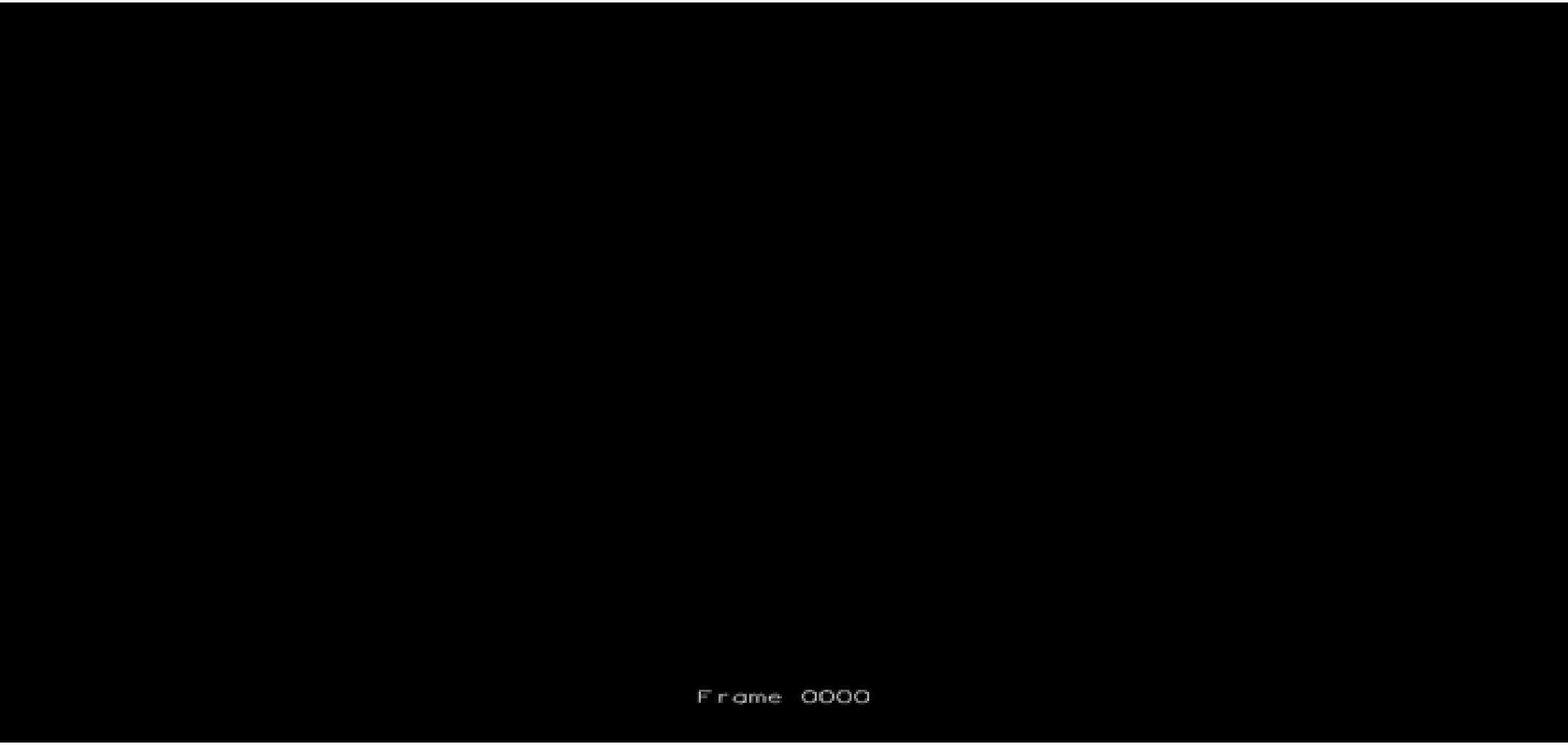
Accelerators and Societal Grand Challenges for the 21st Century



Plasma density isocontours in laser wake. Courtesy F. Tsung

SLAC Duke UNIVERSITY UCLA USC

Accelerators and Societal Grand Challenges for the 21st Century

Tom Katsouleas

Professor and Dean

Duke University, Pratt School of Engineering

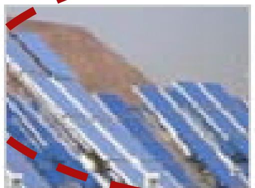
↑

NAE Engineering Achievements of the 20th Century

technology devices

1. Electrification
2. Automobiles
3. Jets and planes
4. Water distribution
5. Lasers
6. Computers
7. Imaging Tech (PET)
8. Agro machinery
9. Highways
10. Electronics, TV,…
11. Nuclear technologies
12. Space travel
13. The Internet
14. Advanced materials

NAE Grand Challenges for the 21st Century


Make solar energy economical


Provide energy from fusion

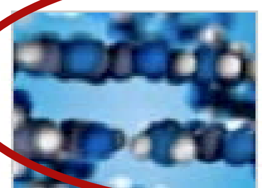

Develop carbon sequestration methods


Manage the nitrogen cycle


Provide access to clean water


Restore and improve urban infrastructure

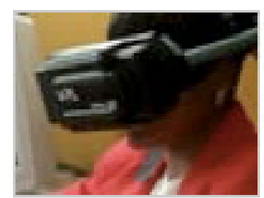

Advance health informatics


Engineer better medicines


Reverse-engineer the brain


Prevent nuclear terror


Secure cyberspace


Enhance virtual reality


Advance personalized learning

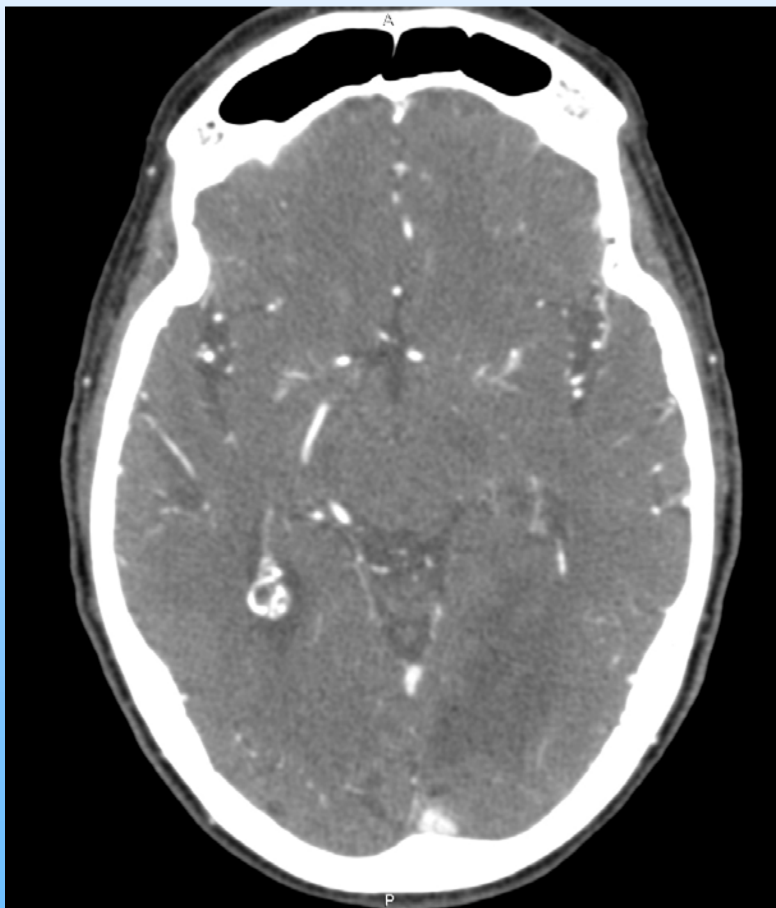

Engineer the tools of scientific discovery

Engineering Better Medicines

CT has revolutionized clinical medicine

X-ray source advances: One slice in 30 min 1973 to 40 slices/sec in 2009

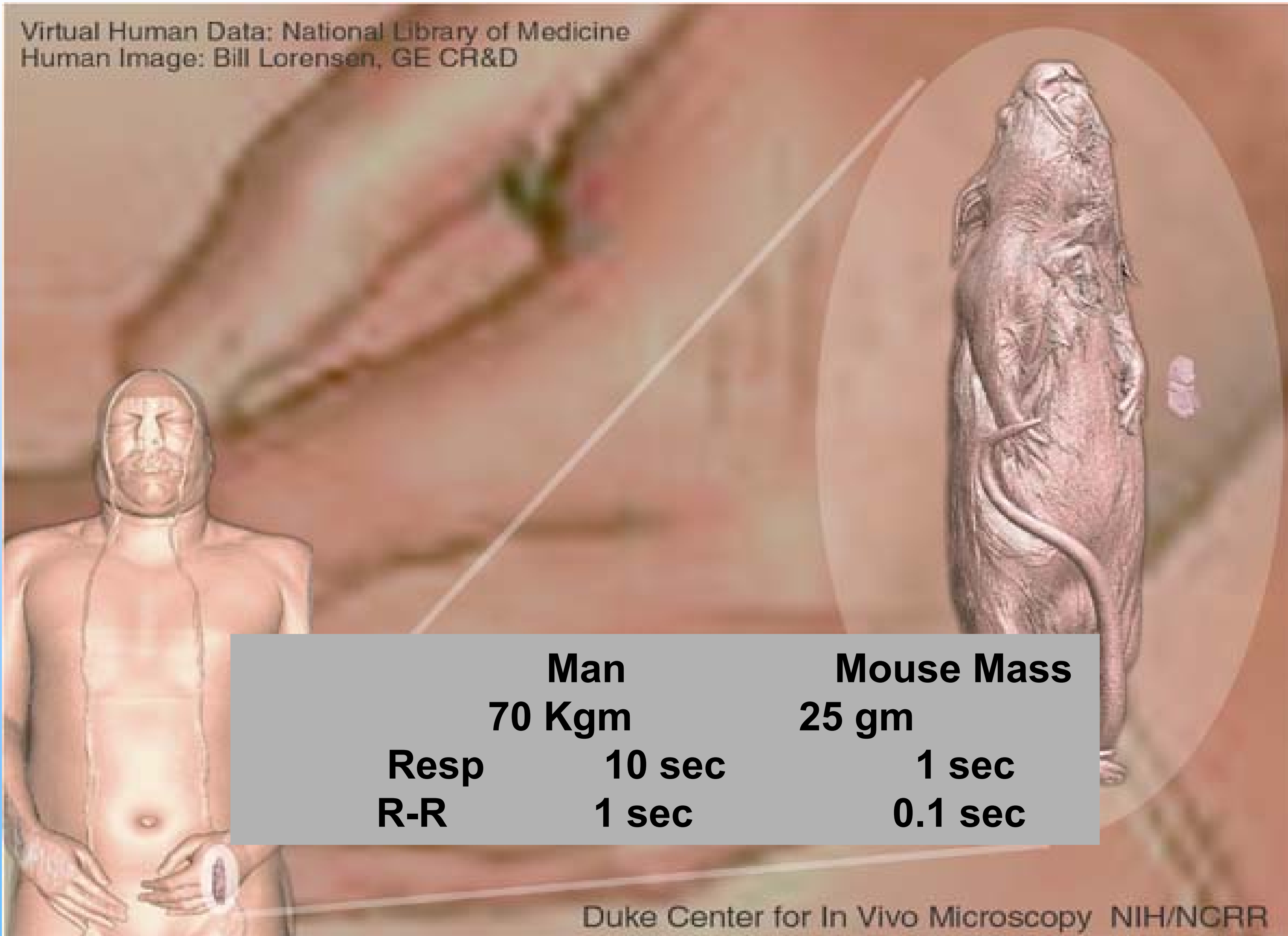
Single CT Slice



Volume rendered Stack of 500 slices

Engineer Better Medicines

Small animal testing requires 30,000 times more X-ray flux



	Man	Mouse Mass
	70 Kgm	25 gm
Resp	10 sec	1 sec
R-R	1 sec	0.1 sec

Engineering Better Medicines

"Brighter, tunable and portable sources will revolutionize the basic sciences as it has clinical science:"

--Allen Johnson, Duke Medical School

Animals Models in
Genetics
Drug Discovery
Environmental Safety
Basic Physiology
Drug Approval and Safety

Provide Energy from Fusion

Inertial Confinement Fusion concepts require accelerator development

From Lawrence Berkeley National Lab

Prevent Nuclear Terror

X-ray Cargo Imaging, Transmutation of nuclear fuels

From SAIC

Provide Clean Water

Treatment of industrial effluents using electron beam accelerator and adsorption with activated carbon: a comparative study

Maria Helena de Oliveira Sampa, Paulo Roberto Rela, Alexandre Las Casas, Manoel Nunes Mori and Celina Lopes Duarte

Instituto de Pesquisas Energéticas e Nucleares-IPEN-CNEN/SP, Av. Lineu Prestes 2.242, Cidade Universitária, São Paulo 05508-000, Brazil

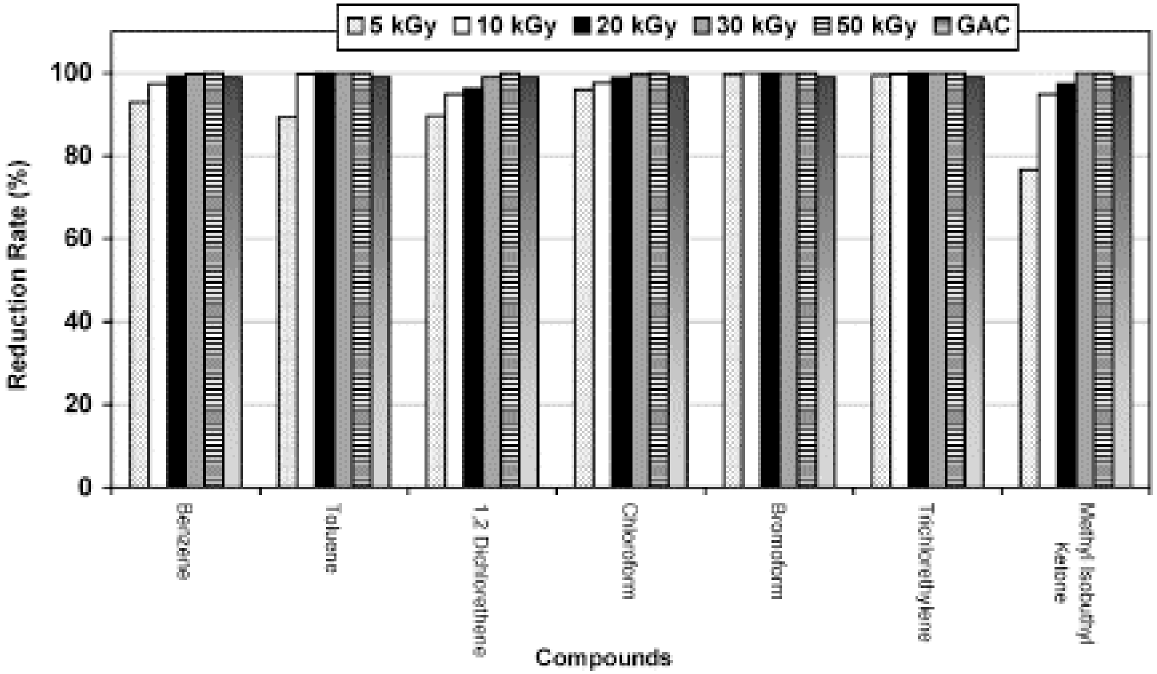


Fig. 1. Organic compounds removal by irradiation and by granular activated carbon (GAC).

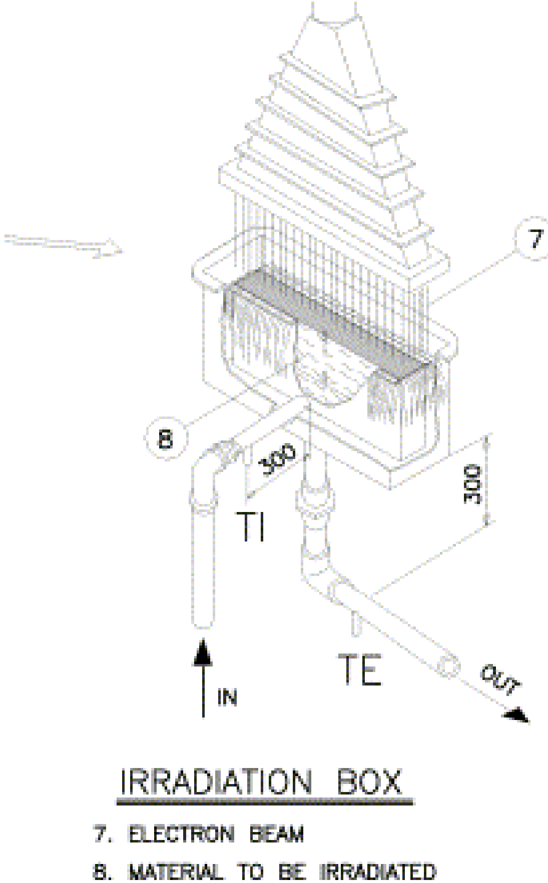


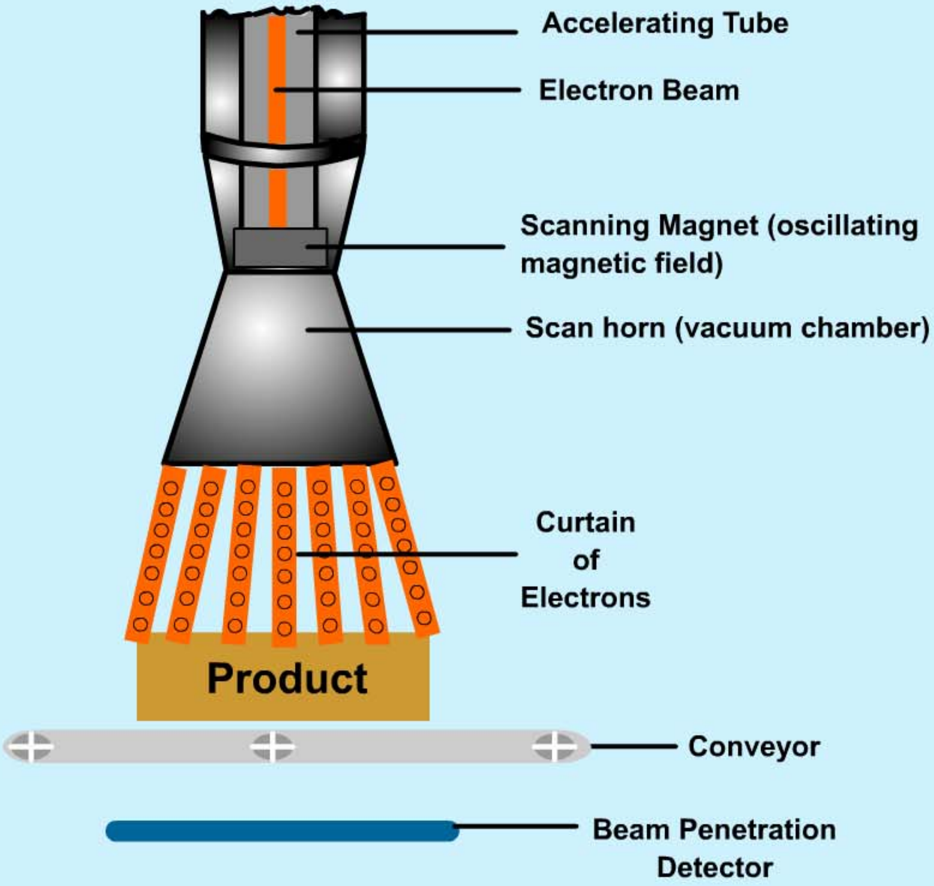
Fig. 1. Schematic diagram of the Pilot Plant for liquid wastewater treatment.

Food Safety and Bio-Security

E. Coli to anthrax

Back

The electron beam passes through a scanning magnet at the end of the accelerator tube that sweeps it back and forth creating a sheet of electrons across the scan horn window.



Scan Horn

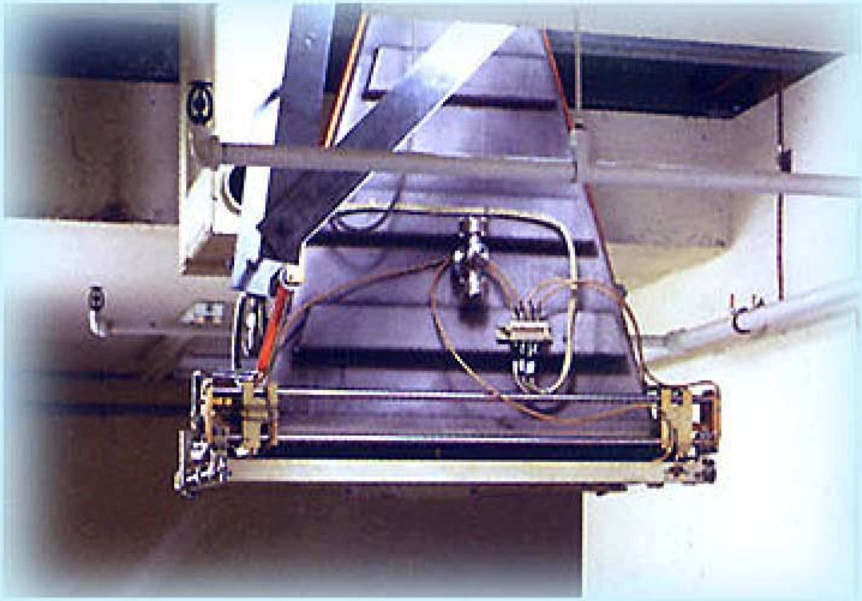
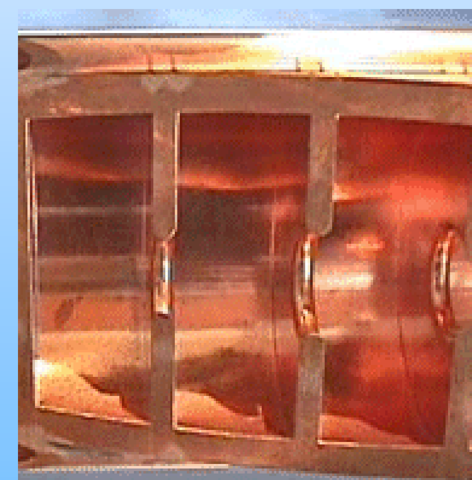
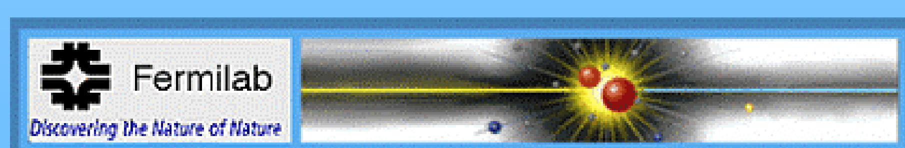


Photo Courtesy of Atomic Energy of Canada Limited

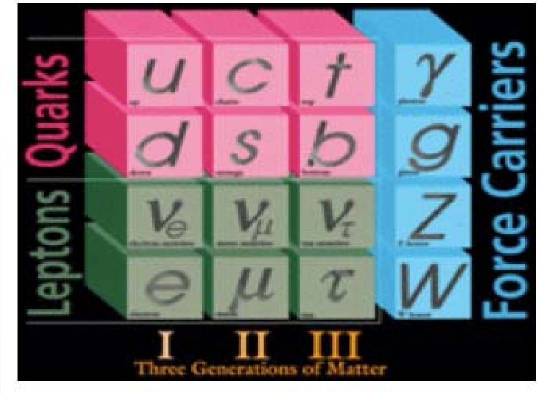
Tools of Scientific Discovery

Accelerators!





