# Surfing at the Speed of Light

*Can a Grand Challenge of Engineering Answer Big Questions of Physics?*

Tom Katsouleas

Provost and Robert C. Taylor Professor

of Electrical Engineering and Physics

Co-chair NAE Grand Challenges Advisory Committee

UVA Physics Department

October 17, 2015

University of Virginia

# NAE Grand Challenges for the 21$^{st}$ Century


Make solar energy economical


Provide energy from fusion


Develop carbon sequestration methods


Manage the nitrogen cycle


Provide access to clean water


Restore and improve urban infrastructure


Advance health informatics


Engineer better medicines


Reverse-engineer the brain


Prevent nuclear terror


Secure cyberspace


Enhance virtual reality


Advance personalized learning


Engineer the tools of scientific discovery

# Looking Back to the 20th Century:

## Greatest Engineering Achievements OF THE 20TH CENTURY

◆ About ◆ Timeline ◆ The Book

**Welcome!**
How many of the 20th century's greatest engineering achievements will you use today? A car? Computer? Telephone? Explore our list of the top 20 achievements and learn how engineering shaped a century and changed the world.

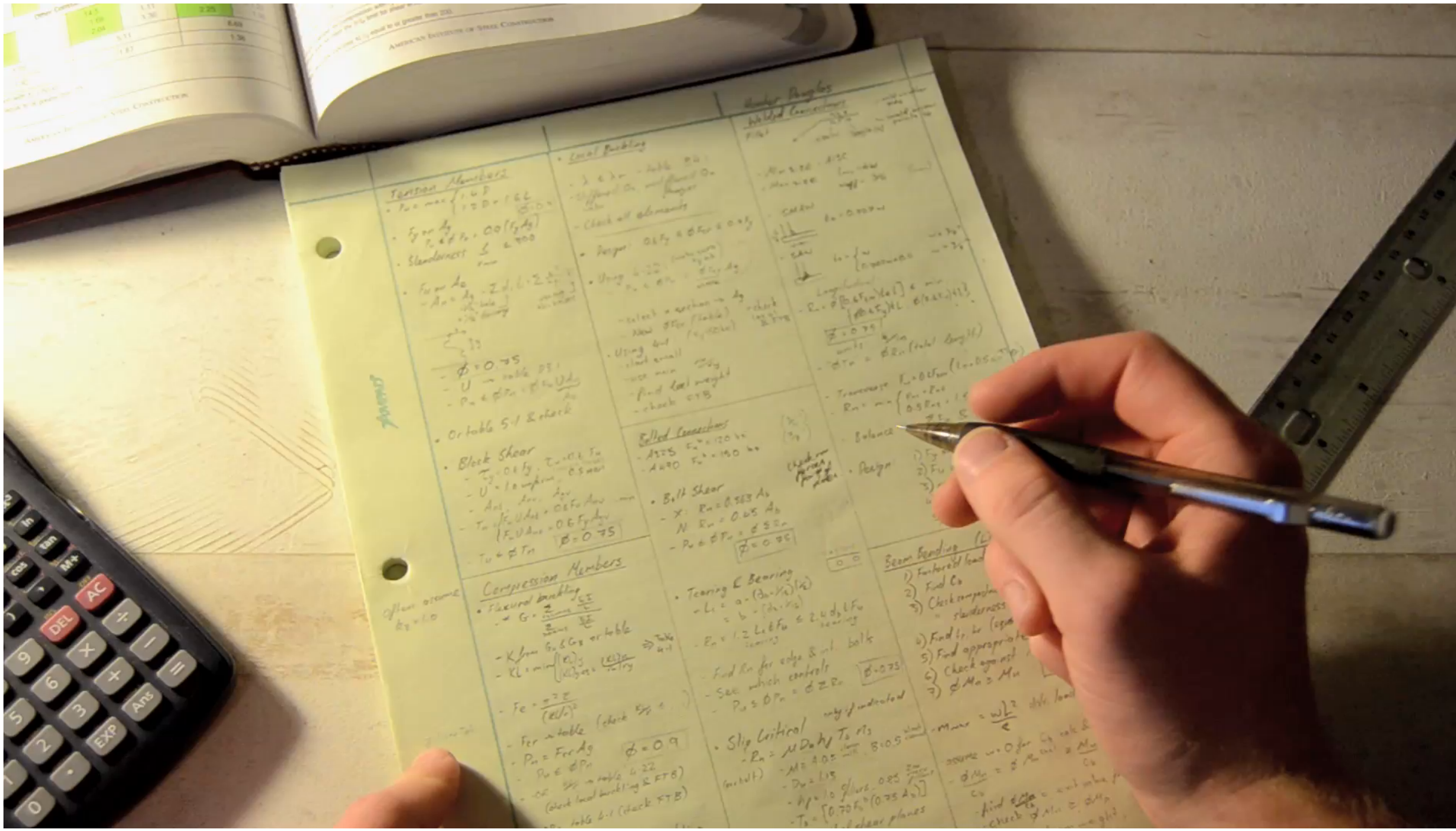
1. Electrification
2. Automobile
3. Airplane
4. Water Supply and Distribution
5. Electronics
6. Radio and Television
7. Agricultural Mechanization
8. Computers
9. Telephone
10. Air Conditioning and Refrigeration
11. Highways
12. Spacecraft
13. Internet
14. Imaging
15. Household Appliances
16. Health Technologies
17. Petroleum and Petrochemical Technologies
18. Laser and Fiber Optics
19. Nuclear Technologies
20. High-performance Materials

Greatest Achievements

 Printer-Friendly Version. Text-Only Version. Contact Us.

# Implications of the Grand Challenges

- Don't fit within any one discipline, or even within engineering
- Describe engineering in human-facing terms:
  - Sustainability, Health, Security, Joy
- Powerful tool for "Changing the Conversation"


Tension Members
Block Shear
Local Buckling
Bolted Connections
Bolt Shear
Compression Members
Tearing & Bearing
Slip Critical
Beam Bending

# NAE Grand Challenge Scholars

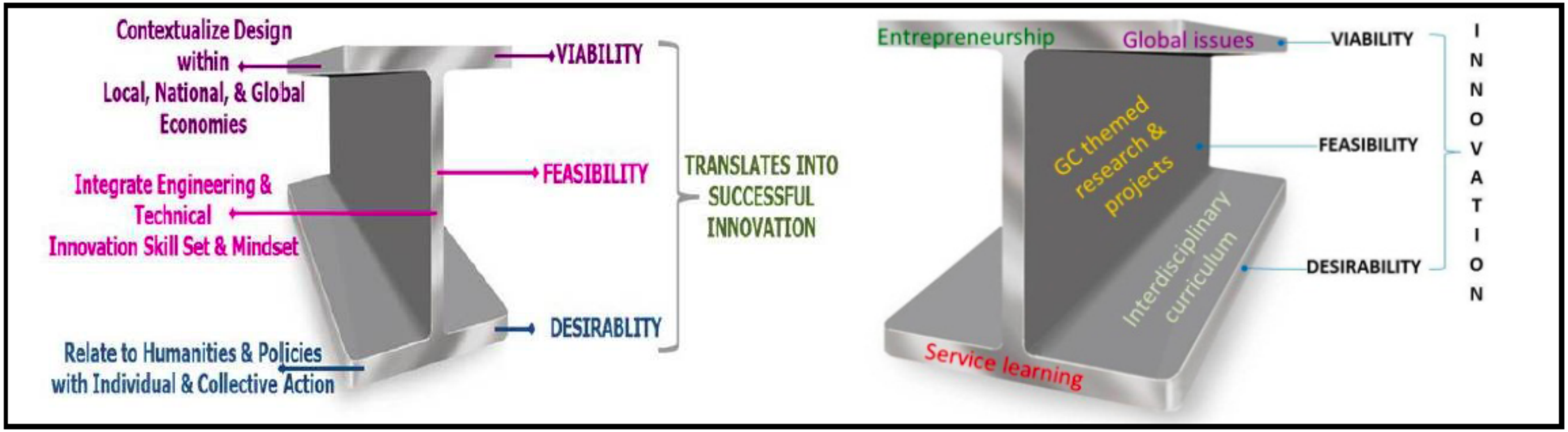
- To prepare UG engineering students with the skillset and mindset to address GCs over the course of their careers

- Five critical components
  1. Project or research activity engaging a Grand Challenge
  2. Interdisciplinary curriculum – behavior, business, policy
  3. Entrepreneurship
  4. Global dimension
  5. Service learning

Simon GC Scholar Maggie Hoff working on potable water project in Peru

Courtesy Martha Absher

# Solving Grand Challenges will require I-Shaped Engineers



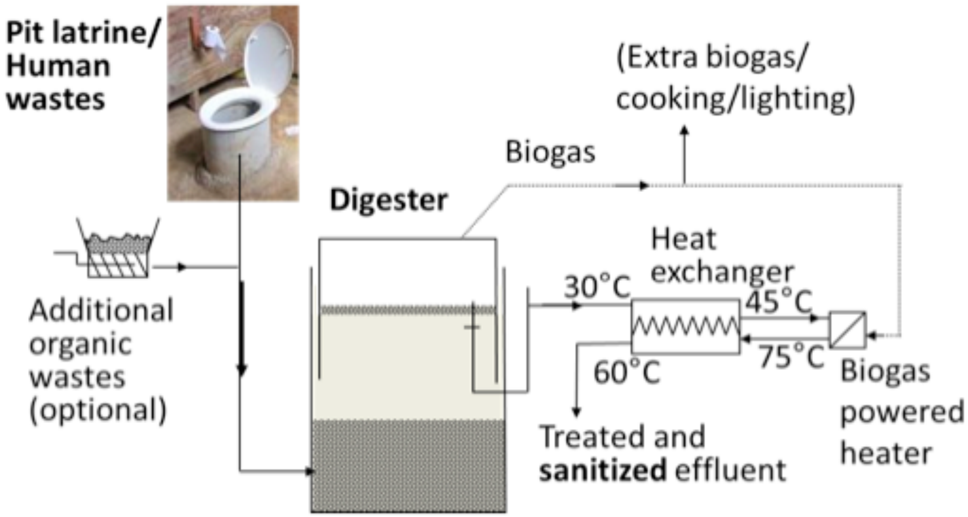

Courtesy Christina White, UT

- Solutions must be Feasible, Viable, Desirable
  - Feasible → Engineering fundamentals
  - Viable → Economics and business knowledge
  - Desirable → Context of culture and social policy

A couple of stories…

# Project Example: Revenue-generating Public Toilets in Togo

**Reinventing the pit latrine**
**Human waste digested to biogas, then used to heat sterilize effluent.**




Not to scale

Duke Prof. Marc Deshusses, Gates Foundation Grand Challenge Scholar: Conner Cotton

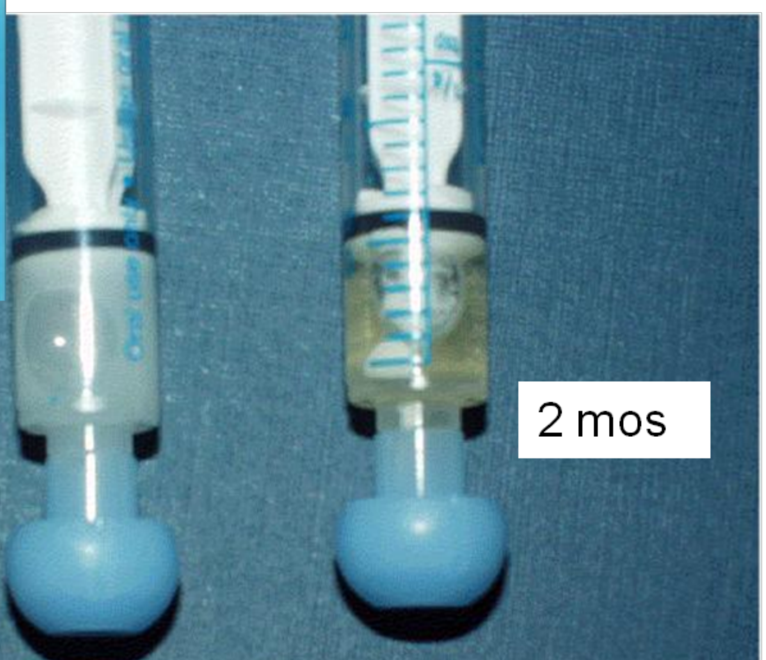
# Project Example: Sustainable fishery in Kenya

Teaching wave mechanics to protect fragile shallow water reefs

# Project Example: Pratt Pouch

- HIV+ Women who give birth at home
  - 20-50% have HIV+ children [1]
  - Majority transmitted during delivery [1]
- 3TC, NVP and/or AZT can prevent transmission
  - Drugs expires quickly out of the bottle (<1mos)

[1] WHO (2006) 'Antiretroviral drugs for treating pregnant women and preventing HIV infection in infants in resource-limited settings: towards universal access'




Duke Pouch 12 mos NVP
Duke Pouch 12 mos AZT
Duke Pouch 12 mos 3TC

Clinical Trials
Ecuador
Zambia
Tanzania
Namibia

Courtesy:Bob Malkin


PRISM
OCTOBER 2014
HIGHER CALLING
An idealistic generation rises to the Grand Challenges.


KAΘ

TEACHING FOR THE FUTURE FIRST IN A SERIES

# MORE ENGINEERING STUDENTS GET REAL-WORLD EXPERIENCE

## Schools try to debunk it as a 'field for geeks'

PHOTOS BY GARRETT HUBBARD FOR USA TODAY

**Grand Challenge scholar Kathryn Latham went to Bolivia with other students to help link two villages.**

**Dan Vergano**
USA TODAY

**DURHAM, N.C.**

Hoover Dam. The Panama Canal. The new iPhone folks are camping out to buy.

In ways massive and handheld, engineers have changed the world. Now the time has come for the world to change engineers. One student at a time.

