Coherent Optical Transition Radiation Imaging for Laser-driven Plasma Accelerator Electron-Beam Diagnostics

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Workshop on Beam Acceleration in Crystals and Nanostructures

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Introduction and Context

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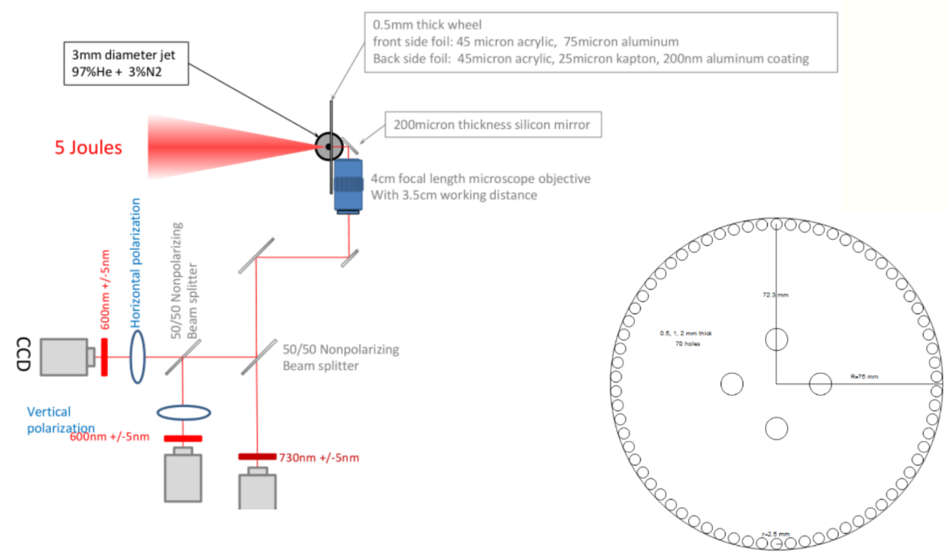
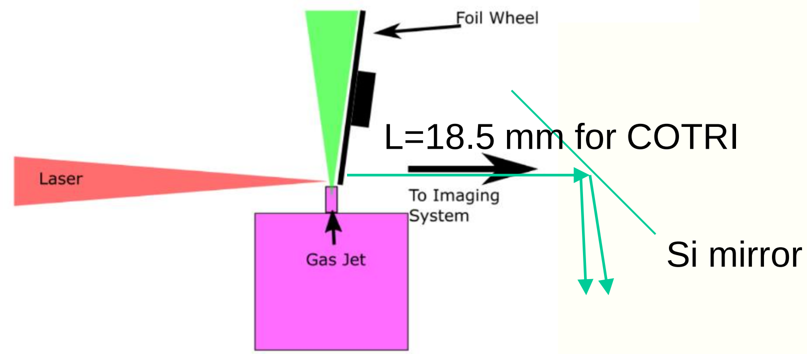
- Recent reports of quasi-monoenergetic laser plasma accelerator (LPA) beams at 2 GeV and 100 MeV demonstrated normalized transverse emittances below 1 mm-mrad and divergences less than 1/gamma in both cases [1,2].
- Such unprecedented LPA beam parameters can, in principle, be addressed by utilizing the properties of coherent optical transition radiation (COTR).
- Practical challenges of utilizing these techniques with the LPA configurations will also be discussed.

1. Xiaoming Wang et al., Nature Communications, June 11, 2013.
2. Hai-EnTsai, Chih-Hao Pai, and M.C. Downer, AIP Conf. Proc. **1507,** 330 (2012).

HZDR LPA Setup

- Use 1 mm and 0.5 mm wheels
- Al foil in front, Al coated Kapton tape back
- Microscope Objective ~4 cm from foil for near field (NF).
- 4 cameras to measure 2 polarizations and unpolarized signal at 600 nm plus far field (FF) at 633 nm
- Ability to move the wheel & objective along beam axis
- Two COTR sources at L=18.5 mm form interference fringes in FF.



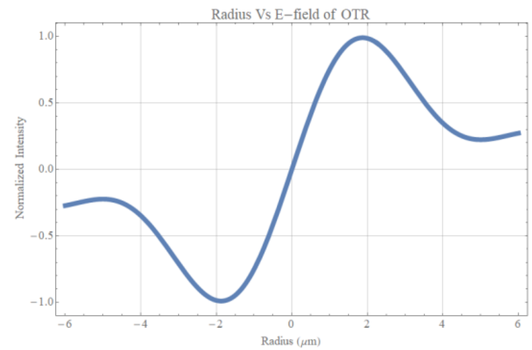


Courtesy of M. LaBerge, rev

Optical Transition Radiation In Laser Plasma Accelerators

Coherent Optical Transition Radiation (COTR)

