High Quality GeV Electron Beams from Laser-Plasma Accelerators

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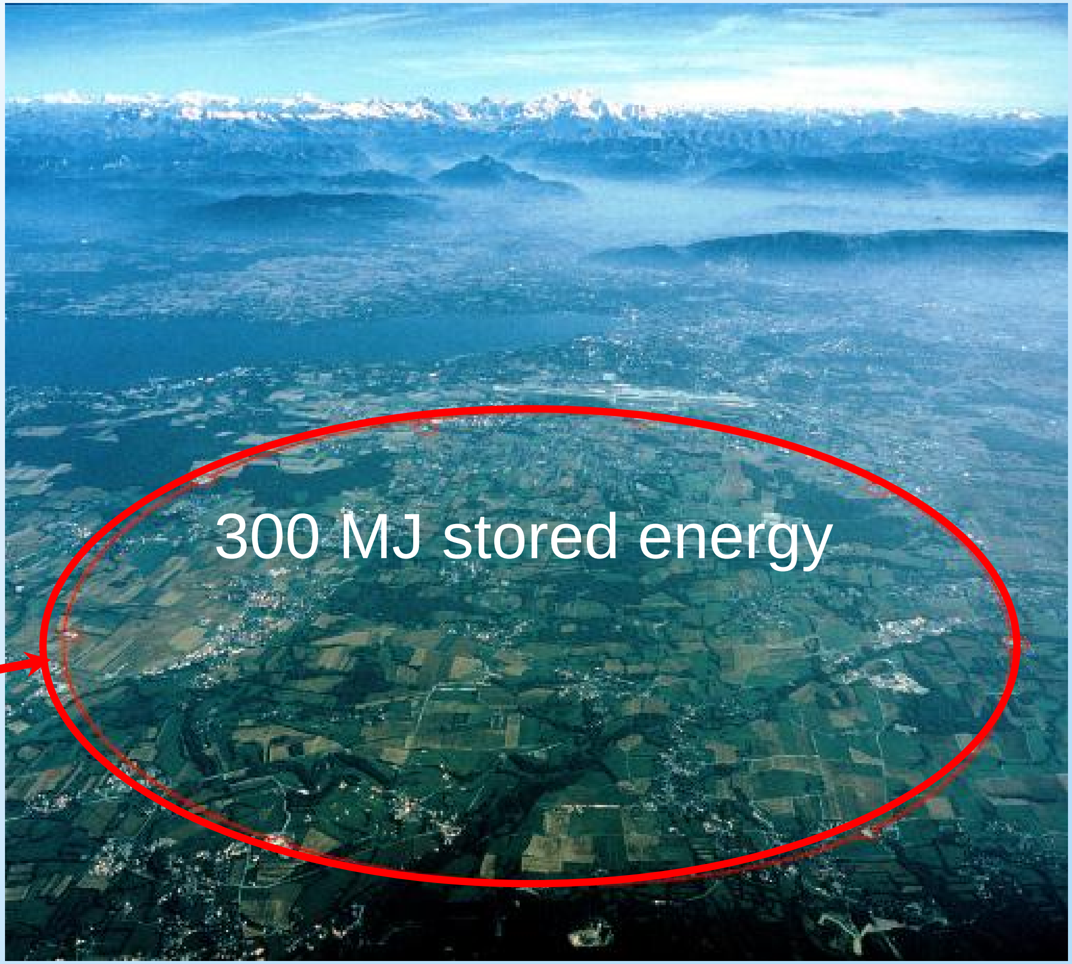
http://loasis.lbl.gov/

Accelerators: from handheld to size of a small country

1929

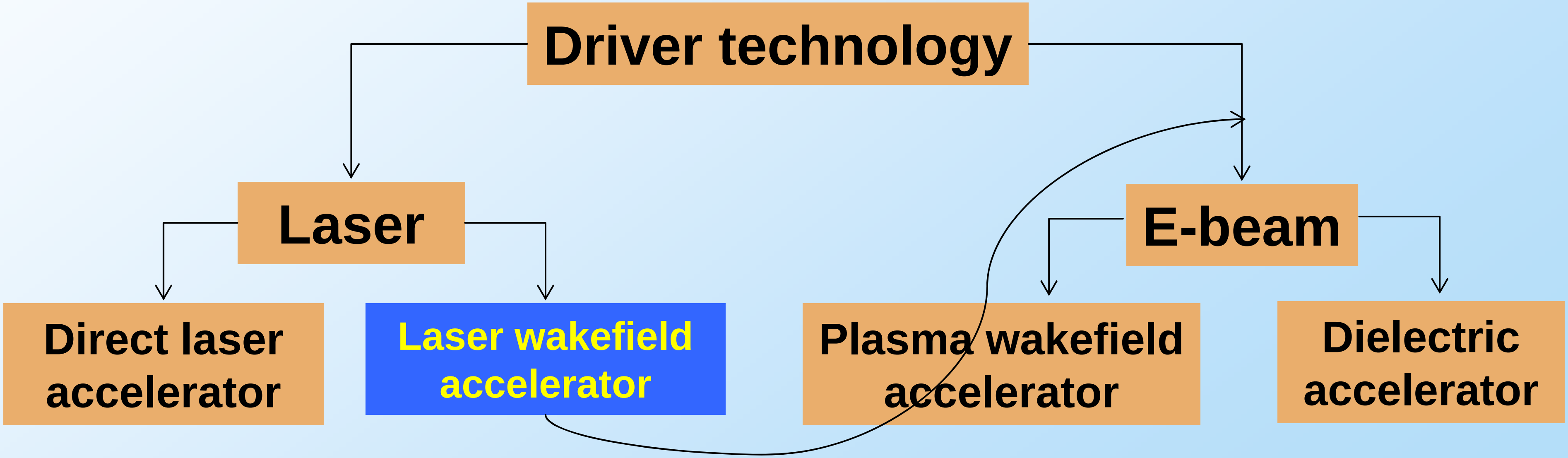
LHC, 2008



Size x 10^5 Energy x 10^9

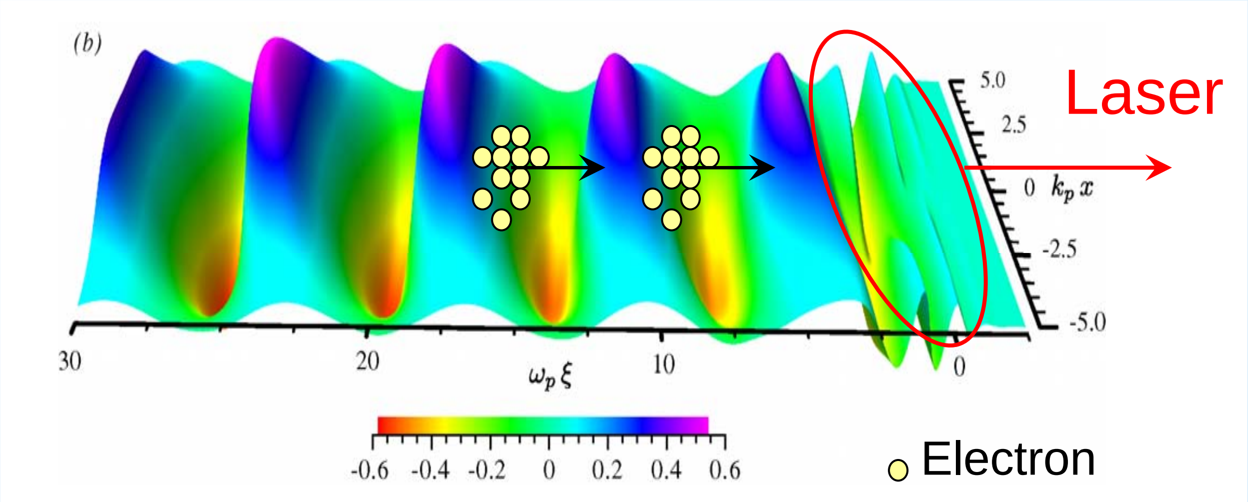
Motivation and overview

- Collider size set by maximum particle energy and maximum achievable gradient: breakdown limitation
- Plasma accelerators 1000 x higher gradient
- Motivates R&D for ultra-high gradient technology



Linear laser/plasma wakefield accelerator

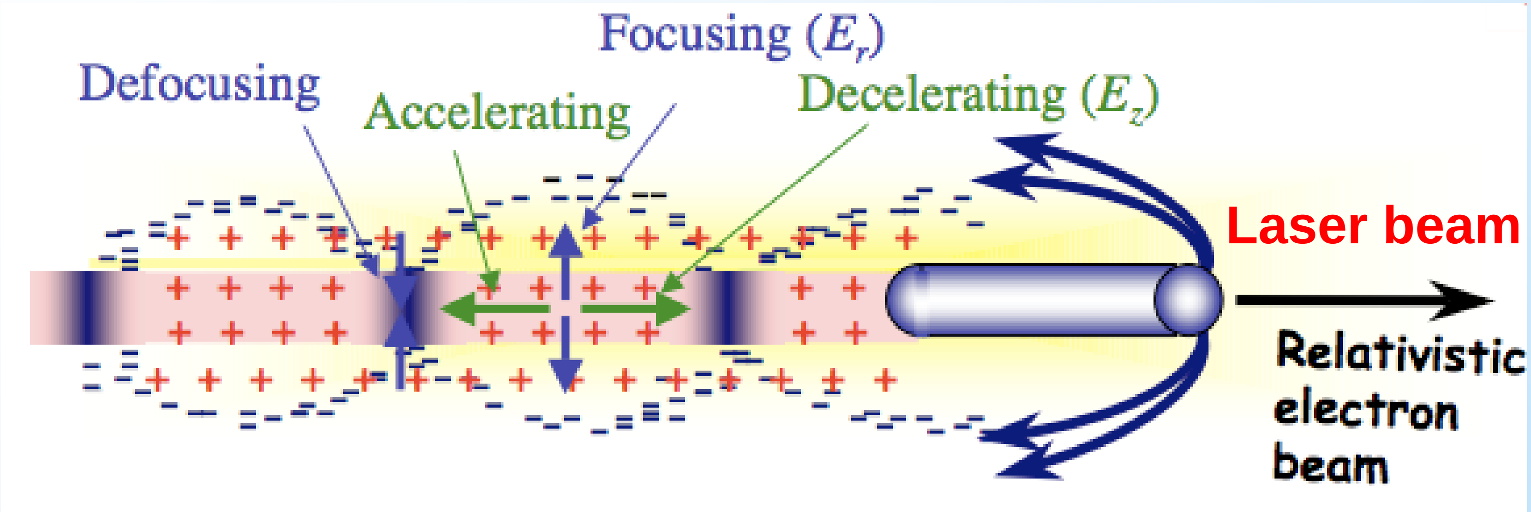
Laser in plasma displaces electrons
Wake velocity = Group velocity of light



- 10's to 100's GV/m, scales as $\sqrt{n}$
- Accelerate e^- and e^+
- Must provide laser guiding mechanism: no non-linear self-guiding
- Must provide injection mechanism: no self-trapping

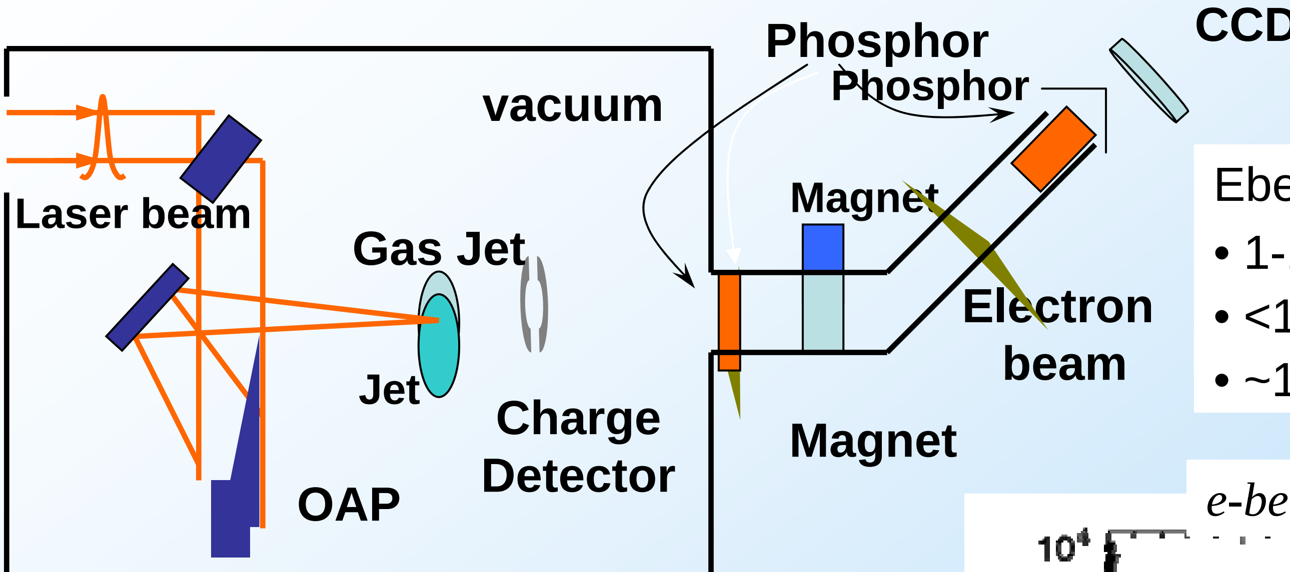
T. Tajima and J.M. Dawson, PRL 1979

Non-linear laser/plasma wakefield accelerator



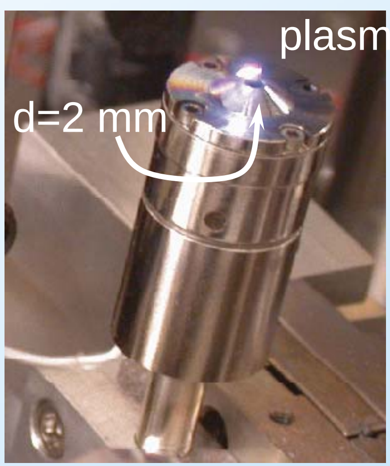
- Blow-out or bubble regime
  - Large gradients
  - Self-trapping
- Two major experimental results:
  - GeV with few % ΔE/E in 3 cm using a laser (LBNL)
  - Up to 85 GeV electrons using a 42 GeV beam (SLAC)
- Insufficient control
- Ineffective for positrons: very small accelerating region

