A Perspective on Plasma Accelerators

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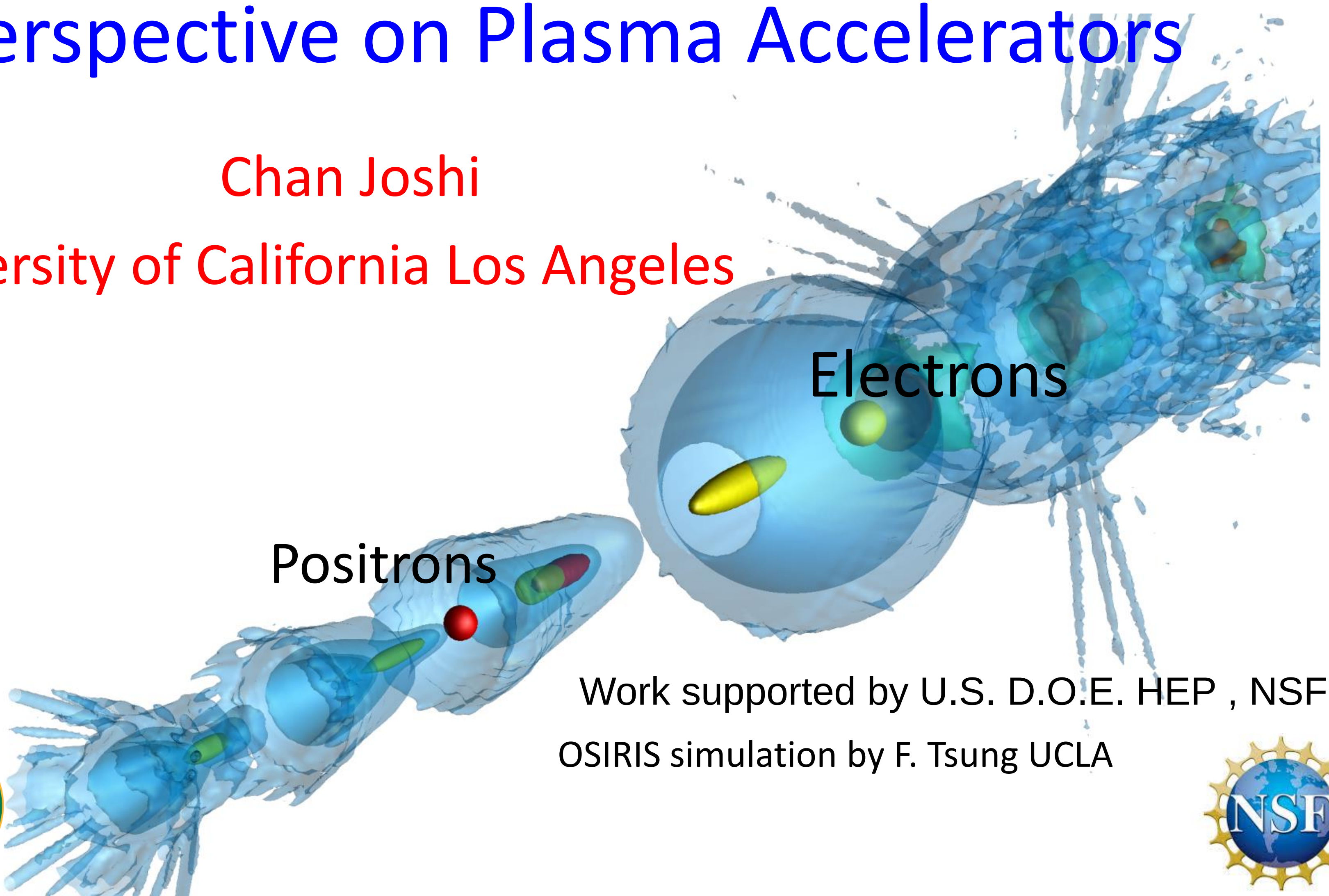
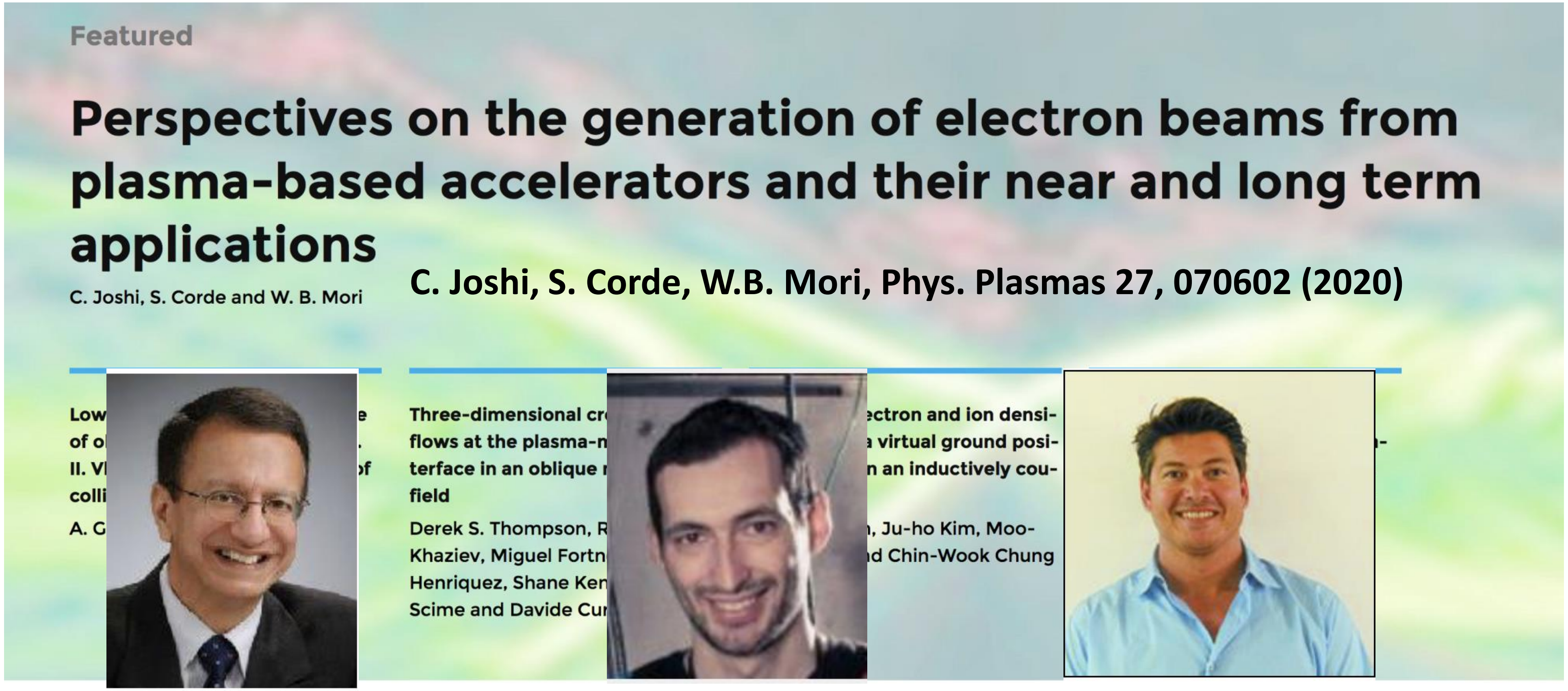


Work supported by U.S. D.O.E. HEP , NSF

OSIRIS simulation by F. Tsung UCLA

Talk based on



C. Joshi, S. Corde, W.B. Mori, Phys. Plasmas 27, 070602 (2020)

Special Thanks to
M. Hogan, T. Katsouleas, W. Lu, C.E. Clayton, K. Marsh, M. Litos , W. An, F. Tsung, F. Albert, B. Dangor
V. Yakimenko , R. Siemann, J.M. Dawson
All our former students, postdocs and Colleagues

Accelerator based Experiments are necessary to address Important Science Questions in this Century

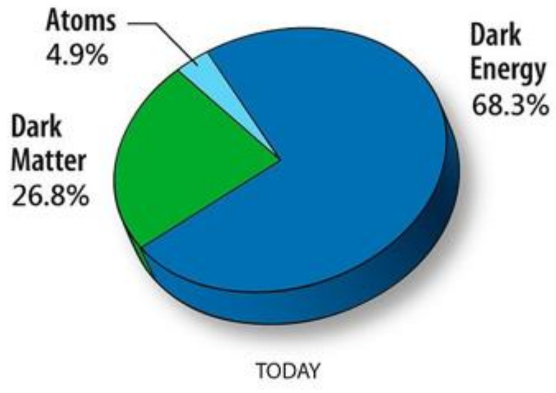
Are there additional dimensions of space?

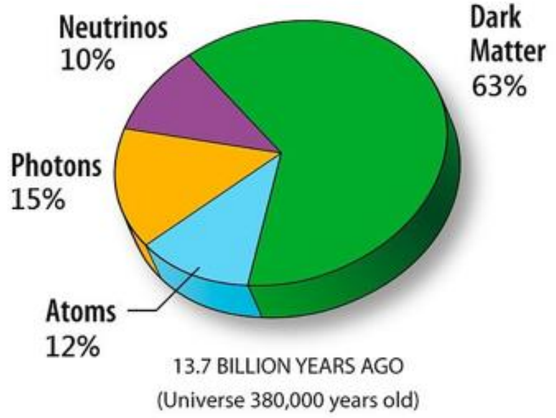
Why is there matter-antimatter imbalance?

How did the universe begin?

What is dark matter?

How were heavy elements created?



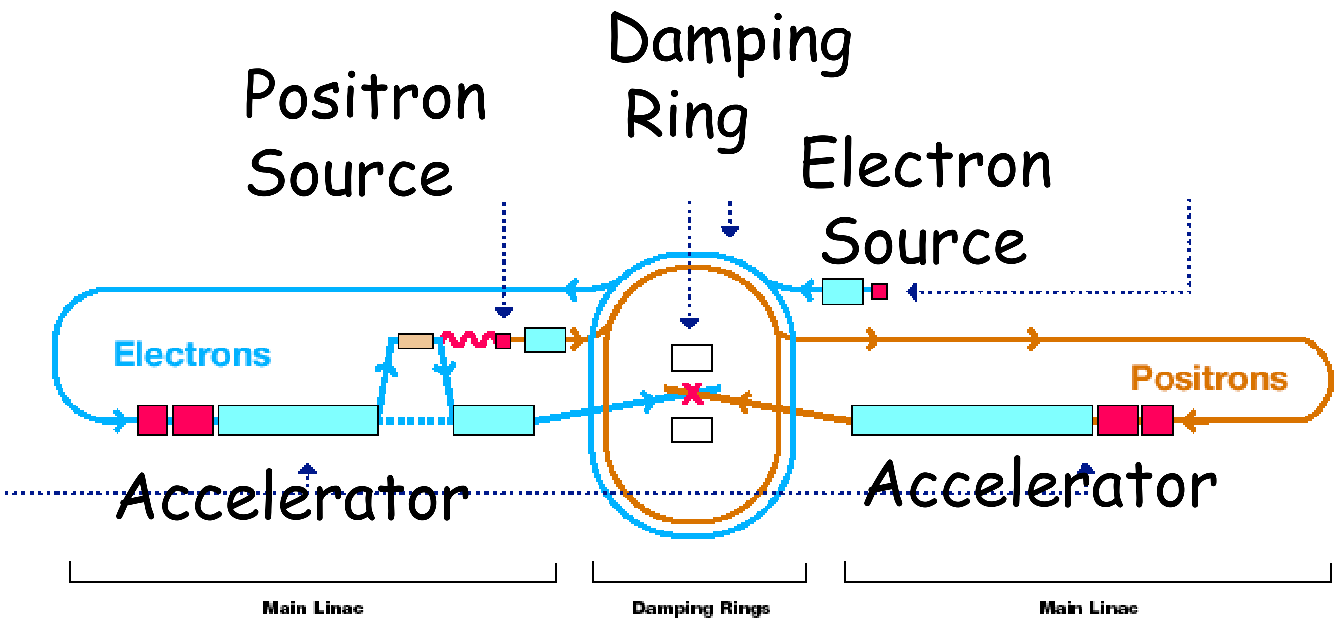


Particle colliders 21st Century

UCLA

Other Contenders:

