Accelerating Into the Future:

From 0 to 1 GeV in a Few Centimeters

Wim Leemans

LOASIS Program, AFRD

Summer series lecture

July 8, 2008

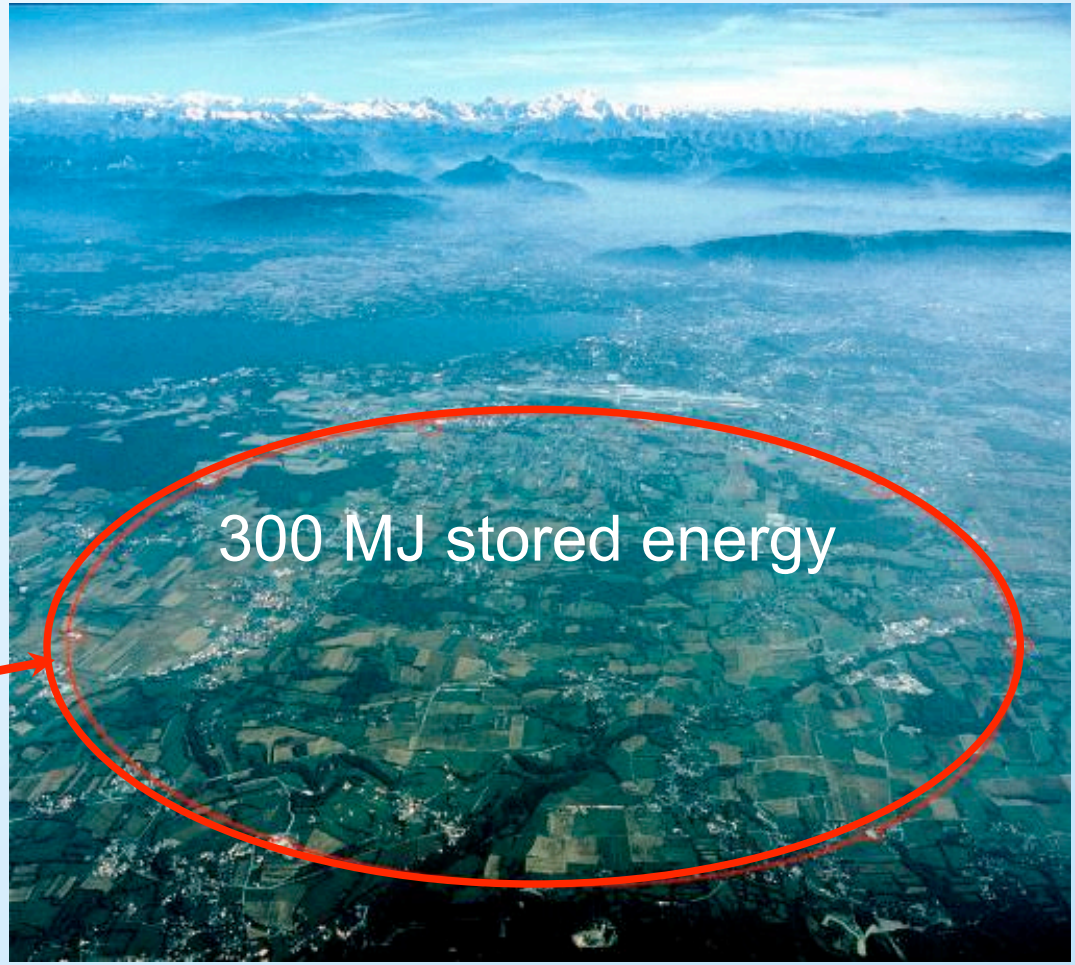
http://loasis.lbl.gov/

Office of Science

Accelerators: from handheld to size of a small country

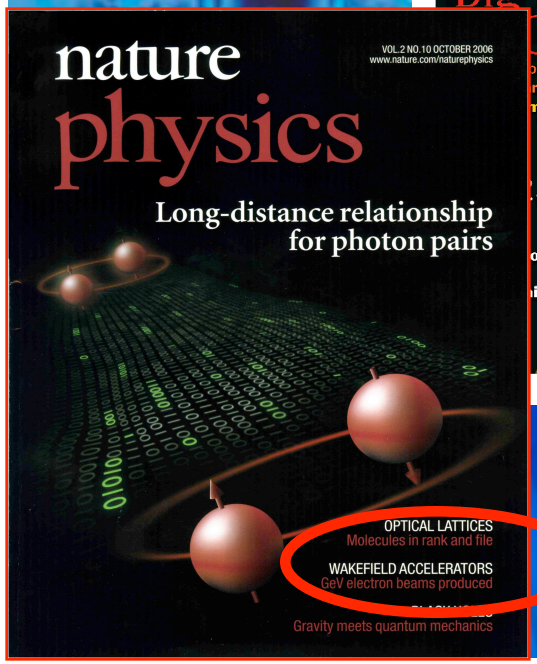
1929

LHC, 2008



Size x 10^5 Energy x 10^9

Can lasers and plasmas play a role in future high energy accelerators?



14 TeV *CM pp*, LHC at CERN

-27 km, $6 Billion+

RF: 10- 100 MV/m

Plasma: 10-100 GV/m

Smaller ?

Cheaper?

Science & Technology

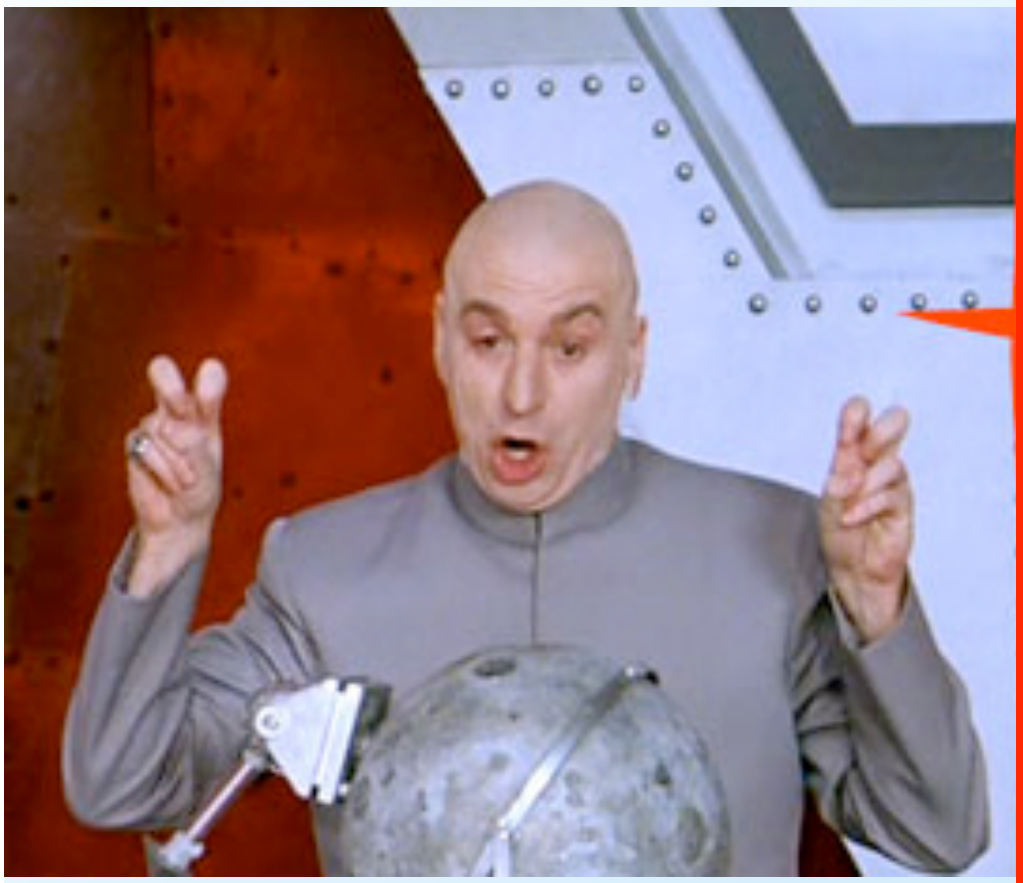
Particle physics

The light fantastic

Sep 28th 2006

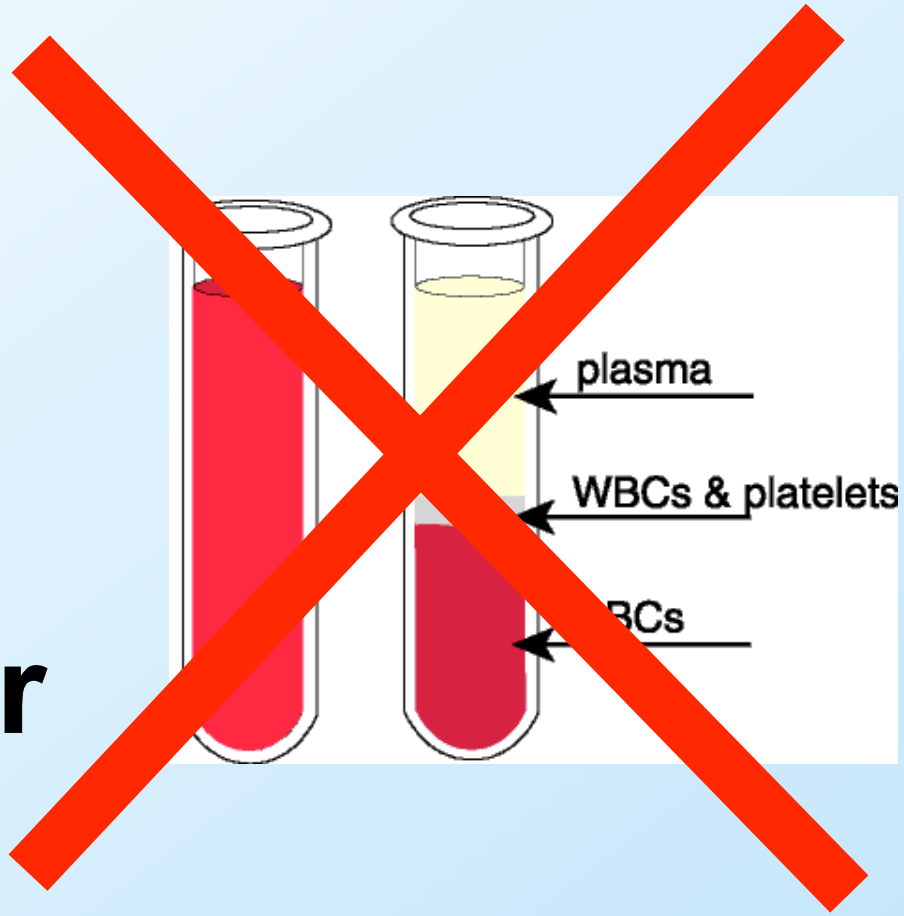
From *The Economist* print edition

A way of building particle accelerators on a table top

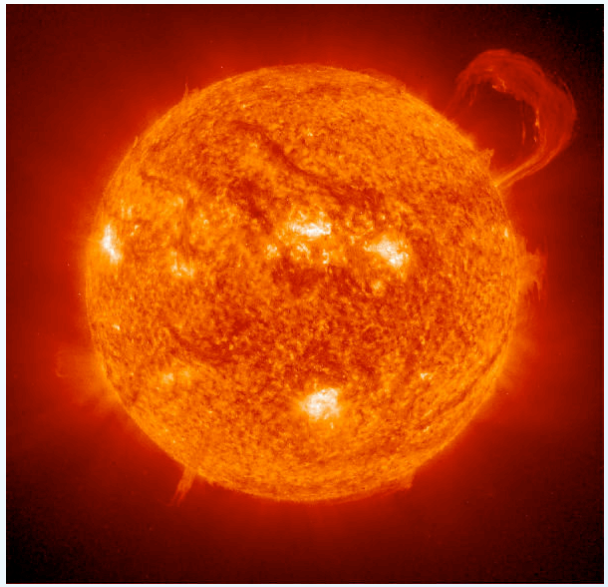


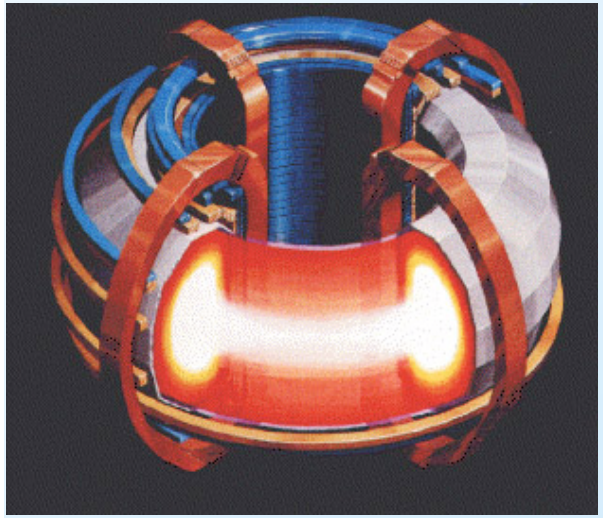
...and then we fire the "laser" in the "plasma" to do this thing called "laser wakefield acceleration"

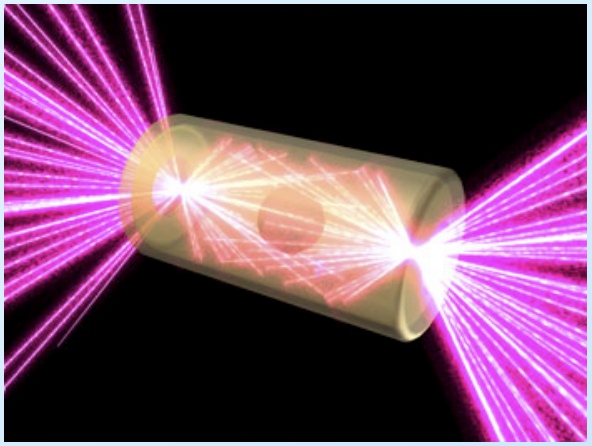
Laser
Plasma
Wakefield
Accelerator

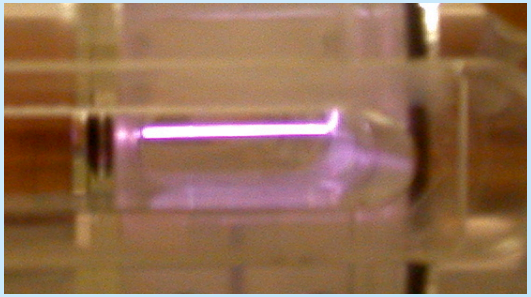


Plasma: 99% of visible universe

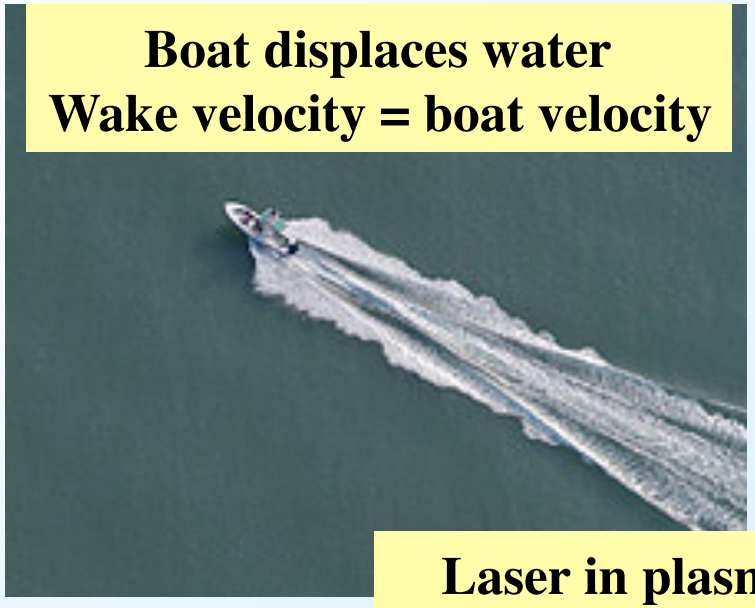




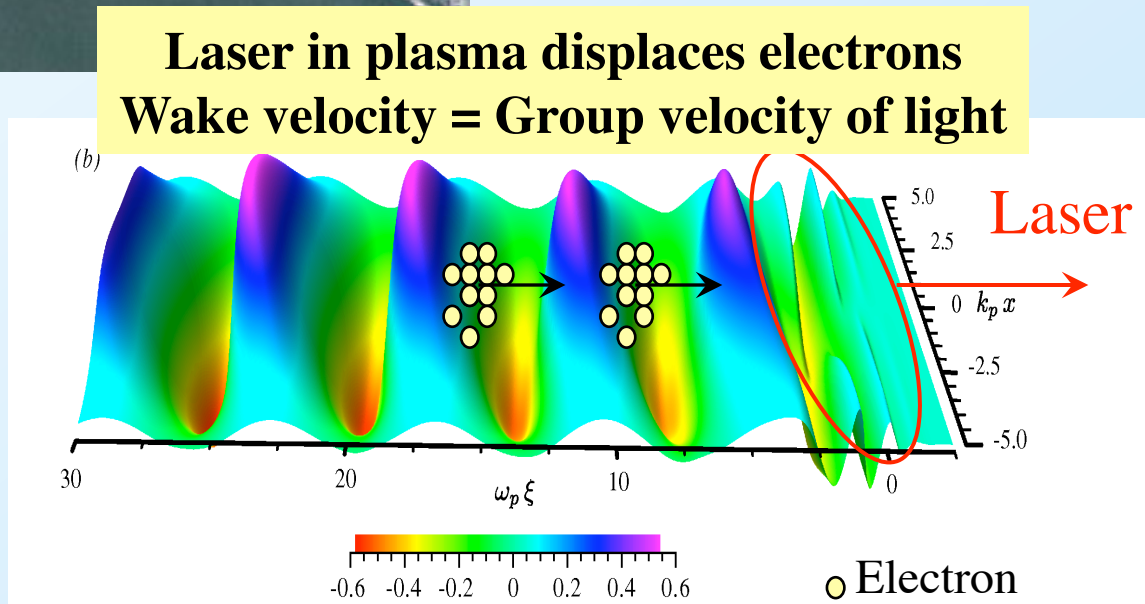




Laser wakefield accelerator: basic concept

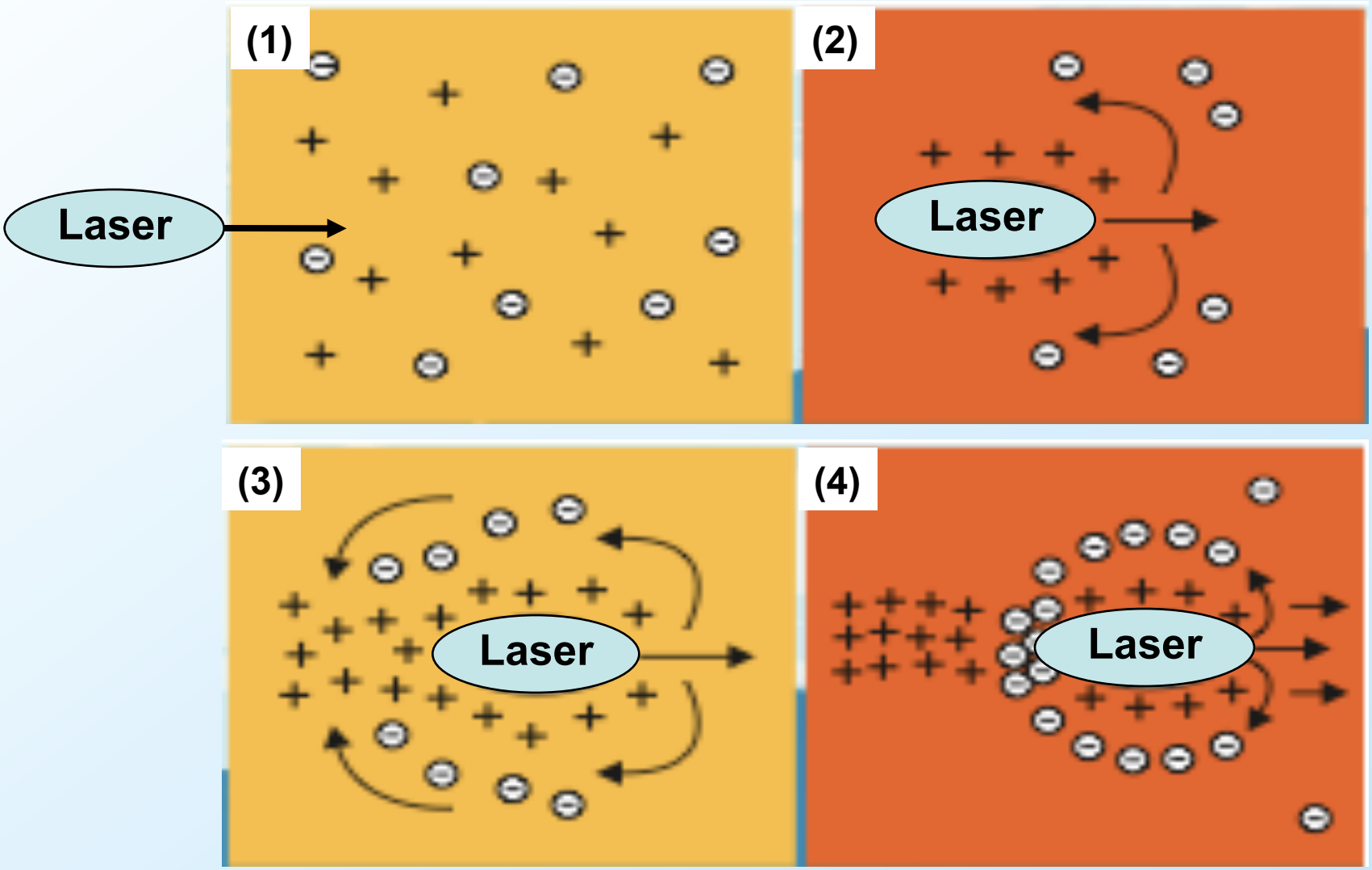


- **Electric field scales like** $\sqrt{n}$
- **Example:**
  - **Atmospheric density plasma**
    - **n ~ 3x10^{19} electrons/cm^3**
    - **E_z ~ 500 GV/m**

