Injection for Laser Plasma Acceleration using a Gas Jet Embedded into a Discharge Waveguide

LOASIS Program

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PAC 2009

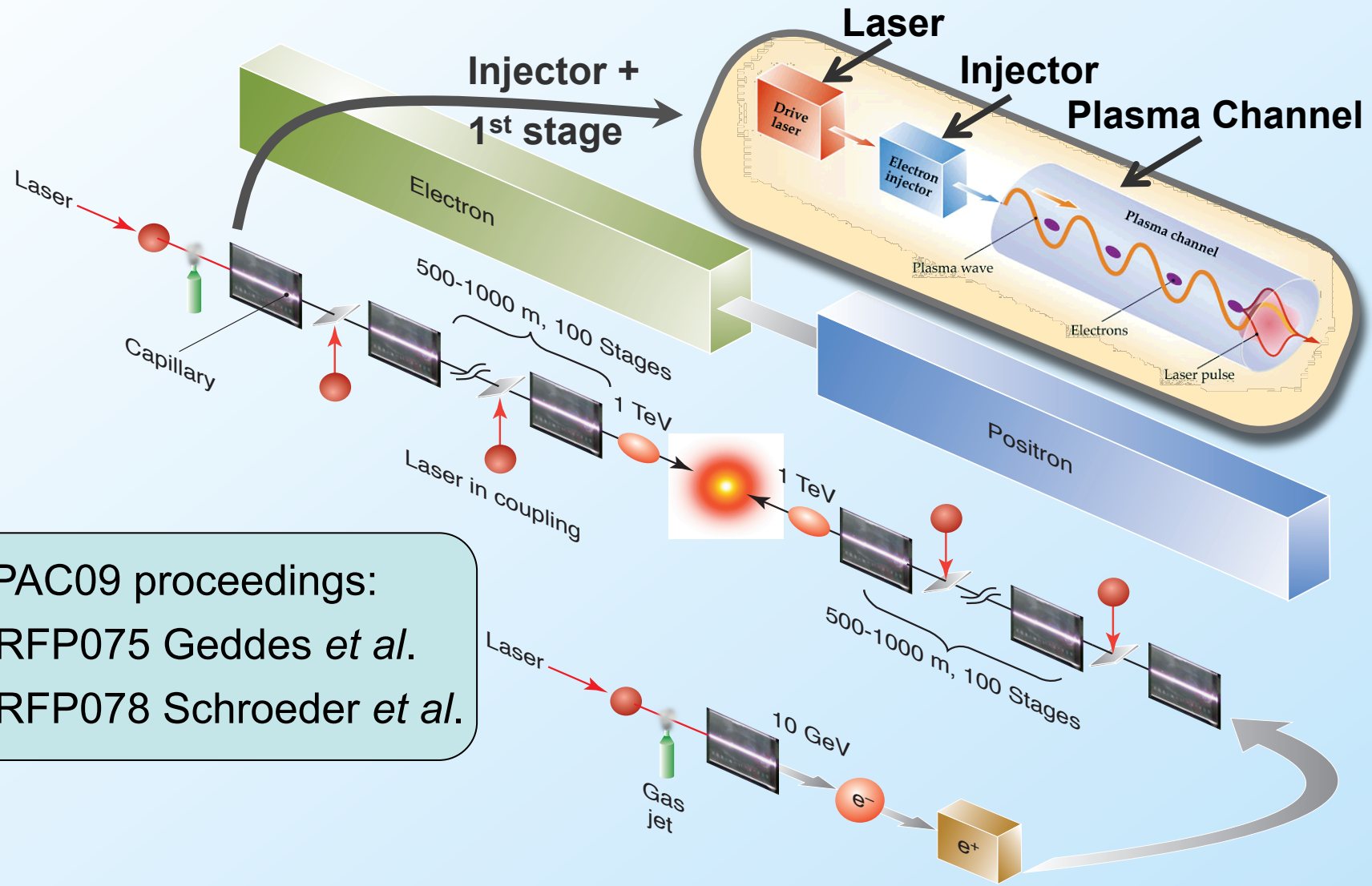
http://loasis.lbl.gov/

DARPA

National Nuclear Security Administration

U.S. DEPARTMENT OF ENERGY | Office of Science

High Acceleration Gradient ➔ TeV LPA Collider in <1km?



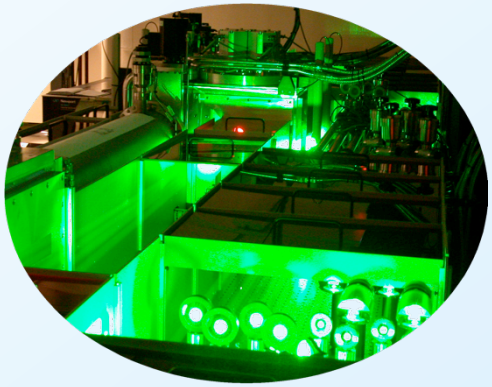
See PAC09 proceedings:
WE6RFP075 Geddes *et al*.
WE6RFP078 Schroeder *et al*.

Leemans & Esarey, Physics Today, March 2009

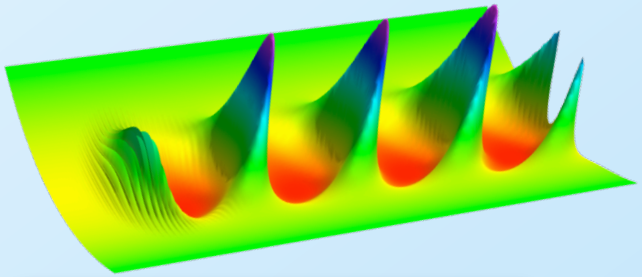
Challenges in Next 10 Years

High-quality stable beams

Staging, optimized structures



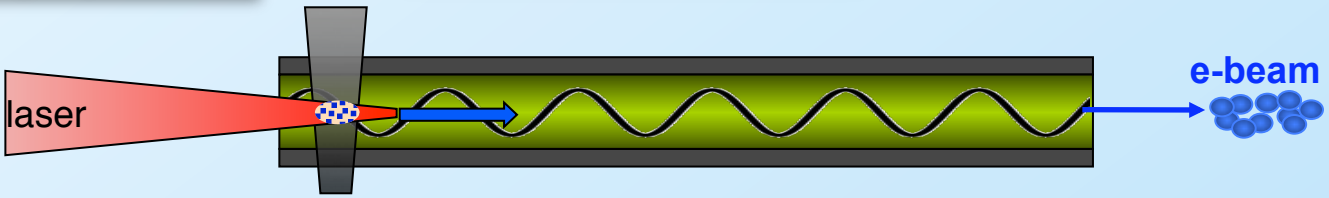
BELLA
(1PW laser)



Lasers:
high average power

Multi-GeV beams

Modeling



Quasi-Monoenergetic Beams with Laser-produced Waveguide

- Pre-2004 electron beams had Boltzmann-like energy distribution with few particles at high energy
- LOASIS group produced low energy spread beams by employing a laser-produced waveguide (overcame diffraction) to accelerate to L_{deph}

