GeV electron beams from cm-scale laser-driven plasma accelerators

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Outline

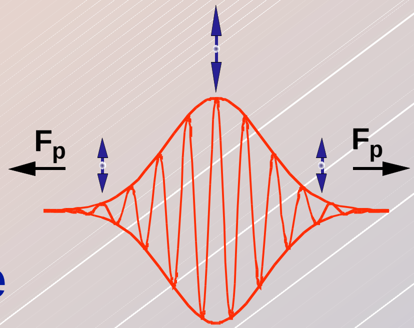
- **Laser Wakefield Acceleration (LWFA) and Recent Experiments**

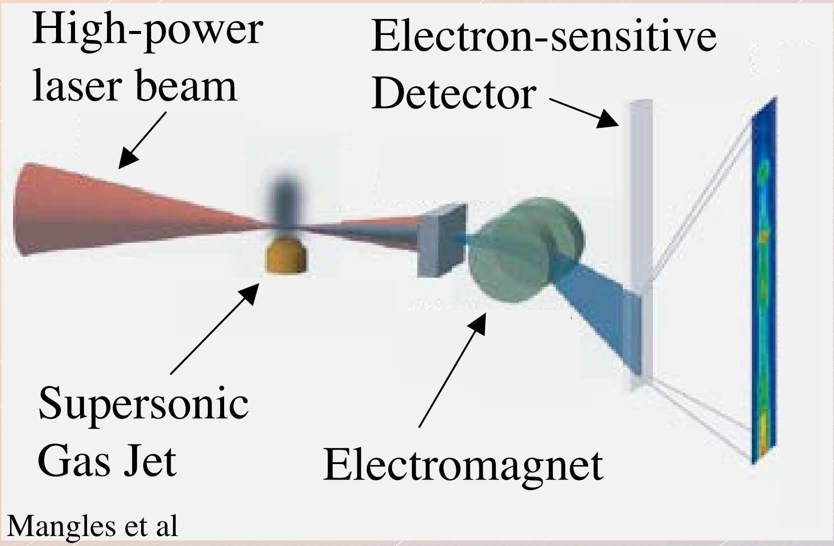
- **GeV Beams Using Channel Guiding**
  - ➢The Waveguide
  - ➢Experiments

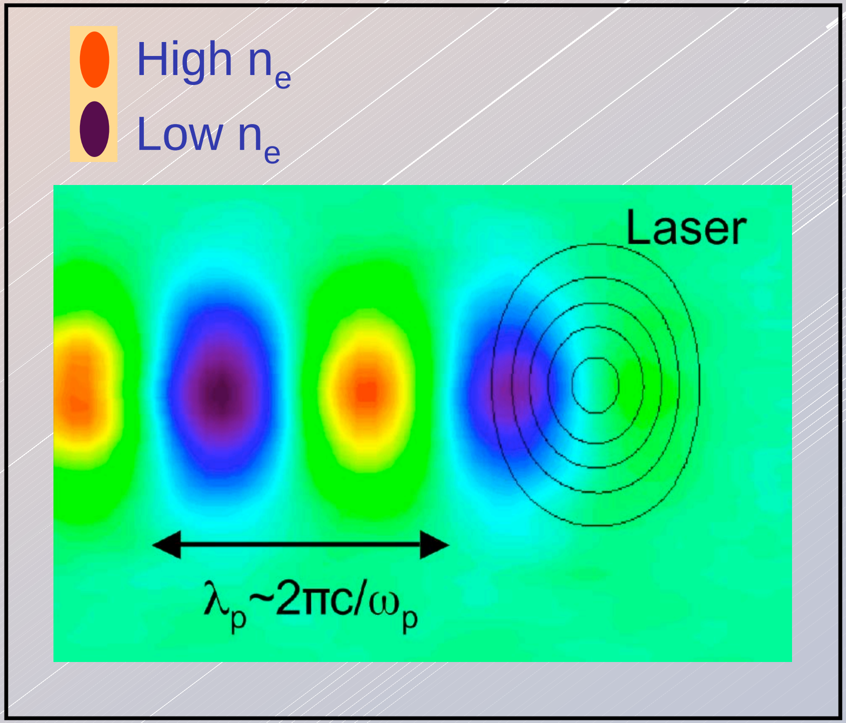
- **Summary**

Laser Wakefield Accelerator (LWFA)

- **Plasma accelerators - Ultra-high axial electric field gradients (10 GV/m)**
  - ➢COMPACT ACCELERATORS
- **Can excite large plasma waves with ponderomotive force of intense laser pulse**

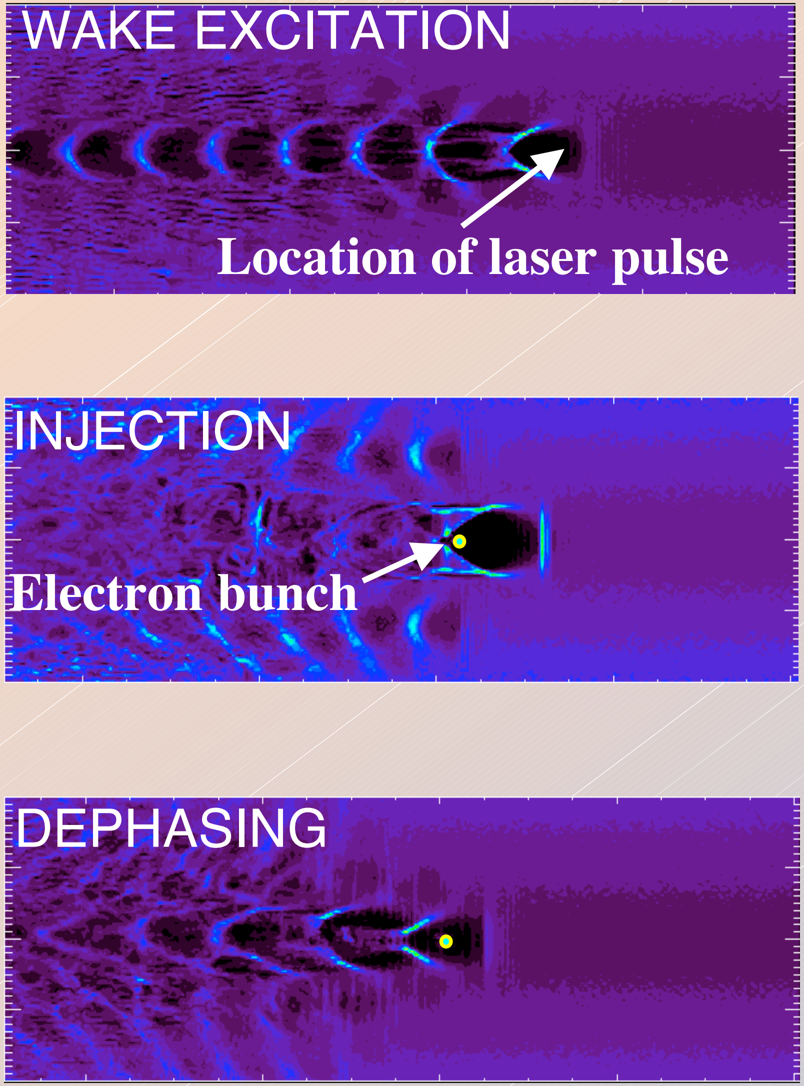






Tajima & Dawson (79)

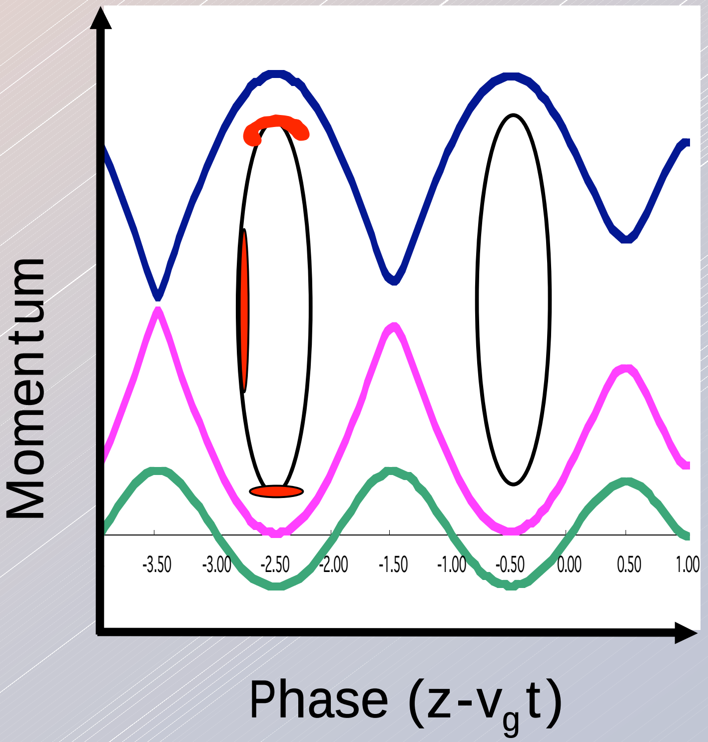
Regime of Recent Experiments



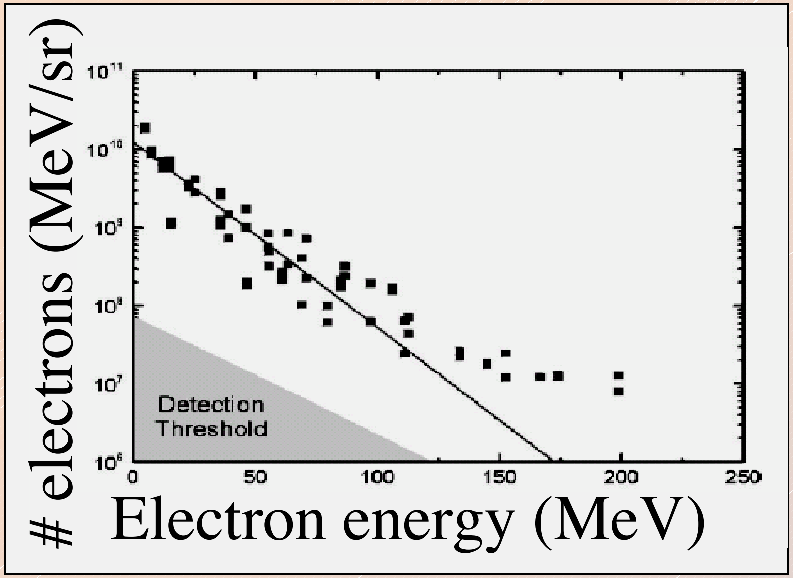
I. Wake excitation

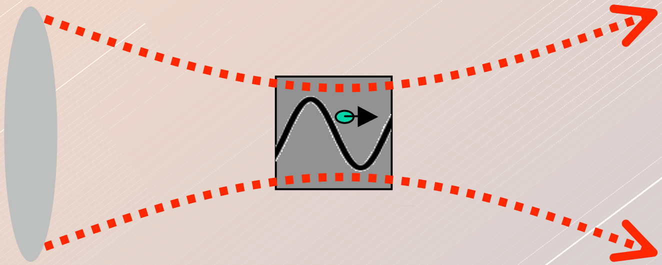
II. Trapping (and termination of trapping)

