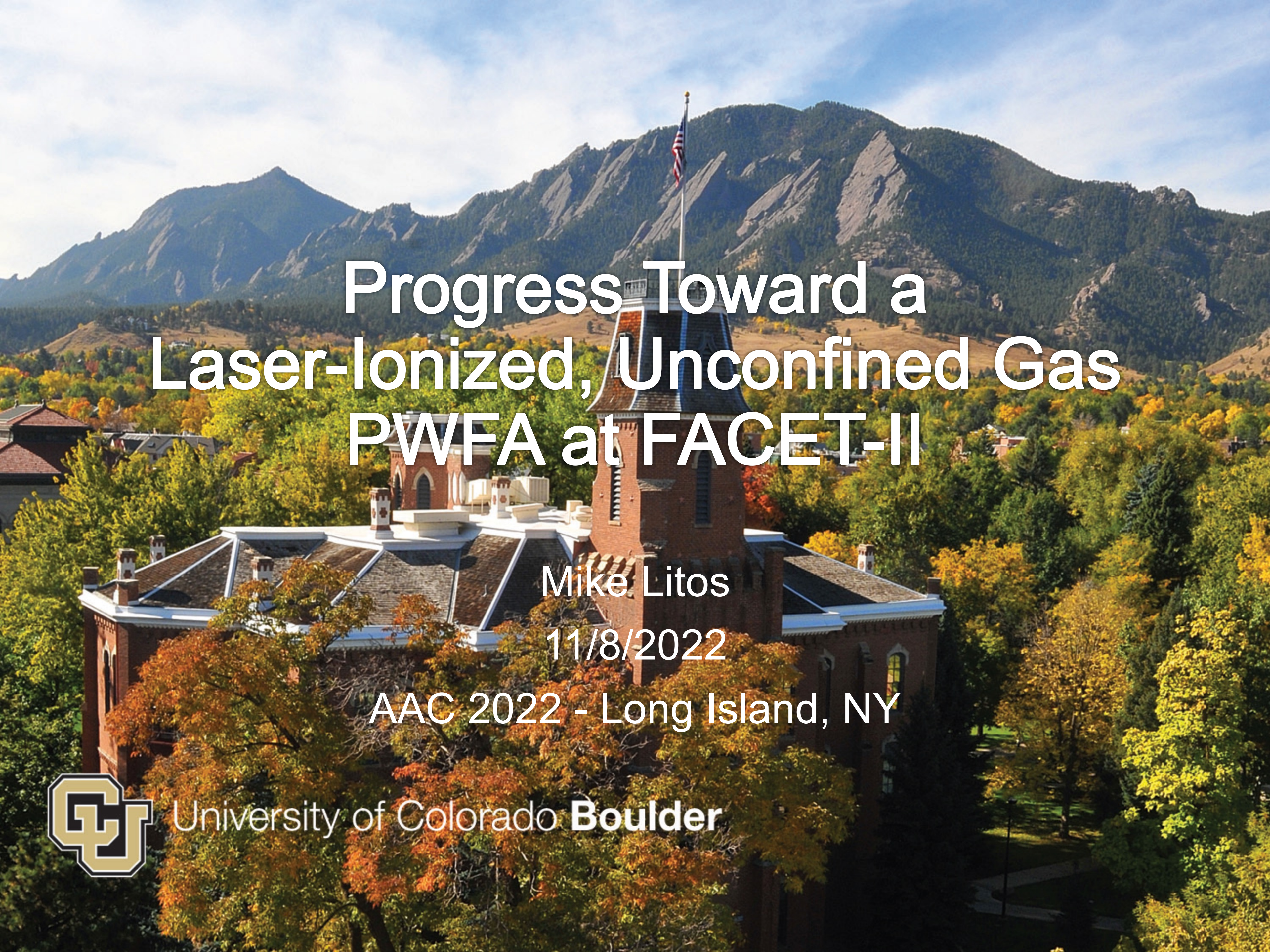


Progress Toward a Laser-Ionized, Unconfined Gas PWFA at FACET-II

Mike Litos

11/8/2022

AAC 2022 - Long Island, NY

University of Colorado Boulder

Our Research Is Funded By...

U.S. Department of Energy, Office of Science, Office of High Energy Physics, under Award Number DE-SC001796.

And most of the work was done by...

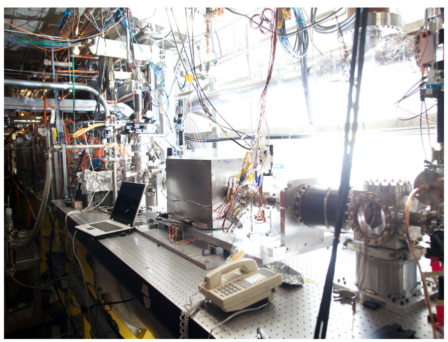
Mike & Robert
hiking the Flatirons

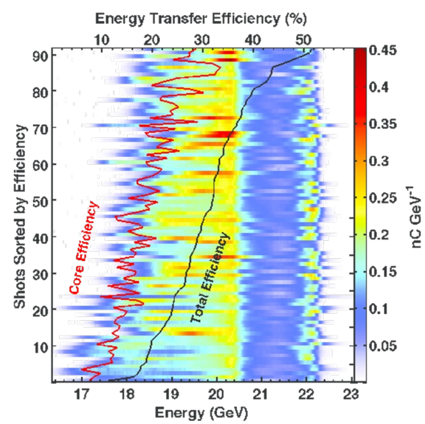
Dr. Robert Ariniello
Ph.D. from CU Boulder in May
Now a postdoc at FACET-II