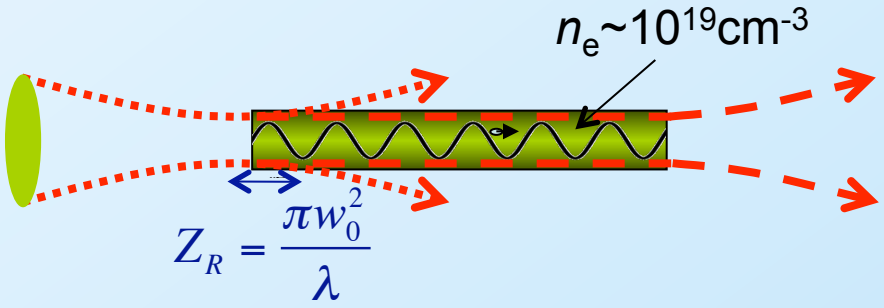
To obtain higher energy

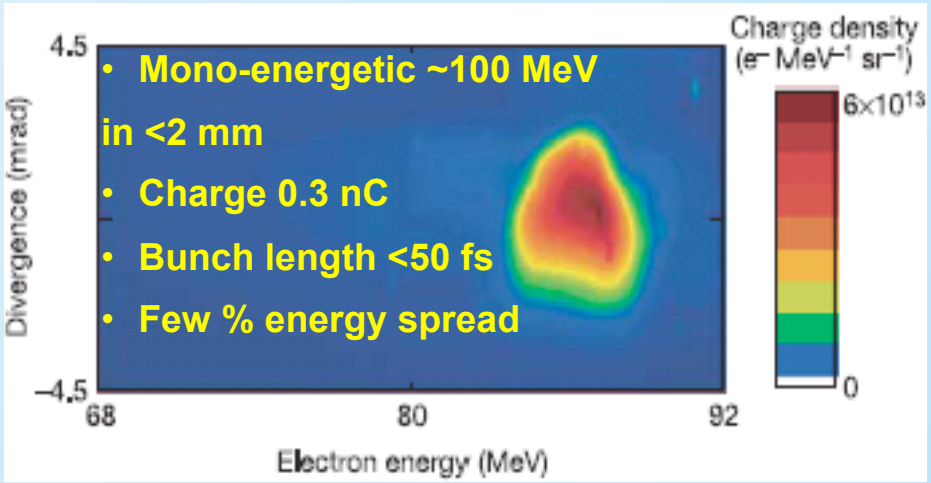
$$\text{Energy Gain} = E_0 L_{acc} \propto \frac{I}{n_e}$$

Lower density + longer guiding structure

But laser-produced waveguide:

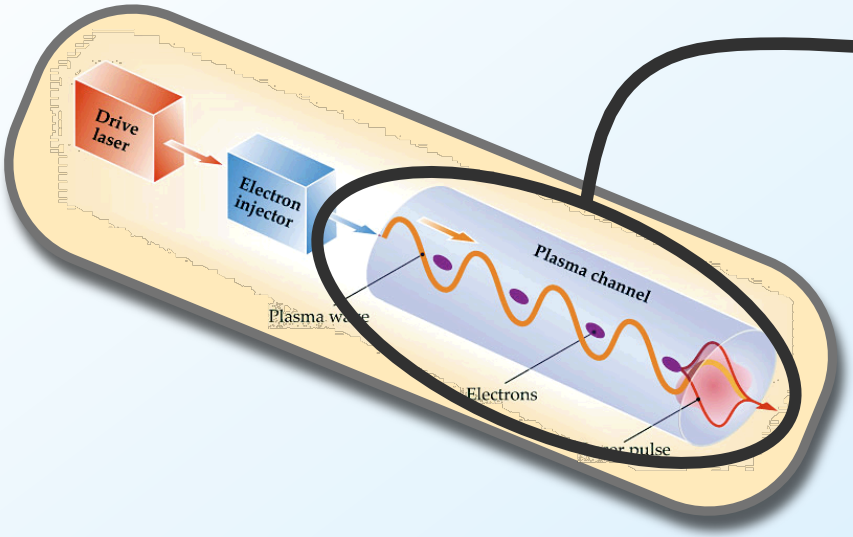
1) Linear scaling of laser energy required with accelerator length
2) Efficient only for high n_e

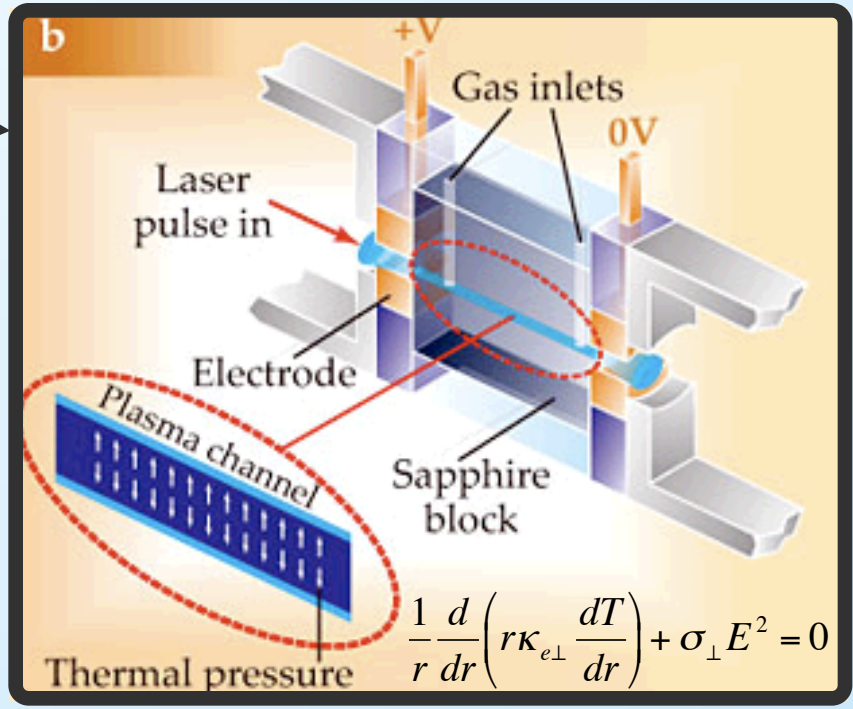




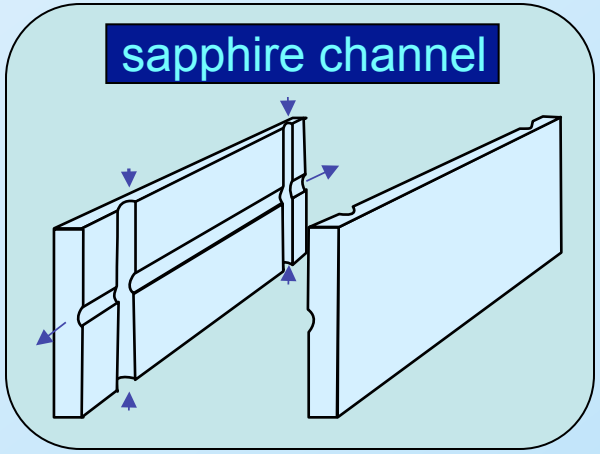
Geddes, *Nature* 431 02900 (2004)

