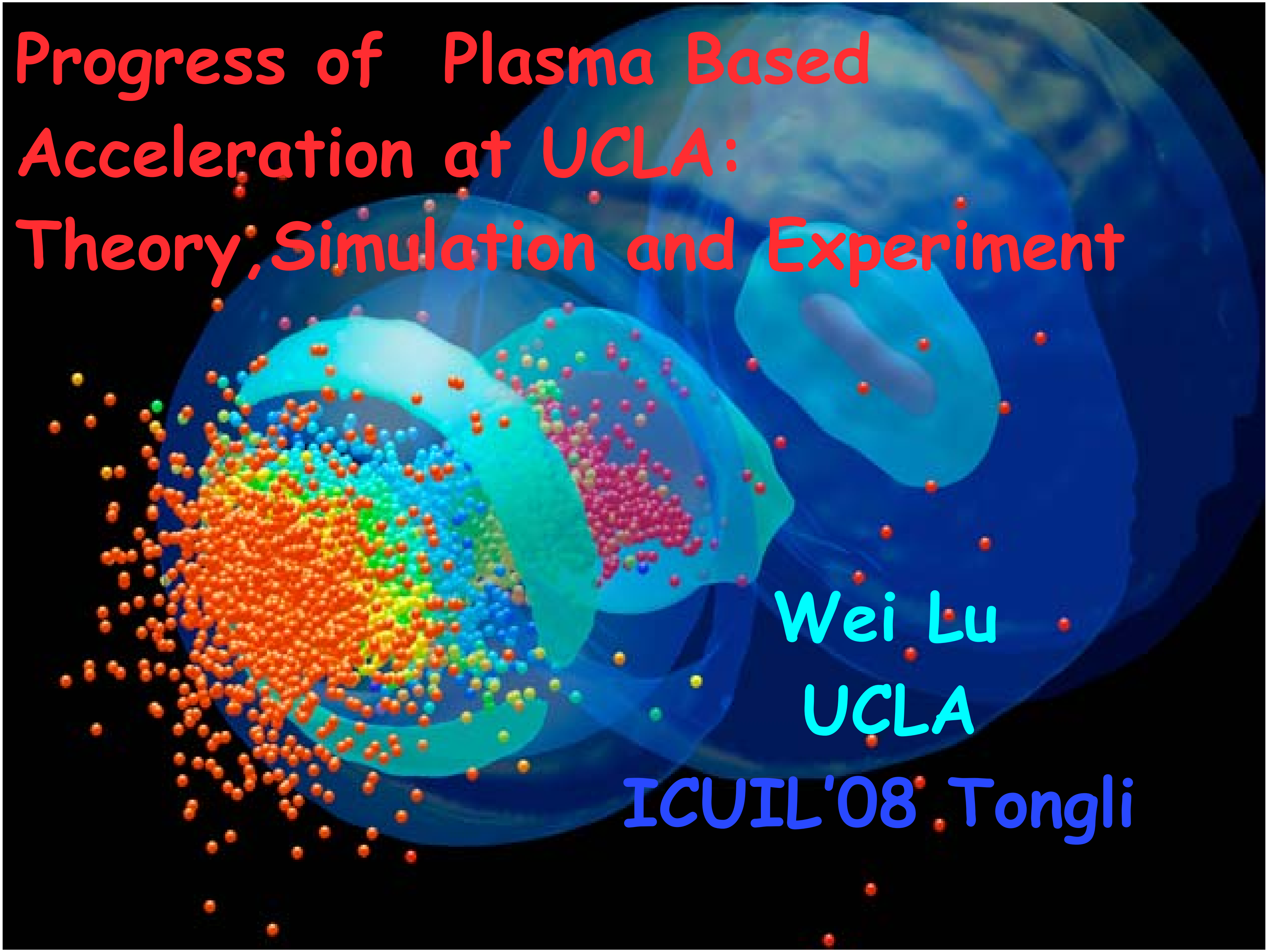


Progress of Plasma Based Acceleration at UCLA: Theory,Simulation and Experiment

Wei Lu
UCLA
ICUIL'08 Tongli

Collaborators

UCLA: *C. Clayton, K. Marsh, M. Zhou, M. Tzoufras, T.S. Tsung, C. Huang, J. Ralph, A. Pak, D.K. Johnson, W. B. Mori, C. Joshi*

USC&Duke: *P. Muggli, E. Oz, S. Deng, T. Katsouleas*

SLAC: *M.J. Hogan, I. Blumenfeld, F.J. Decker, R. Ischebeck, R. H. Iverson, N.A. Kirby, P. Krejcik, D. Walz*

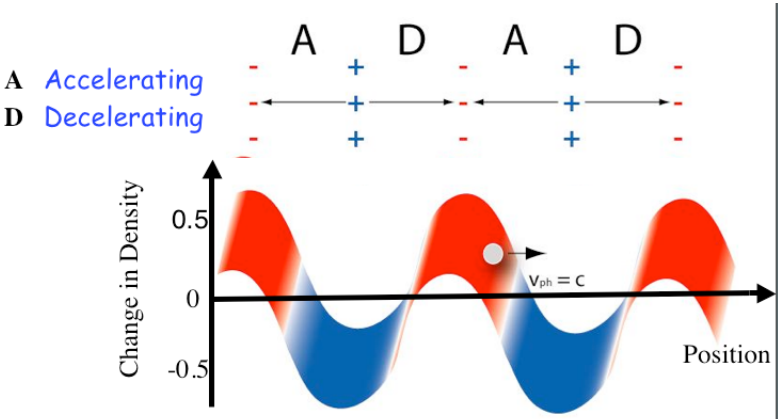
IST: *S.F. Martins, J. Vieira, R. A. Fonseca, L. O. Silva*

LLNL: P. Michel, L. Divol, T. Doeppner, J. Palastro, V. Leurent, J. Bonlie, D. Price, C. Siders, C. Ebbers, D. Froula

A crazy idea!

Plasma wave wakes driven by lasers and charged particle beams, and Particles surfing on such wakes

T.Tajima and J.M. Dawson PRL (1979)
P.Chen, J.M. Dawson et.al. PRL (1983)



Accelerating Field= 30GeV/m$(10^{17}/n_o)^{1/2}$

Early Development

Active theoretical, computational and experimental research of plasma based acceleration was launched shortly after the 1979 Paper. UCLA played a dominate role for boosting this field to a scientifically respectable level through original, well-designed and carefully implemented simulations and experiments

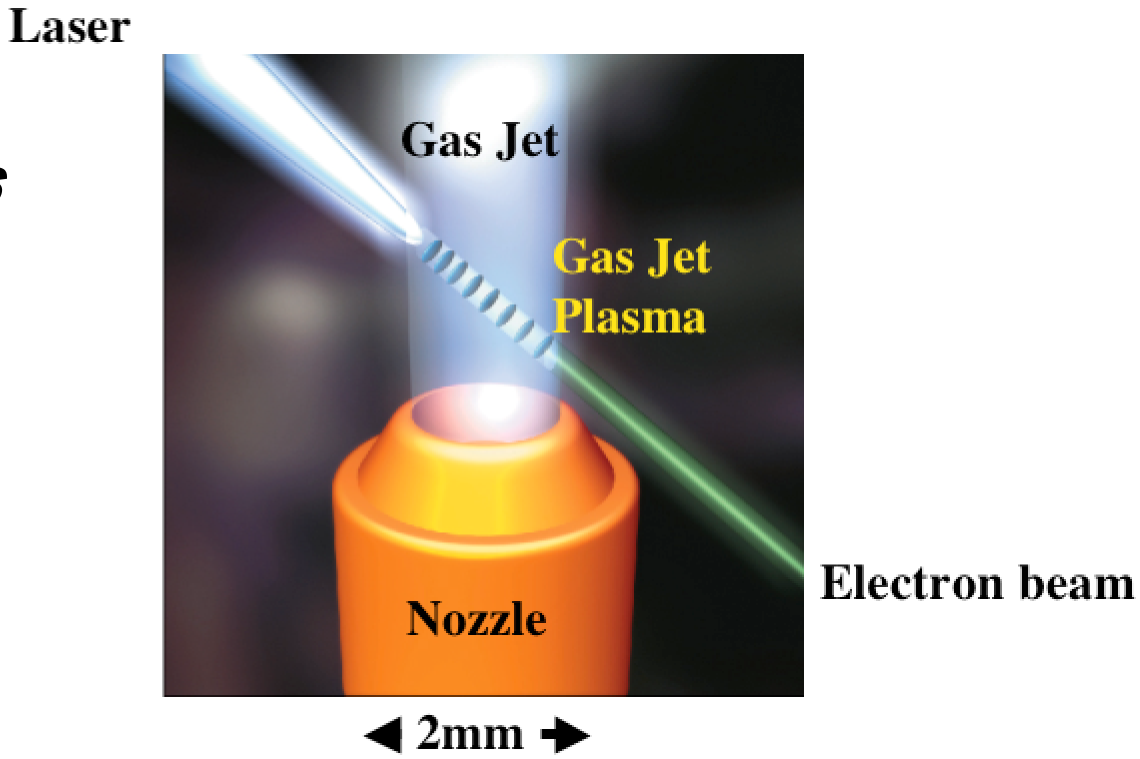
C. Joshi et al.,	Nature	(1985)
C. Clayton et al.,	PRL	(1985)
C. Clayton et al.,	PRL	(1993)
M. Everett et al.,	Nature	(1994)
A. Modena et al.,	Nature	(1995)

A thorough review on the early development of plasma based acceleration (up to 1996) was provided by Dr. E. Esarey of LBNL: IEEE Trans. Plasma Sci. (1996)

CPA lasers and the jet age

With the invention of CPA laser and its rapid development to sub-ps TW level, laser plasma accelerators went into the SMLWFA regime and the jet age, and eventually get close to the simplest version LWFA

A breakthrough is awaiting ....



