Control, Stability and Staging in Laser Wakefield Accelerators

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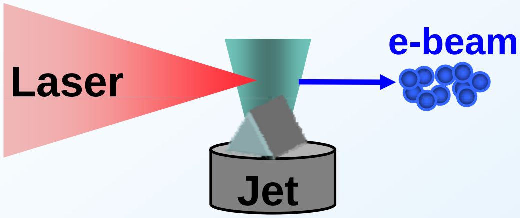
Outline

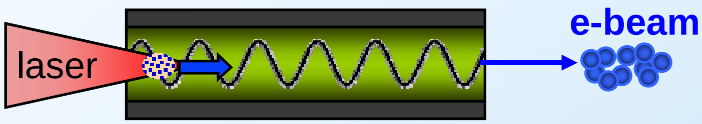
1. Introduction
2. Laser Wakefield Acceleration in Capillary Waveguide
3. Controlled injection
4. Staging
5. Summary

Progress in LWFA

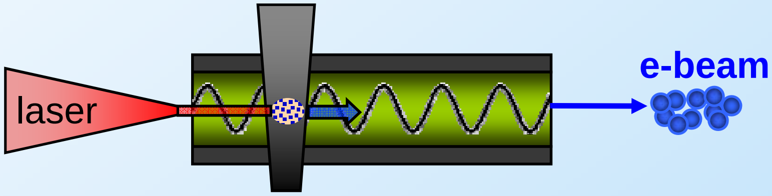
- Self-injection in gas jets – monoenergetic beams



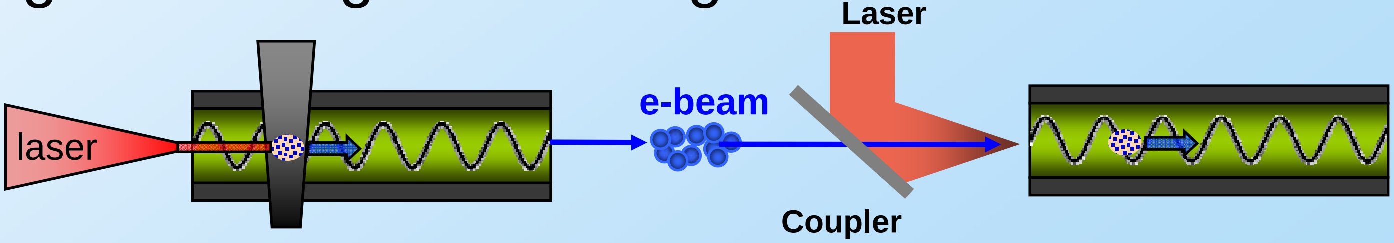
- Self-injection in Capillary – GeV energies



- Controlled injection – stability and tunability

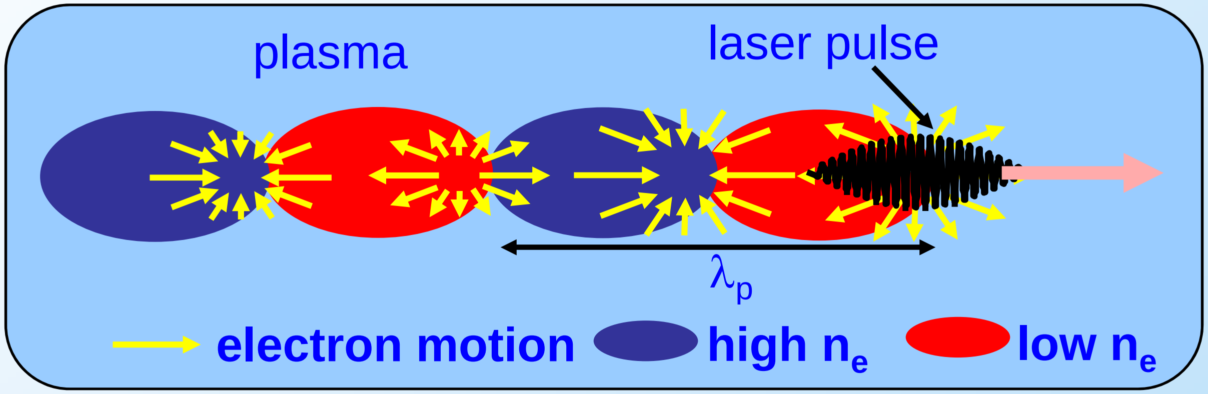


- Staging – toward greater energies



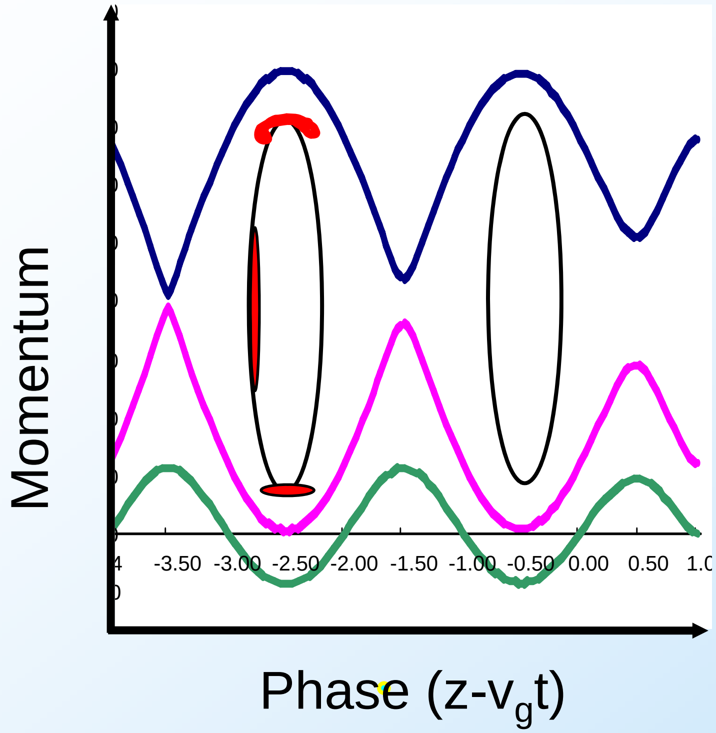
Laser Wakefield Acceleration

- Intense (I~10^{18}W/cm^2) laser field excites plasma wave
- Electrons may become trapped and accelerated
- Accelerating gradients ~100GeV/m



- LWFA allows development of ultra compact electron accelerators *(J. Faure et al, Nature (2004); Mangles et al, Nature (2004); C. Geddes et al, Nature 431 (2004) 538)*