Gas-filled Capillary Discharge Waveguide





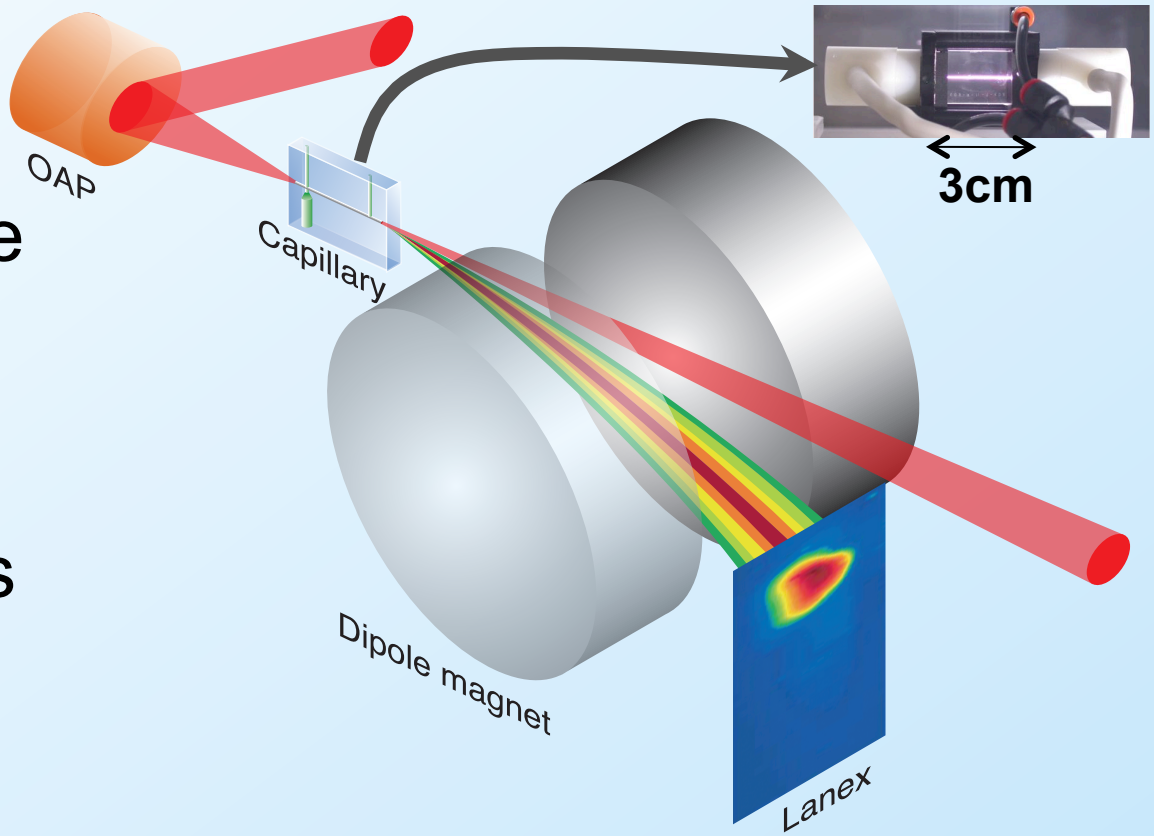
- Gas injected near each end of channel
- $n_e \sim 10^{17}$ - 10^{19} cm^{-3}
- Gas ionized and heated by pulsed discharge
- Guiding channel formed by heat conduction to capillary wall

