Questions for: Energies Beyond LHC

CSS2013

Mark Hogan August 2, 2013

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Tough Question 4:

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Exotic acceleration mechanisms for electrons have been demonstrated to give accelerations of GeV/m and even tens of GeV/m. But these devices operate with low efficiency both in power use and in throughput of particles. Is there a path to an accelerator based on these technologies that will deliver high luminosity and TeV energies?

Accelerators and Particle Physics

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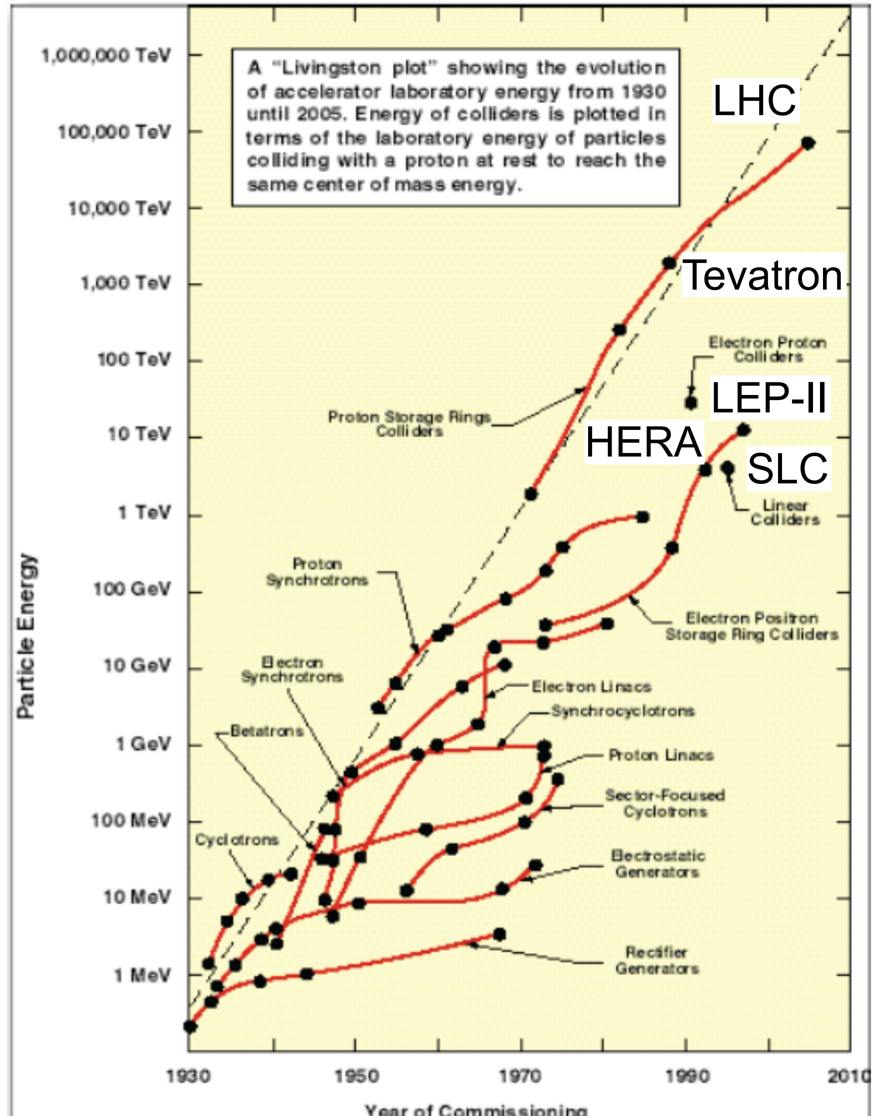
- Particle physics addresses fundamental questions that are often answered at the energy frontier
- The Livingston curve shows the exponential growth in CM energy that has come from new accelerator physics & technology
- This growth has been followed by profound discoveries - CP violation in K's, two ν's, J, quarks, ψ, τ, gluons & QCD, W, Z, top quark, Higgs



The Evolution of Particle Accelerators & Colliders
by W. K. H. Panofsky

2-017

Largest Cost Driver for a Linear Collider is the Acceleration

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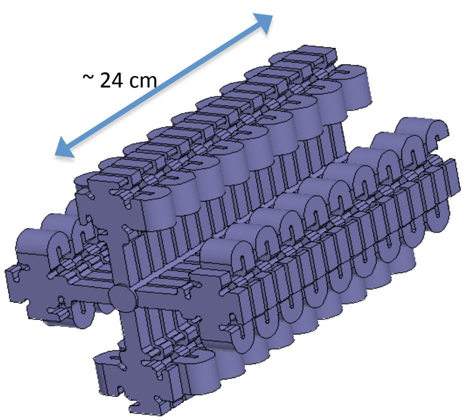
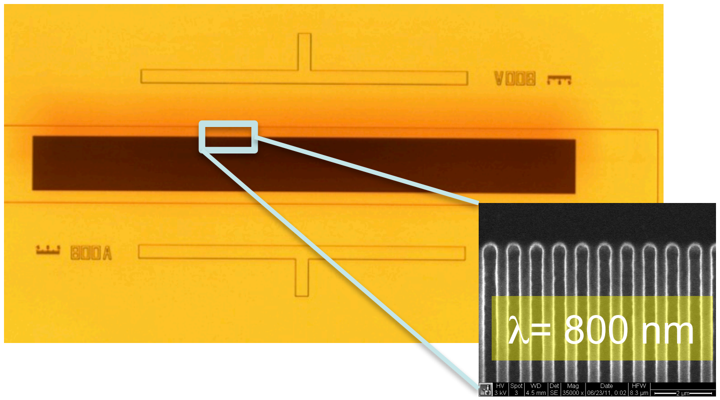
- ILC geometric gradient is ~20 MV/m → 50km for 1 TeV
- Looking to advanced concepts to shrink the size and cost of these accelerators by factors of 10-1000
  - High gradient acceleration requires high peak power and structures that can sustain high fields
  - Combine efficient accelerator drivers with high-field dielectric and plasma structures to develop new generation of particle accelerators