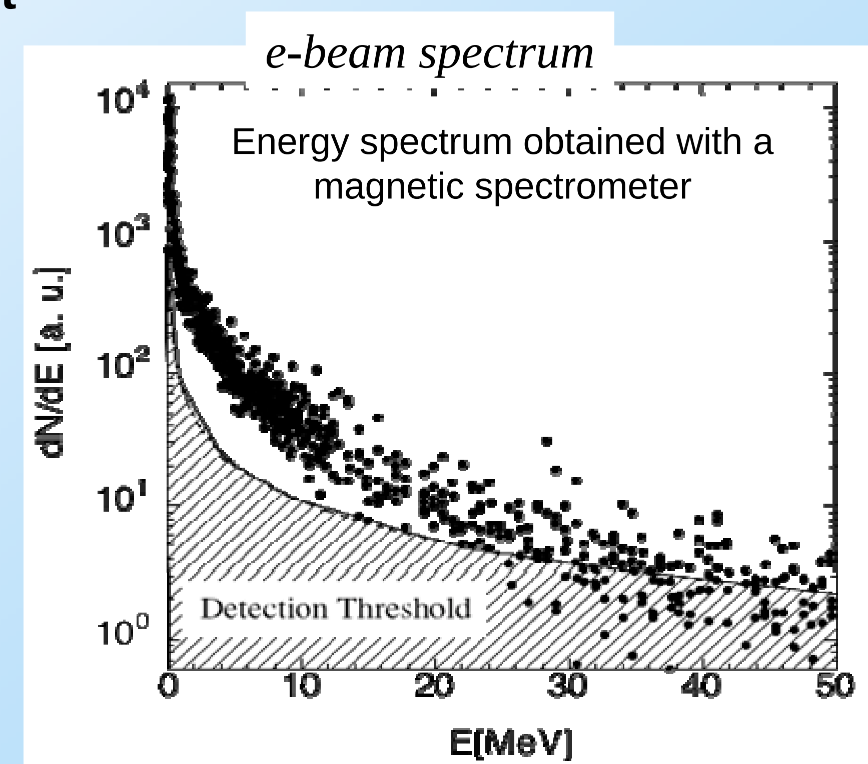
Mid 90's -2003: lasers generate electron beams with 100 % energy spread



Ebeams:

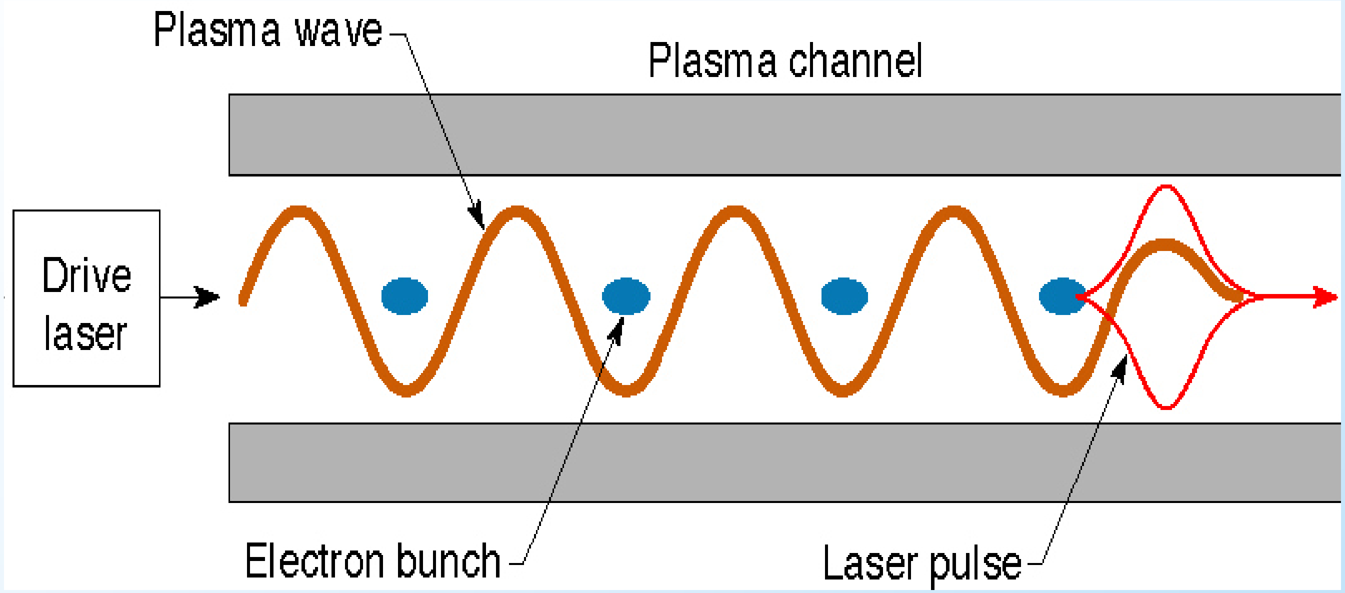
- 1-100 MeV, nC
- <100 fs,
- ~10-100 mrad divergence





Modena *et al*. (95); Nakajima *et al*. (95); Umstadter *et al*. (96); Ting *et al*. (97); Gahn *et al*. (99); Leemans *et al*. (01); Malka *et al*. (02)

Building a laser wakefield accelerator using conventional accelerator paradigm



- Drive laser: Ti-sapphire (chirped amplification technology)
- Structure: plasma fiber
- Injector: source of electrons/positrons commensurate with LWFA technology

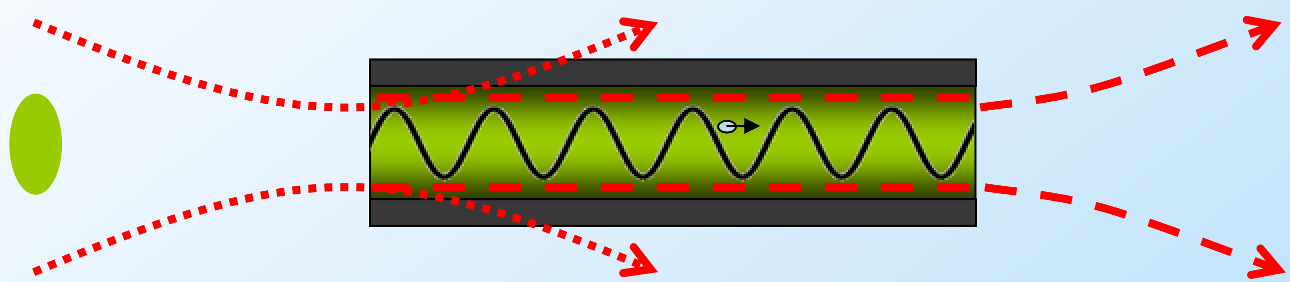
W.P. Leemans et al., IEEE Trans. Plasma Science (1996); Phys. Plasmas (1998)

Limits on acceleration: $\Delta W = E_z \, . \, L$
How to pick the accelerator length?

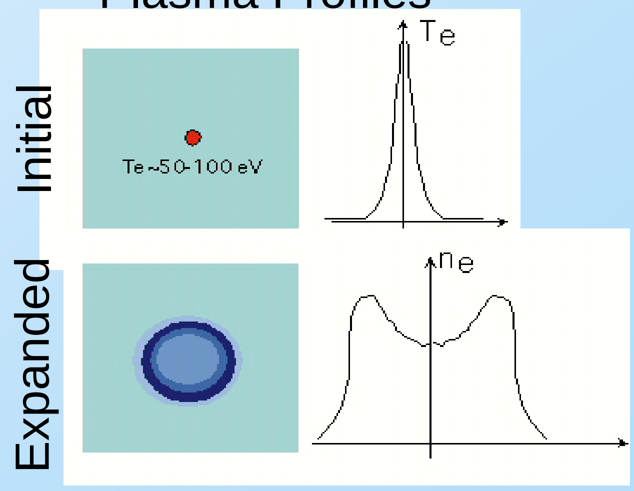
1. Diffraction: laser beam defocuses

- Option 1: increase spot size so that diffraction distance = O(gas jet)

- Option 2: make a waveguide



Plasma Profiles



Radial control of refraction index:

- **Hydro-dynamically expanding:**
  - **Laser heated plasma[1]**
  - **Resistive (current) heating[2]**

[1]Geddes et al., Nature 2004
[2]Leemans et al., Nature Physics 2006

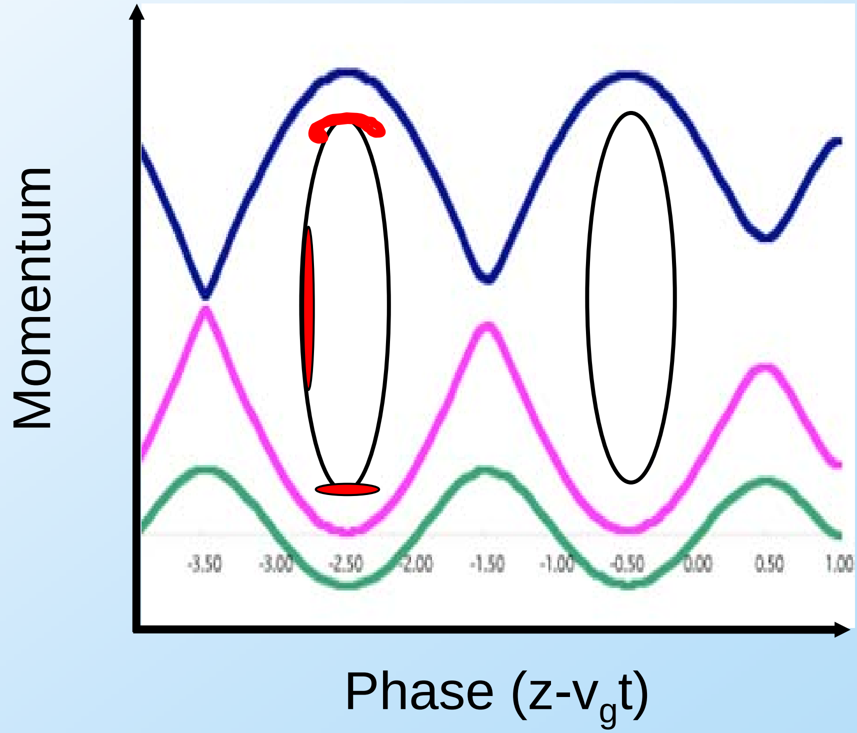
Limits on acceleration
How to pick the accelerator length? – cont'd

- **Dephasing: particle outruns wave**

Length scale set by density

Energy gain: $\Delta W_d[\mathrm{GeV}] \sim I[\mathrm{W/cm^2}] / n_p[\mathrm{cm^{-3}}]$