Mechanisms for obtaining high quality beams

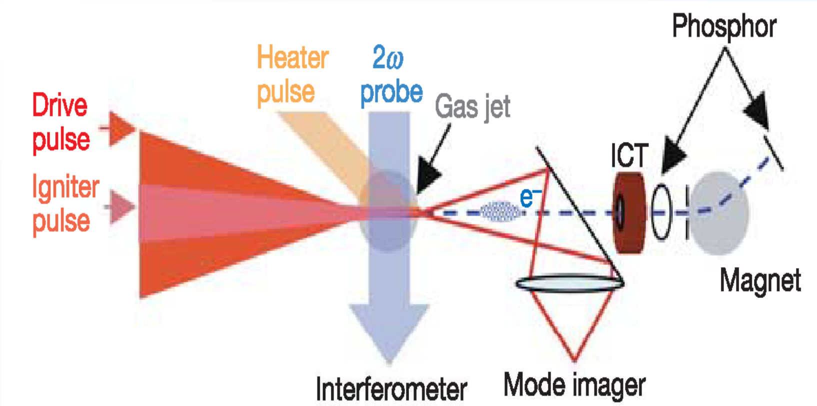


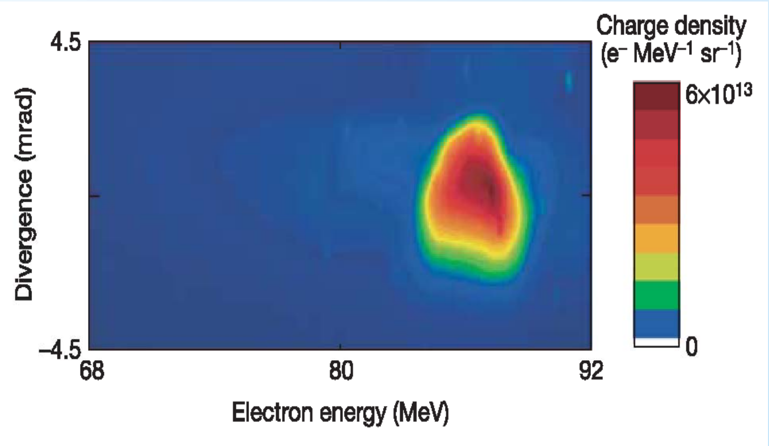
1. Wake excitation
2. Trapping:
   - wave breaking
   - beam loading
3. Acceleration over dephasing length
   - Electrons outrun the wake concentrating in energy

Scaling laws:

- Dephasing Length: $L_D \sim n_e^{-3/2}$
- Energy gain: $\Delta W \sim I / n_e$

Low energy spread beams at 100 MeV using plasma channel guiding





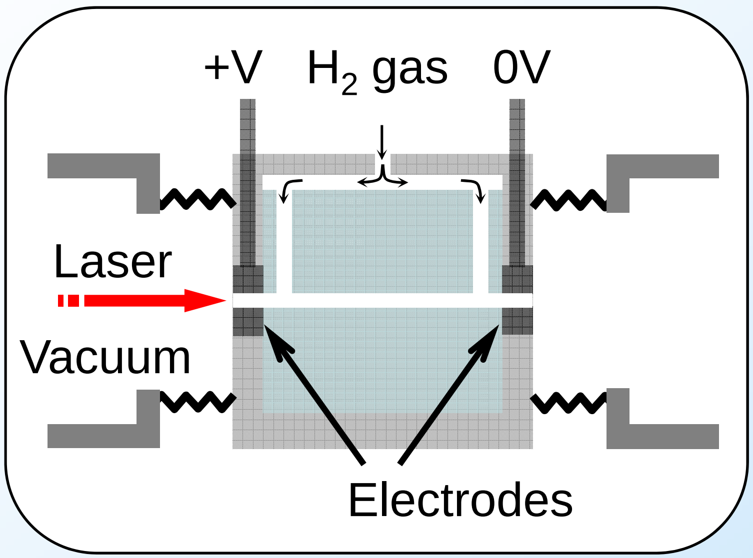
C. G. R. Geddes,et al, "*High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding*", Nature,**431**, p538, 2004

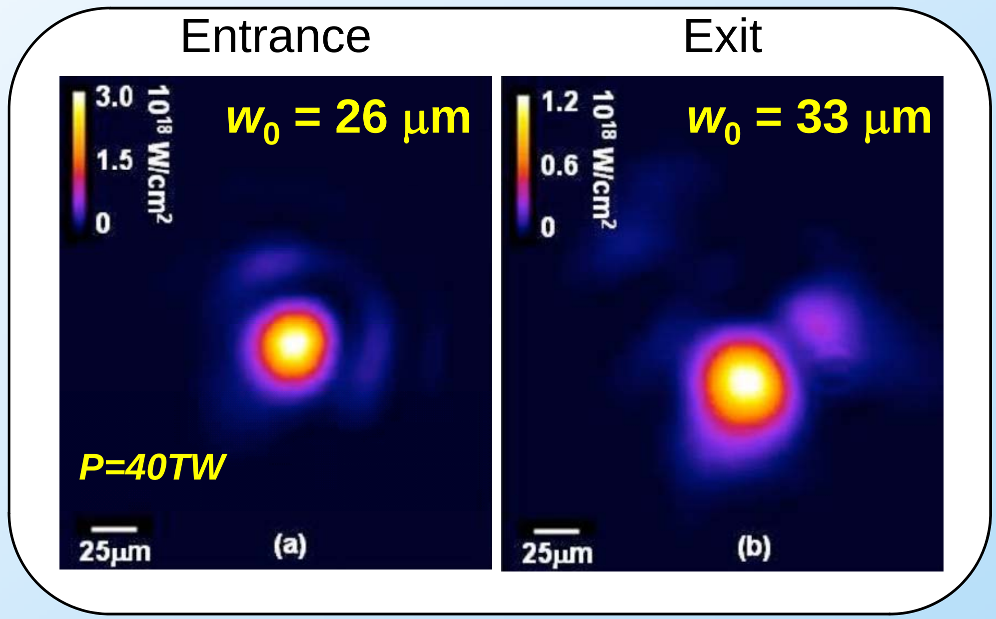
- Hydrodynamic expansion waveguide(n_e~$10^{19}cm^{-3}$) guides laser over >$10Z_r$
- Beam loading controls trapping creating isolated bunch
- Plasma length is matched to the dephasing length generating narrow energy spread (2%) bunches

Increasing beam energy requires increasing dephasing length – lower density

LWFA in capillary waveguides

- Laser heated plasma channel formation at low density is inefficient
- Use capillary plasma channels for cm-scale, low density plasma channels



