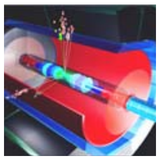
Accelerators Beyond LHC and ILC

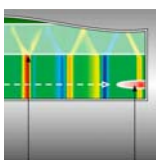
Rasmus Ischebeck, Stanford Linear Accelerator Center



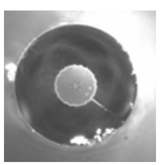
Accelerators for TeV-Energy electrons

Present Technologies

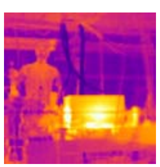
Advanced Accelerator Research at SLAC



Electron beam driven Dielectric Structures



Laser-driven Dielectric Structures



Plasma Wakefield Accelerators

STANFORD LINEAR ACCELERATOR CENTER

Advanced Accelerator Research

explores new acceleration principles

- Extending RF to higher frequencies
- Dielectrics at optical* frequencies
- Nonlinear Plasma Wakes

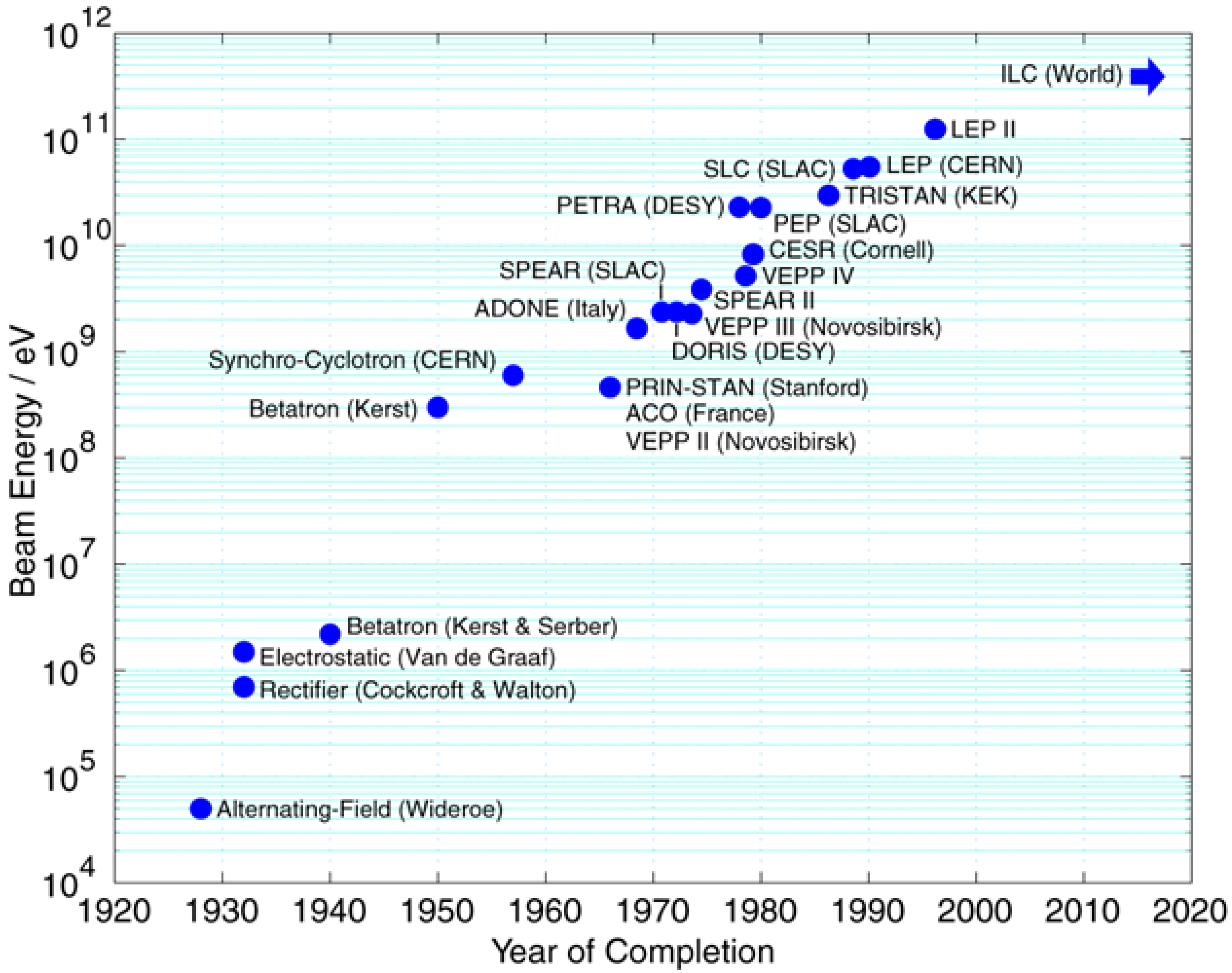
Accelerator Technology

focuses on

- Applications
- Stability
- Efficiency
- Cost

*actually, infrared

History of Electron Accelerators
Livingston Plot



Basic Requirements for Electron Accelerators beyond ILC

- Energy $W \gtrsim 5 \ldots 10$ TeV $W = E \cdot e \cdot L$ (Linac)
- Luminosity $\mathfrak{L} \gtrsim 10^{36}$ cm^{-2} s^{-1} $\mathfrak{L} = \frac{N^2 f}{4\pi \sigma_x \sigma_y}$