III. ACCELERATION TO THE DEPHASING LENGTH



Monoenergetic Beams - Unguided Laser



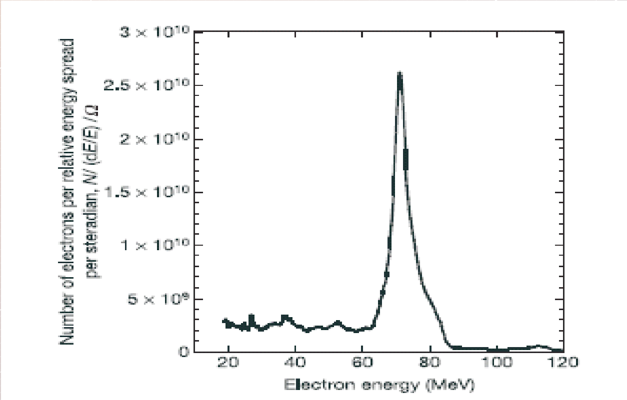


- $n_e \Rightarrow$ control of L_D

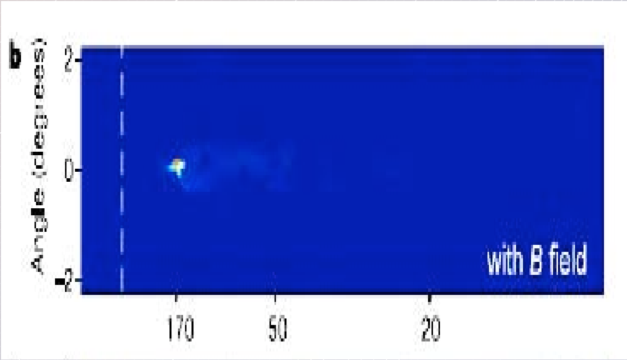
$$\left(L_D \propto \frac{1}{n_e^{3/2}} \right)$$

- $W_0 \Rightarrow$ *some* control of L_{prop}

$$\left(Z_R = \frac{\pi w_0^2}{\lambda} \right)$$



- RAL/IC
- 12.5 TW
- 20 pC
- 80 MeV)

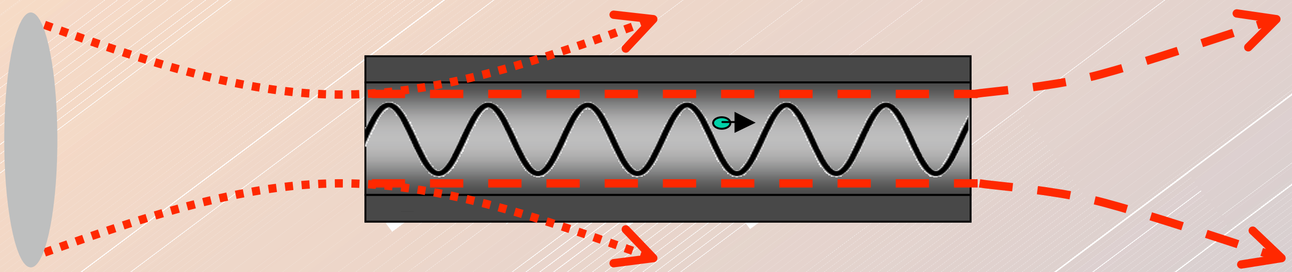


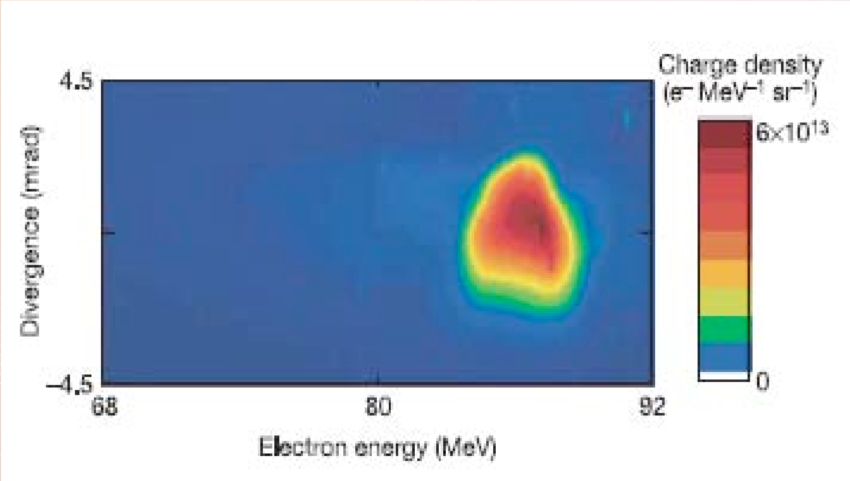
- LOA
- 33 TW
- 500 pC
- 170 MeV)

Faure et al., *Nature* **431** 02963 (2004); Mangles et al., *Nature* **431** 02939 (2004);
Z. Najmudin et al. *Phys. Plasma* **10** 2071 (2003)

Monoenergetic Beams With Laser Guiding

Laser-Driven Hydrodynamic Expansion Waveguide + 9TW laser…





- **Mono-energetic ~100 MeV electron beams in <2 mm**
- **Few % energy spread**
- **Charge 0.3 nC**
- **Bunch length <50 fs**

Geddes, *Nature* **431** 02900 (2004)

Increasing Electron Beam Energy

Dephasing Length: $L_D \propto \frac{1}{n_e^{3/2}}$

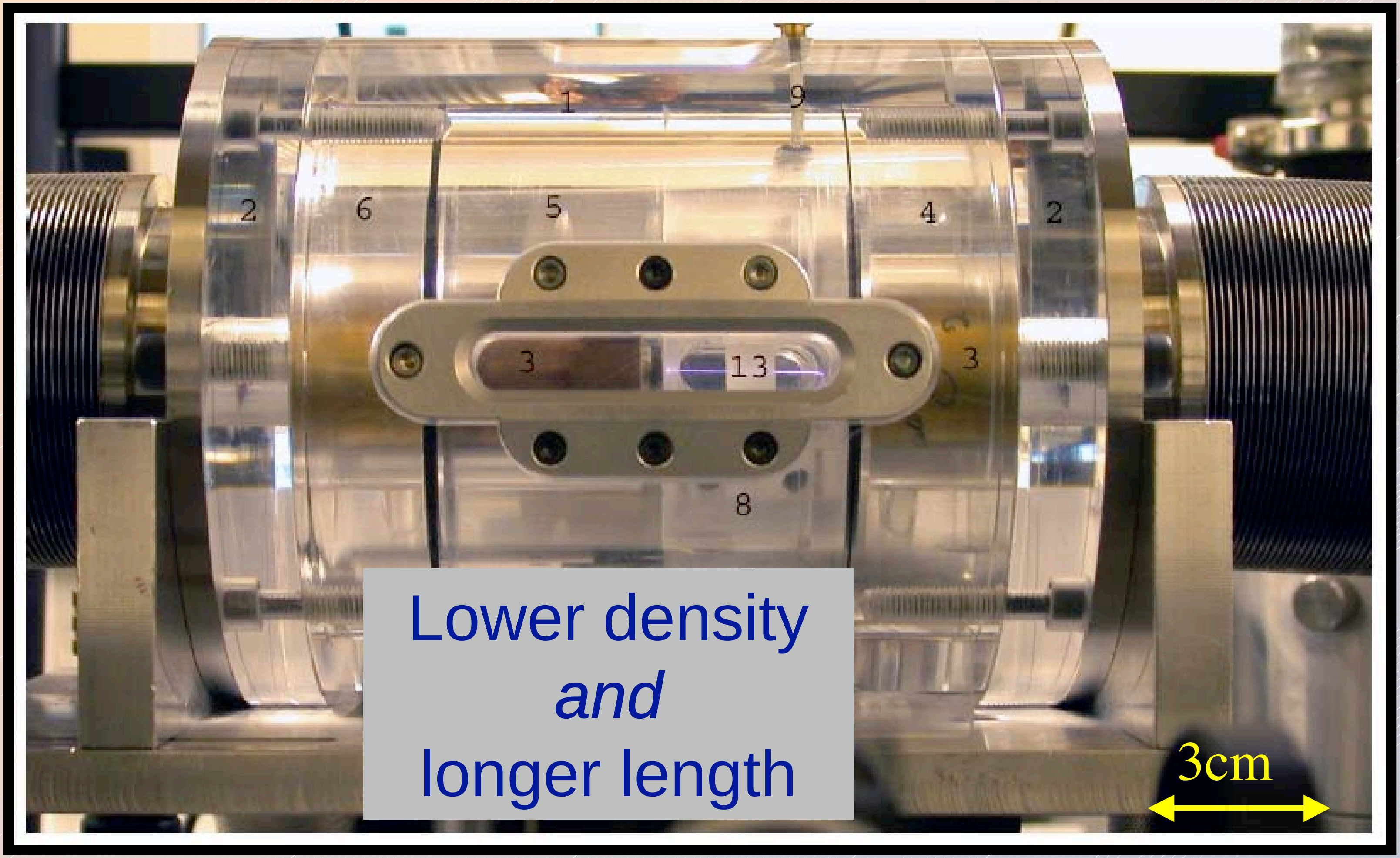
Energy gain: $\Delta W_D \propto \frac{I}{n_e}$

Reduce n_e
and increase *I*

- **Guiding minimizes required laser power***
- **Guiding allows operation in a more stable regime**
- **But laser-driven hydrodynamic expansion waveguides**
  - ➢Rely on inverse-bremsstrahlung heating: only efficient for high n_e
  - ➢Laser pump energy scales linearly with length