Real Breakthroughs

nature

Dream beam

The dawn of compact particle accelerators

Disease control

Protein folding

The Earth's hum

"Dream Beam" (Nature, 2004)

PHYSICAL REVIEW LETTERS

Articles published week ending 29 JULY 2005

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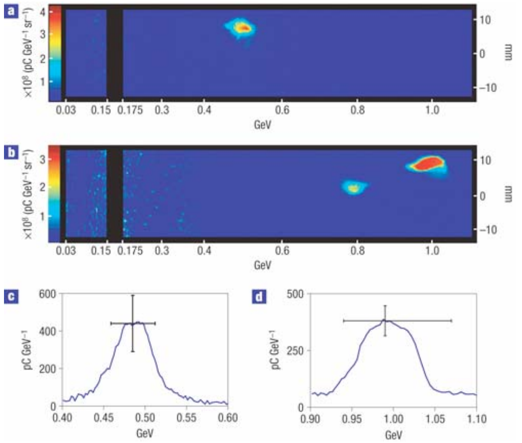
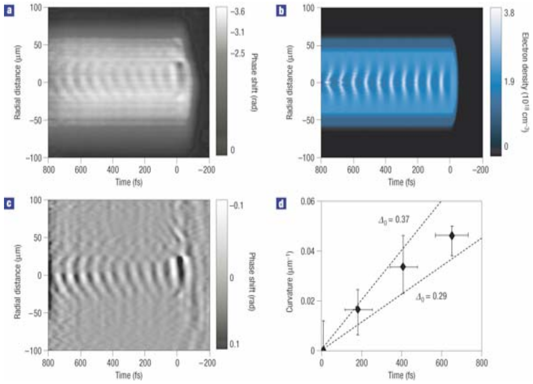
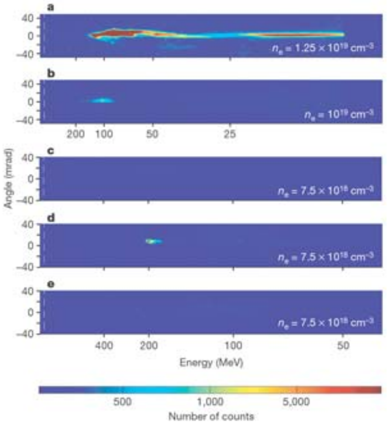
GeV PWFA (July 2005)



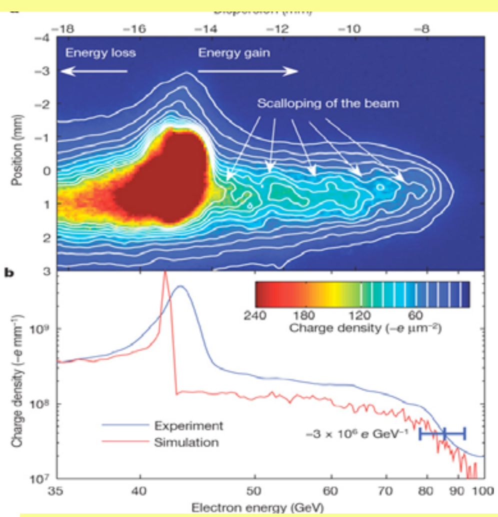
GeV LWFA in cm scale plasma



Snap shot of wakefield



Controlled electron injection



42 GeV in less than one meter!

A 3D nonlinear regime!

The first hint? "cavitation"

Self-focusing of short intense pulses in plasmas

Guo-Zheng Sun, Edward Ott,[a,b] Y. C. Lee,[b] and Parvez Guzdar
Laboratory for Plasma and Fusion Energy Studies, University of Maryland, College Park, Maryland 20742

(Received 14 July 1986; accepted 14 October 1986)

The self-focusing of relativistically intense laser light pulses is analyzed, where the pulse length is short enough that ion inertia prevents any significant motion of ions. Self-focusing occurs as a result of an increase of the wave refractive index arising from two effects: the mass increase of electrons caused by their relativistic quiver velocity in the light wave, and the reduction of the electron density as a result of ponderomotive force expulsion of the electrons. The latter effect is significant even for rather small values of $(P - P_L)/P_L$, where P is the laser beam power and P_L is the critical power above which self-focusing occurs. In fact, for $(P - P_L)/P_L \gtrsim 0.1$ the effect is so strong that *all* electrons are expelled within a core radial region of the self-focused laser light channel (this new phenomenon is called *electron cavitation*).

Perfect for electron acceleration, made by an electron bunch

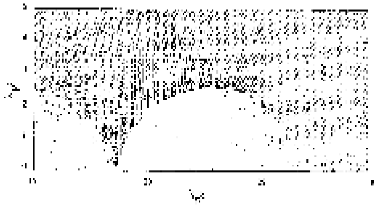
PHYSICAL REVIEW A VOLUME 44, NUMBER 10 15 NOVEMBER 1991

Acceleration and focusing of electrons in two-dimensional nonlinear plasma wake fields

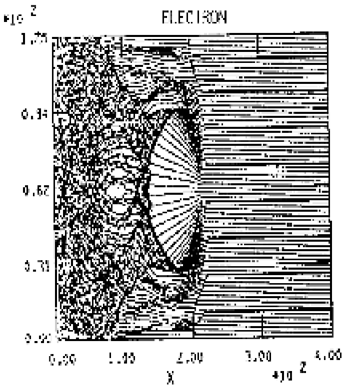
J. B. Rosenzweig, B. Breizman,[*] T. Katsouleas,[1] and J. J. Su
Department of Physics, University of California at Los Angeles, Los Angeles, California 90024

(Received 10 June 1991)

A regime of the plasma wake-field accelerator (PWFA) is proposed, in which a high-intensity electron beam is used to excite extremely nonlinear, transverse motion-dominated plasma oscillations. Through computational analysis of the plasma electron motion and the associated wake fields, it is shown that if the beam is dense enough to eject nearly all of the plasma electrons from the beam channel then the short-range wake fields are of excellent quality for acceleration and focusing of electron beams. These results clear up many conceptual difficulties with the practical realization of a PWFA.



It can also be made by a laser



Laser Wakefields at UCLA and LLNL*

W. B. Mori(1), T. Katsouleas(2), C. B. Darrow(3), C. E. Clayton(1), C. Joshi(1)
J. M. Dawson(1), C. B. Decker(1), K. Marsh(1) and S. C. Wilks(3)

Generating a new electron beam!

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

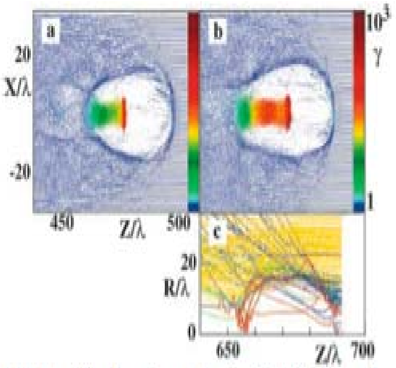
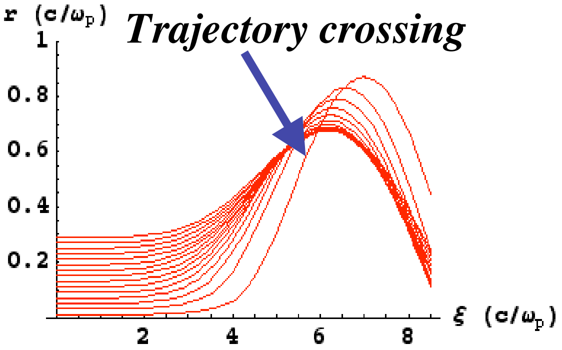
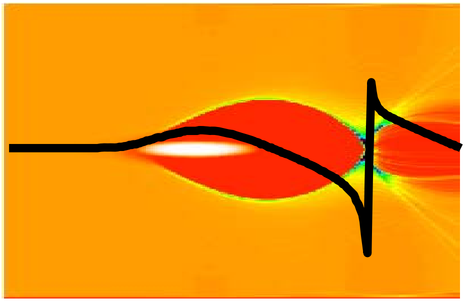


FIGURE 4 Solitary laser-plasma cavity produced by 12-J, 33-fs laser pulse. **a** $ct/\lambda = 500$, **b** $ct/\lambda = 700$, **c** electron trajectories in the frame moving together with the laser pulse; color distinguishes electron groups with different distances from the axis initially

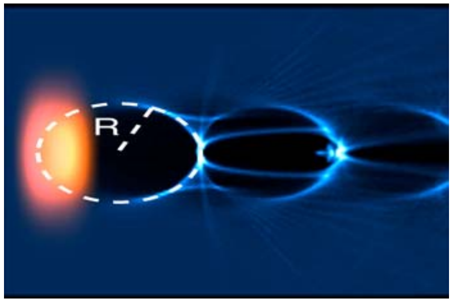
Physics relevant to a realistic Plasma based accelerator



Driven by an electron beam



Driven by a laser pulse



- Ion channel formed by crossing
- Ideal linear focusing force
- Uniform acceleration
- Fluid model breakdown!
- 2D/3D and electromagnetic in nature!
- Trapping and crossing are different!