FCC : CERN e-e or p-p
CEPC: China e-e+



International Linear e-e+ Collider

Energy Frontier of particle Physics
Very large
Very Expensive

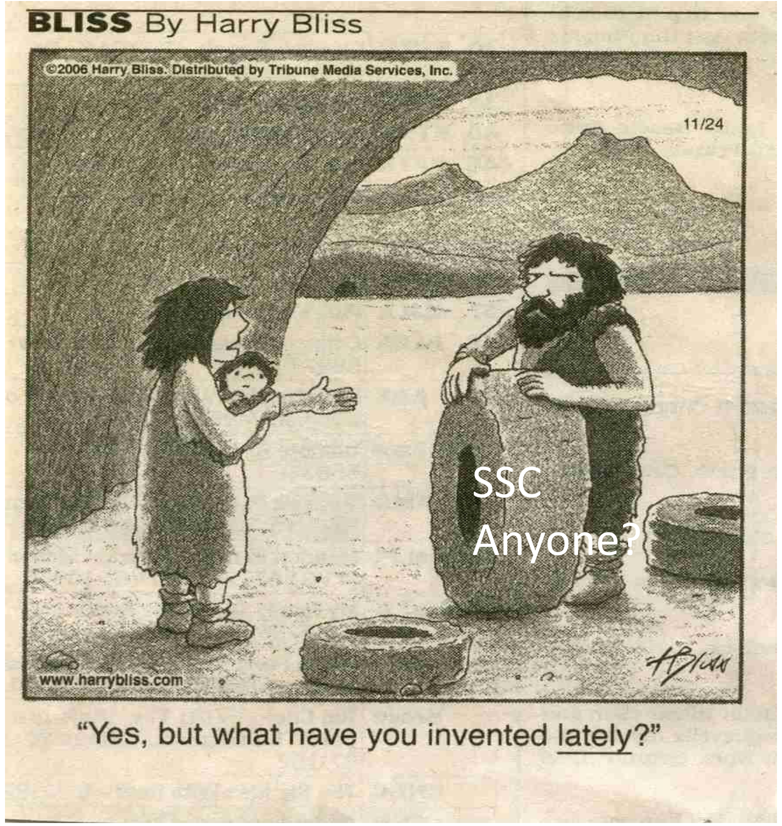
500 GeV CM
30 km (<20 MeV/m)
$ 20+ B (DOE Estimate)

Can we make accelerators at energy frontier smaller and cheaper?

Laser Acceleration of Particles Workshop
Los Alamos 1982

Can high electric fields of laser pulses or beams be used to accelerate particles?

a) At ultra high gradients?
b) To very high energies?



Relativistic Wakes in Plasmas

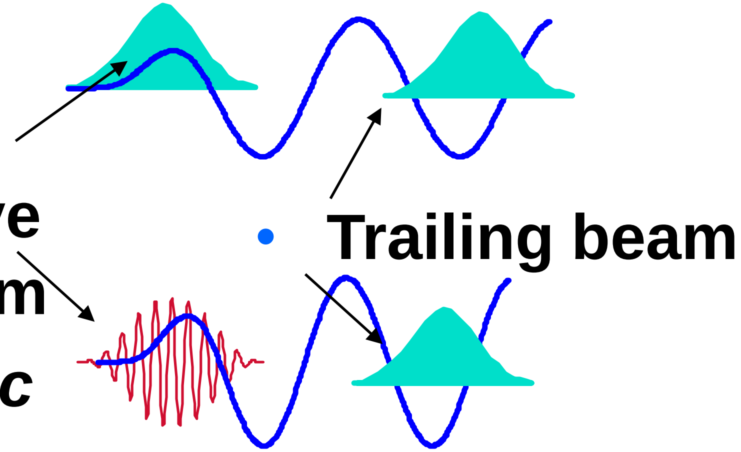
as particle accelerators?

- **Plasma Wake Field Accelerator**

  A high energy electron bunch

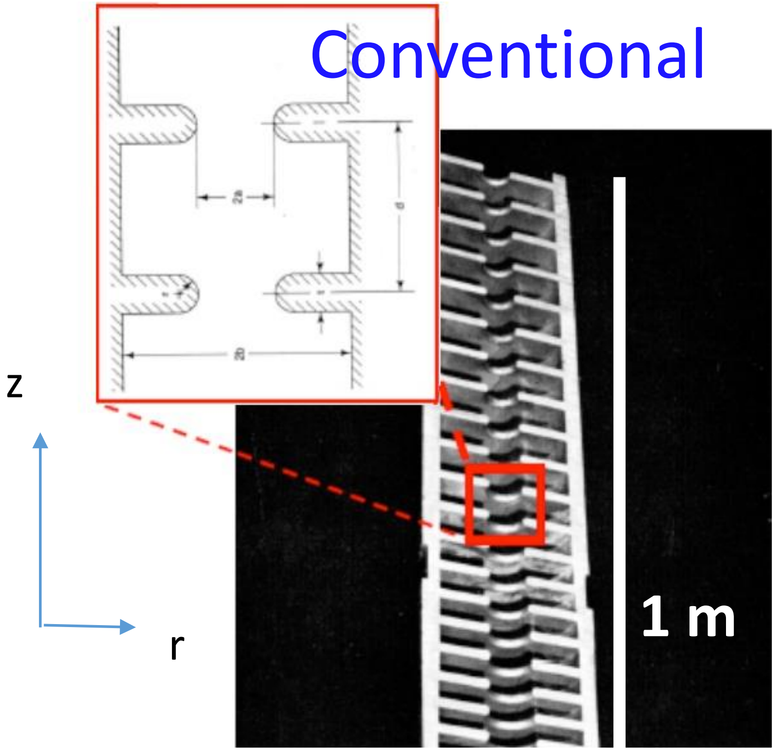
- **Laser Wake Field Accelerator**

  A single short-pulse of photons



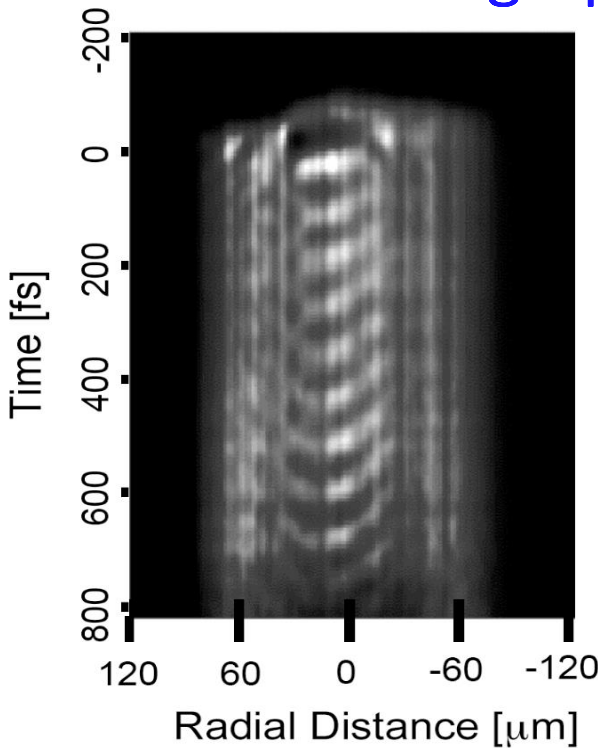
RF and Plasma Accelerators

Conventional



TM mode in a SW Structure
E_z, E_r and B_θ
20 MeV/m
3-30 cm diameter permanent Cu structure

Plasma: Holographic Interferometry

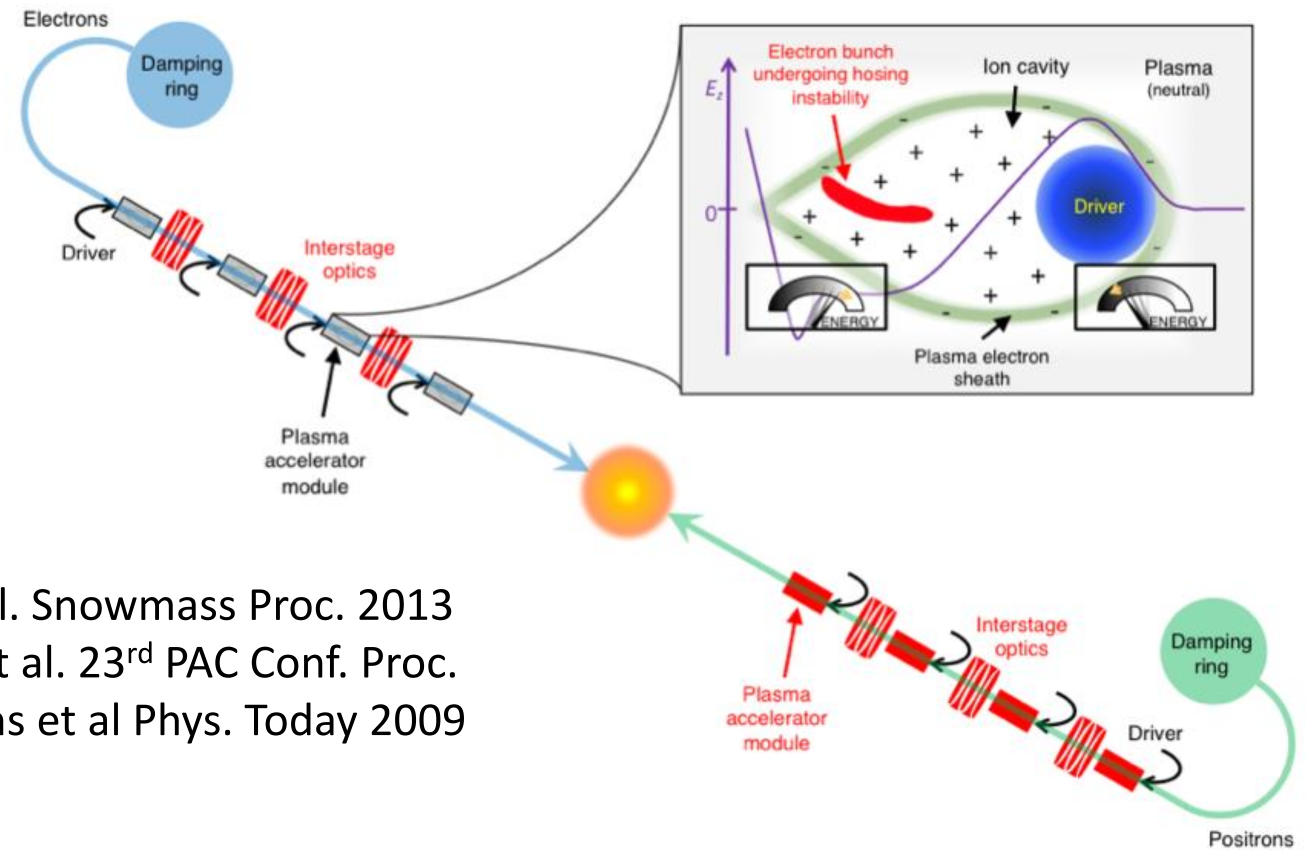


Courtesy
M. Downer

TM mode in Plasma
E_z, E_r and B_θ
20 GeV/m
30-300 um diameter transient structure

Multi-stage Plasma based Linear Collider

(basic design follows the ILC collider concept)



E. Adli et al. Snowmass Proc. 2013
A. Seryi et al. 23rd PAC Conf. Proc.
W. Leemans et al Phys. Today 2009

Courtesy; S. Corde

Why Use Wakes in Plasmas for Acceleration?