~100MeV/m



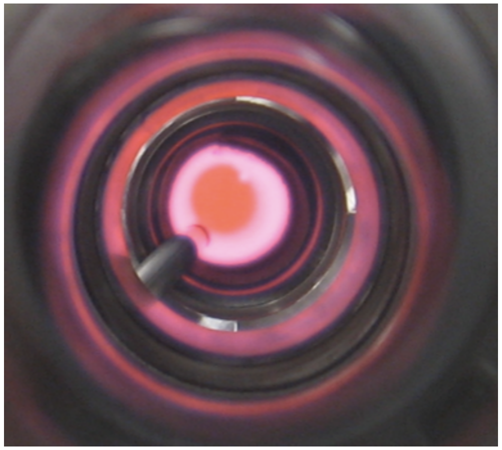
New designs and materials push metal structures to the limit

~1GeV/m



Telecom and Semiconductor tools used to make an 'accelerator on a chip'

~10GeV/m



Extremely high fields in 1,000°C lithium plasmas have doubled the energy of the 3km SLAC linac in just 1 meter

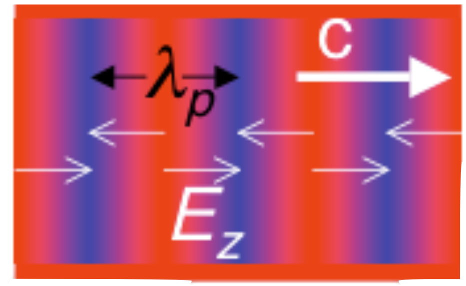
Why Plasmas?

Relativistic plasma wave (electrostatic):

$$\vec{\nabla}\cdot\vec{E} = \frac{\rho}{\varepsilon_0} \qquad k_p E_z = \frac{\omega_{pe}}{c} E_z = \frac{n_e e}{\varepsilon_0}$$

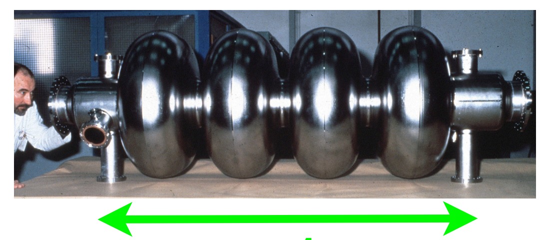
$$E_z = \left(\frac{m_e c^2}{\varepsilon_0}\right)^{1/2} n_e^{1/2} \cong 100\sqrt{n_e(cm^{-3})} = \underline{1GV/m}$$

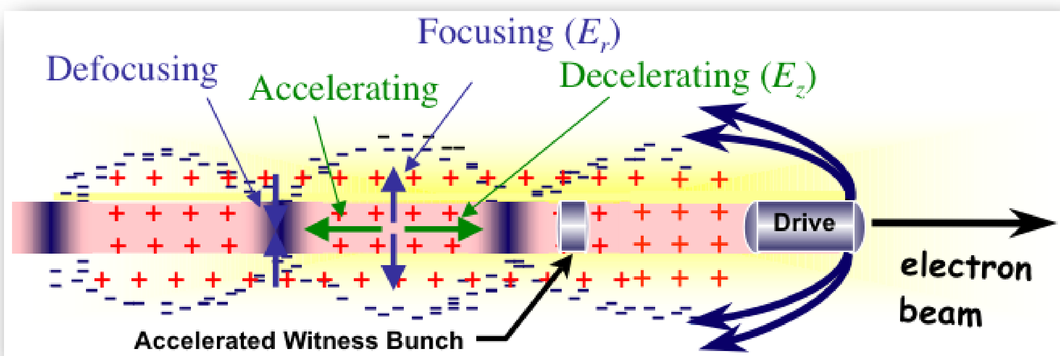
$n_e=10^{14}$ cm^{-3}

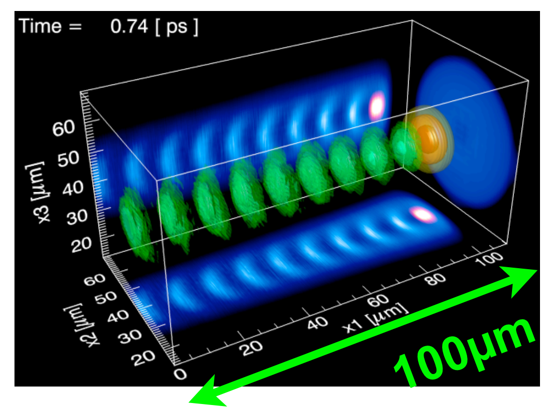


Large
Collective Response!

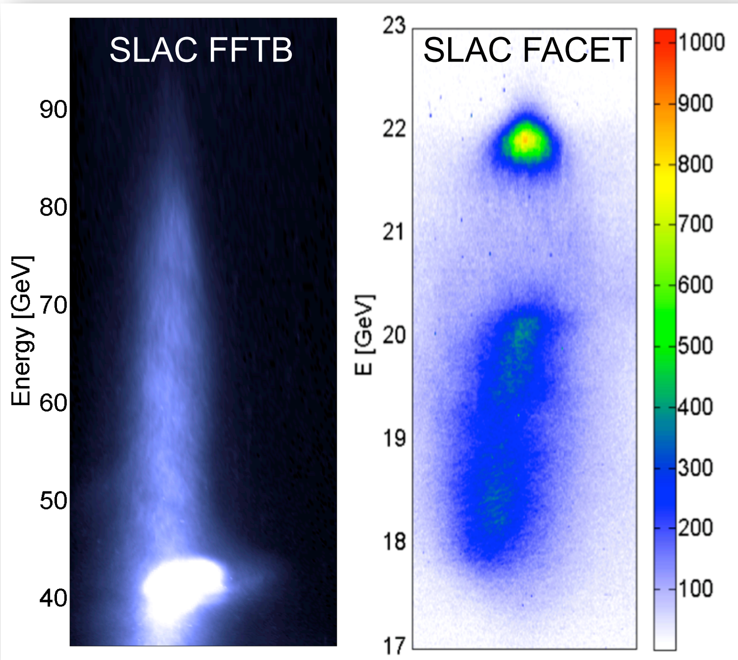
- Plasmas are already ionized, no break down
- Plasma wave can be driven by:
  - Intense laser pulse (LWFA)
  - Short particle bunch (PWFA)