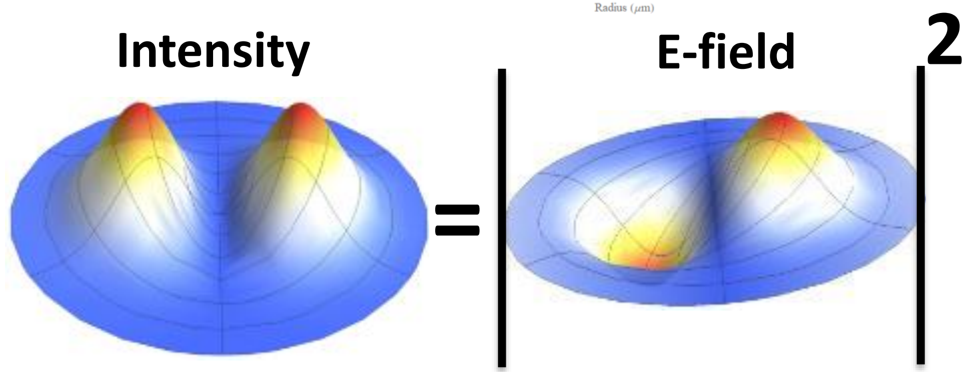
- Coherent signal $\propto N^2$ as opposed to N
- Level of coherence related to Fourier transform of longitudinal bunch profile



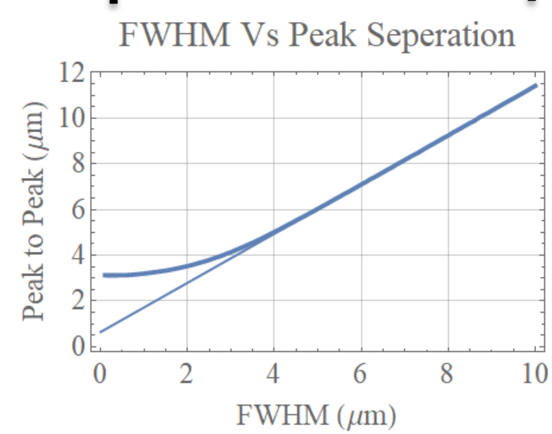
Coherent Point Spread Function

- Single electron E-field pattern

$$E \propto \sin\varphi \int_0^{\theta lens} \frac{\theta^2}{\theta^2+1/(\beta\gamma)^2}\, J_1\!\left(\frac{2\pi}{\lambda}\,\frac{\rho\,\theta}{M}\right) d\theta$$



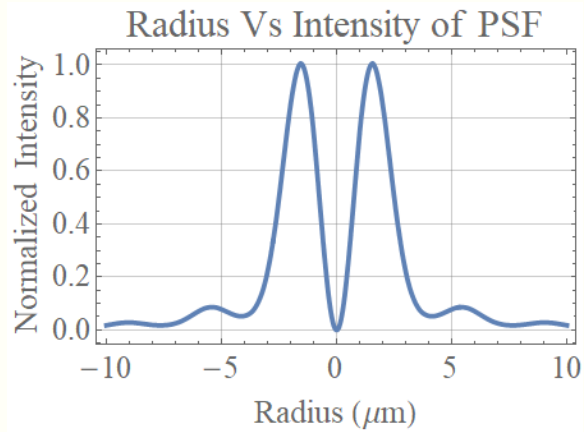
- Central minimum never fills in
- Highly sensitive to skew
- Only samples coherent portion of beam
- Multiple colors + CTR spectra could be used to create a full bunch reconstruction

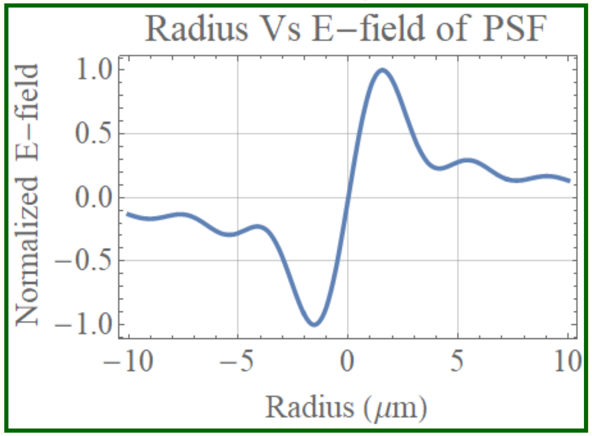


Courtesy of M. LaBerge

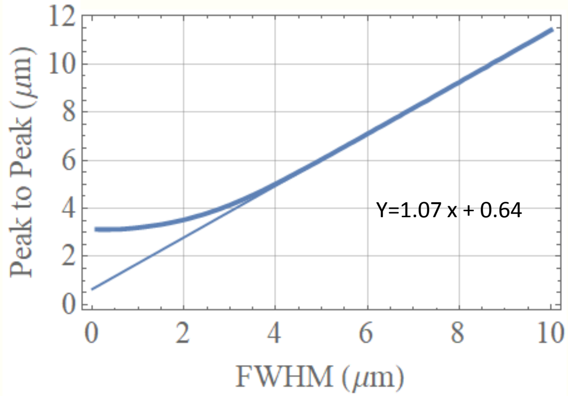
Adding Coherence to PSF Model

- Previous NF OTR work has been on incoherent electron bunches
- Lobe separation does not greatly increase in incoherent model
- Lobe separation increases significantly in coherent model. 600 nm cases below.