⇒ Beam power $P \approx 100$ MW $P = U \cdot I$

- Cost $C \lesssim 5 \cdot 10^9$

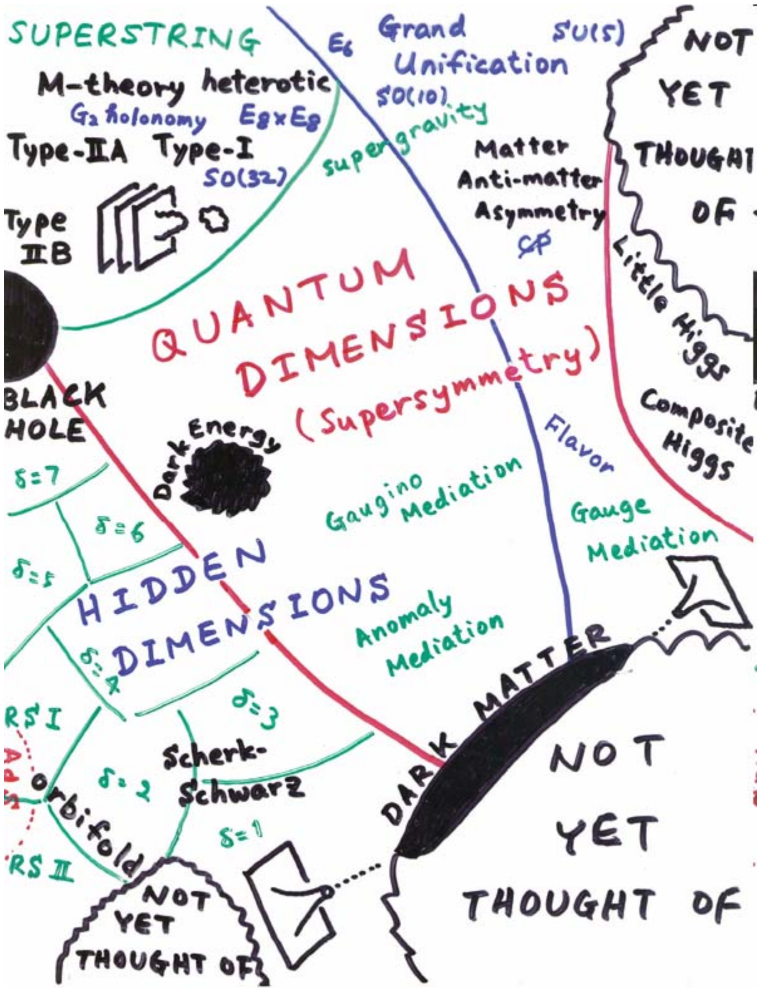
- High accelerating fields
- Low emittance (small diameter)
- High bunch charge
- Good efficiency

Luminosity

- Cross section for e^+e^- collisions goes as $1/E^2$
  - $\Rightarrow$ Need a luminosity of $\mathcal{L} \gtrsim 10^{36}$ cm^{-2} s^{-1}
- Just increasing the number of particles at constant phase space density will lead to a prohibitive AC power
  - $\Rightarrow$ Need to improve
    - The particle density at the source (the source emittance)
    - Control emittance growth in the linacs
    - Final focus optics (considering beam-beam interactions)

 adapted from G. Dugan

Hitoshi Murayama's view of Particle Physics in the 21st Century



Not an Option for 10 TeV

- Build a circular accelerator
  - Synchrotron radiation proportional to E^4
- Build a linear accelerator based on state-of-the-art RF cavities
  - Accelerating field 0.05 GV/m
  - 300 km long (with focus and beam delivery)
  - Cost: $3 \cdot 10^{10}$

