

FACET-II Workshop: Laser Ionized Gas Plasma Source

SLAC, Oct. 17, 2016

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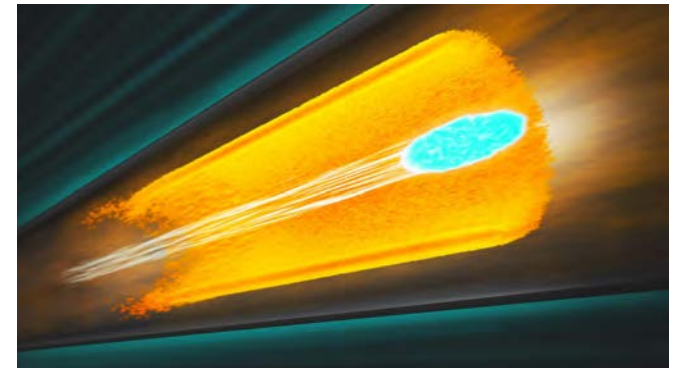


Physics Goals for Future Plasma Sources

- Emittance preservation & positrons

- DOE Advanced Accelerator Development Strategy Report (2016):
“The two areas of beam-plasma physics considered most pressing for research in the next decade are emittance preservation and positron acceleration.”

Hollow Channel e⁺ PWFA



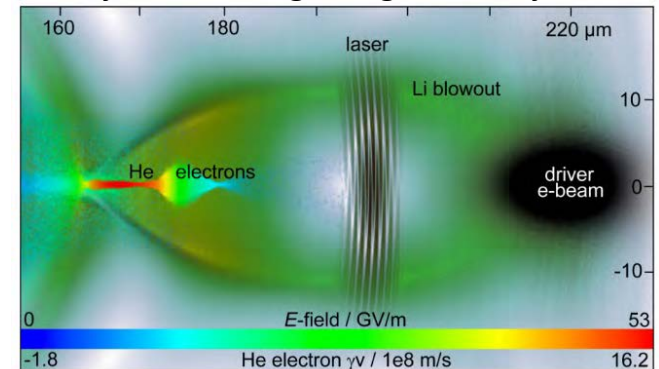
- Controlled injection & acceleration

- Injection in plasma for high-brightness beams
- Lead to first applications for PWFA

- Basic PWFA physics

- Precision scans of plasma parameters
- Observe linear-to-nonlinear transition
- Provide simulation benchmarks

Trojan Horse High-Brightness Injector

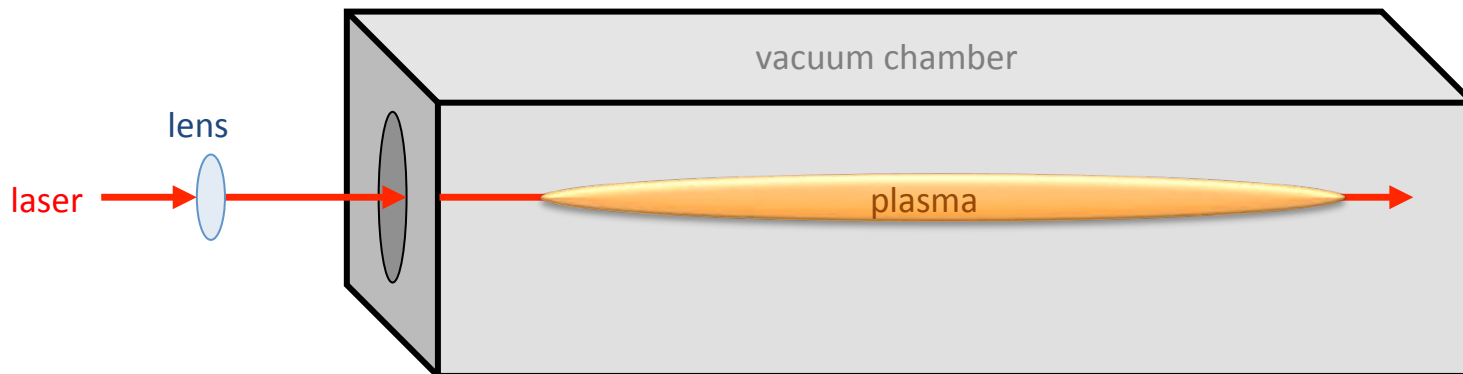


B. Hidding, et al., *Phys. Rev. Lett.* **108** 035001 (2012)



Laser-Ionized Gas Plasma Source

- Vacuum chamber of arbitrary volume
- Static fill of room temperature gas, e.g. H₂ or Ar
- Gas ionized by high intensity laser pulse
 - Not too high! Don't drive wake!
 - Gas won't be ionized by e-beam
- ***Entirely optically determined plasma density profile***

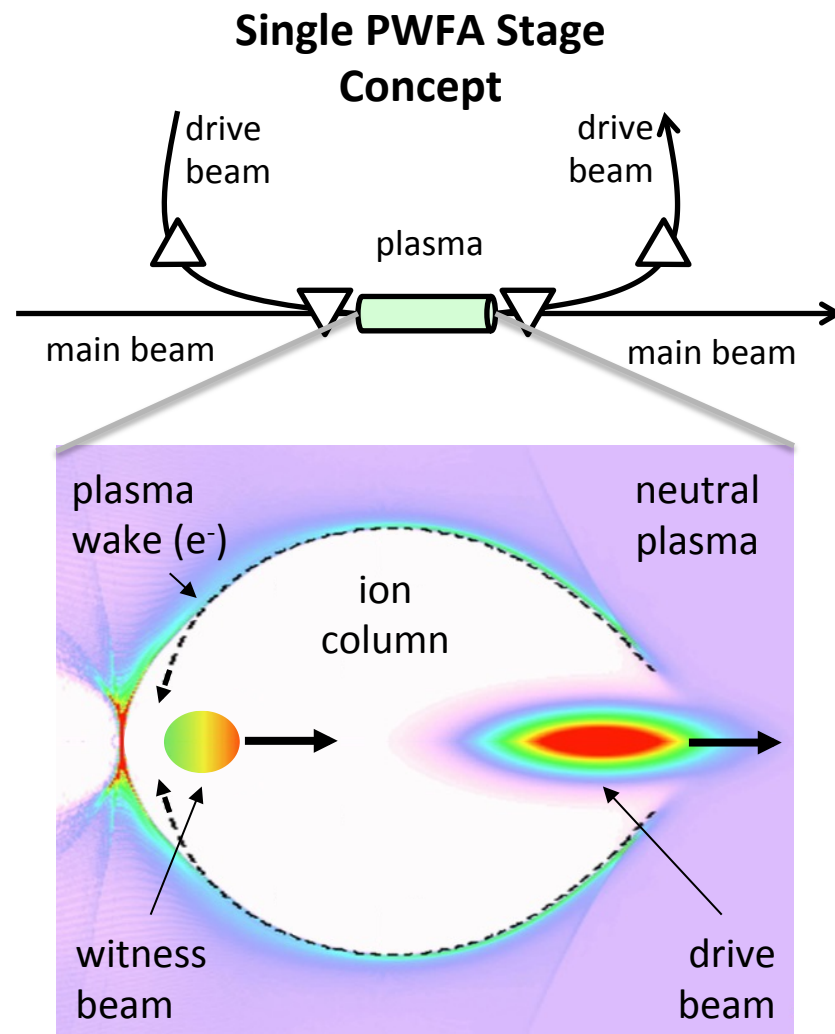




Uniform Density Laser-Gas Plasma Source

Ideal for 2-bunch PWFA in nonlinear regime

- ~ 10 GeV/m $\rightarrow n_e \approx 10^{16}$ - 10^{17} cm $^{-3}$
- ~ 10 - 30 GeV per stage \rightarrow length ≈ 1 - 3 m
- $c/\omega_p \approx 50$ - 150 μ m \rightarrow diameter ≈ 0.5 - 1 mm
- precise ramp profile for emit. preservation
- flat acceleration region for high E-gain
- low temperature plasma
- “fresh” plasma on every shot

