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Advanced Laser-driven Plasma Accelerator Electron-Beam Diagnostics with COTR-Based Techniques

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Motivation for New Single-shot Diagnostics in LPAs

- Many of you are aware of optical transition radiation (OTR) imaging for charged particle beams. Used for decades.
- Standard scintillators such as YAG:Ce with 100-μm thickness, yield about 100x more visible light than OTR. We always wished we had more OTR signal. Although 1 nC in a sub-mm spot of a relativistic electron beam can be imaged via OTR with even 8-bit cameras, charges of 100 pC are a challenge.
- What if the OTR signal were enhanced by 10^5 to 10^6??
- We could split the signal and do multiple parameter measurements on the same, single shot. This is exactly what we need for Laser-driven plasma accelerator (LPA) beams.
- If you have a longitudinal modulation at visible wavelengths in the electrons as seen in FELs and now demonstrated in LPAs, one gets coherent OTR (COTR). An exciting opportunity.

COTRI Model Revised to Address the Beam Size(z) in a Drift

- COTR Interferometry (COTRI) Model initially developed to explain the patterns from microbunched electrons inherent to the FEL process. *W_1*, number of photons *from* single electron.

(1)
$$\frac{d^2W_1}{d\omega d\Omega} = \frac{e^2}{\hbar c}\frac{1}{\pi^2\omega}\frac{(\theta_x^2 + \theta_y^2)}{(\gamma^{-2} + \theta_x^2 + \theta_y^2)^2}$$

Photons Per Unit frequency ω per unit solid angle Ω, *γ is the Lorentz factor, θ_x, θ_y are angles*

(2)
$$\frac{d^2W}{d\omega d\Omega} = |r_{\parallel,\perp}|^2 \frac{d^2W_1}{d\omega d\Omega}[N\boldsymbol{I}(\boldsymbol{k}) + N_b(N_b - 1)\boldsymbol{J}(\boldsymbol{k})]$$

When N_b of the N particles are microbunched.

(3)
$$\boldsymbol{I}(\boldsymbol{k}) = 4\sin^2\left[\frac{kL}{4}(\gamma^{-2} + \theta_x^2 + \theta_y^2)\right]$$

Interference function
$k = |\boldsymbol{k}| = 2\pi/\lambda$
L= foil spacing

(4)
$$\boldsymbol{J}(\boldsymbol{k}) = (H_1(\boldsymbol{k}) - H_2(\boldsymbol{k}))^2 + H_1(\boldsymbol{k})H_2(\boldsymbol{k})\boldsymbol{I}(\boldsymbol{k})$$