"I'm a bit of an idealist, I've always wanted to help people," says Duke University engineering student Kathryn Latham, 21. "I think if more students pursued jobs that made a difference, the world would be a better place."

Latham's idealism took her to Bolivia this summer, leading a team of Duke engineering students building a 213-foot-long steel pedestrian bridge "by hand," she notes, to link two impoverished villages long separated by a deep gorge.

Taking young engineers out of lecture halls to practice their profession represents the cutting edge in reshaping the discipline, say educators and the field's leaders. Change is needed to face coming challenges in delivering energy, food, and clean air and water to the world's 9 billion people expected to be living by mid-century.

"We have done a miserable job, by and large, of explaining just how engineering is essential and can change the world," says National Academy of Engineering chief Charles Vest. In a nutshell, he says, that helps explain why only about 4.5% of U.S. college graduates are engineers, while about 12% are in Europe and 21% are in Asia.

"This is an idealistic generation, despite everything going on in the economy, and they want to help people," Vest says. "We have to get them out of the lecture hall and show them how engineers do just that."

On Oct. 1, the academy will host a Grand Forum event in Washington aimed at showing how the discipline can fix the problem. It will feature educators, industry leaders and

**Thomas Katsouleas sees success in the Grand Challenge program.**

**WATCH ONLINE**
**USATODAY.COM**
Students and faculty at Duke University talk about the changing expectations of higher education

"Khan Academy" online teacher Salman Khan, whose organization's short YouTube lectures on everything from calculus to civics have garnered more than 175 million viewers.

Since 2005, when a National Academy of Sciences report, "Rising Above the Gathering Storm," warned of eroding U.S. leadership in science and technology, alarm bells have rung over the brightest students skipping engineering for finance, medicine or other fields in an era of declining U.S. manufacturing.

Much of the problem comes in the university "pipeline" that carries kids from freshman chemistry to graduation, Vest and others say. Just 34% of women and 31% of men who started out as engineering majors in 2005 finished that way four years later.

Engineering professors in the past tried to wash out students in sink-or-swim programs filled with calculus problems, lectures and little else, but that culture has changed and is changing, Duke Engineering Dean Thomas Katsouleas says.

"It's a funny paradox. We want to make it as easy as possible to master the material, but we don't want to lower the level of mastery," he says.

Instead of a person solely skilled in filling graph-paper pages with neatly answered math problems, the goal is a student grounded in teamwork and entrepreneurship, as well. "We cannot solve all of our problems by technology alone," Katsouleas says. "They will require a deep understanding of human behavior."

"America produces just as many great kids as ever. They just don't see engineering as attractive all too often. Instead it's a 'can't-do' field for geeks," says President Richard Miller of Olin College in Needham, Mass., whose school was chartered in 1997 to reinvent how engineering is taught. "We need people who think differently, people who are creative, people who make things, people who can work in teams, not just alone on a computer."

Most radically at Olin, but increasingly at schools across the country, engineering students build things earlier in their college years. They leaven the heaping helpings of math lectures that for decades have defined their education with the messy business of building things that do, or don't, work.

At Olin, students have to build something in weeks-long projects as freshmen and start a business that sells to real customers before they graduate. "Our model is a music school with engineering as a performance art, and the studio time that students spend with each other is an enormous part of their education," Miller says.

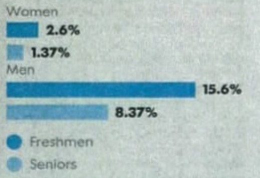
At Duke, Latham is a "Grand Challenge" scholar in a national engineering academy program at a dozen schools. It asks students to tackle 14 big problems around the world, ranging from "preventing nuclear terror" to "reverse-engineering the human brain." She's trying to grow algae in soapy "graywater" in a lab to help clean the water and use the growth in green diesel-fuel projects.

Latham, a transfer into the discipline, says, "I've learned that engineering is really what you want it to be. You really can get out of the classroom and really solve problems."

**IMPROVING THE PIPELINE**

A leaky "pipeline" dogs engineering schools, where only about half of all incoming freshmen engineers graduate as engineers.

U.S. undergraduates starting out as engineers and percentage graduating as engineers (2005 to 2009):




**Sources** National Academy of Engineering, National Science Foundation, National Center for Education Statistics

JANET LOEHRKE, USA TODAY

*Announcing a Special Workshop*

# EDUCATING ENGINEERS TO MEET THE GRAND CHALLENGES

## APRIL 30–MAY 1, 2014

National Academy of Engineering
*in* Washington, D.C.

Leaders of engineering service-learning organizations, associations, industry and academia will gather in the nation's capitol next spring for a workshop focused on how the U.S. can best prepare future engineers to meet the NAE Grand Challenges for Engineering.

The goal of the workshop is to develop a consortium of 50 universities and organizations committed to incenting students to integrate specific curricular and co-curricular experiences that prepare them to address the Grand Challenges over the course of their careers. Attendance by invitation only.

Learn more at
**nae**.edu/**grand**challenges**workshop**

## ORGANIZERS

AAES
epicenter National Center for Engineering Pathways to Innovation
EPICS®
Engineers Without Borders USA
NAE Grand Challenges for Engineering

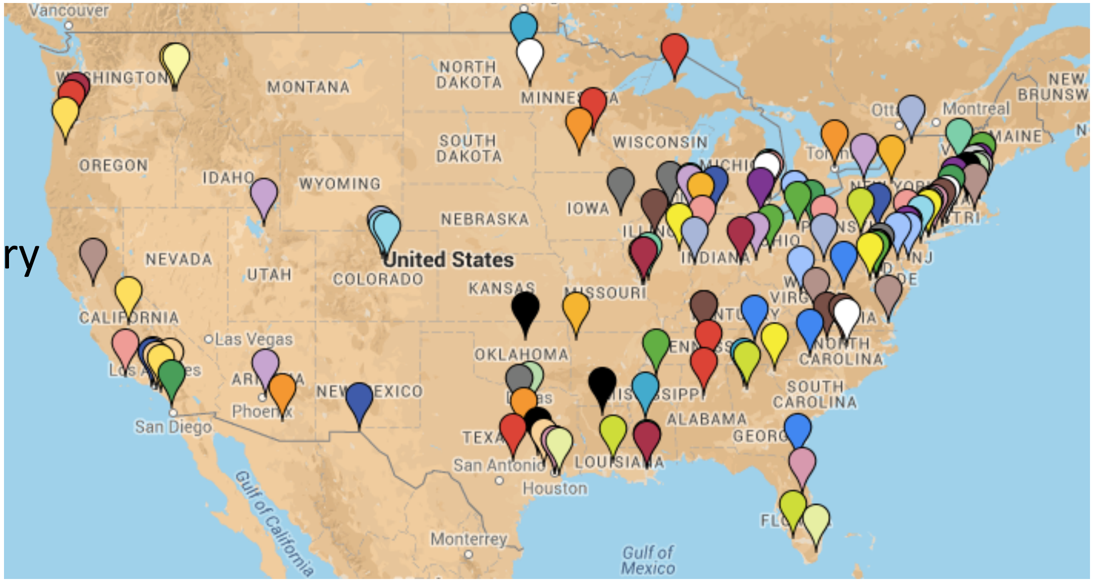
## SPONSORS

Duke Pratt School of Engineering
NC State University College of Engineering
Olin College of Engineering
Purdue Engineering
USC Viterbi School of Engineering
National Academy of Engineering of the National Academies
The University of Tennessee Knoxville

# US Engineering School Deans' Response:

- "We the undersigned deans commit to educate a new generation of engineers expressly equipped to meet [grand] societal challenges…
- "We affirm the importance of such aims as a reflection of our core values, as a source of inspiration for drawing a generation to the call of improving the human condition, as a driver for our nation and world economies, and as essential to US and global security, sustainability, health, and joy of living ….
- "Over the course of the next decade, we commit to graduating from each of our institutions 20 students a year who are prepared with this unique combination of skills, motivation and leadership to address the Grand Challenges….

Signed by 122 deans across the country



# White House receives commitment letter

*March 23, 2015*

# The End Game: Not just education but solutions to Grand Challenges

- Some expected and some unexpected advances since 2007…

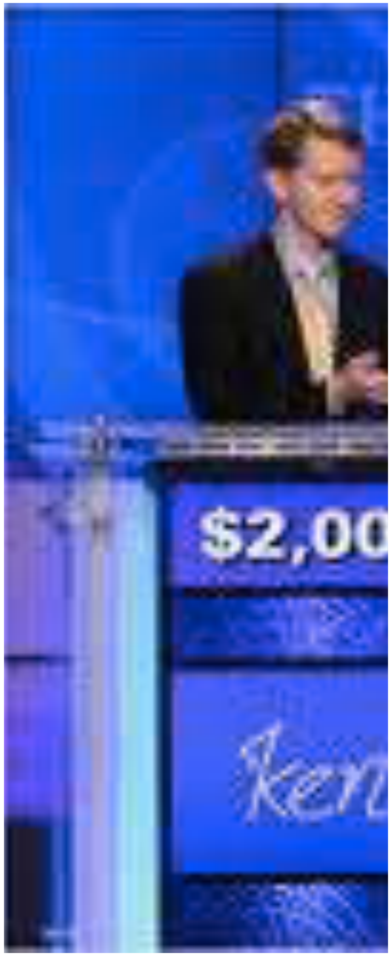
# Provide Clean Water

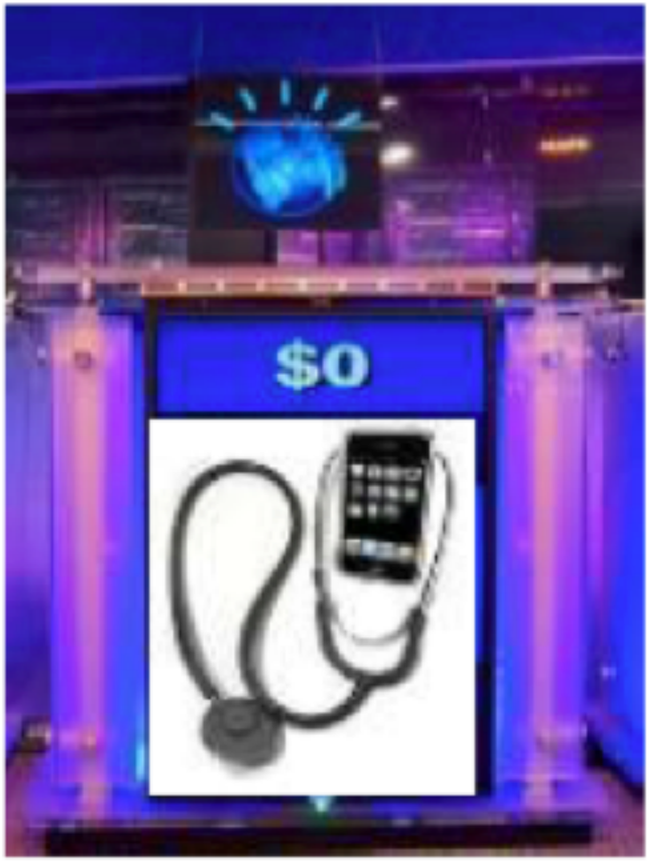
Dean Kamen's Slingshot and Stirling generator