Twentieth Century Revolution in Physics



S,W,G

Standard Model

Gell-Mann

Quarks (74,77,95)

Chadwick

Neutron (1932)

Rutherford

Proton, Nucleus (1911)

Thomson

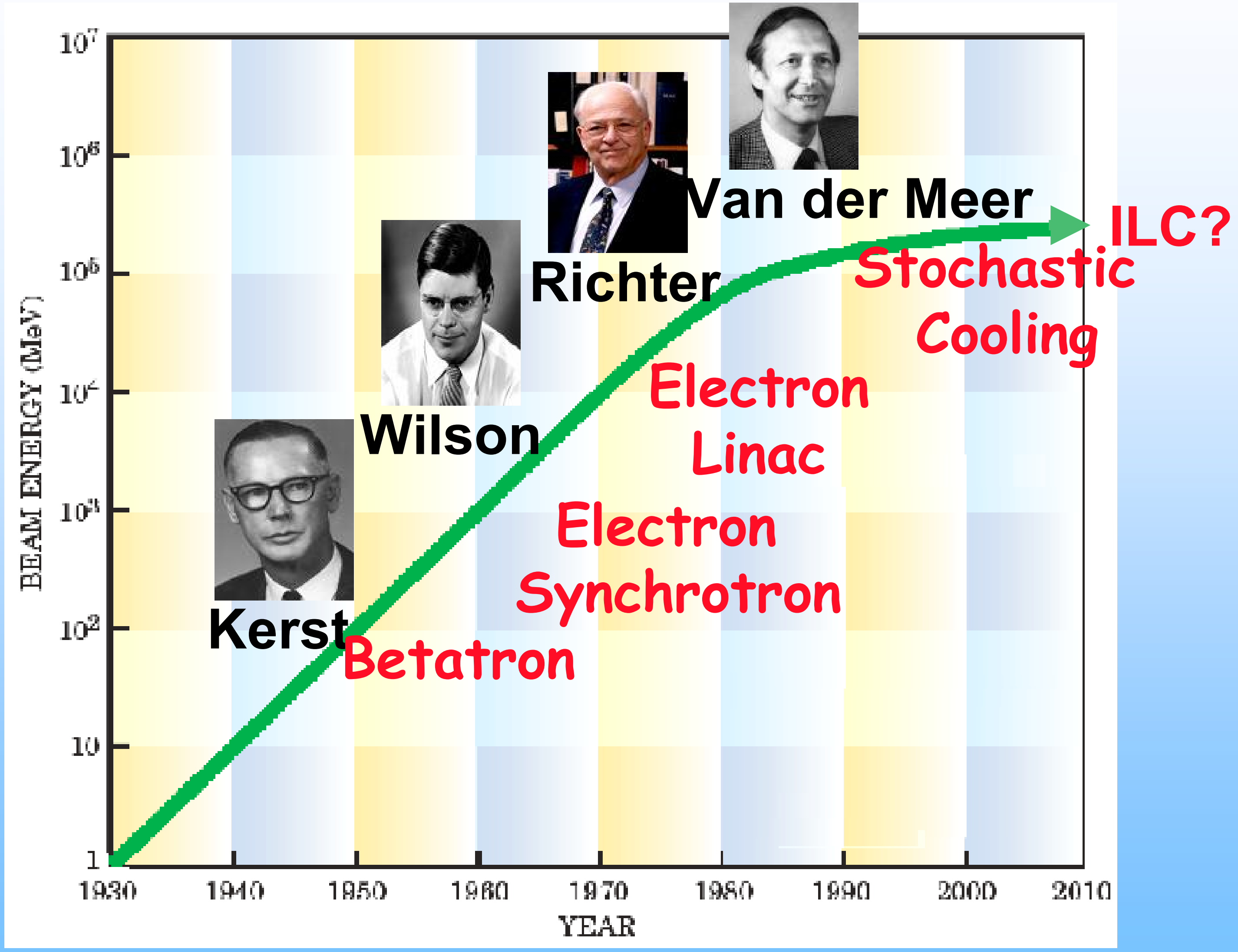
Electron (1897)

NAS Turner Report

11 Science Questions for the 21st Century

1. **What is Dark Matter?**
2. **Dark Energy?**
3. **Early Universe (inflation)?**
4. **Quantum Gravity?**
5. **Neutrino masses?**
6. **Cosmic ray acceleration?**
7. **Protons unstable?**
8. **High density states of matter?**
9. **More space-time dimensions?**
10. **How heavy elements made?**
11. **Beyond the standard model?**

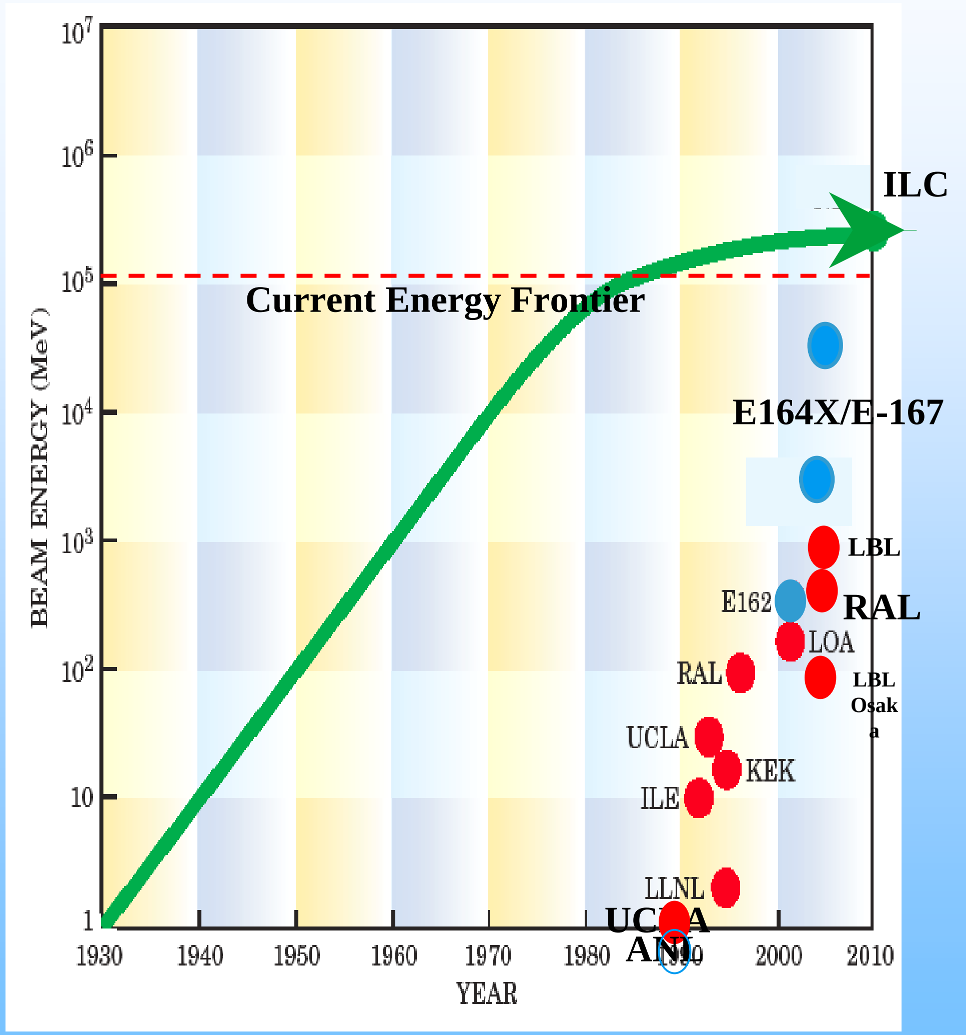
Evolution of Electron Accelerators



New concepts needed to continue advancing

Plasma Accelerators -- Brief History

- 1979 Tajima & Dawson Paper
- 1981 Tigner Panel rec'd investment in adv. acc.
- 1985 Malibu, GV/m *unloaded* laser 'beat' wakes, world-wide effort begins
- 1988 ANL maps beam wakes
- 1992 1st e- at UCLA
- 1994 'Jet age' begins (100 MeV in laser-driven gas jet at RAL)
- 2004 'Dawn of Compact Accelerators' (monoenergetic beams at LBNL, LOA, RAL)
- 2005-7 GeV Beams (SLAC, LBL)
- 2007 Energy Doubling at SLAC



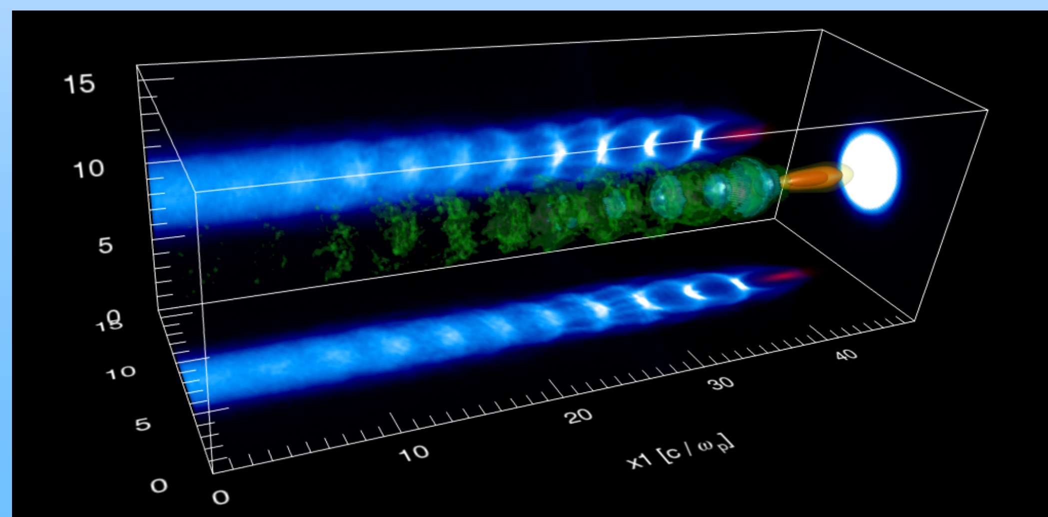
Accelerator Comparison

Plasmas can be miniaturized disposable accelerating structures

Microwave structure

λ~ 30 cm wavelength

E ~ 30 million Volts/meter
"30 MeV/m"



Plasma

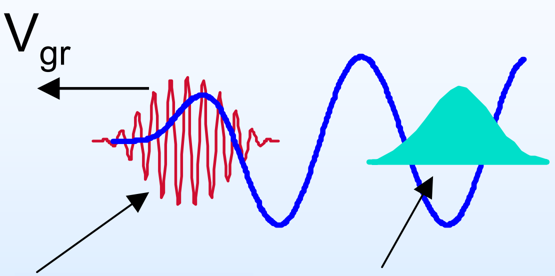
λ ~ 100μm

E ~ 30 billion Volts/meter
"30 GeV/m"

Concepts For Plasma Based Accelerators*

- Laser Wake Field Accelerator

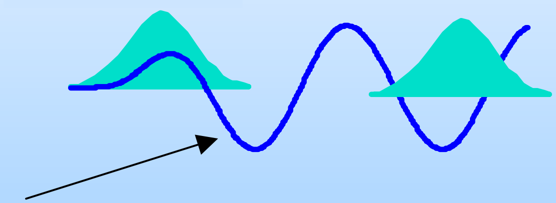
  A single short-pulse of photons



- Drive beam
- Trailing beam

- Plasma Wake Field Accelerator (PWFA)

  A high energy electron bunch



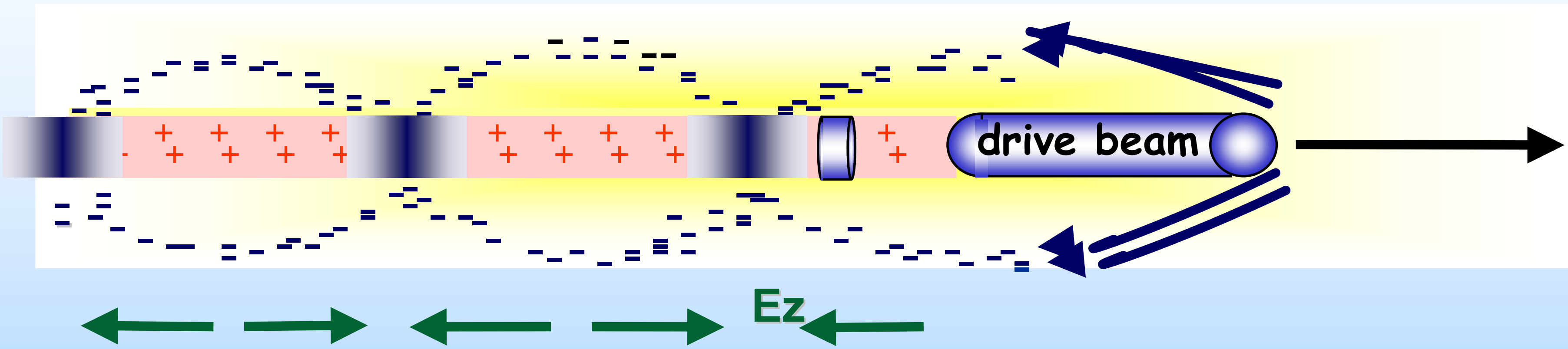
- Wake: phase velocity = driver velocity (V_{gr} or V_b)

***Proposed by John Dawson**

Nonlinear Wakefield Accelerators

(Blowout Regime)

Rosenzweig et al. 1990 *Pukhov and Meyer-te-vehn 2002 (Bubble)*

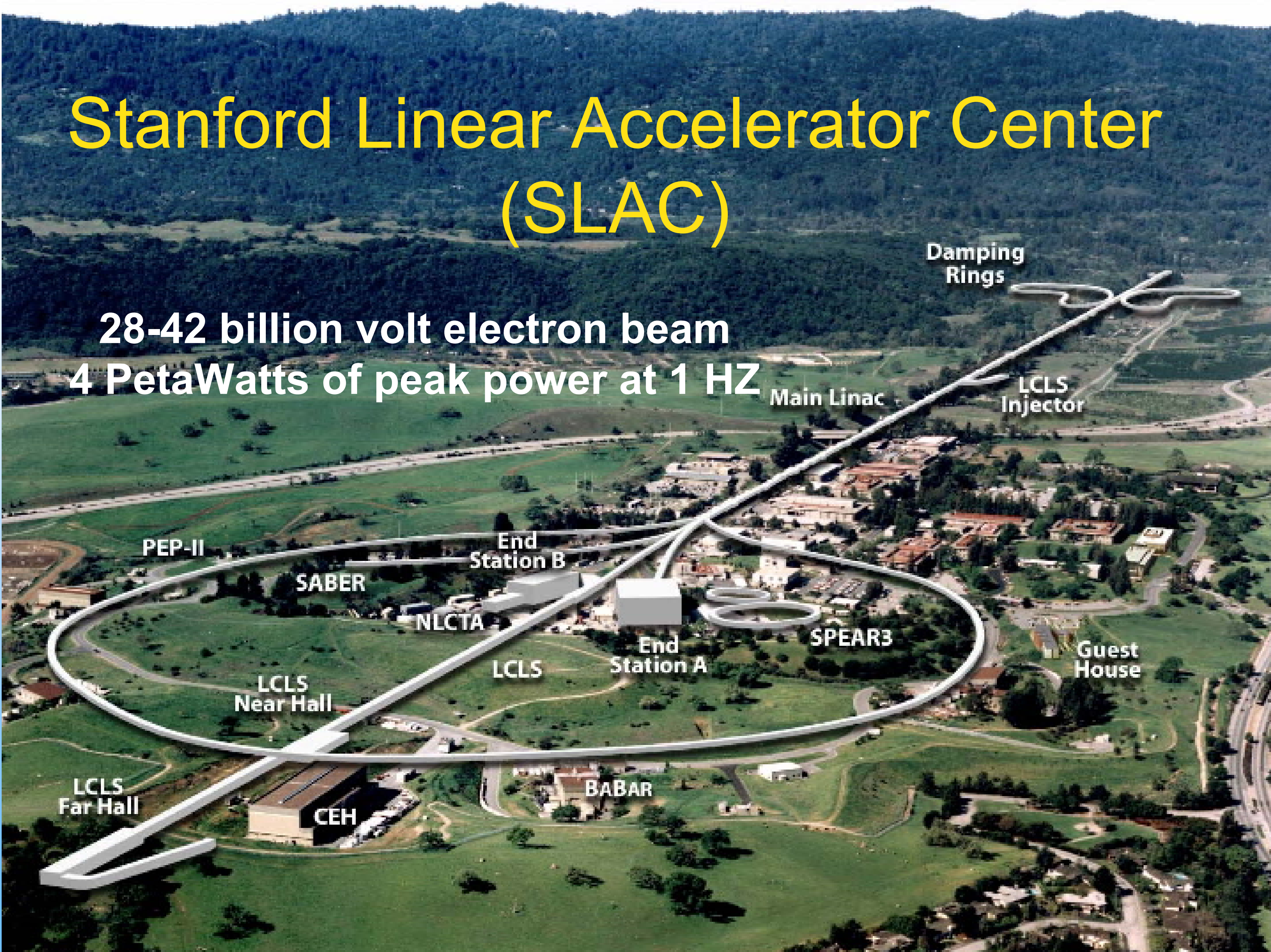


- Space charge or radiation pressure of driver displaces plasma electrons
- Plasma ion channel exerts restoring force => space charge oscillations
  - Focusing force on beams
  - Fiber optic-like guiding of lasers

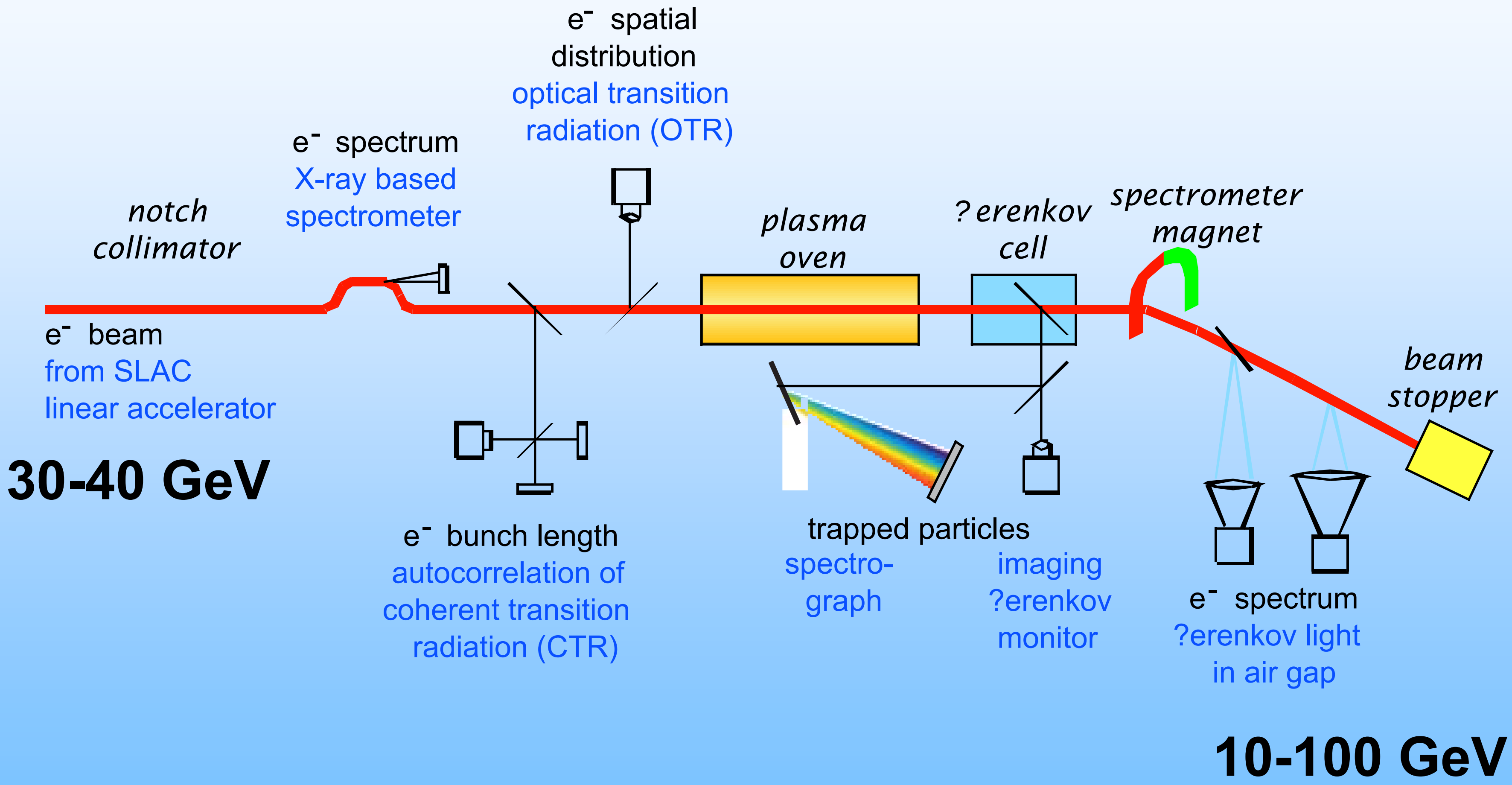
Stanford Linear Accelerator Center (SLAC)

28-42 billion volt electron beam

4 PetaWatts of peak power at 1 HZ



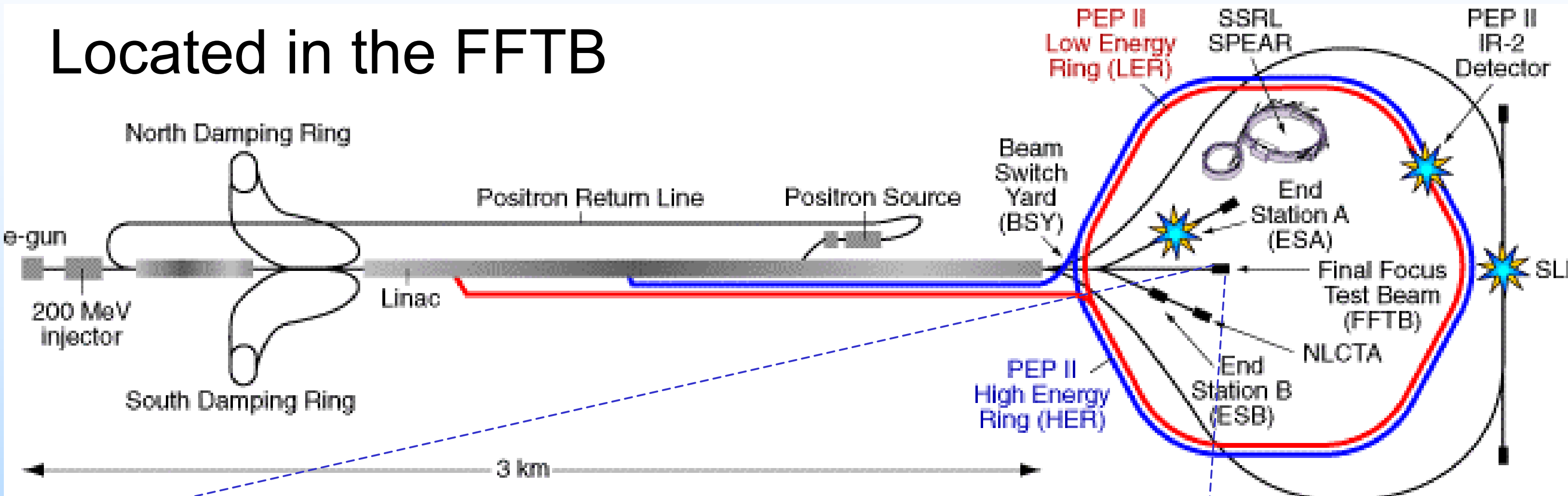
Experimental Setup



PWFA Experiments @ SLAC

Share common apparatus

Located in the FFTB



Ionizing

σ_z=0.1 mm
E=30 GeV

Optical Transition
Radiators

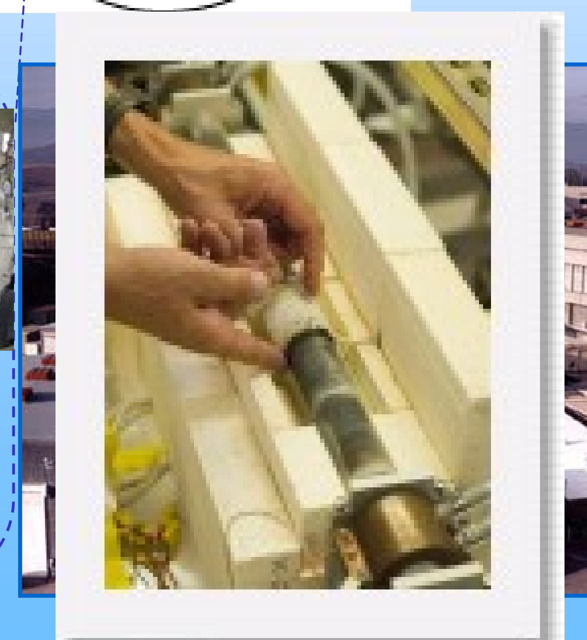
Spectrometer

Cerenkov
Radiator

Dump

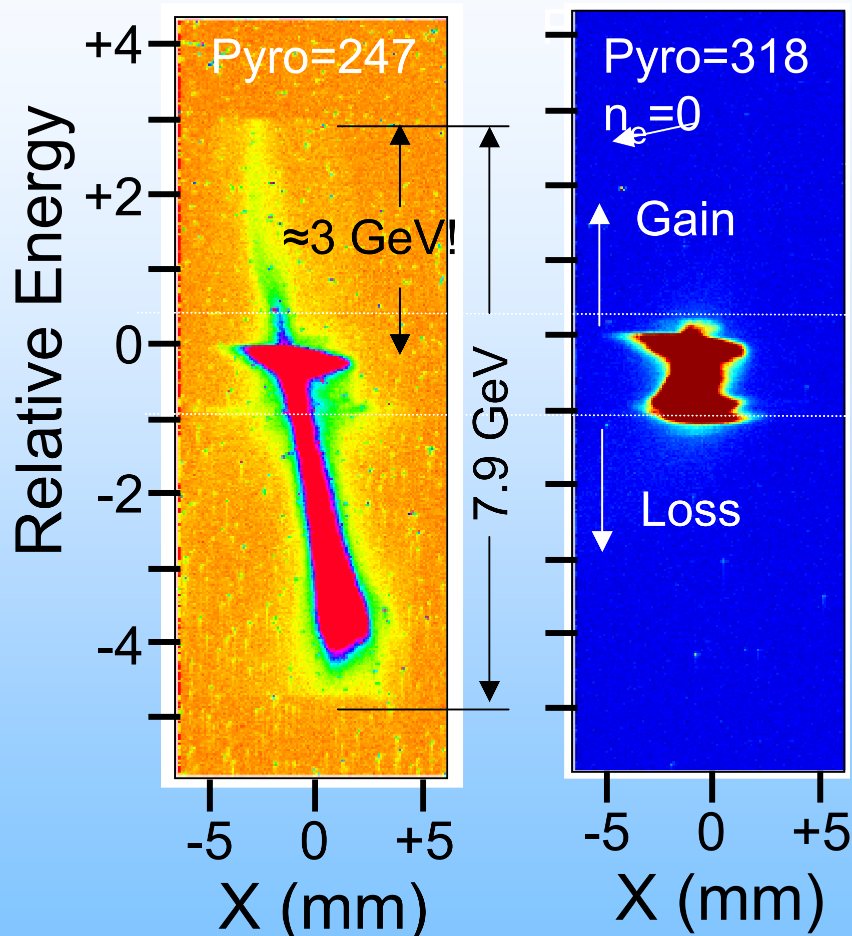
25 m

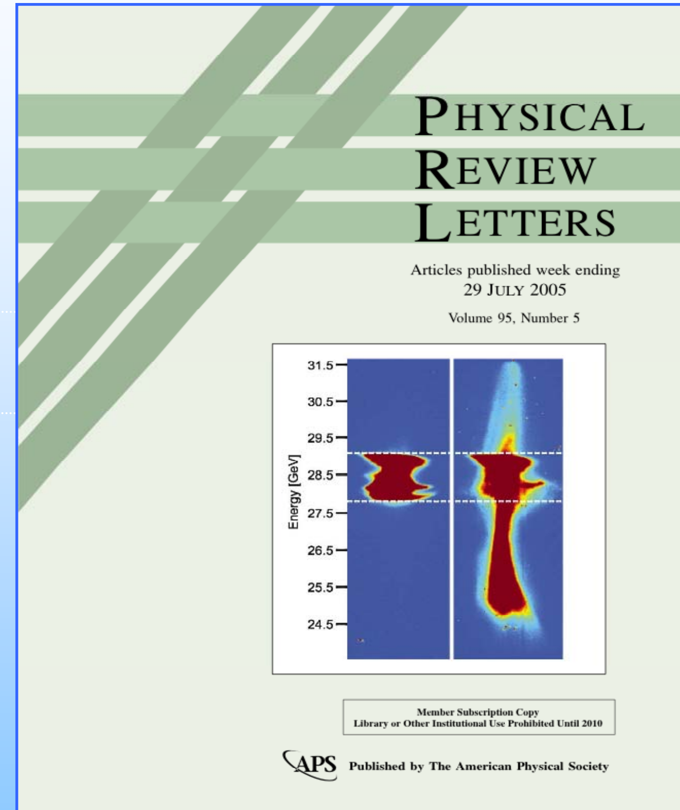
Not to scale!