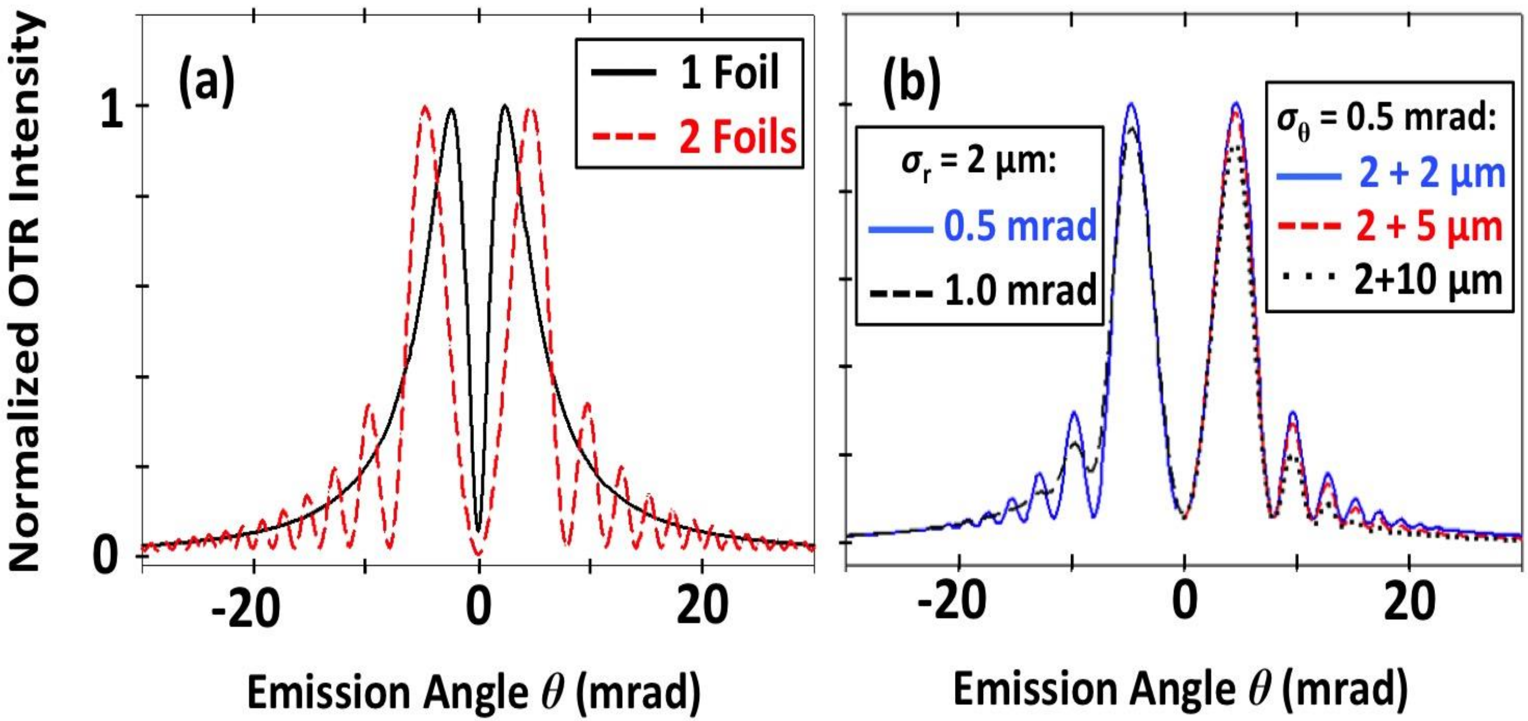
J(k)* is *Coherence function

where $H_j(\boldsymbol{k}) = r_j(\boldsymbol{k})/Q = g_j(k_x)g_j(k_y)F(k_z)$ for a microbunch of charge distribution $\rho_j(\boldsymbol{x})$ and total charge Q, with j = 1, 2.

Lumpkin et al., PRL July 2020

COTRI Model Shows Divergence and Beam size Effects

- OTR and COTRI exhibit beam parameter sensitivity effects in the far field (FF). Beam sizes measured in near field (NF).
- L=18.5 mm, λ=633 ± 5nm, E=215 MeV.

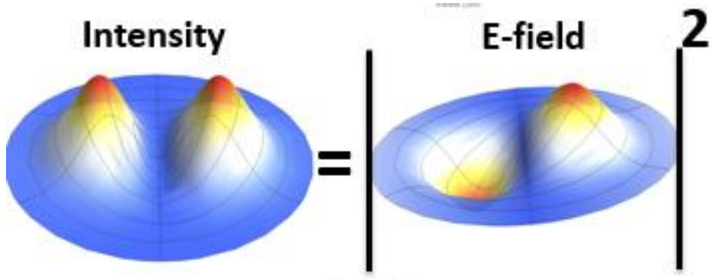


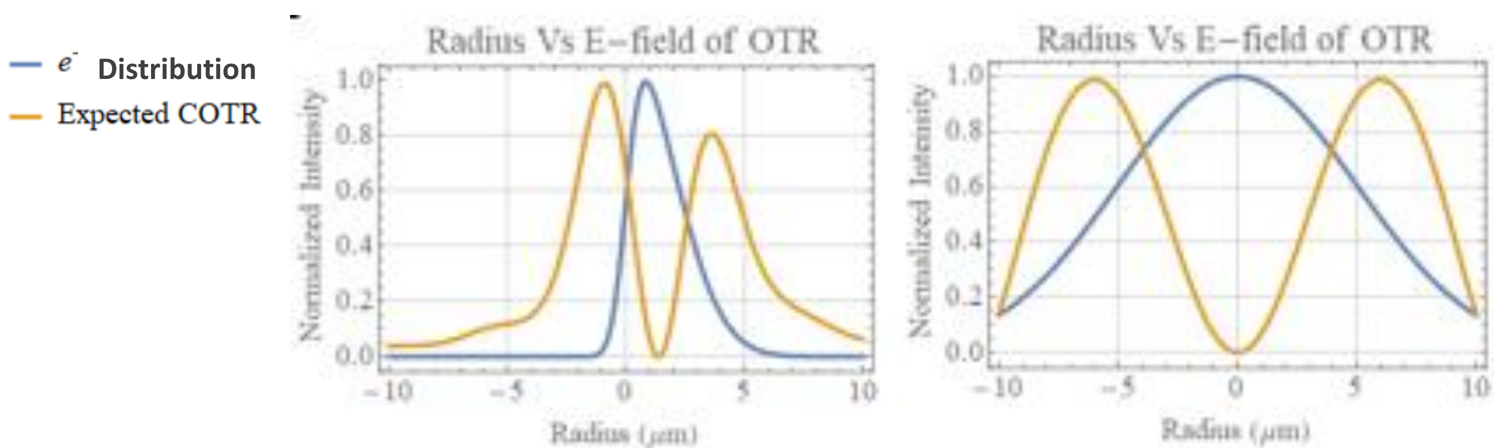
Lumpkin et al., PRL July 2020

COTR Point Spread Function (PSF) Model

- OTR is predominately coherent from electrons transiting foil near LPA exit. In near field (NF) one sees annular shape also.
- Central minimum of COTR PSF does not fill in with increased beam size, but *lobes separate*.