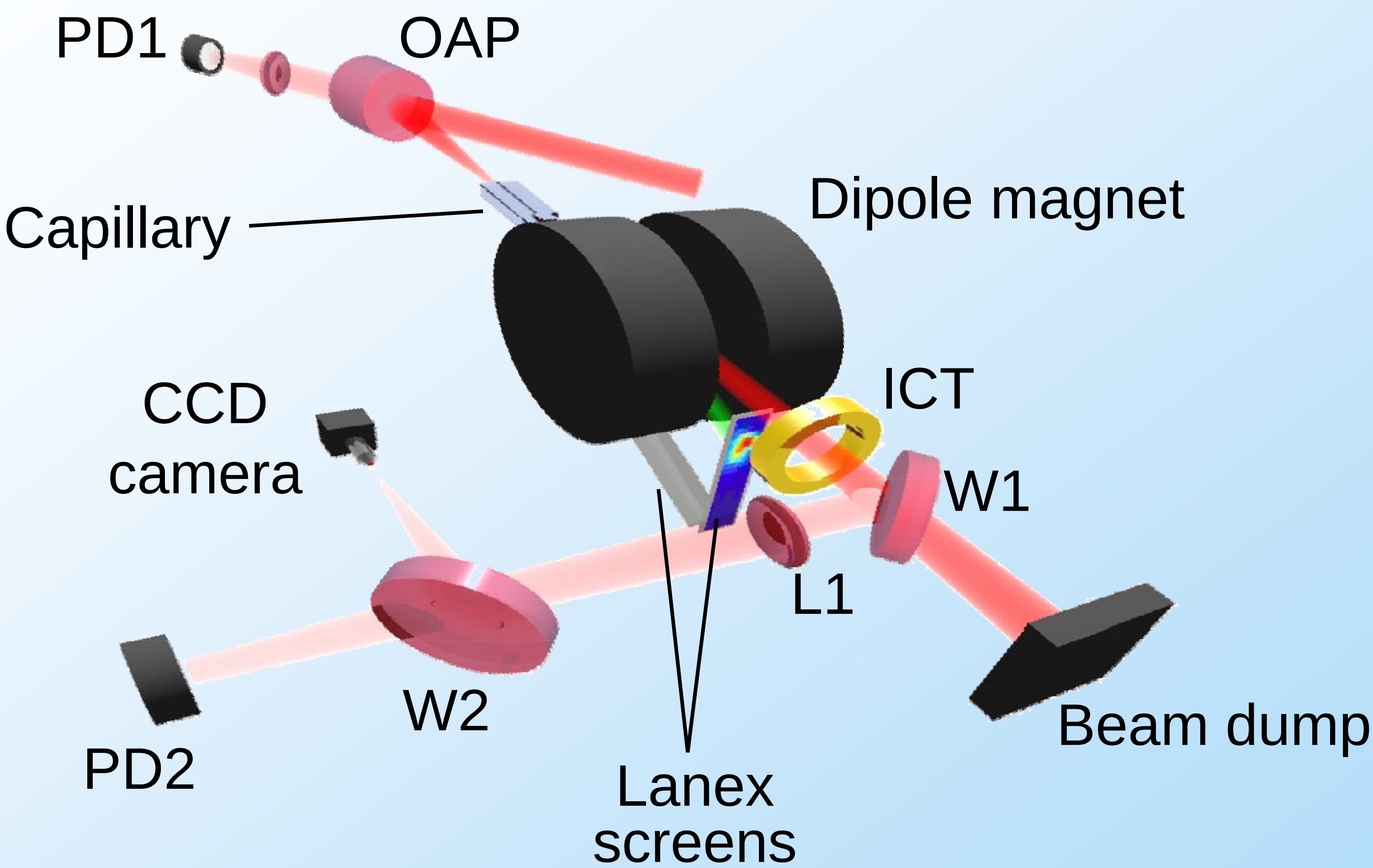


Capillary:

- Laser machined in sapphire
- High voltage discharge ionizes gas (n_e~$1x10^{18}cm^{-3}$)
- Guiding channel forms due to thermal balance between walls and ohmic heating

A.J.Gonsalves et. al. PRL (2007), W.P. Leemans et al., Nature Physics (2006);

Experimental Setup for GeV Accelerator

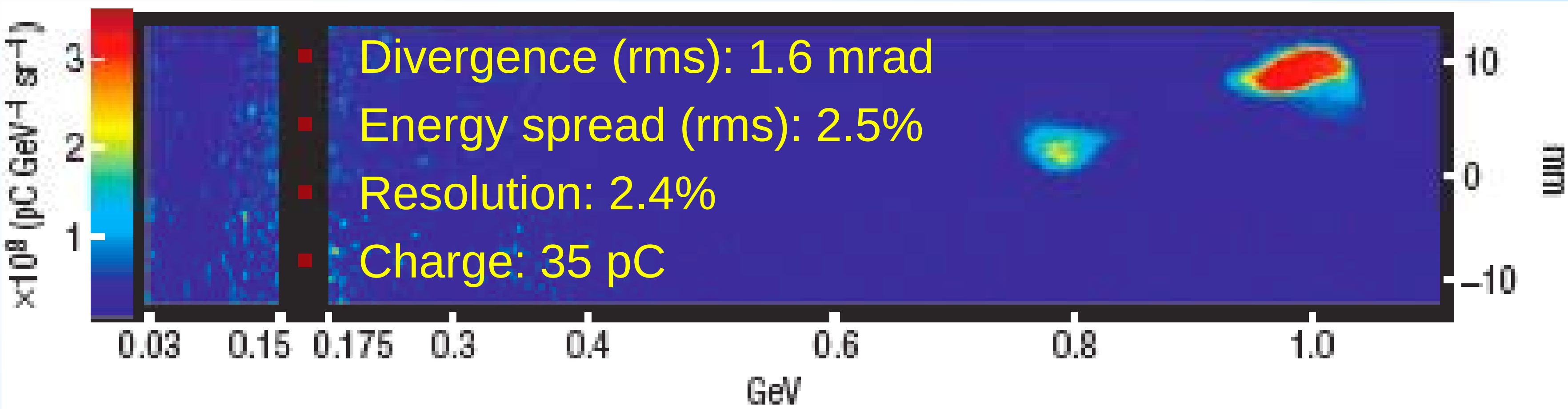


W.P. Leemans et al., *Nature Physics* **2**, 696 (2006); K. Nakamura et al., *Physics of Plasmas,* (2007)

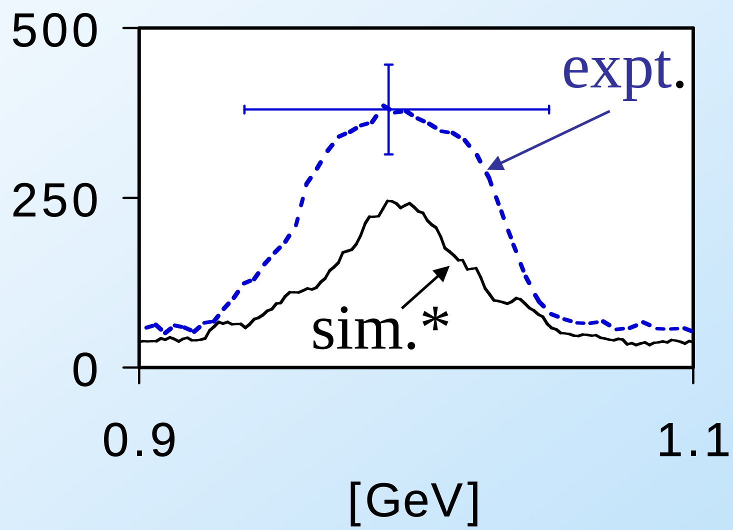
First GeV Electron Beam from LWFA

- Laser: a0 ~ 1.46 (40 TW, 37 fs)
- Capillary: D = 312 mm; L = 33 mm

1 GeV beam



- Divergence (rms): 1.6 mrad
- Energy spread (rms): 2.5%
- Resolution: 2.4%
- Charge: 35 pC