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

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APS Published by The American Physical Society

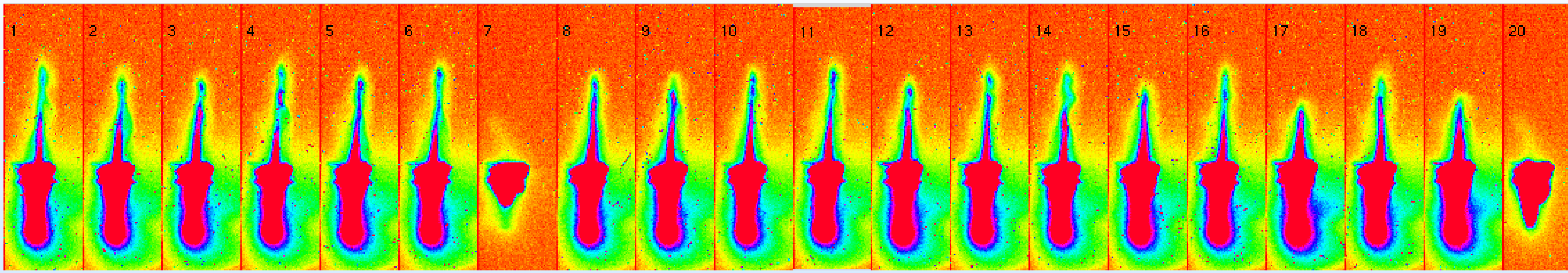
Energy gain exceeds ≈ 3 GeV in 10 cm

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

UCLA

USC

Data is very reproducible!



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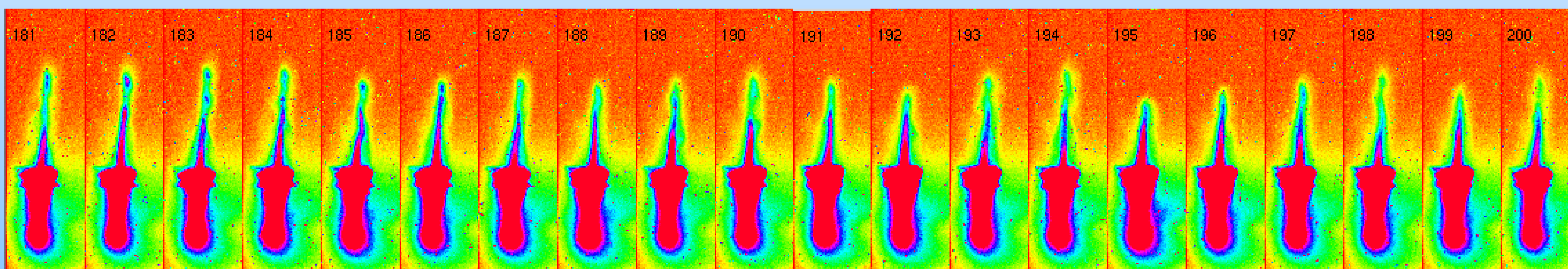

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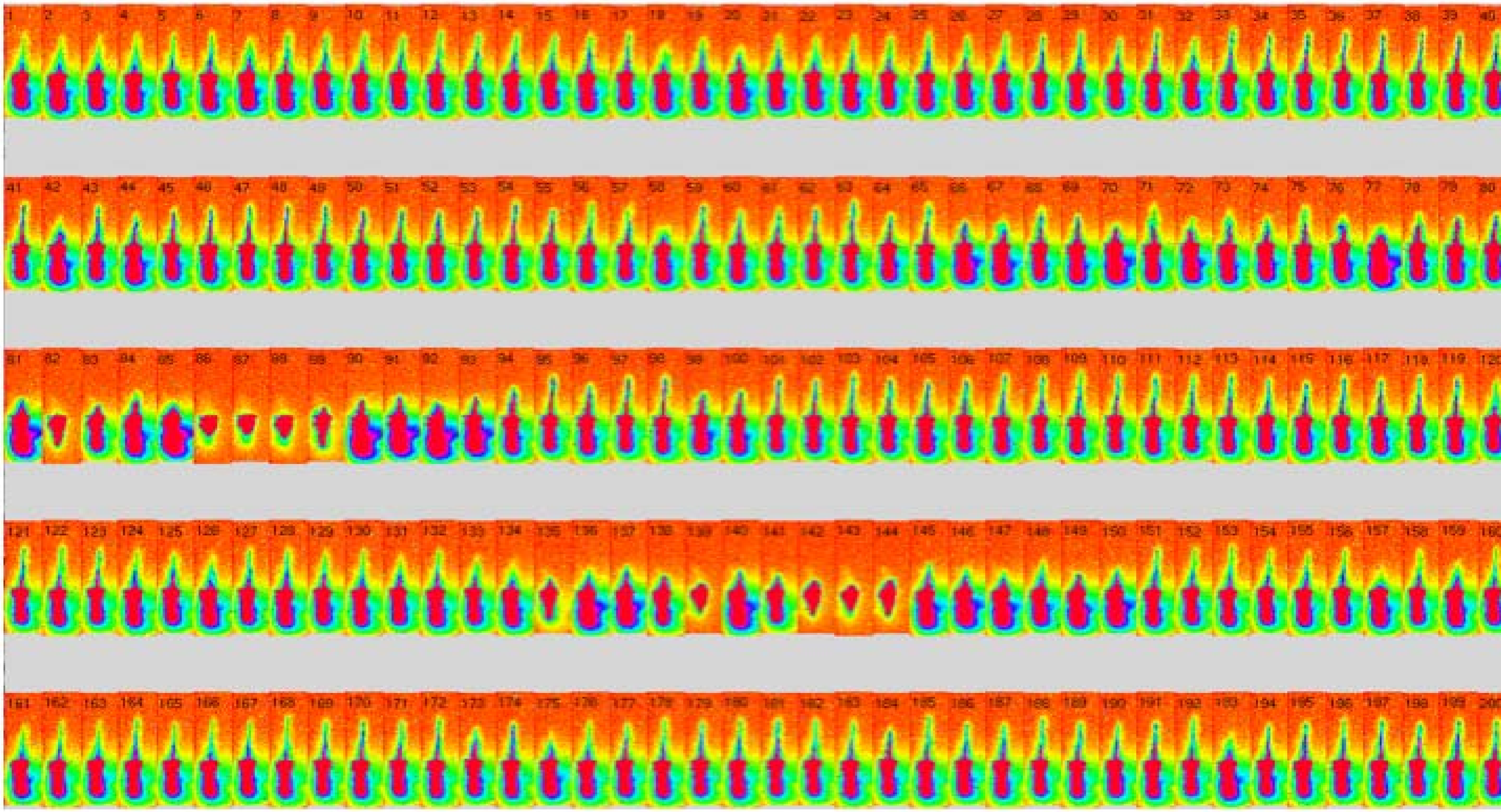
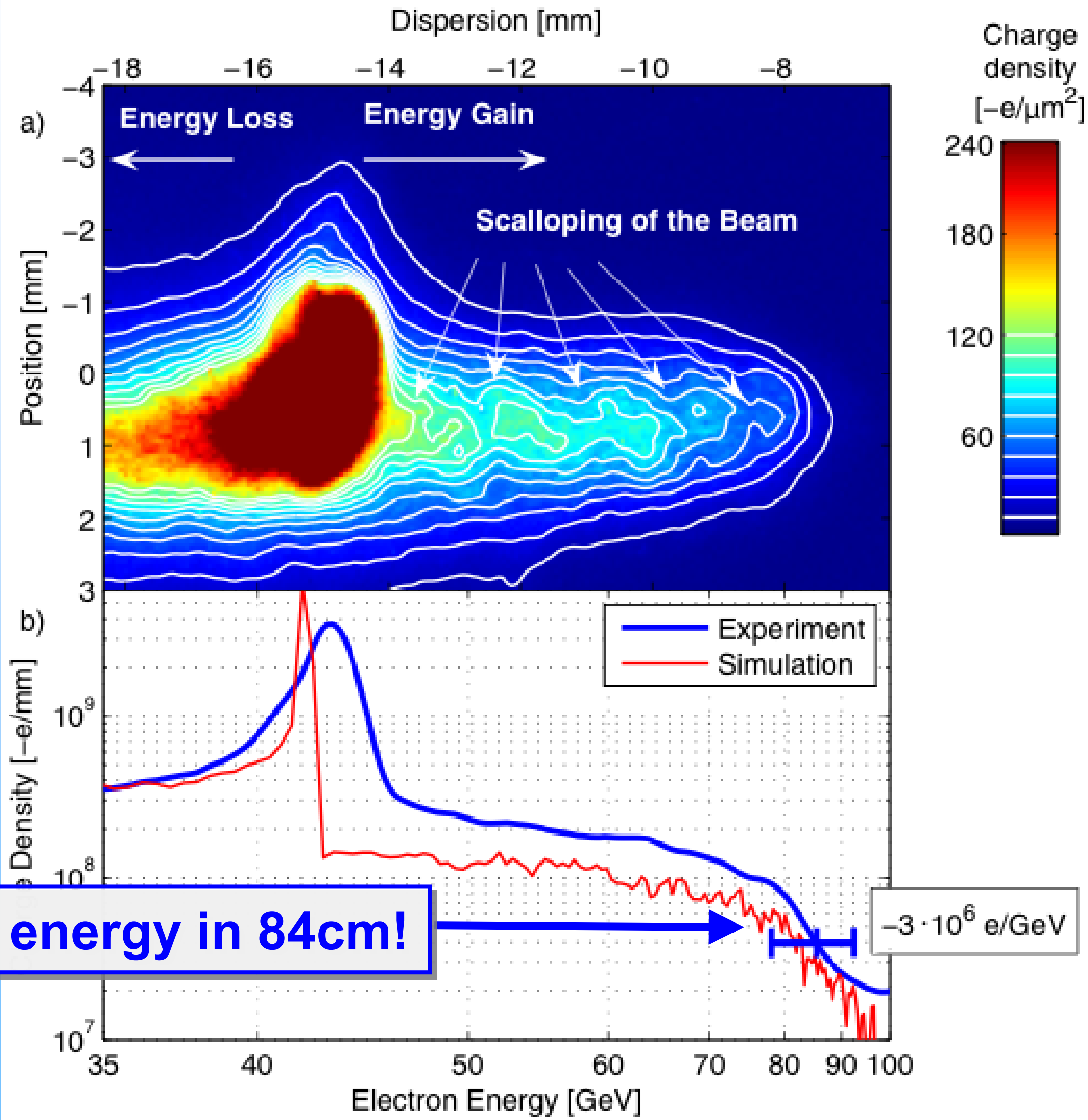


E-167: Energy Doubling with a Plasma Wakefield Accelerator in the FFTB

Linac running all out to deliver compressed 42GeV Electron Bunches to the plasma
Record Energy Gain
Highest Energy Electrons Ever Produced @ SLAC
Significant Advance in Demonstrating Potential of Plasma Accelerators



Some electrons double their energy in 84cm!

Nature vol 445,p741 (2007)

Shortest Path to a TeV Collider

*from present state-of-the-art**

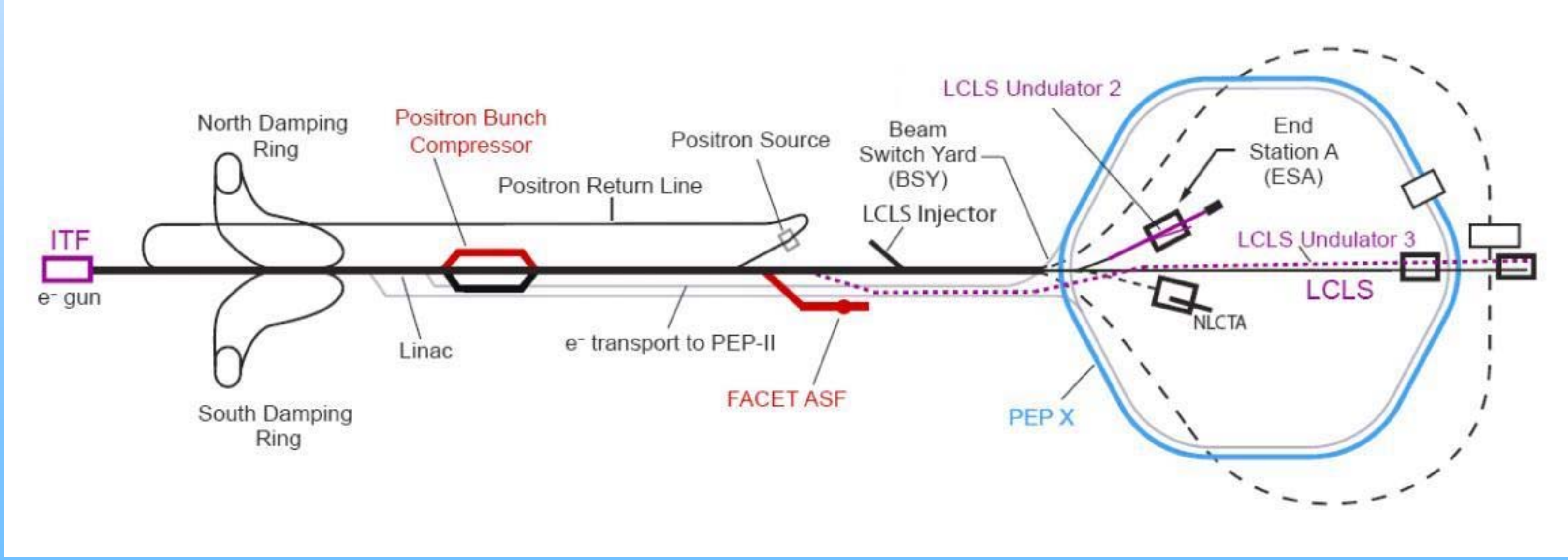
- Starting point: 42 --> 85 GeV in 1m
  - Few % of particles
- Beam load
  - 25 --> 50 GeV in ~ 1m
  - 2nd bunch with 33% of particles
  - Small energy spread
  - Preserve emittance
- Replicate for positrons
- Marry to high efficiency driver
- Stage 20 times

FACET 2010-18 (covers: Beam load through Replicate for positrons)

*** I. Blumenfeld et al., Nature 445, 741 (2007)**

FACET: Facility for Advanced Accelerator Experimental Tests

- Will address critical issues of a single stage
- Uses the SLAC injector complex and 2/3 of the SLAC linac to deliver electrons and positrons
  - "Shovel ready" in 2008
  - Two-year construction funded, underway

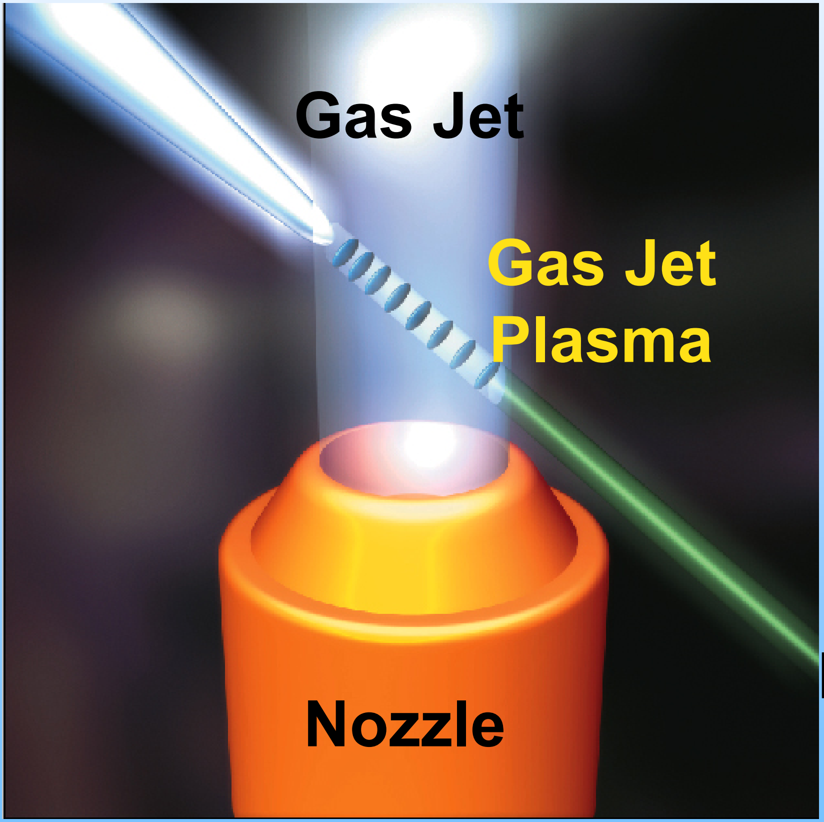


Critical Issues

- Positron acceleration
- Modeling
- Beam loading - create/phase 2nd bunch
- Transverse beam dynamics
  - Hosing
  - Lenses
  - Pointing jitter sub-nm
  - Ion motion (Rosenzweig, 2005)
  - Synchrotron radiation
- Plasma source development
  - Beam-ionized sources, μs - ns refresh?

Table-top Experiments

Jet Age of Laser-Plasma Accelerators (ca. 1994)



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.

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

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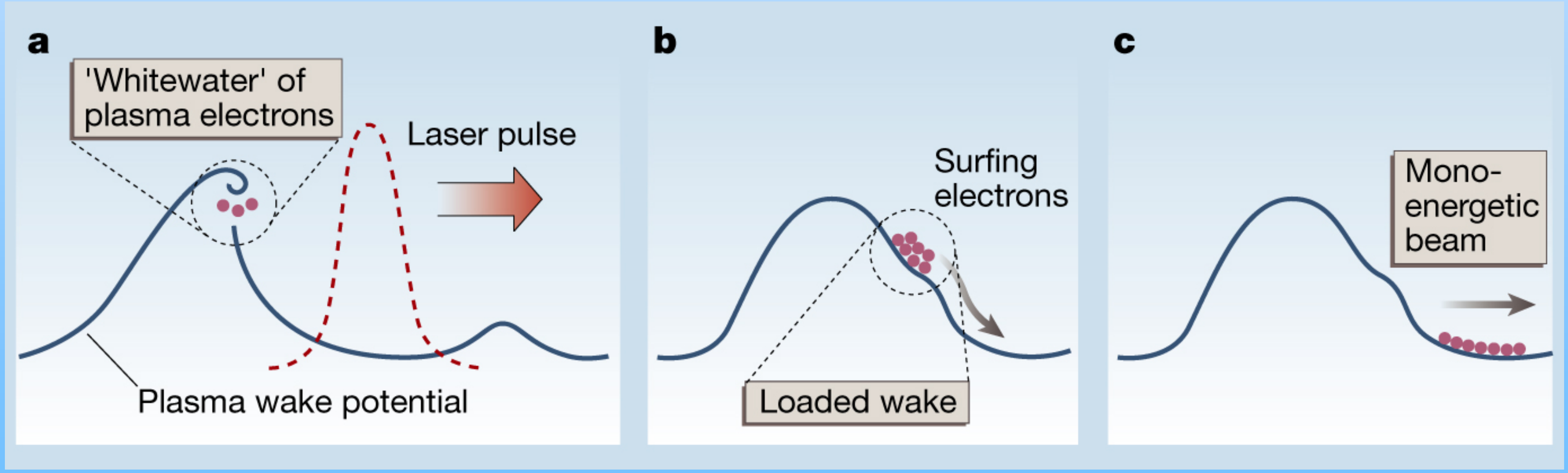
Recipe for a Monoenergetic Beam

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

b. Termination of trapping (beam loading)
Acceleration

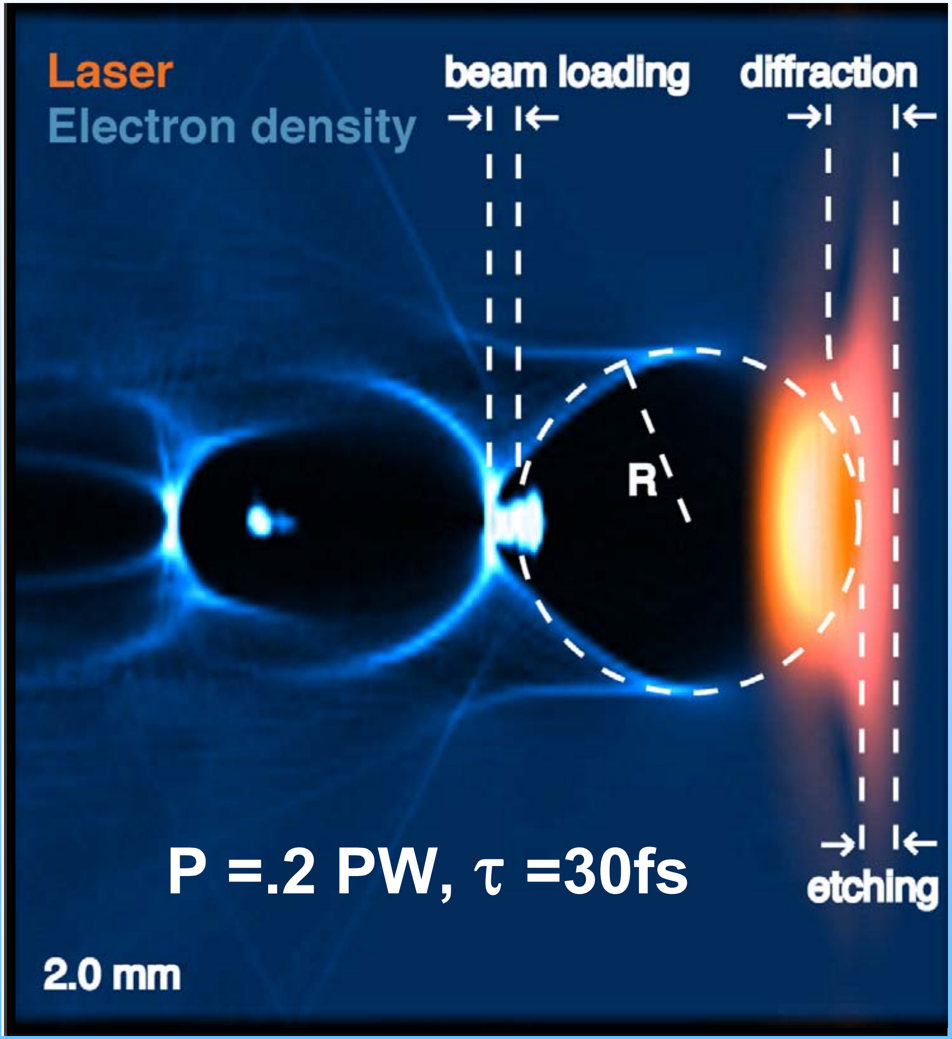
c. Dephasing
If L > or < dephasing length: large energy spread
If L ~ dephasing length: monoenergetic



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 1μ)

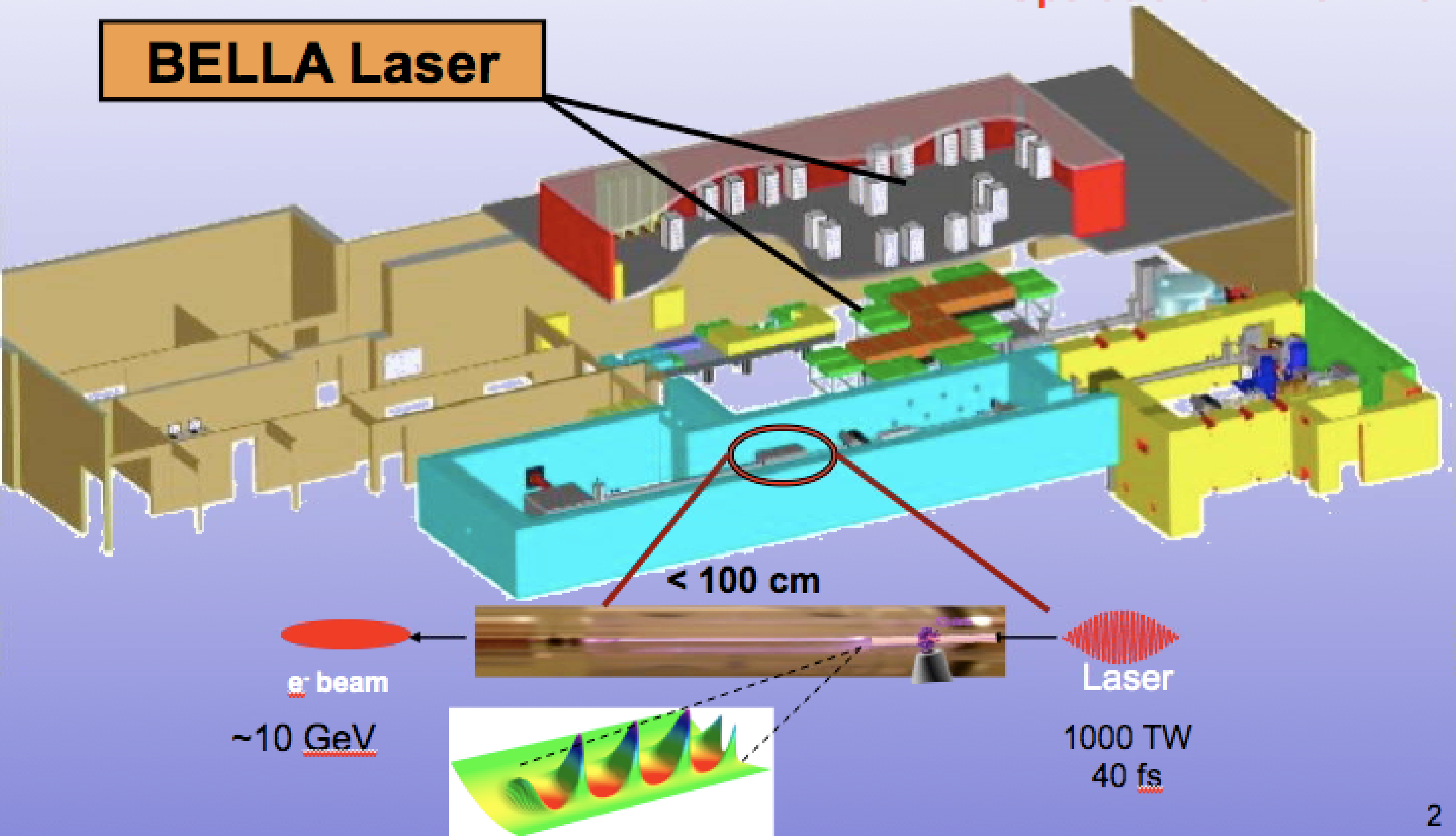
Research Issues - Laser

- Shot-to-shot variability -- **Achieved 2006** Faure, et al. Nature
- Scaling to GeV and beyond **Achieved 2007** Leemans et al, PRL
- Channel guiding **Major progress** Hooker, Milchberg and others
- Laser Avg. Power and Energy
  10^{10} e- at 1 TeV
  @ 10kHz => 100 MegaWatts+
- Staging or Laser combining
- Can we accelerate positrons or protons?