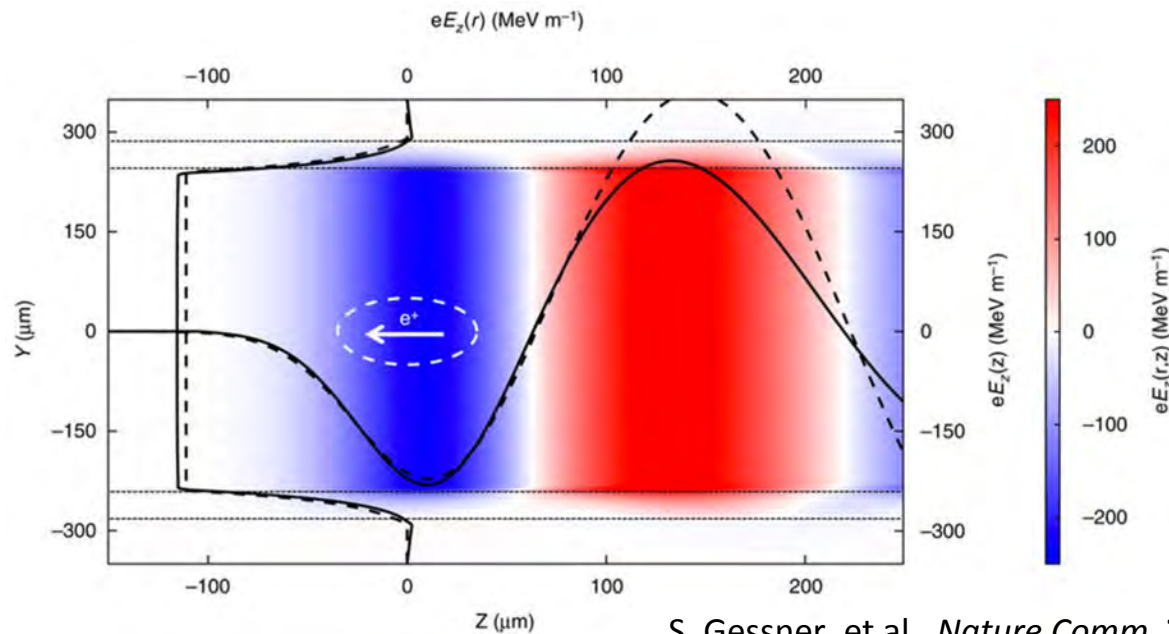




Hollow-Channel Laser-Gas Plasma Source

Ideal for positron acceleration

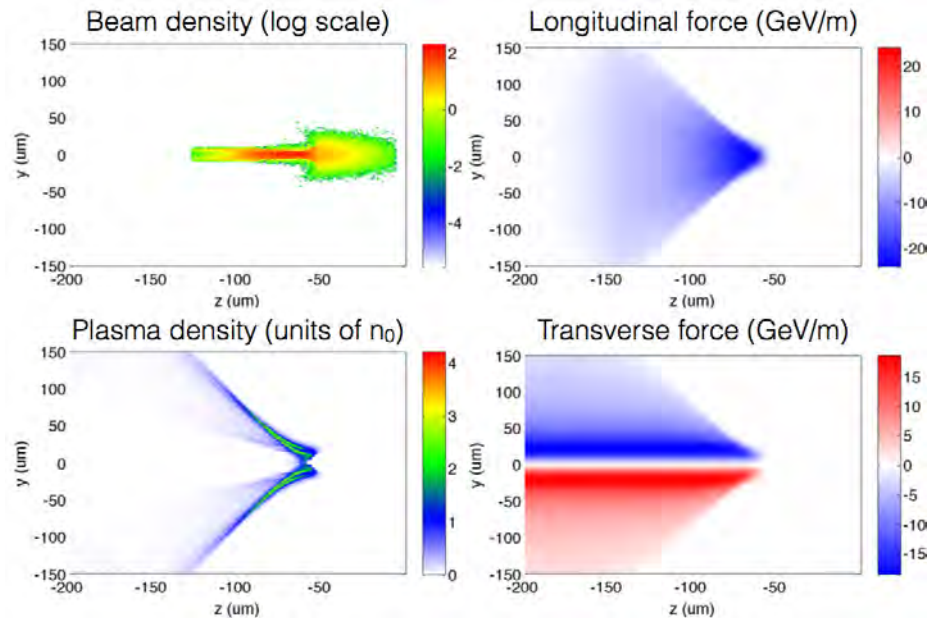
- Thin annulus of ionized gas
- Non-ionized gas in center of channel
- Longitudinal E-field uniform in r
- No focusing forces (no ion channel)
- Not defocusing for positrons (unlike nonlinear blowout)
- Allows electron drive beam for positron acceleration
- Demonstrated at FACET
- See S. Gessner's talk