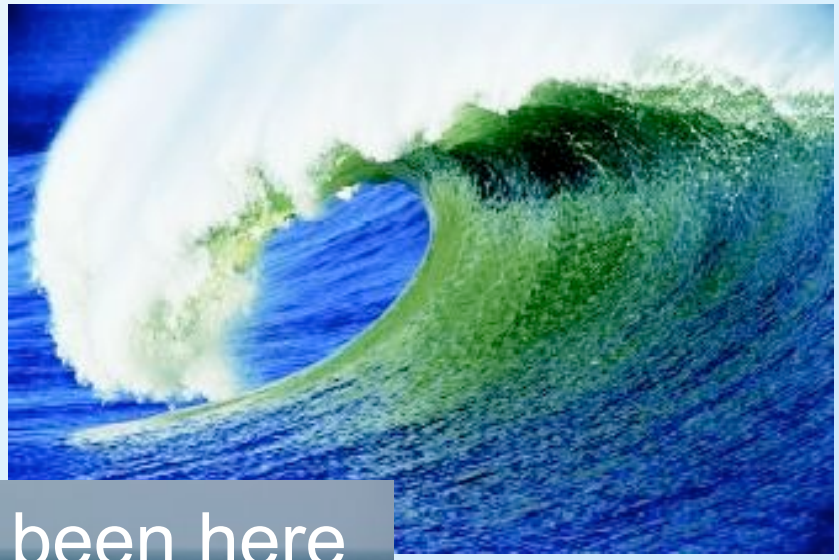


T. Tajima and J.M. Dawson, PRL 1979

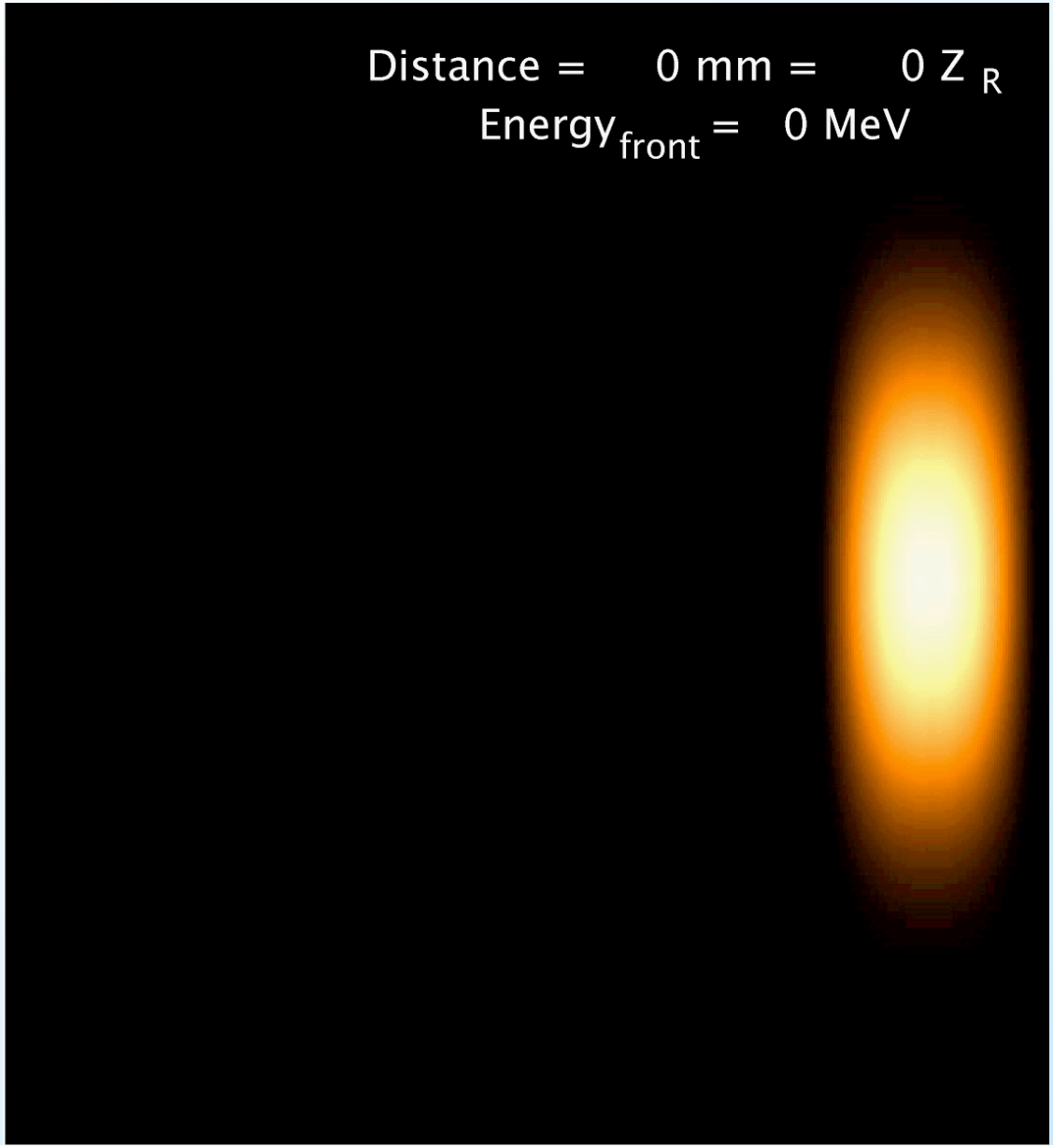
Blow-out or bubble regime: the highly non-linear regime



Wavebreaking results in particle trapping



Operation in bubble or blow-out non-linear regime: most experiments to date



- **High gradients**
- **Can produce narrow energy spread beams**

BUT

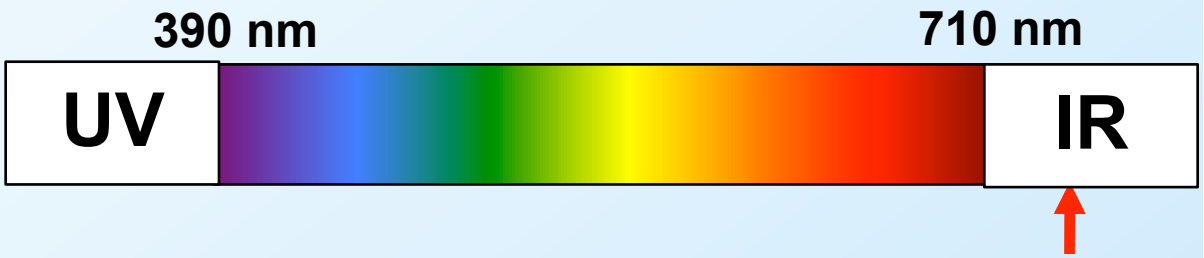
- **Limited control**
- **Self-trapping (dark current)**
- **Can easily go unstable**
- **Does not work well for positrons**

Courtesy of W. Mori, UCLA

Laser Plasma Wakefield Accelerator

What type of laser do we use ?

- Near infra-red: Ti-sapphire,~ 800 nm



- Short pulse: < 50 fs
- High peak power: 10 – 60 TW presently
- Repetition rate: 10 shots/second
- Focused to a spot ~ 8 – 25 micron
- Intensity ~ 10^{18} – 10^{19} W/cm^2

Comparison:
Intensity of sun on a sunny day~ 0.1 W/cm^2

Power and time units

- 1 Terawatt = 1 TW = 1,000 billion Watt = 1,000,000,000,000 Watt
- 1 Petawatt = 1 PW = 1,000 TW
- Typical laser in our research: 10 – 100 TW and moving towards PW

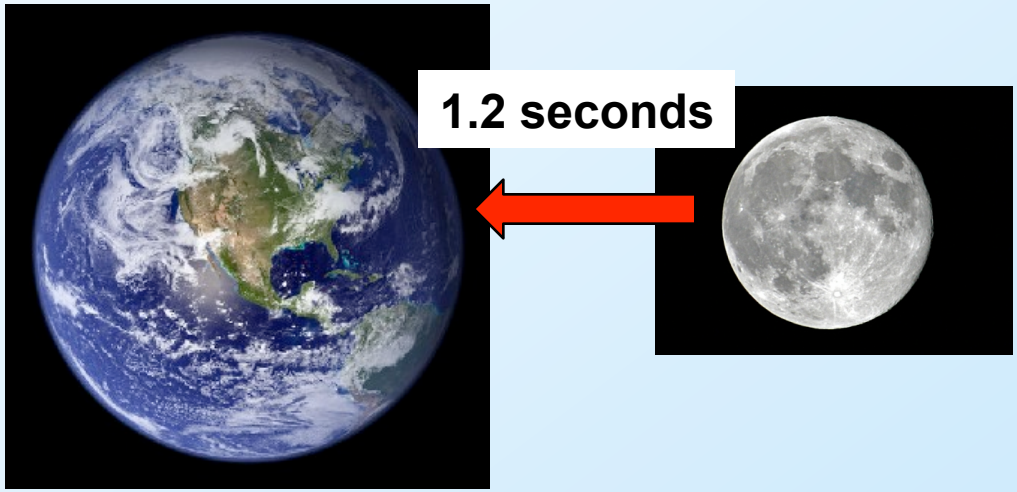
Comparison: world consumption ~ 13-14 TW in 2005

How can we produce so much peak power ?

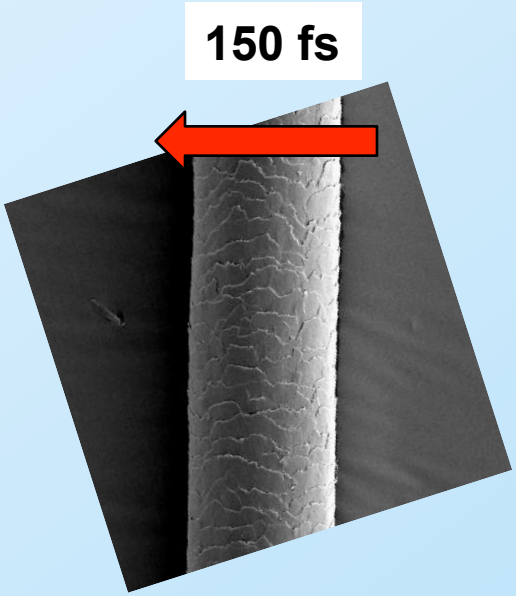
Power = Energy/Duration

- 1 Femtosecond = 1 fs = 0.000000000000001 seconds
- Typical laser pulse duration: 50 fs
- Only need 0.5 J in 50 fs to get 10 TW

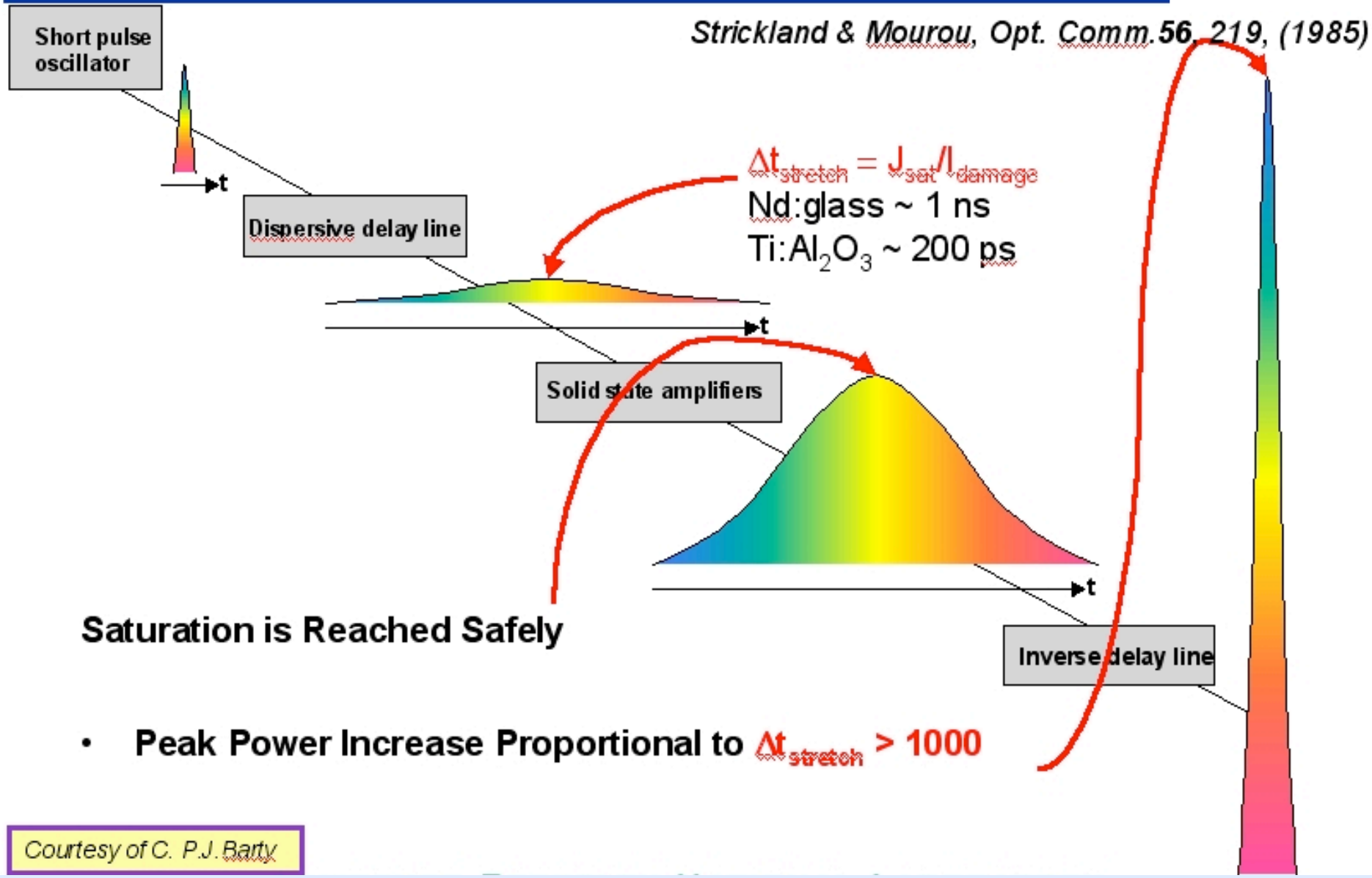
Earth to moon



Human hair



Generic Chirped Pulse Amplification



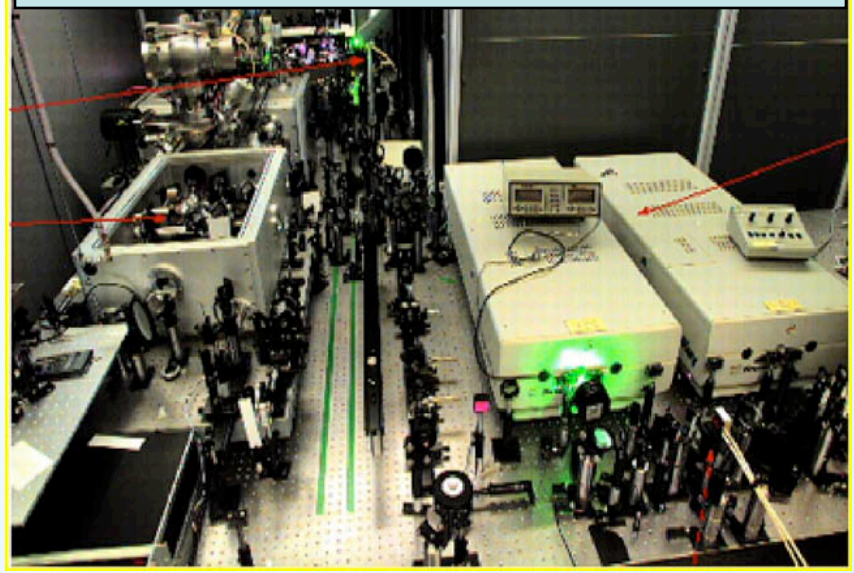
Saturation is Reached Safely

- **Peak Power Increase Proportional to $\Delta t_{stretch}$ > 1000**

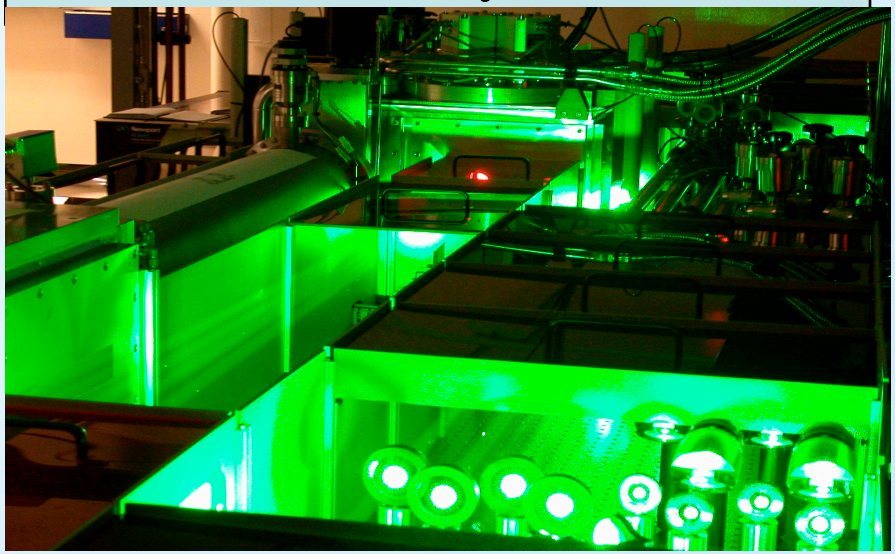
Courtesy of C. P.J. Barty

Example: LOASIS high rep rate, high peak power Ti:sapphire system

10 TW system



100 TW system



<u>Three main amplifiers (10 Hz):</u>

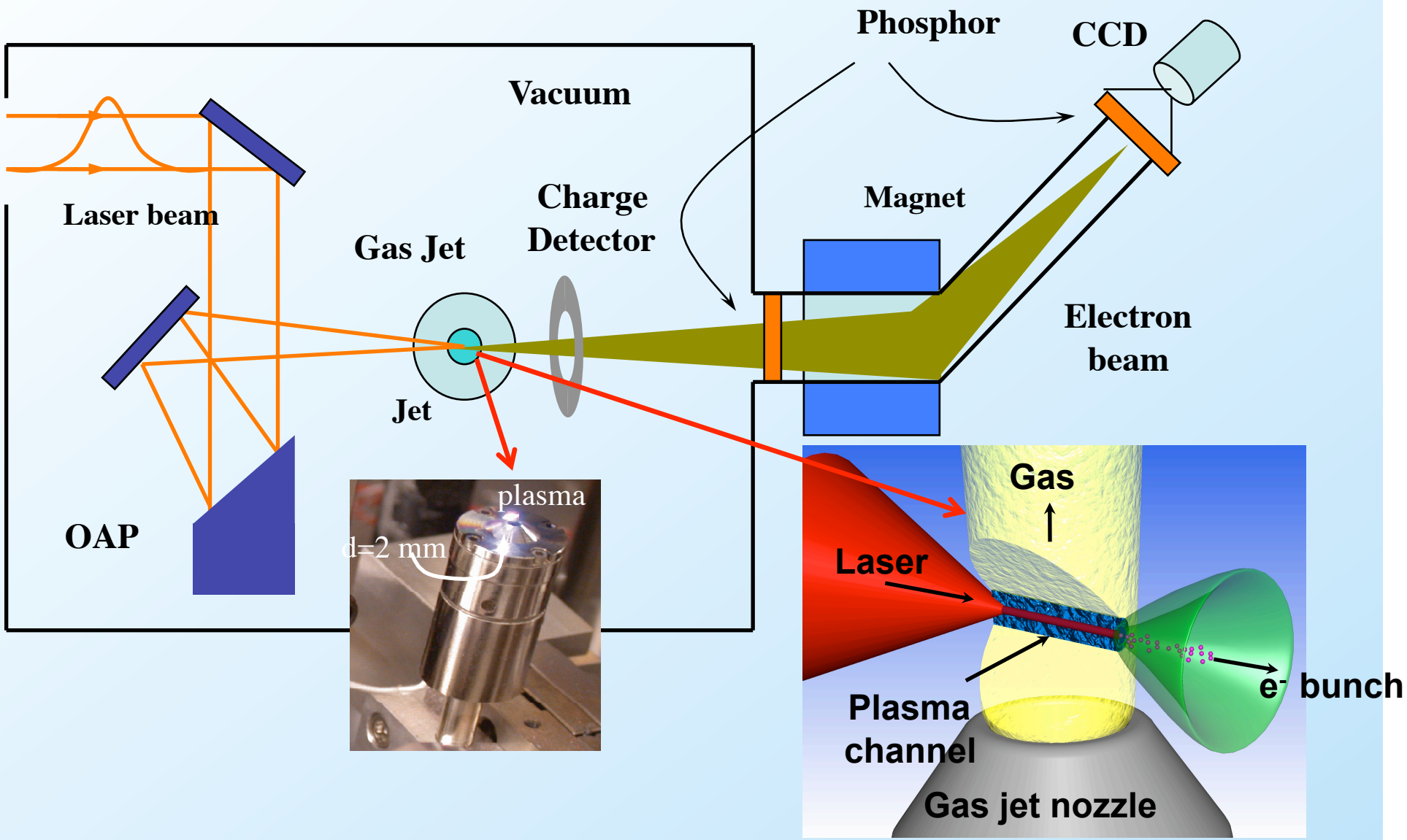
- Godzilla:
  - 0.5-0.6 J in 40-50 fs (10-15 TW) ===> drive beam
- Chihuahua:
  - 0.4 J in < 40 fs ===> ignitor beam
  - 250-300 mJ in 200-300 ps ===> heater beam
- TREX:
  - 2.7 J in 35-40 fs (at present) ===> capillary guiding

