Indirect Characterization of Photoinjector Parameters & their Correlations

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Advanced Accelerator Concepts 2026

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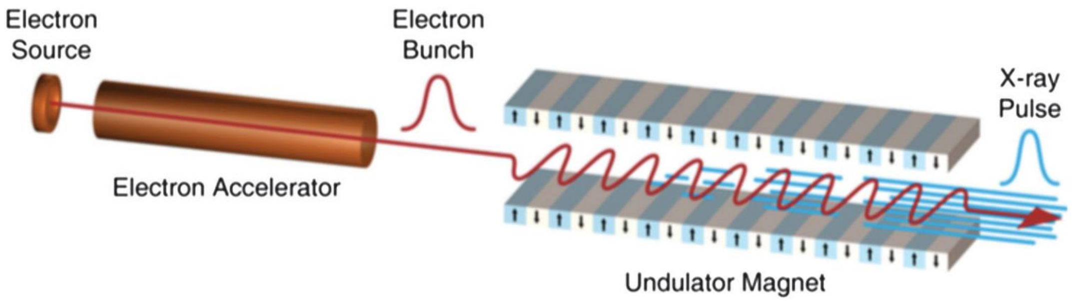
The Center for BRIGHT BEAMS
A National Science Foundation Science & Technology Center

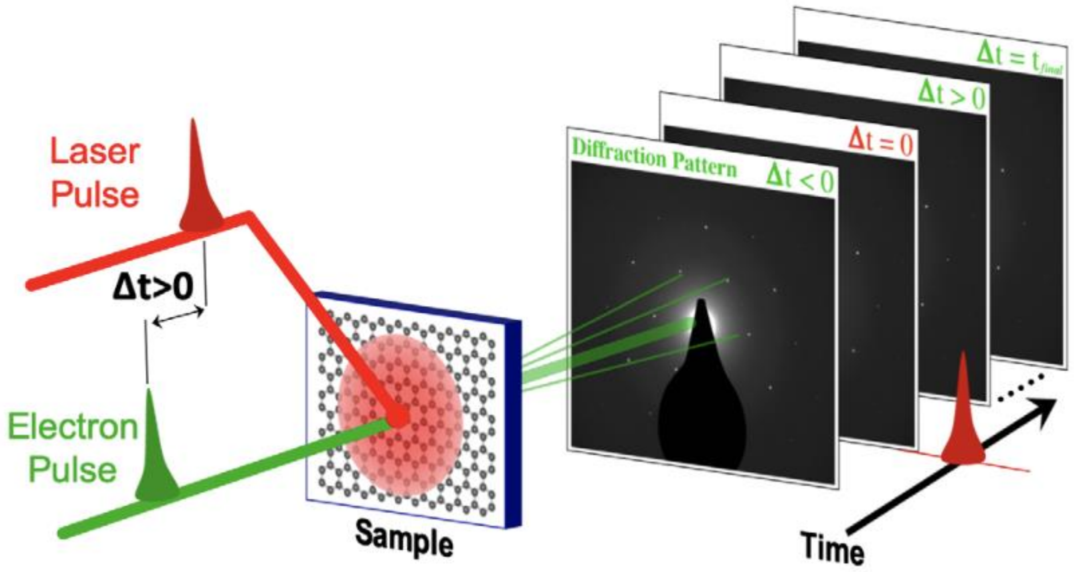
Outline

- ❑Motivation
- ❑Measurement of the cathode re-entrance and intrinsic emittance
  - Degeneracies
- ❑Surrogate model + MCMC technique
- ❑Extracting the photocathode intrinsic emittance from a beam with:
  - Projected emittance growth
  - Space charge emittance growth
- ❑Towards a measurement of the cathode time response
- ❑Conclusion & Outlook

Motivation

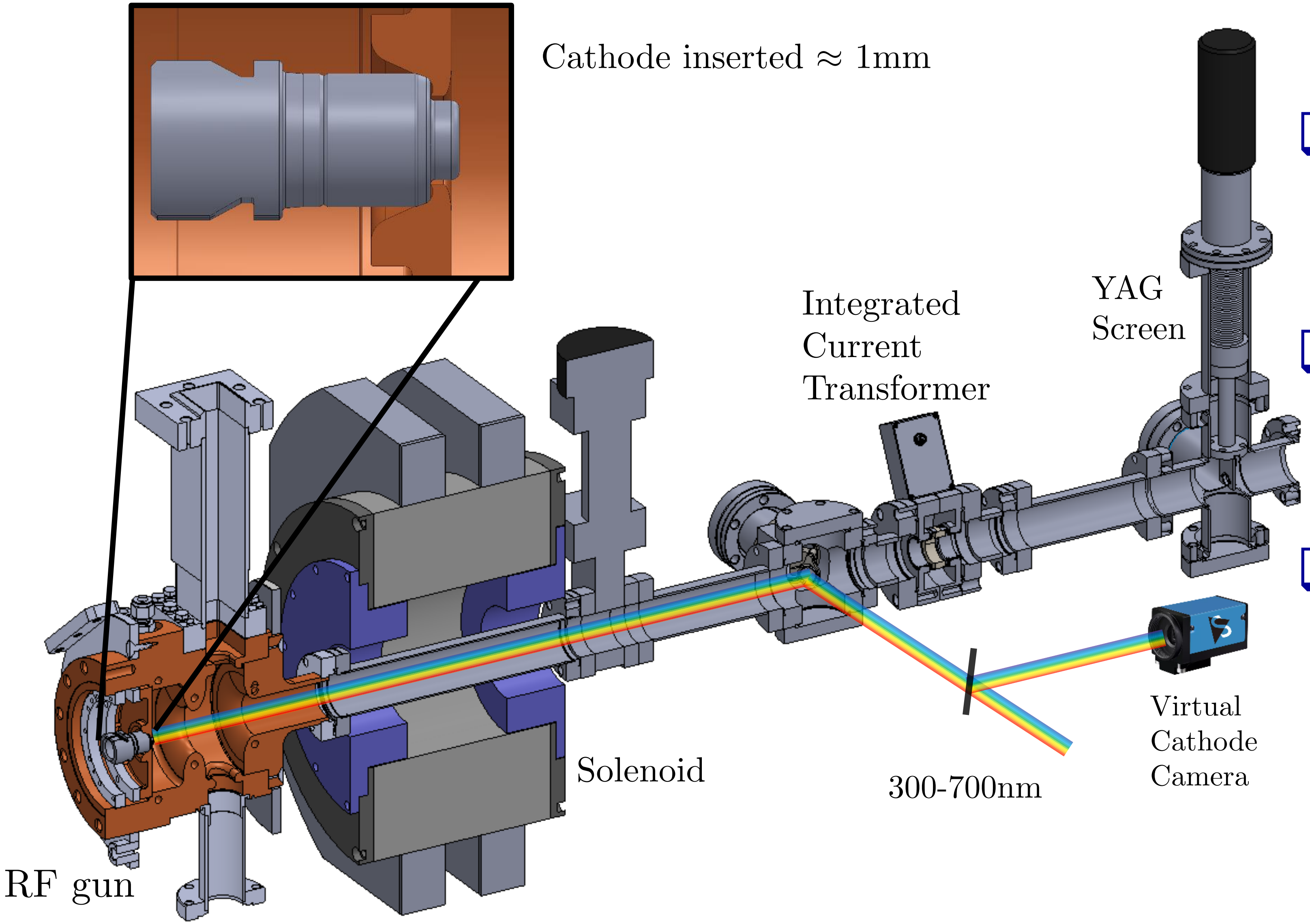
- Electron sources for next generation FELs & UED machines must be well tuned in order to provide high brightness beams
- Characterization of hard to measure parameters often requires additional diagnostics
  - Intrinsic emittance: apertures/slits
  - Pulse length: transverse deflecting cavity





Pegasus S-band Gun

PBPL



- OPA produces a short pulse tunable through the visible and UV spectrum
- Photoelectrons accelerated to 3MeV & focused using solenoid
- Charge, laser energy & transverse distribution at both the cathode & YAG screen are recorded

