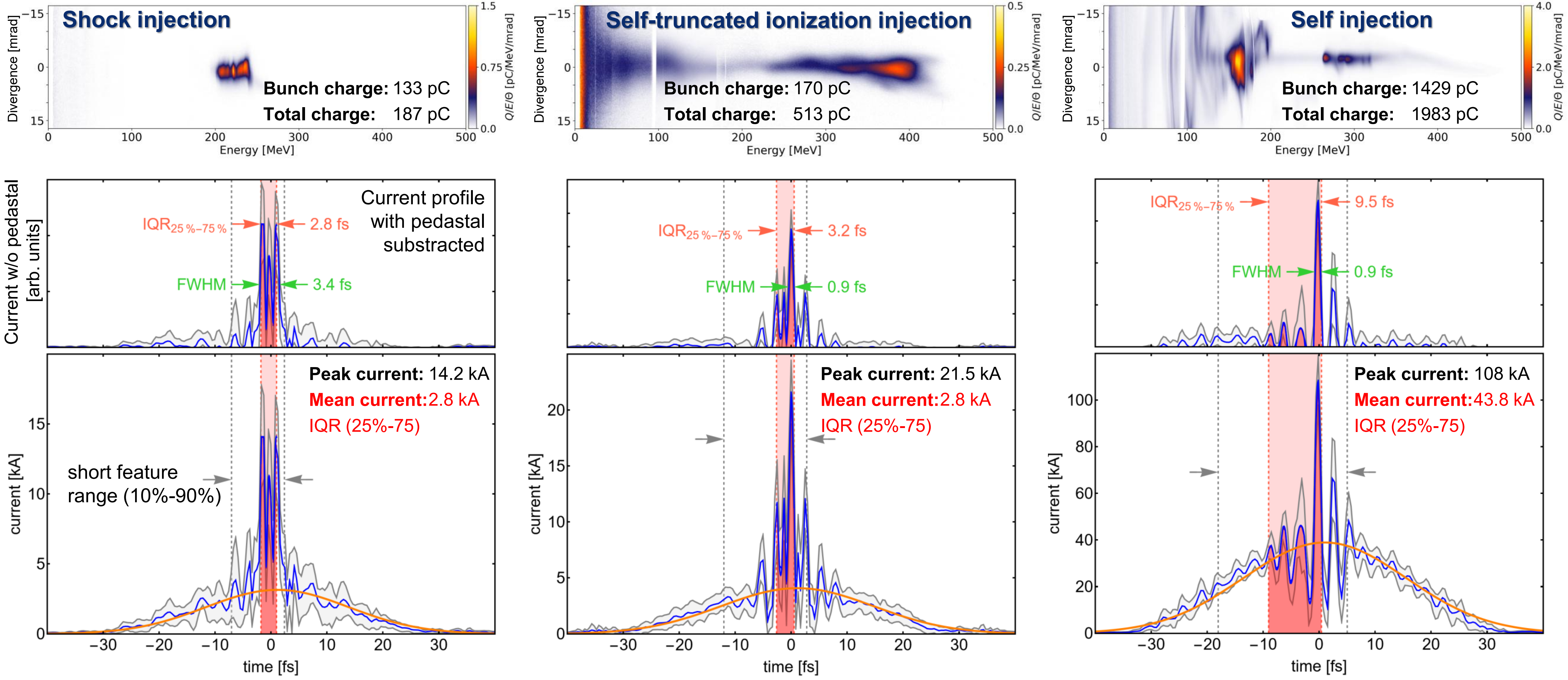
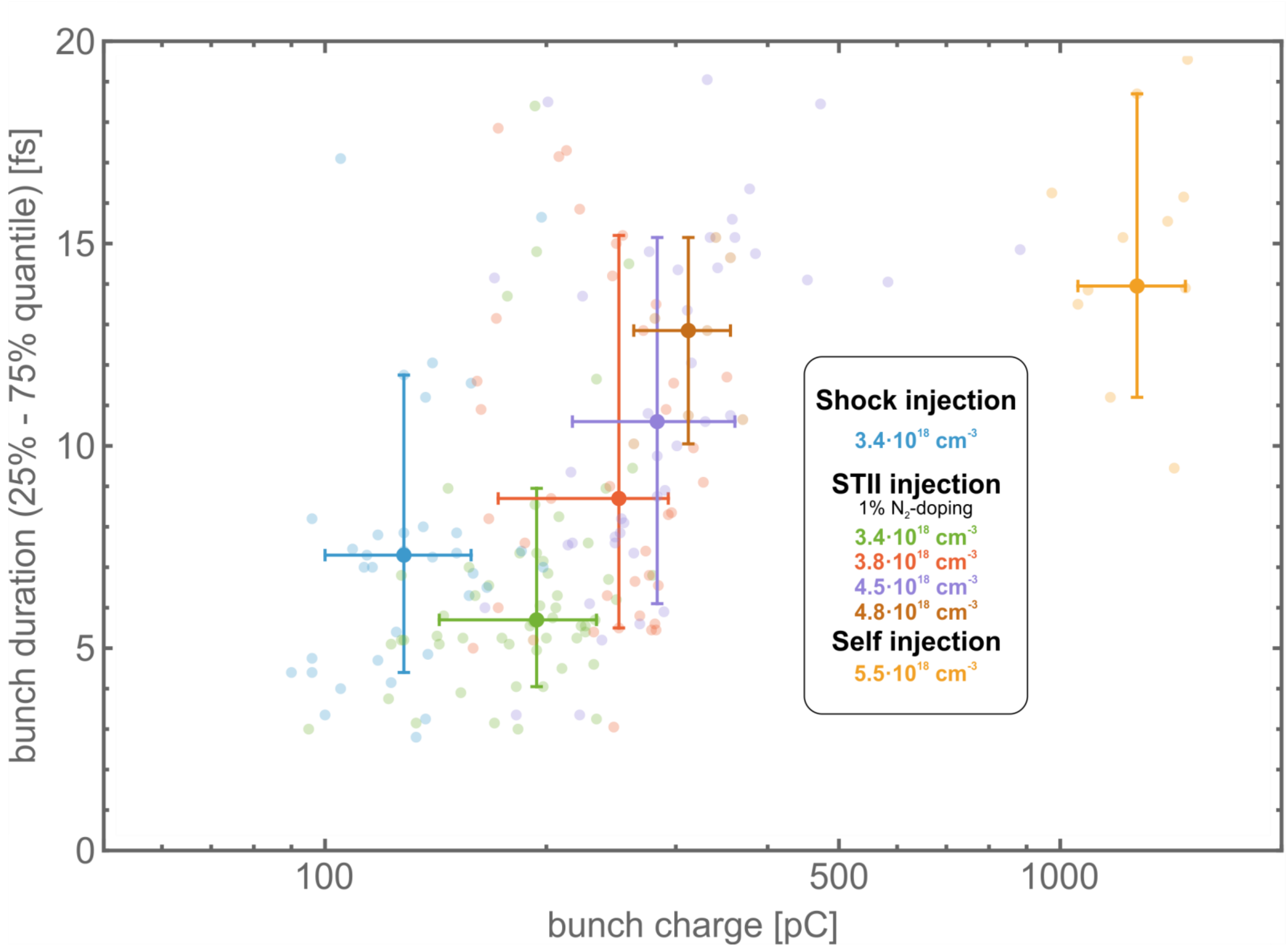