Laser Plasma Wakefield Accelerator

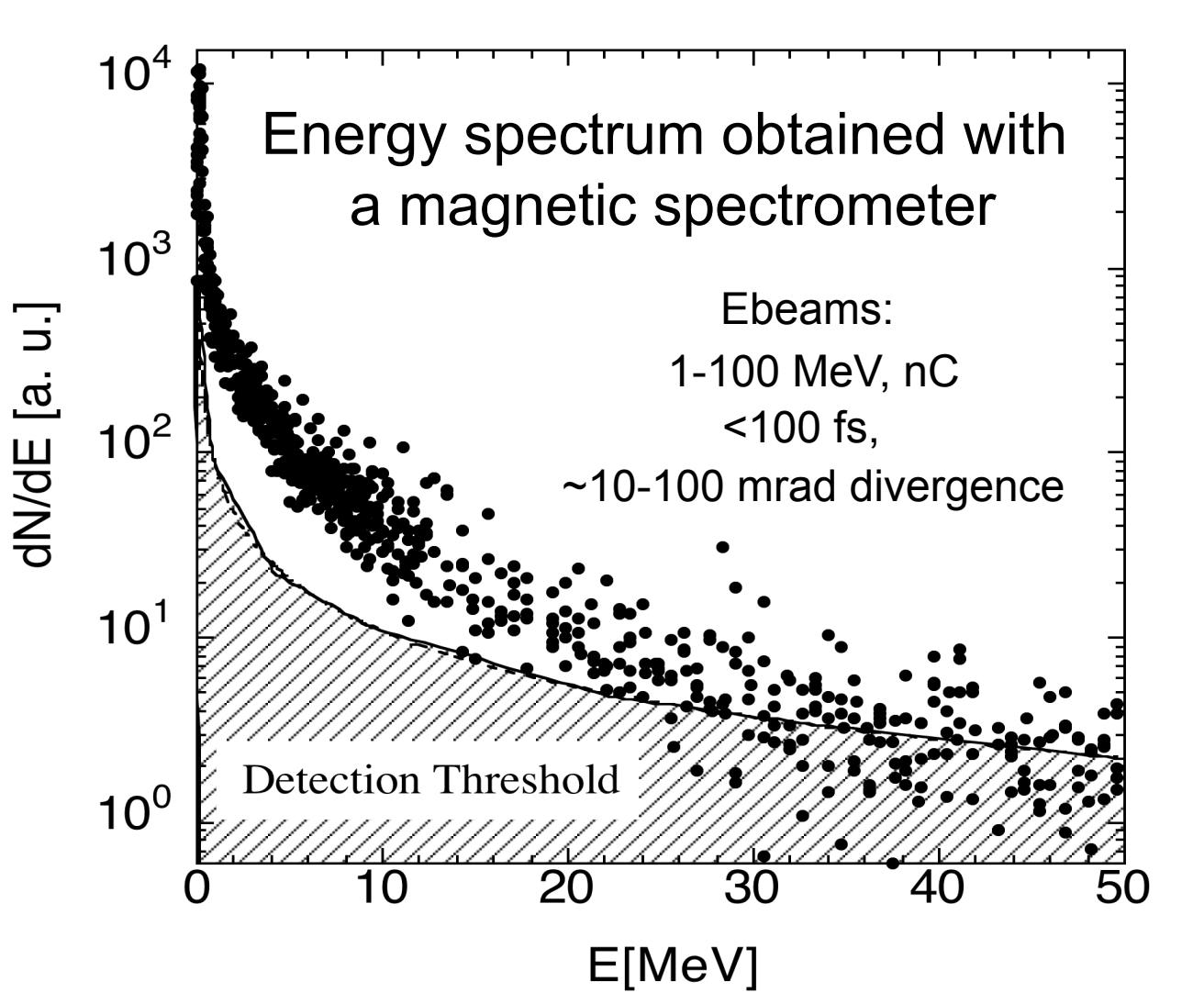
Particle energy = Electric field (V/m) x Distance

$$\Delta W = E_z \cdot L$$

Typical experimental set-up – pre-2003



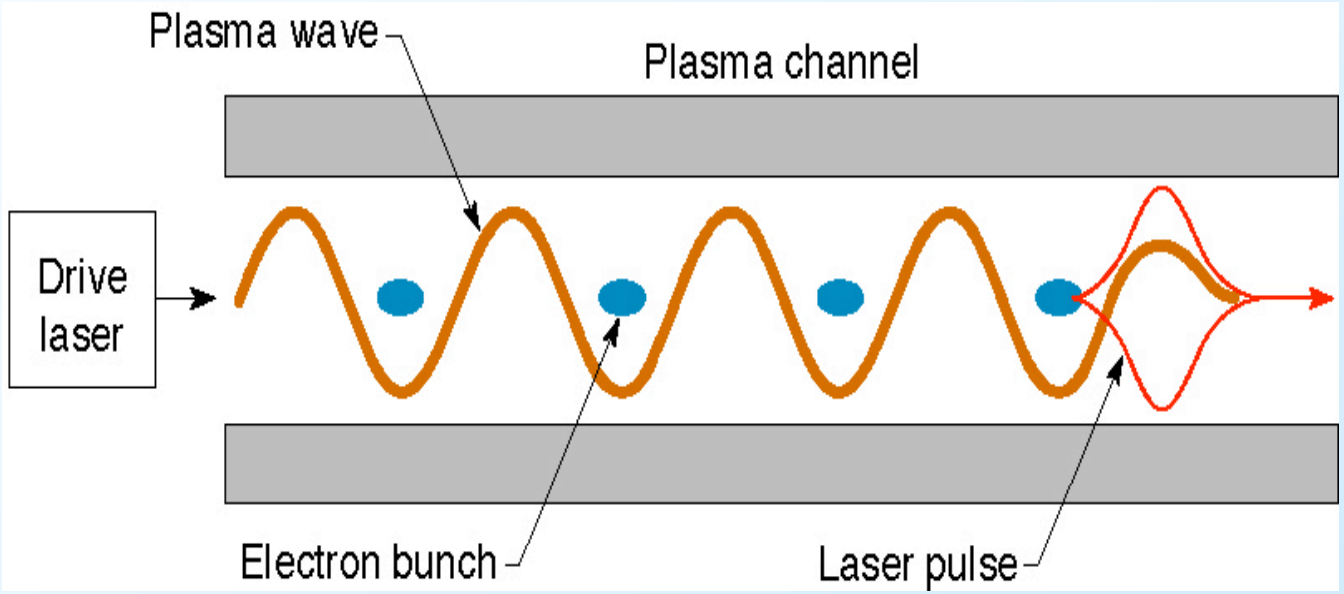
Mid 90's -2003: lasers generate electron beams with 100 % energy spread



- **2-3 mm gas jet**
- **~100 MeV electrons**
- **Confirms large E_z**

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

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

$\Delta W = E_z \cdot L$
How to pick the accelerator length?

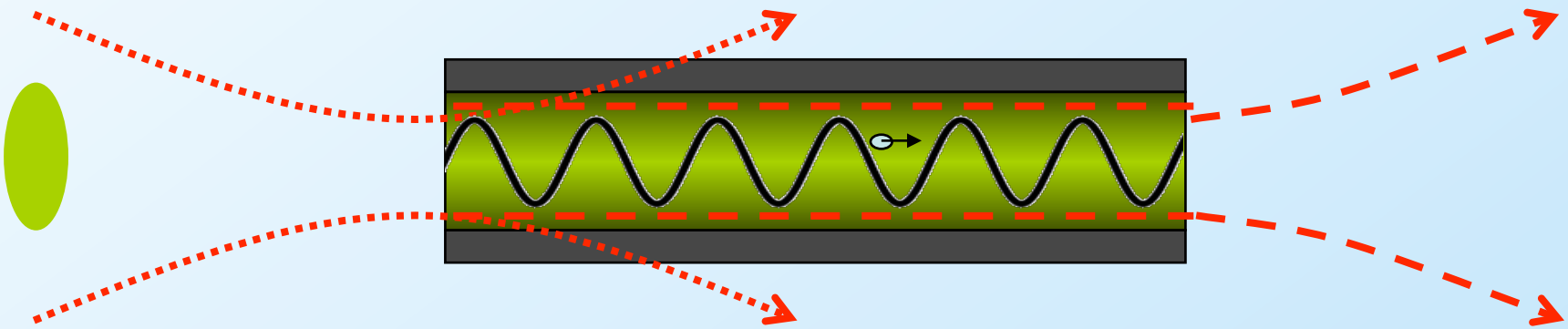
"The 3D's of laser accelerators"

- Diffraction of the laser pulse
- Dephasing of the particle with the wave
- Depletion of the laser power

Overcoming laser diffraction

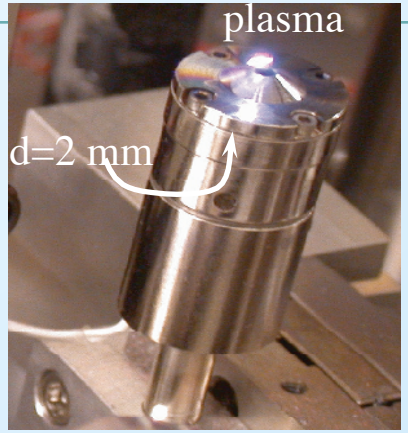
- Diffraction can limit acceleration length - can be overcome by employing large spot sizes but this is inefficient

- Self-focusing (inefficient, limits options, lack of control) - current experiments demonstrate need for waveguide



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

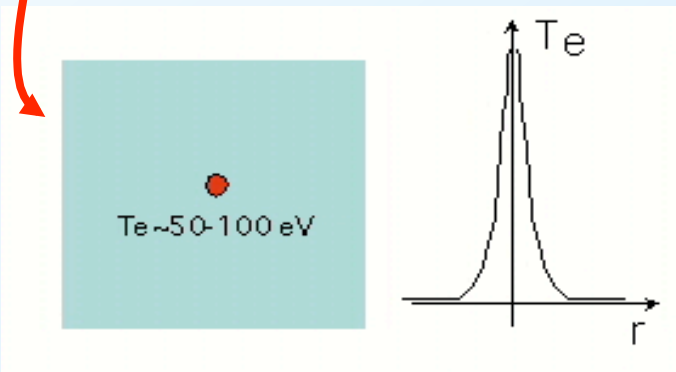
Making a plasma based optical fiber: radial density profile shaping



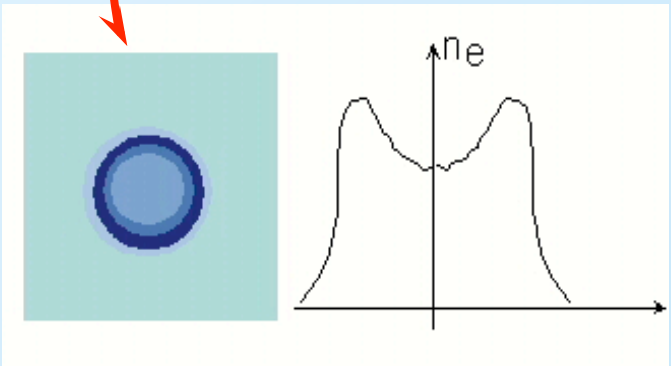
- Step 1: Ionize gas – produce plasma
- Step 2: Heat plasma
- Step 3: Hydrodynamic expansion

Plasma Profiles

INITIAL



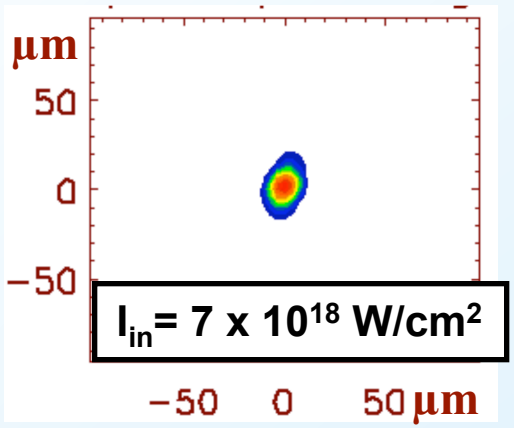
EXPANDED

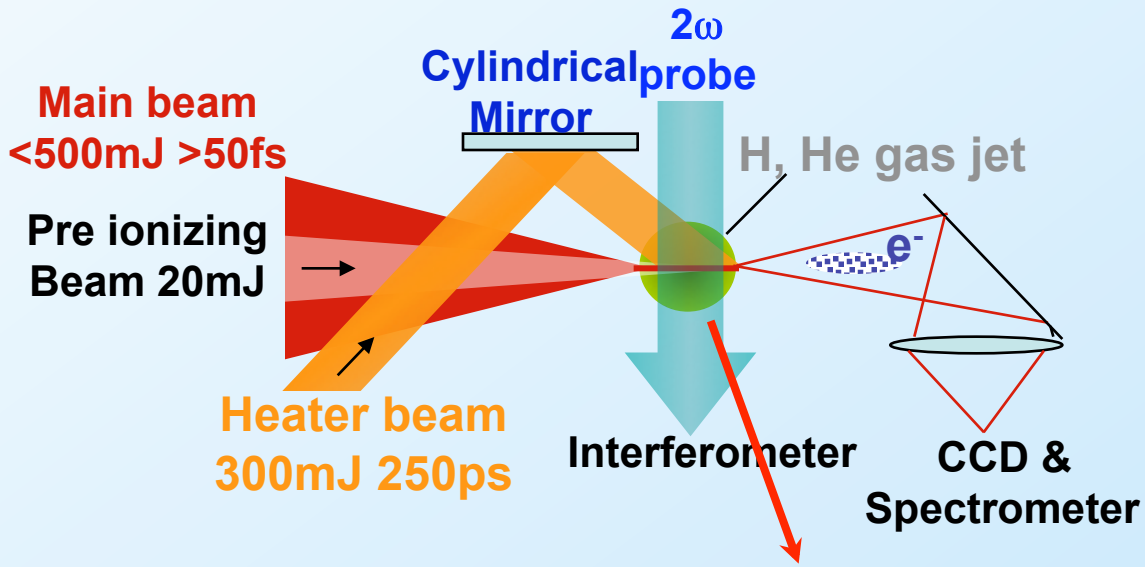


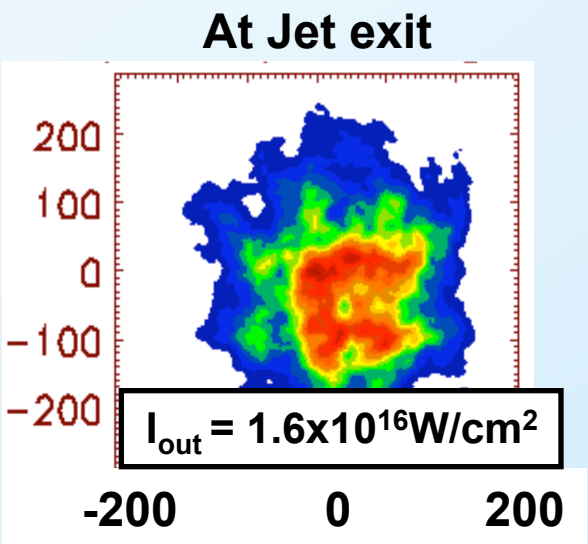
- Laser heated waveguide[1]
- Discharge based waveguide[2]

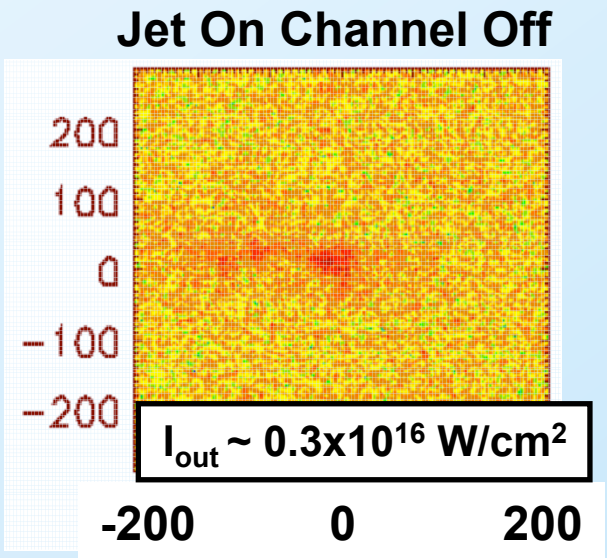
[1]Geddes et al., Nature 2004
[2]Leemans et al., Nature Physics 2006

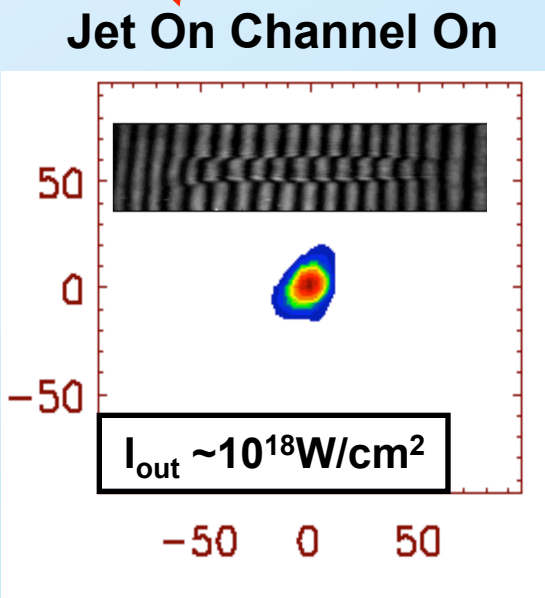
2004: Laser guiding in laser preformed channels
Building block for a laser accelerator





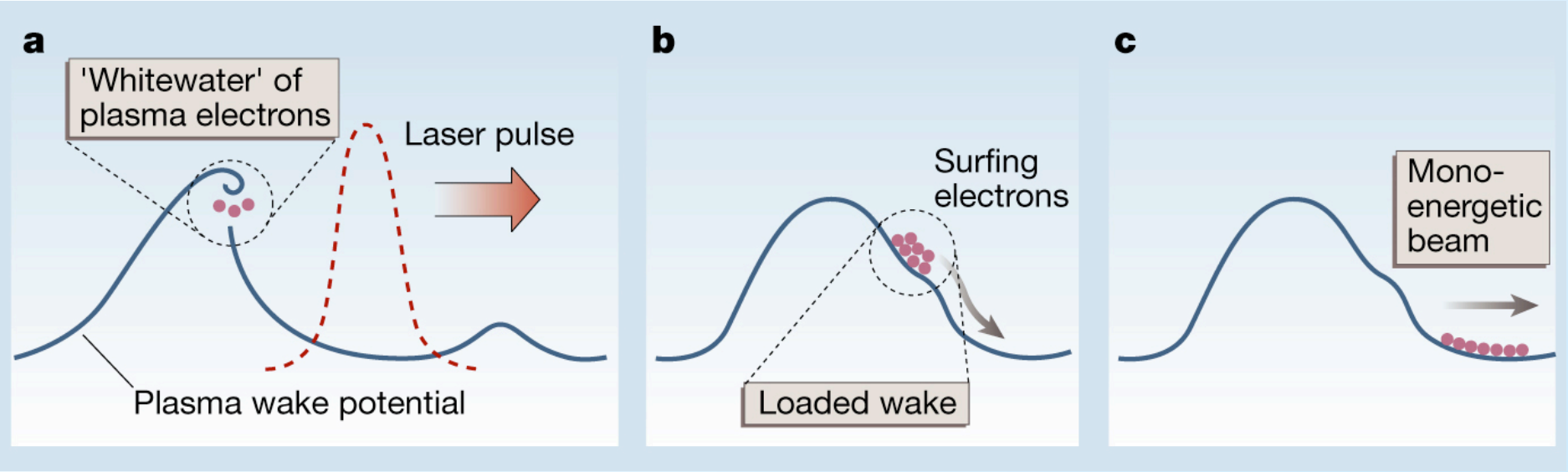






C. Geddes et al., Nature 431 (2004)

Dephasing: particle outruns wave



Graphics courtesy of T. Katsouleas, Nature 2004

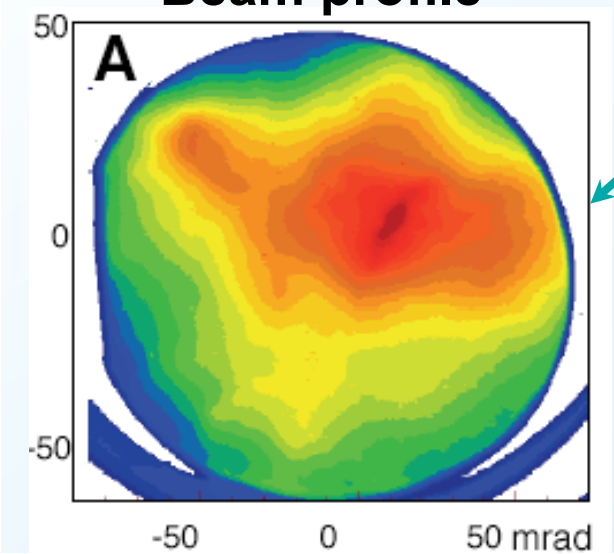
- **Length scale for dephasing set by density**
- **Energy gain:** $\Delta W_d[\mathrm{GeV}] \sim I[\mathrm{W/cm^2}]/n_p[\mathrm{cm^{-3}}]$

Reduce n_p

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

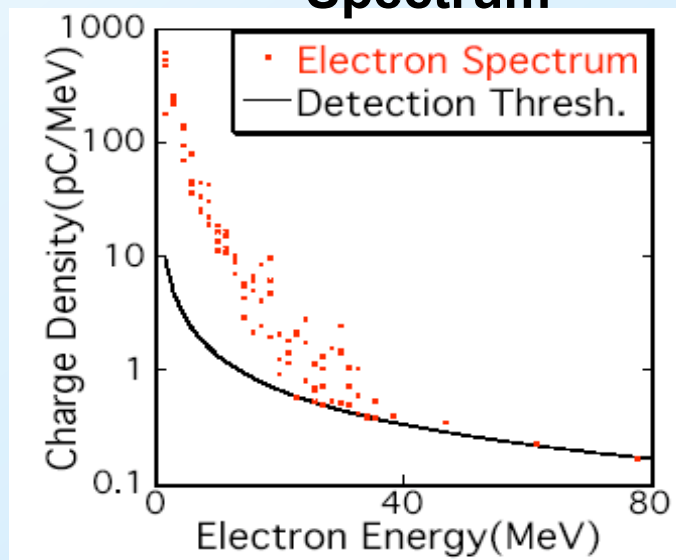
Breakthrough: 85 MeV e-beam with %-level energy spread from laser accelerator

Beam profile

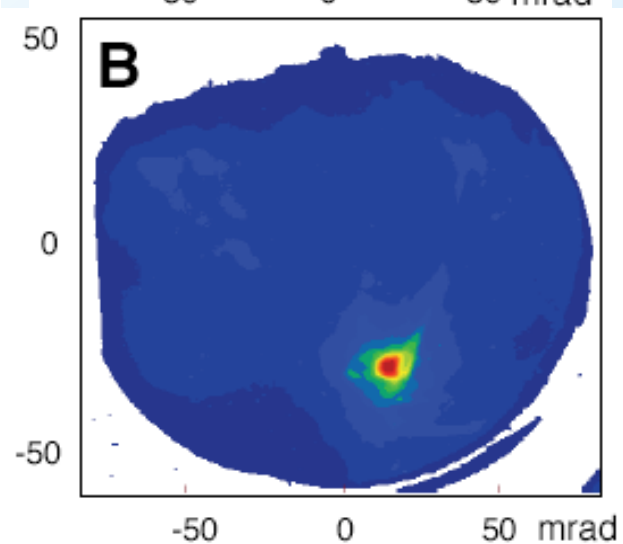


Unguided

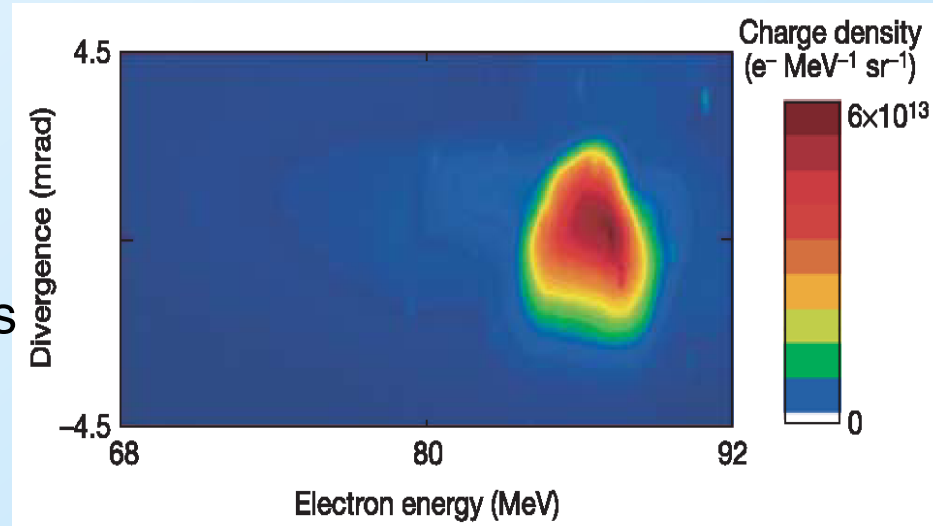
Spectrum



Guided



9 TW
50 fs
1.8e19 cm^{-3}
1.7 mm
2e9 electrons
3 mrad
$\Delta E < 4$ MeV



C.G.R Geddes *et al*, Nature, Sept 30 2004

Laser Wakefield Particle Acceleration

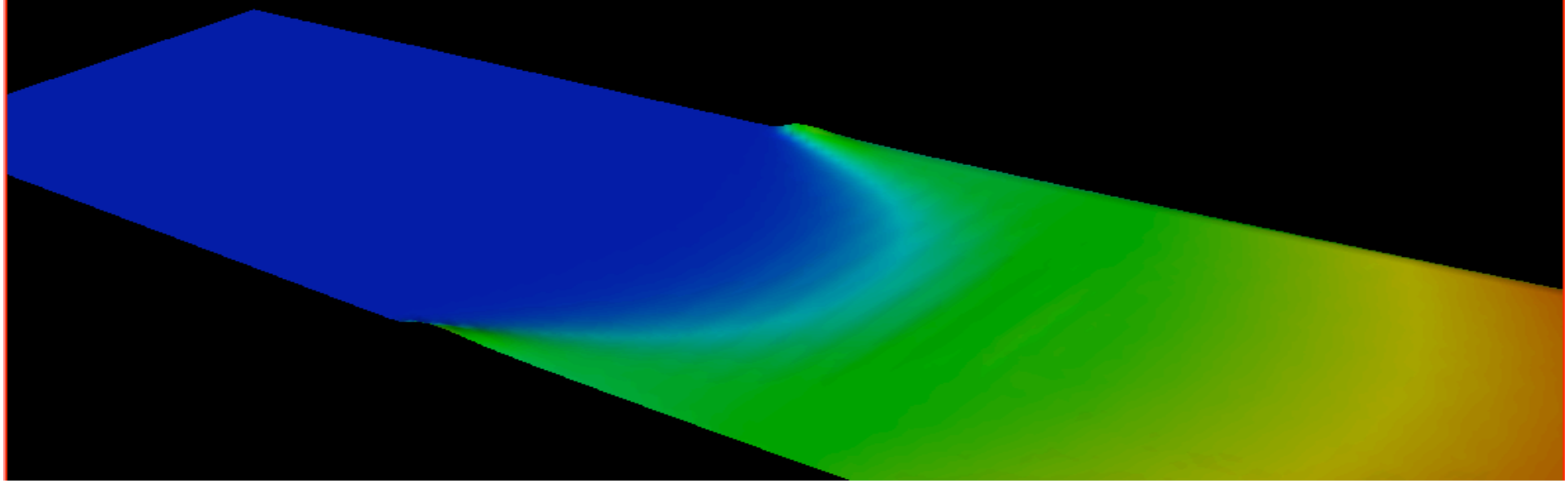
High Quality Electron Bunches in Millimeters