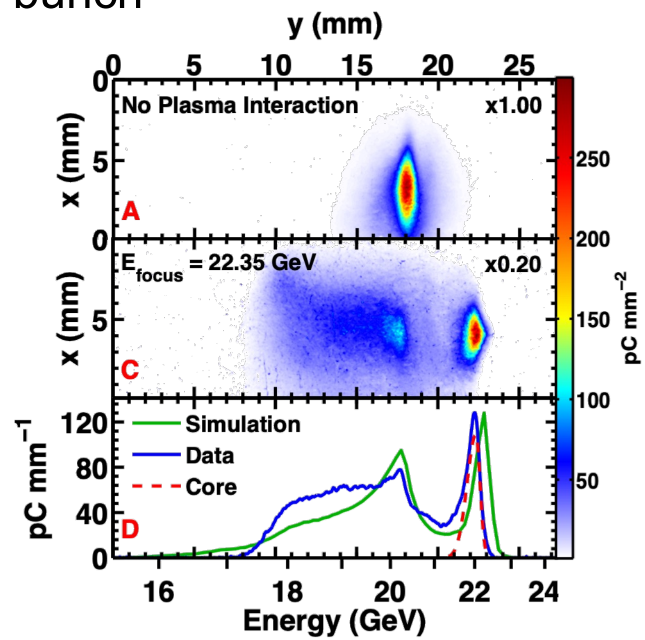
History of PWFA at FACET: E200

High energy gain and high efficiency at FACET-I

- **Beam:** drive & witness ~1 nC, ~20 GeV, ~100 µm-rad
- **Plasma Source:** ~1m long, ~10^{16} cm^{-3}, Li oven
- **High Gain:** 2-9 GeV energy gain for discrete witness bunch
- **Low E-Spread:** ~1% energy spread
- **High Efficiency:** ~30% energy transfer efficiency







Conclusions:

- Good energy gain, good longitudinal beam loading
- Bad emittance, bad witness capture efficiency, no matching
- Longitudinal dynamics pretty good
- Next step: make transverse dynamics also good

E301 Goal: Emittance Preservation

<u>High energy gain, high efficiency, and emit. preservation at FACET-II</u>

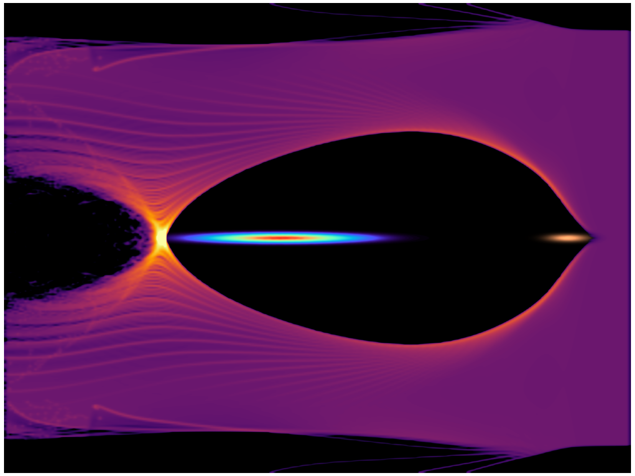
- **Beam:** drive & witness ~0.75 nC, ~10 GeV, ~1 μm-rad
- **Plasma Source:** ~1m long, ~10^{16} cm^{-3}, laser-ionized gas

FACET-II

Good Longitudinal Beam Loading:
- Large energy gain ~10 GeV
- Small (<1%) energy spread
- High energy transfer efficiency

Good Transverse Beam Matching:
- Preserve witness emittance

Requirements and challenges:
- Improve understanding of transverse dynamics
- Design and create appropriate plasma source
- Develop diagnostic plan and diagnostics
- Deliver appropriate e-beam

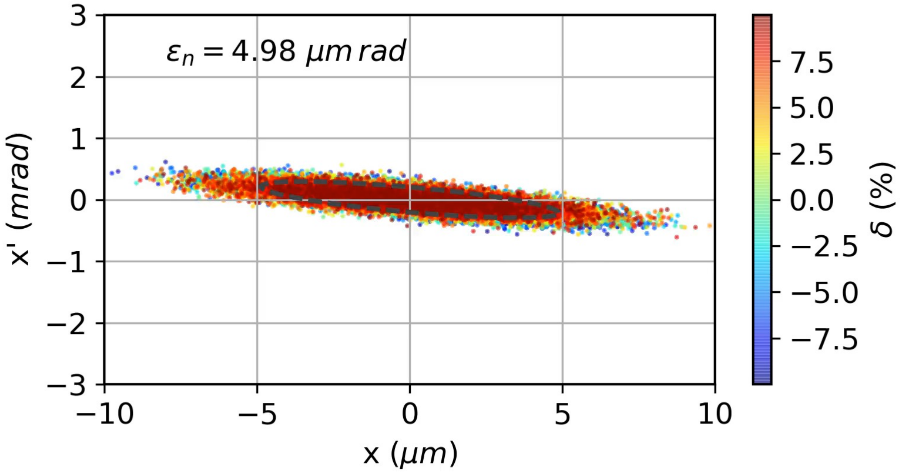


Better beam, better plasma, better performance! COVID had other plans...