1D-Linear Plasma Wakefield Theory

e-beam

$$(\partial_t^2 + \omega_p^2)\frac{n_1}{n_o} = -\omega_p^2\left(\frac{n_b}{n_o} + k_p^2\nabla^2\sqrt{1+a_o^2}\right)$$

Laser

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

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

Wakes are said to be linear when $n_1 < n_o$

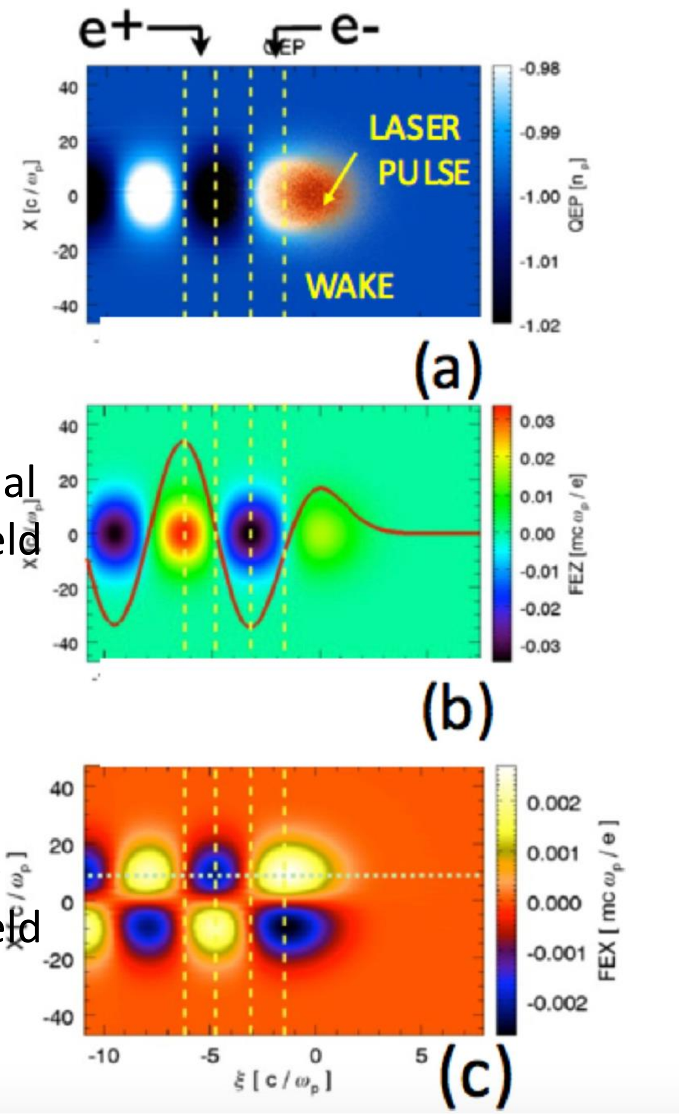
$$\nabla \bullet E = -4\pi e n_1 \Rightarrow \quad eE = \frac{n_1}{n_o}\sqrt{\frac{n_o}{10^{16}cm^{-3}}}10\,GeV/m\,\cos\omega_p(t - z/c)$$

Linear Wakes can Accelerate both e- & e+

PLASMA DENSITY

Longitudinal Electric Field

Transverse Electric Field



Linear Wake when $n_1 < n_o$

Sinusoidal longitudinal electric field

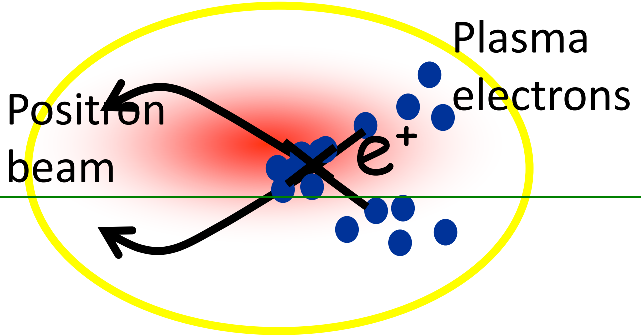
Longitudinal and transverse field out of phase by $\frac{\pi}{2}$ $rads$.

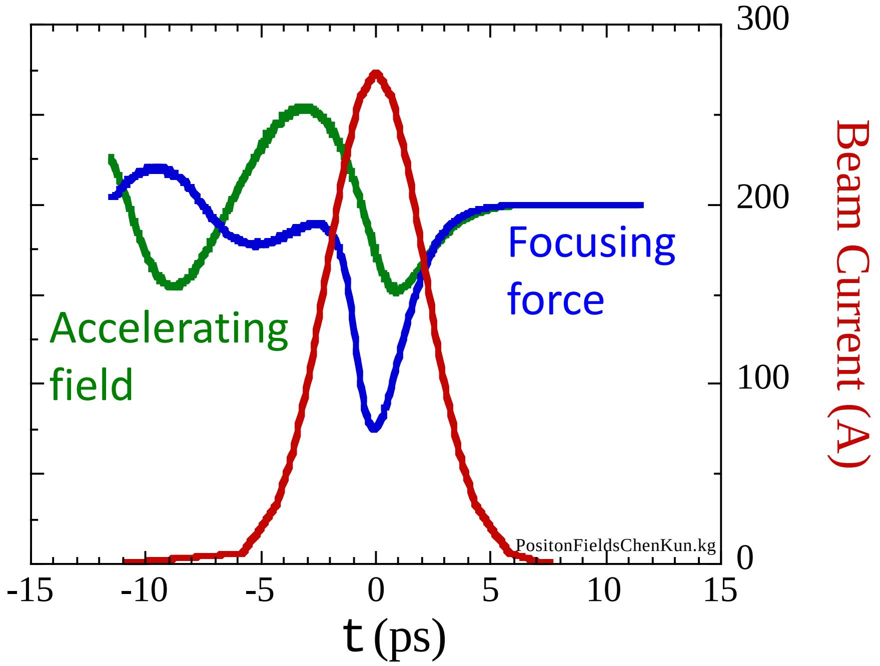
The e- and e+ can be accelerated in a region $\frac{\lambda}{4}$ $wide\ but$ $\frac{\lambda}{2}$ $apart$.

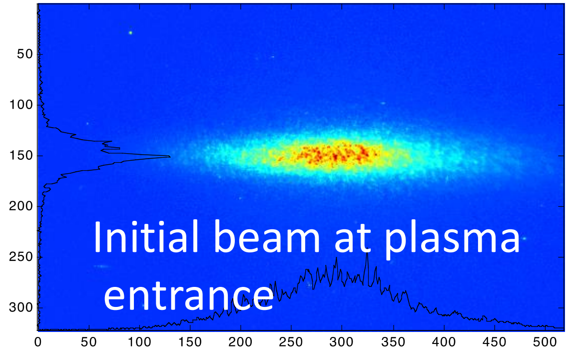
What about positron driven wakes?

Nonlinear dynamics of positron plasma interactions

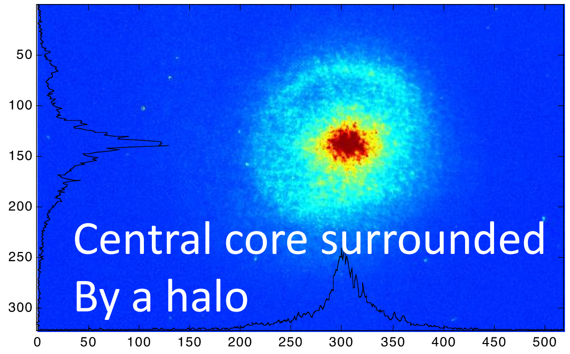
28 GeV Positron Beam at SLAC propagates through a dilute plasma







E 162 Collaboration
P. Muggli et al PRL 2008



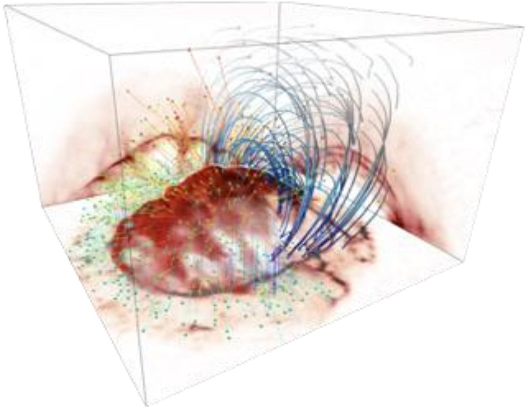
Beam exiting plasma

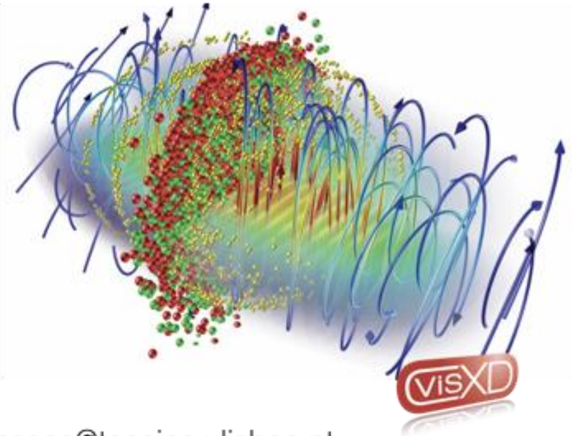
FULL/REDUCED PIC CODES VALIDATED BY NUMEROUS EXPTS and USED TO DESIGN EXPT.s AND CONFIRM NEW IDEAS