3D Vorpal Particle Simulation: INCITE 7 team
Cameron Geddes

Visualization:
Cameron Geddes and Peter Messmer

Experiments:
LOASIS program at LBNL

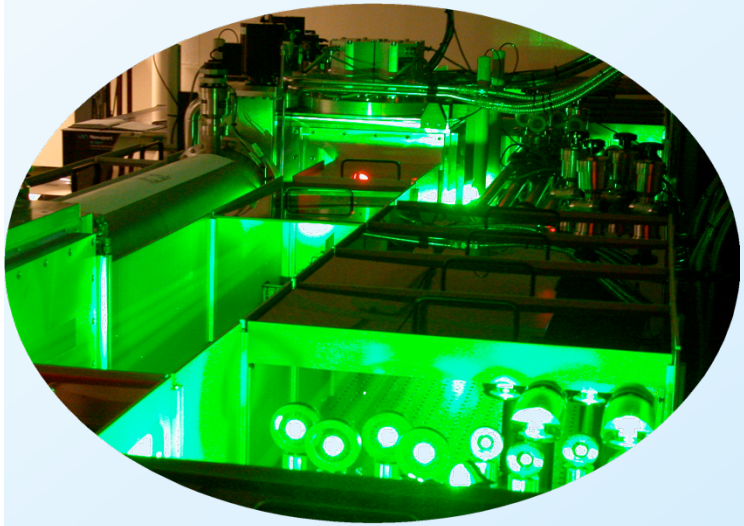
Code:
Vorpal: Tech-X & U. Colorado



Higher beam energy requires lower plasma density

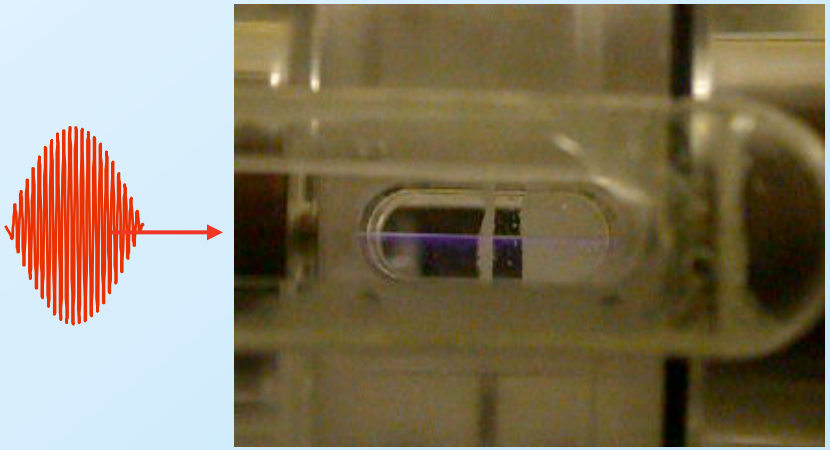
- Higher power laser
- Lower density, longer plasma

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



Laser: 40-100 TW,
40 fs 10 Hz

Plasma channel technology: Capillary

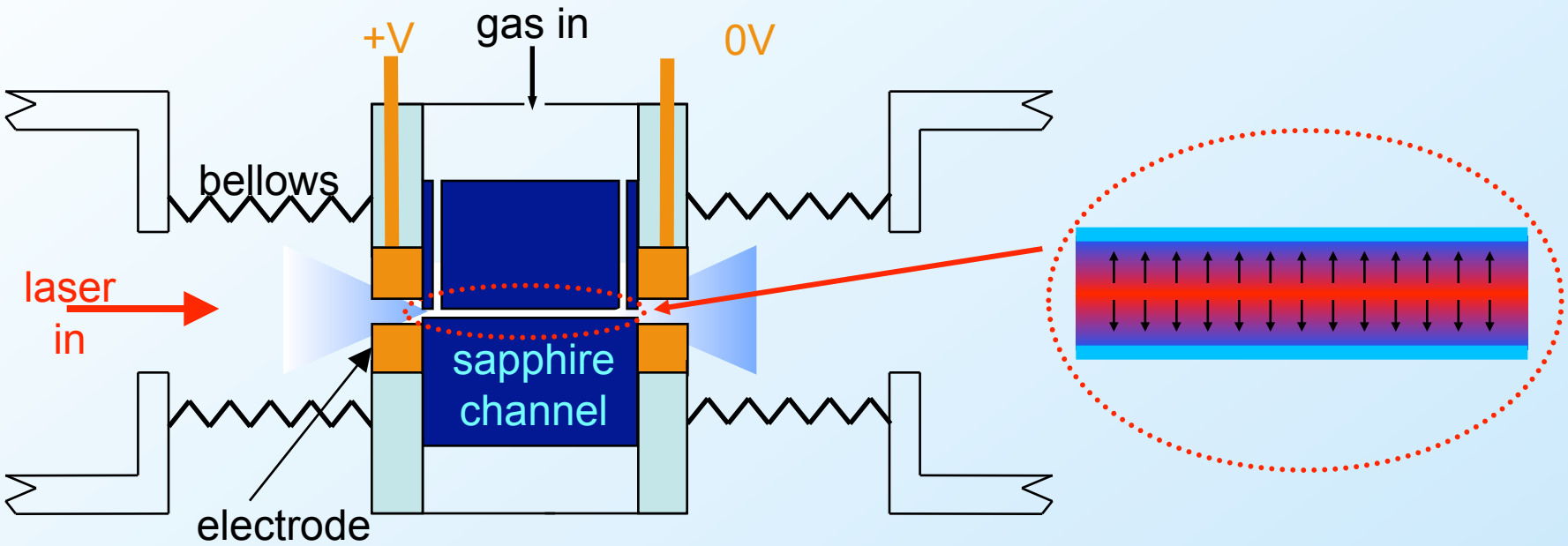


3 cm

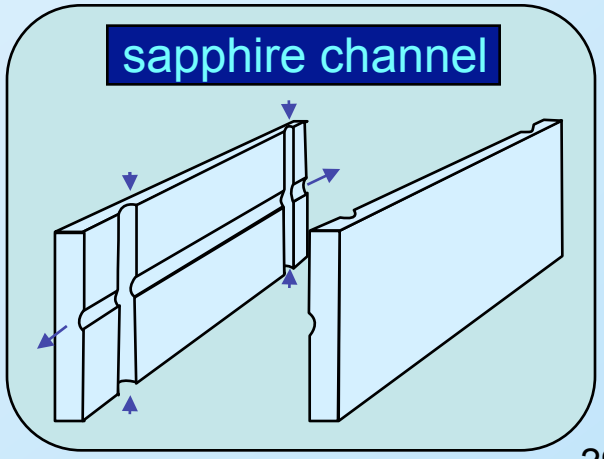
1 GeV

e^- beam

Going to higher beam energy: capillary discharge waveguide

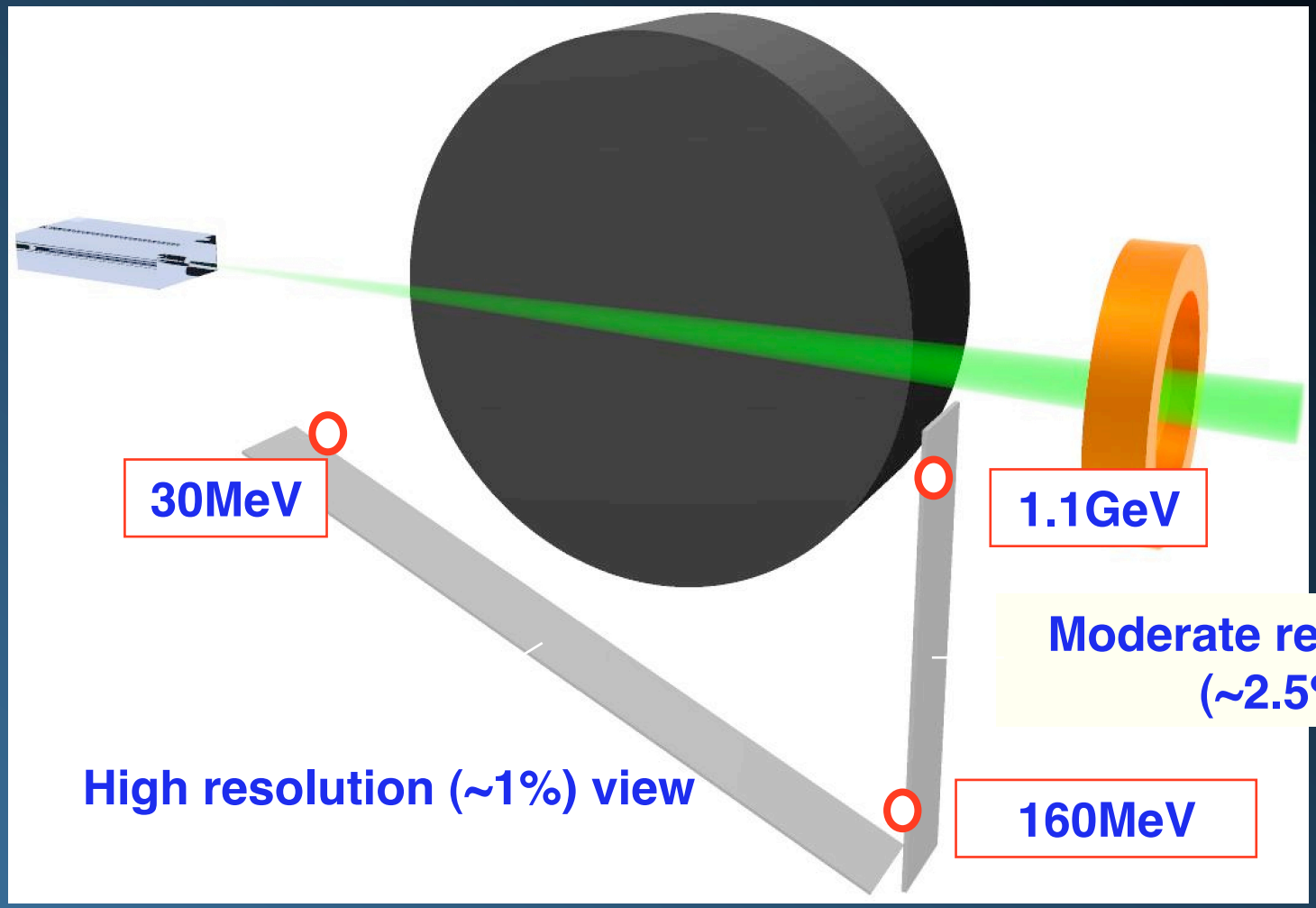


- Gas ionized by pulsed discharge
  - Peak current 200 - 500 A
  - Rise-time 50 - 100 ns



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

LOASIS GeV Spectrometer



Moderate resolution (~2.5%)

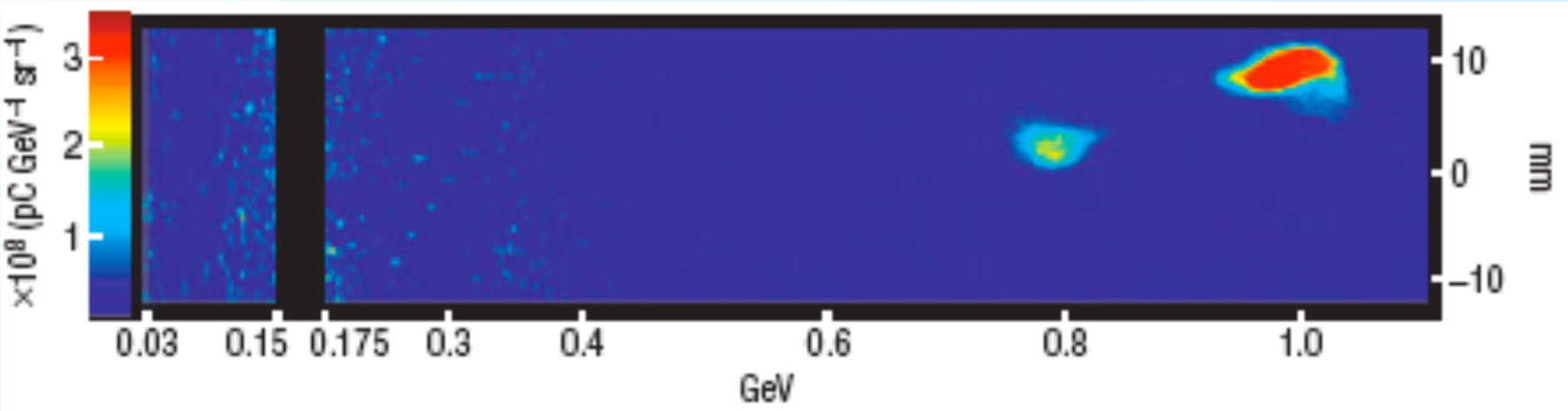
Horizontal profile -> divergence; Vertical profile -> energy

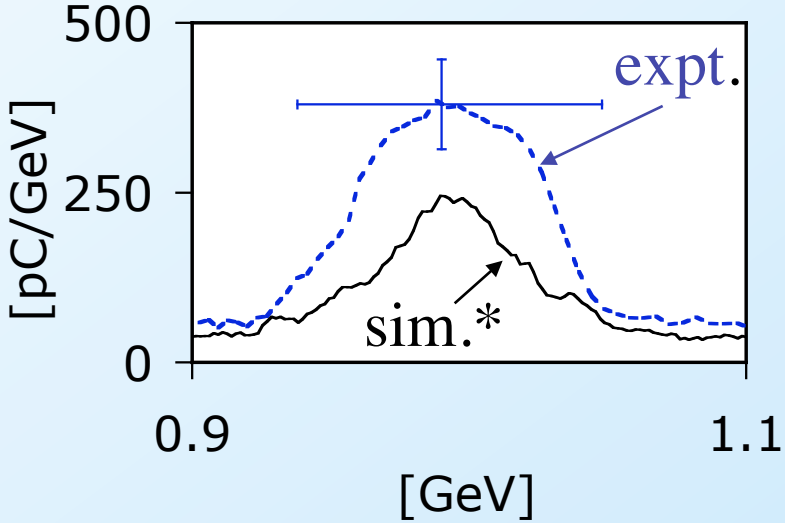
$$\delta E_{obs} = \sqrt{\delta E_{real}^2 + \delta E_{div}^2}$$

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





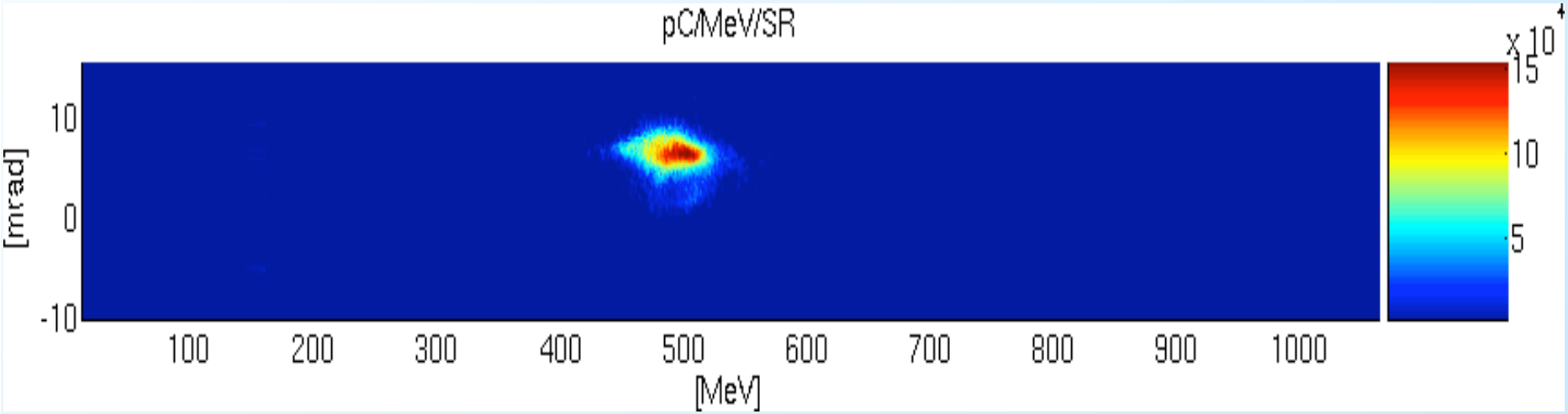
	Sim	Expt
Q (pC)	25-60	35
E (GeV)	1.0	1.1
dE/E RMS (%)	4	2.5
div. (mrad)	2.4	1.6

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

Improved stability at 0.5 GeV

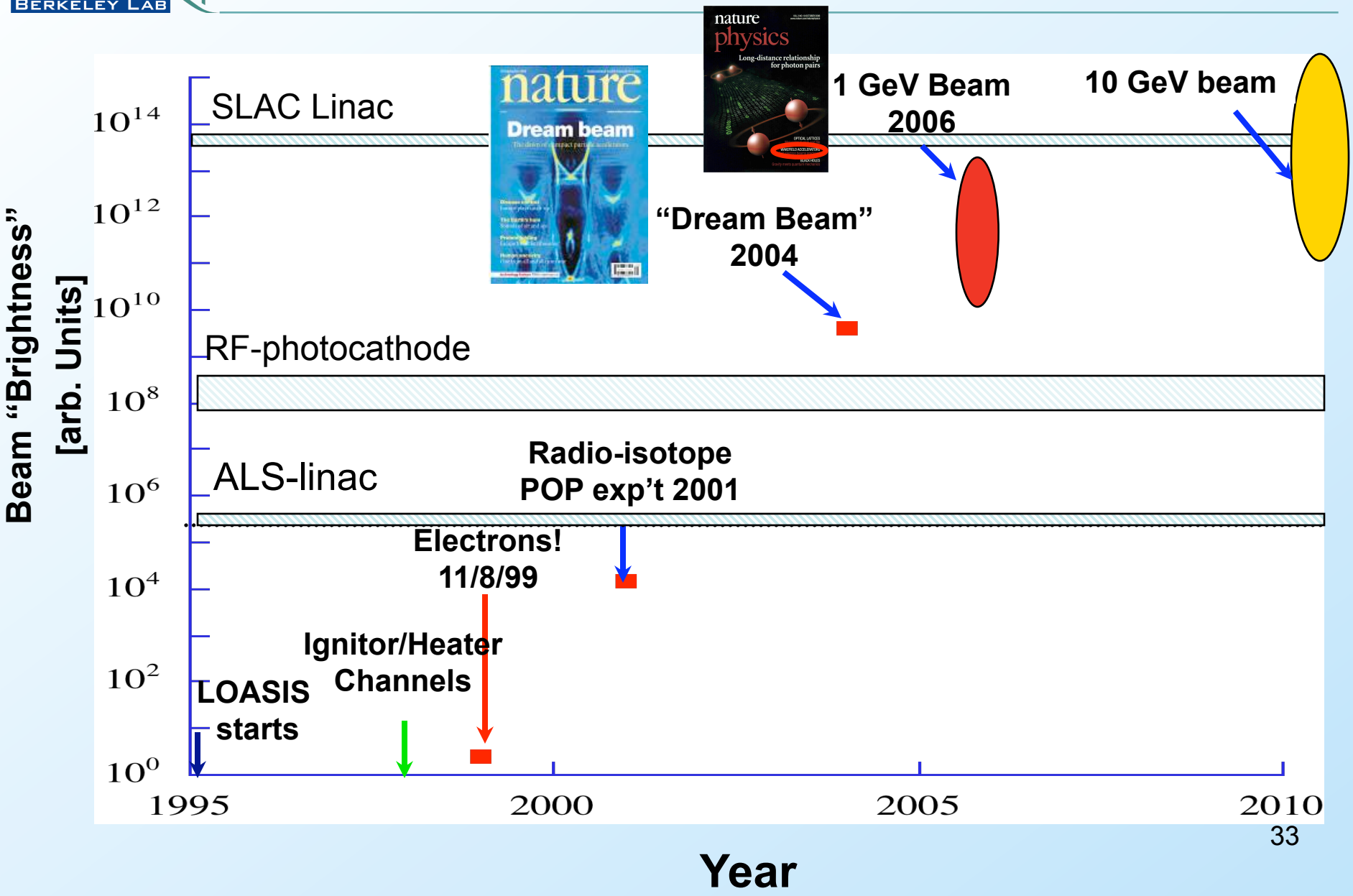
- Laser: a_0 > 0.77 (12 TW, 80 fs)
- Capillary: 225 μm diameter and 33 mm length
- n_e = 3.5x10^{18} cm^{-3}

0.5 GeV beam



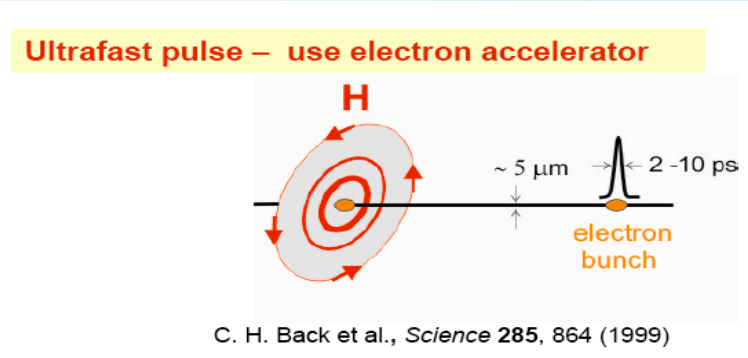
Charge=32±14pC, Energy=456±45MeV, dE/E= 6±3%

