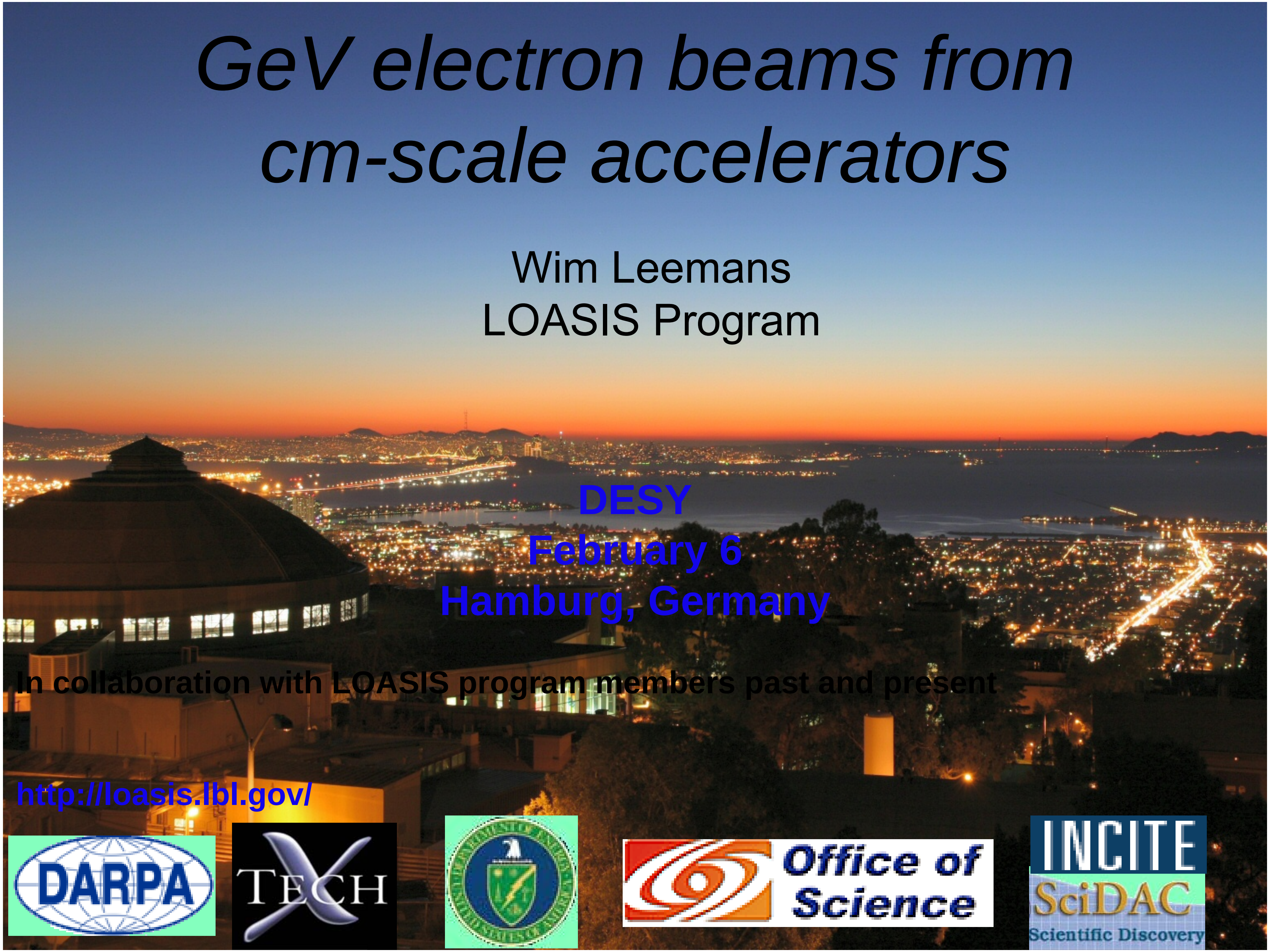


GeV electron beams from cm-scale accelerators

Wim Leemans
LOASIS Program

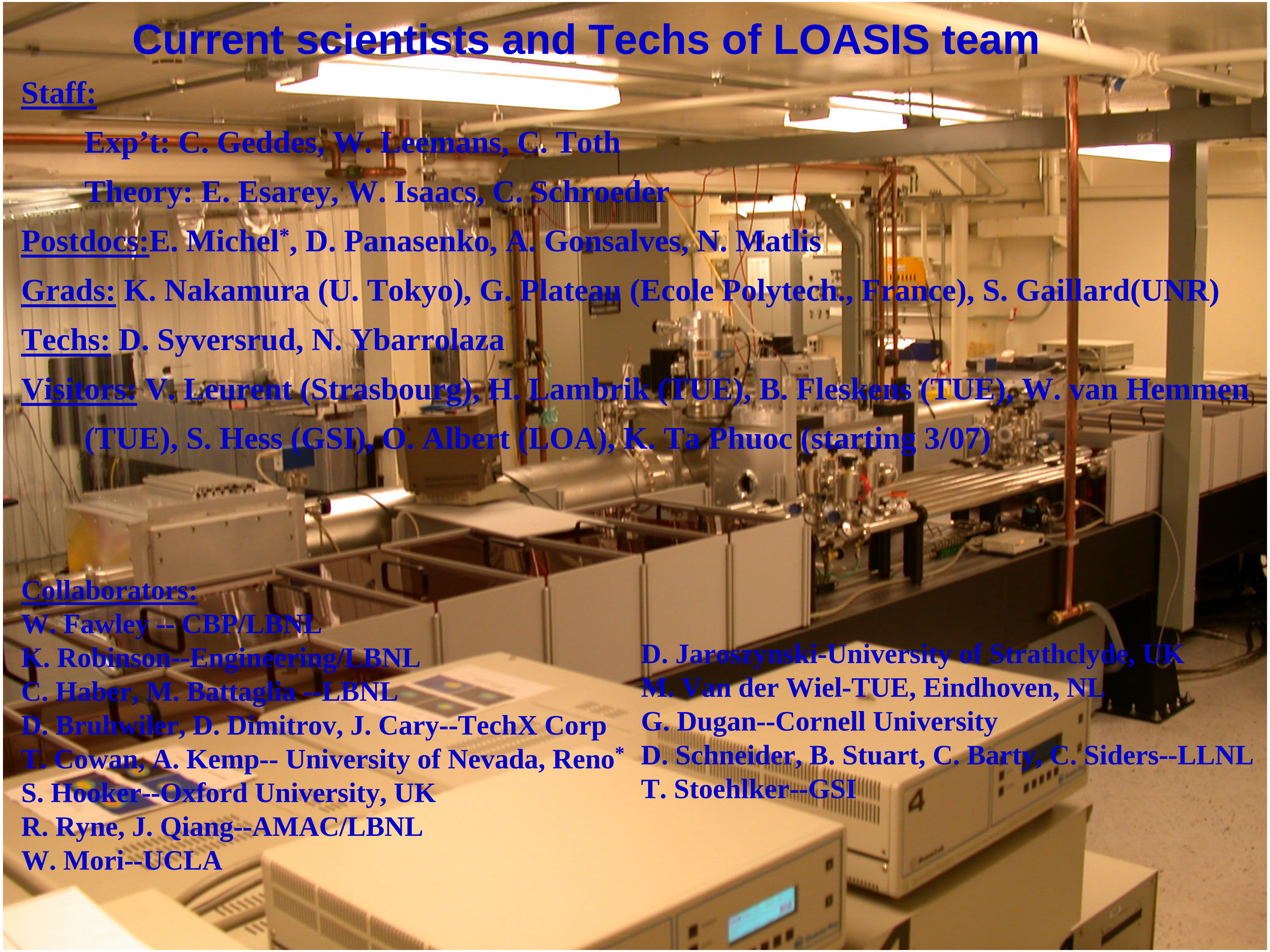
DESY
February 6
Hamburg, Germany

In collaboration with LOASIS program members past and present

http://loasis.lbl.gov/

DARPA TECH-X Office of Science INCITE SciDAC Scientific Discovery

Current scientists and Techs of LOASIS team



Staff:

Exp't: C. Geddes, W. Leemans, C. Toth

Theory: E. Esarey, W. Isaacs, C. Schroeder

Postdocs:E. Michel*, D. Panasenko, A. Gonsalves, N. Matlis

Grads: K. Nakamura (U. Tokyo), G. Plateau (Ecole Polytech., France), S. Gaillard(UNR)

Techs: D. Syversrud, N. Ybarrolaza

Visitors: V. Leurent (Strasbourg), H. Lambrik (TUE), B. Fleskens (TUE), W. van Hemmen (TUE), S. Hess (GSI), O. Albert (LOA), K. Ta Phuoc (starting 3/07)

Collaborators:

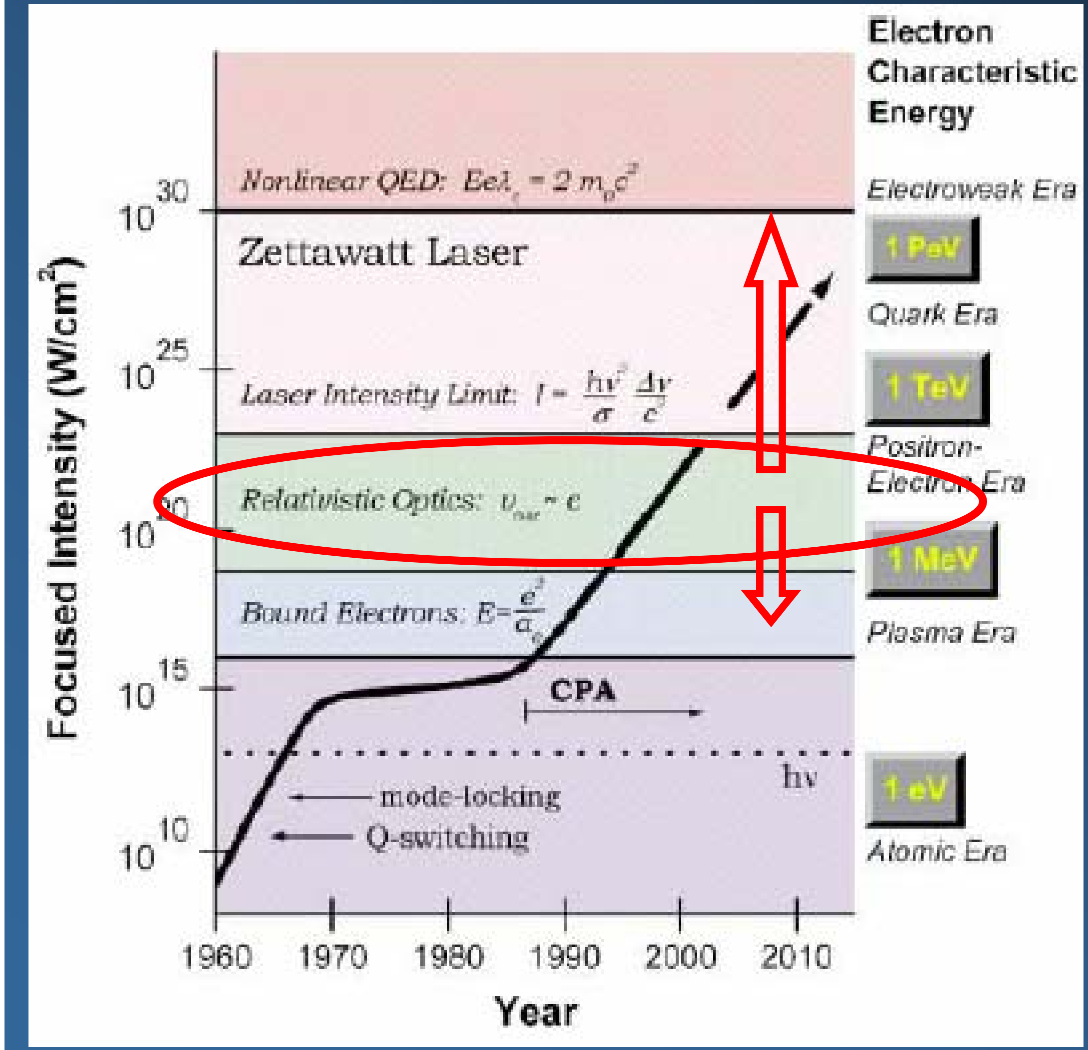
W. Fawley -- CBP/LBNL
K. Robinson--Engineering/LBNL
C. Haber, M. Battaglia --LBNL
D. Bruhwiler, D. Dimitrov, J. Cary--TechX Corp
T. Cowan, A. Kemp-- University of Nevada, Reno*
S. Hooker--Oxford University, UK
R. Ryne, J. Qiang--AMAC/LBNL
W. Mori--UCLA

D. Jaroszynski-University of Strathclyde, UK
M. Van der Wiel-TUE, Eindhoven, NL
G. Dugan--Cornell University
D. Schneider, B. Stuart, C. Barty, C. Siders--LLNL
T. Stoehlker--GSI

1985: Chirped Pulse Amplification Technology

D. Strickland and G. Mourou, Optics Comm. 56 (1985)

Focused Intensity vs. Year

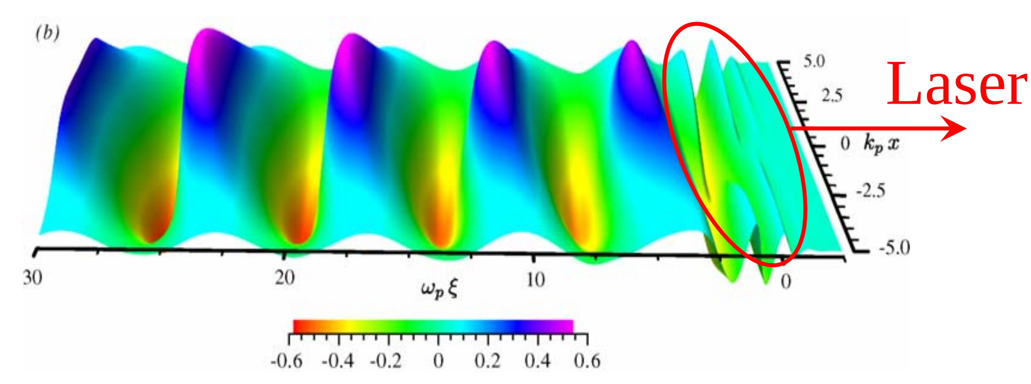


(after T. Tajima and G. Mourou, PRSTAB2002)

- Non-linear QED
- Compact accelerators
- Ultra-high harmonics
- FEL’s
- “Ultra-source”

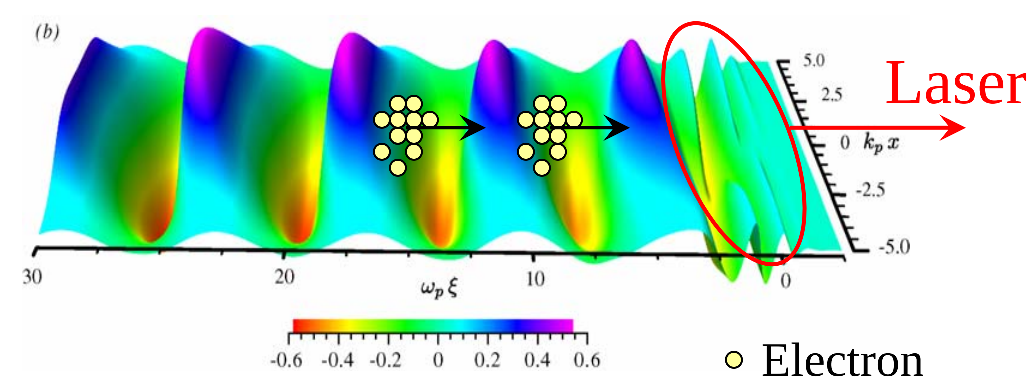
The laser-wakefield accelerator

Shadwick et al., IEEE PS. 2002



Boat on the ocean displaces water
Wake velocity = boat velocity

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

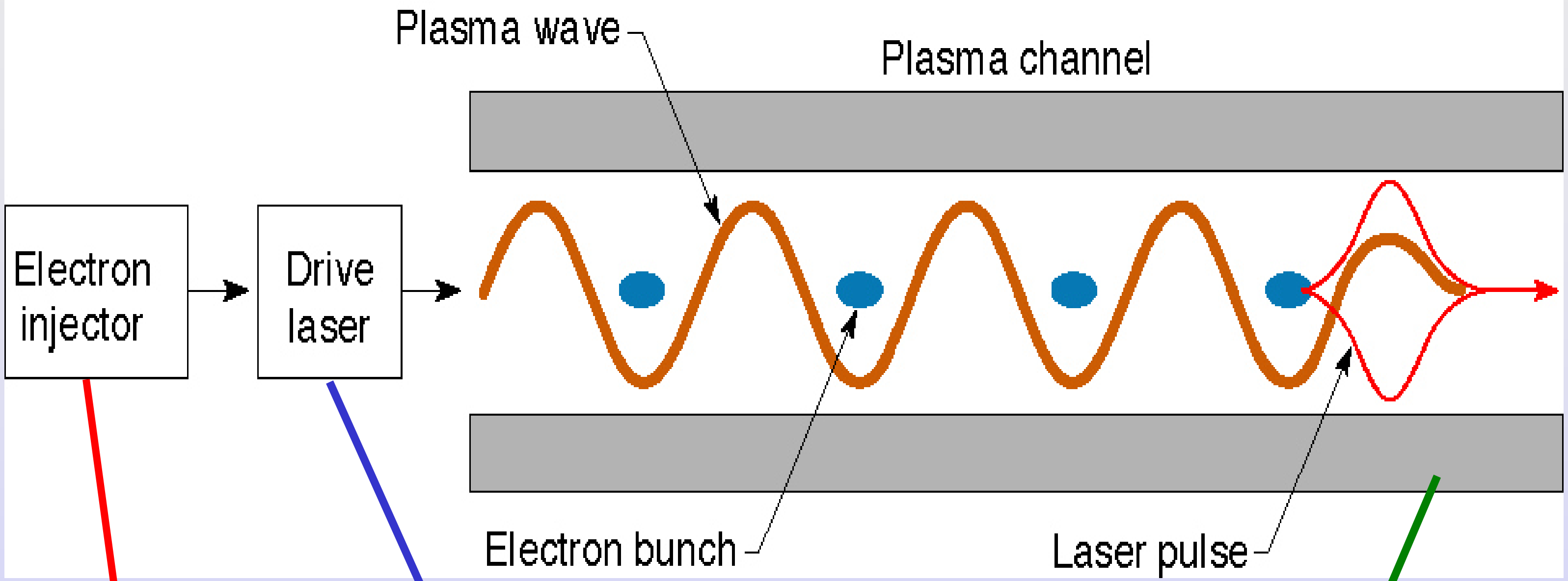


Surfers are 'trapped' by waves

Plasma-electrons are trapped by wakefield
10's - 100's GV/m, scales as $\sqrt{n}$

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

Building a laser wakefield accelerator



- **Electron source**
  - **Self-trapped?**
  - **Injection:**
    - **external?**
    - **internal?**