>1,000 liters/day
<.001 cent per liter
***Less electricity than a hairdryer***


AIC-Chile Plasma Water Sanitization System

# 2010: …pardy

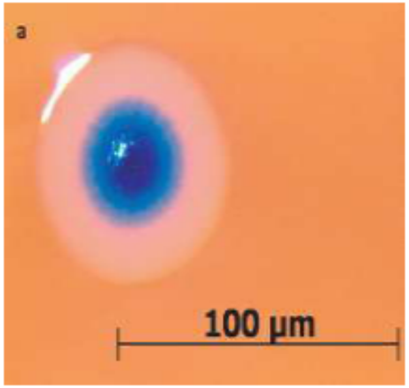


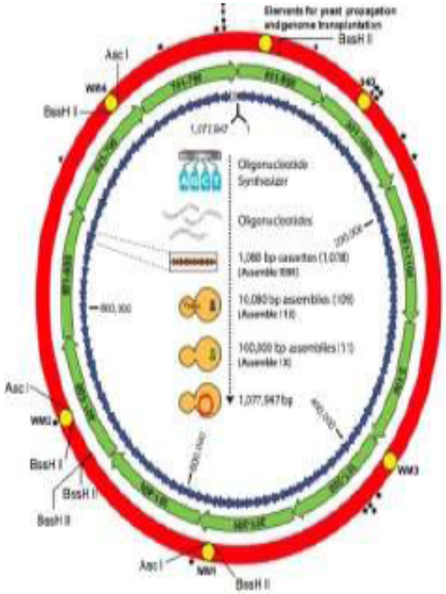





2013 IBM Watson as an AI Physician

# 2010: Make Solar Energy Economical Algae?


May 20, 2010
***First synthetic life form***

- ***FUEL***
- ***FOOD***
- ***VACCINES***

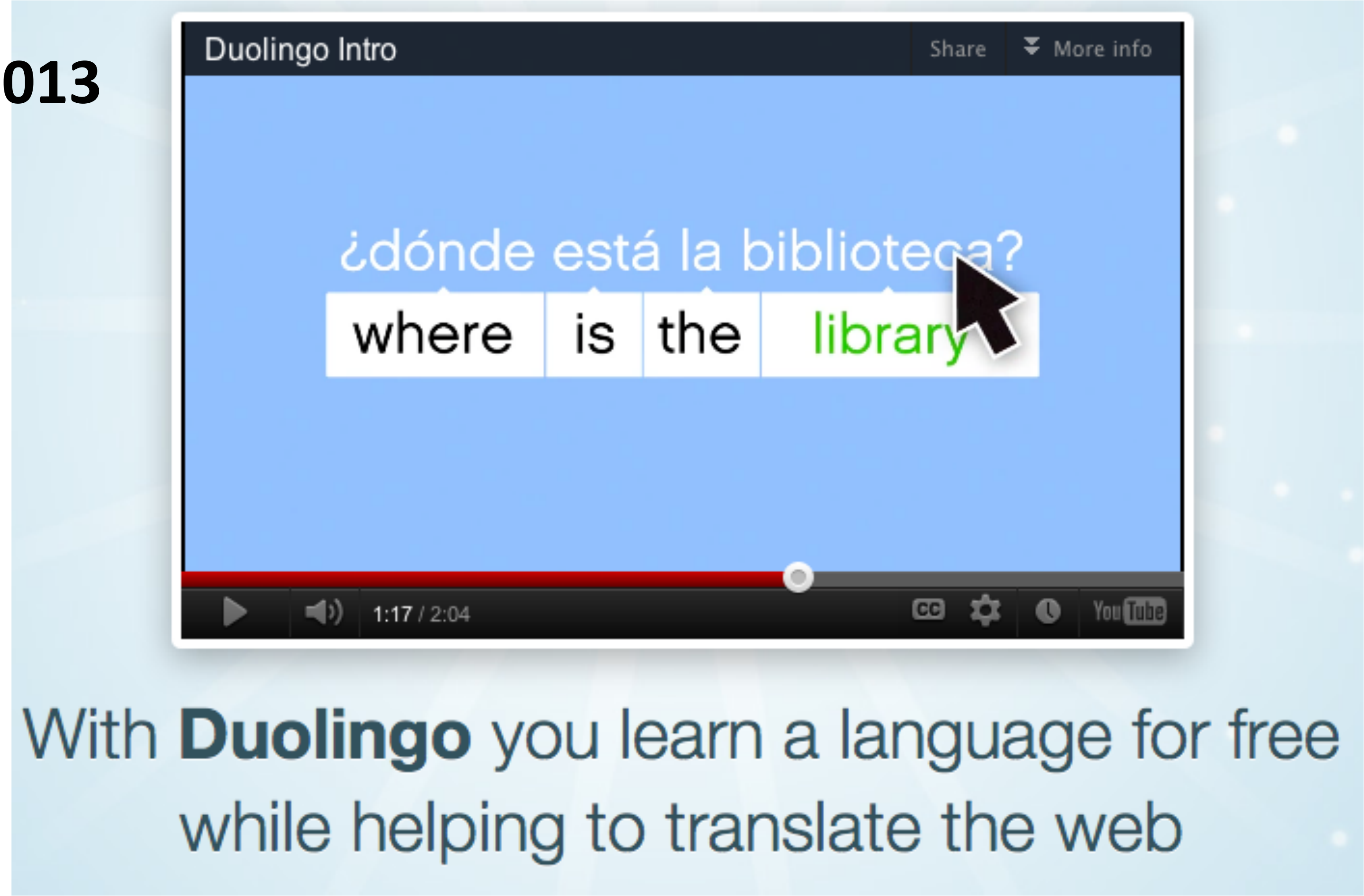
***Algae: 10,000 gal/acre/year***

250M Cars → ~0.0048 of US landmass

# Personalized Learning

## 2011: First MOOC reaches > 100,000

2013




900,000 learners + Machine Learning → surpassing Rosetta Stone

# Engr Tools of Scientific Discovery

Laser and beam-driven plasma wakefields can miniaturize a large particle accelerator:

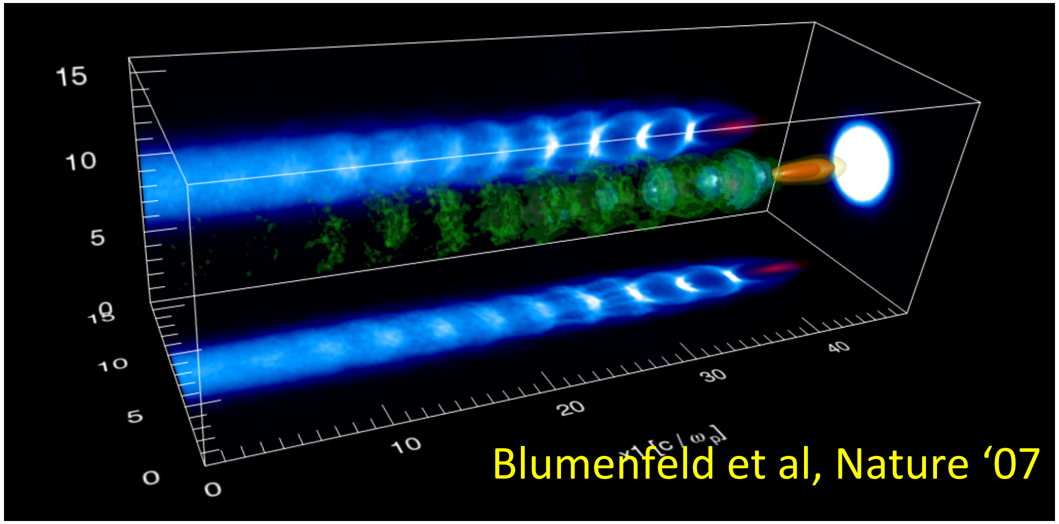
- 

***RF structure accelerator***

**λ ~ 30cm**

***Plasma wakefield***

**λ ~ 100μm**



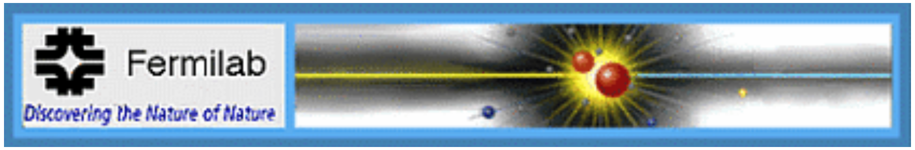

0-42 GeV in 3km

42-85 Gev in 1m

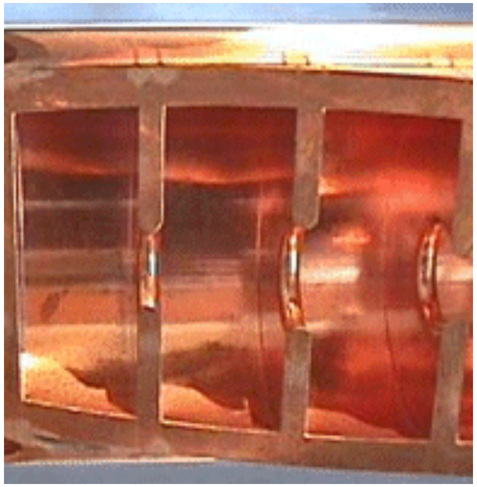
# Grand Challenge: Tools of Scientific Discovery

**Accelerators!**









# Particle Accelerators: compact to country size

*Big Physics Questions and Applications*

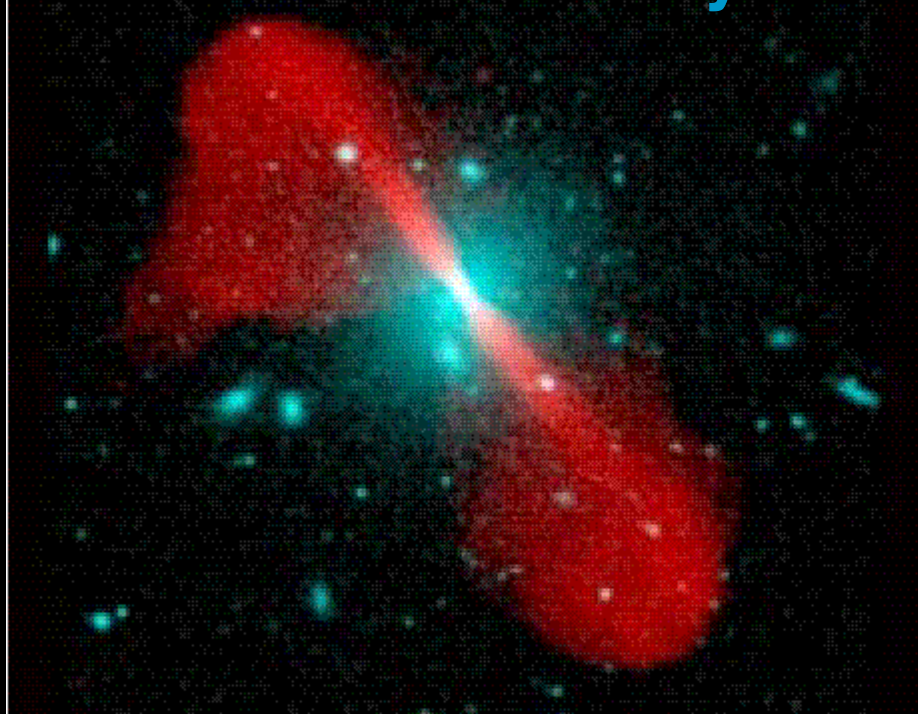
## Large

- Verified Standard Model of elementary particles
- W, Z bosons
- Quarks, gluons and quark-gluon plasmas
- Asymmetry of matter and anti-matter
- Higgs Boson (cause of mass)
- Dark matter and energy?
- Faster than light particles?
- Origin of hi-energy cosmic rays?
- Beyond the Standard Model?

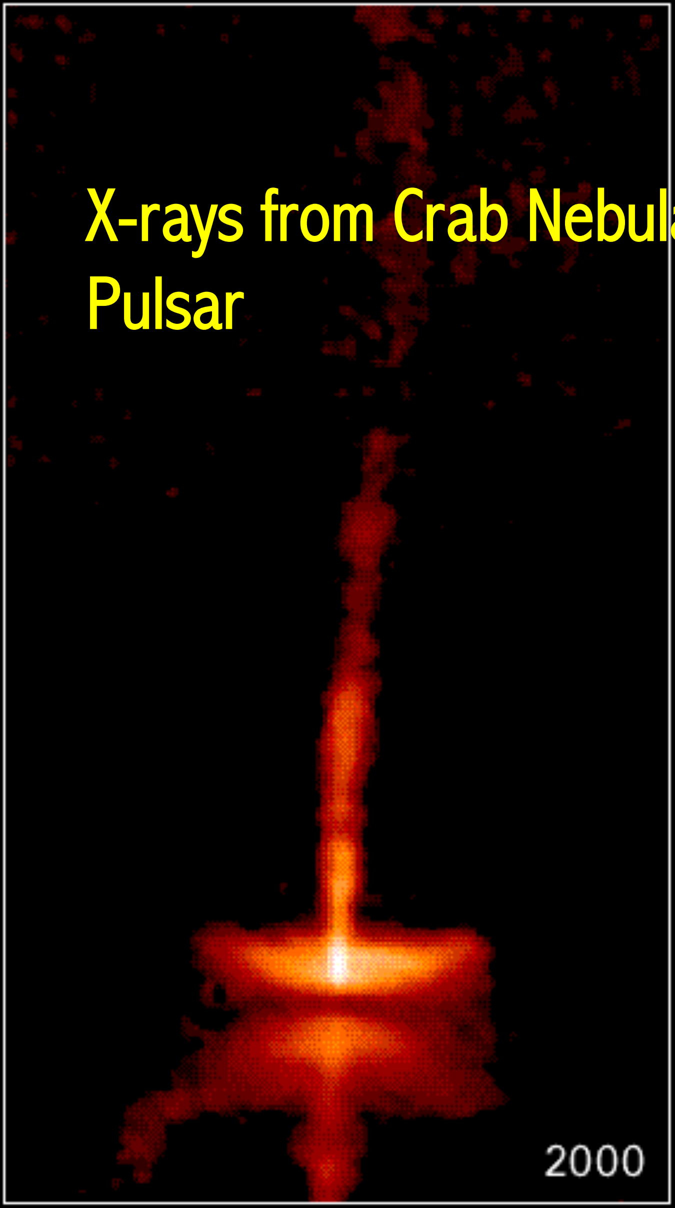
## Compact

- Medicine
  - Cancer therapy, imaging
- Industry and Gov't
  - Killing anthrax
  - lithography
- Light Sources (synchrotrons)
  - Bio imaging
  - Condensed matter science

# Astrophysical Jets -- the ultimate beam-plasma interaction laboratory



Radio Jets from Galaxy 3C296


X-rays from Crab Nebul
Pulsar

# Particle Accelerators

*Requirements for High Energy Physics*

- High Energy
- High Luminosity (event rate)
  - $L = fN^2/4\pi\sigma_x\sigma_y$
- High Beam Quality
  - Energy spread $\delta\gamma/\gamma$ ~ .1 - 10%
  - Low emittance: $\varepsilon_n \sim \gamma\sigma_y\theta_y$ < 1 mm-mrad
- Low Cost (one-tenth of $10B/TeV)
  - Gradients > 100 MeV/m
  - Efficiency > few %

