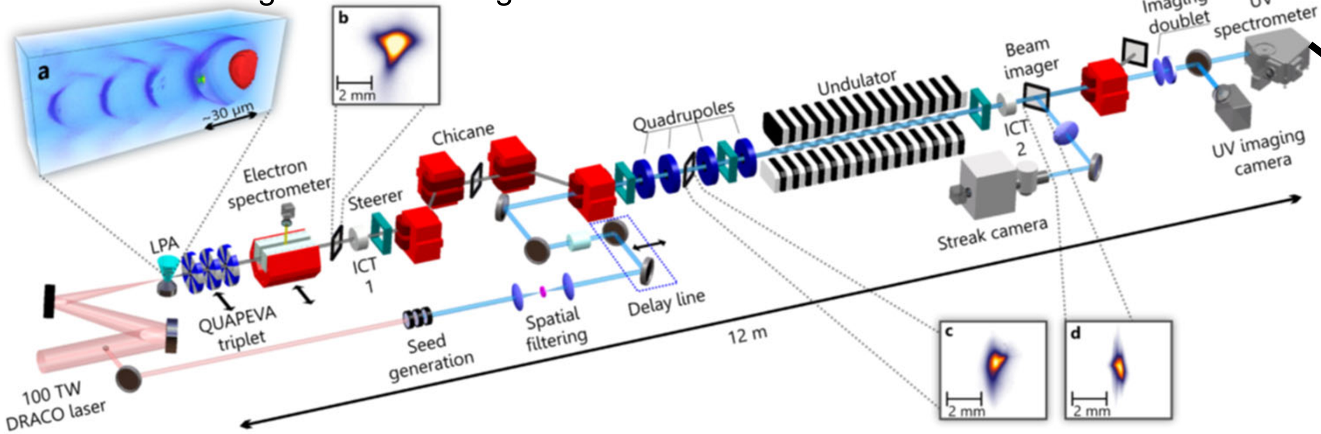
Time-resolved diagnostics: coherent radiation

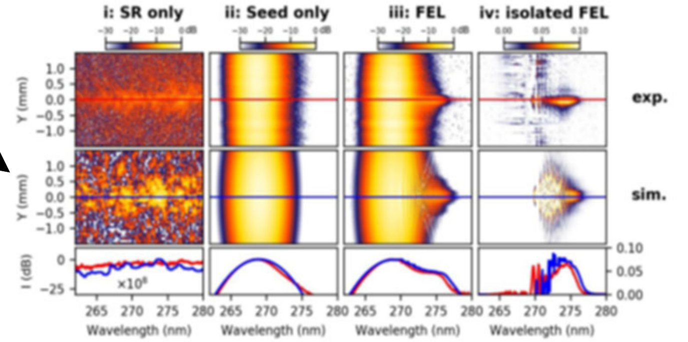
Max LaBerge *Helmholtz-Zentrum Dresden-Rossendorf*

WE HAVE PRODUCED CONSISTENT FEL QUALITY ELECTRON BEAMS AT HZDR

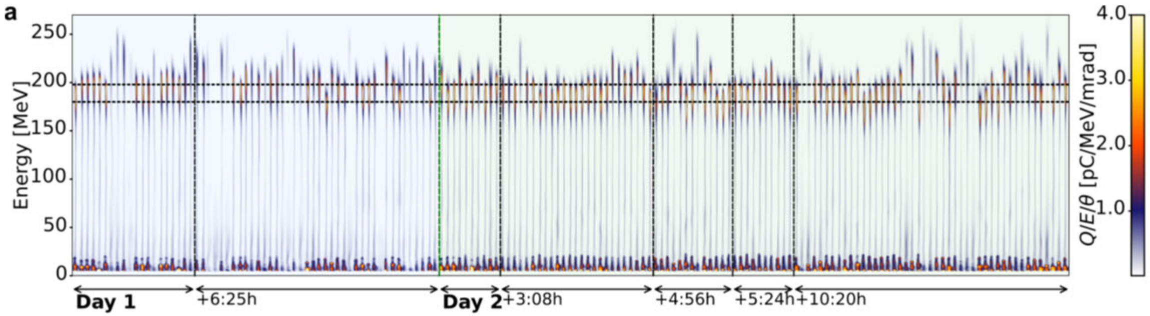
- Comprehensive in-situ diagnostics is important to improve the LPA performance.

- High spectral-charge density LPA beams + COXINEL line enable free-electron lasing in a seed configuration.



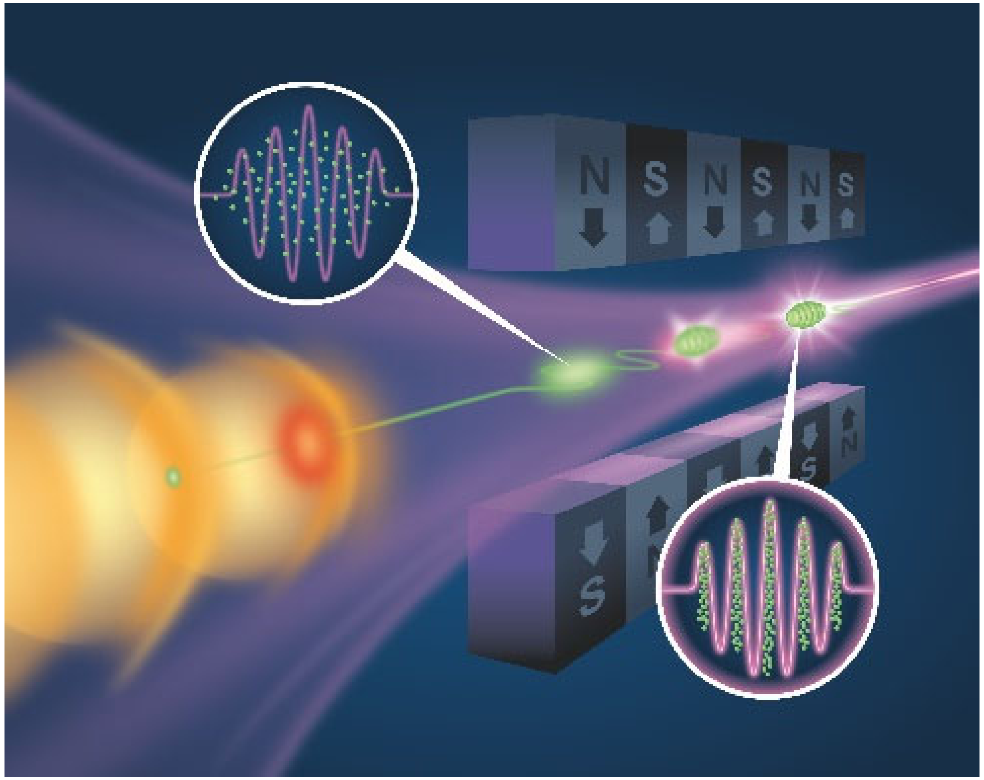


Marie Labat et al., „*Seeded free-electron laser driven by a compact laser plasma accelerator*“, *Nat. Photon.* *17*, *150* (2022). https://doi.org/10.1038/s41566-022-01104-w



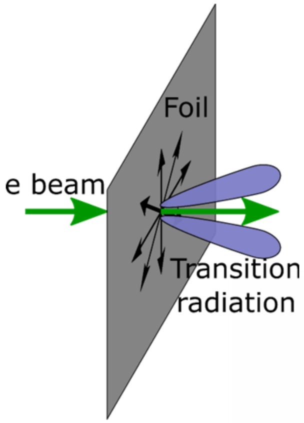
WHAT WOULD WE LIKE TO KNOW ABOUT OUR ELECTRON BEAMS

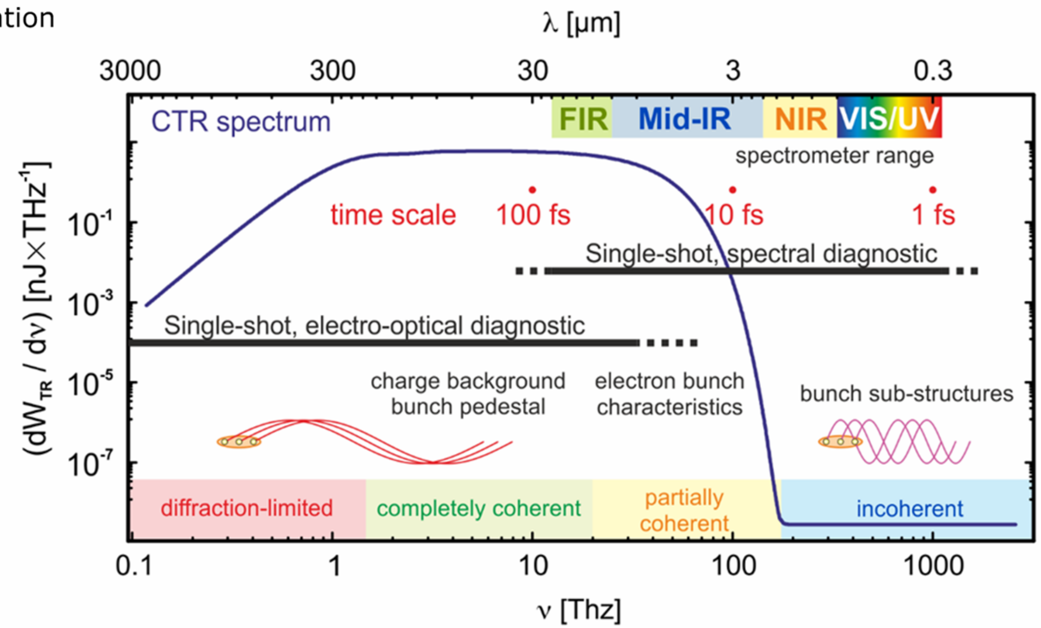
- Size (micron scale resolution)
- Emittance
- Structures
  - Correlations
  - Microbunching
    - Observe the evolution
- Ideally observed in a single shot
- Dependence of these parameters on the injection process
  - Pre-bunched beams



LONGITUDINAL BEAM STRUCTURE IS ENCODED IN THE COHERENT TRANSITION RADIATION SPECTRUM

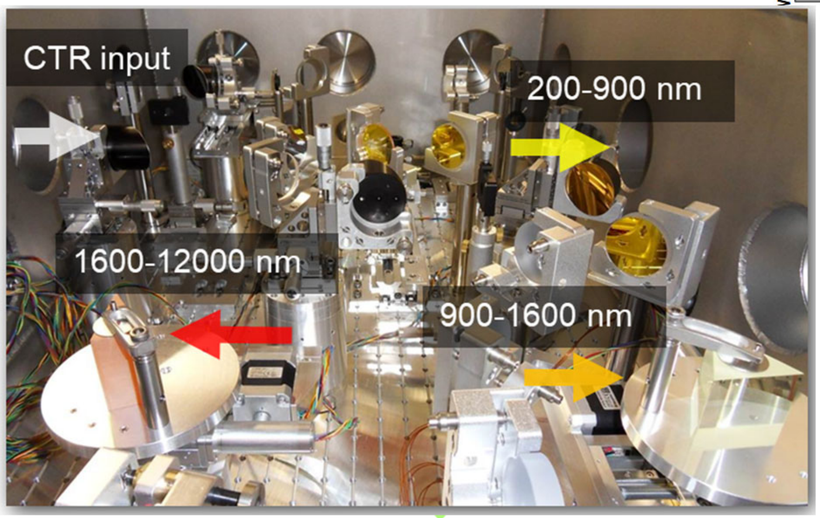
- Currents on the foil surface are driven by the electron beam
- These radial currents give way to broadband transition radiation
- Longitudinal structures in the electron beam are encoded in the transition radiation spectrum