S. Gessner, et al., *Nature Comm.* **7** 11785 (2016)



Narrow-Channel Laser-Gas Plasma Source



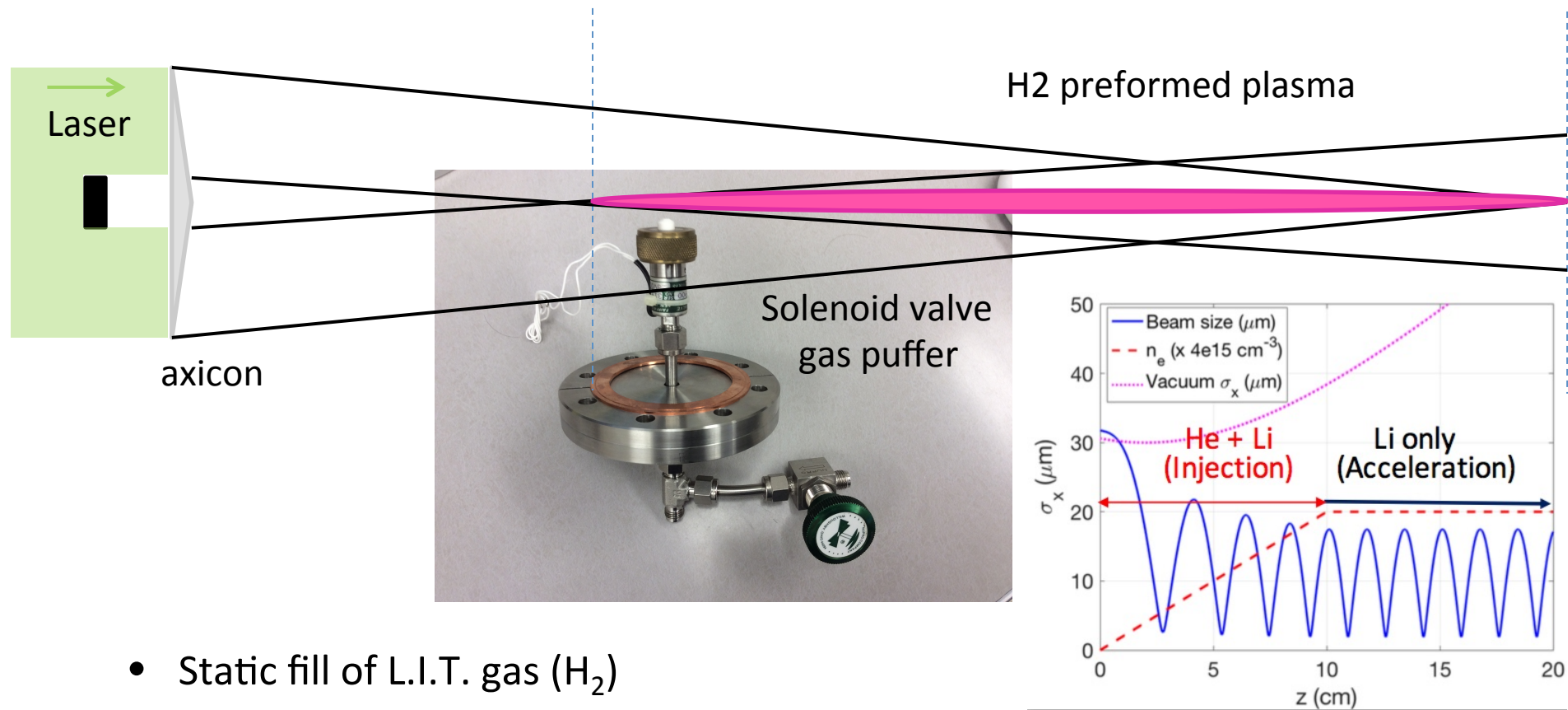
figs. from W. An; see also W. An, et al., *Phys. Rev. ST-AB* **16** 101301 (2013)

Ideal for plasma undulator

- Thin column of ionized gas: $r_p \ll R_b$
- Drive beam expels electrons “never to return”
- Creates “wakeless” ion column
 - no acceleration/deceleration
 - no induced energy spread
- Linear focusing fields in ion column
- See J. Rosenzweig’s talk



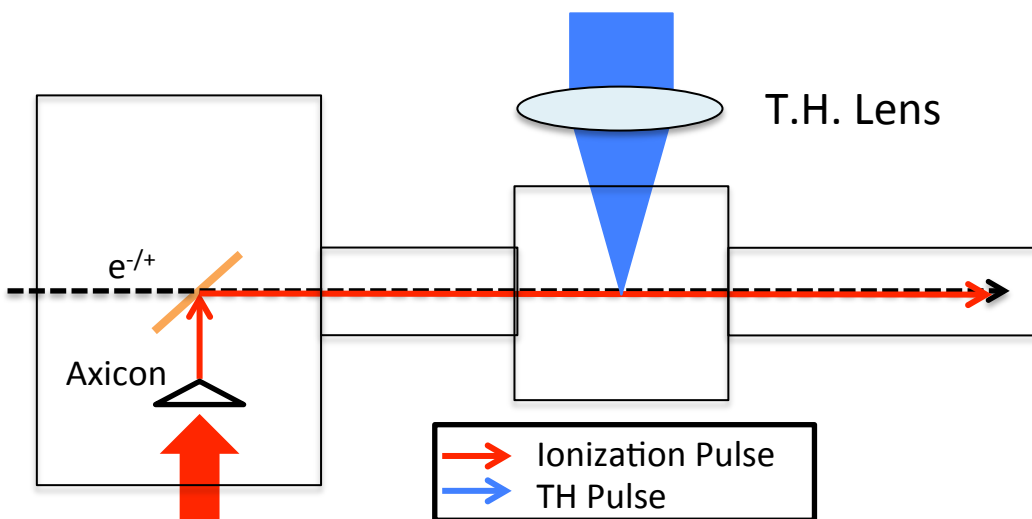
Ionization Injection



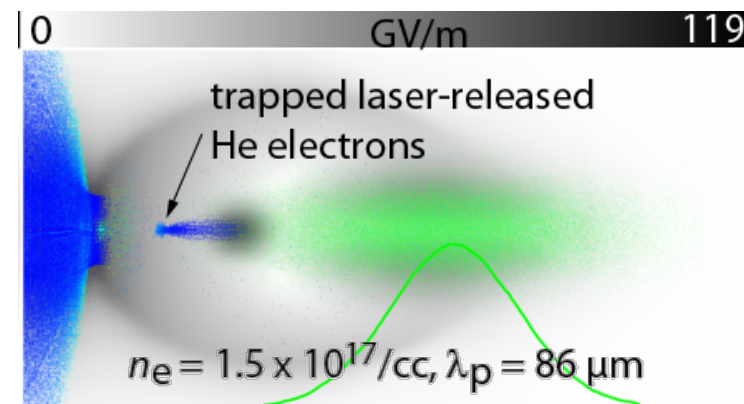
- Static fill of L.I.T. gas (H_2)
- Localized H.I.T. gas jet (He)
- Main laser pulse ionizes L.I.T. gas to form main PWFA plasma column
- **Betatron pinch of drive beam ionizes H.I.T. gas over short distance**
→ high-brightness beam