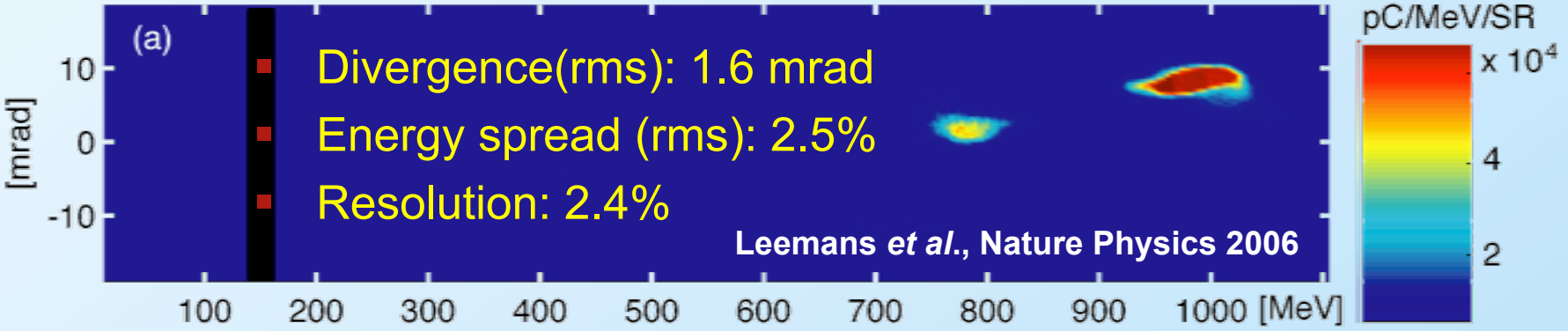


D. J. Spence & S. M. Hooker Phys. Rev. E 63 (2001) 015401 R; A. Butler et al. Phys. Rev. Lett. 89 (2002) 185003.

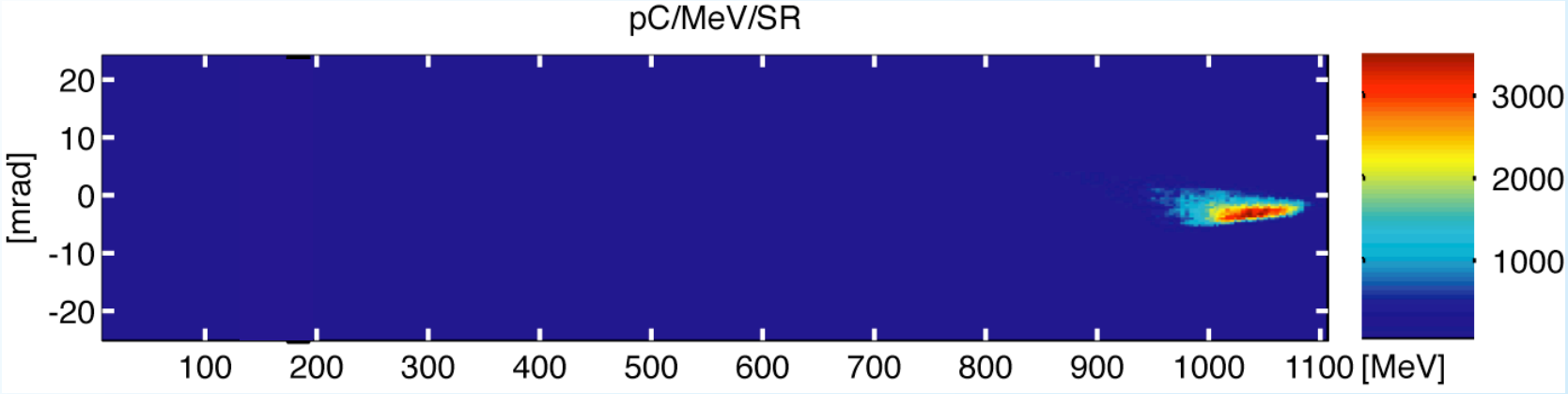
GeV Beams in 3cm

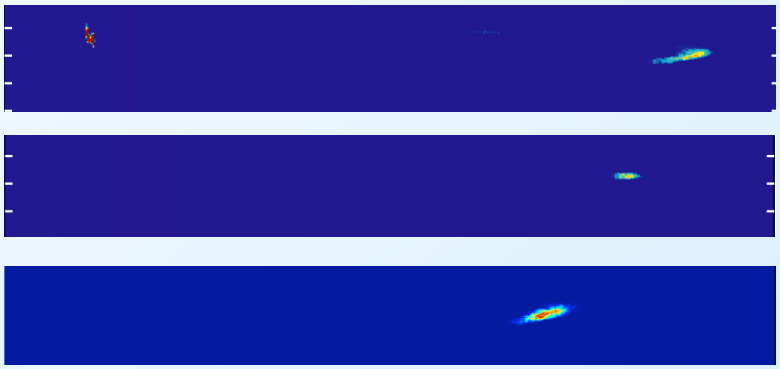
- 40TW laser
- Capillary discharge
- 1 Tesla magnetic spectrometer
- Optical diagnostics (not shown)

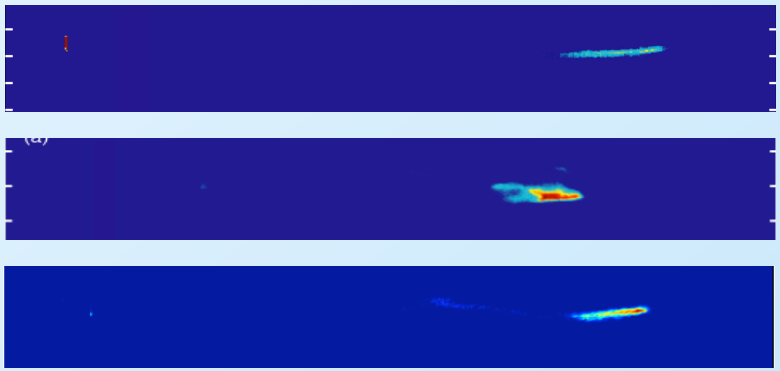




GeV Beams Repeatable but not Stable – Available Controls not Sufficient







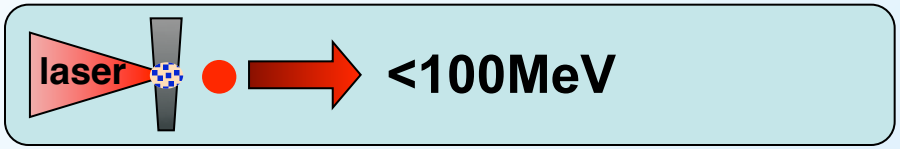
Laser energy, pulse width, plasma density, discharge delay, plasma channel density, depth, and length, degree of ionization

Accelerator performance

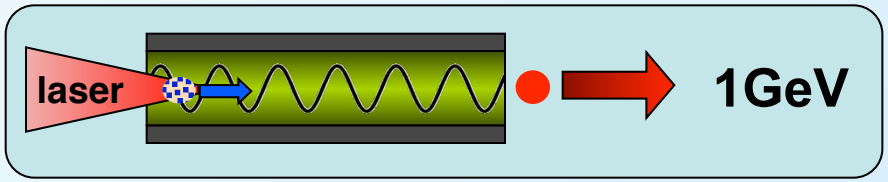
But optimizing injection does not optimize guiding (accelerating structure)
Need to separate injection and acceleration

Lowering the Plasma Density has Increased the Energy of Laser Wakefield Accelerators

- 2004 and previous experiments
  - Density ~ few 10^{19} cm^{-3}, 10TW



- 2006 Experiments
  - Density ~ few 10^{18} cm^{-3}, 40TW

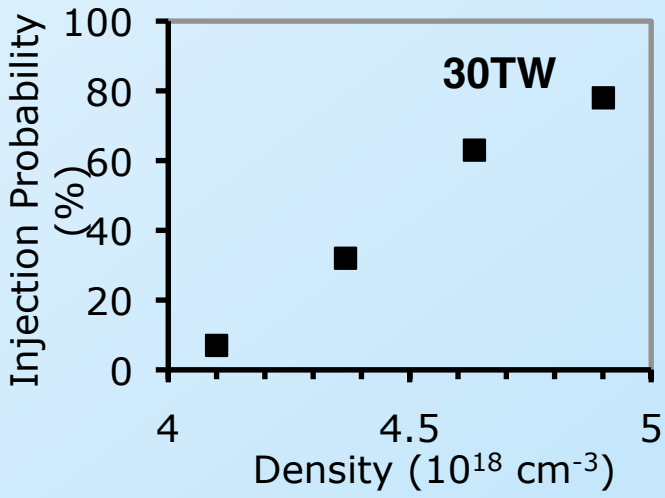


- 2008/2009 Experiments
  - Optimize controlled dark current free accelerating structure
  - Employ injector

Linear Regime

$$\text{Energy Gain} \propto \frac{I}{n_e}$$

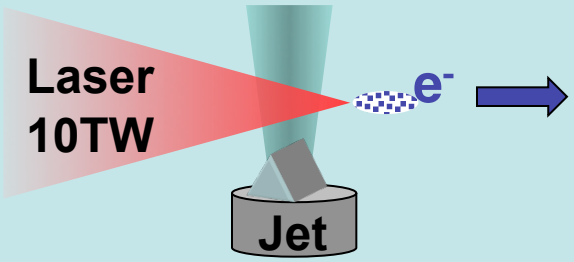
If density lowered for given laser power, injection turned off

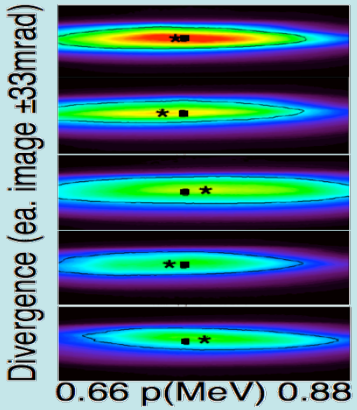


Geddes *et al.*, **Nature**, 2004; Leemans *et al.*, **Nature Physics** 2006; Gonsalves *et al.*, **in prep**

Down-ramp Injector Demonstrated: Simulations Show Injector Coupled to Low Density Accelerator Produces Low Energy Spread Beams