Electron Acceleration in Plasmas



Nature ***445*** *741 (2007)*

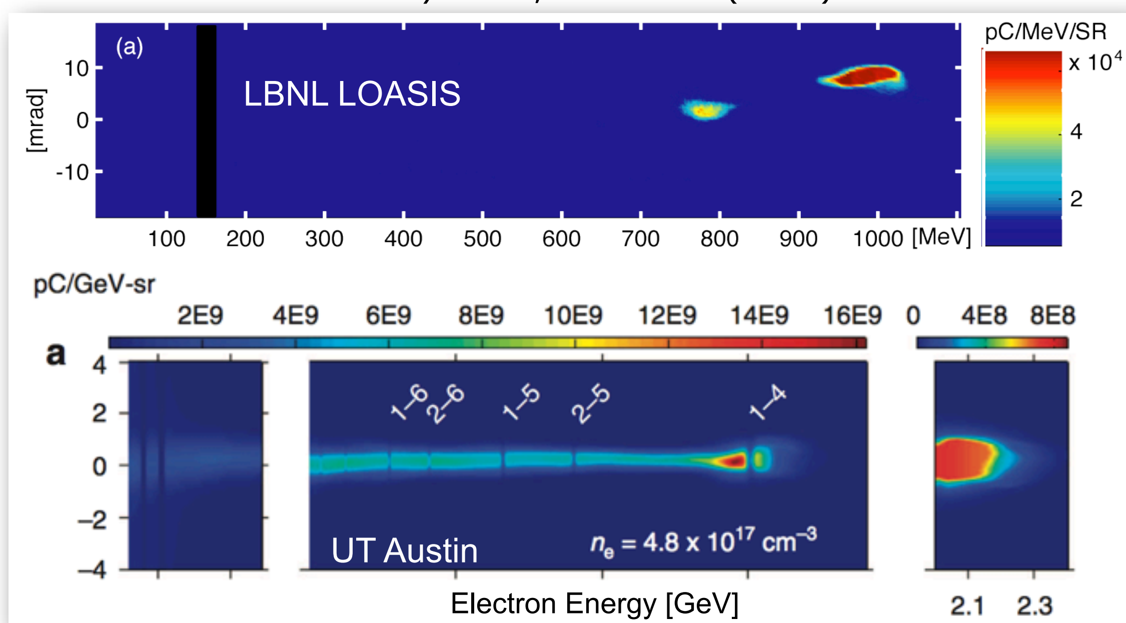
Beam Driven Plasmas:

- 50 GeV/m fields, stable over meter scale for electrons
- Drive/witness bunches injected for stable acceleration over 30cm with narrow dE/E

Laser Driven Plasmas:

- 50 GeV/m fields, stable over cm
- High quality <μm emittance beams created and accelerated in the plasma

Nature Physics **2**, 696 - 699 (2006)



Nat Commun. ***4****:1988 doi: 10.1038/ncomms2988 (2013)*

Is there a path to an accelerator based on these technologies that will deliver high luminosity and TeV energies?

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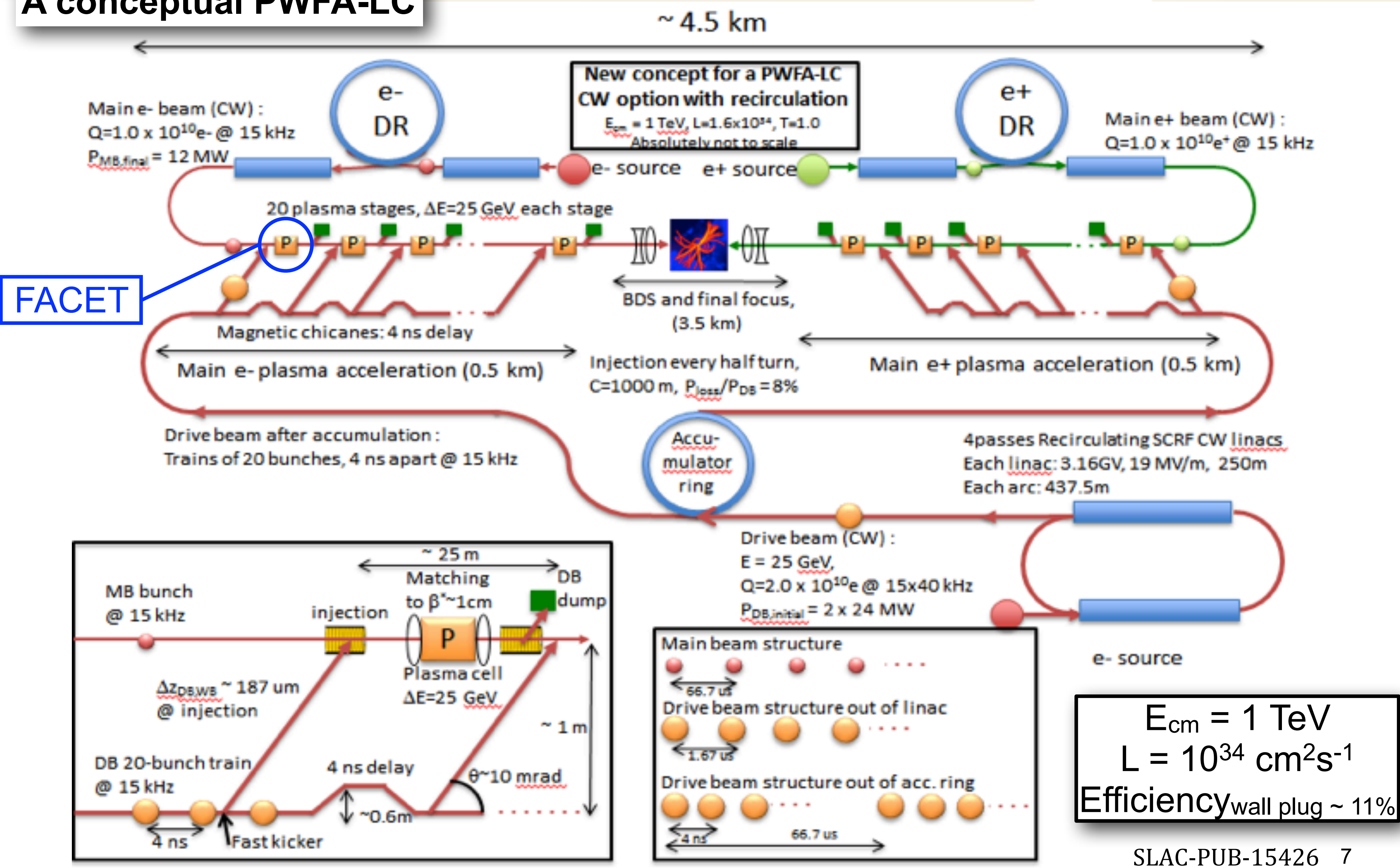
A conceptual PWFA-LC