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





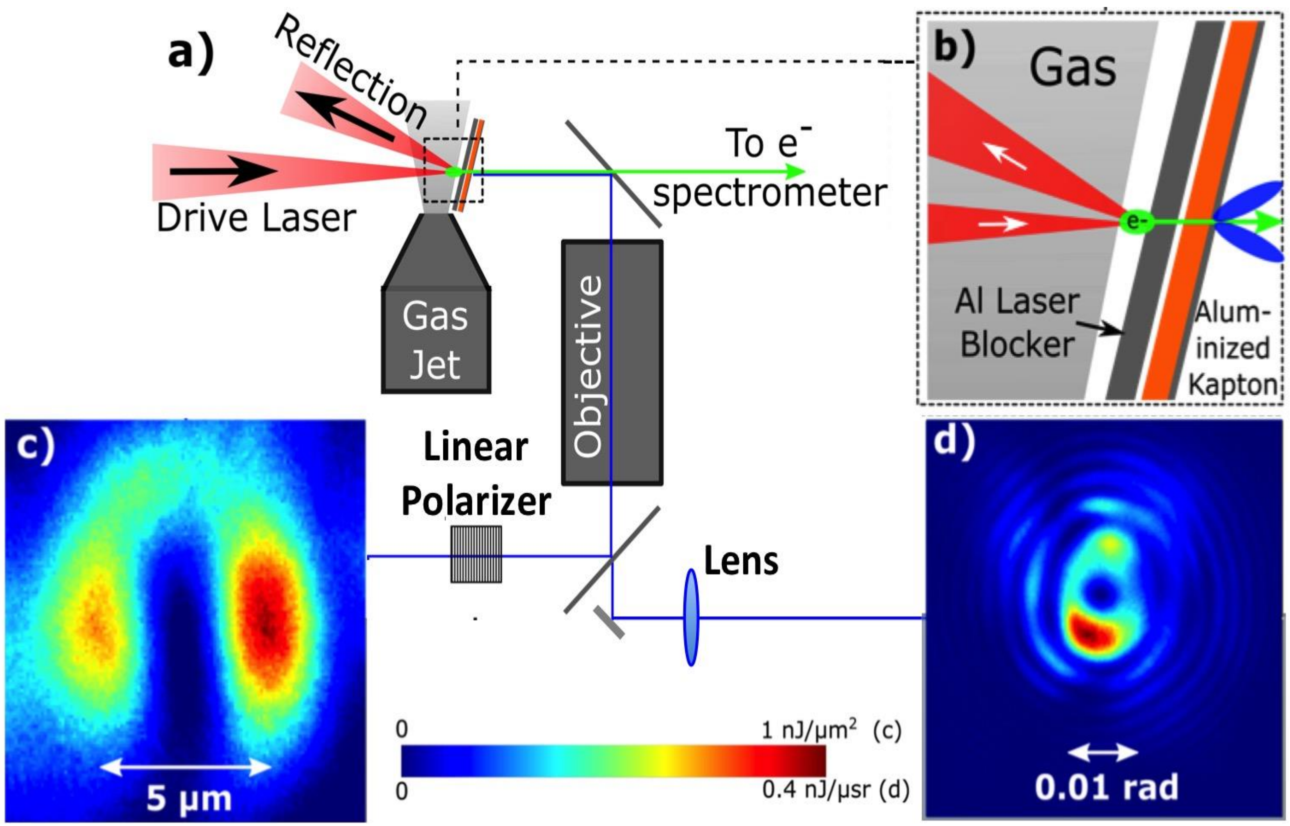
LaBerge et al., EACC17

Schematic of LPA Experiment at HZDR

- High power laser of 150 TW at 800 nm with a pulse length of 30 fs is focused to ~25 µm in a 3-mm long, N_2-doped He gas jet. Energetic electrons are generated and then measured.

Near Field (NF)