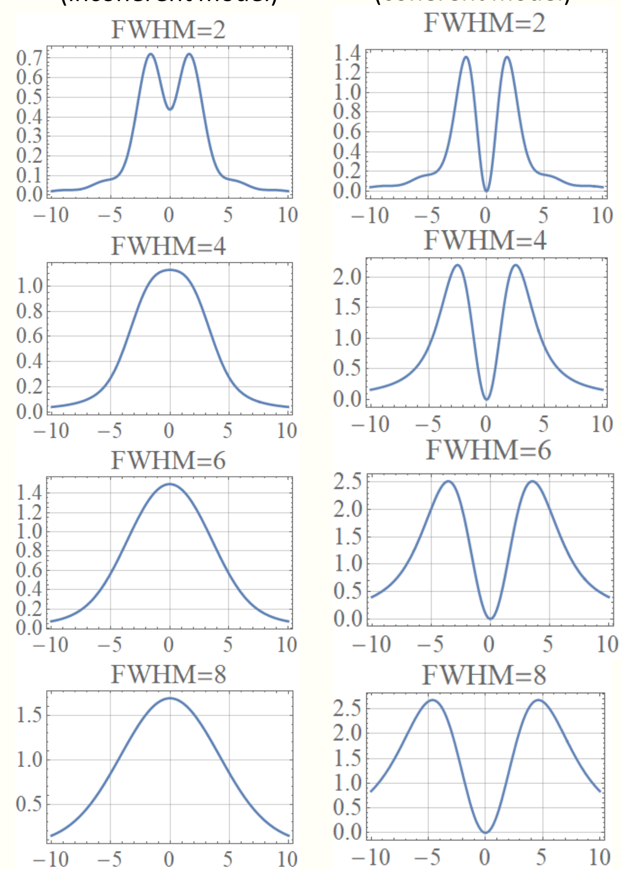




FWHM vs Peak Separation



Summing Intensities (incoherent model) | Summing Fields (coherent model)



Courtesy of M. LaBerge

KEK Experimental OTR PSF

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- **KEK staff used vertical polarizer and small beam to observe PSF and suggested potential use of structure.**
  - **Use PSF valley for profile measurements at the PSF limit.**

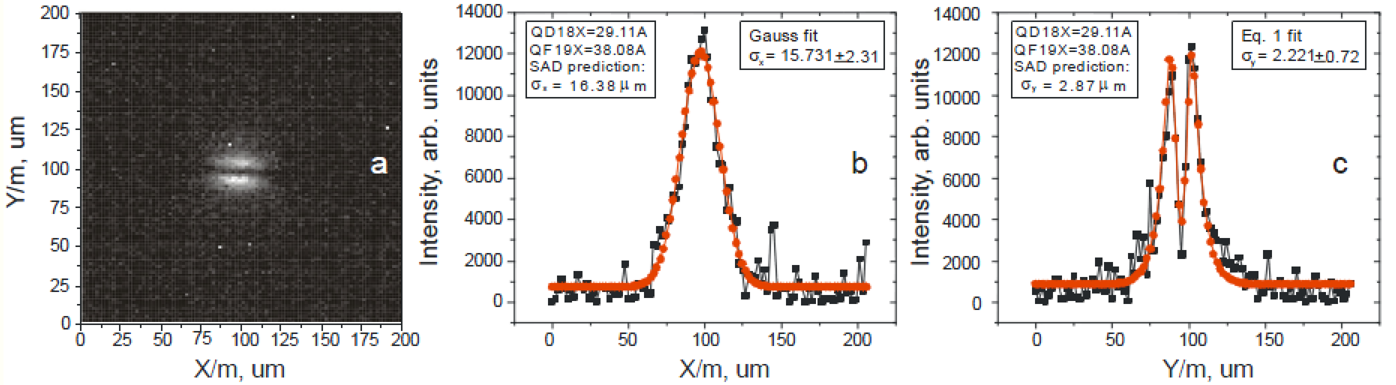


Figure 3: CCD image of the OTR taken with linear polarizer and 500 nm optical filter (a) and two image projections: horizontal (b) and vertical (c).

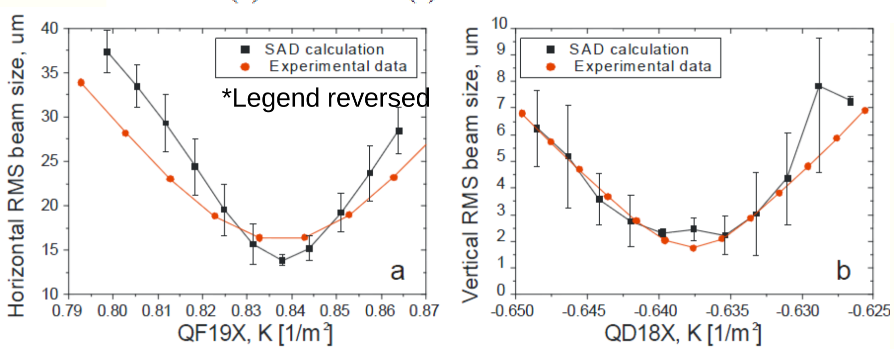


Figure 4: Horizontal RMS beam size as a function of the QF19X strength (a) and the dependence of the smoothing parameter σ (Eq. 1) versus QD18X quadrupole magnet strength. SAD predictions of the vertical beam size for the same magnet strengths are also shown in the picture.