What do we want to know and to predict?

- Wake excitation for given drivers ……
- Beam loading, transformer ratio ……
- Driver evolution, guiding,instabilities ……
- Self-injection, wave breaking ……
- How to choose parameters for a real plasma based accelerator?

Understand the blowout regime

Theory

- Wake excitation and beam loading
- Electron hosing instability
- Laser plasma matching and guiding
- Phenomenological framework of LWFA in the blowout regime

Simulation

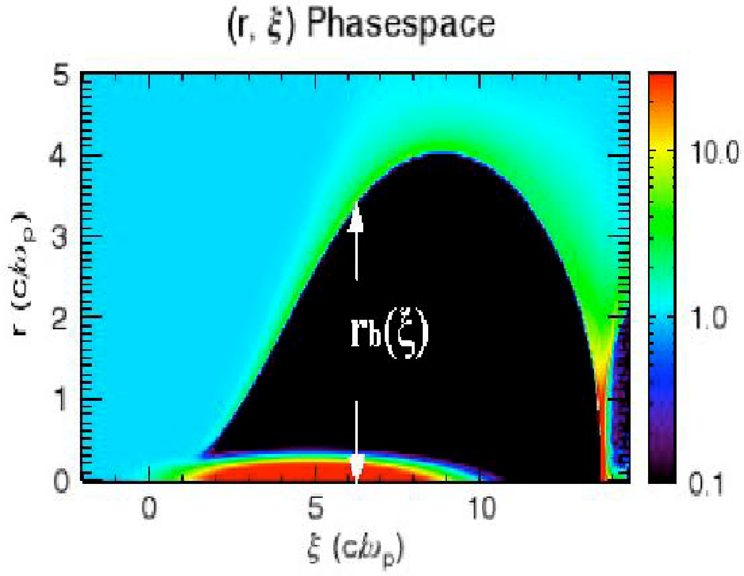
- Development of the capability of large scale parallel PIC simulation
- 3D simulations of LWFA stage from GeV-100GeV
- 3D modeling of PWFA experiments

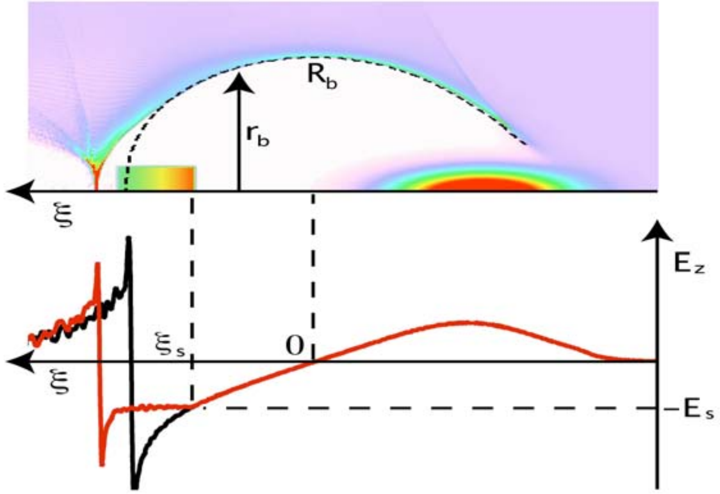
Experiment

- GeV-100GeV level PWFA
- Betatron X-ray and positron production
- Short pulse laser self-guiding
- Self-guided self-injected LWFA experiment at sub-GeV level

2 Nature, 15PRLs in 7 years

A theory for wake excitation and Beam loading





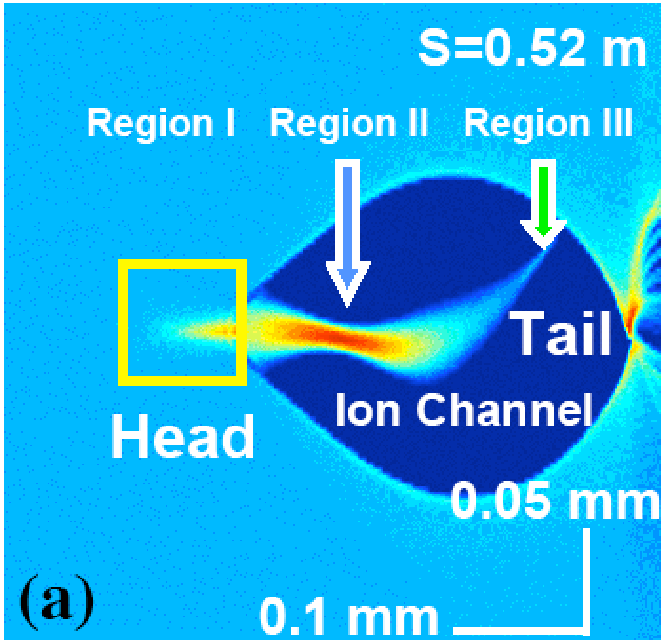
The trajectory of the inner most particle is

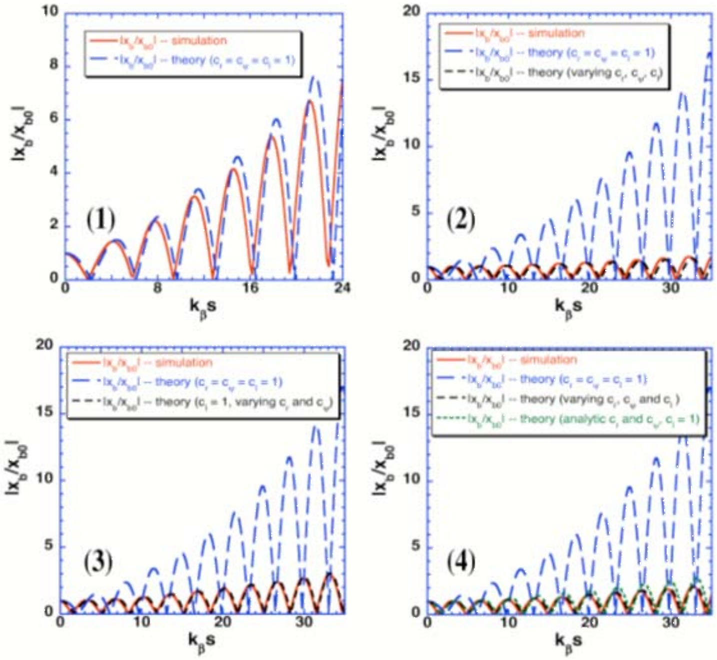
$$A(r_b)\frac{d^2 r_b}{d\xi^2} + B(r_b) r_b \left(\frac{dr_b}{d\xi}\right)^2 + C(r_b) r_b = \frac{\lambda(\xi)}{r_b} - \frac{\nabla_\perp |a|^2}{1+\frac{\beta}{4} r_b^2}$$

W. Lu et al., PoP (2005), PRL (2006), PoP (2006)[invited]

M. Tzoufras, W. Lu et al., PRL (2008), PoP [invited, in preparation]

A theory of electron hosing instability



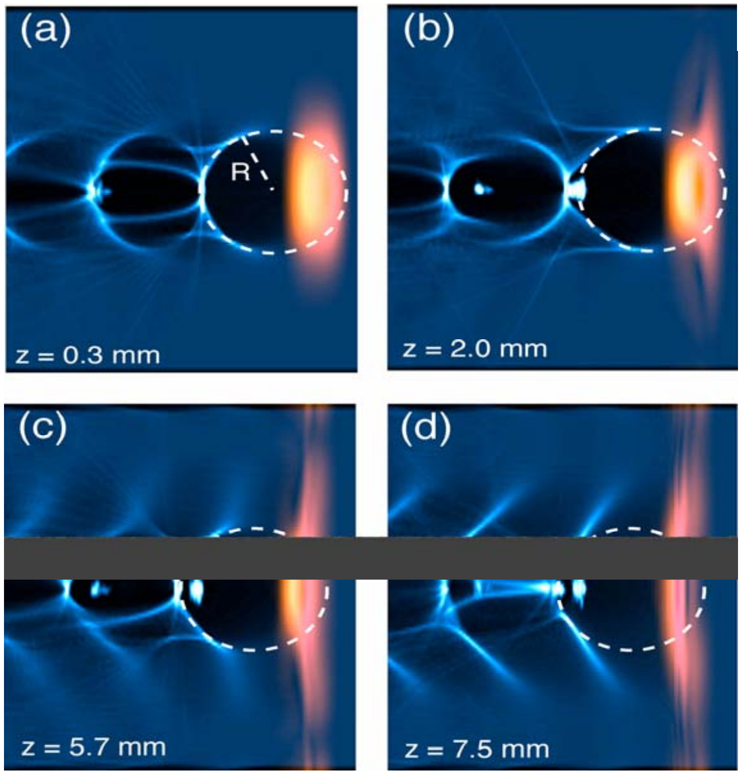


Hosing is an instability due to coupling between the centroid of the beam and the ion channel (focusing force on the beam). We developed a theory that can accurately describe various physical effects of beam plasma parameters on the growth of hosing