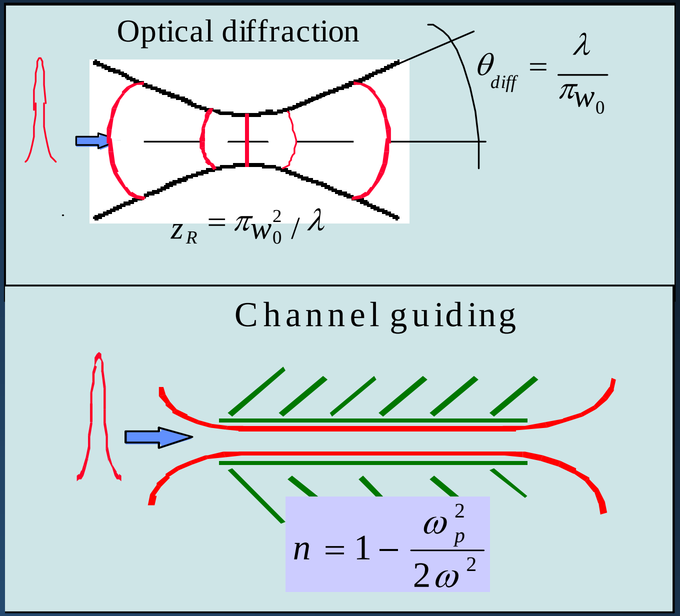
- **Laser**
  - **Ti:Al_2O_3**
  - **Power level?**
  - **Pulse length?**
  - **Focal spot?**

- **Plasma source**
  - **Gas jet, discharge, pinch**
  - **Length ?**
  - **Density ?**
  - **Transverse profile?**

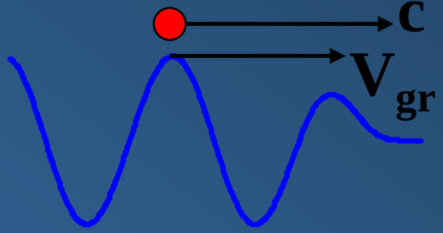
Three Limits to Energy gain $\Delta W = eE_z L_{acc}$

Laser driver

- **Diffraction:** order mm!
  (but overcome w/ channels or relativistic self-focusing)



- **Dephasing:**

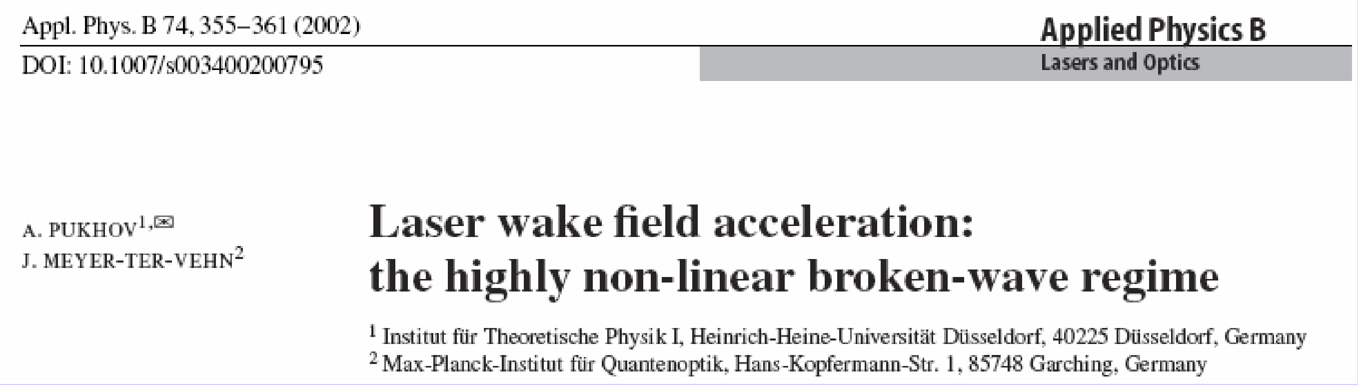


L_{dph} order 10 cm x $10^{16}/n_o$

- **Depletion:** For small intensity ($a_0 < 1$) >> L_{dph}
  For relativistic intensities (a_0 >~ 1), L_{dph} ~ L_{depl}

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

2002: Laser “bubble (or blow-out)” regime



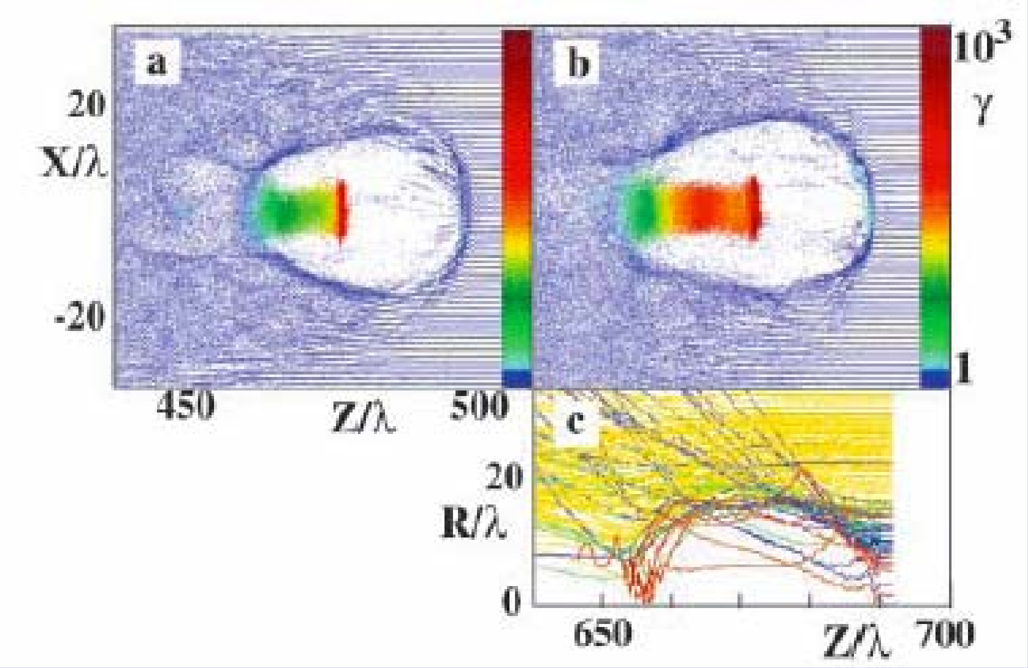
Appl. Phys. B 74, 355–361 (2002)
DOI: 10.1007/s003400200795

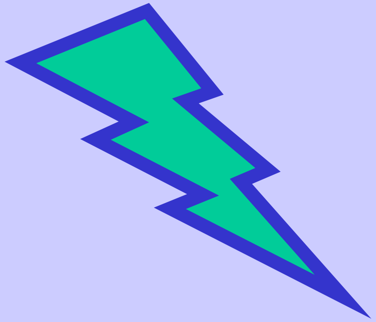
Applied Physics B
Lasers and Optics

A. PUKHOV[1,✉]
J. MEYER-TER-VEHN[2]

Laser wake field acceleration: the highly non-linear broken-wave regime

[1] Institut für Theoretische Physik I, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany
[2] Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany





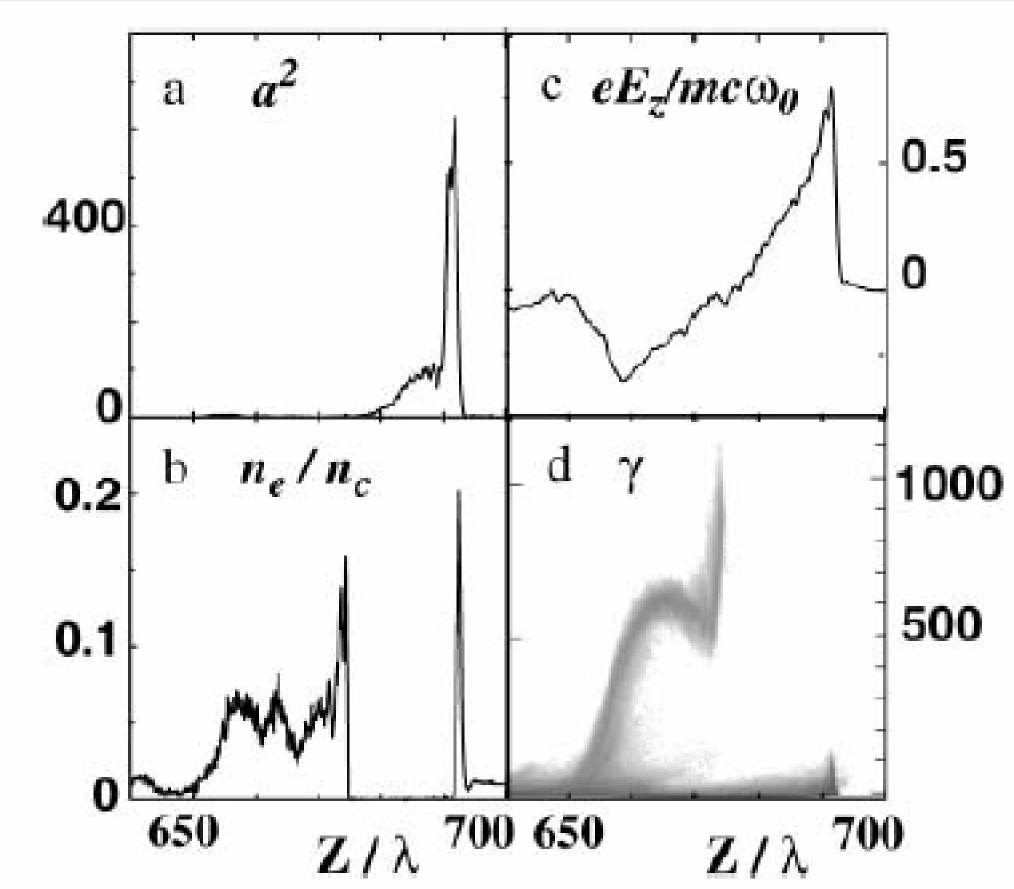
12 J, 33 fs pulse

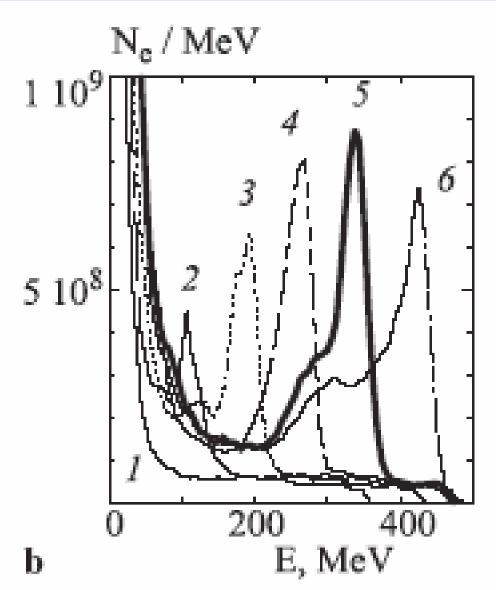
A.Pukhov & J.Meyer-ter-Vehn, Appl. Phys. B, **74,** *p*.355 (2002)

Laser pulse evolution leads to blow-out or bubble regime

A.Pukhov & J.Meyer-ter-Vehn, Appl. Phys. B, **74,** *p.*355 (2002)

VLPL

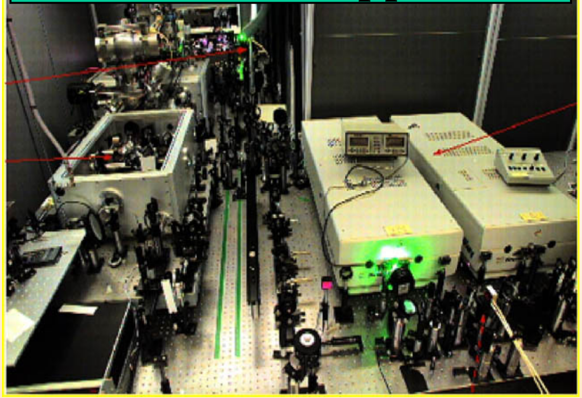




But simulations use a_{in}=10: experimentally not doable…or is it?

Tool: LOASIS multi-terawatt laser

10 TW Ti:sapphire



TREX laser

Shielded target room

LOASIS laser system

Three main amplifiers (Ti:sapphire,10 Hz):

- Godzilla:
  - 0.5-0.6 J in 40-50 fs (10-15 TW) ===> main drive beam (to date)
- Chihuahua:
  - 20-50 mJ in 50 fs ===> ignitor beam } guiding
  - 250-300 mJ in 200-300 ps ===> heater beam } guiding
  - 20-80 mJ in 50 fs ===> colliding beam
- TREX:
  - 2.7 J in 35-40 fs (at present) ===> capillary guiding

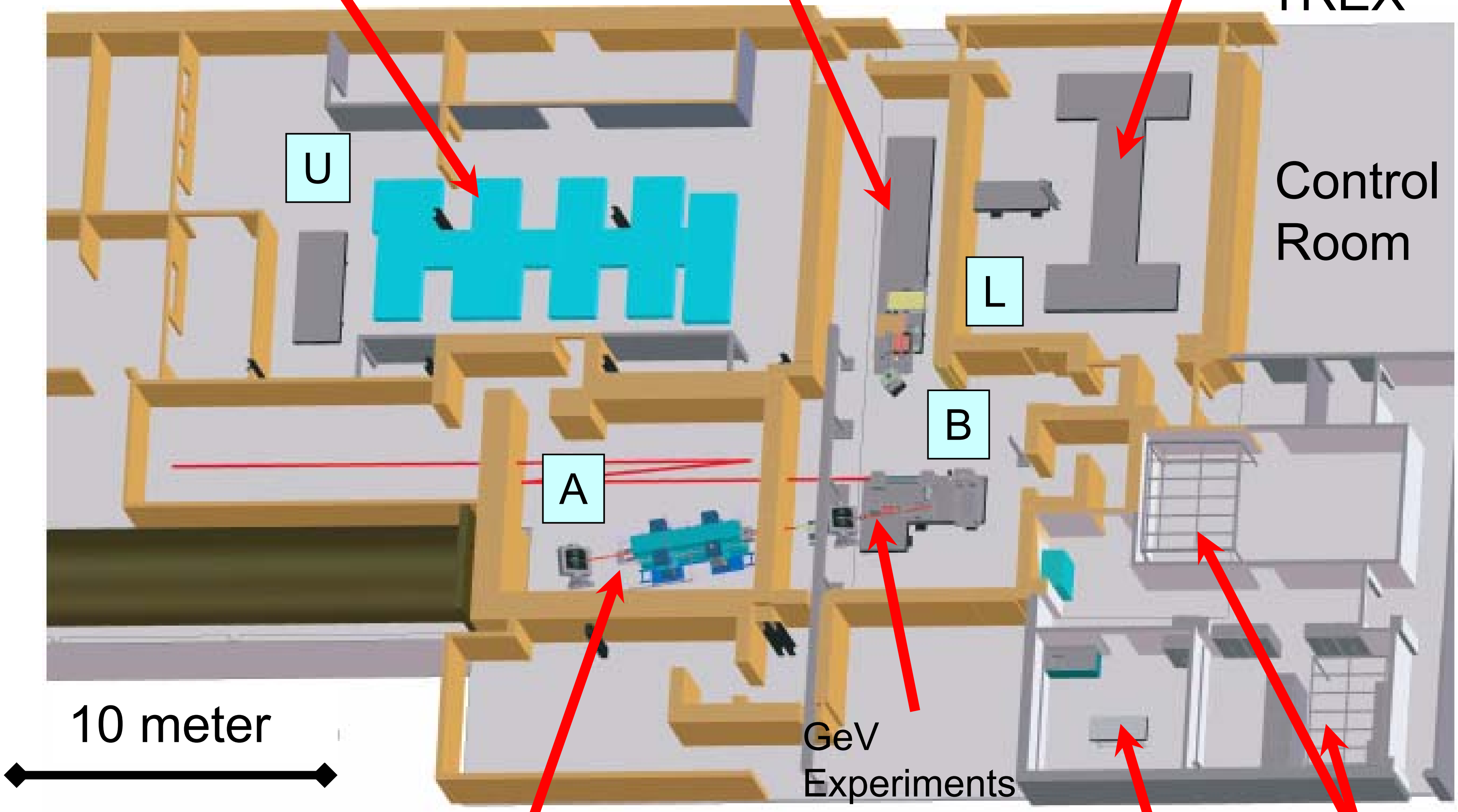
PW-class laser (proposed)

10 TW experiments

Fed by “Godzilla” and “Chihuahua” lasers (upstairs)

100 TW class laser

TREX



Control Room

GeV Experiments Fed by TREX

New area (under construction)

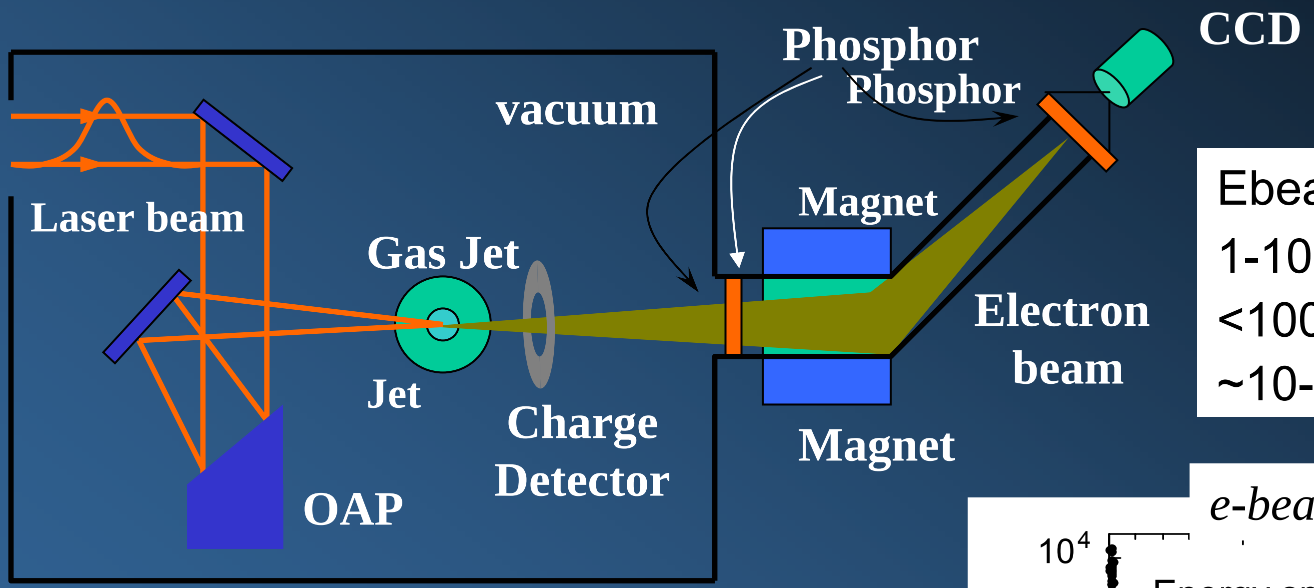
Metrology lab

Clean room

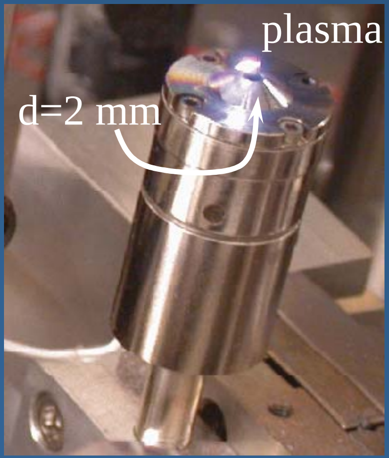
LOASIS Facilities
(Ground Floor, Bldg. 71)

