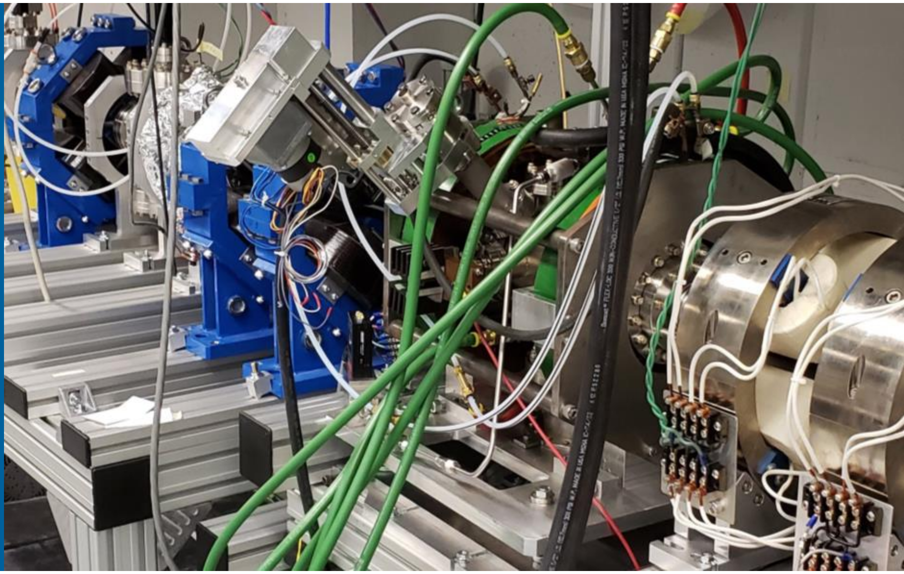
AWA NEEDS AND OPPORTUNITIES WORKSHOP

SINGLE SHOT HIGH TRANSFORMER RATIO MEASUREMENTS IN THE NONLINEAR PLASMA REGIME



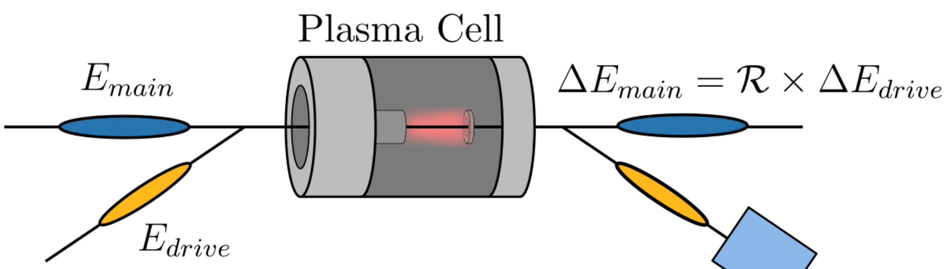
RYAN ROUSSEL
University of California: Los Angeles

OUTLINE

- Motivation
- Experiment Overview
  - Emittance Exchange
  - Plasma Beamline Design
  - Hollow Cathode Arc Plasma Source
- Wakefield Measurements
  - Single shot wakefield measurement
  - Observation of high TR
  - Observation of wakefield flattening
  - Probing nonlinearities in the plasma response
- Conclusion

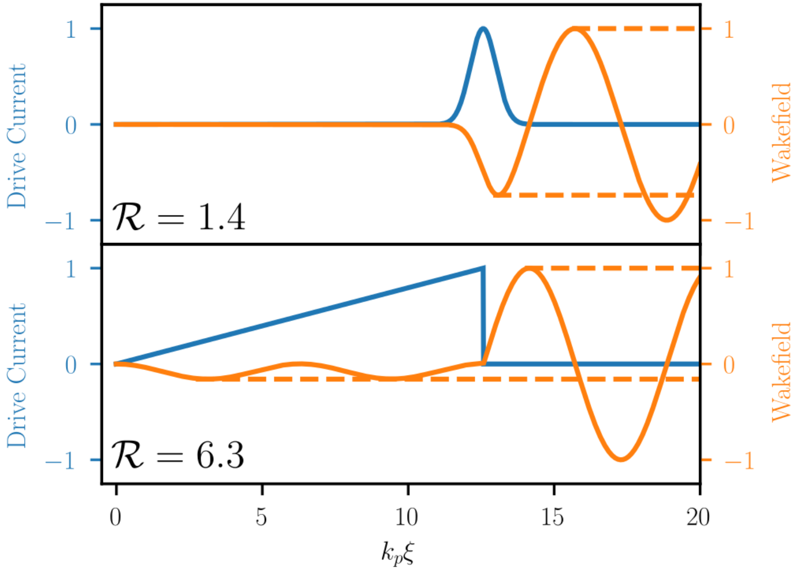
MOTIVATION

Maximum energy delivered to main beam is limited by the **drive energy** and the **transformer ratio (TR)**



$$\mathcal{R} = \left| \frac{W_+}{W_-} \right|$$

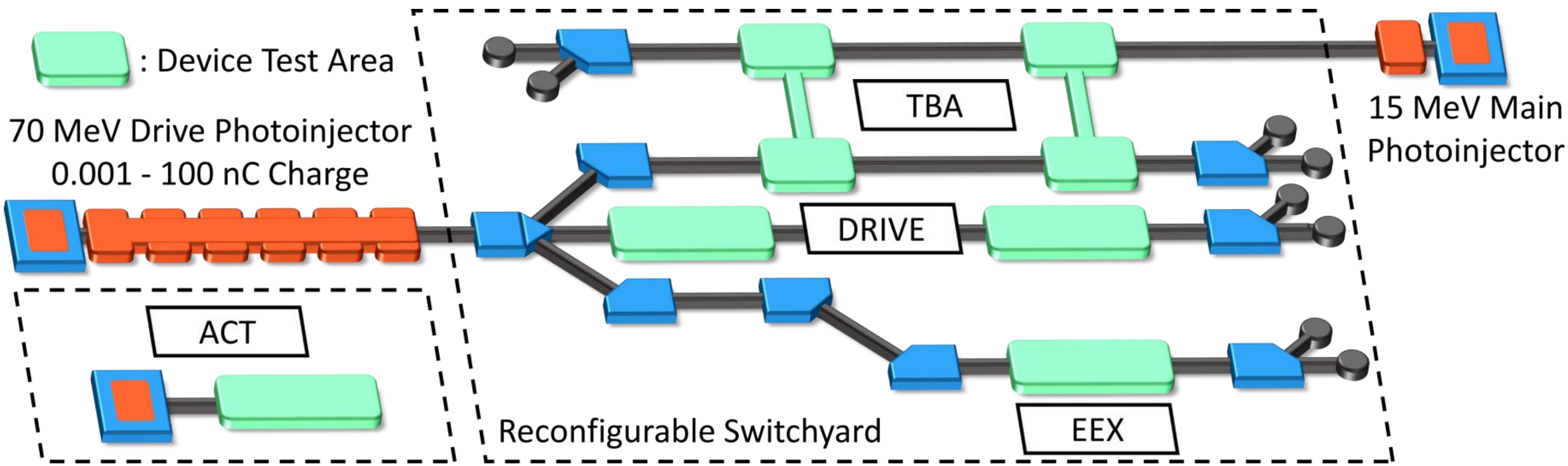
TR < 2 for symmetrical beams in a linear wakefield



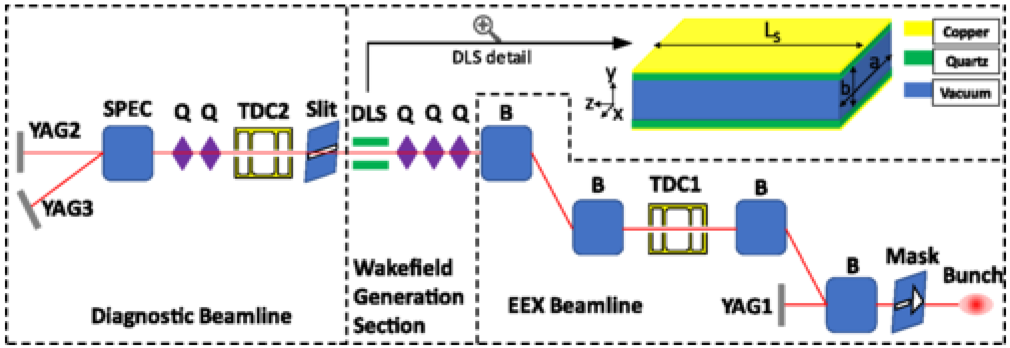
Transformer ratio can be increased using