Trojan Horse Injection



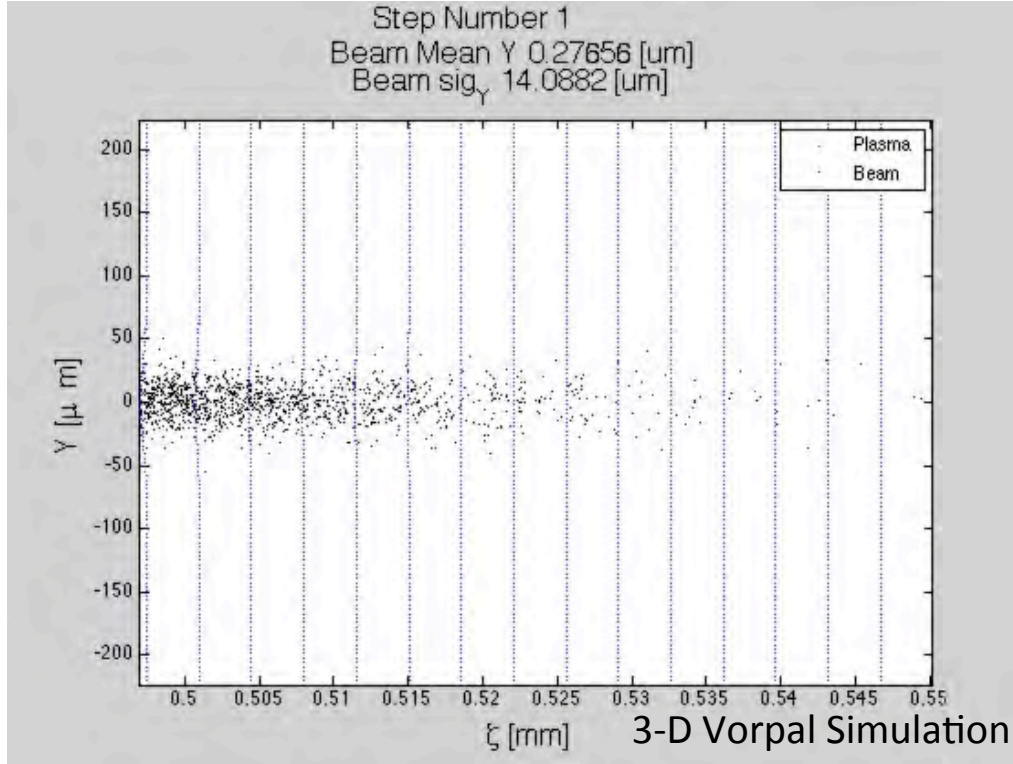
Trojan Horse Injection



- Static fill of L.I.T. gas (H_2) and H.I.T. gas (He) mixture
- Main laser pulse ionizes L.I.T. gas to form main PWFA plasma column
- **Well timed T.H. laser pulse focused into the middle of the plasma wake ionizing H.I.T. gas \rightarrow high-brightness beam**



Transverse Injection



- Wide-to-narrow plasma transition
- Rapid decrease in ion channel radius to $r_{\text{ion}} < R_b$ slows phase velocity of the rear of the wake (like density downramp)
- **Plasma electrons injected into wake from the side**
→ **high brightness beam**



Advantages

1. Profile determined with optical precision and resolution
2. Rapid profile manipulation
3. Highly accessible for diagnostics
 - large chambers
 - large apertures
 - room temp.
4. Multi-gas species for injection
5. Hollow-channel plasma source (positrons)
6. Narrow-channel plasma source (“wakeless”)
7. Readily upgradeable: just add or improve optics

Challenges

1. At mercy of laser
 - pointing jitter
 - energy jitter
 - phase front
 - intensity profile
 - etc.
2. Must compensate for ionization defocusing of laser
3. Complex and tedious plasma source compared to others



Finding an Optimal Plasma Profile

1. Hill's equation
$$\frac{d^2 x}{dz^2} + f(z) k_{\beta_0}^2 x = 0$$

2. Choose density function
$$f(z) = \frac{1}{\left(1 - \frac{z-L}{l}\right)^2}$$

3. Solve evolution of CS parameters $\beta_l(z), \alpha_l(z)$

4. Minimize saturation emittance to optimize l

$$\frac{\epsilon_{n,sat}}{\epsilon_{n,i}} = \frac{1}{2} \left(\frac{\beta_0}{\beta_l(L)} (1 + \alpha_l(L))^2 + \frac{\beta_l(L)}{\beta_0} \right)$$

See X. Xu, et al., *Phys. Rev. Lett.* **116** 124801 (2016)

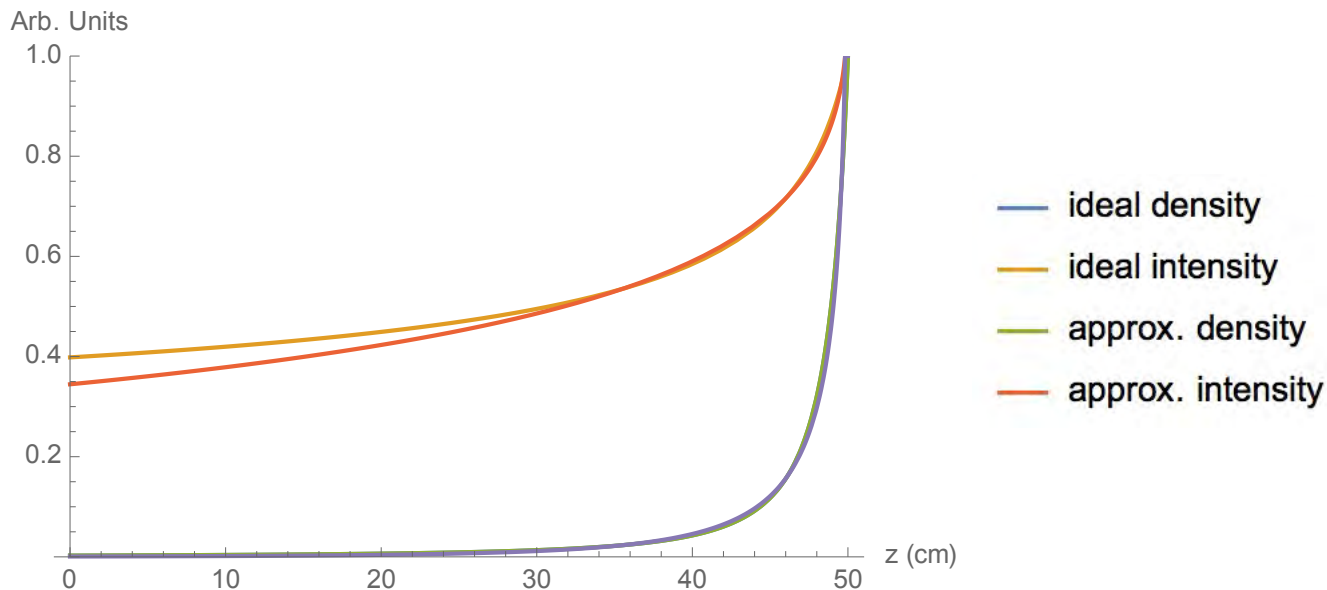


Laser Intensity Profile

Use Experimental Parameters:

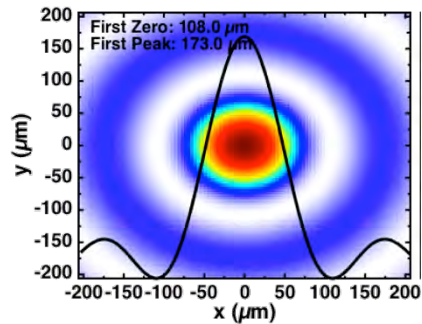
- plasma density: $n_0 = 10^{16-17} \text{ cm}^{-3} \rightarrow k_{\beta 0}^{-1} = \beta_{\text{target}} \approx 5 \text{ mm}$
- e-beam: $E = 10 \text{ GeV}, \beta_i \approx 10 \text{ cm}$
- ramp length: $L = 50 \text{ cm} \rightarrow$ matching solution: $l = 2.6 \text{ cm}$
- Use ADK to find laser intensity profile
- Near perfect profile with generalized Gaussian:

$$I(z) = I_0 A e^{-\left(\frac{|z-L|}{Cl}\right)^B} \quad I_0 = 4 \times 10^9 (E_i[\text{eV}]^4 / Z^2) \text{ W/cm}^2$$