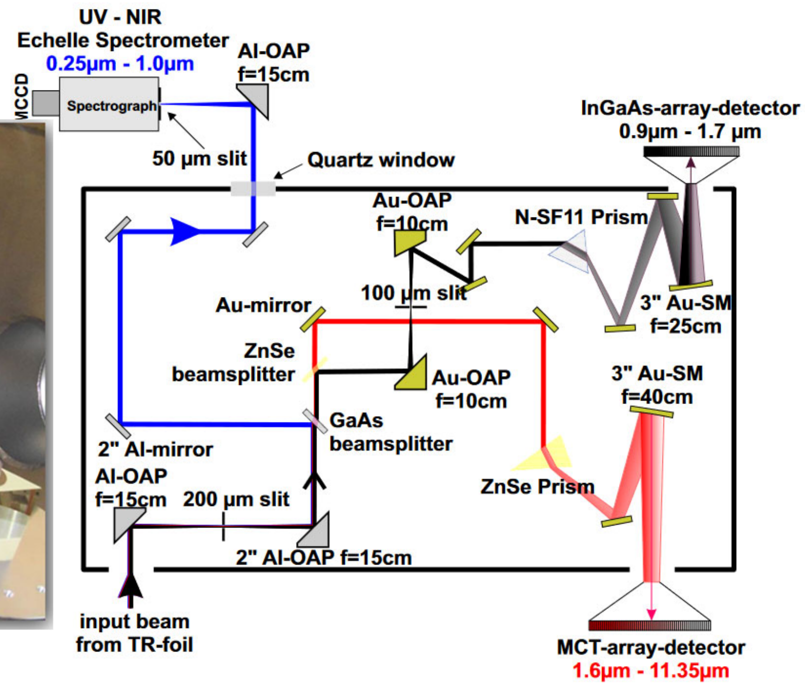




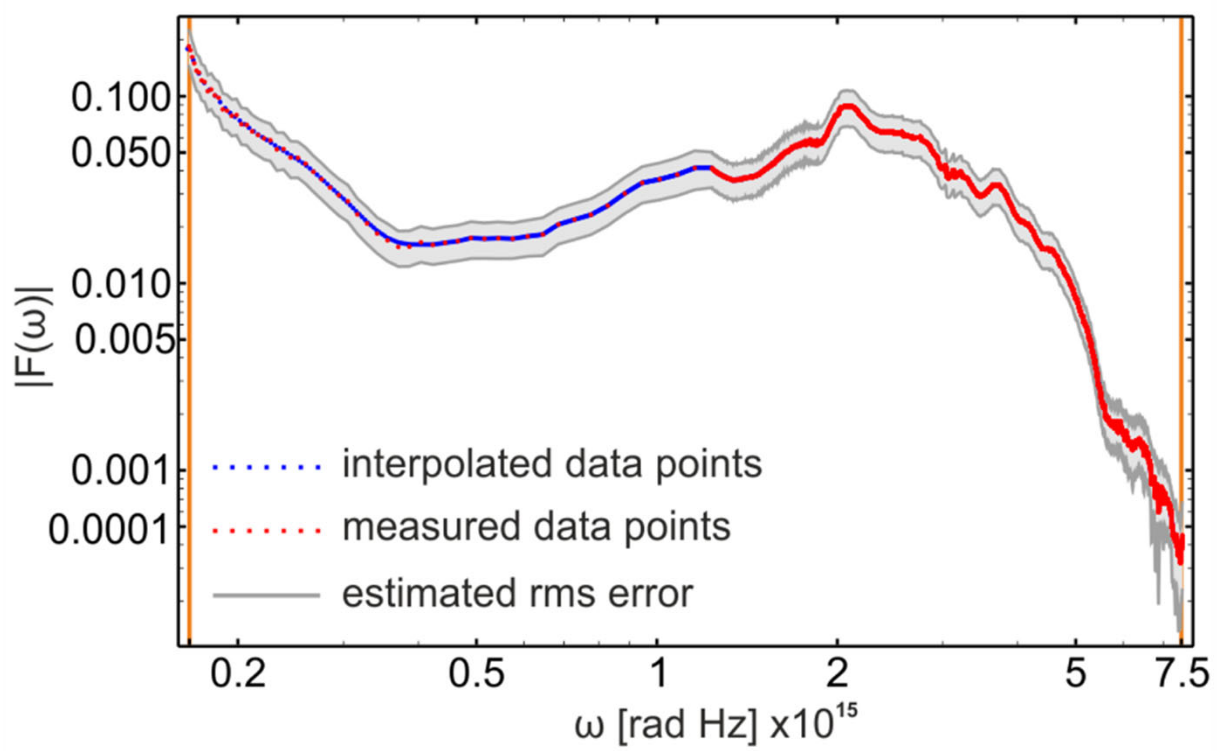
WE USE A MULTI-OCTAVE SPECTROMETER TO MEASURE COHERENT TRANSITION RADIATION FROM LPA ELECTRON BUNCHES

- Single shot capability
- 5.9 octave frequency ran[g
- Absolutely and relatively calibrated
- Detection limit ~ 50 fC
- Time resolution of ~0.5 fs

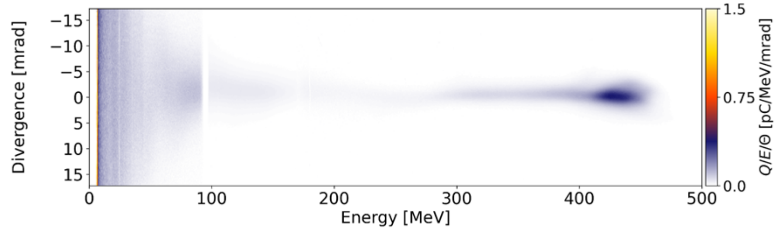


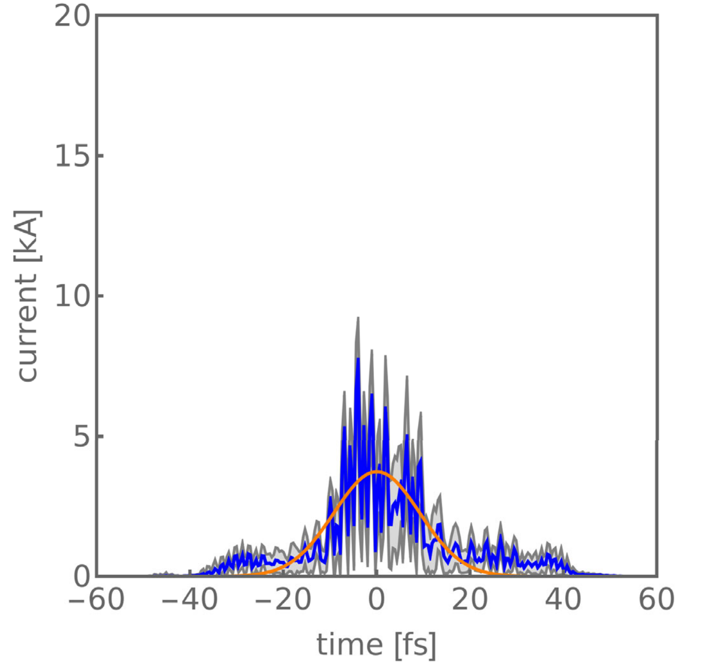


USING THE RADIATION SPECTRUM AND AN ITERATIVE PHASE RECONSTRUCTION ALGORITHM, WE DETERMINE THE LONGITUDINAL BEAM PROFILE



Zarini *et al.* (2021), Phys. Rev. Accel. Beams 25, 012801

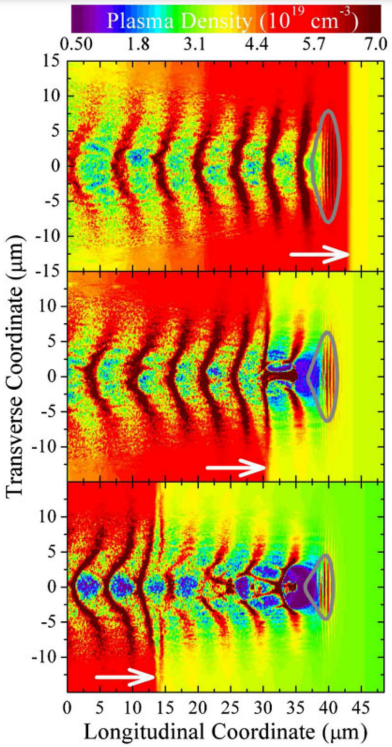




Bakkali Taheri, F., Konoplev, I.V., Doucas, G., Baddoo, P., Bartolini, R., Cowley, J., Hooker, S.M.: Electron bunch profile reconstruction based on phase-constrained iterative algorithm. Physical Review Accelerators and Beams 19(3), 1–7 (2016).

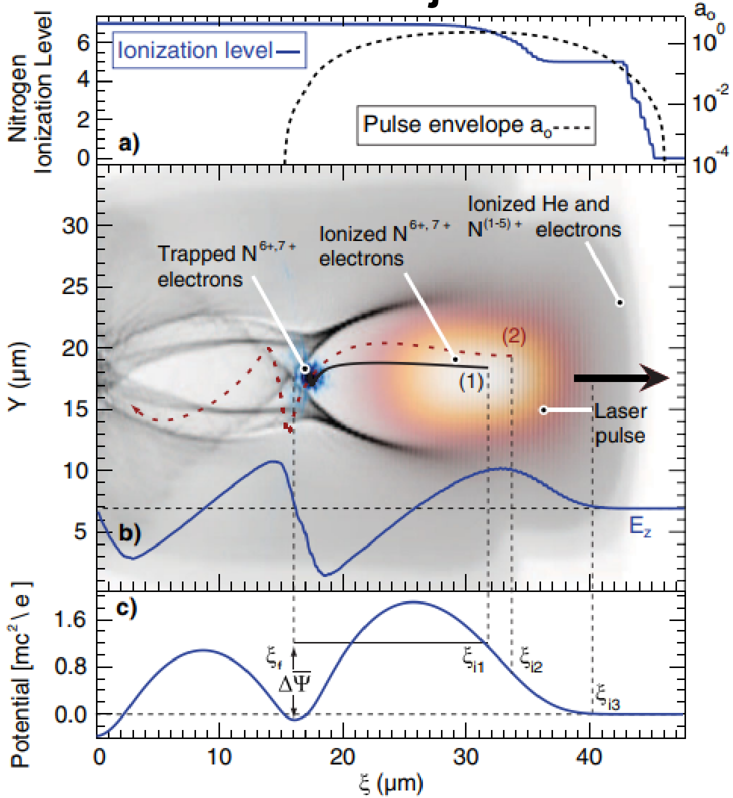
INJECTION MECHANISMS HAVE A CRITICAL EFFECT ON THE STRUCTURE OF THE ELECTRON BUNCH

Down-ramp injection



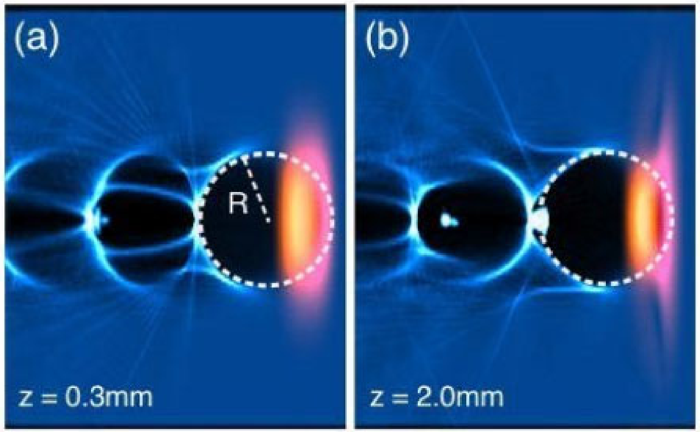
K. Schmid *et al.*, "Density-transition based electron injector for laser driven wakefield accelerators", *Phys. Rev. ST Accel. Beams*, Vol. 13 pp. 091301, 2010

Ionization injection



Pak *et al.*, "Injection and Trapping of Tunnel-Ionized Electrons into Laser-Produced Wakes", *Phys. Rev. Lett.*, vol 104, no. 2 pp. 025003, 2010.