CTR spectra probe longitudinal injection dynamics (STII)



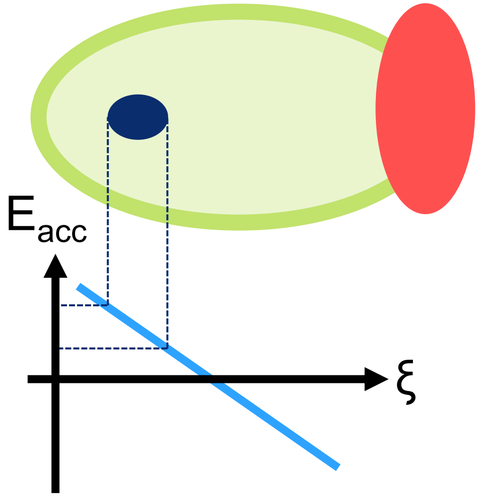
- Vary electron density by 20% at same doping concentration and same laser pulse energy.
- Plasma wavelength reduces by ~10%, but pulse duration increases 2.5x at ~50% more bunch charge.

→ Heavy-bunch loading extends self-truncated ionization trapping condition.

CTR spectra probe longitudinal injection dynamics (Shock injection)

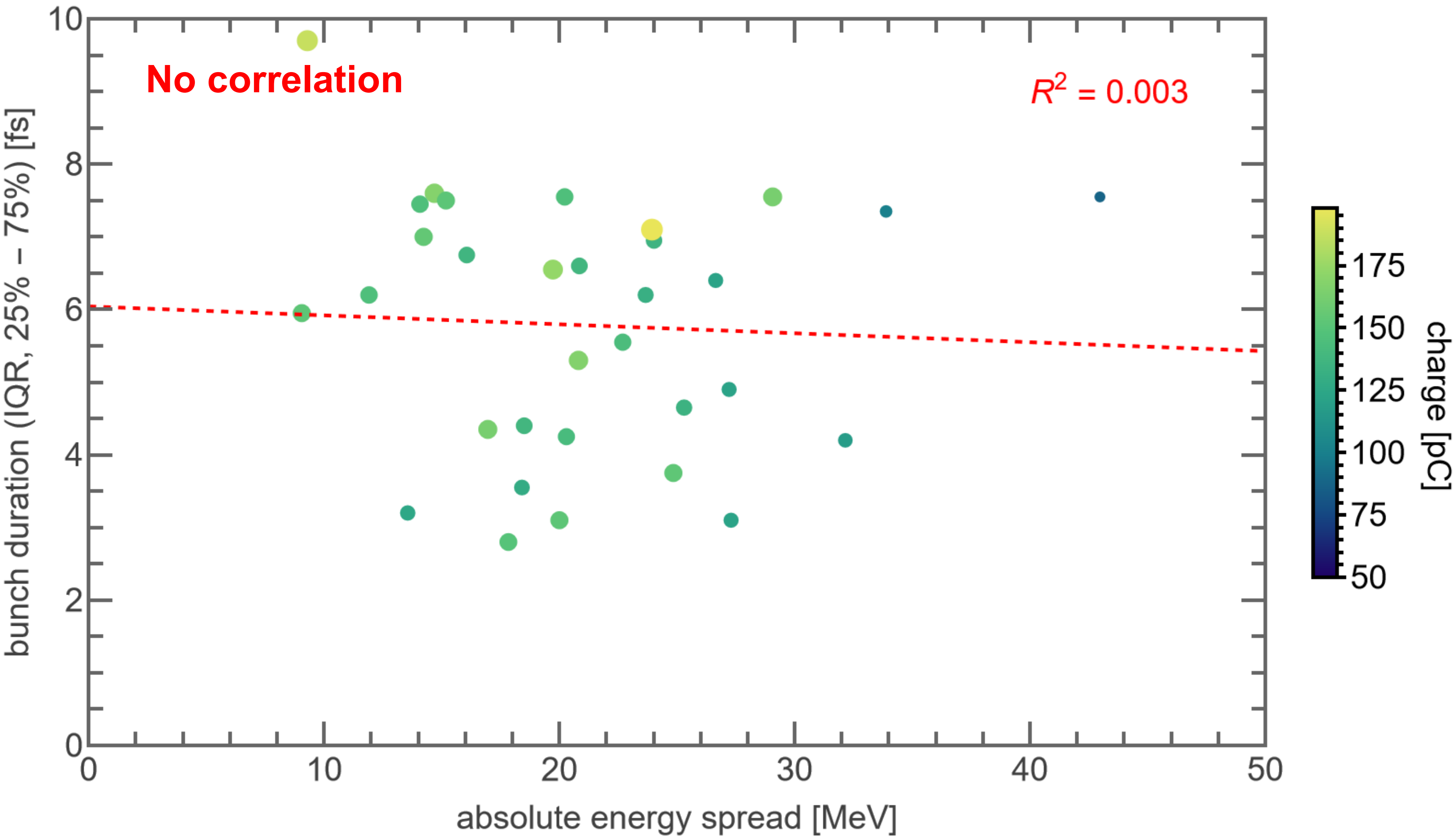
Can we predict the shock injected bunch duration from its electron spectrum?