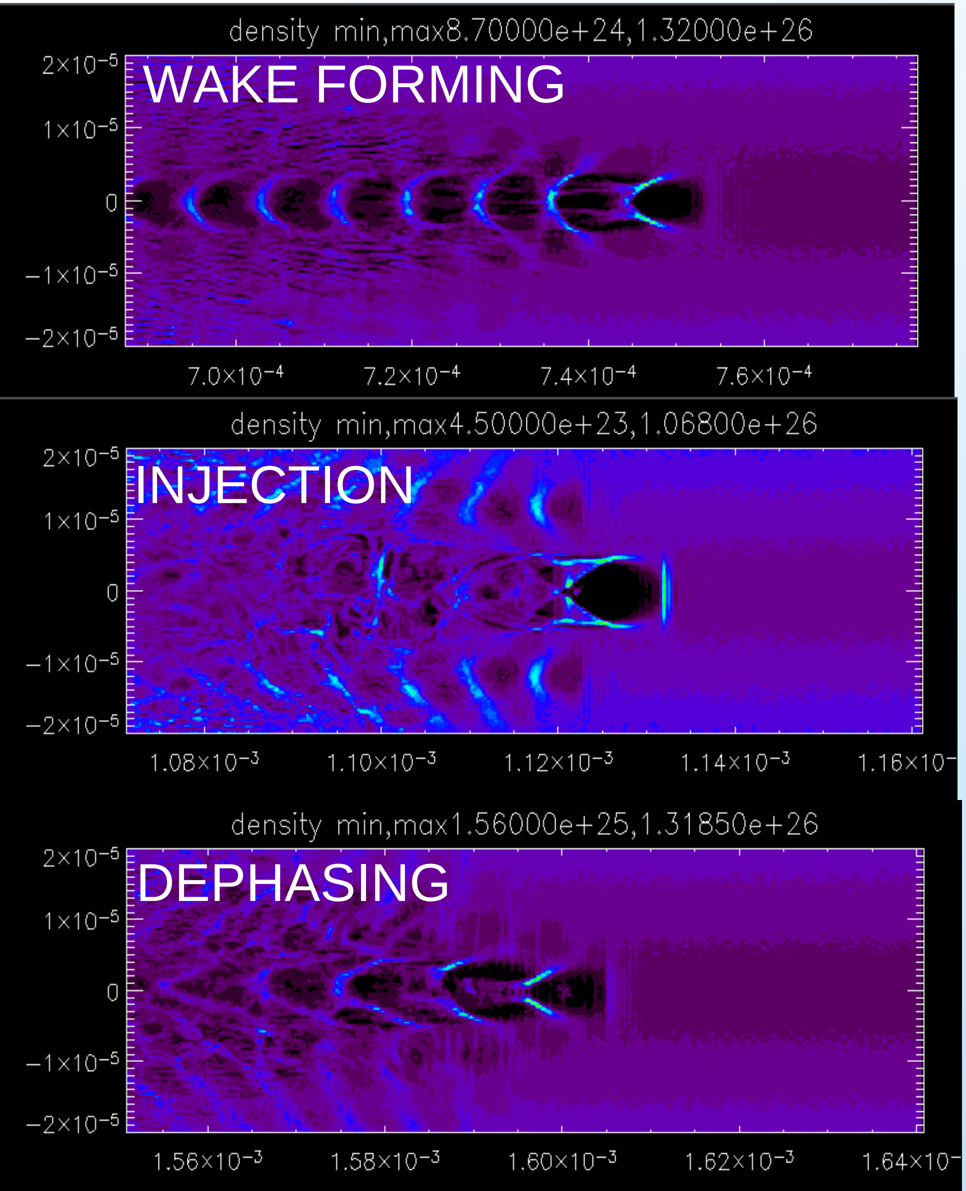
Reduce n_p

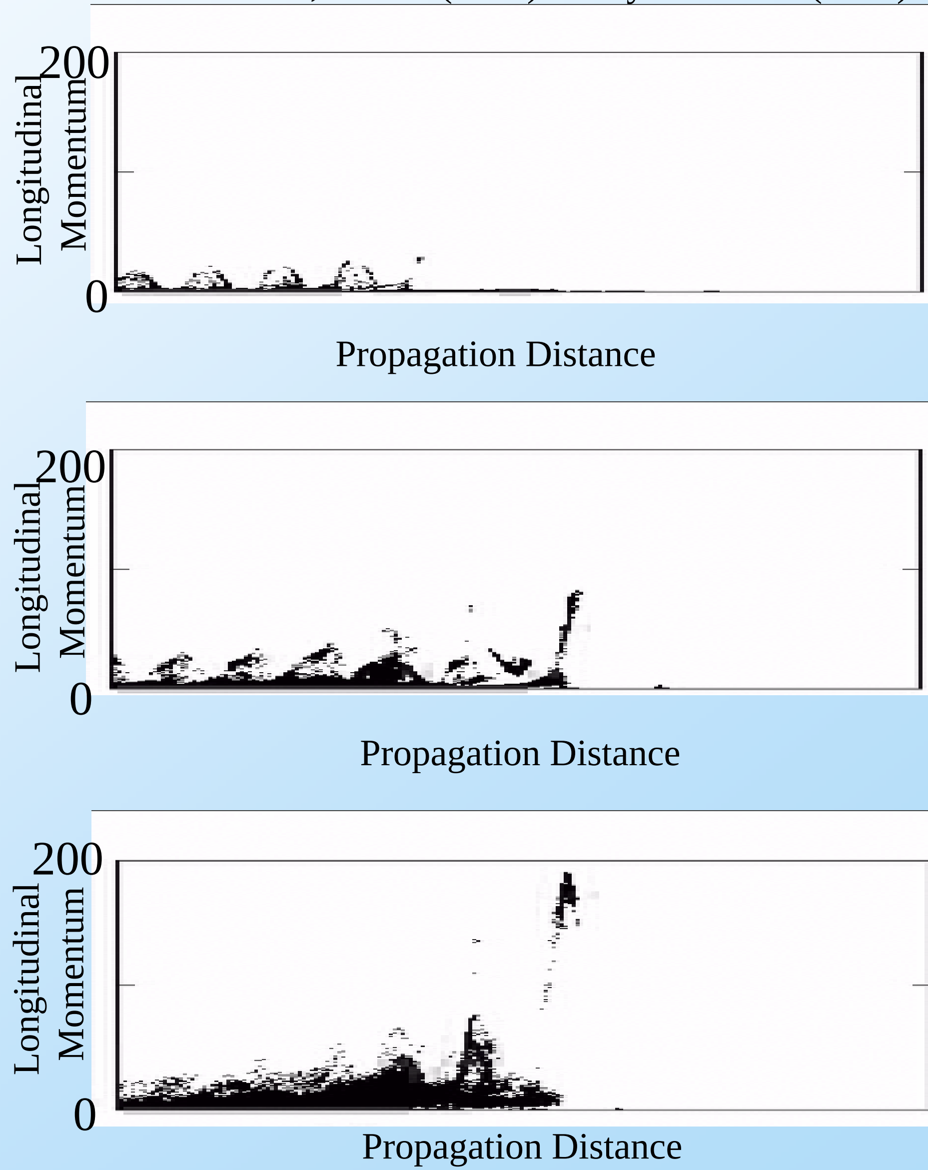


Esarey et al., IEEE 1996; Leemans et al., IEEE 1996

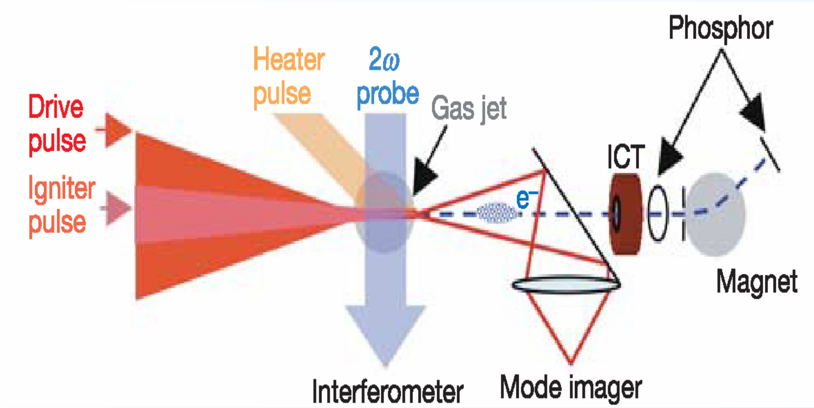
Wake Evolution and Dephasing Yield Low Energy Spread Beams in PIC Simulations

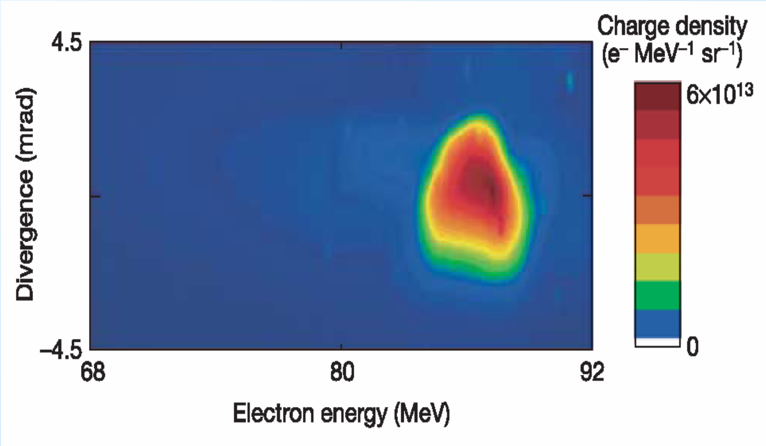
Geddes et al., Nature (2004) & Phys. Plasmas (2005)





Low energy spread beams at 100 MeV using plasma channel guiding





- 86 MeV, 300 pC, 1-2 mrad divergence

C. G. R. Geddes,et al, Nature,**431**, p538 (2004)

- Bunch duration: sub-50 fs measured using electro-optic technique
- Simulations indicate < 5 fs bunches

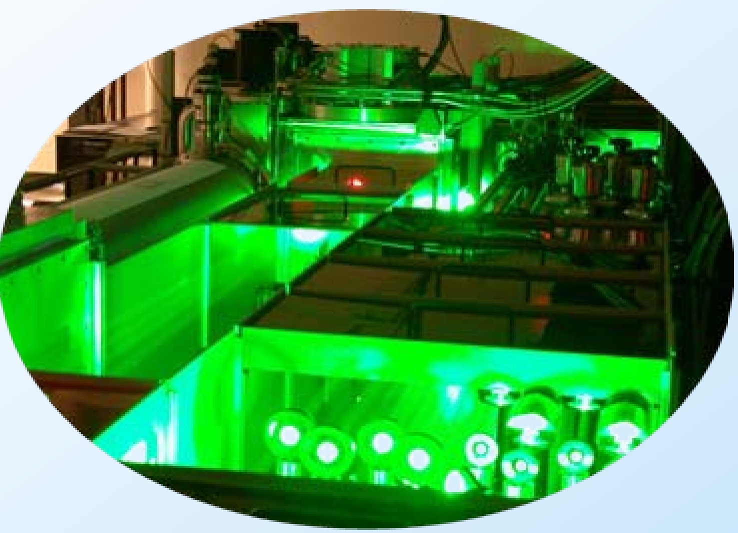
•**Alternative: bigger spot**

- RAL/IC+ (12.5 TW -> ~20 pC, 80 MeV)
  - •Mangles et al., Nature 431, p535 (2004)
- LOA^ (33 TW -> ~500 pC, 170 MeV)
  - •Faure et al., Nature **431**, p541, 2004

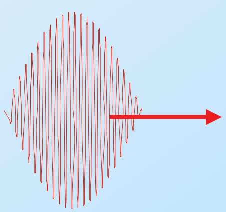
Higher beam energy requires lower plasma density

- Higher power laser
- Lower density, longer plasma

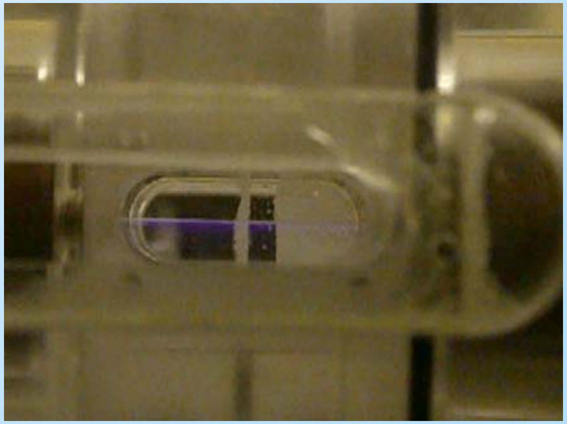
$$\Delta W_d[\mathrm{GeV}] \sim I[\mathrm{W/cm}^2] \big/ n_p[\mathrm{cm}^{-3}]$$