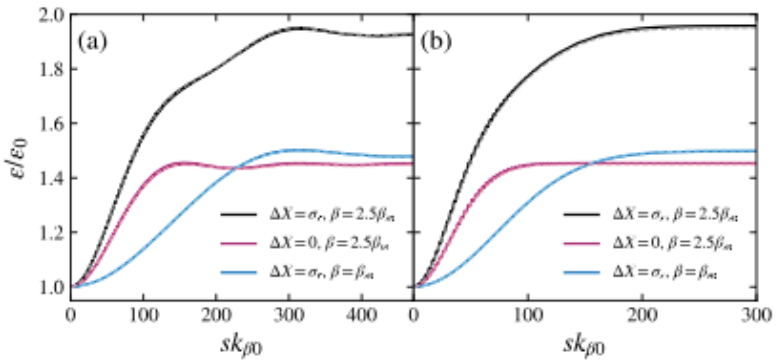
Development of Beam Dynamics Theory

Transverse beam dynamics are key – More theory was needed

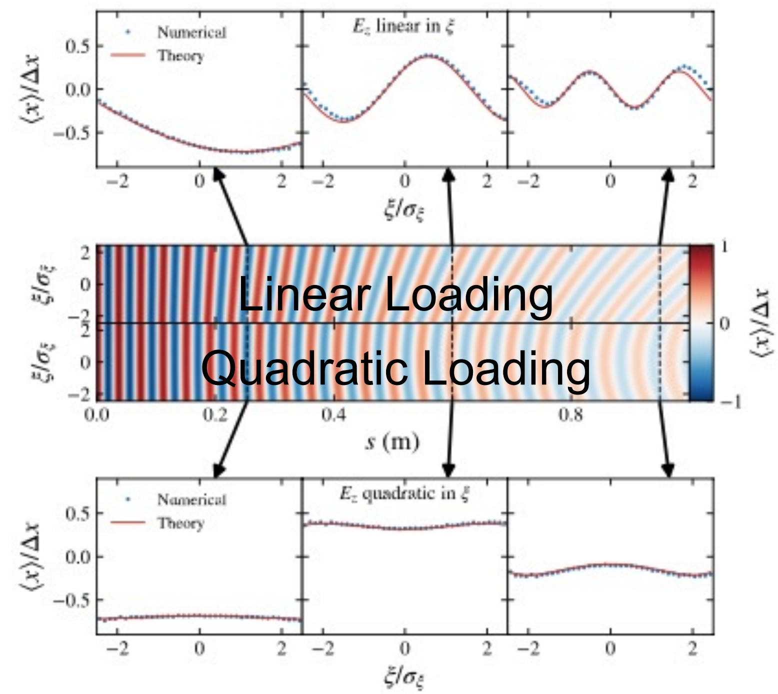
Mismatched Beam



Mismatched Beam   Offset Beam



Longitudinal Slice Evolution



- **See R. Ariniello's talk: Thur. WG4 10:30am**
- R. Ariniello, et al., (accepted PRR 2022) arXiv:2111.02332
- R. Ariniello, et al., Phys. Rev. Accel. Beams 22, 041304 (2019)

Development of Faster, Reduced Codes

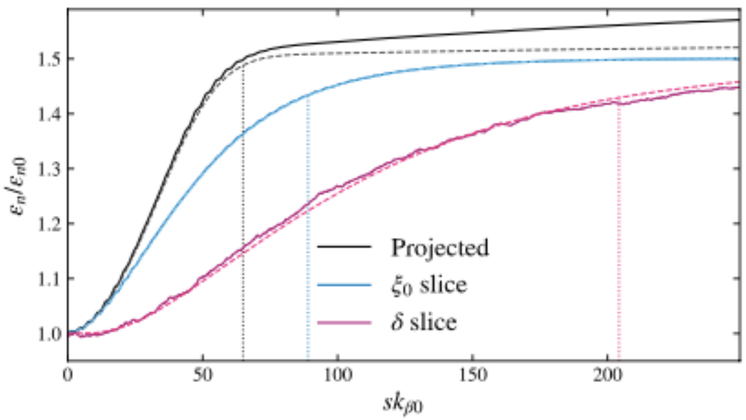
<u>PIC is excellent for many things, but not suitable for all things</u>