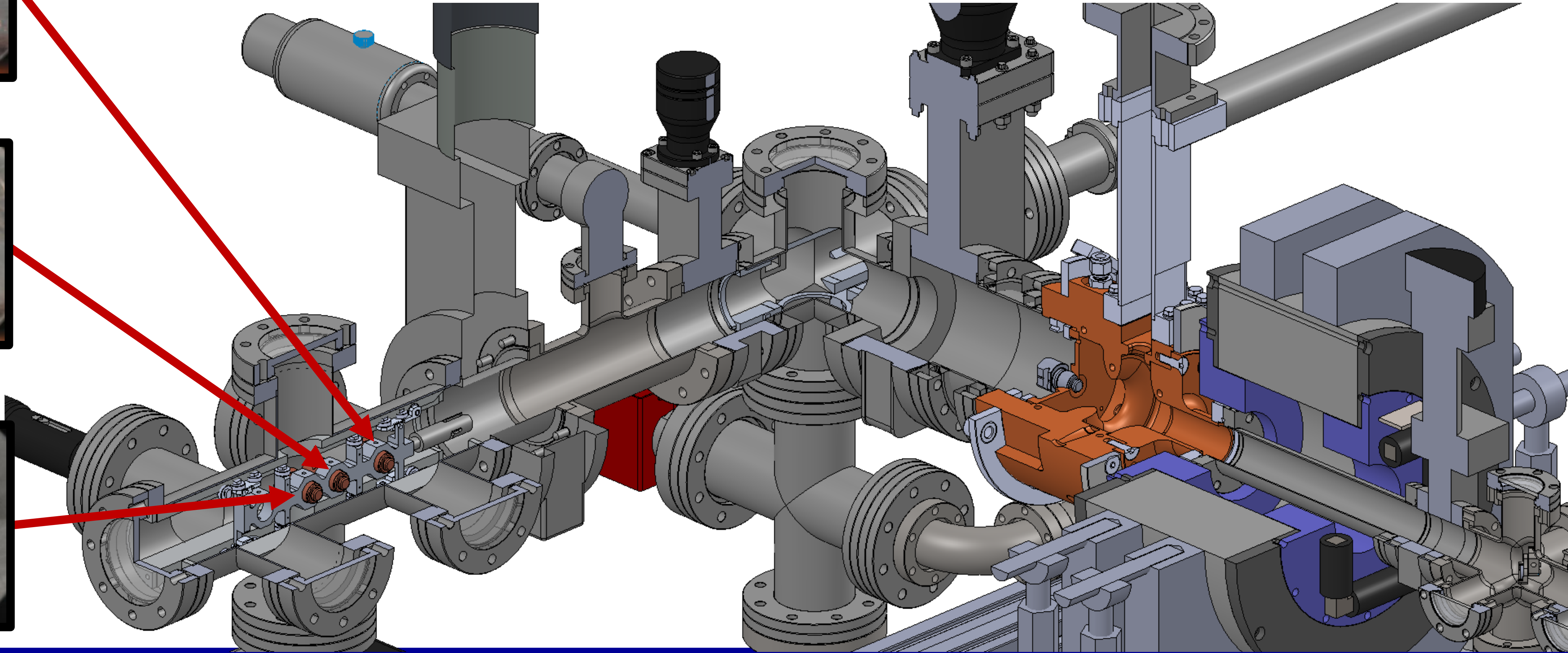
Semiconductor Photocathodes

- Load-lock chamber behind RF permits exchange of air sensitive cathode under UHV conditions (<1e-9 Torr)
  - 1 Cs-Te & 2 Cs3Sb cathodes grown at SLAC & transported to UCLA