Laser: 40-100 TW, 40 fs 10 Hz



Plasma channel technology: Capillary

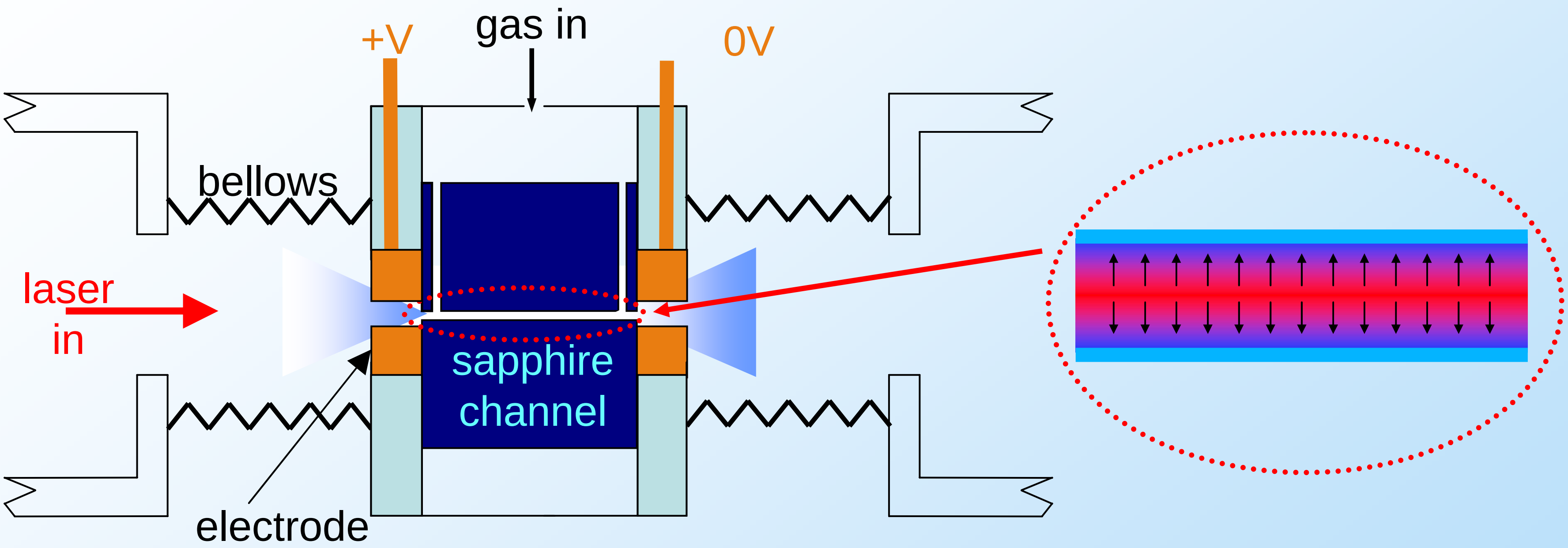


3 cm

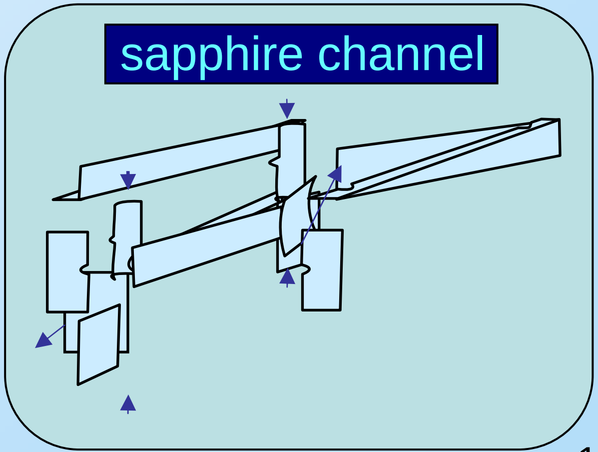
1 GeV

e^- beam

Going to higher beam energy

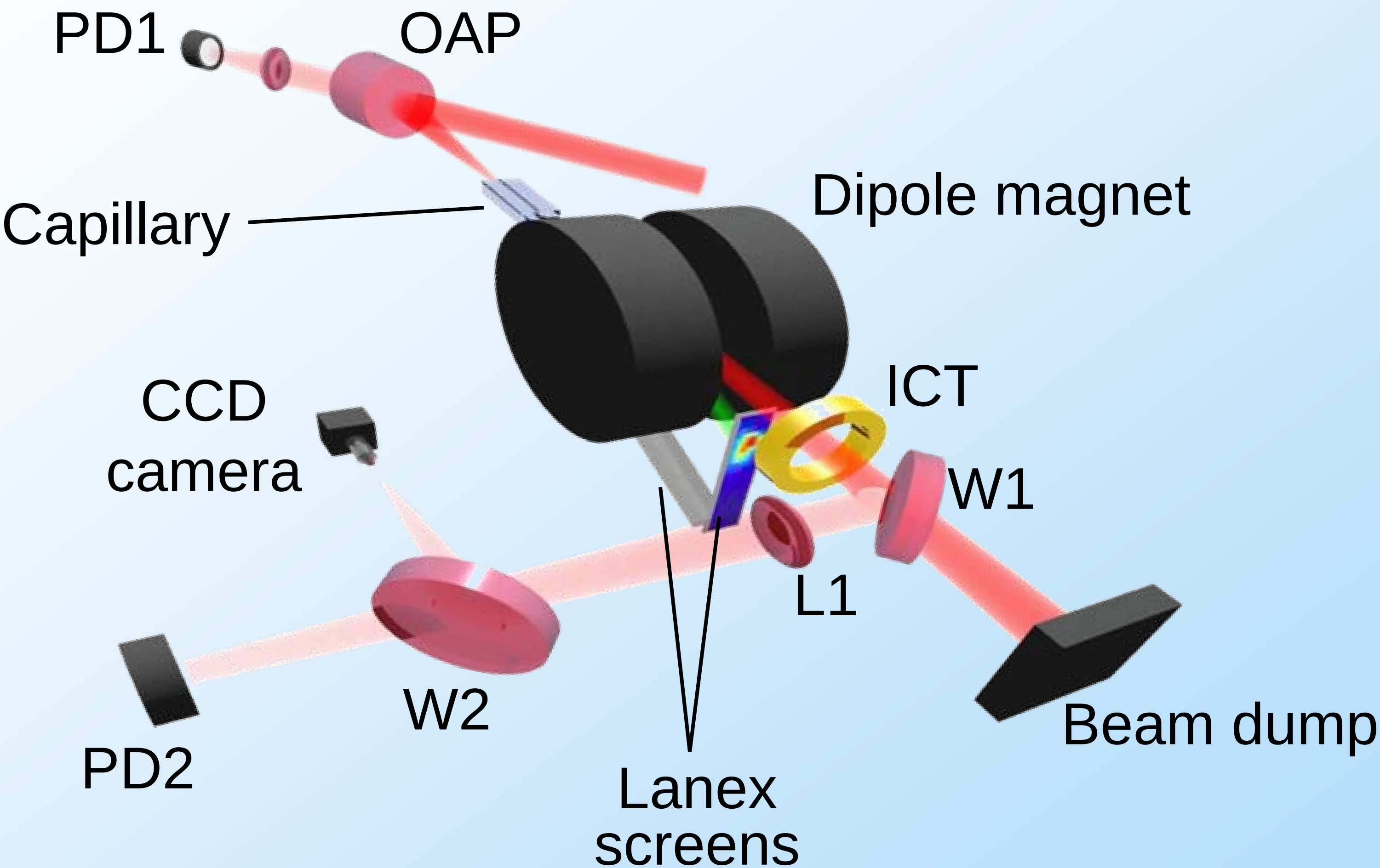


- Gas ionized by pulsed discharge
  - Peak current 200 - 500 A
  - Rise-time 50 - 100 ns



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

Experimental Setup for GeV Accelerator

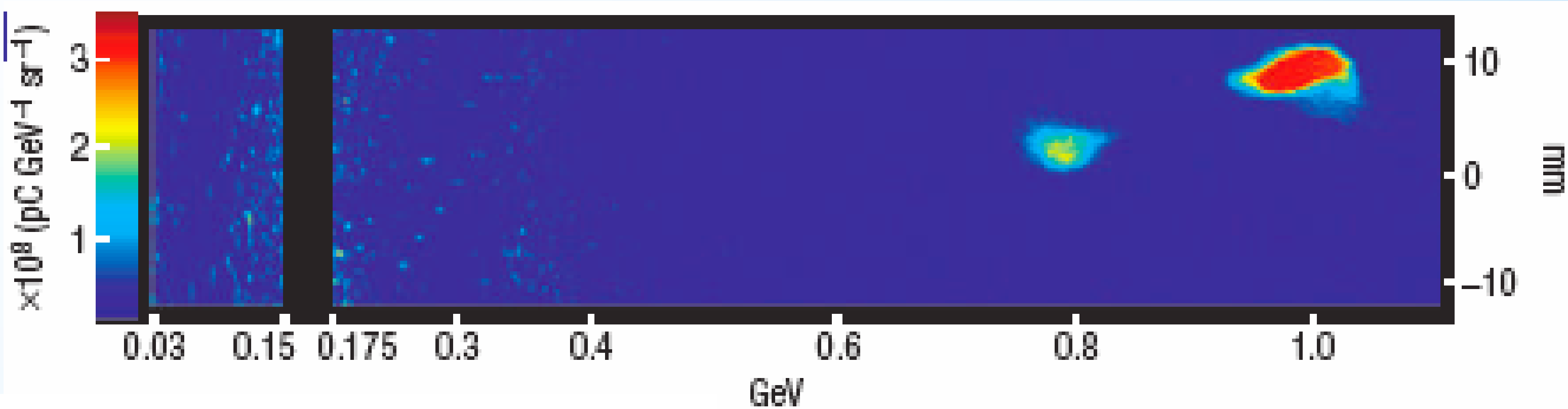


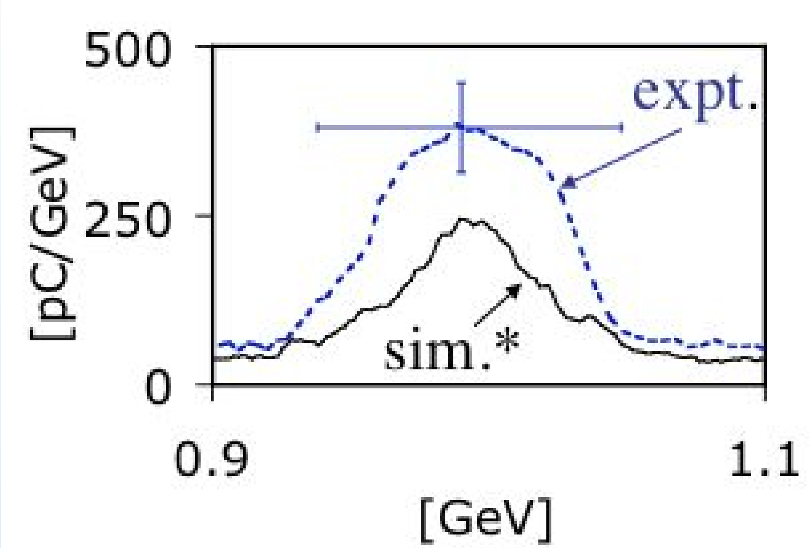
- W.P. Leemans et al., *Nature Physics* **2**, 696 (2006); K. Nakamura et al., *Physics of Plasmas,* **14** 056708 (2007)

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**

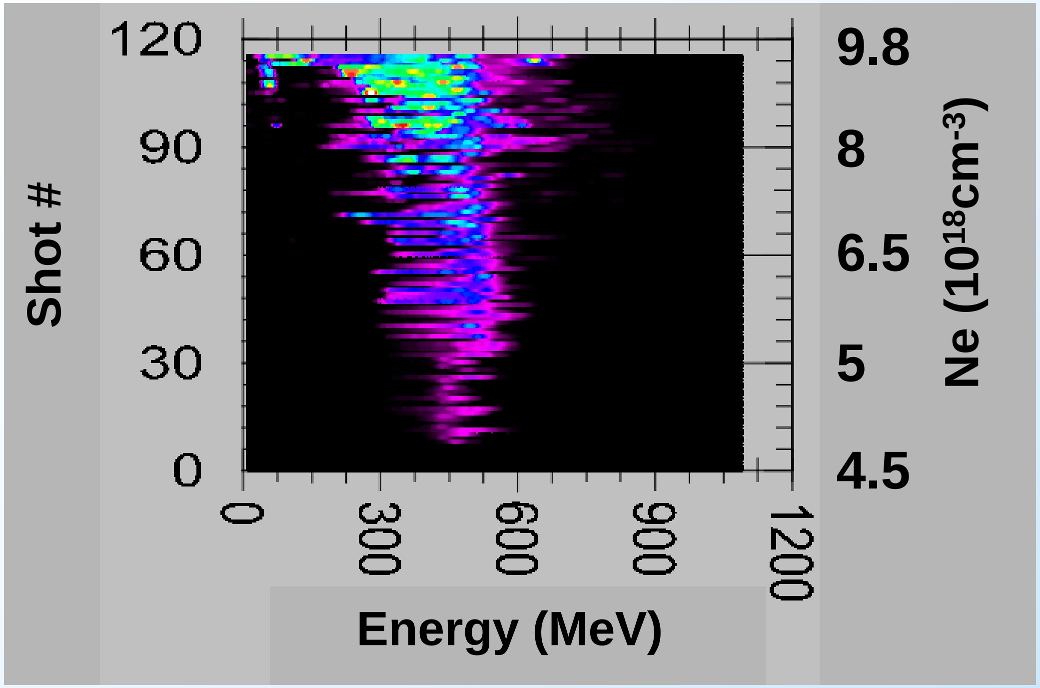


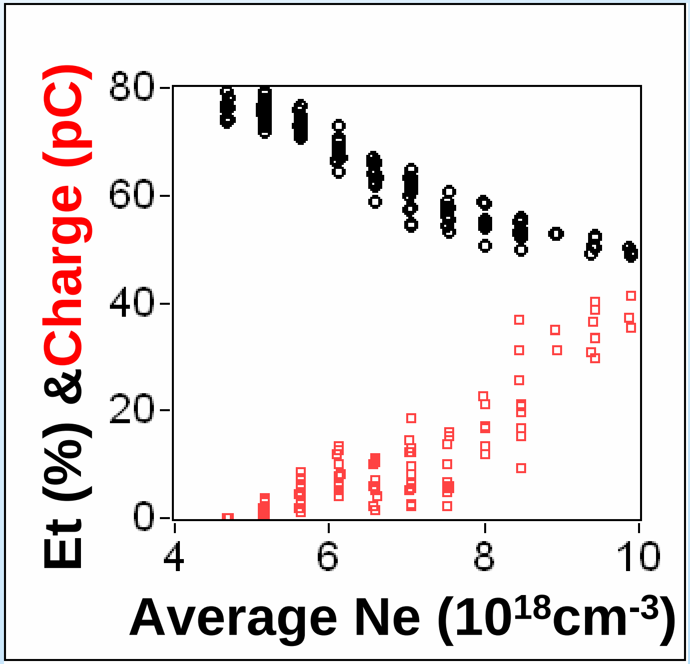


	Sim	Expt
Q (pC)	**25-60**	**35**
E (GeV)	**1.0**	**1.1**
dE/E RMS (%)	**4**	**2.5**
div. (mrad)	**2.4**	**1.6**

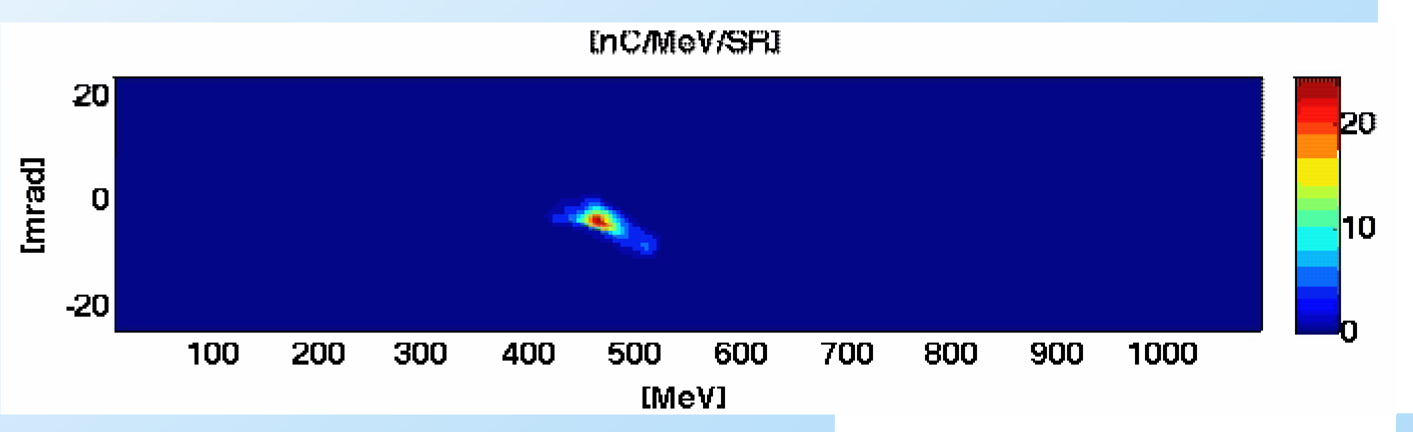
W.P. Leemans et. al, *Nature Physics* **2**(2006) 696; *Simulation using VORPAL