Need faster codes based on reduced models to explore parameter space

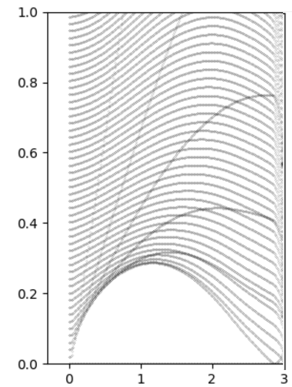
Progress on many individual fronts

Goal: create integrated framework

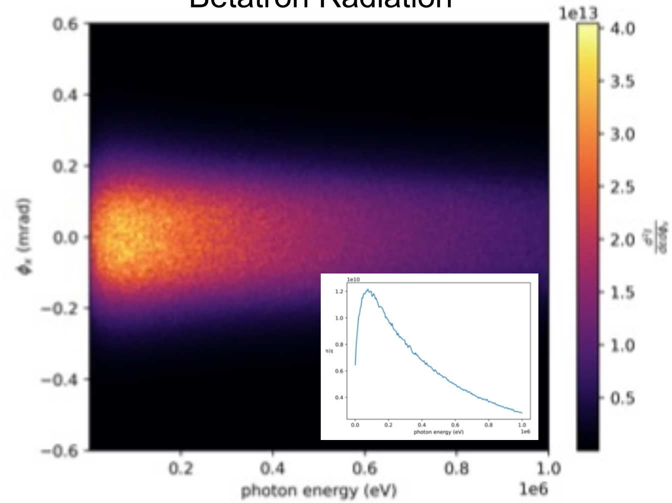
Emittance Evolution



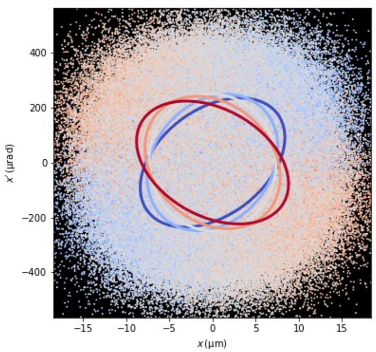
Wake Formation & Loading



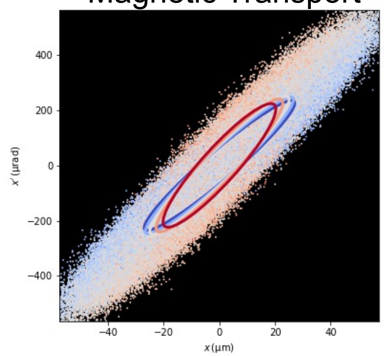
Betatron Radiation



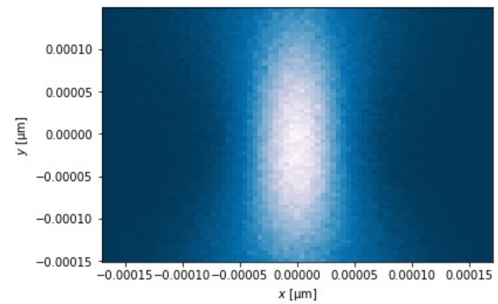
Plasma Exit



Magnetic Transport

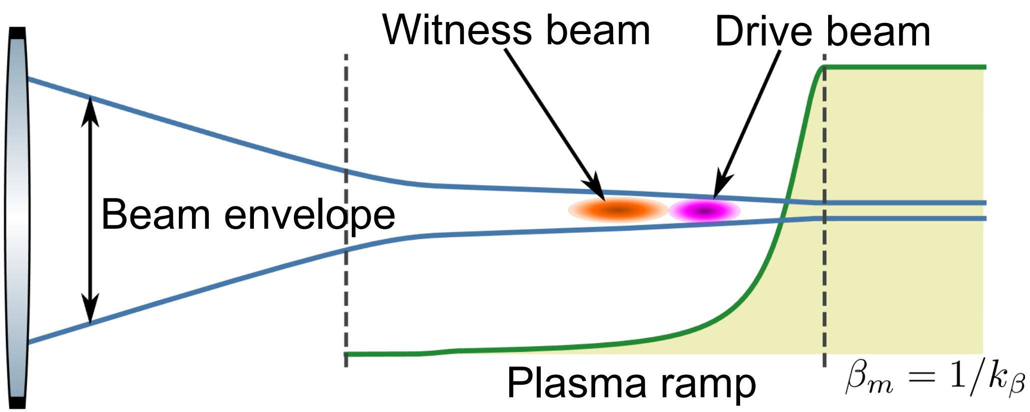


Imaging Spectrometer
Screen Profile

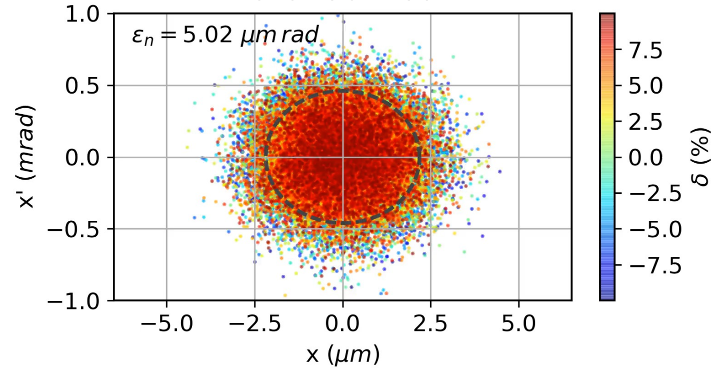


Design of Plasma Source

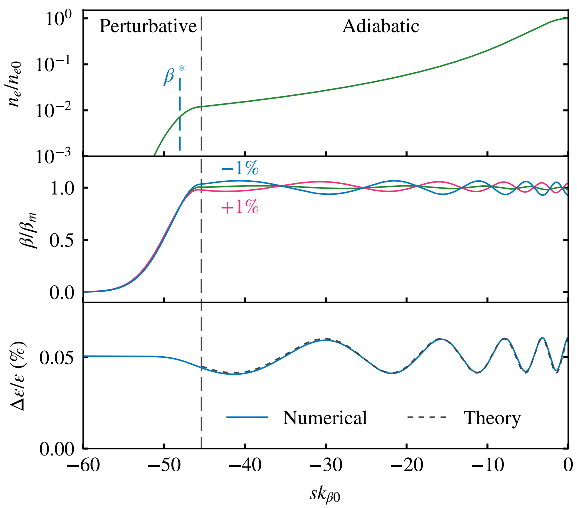
Must acheive beam matching – Requires appropriate density ramp