November, 2006

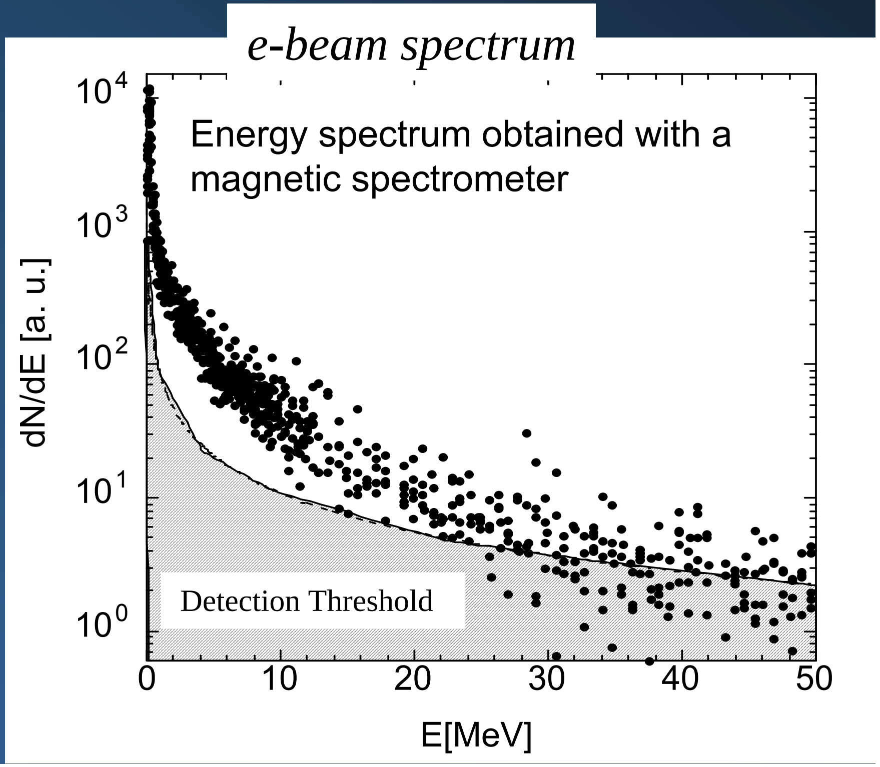
Mid 90’s -2003: lasers generate electron beams with 100 % energy spread



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



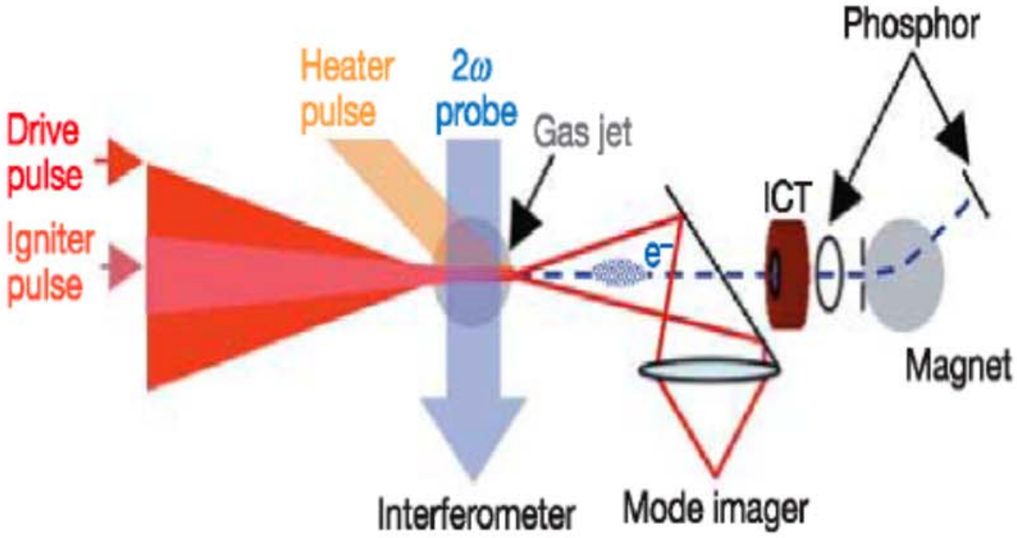
Modena *et al.* (95); Nakajima *et al.* (95); Umstadter *et al.* (96); Ting *et al.* (97); Gahn *et al.* (99); Leemans *et al.* (01); Malka *et al.* (02)


e-beam spectrum

Energy spectrum obtained with a magnetic spectrometer

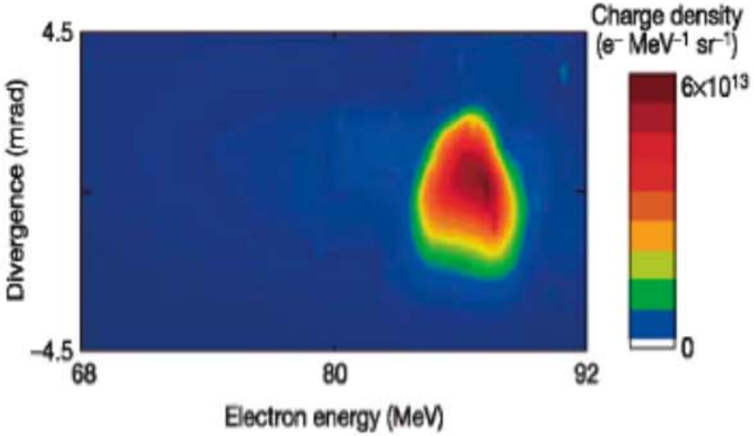
Laser preformed channel guided laser accelerator resulted in quality electron beams

- 10 TW class LOASIS drive laser
- ~100 MeV level e-beams with 0.3 nC charge



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

- Mono-energetic electron beams

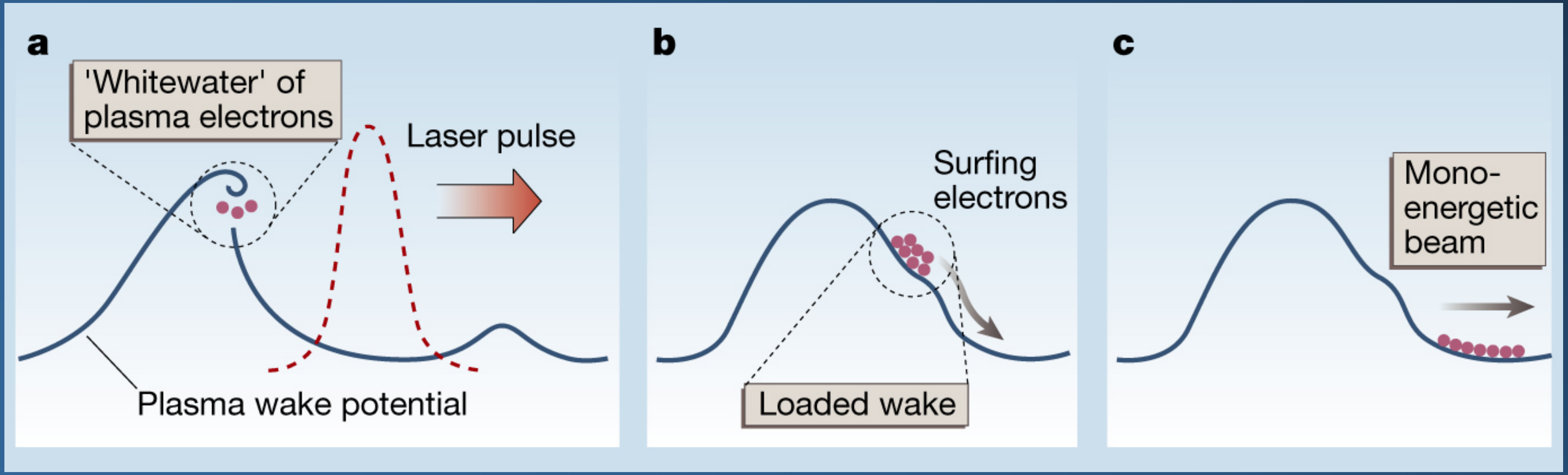


Recipe for a Monoenergetic Beam

a. **Excitation of wake (self-modulation of laser)**
   Onset of self-trapping (wavebreaking)

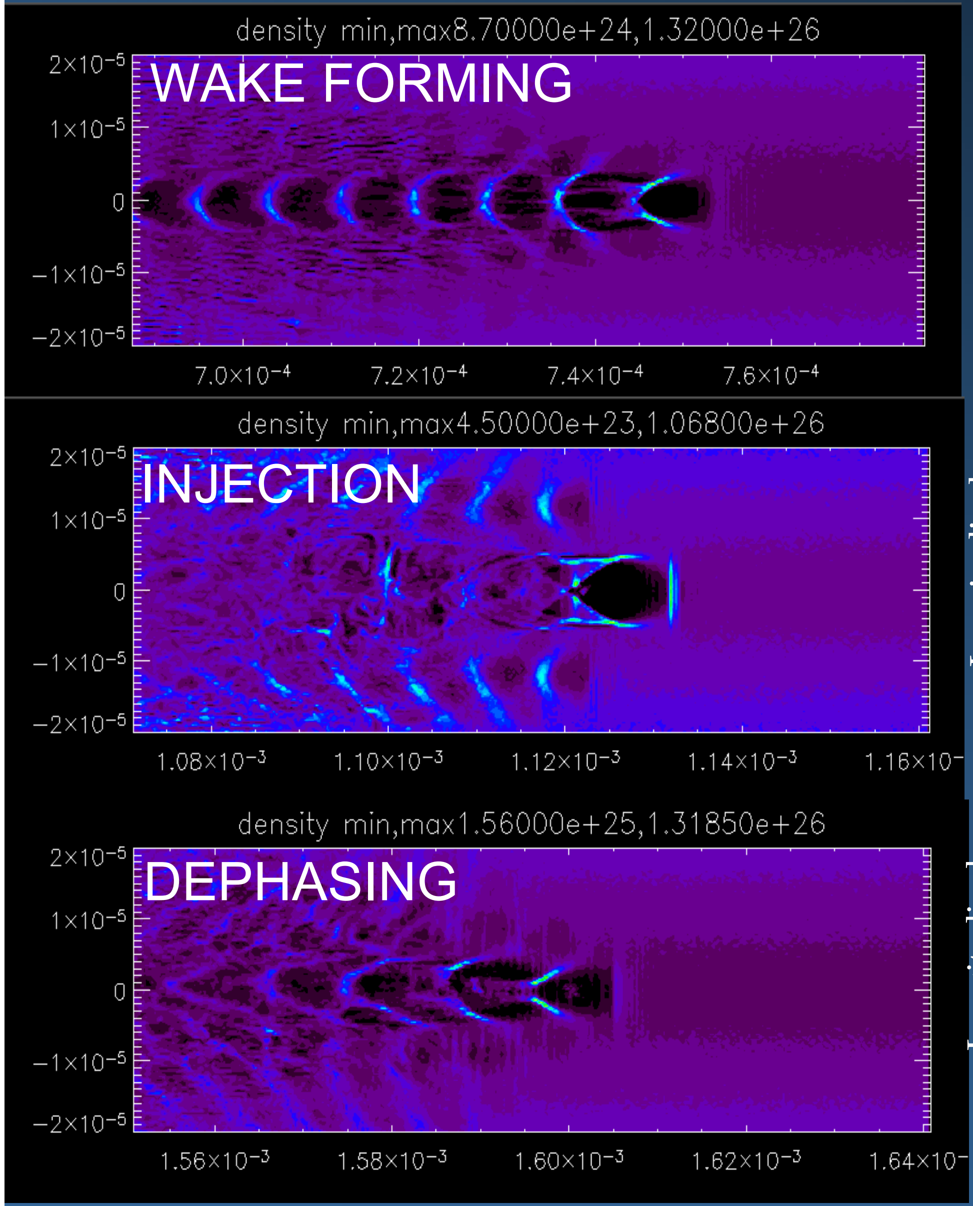
b. **Termination of trapping (beam loading)**
   Acceleration

c. **Dephasing**
   If L > or < dephasing length: large energy spread
   If L ~ dephasing length: monoenergetic

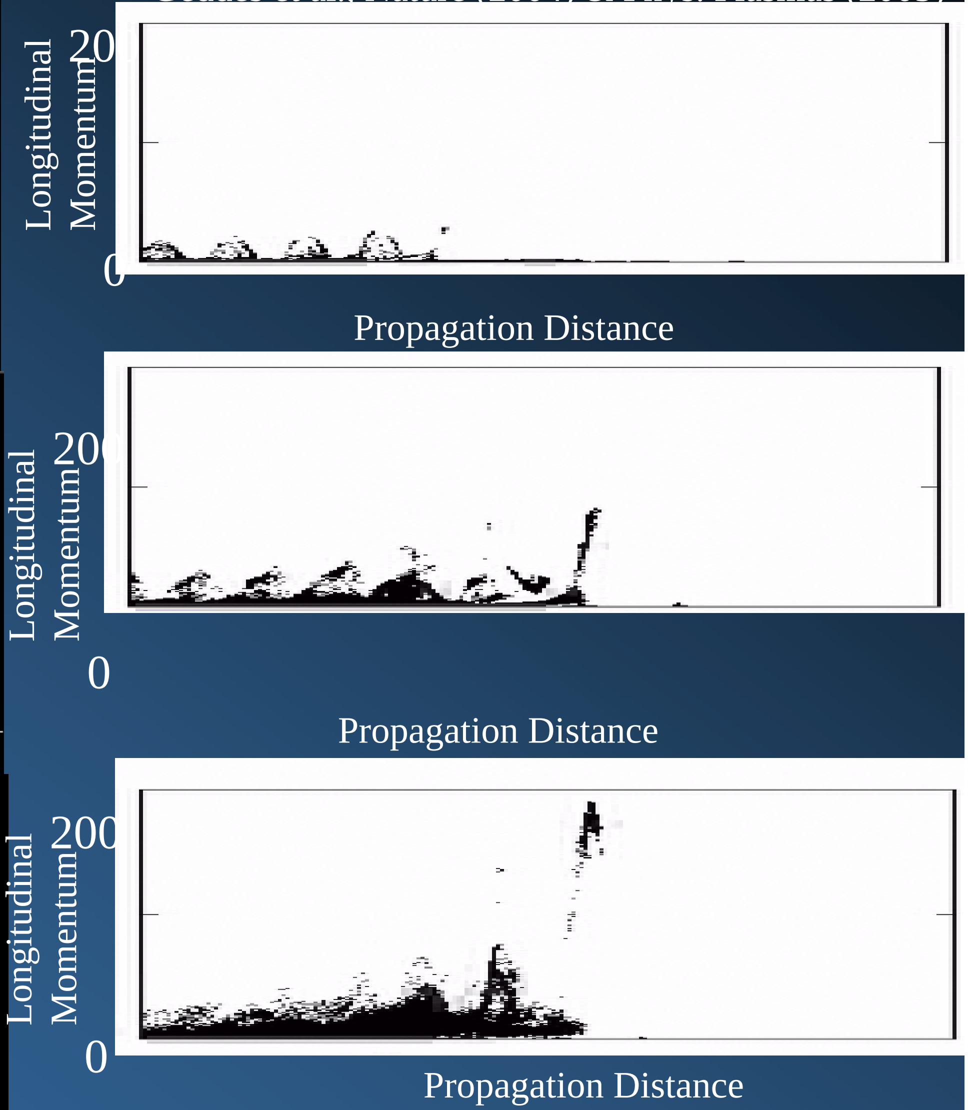


T. Katsouleas, Nature 2004

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



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



INCITE Proposal: 3 D simulation

Laser Wakefield Particle Acceleration

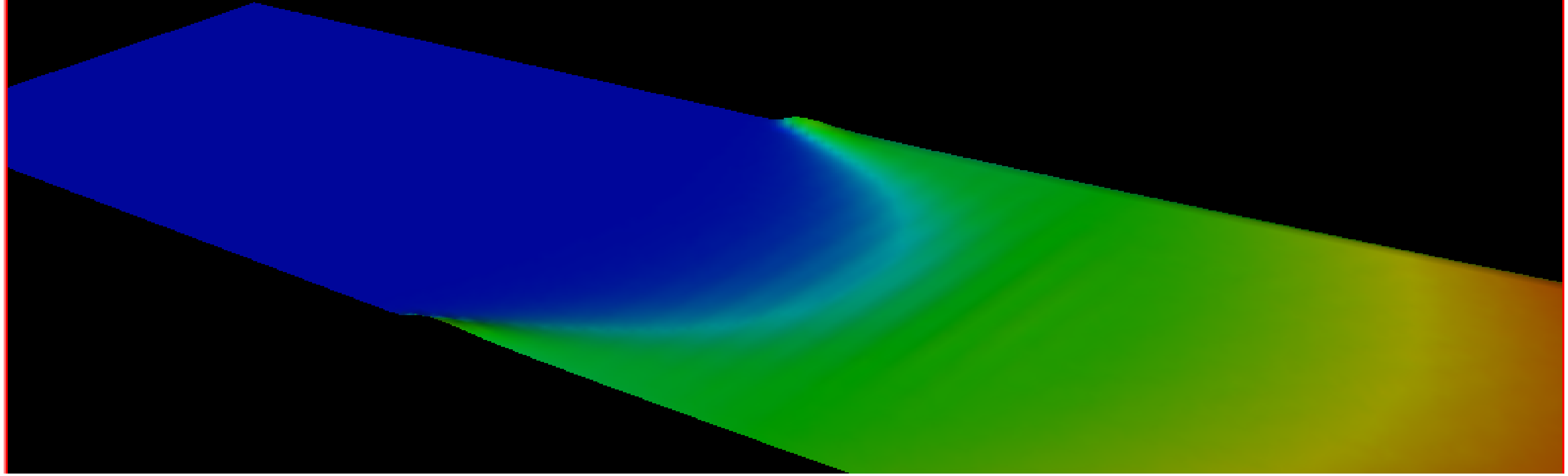
High Quality Electron Bunches in Millimeters

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



2004 Results: High-Quality Bunches

- **Approach 1: bigger spot**
    - RAL/IC[+] (12.5 TW -> ~20 pC, 80 MeV)
    - LOA[^] (33 TW -> ~500 pC, 170 MeV)
    - **For GeV -> 1 PW class laser**

- **Approach 2: preformed channel guided**
    - LBNL* (9TW, 2mm channel -> ~300 pC, 86 MeV)
    - **For GeV -> ~10-50 TW class laser[$], longer guiding structure**

nature

Dream beam

The dawn of compact particle accelerators

Offshore tuna ranches
A threat to US waters?

The Earth's hum
Sounds of air and sea

Protein folding
Escape from the ribosome

Human ancestry
One from all and all from one

technology feature RNA interference

[+] S. Mangles et al, *Nature* **431**(2004) 535; ^J. Faure et al, *Nature* **431**(2004) 541
*C.G.R. Geddes et al, *Nature* **431** (2004) 538; [$] W.P. Leemans et al, *IEEE Trans. Plasmas* Sci. **24** (1996) 331.