# Particle Accelerators

*Why Plasmas?*

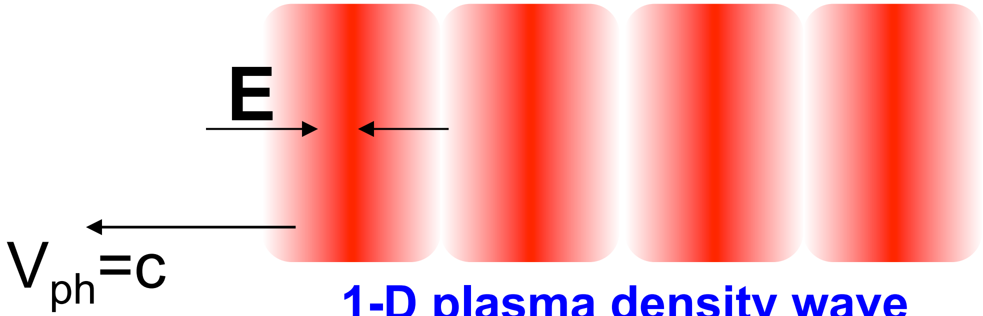
Conventional Accelerators

- Limited by peak power and breakdown
- 20-100 MeV/m
  - **ILC = 20km /0.8 TeV**

Plasma

- No breakdown limit
- 10-100 GeV/m

# Simple Wave Amplitude Estimate




**1-D plasma density wave**

$$\nabla \bullet E \sim ik_p E = -4\pi e n_1$$

**Gauss' Law**

$$k_p = \omega_p / V_{ph} \approx \omega_p / c$$

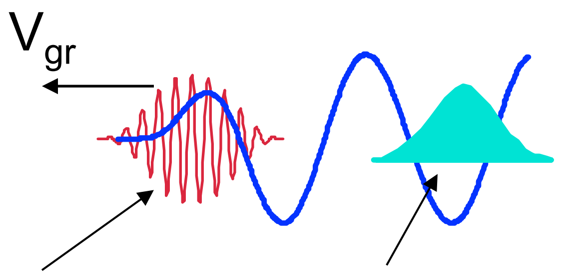
$$n_1 \sim n_o$$

$$\Rightarrow eE \sim 4\pi e n_o e^2 c / \omega_p = mc\omega_p$$

$$or \quad eE \sim \sqrt{\frac{n_o}{10^{16} cm^{-3}}} 10\, GeV/m$$

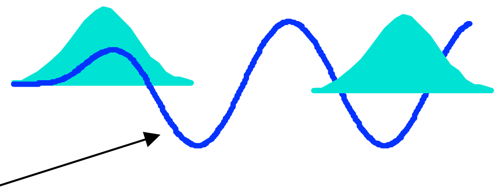
# Concepts For Plasma Based Accelerators*

- Laser Wake Field Accelerator
  *A single short-pulse of photons*




- Drive beam
- Trailing beam

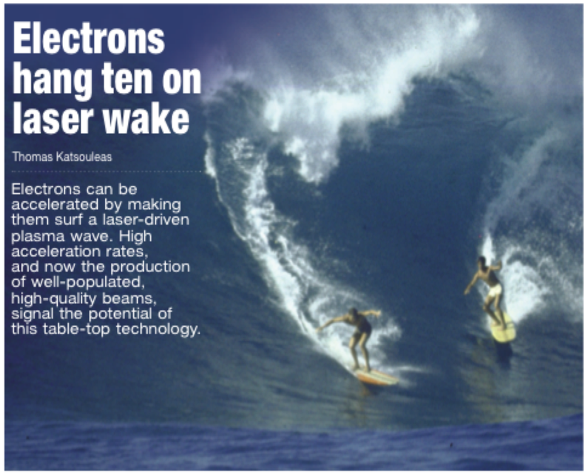
- Plasma Wake Field Accelerator (PWFA)
  *A high energy electron bunch*



- Wake: phase velocity = driver velocity ($V_{gr}$ or $V_b$)

***Proposed by John Dawson**



# Electrons hang ten on laser wake

Thomas Katsouleas

**Electrons can be accelerated by making them surf a laser-driven plasma wave. High acceleration rates, and now the production of well-populated, high-quality beams, signal the potential of this table-top technology.**

TIME LIFE PICTURES/GETTY IMAGES

Huge particle accelerators have been at the vanguard of research in particle physics for more than half a century; through high-energy collisions of accelerated particles, the fundamental building-blocks and forces of nature have been revealed. The latest project, the Large Hadron Collider (LHC) currently under construction at CERN in Geneva, will attempt to find the Higgs boson, a particle associated with the mechanism through which all other known particles are thought to acquire their masses. But the size and cost of such machines — for the LHC, a 27-km circumference and several billion euros — are fuelling a serious effort to develop new and more compact accelerator technologies. Three reports[1–3] in this issue (from page 535) announce fresh progress, using a principle known as plasma wakefield acceleration.

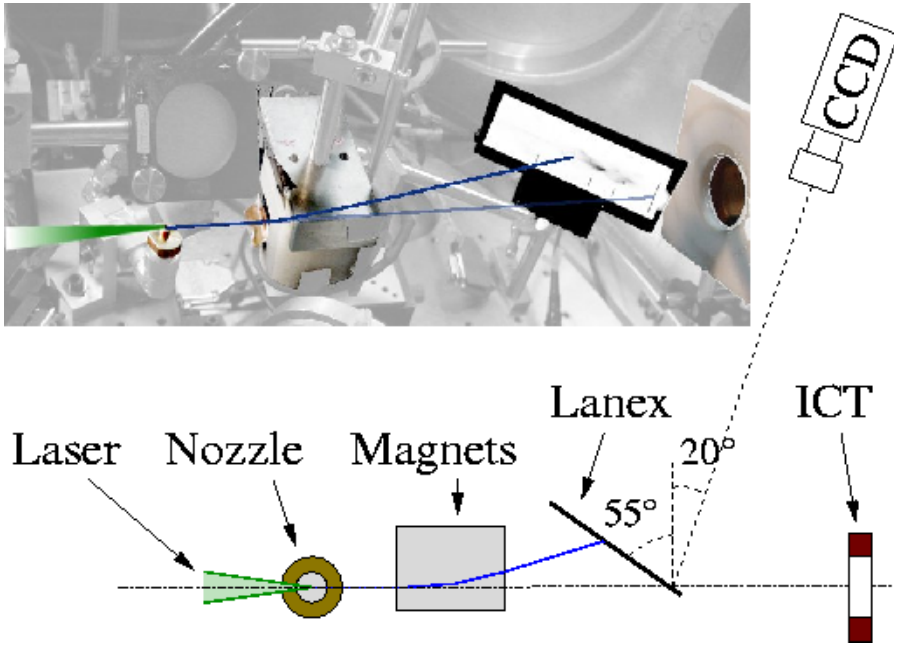
Plasmas — gaseous 'soups' of dissociated electrons and ions — offer a means of acceleration that could be realized on a table top[4]. Waves can be generated in a plasma using short laser pulses; electrons or their antimatter counterparts, positrons, can then 'surf' the electric field of a wave's wake. Particles have been accelerated in wakefields at rates that are more than a thousand times higher than those achieved in accelerators based on conventional large-scale technology. However, whether plasma wakefield accelerators could produce the high quality of beam needed for applications in high-energy physics, and in other areas of research and medicine, remained in question. The results now presented by Geddes *et al.*[1], Mangles *et al.*[2] and Faure *et al.*[3] are a milestone in this regard. They provide the first demonstration that a beam of electrons can be accelerated in a wakefield to a single energy. Moreover, their beams are of high quality (having a small angular divergence) and significant charge (about $10^9$ electrons).

In a conventional accelerator, charged particles such as electrons, protons or their antiparticles are accelerated by an alternating, radio-frequency electric field through long metallic cavities (around a metre long for medical applications, but several kilometres long for high-energy physics). The rate of acceleration is limited by the peak power of the radio-frequency source and, ultimately, by electrical breakdown at the metal walls of the accelerator. Laser-driven plasma waves overcome both of these limitations: the high peak power of lasers is unmatched, and the plasma, as it is already an ionized gas, is impervious to electrical breakdown. In 1995, Modena *et al.*[5] made clear the remarkable potential of this scheme, and it has been confirmed by subsequent experiments. Using the radiation pressure of a laser to drive a compressive oscillation in the plasma (like a sound wave, but with electrostatic repulsion rather than pressure as the restoring force), electrons have been accelerated from rest to an energy of 100 megaelectronvolts (MeV) within a distance of 1 mm — more than 5,000 times shorter than the distance required to reach that energy in a conventional accelerator.

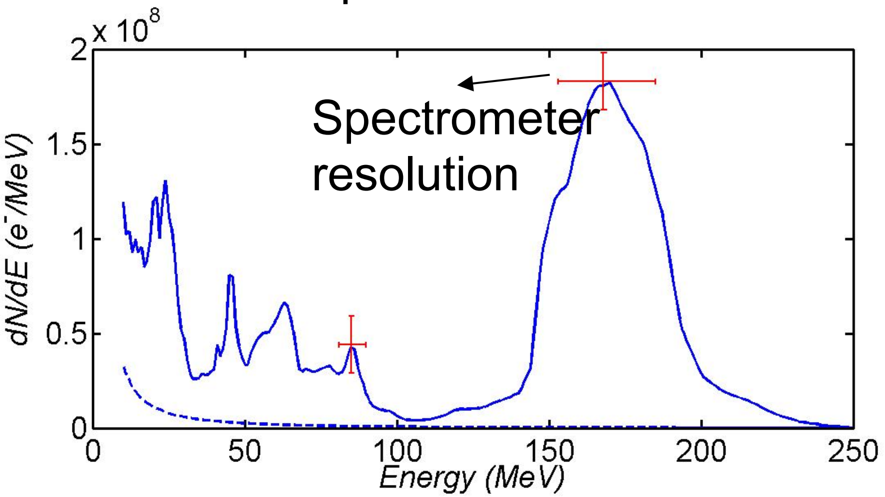
But acceleration rate is only one measure of a good accelerator. The number of particles in a beam, and their spread in angle and energy, also matter. In 2002, Malka *et al.*[6] showed that well-collimated beams of $10^8$ electrons could be produced within an angular spread of 3° by a laser-driven wakefield; in these experiments, however, the energy spread of the beams was 100%. This wide range of energies occurred because the particles were trapped from the background plasma — in much the same way that white-water gets trapped and accelerated in an ocean wave — rather than injected into a single location near the peak of the wave (as is done in a conventional accelerator). But injection is difficult in a wakefield accelerator because the wavelength of the plasma wave is tiny — typically 10,000 times shorter than the usual 10-cm wavelengths of the radio-frequency fields in conventional accelerators. Successfully injecting tightly packed bunches of particles near the plasma-wave