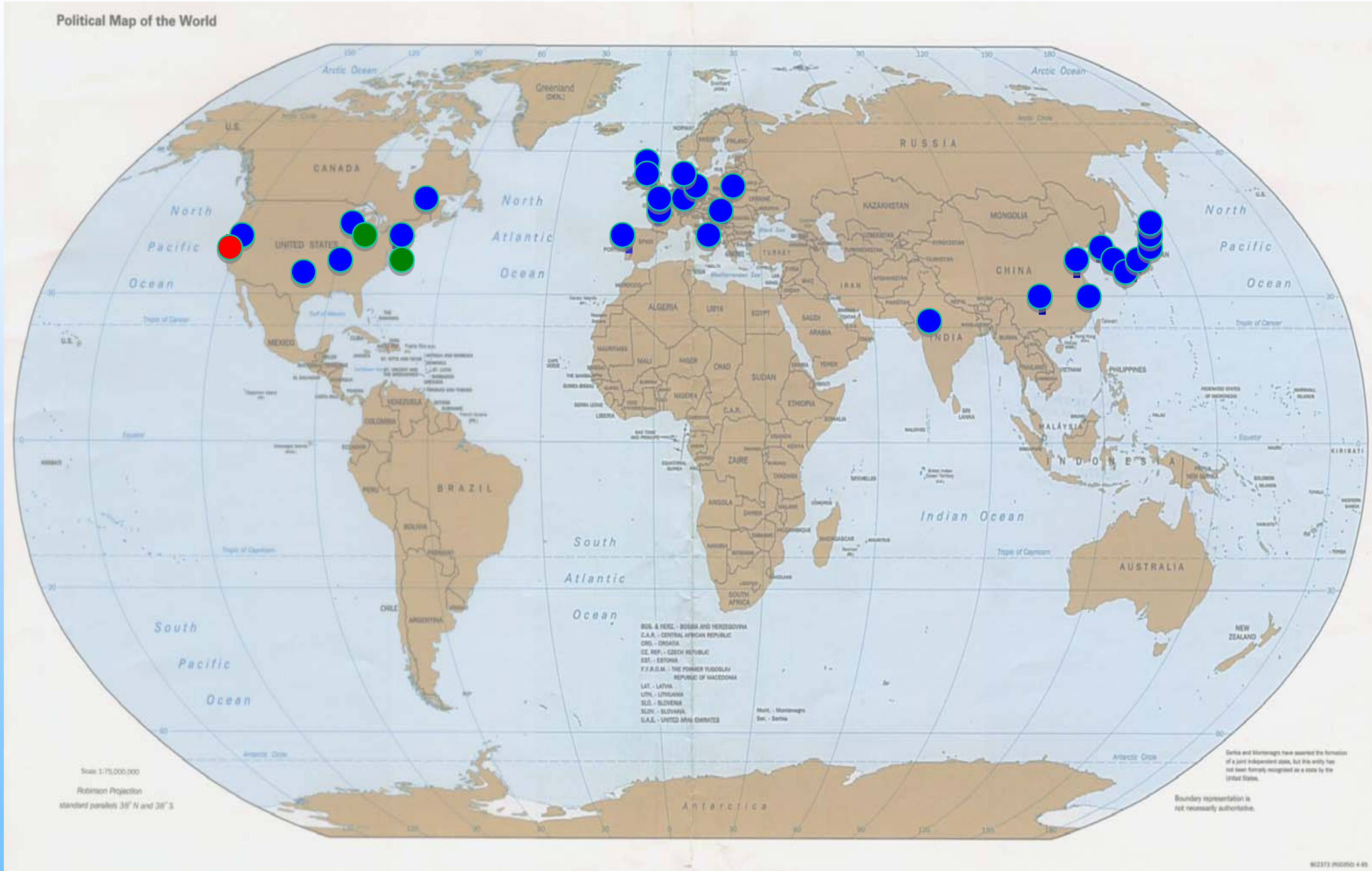
DOE-HEP's laser acceleration science: BELLA Project enables 10 GeV module development

- High rep rate (1 Hz), Petawatt class laser (>40 J in < 40 fs)

Operational in 2012-13



US and Worldwide Experimental Effort on Plasma Accel



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

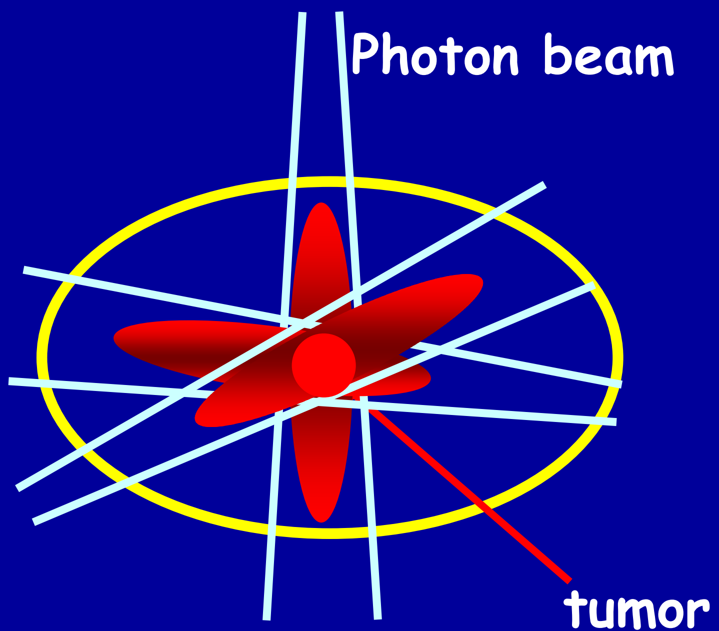
Accelerator physics is at the forefront of science

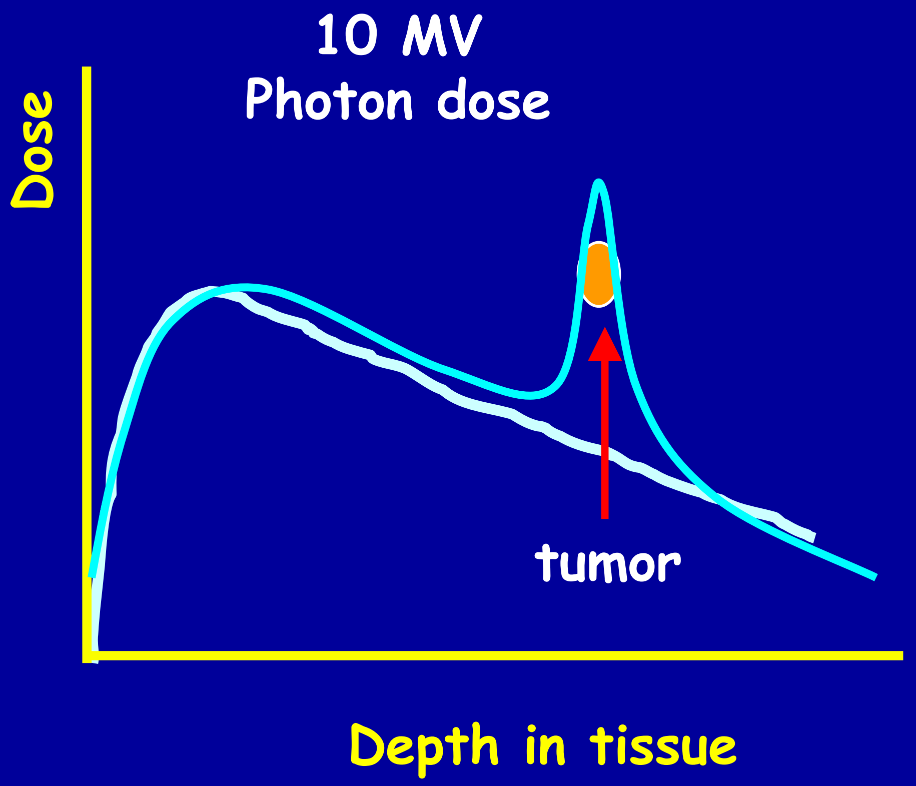
Acceleration, Radiation Sources, Refraction, Medical Applications

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

X-Ray Radiation Therapy

Photon beams are commonly used for radiation therapy

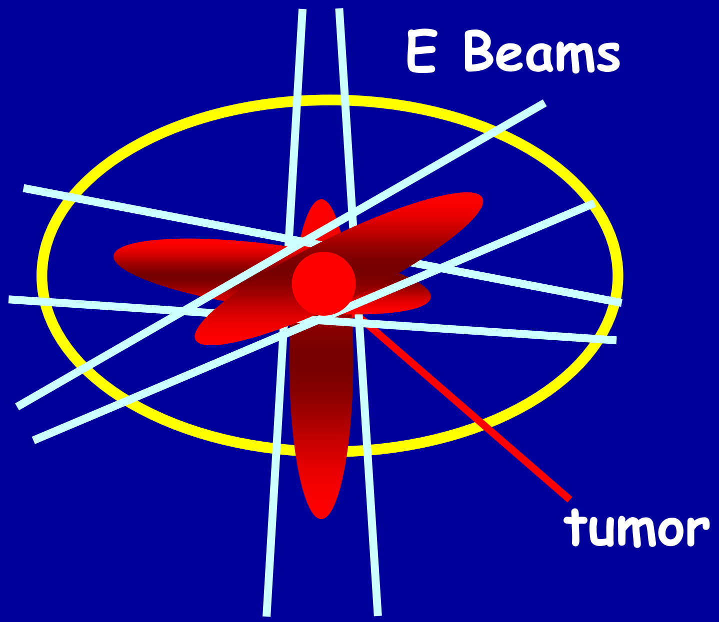


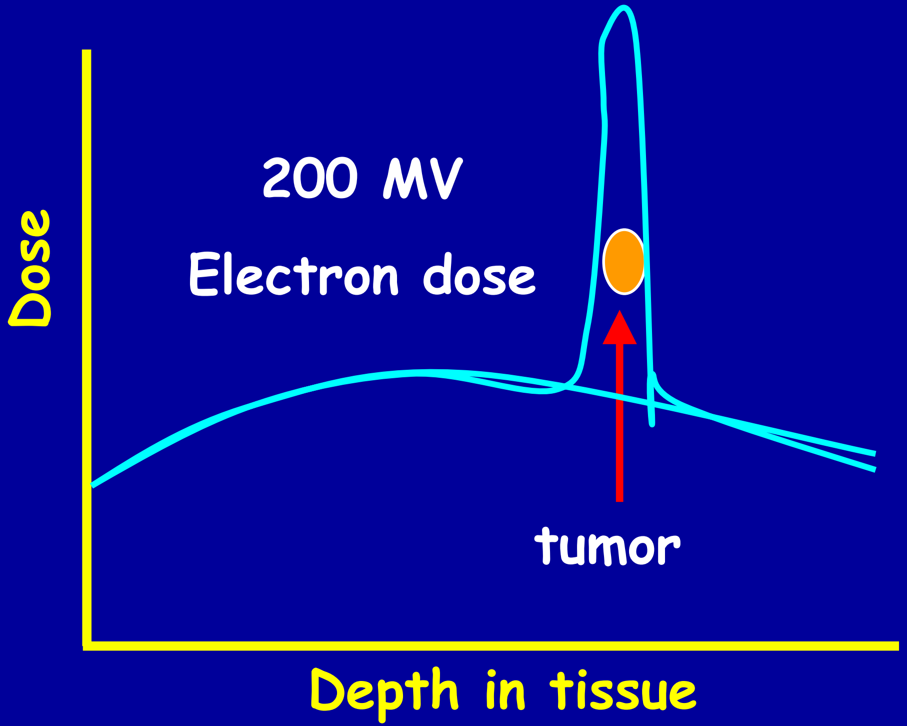


V.Malka:LOA

200 MV Electron Therapy

- Reduced dose near surface
  - Treatment of deep tumors

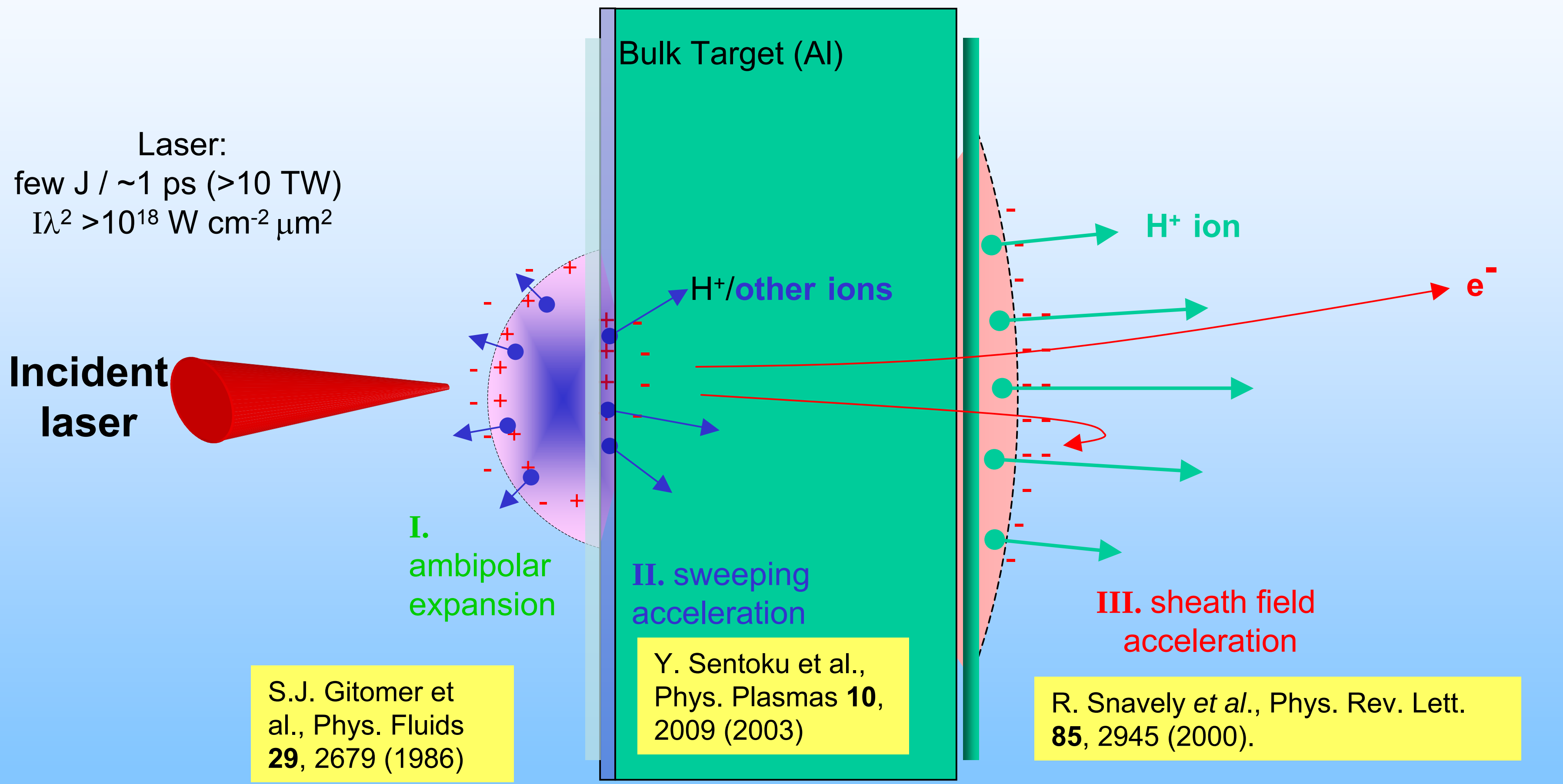




V.Malka:LOA

Laser acceleration of *ions* from solid targets

Courtesy J. Fuchs



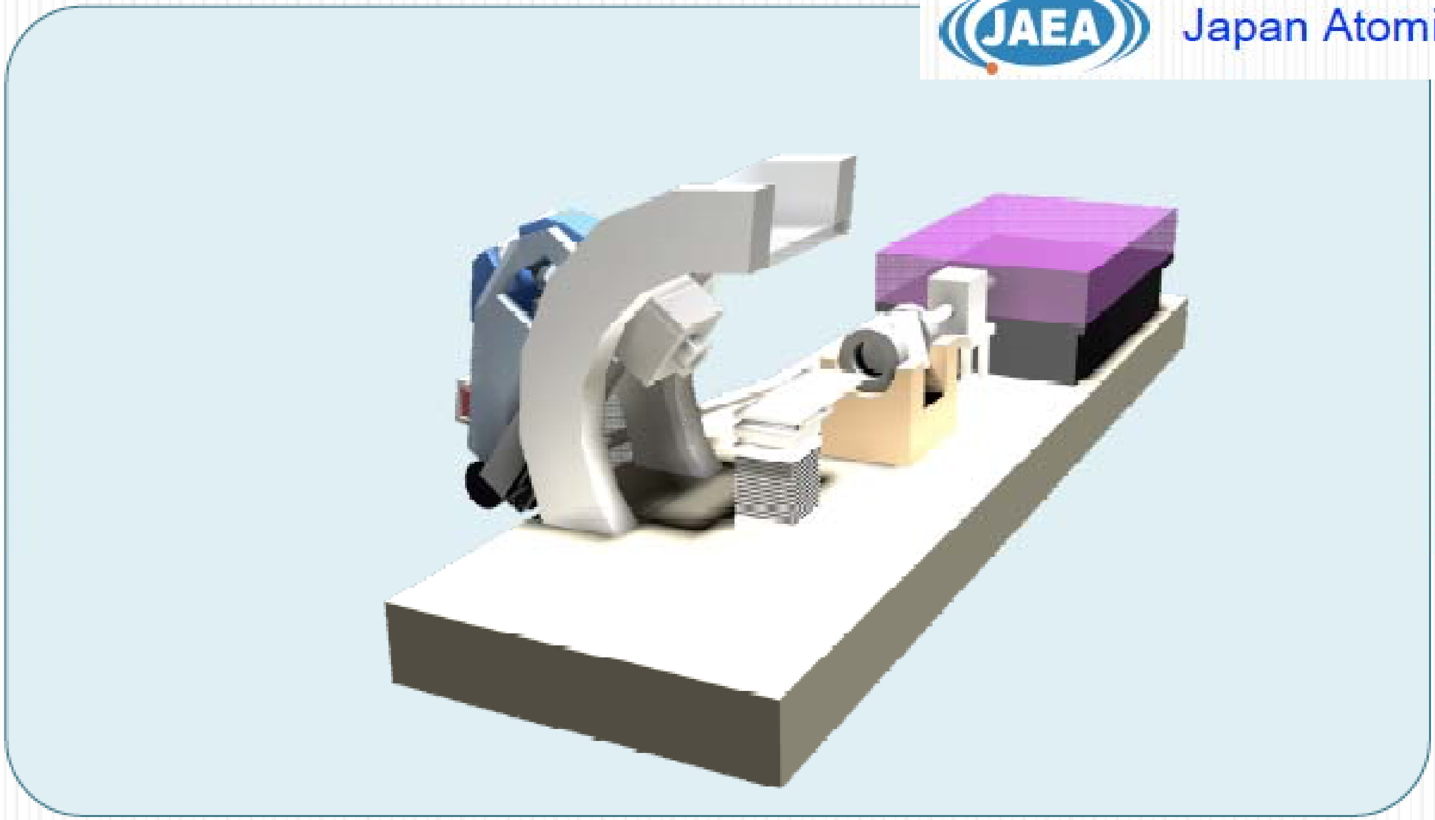
if target is heated ➔ efficient acceleration of heavy ions

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

Toward cancer therapy using laser-driven ion source

Development of compact proton beam therapy system supported by the Japanese government has been progressed since 2007

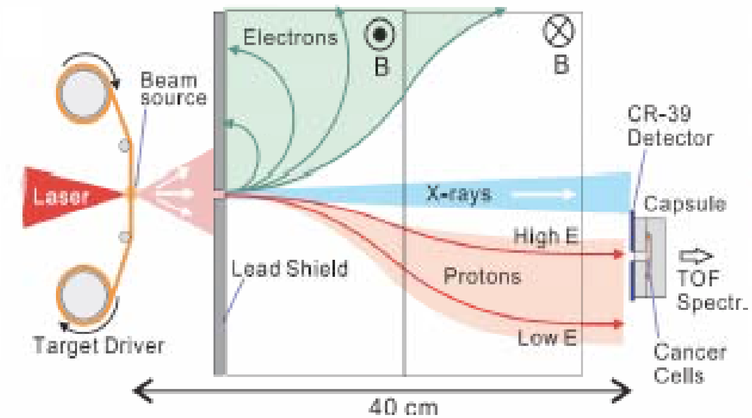
JAEA Japan Atomic Energy Agency



We must clear several hurdles (e.g.)