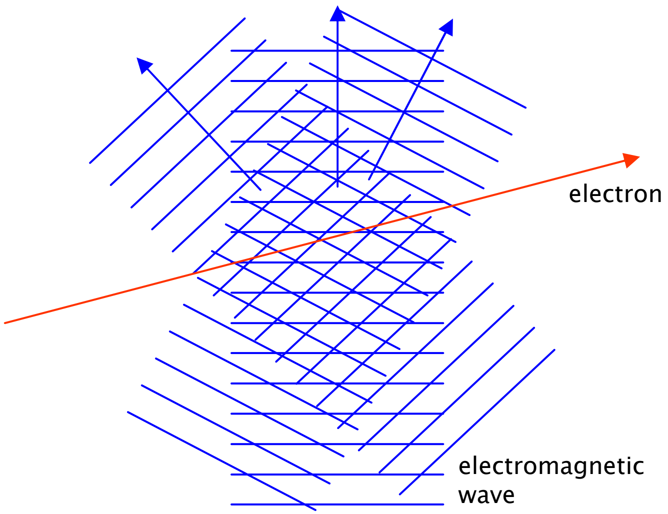
Therefore

- Need to increase the accelerating fields
  (without increasing the cost by the same factor)
- Explore alternative acceleration techniques

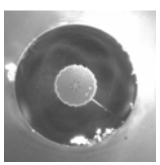
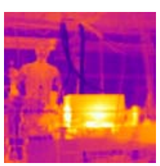
Electromagnetic Waves in Vacuum

- Transverse electric fields
- Moreover, the Lawson–Woodward Theorem states:
  - the total acceleration
    - of ultrarelativistic particles
    - by far-field electromagnetic waves
  - is zero

⇒ Need near-field structures



Possibilities for Accelerating Structures

	Structure	max. Field (V/m)	Power Sources	
	Superconducting	$5 \cdot 10^7$	solid state	electron beams: klystrons
	Metallic	$2 \cdot 10^8$	solid state	electron beams: klystrons or integrated structure
	Dielectric	10^9	laser	electron beams
	Plasma	10^{11}	laser	electron beams

Plus: Inverse FEL, disposable structures, excited atoms, muon colliders

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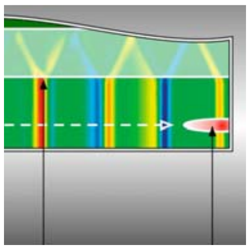
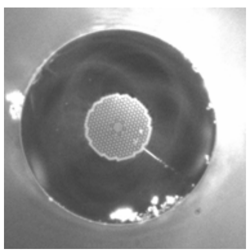
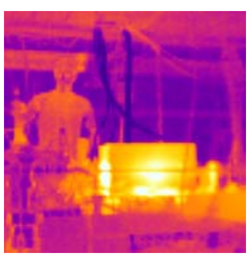
Advanced Accelerator Research at SLAC



