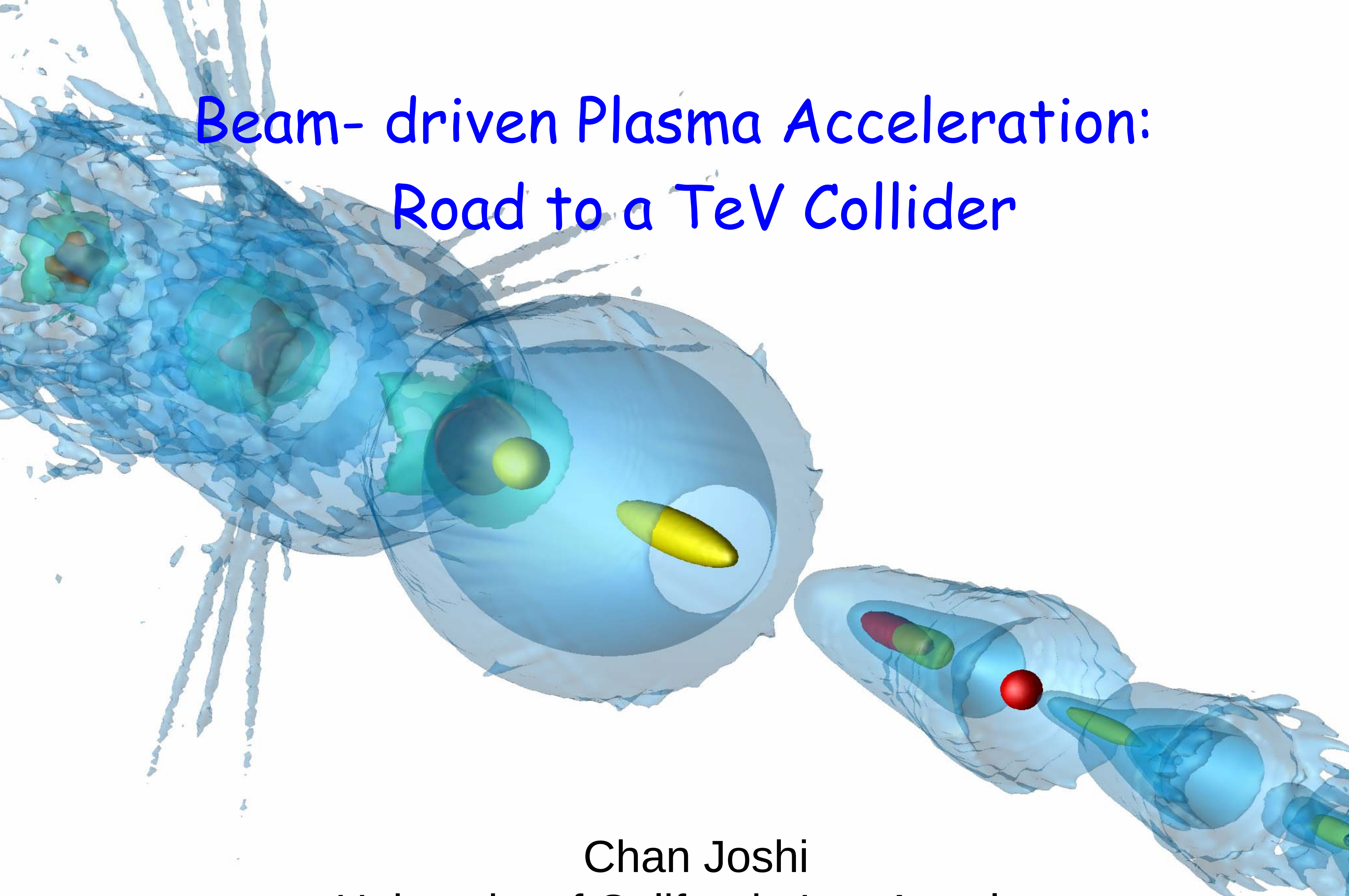
Beam- driven Plasma Acceleration: Road to a TeV Collider



Chan Joshi
University of California Los Angeles
IPAC Conference Kyoto Japan May 2010

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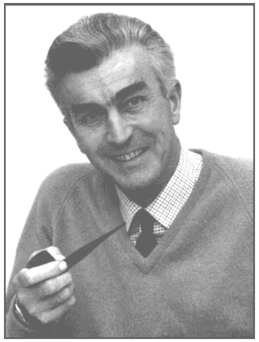
		* W. Wittmer	SLAC