Electron beam properties can be tuned by scanning input parameters - e.g density

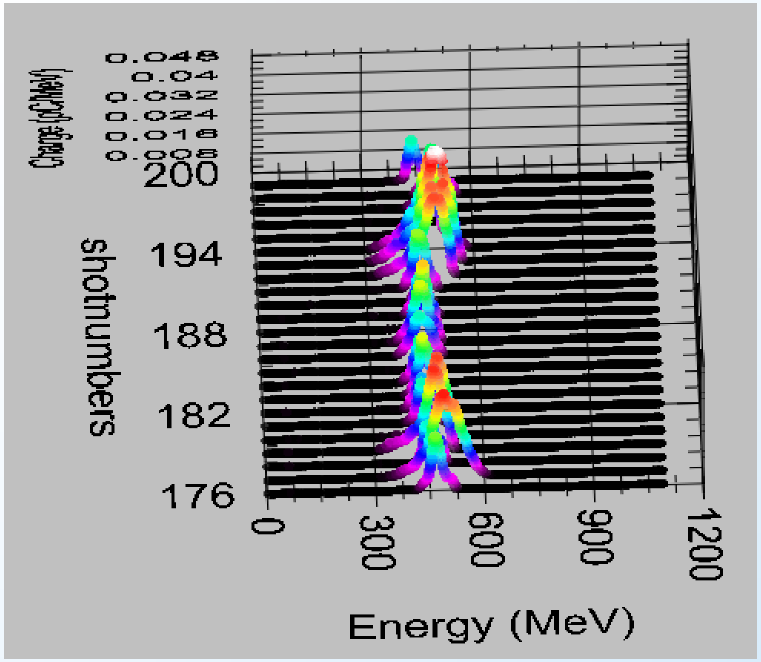




- Laser Energy: 1.4 to 1.7J (a_0=1.2 to 1.3)
- Laser Pulse Length 45fs

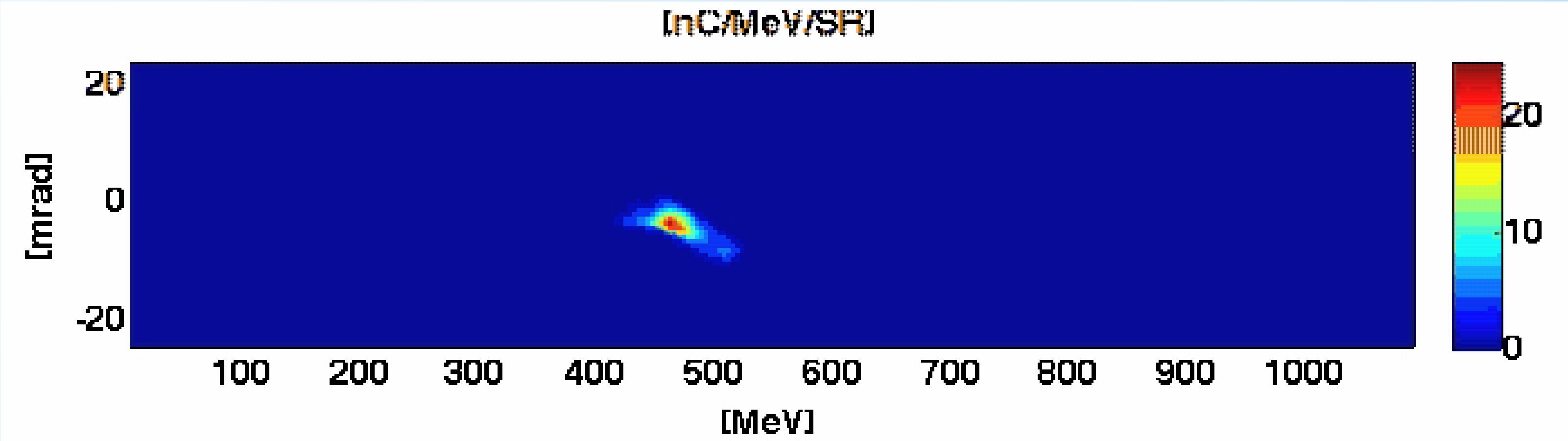


Low Plasma Density can produce narrow energy spread beams without "external" injection



Subsequent shots during pressure scan

- **Density: $5 \times 10^{18} cm^{-3}$**
- **Laser intensity: a_0=1.2 to 1.3**
- **Laser Pulse Length 45fs**



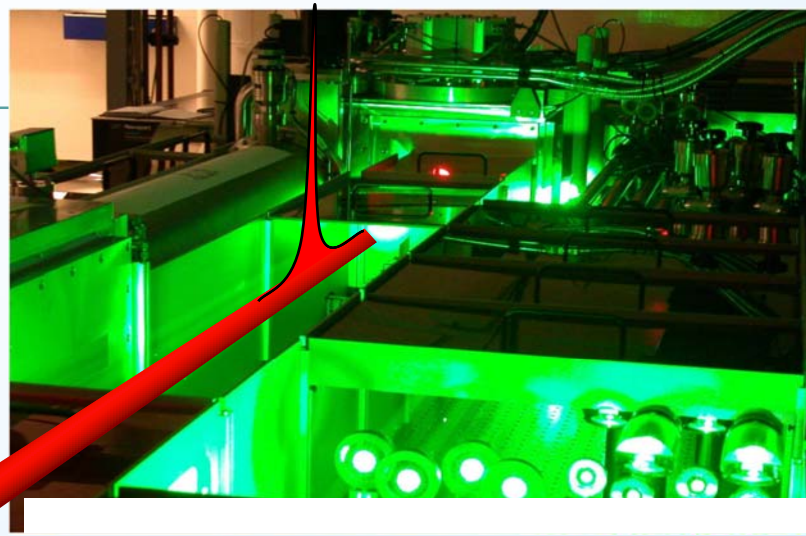
Is the beam quality sufficient for an FEL?

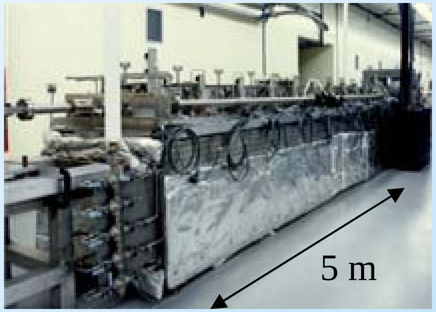
Energy spread

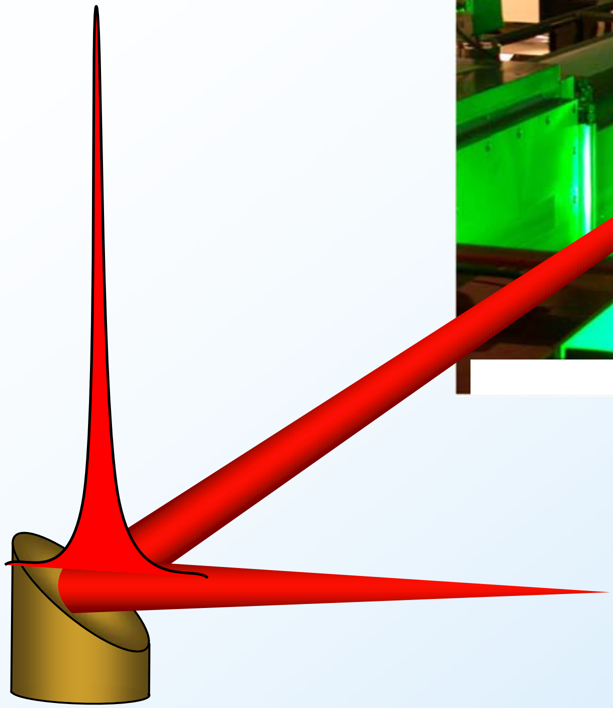
Emittance

Stability

An EUV Free electron laser



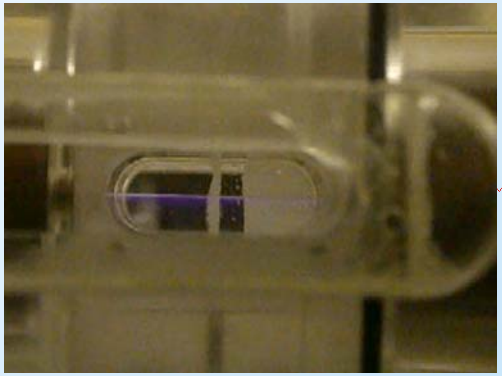




T-REX laser system

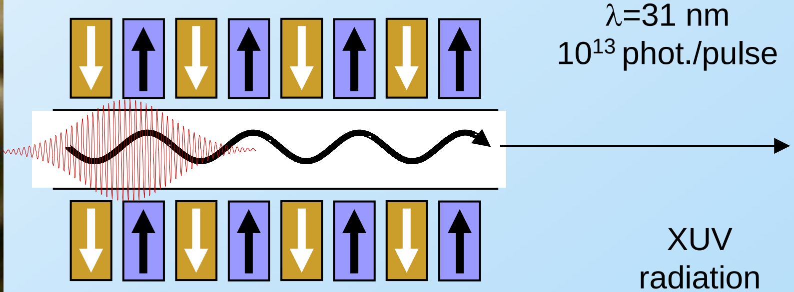
I_{pk} ~ 10^{18} W/cm^2

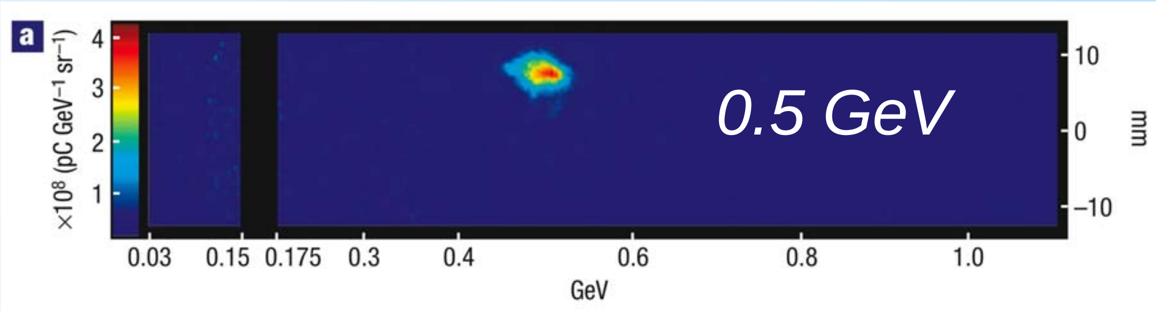
40 TW, 40 fs



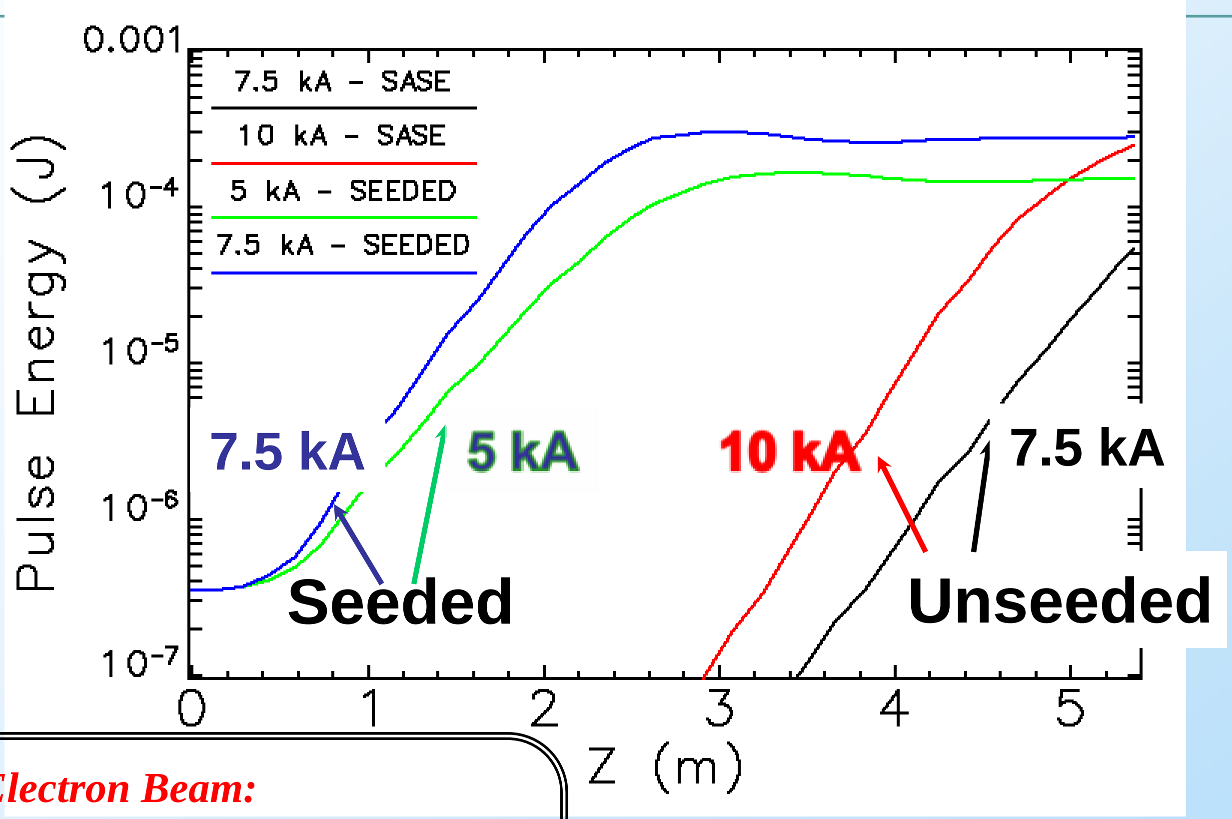
Plasma capillary technology

Undulator





FEL places tight constraints on e-beam quality



LWFA Electron Beam:

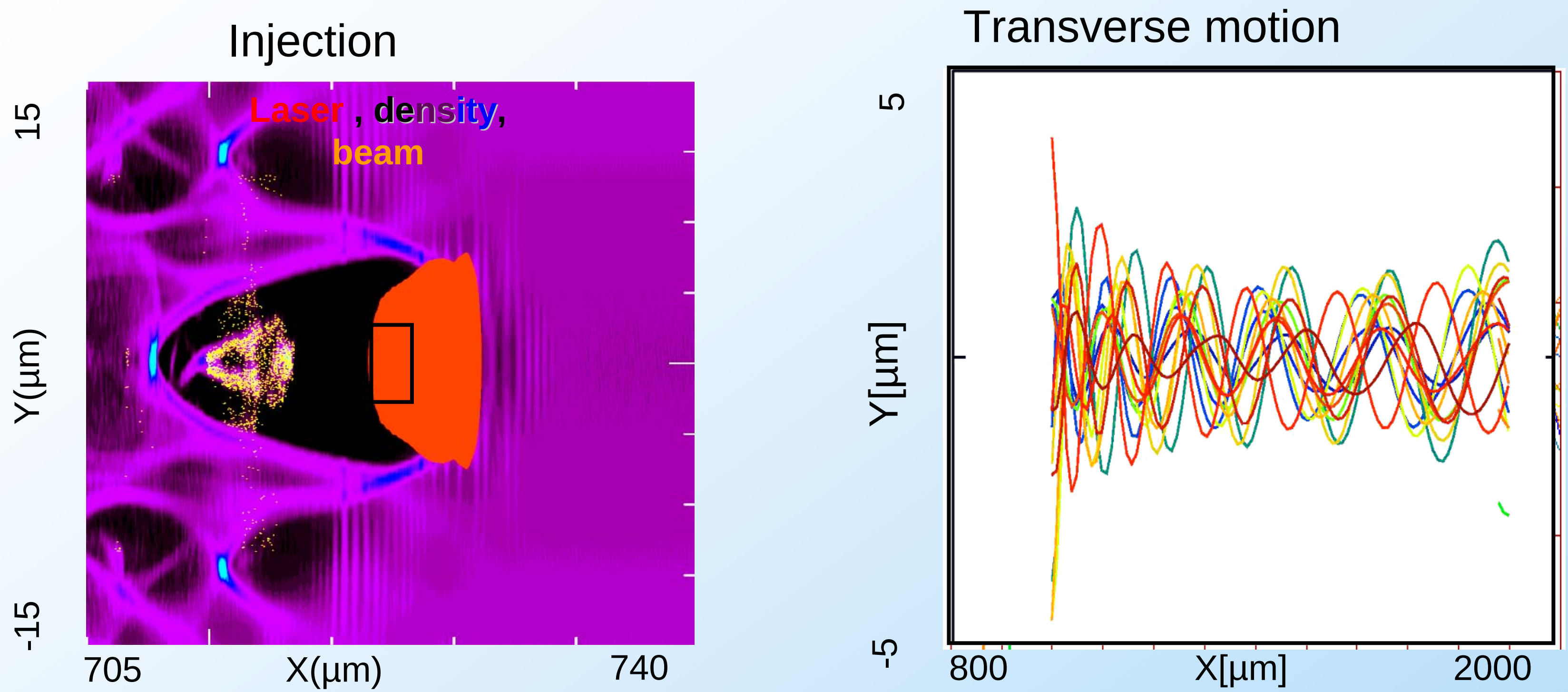
Beam Energy	0.5 GeV
Peak current	10 kA
Charge	0.2 nC
Bunch duration, FWHM	20 fs
Energy spread (slice)	0.25 %
Norm. Emittance	1 mm-mrad

Photon beam:

λ=31 nm

10^{13} photons/pulse in 5 fs

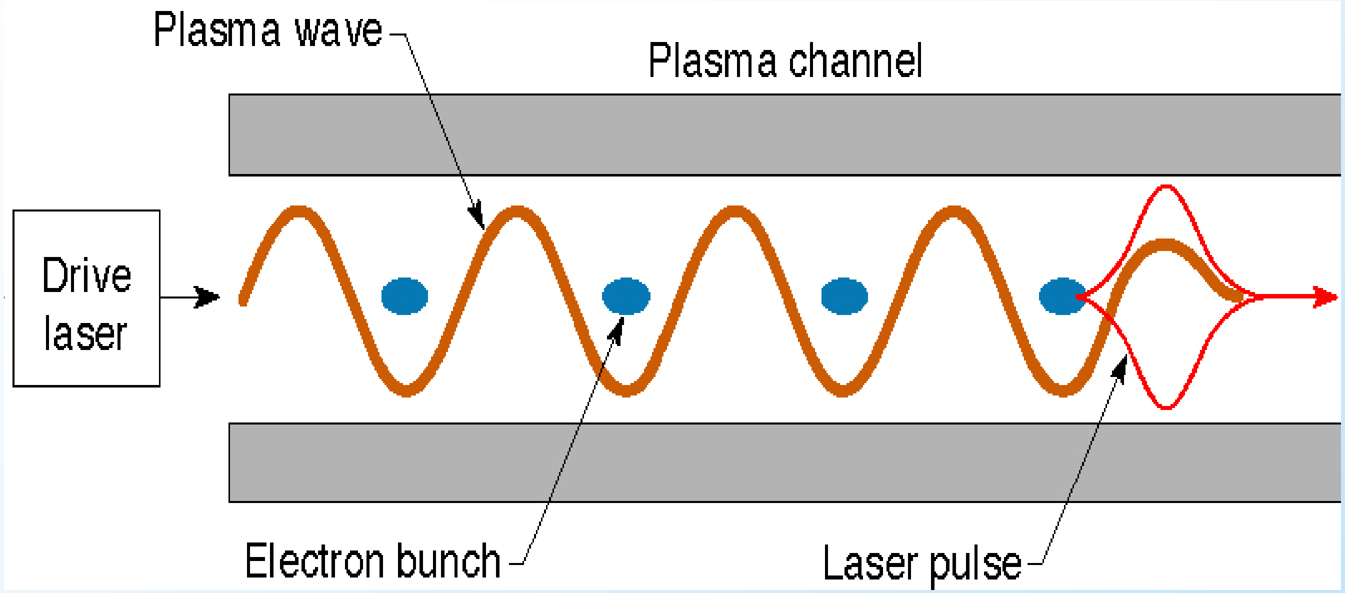
Injection in blowout regime degrades emittance due to high transverse field



- Consistent with few mrad divergence in experiments
- Degrades emittance for high energy self-injected stages
- Use controlled trapping at low wake amplitude to reduce emittance

*Geddes Ph.D dissertation 2005, Tsung PRL 2004

Building a laser wakefield accelerator using conventional accelerator paradigm

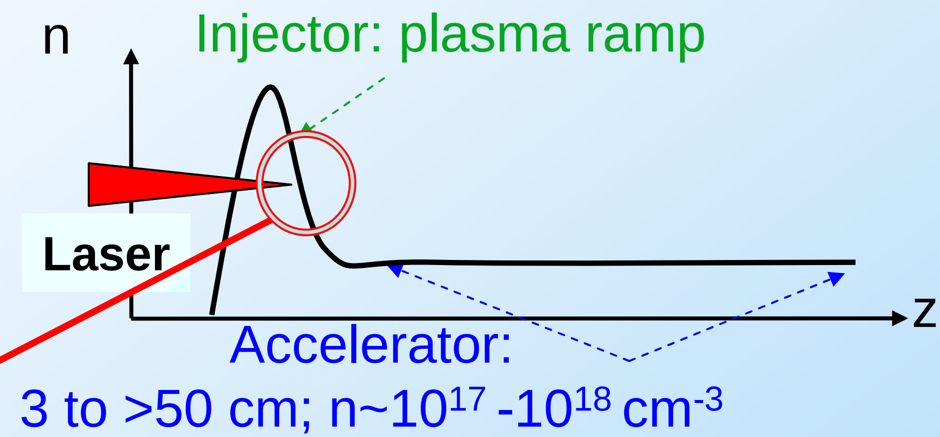


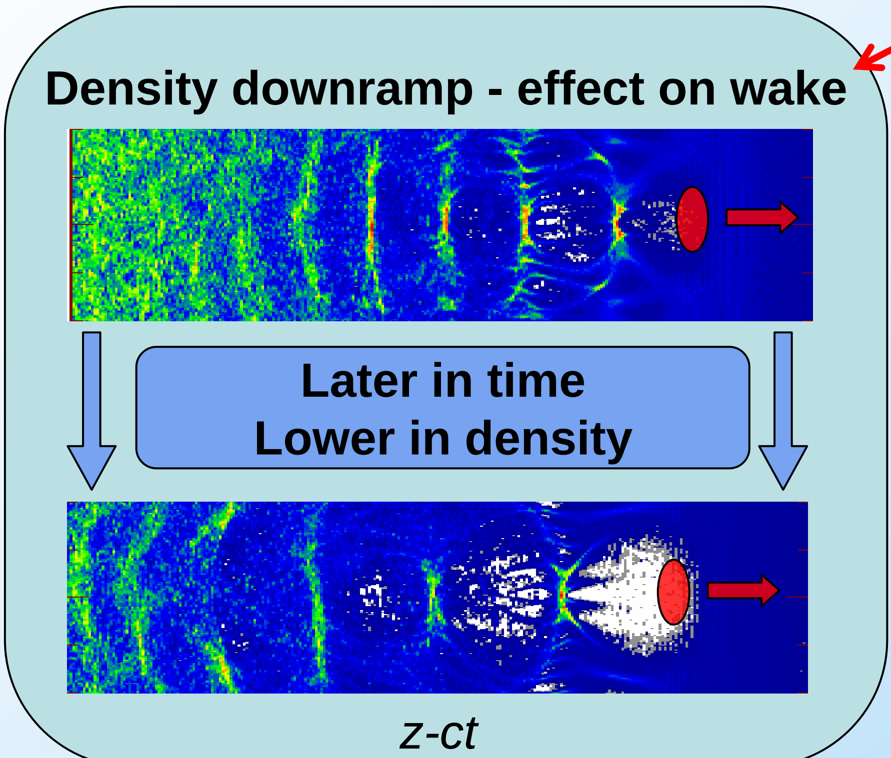
- Drive laser: Ti-sapphire (chirped amplification technology)
- Structure: plasma fiber
- Injection: source of electrons, controlled

W.P. Leemans et al., IEEE Trans. Plasma Science (1996); Phys. Plasmas (1998)

Techniques for Controlled Injection

- Additional laser pulses
  - LIPA*
  - Colliding pulse[†], etc
- Density downramp[‡]

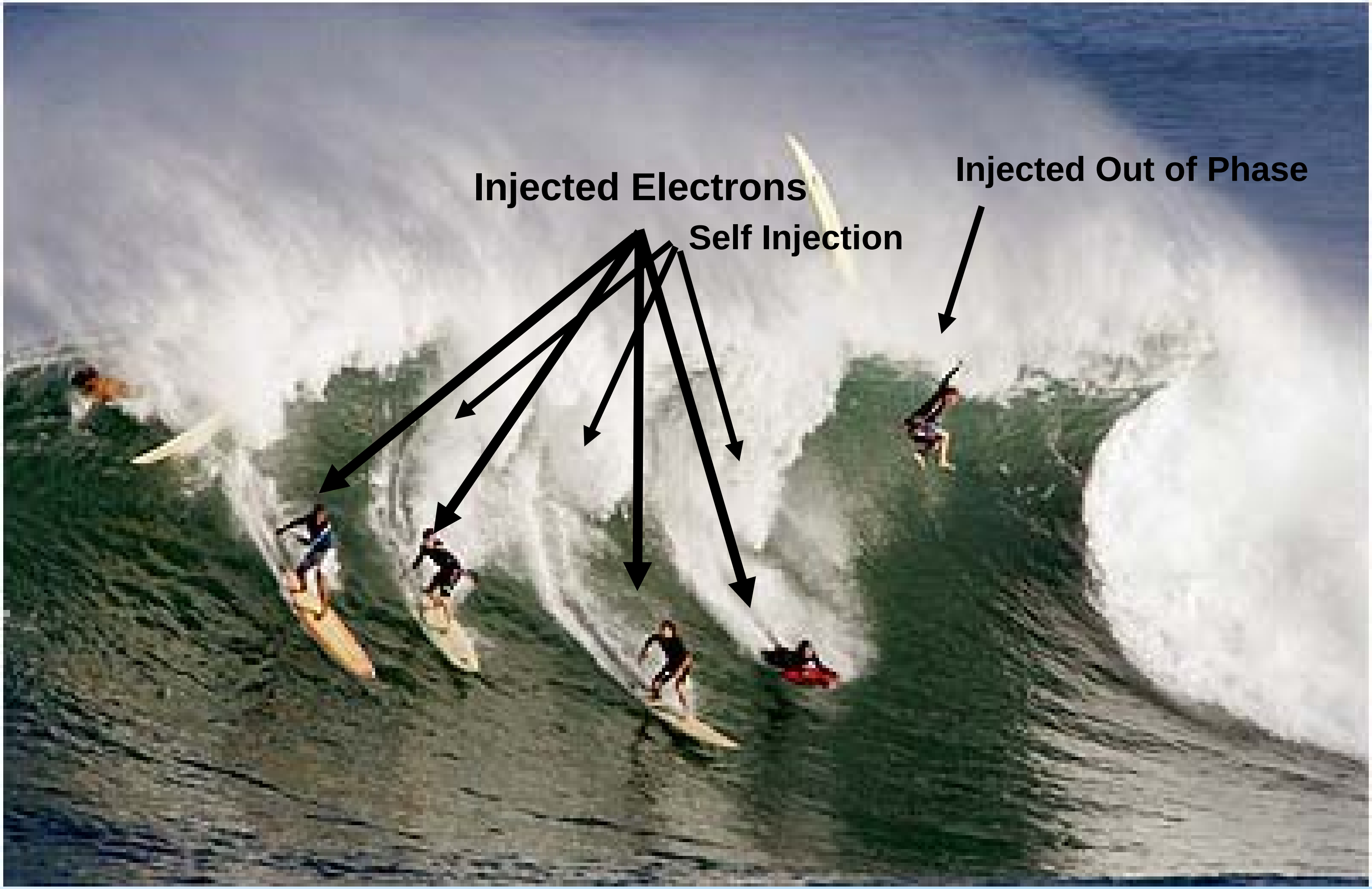




- Improved stability
- Higher Energy
- Reduced energy spread: fluid simulations indicate ΔE at injection remains “frozen” in =>ΔE/E reduces with E