σ_x =2.75 µm



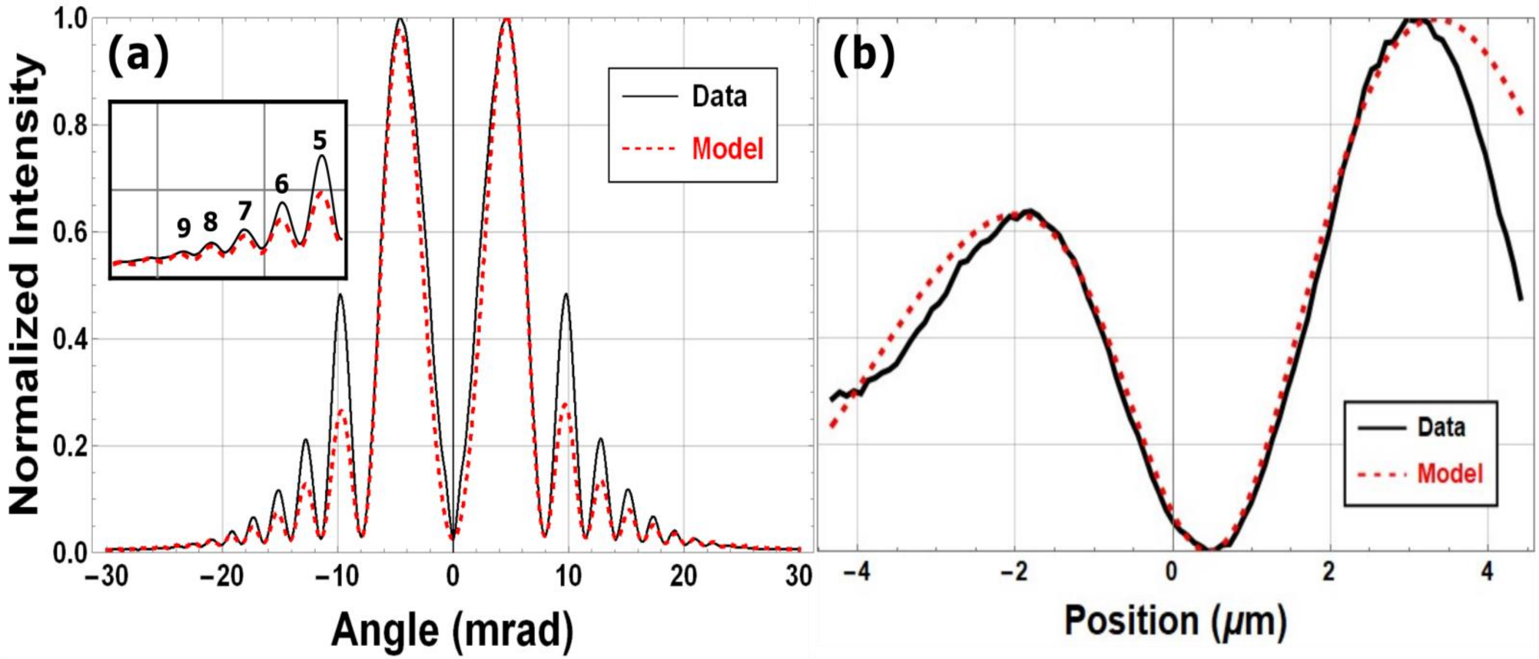
Far Field (FF)

$\sigma_{x'}$ =0.33 mrad

Lumpkin et al., PRL July 2020

Comparison of Models to Experiment

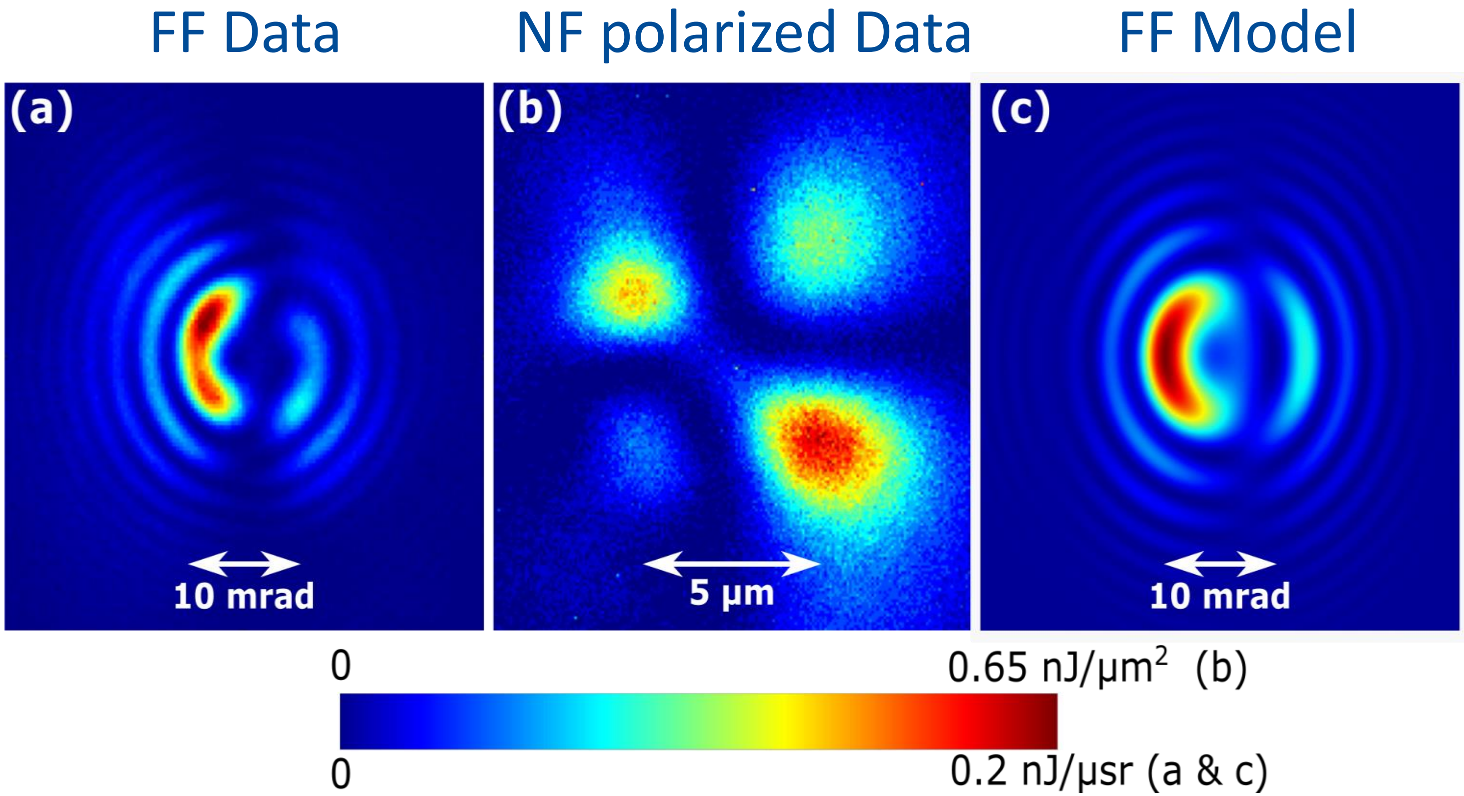
- FF and NF imaging results with comparisons to models.
- Analyses give $\sigma_{x'}$=0.33 ±0.12 mrad and σ_x =2.75 ±0.40 μm.
- Normalized Emittance estimate of 0.36 ±0.15 mm mrad (rms)