# Nature Experiments 2004: Mono-energetic Beams

*3 Labs--LOA, RAL, LBL*




Quasi-monoenergetic spectrum
Hundreds of pC at 170 MeV +/- 20 MeV



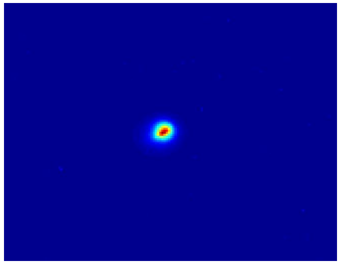

Parameters: $n_e$=6x$10^{18}$ $cm^{-3}$,
$a_0$=1.3, t=30 fs

P=30 TW

Results obtained with 1m off-axis parabola:
$w_0$=18 μm, $z_R$=1.25 mm

*J. Faure et al., Nature 2004*

*Electron beam profile on LANEX*



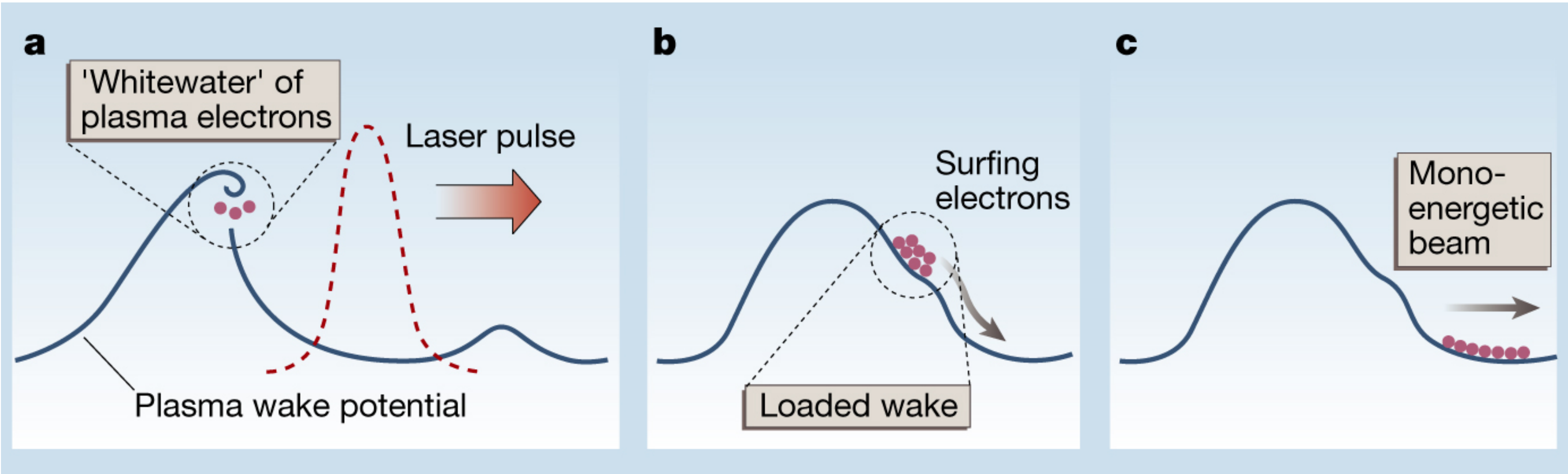
Divergence FWHM = 6 mrad

# 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

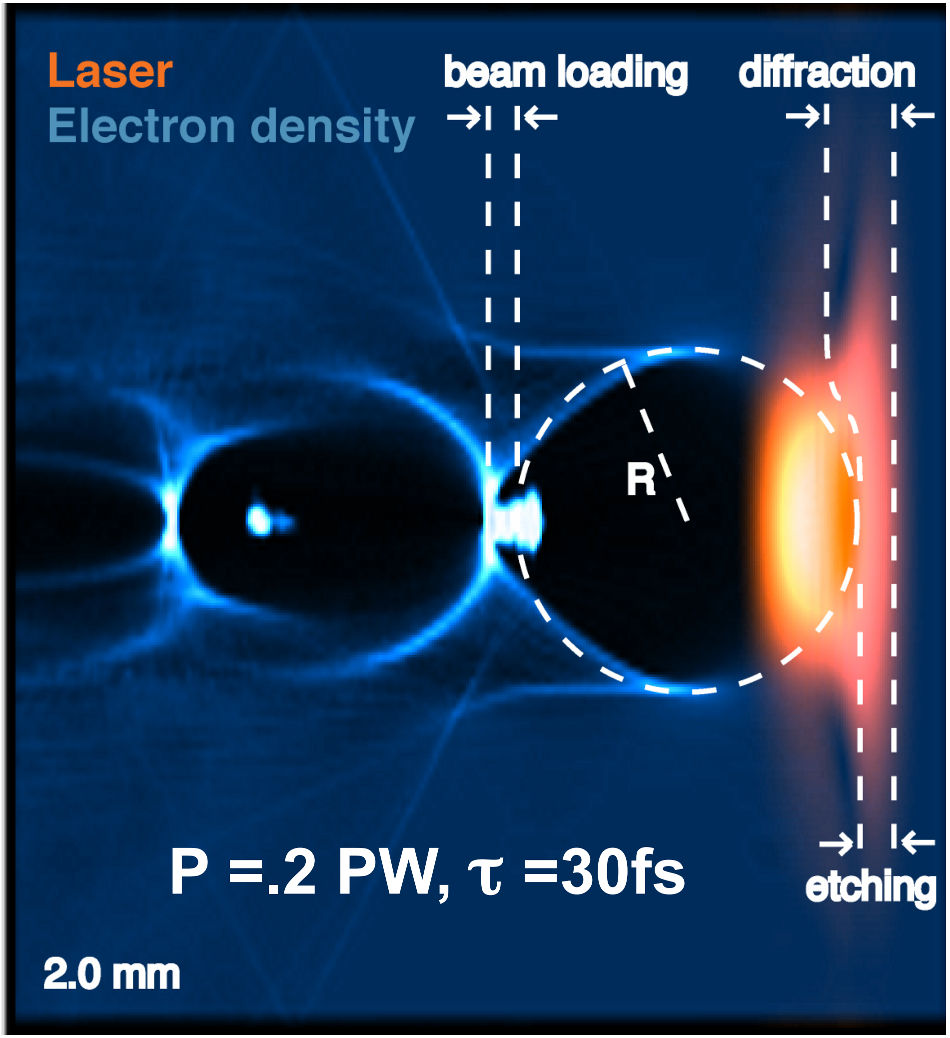
**c.** Dephasing
If L > or < dephasing length: large energy spread
If L ~ dephasing length: monoenergetic




*T. Katsouleas, Nature 2004*

# GeV Laser WFA Simulation (3D PIC)

*Experiments are at threshold of a scalable robust regime*




*W. Lu, M. Tzoufras et al., UCLA*

- Similar sequence of events:
  - The front of the laser pulse loses energy (*local pump depletion*) and etches back.
  - Wake grows and electrons are self-injected at the tail of the ion channel
  - High quality beam load forms

    $\varepsilon_N \sim r\ \theta \sim 1\mu$ x 1 rad=1 mm-mrad

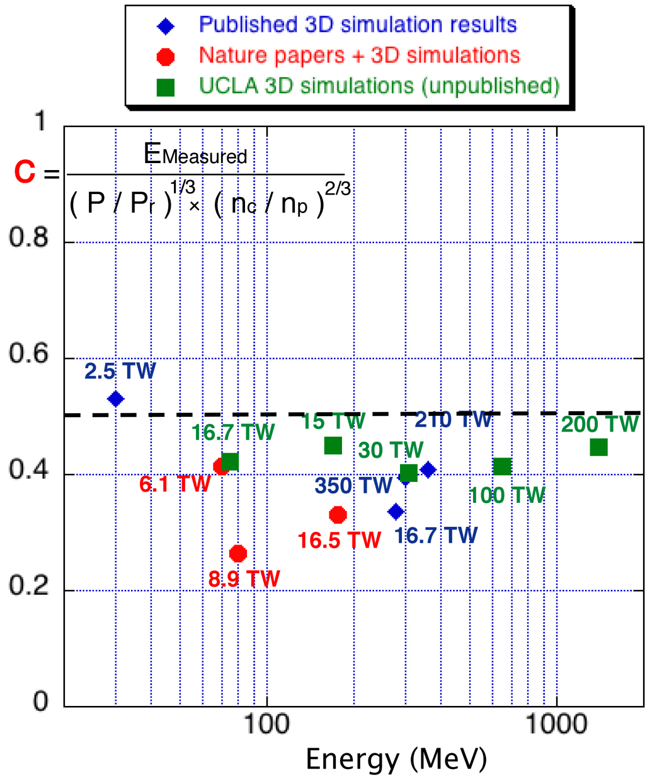
(100's of pCoul from a "cathode" spot of $1\mu$)

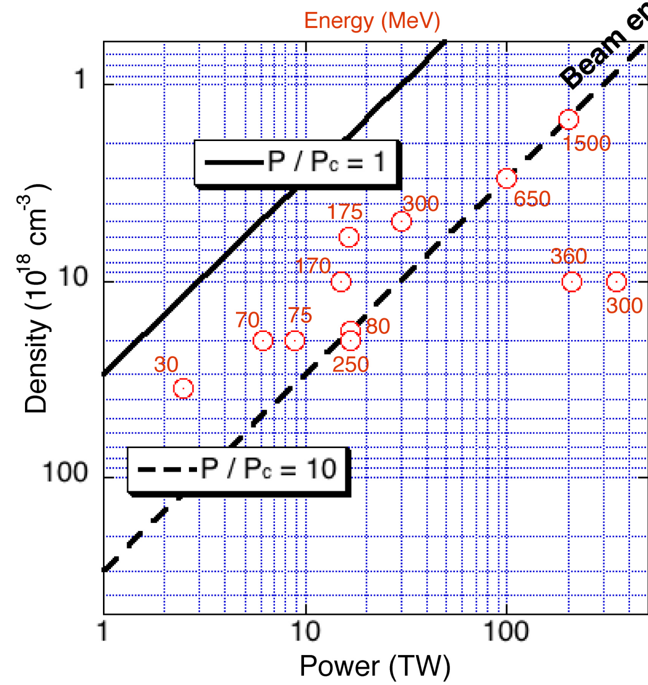
# Scaling laws for monoenergetic regime

*Verification of the scaling through simulations*

If the laser can be guided (either by itself or using a plasma density channel), one can increase laser power and decrease plasma density to achieve a linear scaling on power:

$$\Delta E \propto P$$



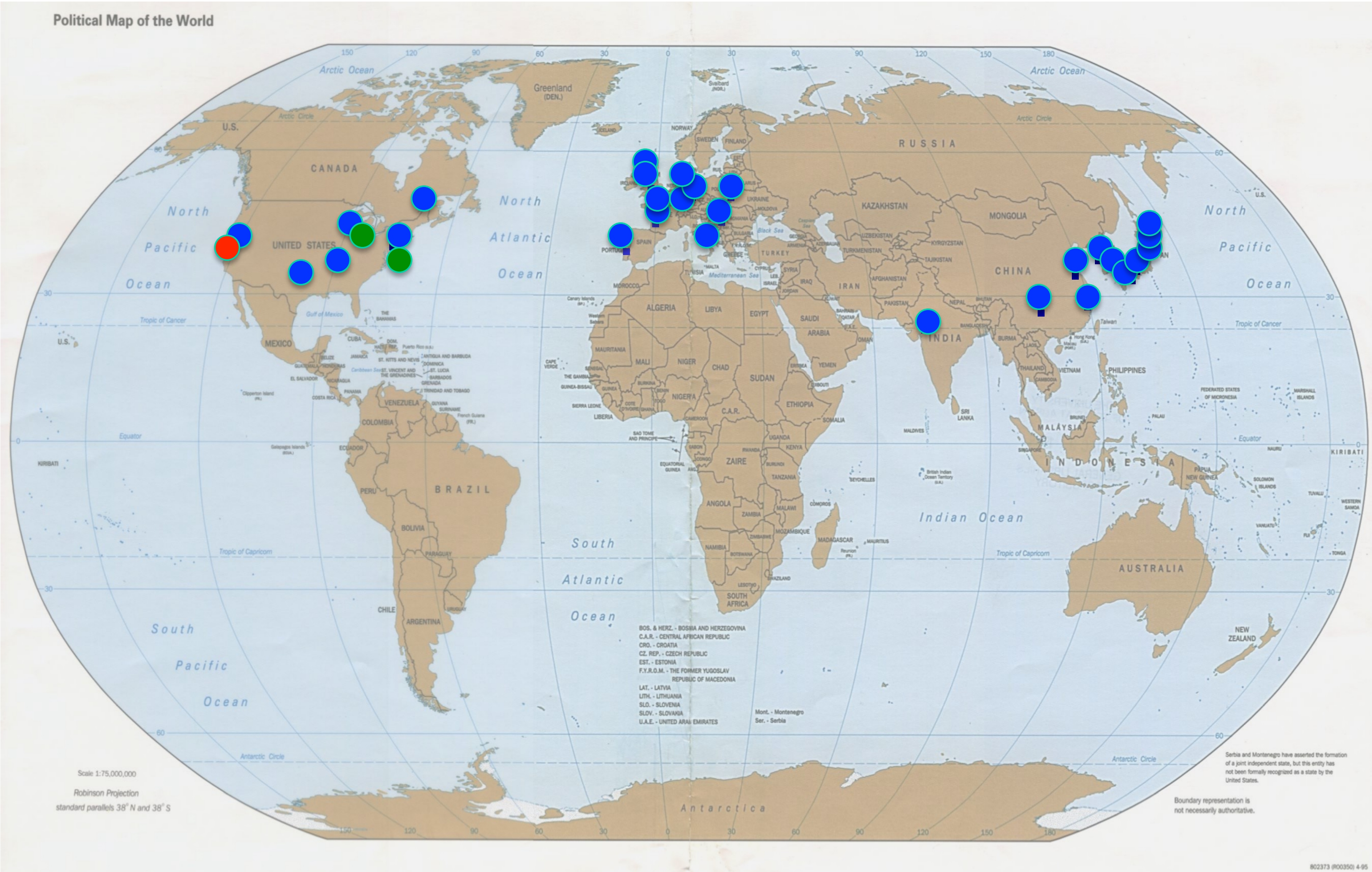

1.5 TeV

Beam energy ∝ Laser power

**P=100 kJ/ 1ps**
**L=200 m**
**N=$10^{11}$ e-' s!**

*W. Lu et al., UCLA*

# US and Worldwide Experimental Effort on Plasma Accel




Laser Wake Expts  Electron Wake Expts  e-/e+ Wake Expts

# Review of Experiments

*Beam drivers*

## The E-162/E-164 Collaboration:

C. Barnes, I. Bluenfield, F.-J. Decker, P. Emma, M. J. Hogan, R. Iverson, R. Ischebeck, N. Kirby, P. Krejcik, C. O' Connell, P. Raimondi, R.H. Siemann, D. Walz

*Stanford Linear Accelerator Center*

B. Blue, C. E. Clayton, C. Huang, C. Joshi, D. Johnson, K. A. Marsh, W. B. Mori, W. Lu, M. Zhou

*University of California, Los Angeles*

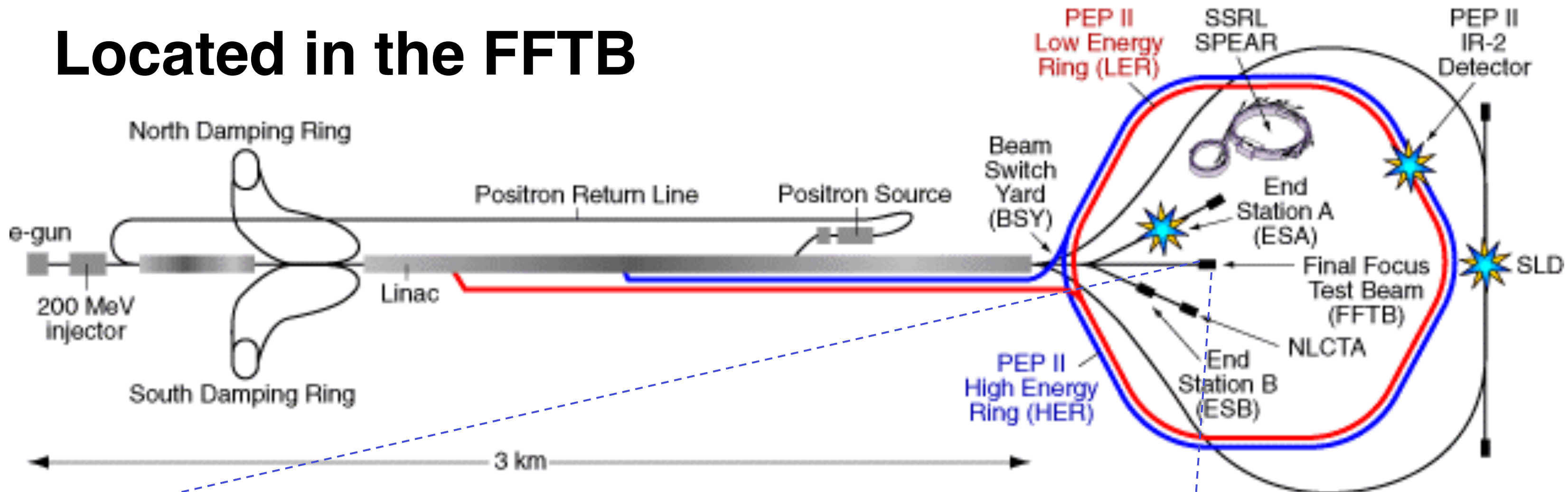
T. Katsouleas, S. Deng, S. Lee, P. Muggli, E. Oz