Osiris 4.0

osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST





TÉCNICO LISBOA

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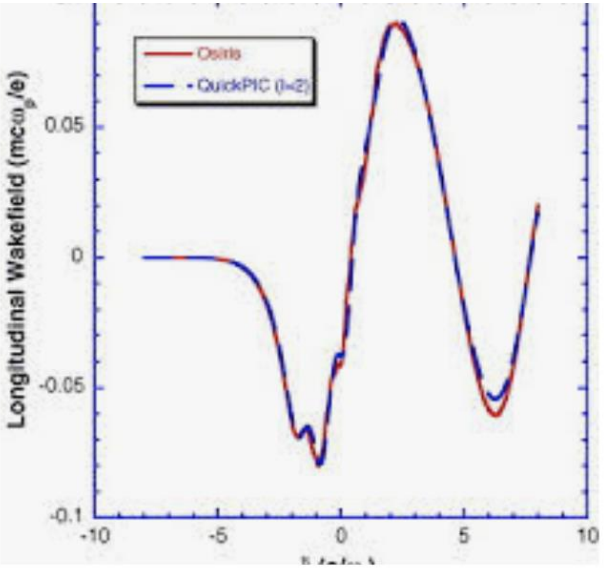
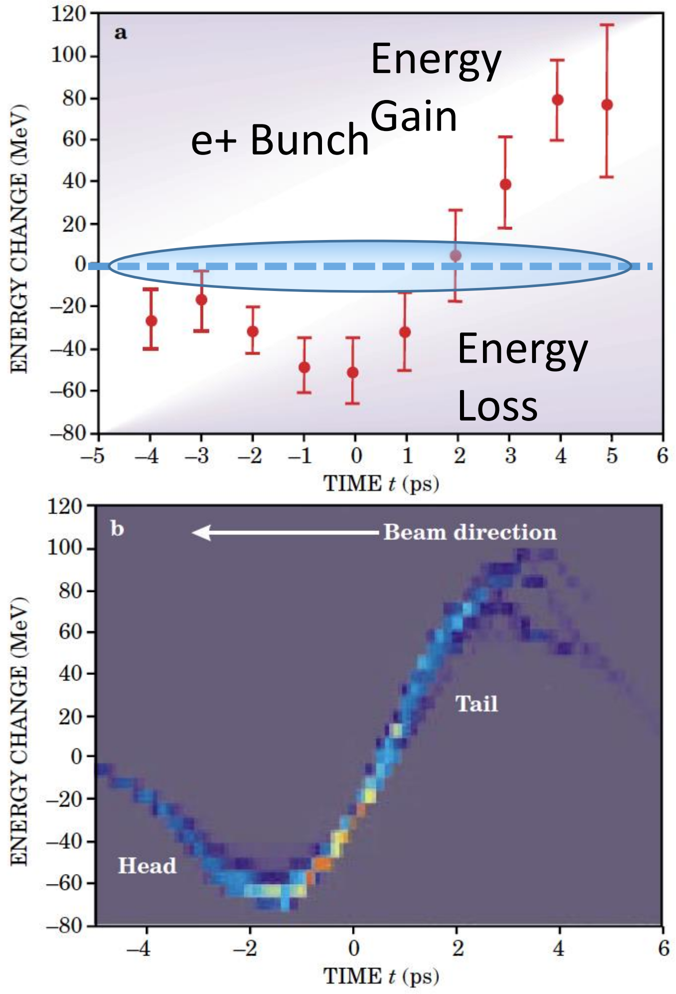
http://epp.tecnico.ulisboa.pt/
http://plasmasim.physics.ucla.edu/



QuickPIC

Ucla

Linear wake formation, energy loss and energy gain of a positron bunch in plasma



Experiment

PIC Simulation

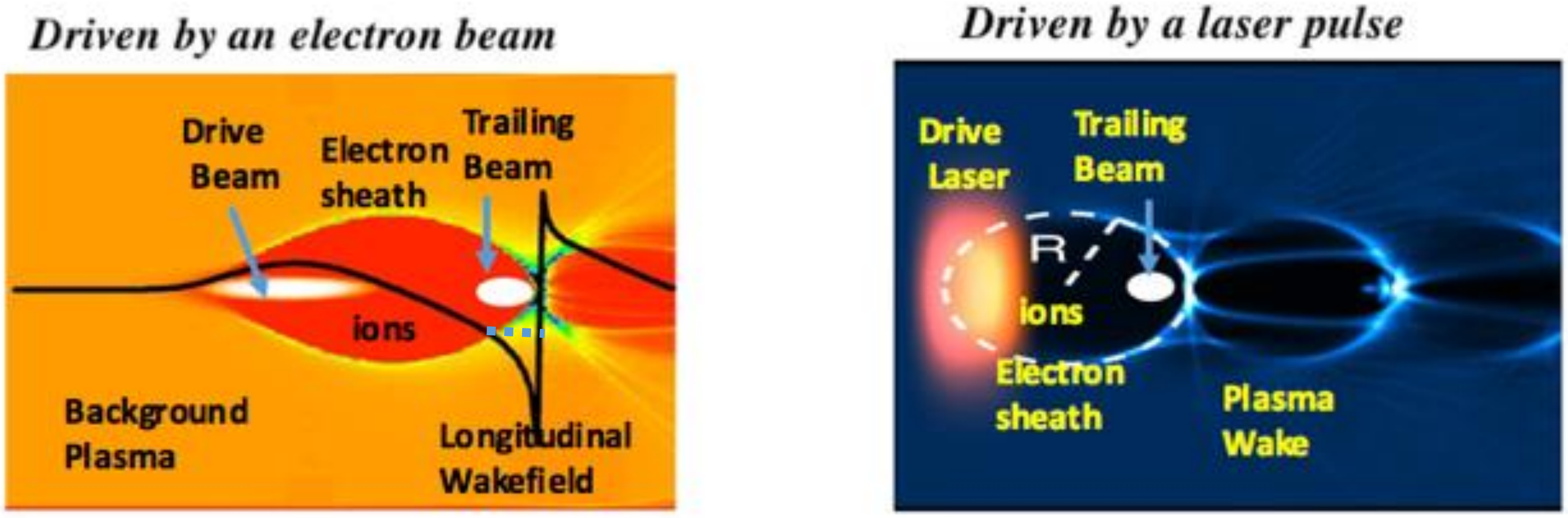
Energy gain of 80 MeV in 1m

Typical e+ acceleration gradient < 20 MeV/m

Ref. B. Blue etal. PRL 2002
Expt. Done on FFTB
@ SLAC

Nonlinear Wakes in the blowout regime driven by laser pulse or e-bunch

Need < 100fs (FWHM) driver beams with a_0 >2 0r a > 10 KA electron beam

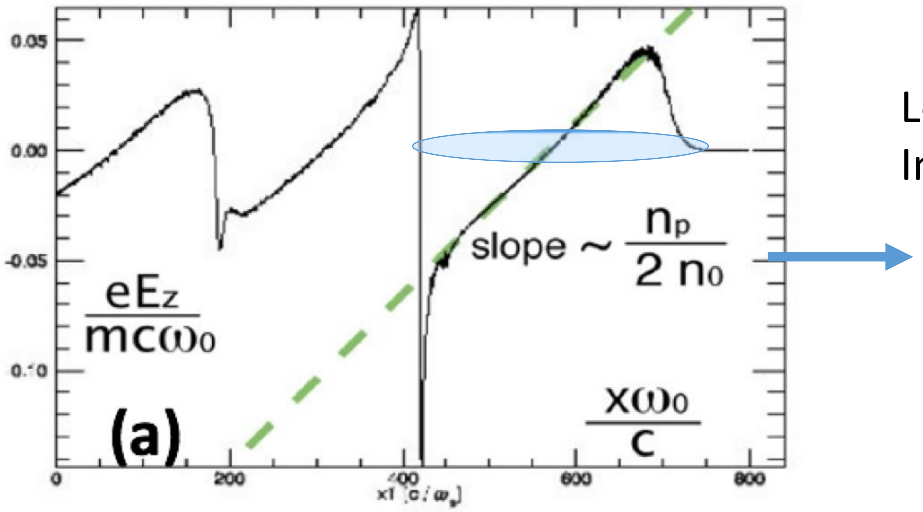


(a) (b)

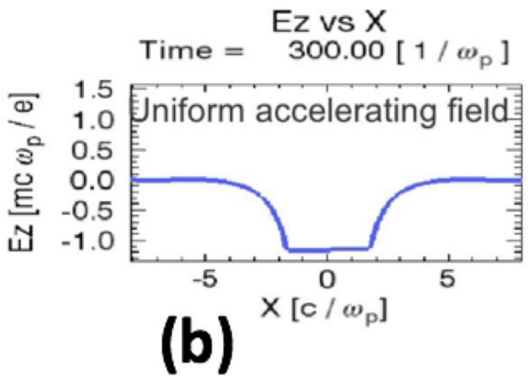
Ref. T. Tajima and J,M, Dawson PRL 1979
P. Chen, J.M. Dawson et al. P.R.L. 1985
Nonlinear wakes: Rosenzweig, Katsouleas, Mori, Lu, etc.

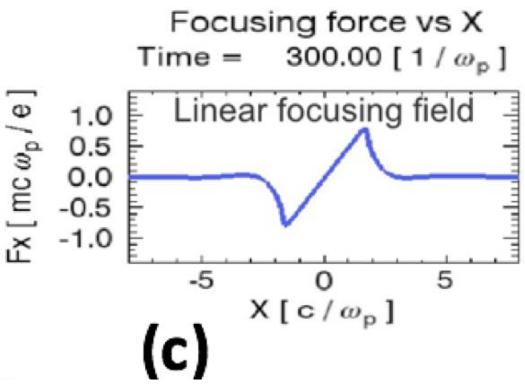
Longitudinal and transverse fields in blowout regime

(ideal for preserving emittance or beam quality)



Longitudinal Field
In direction of propagation





Longitudinal Field
In transverse direction

Transverse Field
In transverse direction

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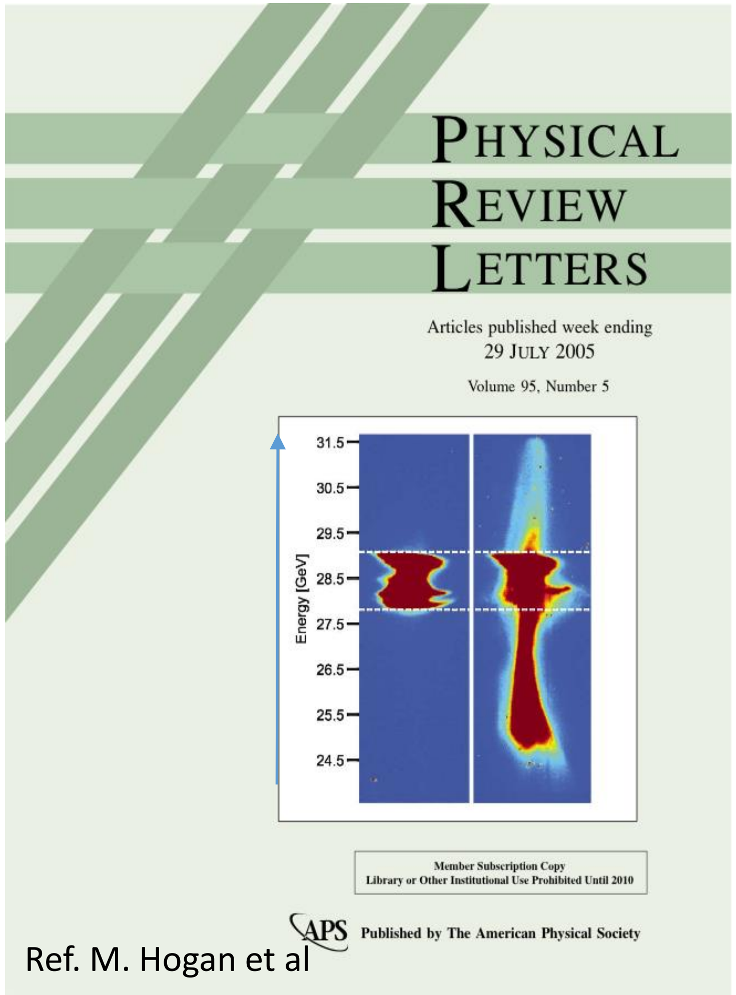
BREAKING THE 1 GeV BARRIER
With 15 micron long bunches