- **Asymmetric beams**
- **Nonlinearities in the wakefield response**

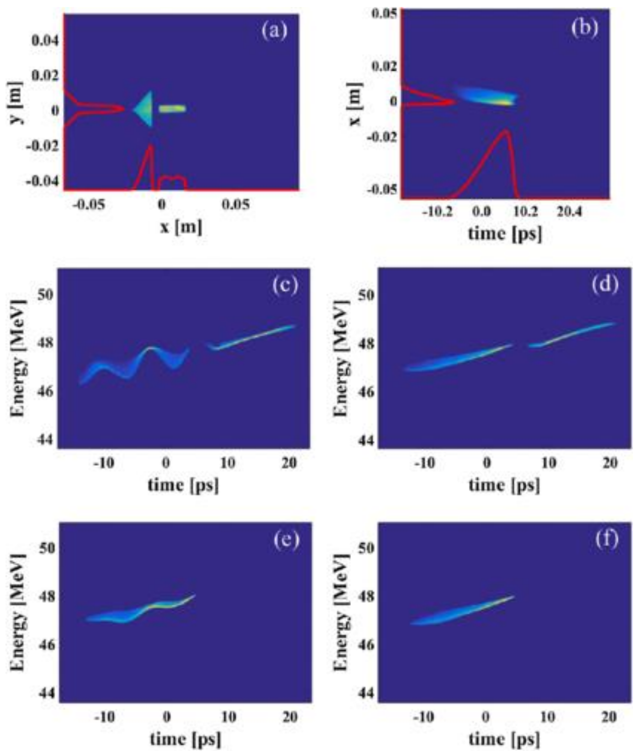
THE ARGONNE WAKEFIELD ACCELERATOR

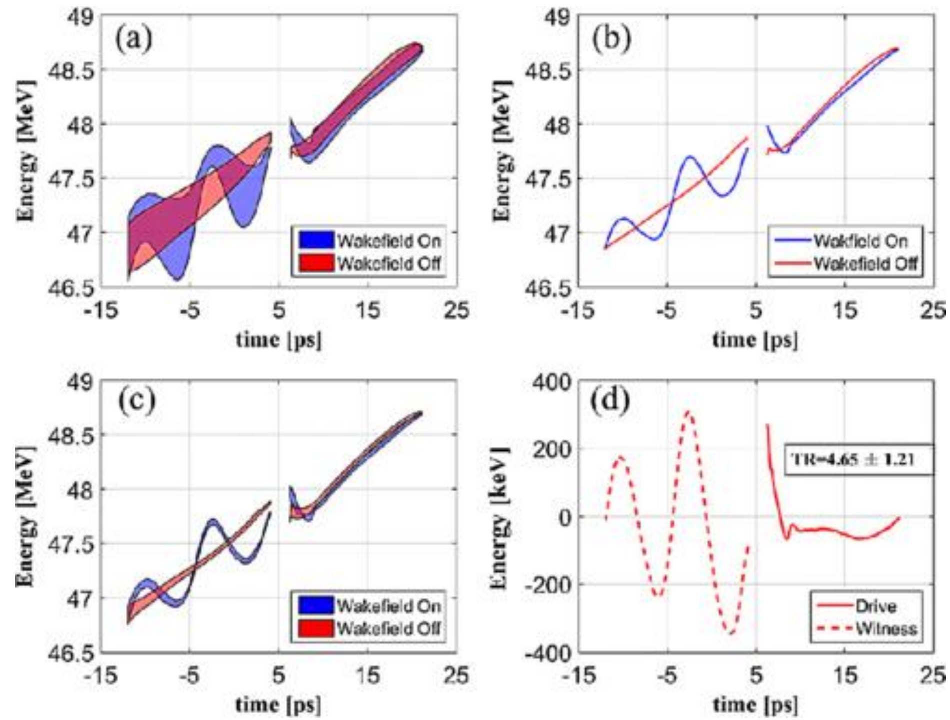


HIGH TR DIELECTRIC MEASUREMENTS AT AWA



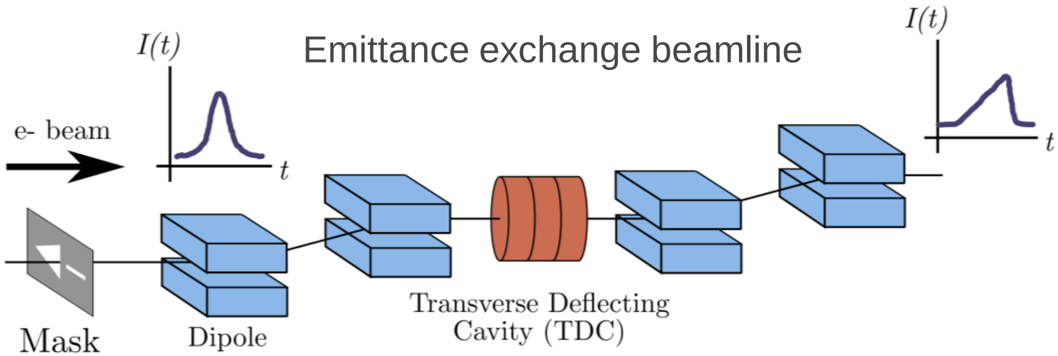
$$\mathcal{R} = 4.94^{+1.53}_{-1.53}$$





Gao, Q., et al. Phys. Rev. Lett. 120.11 (2018): 114801.

EXPERIMENT GOALS AT AWA

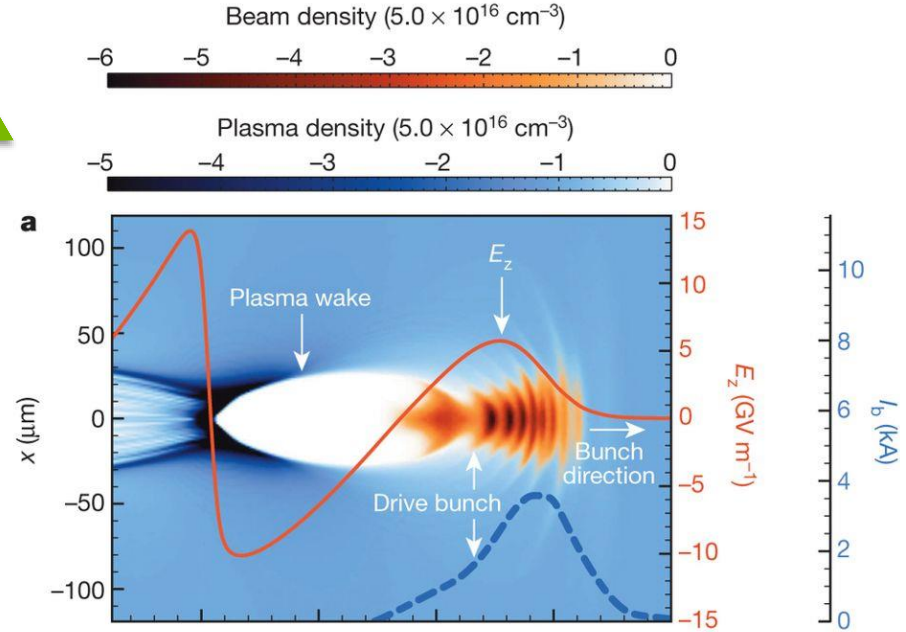


Apply **Emittance Exchange** shaping techniques…

- High charge (> 2 nC)
- Near arbitrary current profiles
- Long witness for wake sampling in a single shot

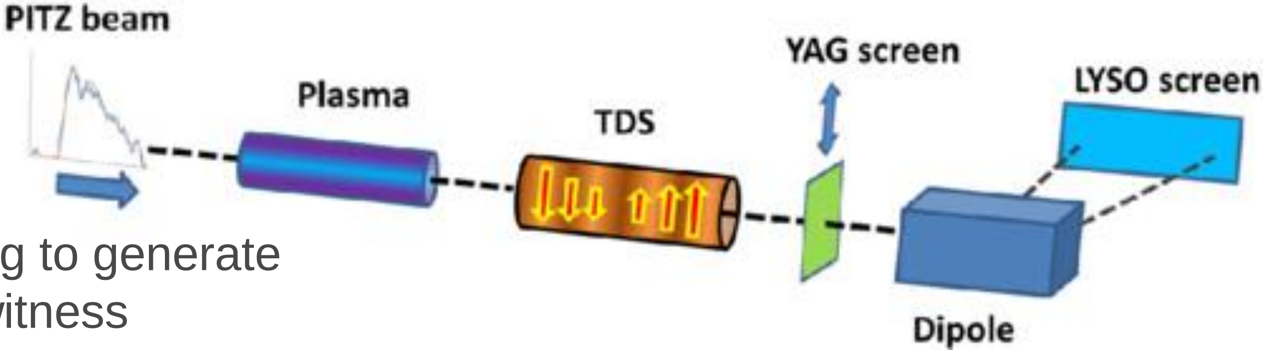
… to study high TR
plasma wakefield acceleration

- Tunable wakefield wavelength
- Nonlinear transverse blowout effects
- Large wakefield amplitude