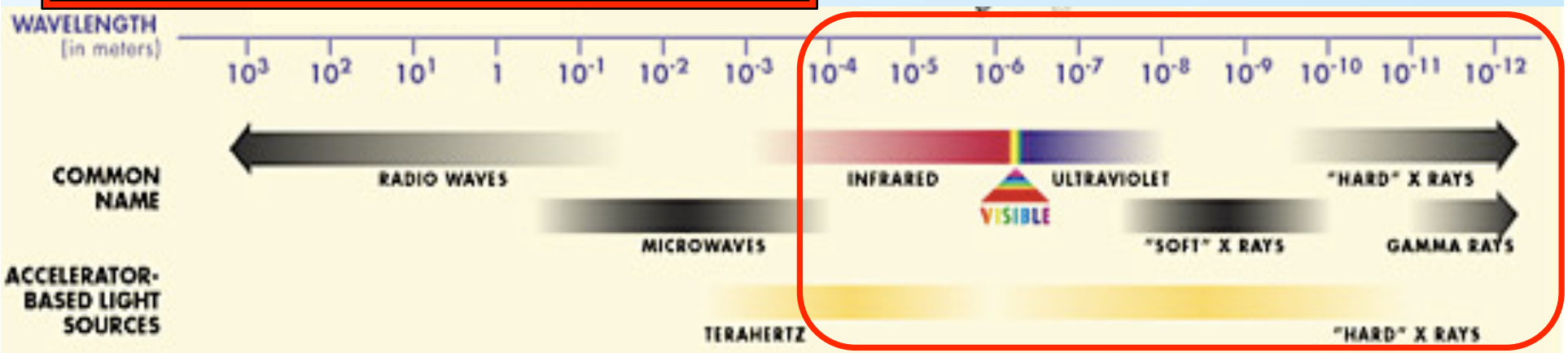
Progress on Laser Acceleration at LOASIS

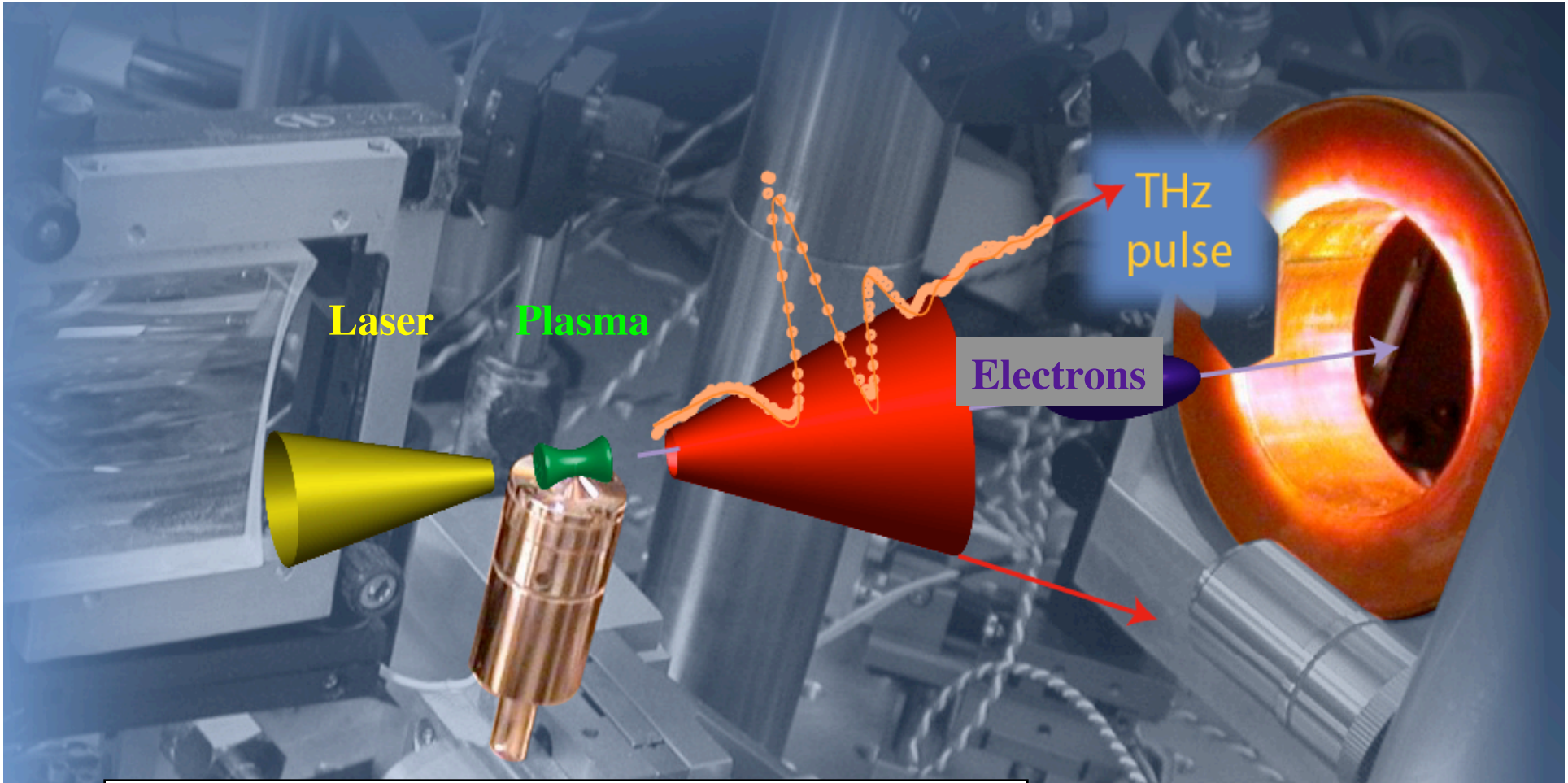


Some of the applications

- Unique properties:
  - Ultra-short electron bunches, high peak current (multi-kA)
  - Intrinsic synchronization with laser pulse
- Direct use of e-bunches:
  - Domain switching in ferromagnets
- Radiation sources:
  - Coherent terahertz emission
  - XUV generation
  - X-rays and gamma rays



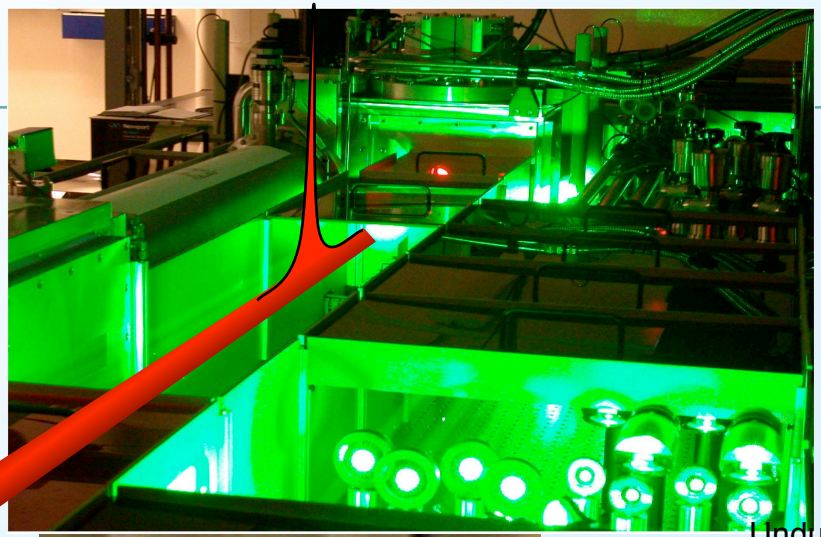


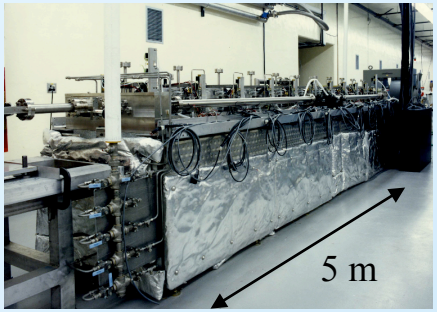


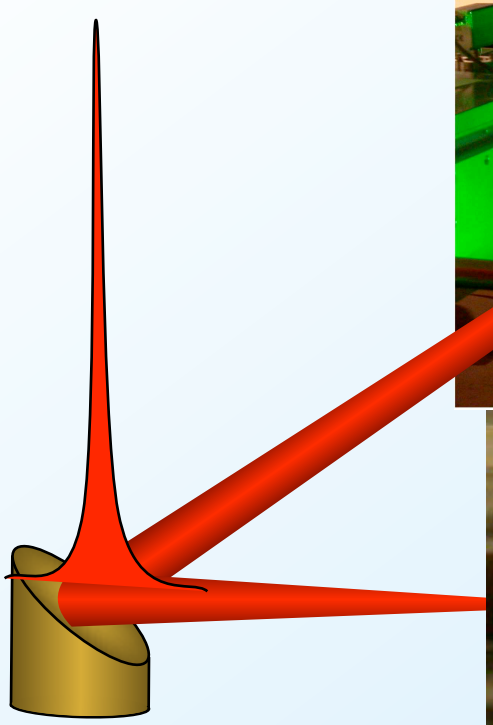
- ‘Traditional’ laser based sources deliver < 100 kV/cm
- We achieved > 4 μJ in a single pulse
- Fields near 1 MV/cm
- Ready for expts using intense THz

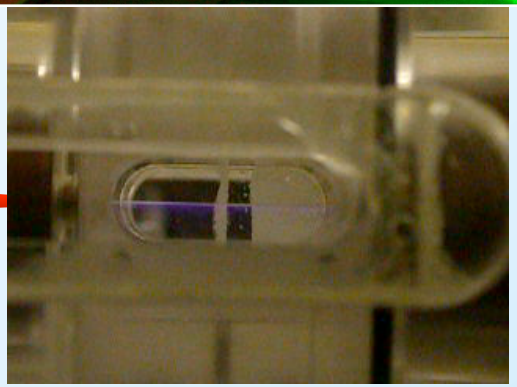
Leemans et al. PRL 2003; POP2004; IEEE2005 Schroeder et al., PRE 2004;
van Tilborg et al., Laser Part. Beams2004; PRL2006; POP2006; Optics Lett. 2006

An XUV Free electron laser

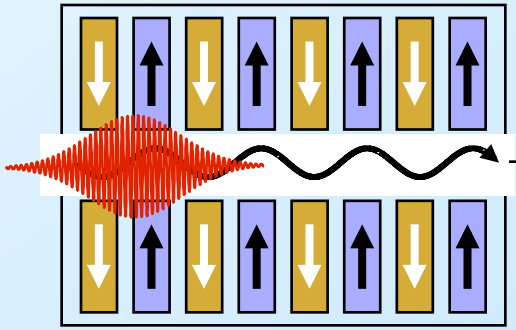








Undulator

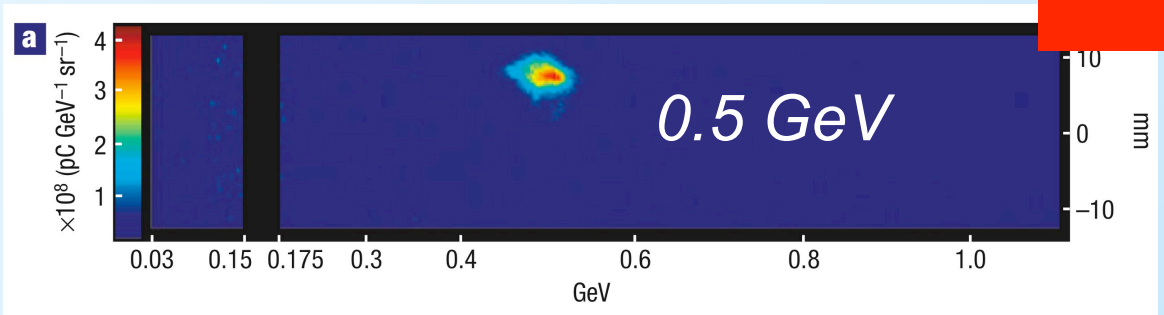


FEL output:
λ=31 nm
10^{13} phot./pulse

T-REX laser system
$I_{pk} \sim 10^{18}$ W/cm^2
40 TW, 40 fs

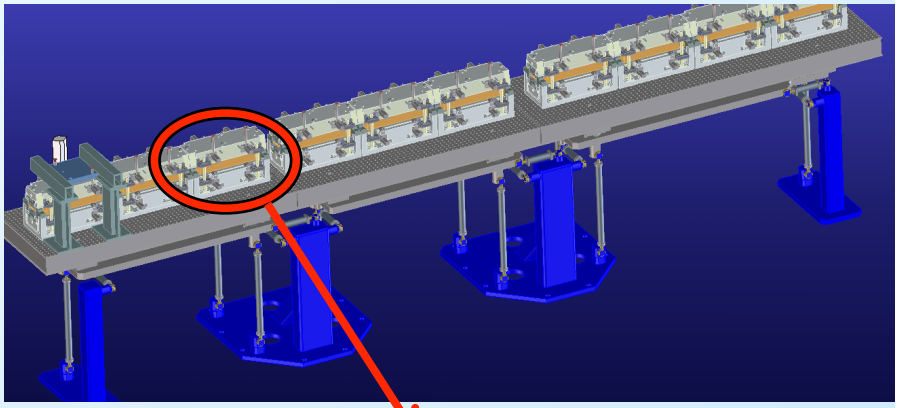
Plasma capillary technology

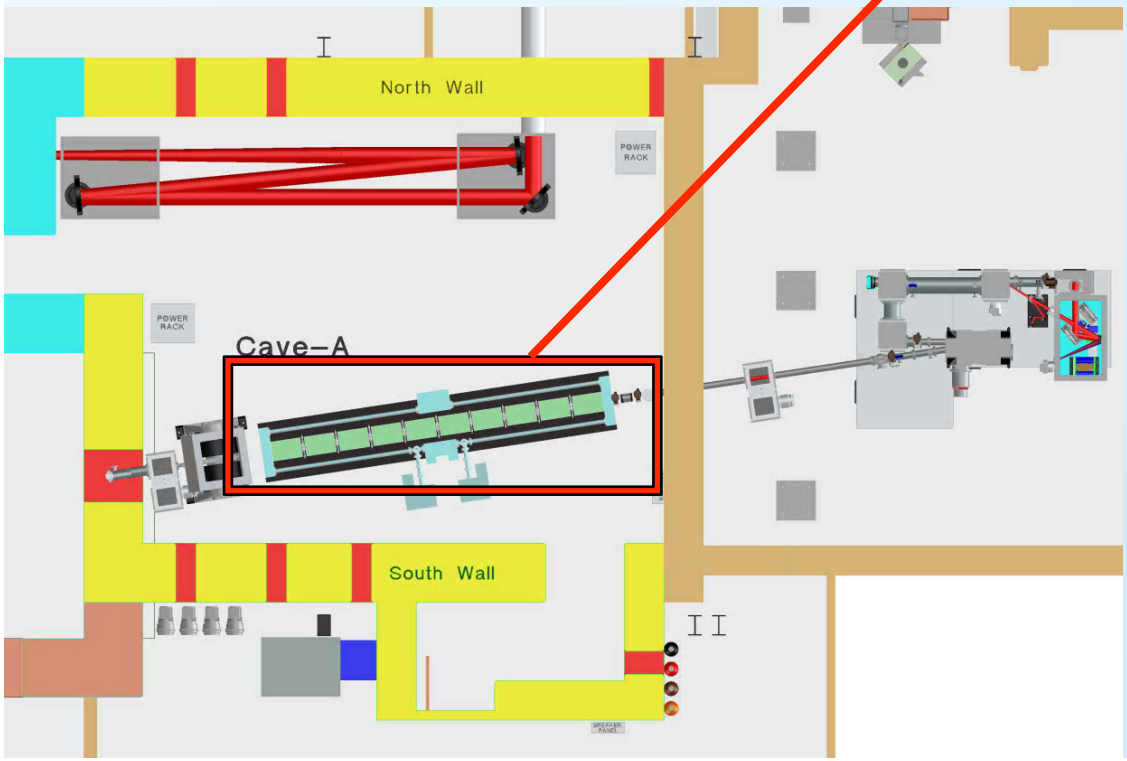
BUT: need 0.25% energy spread (currently >2%)

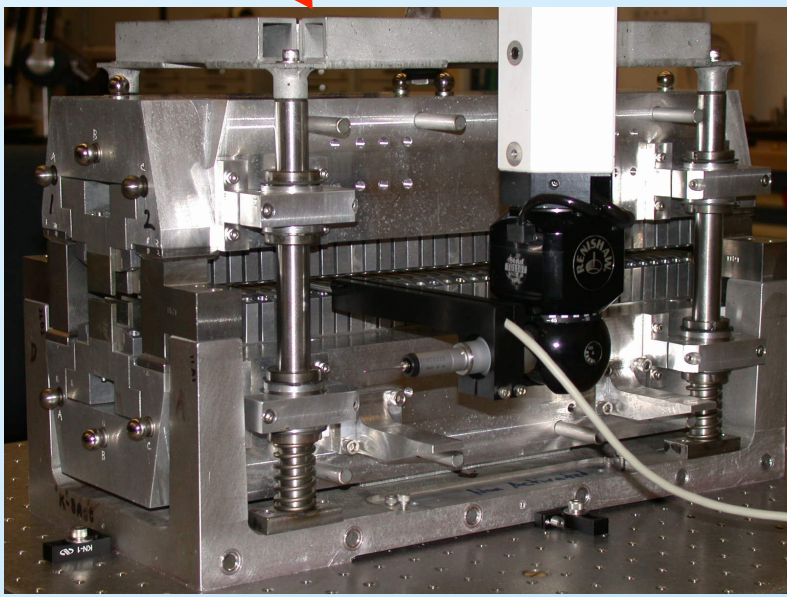


Undulator based diagnostic is first step towards SASE-FEL at 30 nm

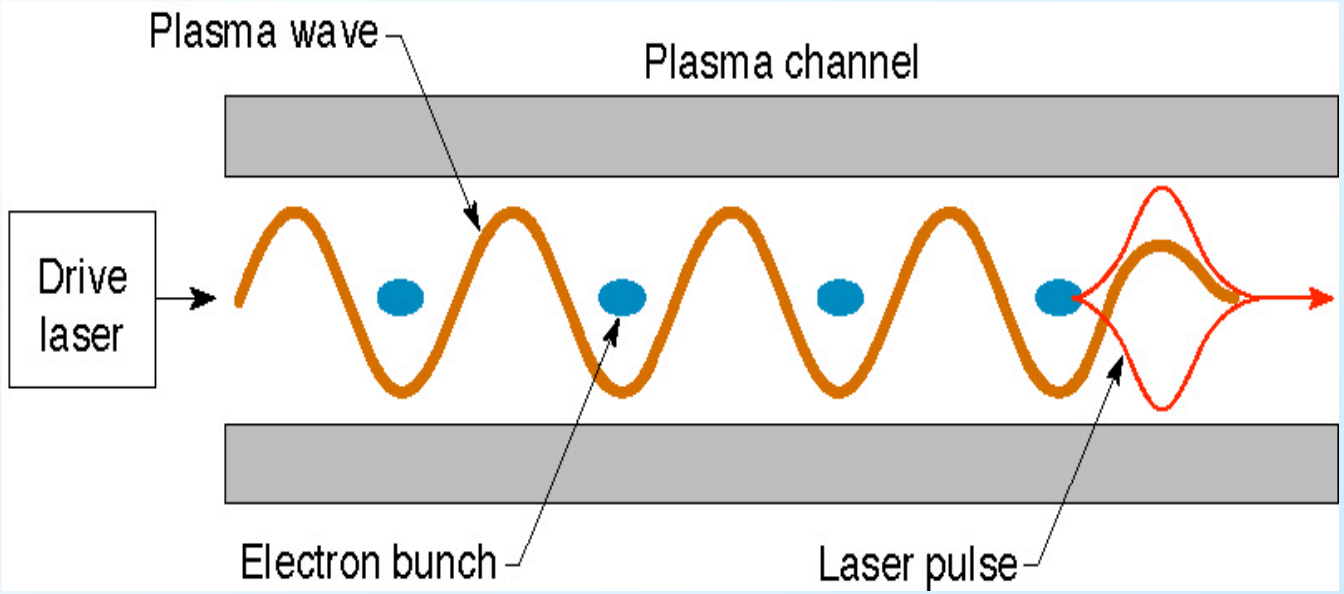
- Undulator from Boeing corp.
- Measure beam properties by looking at radiation properties







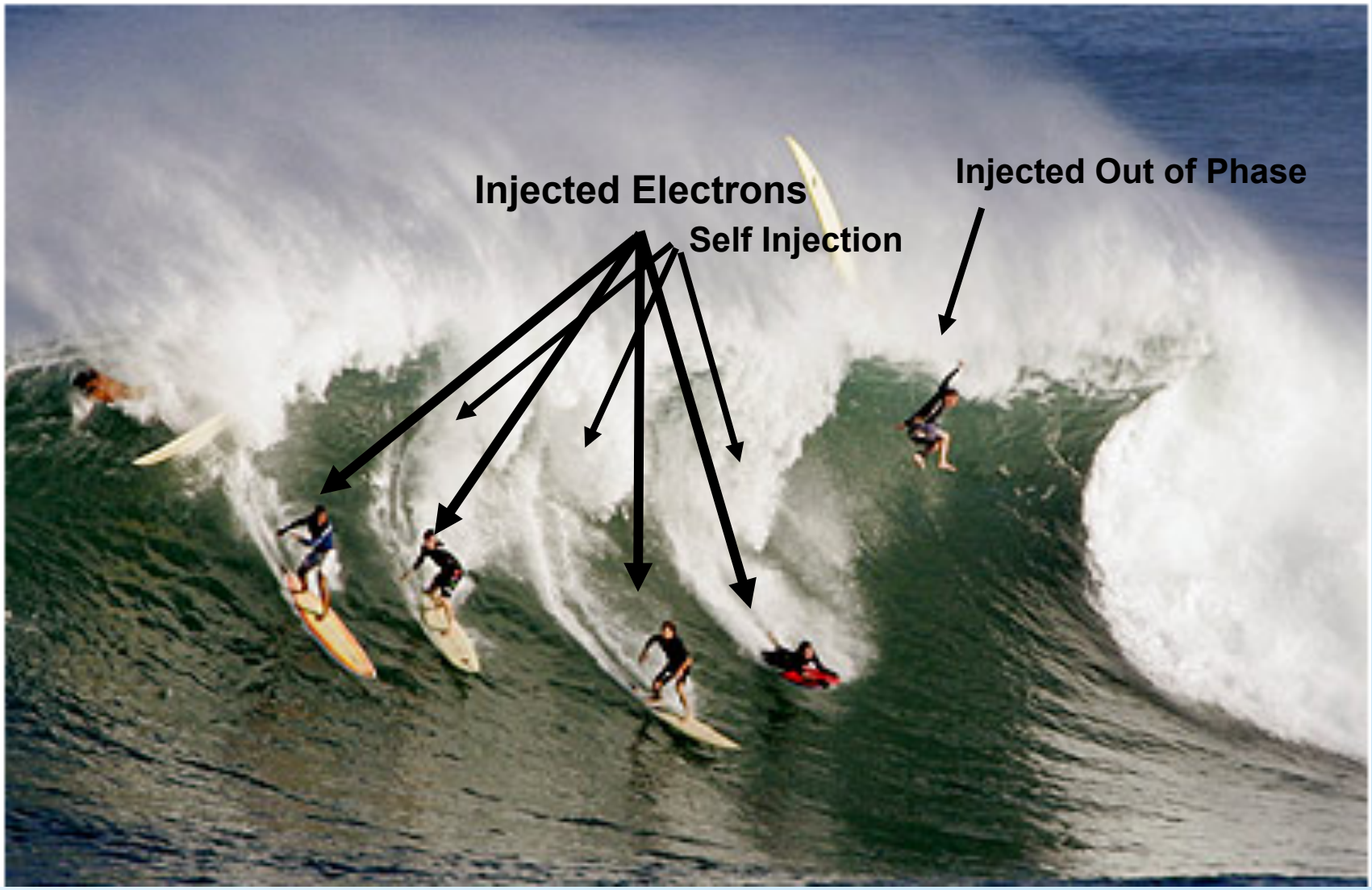
Building a laser wakefield accelerator using conventional accelerator paradigm