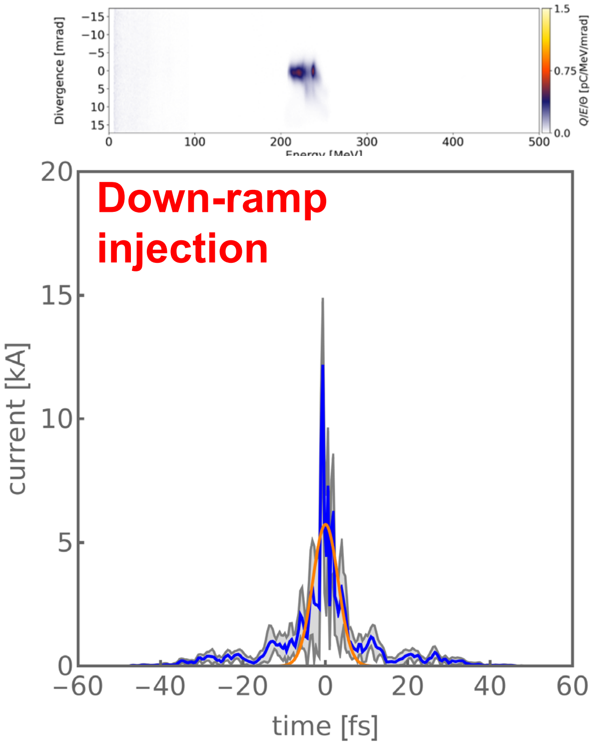
Self injection

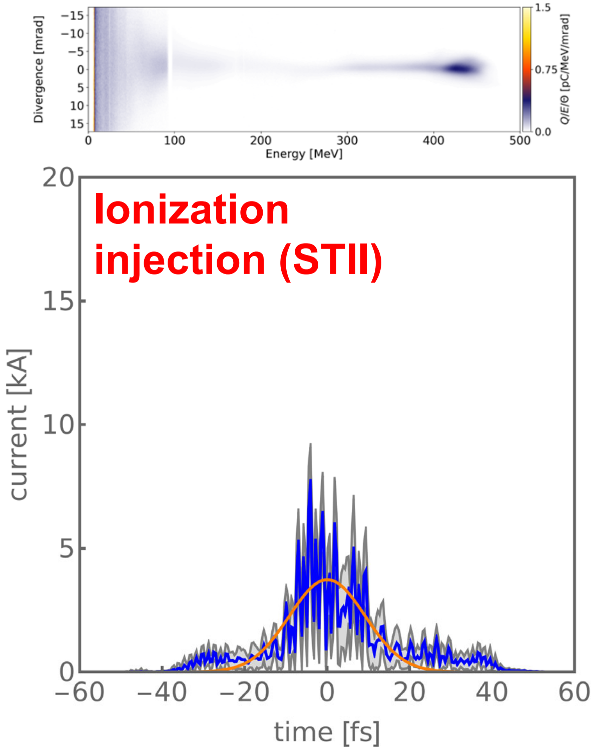


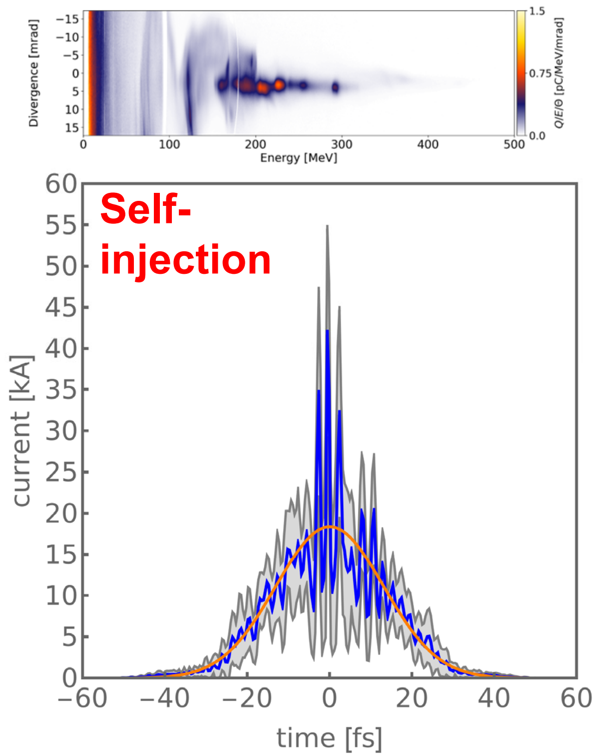
Lu *et al.*, "Generating multi-GeV electron bunches using single stage laser wakefield acceleration in a 3D nonlinear regime", *Phys. Rev. ST Accel. Beams*, vol. 10, no. 6, pp. 061301, 2007.

- Down-ramp: Plasma density gradient changes the shape of the bubble

OBSERVED LONGITUDINAL BUNCH STRUCTURE IS INJECTION REGIME DEPENDENT

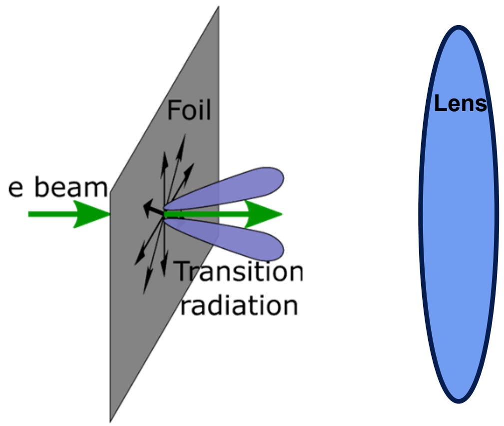




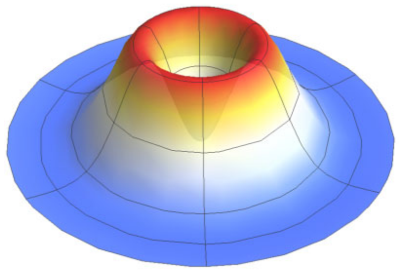


- Injection regime affects both bunch duration and substructure

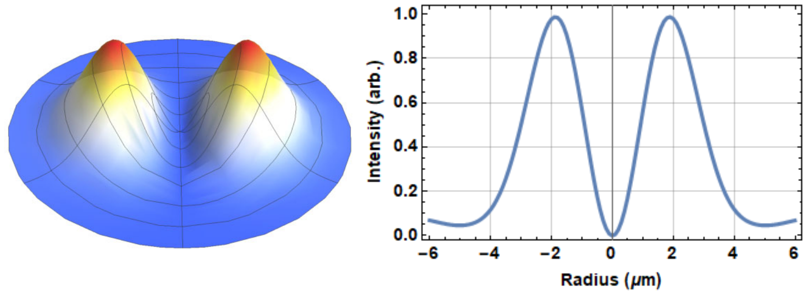
NEAR FIELD OPTICAL TRANSITION RADIATION ENCODES ELECTRON BUNCH SPATIAL INFORMATION



Single electron point spread function (PSF)



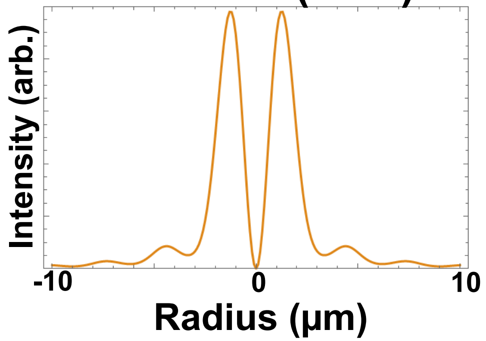
Signal after a horizontal linear polarizer



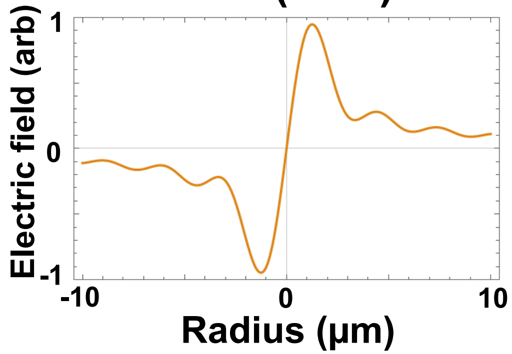
- Radiation from a single electron is annular and radially polarized
- When the foil is imaged (near field), a point spread function intensity pattern occurs around the electron location

COHERENT OTR IS THE RESULT OF SUMS OF FIELDS AS OPPOSED TO INTENSITIES

Point spread function (PSF)



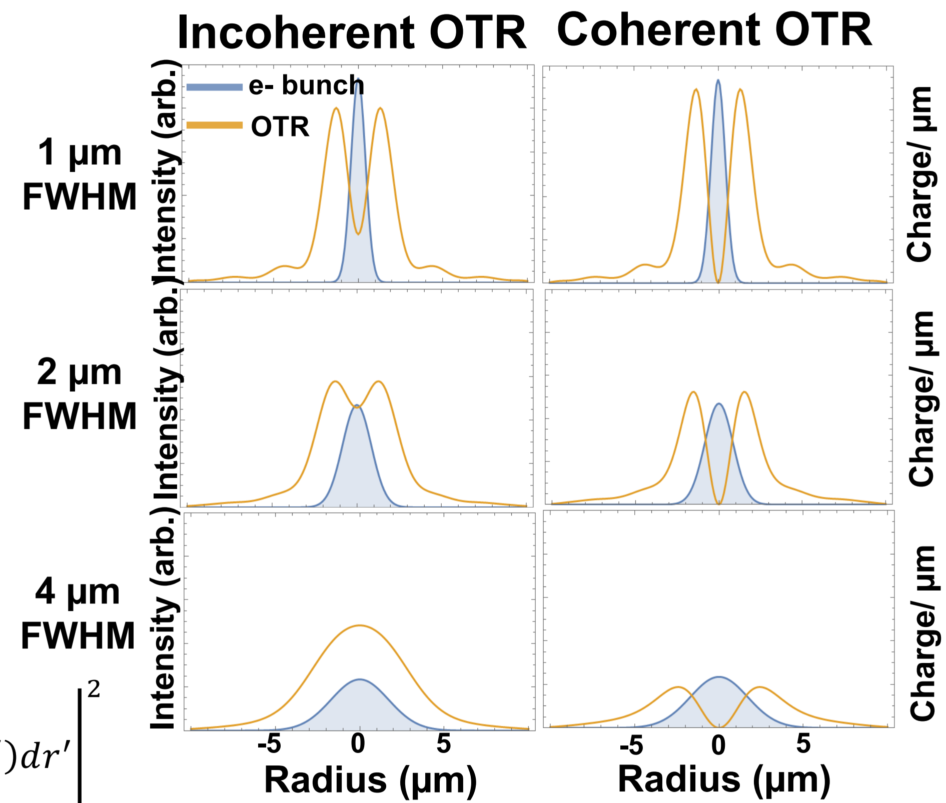
Single particle field (SPF)