UC04: Cs_3Sb

UC01: Cs-Te

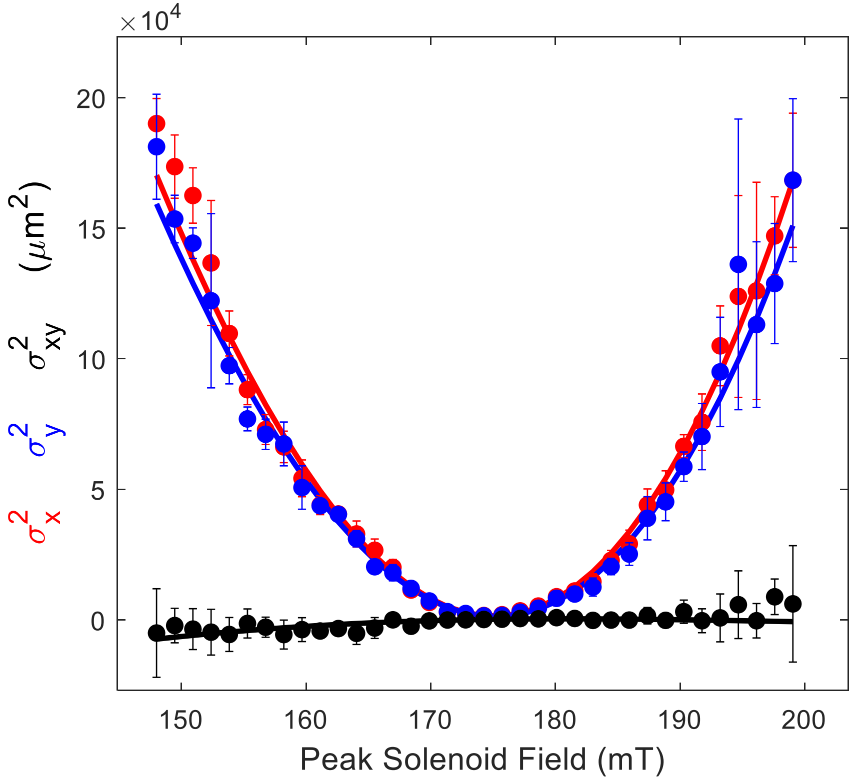
UC03: Cs_3Sb

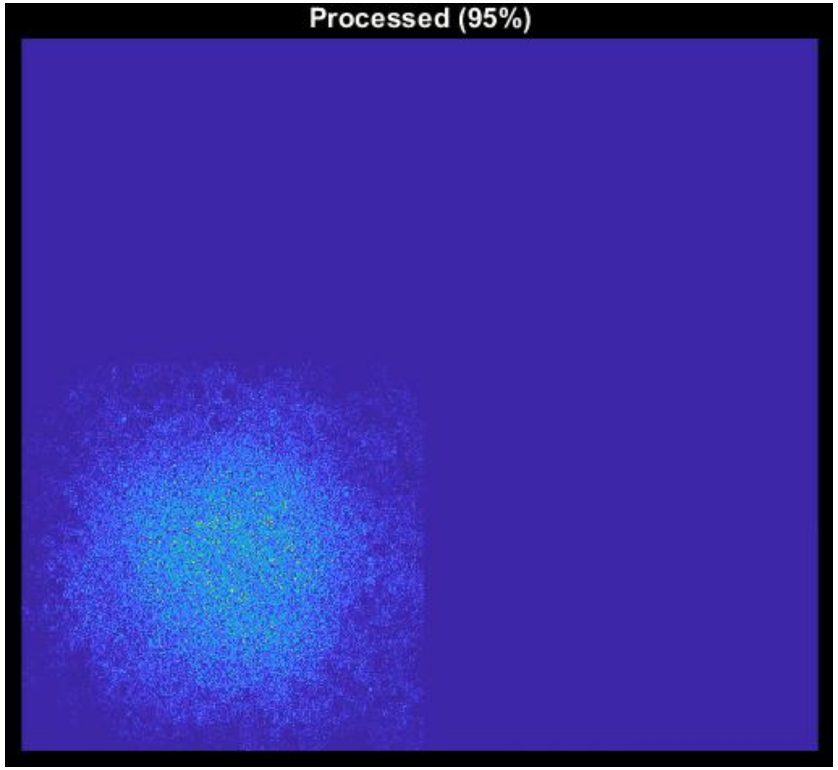


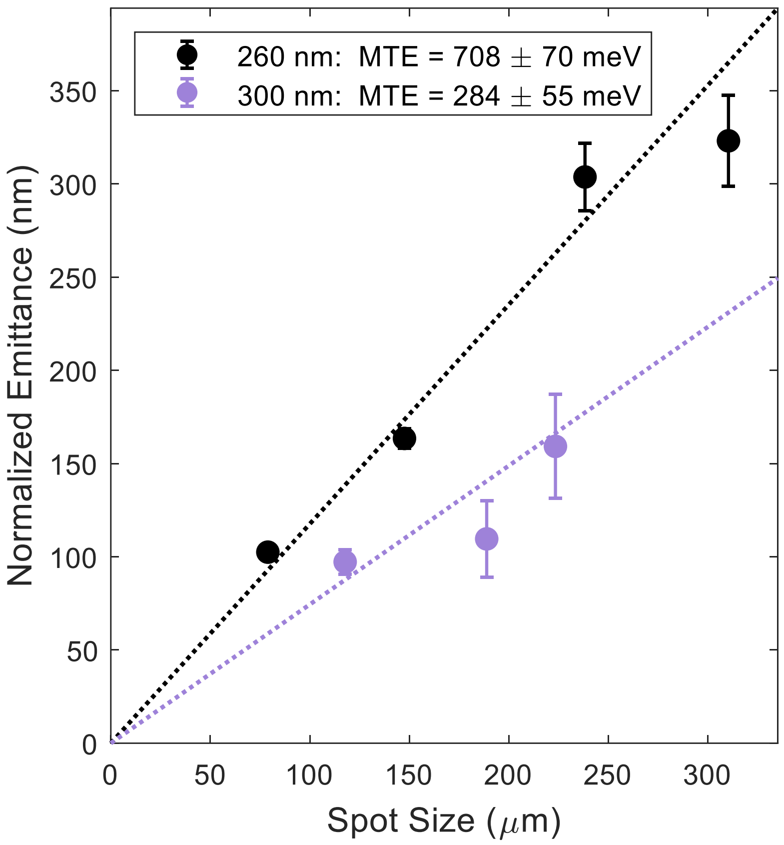
Analytic Analysis of Solenoid Scan

- 95% emittance extracted from solenoid scan using linear transport formalism
  - Low charge (<100fC) and short pulse (<1ps) minimize emittance growth from Coulomb force and RF field

$$\varepsilon_n = \sigma_x \sqrt{\frac{\mathrm{MTE}}{mc^2}}$$

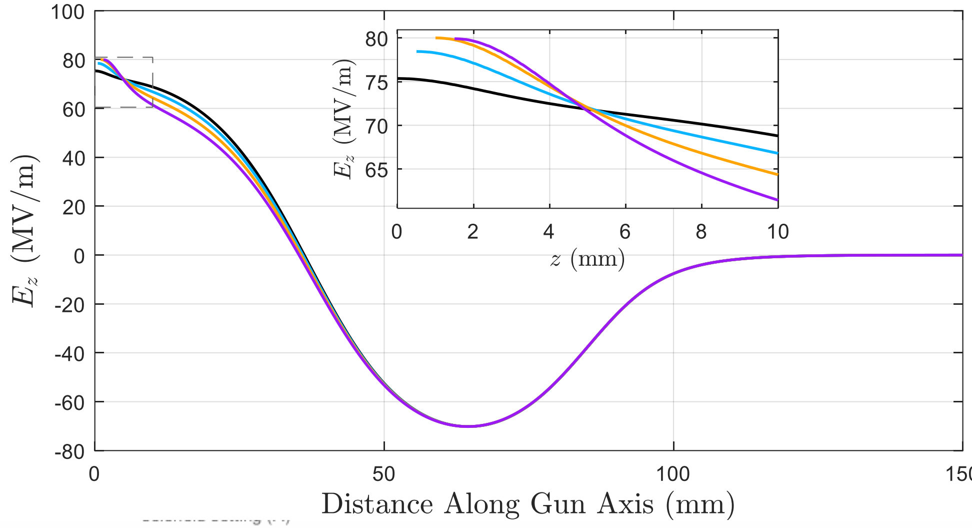


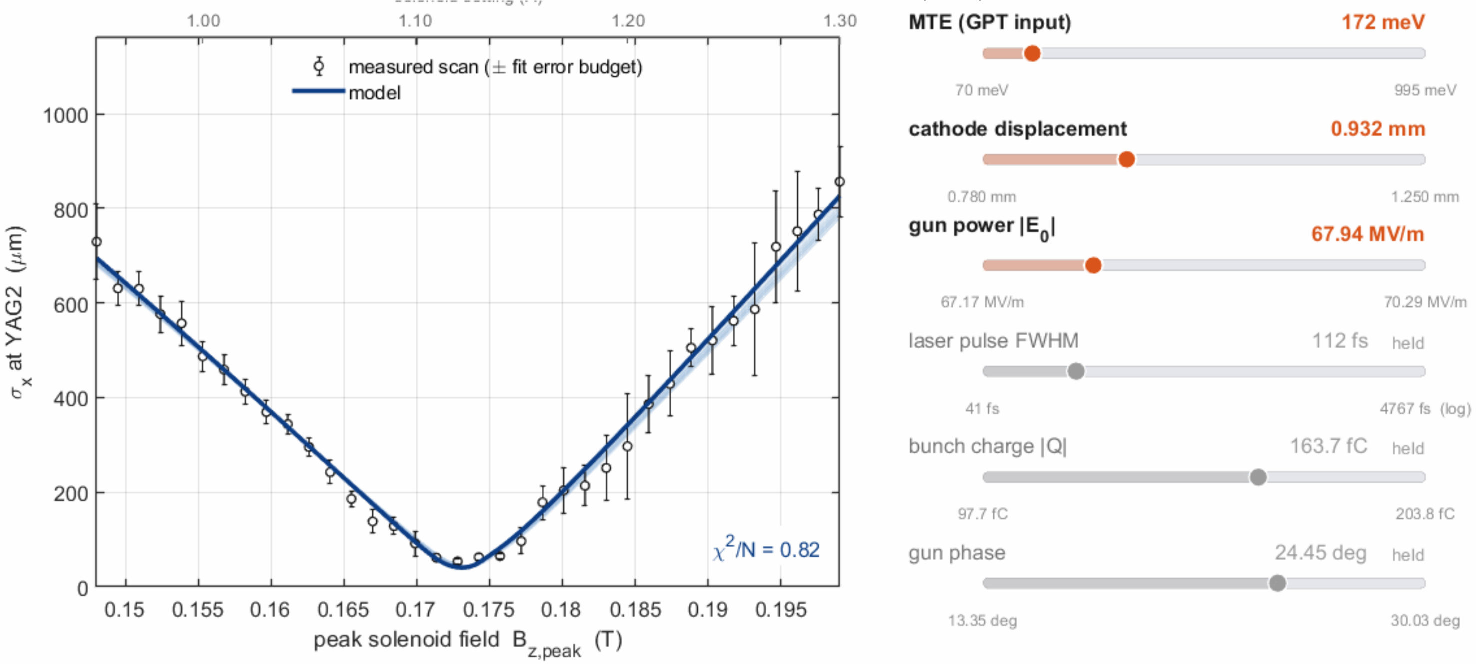




Surrogate Model & Degeneracies

- RF focusing from the re-entrance of the cathode plug is degenerate with the MTE
- Neural Net trained on a library of General Particle Tracer simulations that span the input space of the RF gun gives a fast surrogate model of the RF gun
  - Laser shape & duration (FWHM)
  - MTE & charge
  - Gun phase & power
  - Cathode plug position