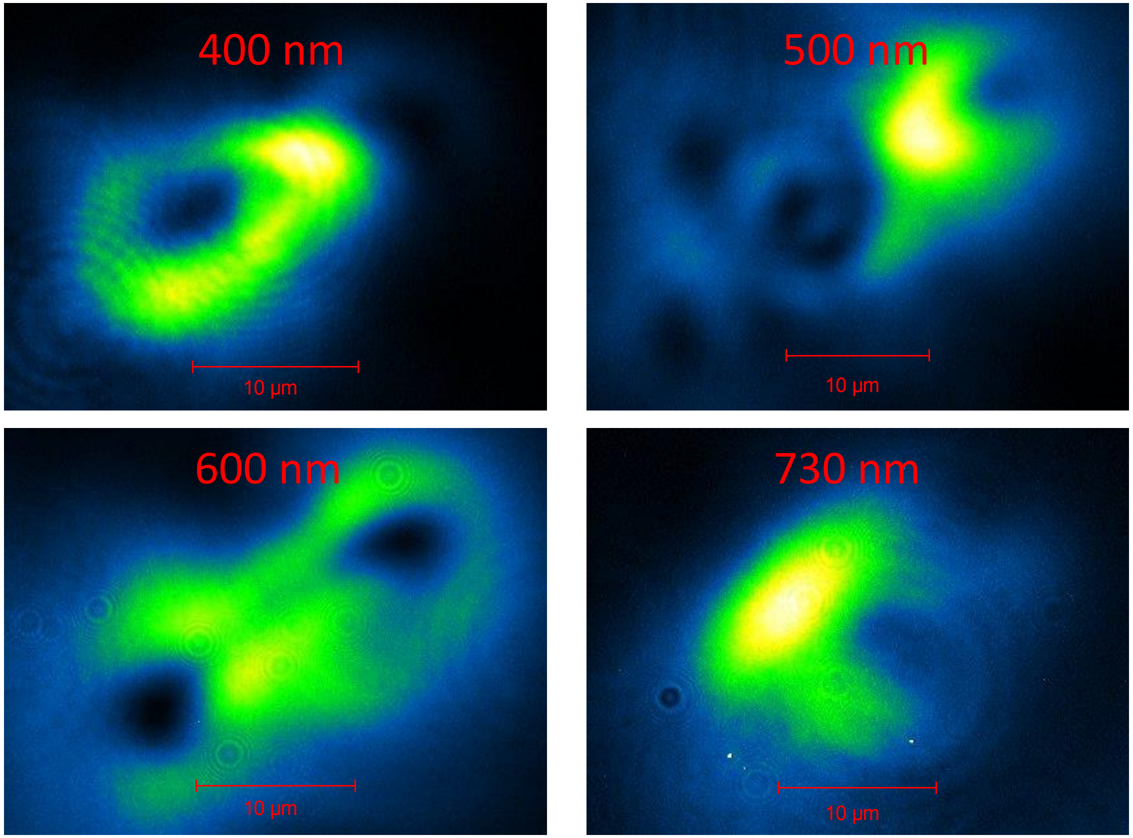
$$f(x) = a + \frac{b}{1+\left[c(x-\Delta x)\right]^4}\left[1 - e^{-2c^2\sigma^2}\cos\left[c(x-\Delta x)\right]\right] \quad (1)$$

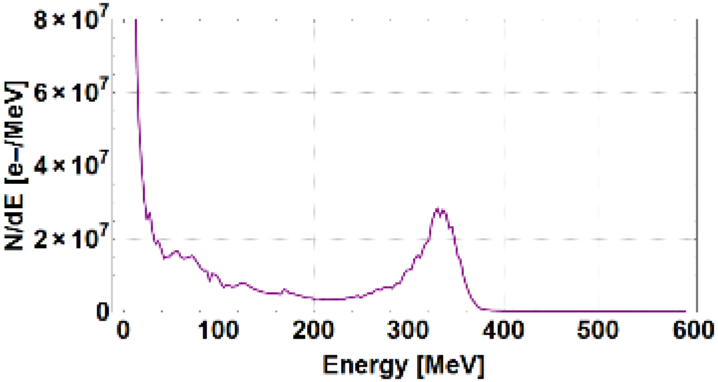
where a, b, c, σ, and Δx are free parameters of the fit function, namely: a is the vertical offset of the distribution with respect to zero which included a constant background; b is the amplitude of the distribution; c is the distribution width; σ is the smoothing parameter dominantly defined by the beam size; and Δx is the horizontal offset of the distribution with respect to zero