Accelerator Physics : A legacy of brilliant 20th Century Scientists

Van der Meer

Richter



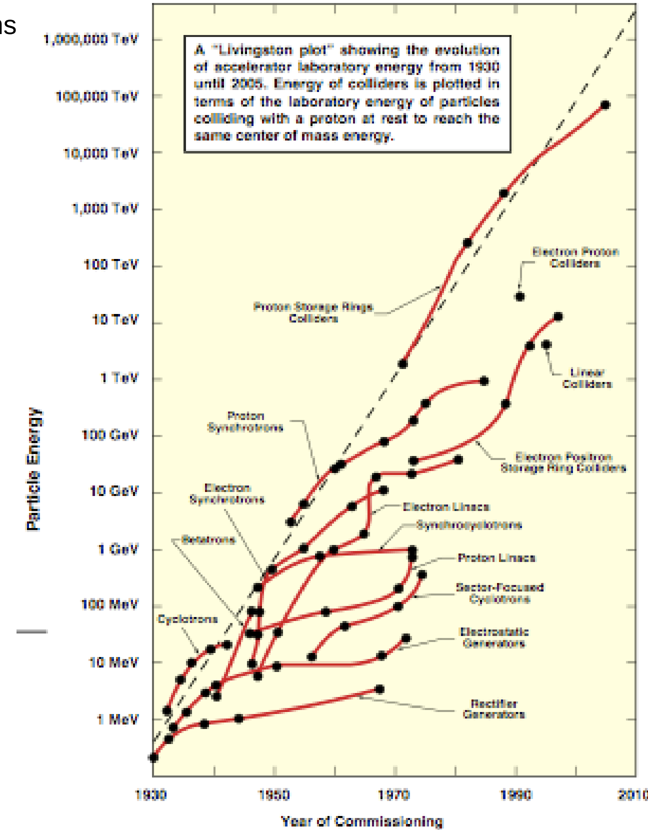
Adams

Wilson

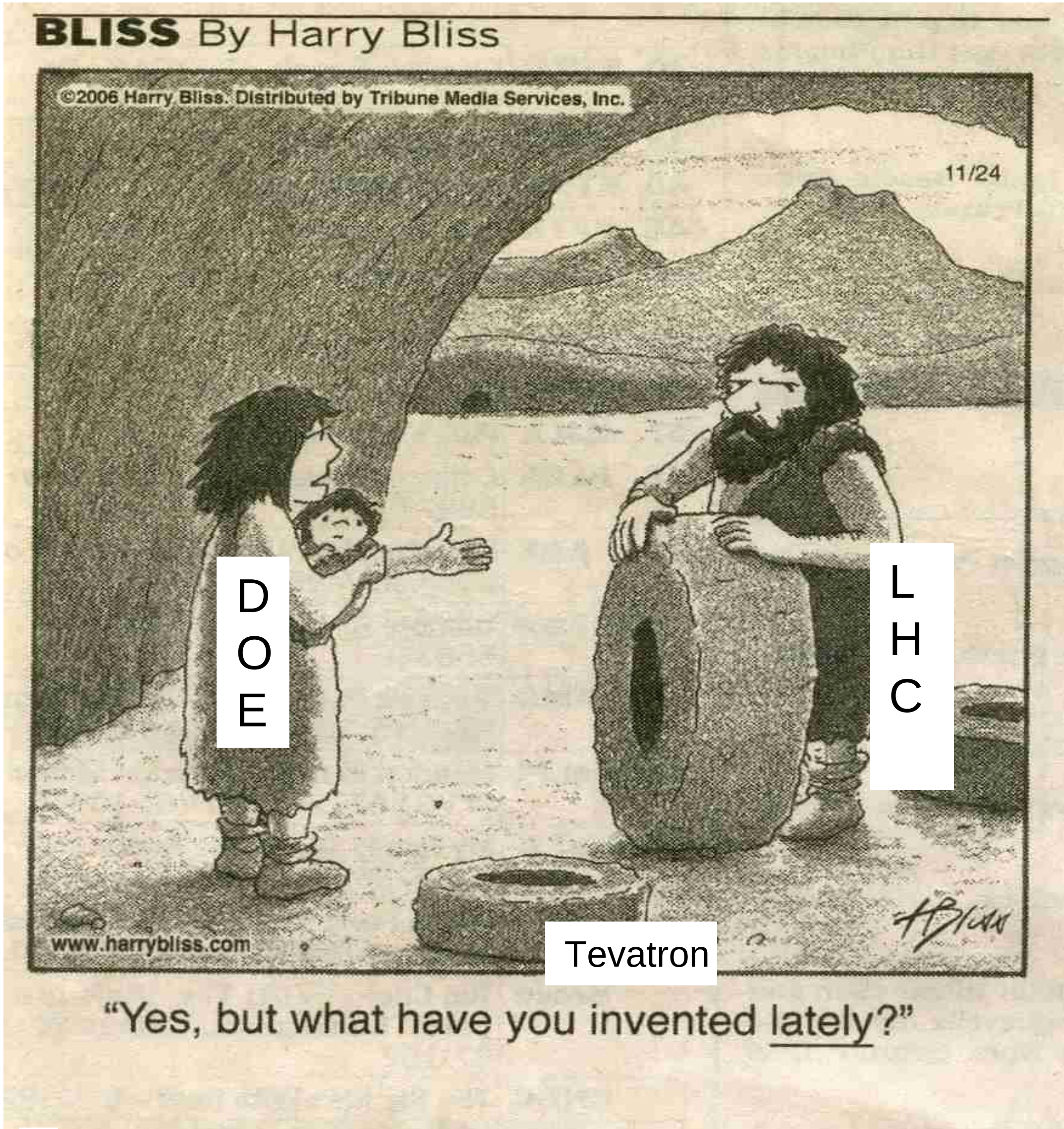
Lawrence

Van de Graaff

Cockcroft & Walton with Rutherford



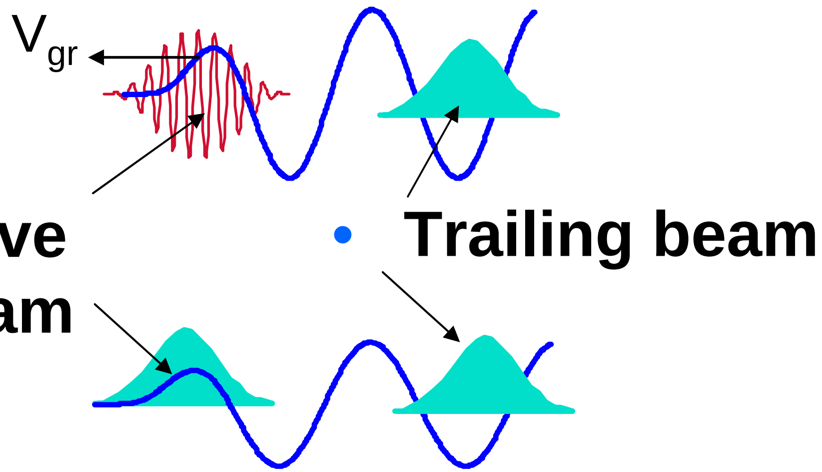
Need a new technology for accelerating charged-particles



Plasma Based Accelerators

- Laser Wake Field Accelerator

  A single short-pulse of photons



Plasma Wake Field Accelerator

A high energy electron bunch

- Wake: phase velocity = driver velocity

Large wake for a laser amplitude, $a_o = eE_o/m\omega_o c \sim 1$ or
a beam density $n_b \sim n_o$

For τ_{pulse} of order $\pi\omega_p^{-1} \sim 100fs\,(10^{17}/n_o)^{1/2}$ and spot size c/ω_p:

P ~ 15 TW $(\tau_{pulse}/100\text{ fs})^2$ laser
I ~ 20 kA Beam

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

Conventional Accelerator

Copper Structure with irises

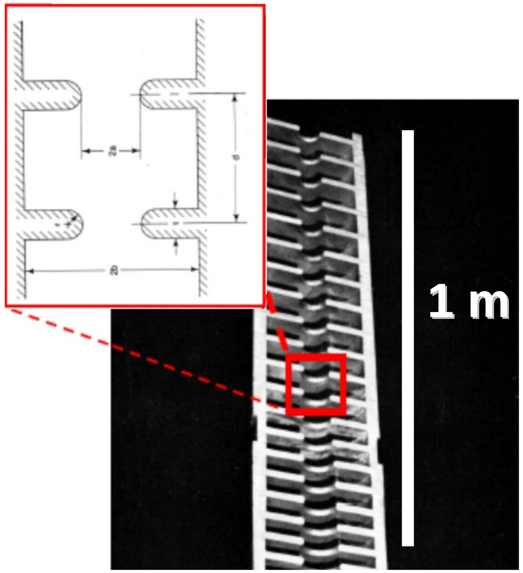
Powered by microwaves

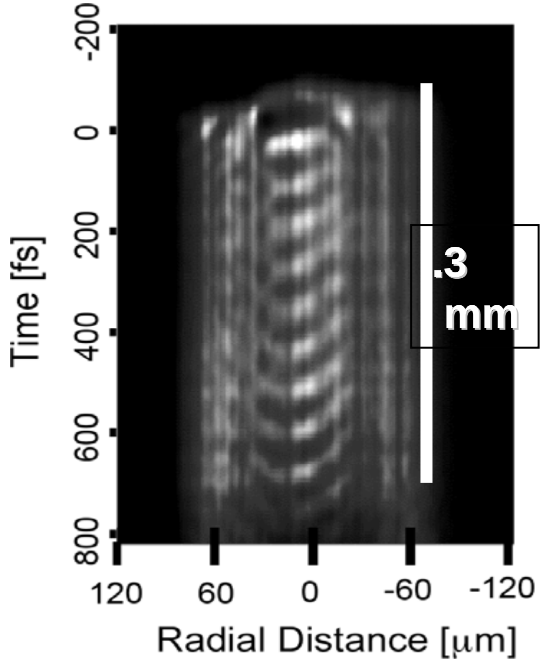
Energy Gain 20 MV/m
Structure Diameter 10cm

Plasma Accelerator

Ionized Gas
Lifetime, few picoseconds
Powered by a Laser or electron beam pulse
Energy Gain 20 GV/m
Diameter 0.1-l mm