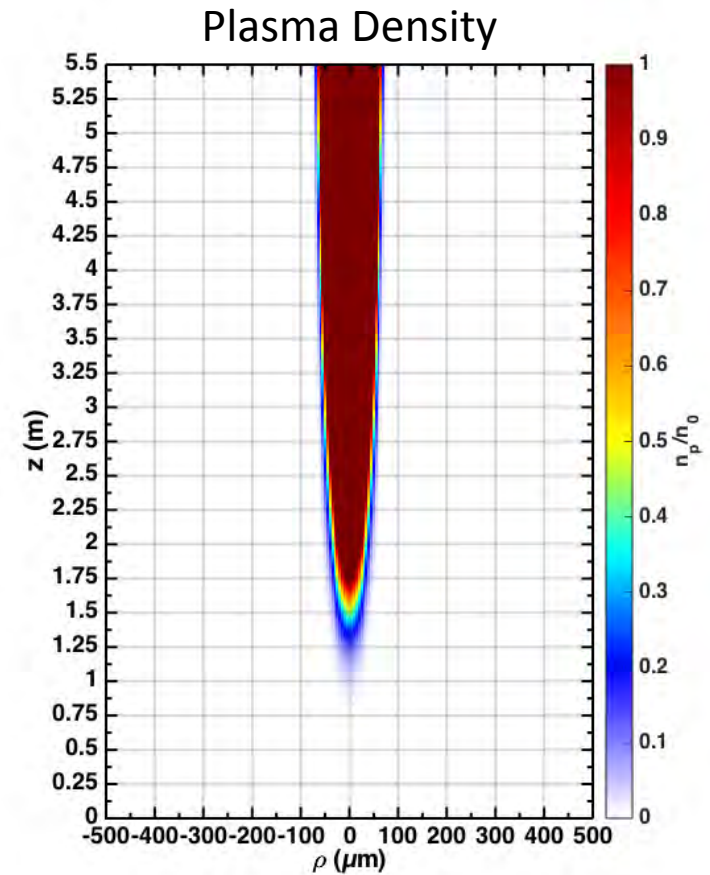
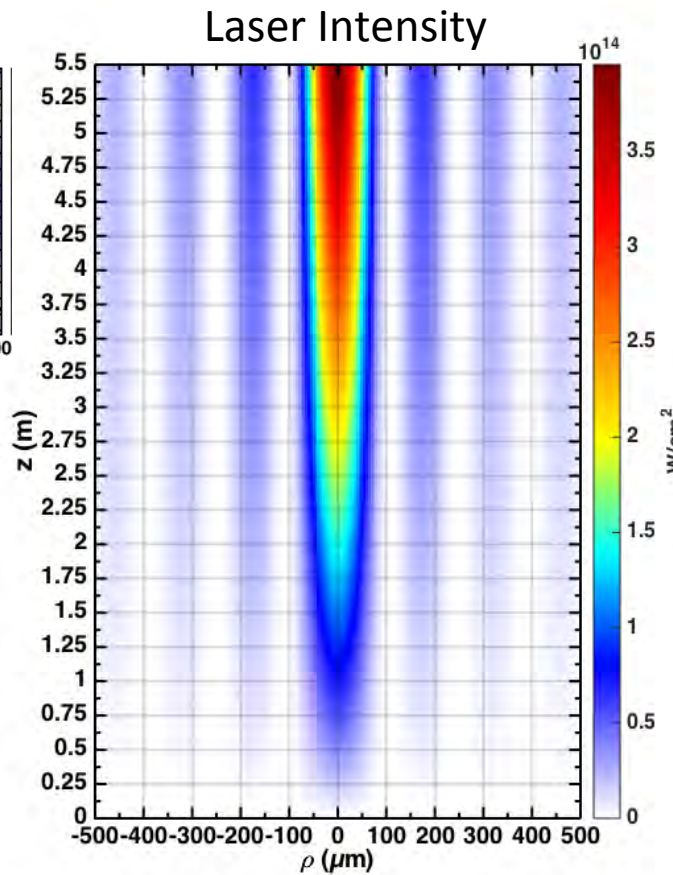