PHYSICAL REVIEW LETTERS

Articles published week ending
29 JULY 2005

Volume 95, Number 5

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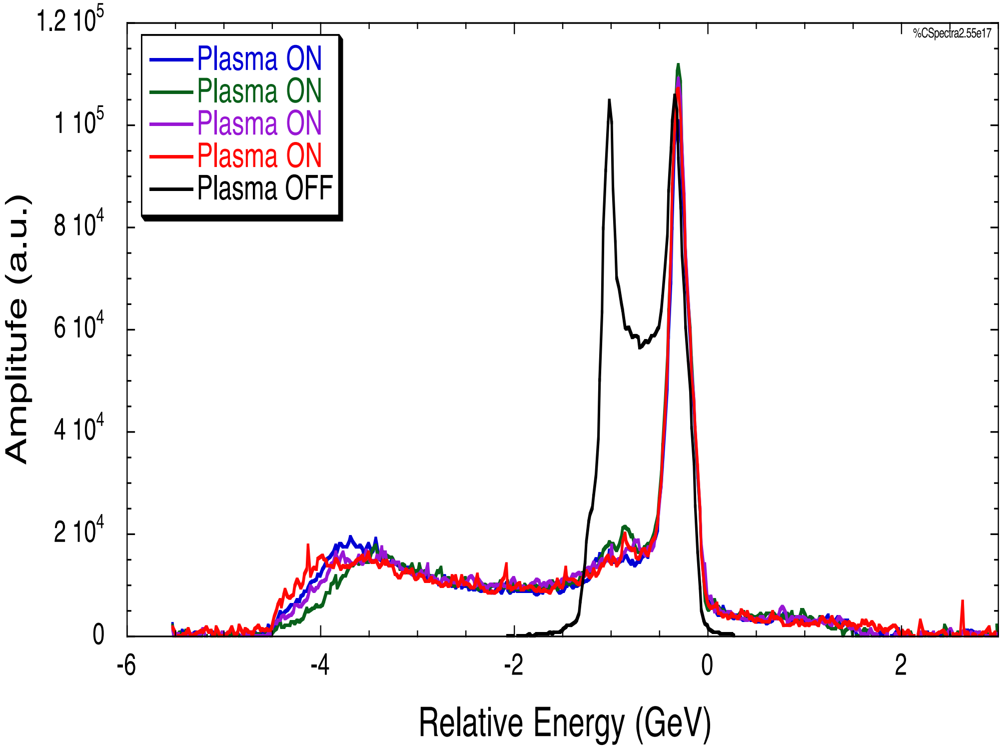
APS Published by The American Physical Society

Ref. M. Hogan et al

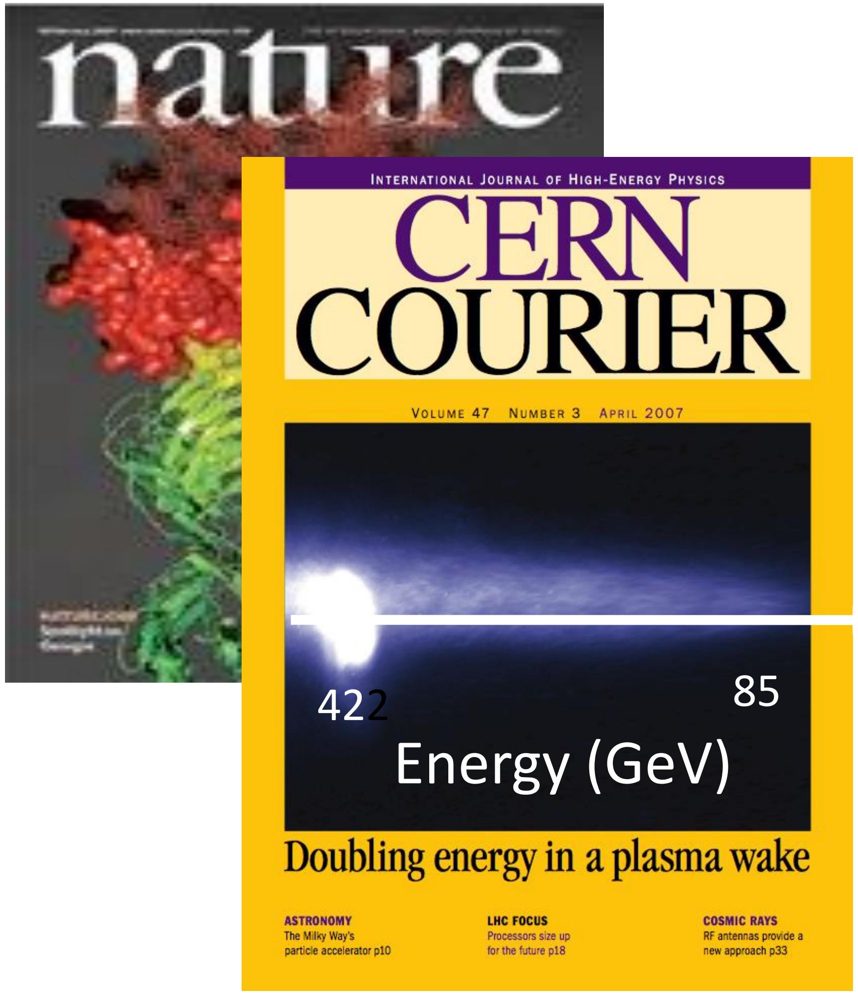


M. Hogan et al. PRL 2005

$n_e \approx 3.5\times10^{17}$ cm^{-3} $L \approx 10$ cm, $N \approx 1.8\times10^{10}$

Charge Fraction > E_0 0.8% 25pC of charge

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



Drive Electron Beam 42 GeV

Particles in the tail gained 43 GeV in just 85 cm

Acceleration gradient of 50 GeV/m sustained over 85 cm

Beam head erosion limited the propagation of the beam to a distance less than pump depletion length.

Ref. I. Blumenfeld et al. Nature 2007
C. Joshi, CERN Courier2007

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Compact and Cheaper High-Energy Colliders a Grand Challenge for Science and Engineering in the 21st century

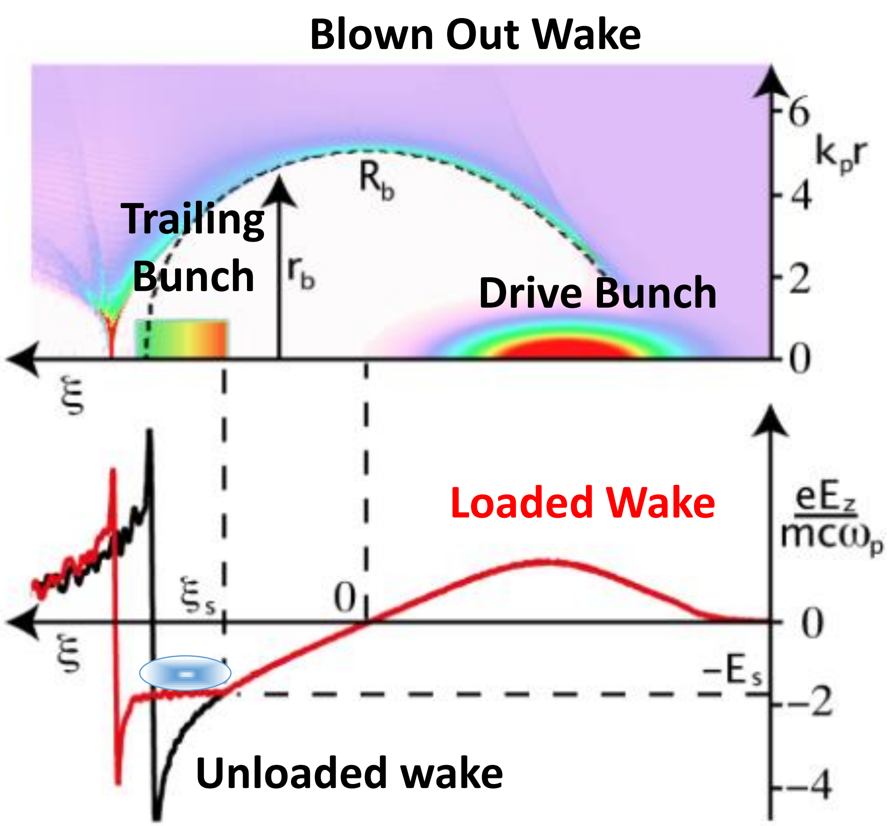
Particle Physics Project Prioritization Panel (P5) Report 2014: Building for Discovery

"A primary goal, therefore, is the ability to build the future generation accelerators at dramatically lower cost. …For e^+e^- colliders, the primary goals are improving the accelerating gradient and lowering the power consumption"

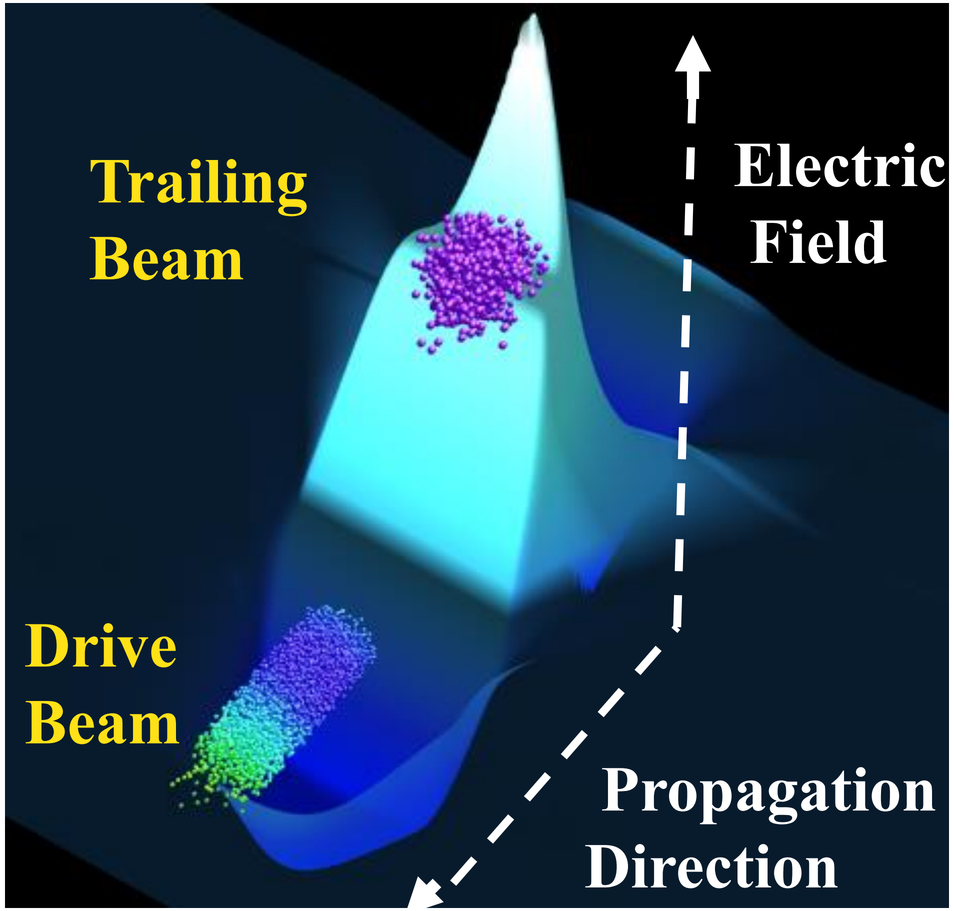
NAE Grand Challenges for Engineering
Engineer Tools of Scientific Discovery

"..engineers will be able to devise smaller, cheaper but more powerful atom smashers, enabling physicists to explore realms beyond the reach of current technology."