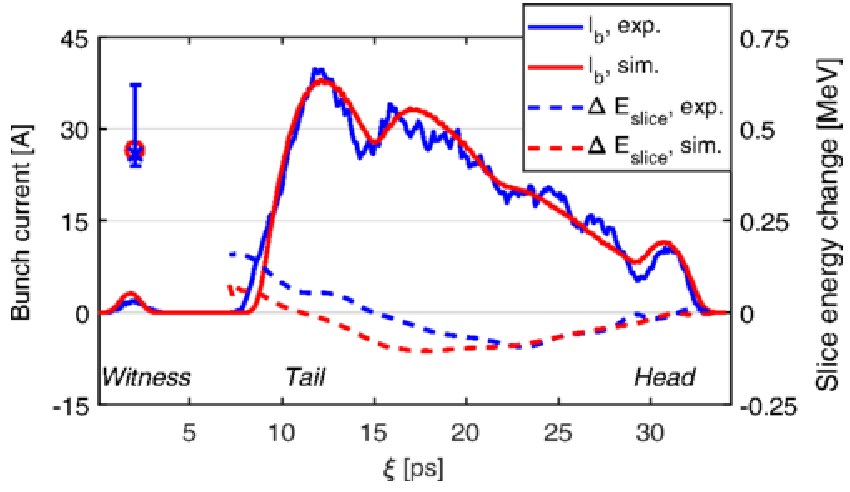


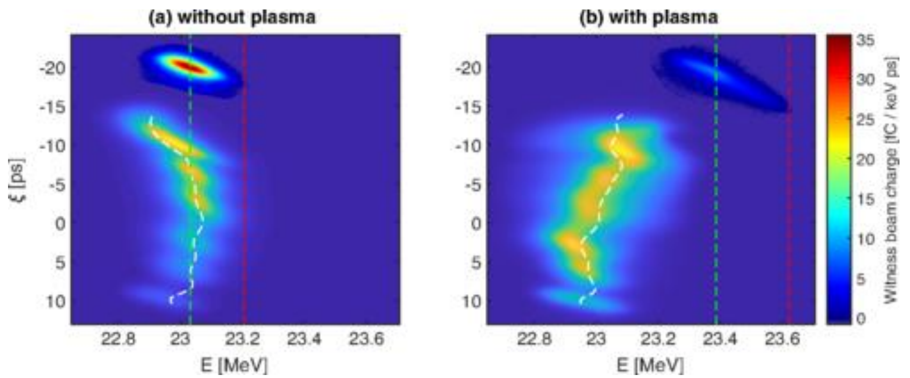
M. Litos , *Nature* **515**, 2014

HIGH TR PWFA MEASUREMENTS AT PITZ



Laser pulse stacking to generate ramped bunch w/ witness

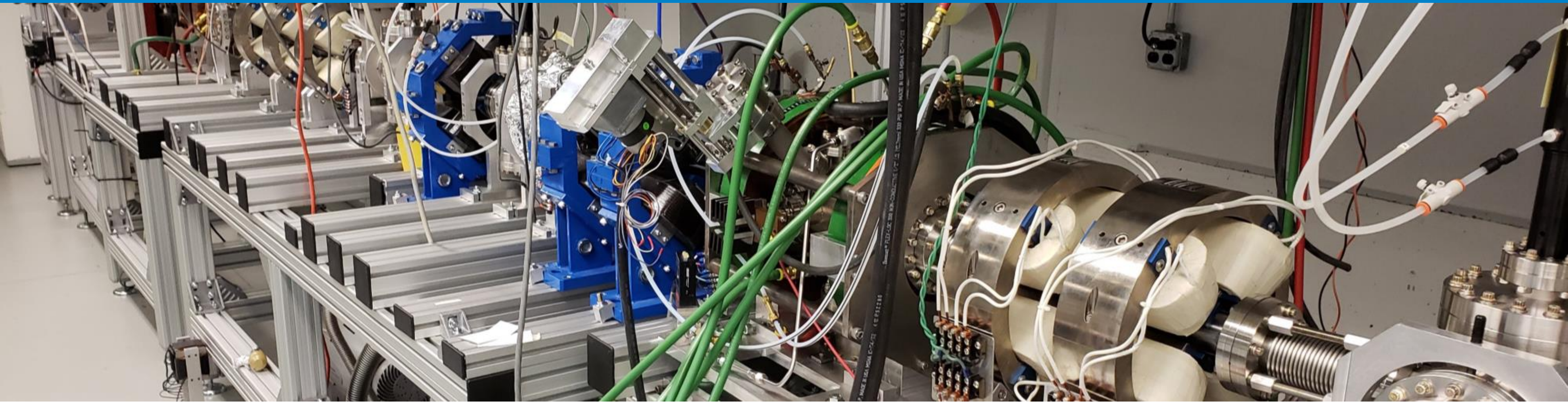




$$\mathcal{R} = 4.6^{+2.2}_{-0.7}$$

G. Loisch, Phys. Rev. Lett. **121**, 064801

AWA EXPERIMENT DESIGN



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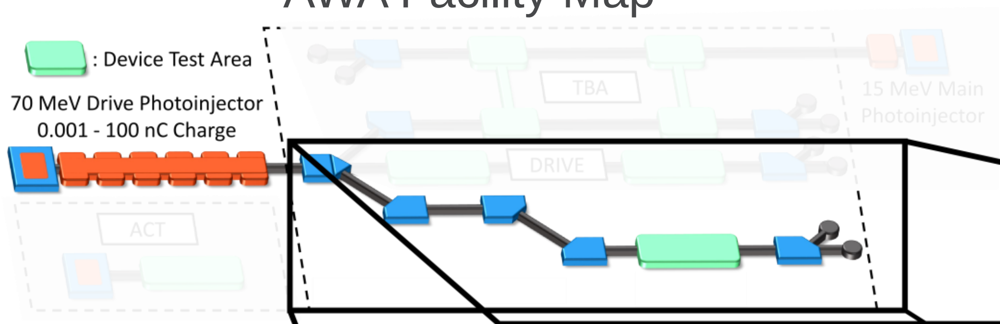
EXPERIMENT OVERVIEW

AWA Facility Map

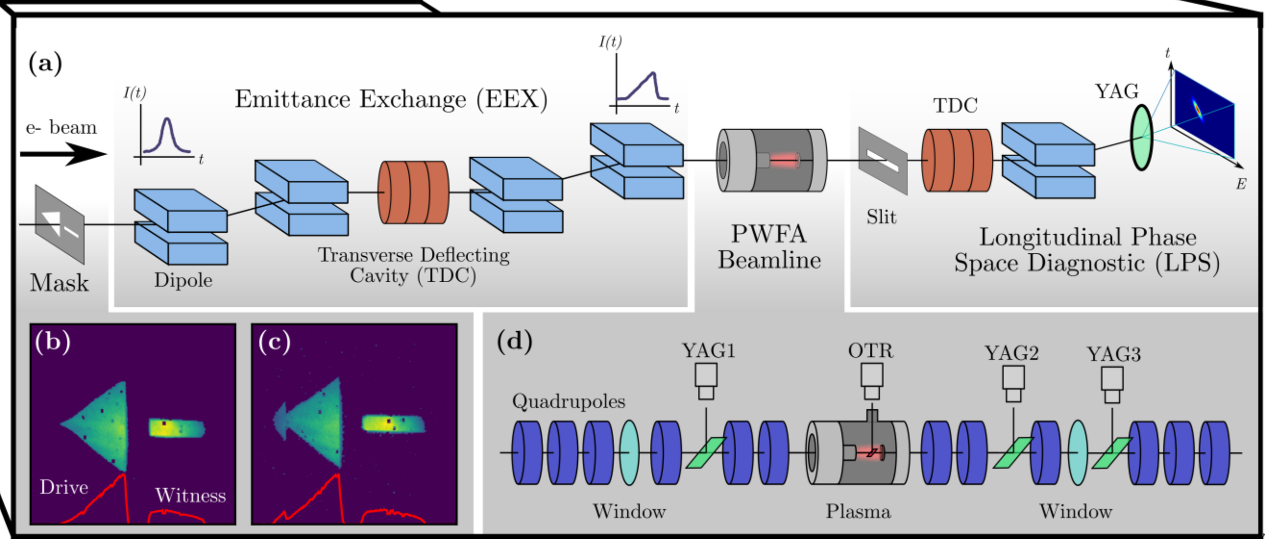


Beam Parameters

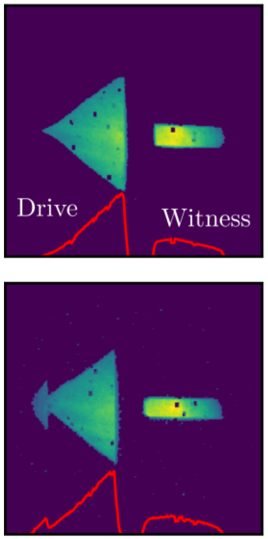
Parameter	Value	Unit
Beam energy	40	MeV
Beam charge (Pre-EEX)	12	nC
Beam charge (Post-EEX)	4	nC
Pulse length (Pre-EEX)	6	ps
Pulse length (Post-EEX)	40	ps

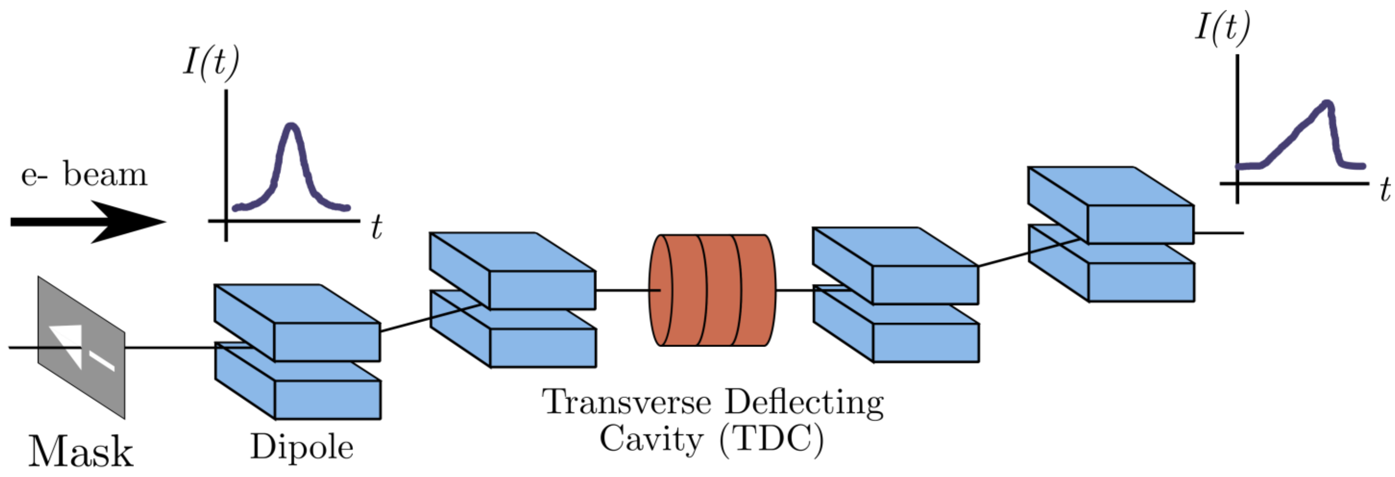
Plasma Parameters

Parameter	Value	Unit
Plasma density	0.3 - 1.5	10^{14} cm^{-3}
Plasma wavelength	6 - 3 (18 - 9)	mm (ps)
Matched β_{eq}	12 - 5	mm
Plasma column length	8	cm