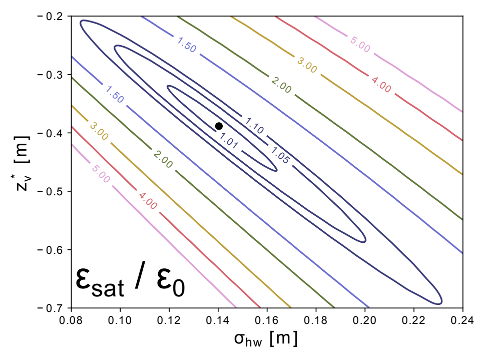
Matched Beam



Evolution in Ramp

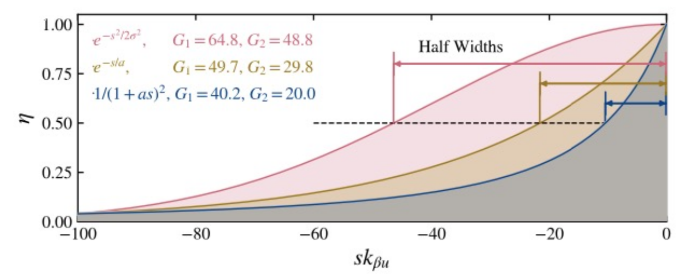


Ramp Shape Tolerance



Ideal ramp:

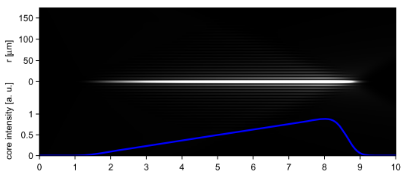
- Short perturbative section followed by adiabatic section
- Beam aberrations scale with integrated density of ramp



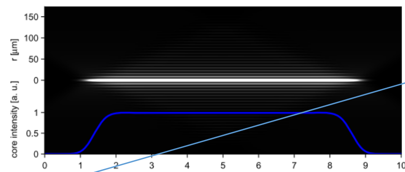
Optical Shaping of Ionization Laser Beam