C. Huang, W. Lu et al., PRL (2007)

A Phenomenological framework of LWFA in the blowout regime and the optimal scaling

- Laser and plasma matching
- Wake excitation
- Laser guiding
- Local pump depletion
- Dephasing
- Self-injection
- Beam loading



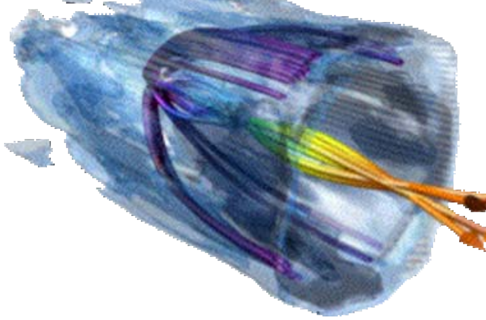
10fs .3nC 1.5GeV electron beam produced by a 200TW 30fs laser pulse

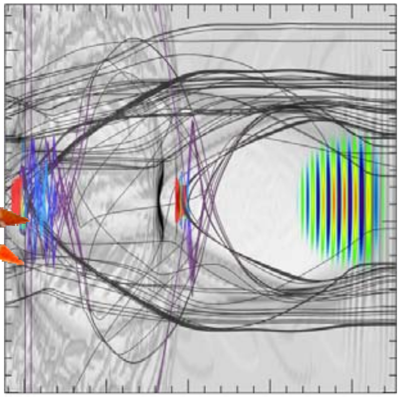
W. Lu et al., PR-STAB (2007)

Massively parallel PIC codes for advanced accelerator modeling

OSIRIS

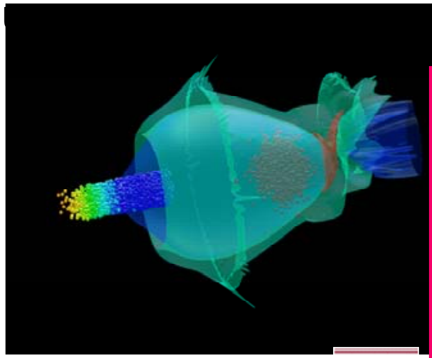
- **Fully Relativistic Electromagnetic PIC code**
- **Massively Parallel (scales well up to > 32000 cpus)**
- **Dynamic Load Balancing, Higher order particle shapes, Open EM boundary conditions, Ionization, Binary Collision Module, Parallel I/O**
- **3D Lorentz Boosted Frame implemented**
- **Examples of applications**
- Mangles et al., Nature 431 529 (2004).
- Tsung et al., Phys. Rev. Lett., 94 185002 (2004)
- Lu et al., Phys. Rev. ST: AB, 10, 061301 (2007)
- **Development institutions**
- UCLA, IST, USC

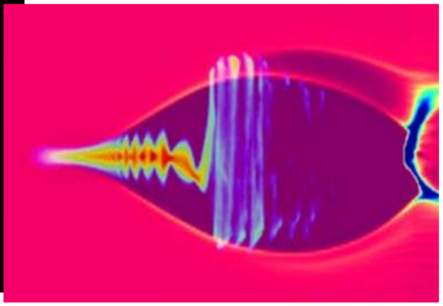




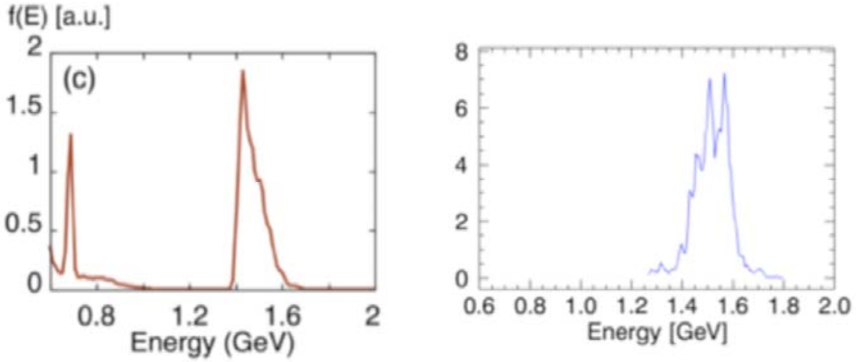
QuickPIC

- **Ponderomotive guiding center + envelope model**
- **Can be 100+ times faster than conventional PIC with no loss in accuracy**
- **Scales to 1000's of processors**
- **Examples of applications**
- Simulations for PWFA experiments, E157/162/164/164X/167 (Including Feb. 2007 Nature)
- Study of electron cloud effect in LHC.
- Plasma afterburner design up to TeV
- Beam loading study using laser/beam drivers
- **Development institutions**
- nd



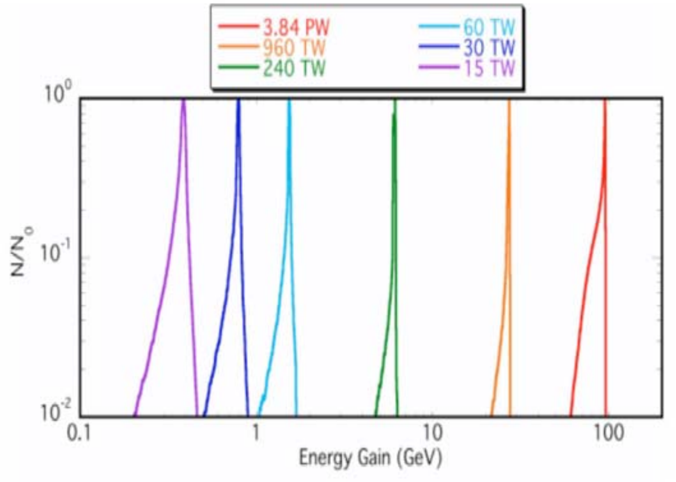


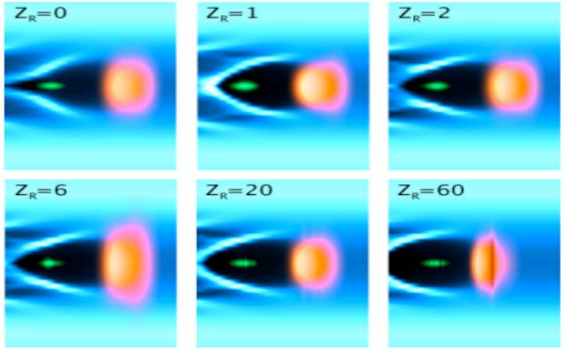
Full scale 3D PIC simulations of LWFA: From GeV to 100GeV



A comparison between 3D PIC Simulation in lab frame and in a Lorentz boosted frame (1.5GeV beam)

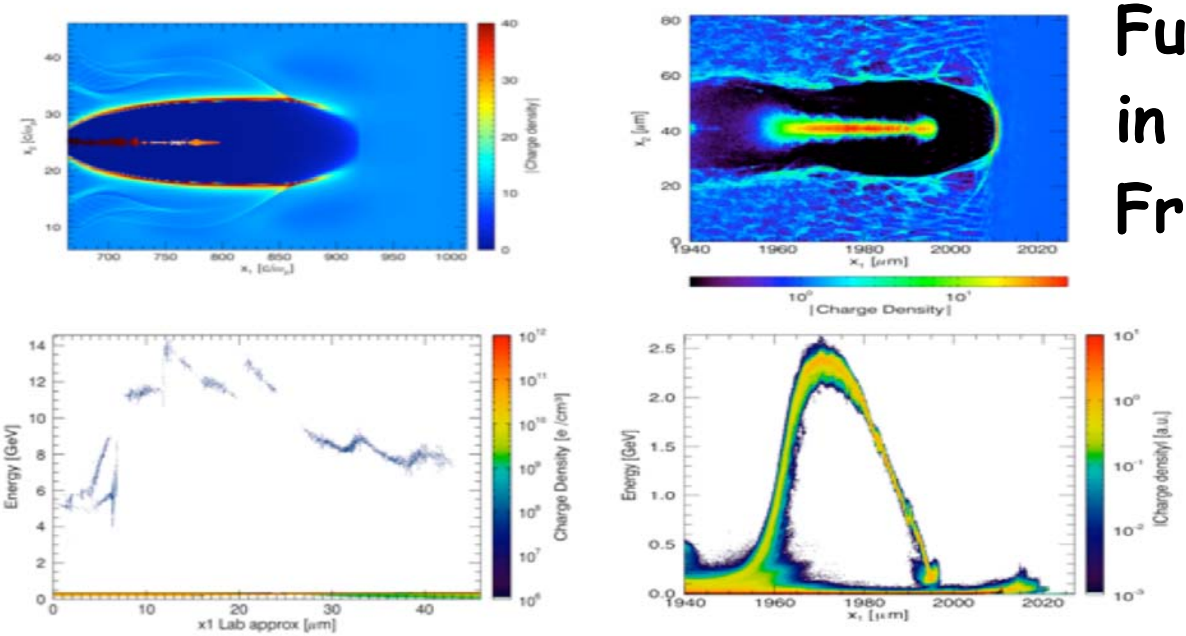
Channel-guided LWFA with external injection (.5-100GeV)





W. Lu et al., PR-STAB (2007), S. Martins et al., in preparation
M. Tzoufras et al., in preparation

What one can do with a 300J short Pulse laser



Full PIC simulations in a Lorentz Boosted Frame for 12GeV!