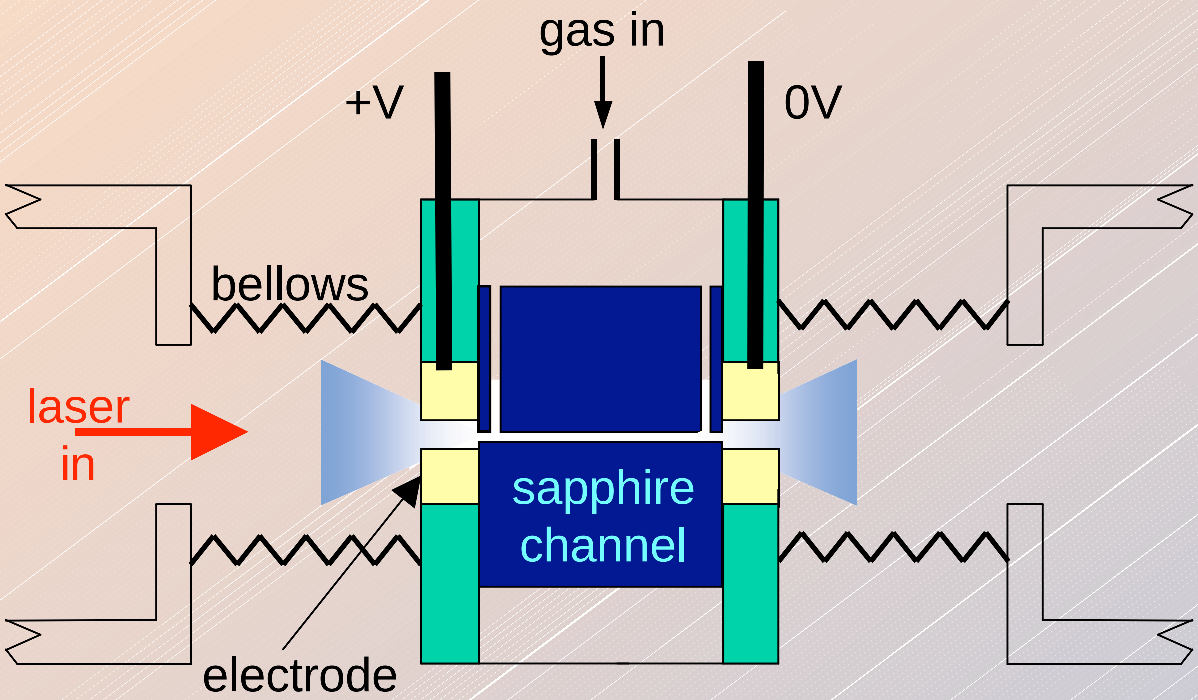
*W.P. Leemans et al, *IEEE Trans. Plasmas Sci.* **24** (1996) 331; Esarey et al., *IEEE* 1996

Gas-Filled Capillary Discharge Waveguide

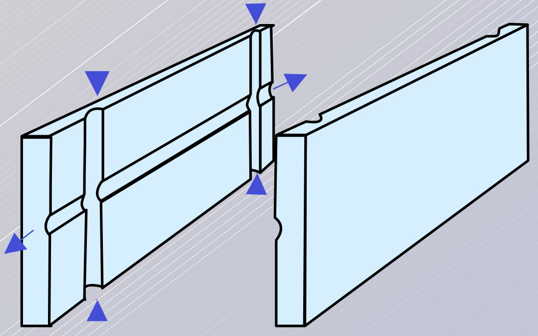


D. J. Spence & S. M. Hooker *Phys. Rev. E* **63** (2001) 015401 R.
A. Butler et al. *Phys. Rev. Lett.* **89** (2002) 185003.
A. J. Gonsalves et al. *Phys. Rev. Lett.* ***98* (2007)** 025002.

Gas-filled Capillary Discharge Waveguide

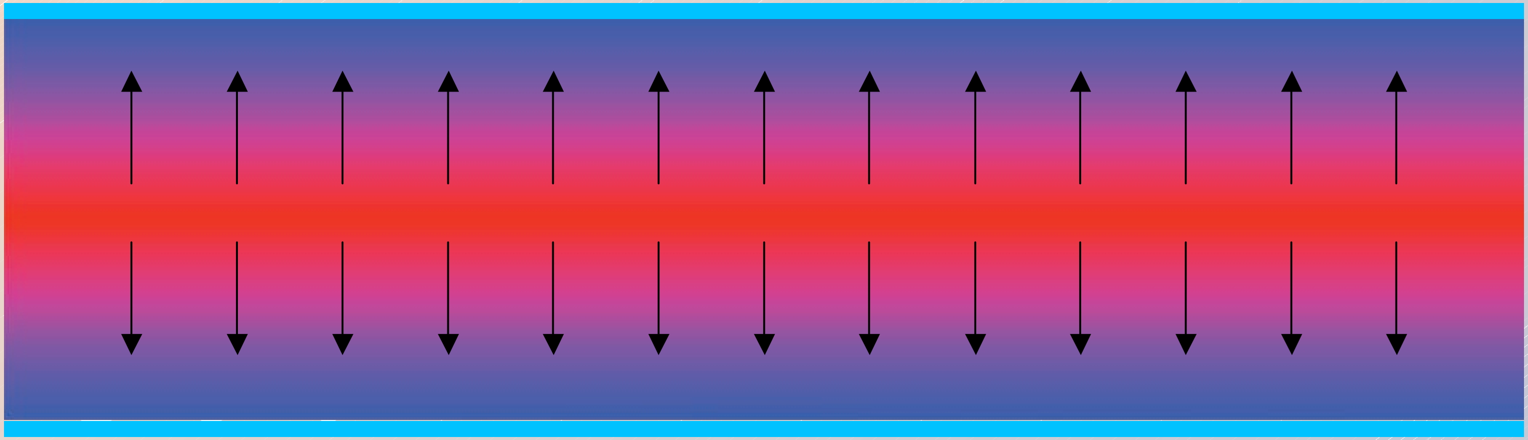


- **Capillary diameter = 100 - 400 µm**
- **Gas injected near each end of channel**
- **Gas ionized by pulsed discharge**
  - Peak current 200 - 500 A
  - Rise-time 50 - 100 ns



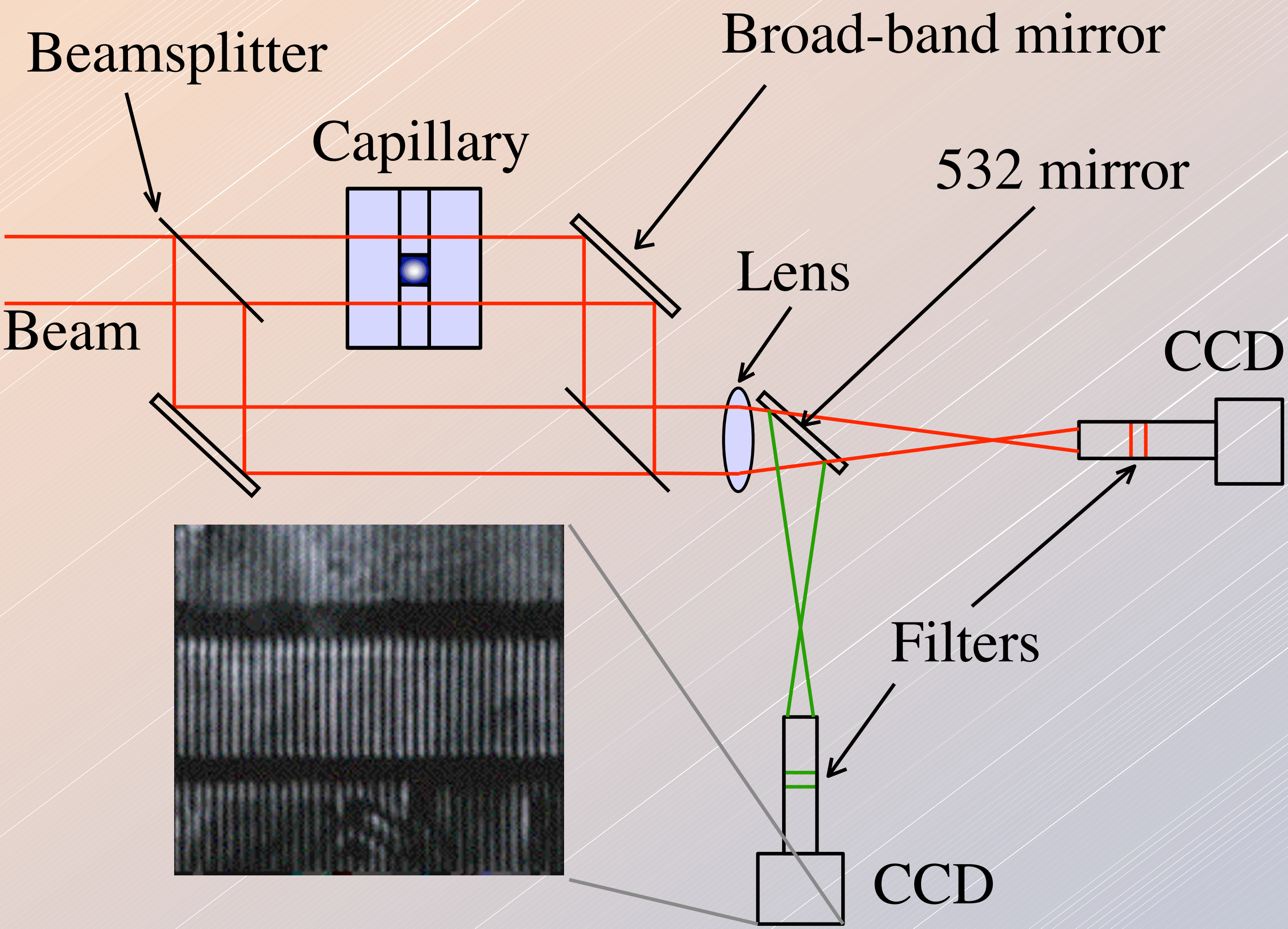
Plasma Channel formation

- Plasma fully ionized for t > 50 ns
- After t ~ 80 ns plasma is in quasi equilibrium in which Ohmic heating of plasma is balanced by conduction of heat to wall
- Ablation rate small - capillary lasts for at least millions of shots



Bobrova *et al*. *Phys. Rev. E* **65** 016407 (2001).