simple assumption:
bunch length is subject to acceleration gradient



$$\frac{\Delta\tau}{\Delta E_{bunch}} = \frac{2\,\epsilon_0}{e^2 n_e\, L\, c} \cong \mathbf{0.11\ fs/MeV}$$

L ~ 1mm, $n_e = 3.4\cdot10^{18}\ cm^{-3}$



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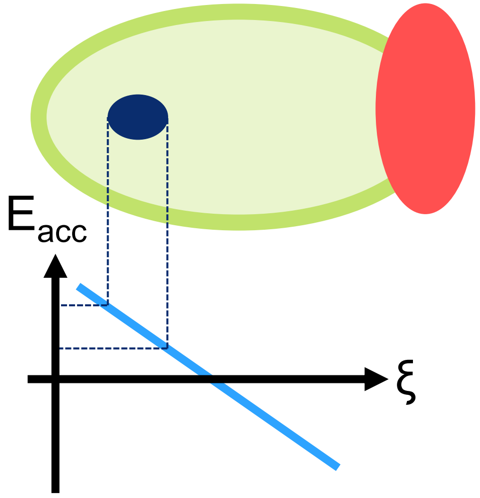

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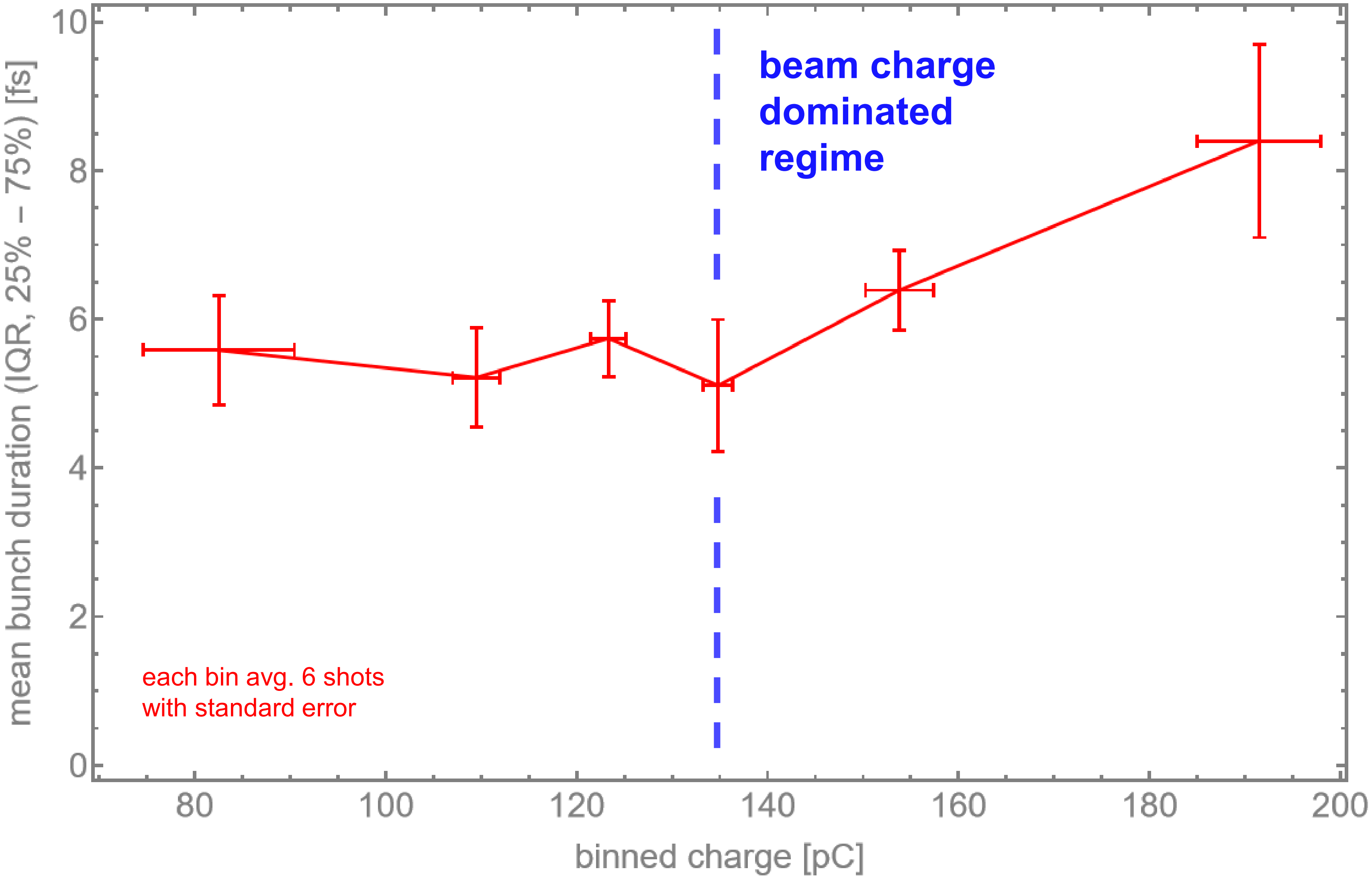

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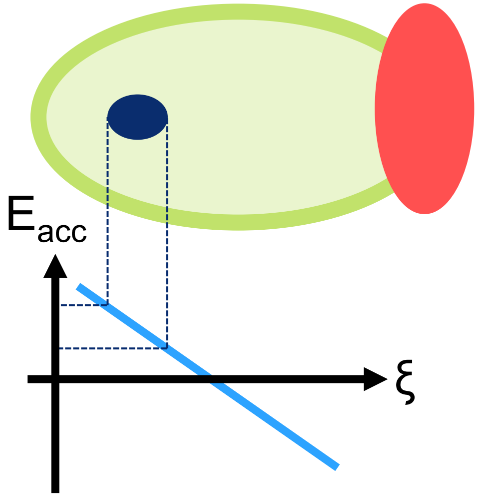