BIG PHYSICS BECOMES SMALL



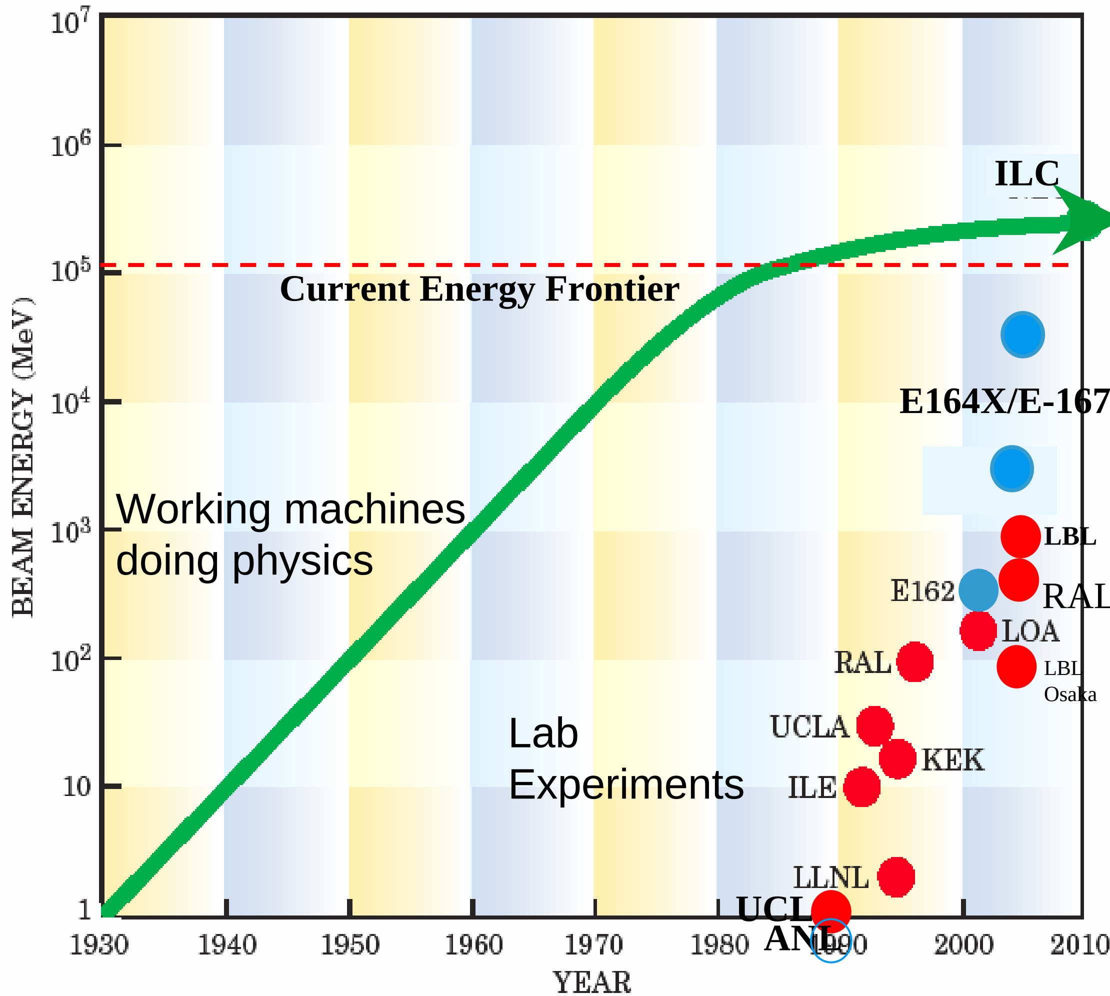


M.Downer U.Texas

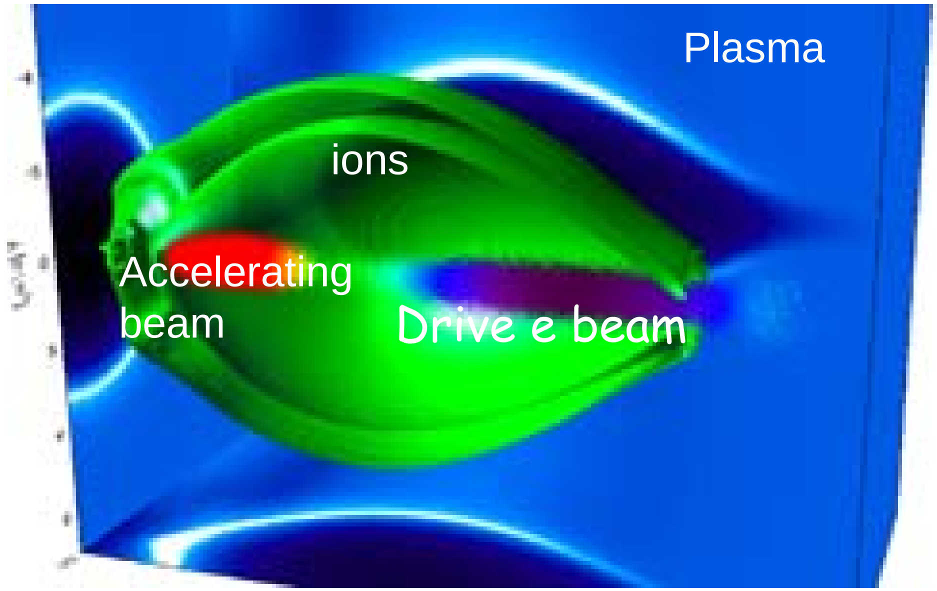
Plasma Accelerators

"Story of Science as a living thing" J.M.Dawson

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



Plasma Wakefield Acceleration



- Space charge force of the beam pulse displaces plasma electrons
- Plasma ion channel exerts restoring force => space charge wake

No dephasing between the particles and the wake

P.Chen et.al.PRL(1983)

OUR VISION

To address critical issues for realizing a plasma-based accelerator at the energy frontier in the next decade. A by- product will be compact accelerators for industry & science