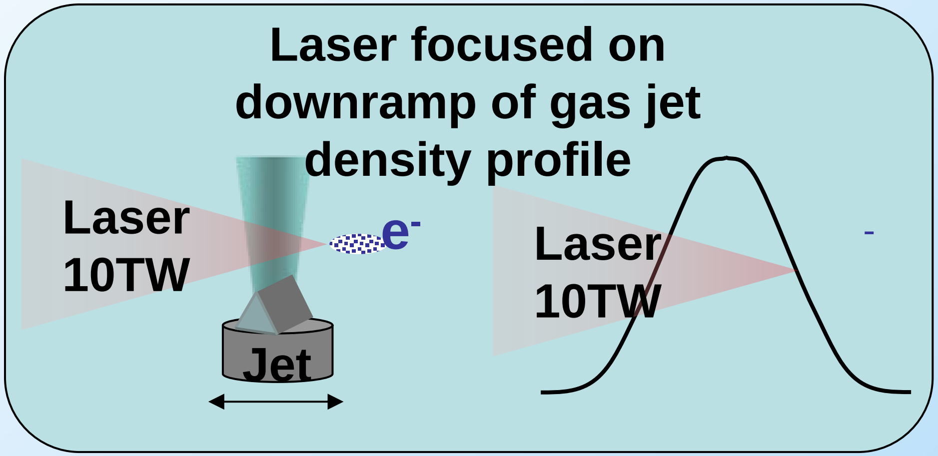
*Ting et al., *Phys. Plasmas* **12**, (2005); [†]Esarey et al., *PRL* **79**, (1997); Faure et al., *Nature (2006),*
[‡]Bulanov et al., *PRL* **78**, (1997), Geddes et al., PRL (2008)

“Electrons” accelerating on a wave: controlled injection

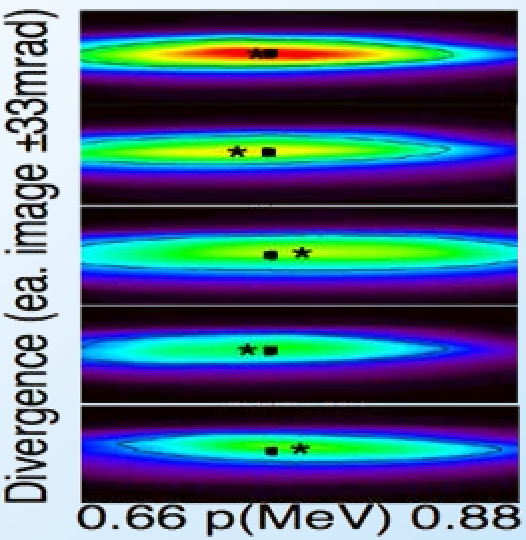


E-beam quality: energy spread

- Goal: Reduce energy spread from ~2% to <0.25 %
- Approach:
  - Produce MeV beam with <20% ΔE/E
  - Accelerate to GeV: ΔE/E<0.2%



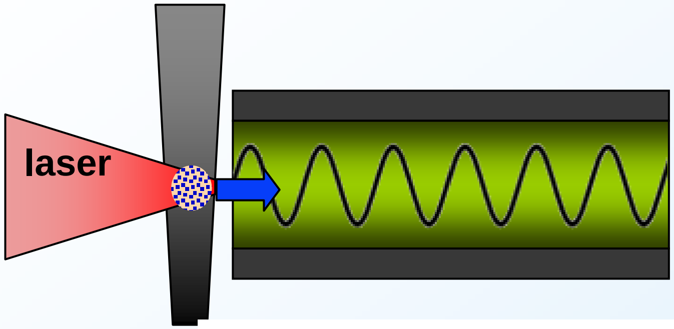
Sequential spectra
***centroid, avg**

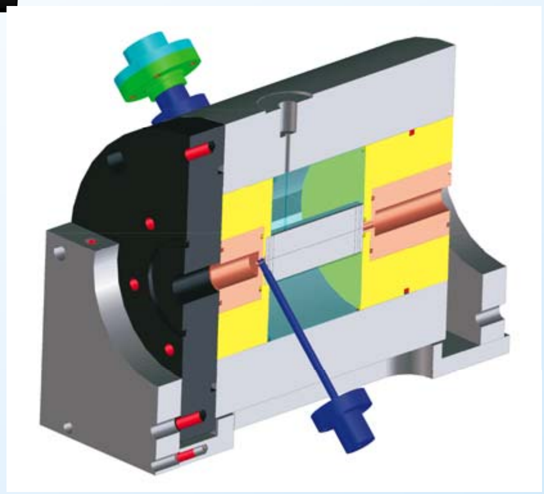


- **MeV beam produced with**
  - **Low absolute energy spread (170keV)**
  - **Good stability**
    - **Central energy (760keV ± 20keV rms)**
    - **Energy spread (170 keV ± 20keV rms)**
    - **Beam pointing (1.5 mradrms)**

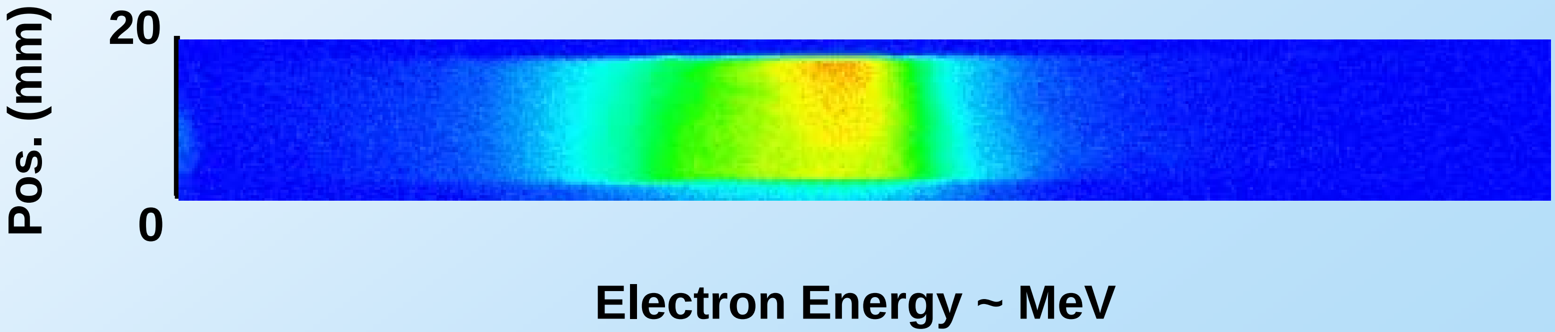
Geddes et al., PRL2008

E-beam quality: energy spread – continued
Staged injector and accelerator structure



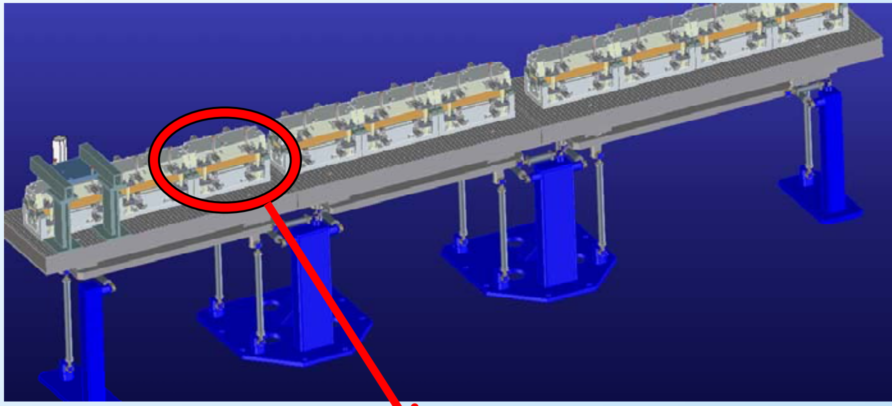


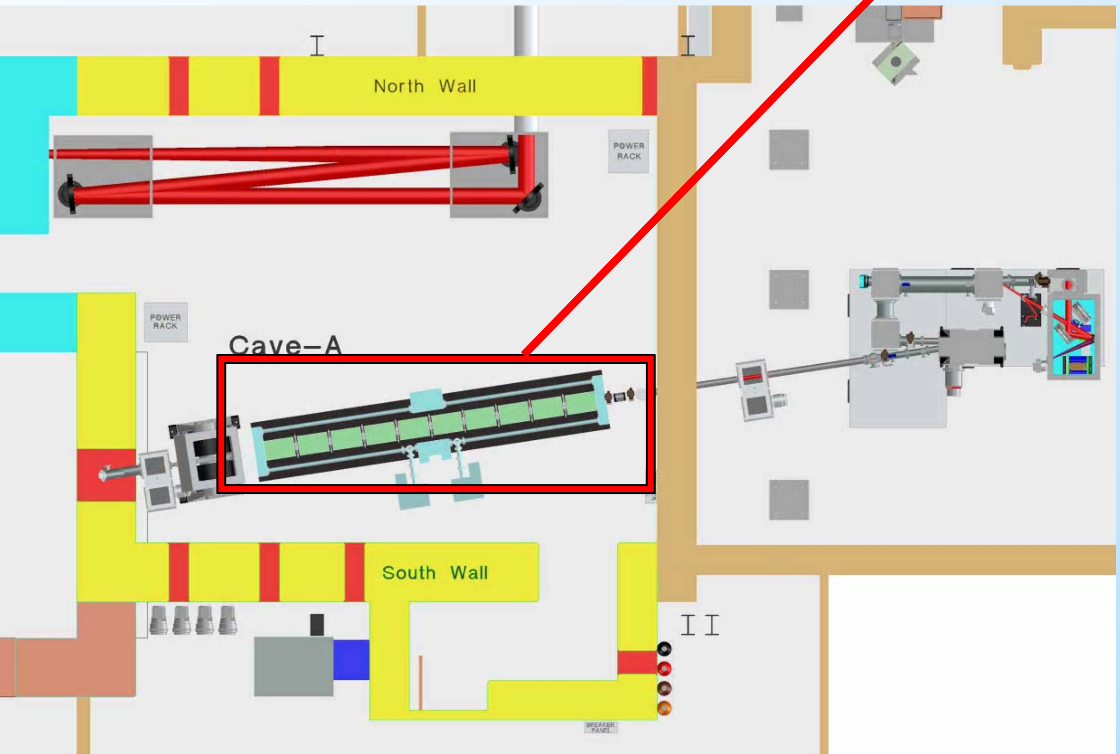
- Gas jet Injector + capillary
- Reproducible electron beam (few nC charge) achieved with 40 TW-laser pulses and gas jet
- High laser beam transmission
- Simulations indicate ~ O(0.2%) ΔE/E

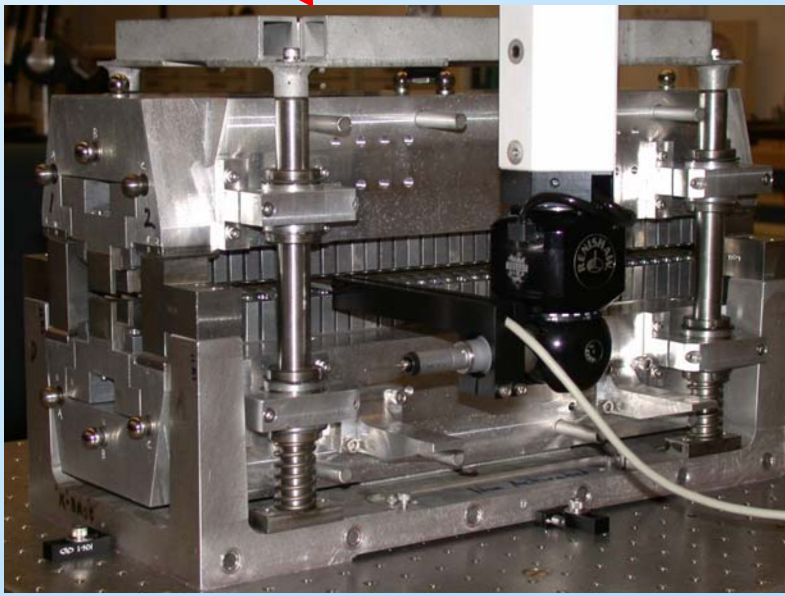


Undulator based diagnostic is first step towards SASE-FEL at 30 nm

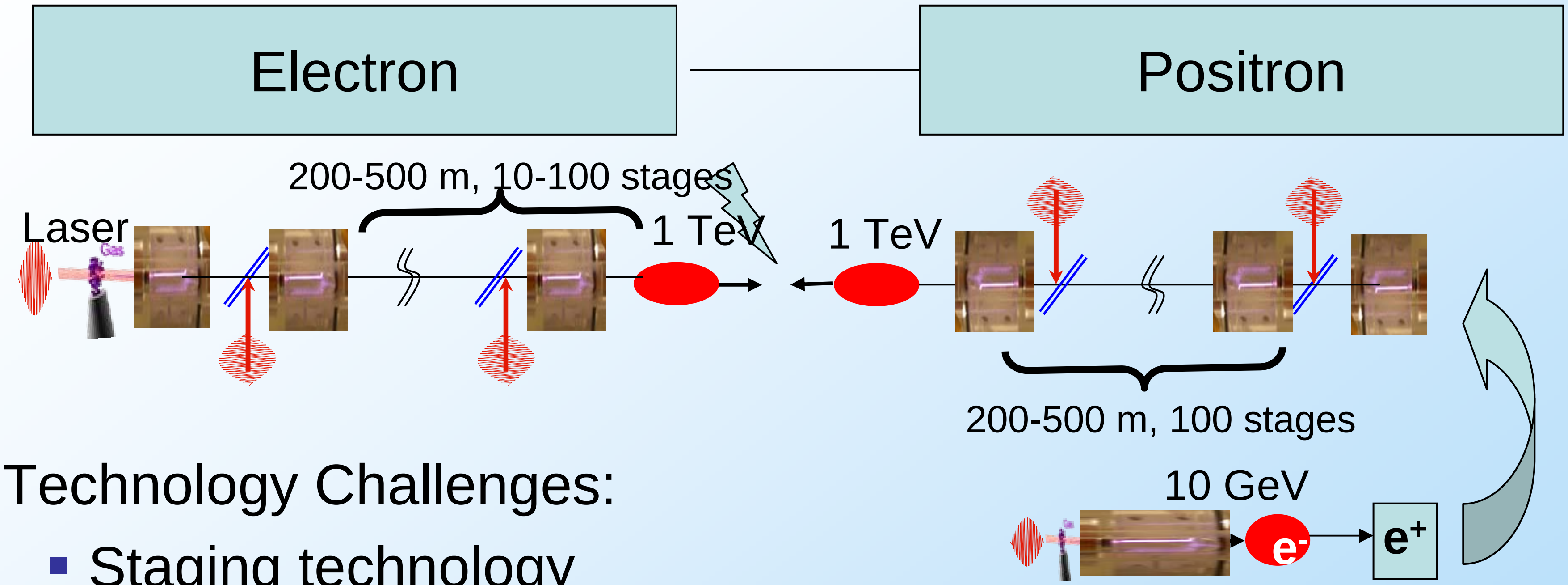
- Undulator from Boeing corp.
- Measure emittance and ΔE/E through undulator spectrum
- SASE-FEL