Ionization Profile from Bessel Beam Laser



Bessel beam
generated by
axicon lens

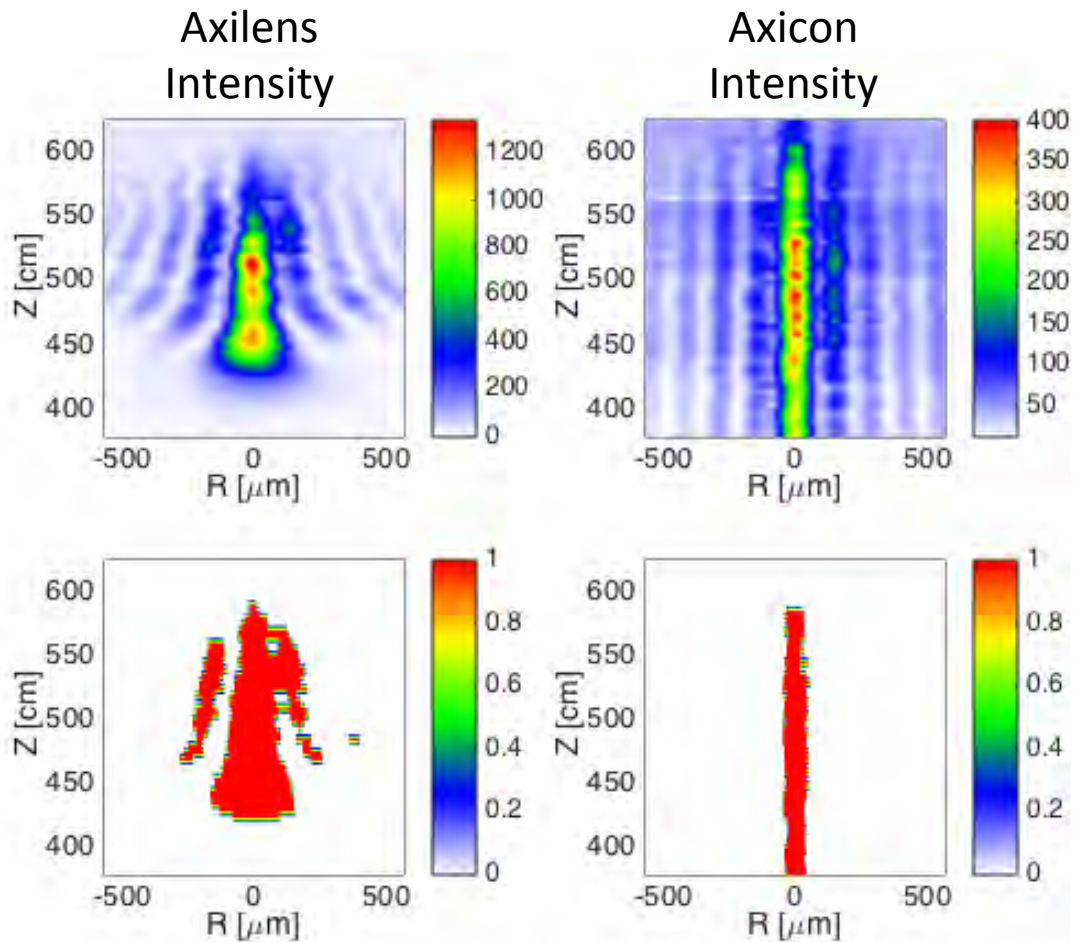


Numerical modeling of ionization rate of hydrogen for laser pulse focused by an axicon lens using ADK.



Sophisticated Phase Manipulation

- **Axicon (refractive optic)**
 - simple
 - cheap
 - higher tolerance to aberrations
 - low efficiency of laser energy usage
 - fine for Li oven
- **Axilens (diffractive optic)**
 - complex
 - expensive
 - sensitive to aberrations
 - higher efficiency of laser energy usage
 - shorter throw than axicon
 - better than axicon for gas





Even More Sophisticated Phase Manipulation

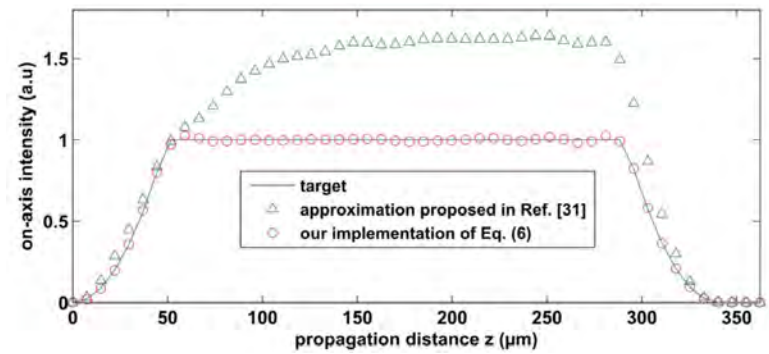
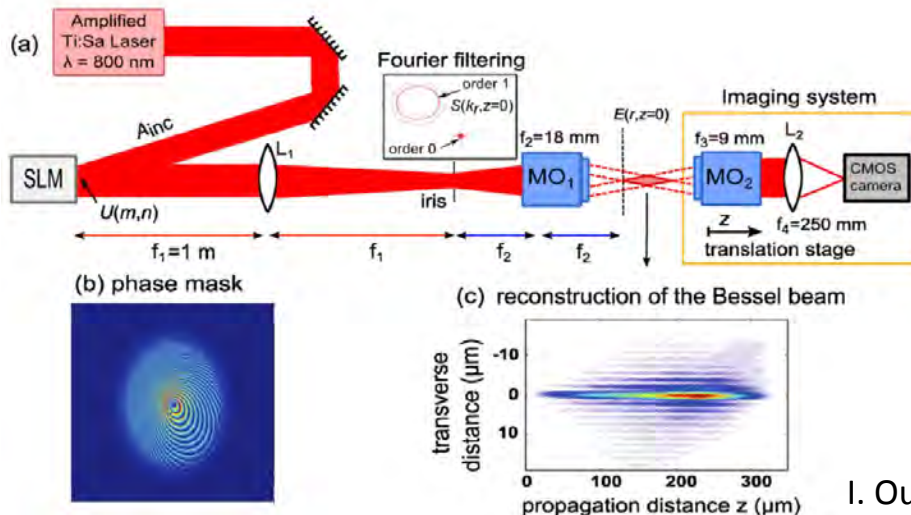
Calculation Method:

Huygens-Fresnel integral to calculate propagation of phase front (forward or backward):

$$u(x, y, z) = \frac{i}{(z - z_0)\lambda} e^{-\frac{i\pi r^2}{(z-z_0)\lambda}} \iint_{-\infty}^{\infty} u_0(x_0, y_0, z_0) e^{-\frac{i\pi r_0^2}{(z-z_0)\lambda}} e^{-\frac{i2\pi(xx_0+yy_0)}{(z-z_0)\lambda}} dx_0 dy_0$$

Experimental Method:

Adaptive optics (deformable mirror) + custom diffractive optic (kinoform) to manipulate phase.

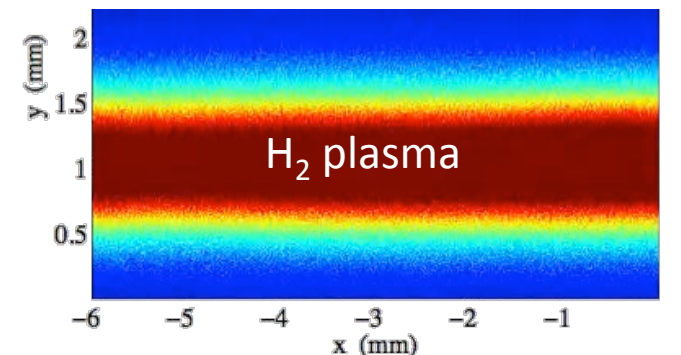
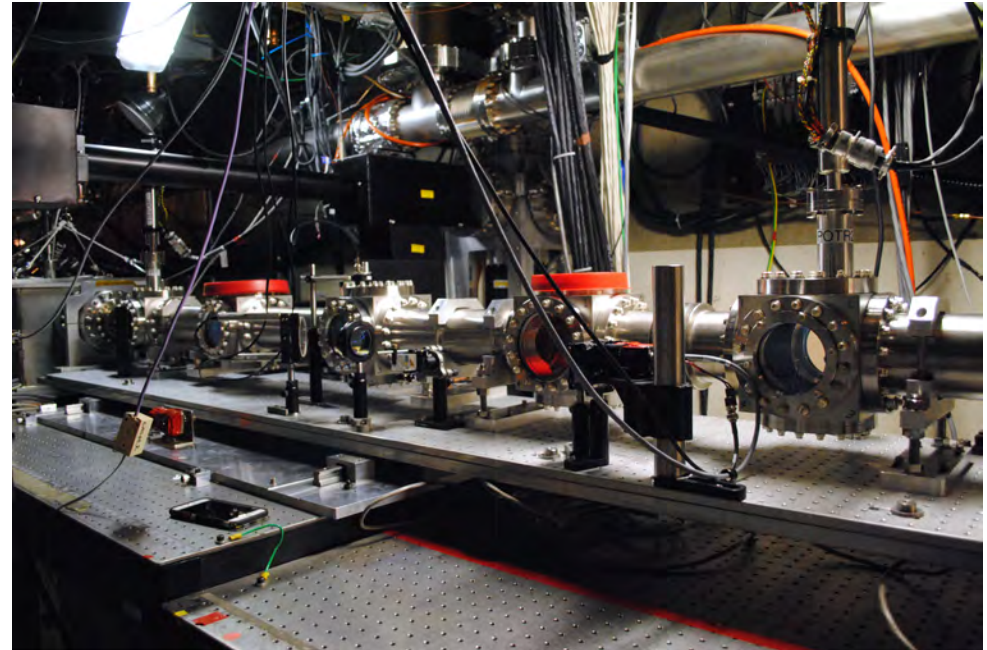