MCMC Methods

PBPL

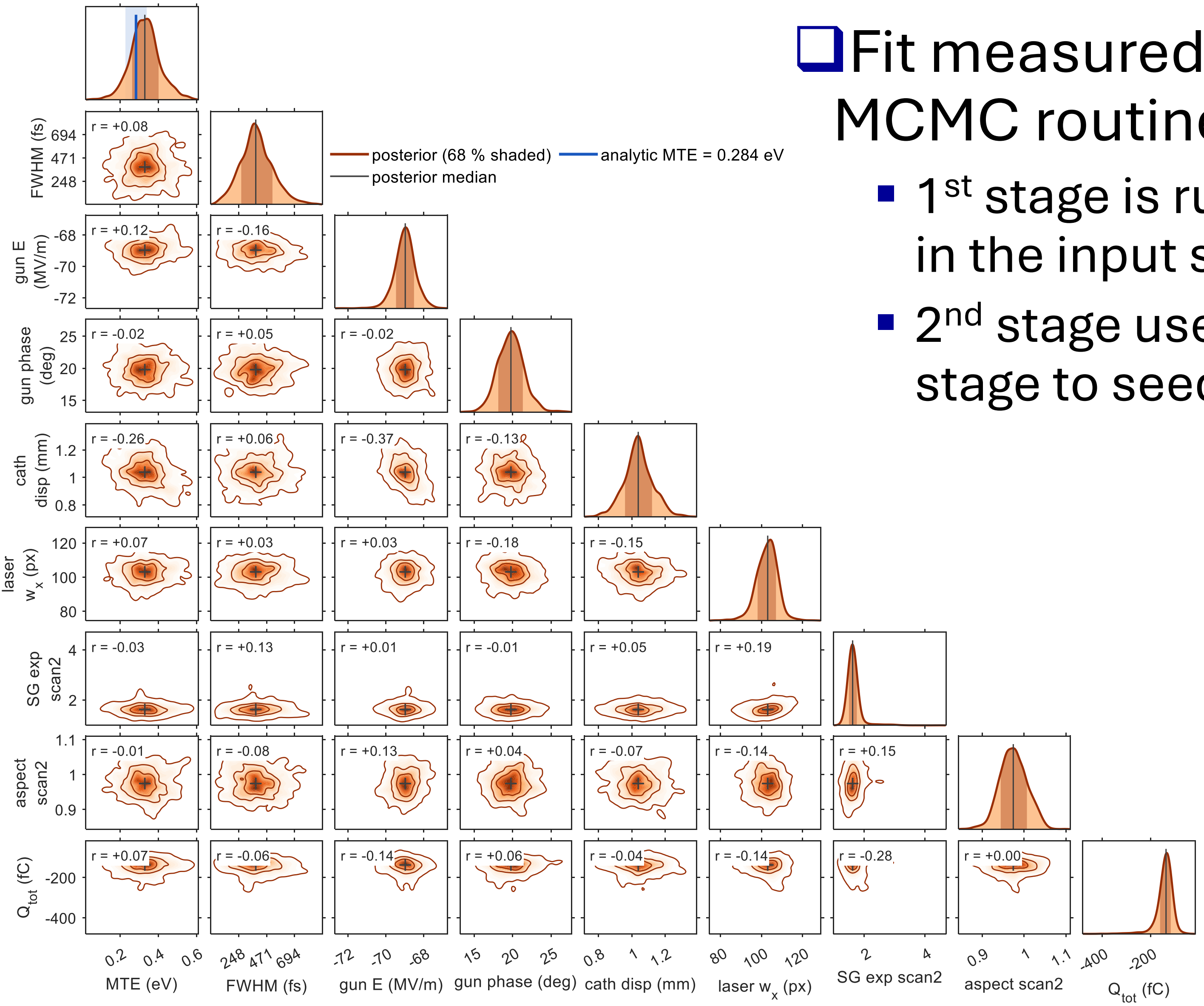
- Markov Chain Monte Carlo (MCMC) methods use Bayesian inference to retrieve posterior probability distributions of the model parameters θ_{M} given the data set D
  - Information on measured parameters (charge, gun phase, ...) enter through prior probabilities

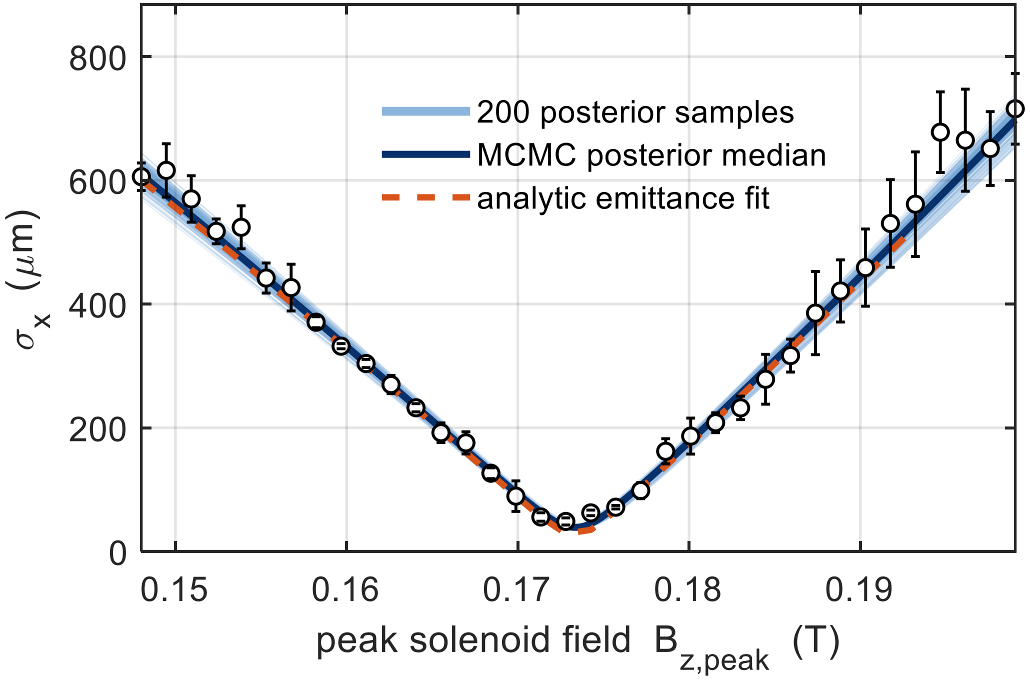
$$\underbrace{P(\theta_M|D)}_{\text{Posterior probability}} \propto \underbrace{P(D|\theta_M)}_{\text{Likelihood}}\underbrace{P(\theta_M)}_{\text{Prior probability}}$$

- GW-MCMC algorithm uses an ensemble of simultaneous walkers
  - Walkers talk to each other & give collective effects
  - Affine invariance means the algorithm works well on oddly shaped spaces

MCMC results

- Fit measured data from Cs-Te with a 2 stage MCMC routine:
  - 1st stage is run with a uniform distribution of walkers in the input space
  - 2nd stage used regions of high likelihood from the 1st stage to seed ½ of the walkers