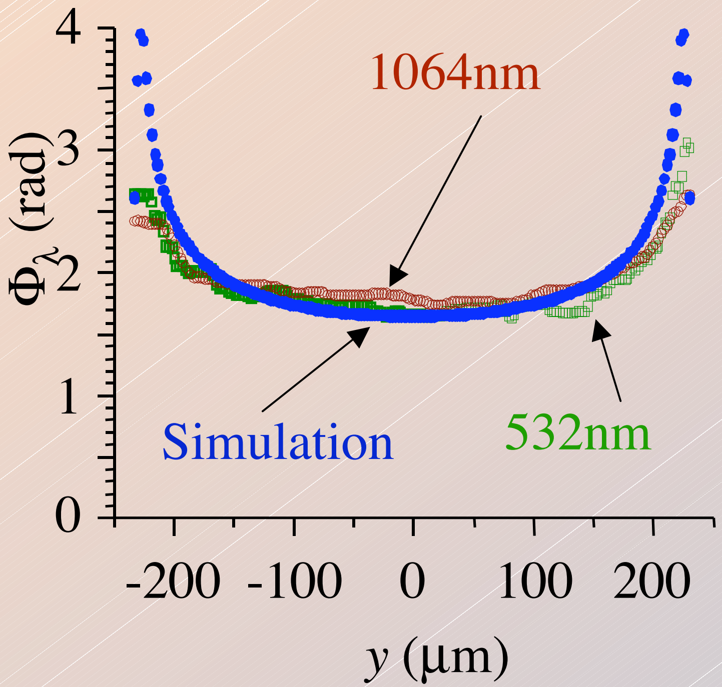
Interferometry of Plasma Channel



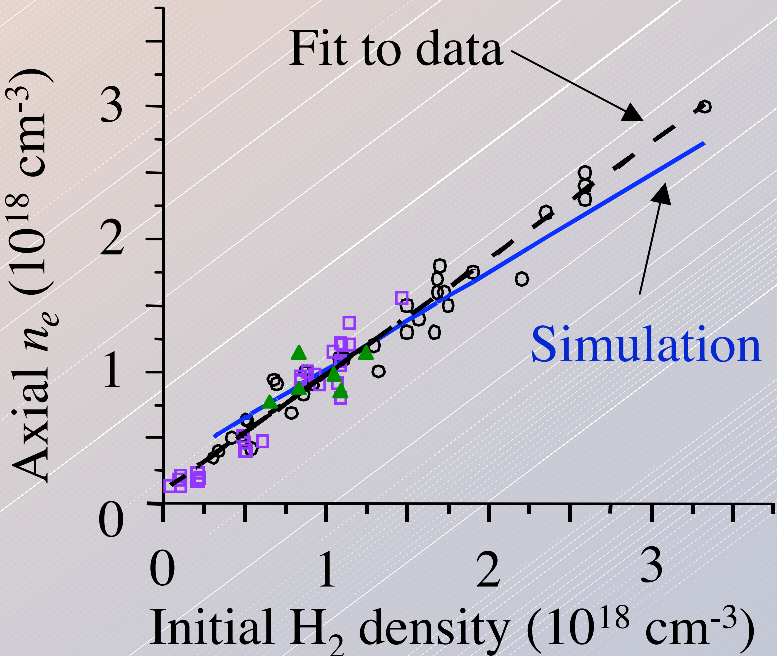
A. J. Gonsalves et al., *PRL* **98** 025002 (2007)

Interferometry

- **Simulation and experiment in excellent agreement**
- **Example for 465μm-diameter capillary and 40mbar hydrogen:**



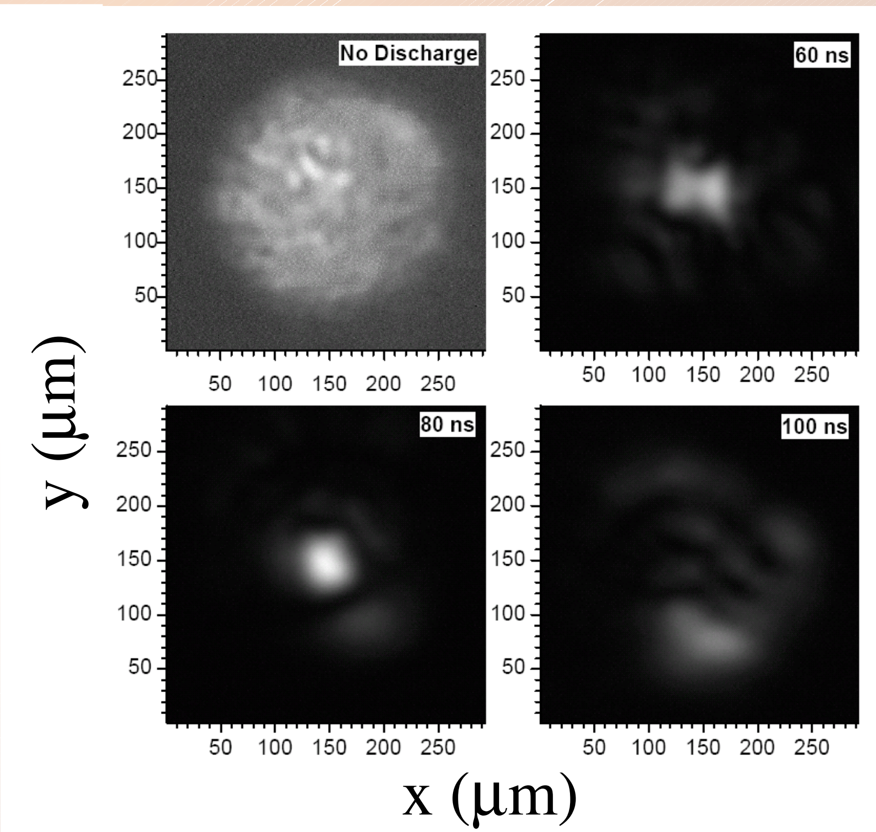
- **Good agreement over wide range of parameters**
- **Axial n_e measured for 125, 210, 465 μm diameter capillaries:**

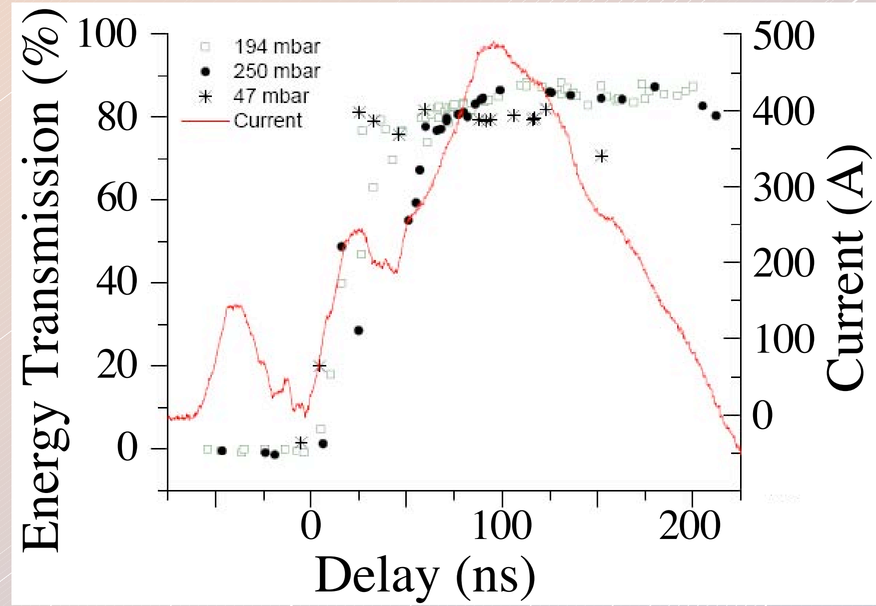


A. J. Gonsalves et al., *PRL* (2007); Broks et al., *Phys Plasmas* (2007)

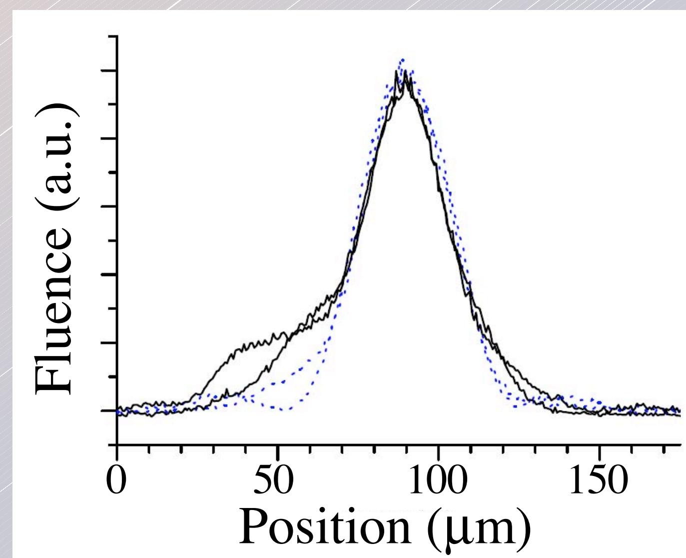
"Low Intensity" Guiding Experiments

- **Capillary: 33 mm long, diameter 250 μm**
- **Input beam: W_0 = 30 μm, I = 5x10^{16} W cm^{-2}**