Intense Beams of Electrons for Plasma Wakefield Acceleration

N = 4 x 10^{10}

Energy 50 GeV

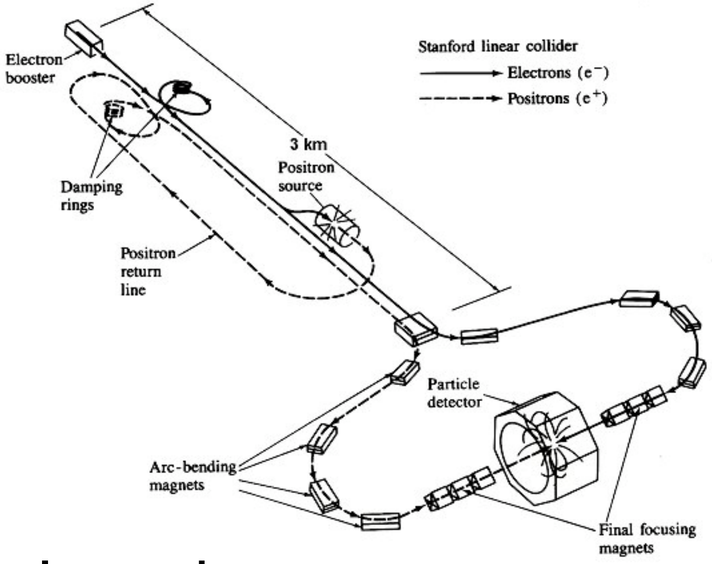
Rep Rate 60 HZ

Energy/pulse 320 J
Focal Spot Size 10 microns

Pulse Width 50 fs

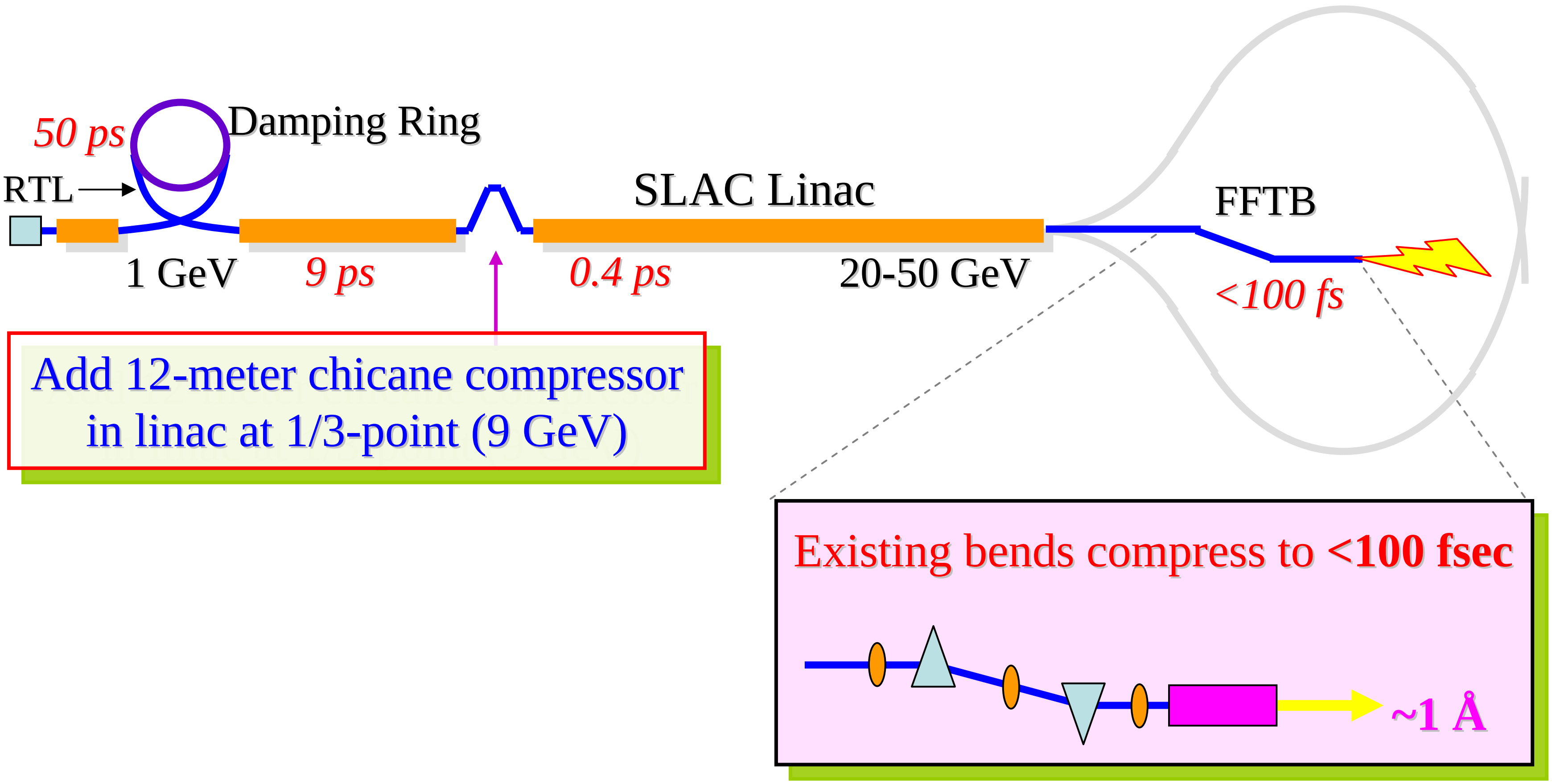
Focused Intensity 7 x 10^{21} W/cm^2

SLAC NATIONAL ACCELERATOR LABORATORY
New SLAC National Accelerator Laboratory logo