E_{cm} = 1 TeV
L = 10^{34} cm^2s^{-1}
Efficiency$_{\text{wall plug}}$ ~ 11%

Primary Challenges for a PWFA-LC

The concept for the PWFA-LC highlights the key beam and plasma physics challenges must be addressed by experimental facilities such as FACET. A reasonable set of design choices for a plasma-based linear collider can benefit from the years of extensive R&D performed for the beam generation and focusing subsystems of a conventional rf linear collider. The remaining experimental R&D is directly related to the beam acceleration mechanism. In particular, the primary issues are:

- Development of a concept for positron acceleration with high beam brightness
- High beam loading with both electrons and positrons (required for high efficiency),
- Beam acceleration with small energy spreads (required to achieve luminosity and luminosity spectrum),
- Preservation of small electron beam emittances (required to achieve luminosity) and mitigation of effects resulting from ion motion
- Preservation of small positron beam emittances (required to achieve luminosity) and mitigation of effects resulting from plasma electron collapse
- Average bunch repetition rates in the 10's of kHz (required to achieve luminosity)
- Synchronization of multiple plasma stages to achieve the desired energy, and
- Optical beam matching between plasma acceleration stages and from plasma to beam delivery systems.

Answering these questions requires dedicated test facilities like FACET & FACET-II

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Positrons, beam quality, efficiency, and staging

- Preservation of small positron beam emittances (required to achieve luminosity) and mitigation of effects resulting from plasma electron collapse
- Average bunch repetition rates in the 10's of kHz (required to achieve luminosity)
- Synchronization of multiple plasma stages to achieve the desired energy, and
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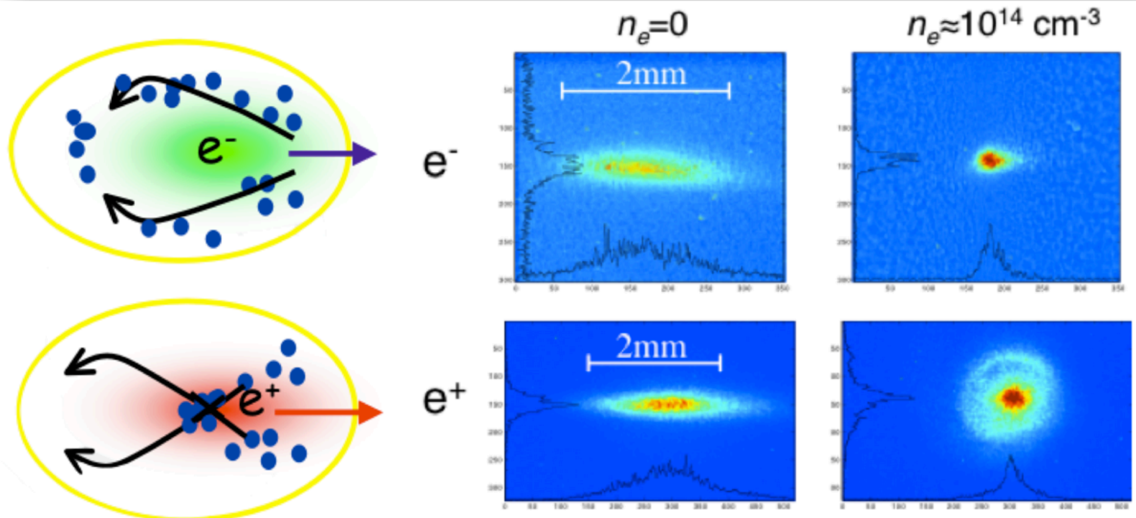
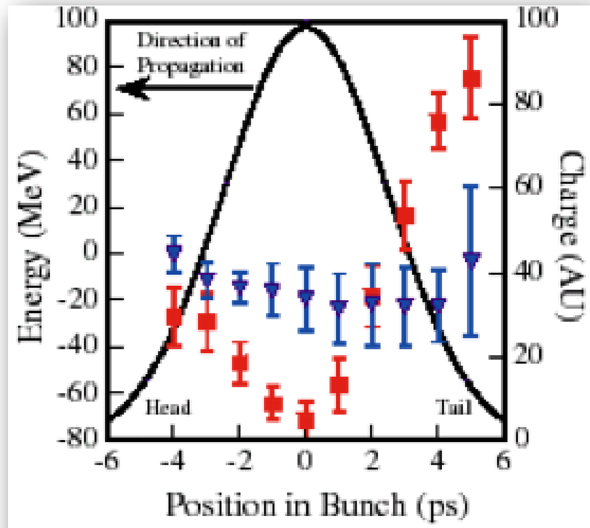
Positron Focussing and Acceleration