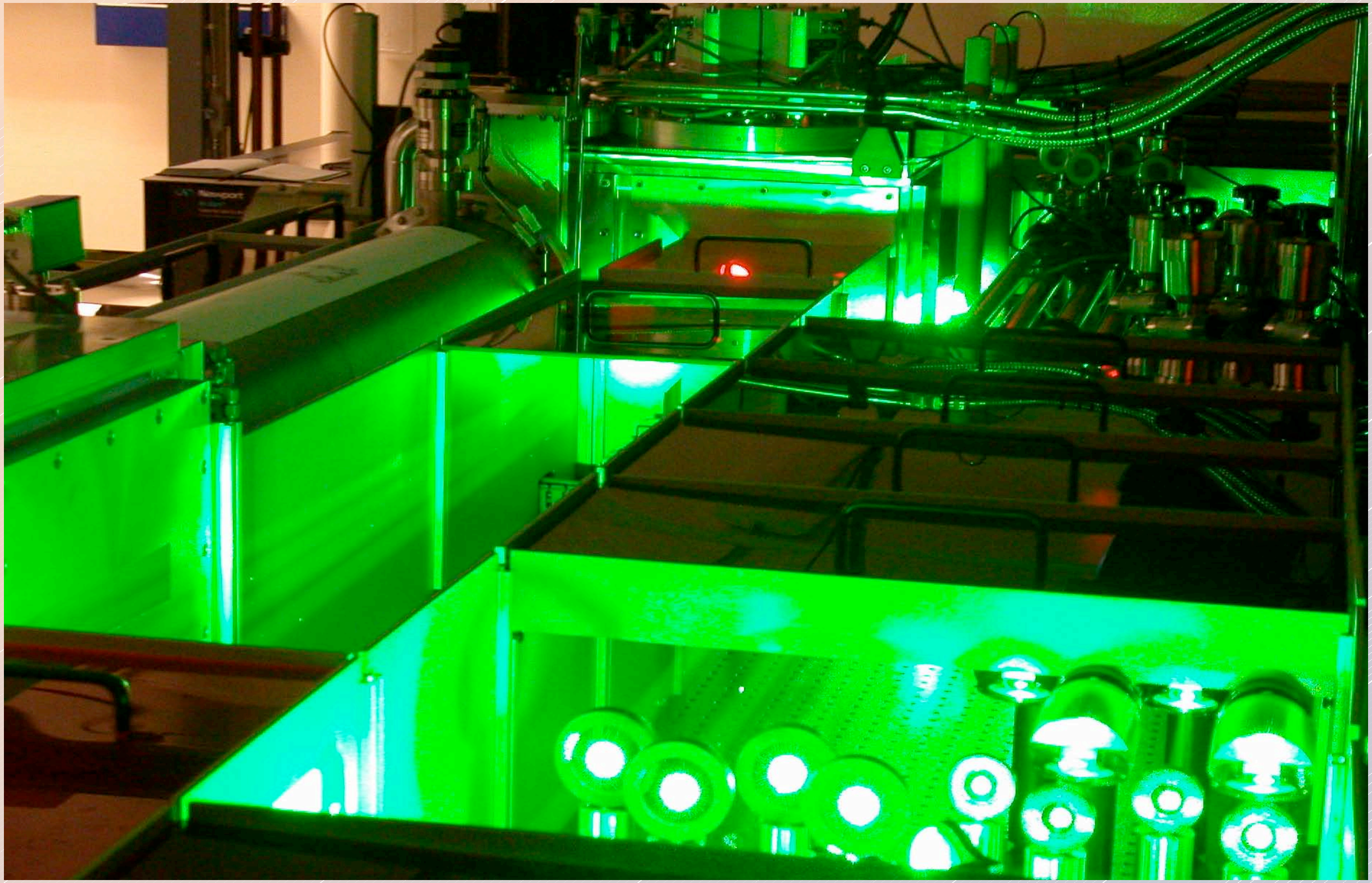




- **Lineout at 80 ns, pressure 195 mbar**
- **Input and output fluences are equal.**

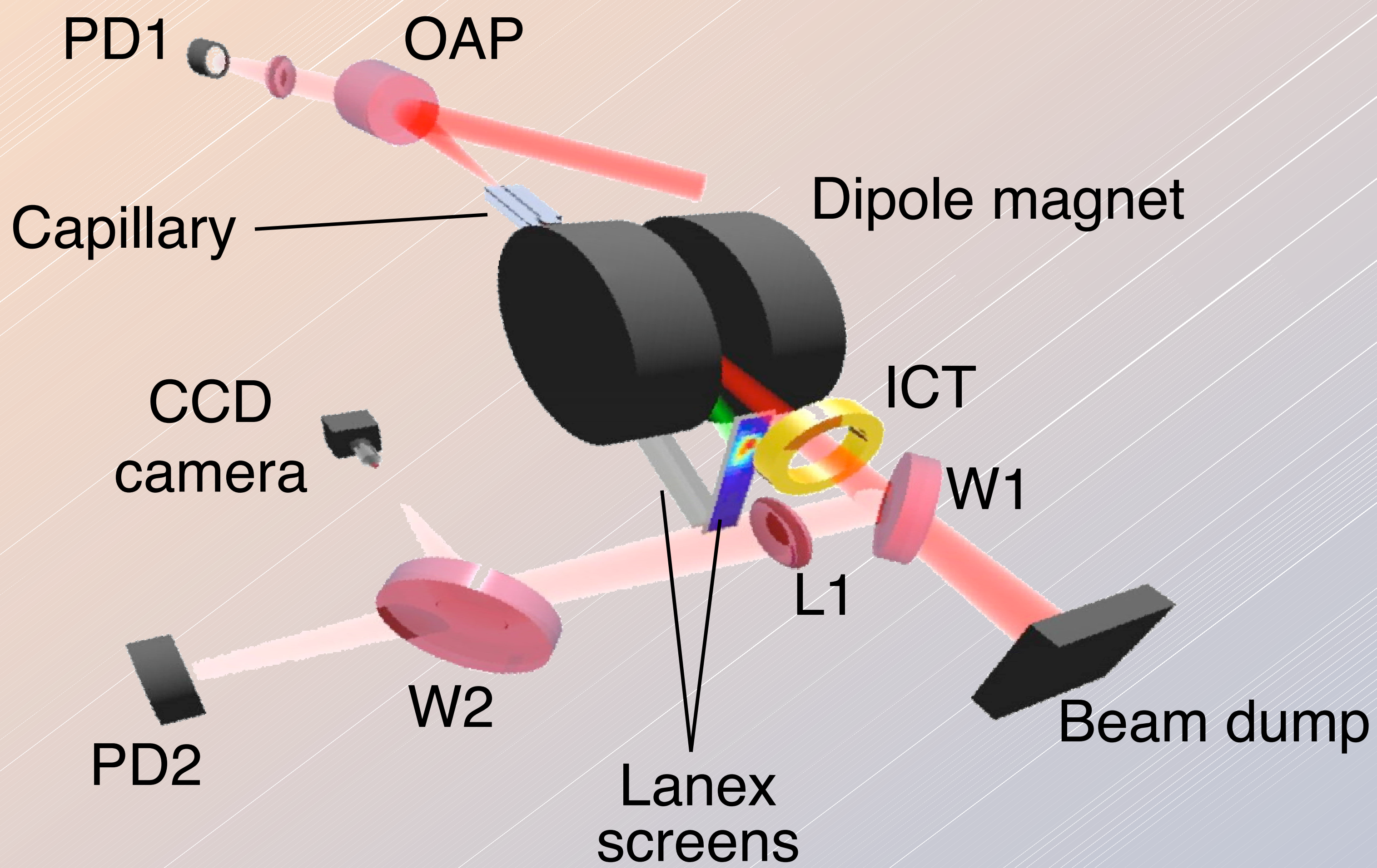


LOASIS TREX Laser System



- Cryogenically cooled Ti:Sapphire amplifier
- Pumped by 1.6 J x 8 - 532 nm
- 2.6J, >37 fs, ~60 TW @ 10 Hz

Experimental Setup for GeV Accelerator

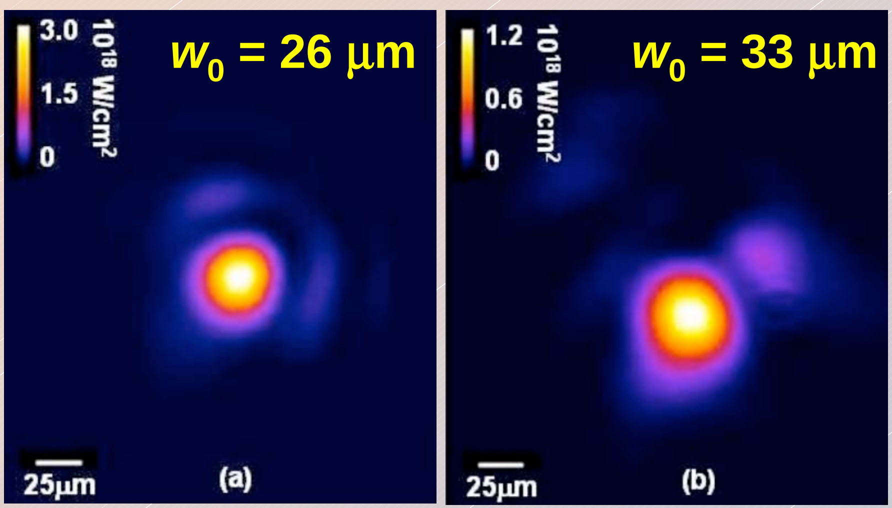


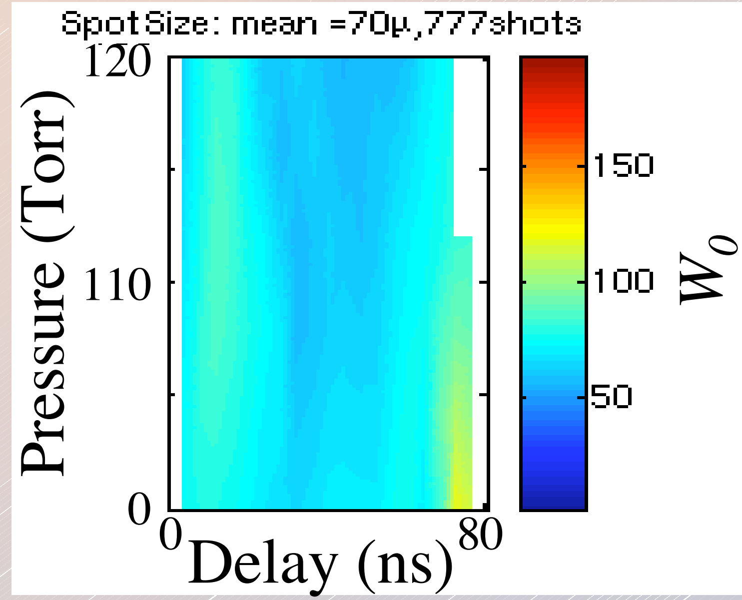
- W.P. Leemans et al., *Nature Physics* **2**, 696 (2006); K. Nakamura et al., *Physics of Plasmas,* **14** 056708 (2007)