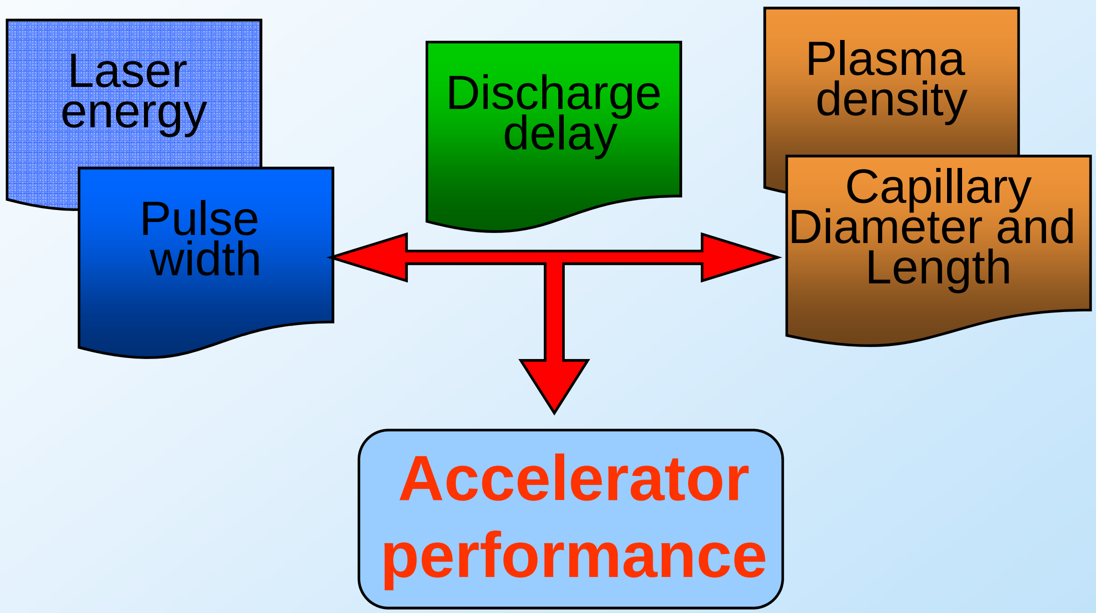


	Sim	Expt
Q (pC)	25-60	35
E (GeV)	1.0	1.1
dE/E RMS (%)	4	2.5
div. (mrad)	2.4	1.6

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

Control parameters and stability

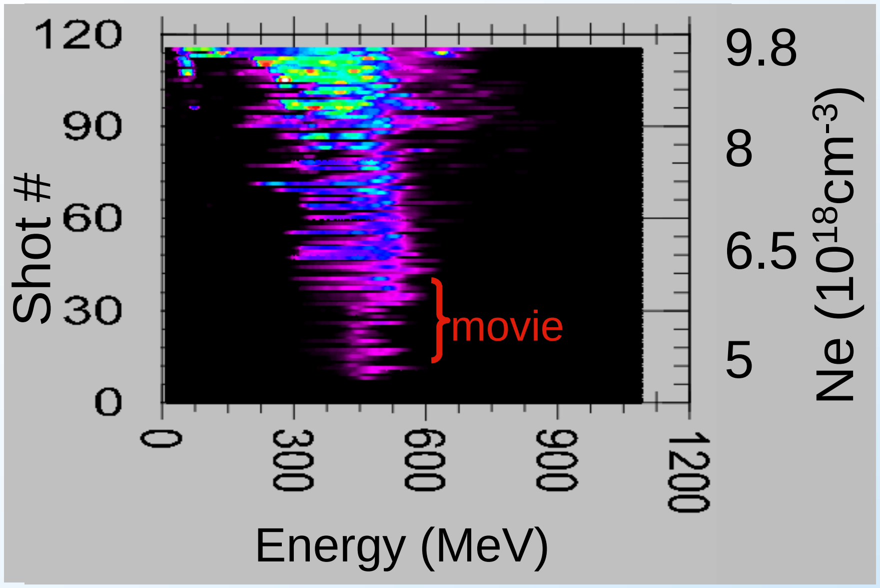
Accelerator parameter space for tunability and control:

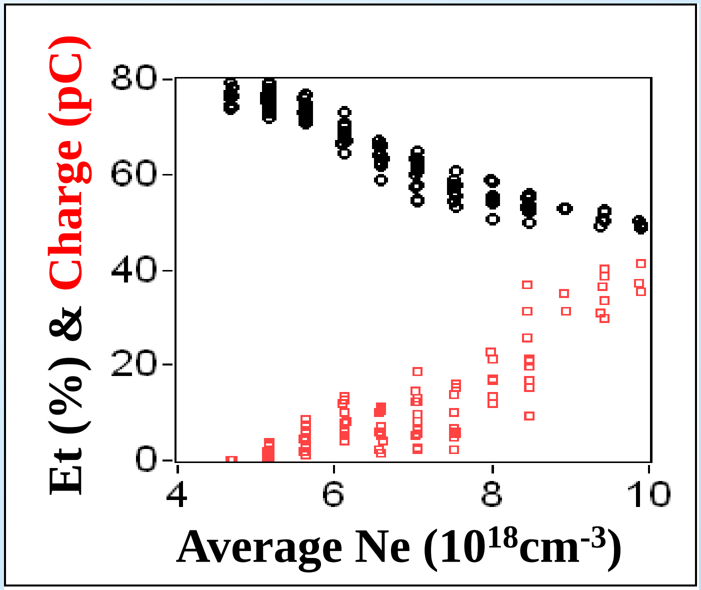


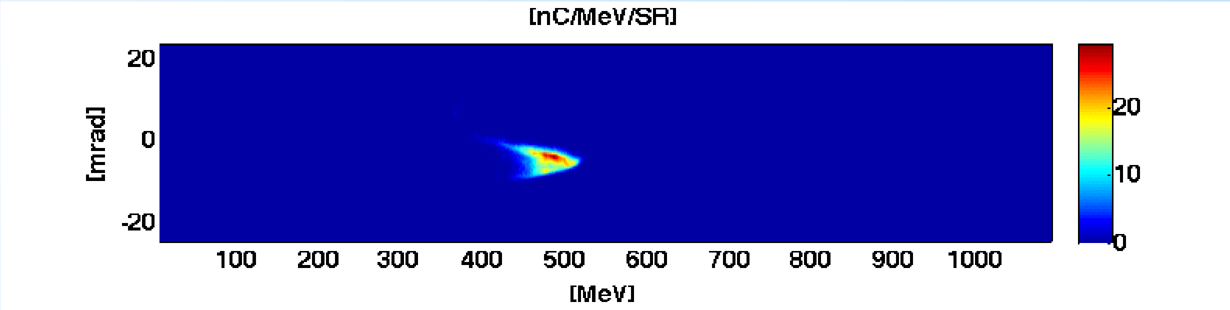
Parameter space of laser system and plasma channel has to be explored to discover control “knobs” and stable conditions