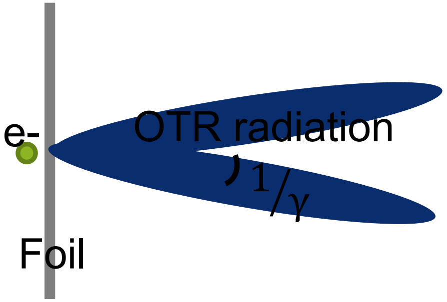
$$\boldsymbol{SPF}(r) = \int_0^{\theta_{max}} \frac{\theta^2}{\theta^2+\gamma^{-2}} J_1(kr\theta)\,d\theta$$

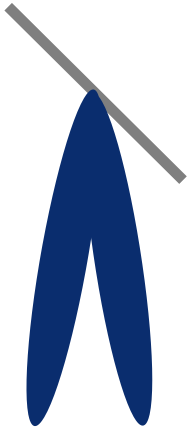
$$\boldsymbol{PSF} = |\boldsymbol{SPF}|^2$$

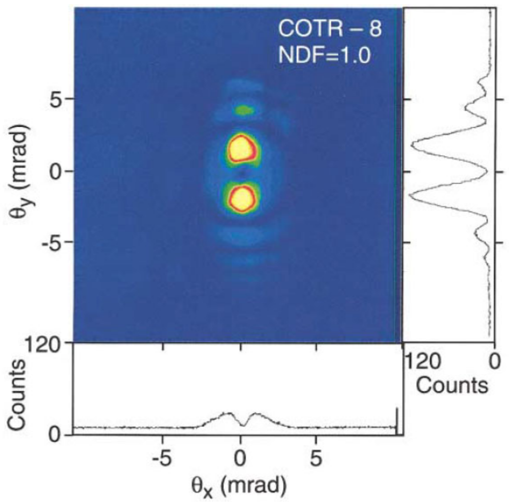
$$I \propto \underbrace{N \int\int \rho(r',z)\,|\boldsymbol{SPF}(r-r')|^2 dr'dz}_{\text{Incoherent}} + \underbrace{N^2 \left| \int\int \rho(r',z)\, e^{-ikz}\, \boldsymbol{SPF}(r-r')\,dr' \right|^2}_{\text{Coherent}}$$



COTR INTERFEROMETRY FRINGES ARE DUE TO INTERFERENCE BETWEEN TWO COTR SOURCES







A. H. Lumpkin *et al*. "Evidence for Microbunching "Sidebands" in a Saturated Free-Electron Laser Using Coherent Optical Transition Radiation", *Phys. Rev. Let.*, vol. 88, pp. 234801, 2002.

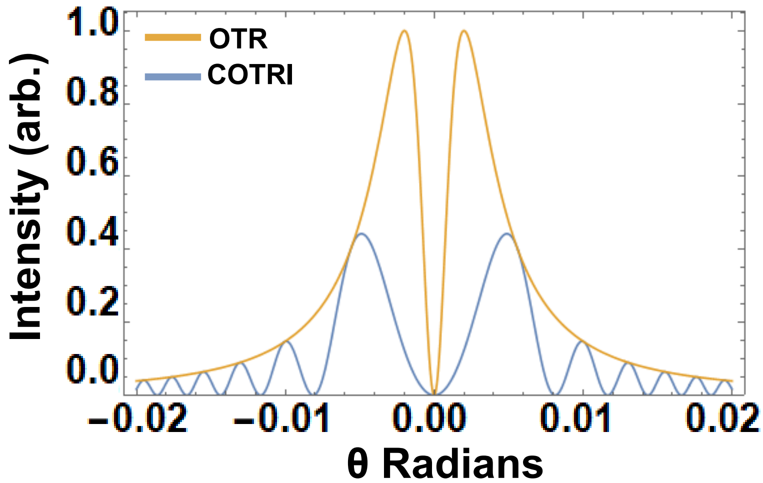
- Two COTR sources close enough together will interfere, resulting in COTR interferometry (COTRI)
- In the far field intensity pattern, this manifests as the single source pattern scaled by an interference function

Far field OTR

$$\frac{d^2W}{d\omega\, d\Omega} \propto \frac{\theta^2}{(\theta^2+\gamma^{-2})^2}$$

Interference Function

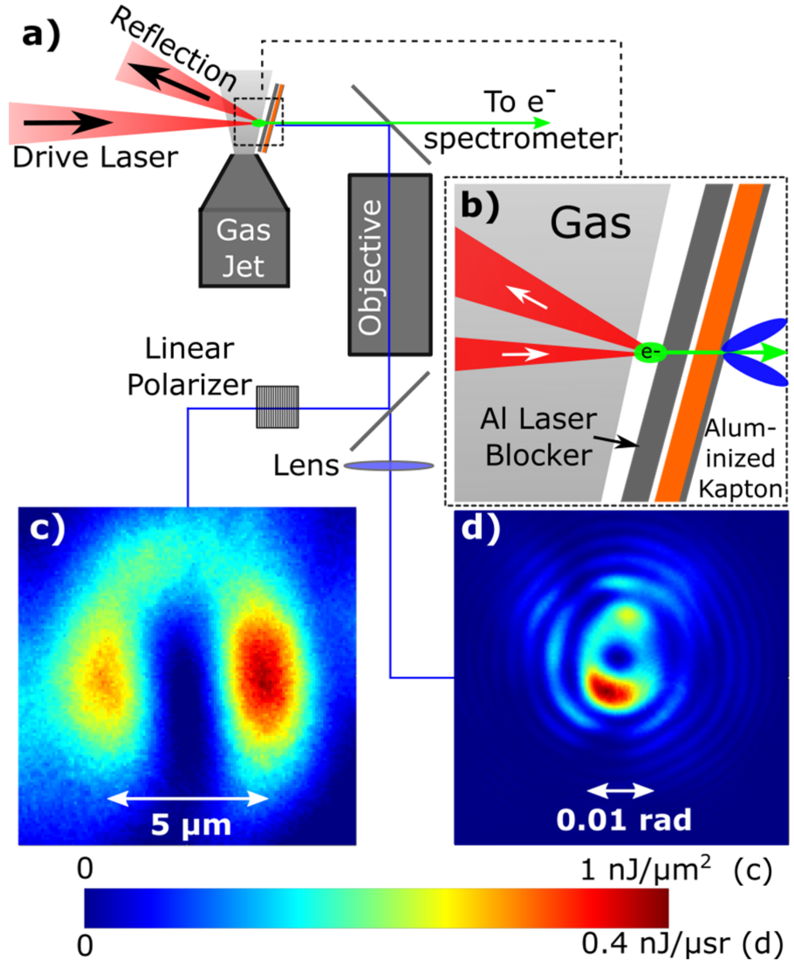
$$I(k) = 4\,\sin^2\left(\frac{k\,L}{4}(\theta^2+\gamma^{-2})\right)$$



WE MEASURE THE FAR FIELD AND NEAR FIELD COTR SIMULTANEOUSLY ON SHOT

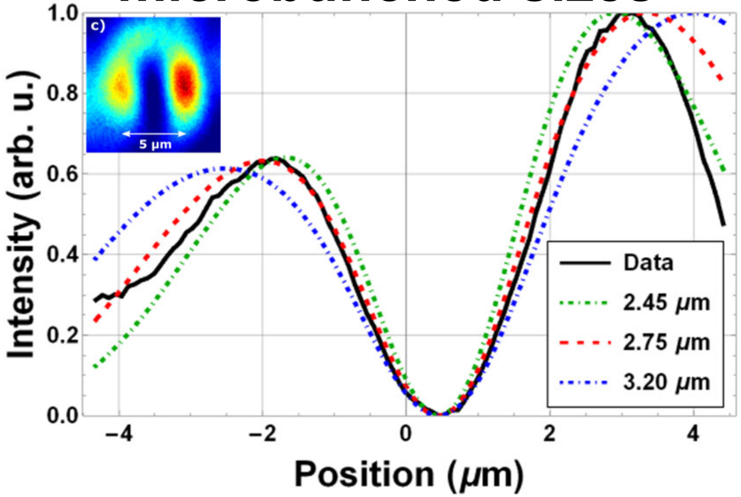
A. Lumpkin, M. LaBerge et al., “Coherent Optical Signatures of Electron Microbunching in Laser-Driven Plasma Accelerators”, Phys. Rev. Lett., vol 88, pp. 234801, 2020.

- Blocking foil reflects ~2.5 J Draco pulse
- Aluminized Kapton foil is first COTR source
- Si wafer is second COTR source
- Linearly polarized near field COTR imaged with microscope objective
  - Only sees COTR from first source
  - 600 nm image
- Focus of objective imaged using second lens to create far field image on camera
  - Sees interference from both COTR sources