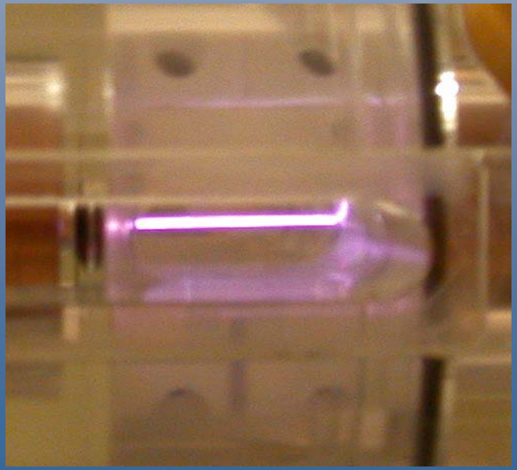
Increasing particle energy requires lower plasma density

Electron dephasing: $L_d \approx \lambda_p^3 / \lambda^2 = n_c / n_p^{3/2}$

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

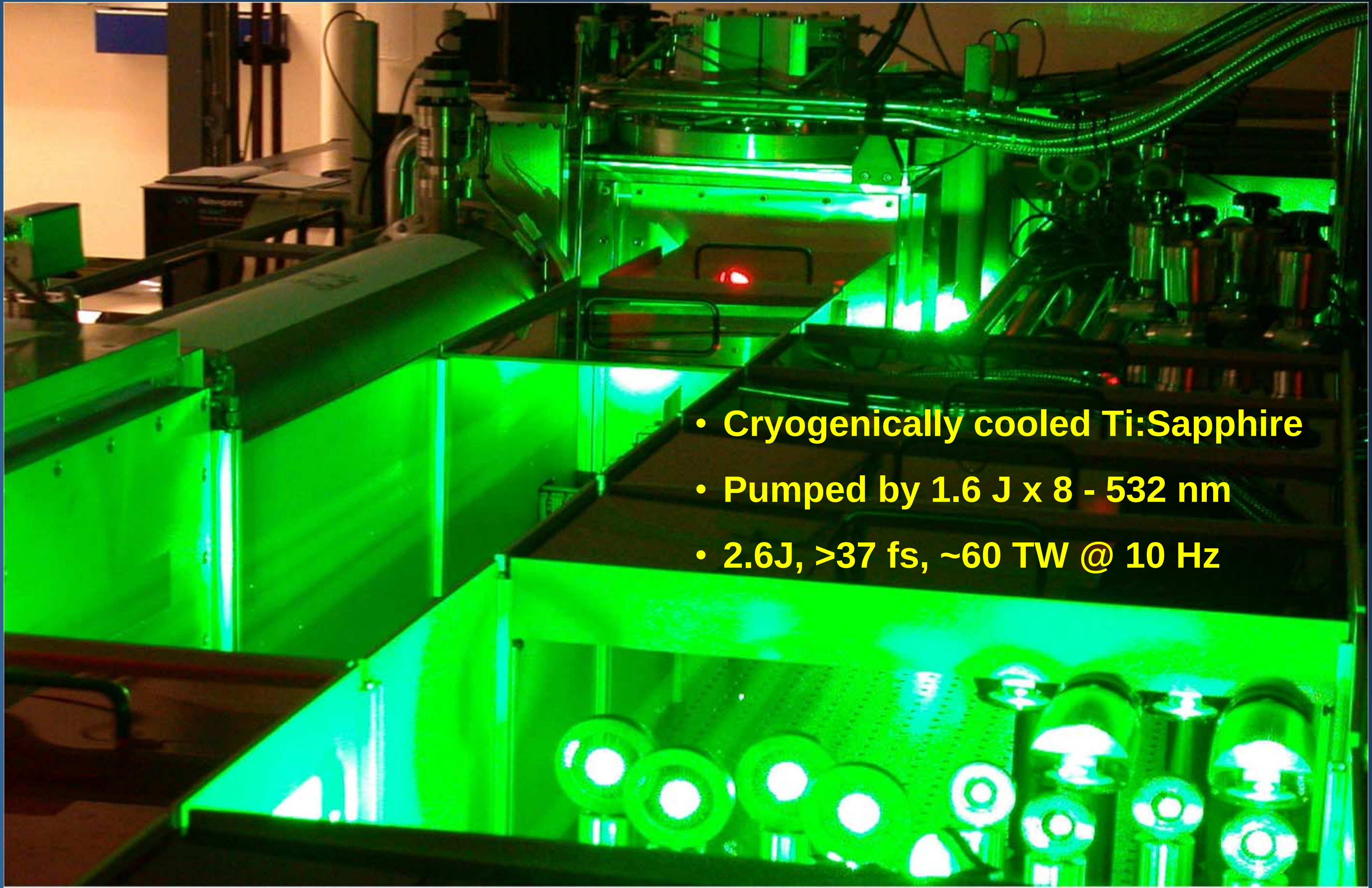
$\Big\}$ *Reduce n_p*

- Hydrodynamically formed channels:
  - Relies on inverse Bremsstrahlung heating
  - Efficient for high density
- Capillary discharge channels:
  - Relies on Ohmic heating
  - Works at low density



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

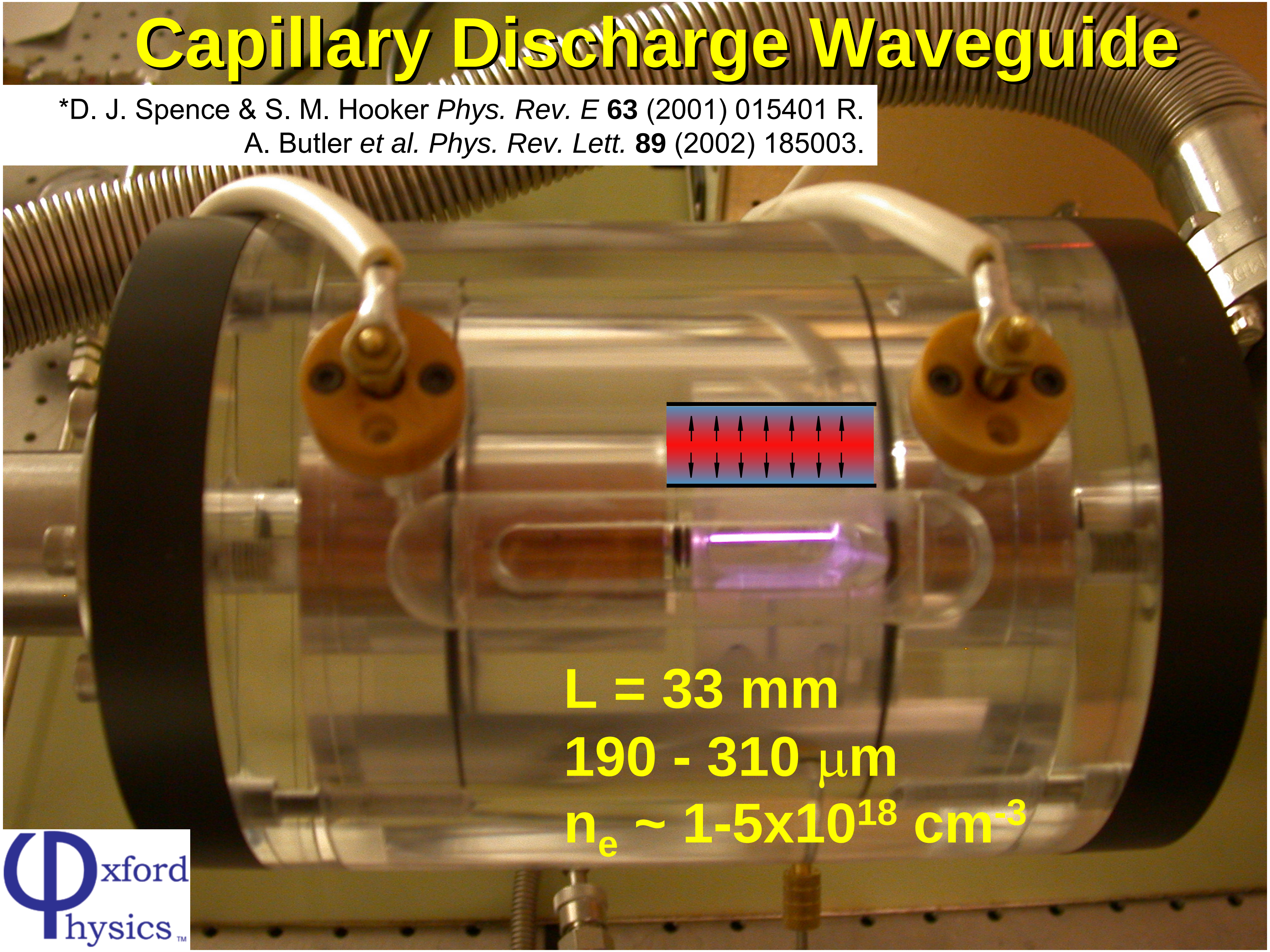
LOASIS TREX Ti:Sapphire Laser System



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

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.

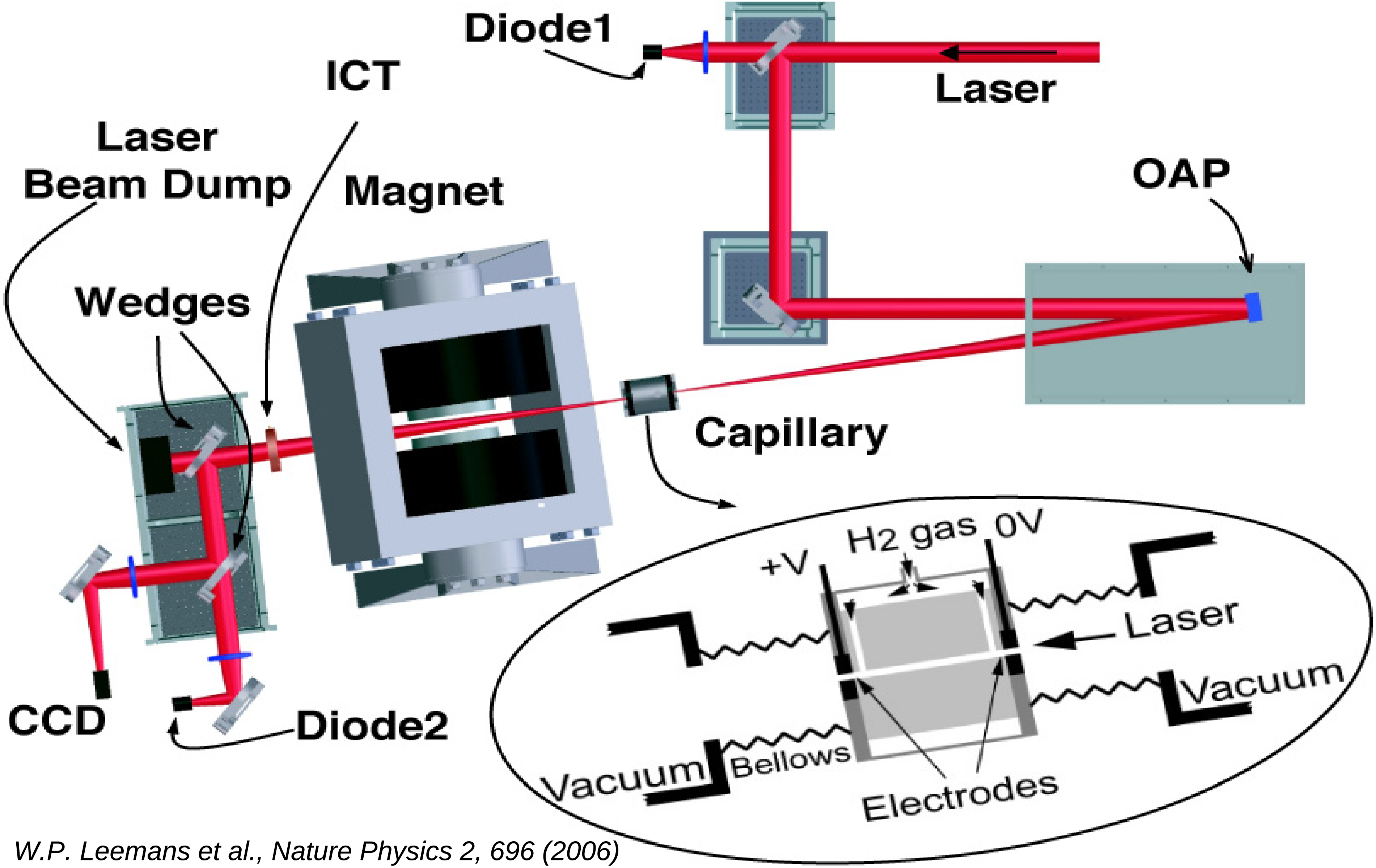


L = 33 mm

190 - 310 μm

n_e ~ 1-5x10^{18} cm^{-3}

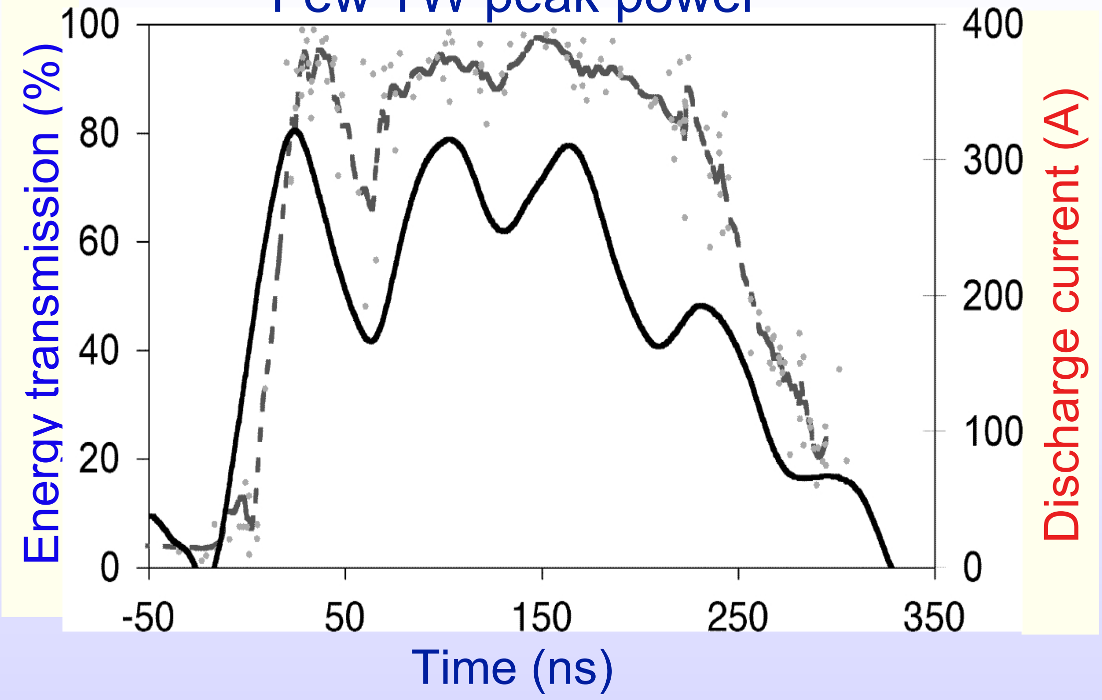
Experimental Setup



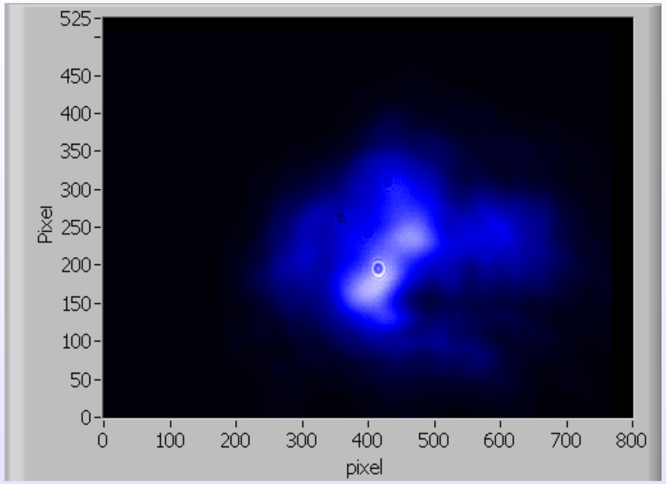
W.P. Leemans et al., Nature Physics 2, 696 (2006)

Energy transmission correlates with discharge current

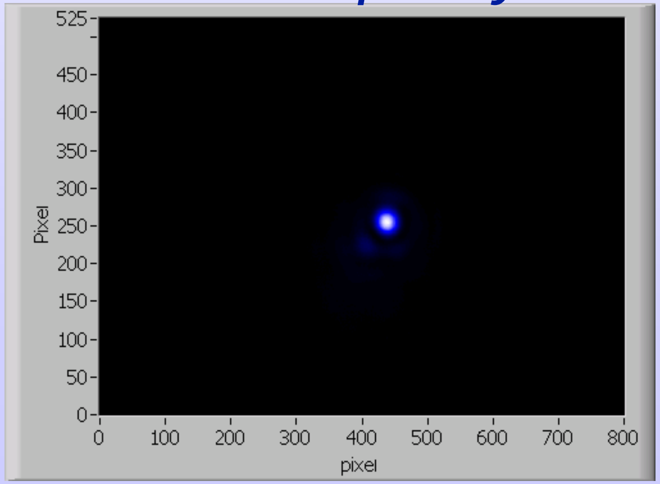
Few TW peak power



No capillary



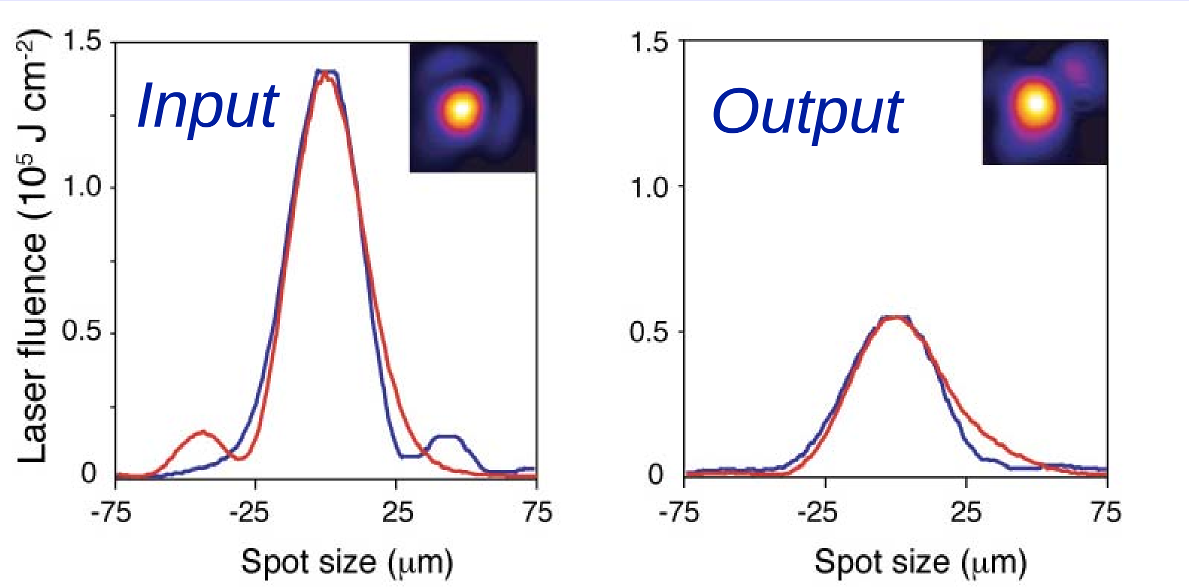
With capillary

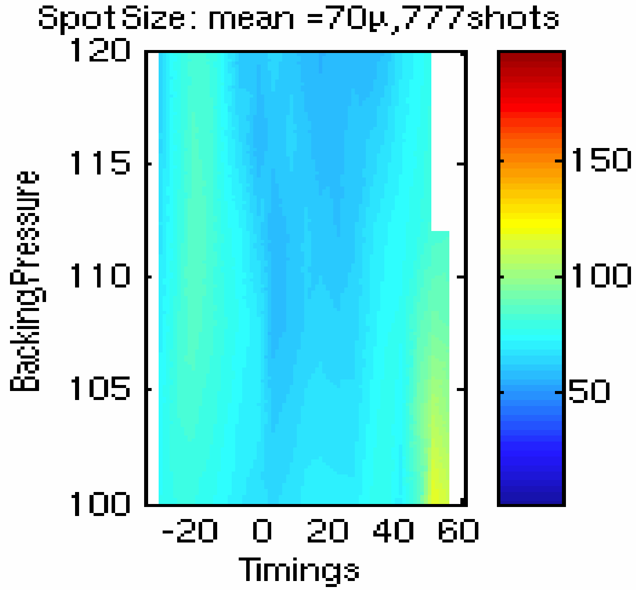


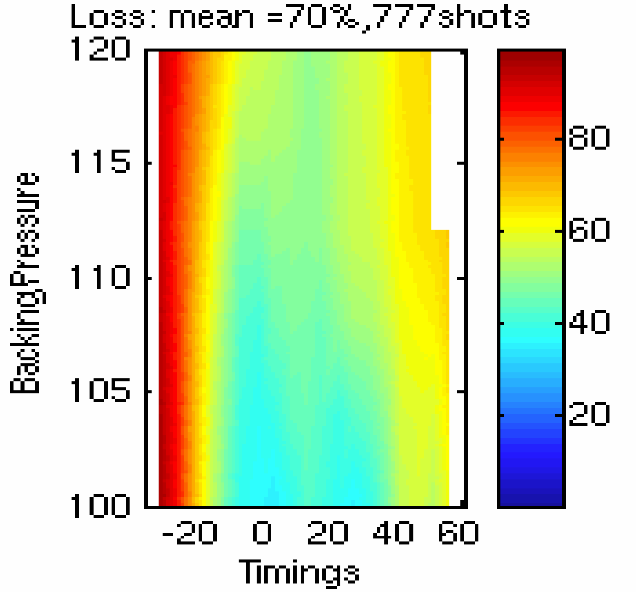
- a = 1.4 (40 TW in 40 fs); $P/P_c \sim 2.5$
- Energy transmission: 10-70 %
- Acceptance: ~ 10 micron
- Spot size depends on pressure and timing