Focusing and acceleration of positrons has been characterized at low densities

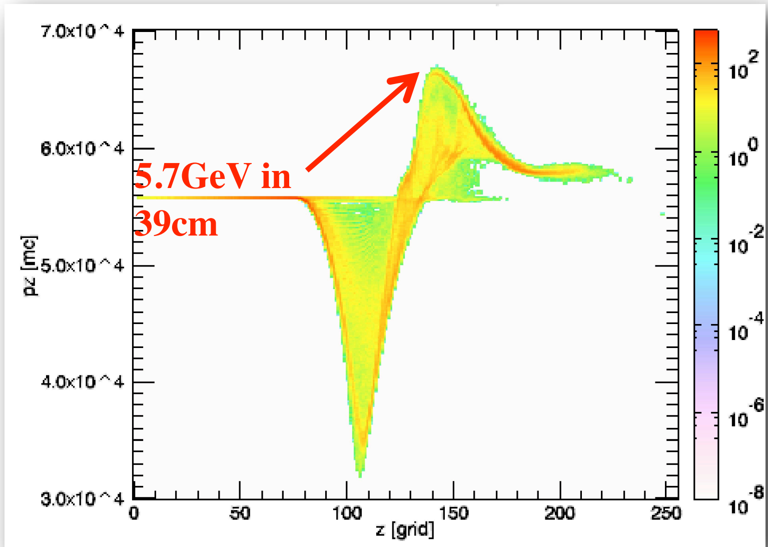


Phys. Rev. Lett. **90**, 205002 (2003) *Phys. Rev. Lett.* **101**, 055001 (2008)



Phys. Rev. Lett. **90**, 214801 (2003)

- High-gradient positron acceleration is possible
  - Can use wake of an electron or positron beam
- Need to iterate plasma source to minimize emittance growth but preserve high-gradients (hollow channels)
- FACET will make first tests of high-gradient positron acceleration in the next couple years

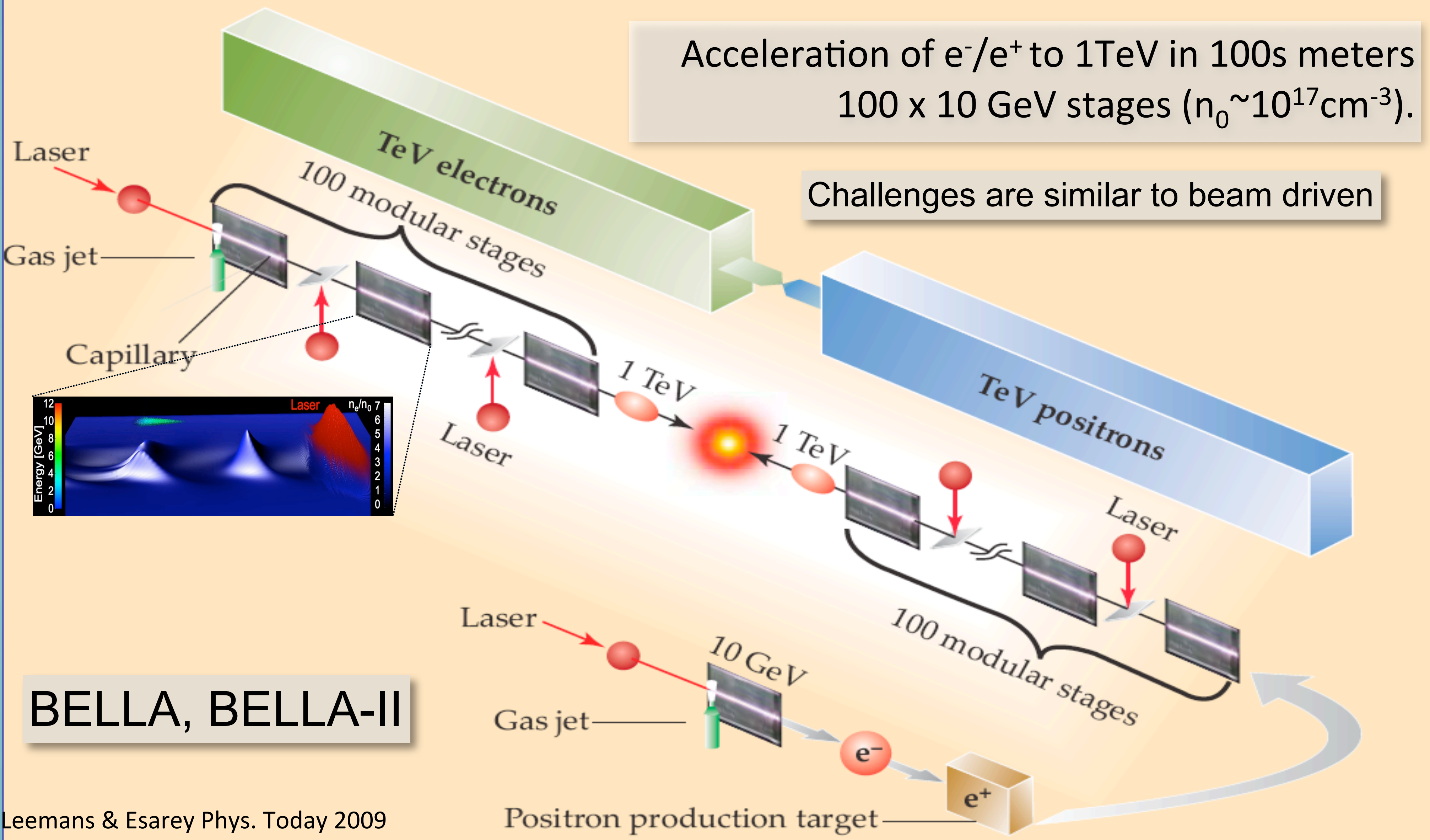


Key steps towards a collider are development of a module and demonstrating multi-module acceleration

Concept of compact TeV collider

Acceleration of e⁻/e⁺ to 1TeV in 100s meters
100 x 10 GeV stages (n_0~$10^{17}cm^{-3}$).