A. Aryshev et al., IPAC10

Coherent Optical Transition Radiation Observed at HZDR (LaBerge)

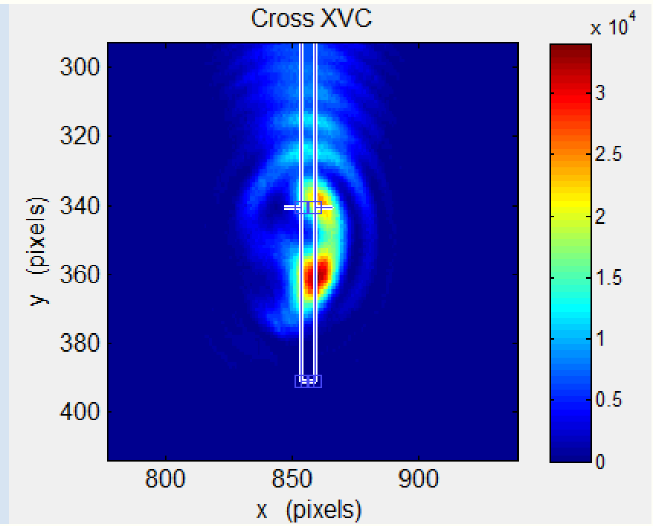
- Significant sub-structure evident across multi-color images
- Structure not apparent on electron spectrometer

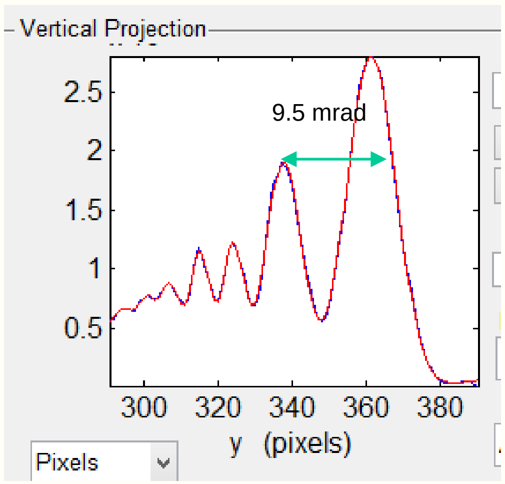


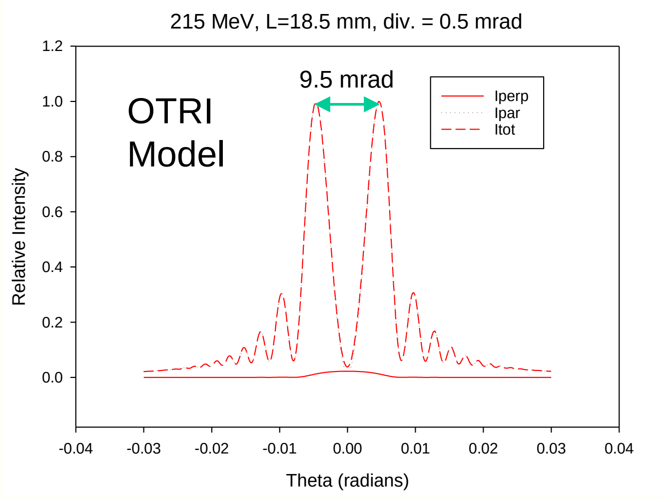


HZDR A.D. Data: June 1, 2017

- Shot #115, Far Field, 633 x10 nm BPF, ND2.6, 215 MeV, L=18.5mm, 100 pC, 9-10 fringes, consistent with OTRI/COTRI.
- Asymmetric divergences and/or beam sizes indicated. Unpolarized COTR>
- Last 8 peaks match model to ~5% with 0.35 mrad/pixel. Delta main peaks= 23.5 pix.
- COTR enhancements of about 10^5 due to microbunching.