- Increasing the ion energy
- Transport of the ion beam to the tumor
- Biological effect at laser-driven ion irradiation

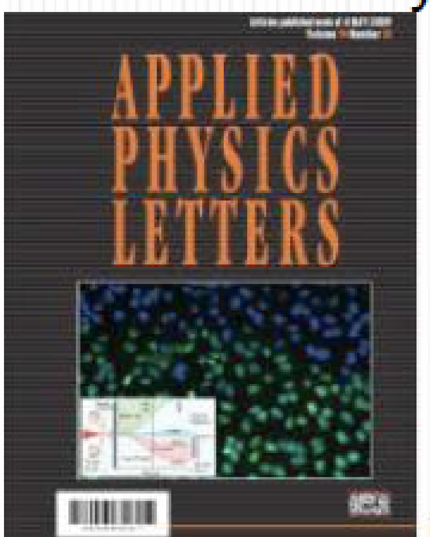
① Cancer cells were damaged by irradiation of 2MeV laser-driven protons



A. Yogo et al., APL **94**, 181802 (2009).

200 accumulation shots

- Remove e-
- Remove x-rays



Intact cells (not irradiated)

Damaged cells (irradiated)

DNA double-stranded breaks only in the region irradiated by laser-driven proton beam

Final Thoughts

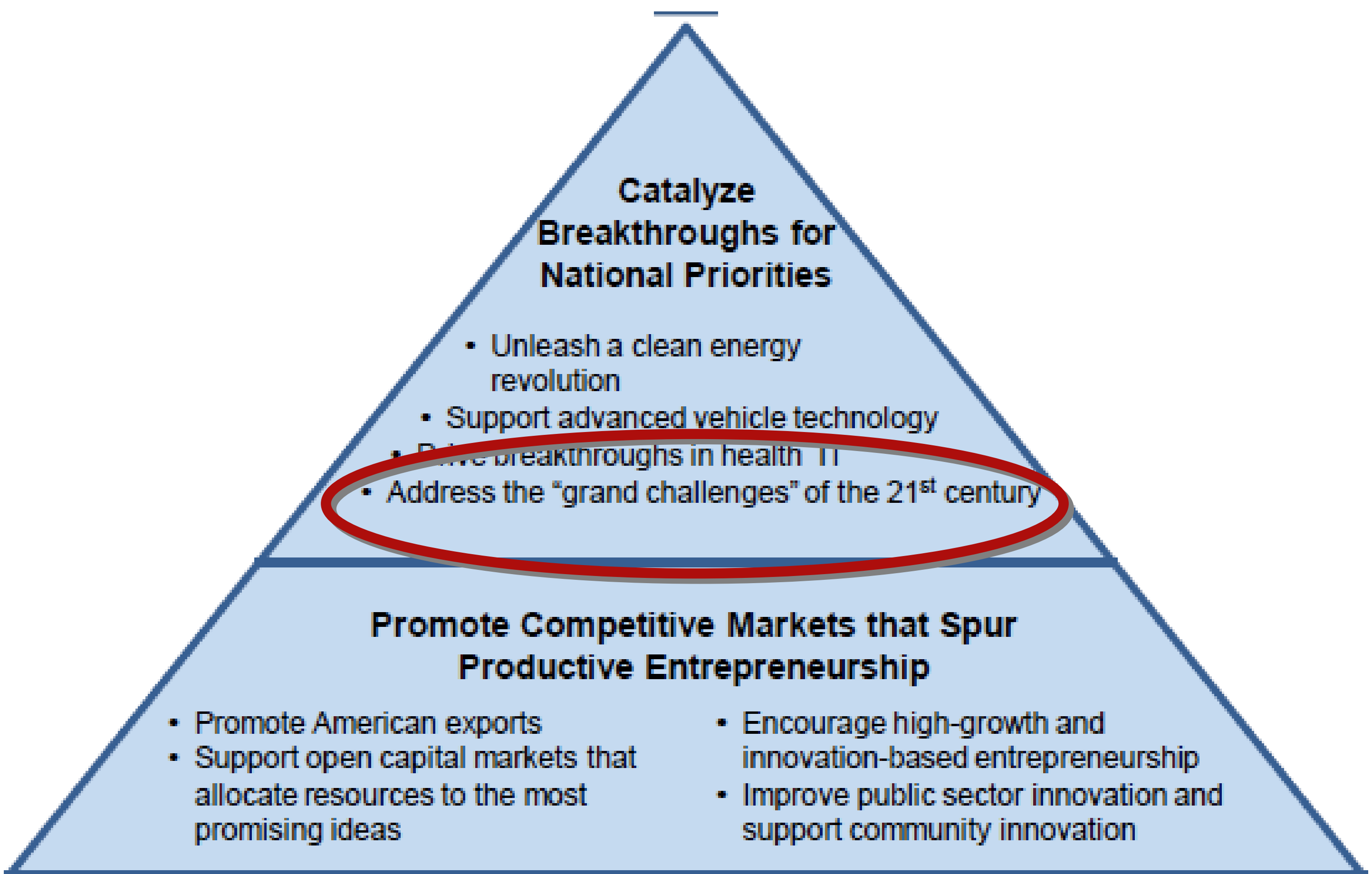
- National Academy of Engineering has identified 14 Grand Challenges for the 21st C
  - Sustainability (energy, environment) -- *Sheffield*
  - Health -- *Debus*
  - Security -- *Davis*
  - Joy of Living (#14. Tools of Scientific Discovery) -- *Tigner*
- Particle accelerators play a key role in all
- A broad accelerator research portfolio (including translational research) → a paradigm shift for cancer therapies to answers about the universe

and new economic growth…

Grand Challenges and the Economy

Sept 12, 2009

A Strategy for American Innovation: Driving Towards Sustainable Growth and Quality Jobs



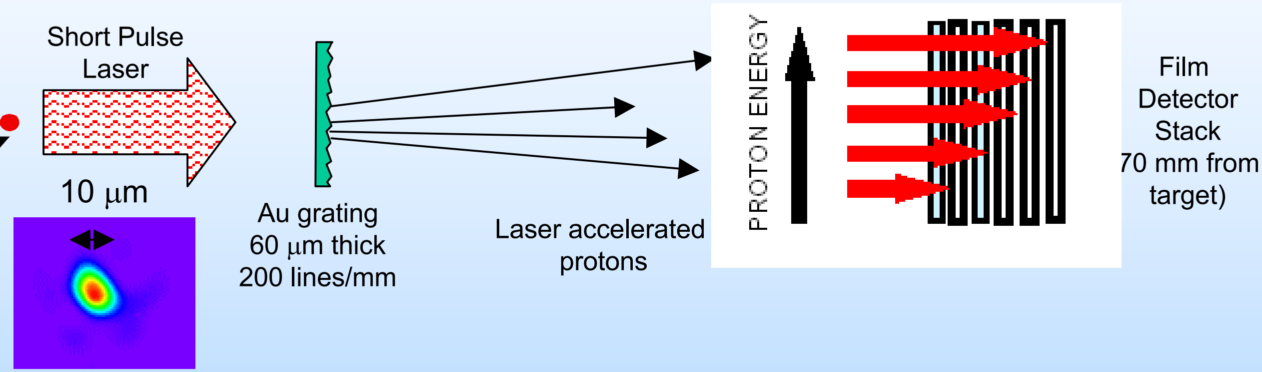
Present Collaborators

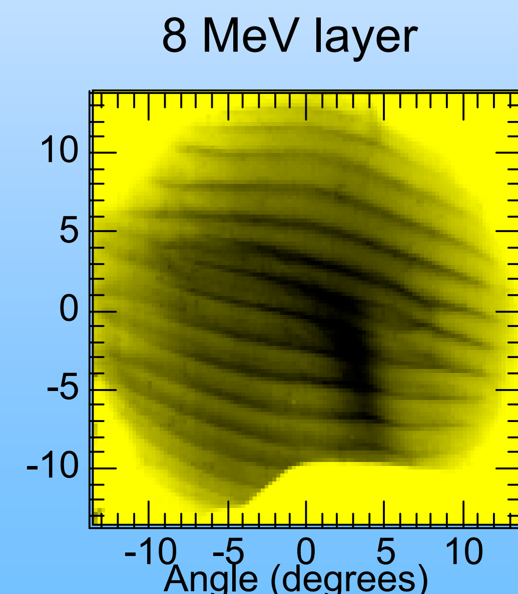
* B. Allen	USC
* W. An	UCLA
* K. Bane	SLAC
* L. Bentson	SLAC
* I. Blumenfeld	SLAC
* C.E. Clayton	UCLA
* S. DeBarger	SLAC
* F.-J. Decker	SLAC
* R. Erickson	SLAC
* R. Gholizadeh	USC
* M.J. Hogan	SLAC
* C. Huang	UCLA
* R.H. Iverson	SLAC
* C. Joshi	UCLA
* T. Katsouleas	Duke University
* N. Kirby	SLAC
* N. Li	SLAC
* W. Lu	UCLA
* D.B. MacFarlane	SLAC
* K.A. Marsh	UCLA
* W.B. Mori	UCLA
* P. Muggli	USC
* Y. Nosochkov	SLAC
* S. Pei	SLAC
* T.O. Raubenheimer	SLAC
* J.T. Seeman	SLAC
* A. Seryi	SLAC
* R.H. Siemann*	SLAC
* P. Tenenbaum	SLAC
* J. Vollaire	SLAC
* D. Walz	SLAC
* X. Wang	USC
* W. Wittmer	SLAC

SLAC Duke UNIVERSITY UCLA USC

Laser-foil protons: Record beam quality

$\mathcal{E}_n$ < .004 mm-mrad!



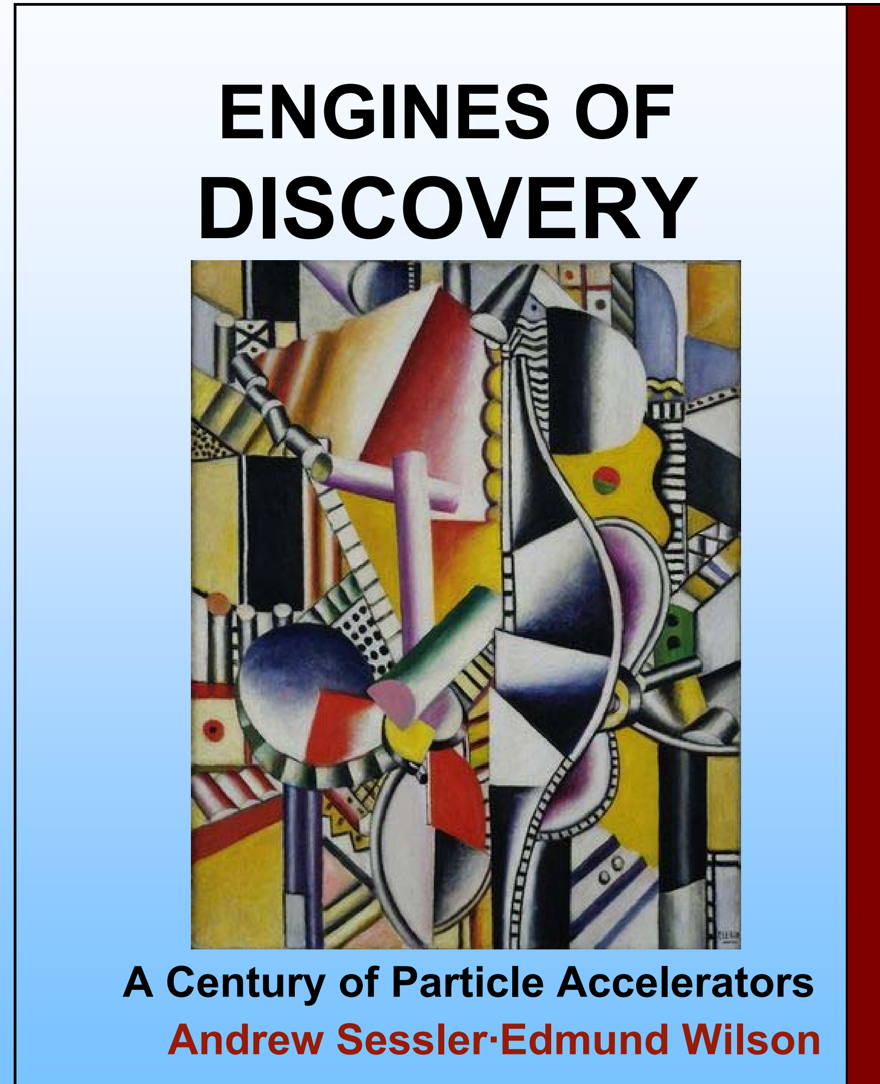


- 10x lower ε than conventional ion injectors

T. Cowan, J. Fuchs. H. Ruhl et al., Phys. Rev. Lett. ***92****, 204801 (2004).*


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?

Further reading:



Lighter: A Hole in Texas
Angels and Demons

NAE Grand Challenges for the 21st 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

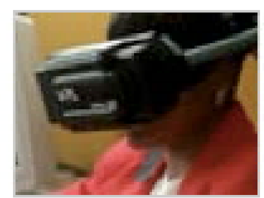
Advance health informatics

Engineer better medicines

Reverse-engineer the brain

Prevent nuclear terror

Secure cyberspace

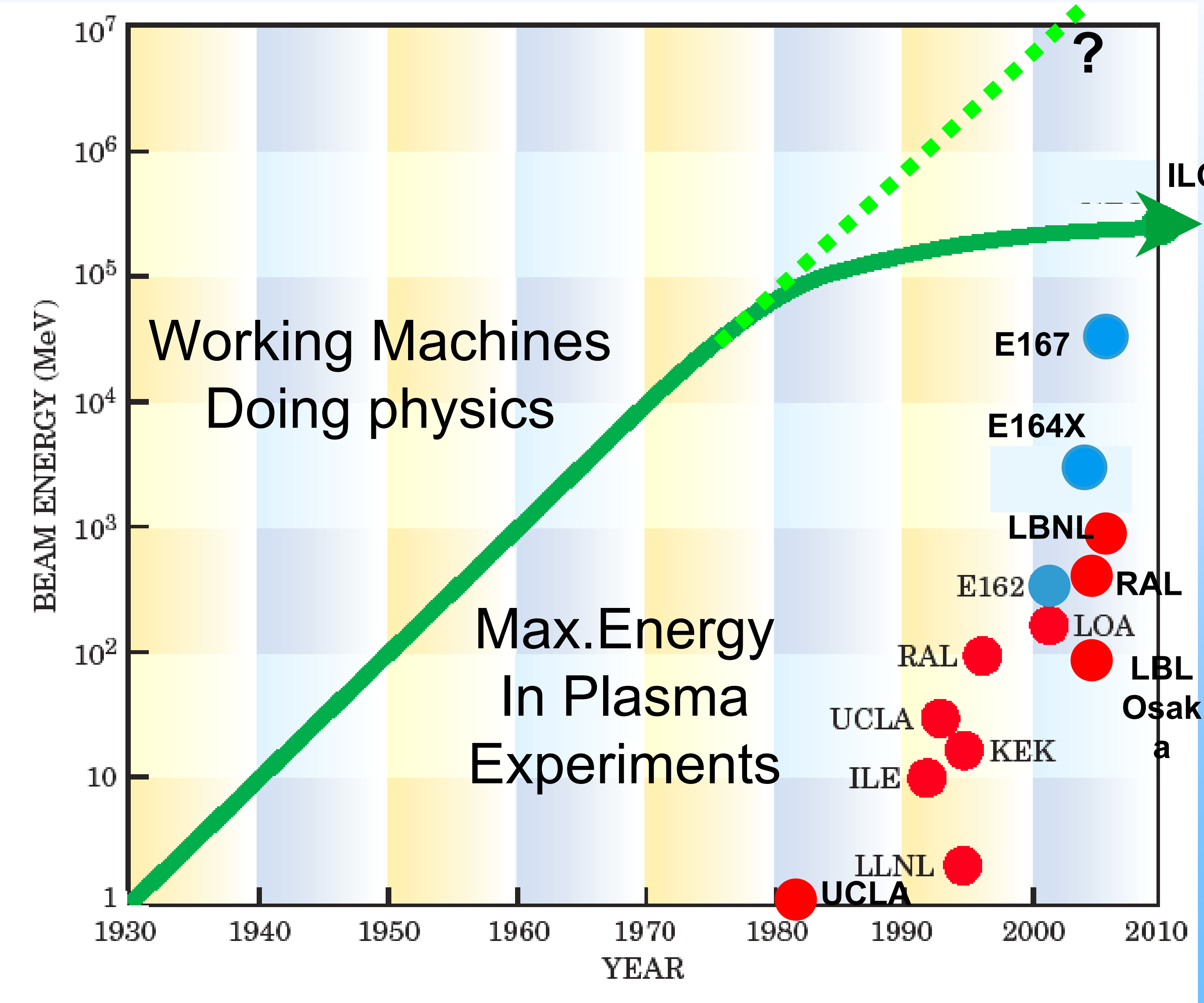


Enhance virtual reality

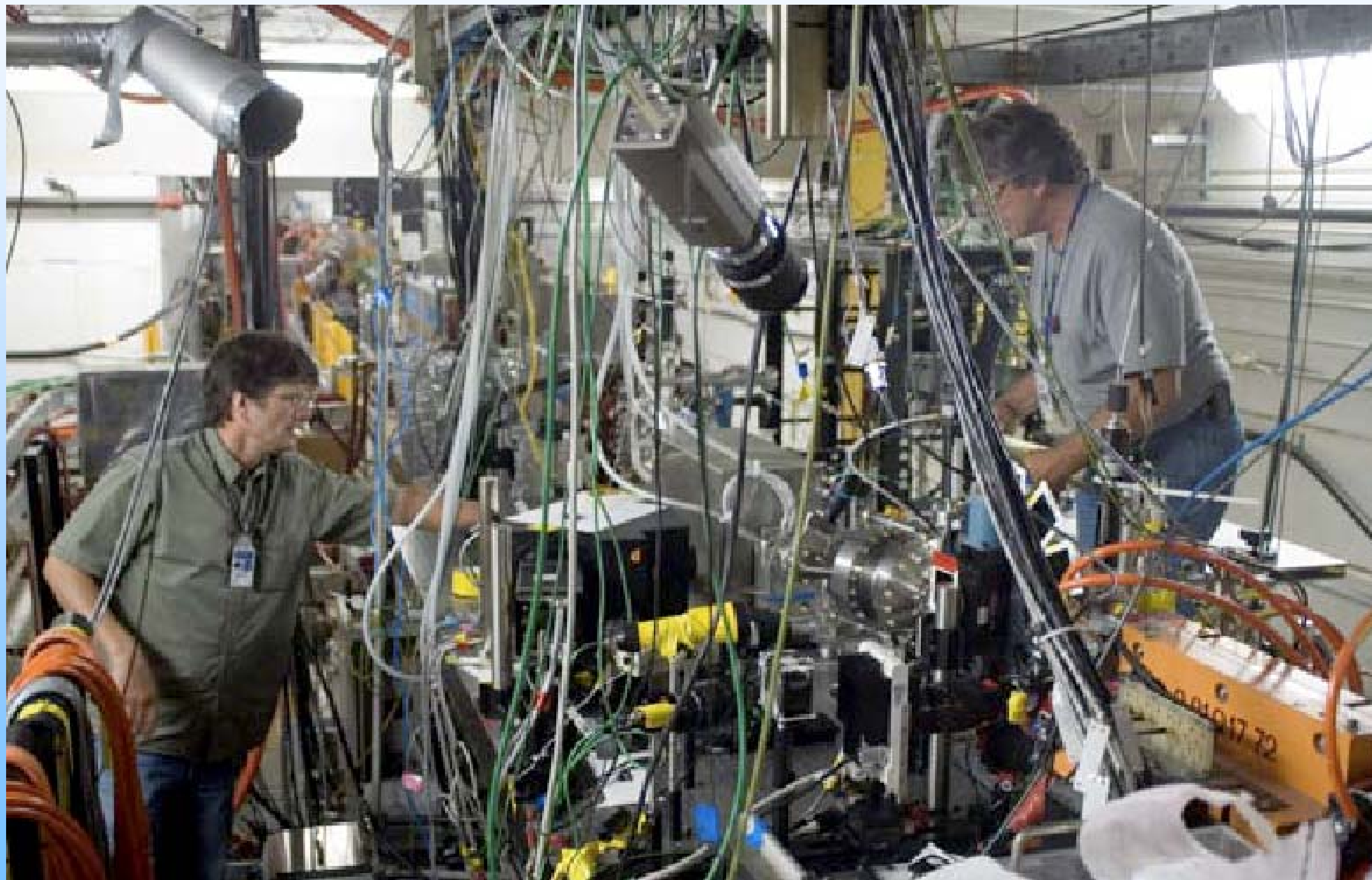
Advance personalized learning

Engineer the tools of scientific discovery

Plasma Accelerator Progress
"Accelerator Moore's Law"

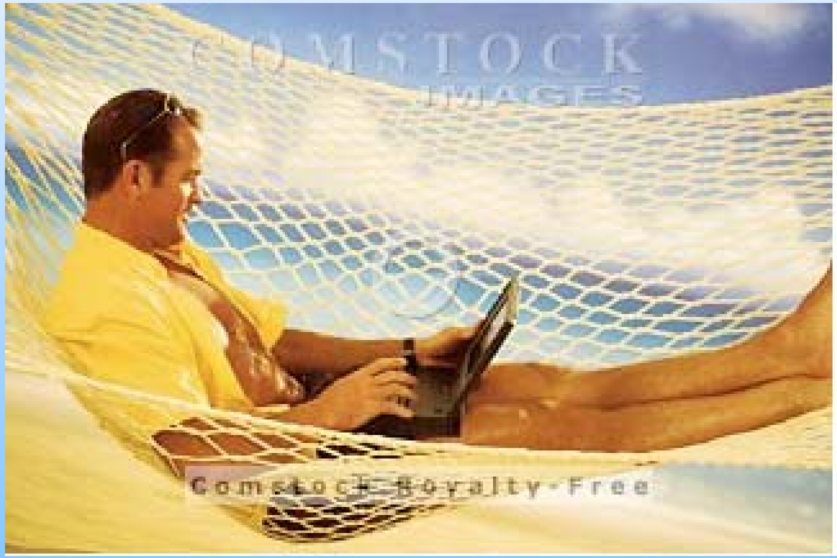


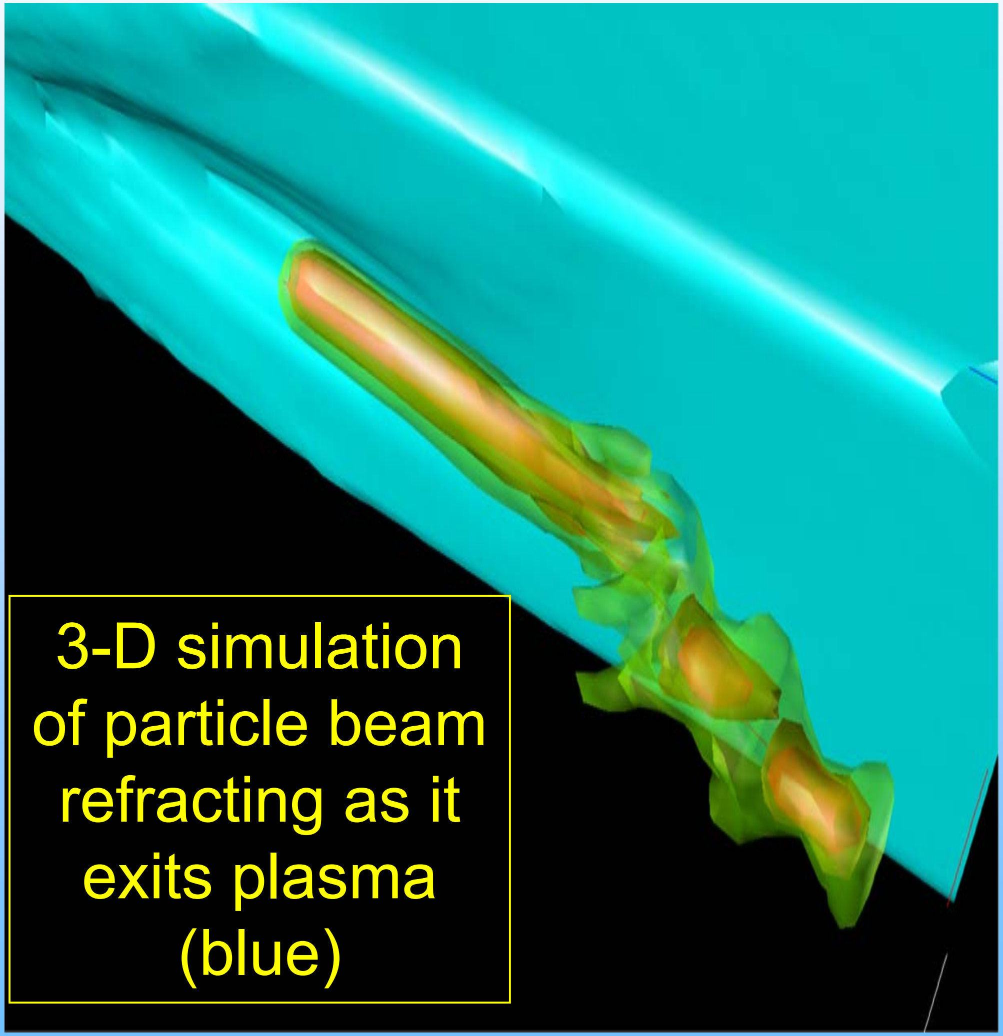
Plasma Accelerator Research: Experimentalist Perspective



From: Chan Joshi, UCLA Personal archives

Plasma Accelerator Research: Computer Simulationist Perspective





Ancient Greece Around 500 BC

Democritus

Matter made of atoms
Atomos = Indivisible

Magnetic properties of lodestones.
Rubbing amber and
wool produces static electricity
Elektron = Amber

For Today Remember “Opposites Attract”