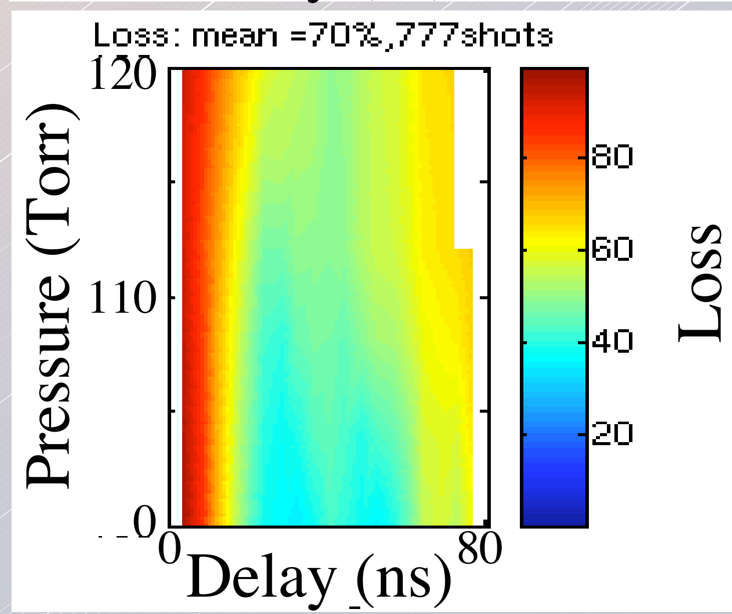
High-power Laser Guiding

- **Guiding achieved over 33 mm:**
  - P = 40 TW; P/Pc ~ 2.5
  - I > 10^{18} W cm^{-2}; a_0 = 1.4;
  - n_e = 2 – 4x10^{18} cm^{-3}
  - T = 10-70 %

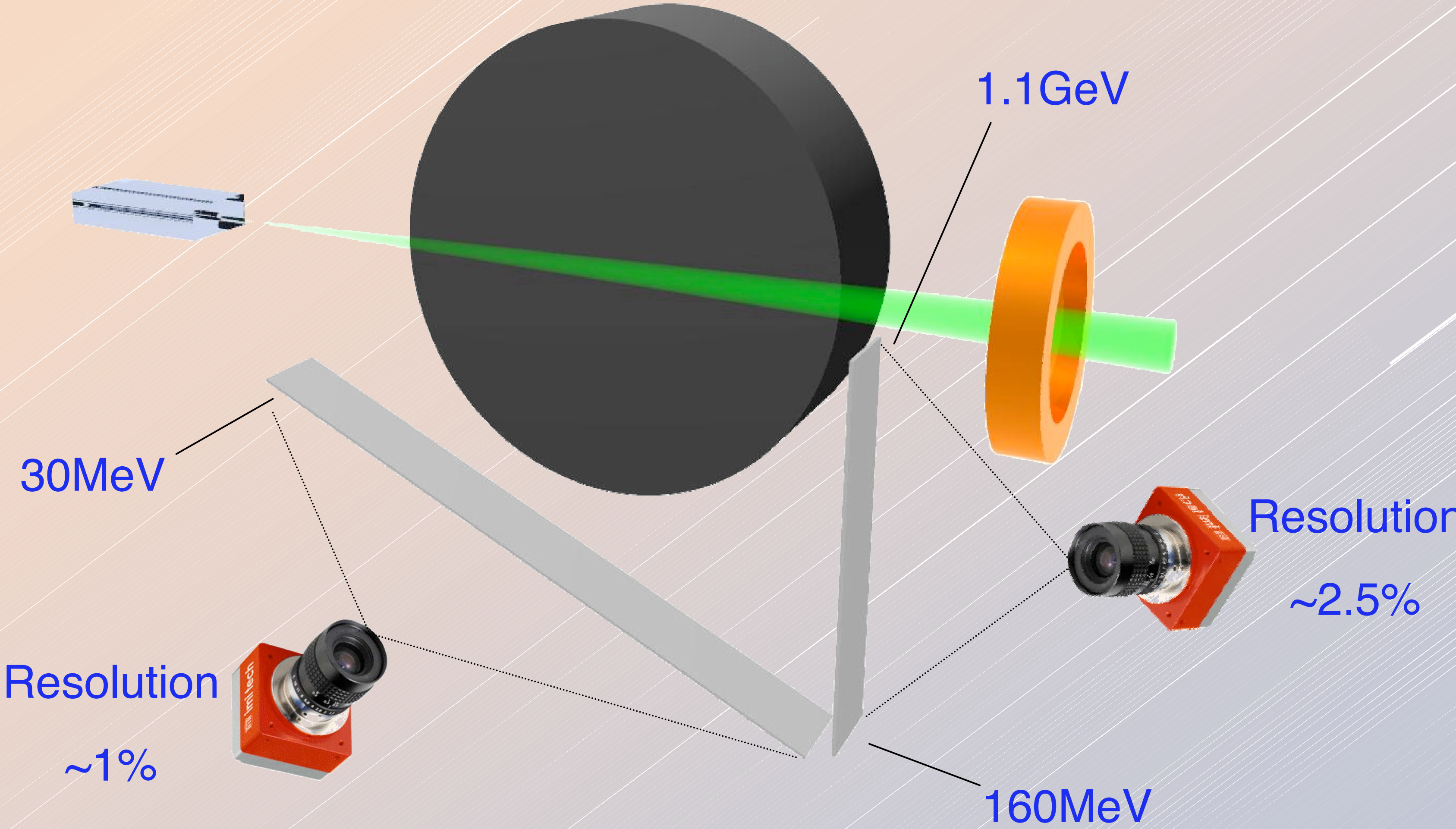
Entrance Exit







LOASIS GeV Electron Spectrometer



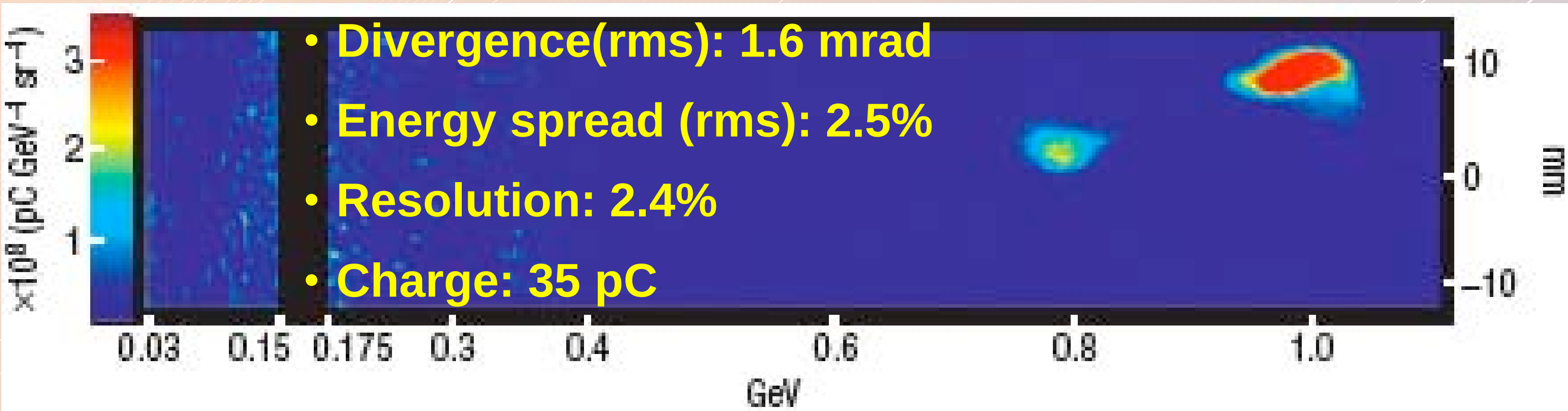
- **Horizontal profile -> divergence; Vertical profile -> energy**

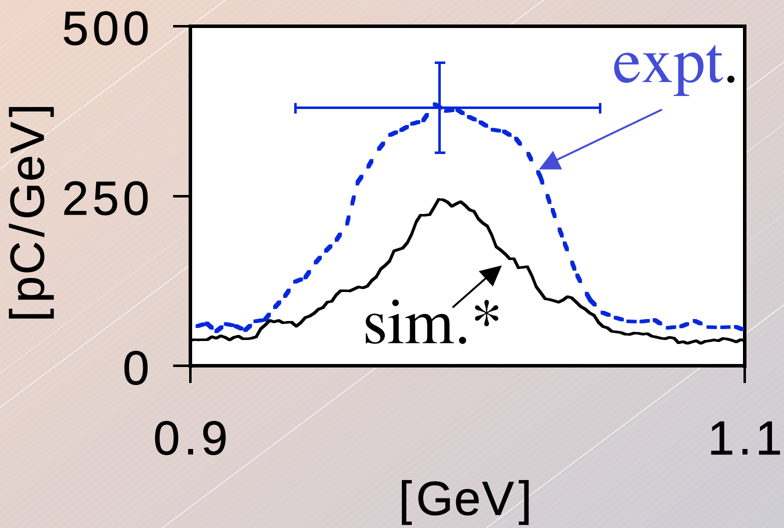
$$\delta E_{obs} = \sqrt{\delta E_{real}^2 + \delta E_{div}^2}$$