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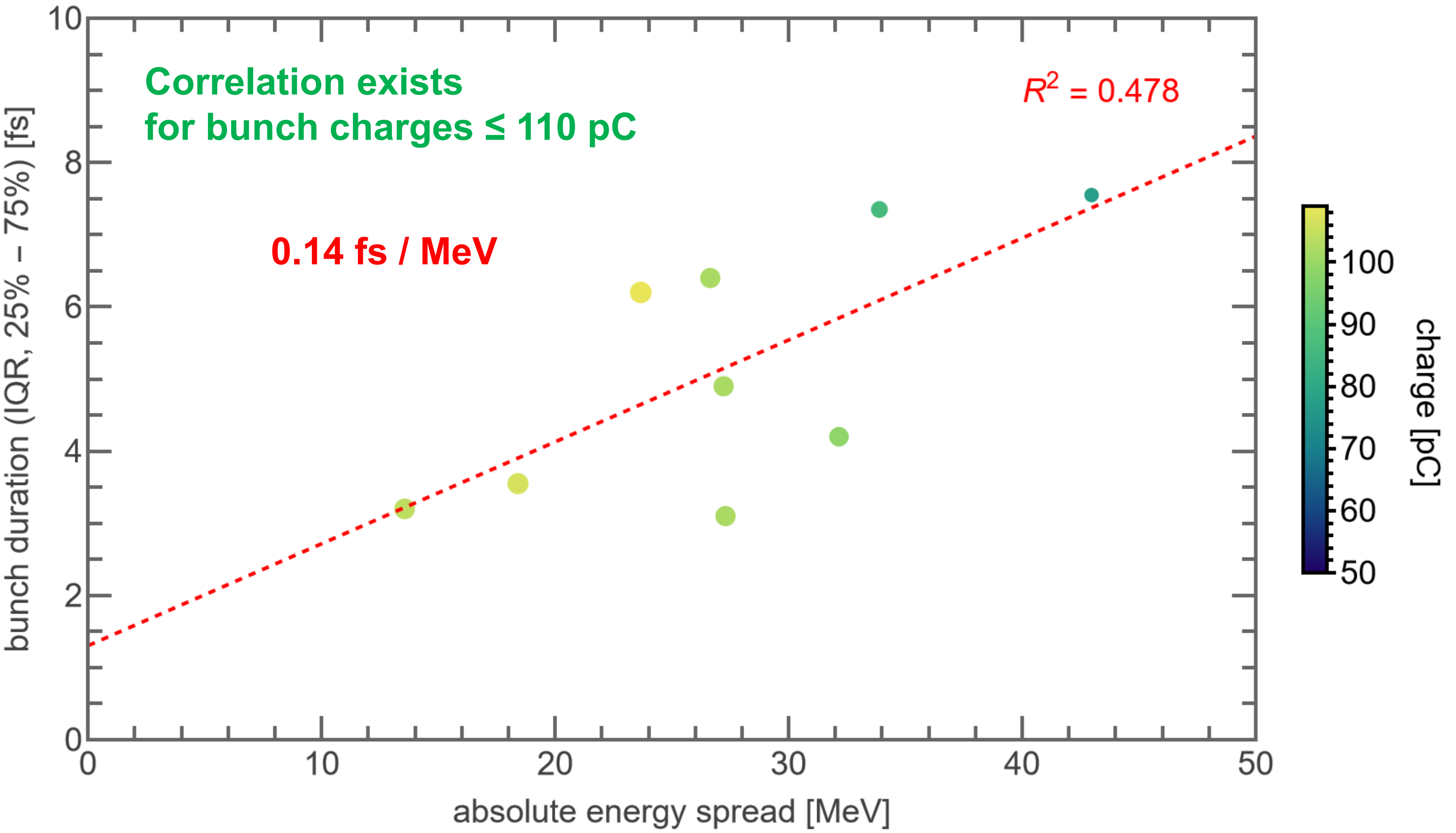
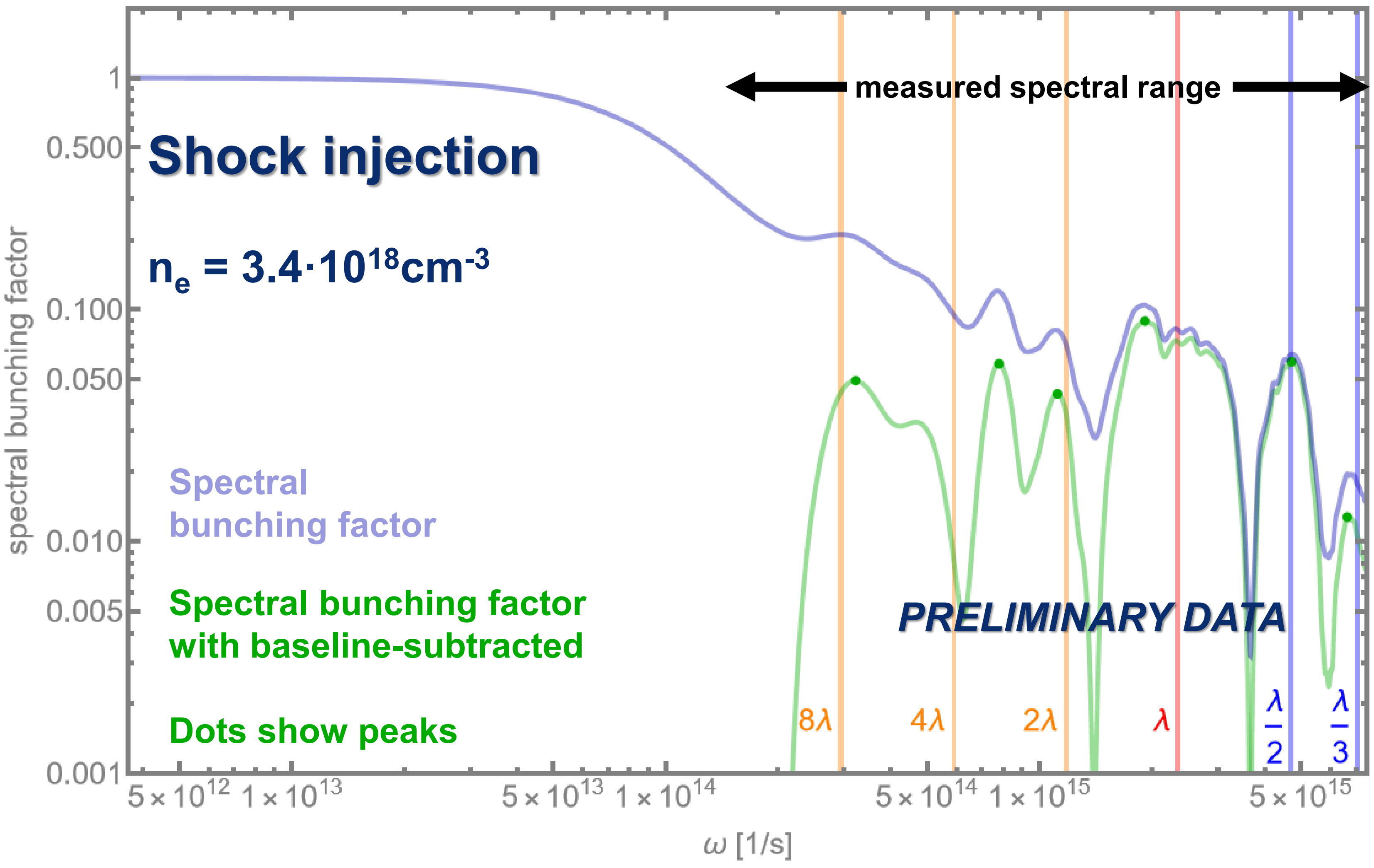