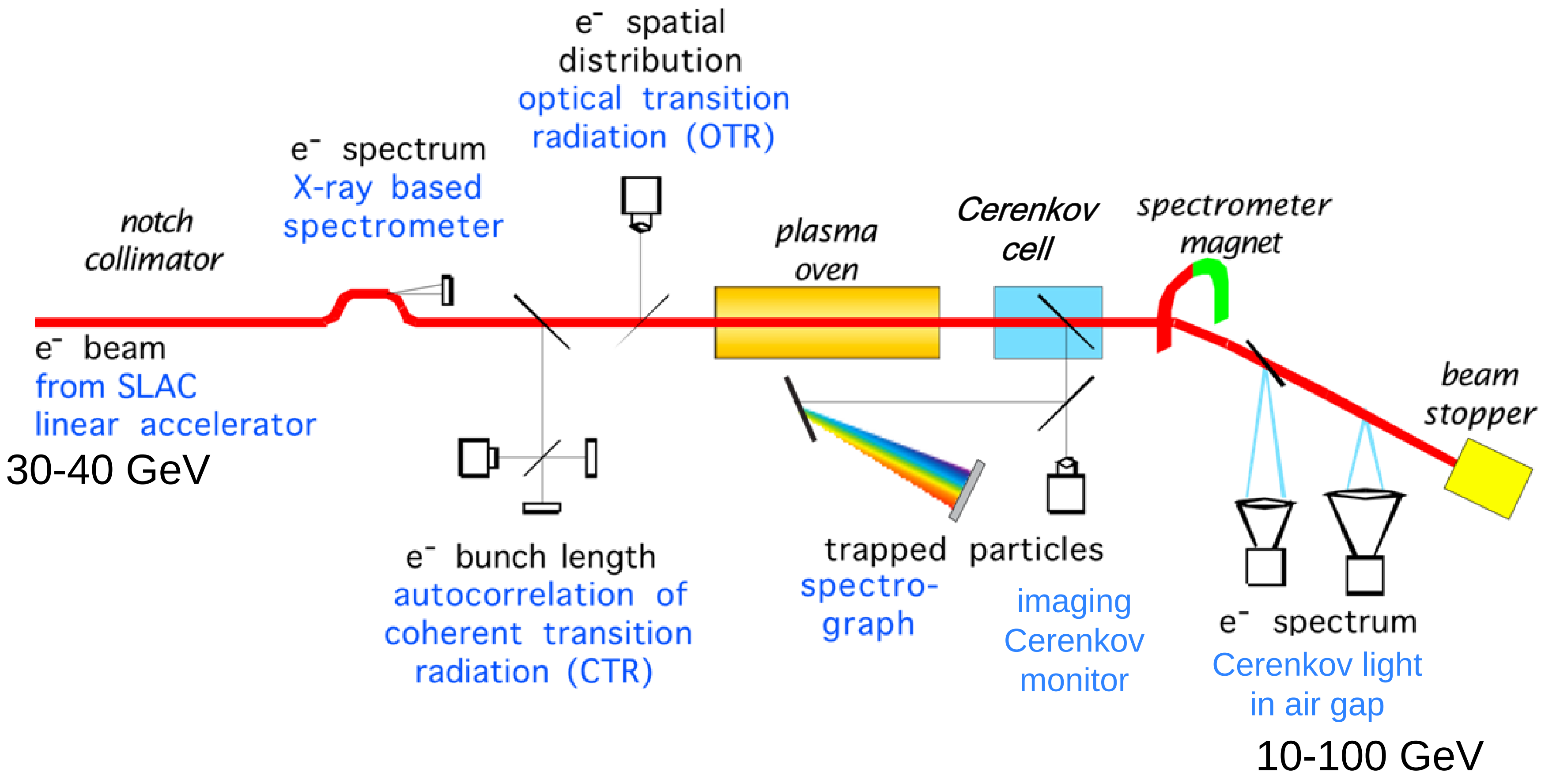


Comparable to the most intense laser beams to-date

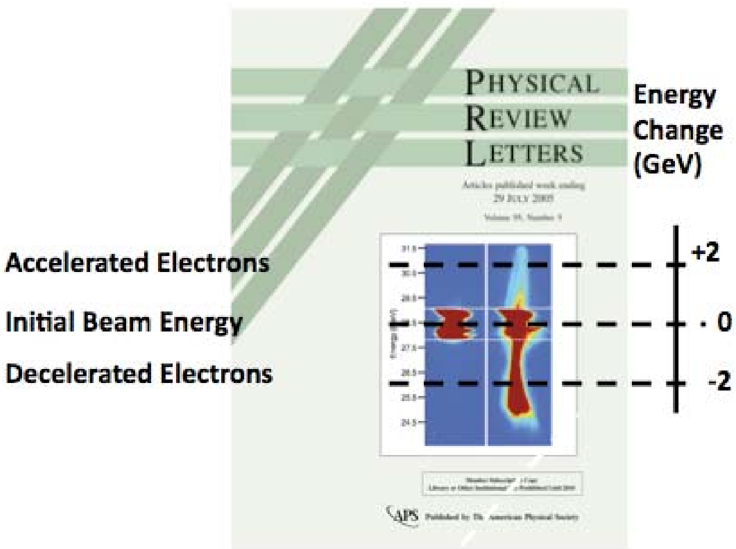
Short Bunch Generation In SLAC Linac



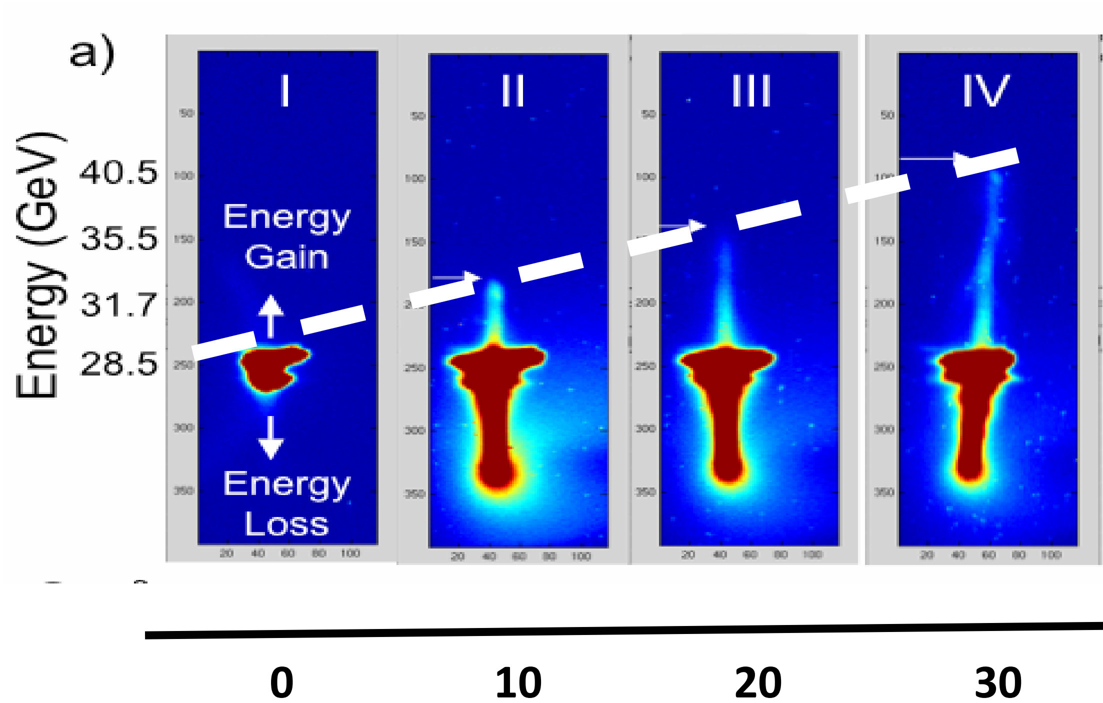
Experimental Setup



Energy Gain Scales Linearly with Length



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



BREAKING THE 1 GeV BARRIER

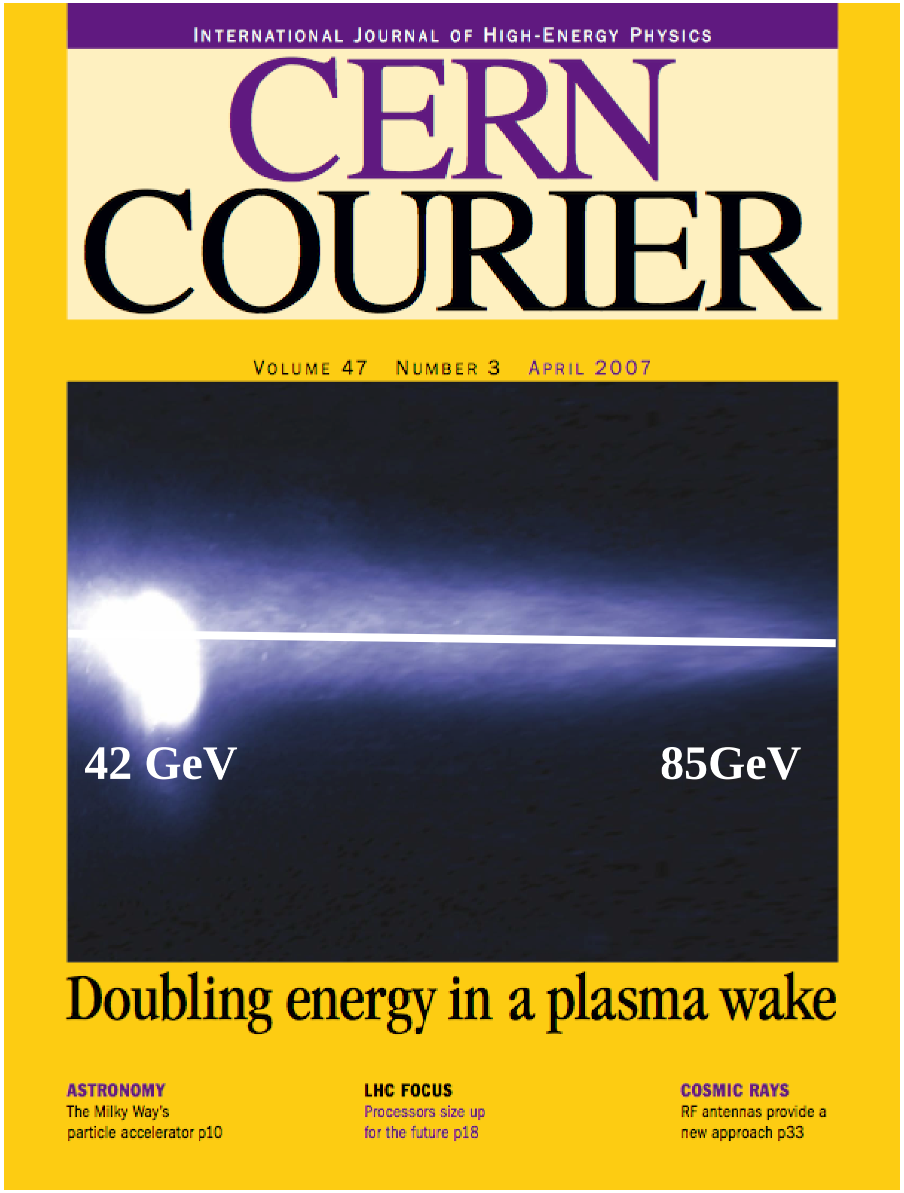
PLASMA LENGTH (cm)

M.Hogan et al Phys Rev Lett (2005)

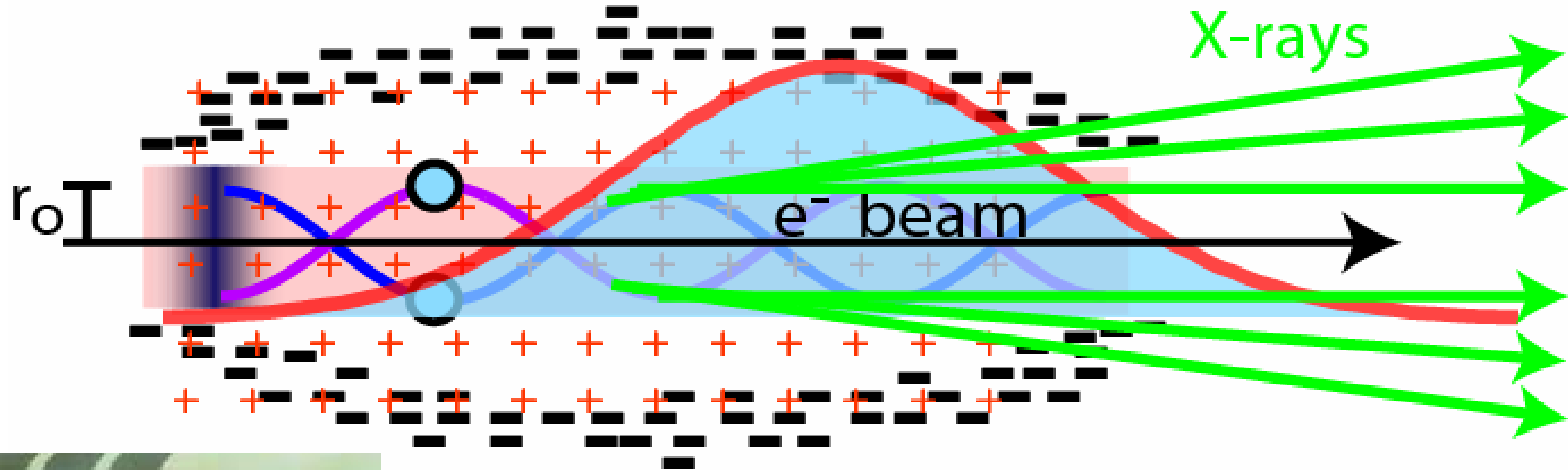
Path to a collider builds on recent success

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

Nature v 445,p741 (2007)



Radiation Loss :Ultimate Limit on Plasma Accelerators @ 2.5 TeV CM with 1 micron beam