I. Ouadghiri-Idrissi, et al., *Opt. Express* **24** 11495 (2016)



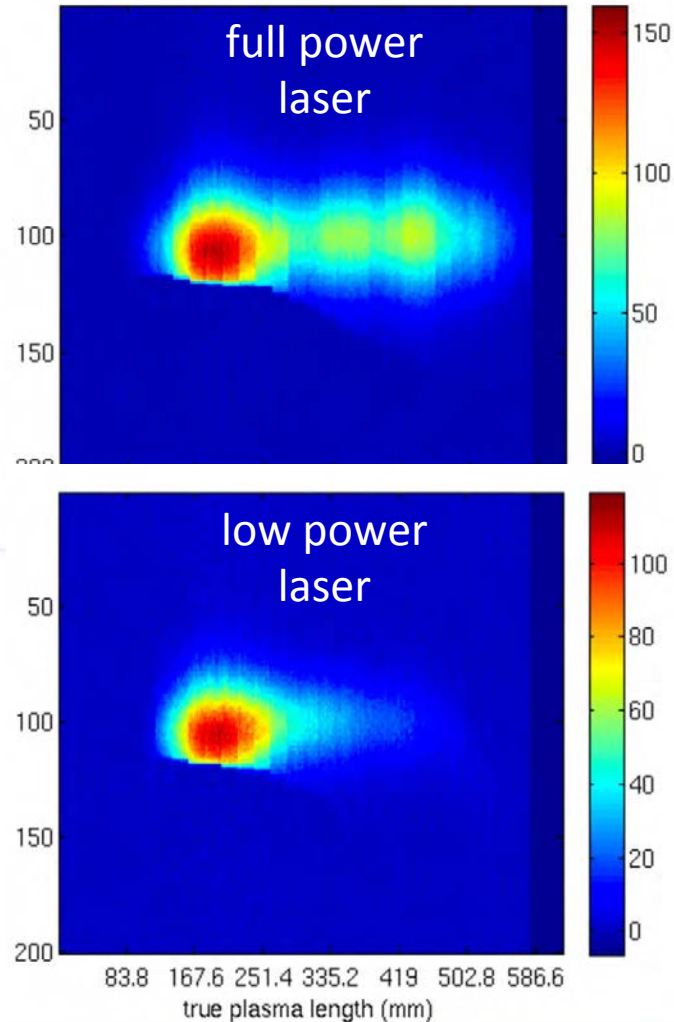
Laser-Gas Plasma Source at FACET

- Experimented with laser-gas plasma source in 2014-2016
- Original motivation: hollow-channel
- Basic setup:
 - H_2 gas at 0.1-20 Torr
 - <10 TW laser pulse
 - kinoform focusing optic
- Successes:
 - Trojan Horse / Plasma Torch [B. Hidding, et al. forthcoming]
 - e-beam attraction to plasma column [E. Adli, et al., *New J. Phys.* **18** 103013 (2016)]
- Failure: “vanilla” 2-bunch PWFA
- **Mixed results; much learned**





Challenges Encountered at FACET



- “Lumpy” plasma column often observed
- Hard apertures detrimental to phase
 - axilens mask
 - holed mirror
- Ionization defocusing from plasma
- Complex H₂ ionization dynamics

Must account for above effects in baseline design of laser-gas plasma system



Plasma Diagnostics

- **Phase contrast imaging**
 - precision measurement of plasma width
 - image of plasma wake itself
 - *See M. Downer's talk*
- **Gated camera**
 - direct observation of plasma light with >2 ns gate
 - plasma length, uniformity
- **Spectroscopic analysis**
 - broadening and shift of lines give plasma density
 - multi-species analysis

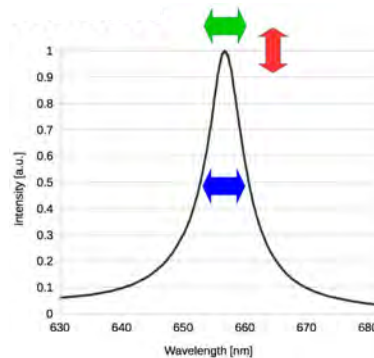
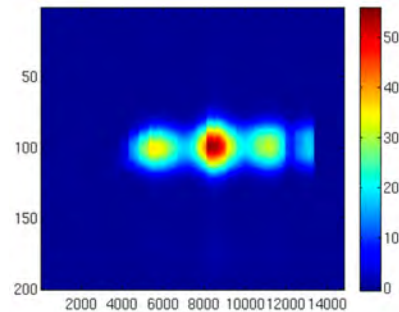
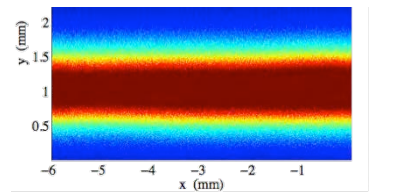
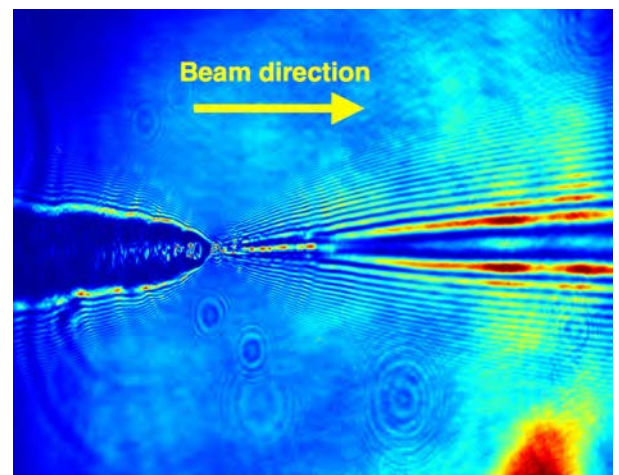
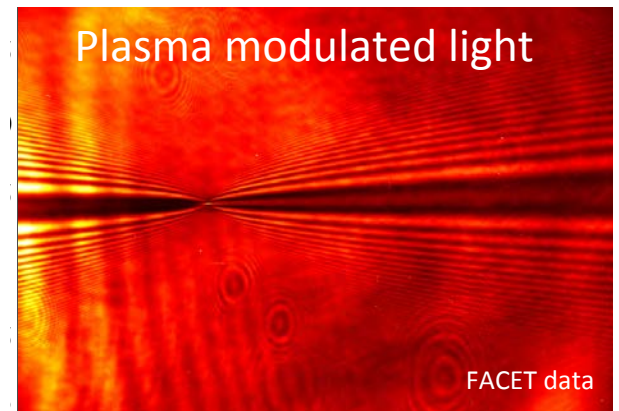


fig. from L. Goldberg





Numerical Modeling and Simulation

- First pass design with numerical calculations using “simple” models of laser propagation
- Simulations required for more realistic prediction of ionization process
- Simulations also needed to predict PWFA behavior for plasma source
- Tech-X has begun work with B. Hidding’s group on ionization dynamics with V-Sim (Vorpal)
- V-Sim (Vorpal) already has PWFA capabilities, and can be optimized for other scenarios (injection, etc.)
- Experiments will provide feedback for model restrictions
→ Simulations will then provide updated target parameters