Microstructures correspond to the laser-wavelength scale

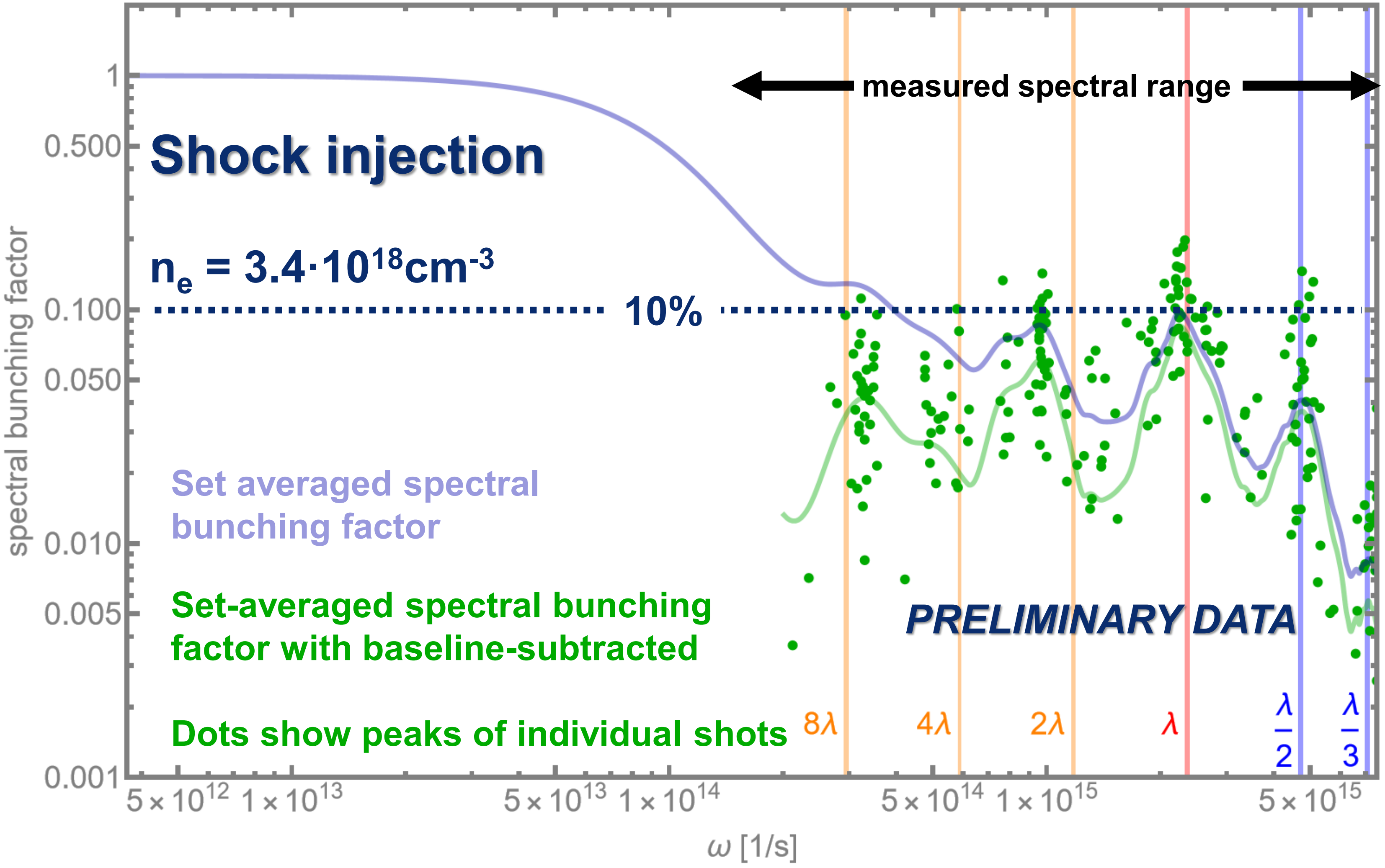


Spectral analysis of electon beam bunching

- The bunching spectrum extend into the UV range.
- Spectral bunching is a critical metric for FELs.
- Spectral bunching characteristics generally can vary strongly shot-by-shot.