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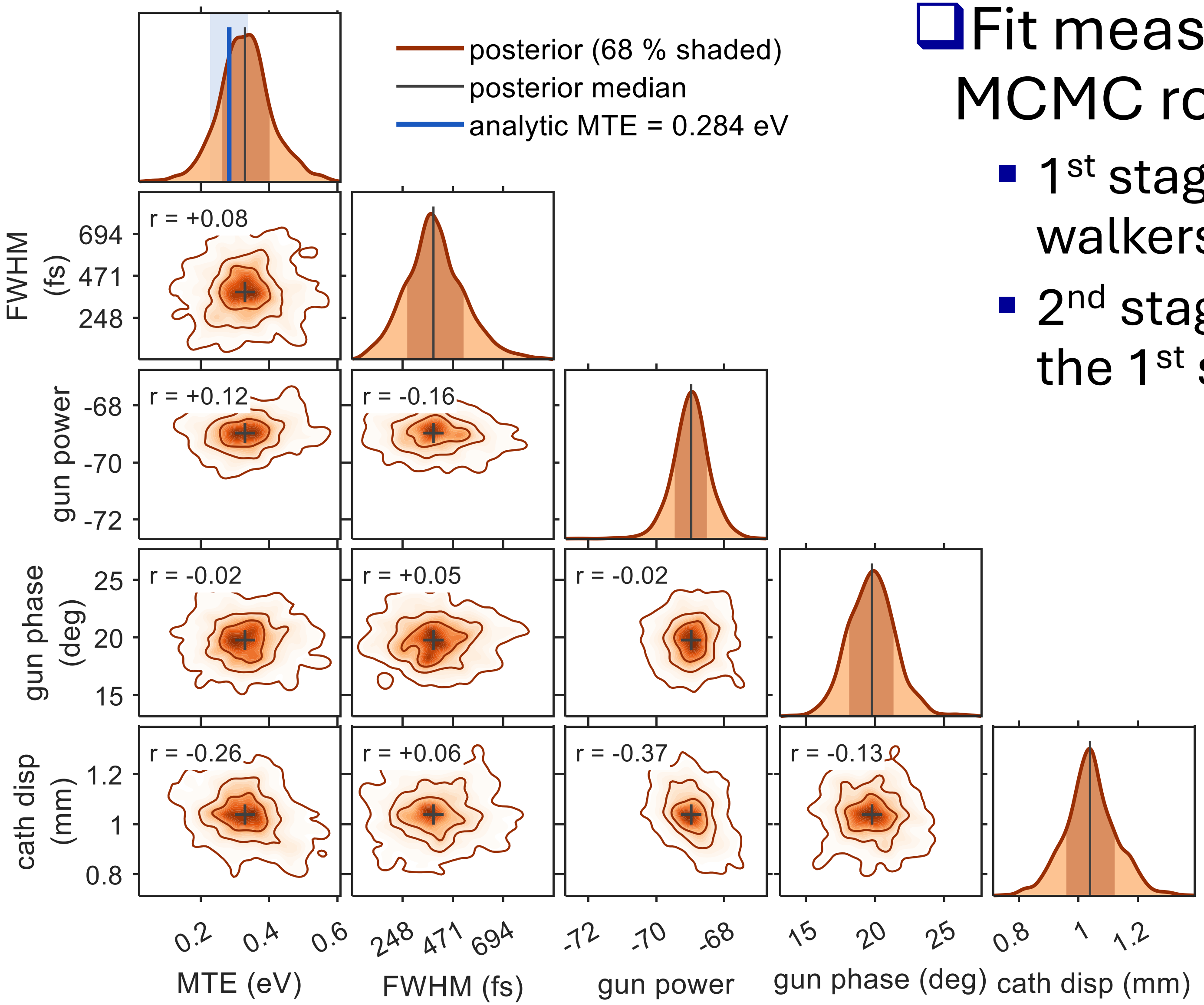

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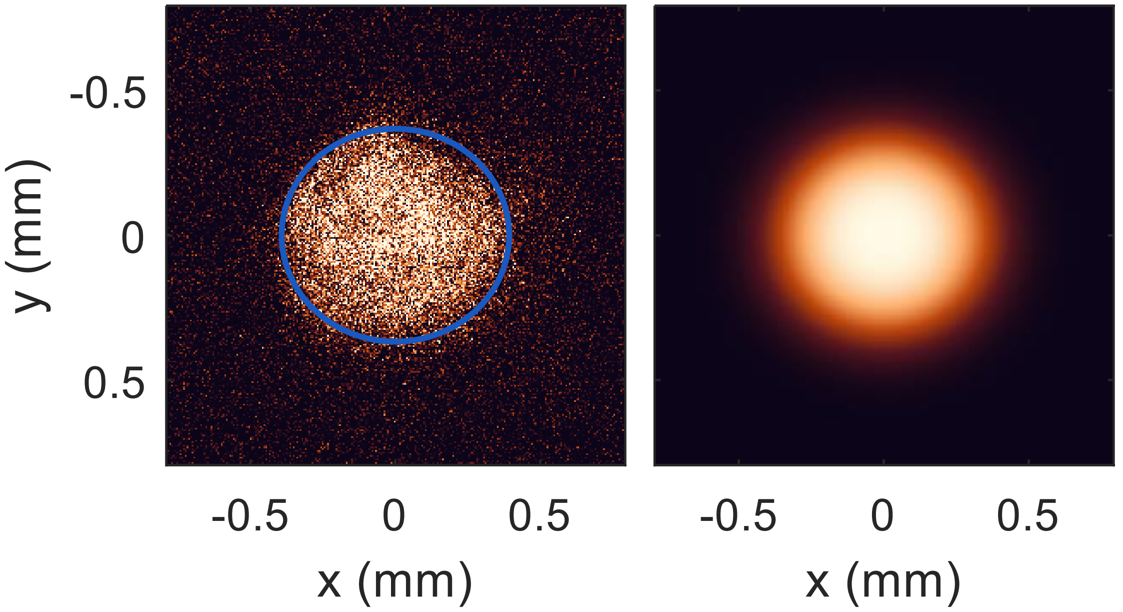
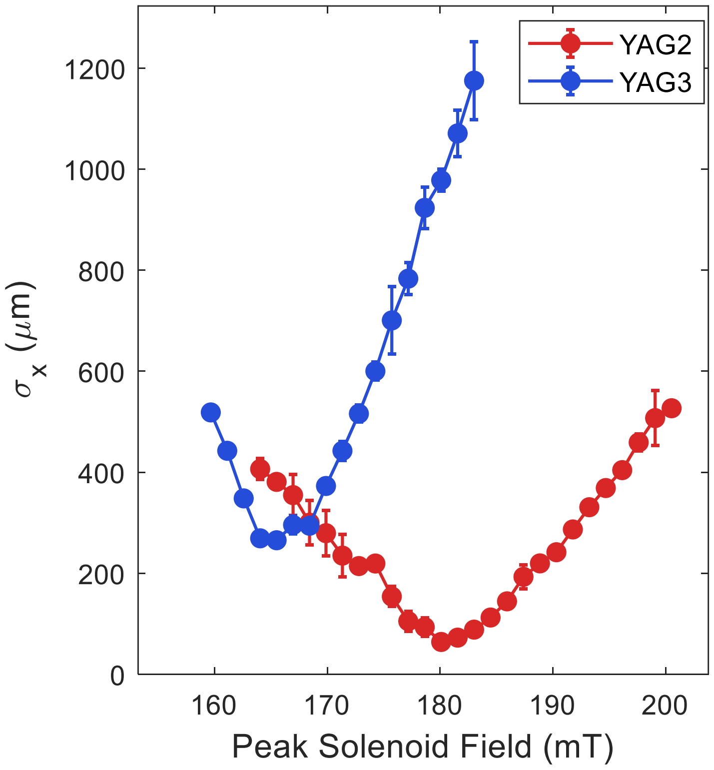


Space Charge Emittance Growth

- Space charge emittance growth is only negligible for a small set of circumstances
  - Our far YAG screen cannot reconstruct the MTE because the beam is too dense for too long
  - Beam out of VHF guns is too soft (<1MeV)
- Rho parameter quantifies when a beam is emittance dominated ($\rho < 1$) or space charge dominated ($\rho > 1$)