Electron beam driven Dielectric Structures

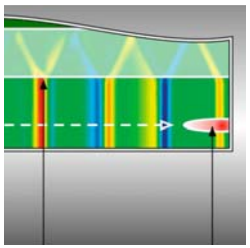


Laser-driven Dielectric Structures

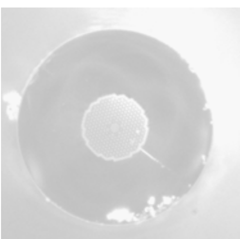


Plasma Wakefield Accelerators

Advanced Accelerator Research at SLAC



Electron beam driven Dielectric Structures

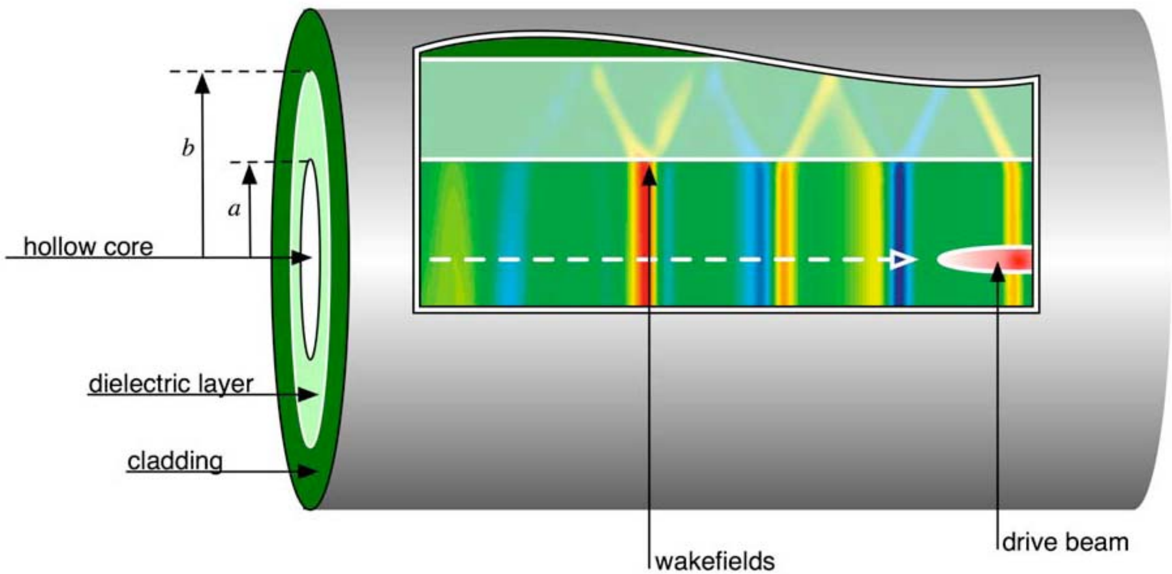


Laser-driven Dielectric Structures

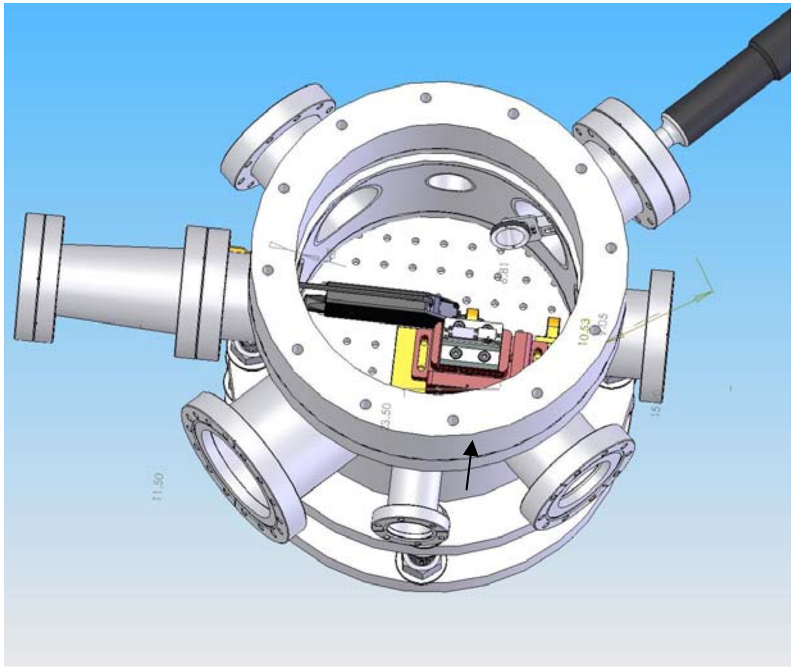
Plasma Wakefield Accelerators

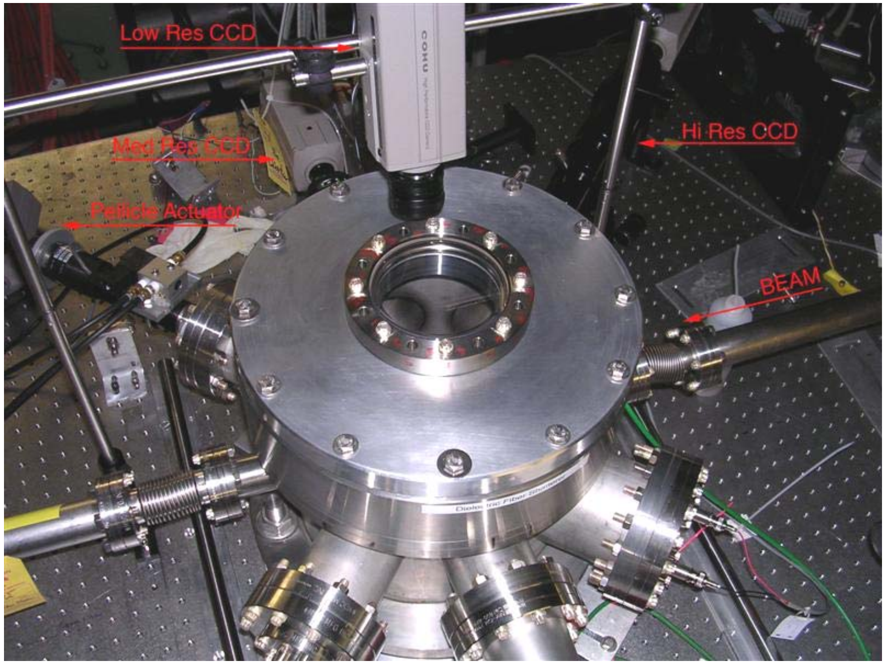
Dielectric Wakefield Acceleration
The T-481 Experiment