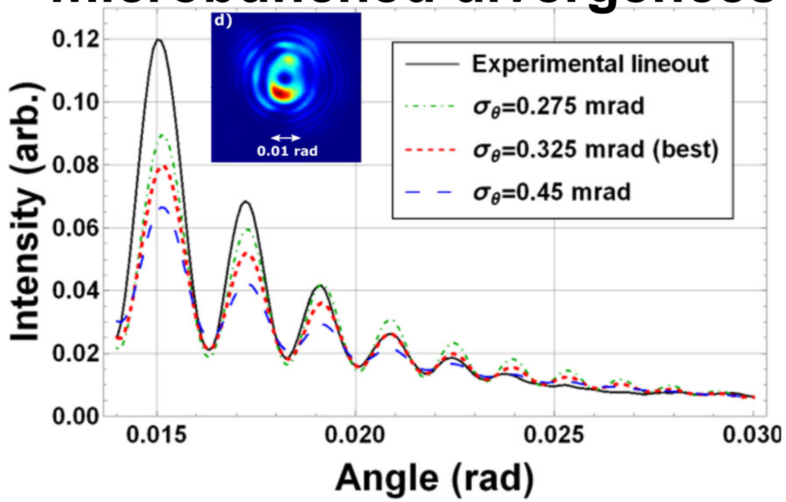


USING NEAR FIELD AND FAR FIELD COTR, WE DETERMINE AN UPPER LIMIT ON THE MICROBUNCHED EMITTANCE

COTR from various microbunched sizes



COTRI from various microbunched divergences

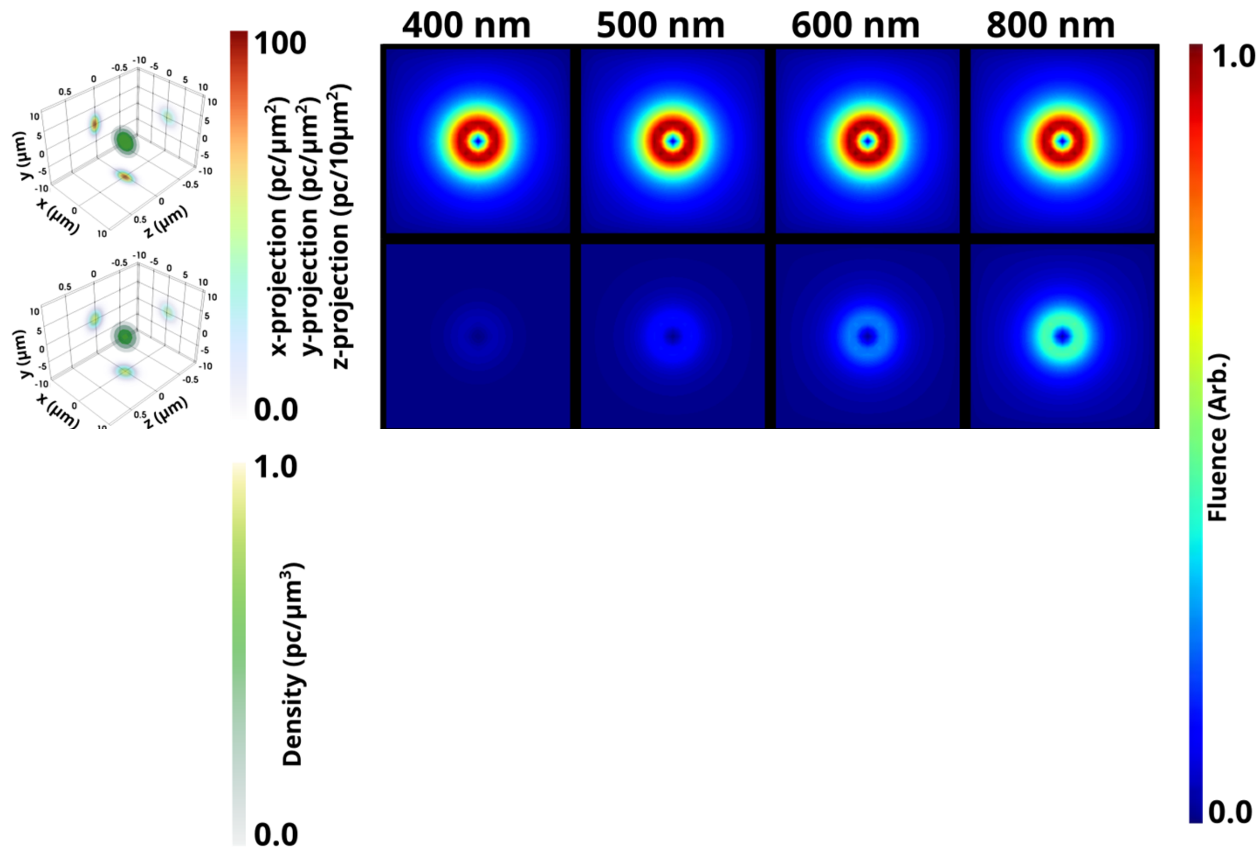


- Microbunching fraction $f_b \approx 0.013$
- Microbunched size measured to be $\sigma_x = 2.75^{+0.45}_{-0.30}$ μm
- COTRI outer fringe visibility is most sensitive to microbunched divergence
- Microbunched divergence measured to be $0.33^{+0.12}_{-0.05}$ mrad
- Microbunched normalized emittance of $0.36^{+0.19}_{-0.09}$ mm mrad

A. Lumpkin, M. LaBerge et al., "Coherent Optical Signatures of Electron Microbunching in Laser-Driven Plasma Accelerators", Phys. Rev. Lett., vol 88, pp. 234801, 2020.

DIFFERENT WAVELENGTH COTR PATTERNS EXHIBIT UNIQUE ASPECTS OF THE BEAM STRUCTURE

- Longer bunches suppress the shorter wavelength COTR

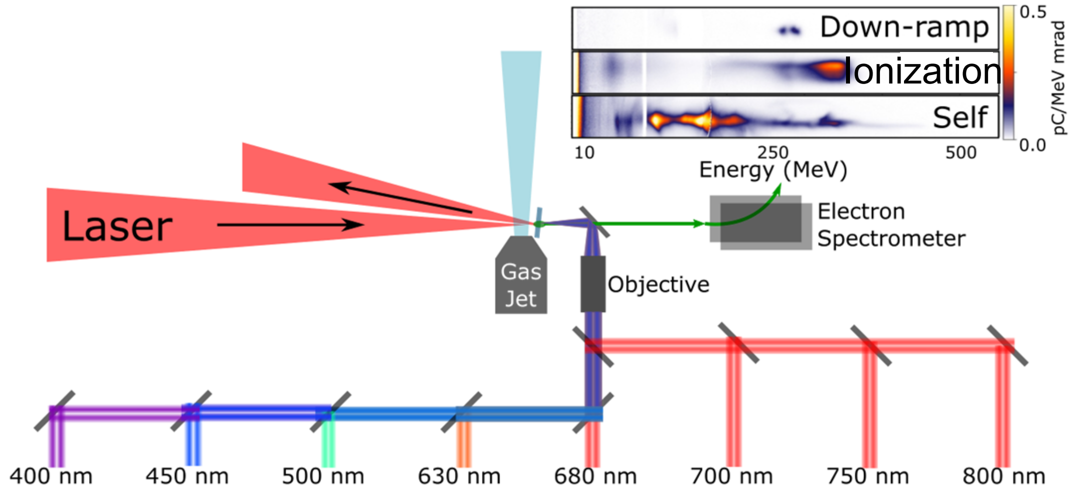


COHERENT OPTICAL TRANSITION RADIATION PATTERNS CORRELATE WITH INJECTION REGIME

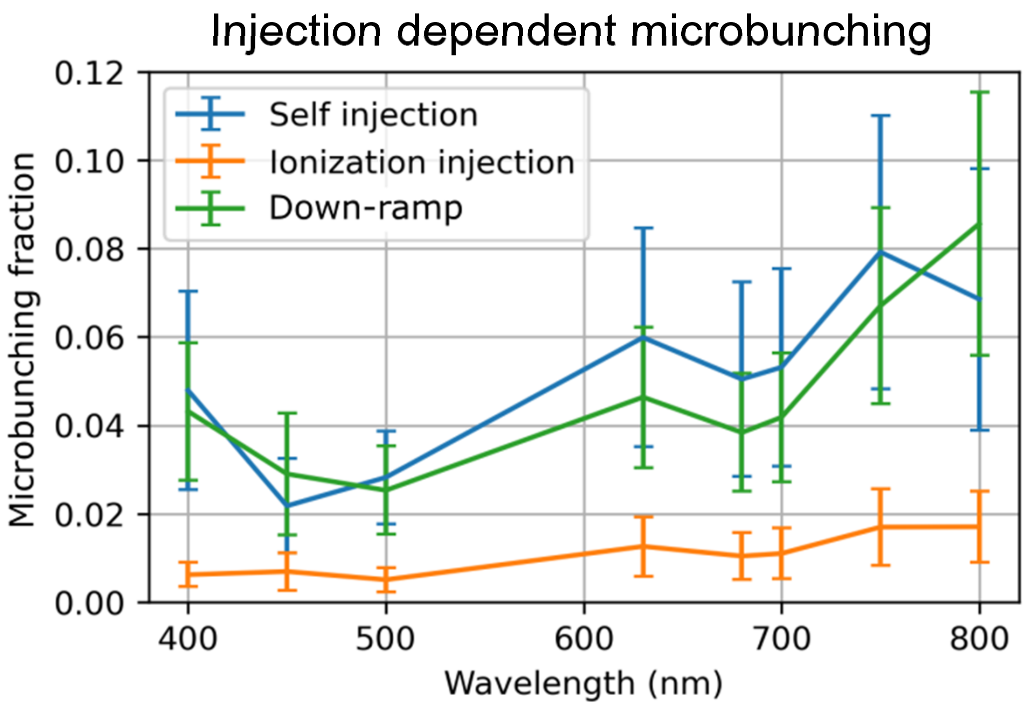
Down-ramp:
- Small (~5 µm size)
- Shape does not dramatically change across wavelengths

Ionization injection:
- Larger (~10 µm size)
- Two annular patterns visible at longer wavelengths

Self injection:
- Largest (~10 µm size) and most complex

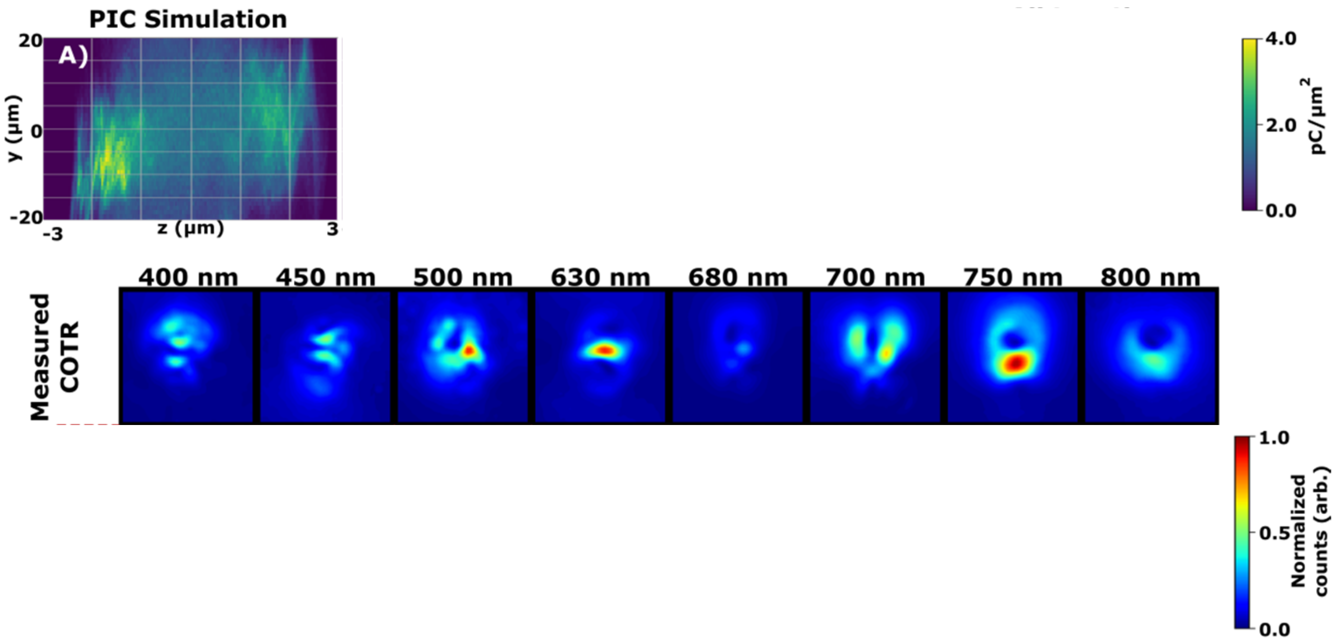


MEASURED MICROBUNCHING FRACTION IS ALSO SENSITIVE TO INJECTION REGIME



- Microbunching fraction (coherence) calculated by fully coherent charge/N
- Pre-bunched beams useful for compact SASE FELs

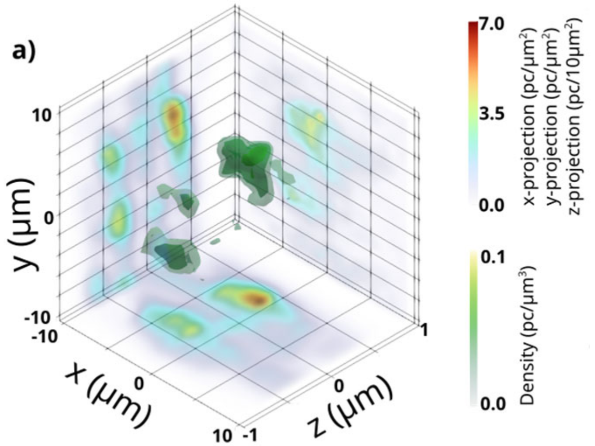
PARTICLE IN CELL SIMULATIONS SHOW STRUCTURES THAT ARE CORROBORATED BY COTR IMAGES