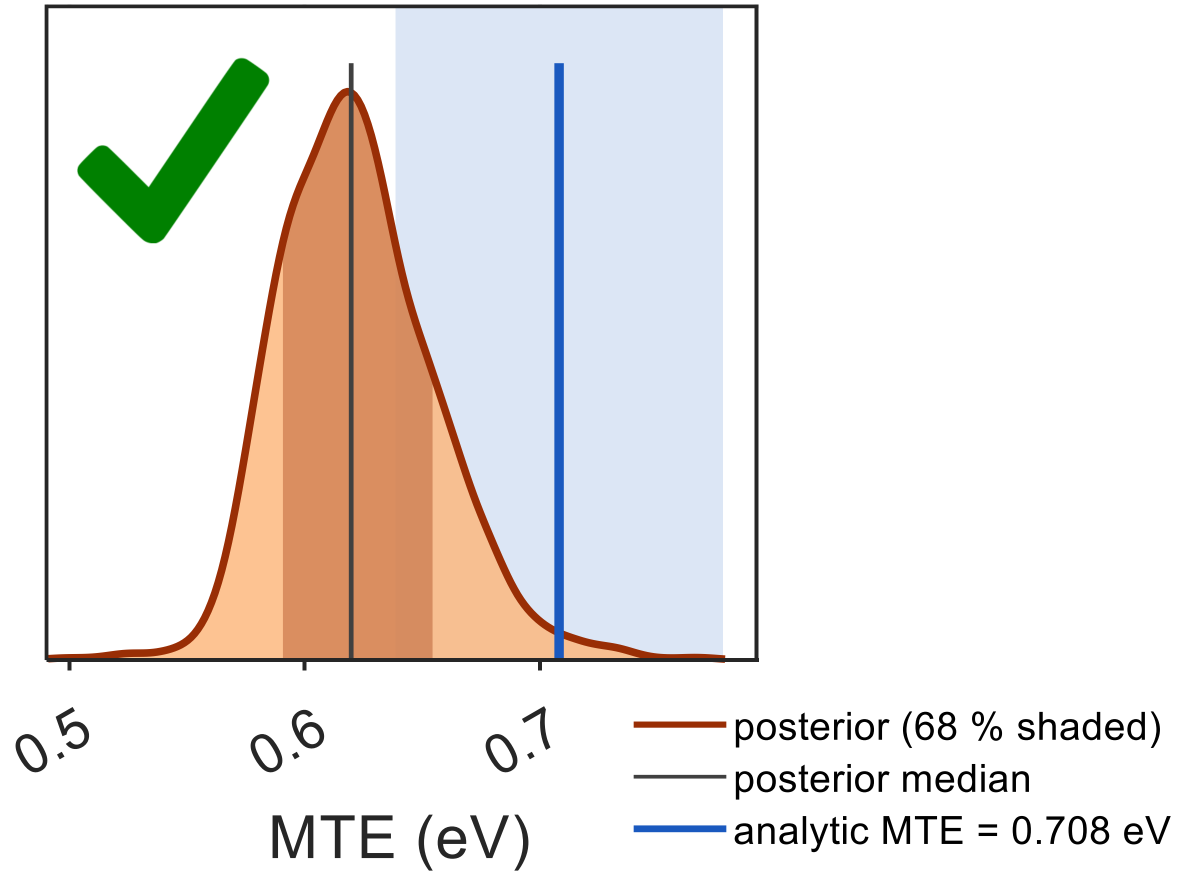


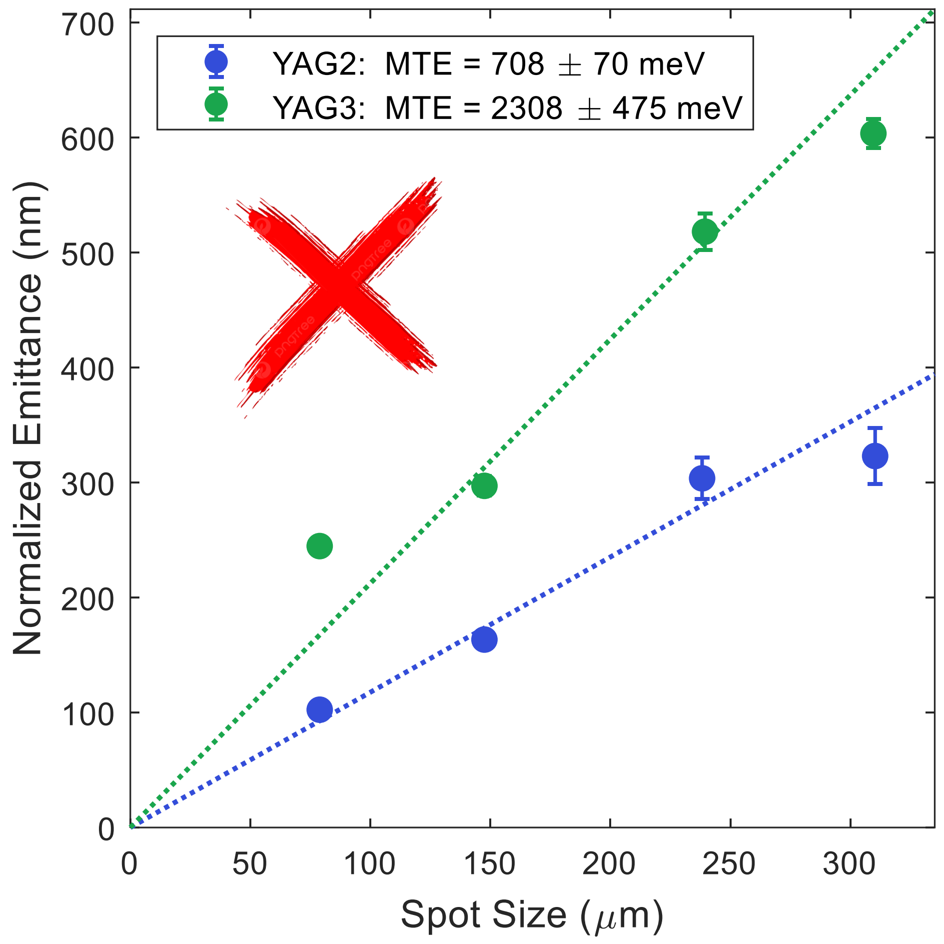
$$\rho = \frac{I \sigma_r^{\,2}}{2 I_o \beta \gamma \varepsilon_n^2}$$

Screen	Position (m)	ρ at waist	Regime
YAG 2	1.3	0.42	Emittance
YAG 3	2.8	3.41	Space charge