James Clerk Maxwell
1831-1879

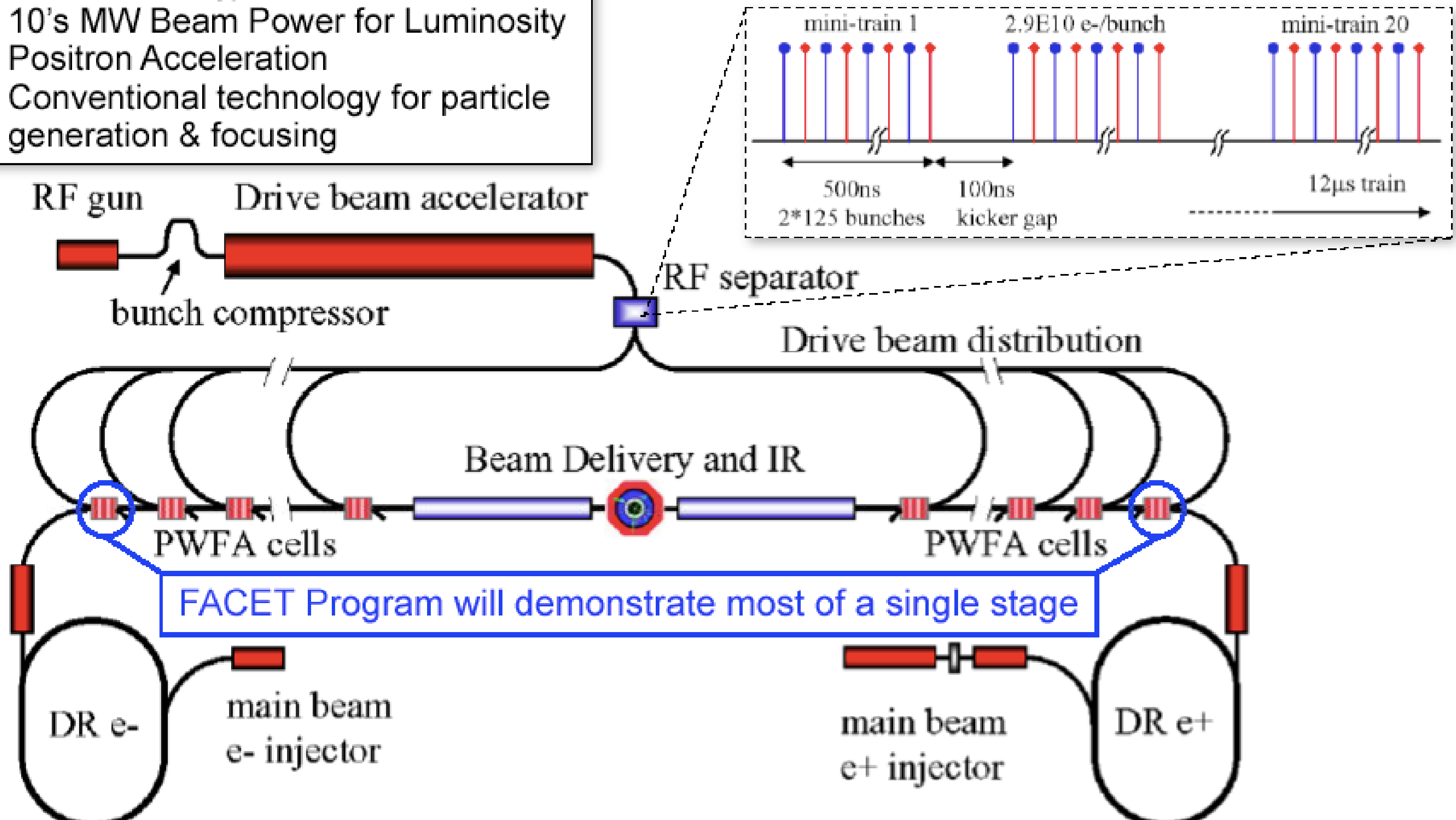
$$\nabla \cdot \mathbf{E} = 4\pi\rho$$
$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{J} + \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t},$$

"Unified" Electricity and Magnetism

"There is nothing new to be discovered in physics now. All that is left is more and more precise measurement."
--Lord Kelvin, 1896

A Concept for a Plasma Wakefield Accelerator Based Linear Collider

- TeV CM Energy
- 10's MW Beam Power for Luminosity
- Positron Acceleration
- Conventional technology for particle generation & focusing

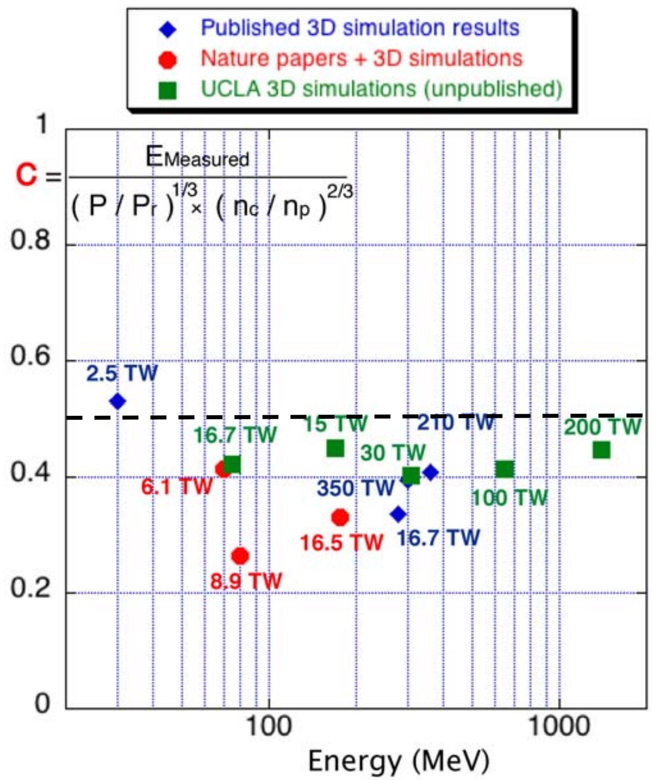


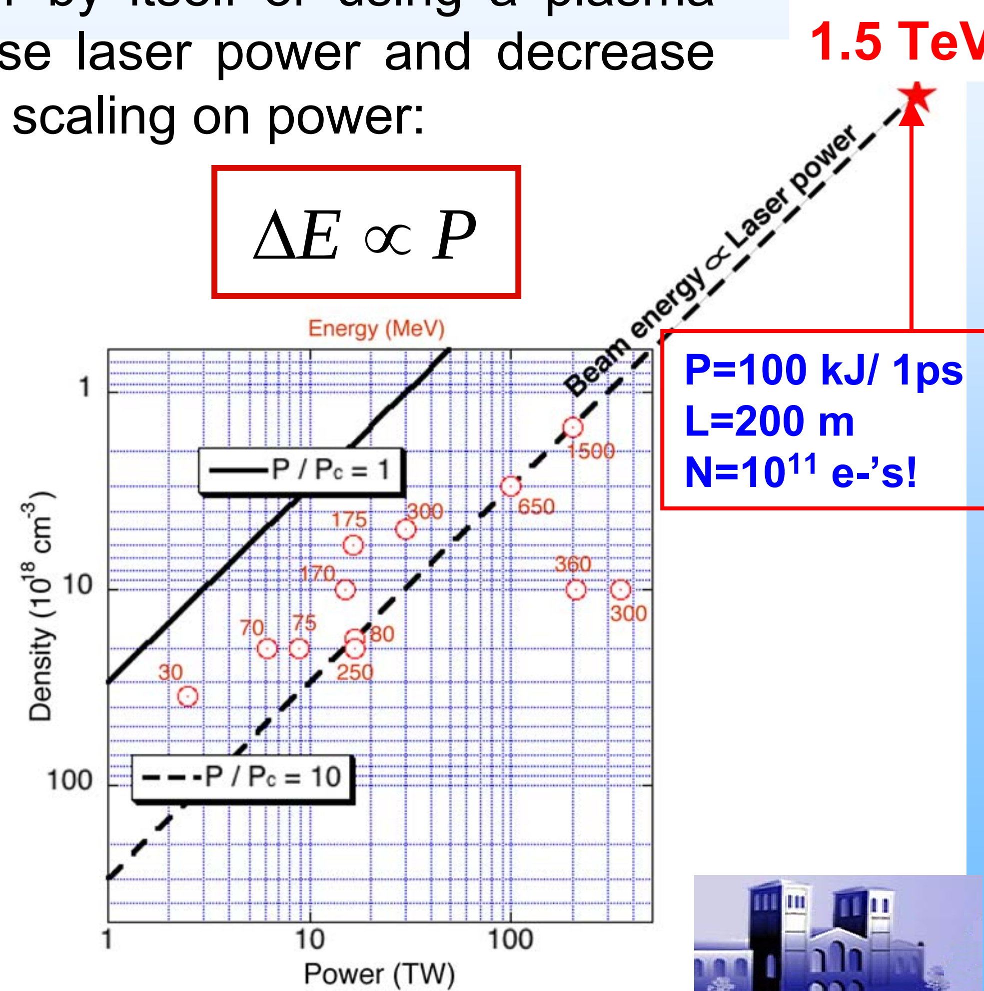
Scaling laws for monoenergetic regime

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:

$$\Delta E \propto P$$





W. Lu et al., UCLA

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

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**

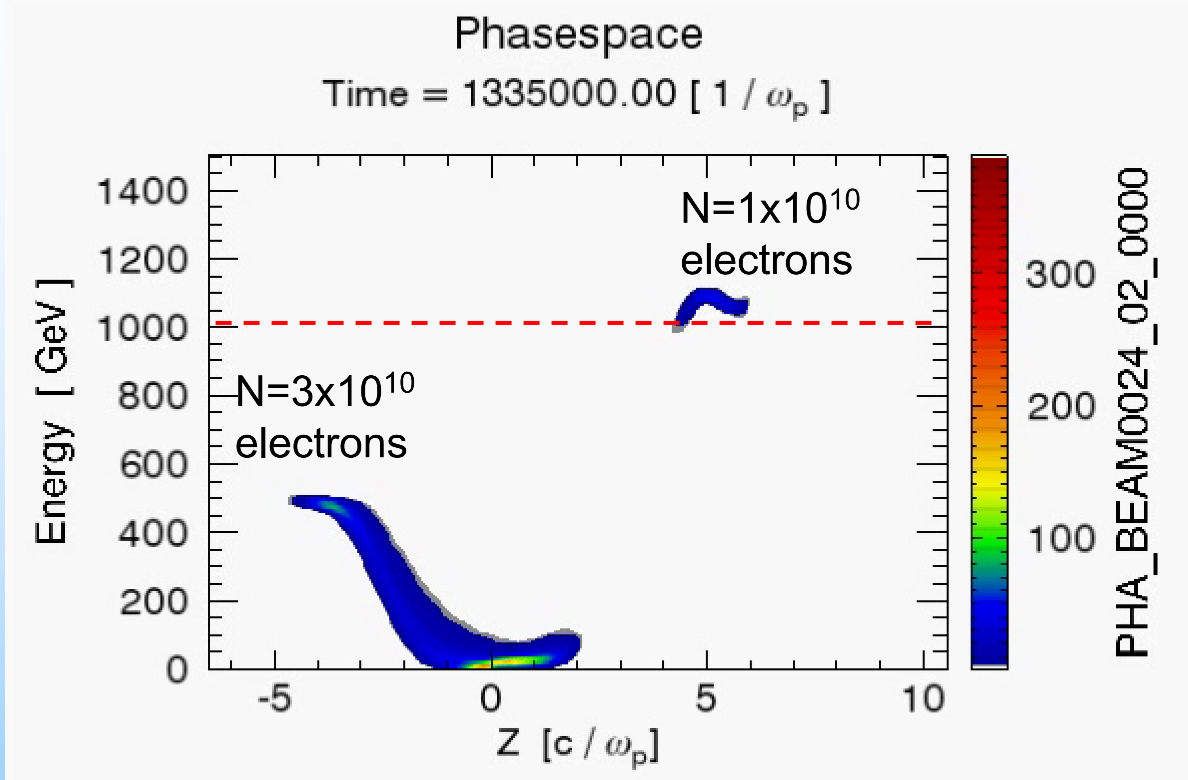
- **Lasers can be bent more easily**

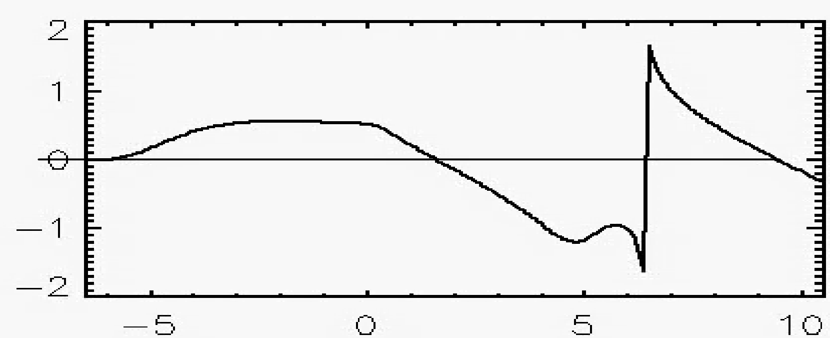
- **Average power cost for beam vs. laser technology sets timescale for HEP app**
  - **$\$10^4$/Watt for lasers currently x 200 MW ~ $20T, but there is much current research on developing high average power lasers.**
  - **$10/Watt for CLIC-type RF x 100 MW**

First Self-consistent PWFA-LC

Luminosity	3.5×10^{34} cm^{-2}s^{-1}
Luminosity in 1% of energy	1.3×10^{34} cm^{-2}s^{-1}
Main beam: bunch population, bunches per train, rate	1×10^{10}, 125, 100 Hz
Total power of two main beams	20 MW
Main beam emittances, $\gamma\varepsilon_x$, $\gamma\varepsilon_y$	2, 0.05 mm-mrad
Main beam sizes at Interaction Point, x, y, z	140 nm, 3.2 nm, 10 μm
Plasma accelerating gradient, plasma cell length, and density	25 GV/m, 1 m, 1×10^{17}cm^{-3}
Power transfer efficiency drive beam=>plasma =>main beam	35%
Drive beam: energy, peak current and active pulse length	25 GeV, 2.3 A, 10 μs
Average power of the drive beam	58 MW
Efficiency: Wall plug=>RF=>drive beam	50% × 90% = 45%
Overall efficiency and wall plug power for acceleration	15.7%, 127 MW
Site power estimate (with 40MW for other subsystems)	170 MW

500 GeV Energy Gain in 20 meters!





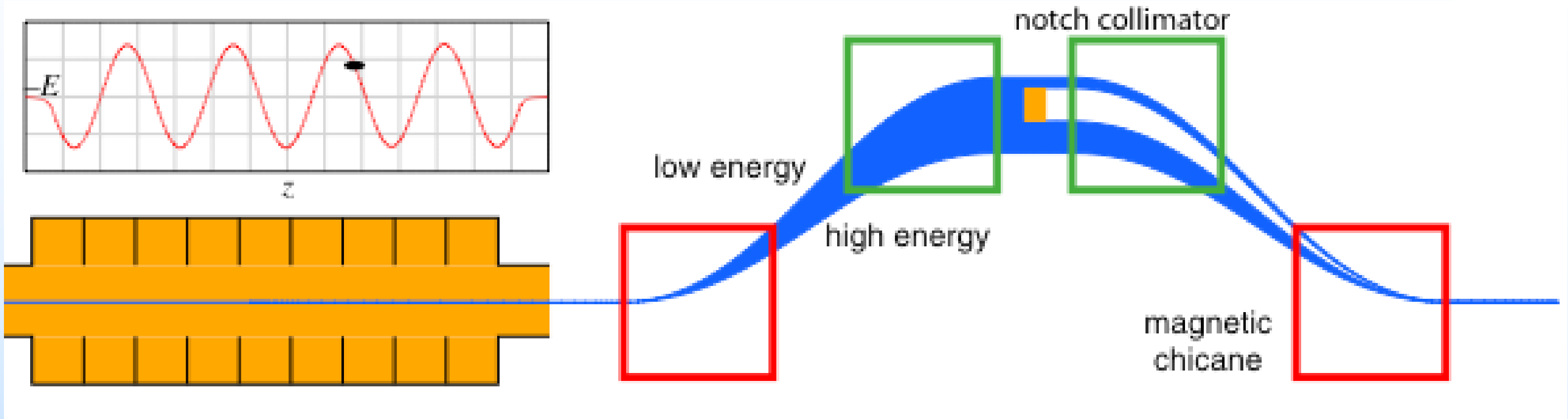
Accelerating field
24GeV/m at the load

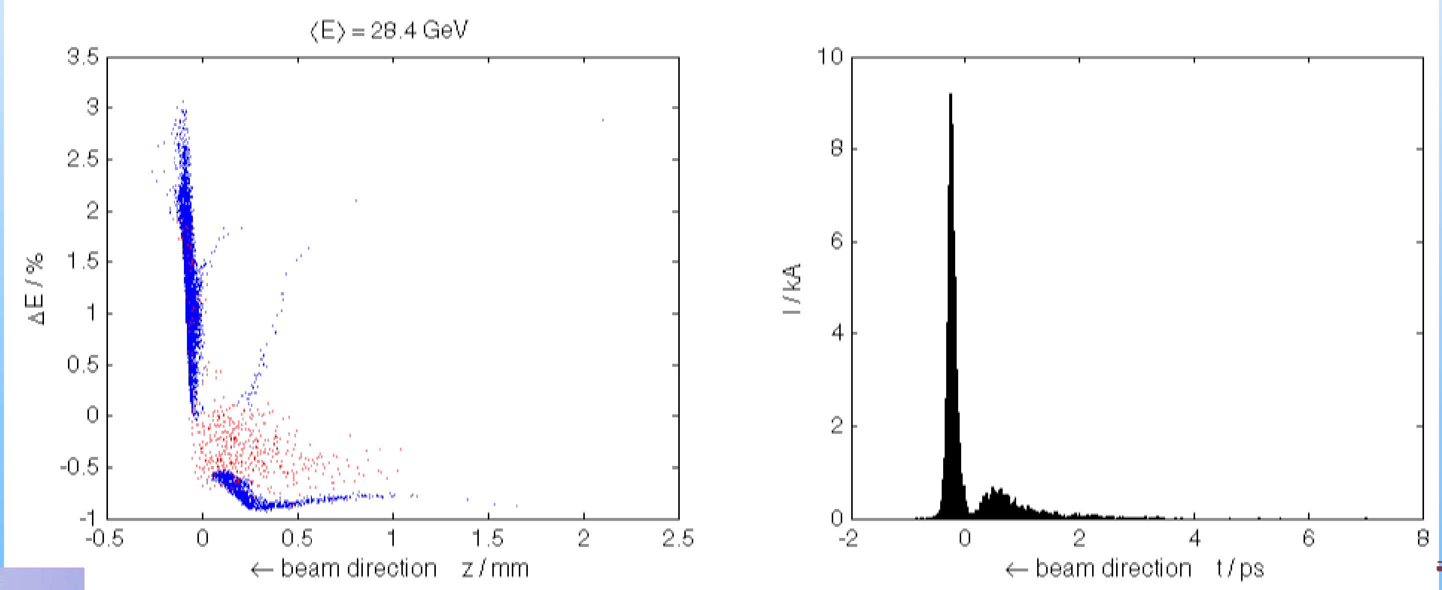
USC

Stanford Linear Accelerator Center

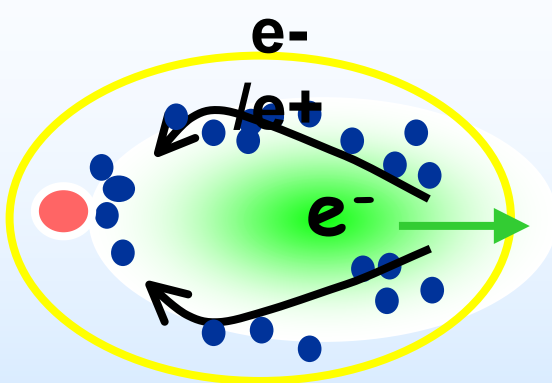
UCLA

Proposed Two-Bunch Experiment

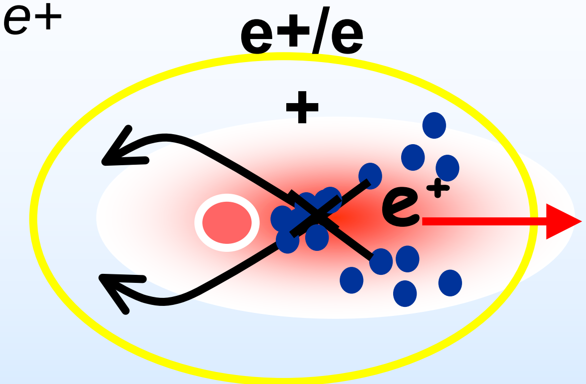


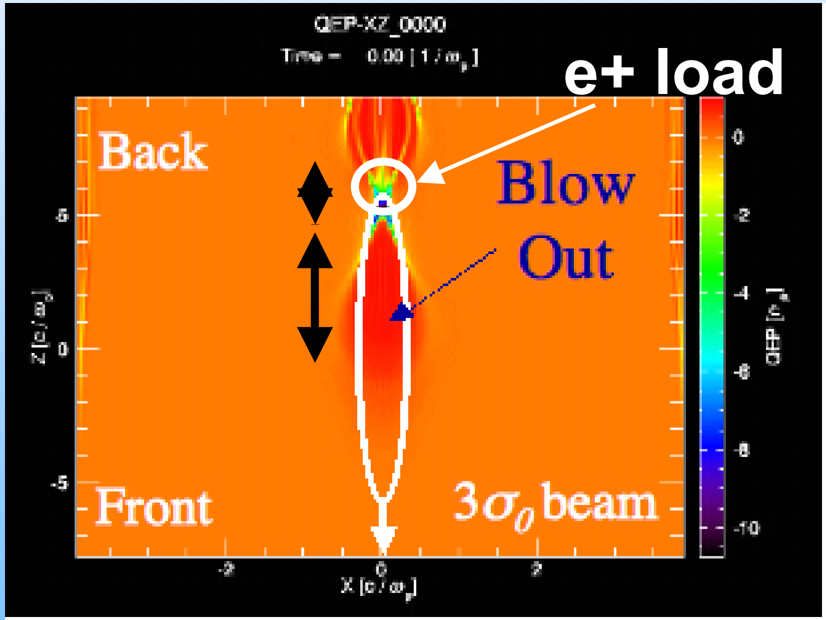


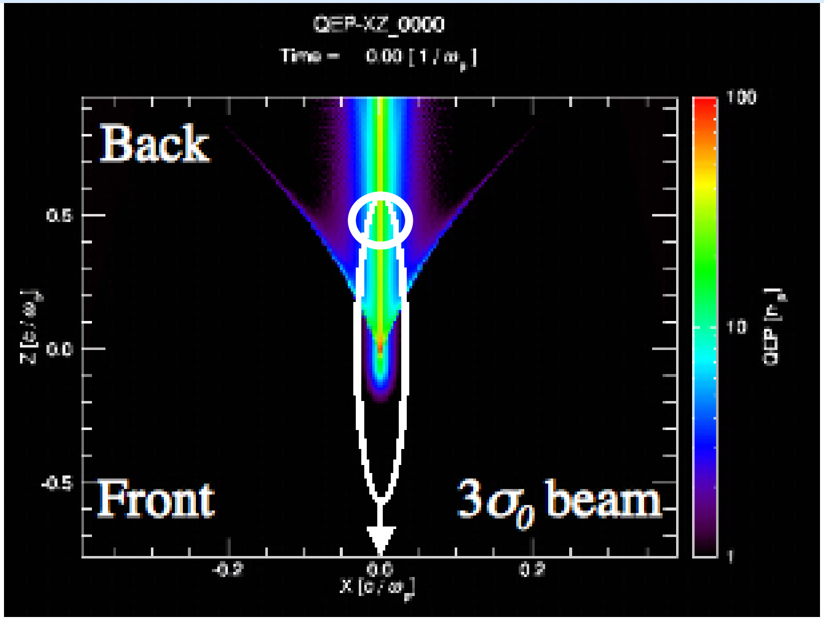
Positron Acceleration -- two possibilities



e- e+ or e+ e+







- **Non-uniform focusing force (*r*,*z*)**
- **Smaller accelerating force**
- **Much smaller acceptance phase for acceleration and focusing**

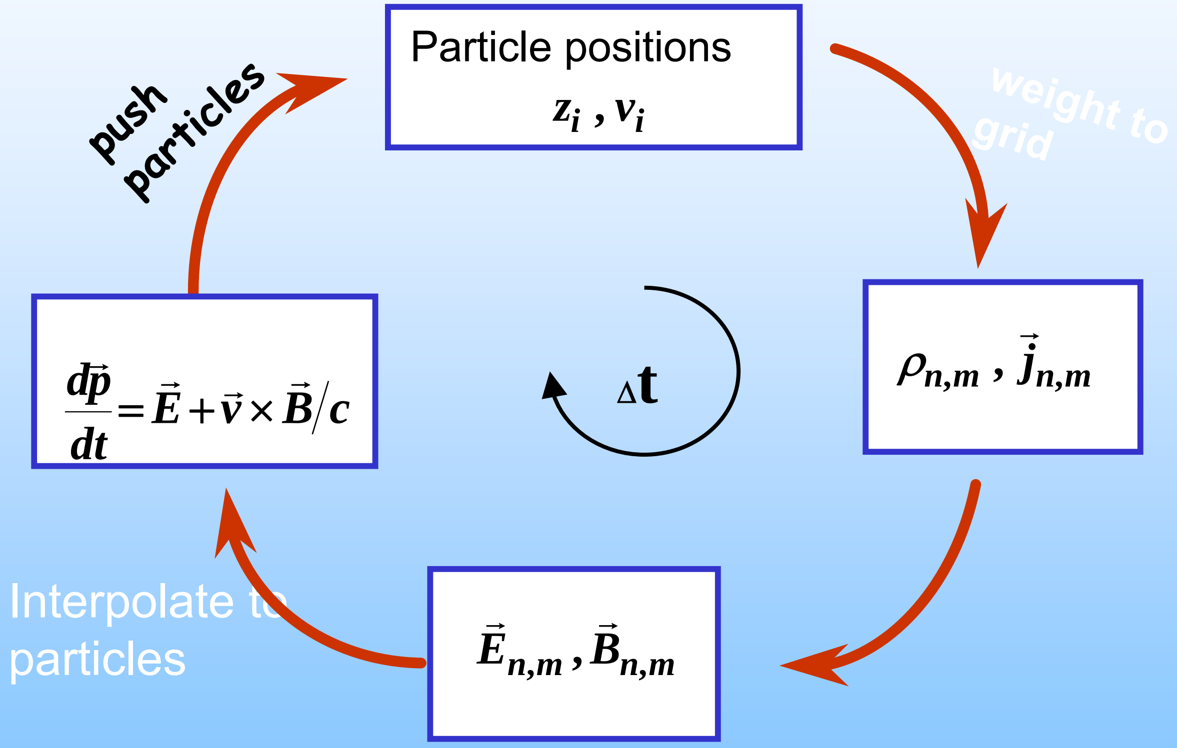
Ref. S. Lee et al., Phys. Rev. E (2000); M. Zhou, PhD Thesis (2008), K. Lotov

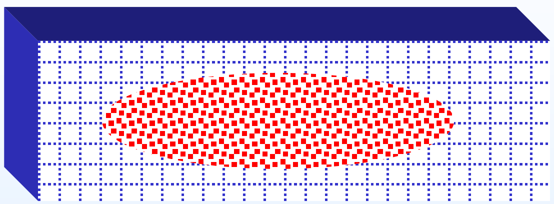
Extra and backup slides

How are the simulations done?

