Accelerators and Societal Grand Challenges for the 21st Century

Plasma density isocontours in laser wake. Courtesy F. Tsung
Accelerators and Societal Grand Challenges for the 21st Century

Tom Katsouleas
Professor and Dean
Duke University, Pratt School of Engineering

Symposium on Accelerators for America’s Future
October 26, 2009
### NAE Engineering Achievements of the 20th Century

**Technology Devices**

| 1. Electrification                      | 8. Agro machinery                  |
| 2. Automobiles                          | 9. Highways                        |
| 3. Jets and planes                      | 10. Electronics, TV,…              |
| 5. Lasers                               | 12. Space travel                   |
| 6. Computers                            | 13. The Internet                   |
| 7. Imaging Tech (PET)                   | 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

<table>
<thead>
<tr>
<th></th>
<th>Man</th>
<th>Mouse Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (Kgm)</td>
<td>70</td>
<td>25</td>
</tr>
<tr>
<td>Resp (sec)</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>R-R (sec)</td>
<td>1</td>
<td>0.1</td>
</tr>
</tbody>
</table>
“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 2242, 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.
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.
Tools of Scientific Discovery

Accelerators

Fermilab

Discovering the Nature of Nature
Twentieth Century Revolution in Physics

- Thomson (Electron 1897)
- Rutherford (Proton, Nucleus 1911)
- Chadwick (Neutron 1932)
- Gell-Mann (Quarks 1974, 1977, 1995)
- Standard Model
  - S, W, G force carriers

Three Generations of Matter:
- First Generation: u, c, t
- Second Generation: d, s, b
- Third Generation: v_e, v_μ, v_τ, e, μ, τ, W, Z

Electron (1897)
Proton, Nucleus (1911)
Neutron (1932)
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
- 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**
\[ \lambda \sim 30 \text{ cm wavelength} \]
E \sim 30 \text{ million Volts/meter}
“30 MeV/m”

**Plasma**
\[ \lambda \sim 100 \mu\text{m} \]
E \sim 30 \text{ billion Volts/meter}
“30 GeV/m”
Concepts For Plasma Based Accelerators*

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

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

- Drive beam
- Trailing beam

- 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

- e⁻ spectrum
- X-ray based spectrometer
- e⁻ beam from SLAC linear accelerator
- e⁻ bunch length autocorrelation of coherent transition radiation (CTR)
- e⁻ spatial distribution optical transition radiation (OTR)
- trapped particles plasma oven
- notch collimator
- imaging spectrometer
- scattered light in air gap
- e⁻ spectrum
- e⁻ spectrum einenkov light
- spectrometer magnet
- 30-40 GeV
- 10-100 GeV
Located in the FFTB

**PWFA Experiments @ SLAC**

*Share common apparatus*

- **Located in the FFTB**
  - Ionizing Laser Pulse (193 nm)
  - Li Plasma ne-6 ·10^15 cm^-3
  - L = 30 cm
  - Cerenkov Radiator
  - Streak Camera (1ps resolution)
  - X-Ray Diagnostic
  - Optical Transition Radiators
  - Spectrometer
  - Cerenkov Radiator
  - Dump
  - \( \sigma_z = 0.1 \text{ mm} \)
  - \( E = 30 \text{ GeV} \)

---

**Not to scale!**
Energy gain exceeds $\approx 3$ GeV in 10 cm

*M. Hogan, et al. (PRL, July 2005)*
Data is very reproducible!
Data is very reproducible!
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: 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)

Laser

Gas Jet

Plasma

Nozzle

Electron beam

2mm
Dream beam
The dawn of compact particle accelerators

Electrons hang ten on laser wake
Thomas Kistler

Electrons can be accelerated by making them surf a laser-driven plasma wake. High-acceleration rates, and thus the production of well-populated, high-charge beams, suggest the potential of this tube-top technology.

Huge particle accelerators have been the bread and butter of high-energy physics for decades. But, for fundamental questions about the nature of matter and forces, these behemoths are a limiting factor. The latest project at the California Institute of Technology (Caltech), a privately funded construction of a 300MeV linear accelerator (CINTA) in Pasadena, will attempt to find a new breed, a particle accelerator with a much smaller footprint. The project is the most ambitious effort to date to build a compact particle accelerator through which all the benefits of high-energy physics are brought to science and industry.

Protein folding
Escape from the ribosome

Human ancestry
One from all and all from one

RNA interference

The Earth’s hum
Sounds of air and sea

Technology feature

30 September 2004
International weekly journal of science
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 $< \text{dephasing length}$: large energy spread
   If $L \sim \text{dephasing length}$: monoenergetic

T. Katsouleas, Nature 2004
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
  \[ \varepsilon_N \sim r \theta \sim 1 \mu \times 1 \text{ rad} = 1 \text{ mm-mrad} \]

(100’s of pCoul from a “cathode” spot of 1\(\mu\))
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)

**BELLA Laser**

- Operational in 2012-13

- Beam: ~10 GeV

- Laser: 1000 TW, 40 fs
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

From good Physics to a good Collider is a Grand Challenge worth pursuing
Photon beams are commonly used for radiation therapy.