Laser focused on down-ramp of gas jet density profile



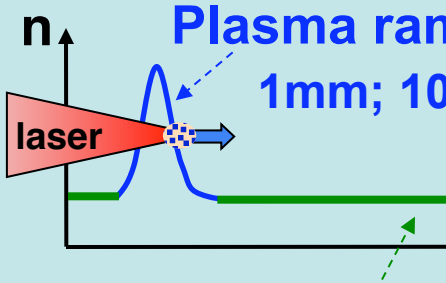


MeV beam produced with

- Low divergence (20 mrad)
- Good stability
- Central energy (760keV/c ± 20keV/c rms)
- Momentum spread (170 keV/c ± 20keV/c rms)
- Beam pointing (1.5 mrad rms)

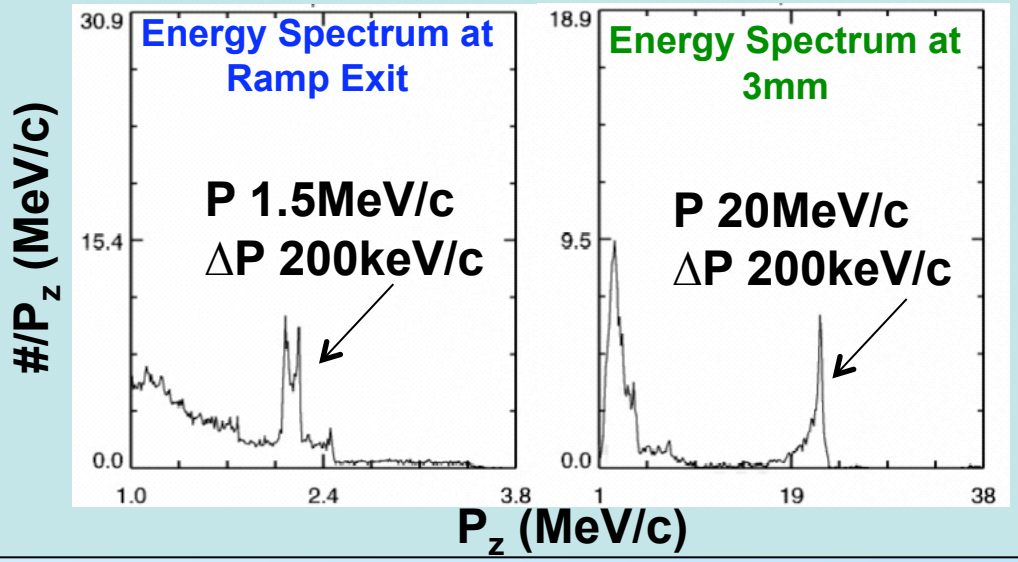
Laser transmission 70% and mode still good for driving wakefield

Inject low ΔE: ΔE conserved during acceleration so as E ↑, ΔE/E ↓



Plasma ramp injector:
1mm; 10^{19} cm^{-3}

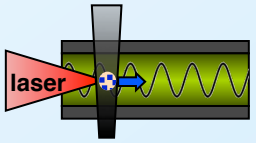
Accelerator:
3 - 50 cm; n~10^{17} -10^{18} cm^{-3}



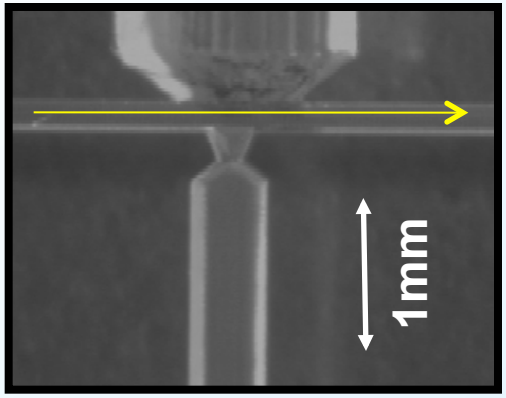
Geddes et al., PRL V 100, 215004 (2008)