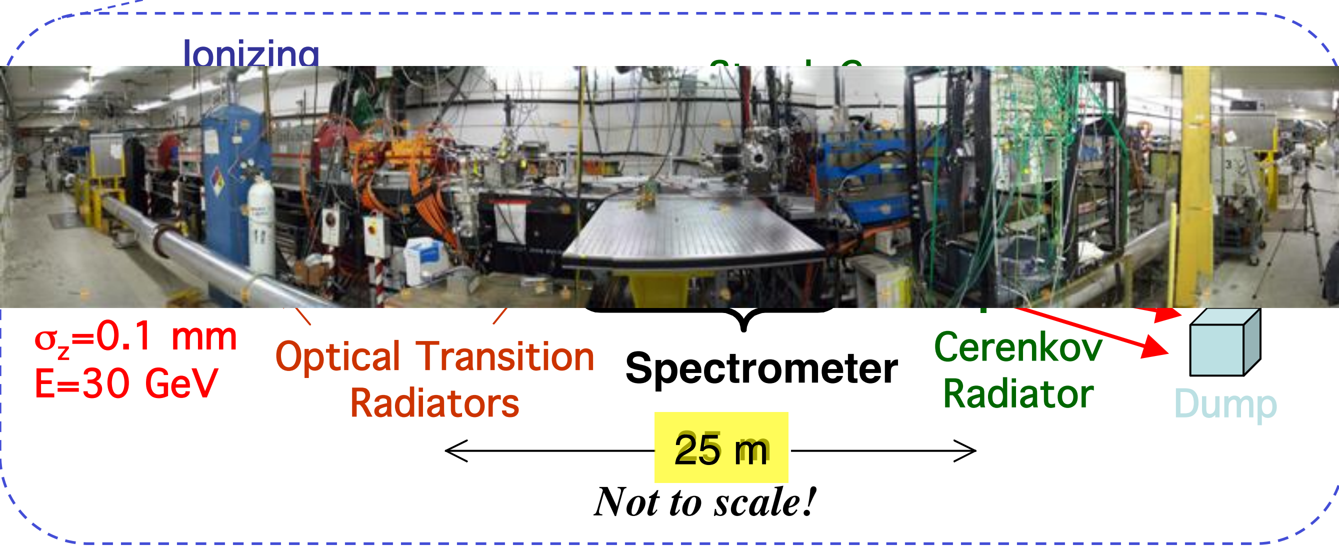
*University of Southern California*

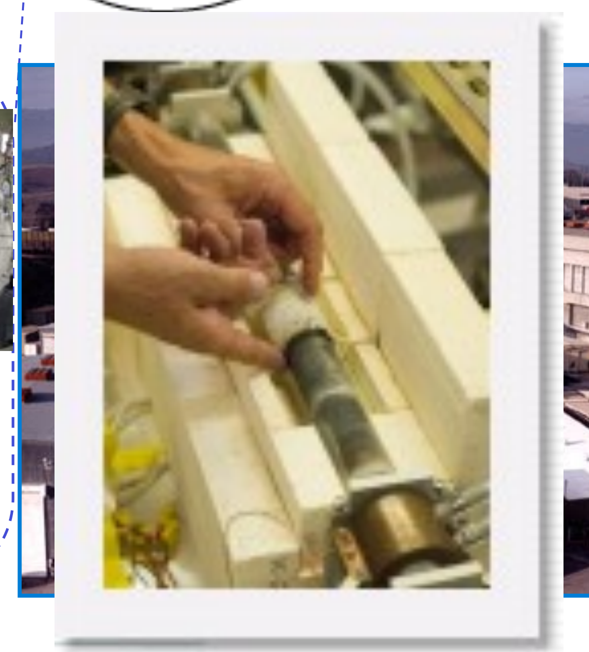
# PWFA Experiments @ SLAC

*Share common apparatus*

## Located in the FFTB

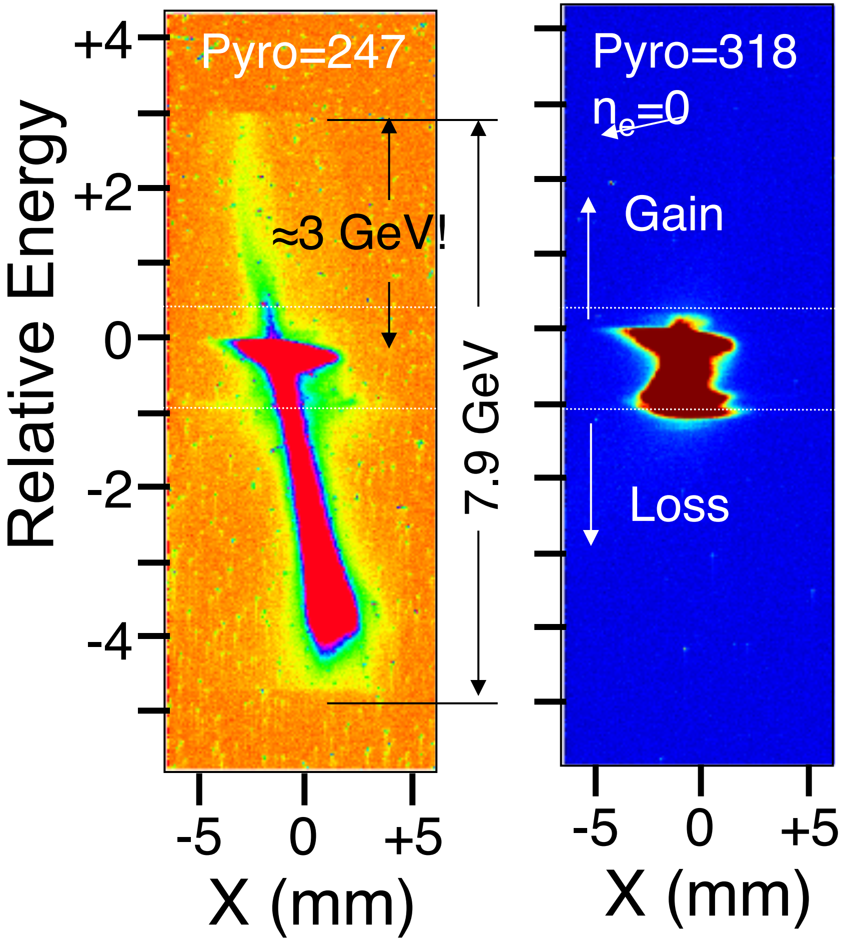


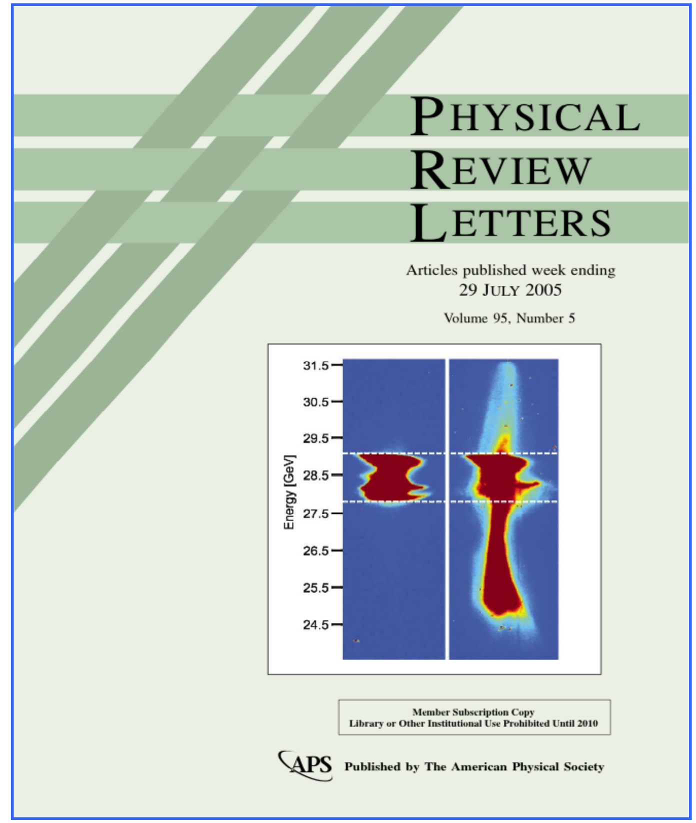



# E164X breaks GeV barrier

*$L \approx 10$ cm, $n_e \approx 2.55 \times 10^{17}$ cm$^{-3}$, $N_b \approx 1.8 \times 10^{10}$*





PHYSICAL REVIEW LETTERS

Articles published week ending
29 JULY 2005

Volume 95, Number 5



Member Subscription Copy
Library or Other Institutional Use Prohibited Until 2010

APS Published by The American Physical Society

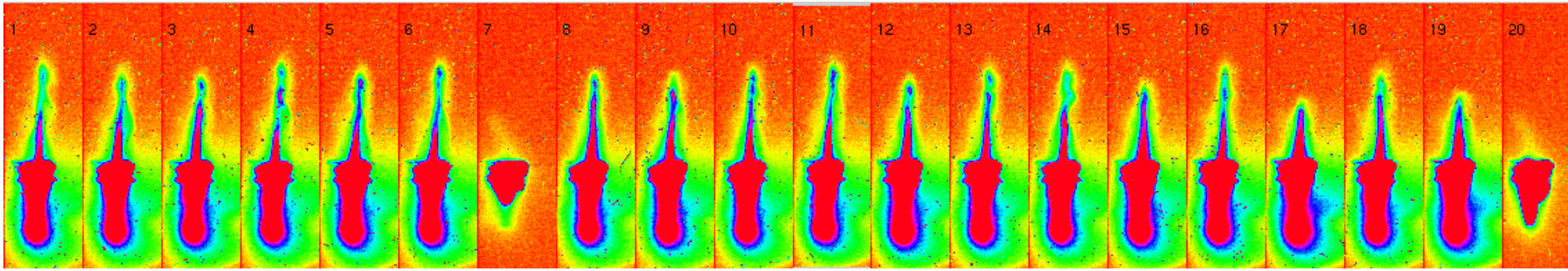
**Energy gain exceeds ≈ 3 GeV in 10 cm**

*M. Hogan, et al. (PRL, July 2005)*

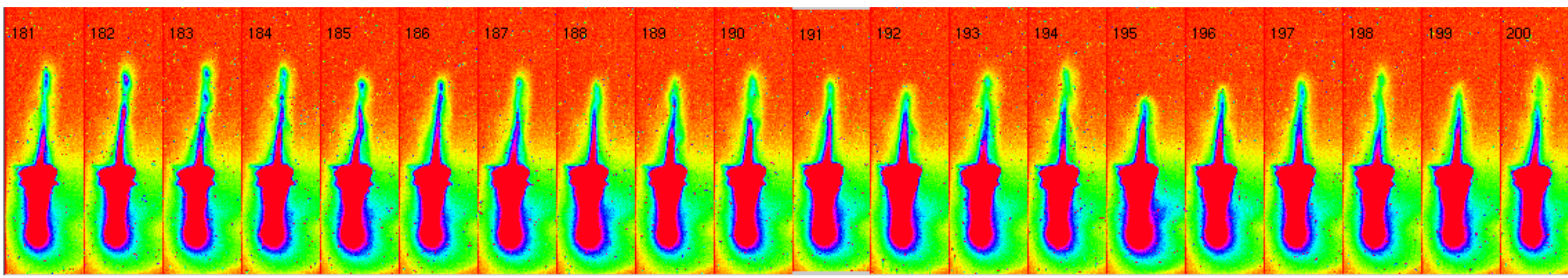
UCLA

USC

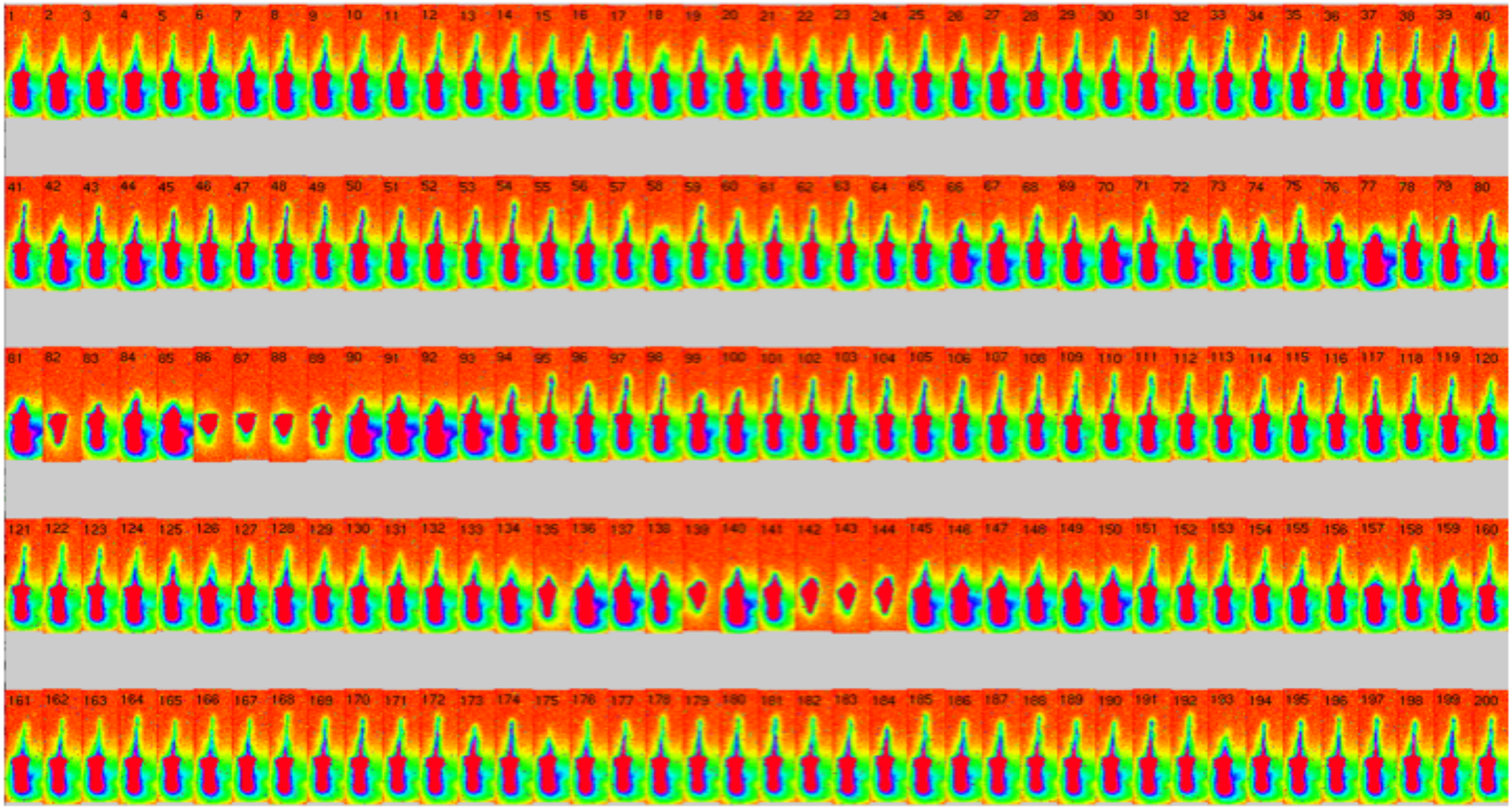
# Data is very reproducible!