12GeV electron bunch produced by a 110fs 300J laser interacting with a 22cm long low density plasma ($2.7*10^{17}cm^{-3}$)

S. Martins et al., in preparation

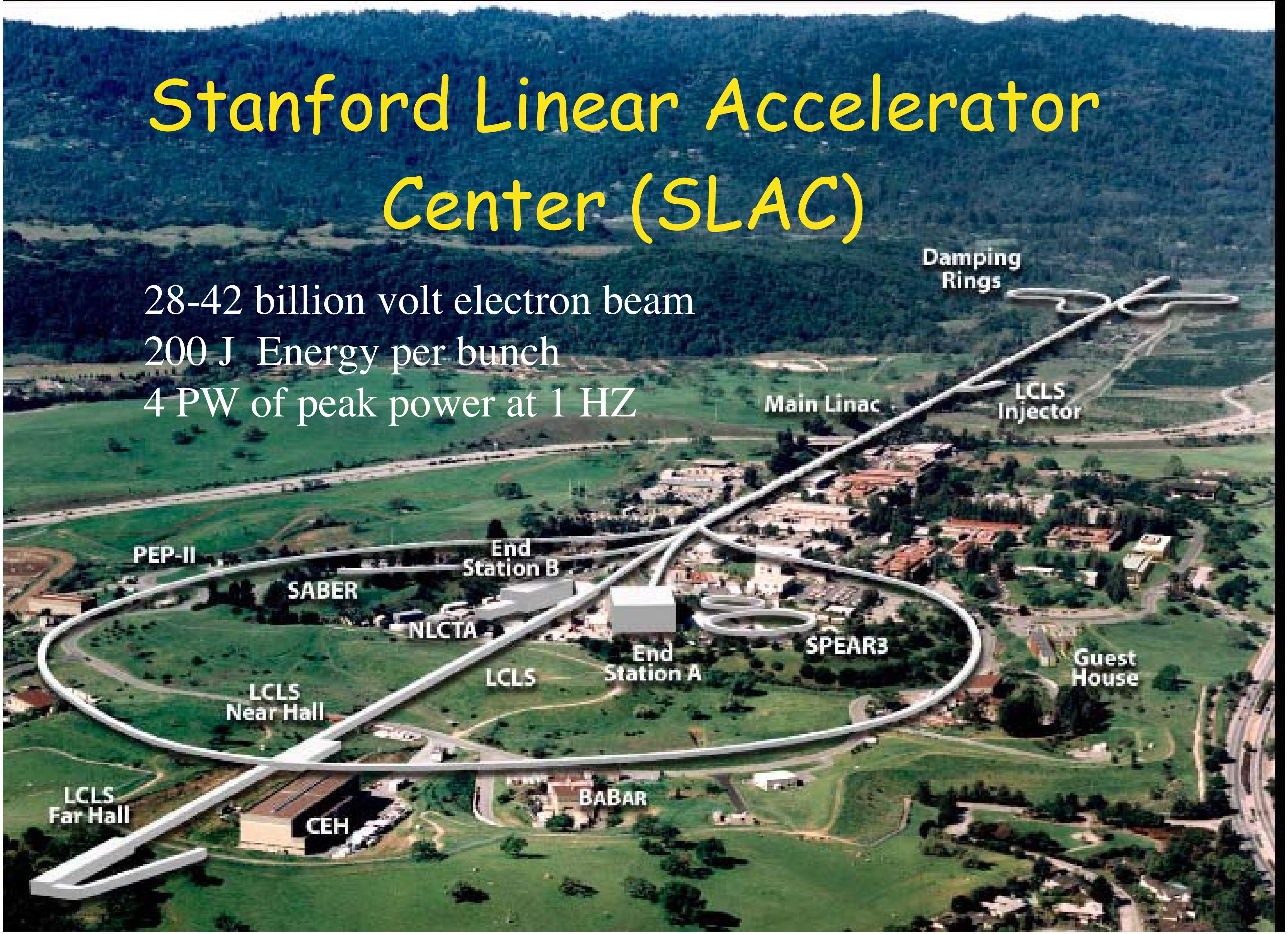
Experimental Campaign to 100GeV

Three observations

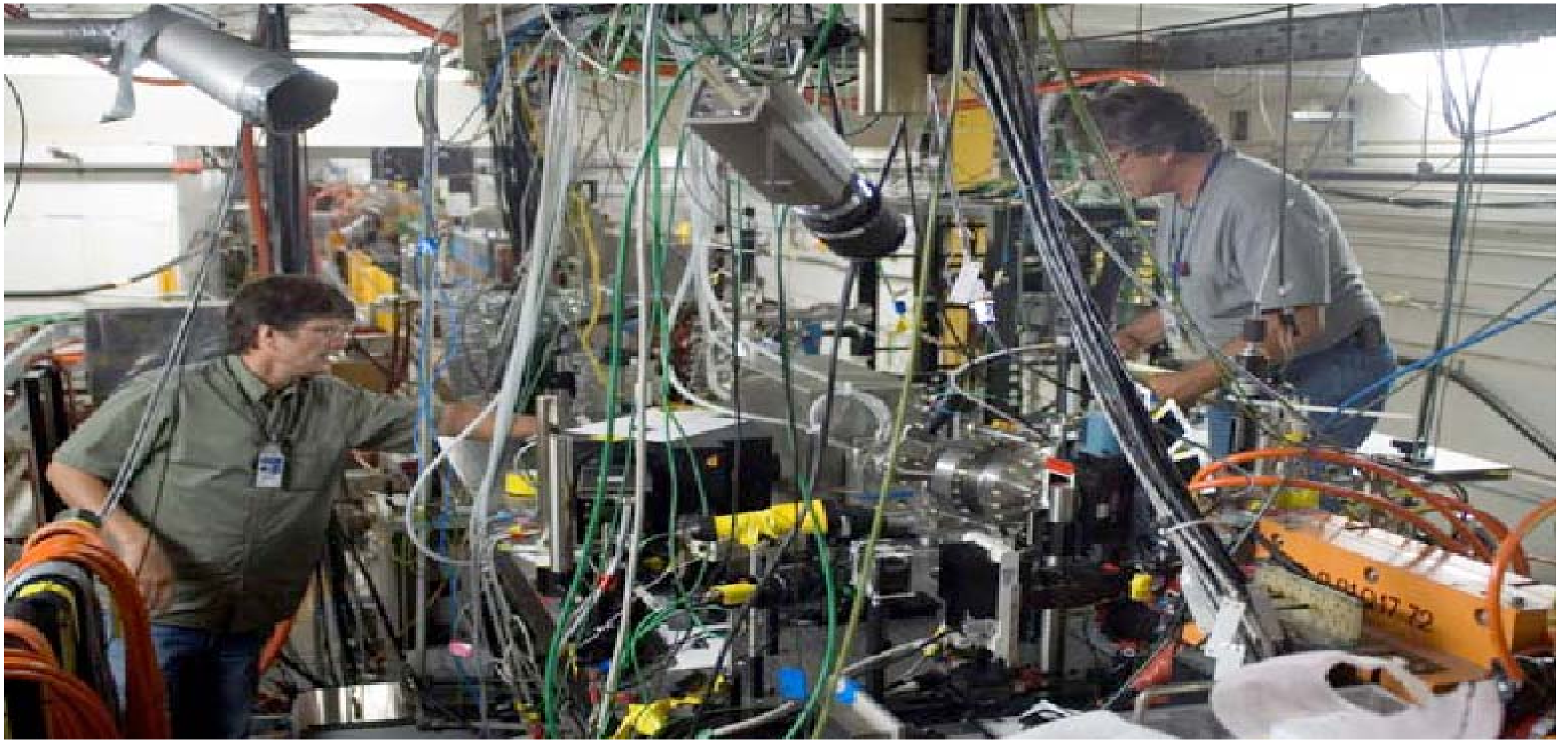
- To reach useful acceleration of10GeV and beyond, one needs PW drivers (with hundreds J of energy) interacting with meter scale low density plasma (~10^{17}cm^{-3})
- To understand the physics better through experiments also needs high repeat rate drivers with extensive diagnostics
- Energy of this scale needs extensive expertise on accelerator physics