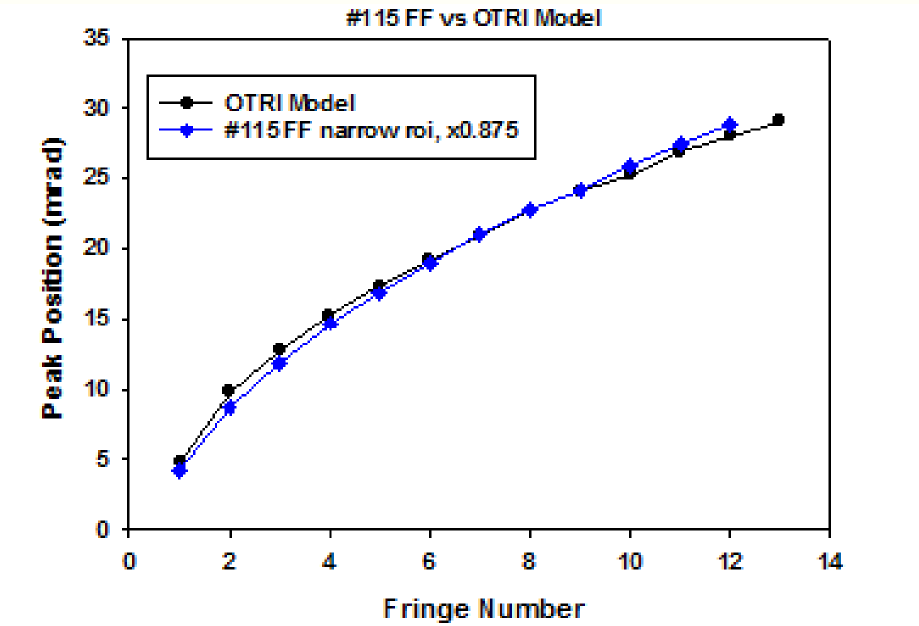


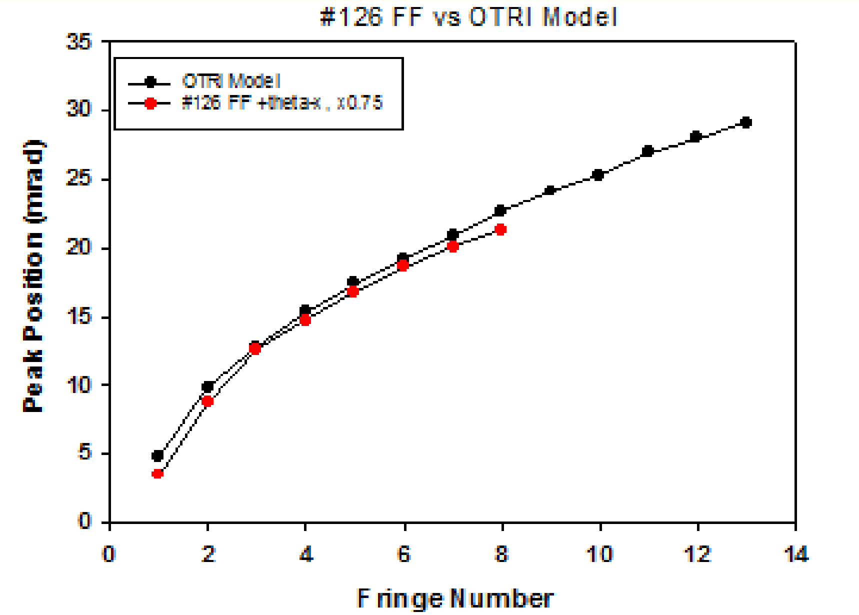




Fringe Peak Positions Checked

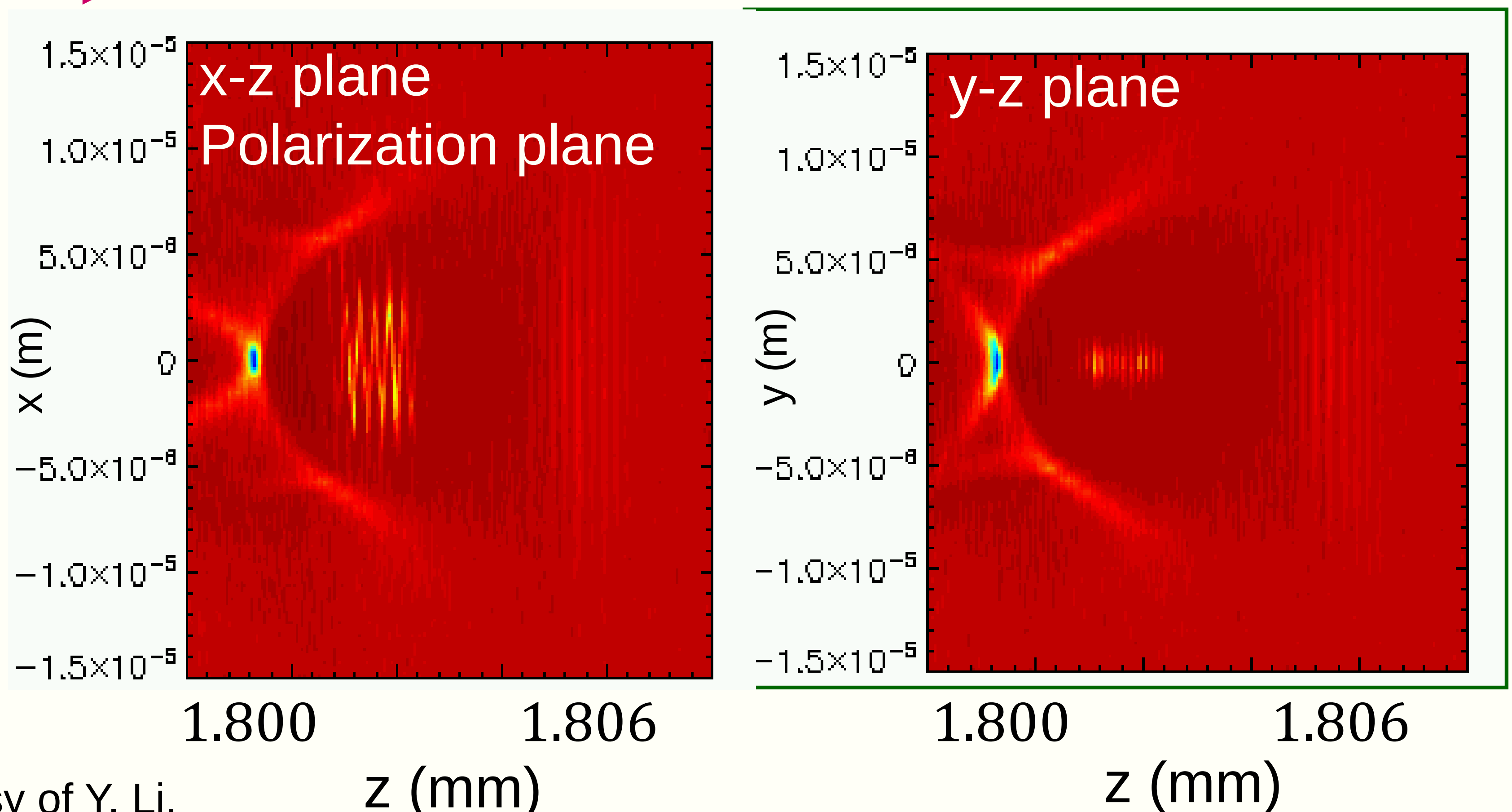
- Experimental fringe peak positions were compared to the OTRI model which are very close to COTRI model.
- Parameters: 215 MeV, 633 nm, L=18.5 mm,
- Angular calibration factor: 0.35 ± 0.05 mrad/pixel