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

$$\frac{dE}{dz} = \frac{1}{3} r_e m_e c^2 \gamma^2 k_\beta^2 K^2 = f\left(n_p^2, r_o^2, \gamma^2\right) = 4.3 GeV / m$$

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

From Science to a Collider

Requirements for High Energy Physics

* High Energy
* High Luminosity (event rate)
  - $L = f_{rep} N^2 / 4\pi\sigma_x\sigma_y$
- High Beam Power
  - ~20 MW
* High Beam Quality
  - Energy spread $\delta\gamma/\gamma$ ~ .1 - 10%
  - Low emittance: $\varepsilon_n \sim \gamma\sigma_y\theta_y$ << 1 mm-mrad
* Reasonable Cost : less than $5 B for 1 TeV CM
  - Gradients > 100 MeV/m
  - Efficiency > few %

Path to a TeV Collider

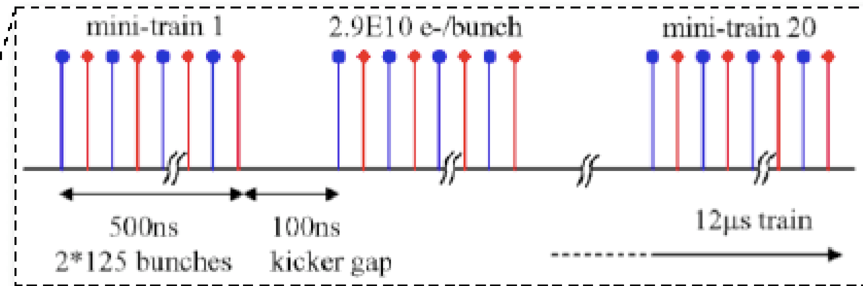
*from present state-of-the-art**

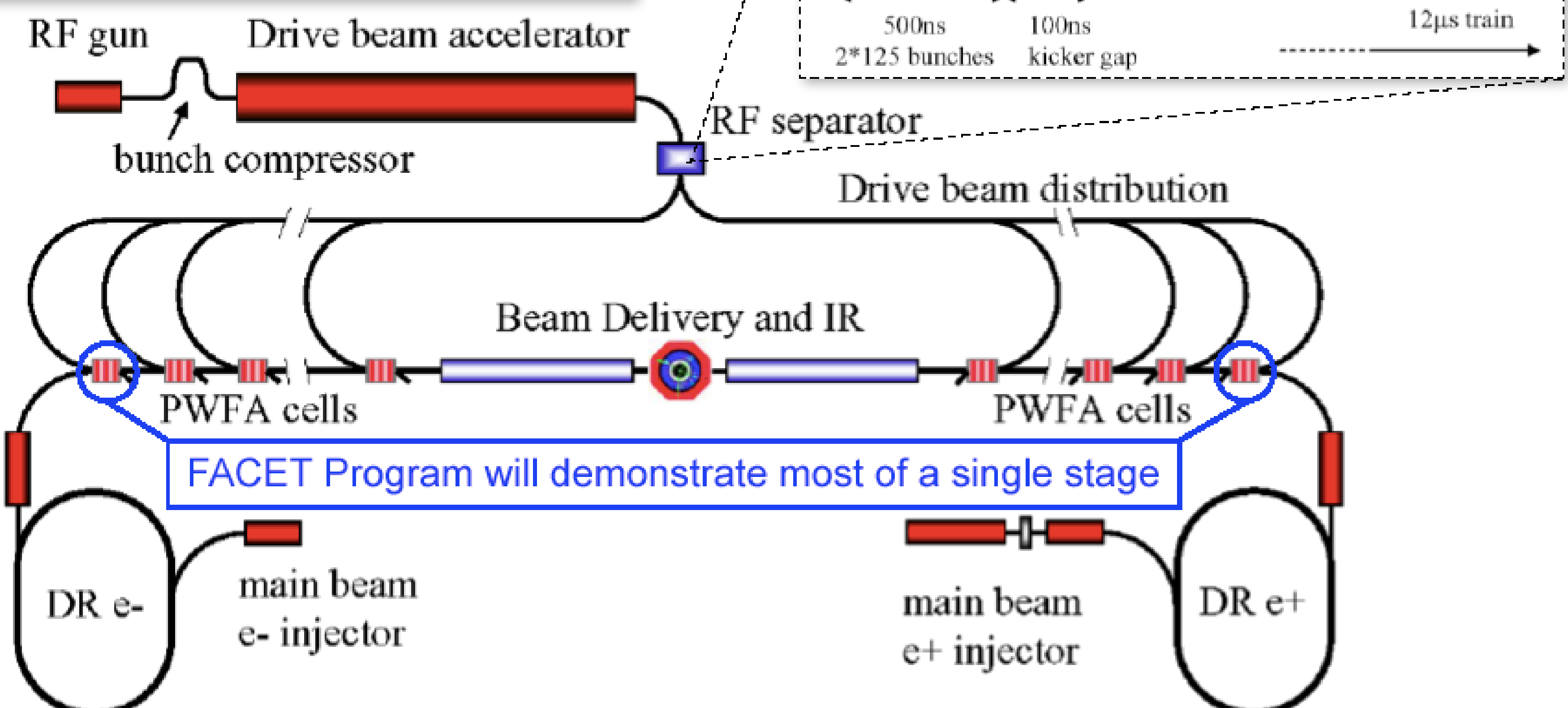
* Starting point: 42 --> 85 GeV in 1m
  - Few % of particles
* Beam load
  - 25 --> 50 GeV in ~ 1m
  - 2nd bunch with 33% of particles
  - Small energy spread
  - Preserve emittance
* Replicate for positrons
* Marry to high efficiency driver
* Stage 20 times