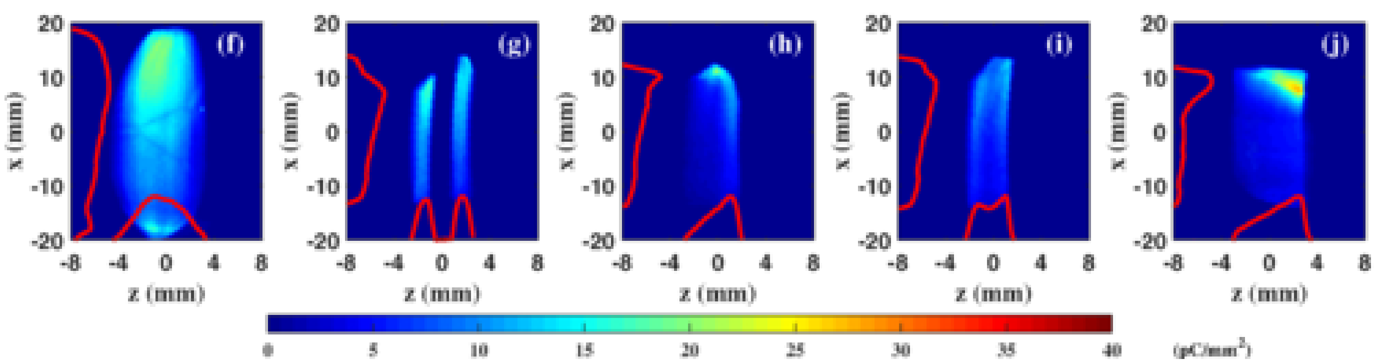


CURRENT SHAPING WITH EMITTANCE EXCHANGE



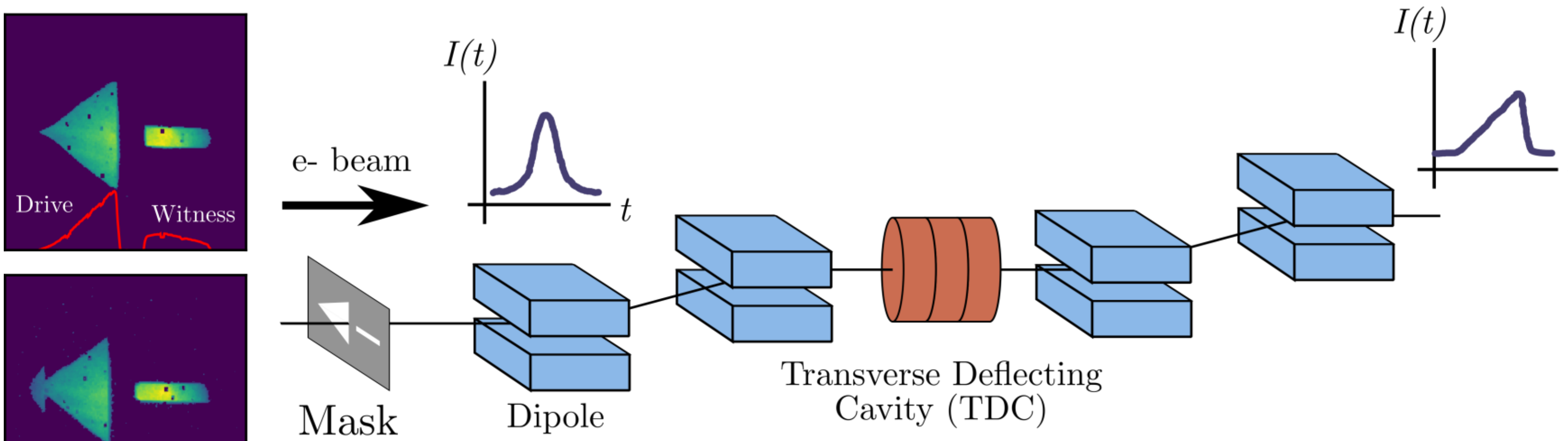


$$M_{EEX} = \begin{pmatrix} 0 & 0 & \kappa(L+L_D) & \eta+\kappa\xi(L+L_D) \\ 0 & 0 & \kappa & \kappa\xi \\ \kappa\xi & \eta+\kappa\xi(L+L_D) & 0 & 0 \\ \kappa & \kappa(L+L_D) & 0 & 0 \end{pmatrix}$$



G. Ha et. al., Phys. Rev. Lett. **118**, 104801

CURRENT SHAPING WITH EMITTANCE EXCHANGE



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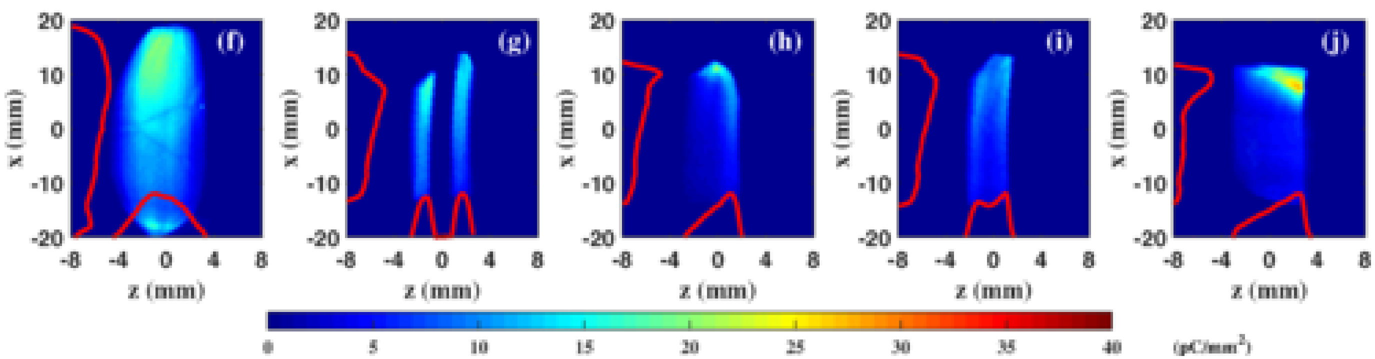
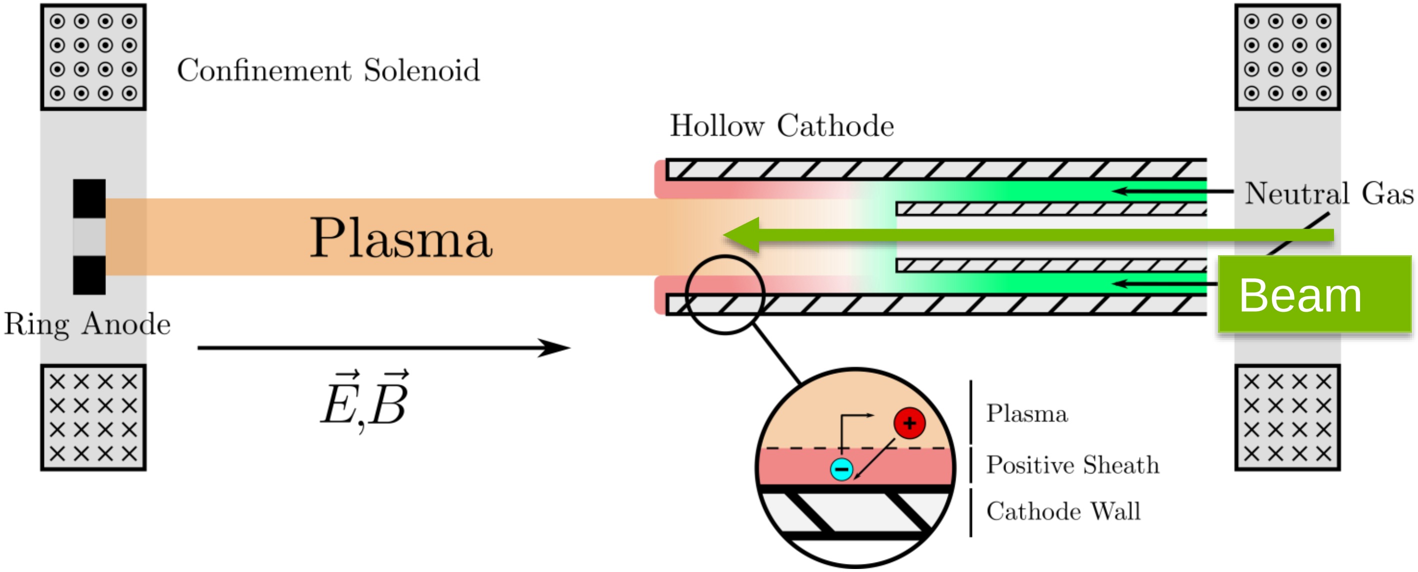
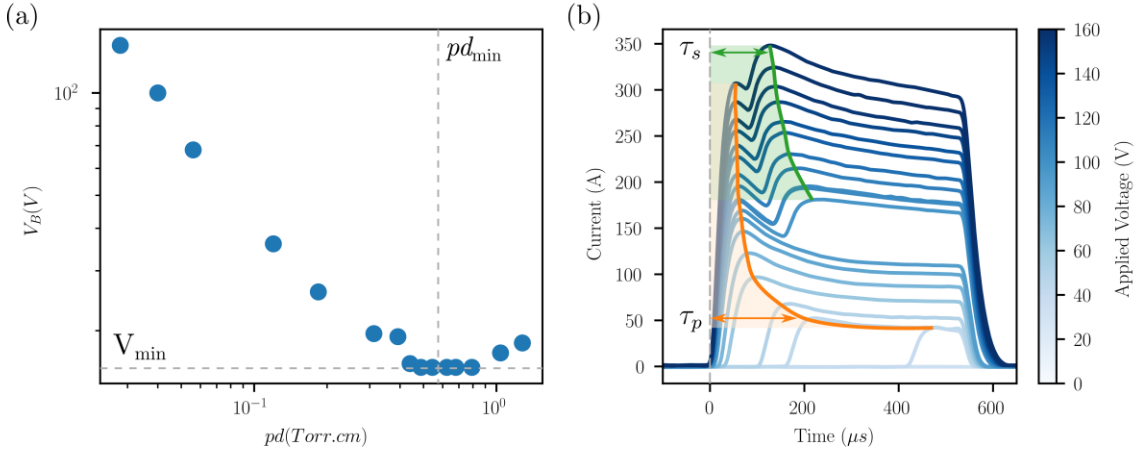