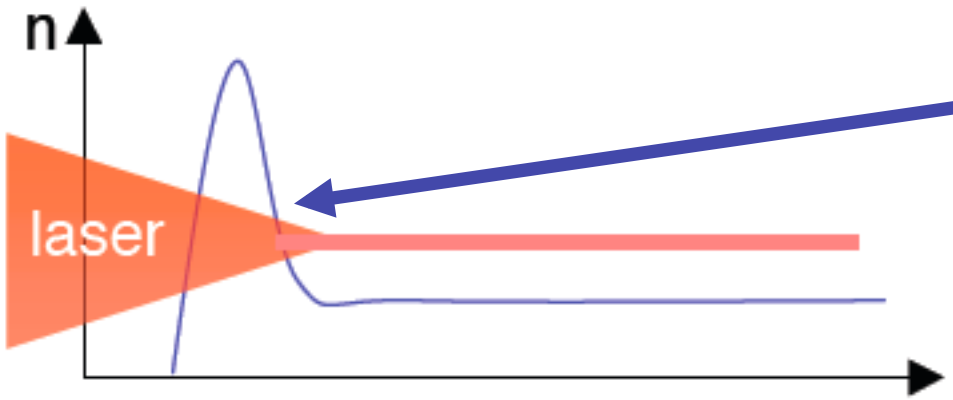
- Drive laser: Ti-sapphire (chirped amplification technology)
- Structure: plasma fiber
- Injection: source of electrons, controlled

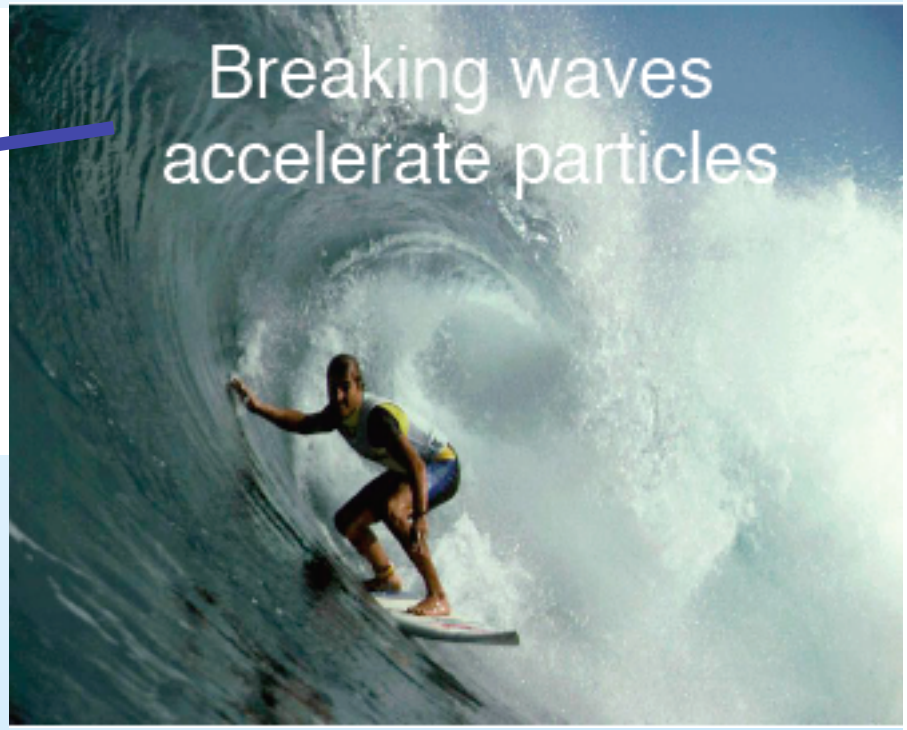
W.P. Leemans et al., IEEE Trans. Plasma Science (1996); Phys. Plasmas (1998)

“Electrons” accelerating on a wave: controlled injection



Staging: decoupling injection from acceleration

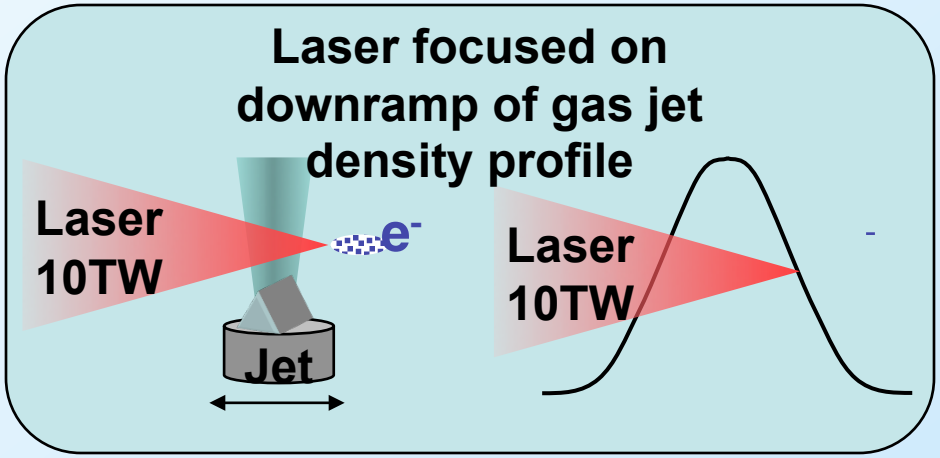




- Integrated structure
- Increased control and stability
- < % energy spread

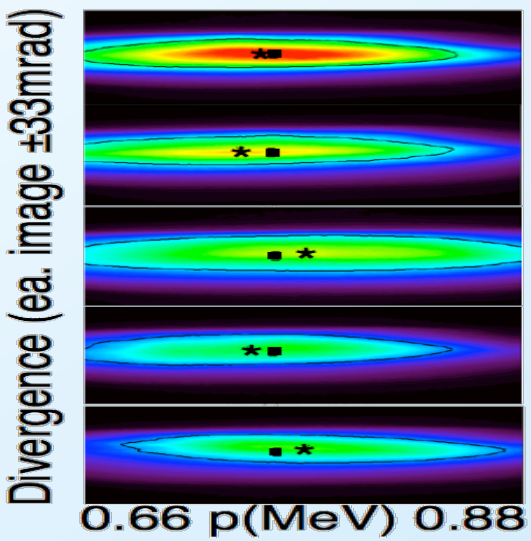
E-beam quality: energy spread

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



Sequential spectra

***centroid, avg**

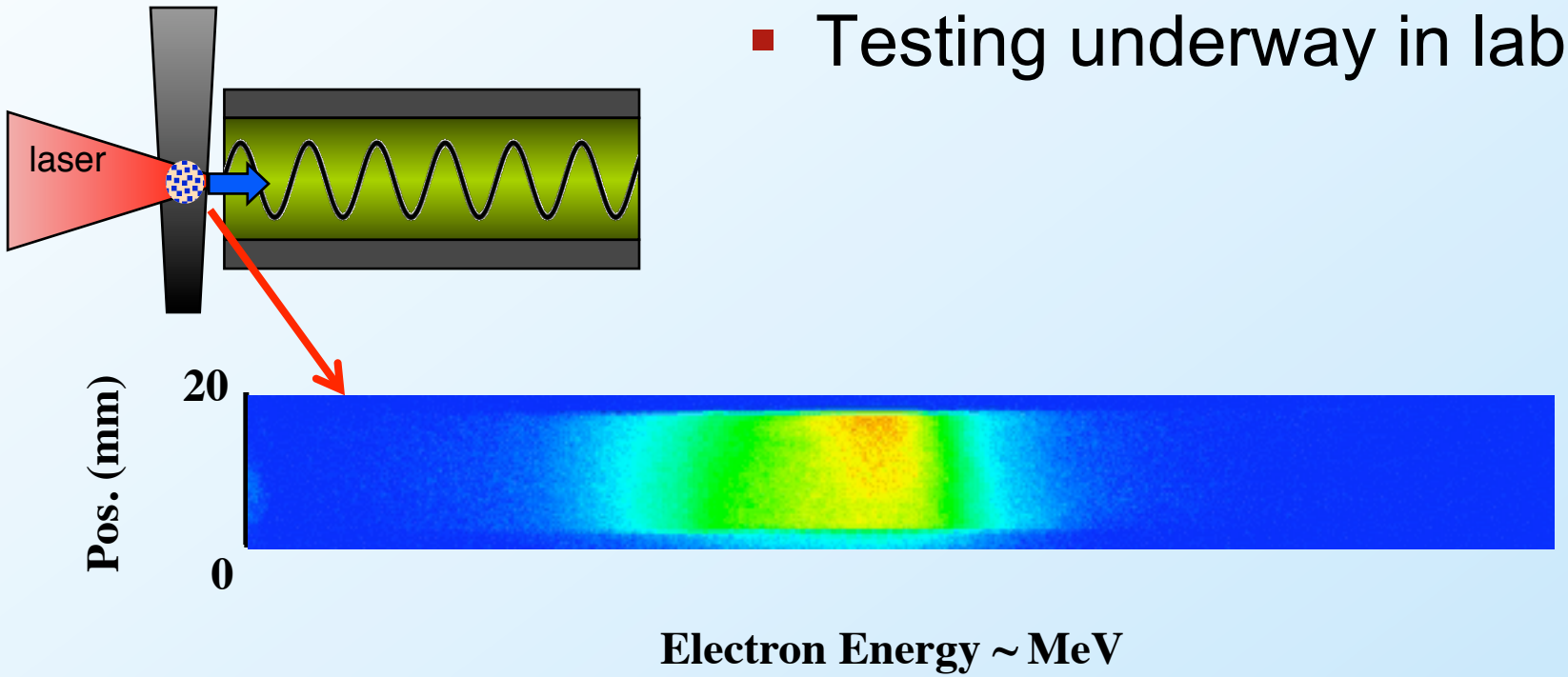


- **MeV beam produced with**
  - **Low absolute energy spread (170keV)**
  - **Good stability**
    - **Central energy (760keV ± 20keV rms)**
    - **Energy spread (170 keV ± 20keV rms)**
    - **Beam pointing (1.5 mradrms)**

Geddes et al., PRL2008

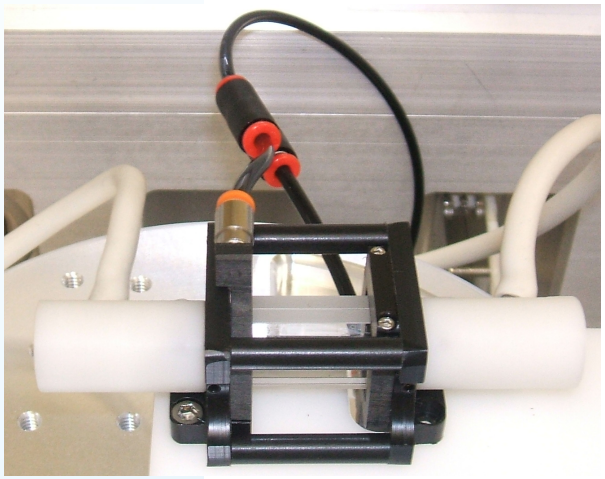
Injector for Capillary - External Gas Jet

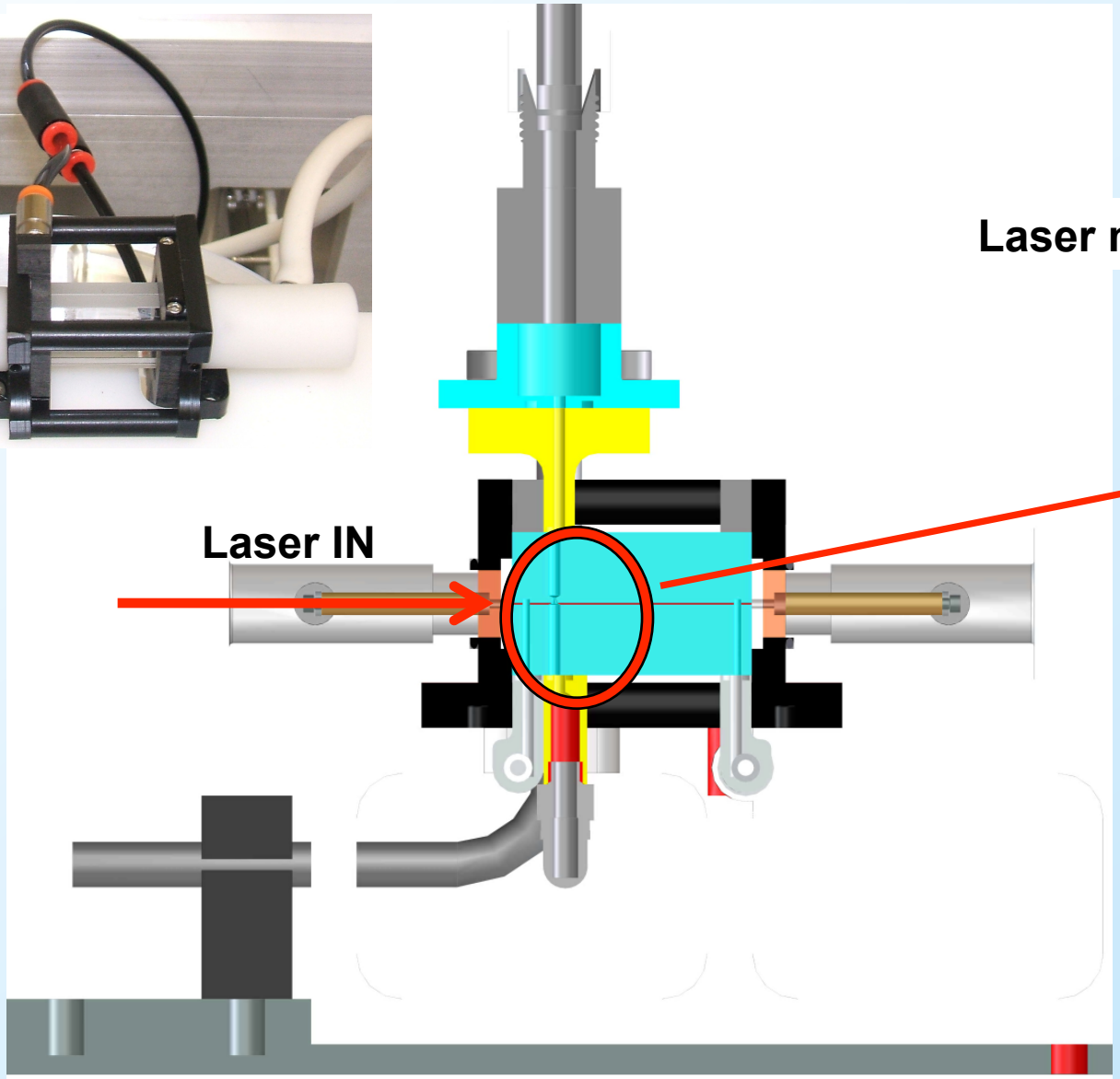
- Concept simulated
- Testing underway in lab



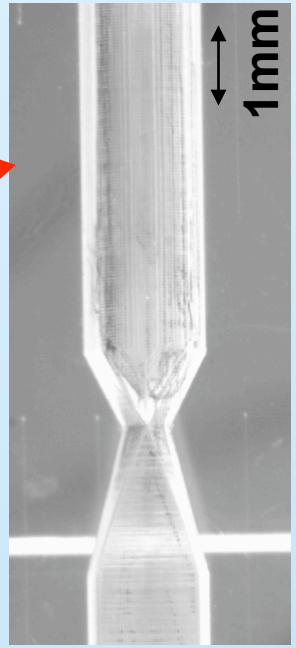
Geddes et al., Phys. Rev. Lett. 2008

Staging of injector and accelerator structure underway



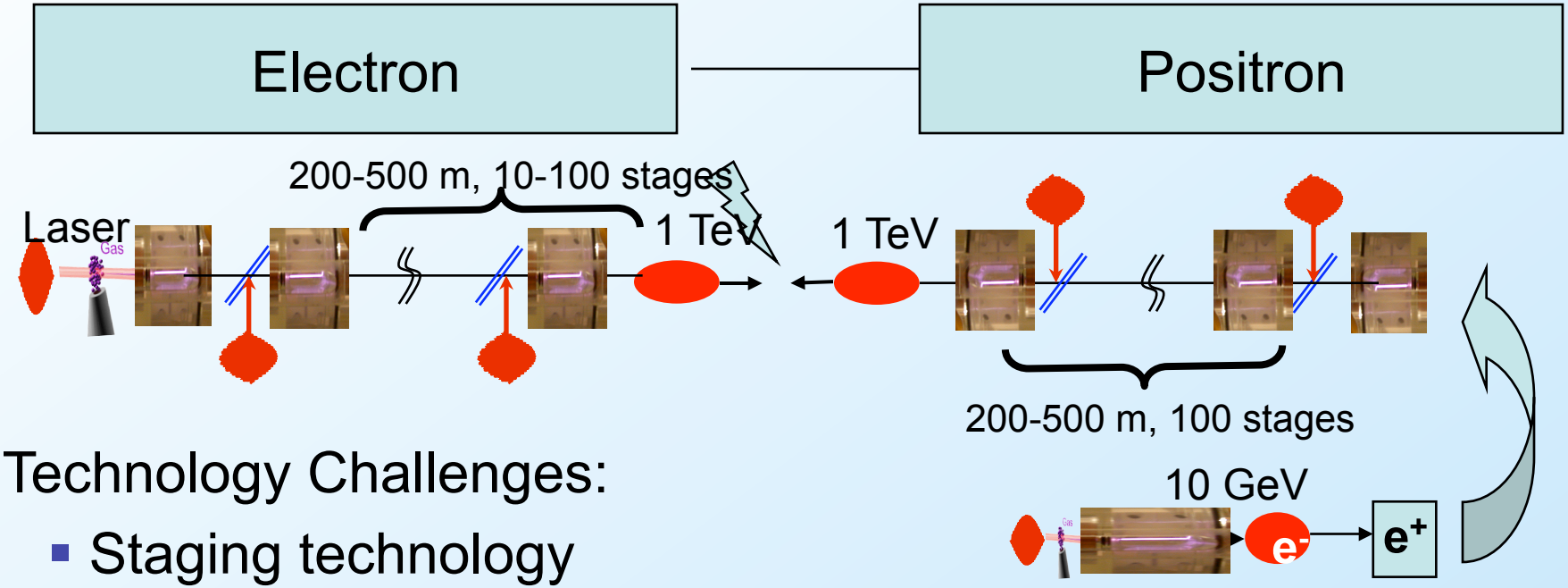


Laser machined gas jet



How about a collider ?

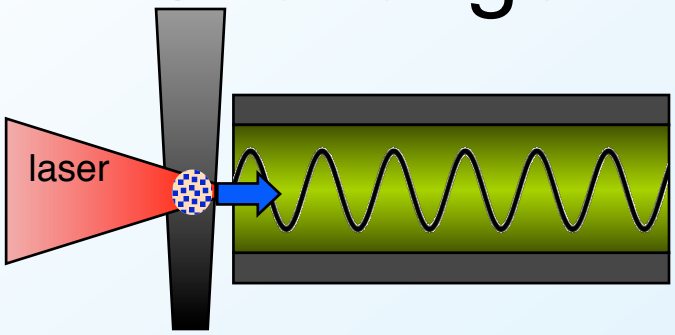
Conceptual (strawman) collider lay-out



- 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



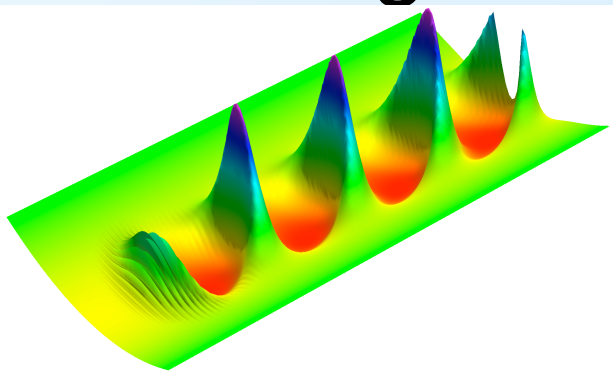
Staging of modules

Challenge 2

Multi-GeV beams

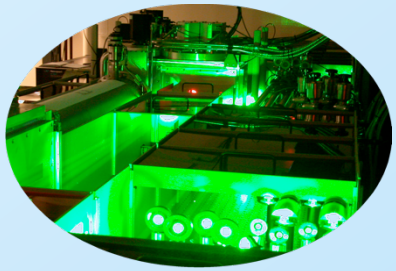
1-> 100 GeV, low energy spread beam, low emittance