Lumpkin et al., PRL July 2020

Beamlets Separated in z Can Interfere in COTRI FF Patterns

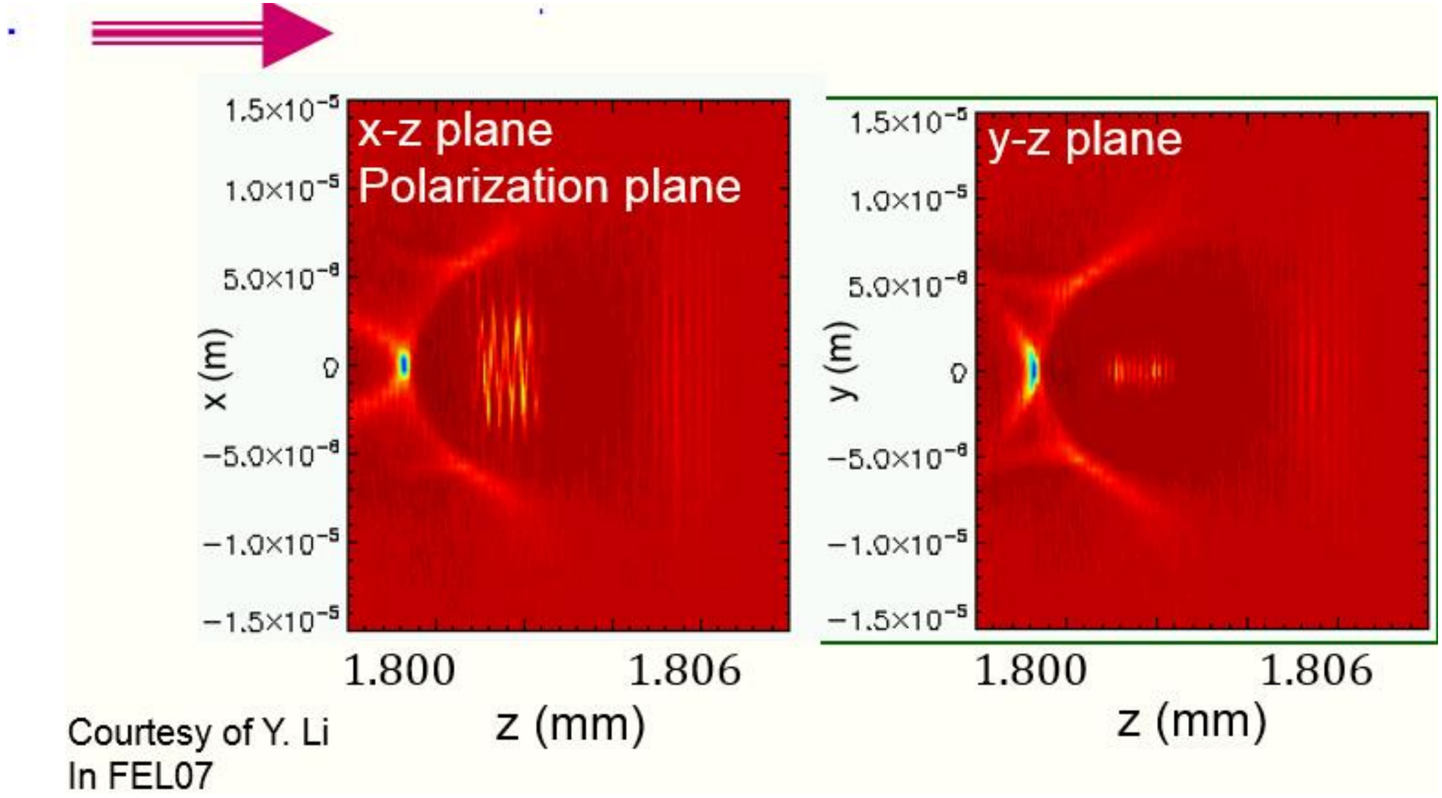
- Modeling of two beamlets, each with σ_θ = 0.6 mrad, with phase and angular trajectories differing by 0.75π and 2 mrad, respectively.