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

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

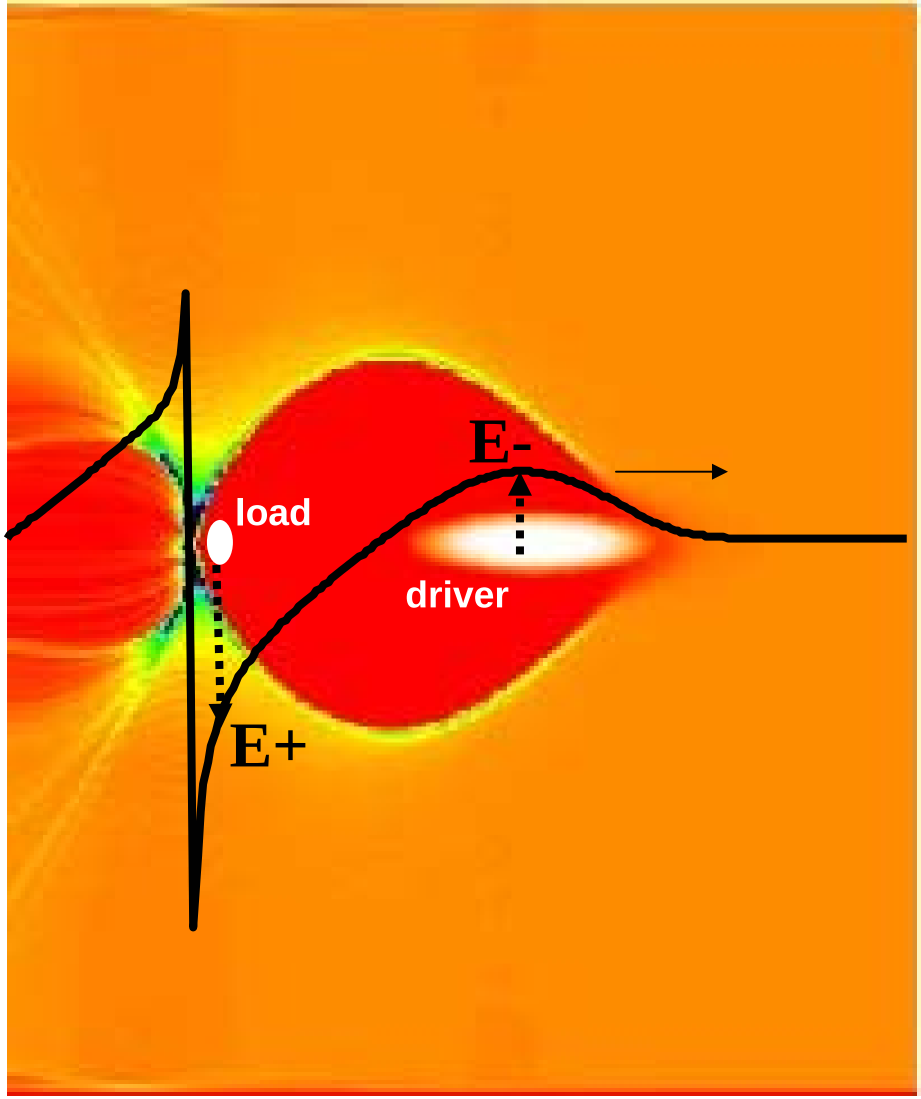




Self-consistent 1 TeV PWFA-LC Design

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

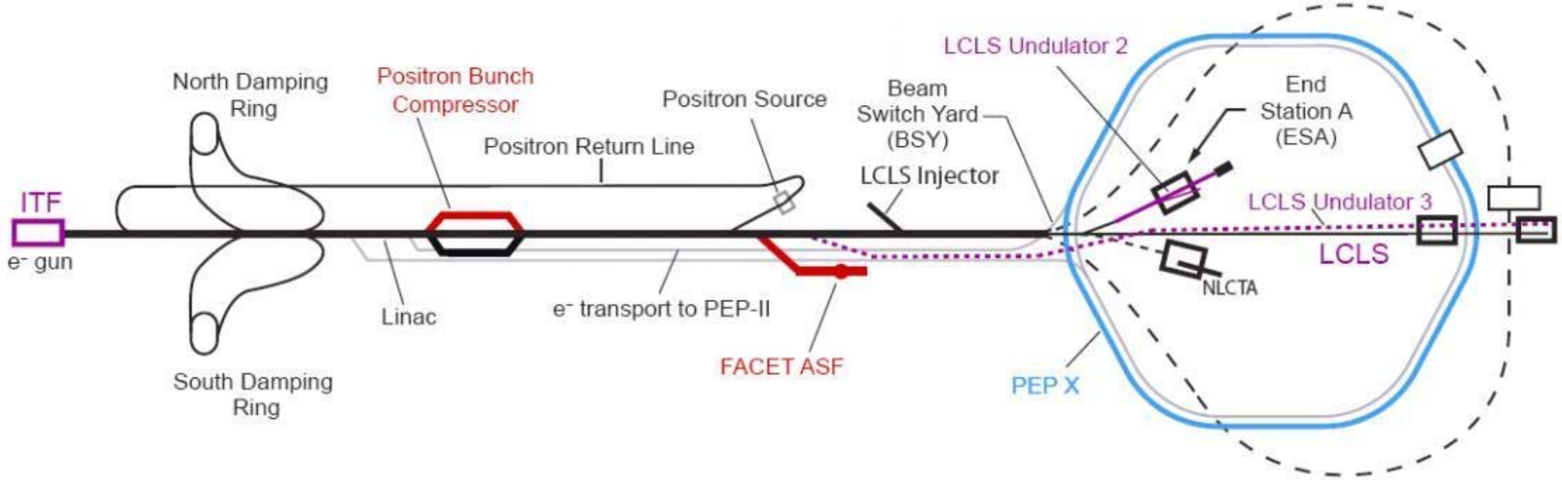
Generation of High Quality Beams



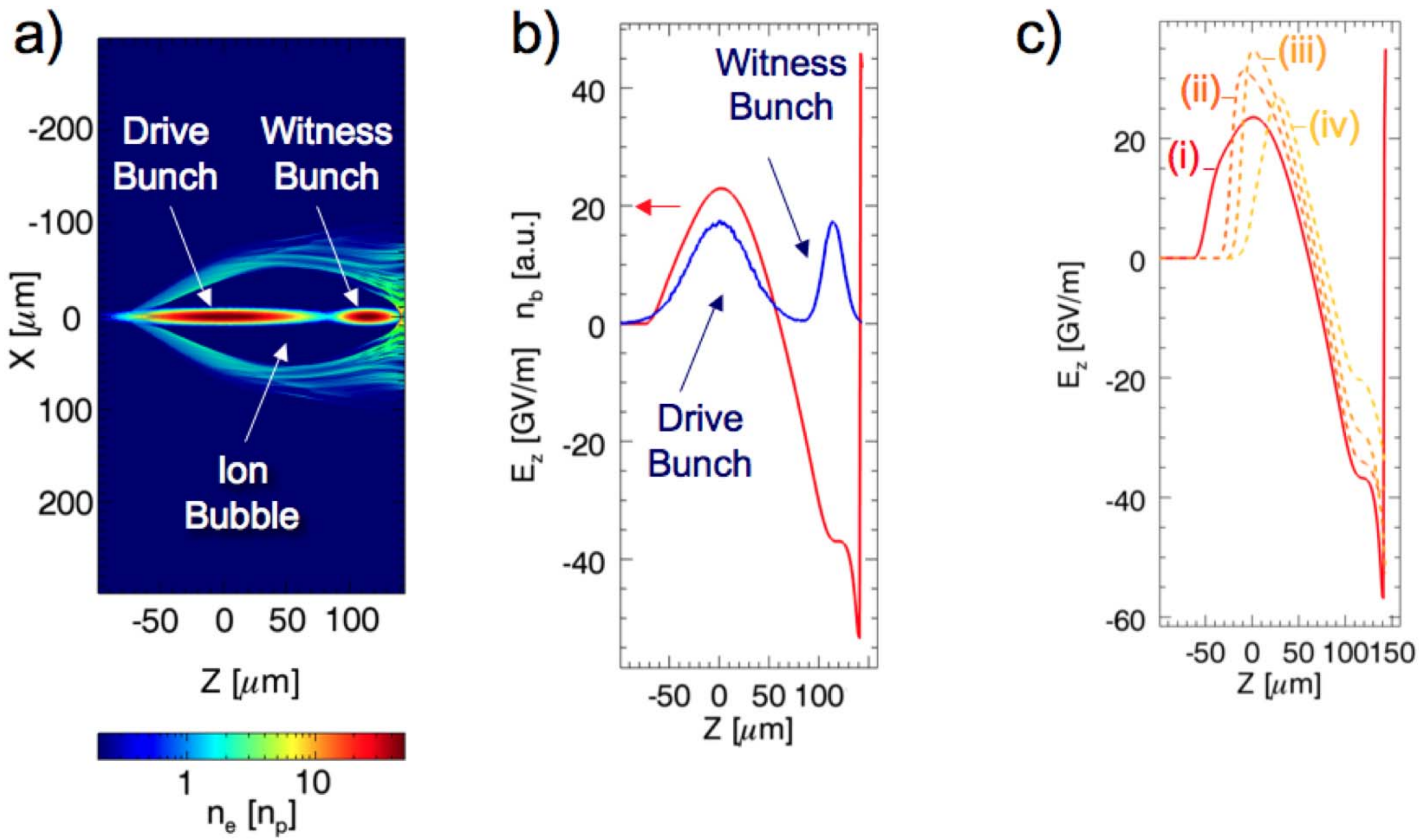
The most pressing goal is the demonstration of one stage of a 10-25 GeV plasma accelerator module with small energy spread & emittance and at least 1nC charge.

FACET: Facility for Advanced Accelerator Experimental Tests

* Use the SLAC injector complex and 2/3 of the SLAC linac to deliver electrons and positrons
  – Compressed 25 GeV beams → ~20 kA peak current
  – Small spots necessary for plasma acceleration studies
* Two separate installations
  – Final bunch compression and focusing system in Sector 20
  – Expanded Sector 10 bunch compressor for positrons



Ideal FACET experiment..