W.P. Leemans, Nature Physics 2, 696 (2006)

High Power Laser Guiding over 33 mm



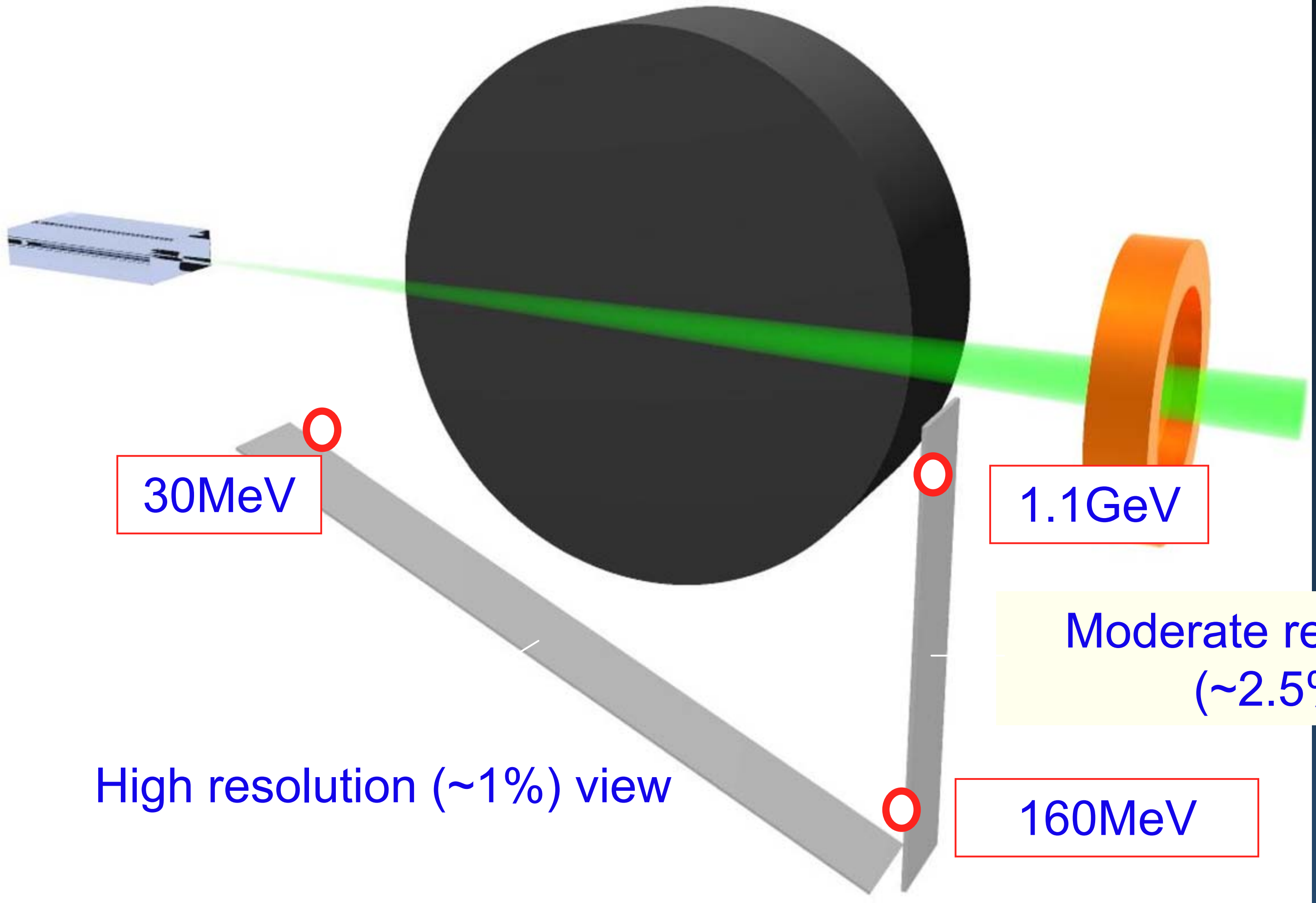




- a = 1.4 (40 TW in 40 fs); P/P_c ~ 2.5
- Energy transmission: 10-70 %
- Acceptance: ~ 10 micron
- Spot size depends on pressure and timing

W.P. Leemans et al., Nature Physics 2, 696 (2006)

LOASIS GeV Spectrometer



Moderate resolution (~2.5%)

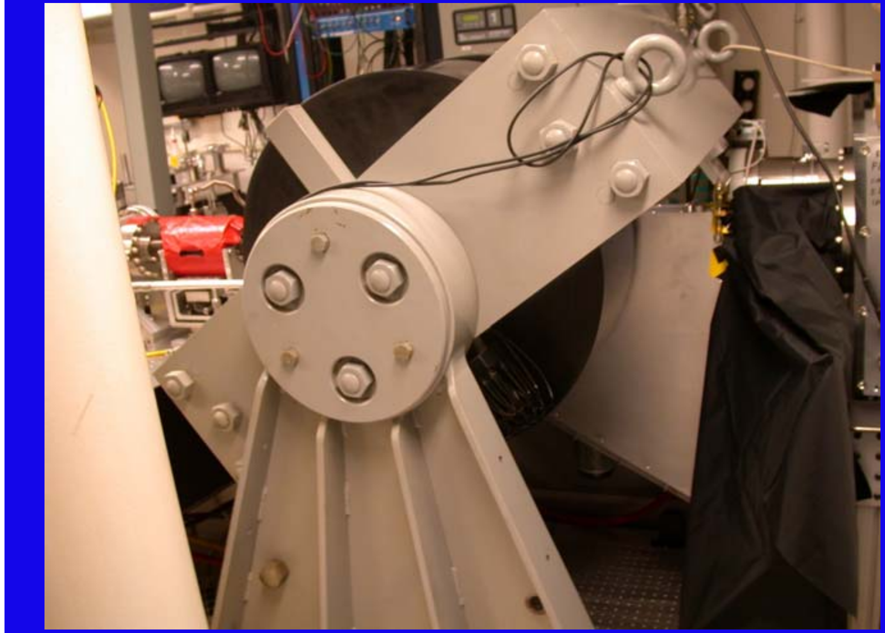
High resolution (~1%) view

Horizontal profile -> divergence; Vertical profile -> energy

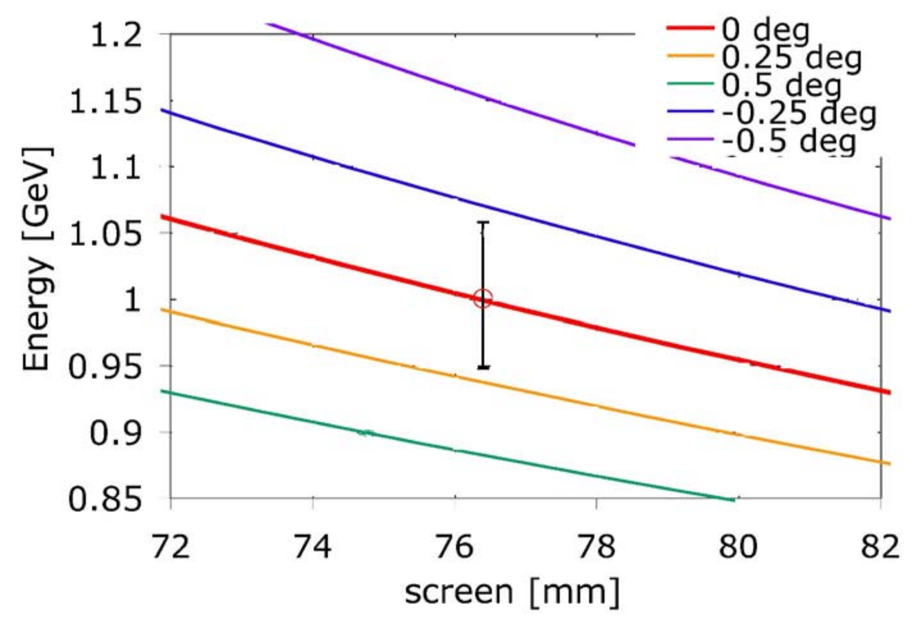
$$\delta E_{obs} = \sqrt{\delta E_{real}^{2} + \delta E_{div}^{2}}$$

Magnetic spectrometer details

- 11” dipole magnet (~1.2 T, 8 kW)
- Momentum acceptance: 0.03 - 1.1 GeV single shot
- Field mapped and optics modeled
- 4 synchronized 12bit CCD cameras
- No slit but limited angular acceptance



Energy vs. screen position

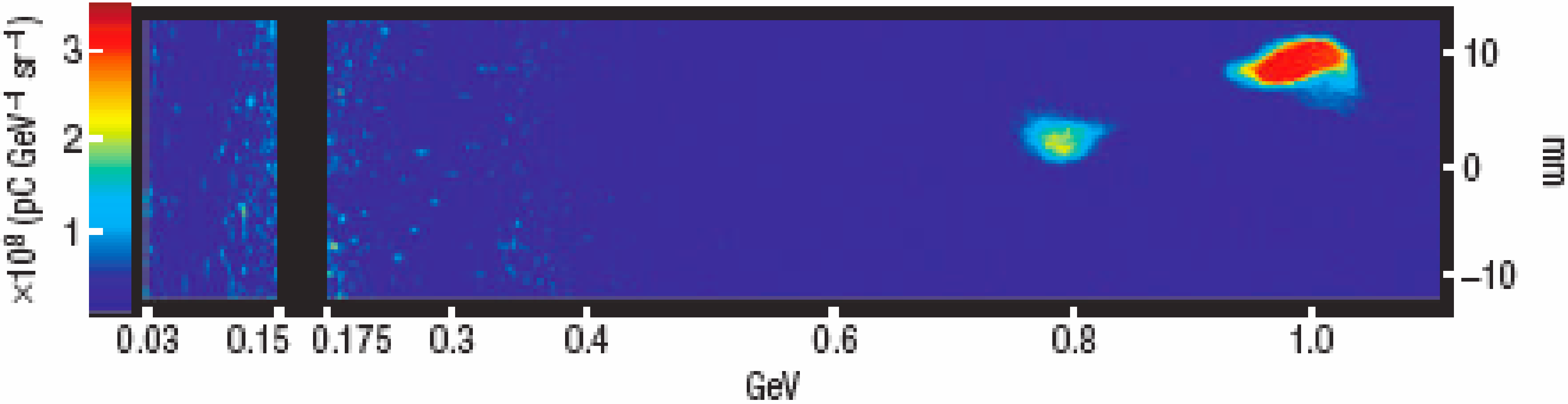


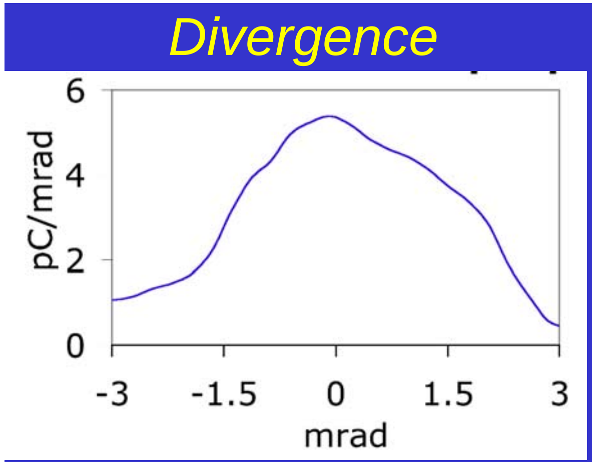
K. Nakamura et al., Phys. Plasmas, submitted

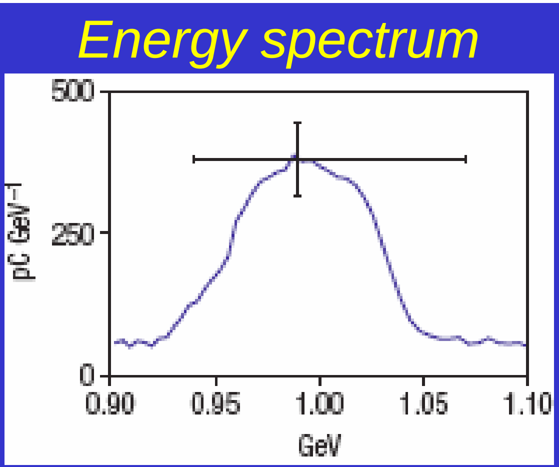
GeV Beam Generation

312 μm diameter and 33 mm length capillary

1 GeV beam: $a_0 \sim 1.46$ (40 TW, 37 fs)







Divergence(rms): 2.0 mrad
Energy spread (rms): 2.5%
Resolution: 2.4%
Charge: >30.0 pC

*W.P. Leemans et. al, *Nature Physics* **2** (2006) 696.

Stable 0.5 GeV Beam Generation

225 μm diameter and 33 mm length capillary

Density: 3.2~3.8x10^{18}/cm^3

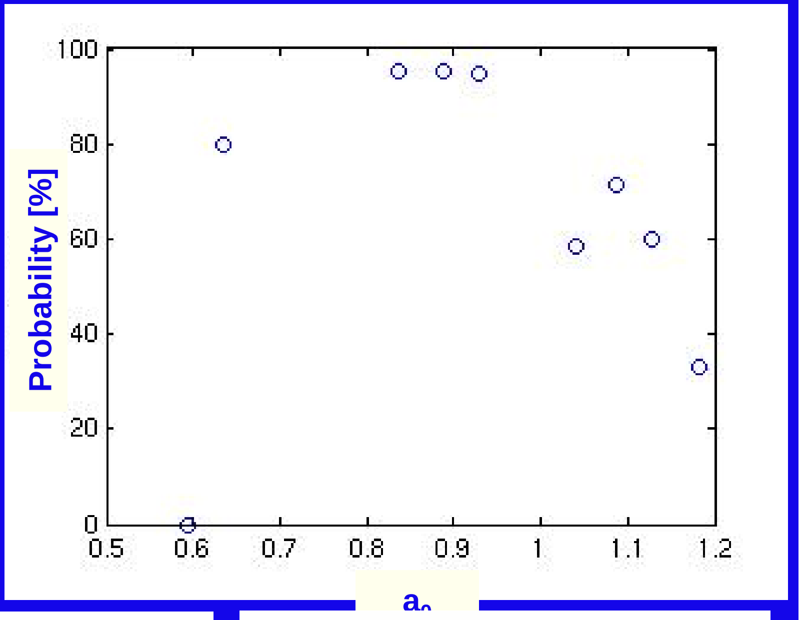
Laser: 950(+-15%) mJ/pulse (compression scan)

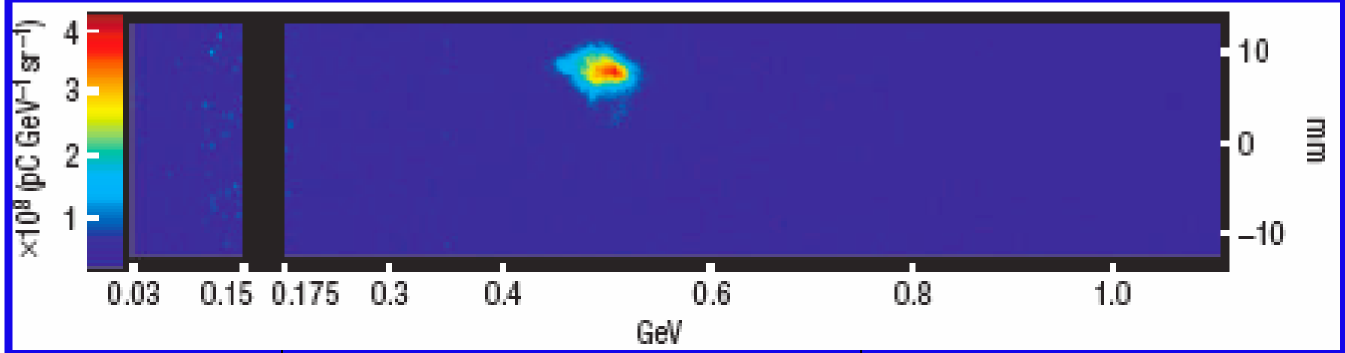
Injection threshold: a_0 ~ 0.65 (~9TW, 105fs)

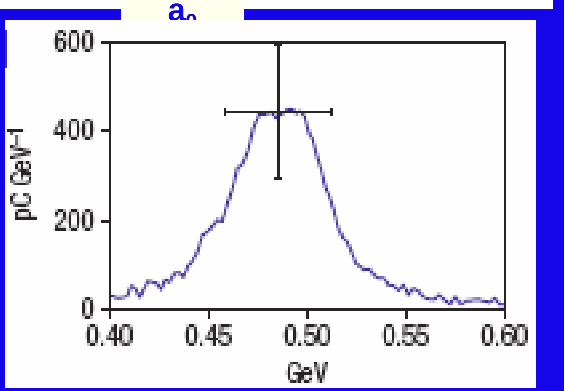
Less injection at higher power

-Relativistic effect?

-Self modulation?