Challenges are similar to beam driven



BELLA, BELLA-II

Leemans & Esarey Phys. Today 2009

Beam Driven Dielectrics: Argonne Flexible Linear Collider

R&D Challenges: Structure material & geometry, beam quality, efficiency, staging

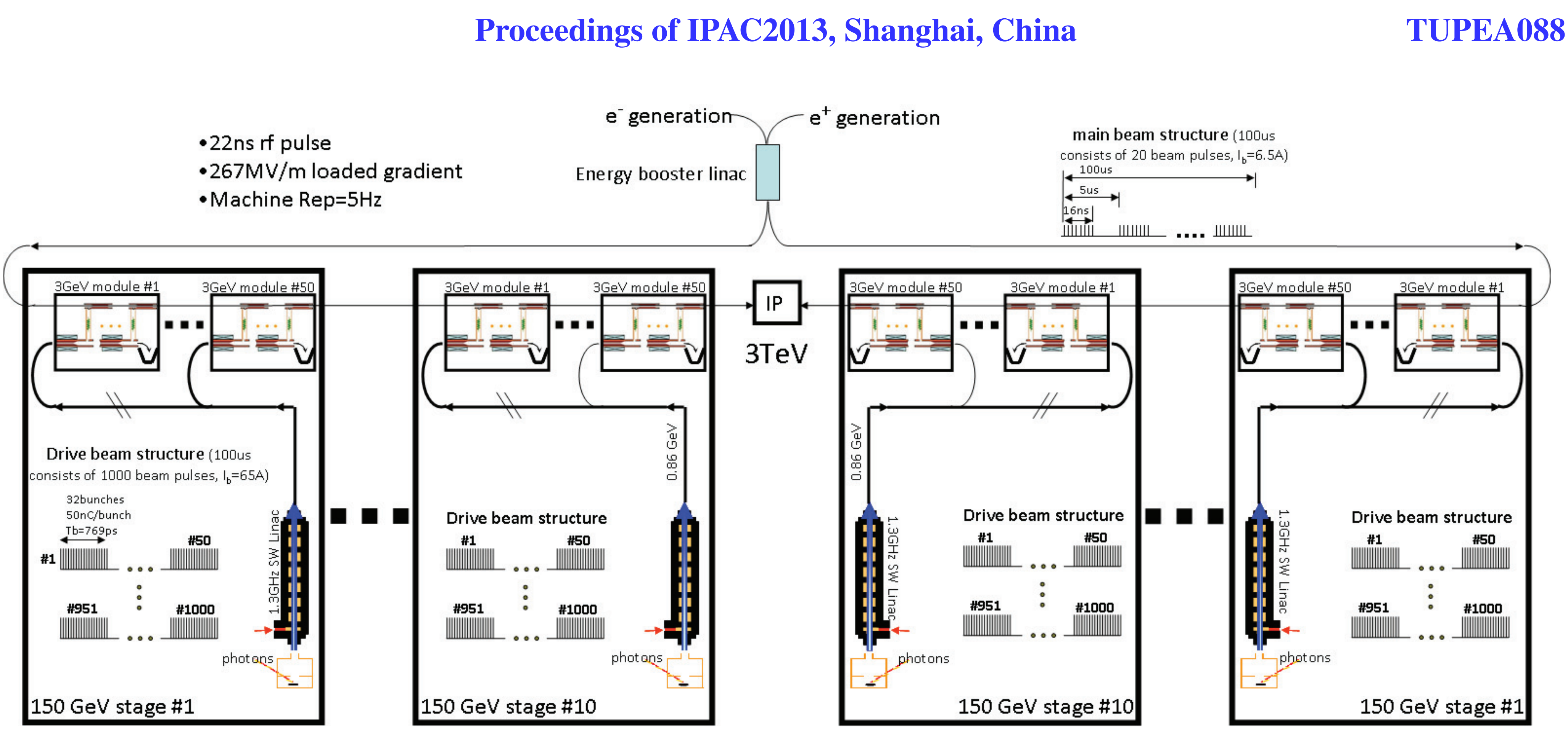
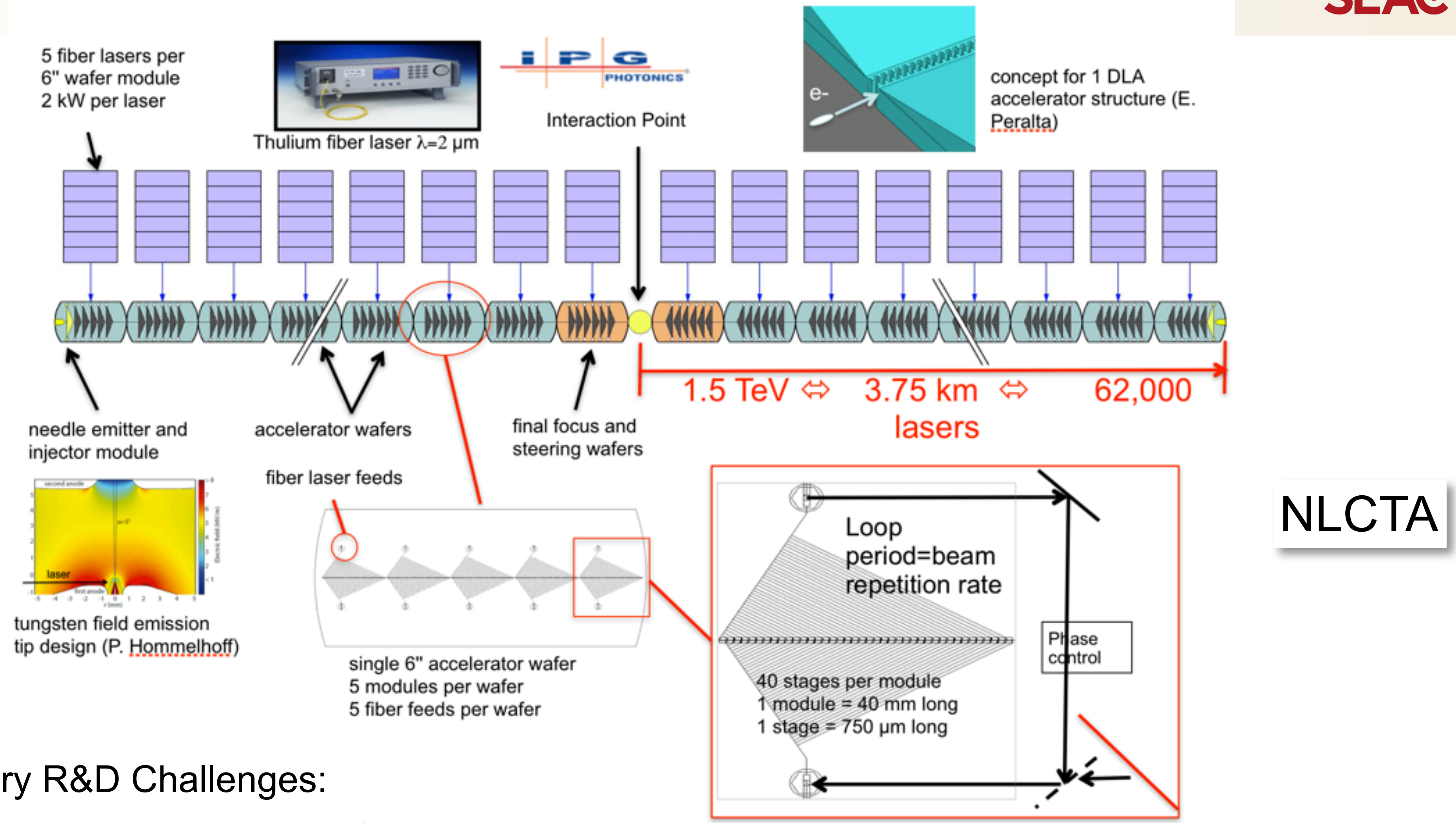