Lumpkin et al., PRL July 2020

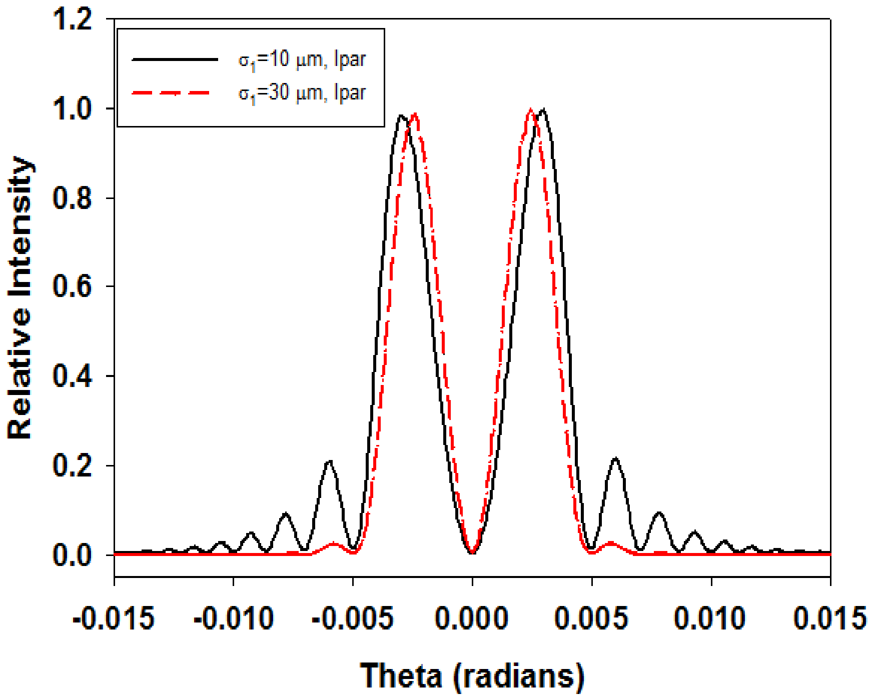
Model Shows Beamlet Structure on Laser Polarization Axis

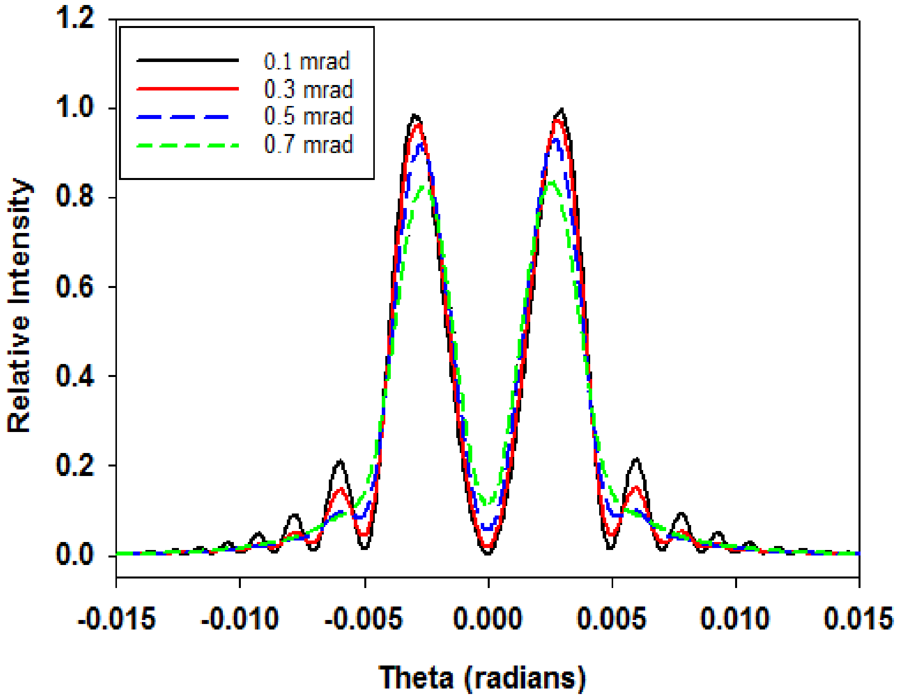
- Bimodal electron distribution on laser polarization axis was predicted in Vorpal simulations in FEL 2007 (Lumpkin et al.)
- Sub-micron longitudinal modulation (microbunching) seen.