. . .

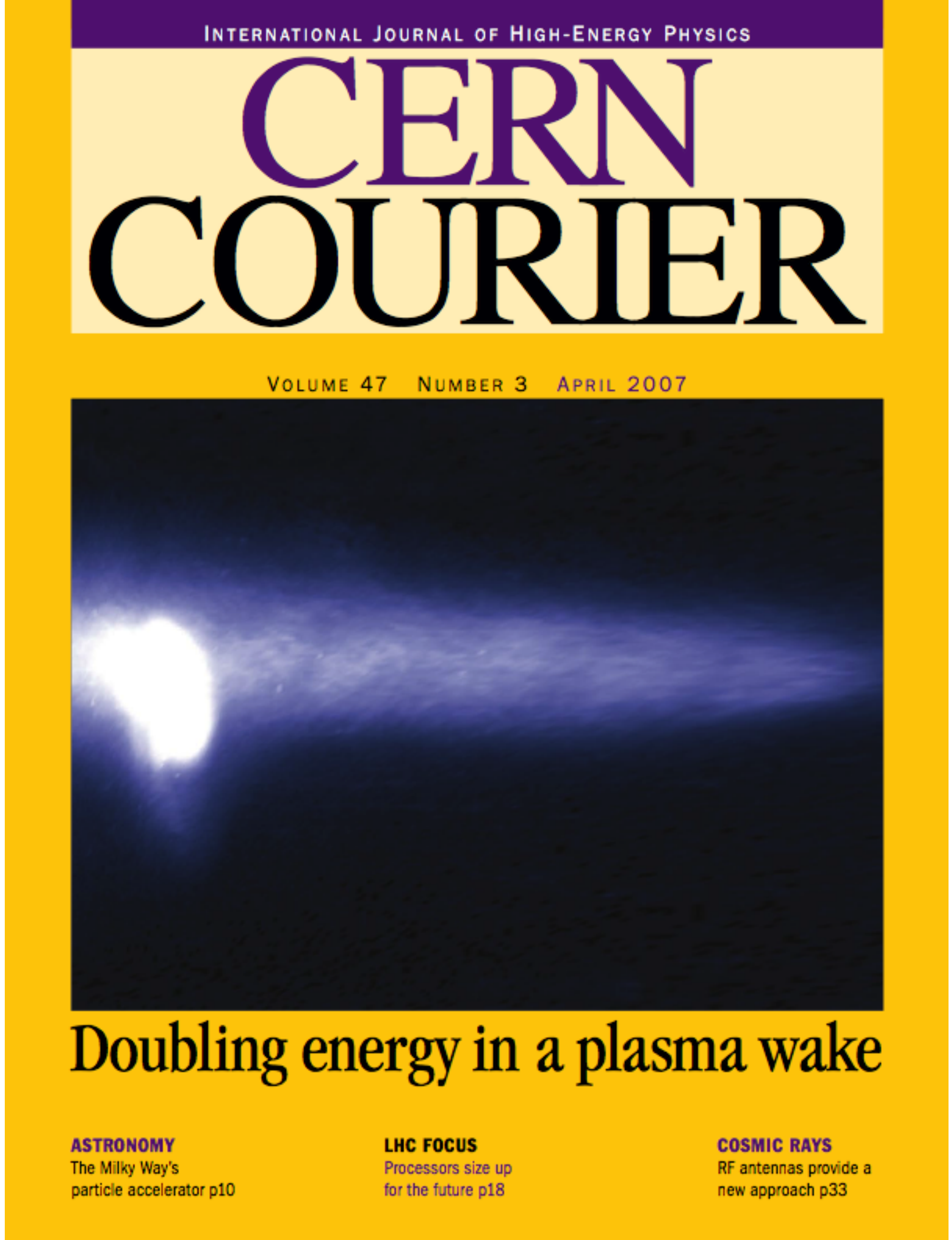


# Data is very reproducible!



Stanford Linear Accelerator Center

USC
UNIVERSITY OF SOUTHERN CALIFORNIA



INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERN COURIER

VOLUME 47 NUMBER 3 APRIL 2007

Doubling energy in a plasma wake

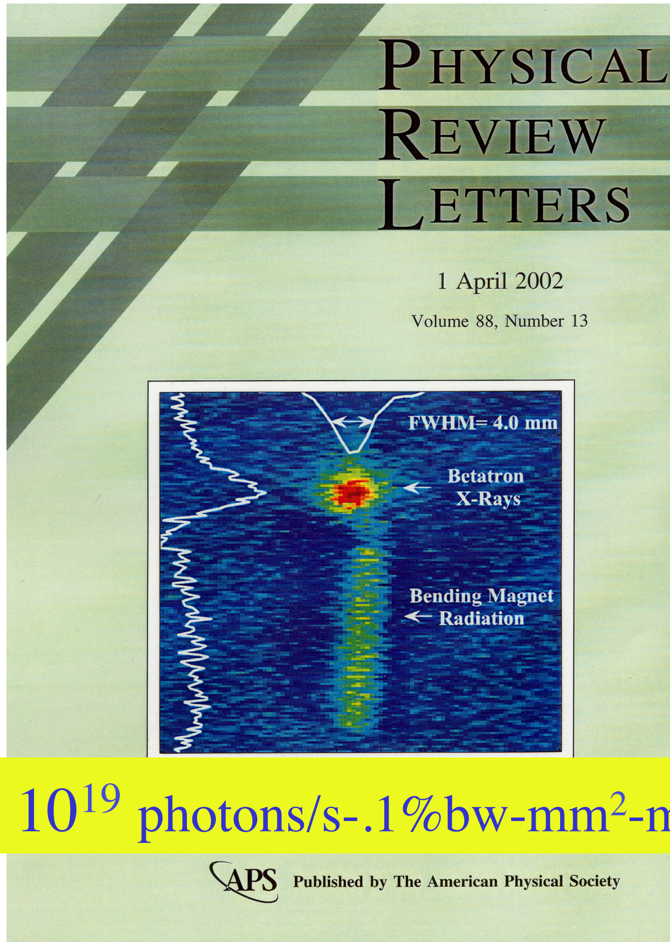
ASTRONOMY
The Milky Way's particle accelerator p10

LHC FOCUS
Processors size up for the future p18

COSMIC RAYS
RF antennas provide a new approach p33

Work supported by DOE

# X-Ray emission from Betatron motion




$I \sim 10^{19}$ photons/s-.1%bw-mm$^2$-mr$^2$ @6 keV

UCLA

USC

*S. Wang et al. Phys. Rev. Lett. Vol. 88 Num. 13*

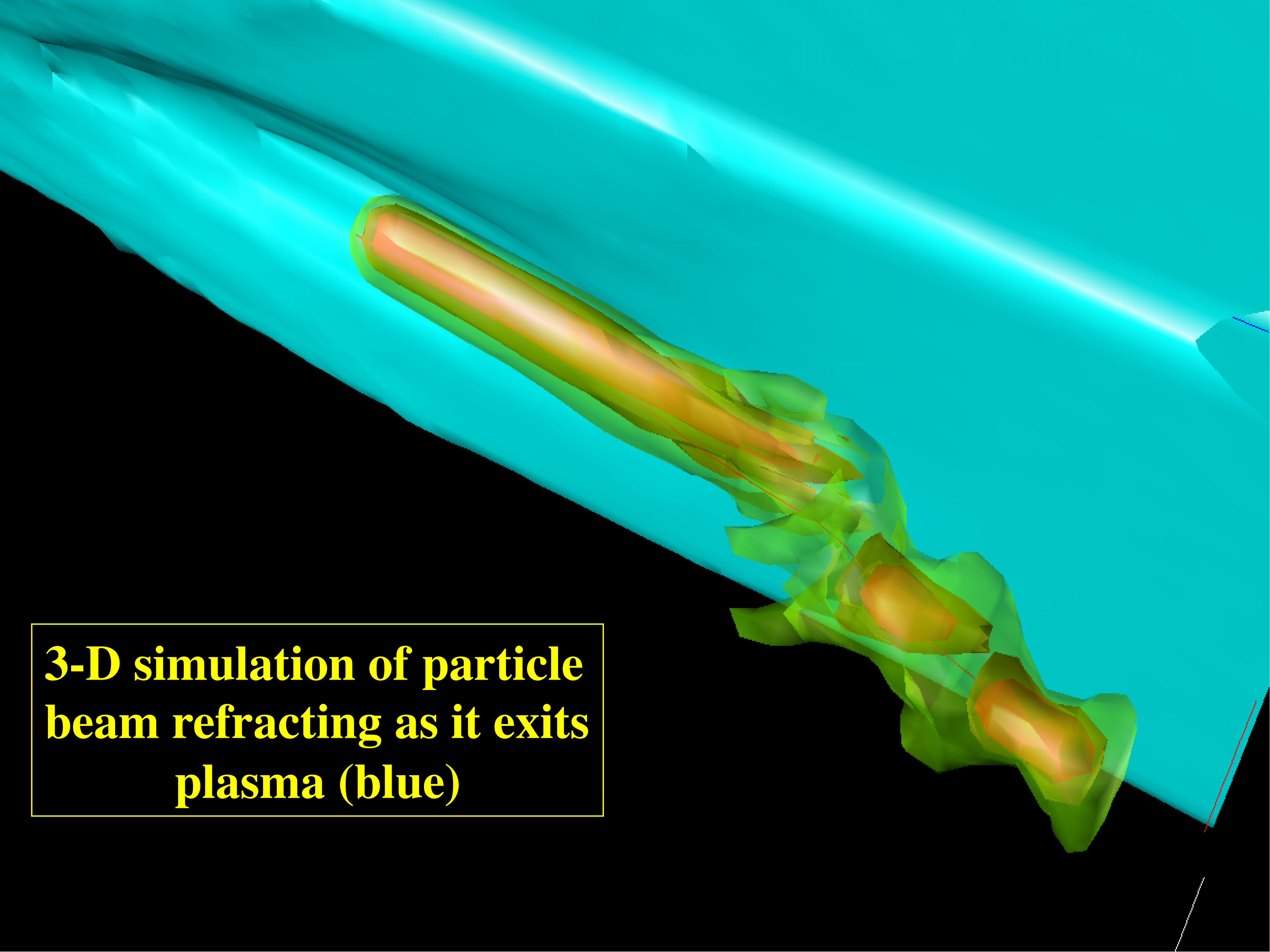
# Beams vs. Lasers?