Figure 2: The conceptual layout of the Argonne Flexible Collider.

AWA, ATF, FACET

DLA Collider Concept
(low charge, small apertures, small emittance, high rep rate)



Primary R&D Challenges:

1. IR laser damage limits of semiconductor materials at picosecond pulse lengths
2. High (near 100%) efficiency power coupling schemes
3. Integrated designs with multiple stages of acceleration
4. Phase stability issues related to temperature and nonlinear high-field effects in dielectrics

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The short answer is YES!

...but...

- Covering the path will take 1-2 decades of R&D at dedicated test facilities at National Labs
- First applications of these technologies will likely be making x-rays (betatron, XFEL)
- If a near term decision is made to move forward with an ILC, should consider how to apply these techniques as an energy upgrade down the road

Plasma Accelerators Showing Great Promise

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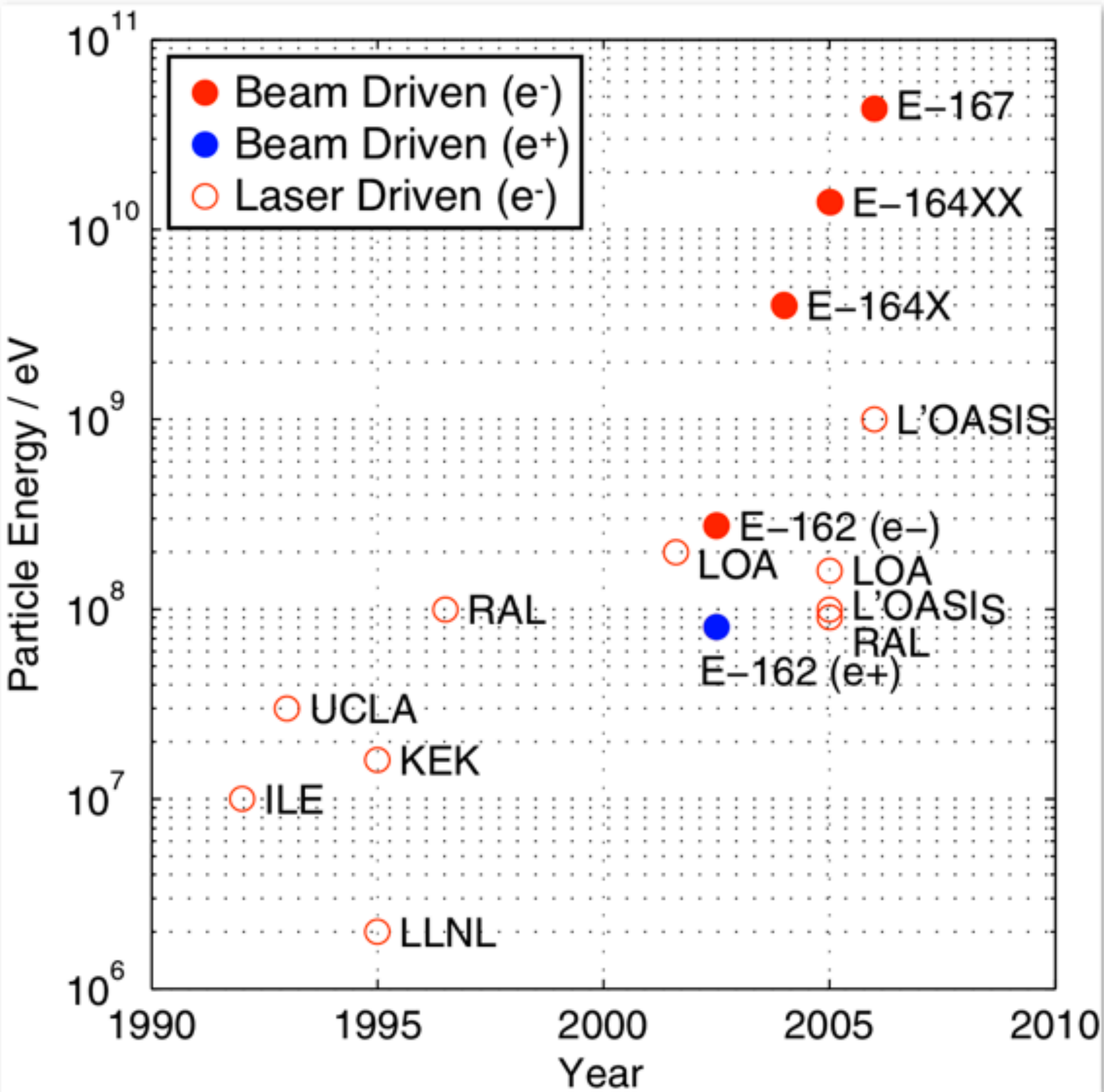