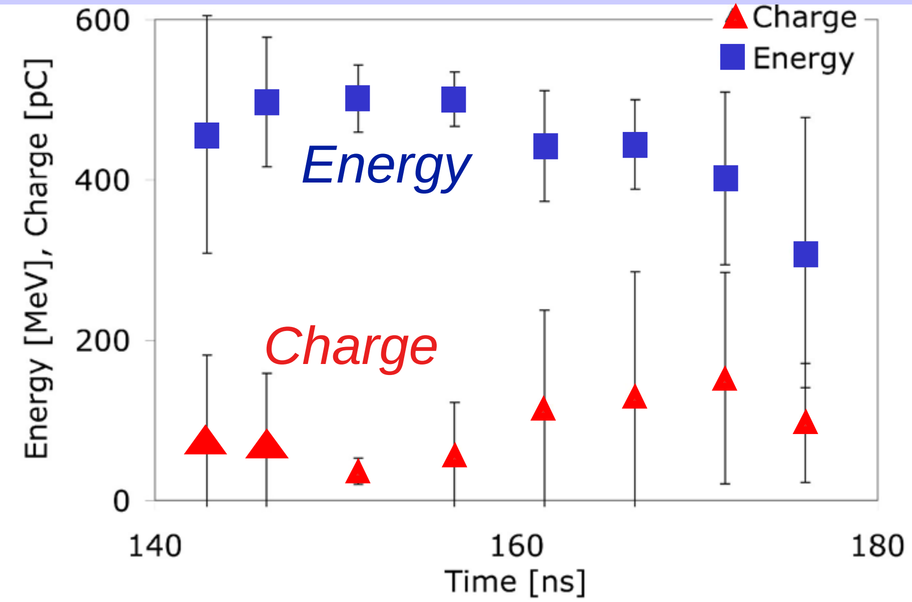




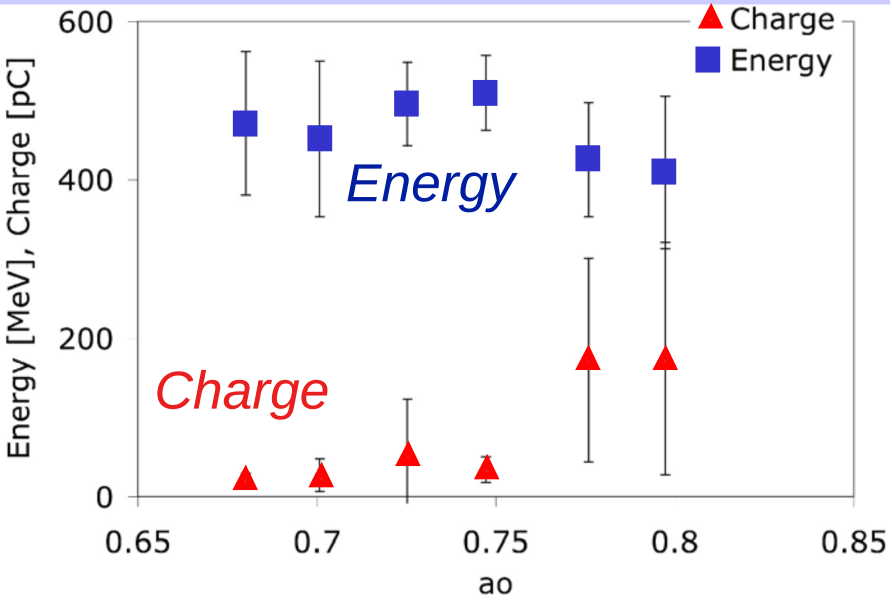
Central energy: 490 MeV
Divergence(rms): 1.6 mrad
Energy spread (rms): 5.6%
Resolution: 1.1%
Charge: ~50 pC

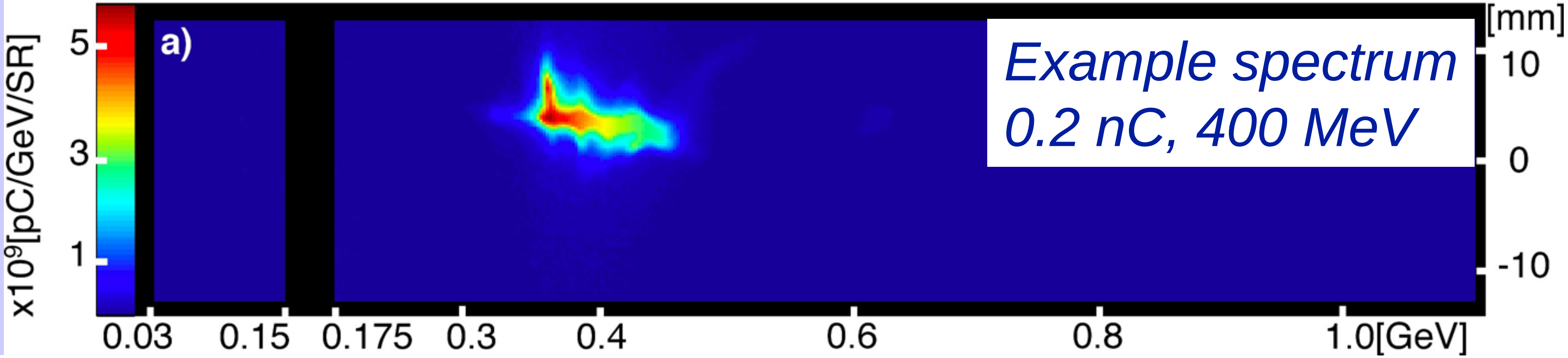
Energy and charge correlation consistent with beam loading effects

Discharge timing dependence



Laser intensity dependence





Example spectrum
0.2 nC, 400 MeV

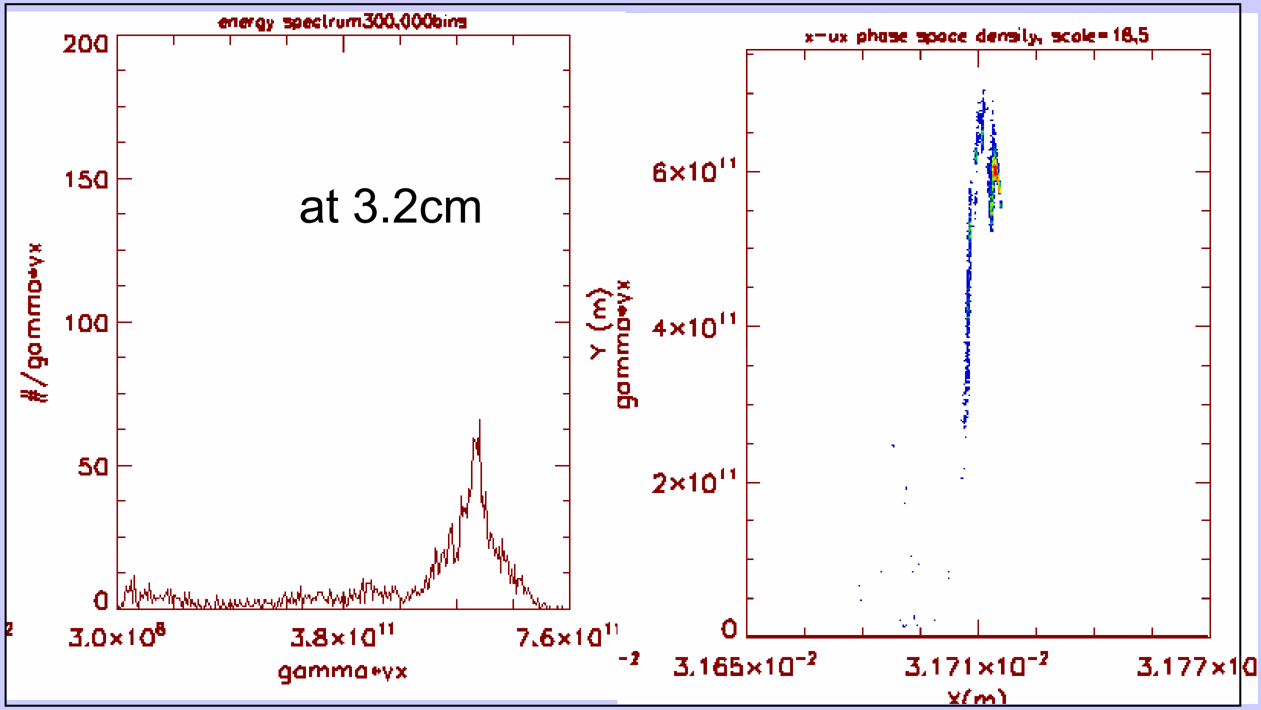
Comments on experience with capillary

- Alignment, timing into discharge and laser power critical
- Cleanest beams near trapping threshold:
  - Lower charge, less beam loading (~ 50 pC)
- Can obtain ~ 0.4 nC but increased energy spread (>20%)
- Energy scaling with power:
  - 12-18 TW -> 0.5 GeV
  - 40 TW -> 1 GeV
  - Fluctuations correlate directly with laser power
- Pump depletion, mode matching requirements, pulse evolution under investigation
- 2D and 3D simulations in progress

2d GeV simulations model experimental bunch

- Beam formed similar to experimental results for parameters close to experiments:
  40 TW, 40 fs, 25 µm spot
  n ~ 5.3 e 18/cm3, 44 µm matched spot

Q=65pC
E=1.02 GeV
dE/E ~ 5% FWHM
divergence ~ 5mrad FWHM


at 3.2cm

- No or weak injection for nominal experimental parameters
  Sensitive dependence on physical parameters

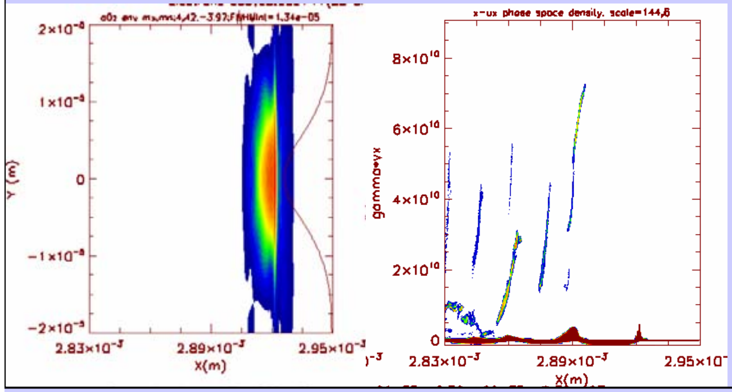
- Consistent with unstable experimental beams at 1 GeV - close to trapping threshold

2d GeV simulations - injection & physical parameters

Injection after significant laser pulse compression & reshaping - similar to 10 TW

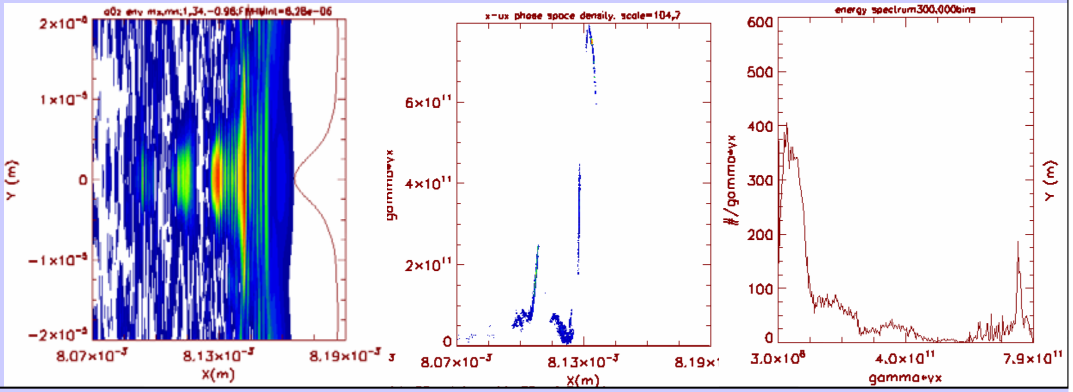
E_{laser}~80% E_0

0.3 cm



E_{laser}~20% E_0

0.8cm



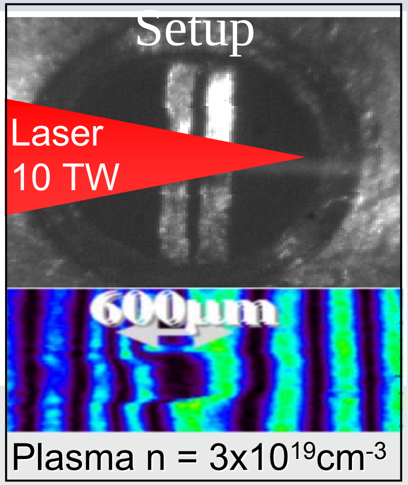
- Laser depletes at ~1cm propagation - beam decelerates (PWF) over last 2 cm

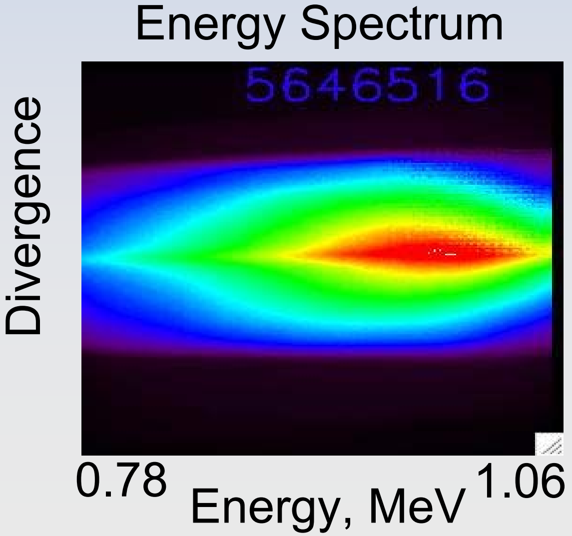
- Electrons injected late:
  only approximately half of available E•dl used
  simulations show sensitivity to density ramp & resultant pulse shaping

- External injection would enable use of lower density
  at n=2e18, same driver allows dephasing & depletion limited ~3 GeV beam

Beam stability--getting better and better

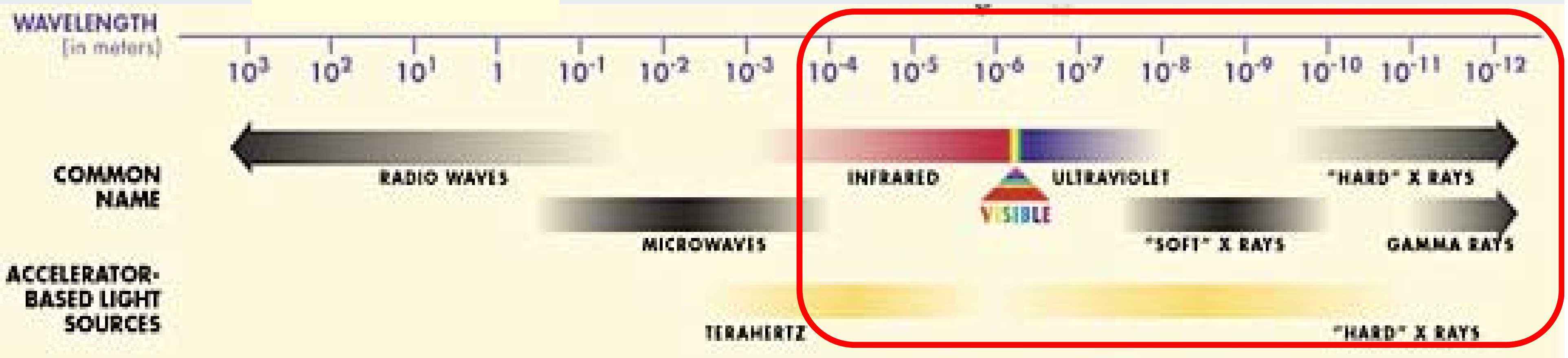
- **Guiding + laser control: stable beams at 0.5 GeV**
  - – W.P. Leemans et al., Nature Physics 2006
- **Laser triggered injection using colliding pulse:**
  - – E. Esarey et al., PRL 1997; C.B. Schroeder et al., PRE 1999 -- three pulse
  - – G. Fubiani et al., PRE 2004; K. Nakamura et al., AIP proceedings, AAC2004 -- two pulse non-collinear and collinear
  - – J. Faure et al., Nature 2006
- **Density transition: stable MeV beam**
  - -C.G.R. Geddes et al., submitted for publication
- **Pre-plasma control**
  - – Hosokai et al., PRL 2006
  - – Mangles et al., 2006





Precision Frontier: femtosecond and attosecond radiation

Radiation and particles for “short” term (next 5 yrs) ultra-fast applications

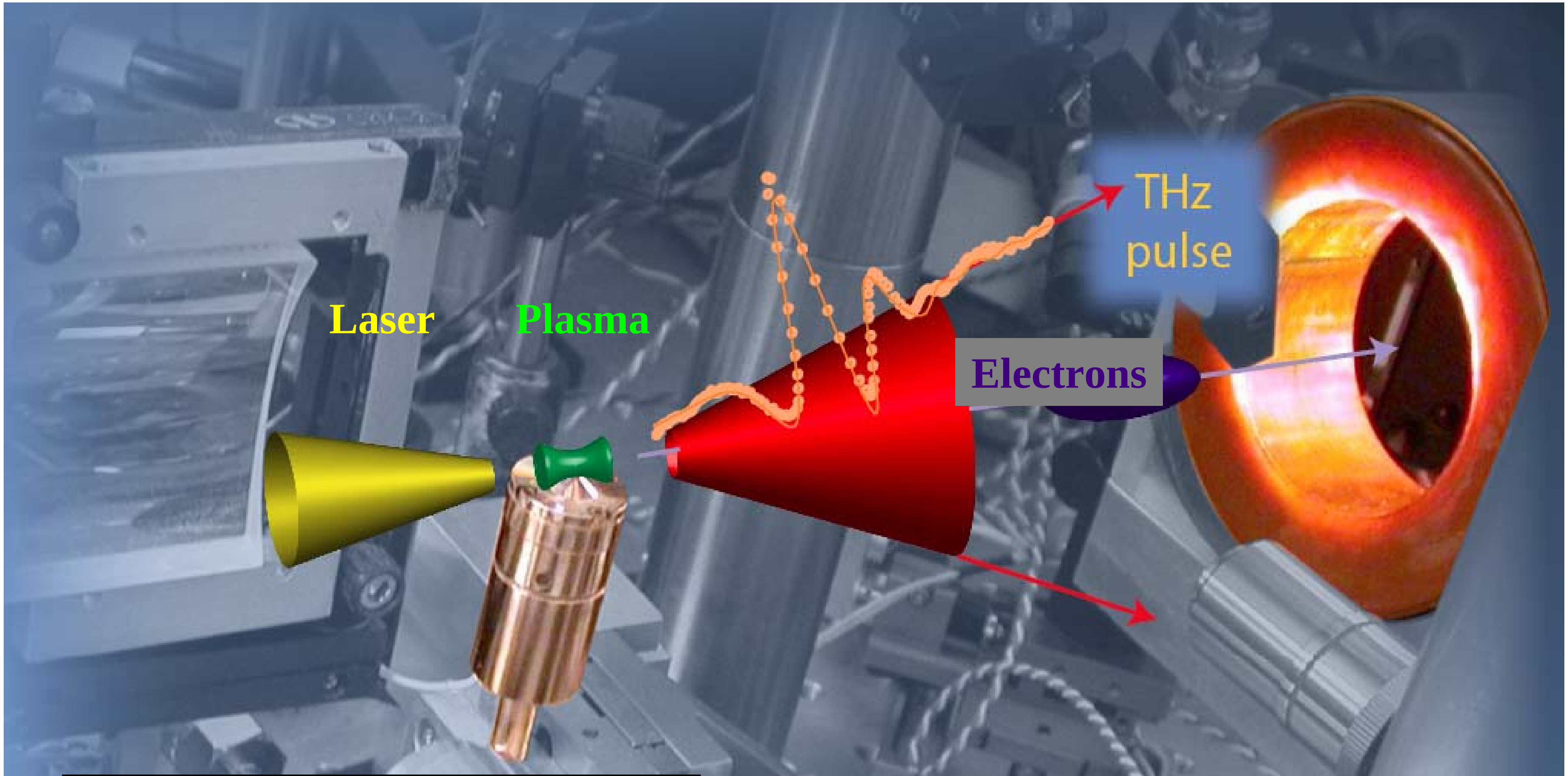


- **Why Laser Driven Accelerators ?**
  - **Peak current, bunch duration**
  - **Free electrons, no material damage issues**
  - **Compactness**
  - **Synchronization**