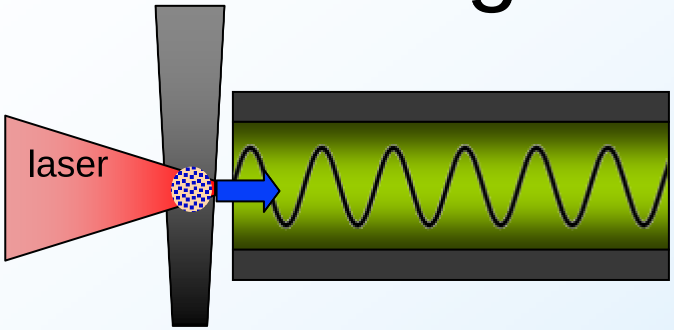
Conceptual (strawman) collider lay-out



- Technology Challenges:
  - Staging technology
  - Diagnostics -- control
  - Positron and polarized electron sources compatible with laser accelerators
  - Emittance and energy spread control (collisions in plasma)
  - High average power, high peak power lasers

Grand technical challenges in next 10 years

Challenge 1

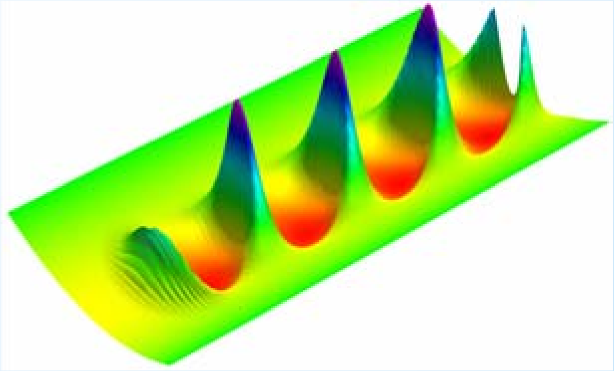


Staging of modules

Challenge 2

1-> 100 GeV, low energy spread beam, low emittance

Challenge 3



One-to-one, 3-D modeling

Challenge 4

Lasers: high rep rate PW lasers

Limits on acceleration
How to pick the accelerator length?

1. **Dephasing:** particle outruns wave

Length scale set by density

Energy gain:

Reduce n_p

2. **Diffraction:** laser beam defocuses

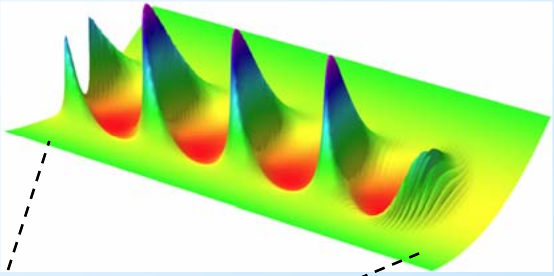
- Option 1: increase spot size so that diffraction distance = O(gas jet)
- Option 2: make a waveguide

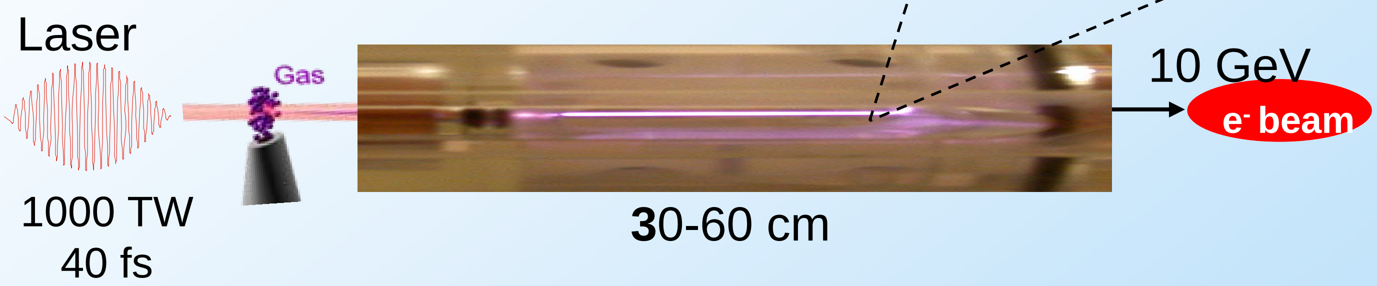
3. **Pump depletion:** laser runs out of energy

- Must figure out way to replenish - > STAGING
- What is optimum stage energy?

BELLA = **Be**rkeley **L**ab **L**aser **A**ccelerator
Critical technology for future laser accelerator

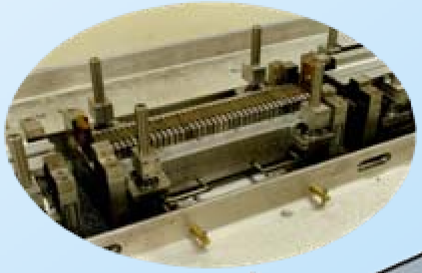
- BELLA Project: 1 PW, 1 Hz laser



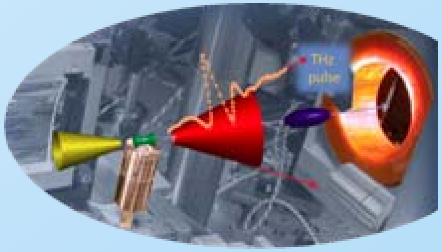


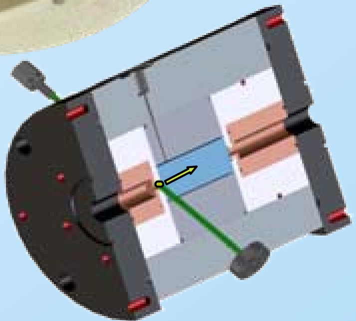
- BELLA R&D:
  - Diagnostics
  - Staged Accelerators

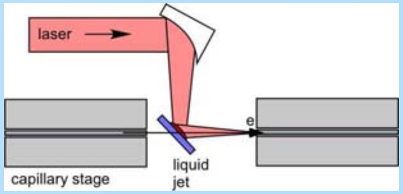
Undulator spectrum



THz

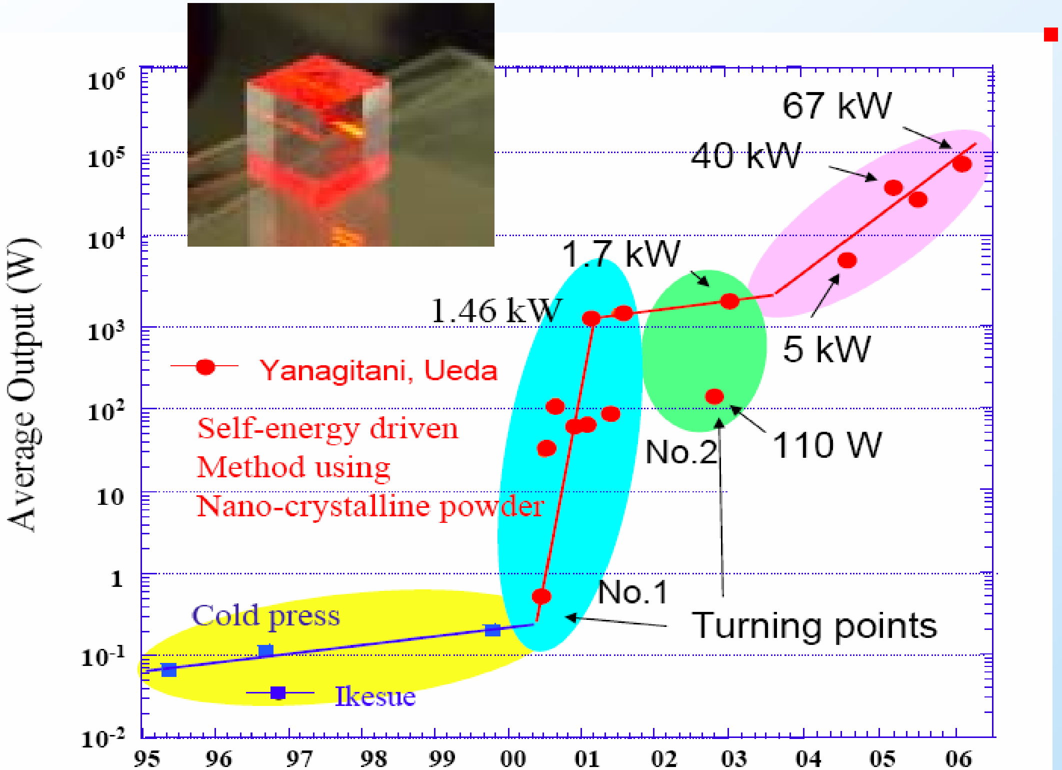






Critical Technology: High average power, high peak power lasers, high wall plug efficiency

- Laser: amplifier material and pump source
- Amplifier material: Ceramics



Courtesy: B. Byer

- Pumping: diodes
  - Efficient, low thermal load
- Leverage: LED Street lights
  - Emerging market
  - 50 million lamps in US alone
  - Volume drives price down

Prospect for kJ, picosecond, multi-kHz systems at 30-50 % wallplug seems possible

Summary

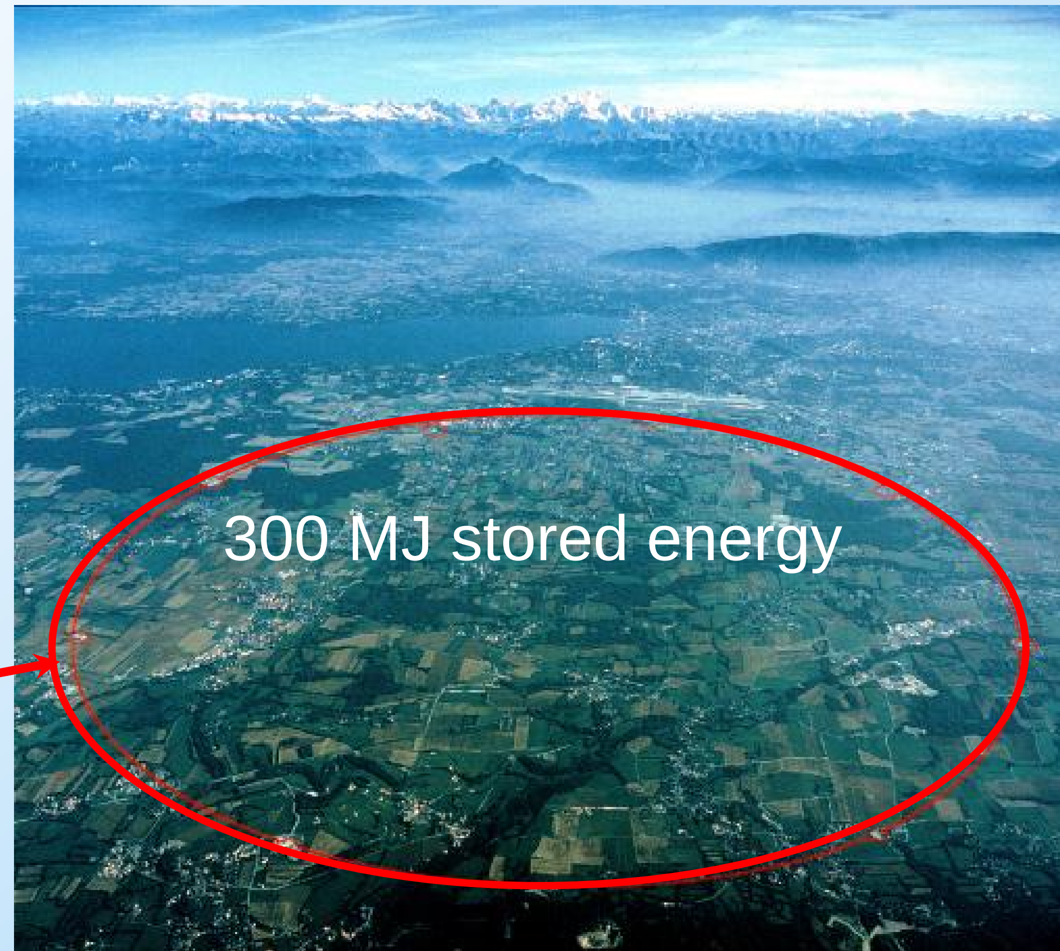
- Laser-plasma based accelerator technology continues to show promise:
  - GeVbeams (~% ΔE/E) demonstrated and 10 GeV is feasible with PW-class laser
  - Key technology: guiding structures and controlled injection via density downramp
- Demonstration experiments underway:
  - Energy spread and emittance reduction using controlled injection
  - Staging technology: how to chain modules together
  - Free electron laser at 30 nm
- Colliders:
  - Many issues remain
  - Key technologies systematically being addressed

People who say it cannot be done should not interrupt those who are doing it.

George Bernard Shaw

1929

LHC, 2008



Size x 10^5 Energy x 10^9

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