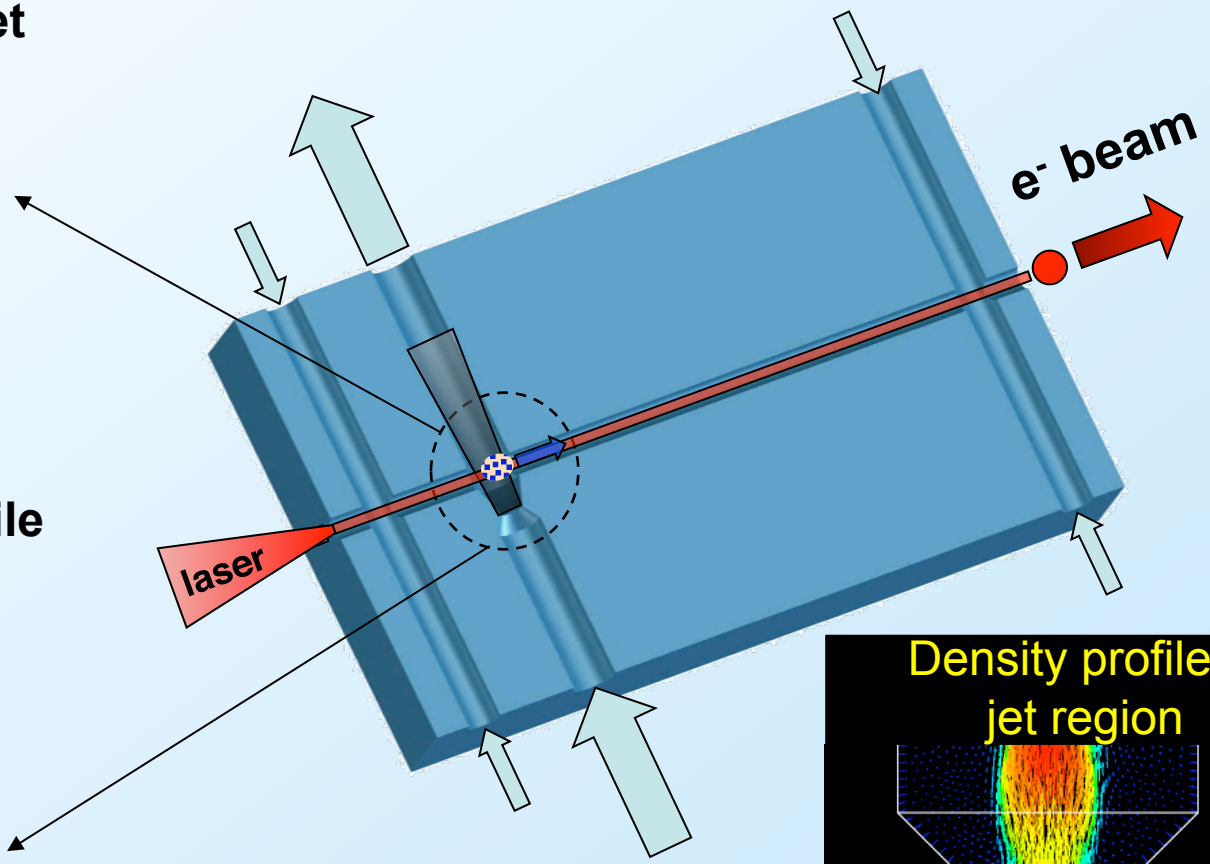
*Nieter et al., JCP 2004

Gas Jet Nozzle Machined Into Capillary Can Provide Local Density Perturbation

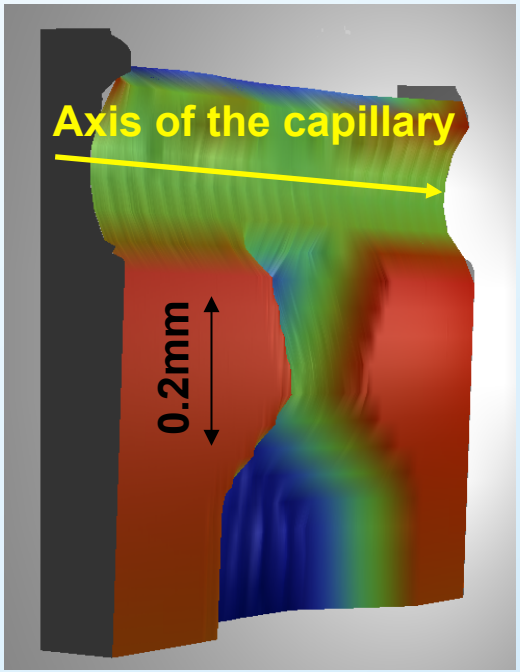


Laser-machined gas jet

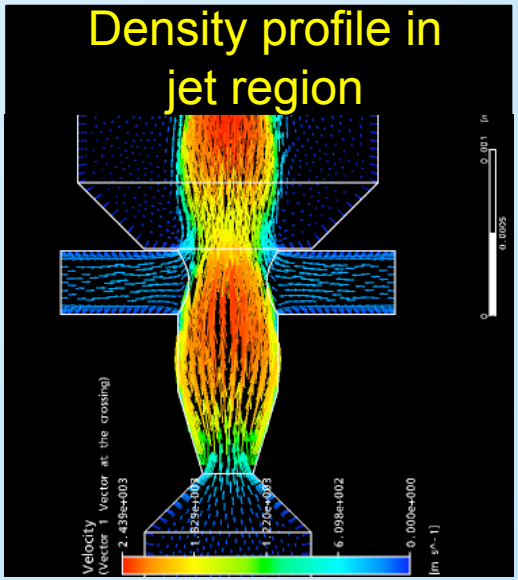




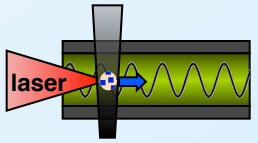
Measured surface profile



Density profile in jet region

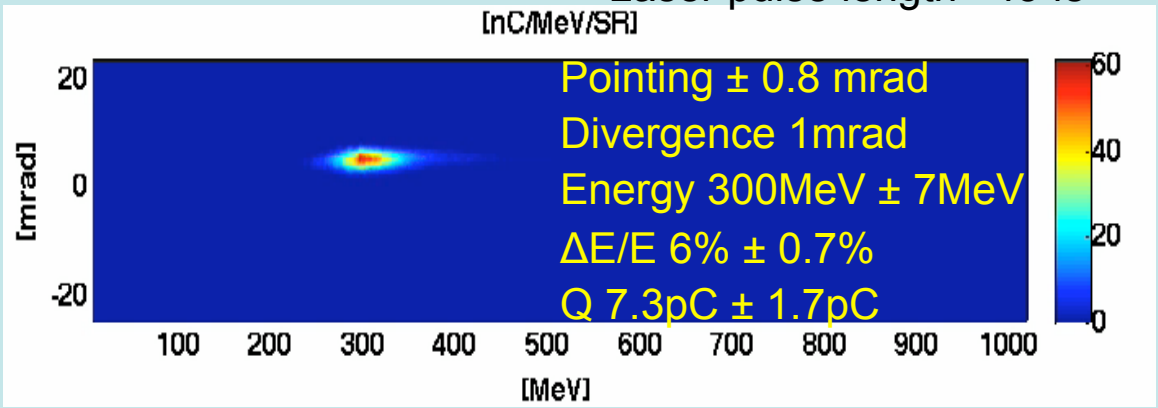


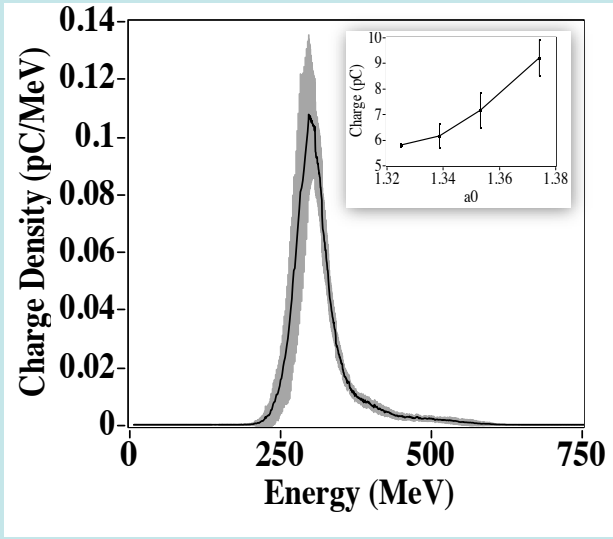
Jet Improves Beam Stability



Stability with jet

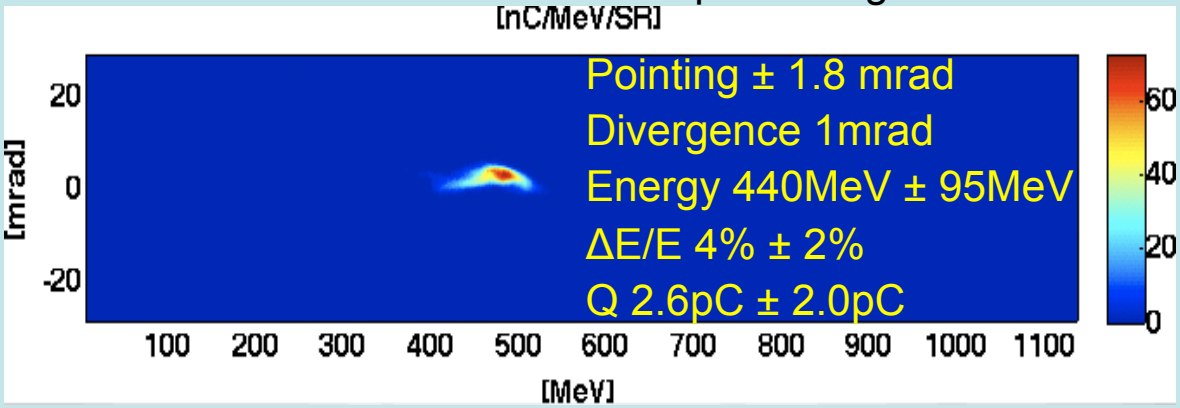
Input Parameters: P_{jet}≈145psi,
$N_e \approx 2x10^{18}\ cm^{-3}$, a_0≈1 (25TW),
Laser pulse length≈ 45 fs