- I. Initial commissioning with single beam**
 1. basic PWFA physics studies
 2. hollow-channel commissioning
 3. narrow-channel commissioning
- II. Two bunches from primary photo-injector: $\sim 10 \mu\text{m} \times 10 \mu\text{m}$ emittance**
 1. first emittance preservation studies
 2. hollow-channel physics studies
 3. narrow-channel physics studies
- III. Witness bunch from secondary photo-injector: $\sim 1 \mu\text{m} \times 1 \mu\text{m}$ emittance**
 1. PWFA staging studies: preserve emittance of witness beam with mismatched drive beam
- IV. Witness bunch injected into plasma wake: $\sim 0.1 \mu\text{m} \times 0.1 \mu\text{m}$ emittance**
 1. clean, controlled injection demonstration
 2. emittance preservation with application parameters
 3. clean, controlled transfer to radiation generation stage



Summary

- **Laser-gas plasma source addresses many challenges of PWFA:**
 - emittance preservation (optical shaping of ramps)
 - positron acceleration (hollow channel)
 - radiation generation (narrow channel)
 - bright beam injection (multi-species gas: H.I.T. + L.I.T.)
- **Experiments at FACET revealed several important challenges:**
 - strict control of laser (profile, phase front, etc.)
 - ionization defocusing
 - complicated H₂ ionization dynamics
- **Two-component development strategy at university:**
 1. computational studies (ionization and PWFA)
 2. experimental program (optics, diagnostics, automation)
- **Phased experimental plan for FACET-II:**
 1. single bunch
 2. two-bunches from primary photo-injector
 3. witness from secondary photo-injector
 4. witness from plasma injection



Thanks!

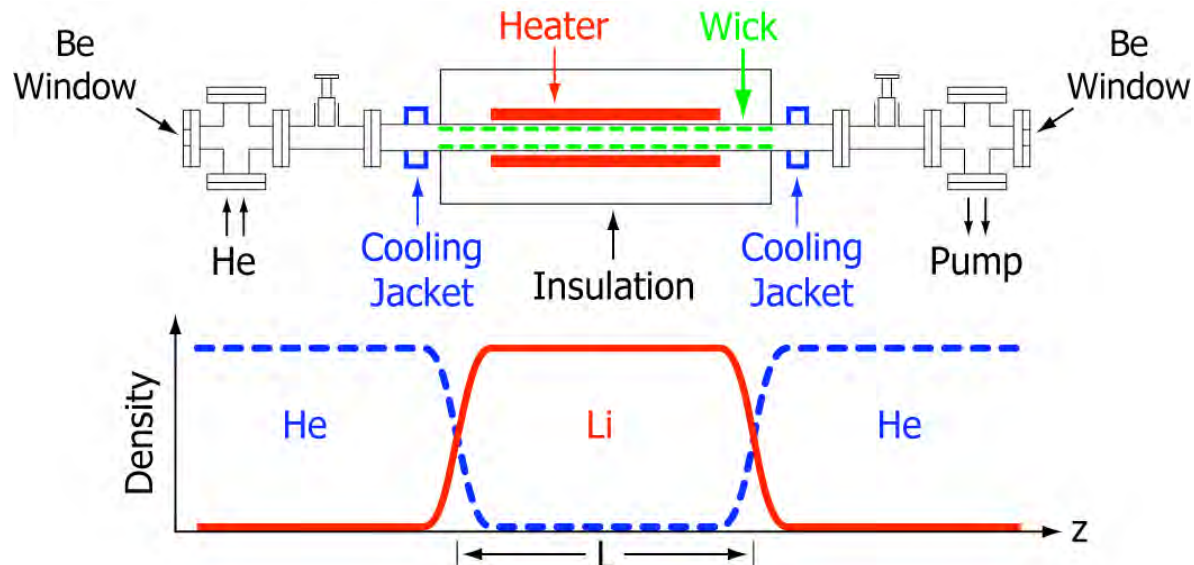
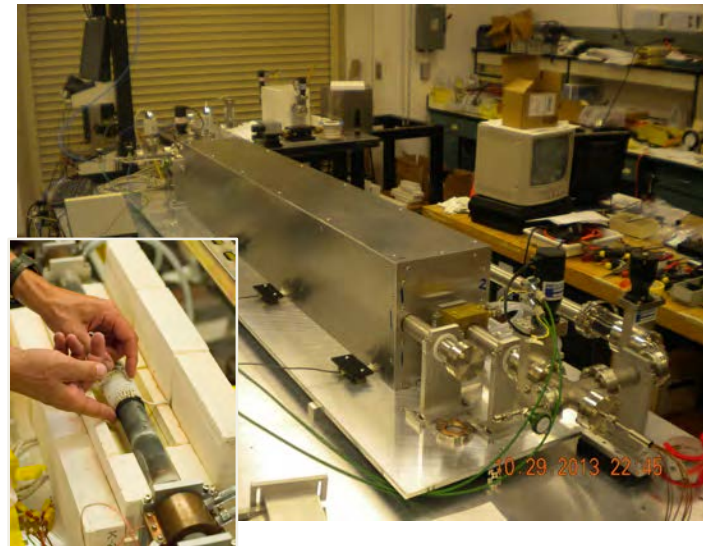


Backup Slides



Plasma Sources Used at FACET: Li Oven

- Workhorse of FACET PWFA program
- Extremely robust & reliable
- Predictable profile
- Challenges encountered:
 - precision control of profile
 - rapid manipulation of profile
 - accessibility / ability to diagnose
 - heating at high rep. rate
- **See C. Joshi's talk**





Laser-Gas Plasma Source Development

- I. Develop plasma source in university laser lab**
 1. Computational component
 - a. simulations of laser-gas ionization process
 - b. simulations of PWFA with plasma source
 - c. best realistic plasma profile for emittance pres.
 - d. corresponding optical parameters
 - e. iterate with feedback from experimental work
 2. Experimental component
 - a. set up adaptive optics with feedback
 - b. design custom optics for final focus
 - c. implement suite of diagnostics for laser & plasma
 - d. develop runtime tech: feedbacks, optimizers
- II. Replicate the whole shebang and re-optimize at FACET-II**