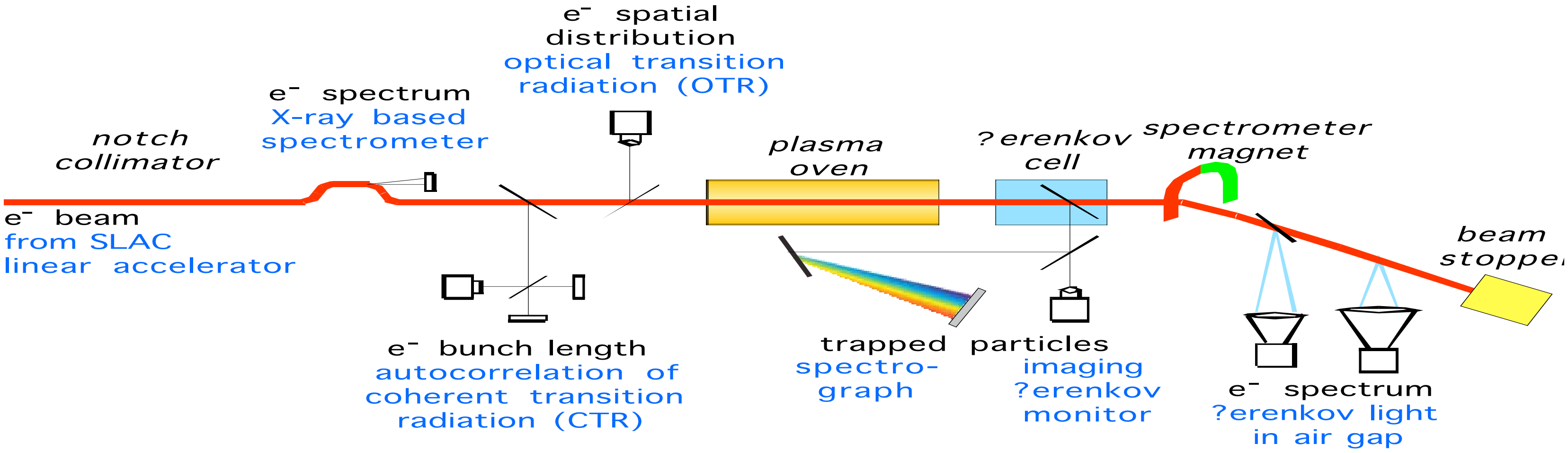
Stanford Linear Accelerator Center (SLAC)

28-42 billion volt electron beam
200 J Energy per bunch
4 PW of peak power at 1 HZ



Experimental Setup





e⁻ beam
from SLAC
linear accelerator

notch
collimator

e⁻ spectrum
X-ray based
spectrometer

e⁻ spatial
distribution
optical transition
radiation (OTR)

e⁻ bunch length
autocorrelation of
coherent transition
radiation (CTR)

plasma
oven

trapped particles
spectro-
graph

? erenkov
cell

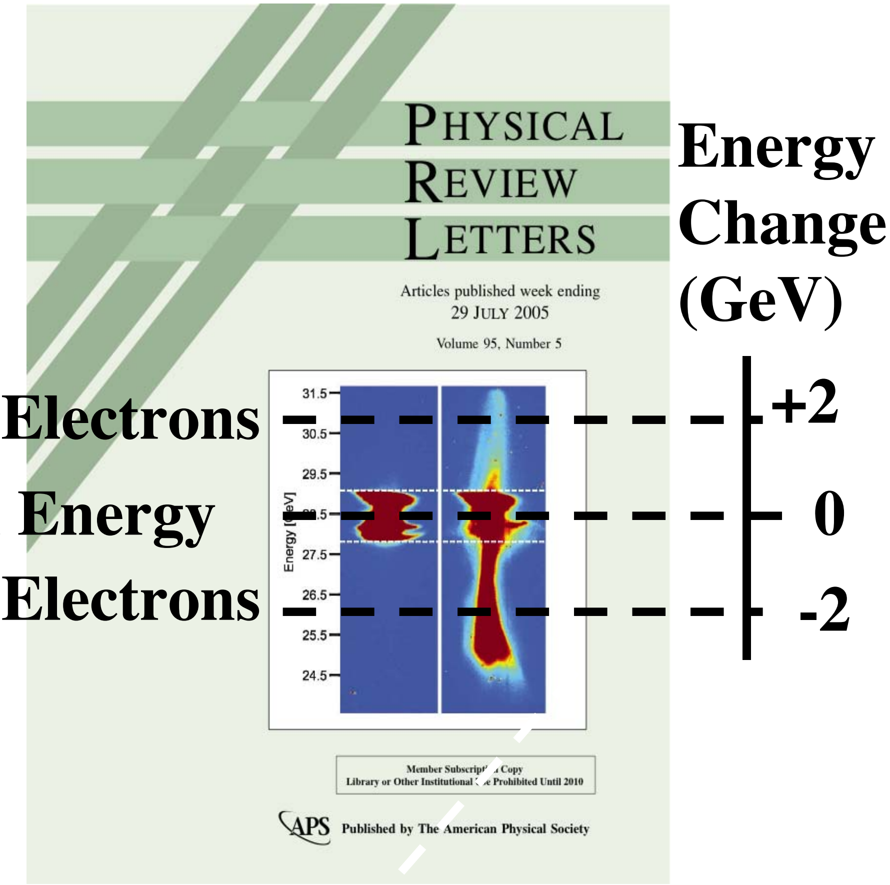
imaging
?erenkov
monitor

spectrometer
magnet

e⁻ spectrum
?erenkov light
in air gap

beam
stoppe

BREAKING THE 1 GeV BARRIER



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Volume 95, Number 5

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APS Published by The American Physical Society

Energy Change (GeV)