- M.C. Thompson, H. Badakov, J. Rosenzweig, and G. Travish (UCLA)
- M.J. Hogan, R. Ischebeck, N. Kirby, R. Siemann, and D. Walz (SLAC)
- P. Muggli (USC)
- A. Scott (UCSB)
- R. Yoder (Manhattan College)



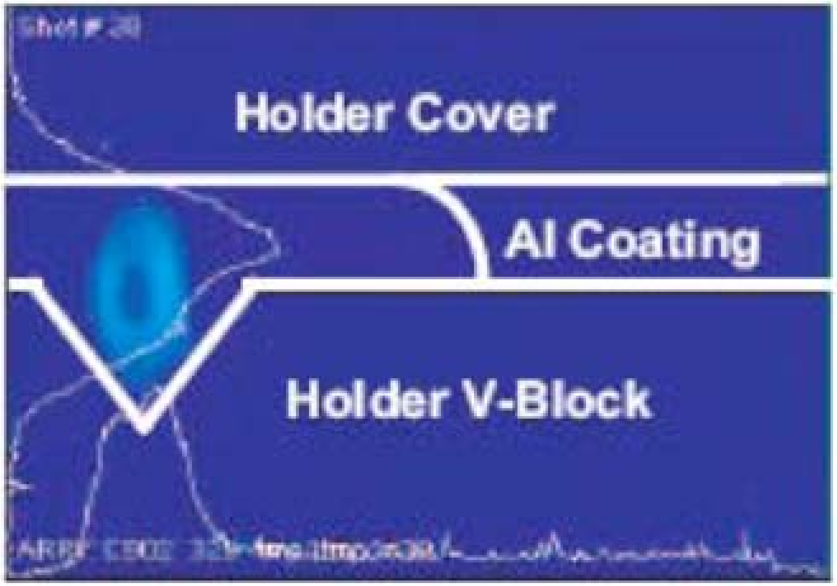
Dielectric Wakefield Acceleration
Experimental Setup