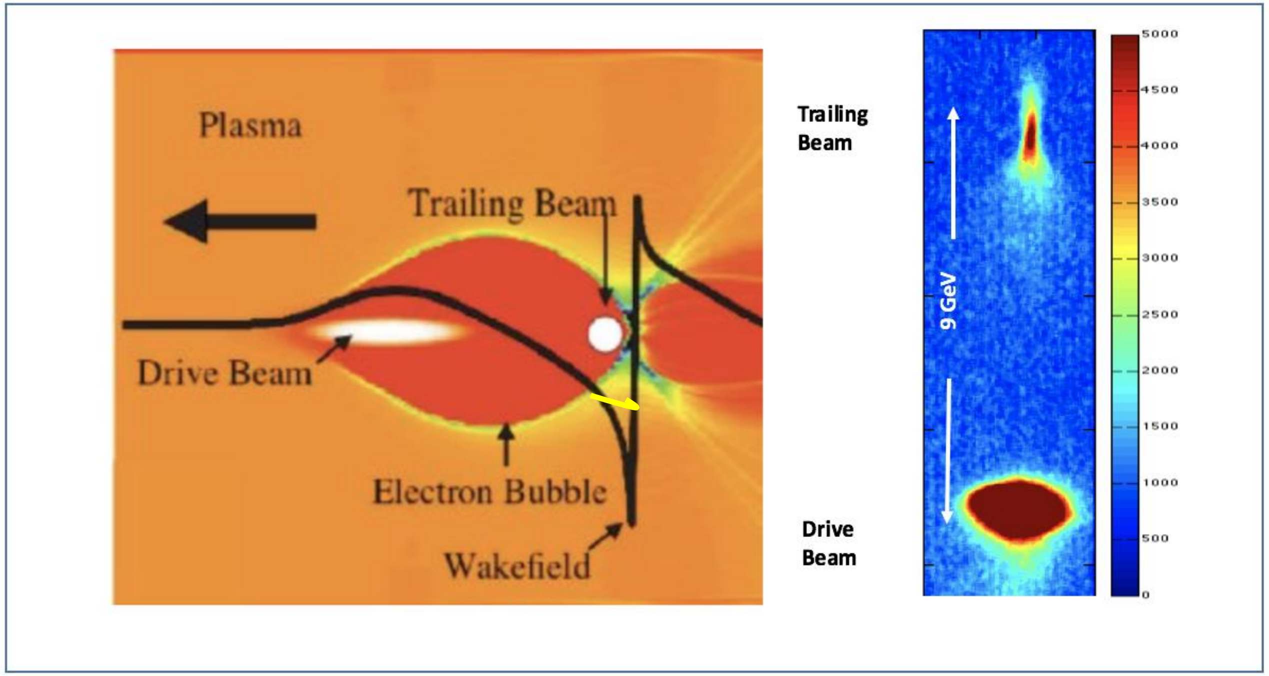
Acceleration of a distinct trailing bunch and beam loading of the Wake



M. Tzoufras et al. P.R.L. 2008



Acceleration of Trailing Bunch of Electrons

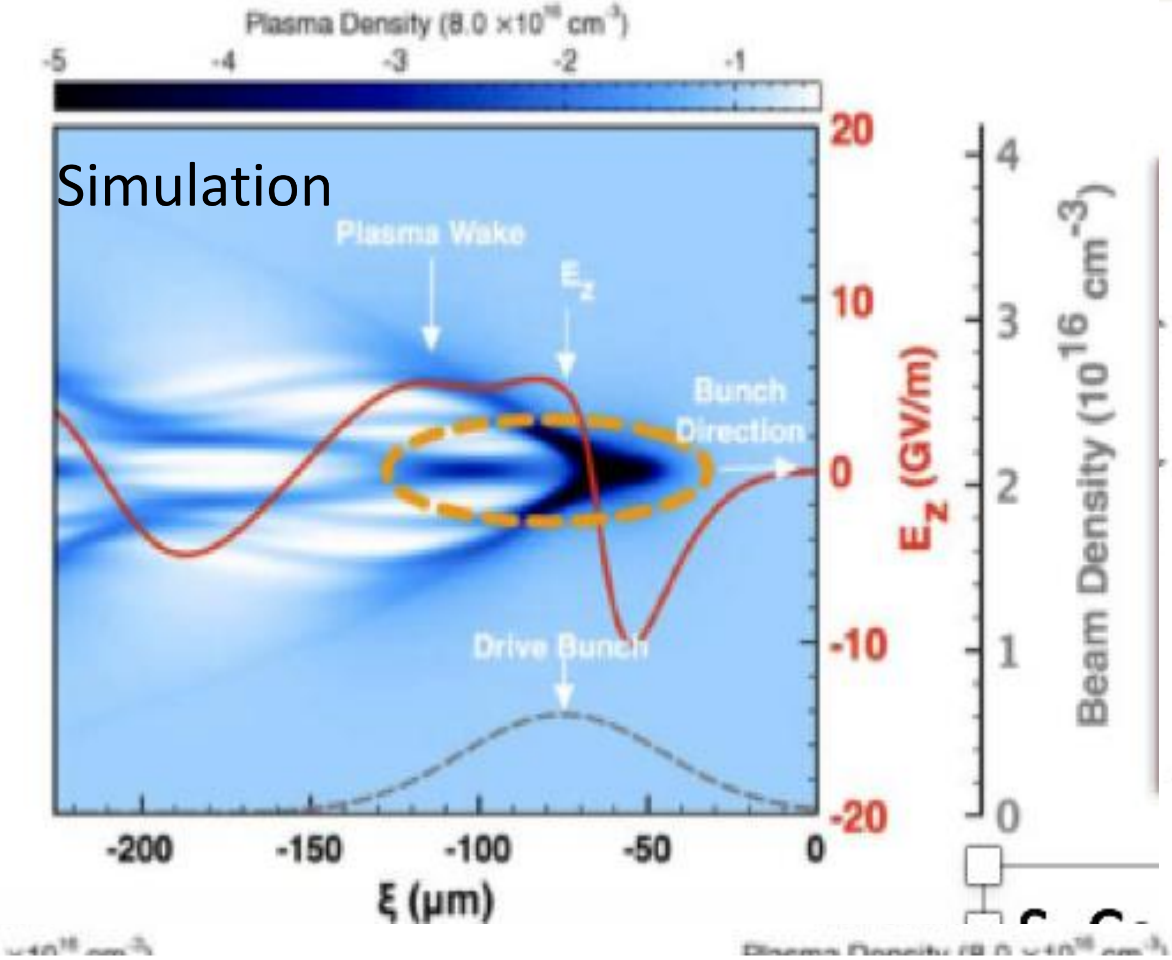


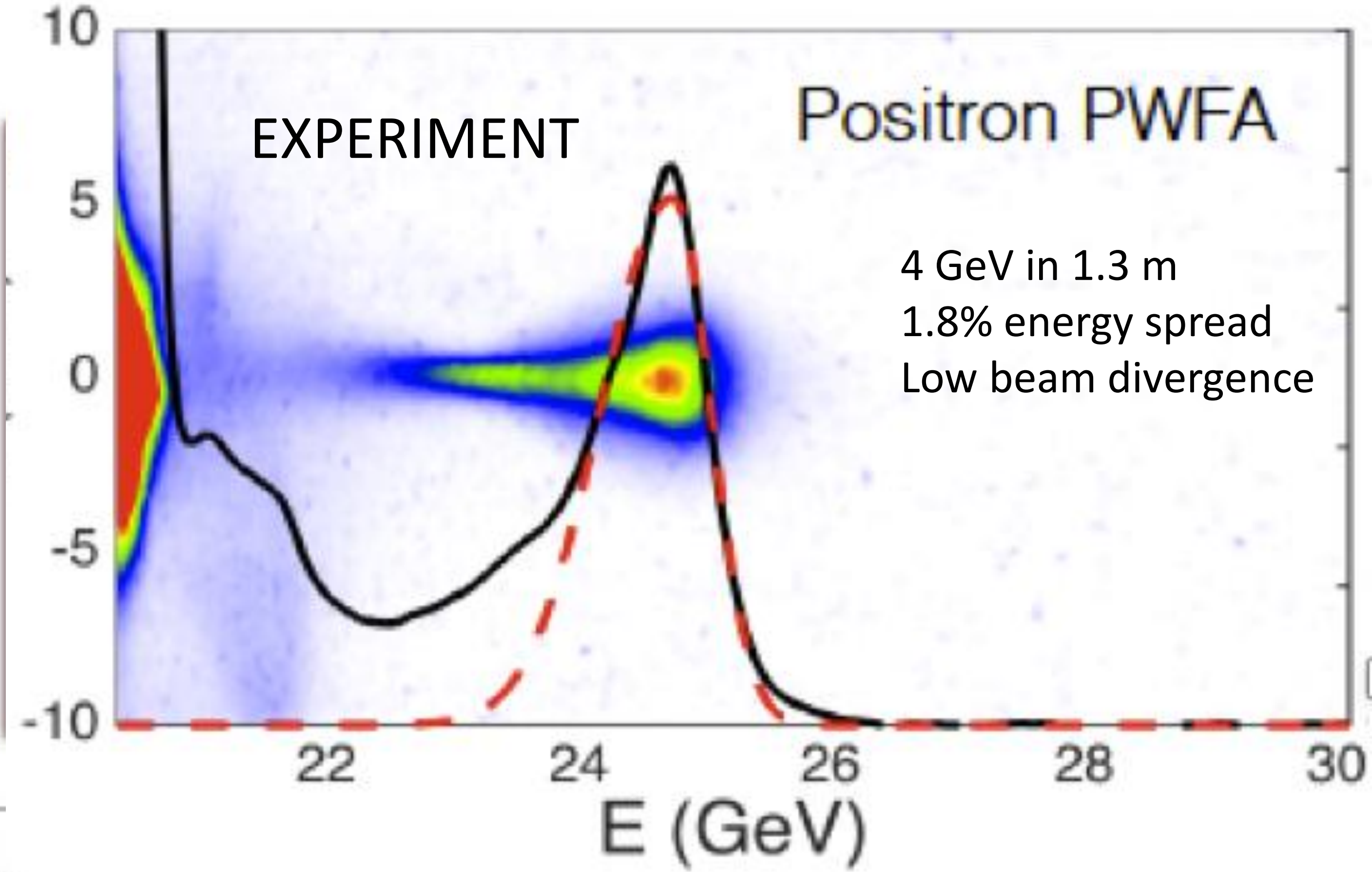
M. Litos et al. Nature 2014
M. Litos et al. PPCF 2016

Max. Energy gain 9 GeV in 1.3m, energy spread <5%, 25% energy extraction efficiency

Acceleration of positrons in nonlinear wakes

S. Corde et al. Nature 2016

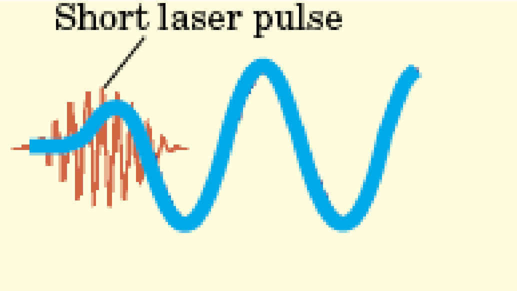




e+ beam produces wake & a dense region of plasma electrons that traps e+

Jet Age of Laser-wakefield Acceleration-LWFA Takes off

RAL/IC, LBNL and LOA Expts show ~ 10% energy spreads



Monoenergetic beams of relativistic electrons from intense laser–plasma interactions