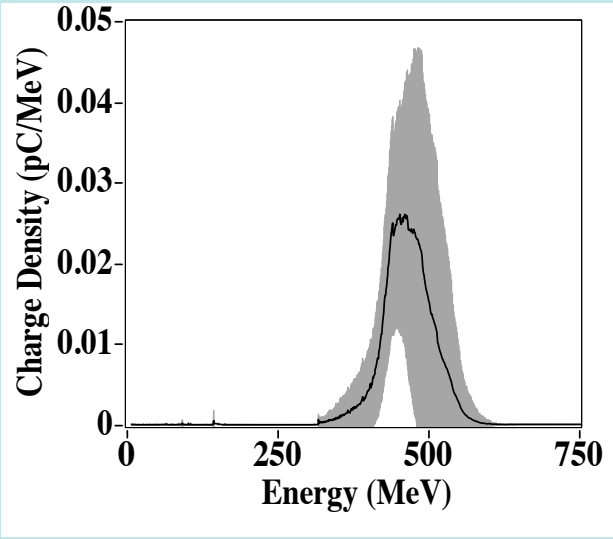




Best stability without jet

Input Parameters: no jet in cap,
$N_e \approx 2x10^{18}\ cm^{-3}$, a_0≈1 (25TW),
Laser pulse length≈ 45 fs

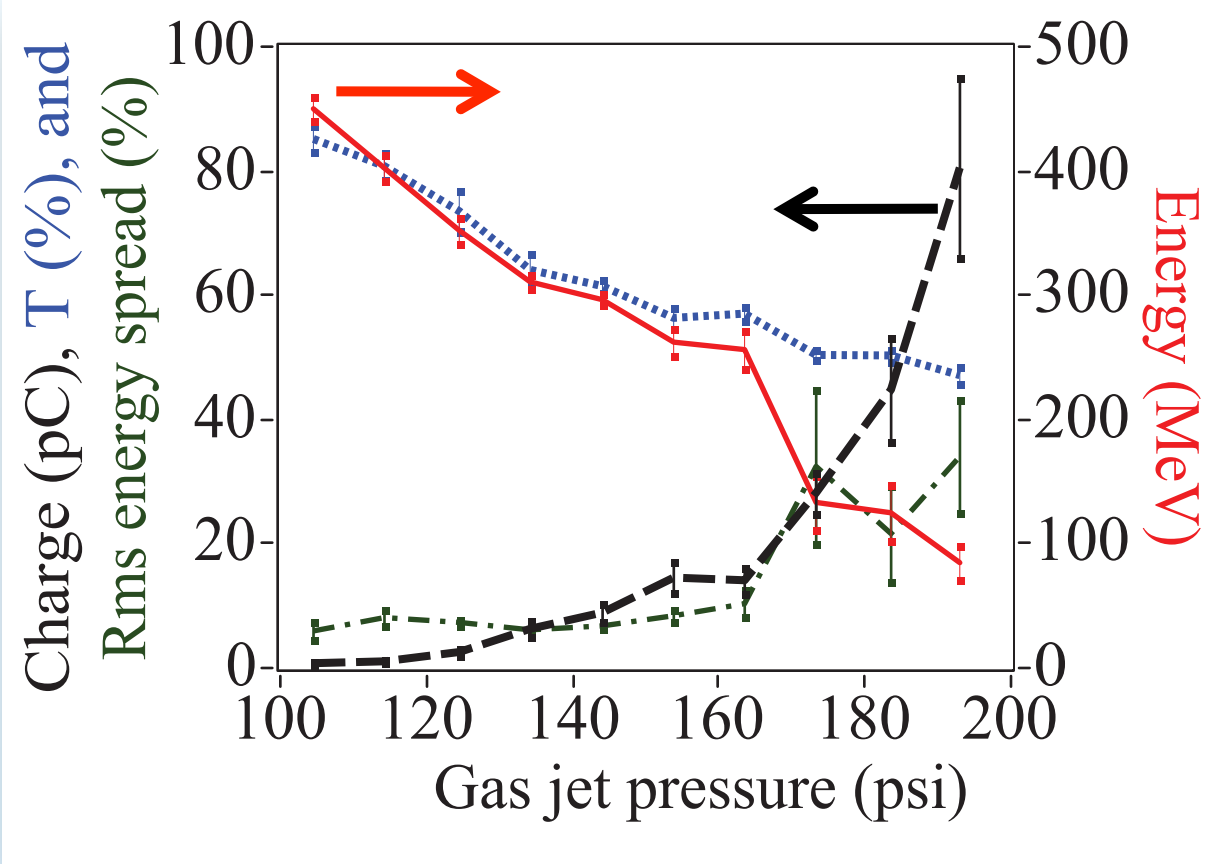




NB: Both data sets show subsequent shots

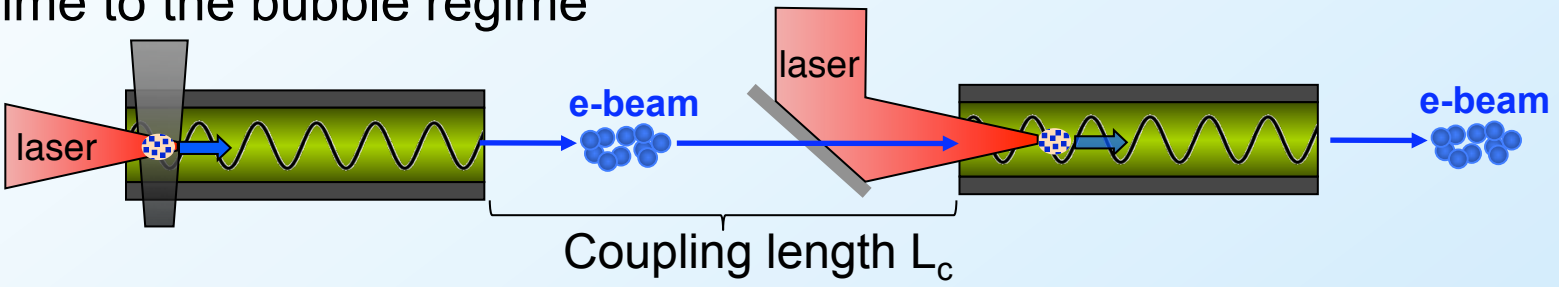
Energy Control by Varying Jet Pressure

- Energy of the beam tuned without significant increase in energy spread
  - BUT Beam parameters not independent *yet*
  - Increased jet pressure ➔ pump depletion, reduced energy
  - Increase further, sharper reduction in energy – beam loading?