First GeV Electron Beam from LWFA

- **Laser: a_0 ~ 1.46 (40 TW, 37 fs)**
- **Capillary: D=312 μm L=33 mm**

1 GEV BEAM

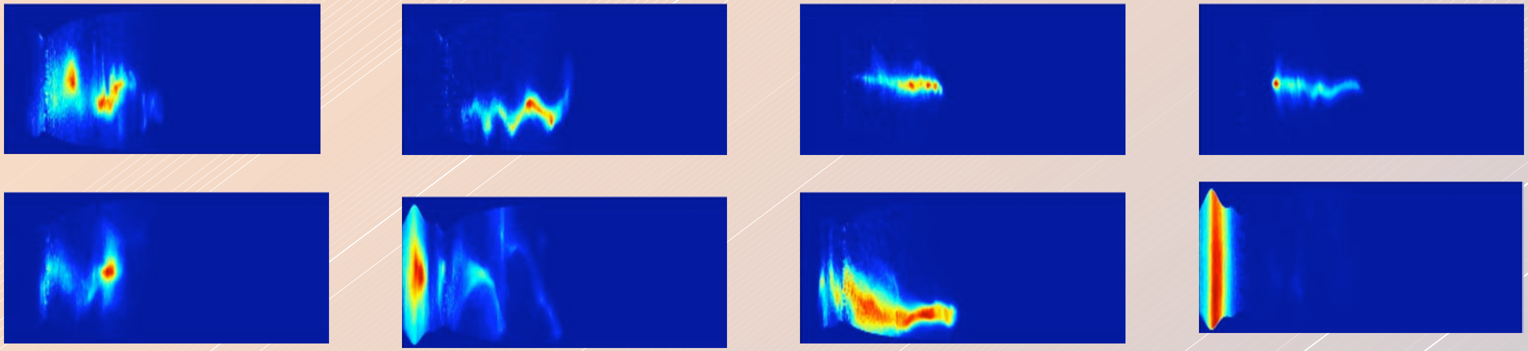




	Sim	Expt
Q (pC)	25-60	35
E (GeV)	1.0	1.1
dE/E RMS (%)	4	2.5
div. (mrad)	2.4	1.6

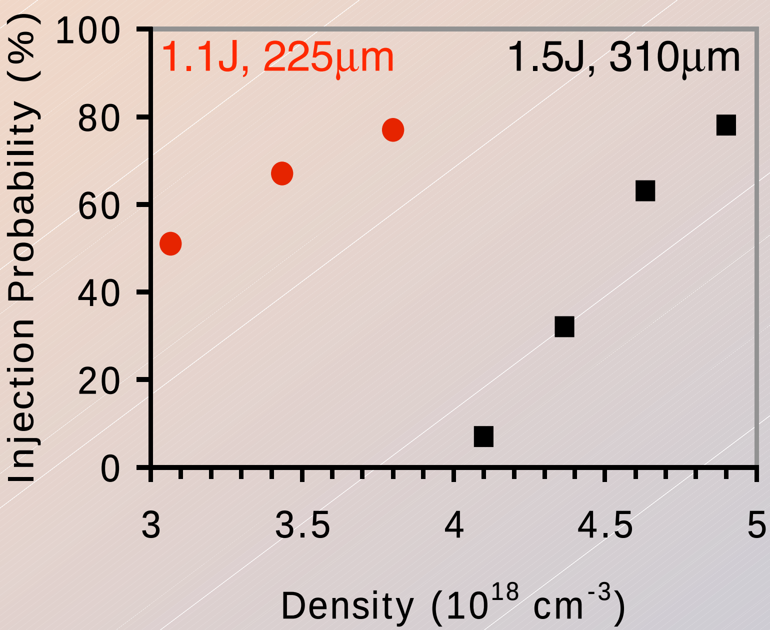
W.P. Leemans et. al, *Nature Physics* **2** (2006) 696; *Simulation using VORPAL

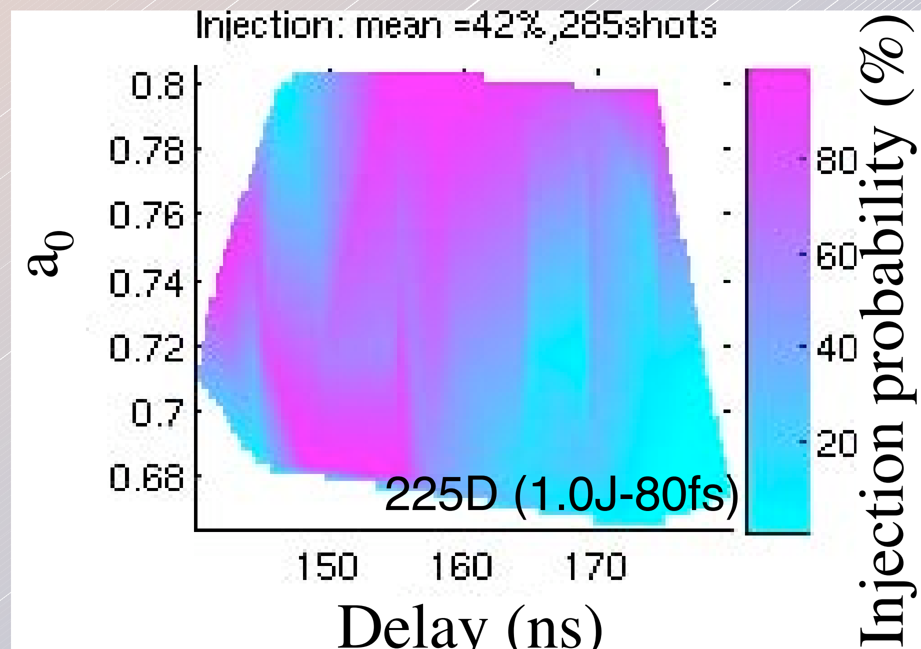
Finding a stable regime



High density, low capillary diameter ⇒ Better injection

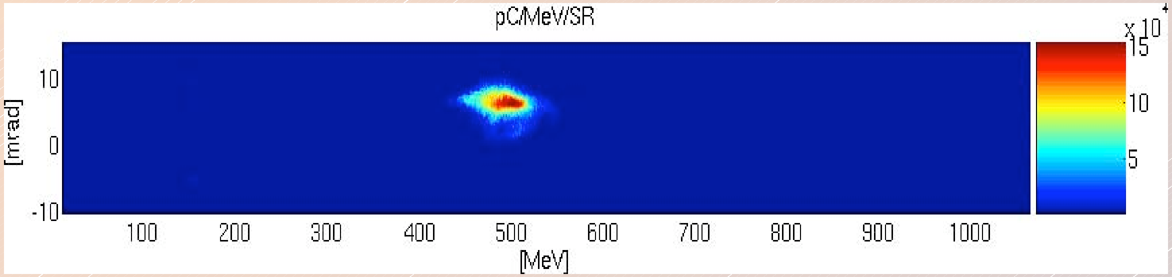
Complicated dependence on laser energy and delay





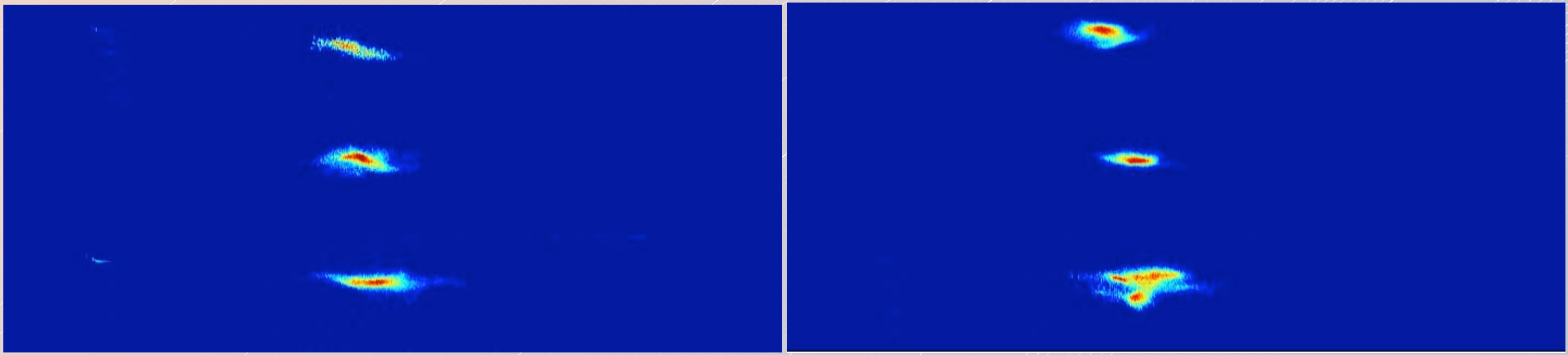
Improved Stability at 500MeV

- **Laser: a_0 > 0.77 (12 TW, 80 fs)**
- **Capillary: 225 μm diameter and 33 mm length** ⇒ **500 MeV beam**
- **n_e = 3.5x10^{18} cm^{-3}**



- Divergence(rms): 1.6 mrad
- Energy spread (rms): 5.6%
- Resolution: 1.1%
- Charge: 50pC

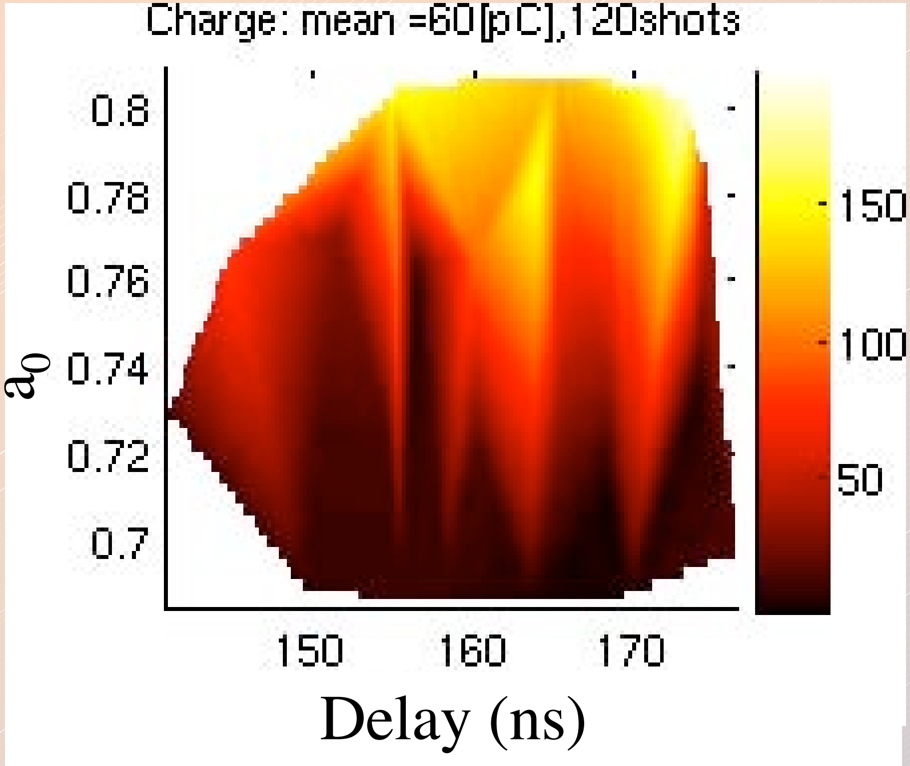
Charge=32±14pC, Energy=456±45MeV, dE/E= 6±3%