S. P. D. Mangles[1], C. D. Murphy[1,2], Z. Najmudin[1], A. G. R. Thomas[1], J. L. Collier[2], A. E. Dangor[1], E. J. Divall[2], P. S. Foster[2], J. G. Gallacher[3], C. J. Hooker[2], D. A. Jaroszynski[3], A. J. Langley[2], W. B. Mori[4], P. A. Norreys[2], F. S. Tsung[4], R. Viskup[3], B. R. Walton[1] & K. Krushelnick[1]

[1]The Blackett Laboratory, Imperial College London, London SW7 2AZ, UK
[2]Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, UK
[3]Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK
[4]Department of Physics and Astronomy, UCLA, Los Angeles, California 90095, USA

IC Rutherford

High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding

C. G. R. Geddes[1,2], Cs. Toth[1], J. van Tilborg[1,3], E. Esarey[1], C. B. Schroeder[1], D. Bruhwiler[4], C. Nieter[4], J. Cary[4,5] & W. P. Leemans[1]

[1]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA
[2]University of California, Berkeley, California 94720, USA
[3]Technische Universiteit Eindhoven, Postbus 513, 5600 MB Eindhoven, the Netherlands
[4]Tech-X Corporation, 5621 Arapahoe Ave. Suite A, Boulder, Colorado 80303, USA
[5]University of Colorado, Boulder, Colorado 80309, USA

LBNL

A laser–plasma accelerator producing monoenergetic electron beams

J. Faure[1], Y. Glinec[1], A. Pukhov[2], S. Kiselev[2], S. Gordienko[2], E. Lefebvre[3], J.-P. Rousseau[1], F. Burgy[1] & V. Malka[1]

[1]Laboratoire d'Optique Appliquée, Ecole Polytechnique, ENSTA, CNRS, UMR 7639, 91761 Palaiseau, France
[2]Institut fur Theoretische Physik, 1, Heinrich-Heine-Universitat Duesseldorf, 40225 Duesseldorf, Germany
[3]Département de Physique Théorique et Appliquée, CEA/DAM Ile-de-France, 91680 Bruyères-le-Châtel, France

LOA

Coming of age of Laser Wakefield Accelerators 2003-today

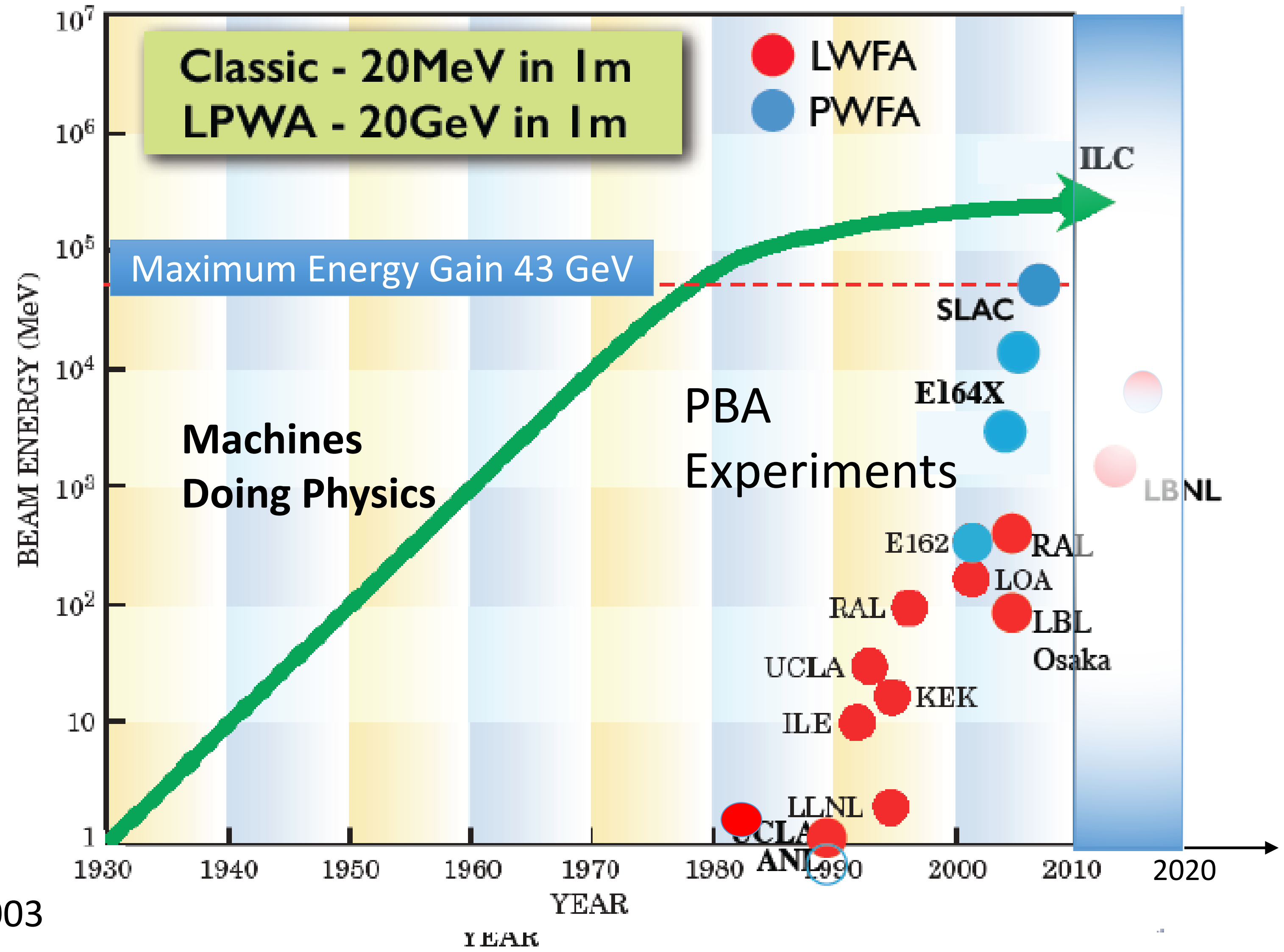
Maximum energy gain of 8 GeV seen at BELLA.
Percent level energy spreads
@4 hour operation of a LWFA in Germany

Numerous new ideas: colliding pulse injection, self beam loading, Photon acceleration and deceleration, overcoming dephasing ,DLA wake assisted relativistic guiding. Ionization injection

A phenomenological theory for nonlinear wakes, nonlinear beam loading, beam matching, transverse beam instabilities -essential to our understanding and charting a path forward.

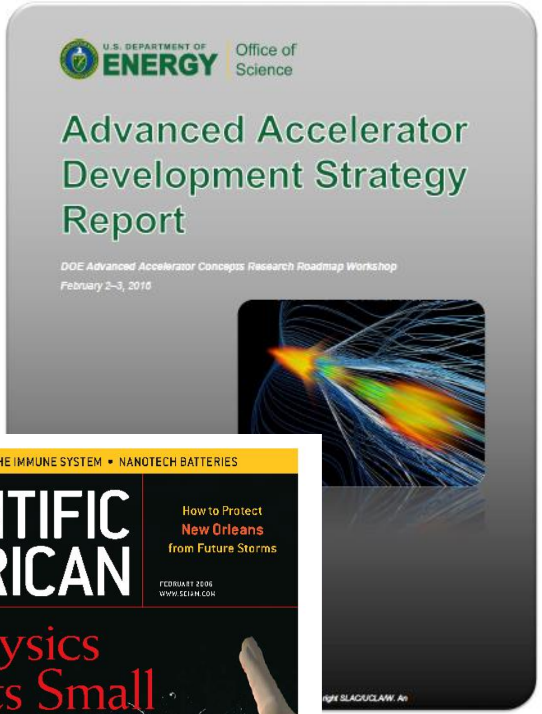
Plasma Accelerator Progress

"Accelerator Moore's Law"



C.Joshi and
T. Katsouleas
Physics Today 2003

U.S. Plasma Accelerator Scenario Big picture: R&D still Discovery Science



C. Joshi Scientific American

Can critical physics issues for a multi-stage e+e- collider be quantified via experiments and/or simulations in the next decade : 2017-2027?

Can the then remaining critical issue be solved by 2032 ?

Can an important enough first application of a plasma accelerator be identified?

Can a plasma accelerator built for this application (for << $1B) serve as a prototype for a LC by 2035?

Can the community come up with a CDR for a Plasma-Based LC by 2035?

Next big challenge for Plasma-Accelerators is demonstration of All the necessary parameters for a single stage of a multi-stage collider

No single experimental facility is suitable such a demonstration
So must rely on a combination of experiments and 1:1 PIC simulations