G. Ha et. al., Phys. Rev. Lett. **118**, 104801

HOLLOW CATHODE ARC PLASMA SOURCE



External heating of the cathode allows **arc regime access < 50V**

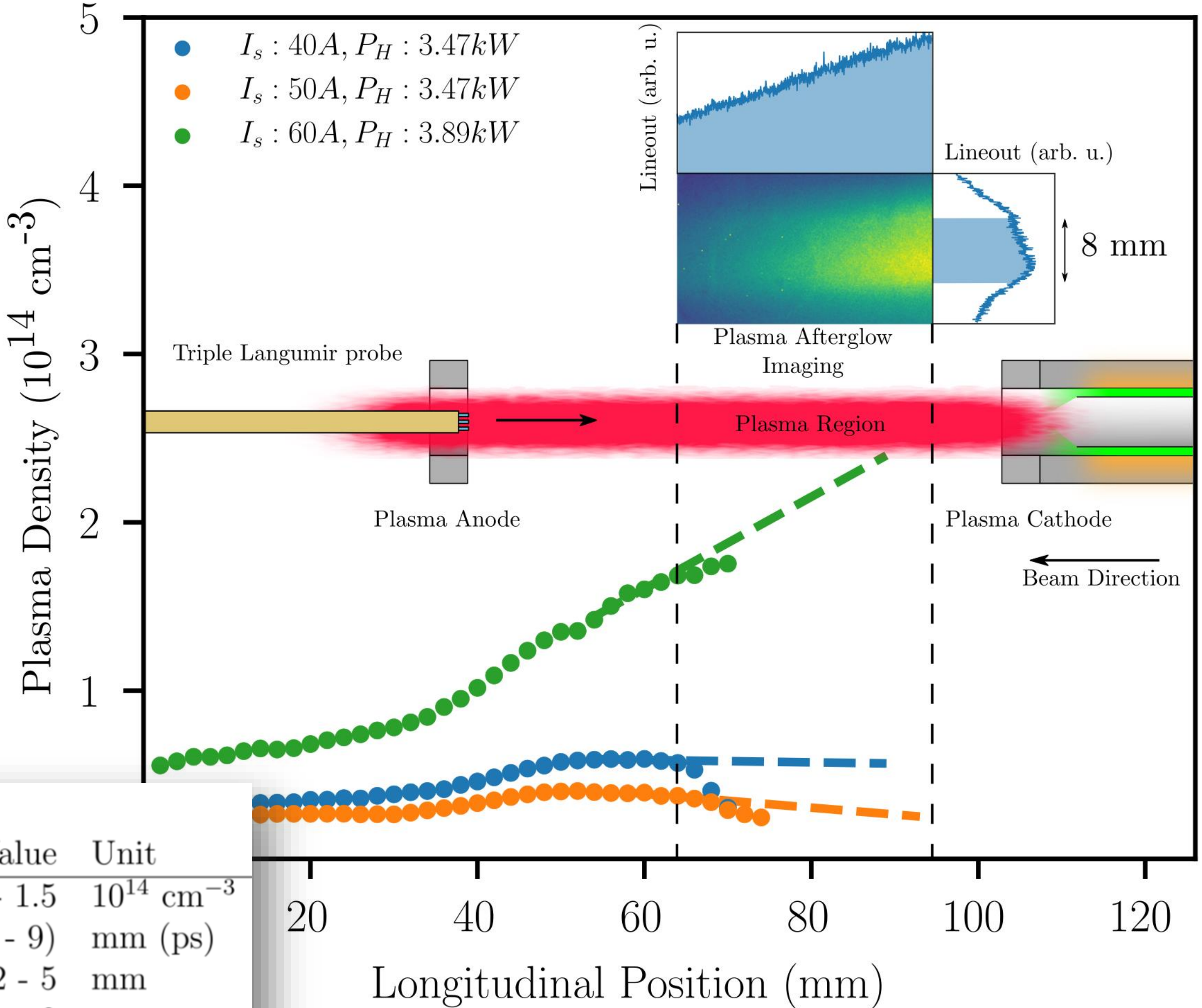


HOLLOW CATHODE ARC PLASMA SOURCE

Longitudinal plasma density is measured using a **triple Langmuir probe**

Further relative measurements were done with **plasma afterglow imaging**

Matches well with AWA beam parameters



Plasma Parameters

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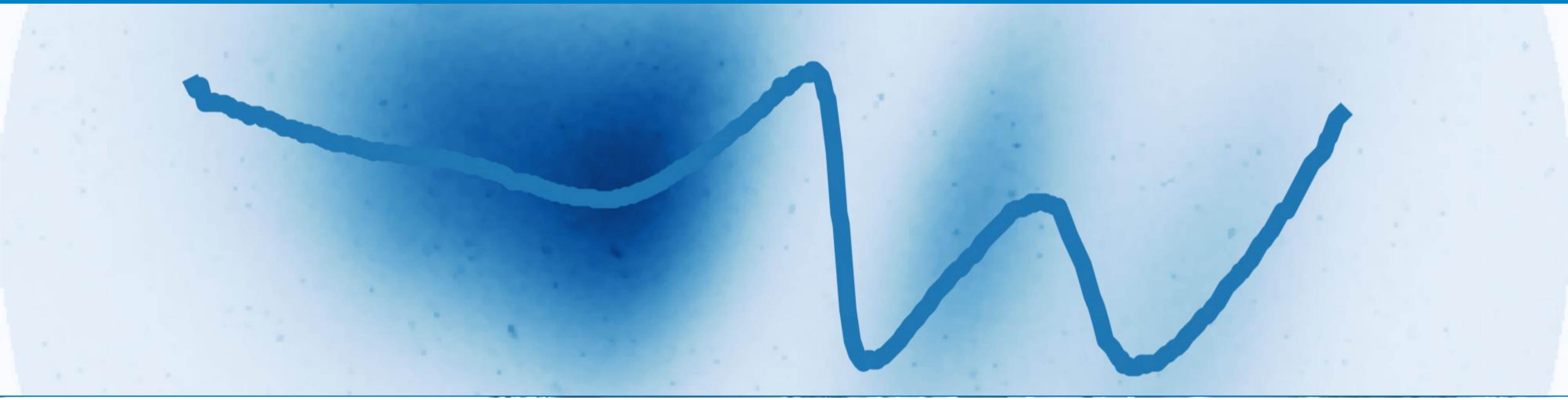
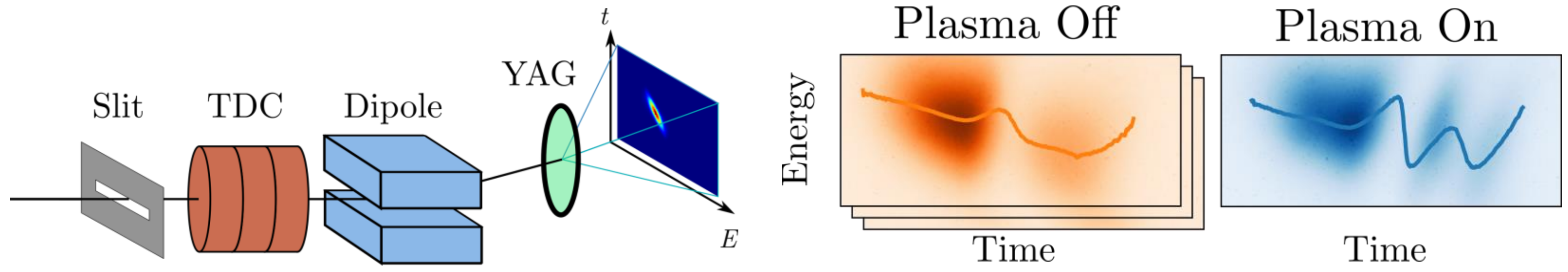
Plasma column length	8	cm