Laser Modulation of the Beam Structure in the Bubble

Laser



Courtesy of Y. Li,
A. Lumpkin in FEL07

SUMMARY

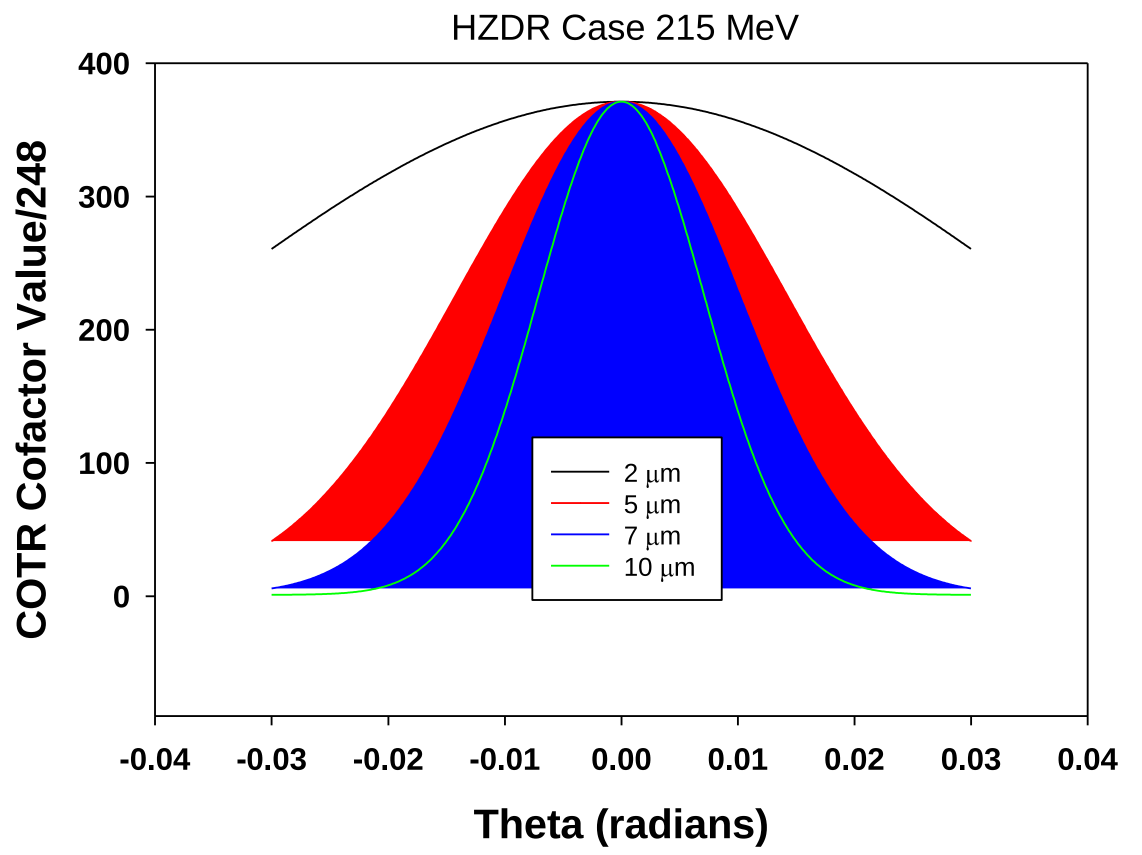
- For the first time electron-beam divergence information at sub-mrad range was obtained just outside the plasma bubble using COTRI imaging. Hot Foil scattering issue.
- A model of the COTR PSF shows beam size dependencies in the lobe separation and lobe width.
- COTR PSF plus COTRI techniques provide emittance estimates of microbunched electron beamlets uniquely.
- Signal enhancements are in 10^4 to 10^5 range indicating significant microbunching occurred at visible wavelengths within the LPA process. New insights!
- The COTR provides a unique way of measuring the microbunching in the beam: single shot, minimally invasive, and high resolution. LPA Simulations needed.