LWFA: T. Tajima and J. M. Dawson
Phys. Rev. Lett. 43, 267 - 270 (1979)

Laser Driven Plasma Accelerators:

Large Gradients:
- Accelerating Gradients > 100GeV/m (measured)
- Narrow Energy Spread Bunches
- Interaction Length limited to cm's

Specialized Facilities:
- Multi-TW lasers
- Plasma Channels/Capillaries

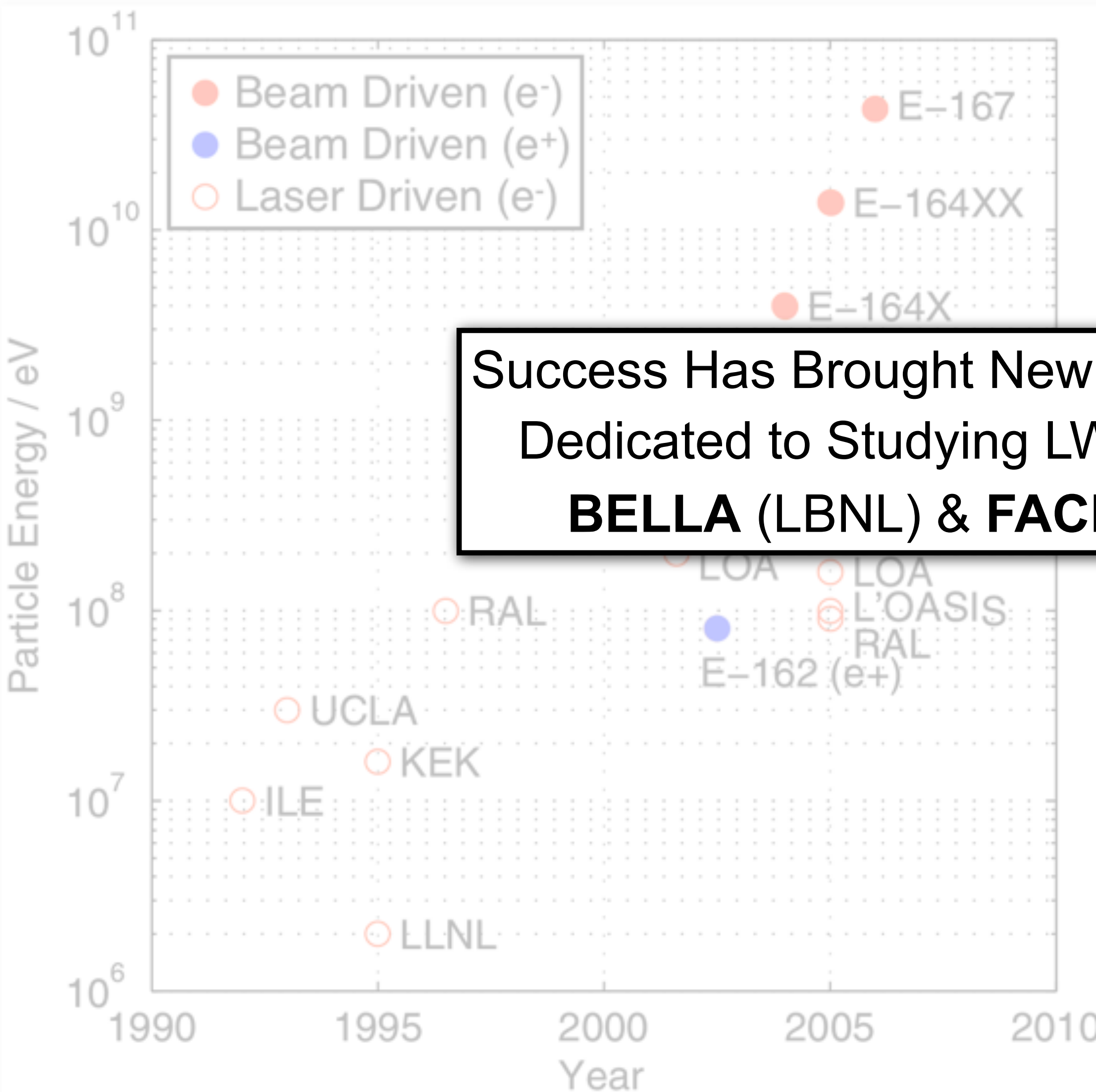
Beam Driven Plasma Accelerators:

Large Gradients:
- Accelerating Gradients > 50 GeV/m (measured!)
- Focusing Gradients > MT/m
- Interaction Length ~ meters

Unique SLAC Facilities:
- FFTB < 2006, FACET > 2011
- High Beam Energy
- Short Bunch Length
- High Peak Current
- Power Density
- e- & e+

PWFA: P. Chen et al
Phys. Rev. Lett. 54, 693 - 696 (1985)

Plasma Accelerators Showing Great Promise



Success Has Brought New DOE Facilities Dedicated to Studying LWFA & PWFA
BELLA (LBNL) & **FACET** (SLAC)

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