COTRI Model Calculations for 1-GeV Beam

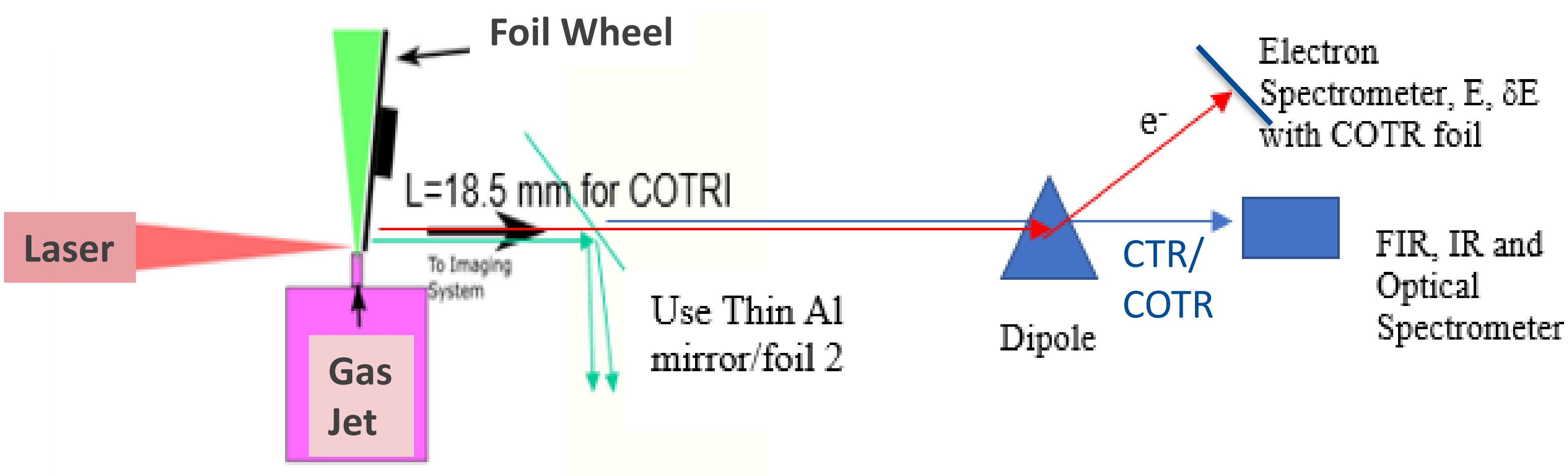
- COTRI Model for 1-GeV, L=50.8 mm, λ=633 ± 5 nm, sigma-1 = 10 μm, microbunching fraction of 1 %. 1/γ = 0.5 mrad.
- Beam size effect (L) and divergence effects (R) are seen.





Schematic of the Proposed Configuration

- Propose changing 200-µm thick Si mirror to a thin Al orTi foil at 45º in the interferometer and adding an Al foil in the electron spectrometer to assess energy, energy spread, N_b/N fraction.
- Thin foil stopping power at the 10^{-4} level for few hundred MeV beams and should not degrade microbunching due to scattering. Dispersion effect in bend to be checked.



Summary

- Microbunching fraction of electron beams identified in LPAs at the 1% level led to COTR gains of >100,000 in the visible wavelength regime!
- COTR signals can be split into multiple camera paths for single-shot evaluations of beam size, divergence, emittance, and microbunching fraction.
- Coherent point-spread-function model and COTRI model used to characterize uniquely the microbunched electrons' properties.
- The emittance and energy spread of the microbunched set are estimated to be 10x better than the ensemble of electrons!
- New implementation could provide energy, energy spread, and microbunching fraction transported on same single shot. This multi-parameter data can guide LPA beam-quality development.

Acknowledgments

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Recap Slides for Thursday AM Panel Discussion

- 3 slides follow

THAO05: Recap on Advanced LPA Diagnostics with COTR

- We identified the existence of microbunching in subsets of the electron beam from Laser-driven Plasma Accelerators (LPAs).
- As the beam transits the interface of the metal foil or Si mirror, coherent optical transition radiation (COTR) was generated by the microbunched electrons with gains of >100,000 over OTR.
- Using a COTR point-spread function model by M. LaBerge and a COTR interferometry (COTRI) model by D. Rule, we measured in single-shot the beam size, divergence, emittance, and microbunching fraction of the subset of electrons.
- This subset has ~10x better emittance and energy spread than the ensemble of electrons with $\sigma_x = 2.75$ μm, $\sigma_{x'} = 0.33$ mrad, and ε_n=0.36 mm mrad with estimated <1 % energy spread.
- Proposed a technique also for energy, energy spread, and microbunching fraction to guide improvement in LPA beams.