Example 2: Density

Density dependence for L = 33 mm, D = 300 μm cap. a_0=0.95







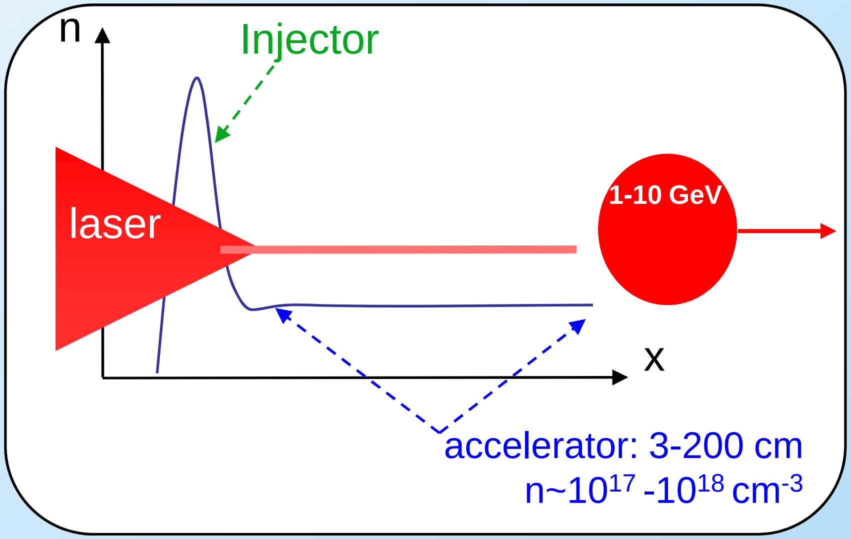
Available controls not flexible enough to optimize all the parameters of the e-beam

Towards greater control – separating injection and acceleration

- Laser triggered injection*
- Density triggered injection**
  - Longitudinal modulation of density

Longitudinally decreasing plasma density results in phase velocity decreasing with propagation, reduces trapping threshold

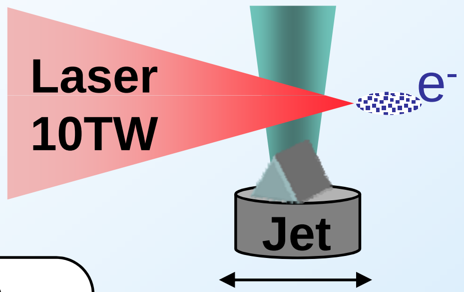
Approach to staged injector+accelerator:

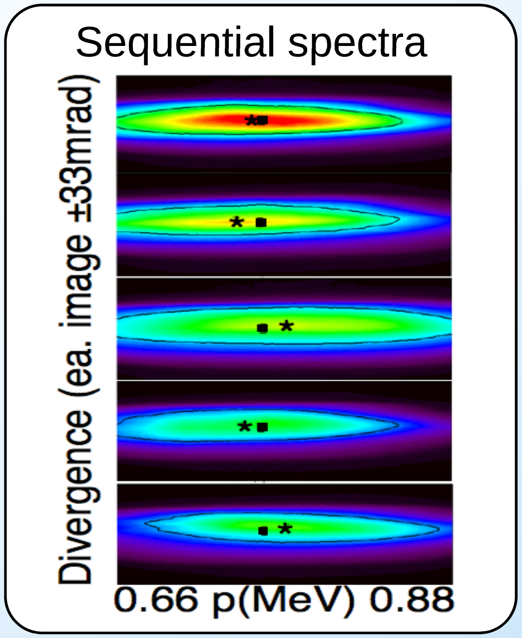


*J.Faure et. Al. Nature(2006)
** Bulanov et al. Phys. Rev.E (1998)

Experimental demonstration of density downramp injection

Laser focused on downramp of gas jet density profile:





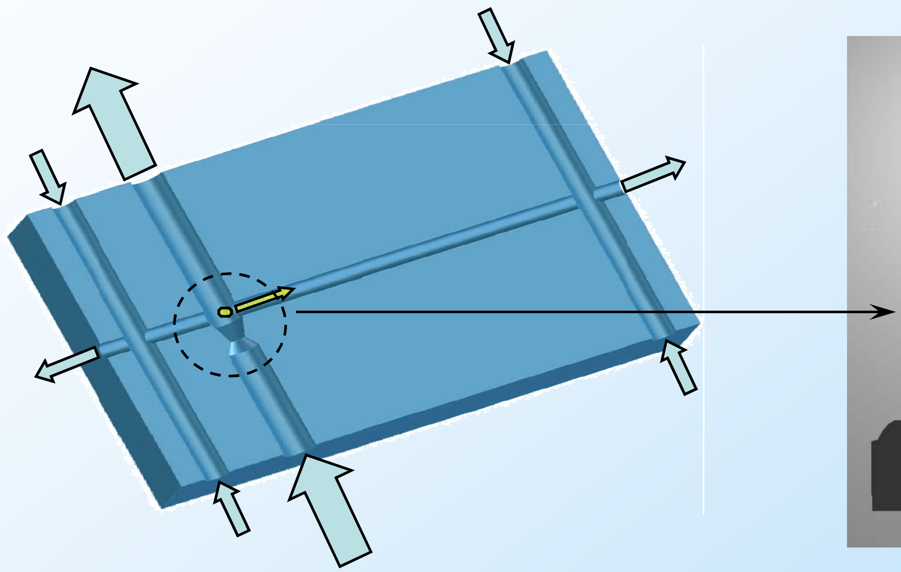
- Low absolute energy spread (170keV)
- Low divergence (20 mrad)
- Good stability
  - Central energy (760keV ± 20keV rms)
  - Energy spread (170 keV ± 20keV rms)
  - Beam pointing (1.5 mrad rms)

Density down ramp is suitable for use as injector

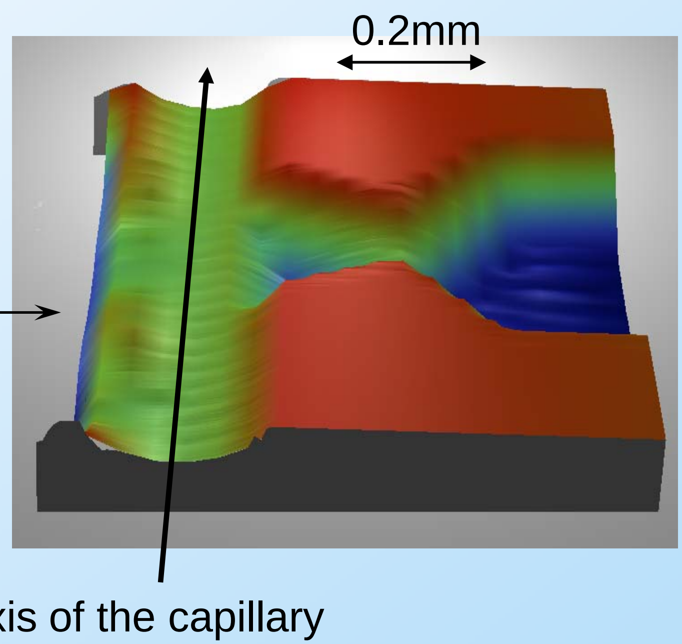
Geddes et.al. PRL (2008)