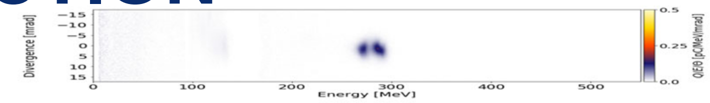


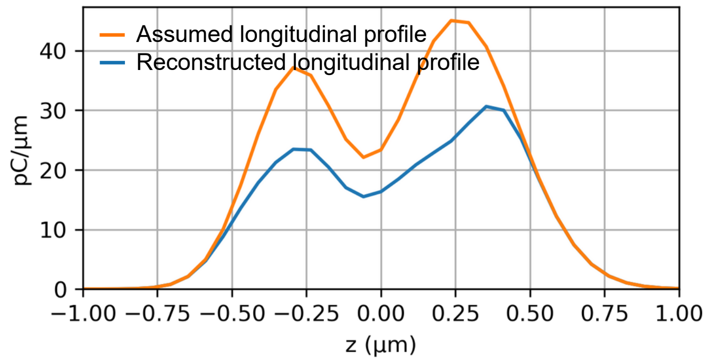
- Observed COTR patterns show evidence of laser-induced transverse-longitudinal modulation

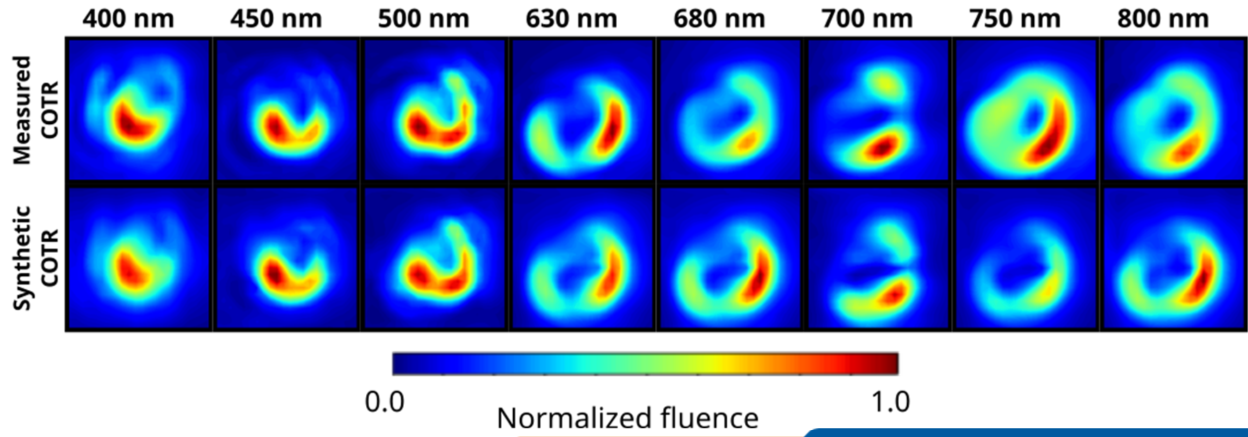
USING INDEPENDENT INFORMATION ABOUT THE BEAM'S LONGITUDINAL PROFILE AND COTR IMAGES, WE MAKE A 3D BUNCH RECONSTRUCTION

- The geometry of down-ramp induces injection leads to a chirp in the bunch
- With a reasonable chirp estimate, we back out the beam profile
- Using the COTR images and beam profile, we can make a 3D bunch reconstruction



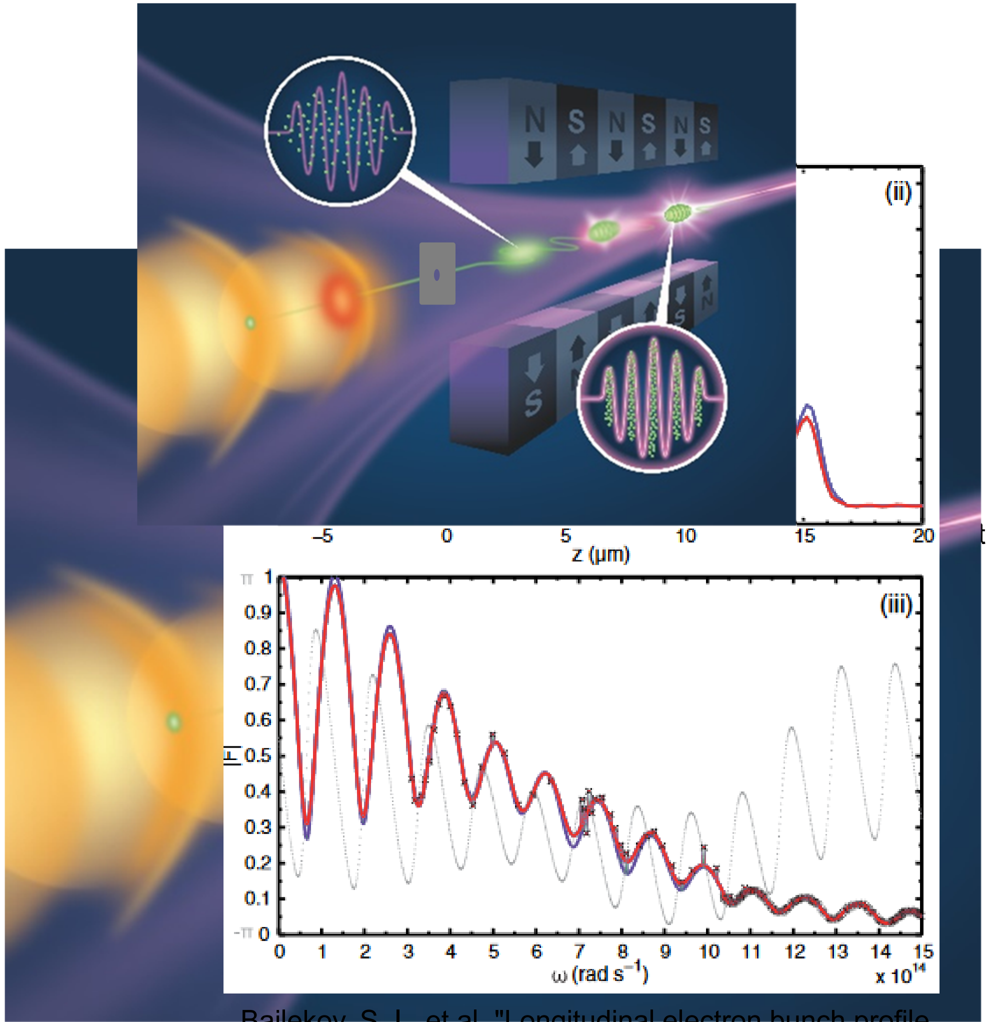






OUTLOOK

- Pre/post undulator CTR
- CTR from a beam driven geometry
- Coherent x-ray transition radiation
- Coherent diffraction radiation
- Coherent Smith-Purcell radiation



Surface charge

Bajlekov, S. I., et al. "Longitudinal electron bunch profile reconstruction by performing phase retrieval on coherent transition radiation spectra." Physical Review Special Topics-Accelerators and Beams 16.4 (2013): 040701.

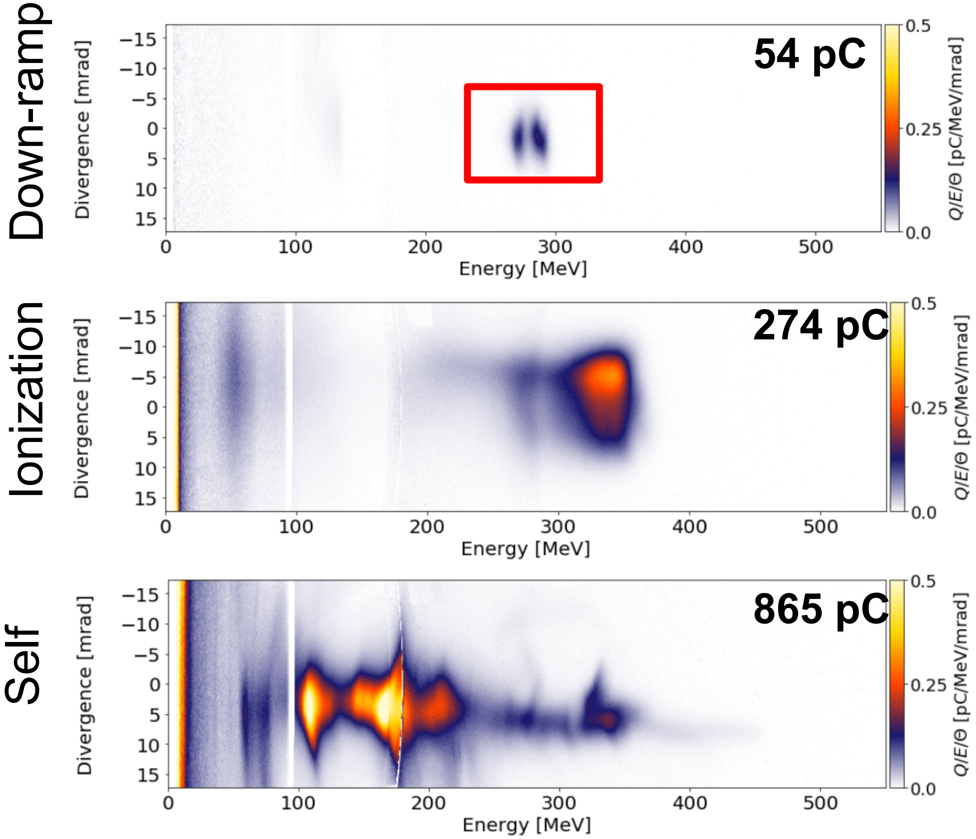
Konoplev, I. V., et al. "Single-shot, nondestructive monitor for longitudinal subpicosecond bunch profile measurements with femtosecond resolution." Physical Review Accelerators and Beams 24.2 (2021): 022801.