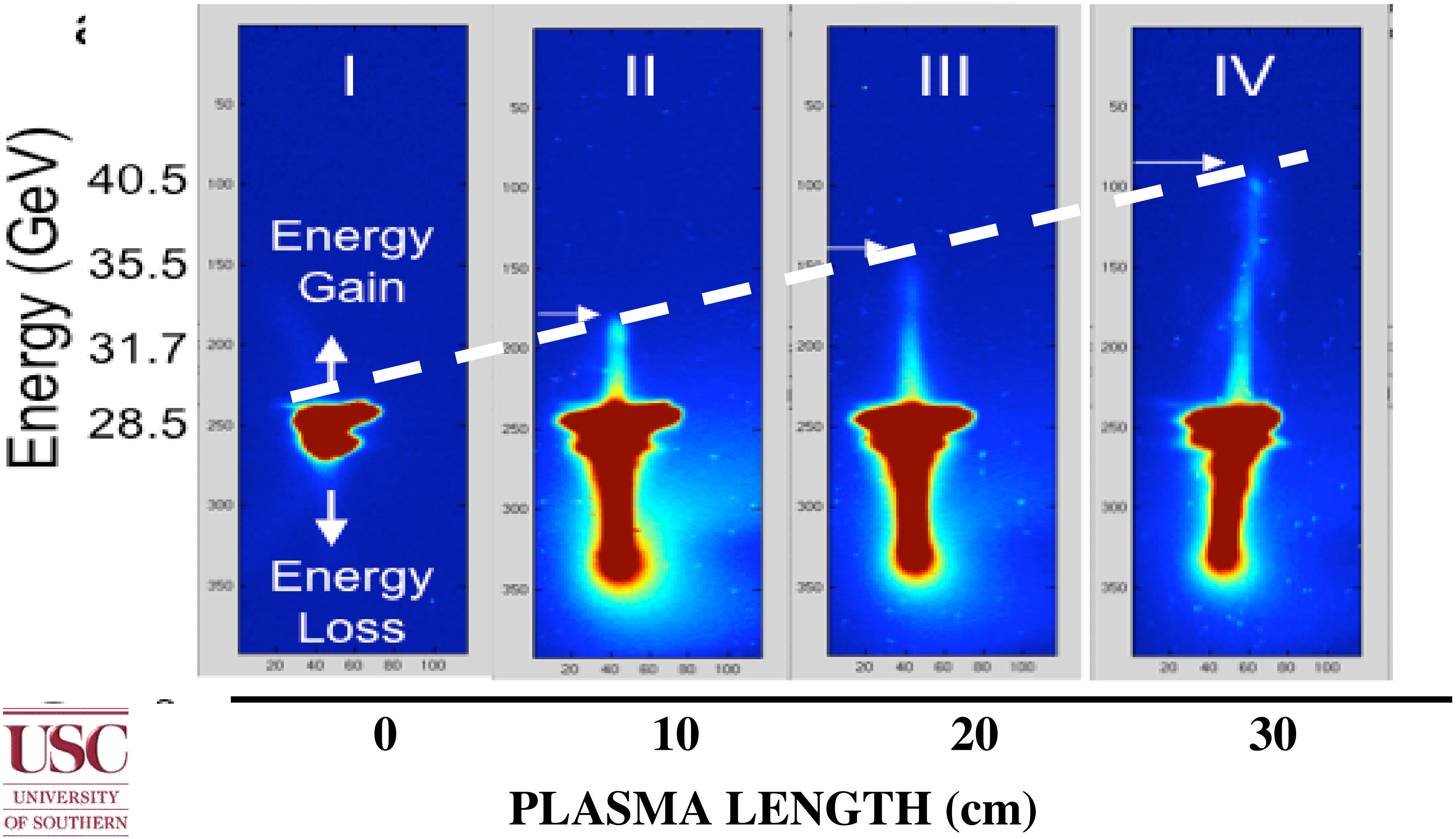
Accelerated Electrons

Initial Beam Energy

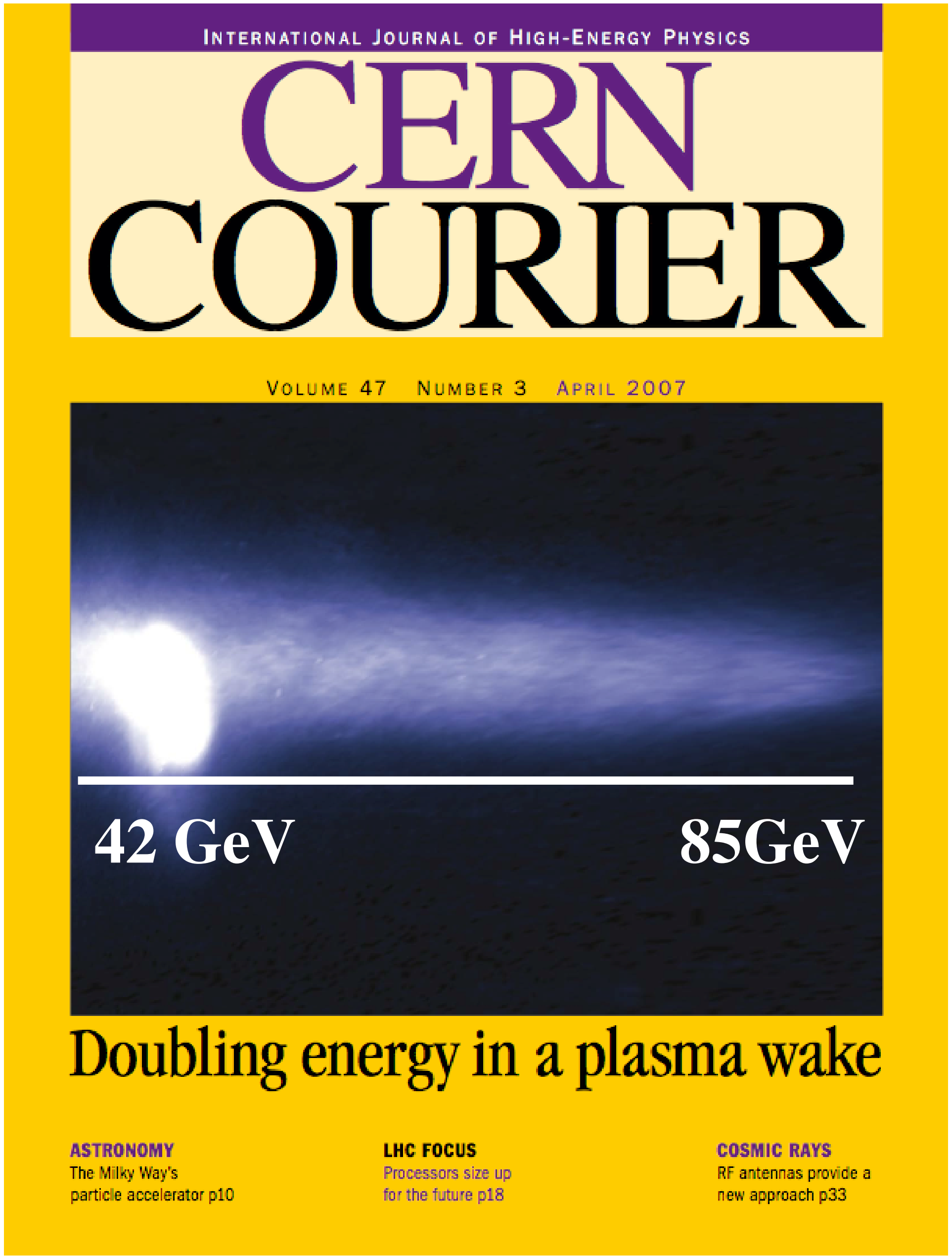
Decelerated Electrons

$n_e \approx 3.5\times10^{17}$ cm^{-3} L≈10 cm, N ≈ 1.8×10^{10}, $\tau \approx 50$ fs

Energy Gain Scales Linearly with Length



Energy Doubling of 42 Billion Volt Electrons Using an 85 cm Long Plasma Wakefield Accelerator



INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERN COURIER

VOLUME 47 NUMBER 3 APRIL 2007

42 GeV

85GeV

Doubling energy in a plasma wake

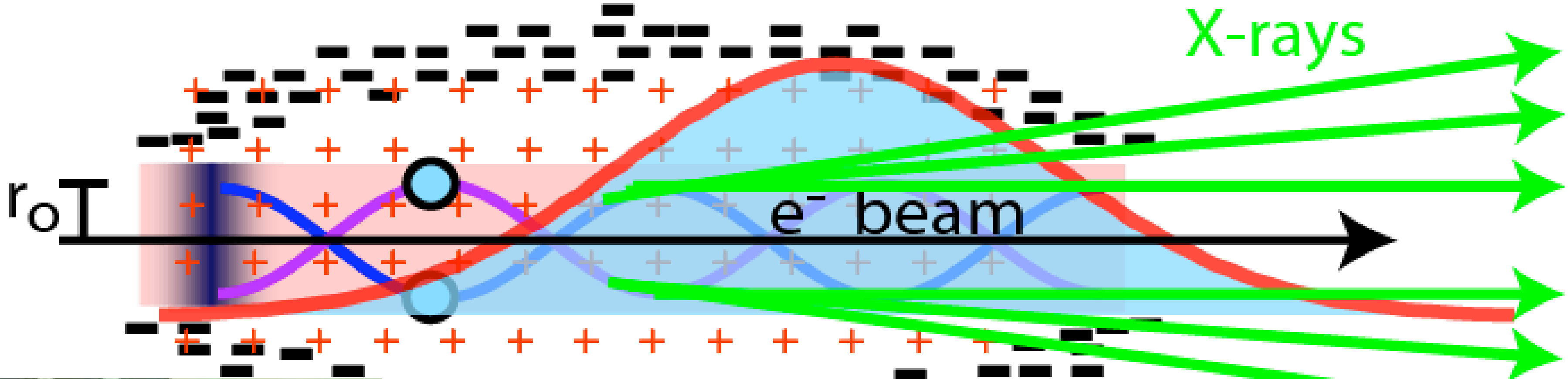
ASTRONOMY
The Milky Way's particle accelerator p10

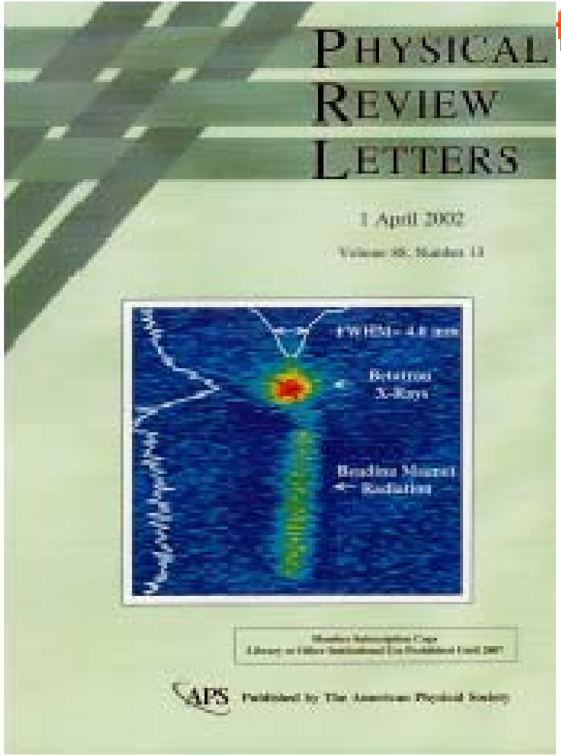
LHC FOCUS
Processors size up for the future p18

COSMIC RAYS
RF antennas provide a new approach p33

Nature v 445,p741 (2007)

Radiation Loss :Ultimate Limit on Plasma Accelerators




PHYSICAL REVIEW LETTERS

1 April 2002

Volume 88, Number 13

APS Published by The American Physical Society

Plasma Wiggler for collimated X-ray production 10 KV-100 MV

S. Wang et al. Phys. Rev. Lett. Vol 88. 13, pg. 135004, (2002)
D. Johnson et al., PRL (2006)

Can self-guiding work for a short laser Pulse in a plasma

Probe Beam
l = 815 nm
Pulse Length: ~60 fs FWHM
Pulse Energy: 500 µJ

Pump Beam Ti:Sapphire
λ = 815 nm
Pulse Length: ~50 fs FWHM
Pulse Energy: 150 mJ to 500 mJ