Designing integrated downramp injector in capillary

- Gas jet nozzle laser machined in the capillary:

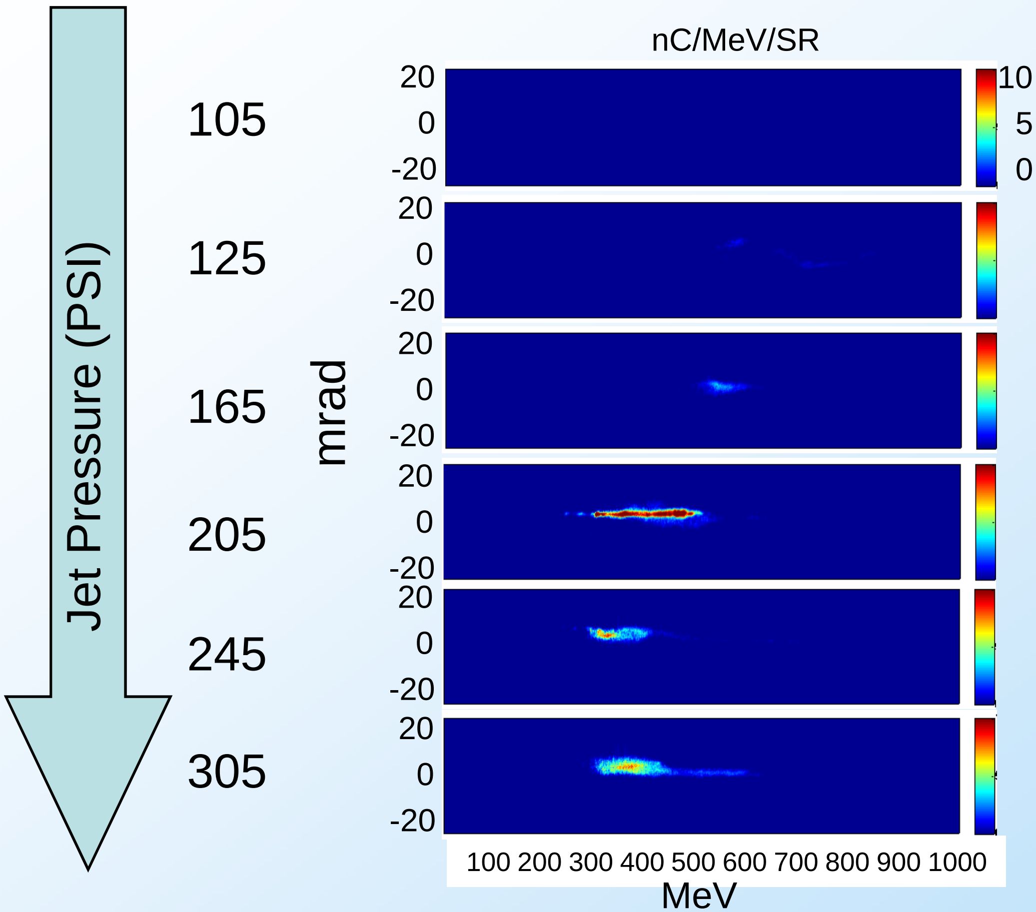


- Measured 3D profile



Gas jet integrated with capillary waveguide provides density modulation for e^- injection

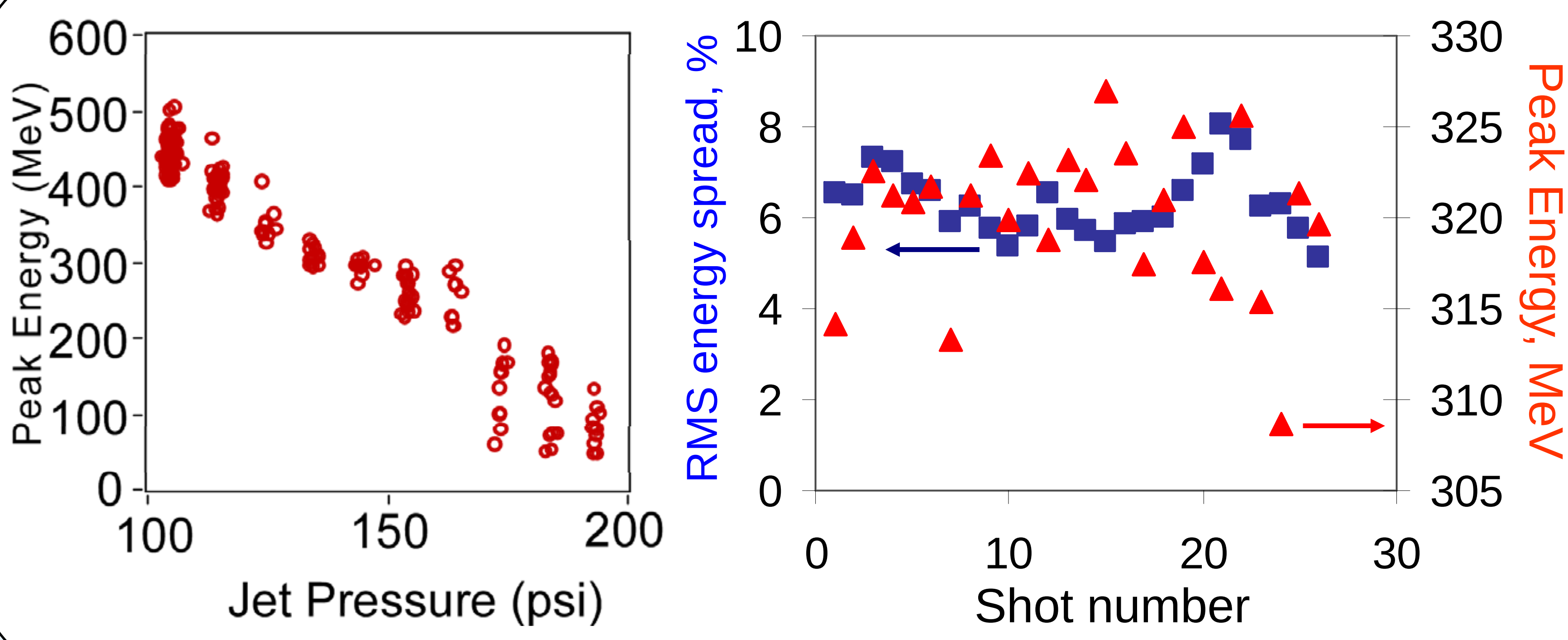
Injection controlled with gas jet pressure



- Capillary pressure too low for injection without jet
- Threshold jet pressure approx 125 psi
- Parameters
  - On-axis density 1.3 x 10^{18} cm^{-3}
  - Pulse length 45 fs
  - a_0 1.1 (25TW)