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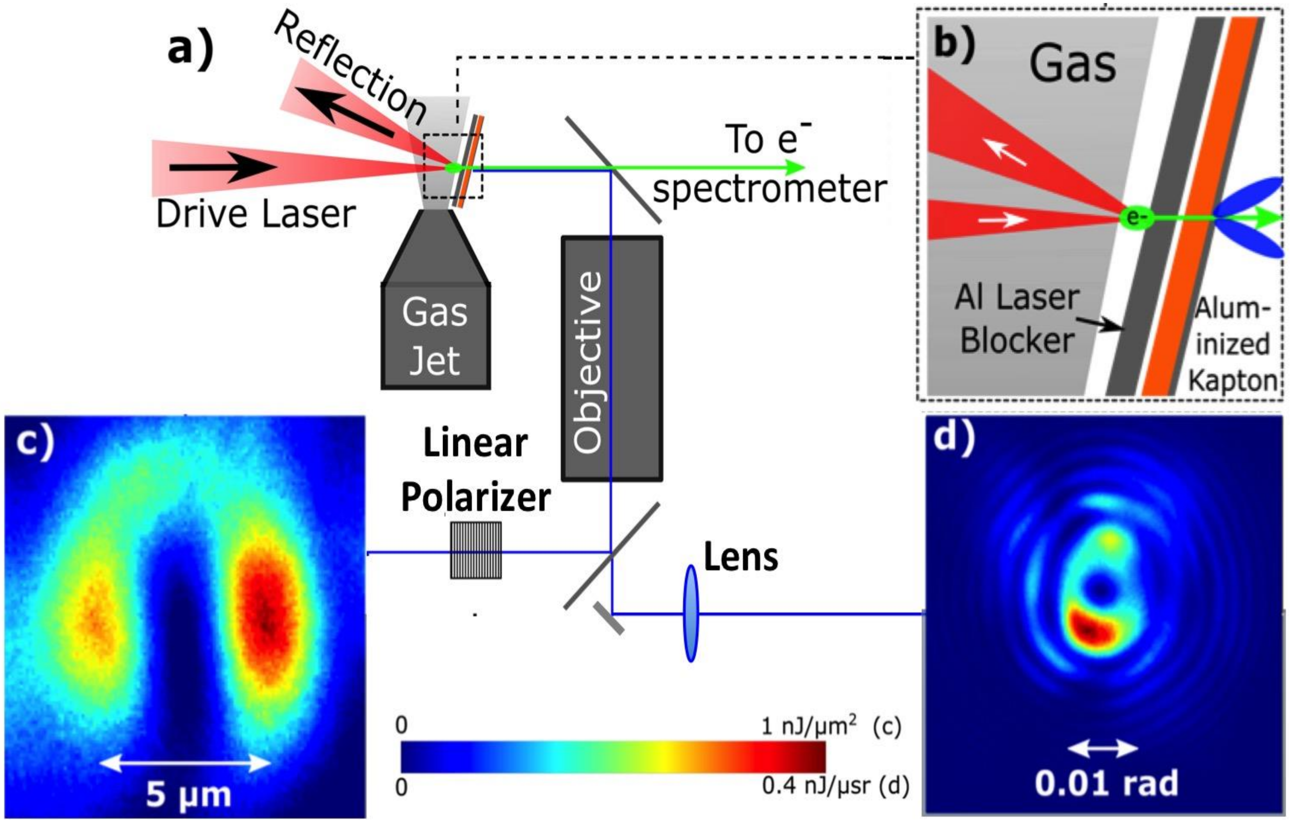


Far Field (FF)

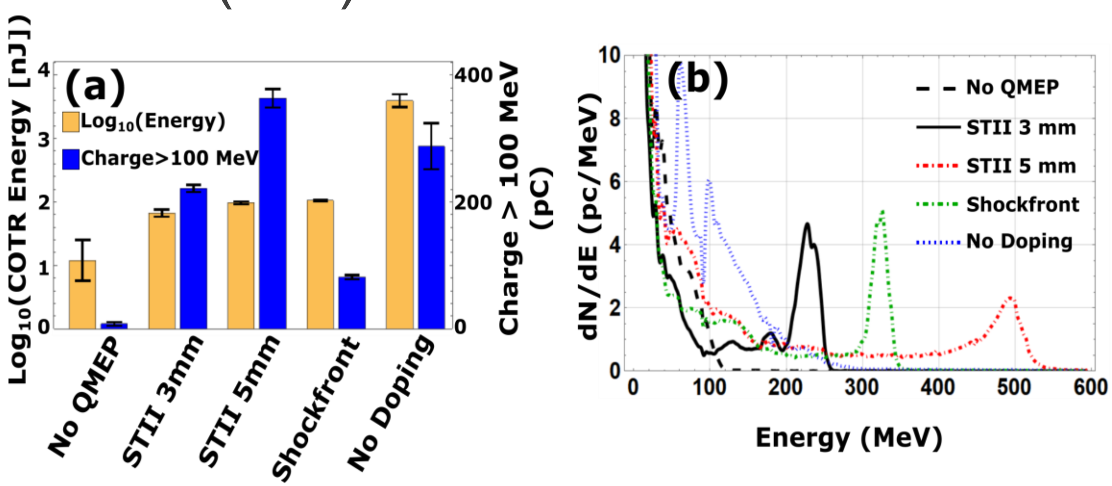
$\sigma_{x'}$ =0.33 mrad

Lumpkin et al., PRL July 2, 2020

COTR Techniques Apply When Microbunching Occurs

- Laser-driven plasma accelerators across 5 injection schemes exhibit COTR gains. Can use techniques to improve beam quality and increased microbunching fraction. Letter of Interest (LOI) submitted to Snowmass21 process.

-Quasi-monoenergetic Peak (QMEP)
-Self-Truncated Ionization injection (STII)



- Free-electron laser process inherently generates microbunching of electrons at 10-20% level at saturation.
- Longitudinal-space-charge-induced microbunching instability present in many linacs with high-brightness beams.