→ **Shot statistics exposes a pattern.**

Microstructures correspond to the laser-wavelength scale

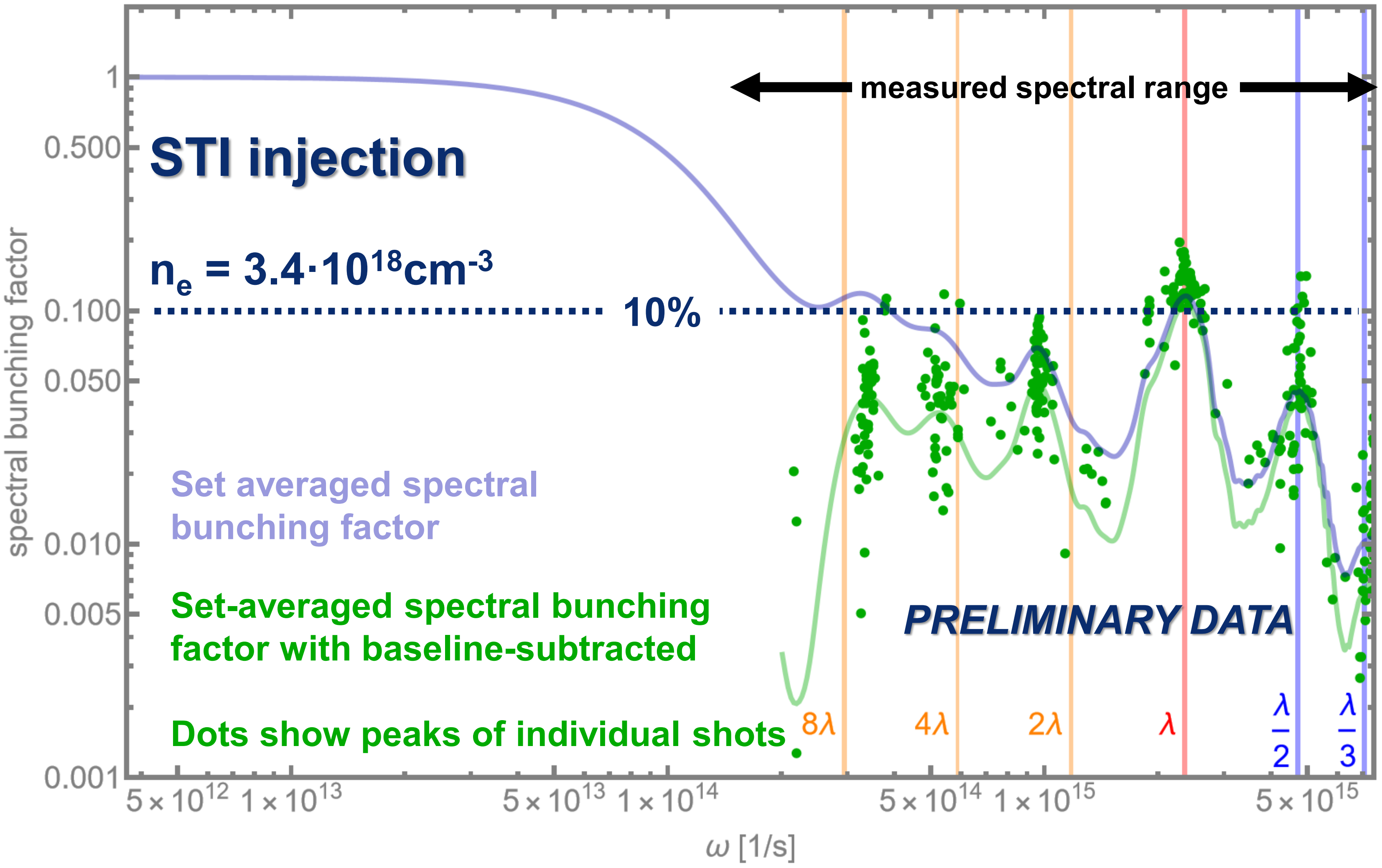


Spectral analysis of electon beam bunching

- Shot statistics shows microstructures to be primarily determined by laser wavelength.
- Laser fundamental dominates with ~10% bunching factor.

  Robust result, agrees across different campaigns and also shows in transverse CTR spectrometer.
  → LaBerge *et al. Nat. Photon.* (2024)
- Significant bunching at laser harmonics exists.
- Bunching could be explained by laser-driven betatron dynamics after free-space propagation to CTR foil.