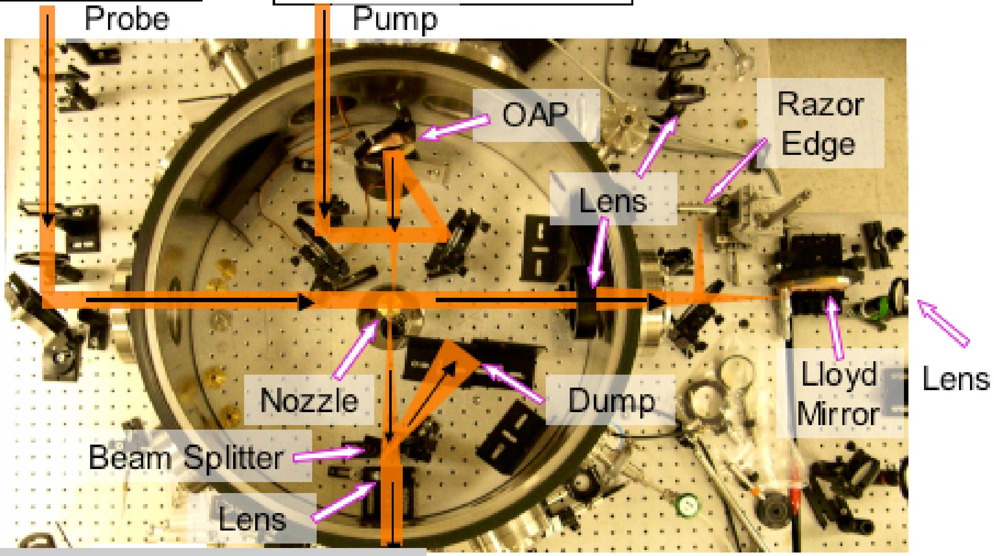
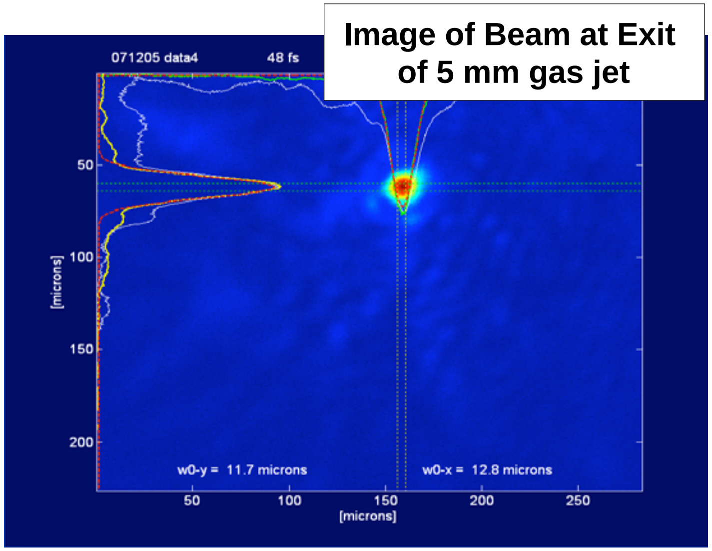
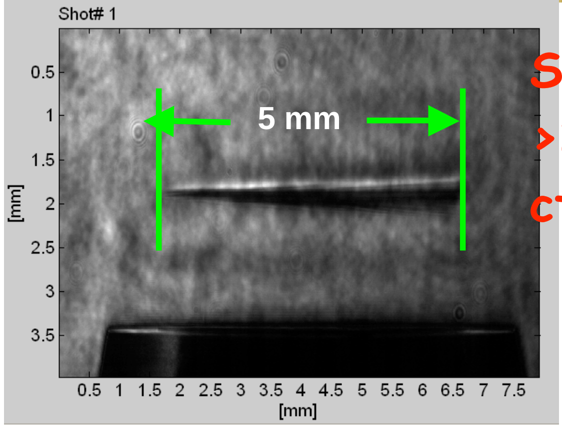


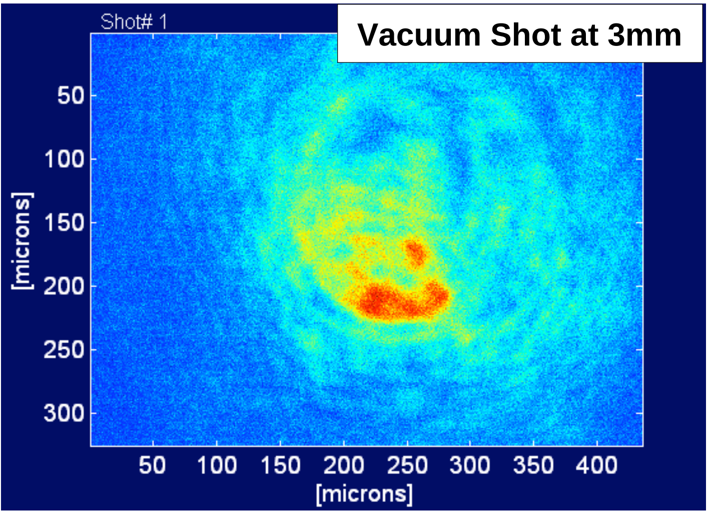
Image of Beam at Exit of 5 mm gas jet





Self-Guiding In a 5mm Jet
>20 Rayleigh Length for
$c t_{laser} \sim 2pi\ c/w_p$

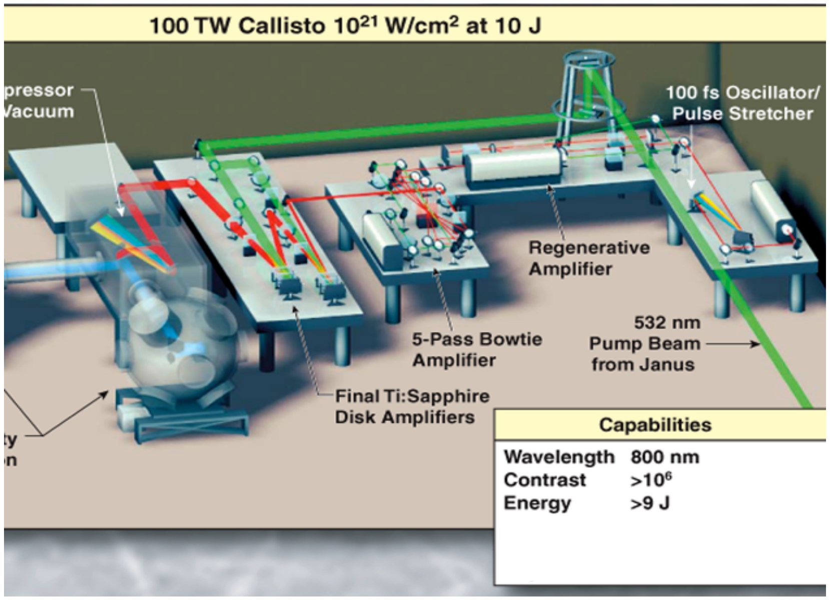
Vacuum Shot at 3mm

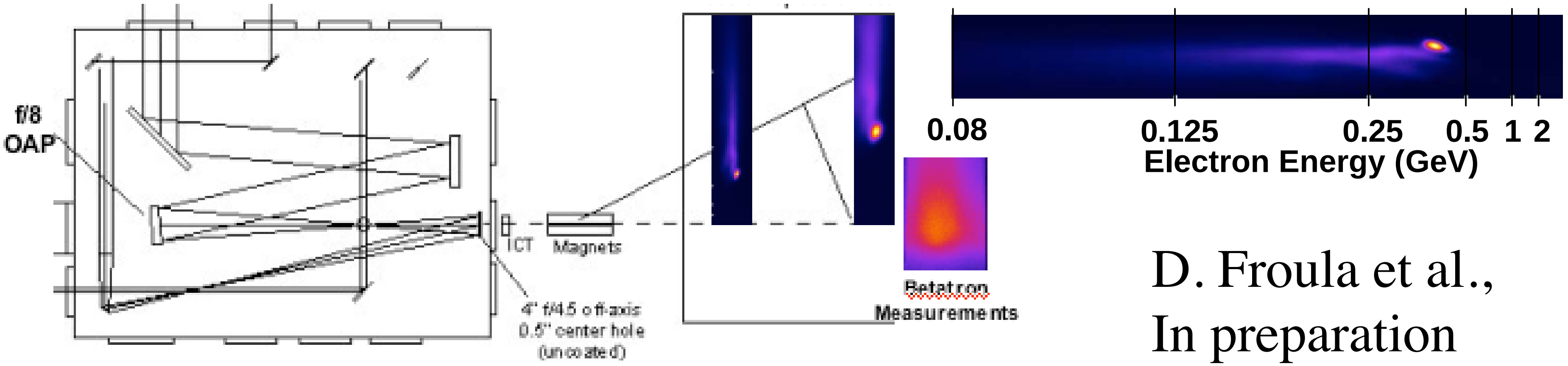


J. Ralph et al., submitted

Toward to a GeV level self-guided and Self-injected LWFA at LLNL

- A collaboration of UCLA, LLNL and UCSD
- Upgrading the Callisto laser at LLNL for LWFA experiments
- Results from our first campaign show monoenergtic electrons of energy up to 400MeV and betatron x-rays





D. Froula et al.,
In preparation

SCIENTIFIC AMERICAN

How to Protect
New Orleans
from Future Storms

FEBRUARY 2006
WWW.SCIAM.COM

Big Physics Gets Small

Tabletop Accelerators
Make Particles Surf on
Plasma Wakes

-Smaller?
-Cheaper?