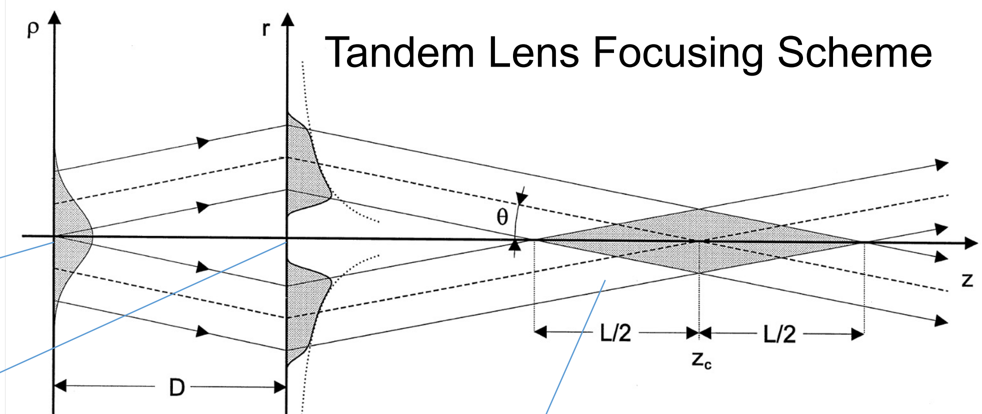
From this... *to this!*

Axicon

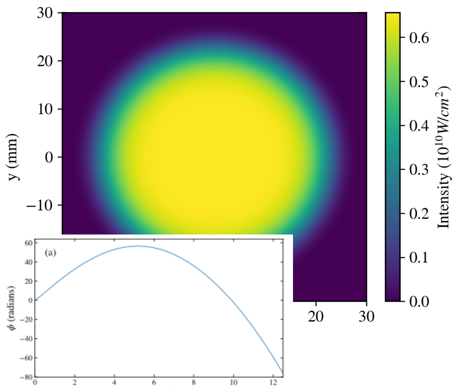


Tandem Lens Scheme

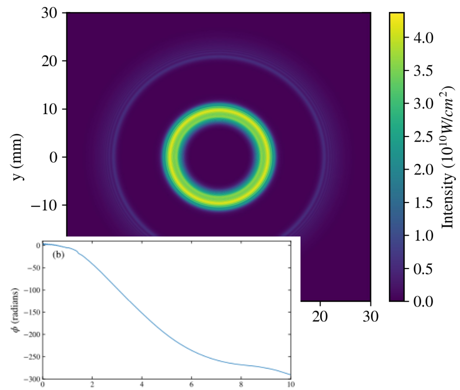




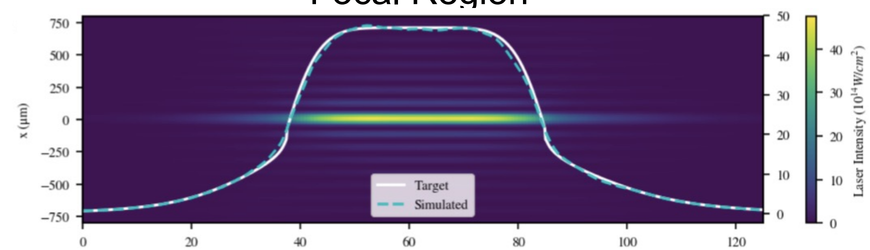
Intensity at Lens 1



Intensity at Lens 2



Intensity Along Focal Region

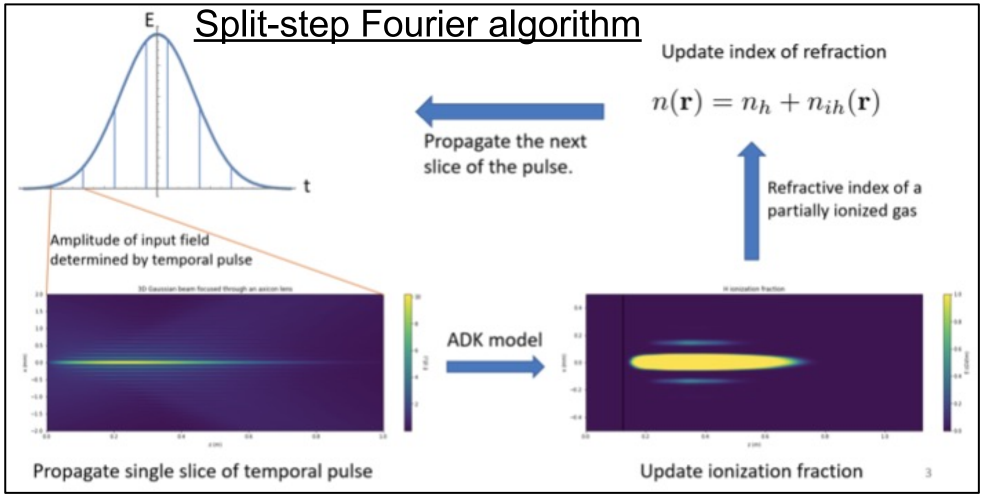


<u>Tandem pair of diffractive lenses used to provide special focusing of laser</u>

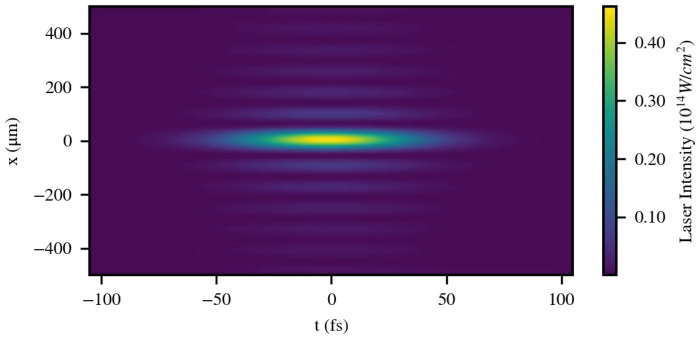
- First lens used to shape radial intensity profile (make donut beam)
- Second lens removes residual phase and add axicon-like focus

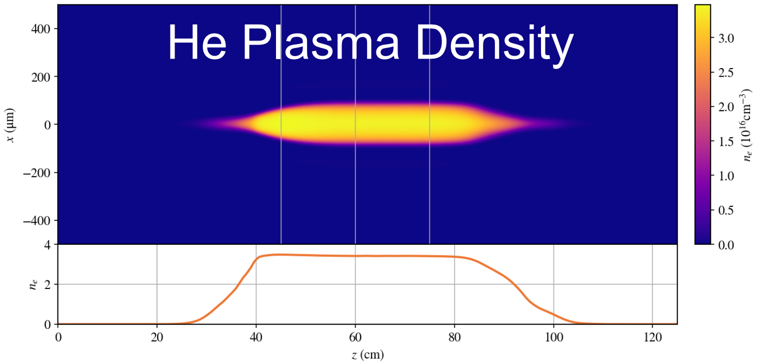
Developed custom split-step Fourier code to simulate...

- Propagation of laser after arbitrary phase manipulation (e.g. diffractive lenses)
- Time-slice resolved ionization of gas
  - performed deep dive into ionization models (ADK, PPT, TDSE models)
- Time-slice resolved refractive response to plasma formation
- Found that plasma refraction can be advantageous, widening plasma filament



Wider plasma due to refraction





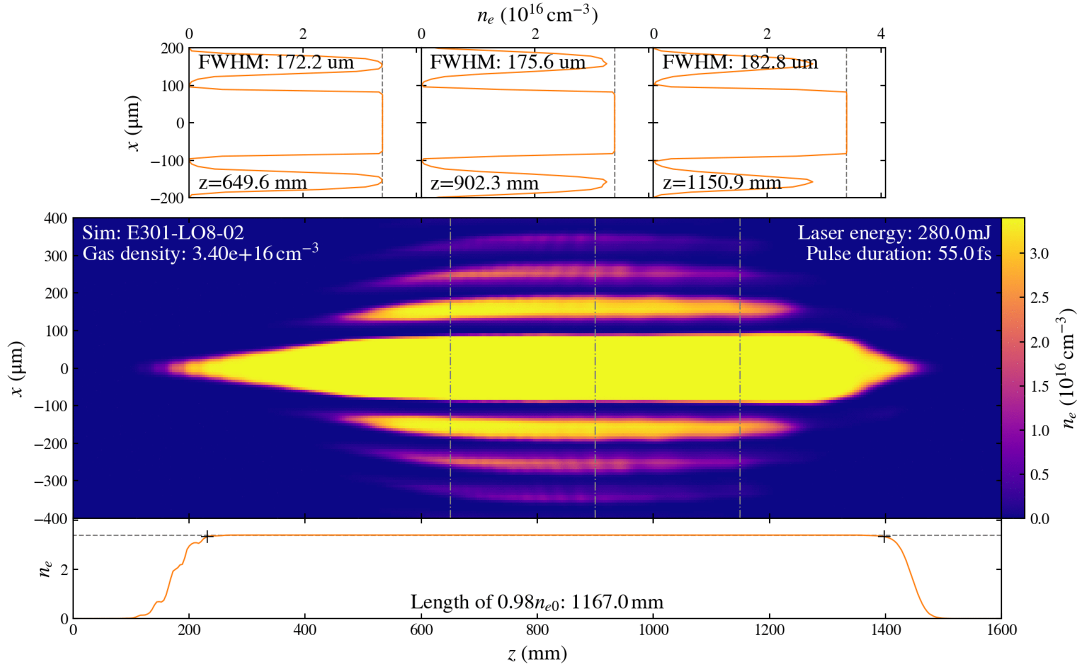
Laser Ionization of Unconfined Gas Plasma Source