- **Photon beam**
- **Dose**
- **10 MV Photon dose**
- **tumor**
- **Depth in tissue**
200 MV Electron Therapy

- Reduced dose near surface
- Treatment of deep tumors

V. Malka: LOA
Laser acceleration of ions from solid targets

I. ambient expansion
II. sweeping acceleration
III. sheath field acceleration

Laser: few J / ~1 ps (>10 TW)
$I\lambda^2 > 10^{18}$ W cm$^{-2}$ μm$^2$

Bulk Target (Al)

H$^+$ ion
H$^+$/other ions

Incident laser


if target is heated $\Rightarrow$ efficient acceleration of heavy ions


Courtes J. Fuchs

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

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


- Remove e-
- Remove x-rays

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

200 accumulation shots

Intact cells (not irradiated)

Damaged cells (irradiated)
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...
A Strategy for American Innovation: DRIVING TOWARDS SUSTAINABLE GROWTH AND QUALITY JOBS

- Catalyze Breakthroughs for National Priorities
  - Unleash a clean energy revolution
  - Support advanced vehicle technology
  - Drive breakthroughs in health
  - Address the "grand challenges" of the 21st century

- Promote Competitive Markets that Spur Productive Entrepreneurship
  - Promote American exports
  - Support open capital markets that allocate resources to the most promising ideas
  - Encourage high-growth and innovation-based entrepreneurship
  - Improve public sector innovation and support community innovation
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
Laser-foil protons: Record beam quality

$\varepsilon_n < .004 \text{ mm-mrad!}$

- 10x lower $\varepsilon$ than conventional ion injectors

Big Physics Gets Small
Tabletop Accelerators Make Particles Surf on Plasma Wakes - Smaller? - Cheaper?
Further reading:

- Lighter: A Hole in Texas
- Angels and Demons

**ENGINES OF DISCOVERY**

A Century of Particle Accelerators
Andrew Sessler-Edmund Wilson
### NAE Grand Challenges for the 21st Century

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<td>Advance personalized learning</td>
<td>Engineer the tools of scientific discovery</td>
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Plasma Accelerator Progress

“Accelerator Moore’s Law”

Working Machines Doing physics

Max. Energy In Plasma Experiments

YEAR


BEAM ENERGY (MeV)

1 10 10^2 10^3 10^4 10^5 10^6 10^7

RAL LBL Osak UCLA E164X UCLA E167 LBNL RAL E162 LOA RAL UCLA KEK LLNL
Plasma Accelerator Research: Experimentalist Perspective

From: Chan Joshi, UCLA Personal archives
Plasma Accelerator Research: Computer Simulationist Perspective

3-D simulation of particle beam refracting as it exits plasma (blue)
Ancient Greece Around 500 BC

Matter made of atoms
Atomos = Indivisible

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

For Today Remember “Opposites Attract”
“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

---

The FACET Program will demonstrate most of a single stage.
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

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

W. Lu et al., UCLA
The E-162/E-164 Collaboration:


Stanford Linear Accelerator Center


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 Design

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

500 GeV Energy Gain in 20 meters!

Phasespace
Time = 1335000.00 [1/ωp]

N=3x10^{10} electrons
N=1x10^{10} electrons

Accelerating field
24GeV/m at the load
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

Extra and backup slides
How are the simulations done?

**Computational cycle**

(At each step in time)

- Particle positions: $z_i, v_i$
- Lorentz Force: $\frac{d\mathbf{p}}{dt} = \mathbf{E} + \mathbf{v} \times \mathbf{B}/c$
- Interpolate to particles
- Weight to grid

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

**Typical simulation parameters:**

- $\sim 10^7$-$10^8$ particles
- $\sim 10^4$ time steps
- $\sim 1-10$ Gbytes
- $\sim 10^2$-$10^3$ 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

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 \approx 10^{19} \text{ photons/s} \cdot 1\% \text{bw-mm}^2 \cdot \text{mr}^2 \ @ 6 \text{ keV}
Astrophysical Jets -- the ultimate beam-plasma interaction laboratory

Radio Jets from Galaxy 3C296

X-rays from Crab Nebula Pulsar
Proton Energy Scaling

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

(Courtesy T. Lin, UM)
Time resolved acceleration of positrons

- Loss $\approx 50$ MeV
- Gain $\approx 75$ MeV

Particle Accelerators

Why Plasmas?

<table>
<thead>
<tr>
<th>Conventional Accelerators</th>
<th>Plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Limited by peak power and breakdown</td>
<td>• No breakdown limit</td>
</tr>
<tr>
<td>• 20-100 MeV/m</td>
<td>• 10-100 GeV/m</td>
</tr>
<tr>
<td>• ILC = 20km /0.8 TeV</td>
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</table>
Plasma Acceleration: Critical Issues on the Road to a Collider
### 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

Once more upon the water! Yet once more!
And the waves bound beneath me as a steed
that knows his rider…

Lord Byron 1812

Laird Hamilton: Hydrofoil Surfing in Hawaii
Oh no, not another microwave accelerator!

Plasma Accelerators?

“Yes, but what have you invented lately?”

Advanced Acceleration Techniques, Circa 1990
Full Scale Simulation of E164X

QuickPIC code

- Identical parameters to experiment including self-ionization: Agreement is very good!
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 $<1\mu$-rad emittance

The Great Wave by Hokusai (1760-1849)
Other Areas of Security

Terahertz Imaging requires compact source development