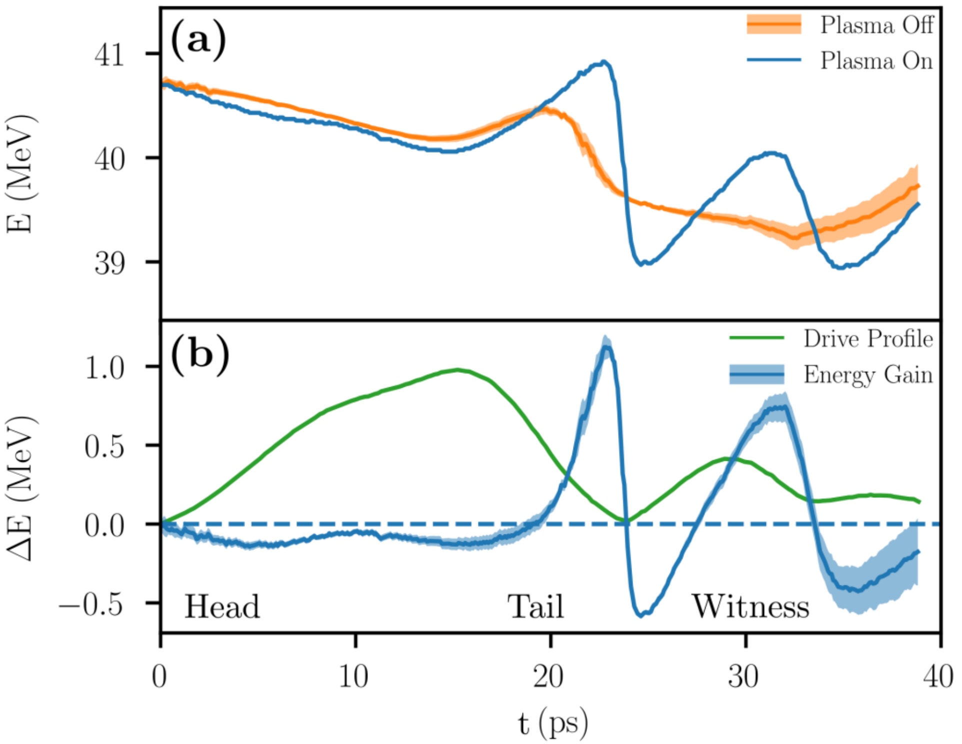
WAKEFIELD MEASUREMENTS



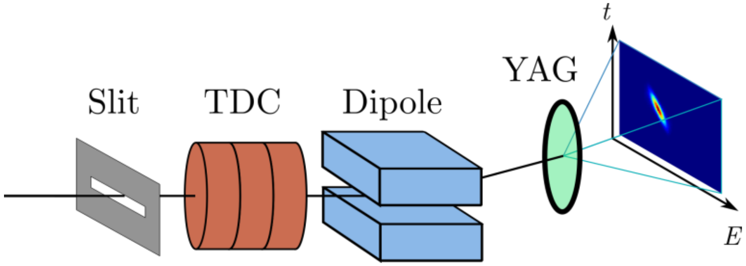
SINGLE SHOT WAKEFIELD MEASUREMENT



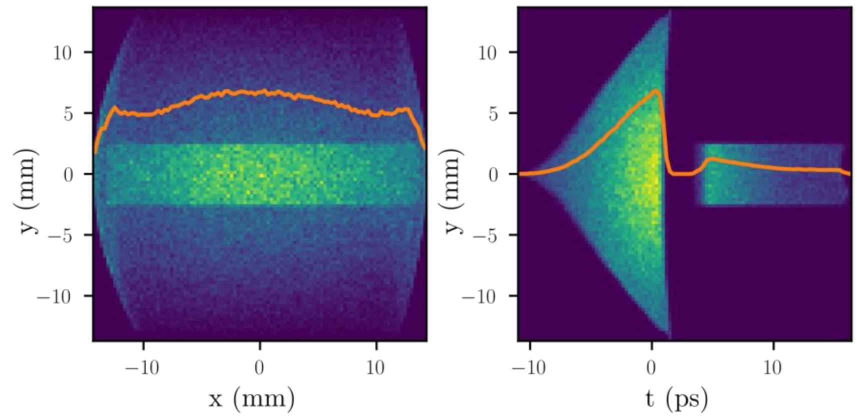
- Horizontal slit increases temporal resolution
- Plasma off/on shots interlaced
- Time dependent energy centroid measured for each shot
- ~50 plasma off shots averaged for background measurement



CURRENT DENSITY RECONSTRUCTION



Horizontal slit increases temporal resolution
BUT at the cost of accurate current measurement due to y-z correlation



Simulated beam dist. out of EEX

We can reconstruct the drive profile (up to a radial form factor) by approximating the **quasi-nonlinear regime** as a **linear plasma response** because $n_b/n_0 \approx 1$in the drive

$$n_b'' + k_p^2(n_b + n_1) = 0$$

$$\nabla \cdot \mathbf{E} = -4\pi e(n_b + n_1)$$

$$n_b(\xi) = -\frac{\epsilon_0}{e}\left[\frac{dE(\xi)}{d\xi} + k_p^2 \int_{-\infty}^{\xi} E(\xi')d\xi'\right]$$

W. Lu Physics of Plasmas **12**, 063101 (2005)

CURRENT DENSITY RECONSTRUCTION

Generated various linearly ramped bunch profile heads

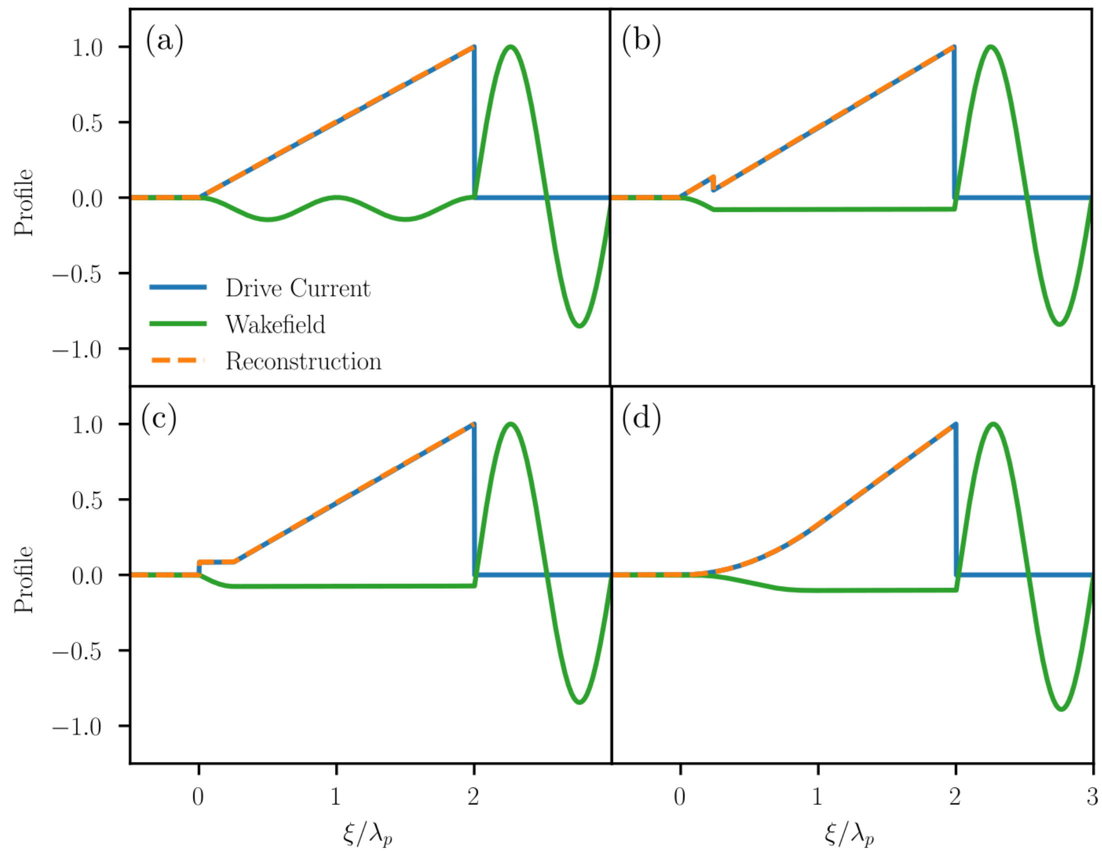
- **double-triangle**
- **doorstep**
- **parabolic**

Profiles taken from Lemery and Piot Phys. Rev. A & B (2015)

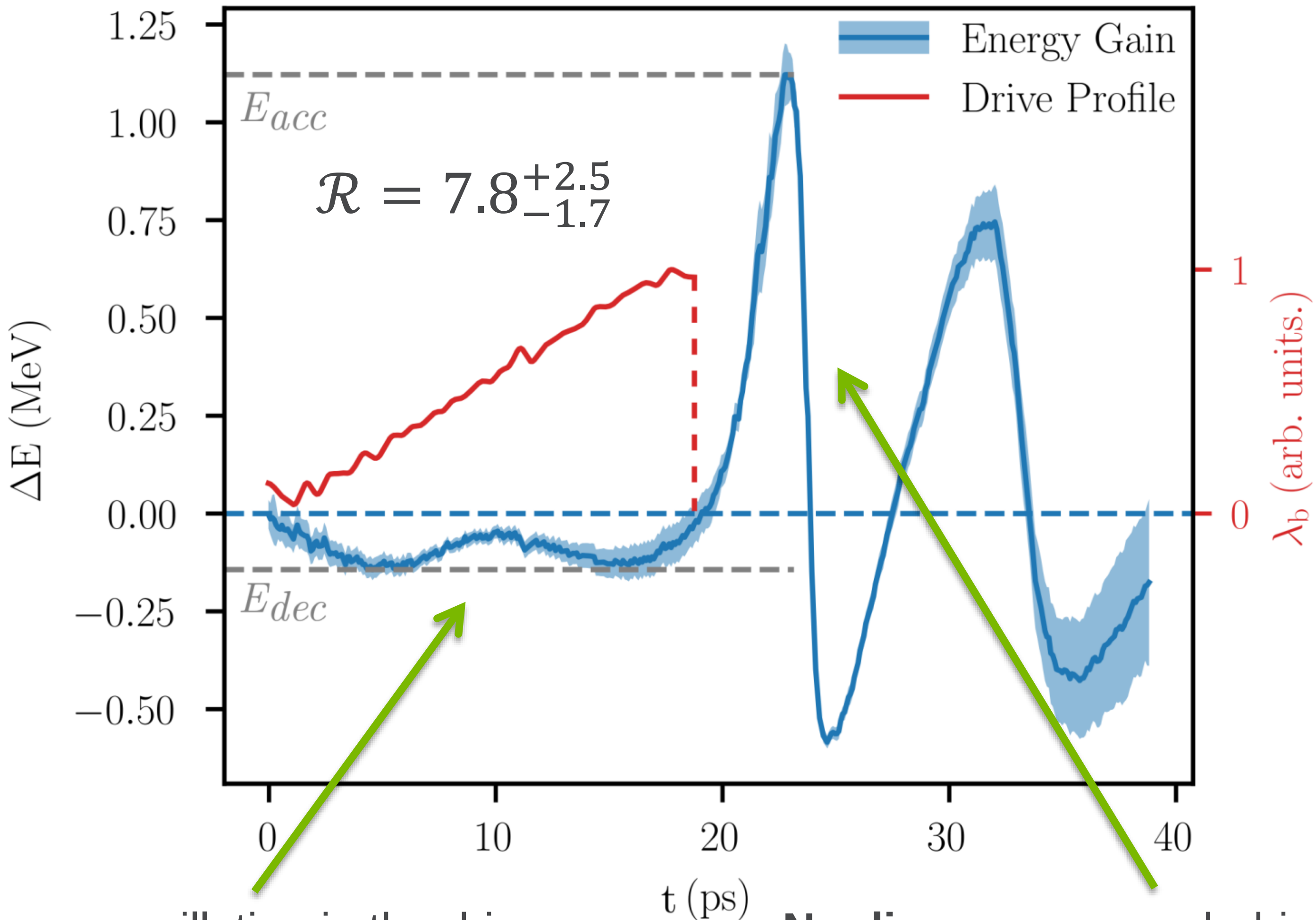
Calculated wakefield from single mode convolution

Reconstructed drive profile from wakefield $0 \le \xi < L_b$

$$n_b(\xi) = -\frac{\epsilon_0}{e}\left[\frac{dE(\xi)}{d\xi} + k_p^2 \int_{-\infty}^{\xi} E(\xi')d\xi'\right]$$