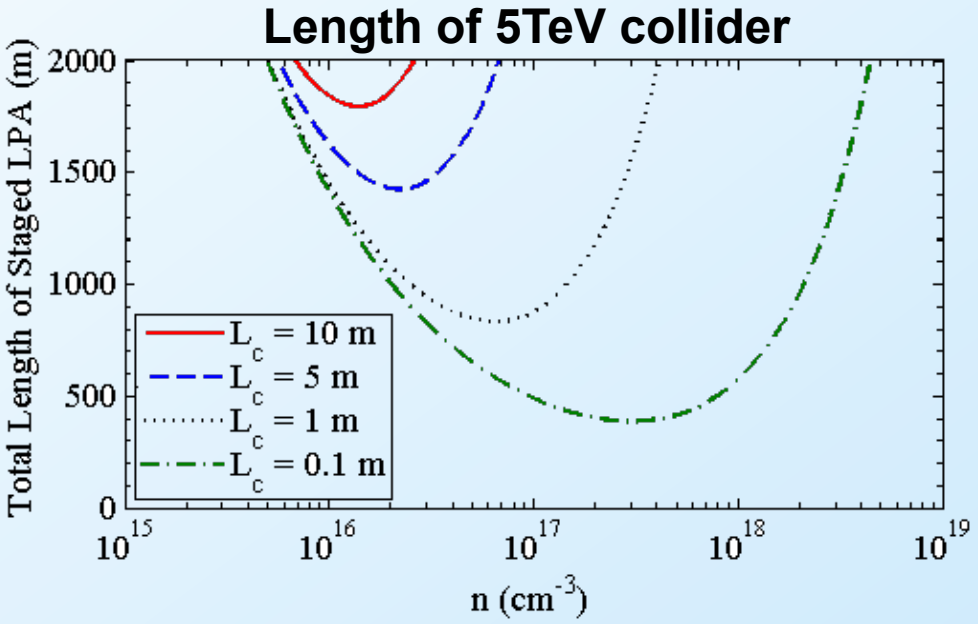


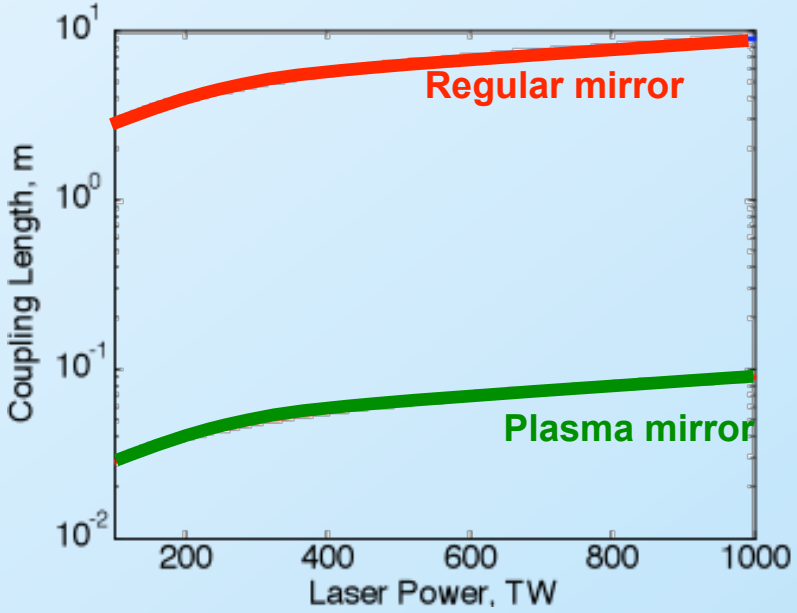
Staging: solving the issue of laser depletion

- Not only vital for achieving higher beam energy but separate stages allows for fully tunable second stage to explore the physics of LPA's from the linear regime to the bubble regime



- Plasma mirror reduces distance between stages and accelerator length

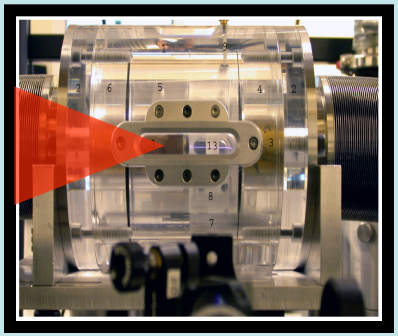


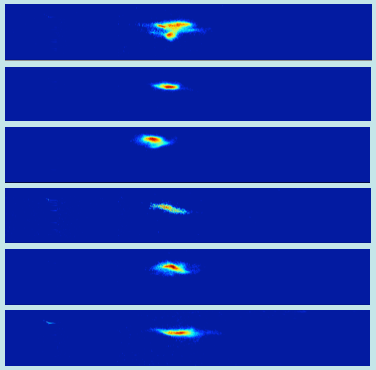


See proceedings Panasenko et al., WE6RFP077

Summary and *Near* Future Experiments

Highest energy beams from LPA with capillary technology

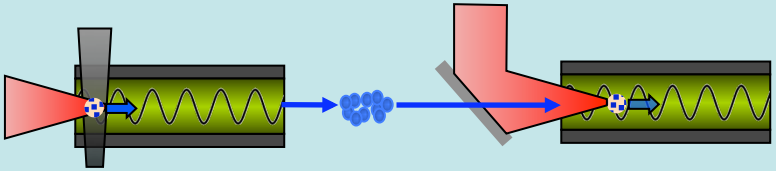




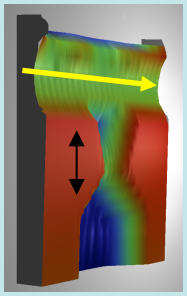
Near Future:

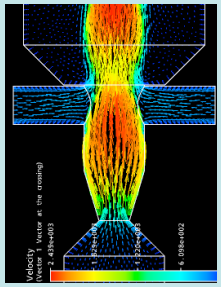
Down-ramp injection

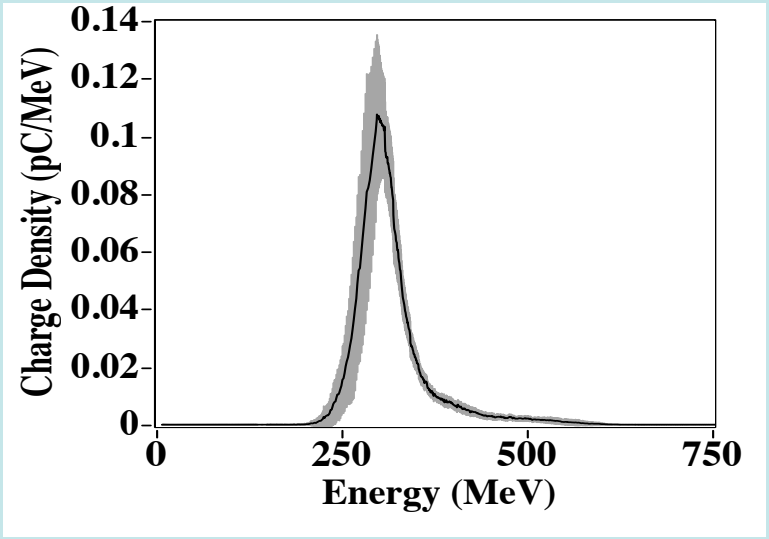
Demonstrate staging (↑E and more)



Tailoring density profile increases beam stability







500 MeV -density below usual injection threshold)
Enhancement of stability in charge and energy
Increase in control over beam parameters
1 mrad divergence and pointing stability