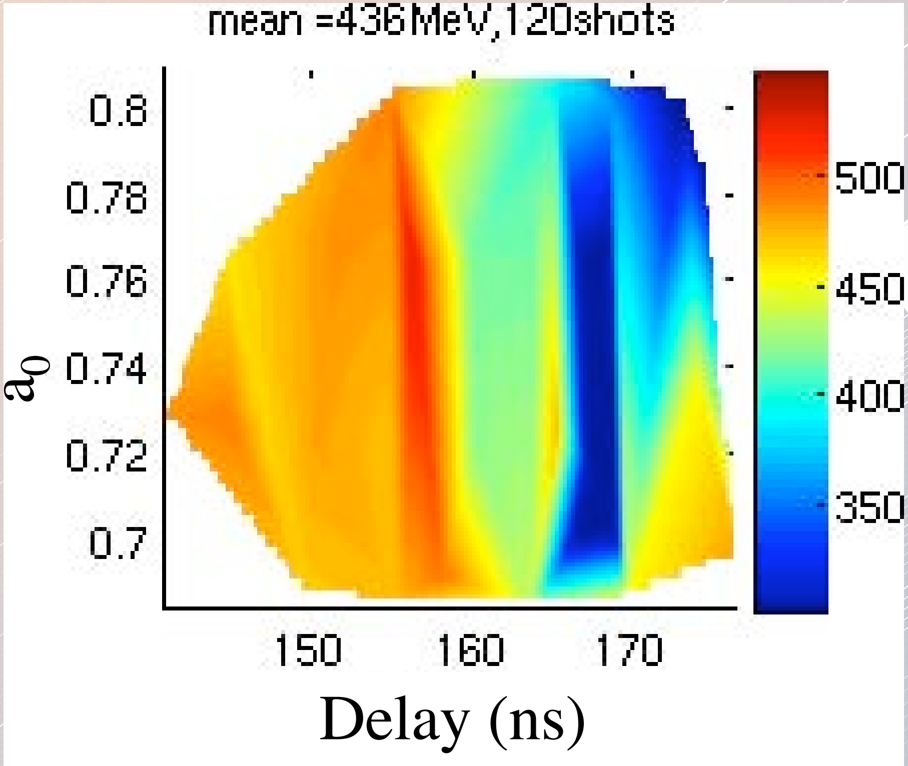
W.P. Leemans et al., *Nature Physics* **2**, 696 (2006); K. Nakamura et al., *Physics of Plasmas,* **14** 056708 (2007)

Controlling Beam Parameters

Charge



Peak energy



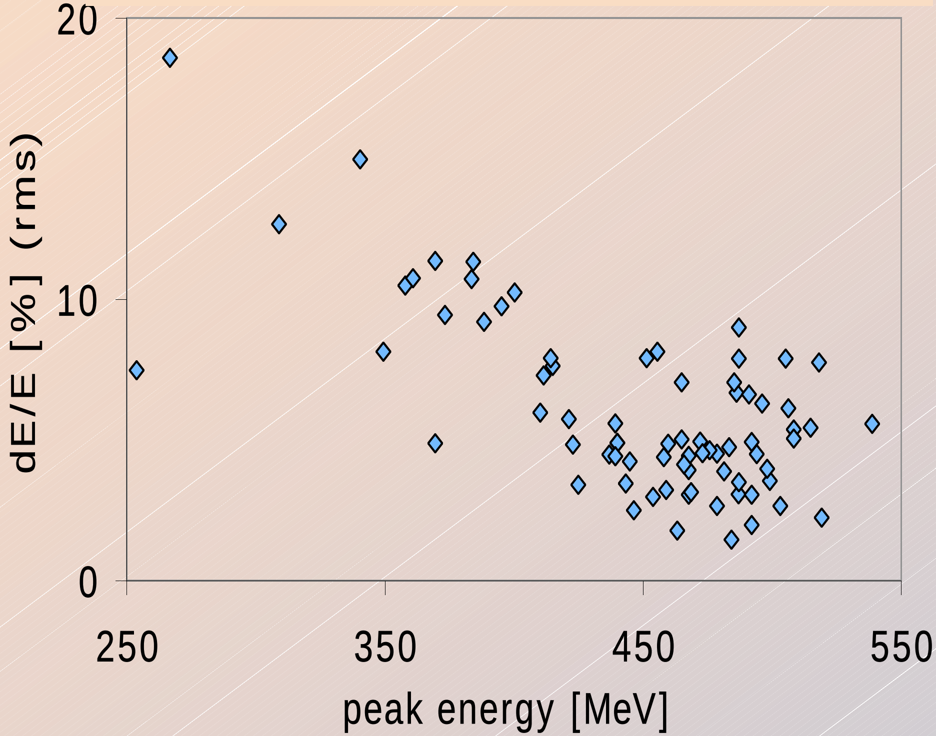
- Higher intensity ⇒ higher charge
- Higher intensity ⇒ lower energy

} Complex delay dependence

Controlling Energy Spread

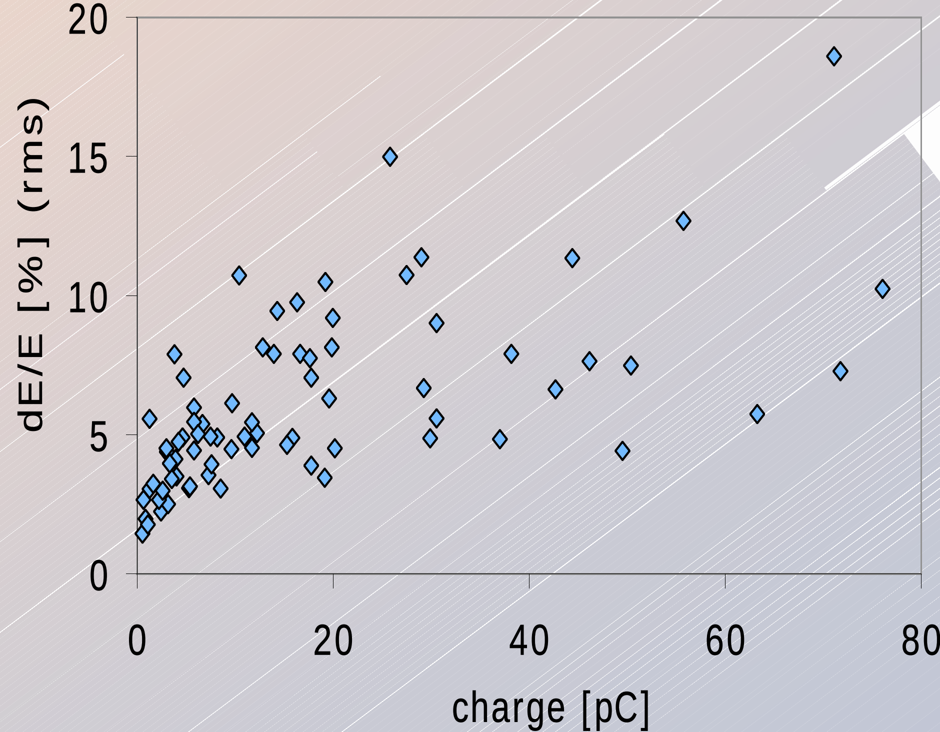
- t = 140-180ns; $a_0 \sim 0.75$; $\tau \sim$ 80fs

Energy Spread vs. Peak Energy



High energy ⇒ low spread

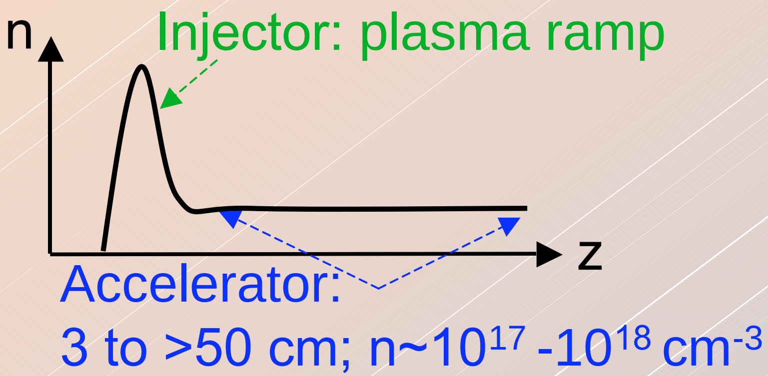
Energy Spread vs. Charge



Low charge ⇒ low spread

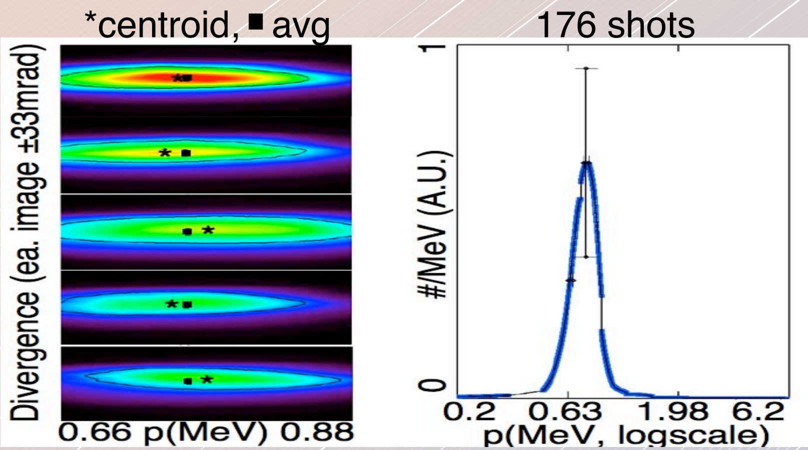
Controlled injection: sub% Energy Spread

- **Injector + capillary**
  - ➢Improved stability
  - ➢Higher Energy
  - ➢Reduced energy spread



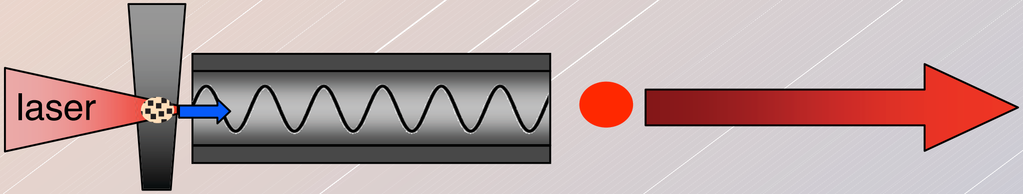
- **MeV injector**

Sequential spectra Average spectrum



170keV/c FWHM spread

20keV/c rms central variation



1-10 GeV e^- beam

*Shadwick et al DPP 2005, **Geddes et al sub. PRL & PAC 2007

Summary

- **Capillary waveguide + 40 TW laser**
  - GeV in 3 cm!!
  - Lower density allowed higher beam energy
  - Requires less laser power than un-guided experiments
  - Stable self-injected beams at 0.5 GeV
  - Further scaling studies under way
- **Next challenges:**
  - Controlled injection + GeV acceleration
  - Stability and phase space control
  - Undulator radiation (diagnostic + FEL)
  - 10GeV