Microbunching Mechanisms

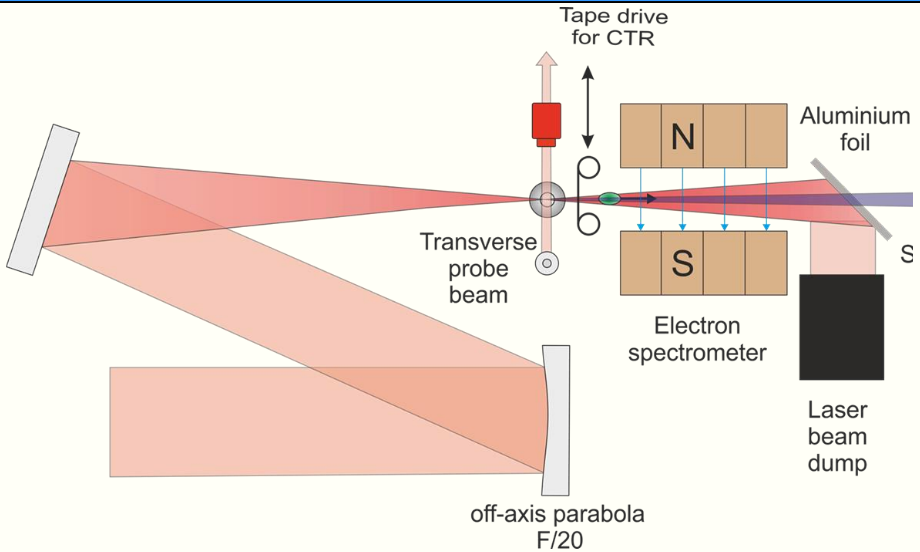
- **Microbunching of an electron beam, or a z-dependent density modulation with a period λ, can be generated by several mechanisms:**
  - **In self-amplified spontaneous emission or (SASE) induced microbunching (SIM) the electron beam is bunched at resonant wavelength and harmonics. This is narrow band.**
  - **The LSC-induced microbunching (LSCIM) starts from noise fluctuations in the charge distribution which causes an energy modulation that converts to density modulation following Chicane compression. This is a broadband case.**
  - **The laser-induced microbunching (LIM) occurs at the laser resonant wavelength (and harmonics) as the e-beam co-propagates through a wiggler with the laser beam followed by Chicane compression. This is narrow-band. (LPA case new.)**
- **A microbunched beam will radiate coherently.(COTR)**

COTRI Cofactors: HZDR Case

- **Beam sizes 2,5,7,10 μm, 100 pC, N_b=2%**



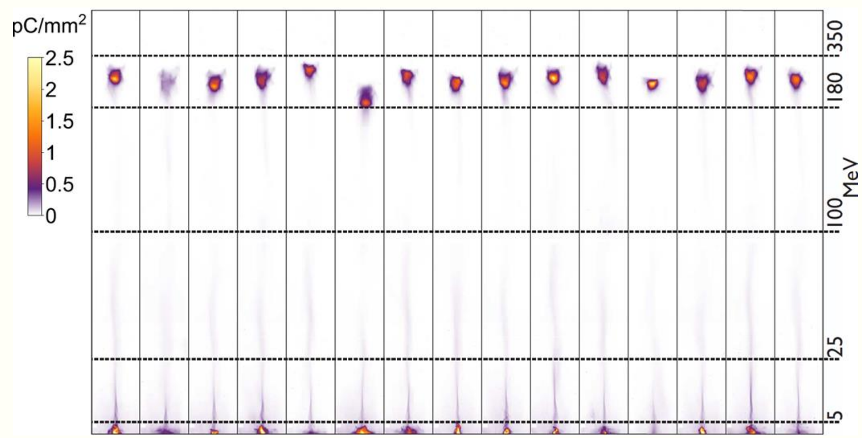
Draco Laser and LPA at HZDR



Draco Laser Parameters

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

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



Courtesy J. Couperus at HZDR

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Coherent Optical Transition Radiation Observed at HZDR (LaBerge)

Evidence of Coherence Dominated OTR

- The level of signal: Radiation split across eight cameras with narrow bandpass
- Central minimum still approximately zero despite the ‘donut’ size