Gas Parameters
Gas species: H2
Gas density: 1.70e16-4.5e16 cm^{-3}
Gas profile: Filled chamber
Gas pressure: 0.52-1.37 Torr

Laser Parameters
Main-amp output: 800mJ
Pulse duration: 55fs FWHM
Wavelength: 800nm
Beam size (w0): 20.24mm
Beam profile: Super-Gaussian

Laser Energy
Energy after optics: 276mJ
Energy to ionize: 6.96-20.12mJ

Simulated Hydrogen Plasma Profile
Gas Density Scan: 3-9x10^{16} cm^{-3}

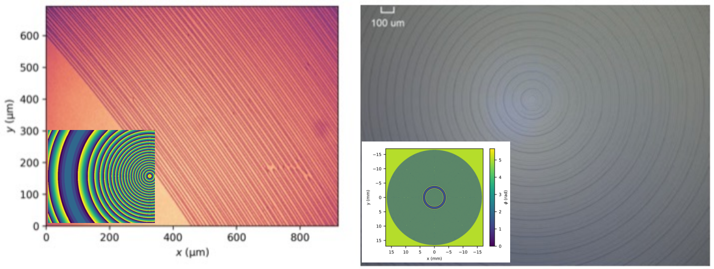


Nominal density: ~3x10^{16} cm^{-3} → Good profile; not too much refraction

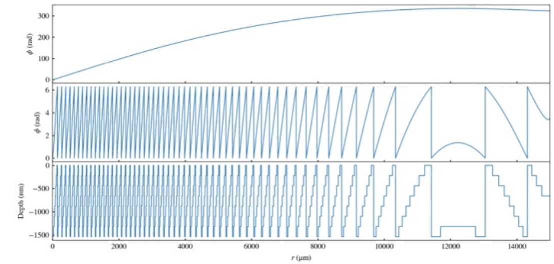
Optical Bench Test of Diffractive Optics at CU

R. Ariniello

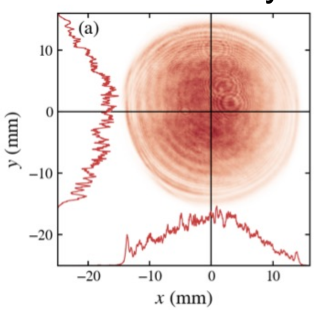
Diffractive Lenses



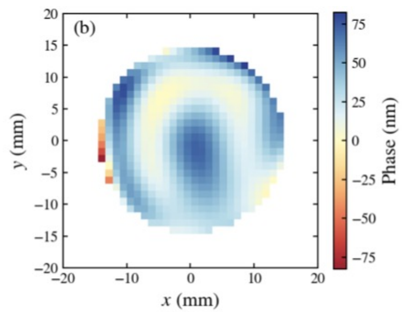
Nano-Etch Profile



Init. Intensity

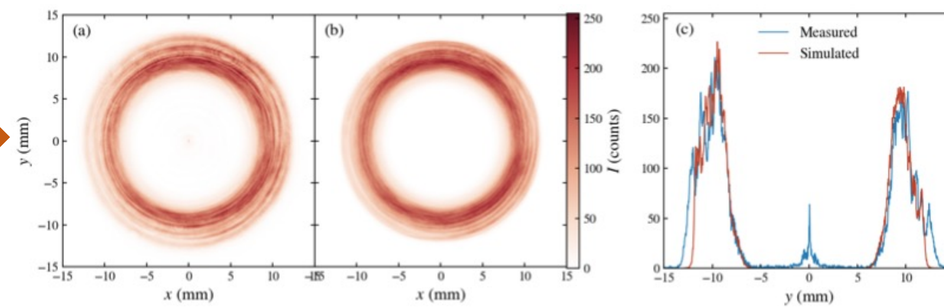


Init. Phase

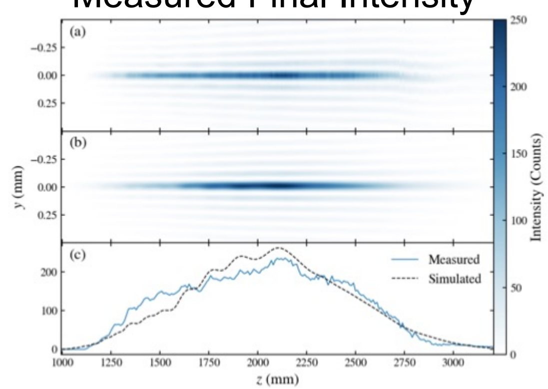


Measured Int.

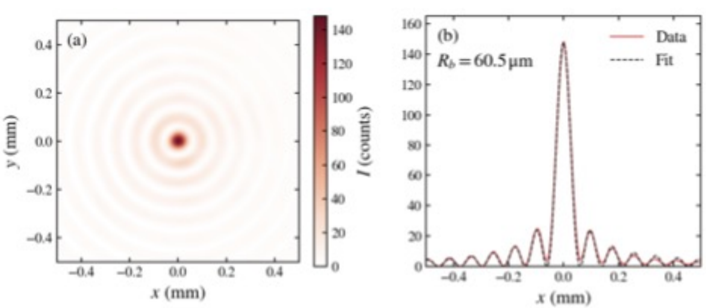
Sim. Int.