$$I_{total}(\omega) = \left\{ N + N(N-1)\left| g(k) \right|^2 \right\} I_e(\omega)$$

$$g(k) = \int_{-\infty}^{\infty} \rho(z) e^{ikz} \, dz$$

Dominates if $\sigma_z < \lambda$

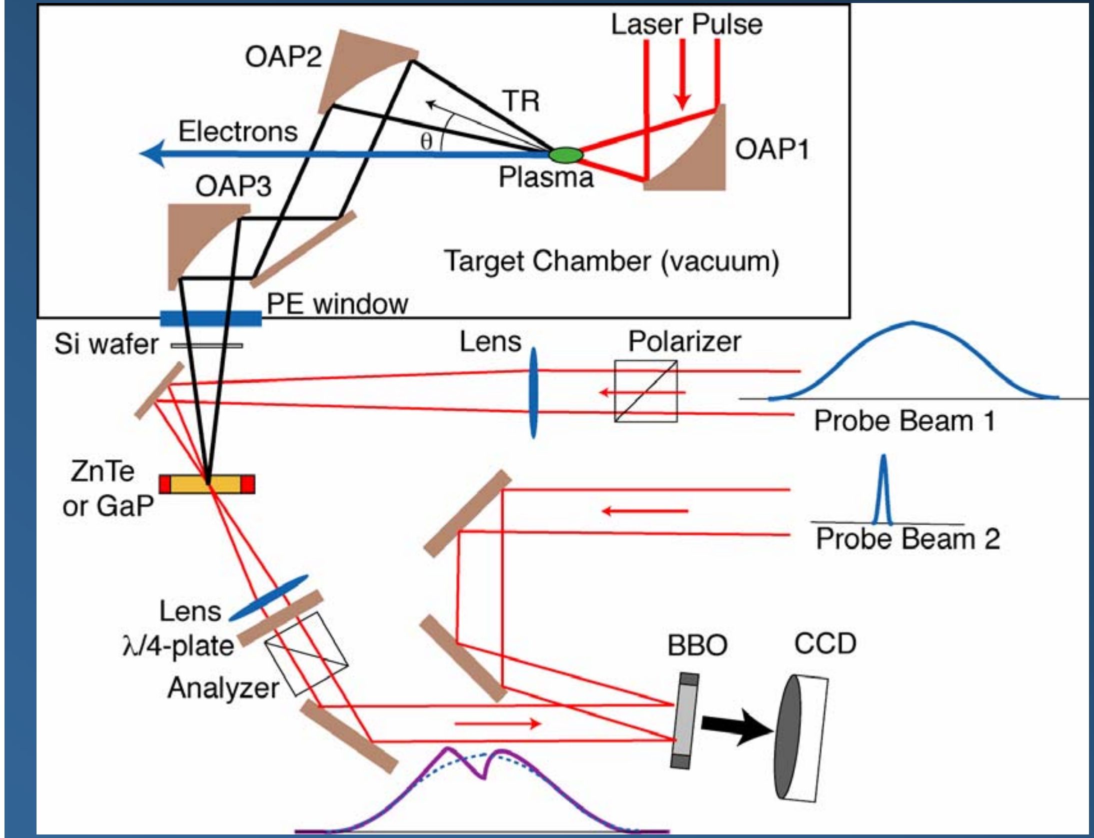


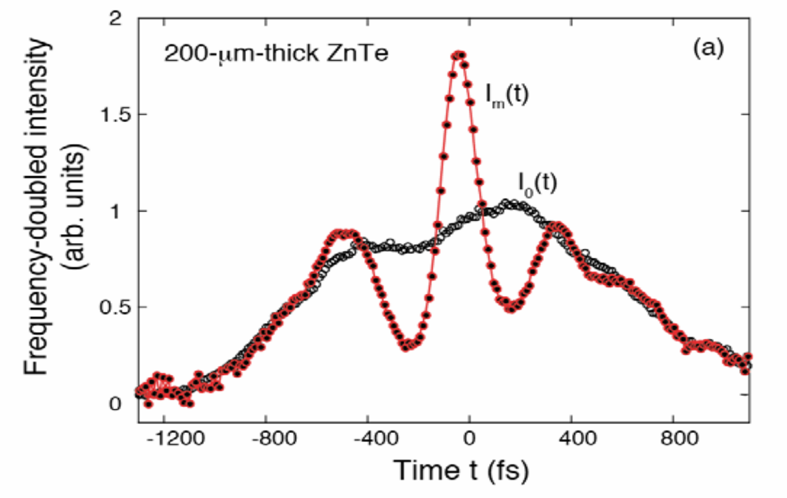
Intense THz source

- **0.01-10 MV/cm** at focus (up to **10’s of μJ** in THz pulse)
- ‘traditional’ laser-based sources deliver <100 kV/cm

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

Example: single shot electro-optic sampling

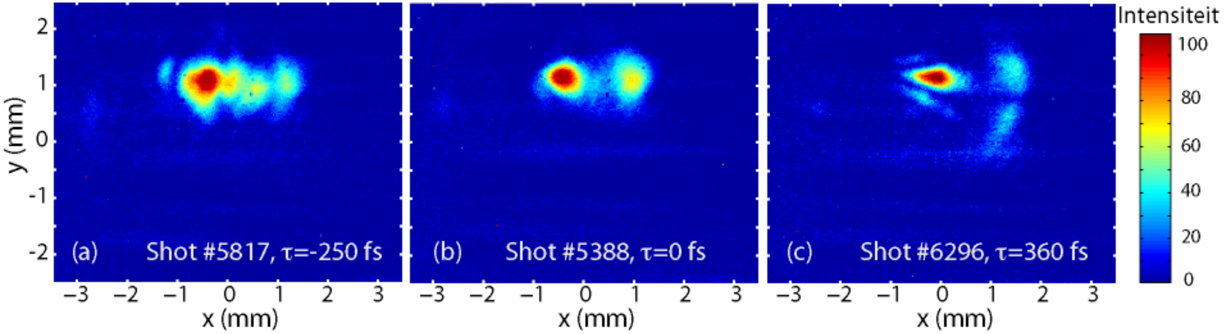




- Peak E-field of $E_{CTR} \approx 0.4$ MV/cm
- Estimated 0.5-1 μJ /pulse
- < 50 fs bunches

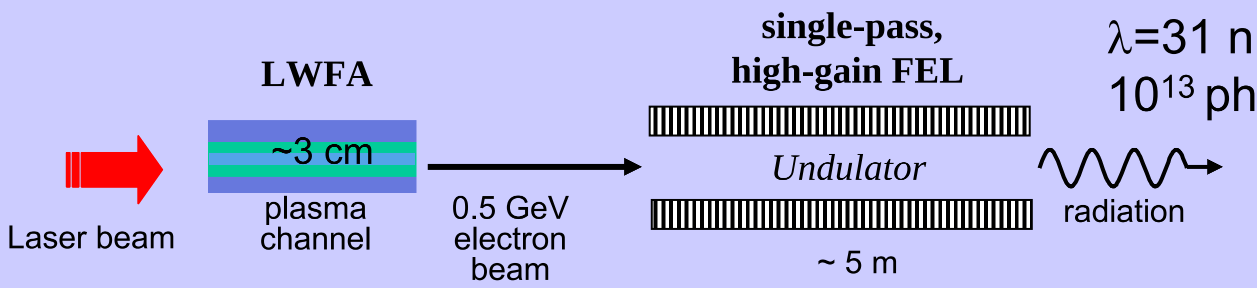
Single shot imaging

- Intrinsic synchronization
- Up to 10 THz



LWFA-driven FEL

Schematic of LOASIS LWFA-driven FEL:


Laser beam

LWFA

~3 cm

plasma channel

0.5 GeV electron beam

single-pass, high-gain FEL

Undulator

~ 5 m

radiation

FEL Output
λ=31 nm
10^{13} photons/pulse

LWFA Electron Beam:

Beam Energy	0.5 GeV
Peak current	5 kA
Charge	0.1 nC
Bunch duration, FWHM	20 fs
Energy spread (slice)	0.25 %
Norm. Emittance	1 mm-mrad

Undulator Parameters (THUNDER):
[K.E.Robinson et al., IEEE J. QE-23, 1497 (1987).]

Undulator type	planar
Undulator period	2.18 cm
Number of periods	220
Peak Field	1.02 T
Undulator parameter, K	1.85
Beta function	3.6 m

FEL radiation parameters:

Resonant wavelength	31 nm
Photon energy	40 eV
FEL parameter	$5\text{x}10^{-3}$
1D Gain length	0.19 m
3D Gain length	0.31 m
Steady-state sat. power	12 GW
Spontaneous rad. Power	4 kW
Slippage length	7 µm
Power fluctuations	53%

D. A. Jaroszynski et al., Phil. Trans. R. Soc. A 364, 698 (2006).

F. Grüner et al., in Proc. of FLS06 (2006).

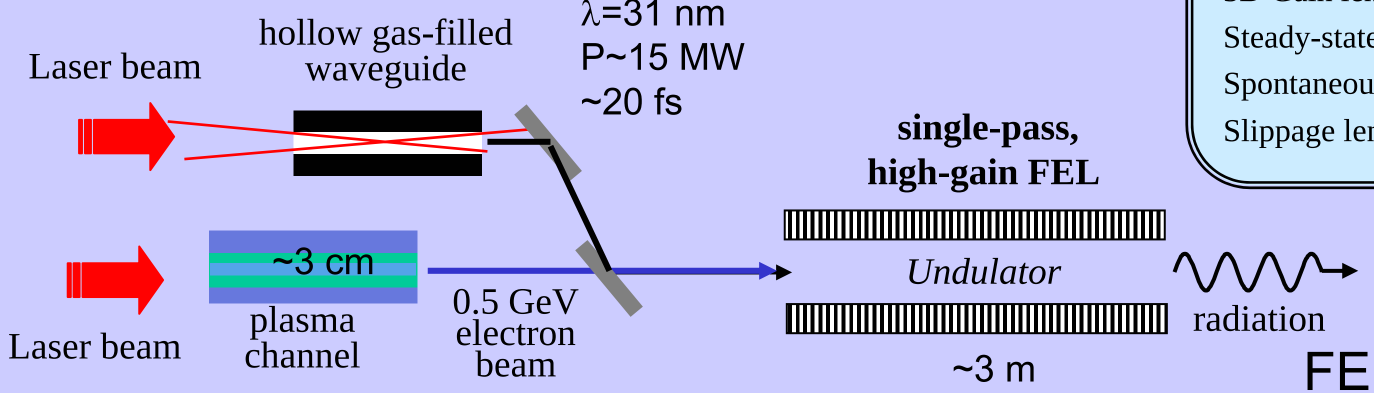
C. B. Schroeder et al., in Proc. of FEL06 (www.jacow.org/) (2006).

HHG-seeded LWFA-driven FEL

Schematic of HHG-seeded, LWFA-driven FEL: [C.B.Schroeder et al., in Proc. of FEL06 (2006).]

HHG [*] ***seed:***	
26th harmonic wavelength	31 nm
Power	15 MW
Duration, FWHM	20 fs

HHG seed



Laser beam

hollow gas-filled waveguide

λ=31 nm
P~15 MW
~20 fs

single-pass, high-gain FEL

~3 cm

plasma channel

Laser beam

0.5 GeV electron beam

Undulator

~3 m

radiation

LWFA

FEL radiation parameters:	
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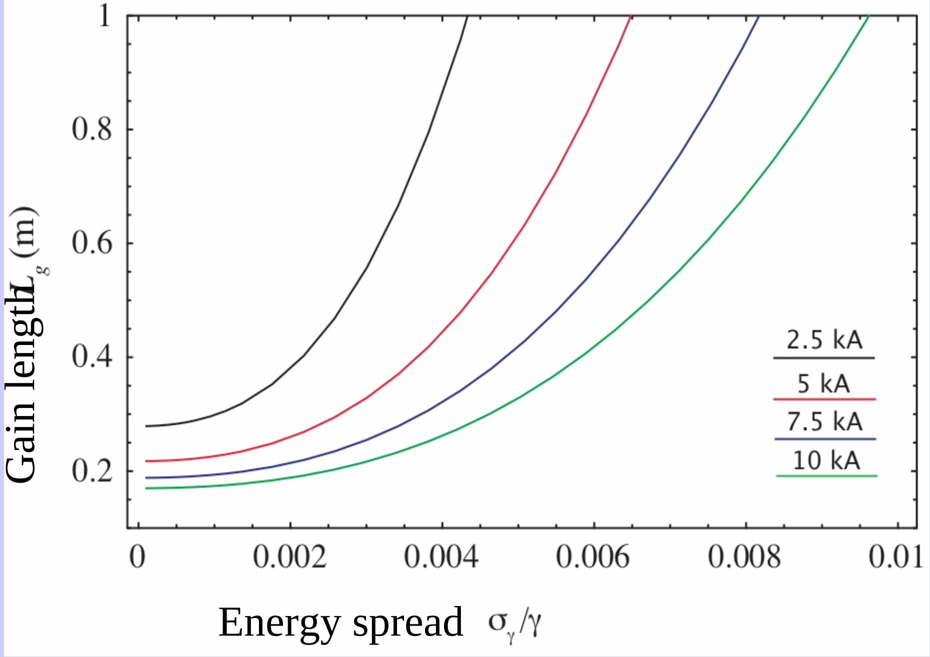
Beta function	3.6 m

[*] E. Takahashi et al., Phys. Rev. E 66, 021802 (2002).

Gain length and Saturation

Exponential Gain Length vs. Energy Spread

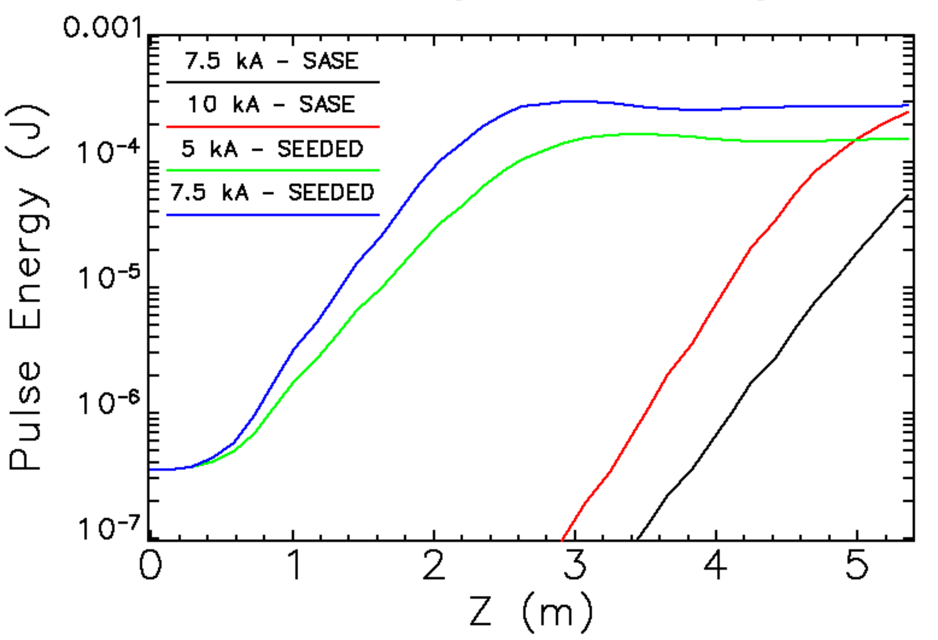
[Xie Gain Length Formula[†]]



ε_N =1 mm-mrad
E=0.5 GeV
λ_u=2.18 cm
K=1.85
β=3.6 m

$L_g < 0.5$ m requires $\sigma_\gamma/\gamma < 0.45\% \times (I/5\ \text{kA})^{2/3}$

Saturation [GINGER[*] calculation]

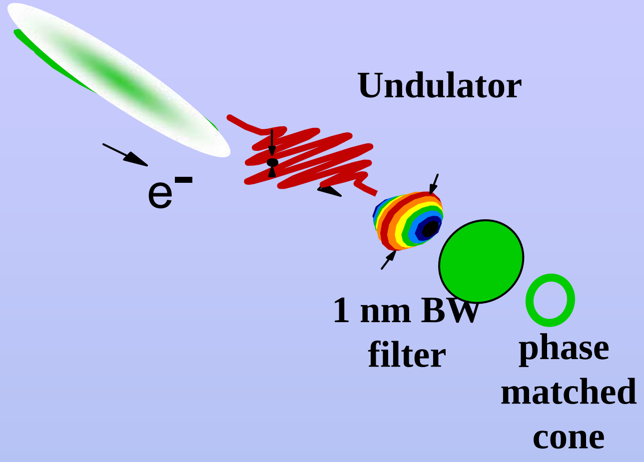


[†] M. Xie, Nucl. Instrum. Methods Phys. Res. A445 59 (2000).

[*] W.M.Fawley, LBNL Tech. Report No. LBNL-49625 (2002).