Microstructures correspond to the laser-wavelength scale



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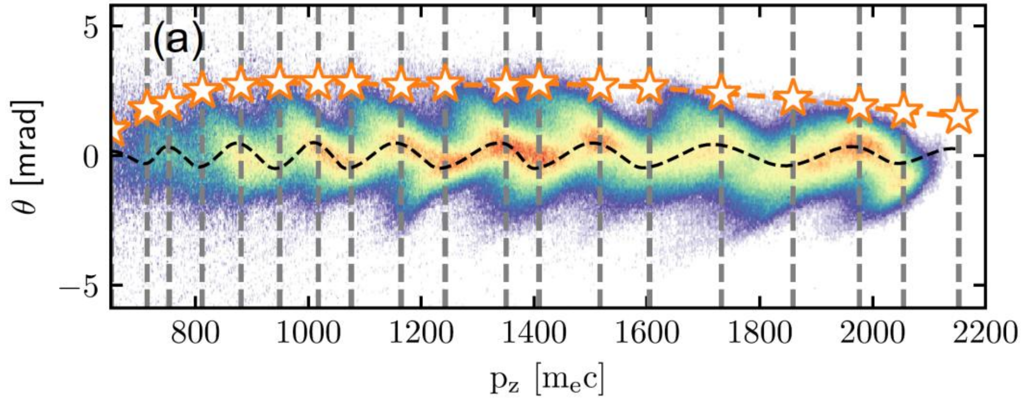
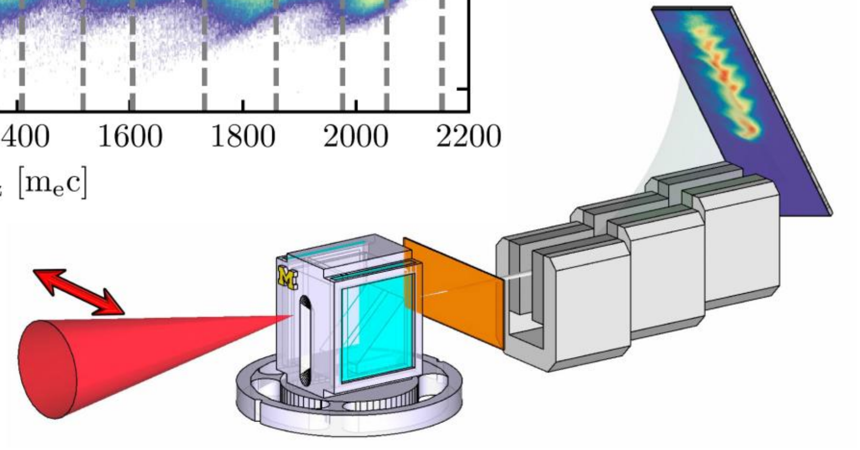
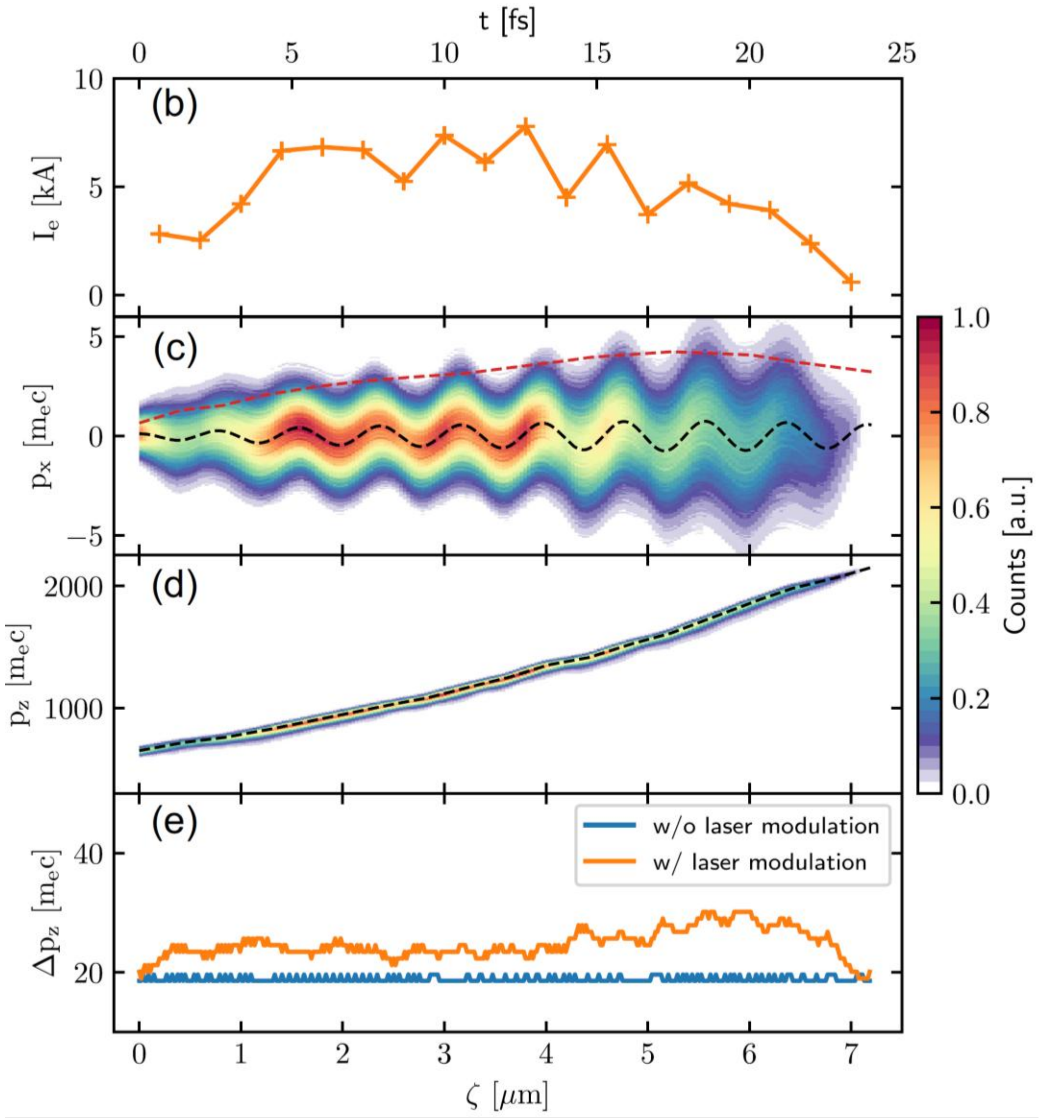
Single-Shot Reconstruction of Electron Beam Longitudinal Phase Space in a Laser Wakefield Accelerator

- Driven betatron oscillation dynamics is used as yardstick to interpret electron spectrometer data. **A TDS analogue for LPAs!**
- Oscillation resolved uses highly chirped, GeV energy beam.
- Longitudinal bunchprofile retrieved including slice energy spread (9.9 MeV, 0.9% - 3%).
- Demonstrates a way to address time-energy correlation problem.