Challenge 3



One-to-one, 3-D modeling

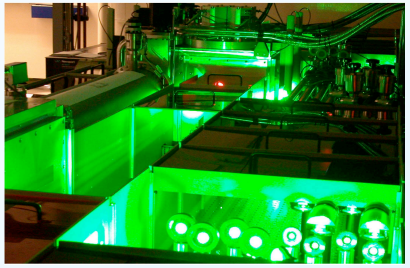
Challenge 4

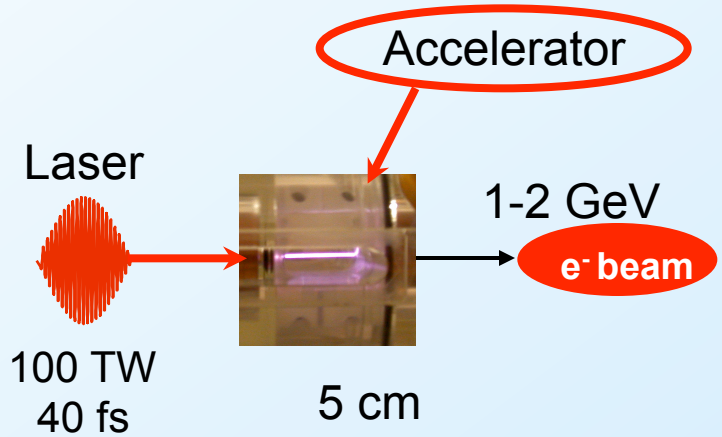


Lasers: high rep rate PW lasers

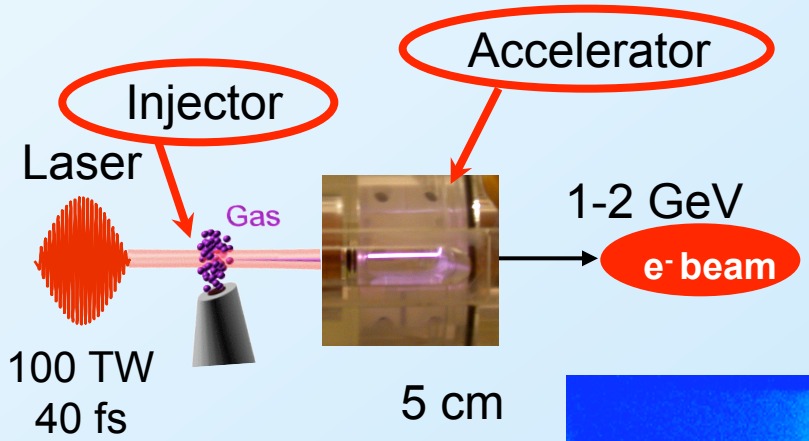
Collider technology: critical steps

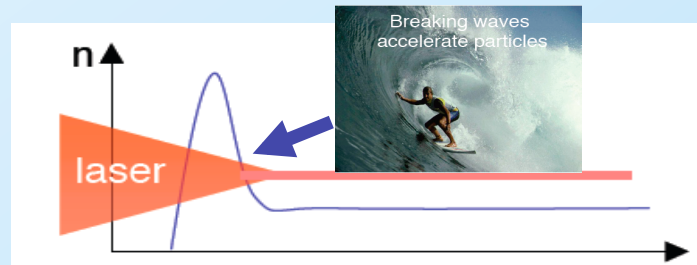
Step 1 (done): 1 GeV in < 5 cm

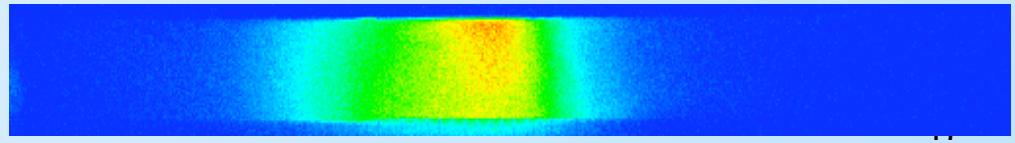




Step 2 (in progress): staging, controlled injection > 1 GeV in < 5 cm





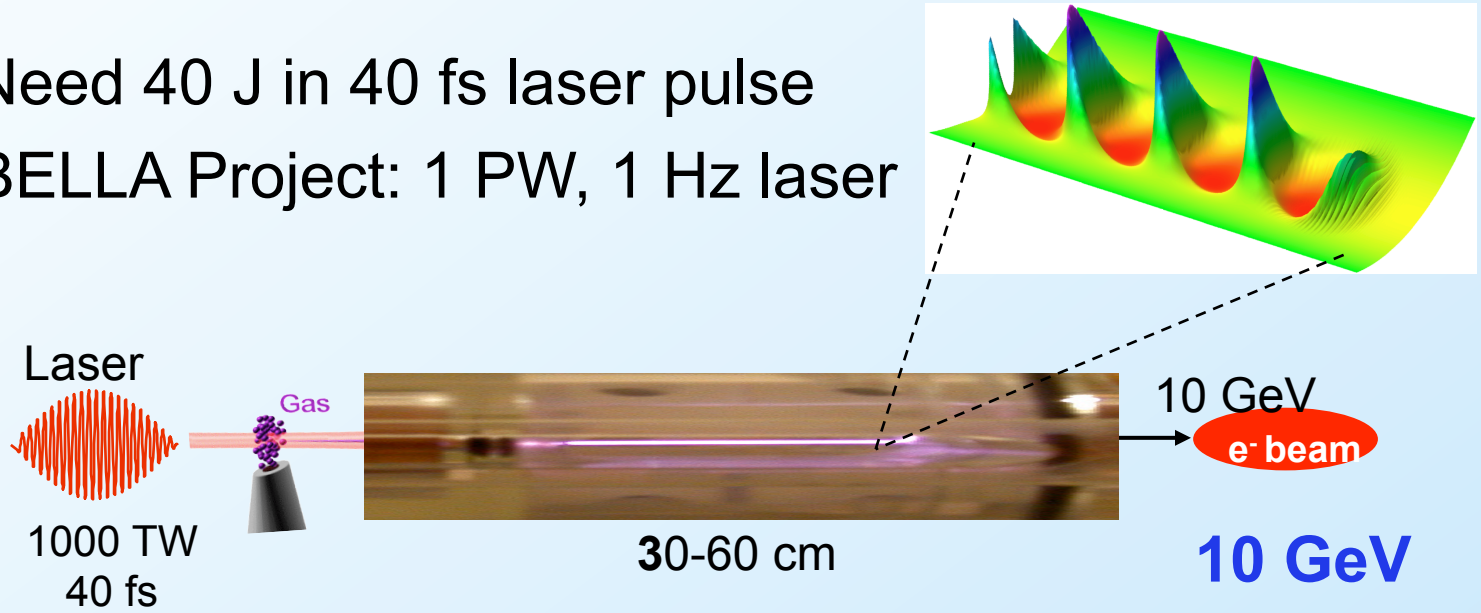


~ 1 MeV

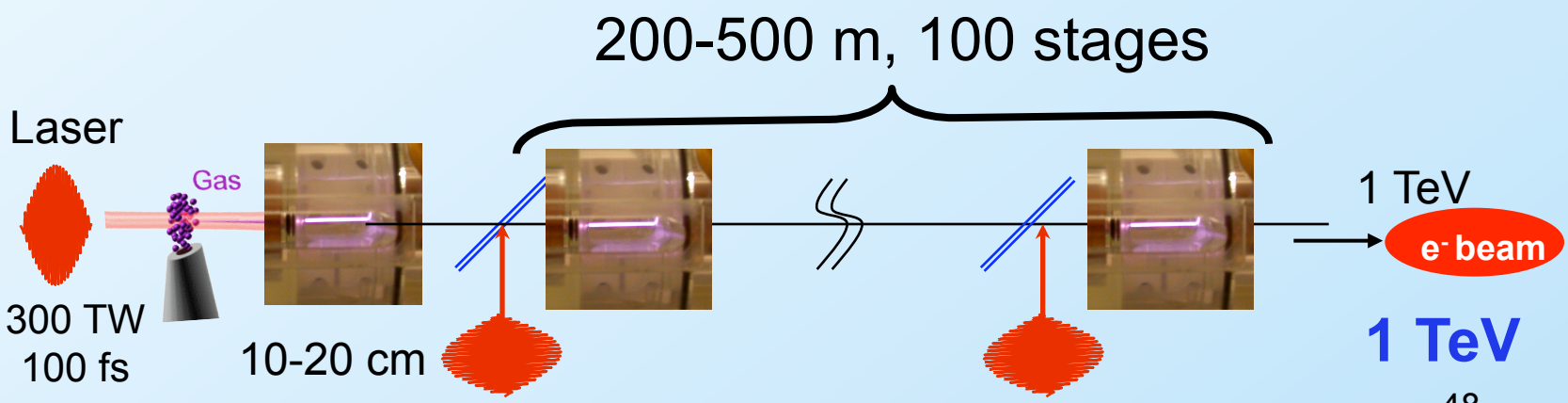
Roadmap towards collider

Step 3:

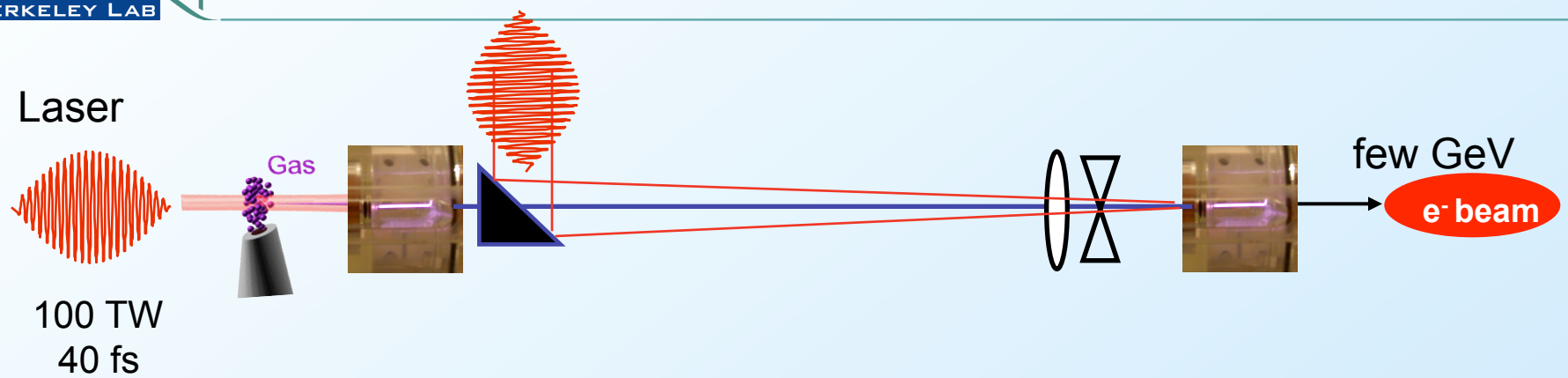
- Need 40 J in 40 fs laser pulse
- BELLA Project: 1 PW, 1 Hz laser



Step 4:

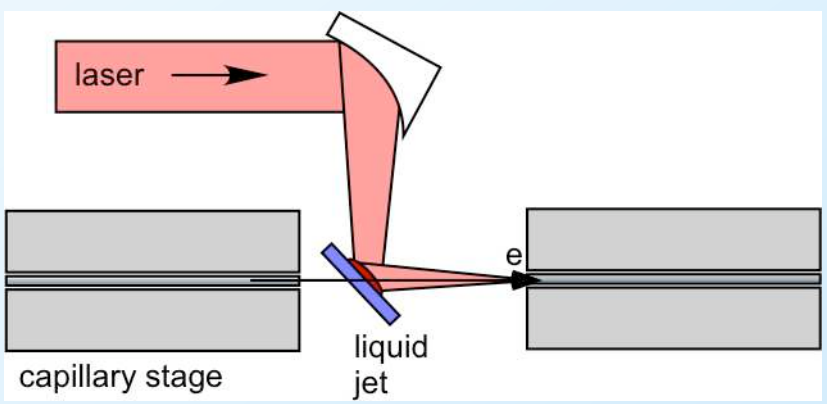


Staging: capillary-to-capillary

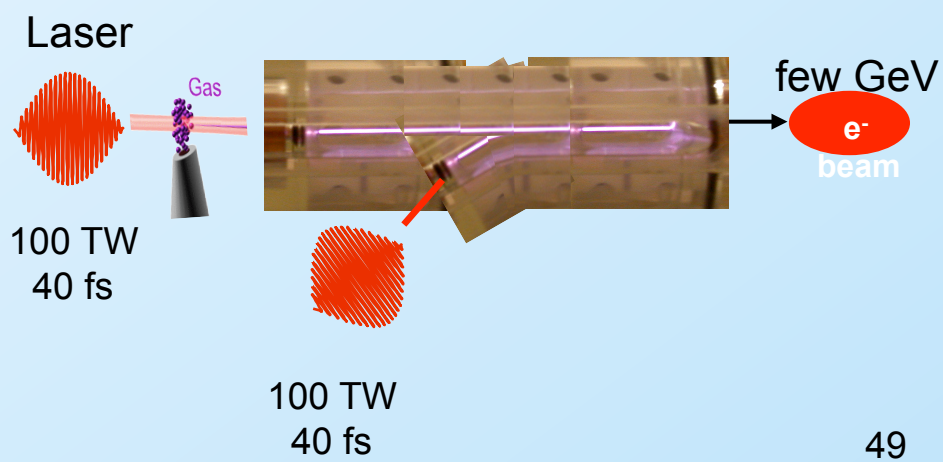


Pump depletion - "fresh" laser pulse
Beam transport

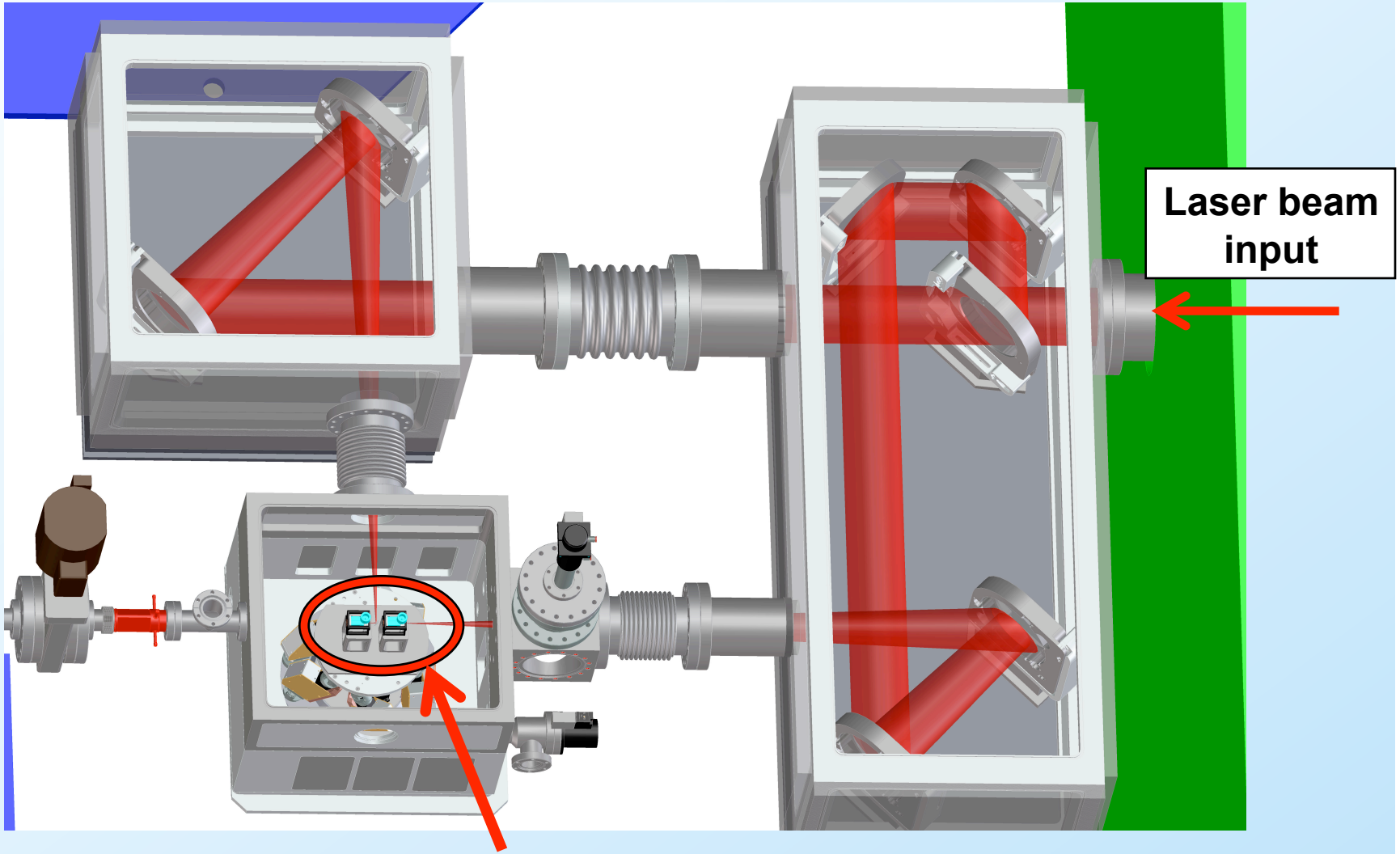
Renewable mirrors



"Freeway on-ramps"

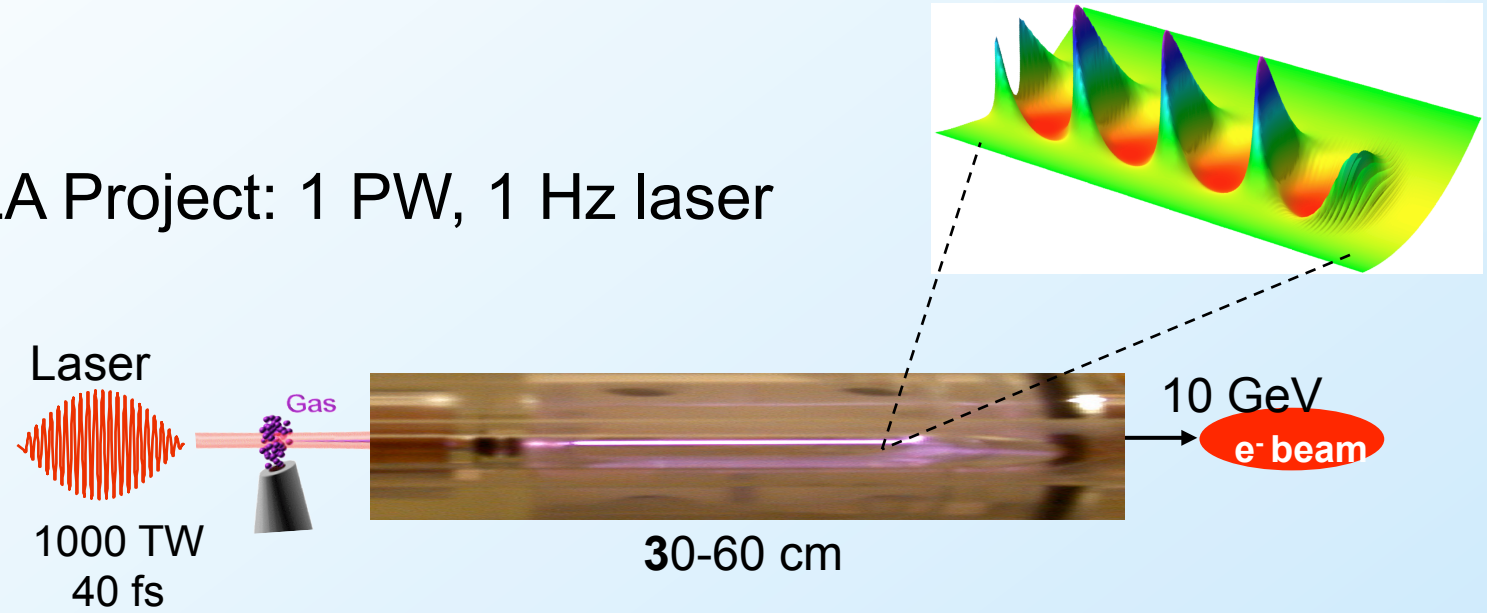


Lay-out for proof-of-principle staging experiments



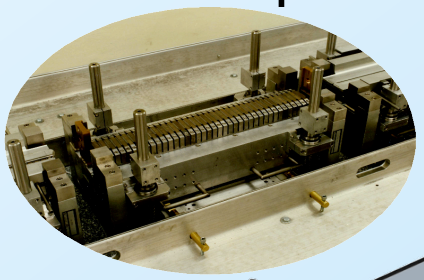
BELLA = **BE**rkeley **L**ab **L**aser **A**ccelerator
Critical technology for future laser accelerator

- BELLA Project: 1 PW, 1 Hz laser

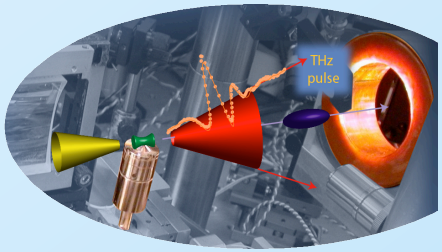


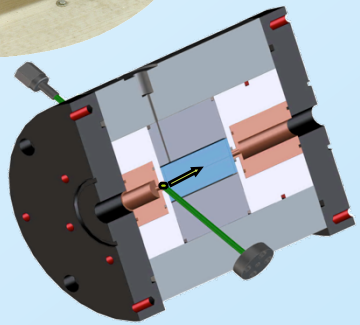
- BELLA R&D:
  - Diagnostics
  - Staged Accelerators

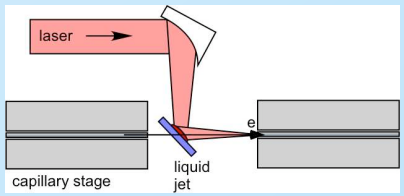
Undulator spectrum



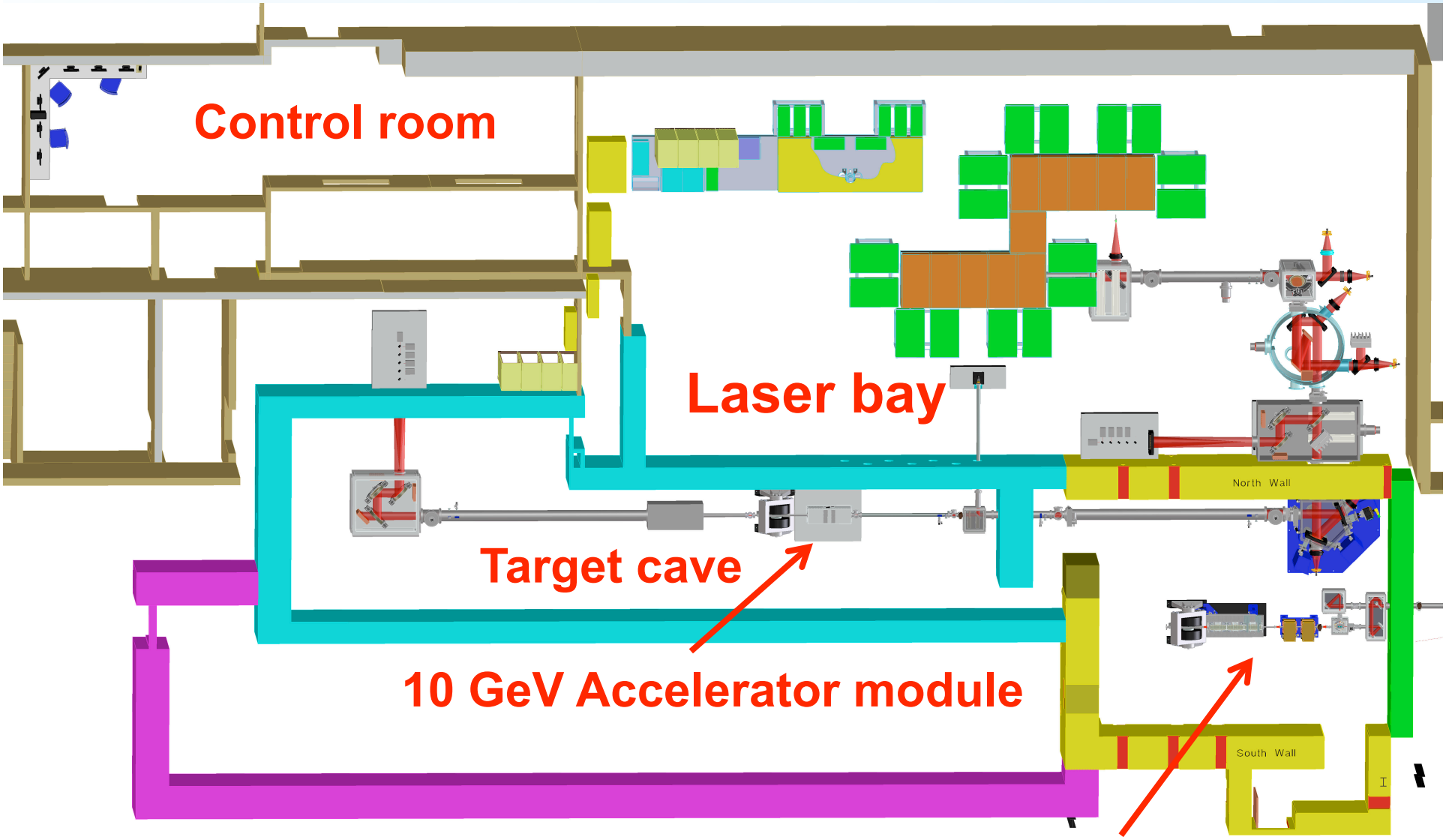
THz







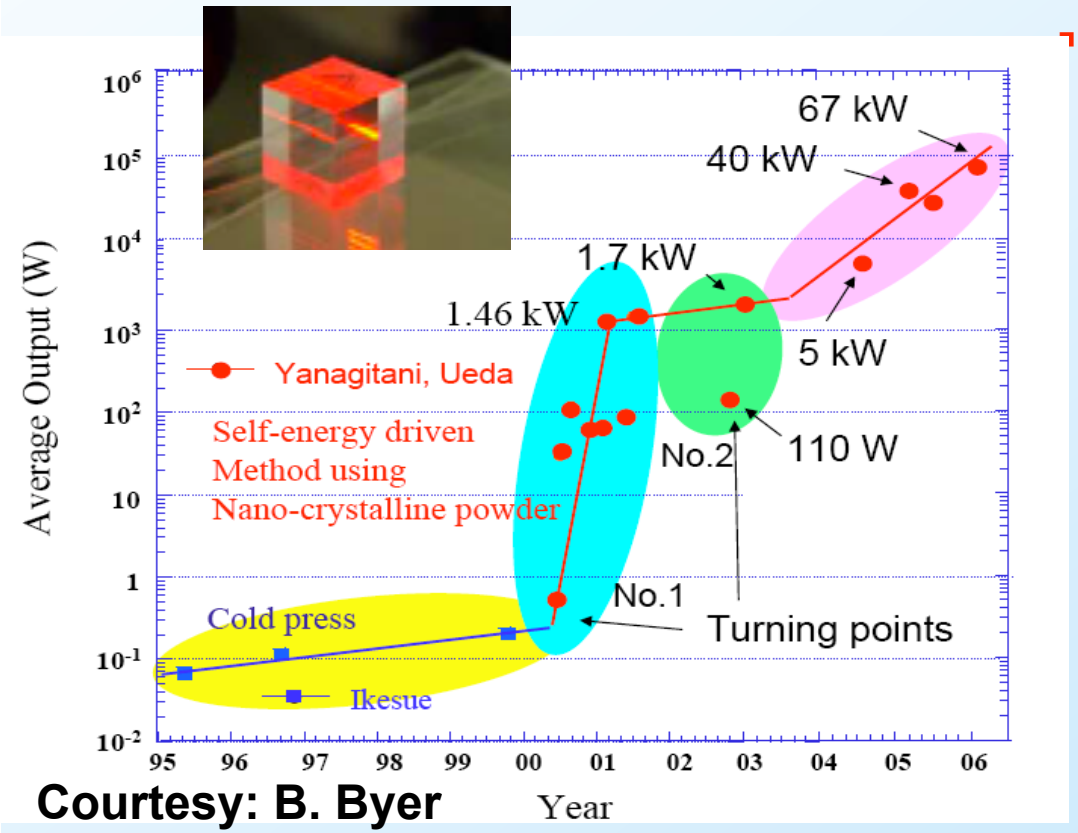
BELLA laser (1 PW at 1 Hz) will enable groundbreaking science