Radiation emission from undulator as diagnostic

- **Sensitive to energy spread and emittance**

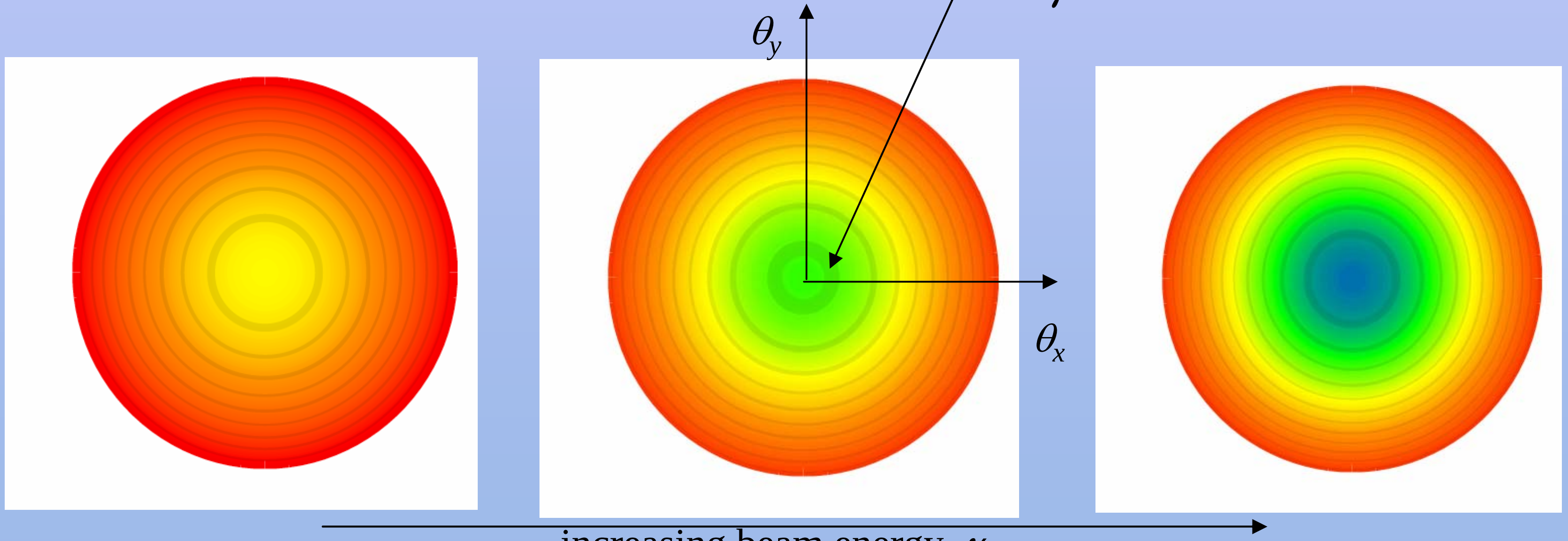


phase matching condition:

$$\lambda = \frac{\lambda_w}{2\gamma^2}\left(1+\frac{a_w^2}{2}+\gamma^2\theta^2\right)$$

on axis (small a_w):

$$\lambda \sim \frac{\lambda_w}{2\gamma^2}$$



increasing beam energy, γ

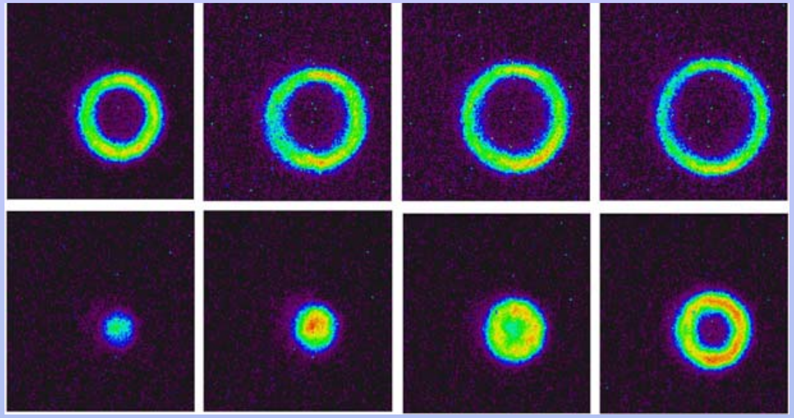
P. Catravas et al., Phys. Plasmas 2002

Undulator experiments

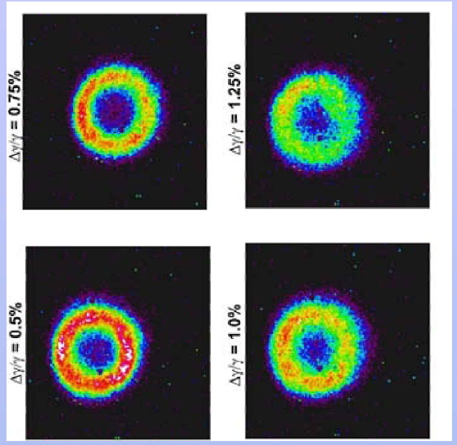
- **Initial experiments at ATF**

P. Catravas et al., Phys. Plasmas 2002

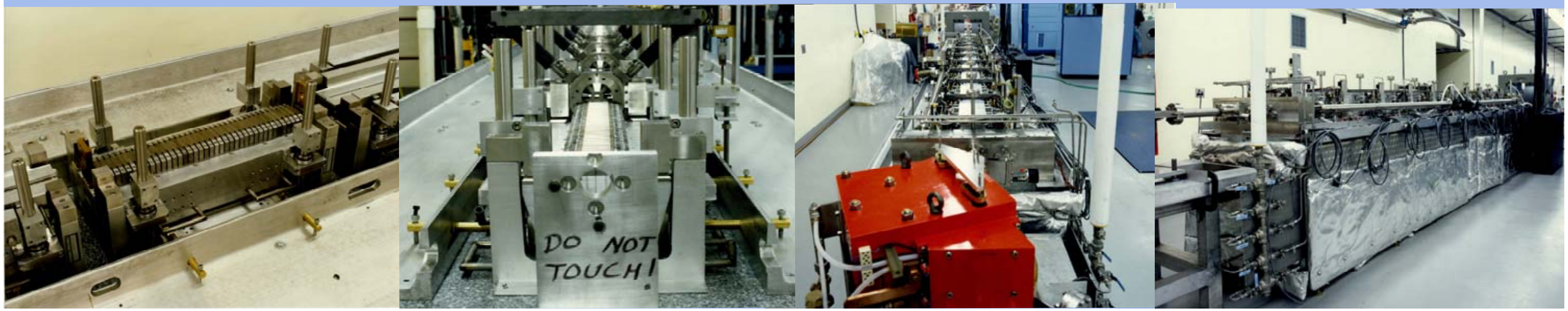
0.5% change in E



0.25% change in ΔE/E

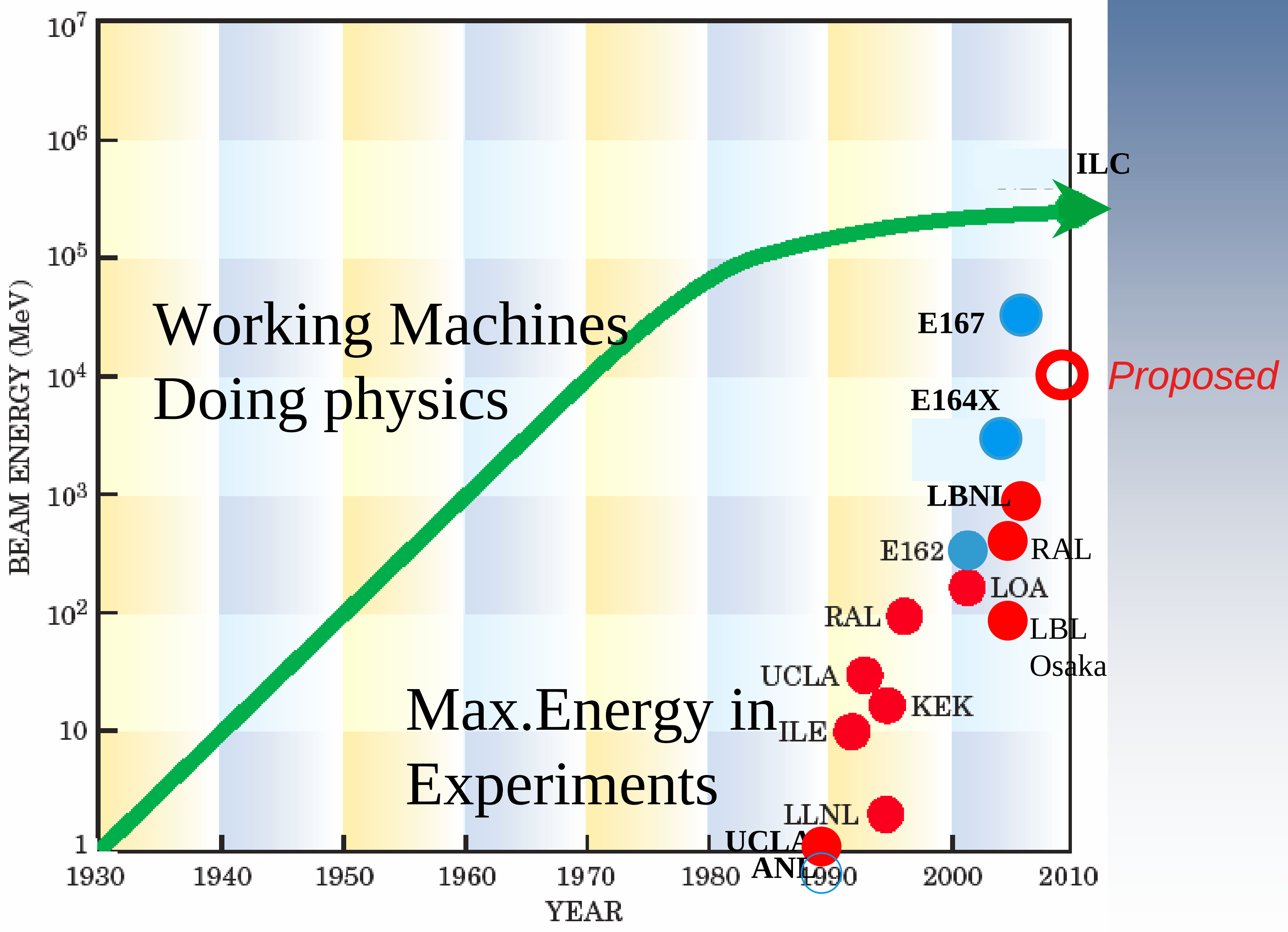


- **Secured THUNDER undulator from Boeing**
  - **Lab retrofitting A-Cave**



Plasma Accelerator Progress

"Accelerator Moore's Law"



From: T. Katsouleas -APS-DPP 2005 + new LBNL 1 GeV result

Going to 10 GeV

Petawatt laser

Longer capillary

Controlled injection

10 GeV Accelerators

1 nC, 10 GeV = 10 Joules

10% Laser-Electron Coupling

100 J / 100 fs = 1 PW

10 GeV Conceptual Design

Spot Size	**50-um**
Channel Length **(capillary or cluster jet?)**	**0.5-1.0 meter**
Density	**few x 10^{17} cm^{-3}**
Laser Energy	**10-100 J**
Pulse Width	**~100-fs**

Rep-Rated High-Energy PW Lasers are a key enabling technology for 10-GeV high luminosity experiments

A multi-stage TeV collider using channel guiding ?

Step 3:

10 GeV

Laser

10 GeV

e$^-$ beam

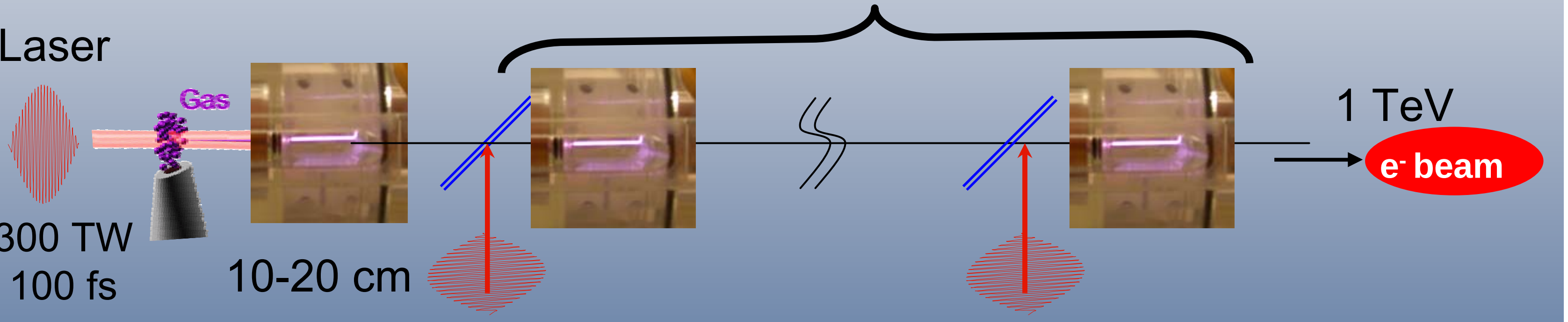
300 TW
100 fs

10-20 cm

Step 4:

1 TeV

200-500 m, 100 stages



Laser

1 TeV

e$^-$ beam

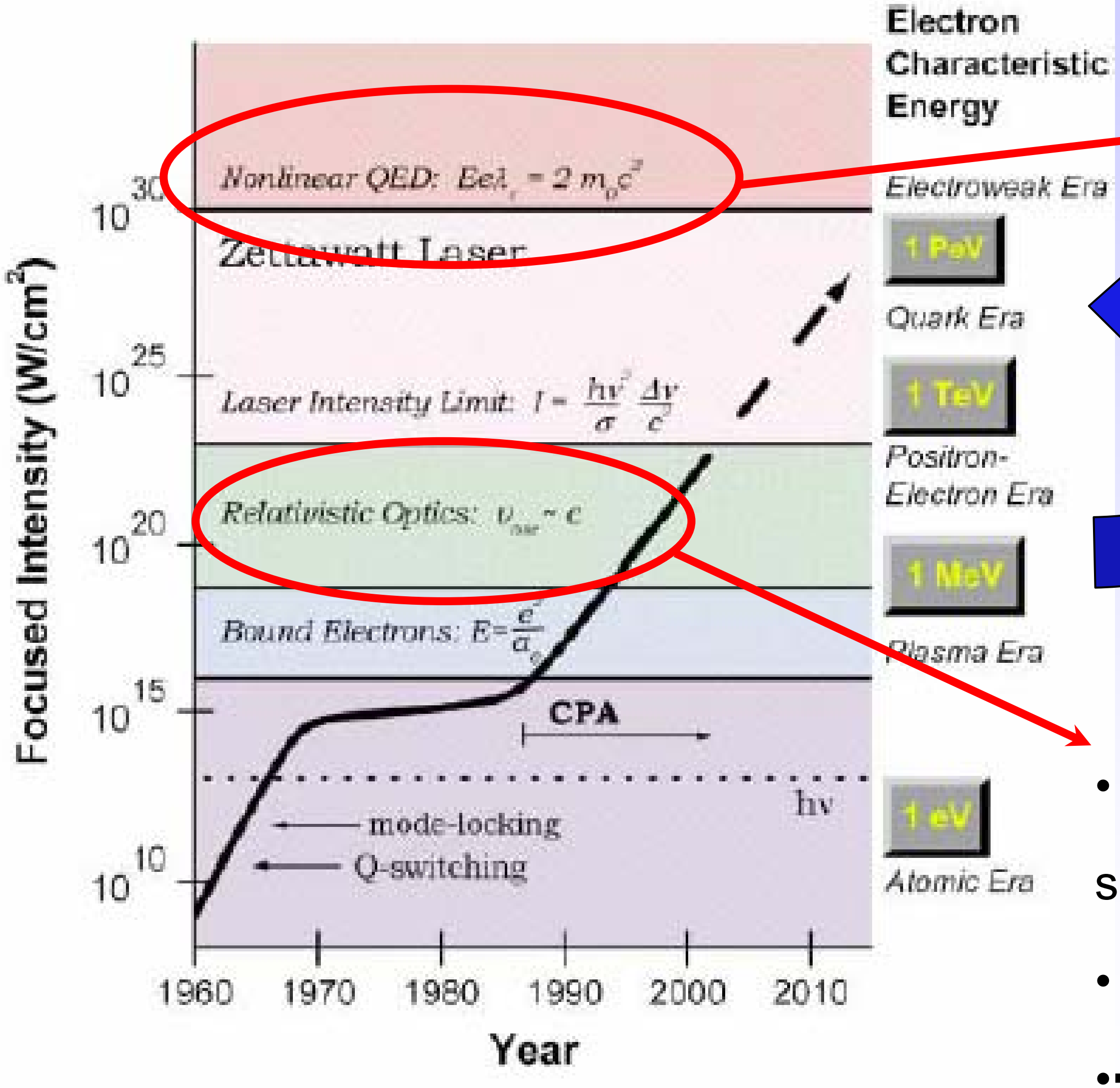
300 TW
100 fs

10-20 cm

- Staging ?
- 100 lasers, 1-10 PW, 100 Hz (or more)
- Wall plug efficiency? Average power multi-MW range

Intensity Frontier: Towards Ultra-Relativistic Physics

- Schwinger critical field
- Vacuum breakdown
- Non-linear QED



Pathway to non-linear QED ?

- Lorentz boosting through Compton

scattering off relativistic e-beam

- Relativistic flying mirrors

•➔ PW-class laser

Focused Intensity vs. Year
(after T. Tajima and G. Mourou, PRSTAB2002)

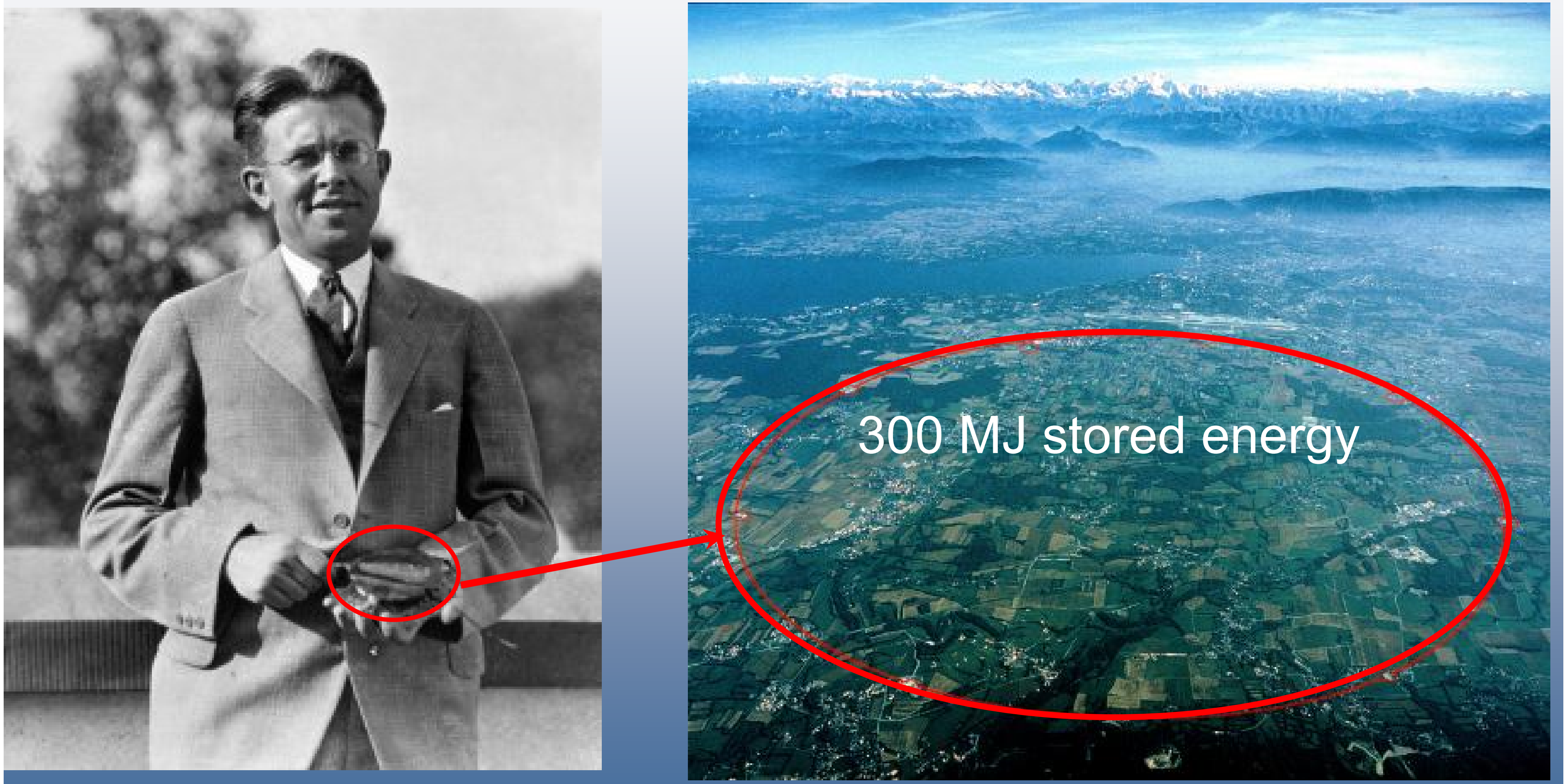
Summary

- High gradient frontier:
  - Capillary channel guided LWFA + up to 40 TW laser
    - Reached energies comparable to “big” accelerators:
      - GeV in 3 cm
      - Lower density allows higher beam energy (dephasing)
    - Stable self-injected beams at 0.5 GeV
- Precision frontier:
  - Femtosecond (and attosecond) intense radiation: THz to x-rays
  - MeV e-beams: electron diffraction ?
- Intensity frontier:
  - Vacuum breakdown becoming reachable
- **Laser and advanced accelerator technology is progressing rapidly and enables future frontier physics and applications**

From handheld to size of a (very) small country

1929

LHC, 2007



Size x 10^5 Energy x 10^9