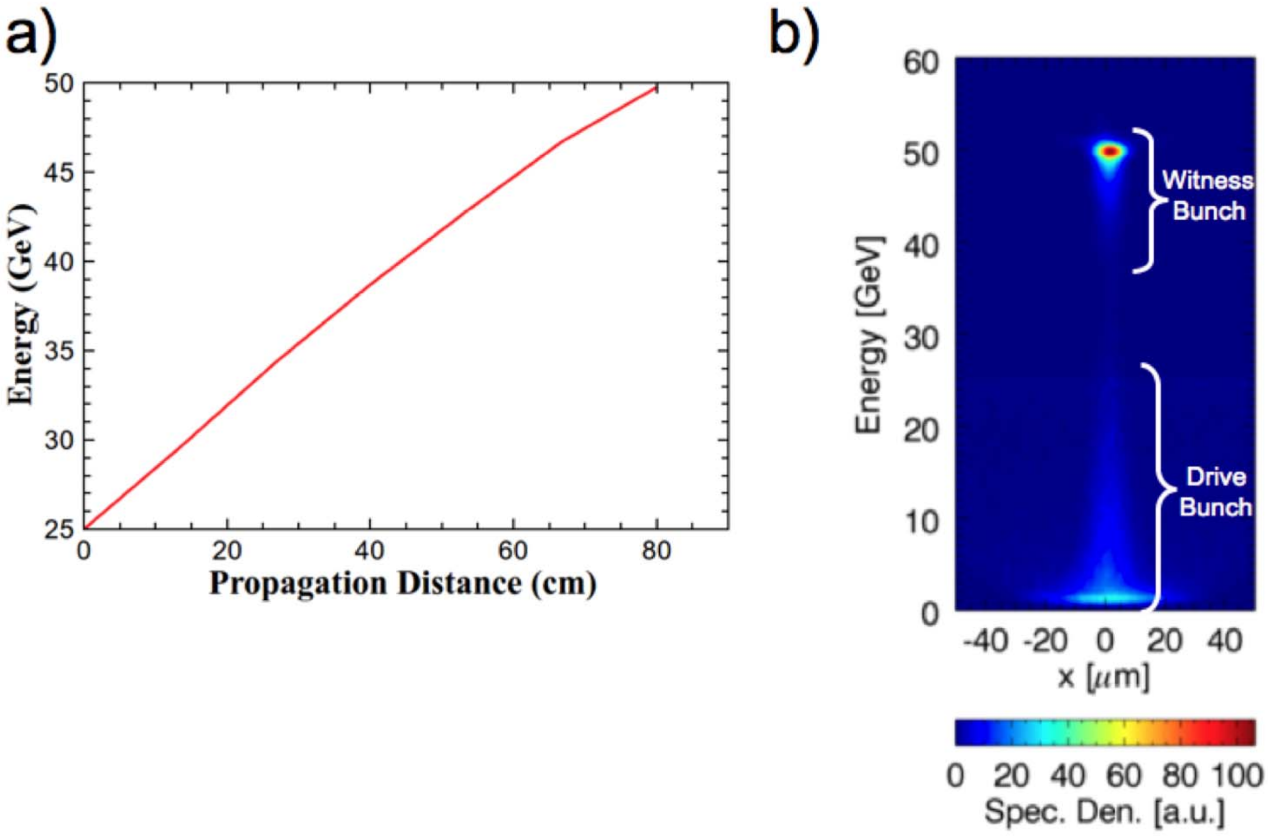


Transformer ratio of 2
Good beam loading efficiency

Drive Bunch
30 micron
3e10

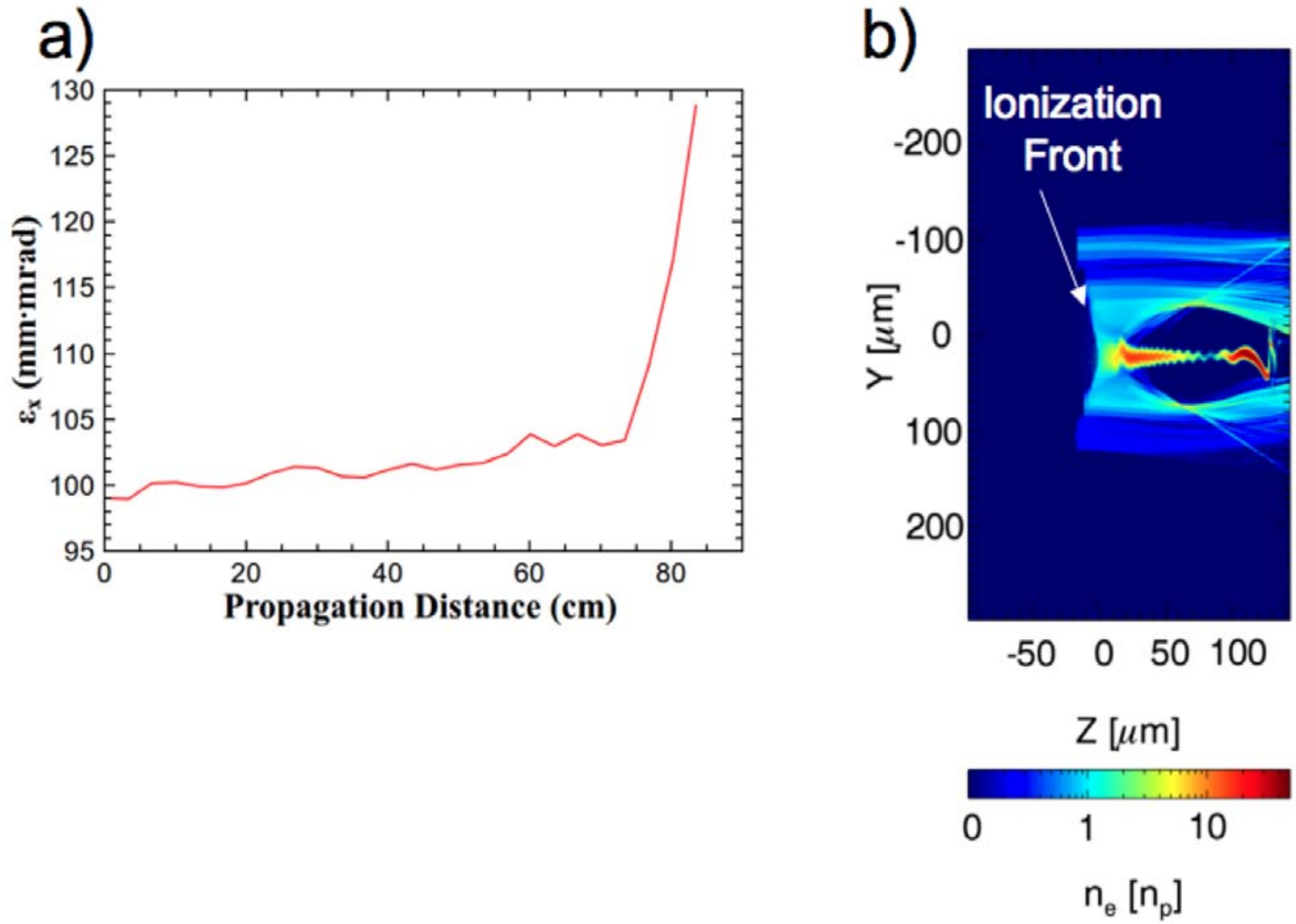
Witness Bunch
10 microns
1e10

Ideal FACET experiment…



5% energy spread
Energy doubling in less than 1 meter

Ideal FACET experiment…



Emittance preservation of the accelerating beam

Beam head erosion finally destroys the wake while and hosing blows up the beam emittance

Summary

Plasma Wakefield Acceleration may be the way forward to a more compact and cheaper TeV class linear collider.

The driver technology is at hand for a beam-driven PWFA

The drive beam architecture is similar to CLIC design with an average accelerating gradient of 250 MeV/m.
(Peak plasma gradient is 10 GeVm)

There is only one place where this scheme can be developed further: SLAC, where both electron and positron beams exist.

SLAC is building FACET in response to : DOE mission need.

CONCLUSION

"The challenge is to undertake and sustain the difficult and complex R&D needed to enable a feasible , cost and energy effective technology on the several decade horizon . Achieving these goals will require creativity and the development and maturation of new accelerator approaches and technologies."

HEPAP Subpanel 2006