Computational cycle

(at each step in time)





- Maxwell's equations for field solver
- Lorentz force updates particle's position and momentum

<u>Typical simulation parameters:</u>

~10^7-10^8 particles

~10^4 time steps

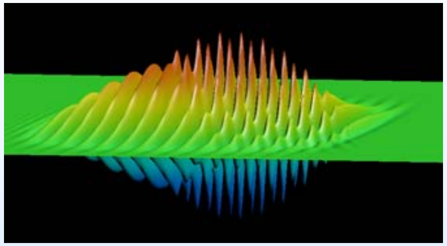
~1-10 Gbytes

~10^2-10^3 cpu hours

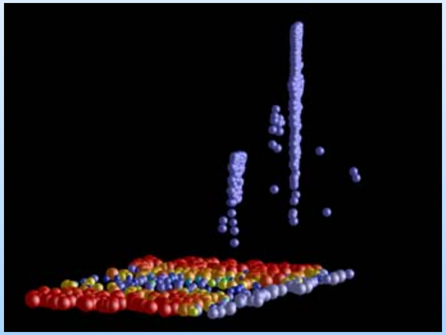
Modeling: *Not* your father's PIC Codes

- High-fidelity particle based codes
  - **OSIRIS, VLPL:** Fully explicit PIC
  - **VORPAL, Turbowave**: Fully explicit PIC+ *ponderomotive guiding center*
  - **QuickPIC:** quasi-static PIC

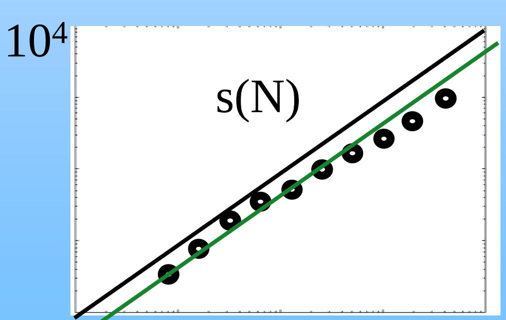
- Codes
  - Are 3-D
  - Are fully parallelized
  - Are load balanced with particle sorting
  - Have moving windows to follow relativistic beams
  - Have specialized wake algorithms for X100 speed (QP)
  - Scale to 1000+ processors



Colliding laser pulses

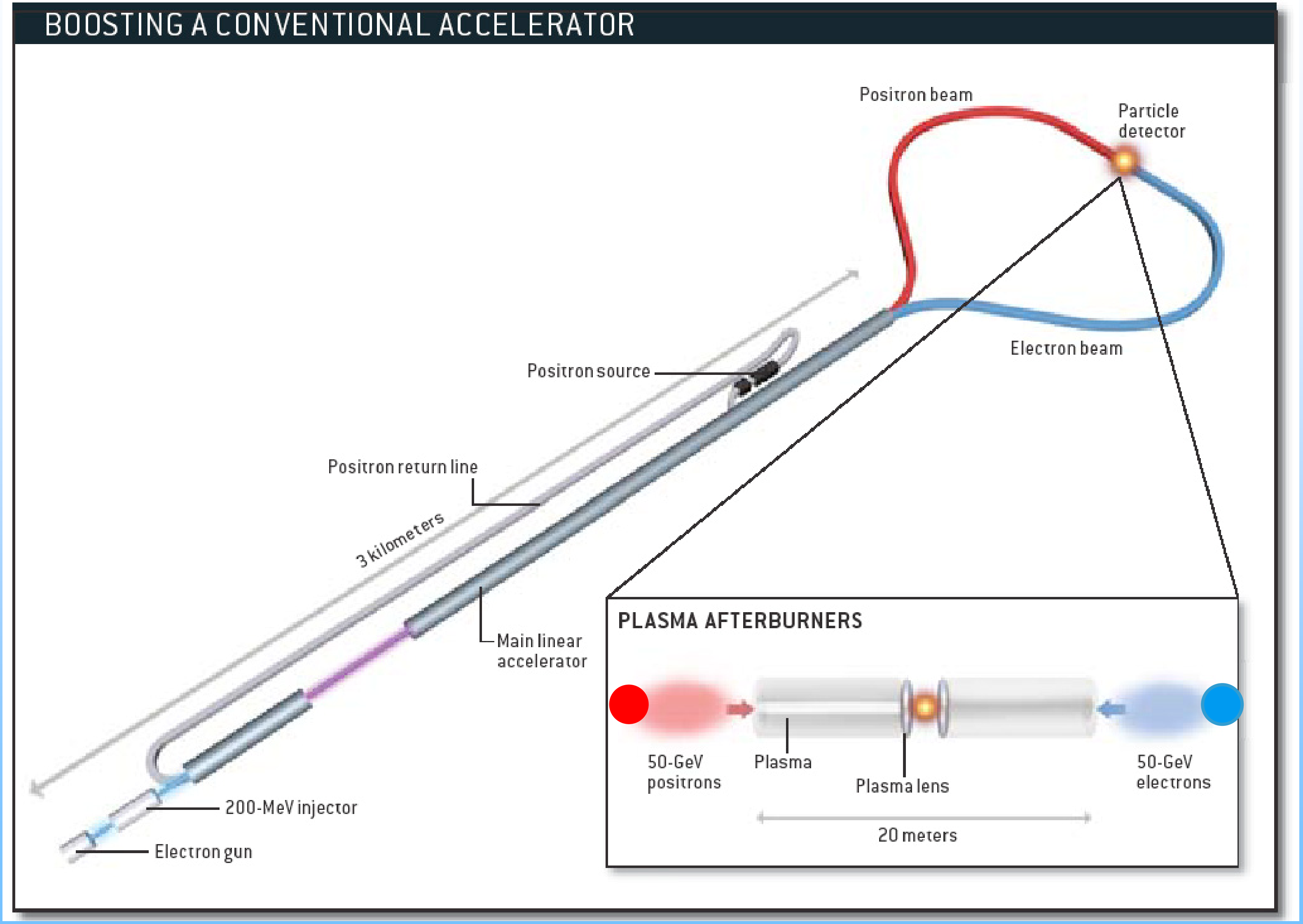


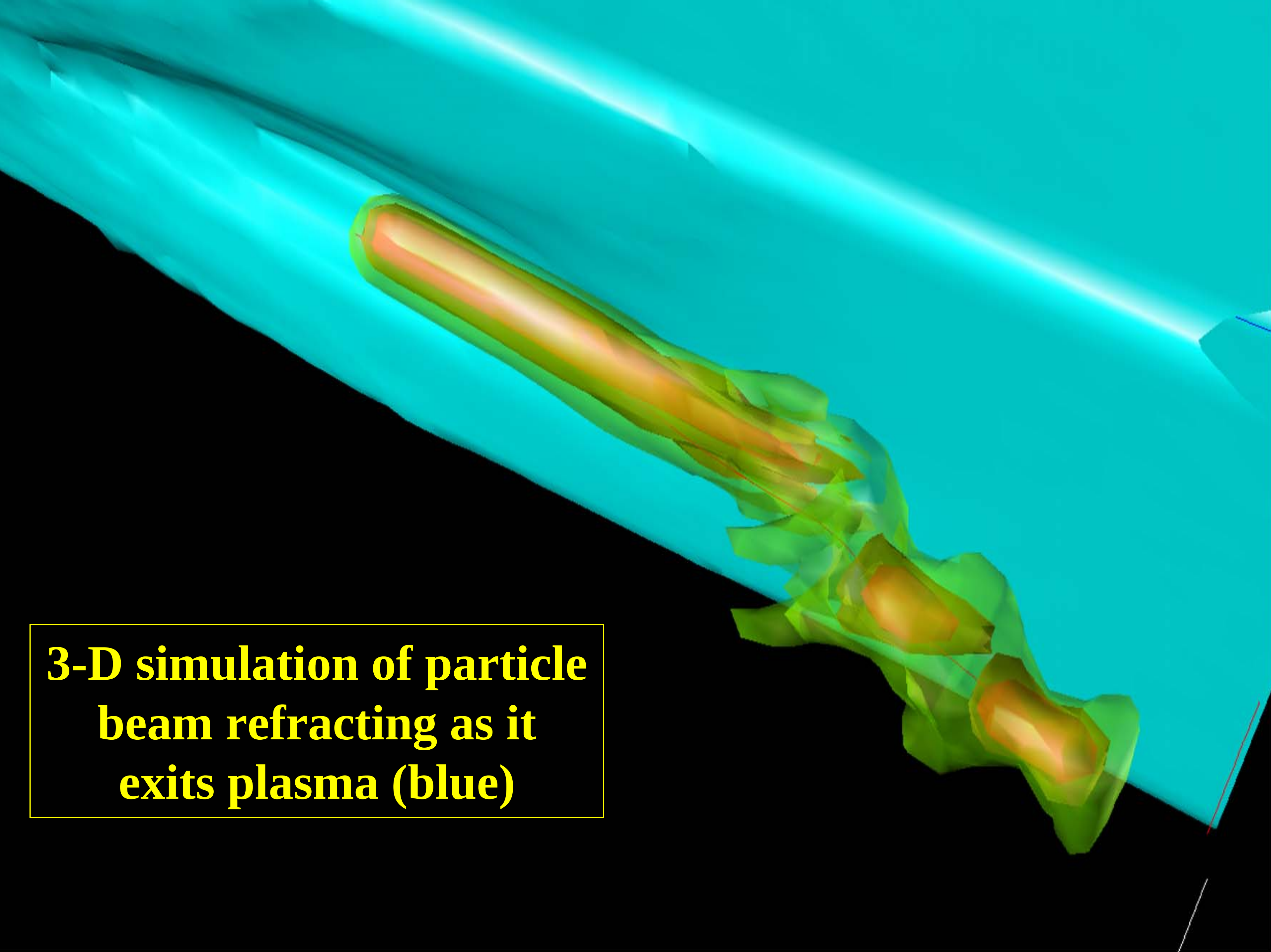
Particle beams



VORPAL scales well to 1,000's of processors

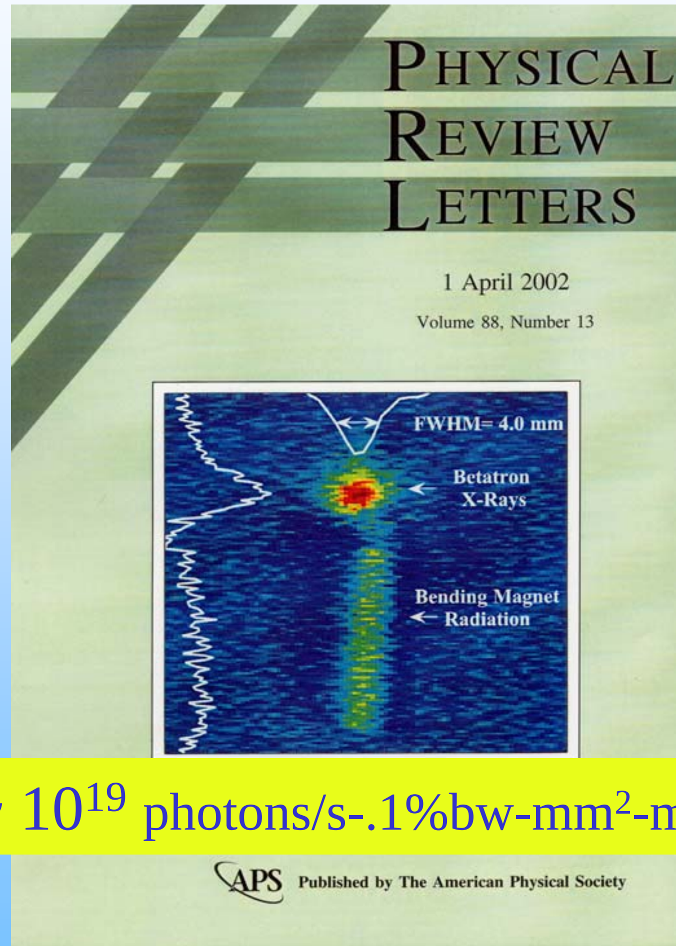
Plasma Afterburner for a Linear Collider





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

X-Ray emission from Betatron motion



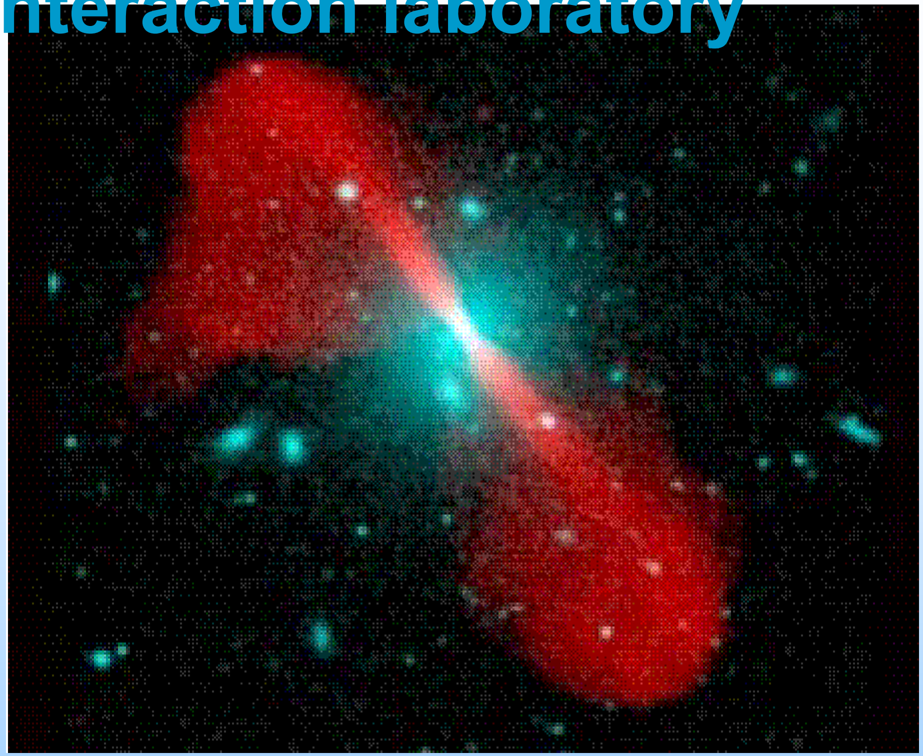
$I \sim 10^{19}$ photons/s-.1%bw-mm^2-mr^2 @6 keV

UCLA

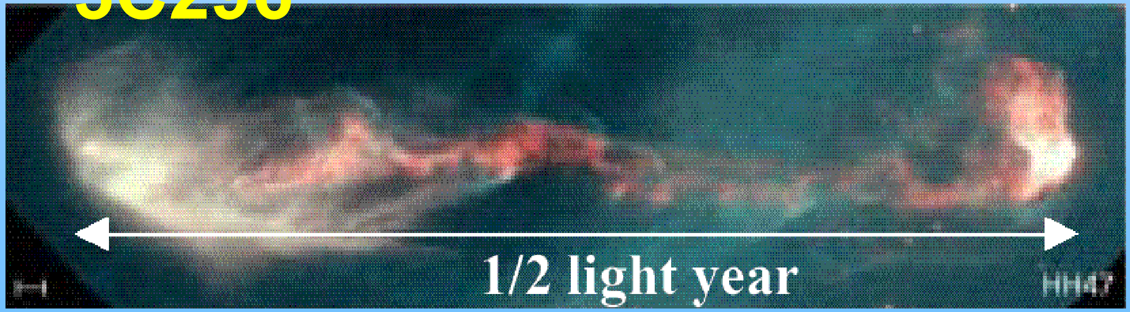
USC

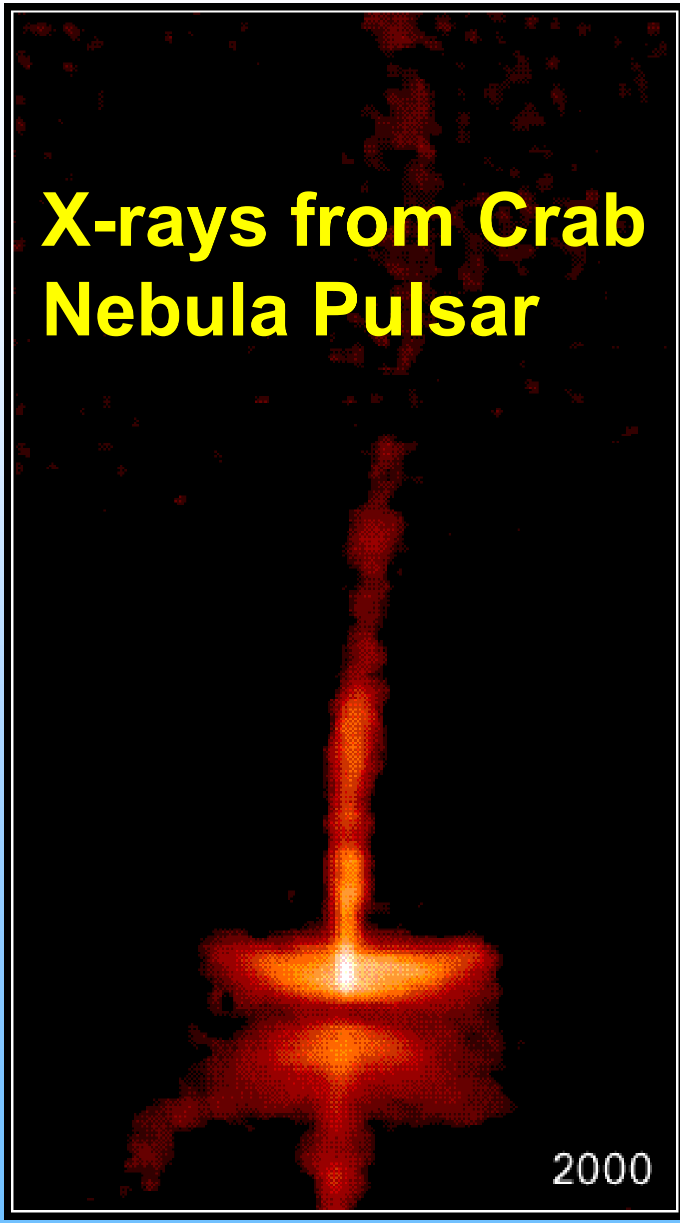
S. Wang et al. Phys. Rev. Lett. Vol. 88 Num. 13

Astrophysical Jets -- the ultimate beam-plasma interaction laboratory



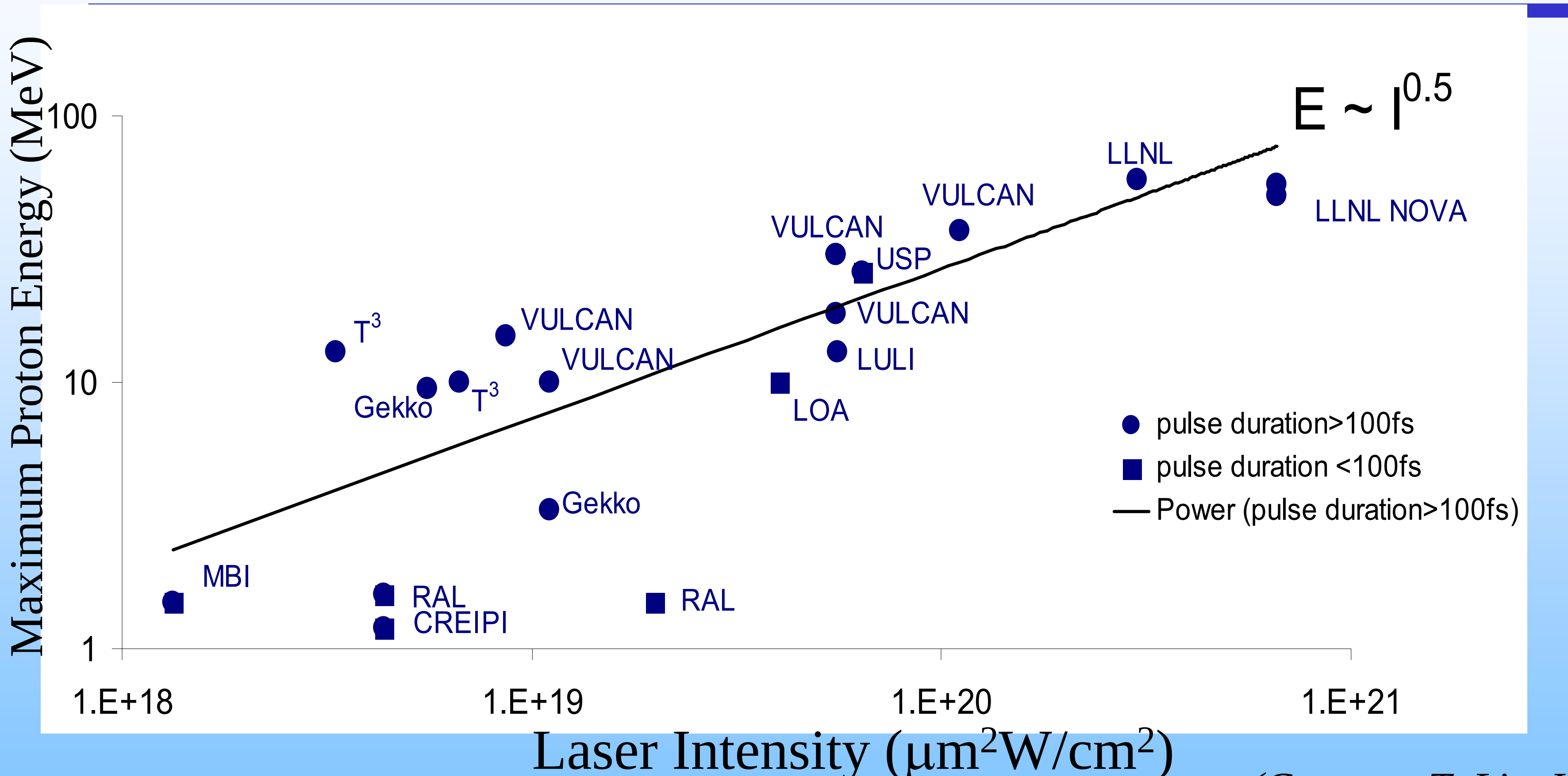
Radio Jets from Galaxy 3C296





X-rays from Crab Nebula Pulsar

Proton Energy Scaling

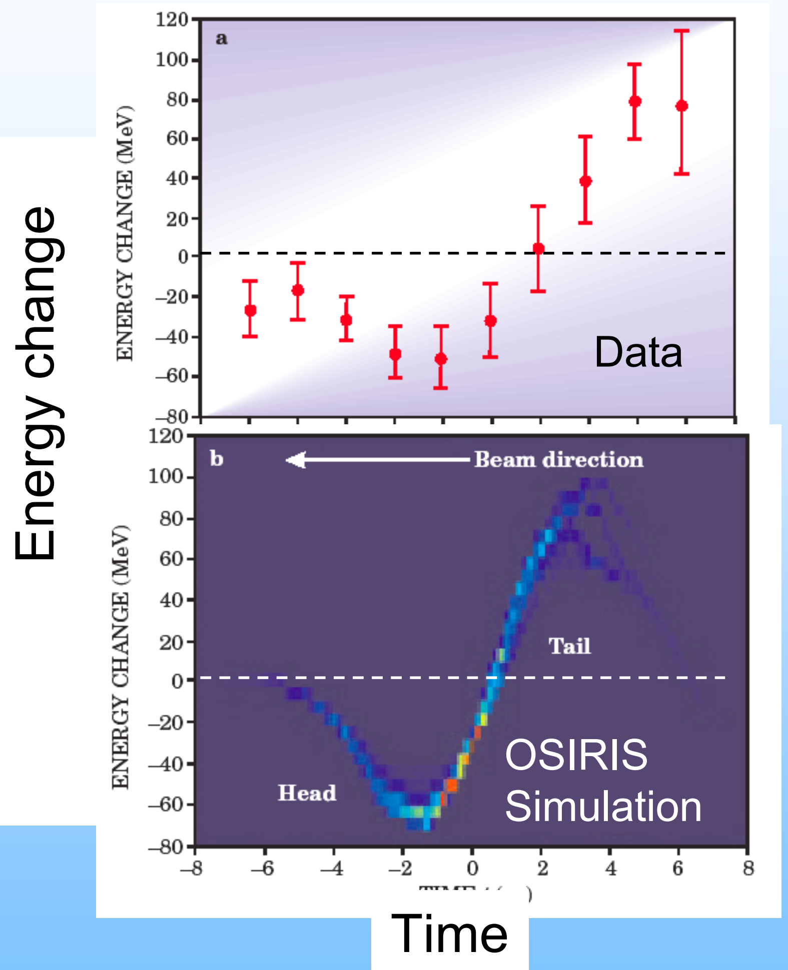


(Courtesy T. Lin, UM)

- Hi charge: 10^{10}-10^{13} ions
- Short pulses
- 100's MA/cm^2

Time resolved acceleration of positrons

E-162



- **Loss ≈ 50 MeV**
- **Gain ≈ 75 MeV**

B. Blue et al., Phys. Rev. Lett. 2003
R. Bingham, Nature, News and Views 2003

U C L A

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Stanford
Linear
Accelerator
Center

USC
UNIVERSITY
OF SOUTHERN
CALIFORNIA

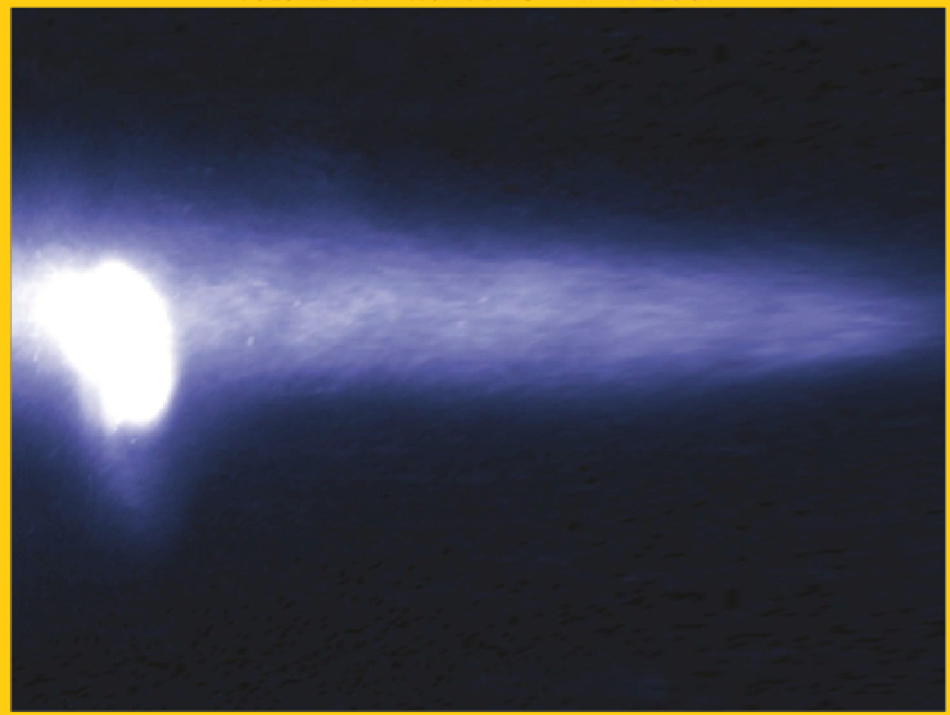
Ucla

Work supported by DOE

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

Particle Accelerators

Why Plasmas?