Measured Final Intensity

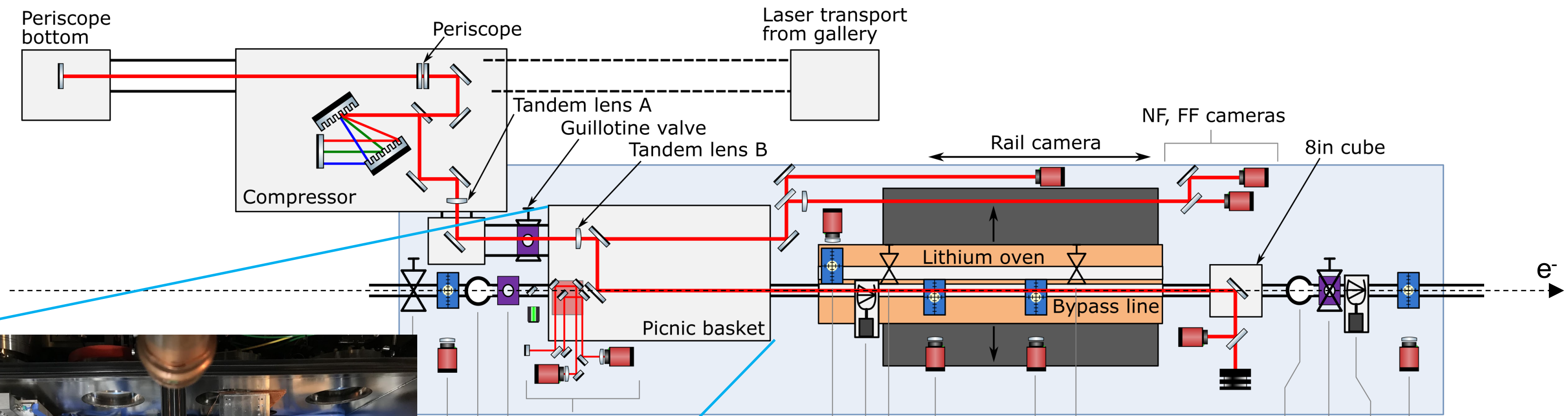


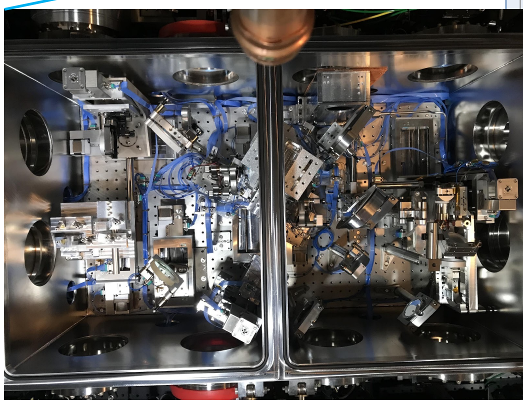
Measured Bessel Int. Profile



Low intensity optical tests showed ideal performance of diffractive lenses

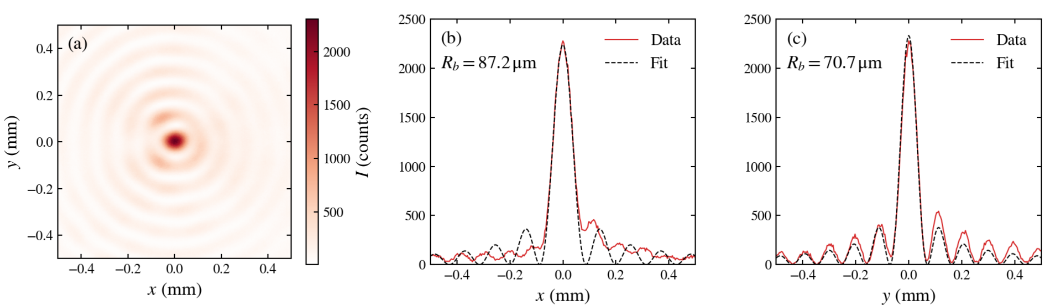
First E301 Plasma Test at FACET-II



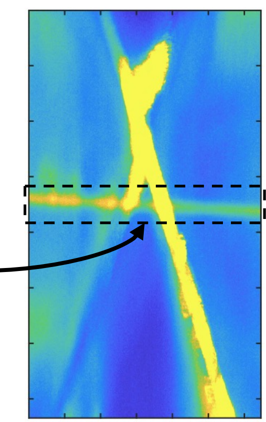


Tandem lens pair installed at FACET-II
First plasma test was on Oct. 27th
Plasma made: moderate success(!)

Measured Bessel Profile at FACET-II



First Plasma from Tandem Lens Pair(!)



Summary and Future Outlook

E301: PWFA using laser-ionized, unconfined gas plasma source

- Developed theory and simulations to study problem, design plasma source
- Laser-ionized gas: can optically control plasma density profile
- Rapid tuning, high repetition rate (10 Hz vs. 1 Hz)
- Well suited for basic research and emittance preservation demonstration
- Custom optics tested and installed at FACET-II
- Prepared for commissioning with single-bunch e-beam

Future Outlook

- PWFA commissioning & initial data planned for 2023 (1 & 2 bunch)
- Emittance preservation in unconfined gas (~2023-2024)
  - ~10 mm-mrad
- Switch to laser-ionized elongated gas jet (~2024-2025)
  - ~1 mm-mrad

E-301 Collaboration

UCLA: C. Joshi's group

SLAC: FACET-II group

Stony Brook: N. Vafaei-Najafabadi's group

Ecole Polytechnique: S. Corde's group

University of Oslo: E. Adli's group

University of Colorado Boulder: M. Litos's group

Thank you very much!