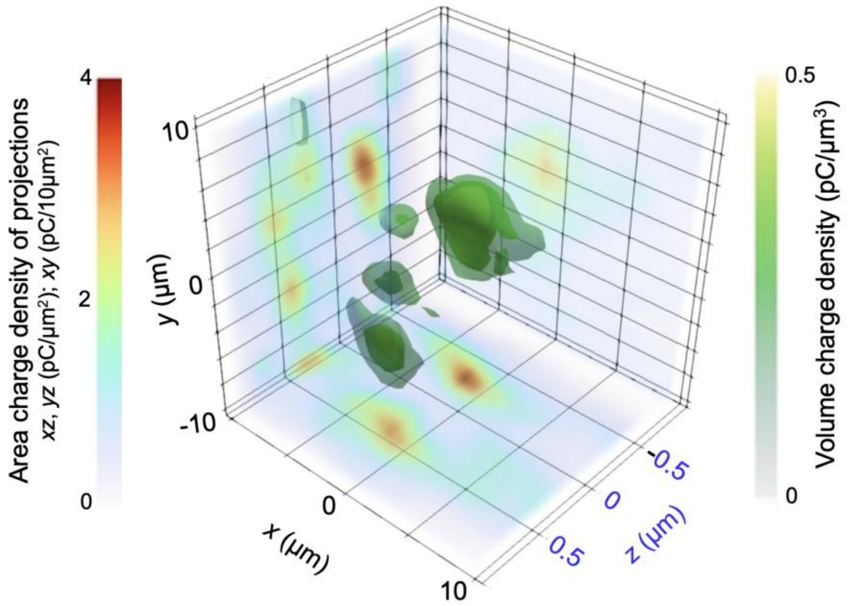




Yong Ma et al.
Phys. Rev. X **15**, 031062
(Sep 2025)

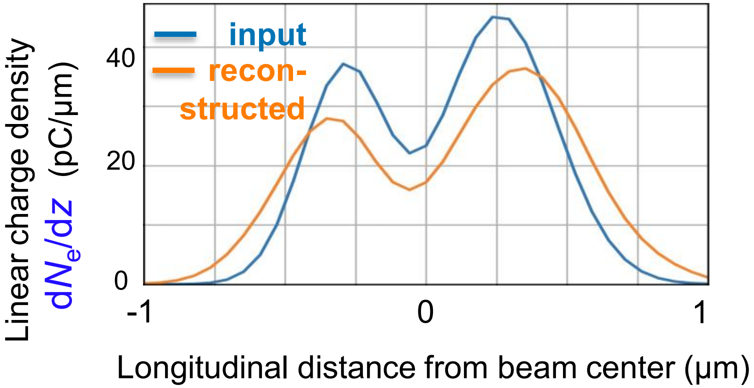
Outlook: Going 3D by combining longitudinal and transverse CTR diagnostics

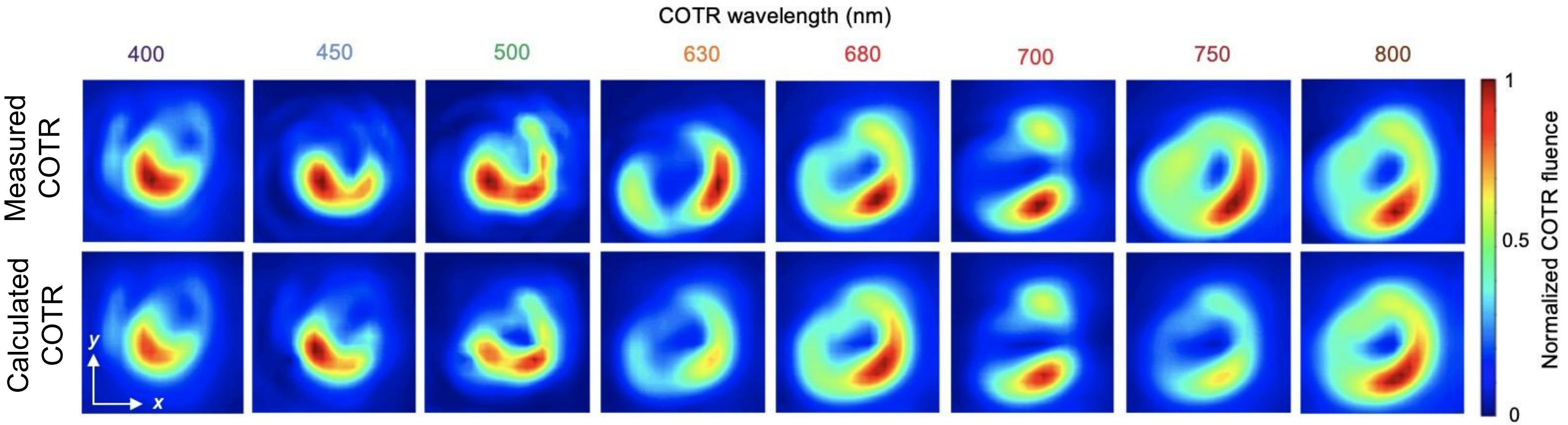
- Original analysis relies on assumed pulse profile based on electron spectrometer.
- Improve resolution and fidelity of reconstruction by combining longitudinal and transverse CTR spectral data.
- Diagnostics requires a single CTR radiator with combined pickup and distribution optics.



LaBerge *et al.* "Revealing the three-dimensional structure of microbunched plasma-wakefield-accelerated electron beams", *Nat. Photon.* **18**, 952–959 (2024).

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF





HZDR

Challenges & Outlook

- **Single-shot diagnostics of general LPA beams are demanding due to their multiscale nature.**
  → Combine multiple diagnostics approaches.

- **1D longitudinal spectral reconstructions do not capture longitudinal-transverse correlations.**
  → Improve constraints by include higher dimensional data.

- **Spectral methods alone have limitations with regard to low-energy and long duration contributions.**
  → Complement with time-domain diagnostics, such as electro-optic approaches.

- **Single-shot electron energy - time correlations are often unknown at single-shot.**
  → Leverage electron to FEL or laser pulse interactions combined with electron spectrometers.

- **CTR diagnostics are semi-interceptive.**
  → Explore alternative concepts (p.ex. diffraction radiation, Smith purcell radiation).

Conclusions

- Single-shot, ultrabroadband CTR diagnostics characterize the multiscale nature of electron beams, encompassing bunches and multiple beamlets including fs-scale micro-structures and long-duration background.

- Quantitative systematics achieved over many shots across different injection regimes.

- Correlations in shot-to-shot variations between electron beam durations and with electron electron spectral properties provide a new window to understand the injection dynamics.

- Microbunching structures at 10% bunching factor scale are found to be dominantly characterized by the laser wavelength, its harmonics and sub-harmonics.


Thank you for your attention!