Pre-BELLA staging and FEL experiments

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

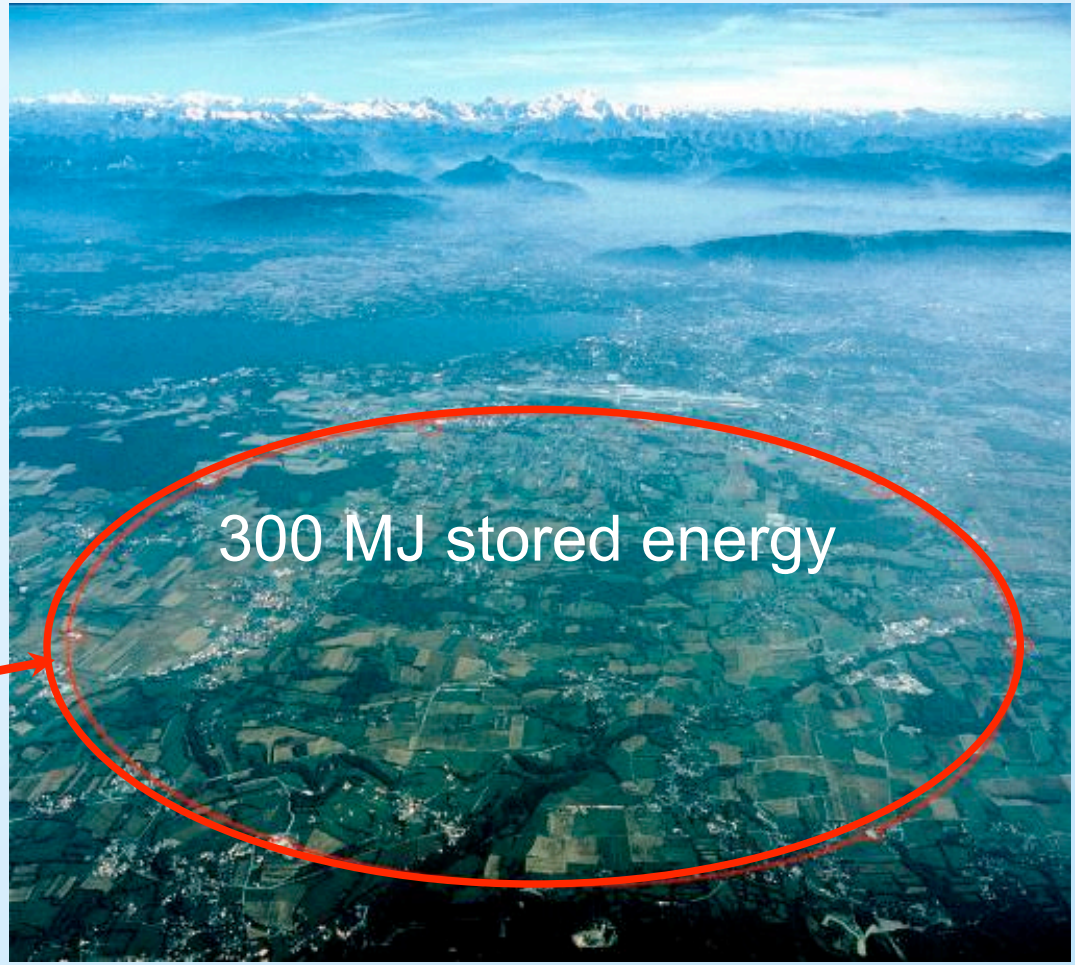
Prospect for kJ, picosecond, multi-kHz systems at 30-50 % wallplug seems possible

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

Acknowledgments

Students

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E. Esarey
C. Geddes
C. Schroeder
D. Syversrud
C. Toth
N. Ybarrolaza
O. Wong
M. Condon

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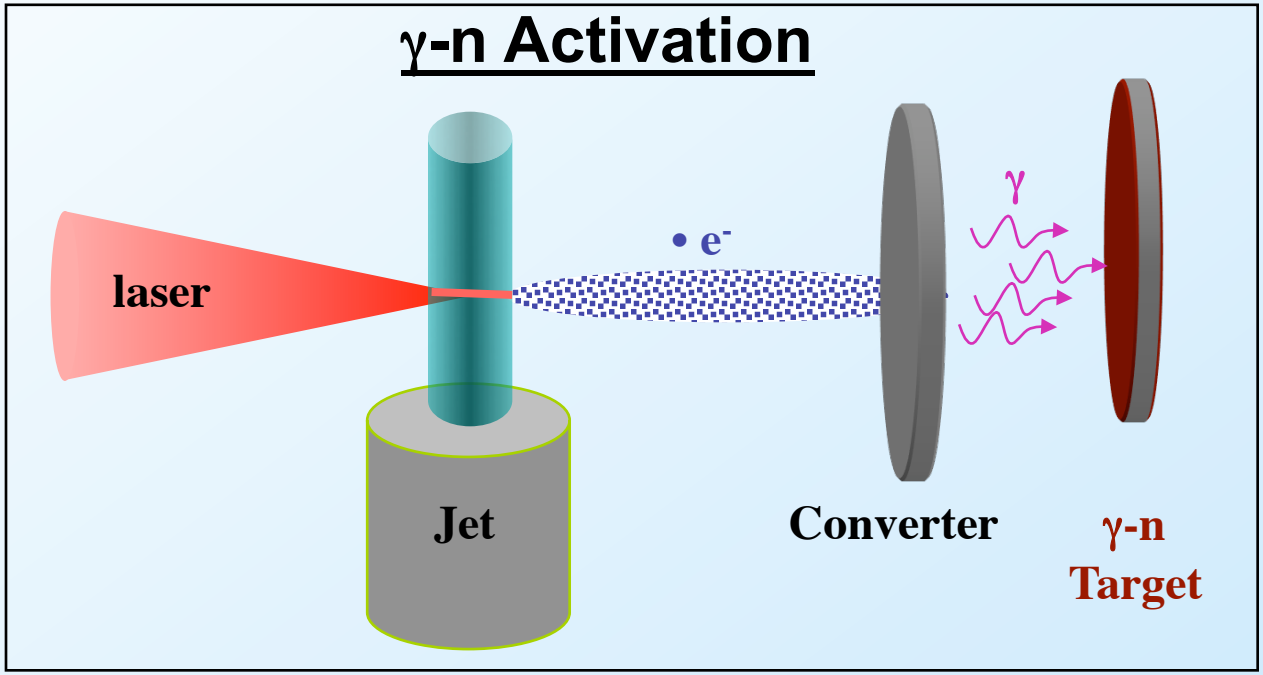
- LBNL: M. Battaglia, W. Byrne, M. Coleman, R. Duarte, L. Exter, W. Fawley, N. Kelez, A. Ratti, K. Robinson, K. Sihler, J. van Tilborg et al.
- TechX-Corp: J. Cary, D. Bruhwiler, et al.
- SciDAC team
- Oxford Univ.: S. Hooker et al.
- MPQ: F. Krausz, F. Gruener et al.
- LOA: O. Albert, F. Canova
- GSI: T. Stoehlker, S. Hess

BERKELEY LAB

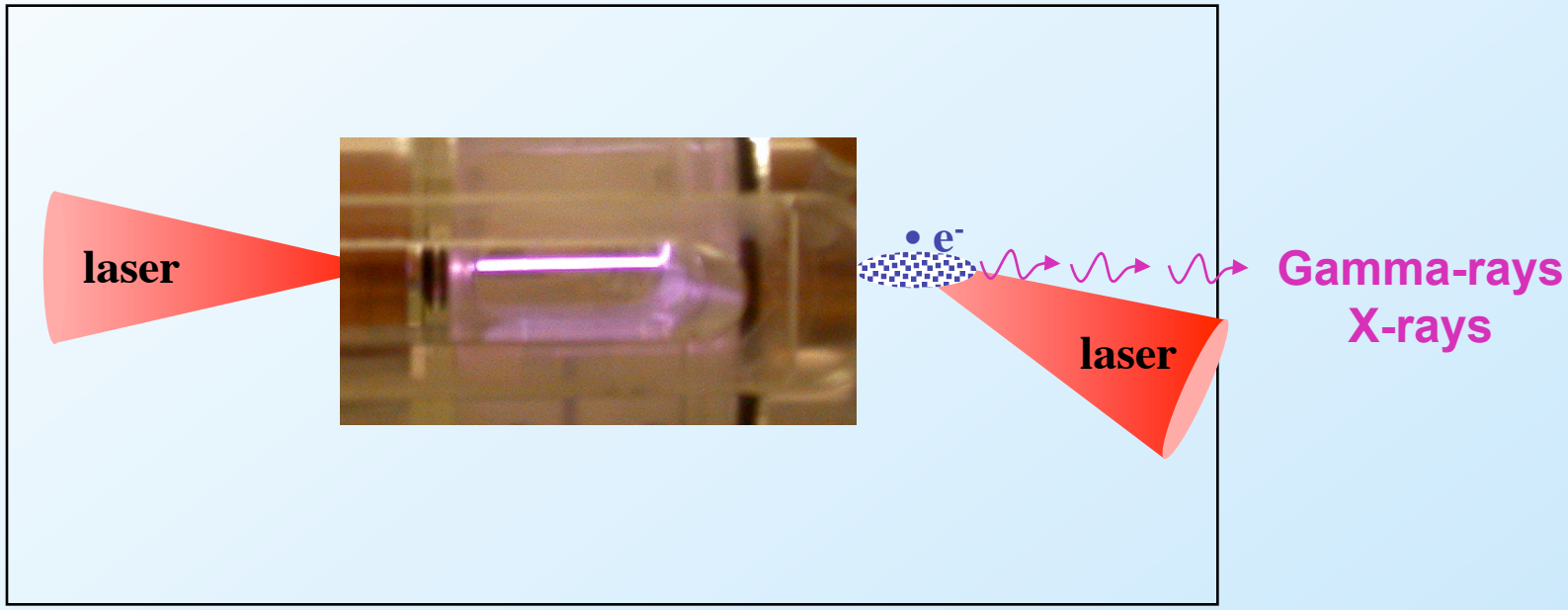
Radioisotope production using laser accelerators



- >70kBq ^{62}Cu using unchanneled accelerator*
- Scaling to channeled beam: ~100MBq ^{18}F = 1/10th patient dose
- Scales with laser energy and rep rate:
  - kHz -> 10 patient dose
  - PW >> 10 patient dose

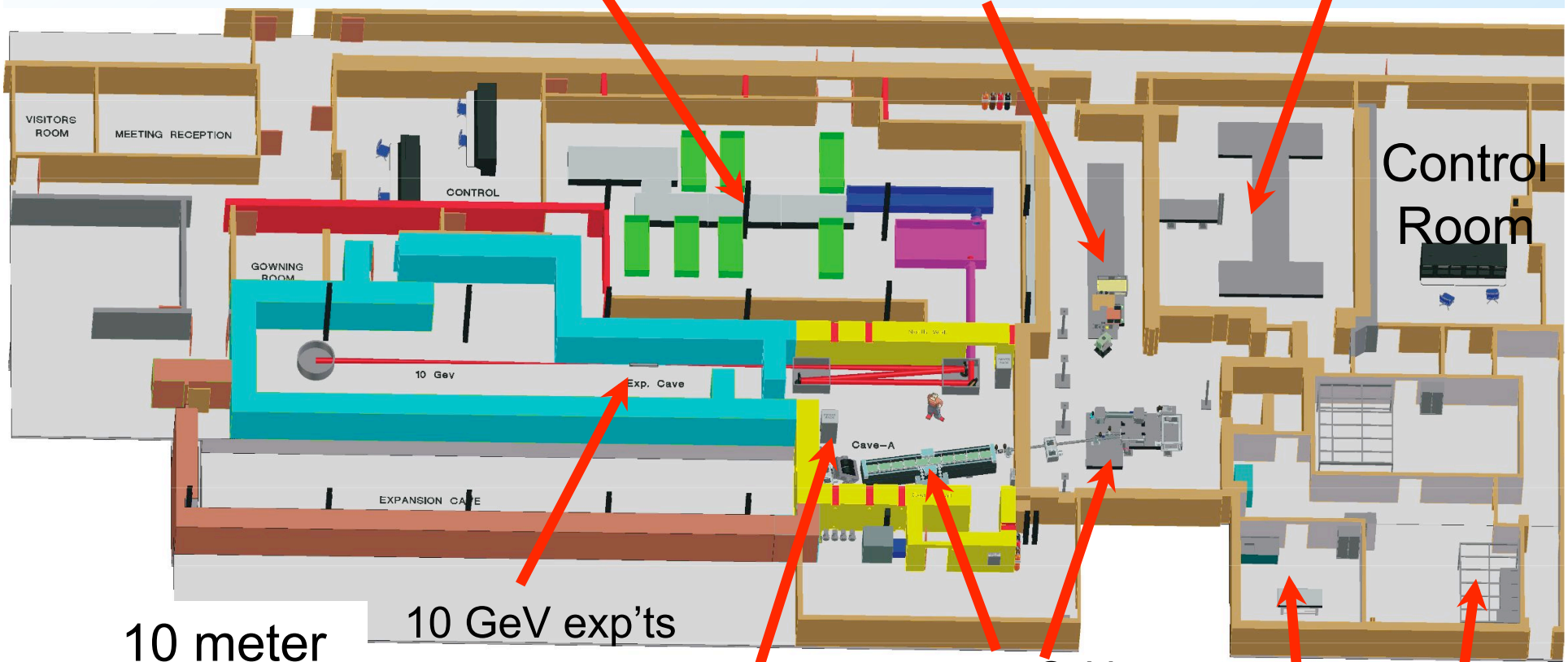
* Leemans et al., Phys. Plasmas 2001

Laser accelerators for incoherent x-ray or gamma-ray radiation sources



- **Thomson scattering source:**
  - **Laser acts like undulator**
  - **Can produce multi-MeV gamma rays for nuclear physics**

BELLA laser will enable 10 GeV expt's

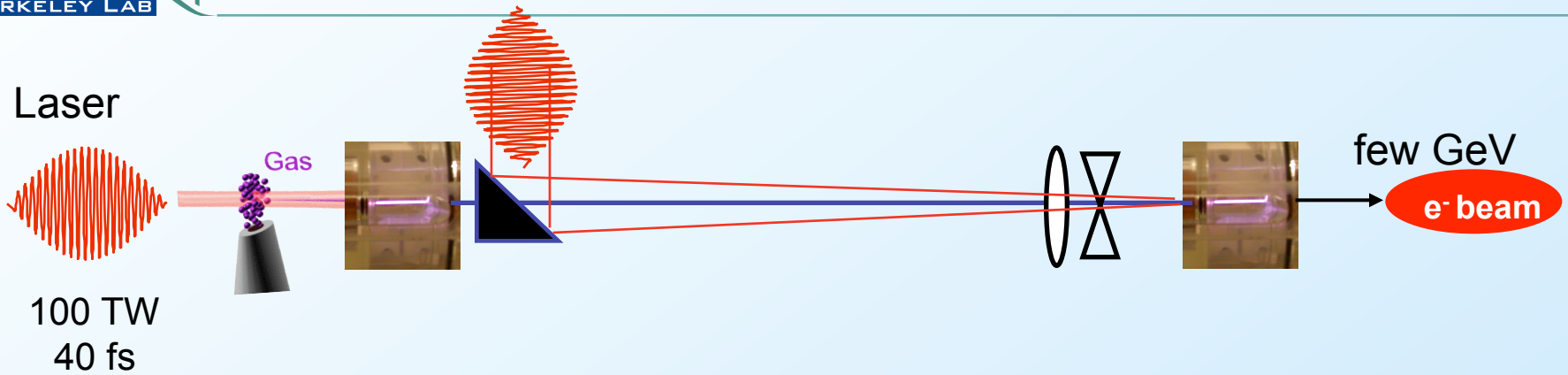


LOASIS Facilities
(Ground Floor, Bldg. 71)

Summary

- Laser-plasma based accelerator technology continues to show promise:
  - GeV beams (~% $\Delta E/E$) 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

Step 4: injector+capillary-to-capillary

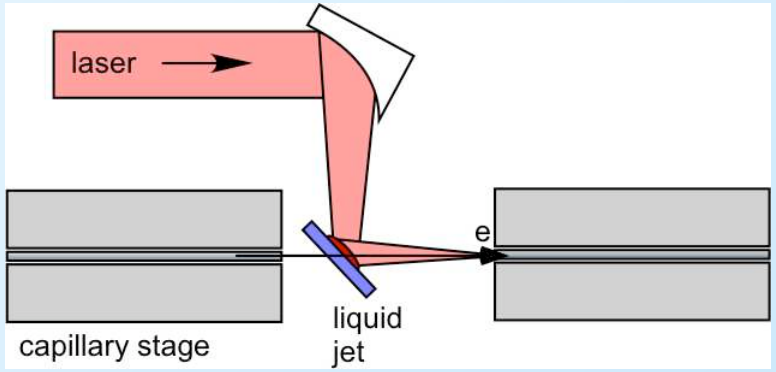


Pump depletion - "fresh" laser pulse
Beam transport

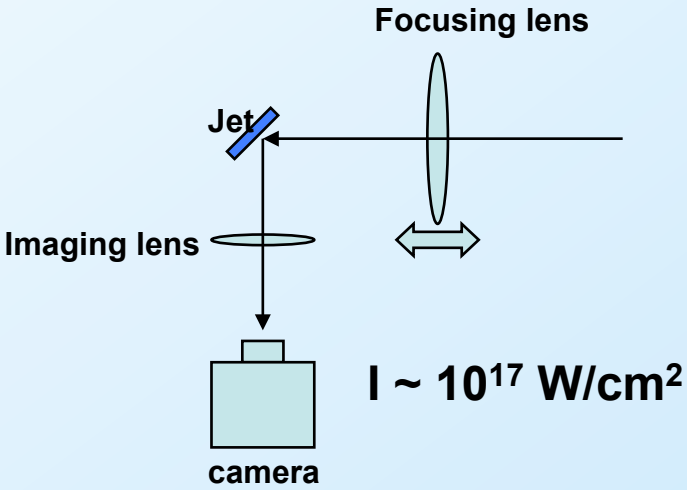
- What do we do in between?
  - Isochronous, achromatic magnets + laser optics ?
    - Complicated + bulky…might work for 10 GeV and beyond if ballistic transport is OK
  - Novel concepts …

Staging: Novel in-coupling techniques

- Concept: Plasma mirror in-coupling
  - "Renewable" mirror needed for high laser intensity
  - Relies on critical density plasma production
  - Thin (< 100 micron) liquid jet
  - Laser contrast crucial

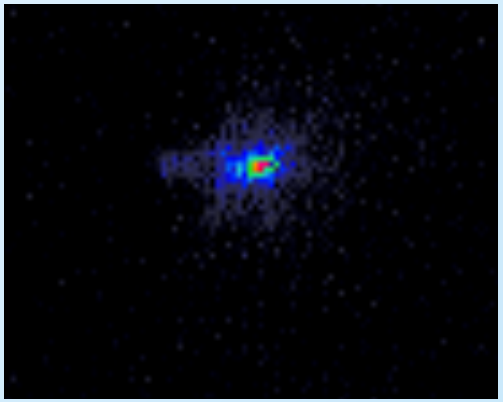


Preliminary testing underway

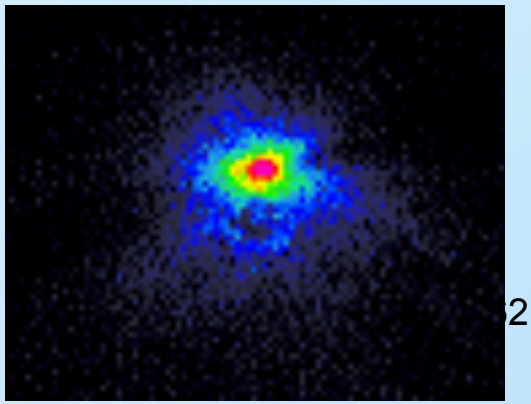


I ~ 10^{17} W/cm^2

Focus downstream



Focus on water jet

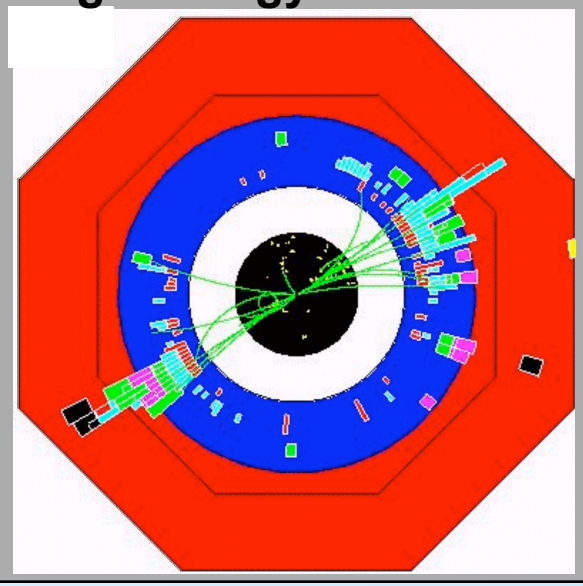


Compact Particle Accelerators for Science and Medicine

- Particle accelerators enable
  - High energy physics
  - High resolution medical imaging and therapy
  - Radiation sources
  - Materials physics

- Current technology is bulky
  - Limits clinical & laboratory applications
  - Higher energies difficult

Vertex Detection of High Energy Particles



X-ray Image of Human Hand

- Compact accelerators could offer
  - Next frontier high energy physics
  - Novel radiation sources
  - High resolution medical imaging
  -