Experiments

More than 90% energy extraction From the pump to the wake

Extraction of 90% of the energy from the wake by the accelerating beam

Emittance preservation at 1um level

Nearly 100% charge throughput

Less than 1% energy spread

0.5 nC charge accelerated per shot

Do all this with both e- and e+

Simulations

Generation and acceleration of ultra-low emittance beams

Generation and acceleration of highly polarized e- and e+ beams

Techniques for high quality beam generation in linear wakes

Staging, radiation loss

Transverse beam instabilities

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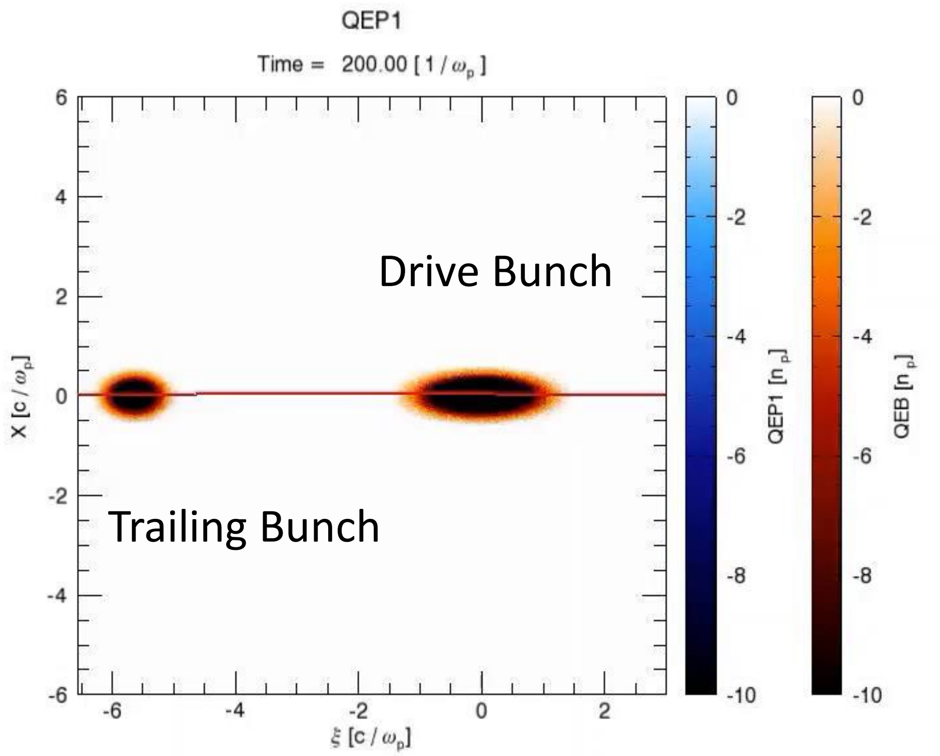
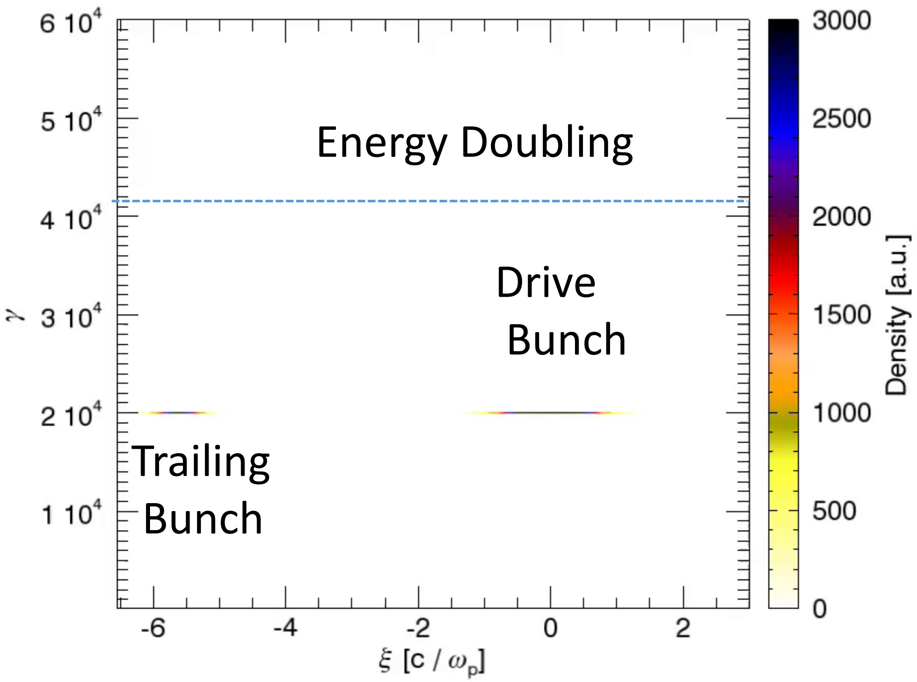
Energy Doubling (10-20+ GeV) with <1% Energy Spread ,Pump Depletion and > 40% energy transfer efficiency

Plasma and beam density with on-axis Ez line out



Beam Energy



Simulations by W. An UCLA, .Joshi et al. PPCF 2018

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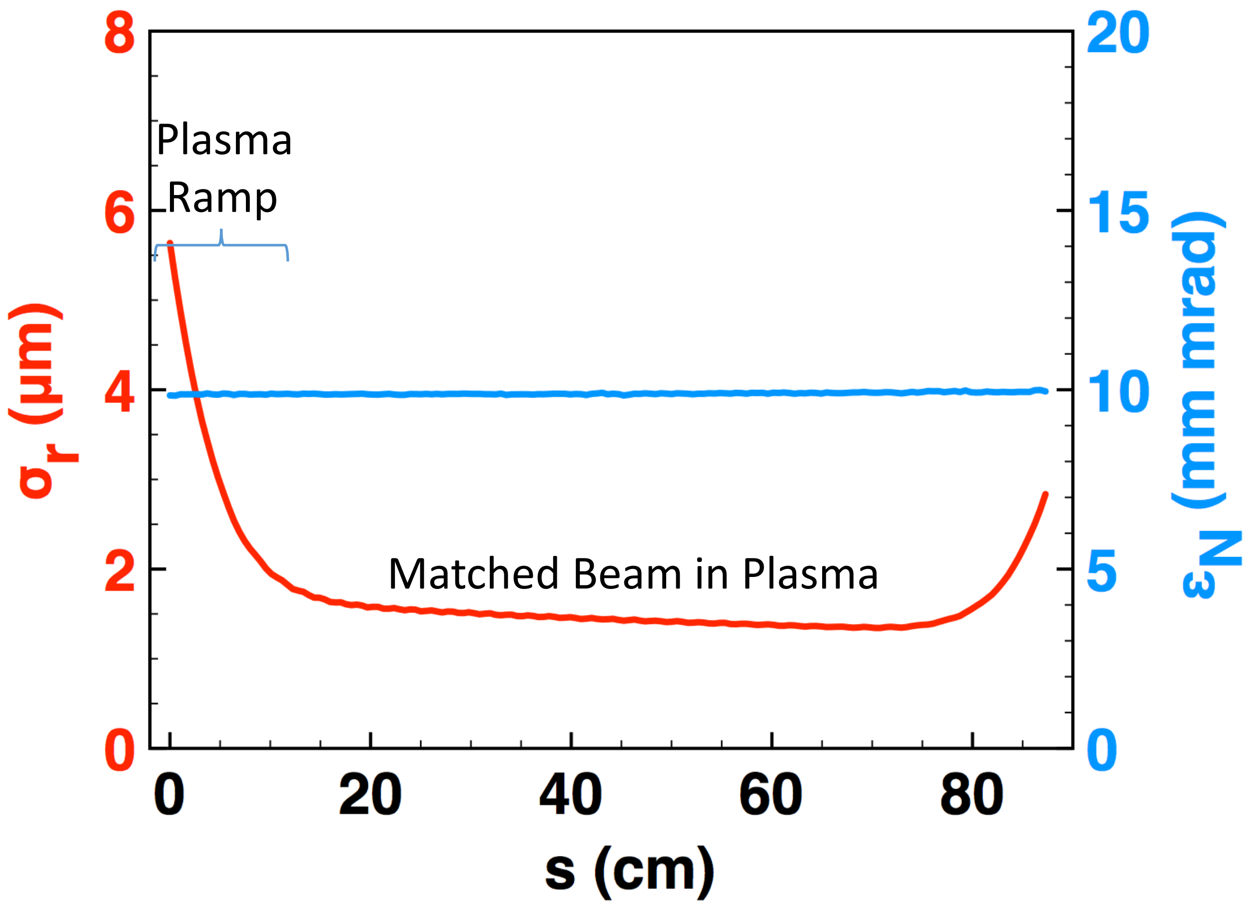
Beam Matching in and out of plasma accelerator And emittance preservation



Simulation Results: Weiming An

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Colliders and 5th Generation Light Sources both need Cheaper and more Compact Accelerators

A true 5th Gen. Light Source that will compete with X-FELs
may be the 1st grand application of the advanced accelerator concepts technology.

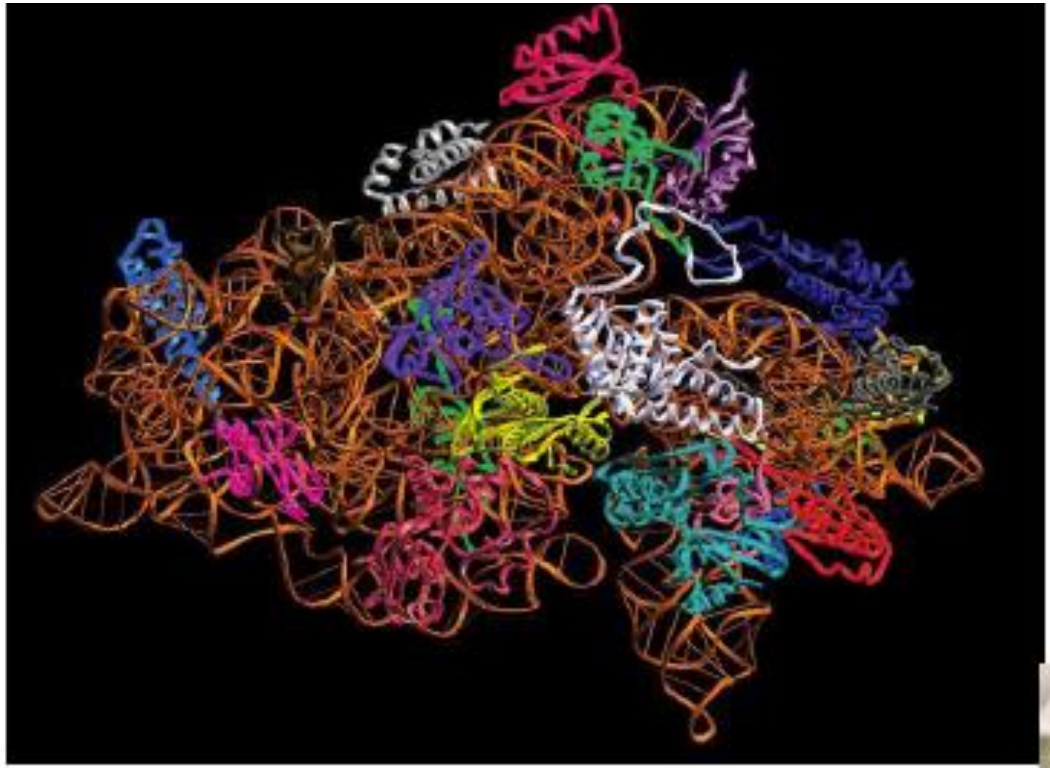
COLLIDERS

e and e+
TeV beams
Spin polarization
Multiple stages
High Luminosity
-nC charge per beam
-nm emittance
-kHZ Rep. rate
->20 MW Average power
-> need 90% driver beam-accelerated bunch energy extraction efficiency

5th Gen Light Source

e
1GeV beams
10 pC charge per beam
Single stage
High beam brightness
-Extremely low energy spread
-nm emittance
-kHZ Rep. rate

Synchrotrons and X-FELs poised to be Breakthrough Tools of Discovery in 21st century

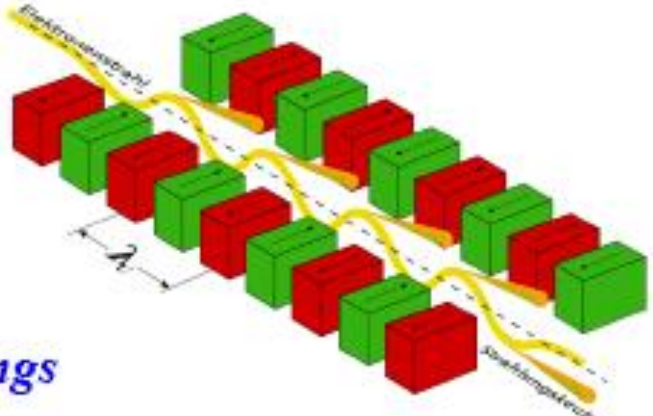


structure analysis with highest resolution Ribosome molecule

Deciphered by Venky Ramakrishnan's Team: Nobel in Chemistry 2009

100,000 proteins in human body
75,000 enzymes
25,000 Genes in each cell

Undulator to enhance the synchrotron radiation in e+/e- storage rings



Conclusions

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1) Developing plasma accelerators that will disrupt an established technology is a long-term endeavor. Beautiful science but limited resources.

2) A team that has diverse expertise, bright young people eager to make their mark and good leadership is essential to success.

3) Long term funding and access to facilities is essential

4) Important to have goals to judge progress but must also have the freedom to pursue unexpected avenues as they open up.

5) The prognosticators must come up with a “killer app” such as 5^{th} Generation Light Source to secure funding for continued R&D within 10 years.