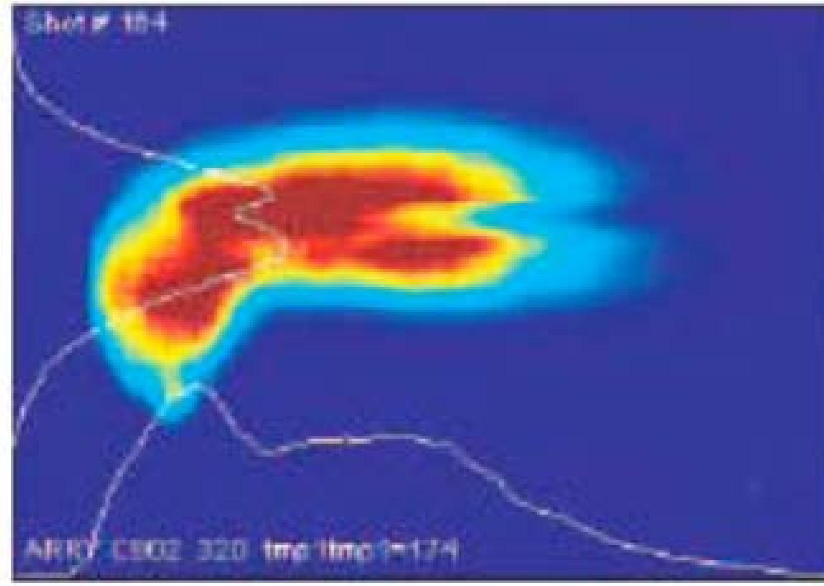


Hristo Badakov, Gil Travish

Dielectric Wakefield Acceleration
Breakdown Studies



100 μm bunch length

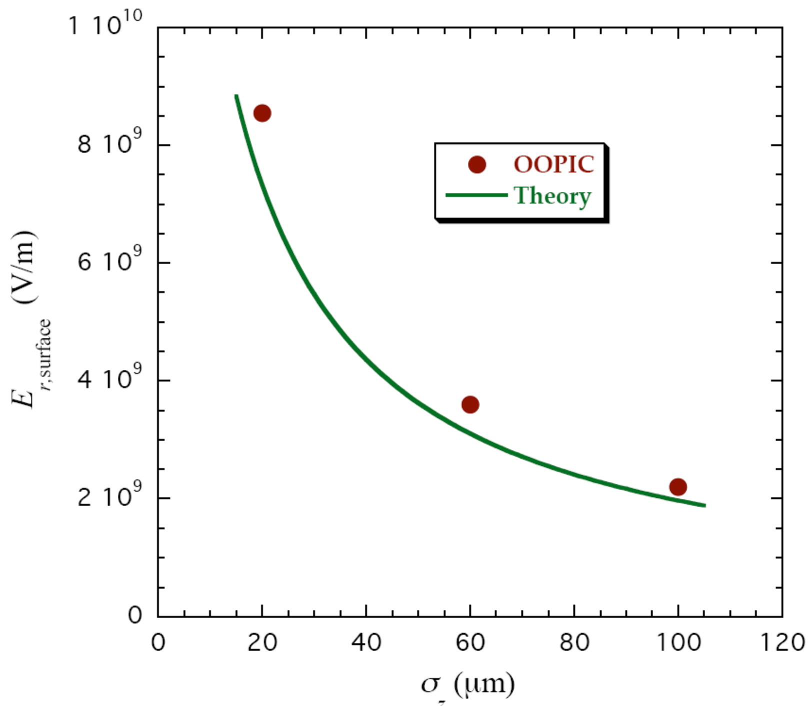


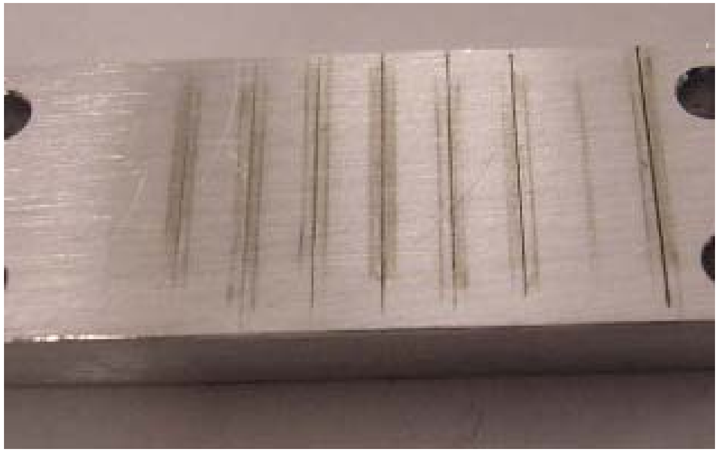
20 μm bunch length

Dielectric Wakefield Acceleration

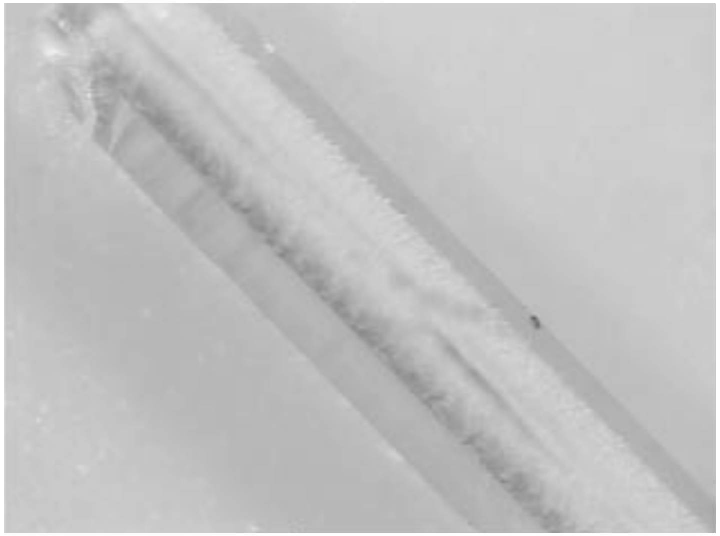
Breakdown Studies

Calculated surface fields





Aluminum cladding has vaporized

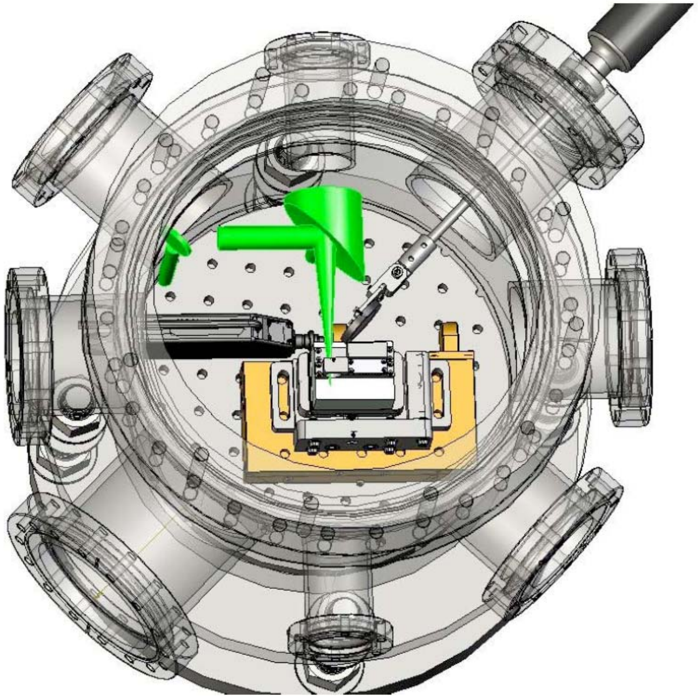


Cracks in the dielectric

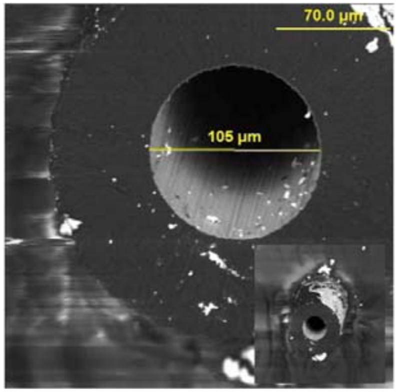