II. Wakes and beam loading are similar but…

- **Lasers can more easily reach the peak power requirements to access large amplitude plasma wakes**
  - **$100k for a T3 laser vs $5M for even a 50 MeV beam facility**

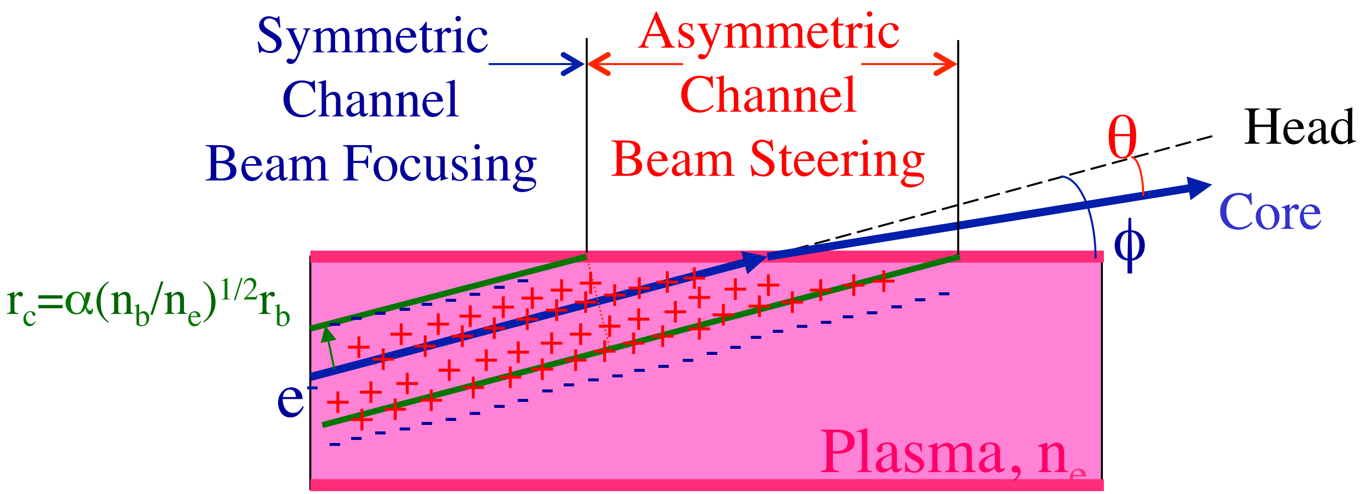
- **Lasers can be bent more easily**

- **Average power cost for beam vs. laser technology sets timescale for HEP app**
  - **$\$10^4$/Watt for lasers currently x 200 MW ~ $20T, but there is much current research on developing high average power lasers.**
  - **$10/Watt for CLIC-type RF x 100 MW**

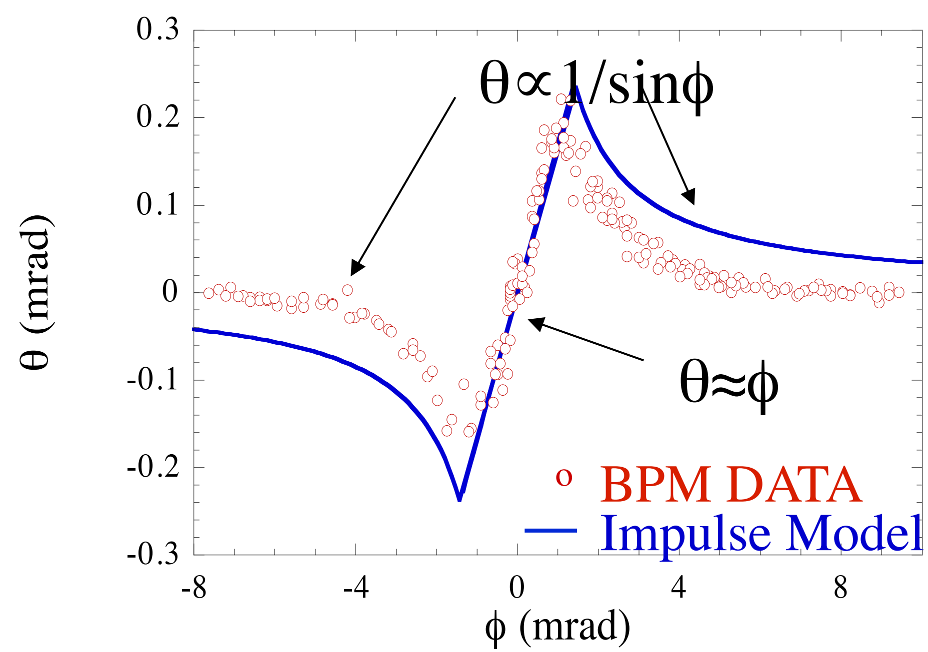


**3-D simulation of particle beam refracting as it exits plasma (blue)**

# Electron Beam Refraction At Plasma–Gas Boundary



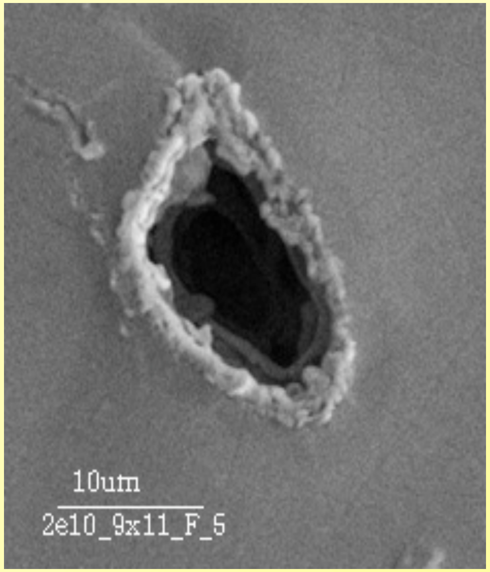

- Vary plasma – $e^-$ beam angle $\phi$ using UV pellicle
- Beam centroid displacement @ BPM6130, 3.8 m from the plasma center




*P. Muggli et al., Nature 411, 2001*

# High power beams tend to blow holes

- 30 GeV e-beam penetrates several mm’s of copper…




Courtesy T. Raubenheimer, M. Ross

# But we have seen…

- 30 GeV beam incident on 1mm of dilute gas (one million times less dense than air)

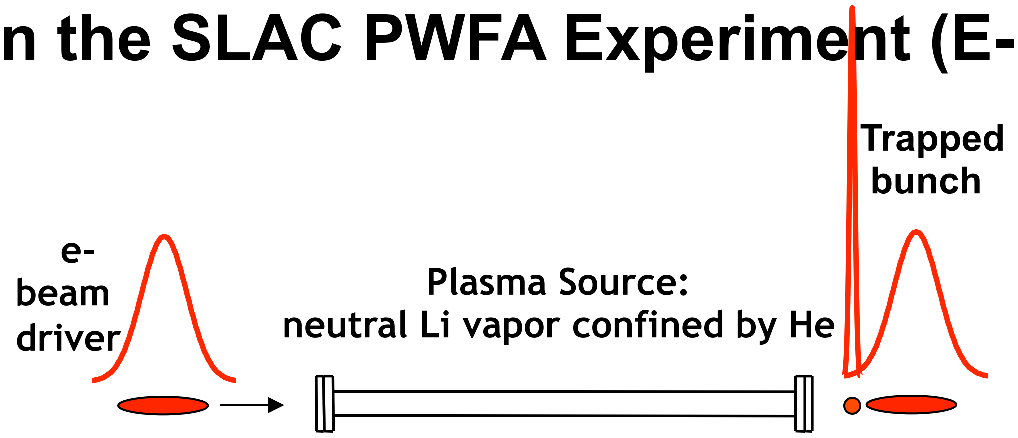
refracts and even...bounces off (total internal reflection)!

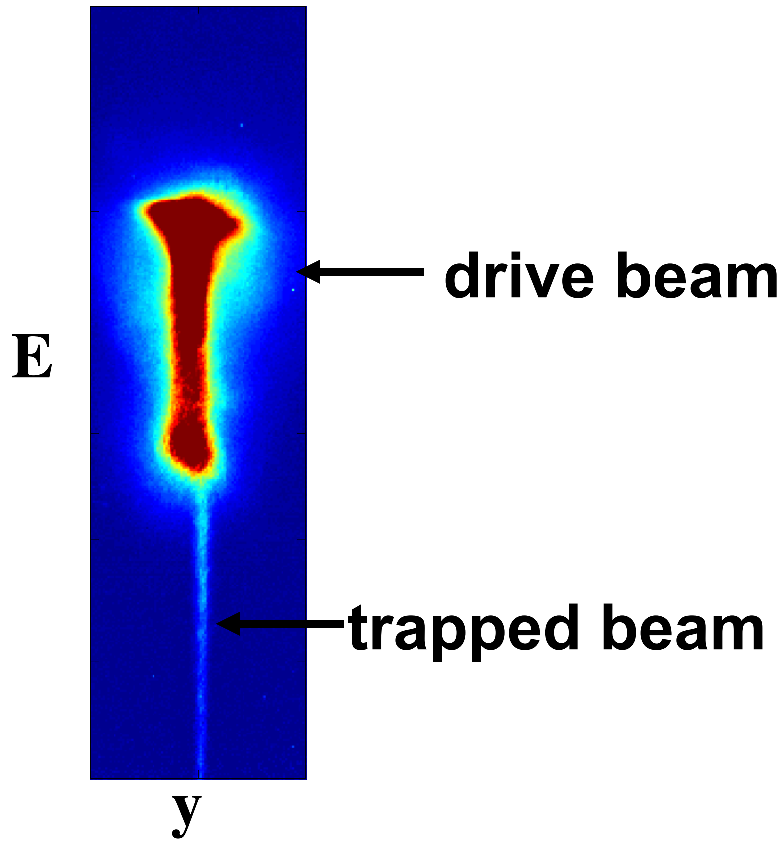
# Plasma Acceleration has put Physics at the Forefront of Science

## Acceleration, Radiation Sources, Refraction, Medical Applications


**From good Physics to a good Collider is a Grand Challenge worth pursuing**

# Evidence for a Brightness Transformer (or 2nd beam generator) in the SLAC PWFA Experiment (E-167)

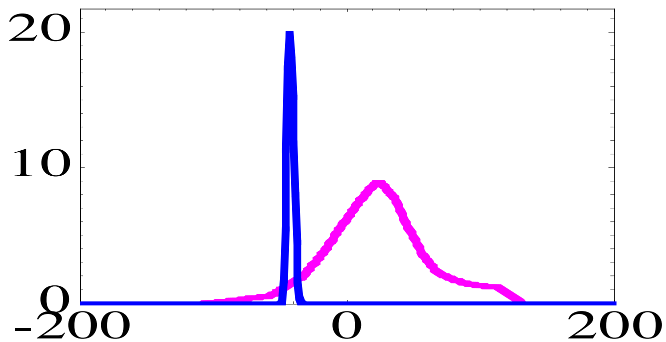


# Unique Source of Bright and Short e- Beams

## Osiris Simulation

| | Trapped Bunch | SLAC Beam Driver |
|---|---|---|
| $I_{peak}$ (kA) | 20 | 9 |
| FWHM (μ) | **2 (6 fs!)** | **65** |
| Emittance (mm-mrad) | **5** | **50** |
| $B_n$ ($A/m^2$-$mm^2$) | **$1.5x10^{15}$ !** | **$7x10^{12}$** |

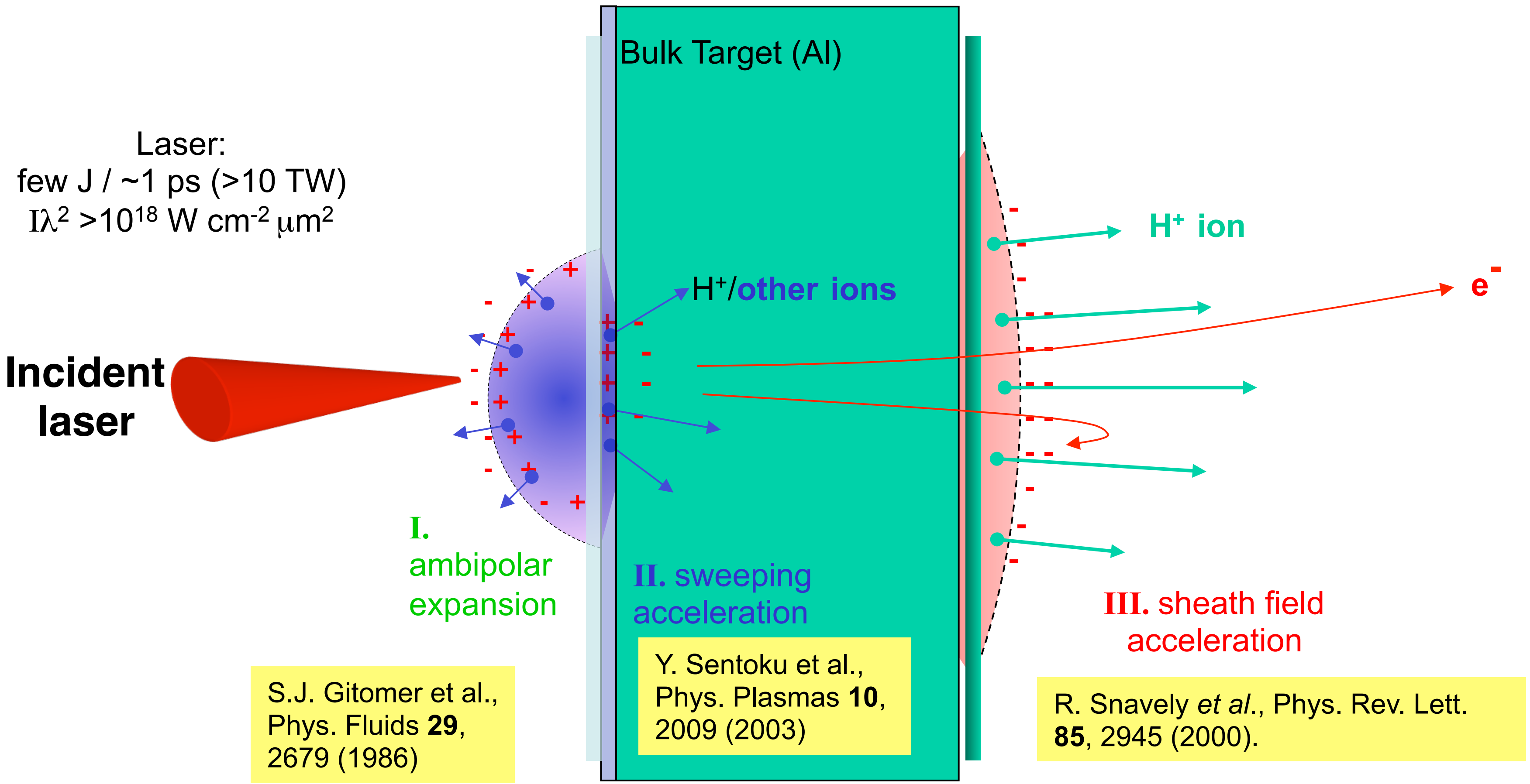



Peak at 11 GeV

FWHM ~%4

# Laser acceleration of *ions* from solid targets

Courtesy J. Fuchs




if target is heated ➔ efficient acceleration of heavy ions

[M. Hegelich et al., Phys. Rev. Lett. **89**, 085002 (2002).]

# Accelerator Summary

On ultra-fast timescales, relativistic plasmas can be robust, stable and disposable accelerating structures

No known show stoppers to a plasma collider, but not enough known to answer the question

The race to the energy frontier is revealing rich physics and applications along the way

*Plasma*

$\lambda$=100μm