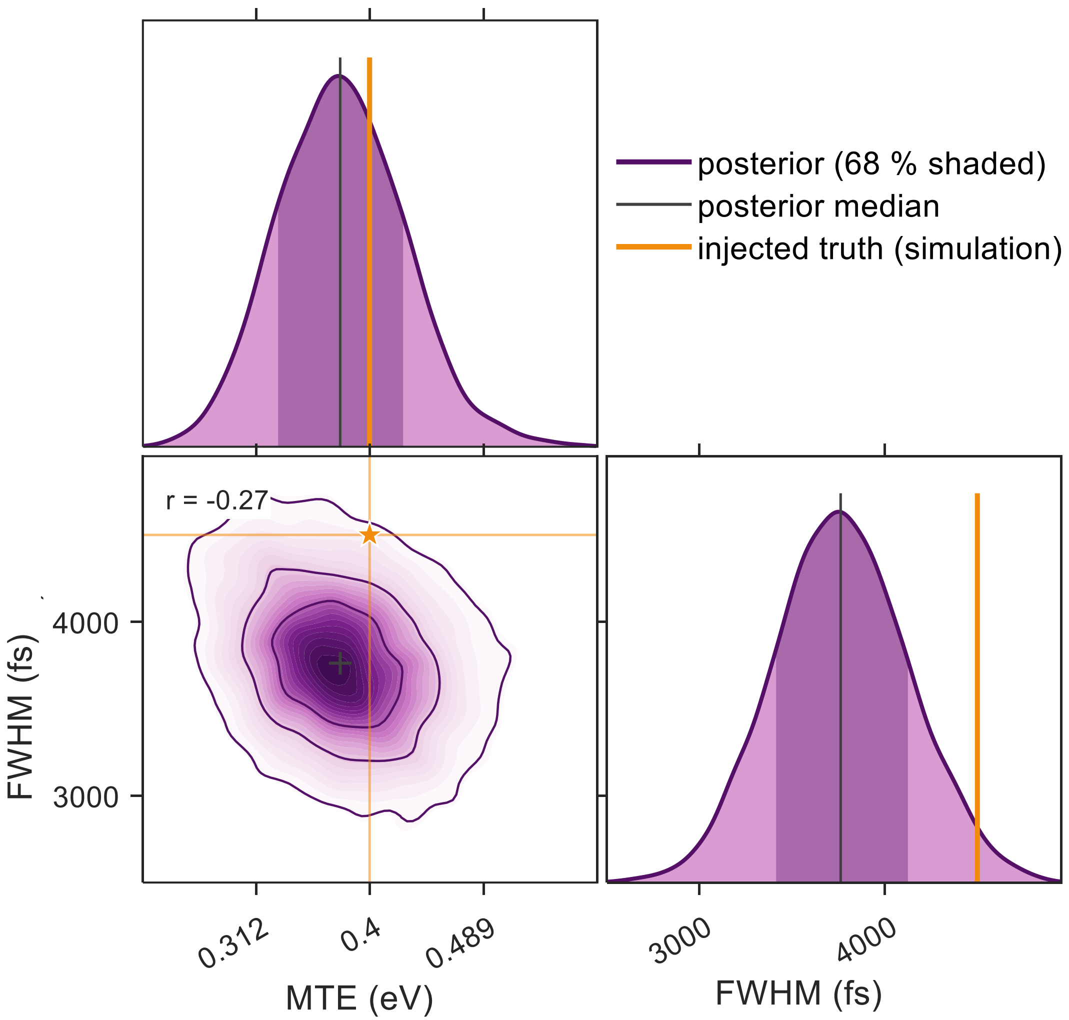
Intrinsic Emittance with Space Charge

- Analytic reconstruction of the MTE fails for YAG3, but the MCMC routine can retrieve the MTE for scans taken on YAG3

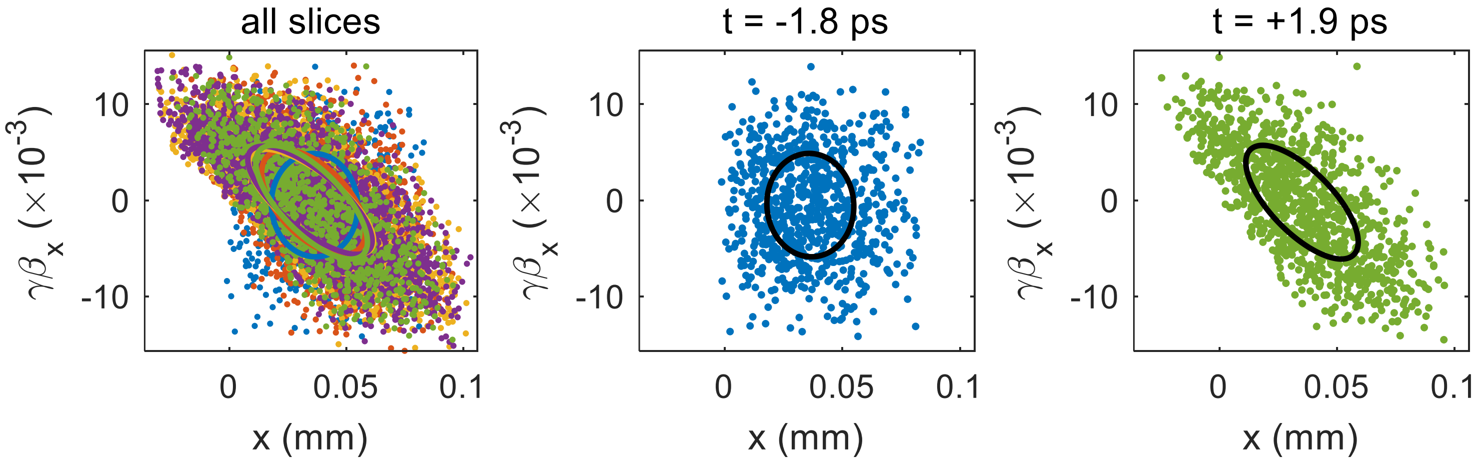




Intrinsic Emittance with a Long Pulse

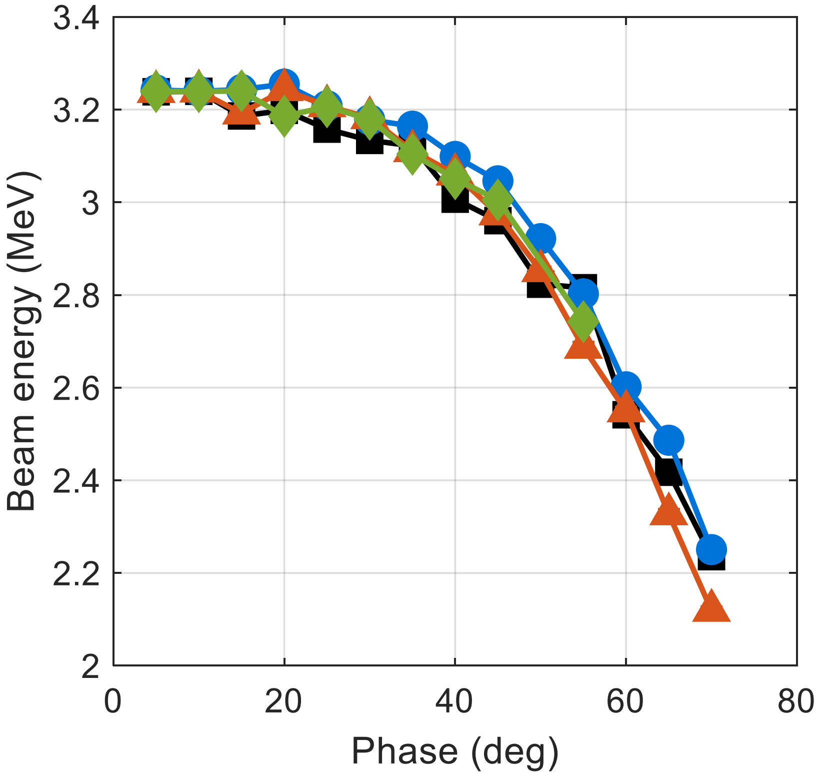


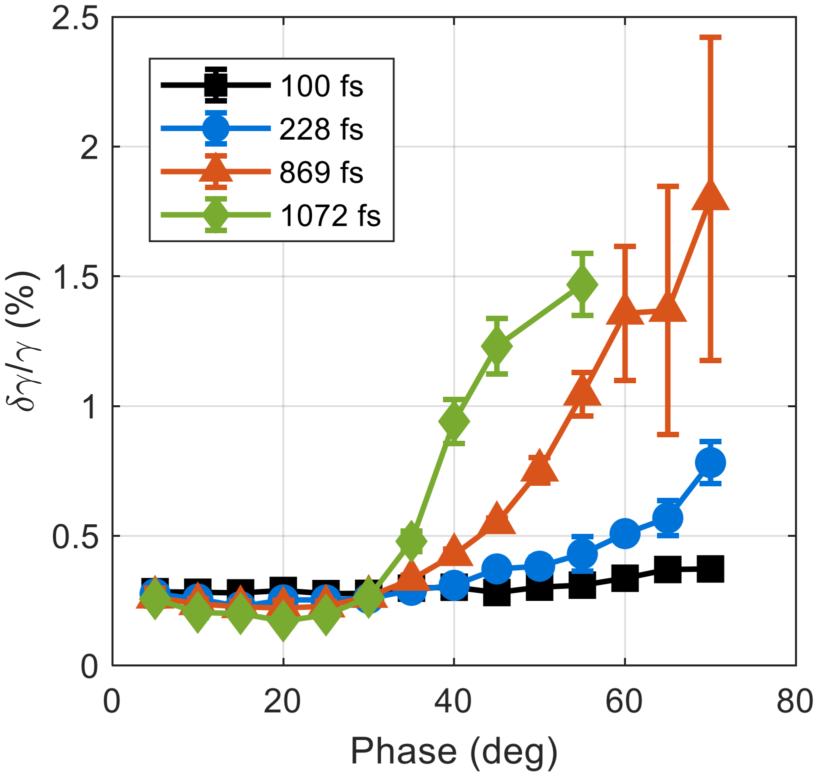
- Simulate stretching the laser from 100 fs to 4.5 ps
  - Suppress nonlinear photoemission near threshold
  - The RF gun will give a time varying transverse kick, resulting in a projected emittance growth for long beams