OBSERVATION OF HIGH TR



Linear oscillation in the drive

Nonlinear response behind the drive

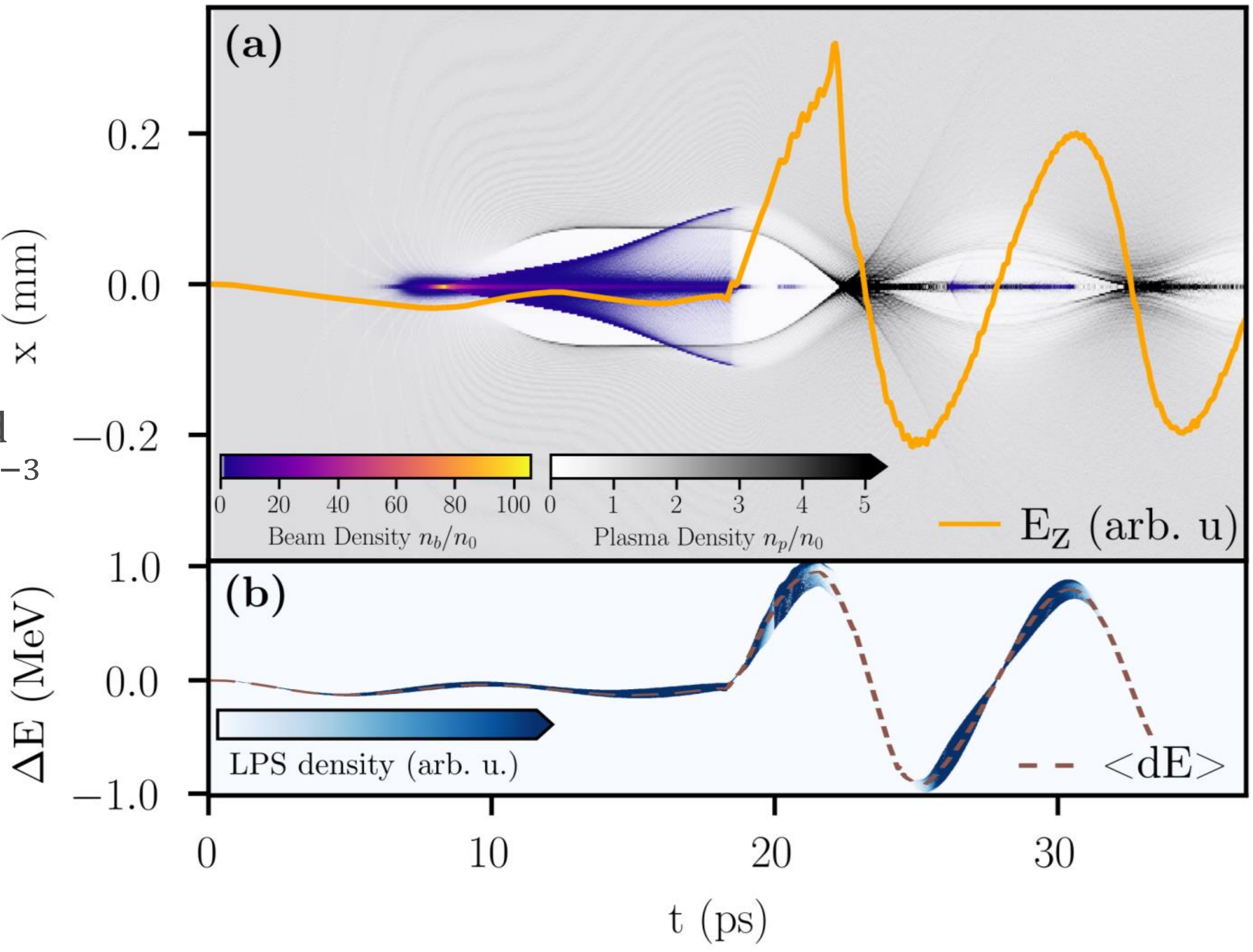
COMPARISON TO SIMULATION

Quasi-3D simulations done in **WARP**

Input params:

- $Q_b = 1.8\ \text{nC}$
- $\sigma_r = 200\ \mu\text{m}$
- $\epsilon_n = 200\ \text{mm. mrad}$
- $n_0 = 1.5 \times 10^{14}\ \text{cm}^{-3}$
- $\lambda_p \approx 3\ \text{mm}$

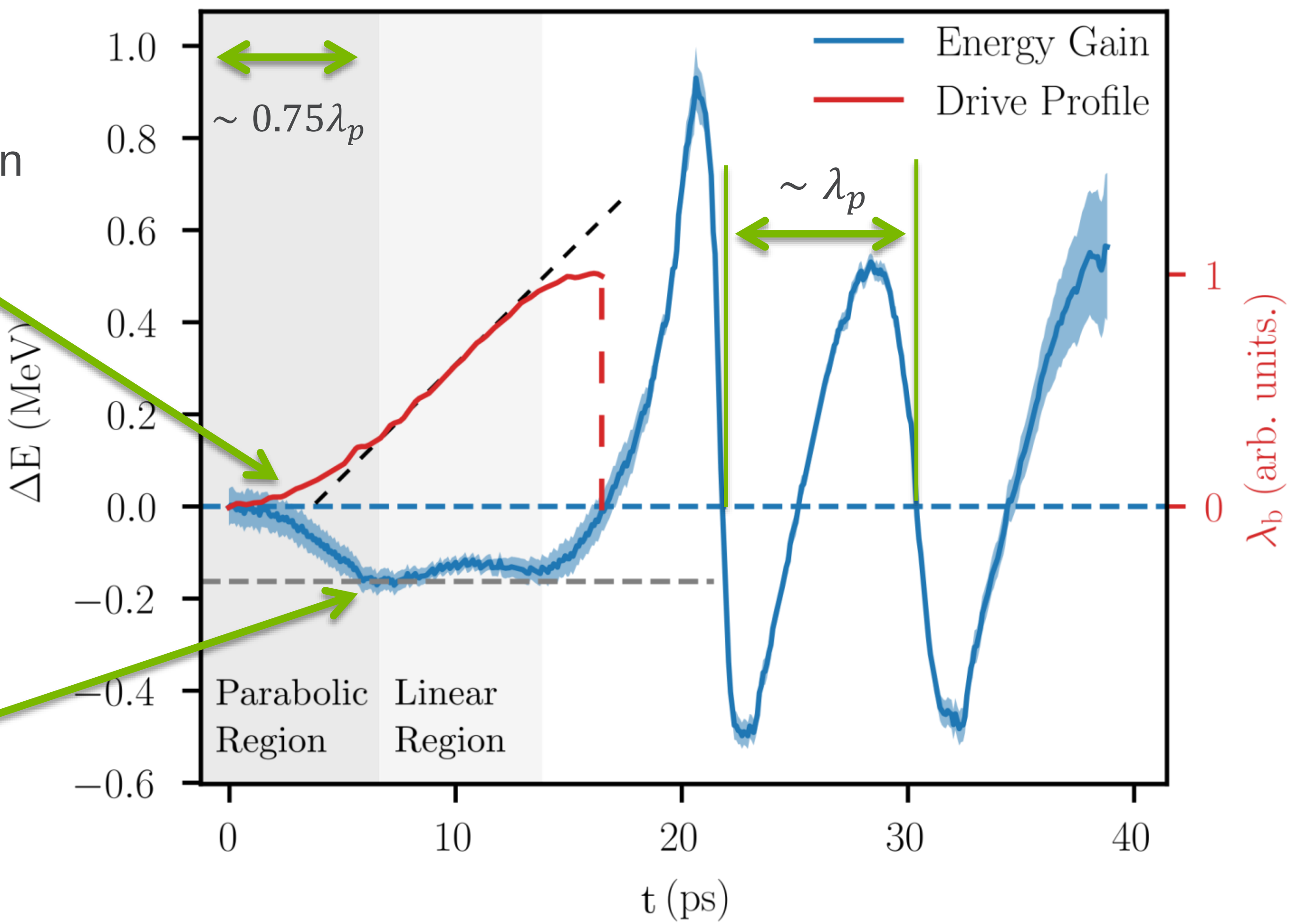
Non-relativistic blowout ($r_m < \lambda_p$) => drive wakefield **approximates linear response**