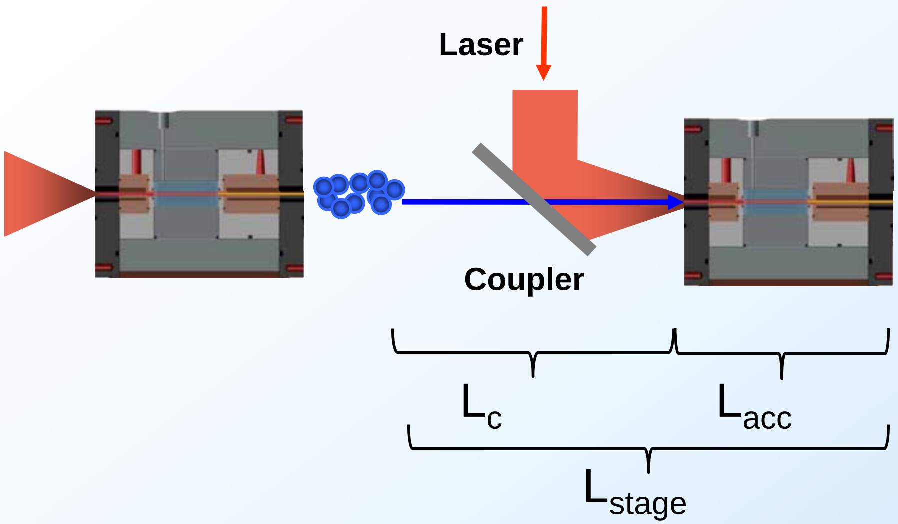
Stable Beams and Indications of Energy Control

Input Parameters: N_e = 2.1 x 10^{18} cm^{-3} , a_0 = 1.1 (25TW), Laser pulse length = 45 fs

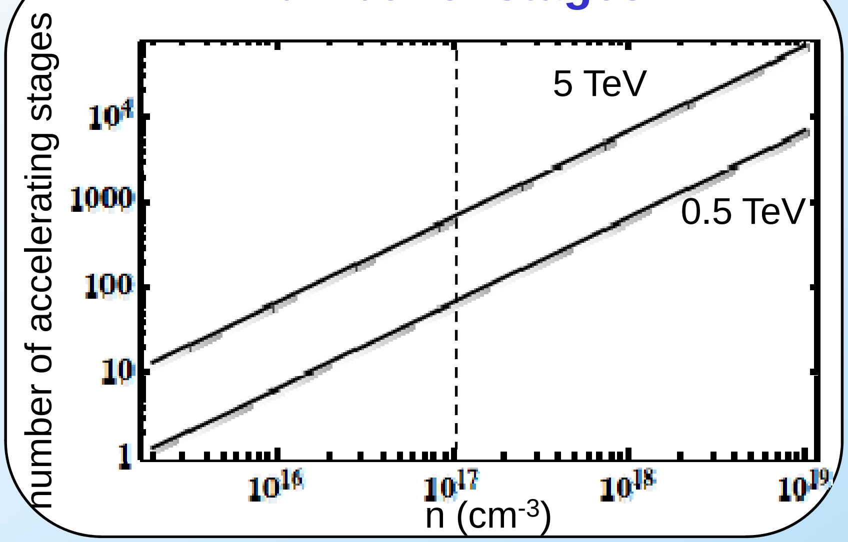


- Electron beam energy controlled by gas jet pressure
- Low energy spread beams generated over all range of gas jet pressures

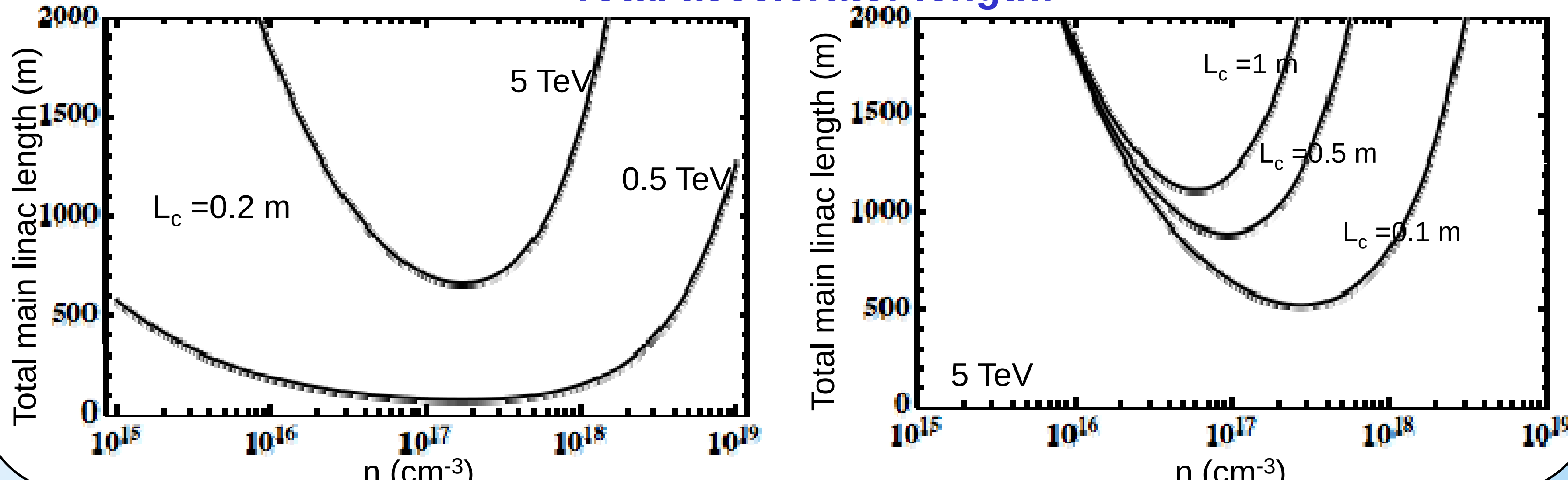
Towards higher energies – staging of laser accelerators



Number of stages:

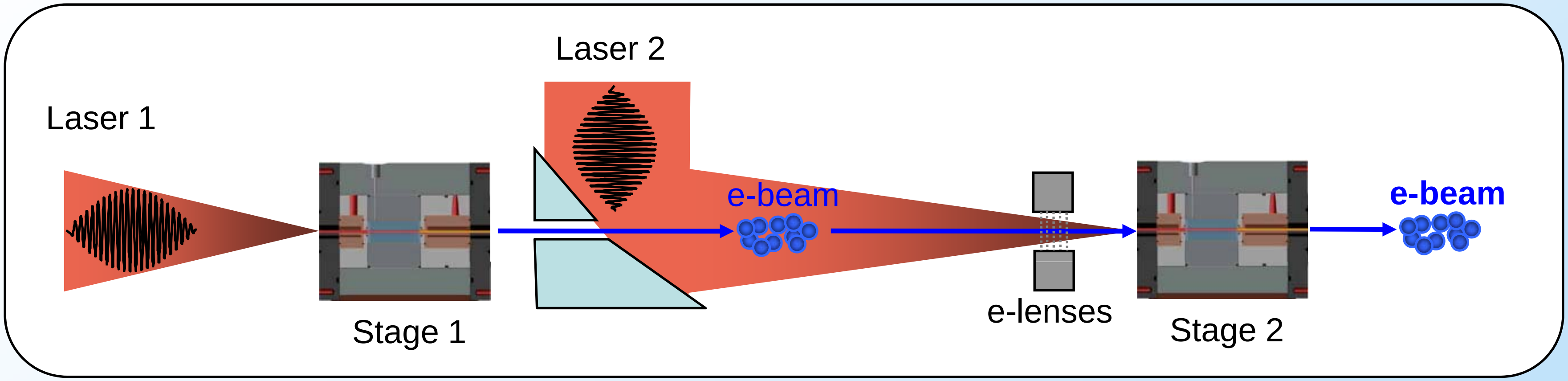


Total accelerator length:



Approach to laser beam incoupling

Direct approach:



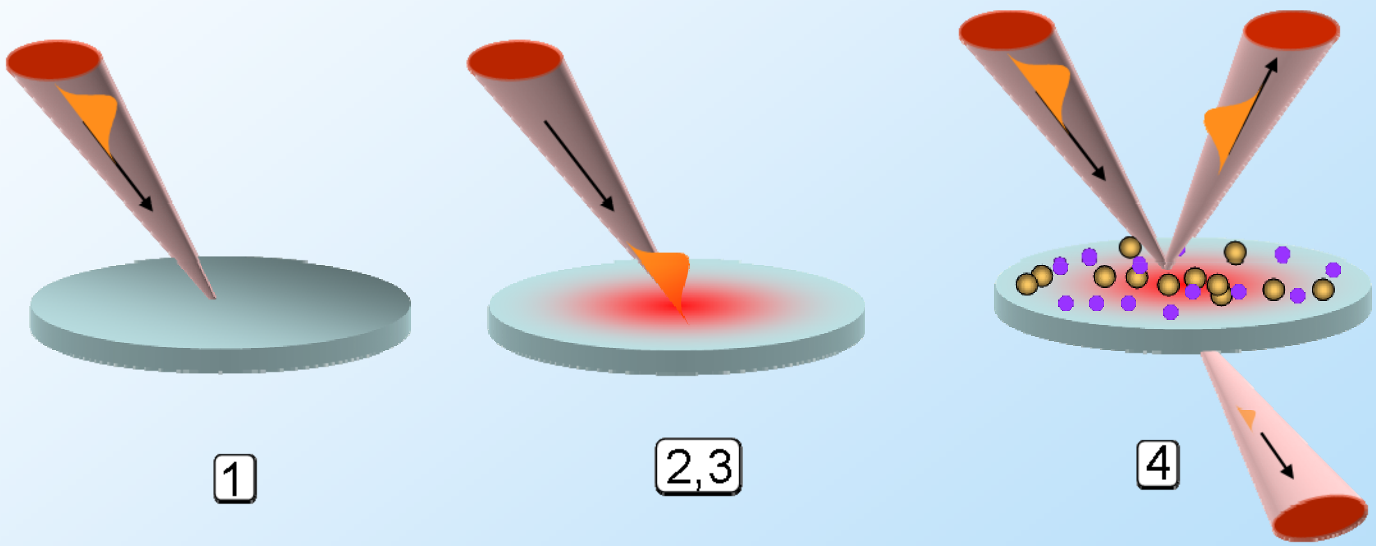
Minimum distance between the stages is limited by mirror breakdown (~10m)

- Need electron beam transport
- Acceleration gradient decreased to ~1GV/m

Alternative approach - use reflection from supercritical plasma – plasma mirror

Principles of plasma mirror

1. Intense laser pulse is incident on dielectric
2. Ionization and plasma formation occurs on the leading edge of the pulse ('Triggering' intensity ~ 10^{14} *W/cm*^{2})
3. Plasma density grows reaching critical density ($n_p=2\text{x}10^{21}cm^{-3}$ for $\lambda=0.8\mu m$)
4. Main part of the pulse reflects from supercritical plasma surface



Plasma mirror is an established method for improving pulse contrast

G. Doumy et. al. Phys. Rev. E (2004), B.Dromey, Rev. of Sc. Instr. (2004), C. Thaury, Nature Phys. (2007)

Plasma mirror for accelerator staging

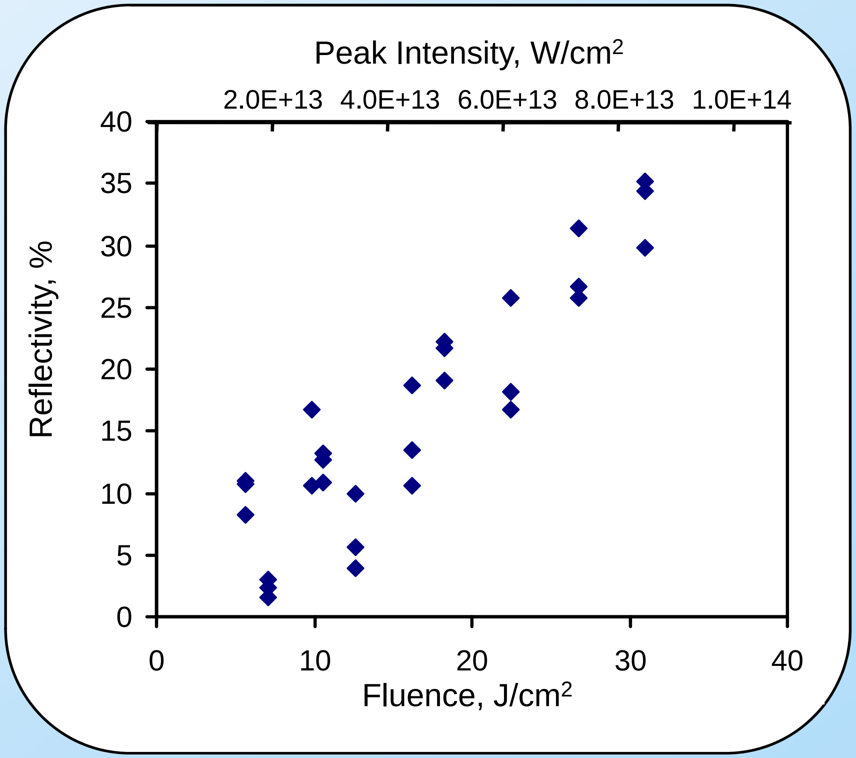
- Plasma mirror operates at intensities ~10^{16}W/cm^2

  ⇒ Can be much closer to laser focus

- Reduces minimum distance between stages to cm scale

Liquid jet plasma mirror:

- provides renewable surface
- water jet: non-contaminating for conventional optics



Summary and Conclusions

- LWFA are generating stable beams with narrow energy spread and small divergence
- Exploring parameters - better understanding of physics involved
- Controlled injection offers superior stability and control
- Staging promises future applicability to high energy physics