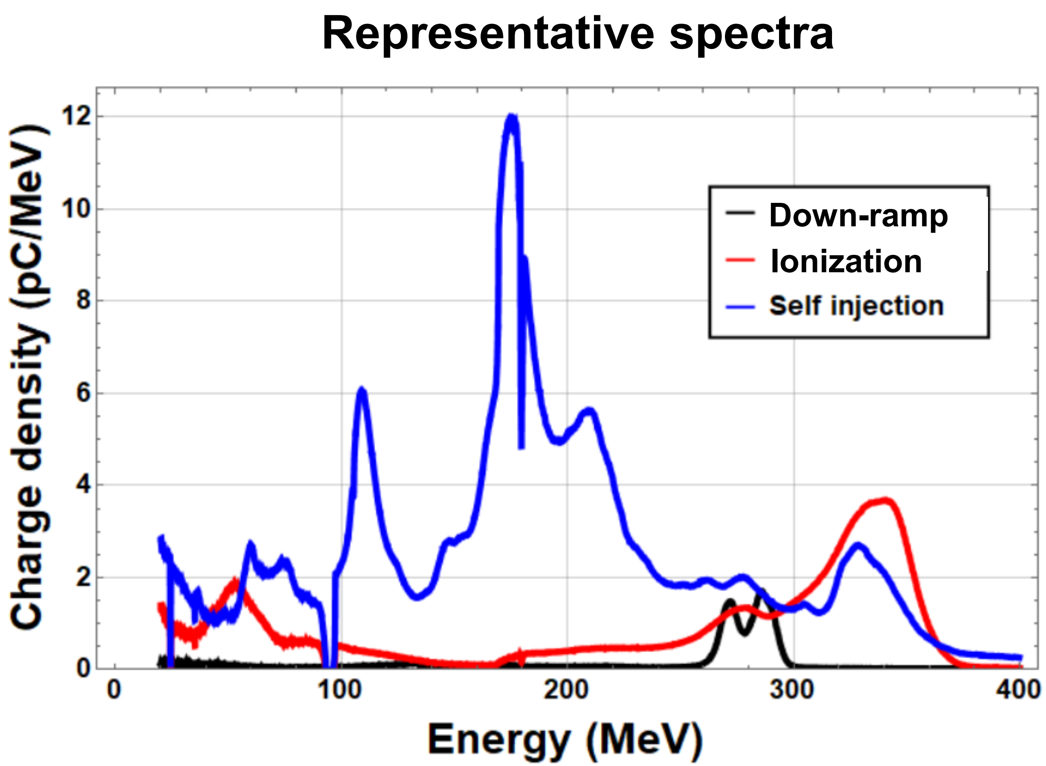
CONCLUSION

- Longitudinal beam information is spectrally encoded in coherent radiation
- With spectrally separated transverse information, 3D beam structure can be gleaned
- Microbunched structures are present in LPA accelerated electron beams
- These structures are injection regime dependent
- At HZDR, we have used coherent radiation to probe the longitudinal and transverse spatial dimensions as well as the transverse momentum dimension of our beams, allowing us to characterize these beams for radiation applications

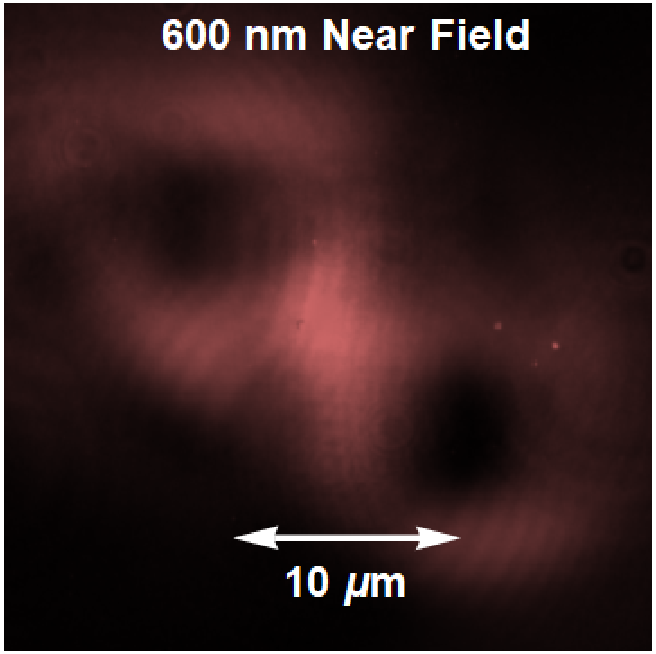

THANK YOU FOR YOUR ATTENTION
University of Texas at Austin
A. Hannasch, B. Bowers, R. Zgadzaj, M. C. Downer
Helmholtz-Zentrum Dresden Rossendorf
O. Zarini, A. Debus, J. P. Couperus Cabadağ, A. Ghaith, Y. Y. Chang, S. Schöbel, P. Ufer, R. Pausch, U. Schramm, A. Irman
Synchrotron Soleil
M. Labat, M. E. Couprie
Fermi Lab
A. Lumpkin
PhLAM
E. Roussel
MORITZSCHLIEB.DE

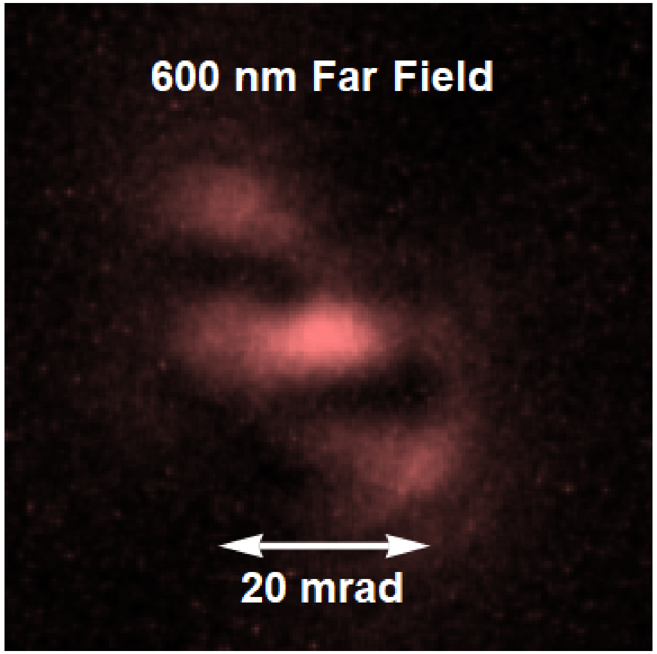
THE LASER WAKEFIELD ACCELERATOR OUTPUT DEPENDS STRONGLY ON INJECTION REGIME





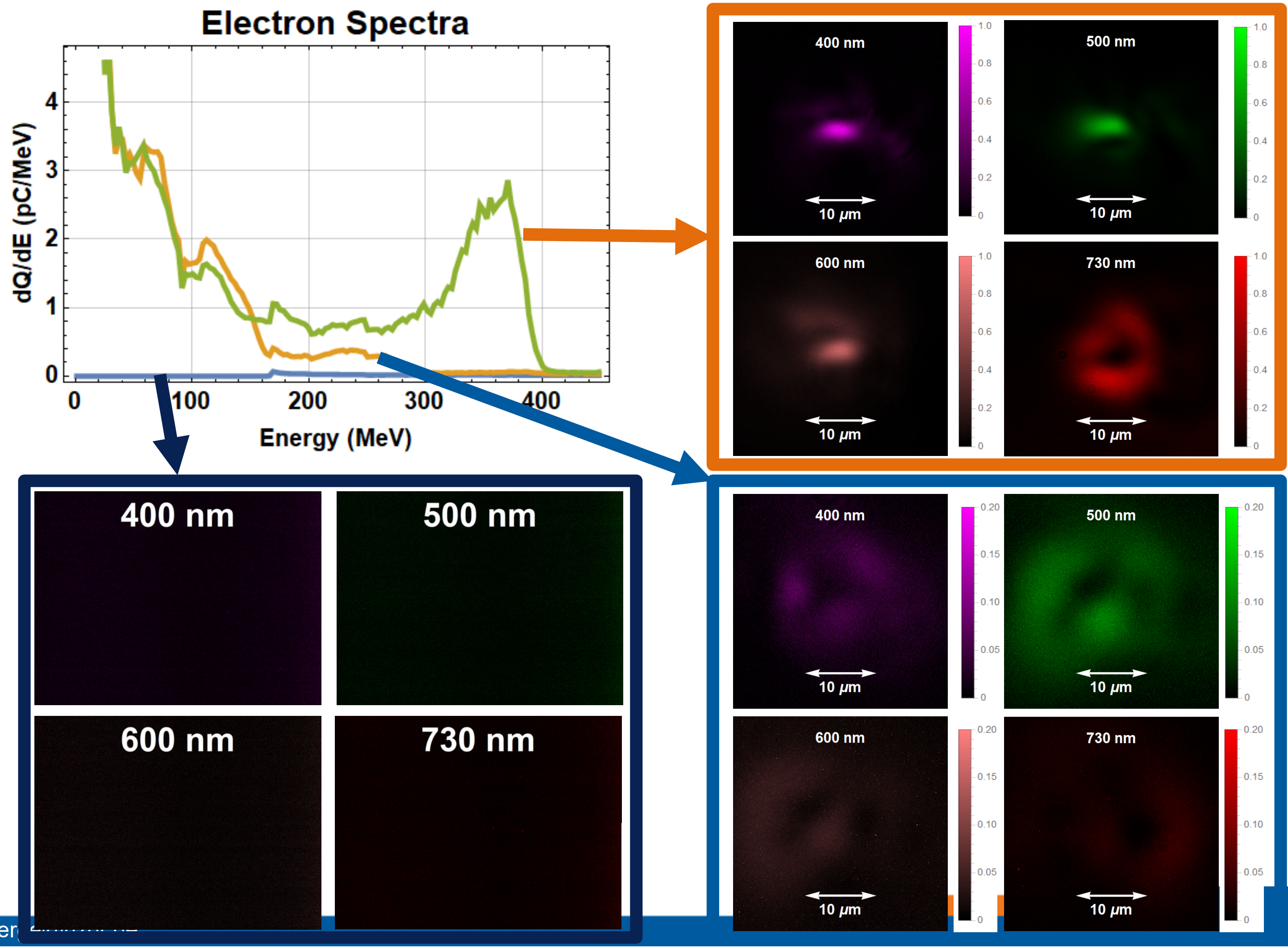
Similar substructure appears in both our near and far field imaging systems





- The far field (FF) images angular space similar to how the near field images position space
- Measurement taken 0.7 mm from exit of jet
- Two beamlets appear to be ~15 μm apart in NF
- Two beamlets appear to be ~20 mrad apart in FF

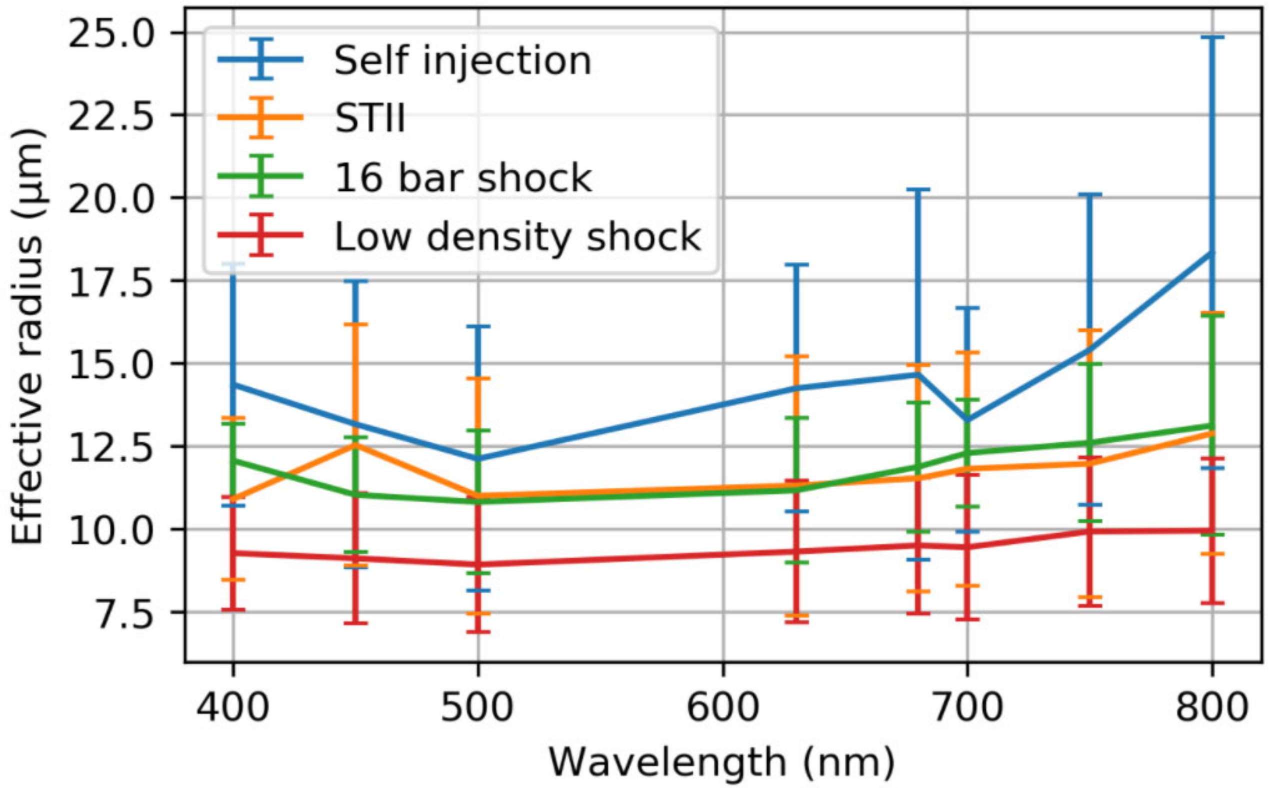
The COTR signal is dominated by the contribution from high energy electrons