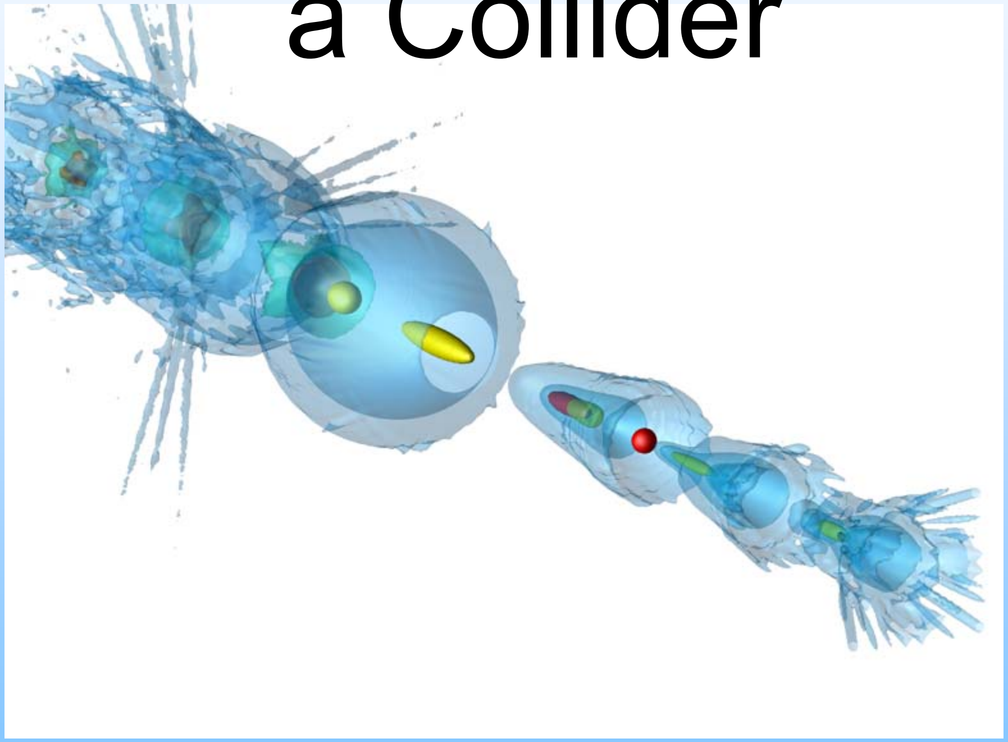
Conventional Accelerators

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

Plasma

- No breakdown limit
- 10-100 GeV/m

Plasma Acceleration: Critical Issues on the Road to a Collider



Duke
UNIVERSITY

Particle Accelerators: Compact to Country Size

Rich Physics and Applications

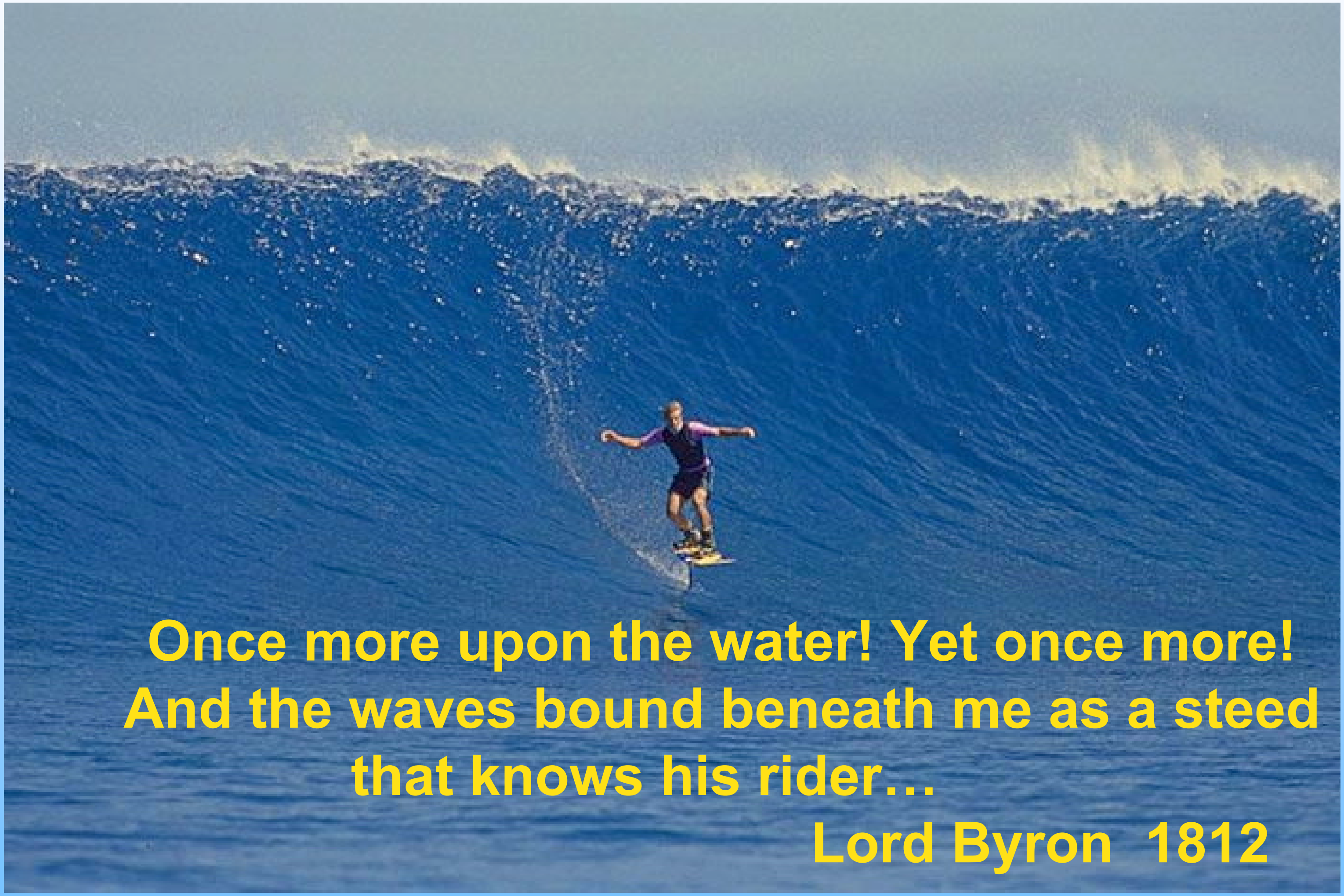
Large

- Verified Standard Model of elementary particles
  - W, Z bosons
  - Quarks, gluons
- Simulate early universe
  - Asymmetry of matter and anti-matter
  - quark-gluon plasmas
- In pursuit of the Higgs Boson (cause of mass)

Compact

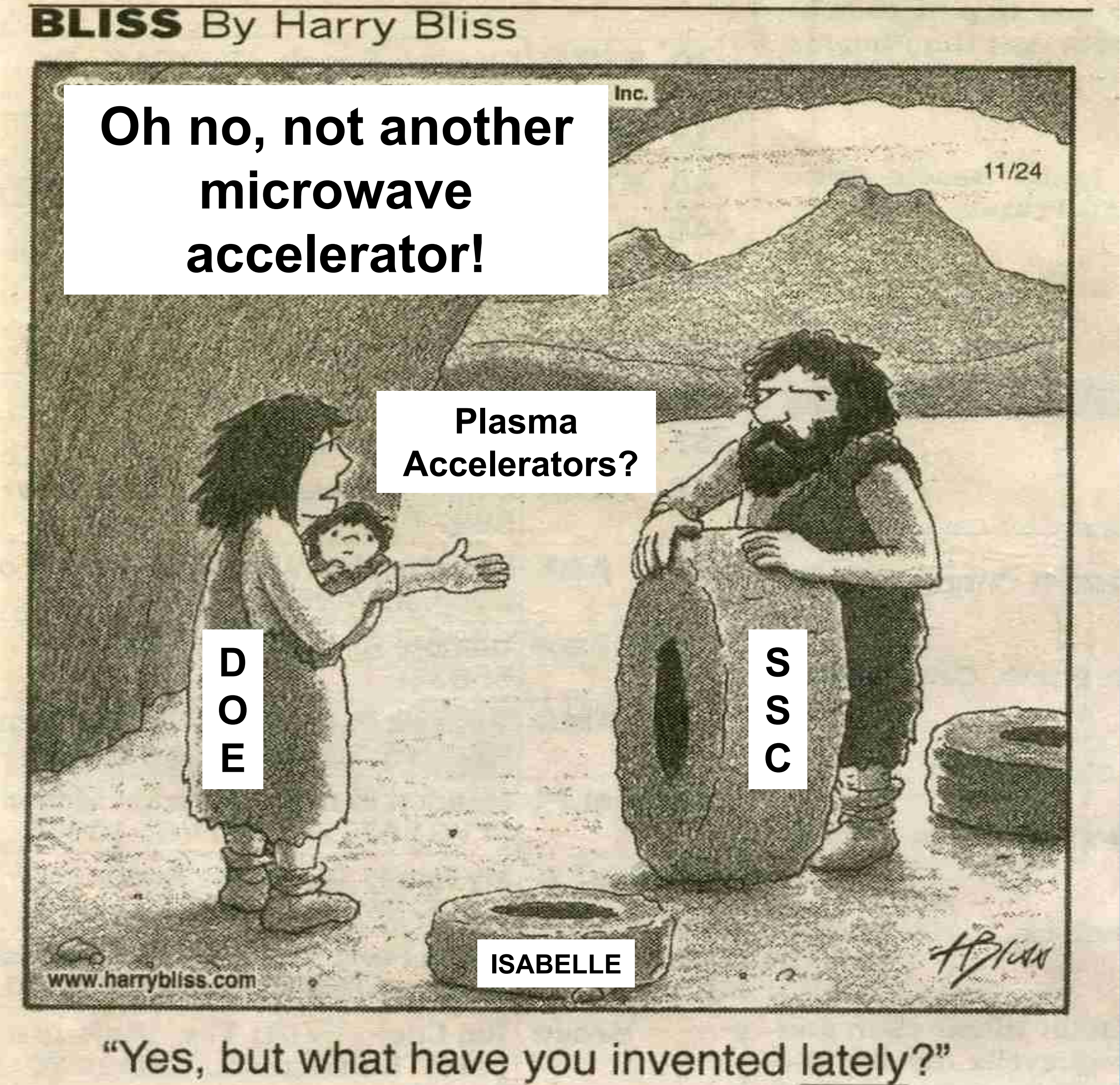
- Medicine
  - Cancer therapy, imaging
- Industry and Gov't
  - Killing anthrax
  - Lithography (microchips)
- Light Sources (synchrotrons)
  - Bio imaging
  - Condensed matter science

Gaining Kinetic Energy by Riding a Wave



Laird Hamilton:Hydrofoil Surfing in Hawaii

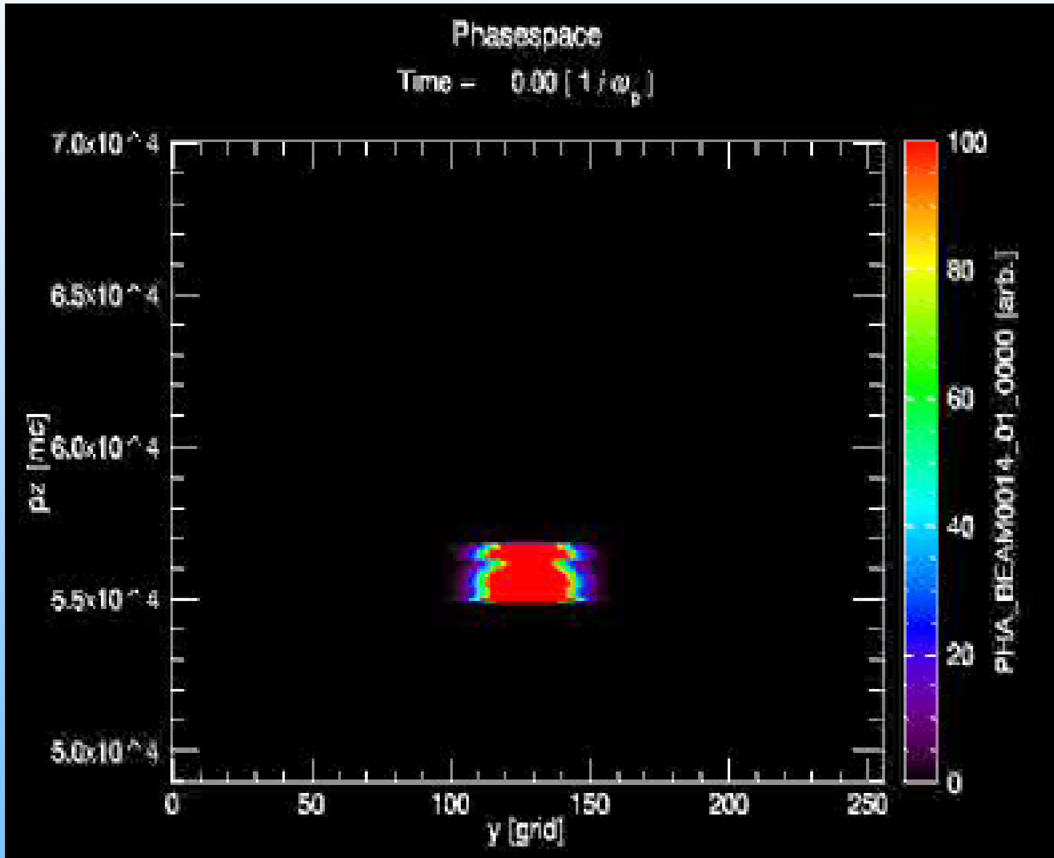
Advanced Acceleration Techniques, Circa 1990

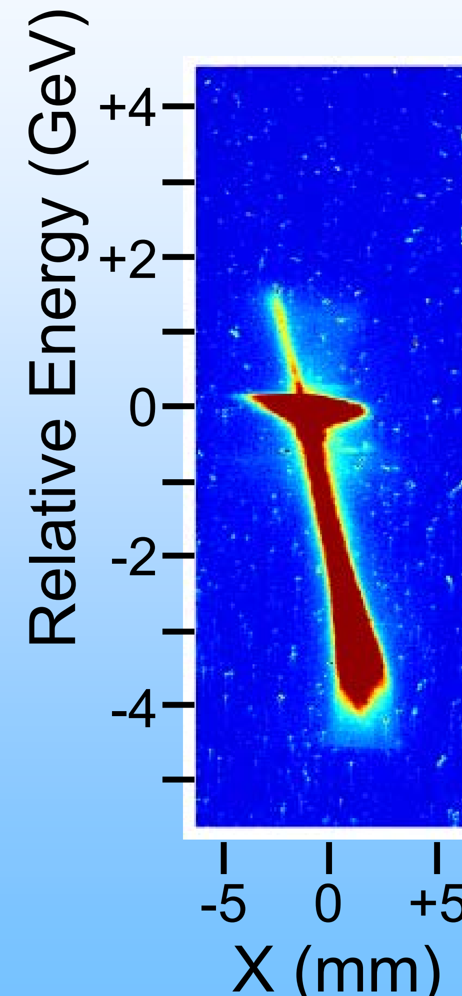


Full Scale Simulation of E164X

QuickPIC code

- Identical parameters to experiment including self-ionization: Agreement is very good!





M. Zhou et al.

UCLA

USC

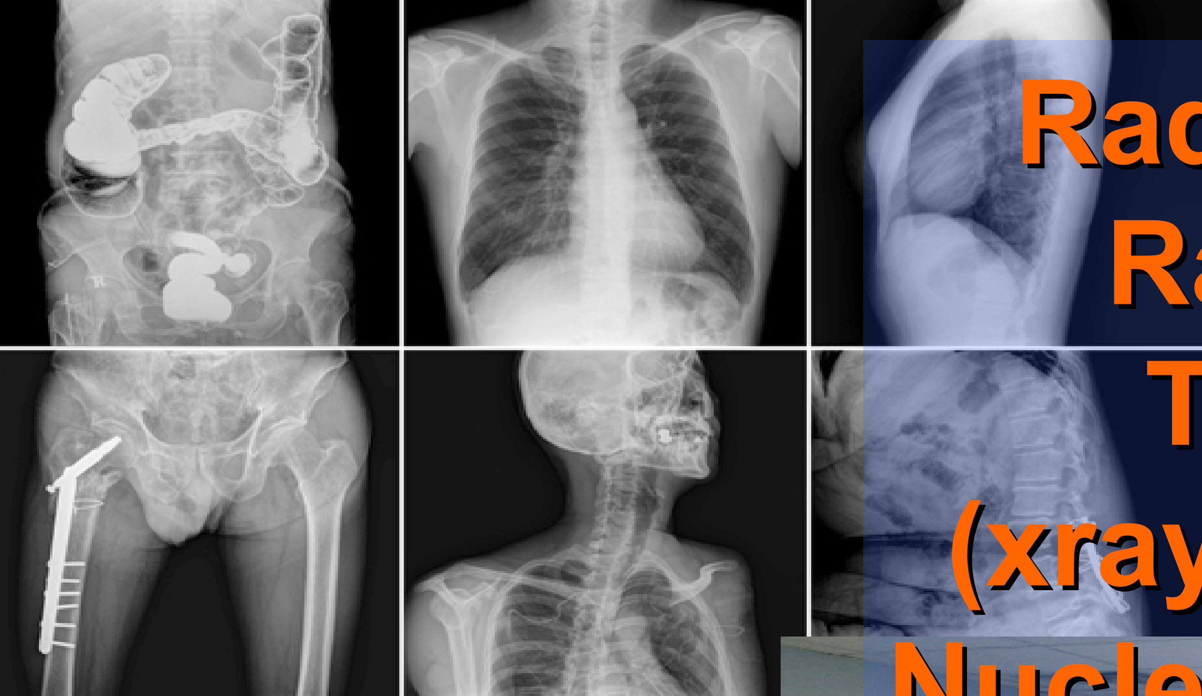
Radiography

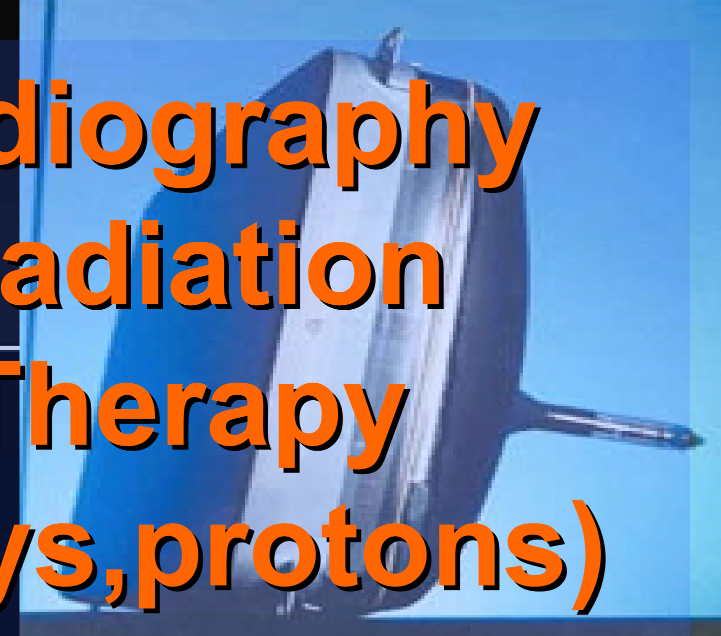
Radiation Therapy (xrays,protons)

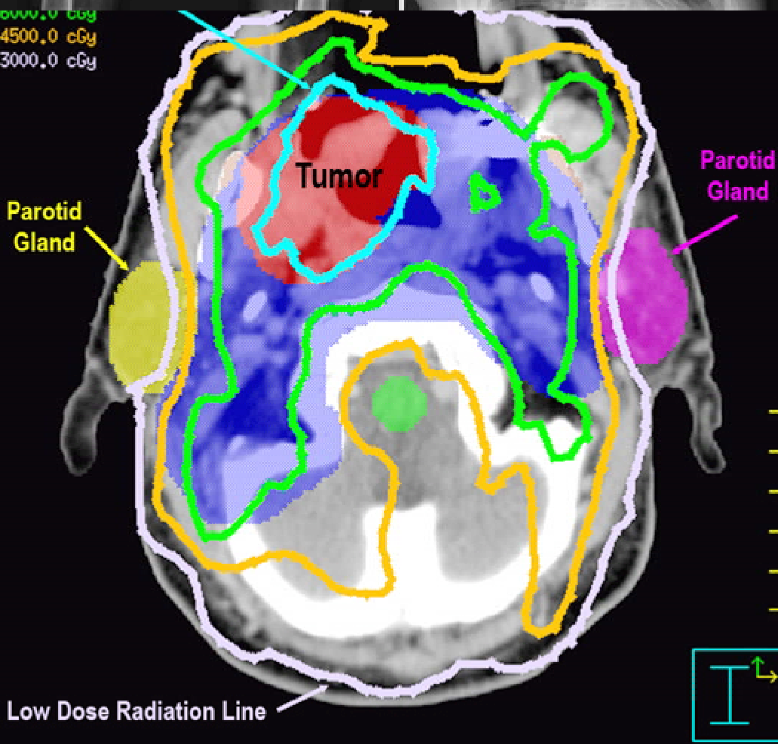
Nuclear medicine

Food sterilization

Disposal of nuclear waste







Limitation of Microwave Accelerators – Electric Breakdown

Leonardo deVinci
Study of Wakes:1509

Wavebreaking converts oscillating particles to surfing particles

Electrons "born" in plasma with <1μ-rad emittance

The Great Wave by Hokusai (1760-1849)

Other Areas of Security

Terahertz Imaging requires compact source development