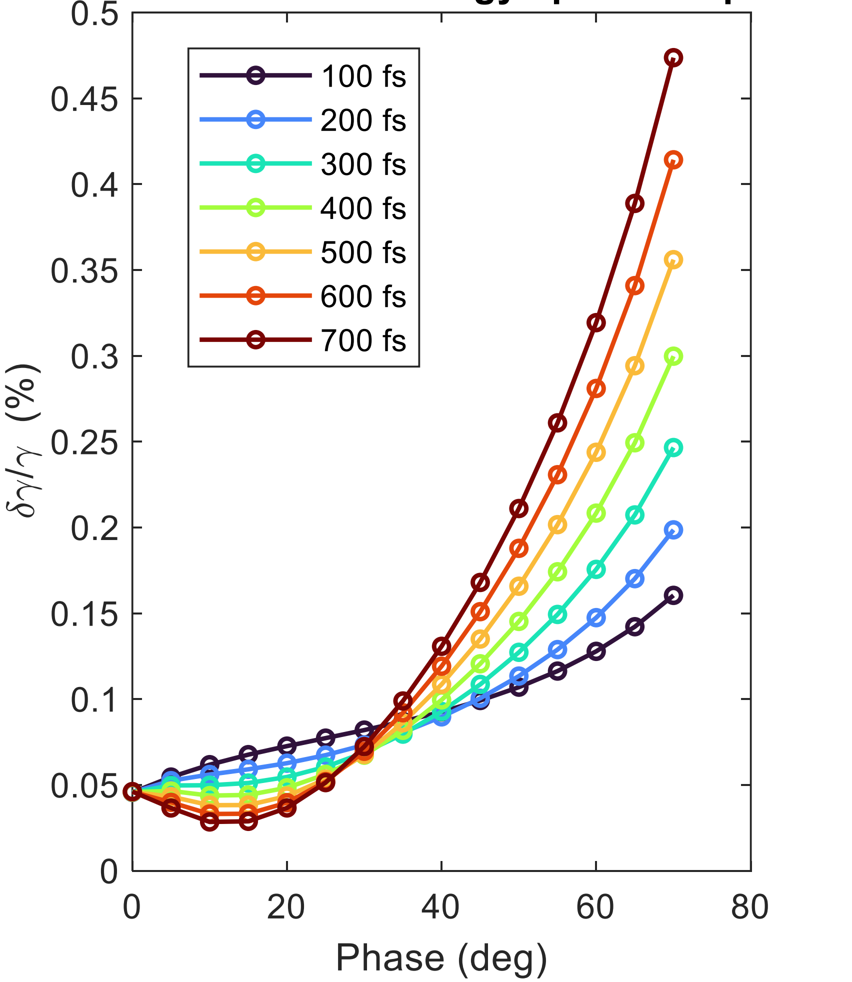
Indirect Measure of Pulse Length

- The energy of the electron beam leaving the RF gun is correlated with the launch phase
  - A longer pulse will sample many different energies, especially at high phase, resulting in a larger energy spread

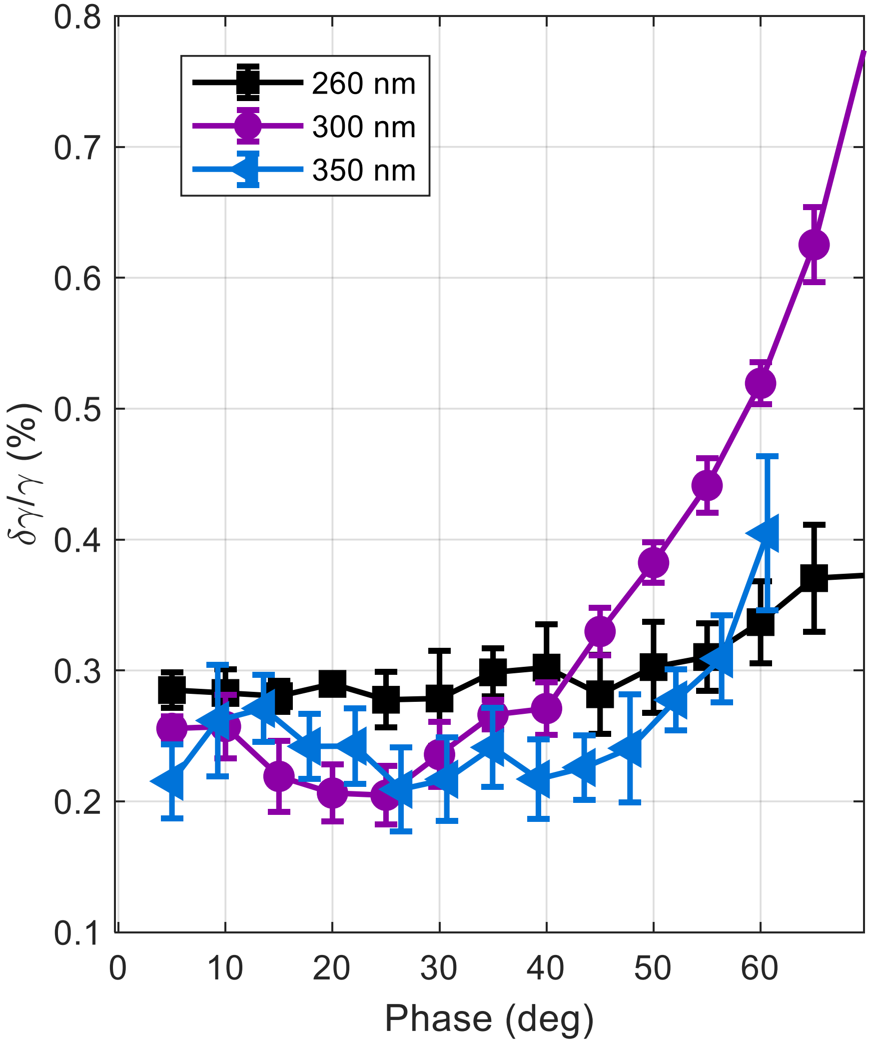




GPT simulation of energy spread vs phase



Time Response vs. Wavelength



- The FWHM (τ_{e^-}) of the electron beam emitted at each wavelength is fit using GPT simulations to calculate the time response (τ_{TR})
- Temporal broadening near threshold transitions to prompt emission when nonlinear

$$\tau_{e^-} = \sqrt{\tau_{\mathrm{laser}}^2 + \tau_{\mathrm{TR}}^2}$$

Wavelength (nm)	Laser Pulse Length (fs)	Electron Pulse Length (fs)	Time Response (fs)
260	100 ± 10	450 ± 20	460 ± 40
300	50 ± 20	1000 ± 200	985 ± 120
350	50 ± 20	$300 - 700$	$350 - 700$

Conclusion & Outlook

- We plan to use these techniques to characterize advanced semiconductor cathodes in the Pegasus RF gun to push towards a 6D characterization of photocathode performance in an RF gun
    - Most useful for long pulse analysis close to threshold
    - Next batch of cathodes coming to UCLA early fall from both SLAC & ASU
- Future expansions
    - More accurate treatment of the initial charge distribution
    - Train NN that spans a larger input space

Acknowledgments

PBPL

- Advisor: Pietro Musumeci
- Support from post docs & students
- Past PBPL students who have worked on this project: Eric Cropp, Gilles Silvi

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- SLAC: T. Vecchione & G. Adhikari
- Cornell: Maxson Lab
- ASU: Karkare Lab

Funding

- CBB/NSF
- DOE

Boersch Effect

- Coulomb repulsion of the electron beam will increase the energy spread if too dense
  - Correlation plots show this effect becomes negligible as the beam is stretched