The effective radius ($\sqrt{Area/\pi}$) of CTR patterns is also very sensitive to injection regime

- Radiation size scales roughly linearly with coherent bunch size
- For lower densities, down-ramp generates slightly smaller radiation patterns
- Self injected electron bunches consistently produced the largest radiation patterns

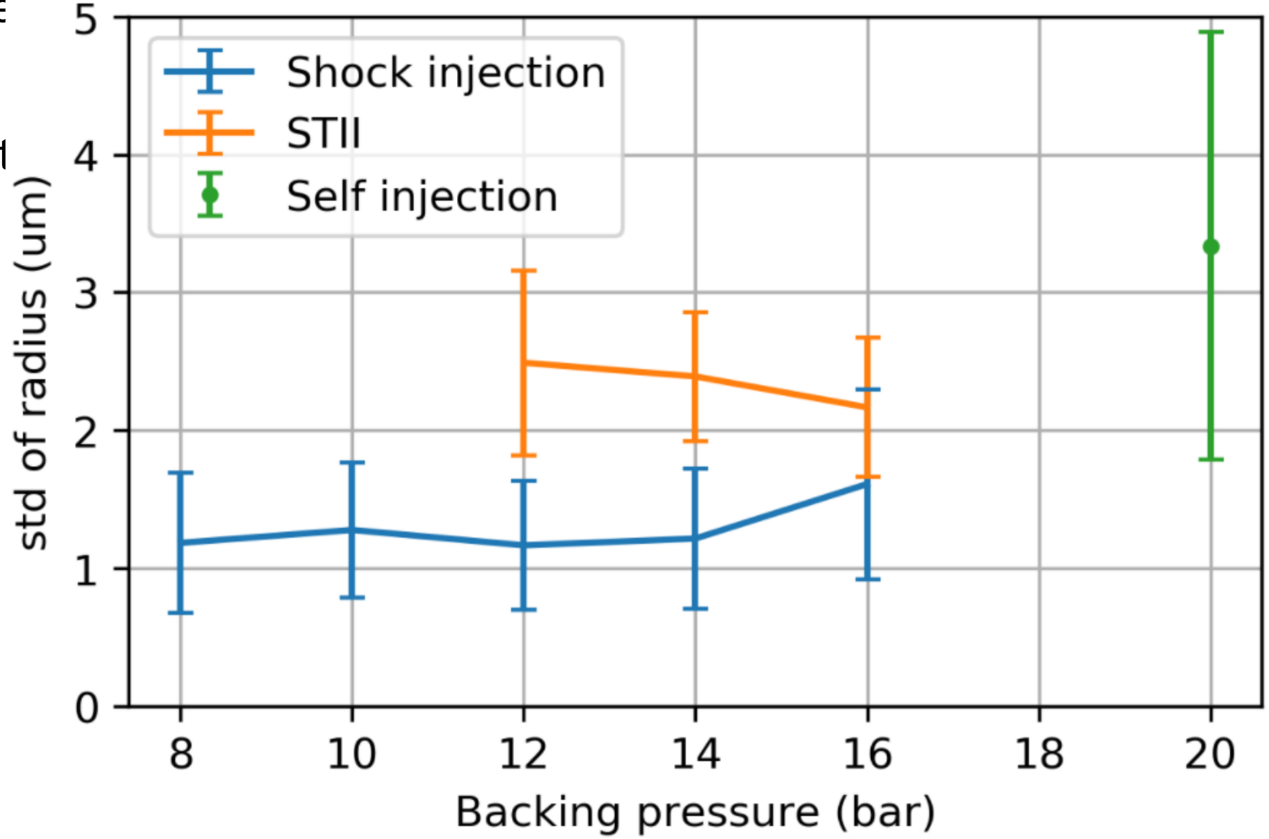
Radiation size across different regimes



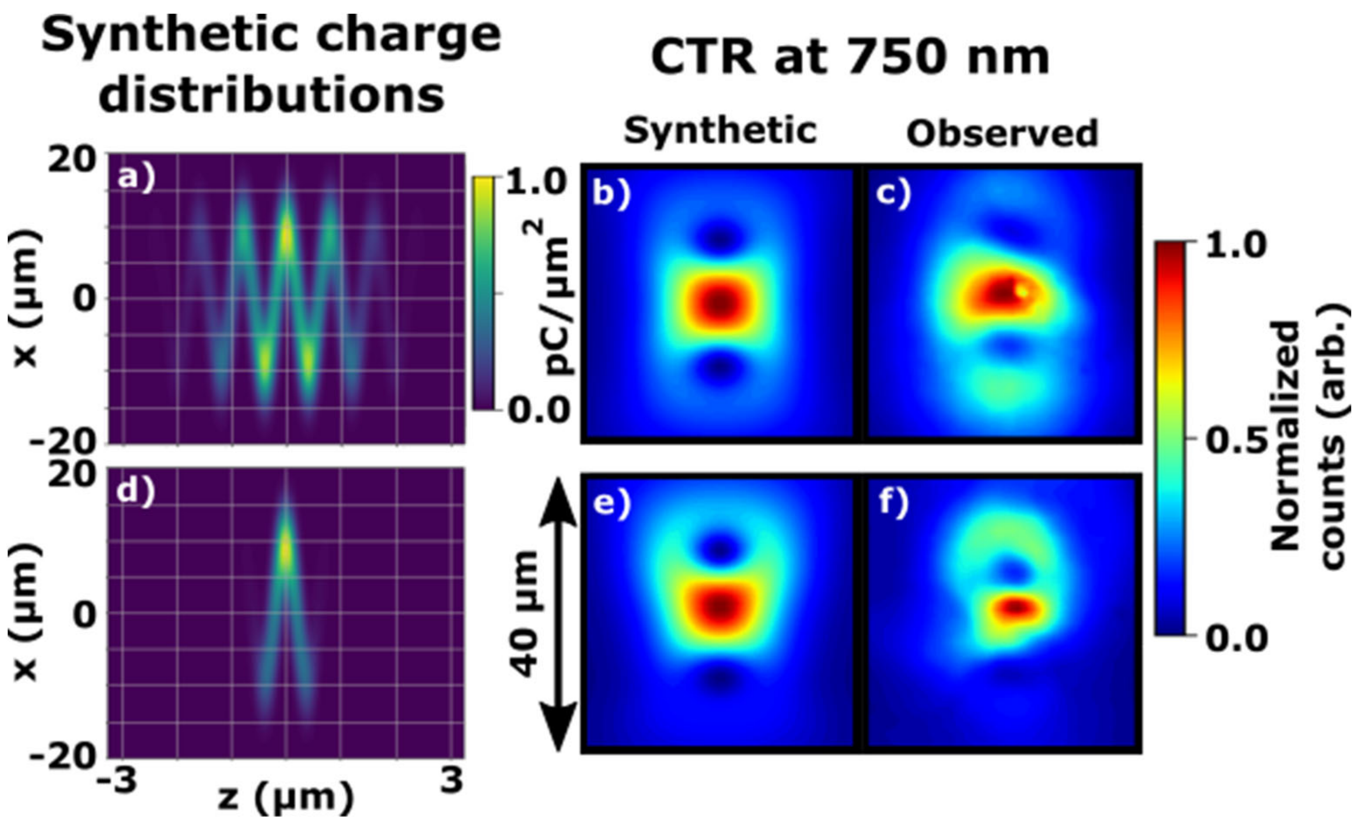
When a beam has non-separable substructure, the COTR size varies by wavelength

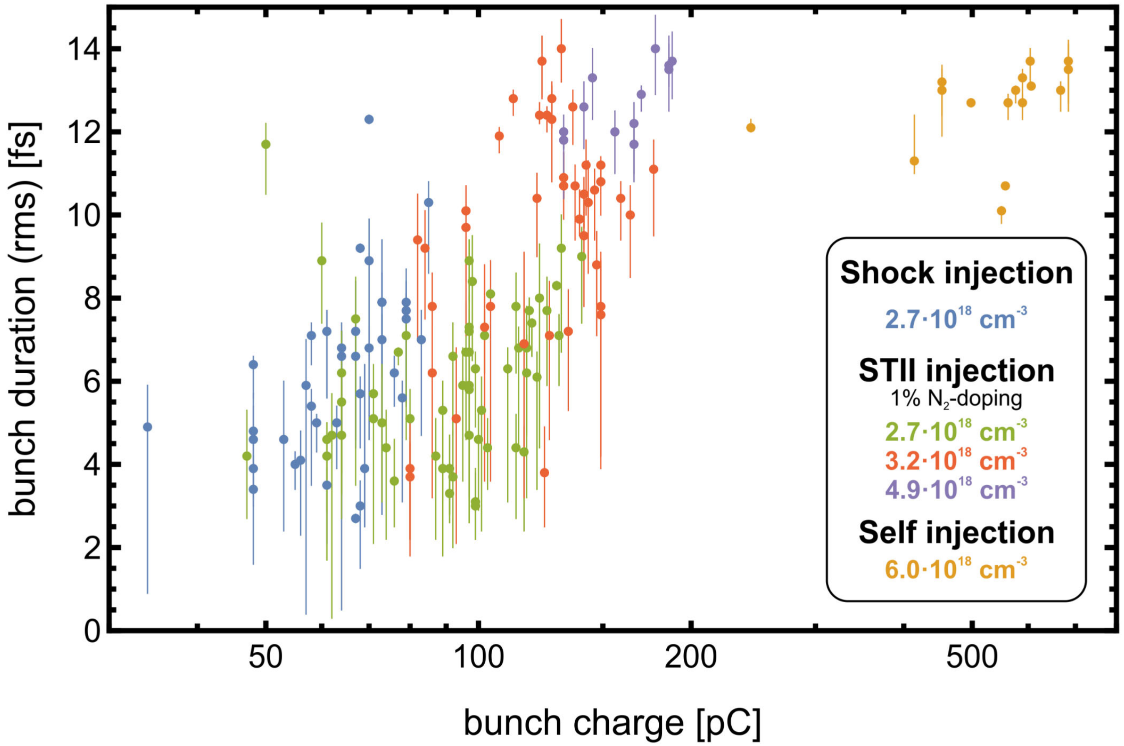
- For a single shot, there is a COTR size measurement at each wavelength
- The variation in this size measurement across wavelengths is a proxy complexity of coherent substructures

Spectral variation in radiation size



Oscillating beams have a signature COTR pattern





bunch duration (rms) [fs]
0
2
4
6
8
10
12
14
50
100
200
500
bunch charge [pC]
Shock injection
2.7·10^18 cm^-3
STII injection
1% N2-doping
2.7·10^18 cm^-3
3.2·10^18 cm^-3
4.9·10^18 cm^-3
Self injection
6.0·10^18 cm^-3