UNIFORMIZATION OF DRIVE WAKEFIELD

Parabolic deviation

Uniform wakefield



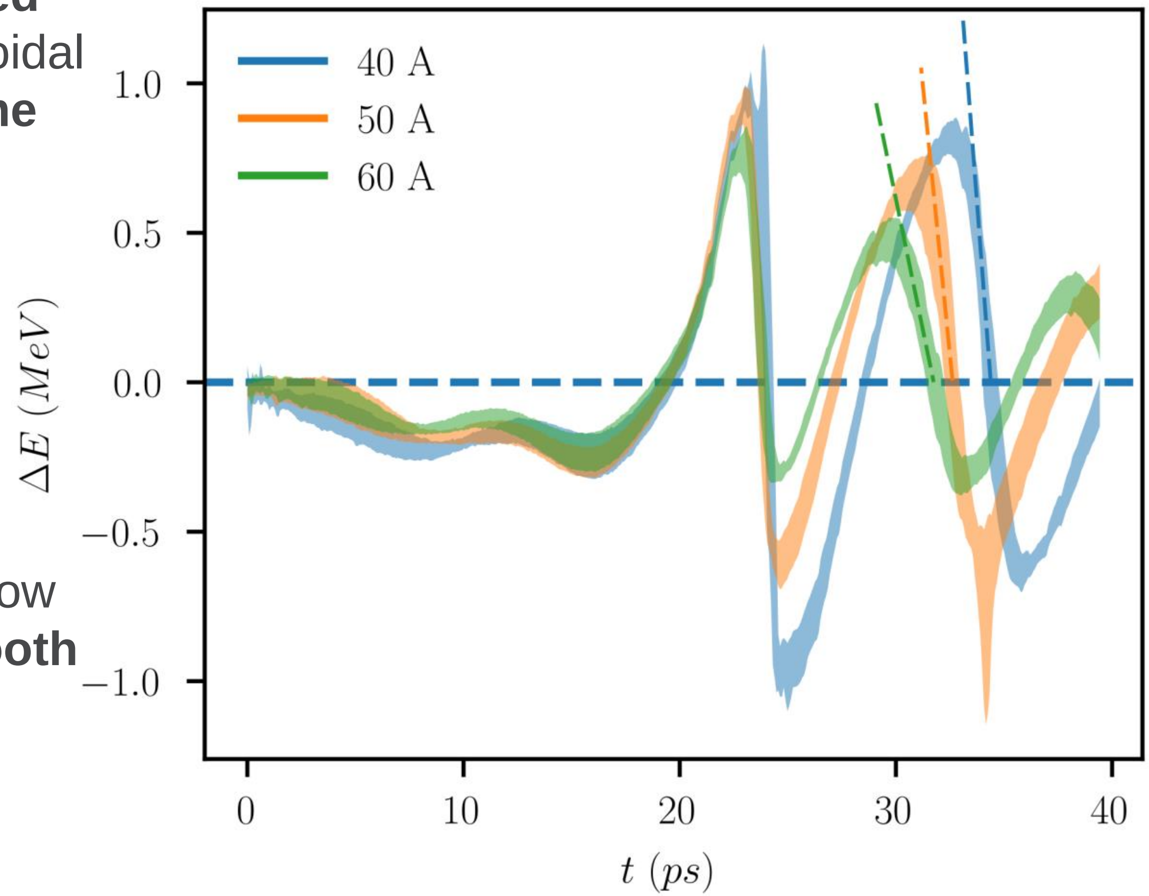
PROBING MULTI-PERIOD NONLINEARITIES

Plasma density is scanned by changing on-axis solenoidal field while keeping the **same beam charge**

Nonlinearity of system
=> $\widetilde{Q} = n_b/n_0$

Increasing plasma density **reduces nonlinearities**

Highest density wakefields appear **sinusoidal**, while low density wakes have **sawtooth** appearance



SUMMARY

- (RE)INTRODUCED PWFA EXPERIMENTS TO AWA
- OBSERVED HIGHEST TR FOR PWFA DUE TO NONLINEAR RESPONSE
- OBSERVED WAKEFIELD FLATTENING DUE TO PARABOLIC HEAD

THANKS TO EVERYONE WHO HELPED!

AWA

- John Power
- Manoel Conde
- Gwanghui Ha
- Jimin Seok
- Eric Wisniewski
- Scott Doran
- Charles whiteford
- Wanming Liu

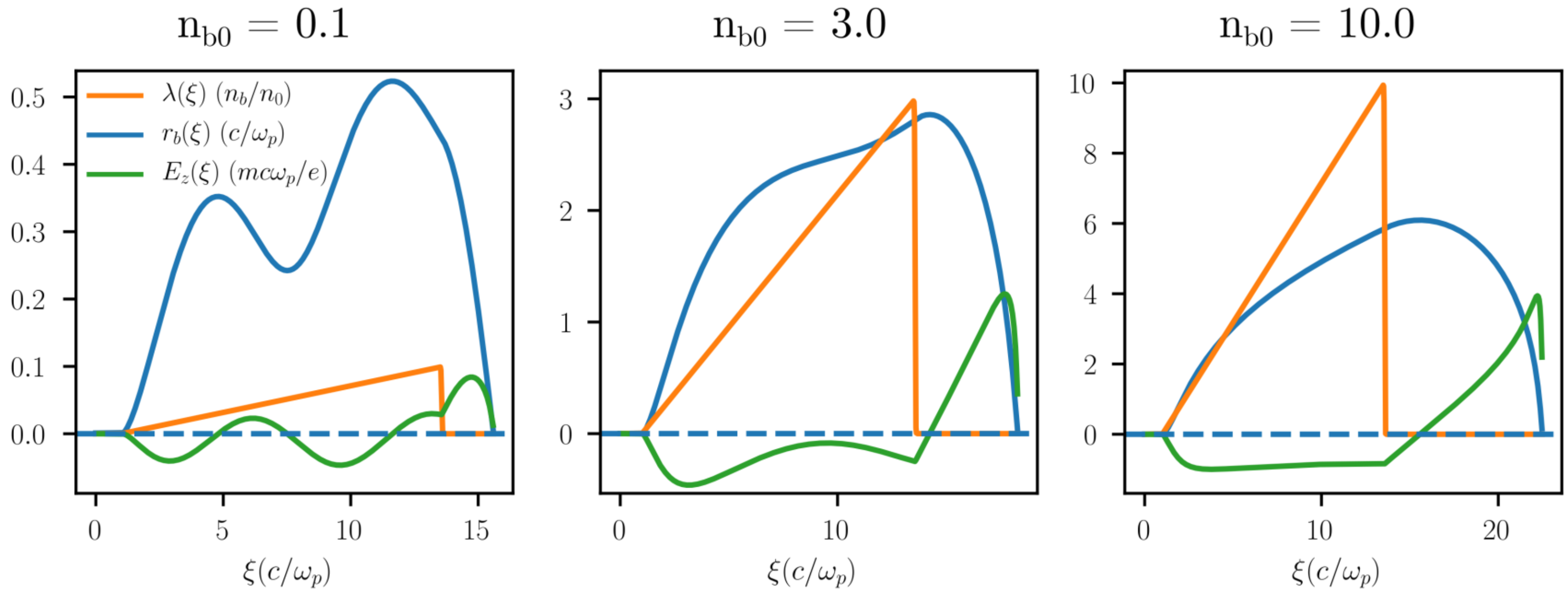
UCLA

- Gerard Andonian
- James Rosenzweig
- Walter Lynn
- Kunal Sanwalka
- River Robles
- Claire Hansel
- Ahiua Deng
- Gerard Lawler

DOE SCGSR + DE-SC0017648

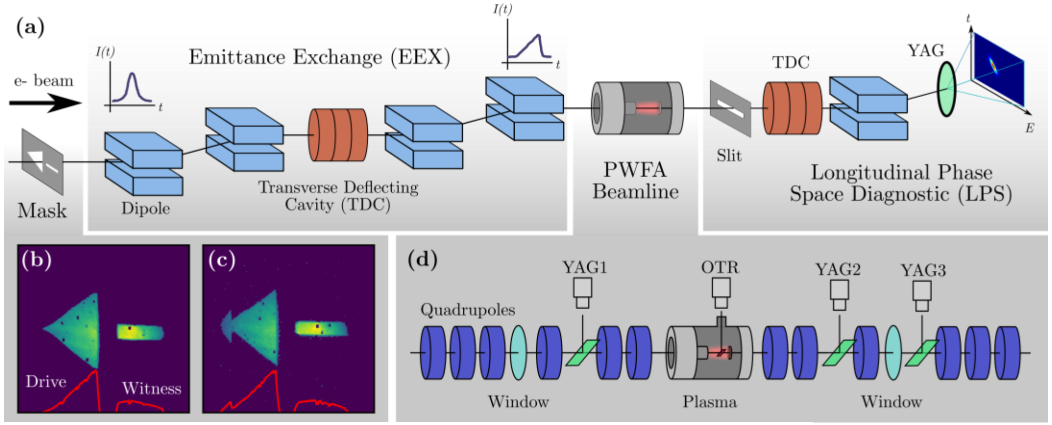
LINEAR RAMPS IN THE BLOWOUT REGIME

- Numerical calculation of blowout radius and on-axis wakefield from Lu. et.al
- At low beam densities blowout is sub-relativistic -> response approximates linear regime
- At high beam densities, blowout is relativistic -> wakefield inside drive becomes uniform

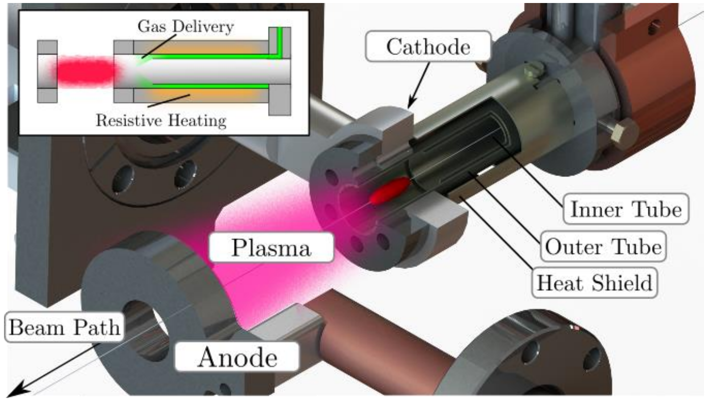


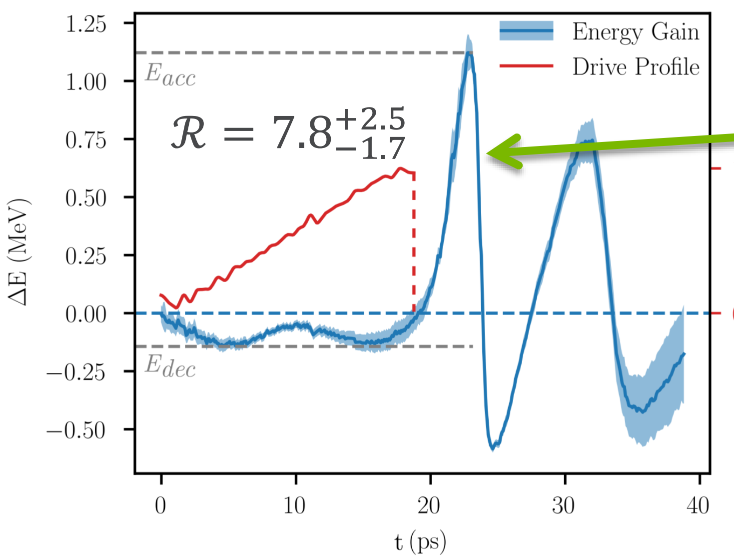
SINGLE SHOT HIGH TRANSFORMER RATIO MEASUREMENTS IN THE NONLINEAR PLASMA REGIME

Experimental beamline at AWA



Hollow cathode arc plasma source





Highest TR observed

Uniform wakefield in drive from parabolic head