Dielectric Wakefield Acceleration

Next Experiments

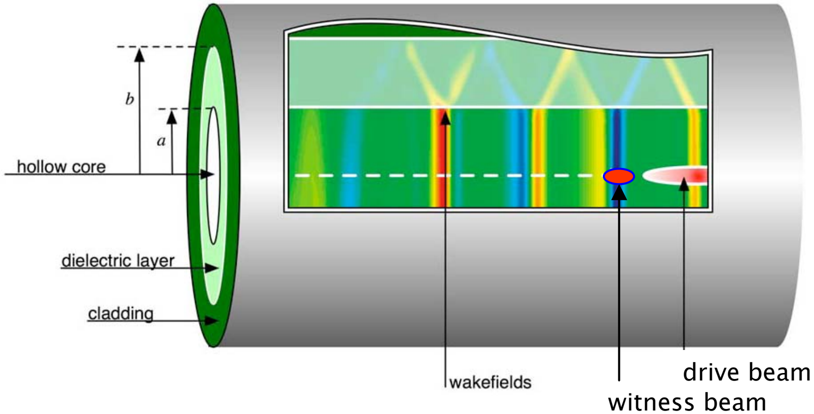
Measure the Cherenkov radiation emitted from the fiber



Try alternative materials (e.g. diamond)



Accelerate Second Bunch



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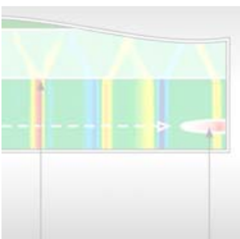
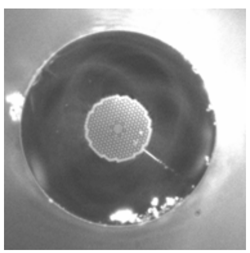
Advanced Accelerator Research at SLAC



Electron beam driven Dielectric Structures



Laser-driven Dielectric Structures

Plasma Wakefield Accelerators

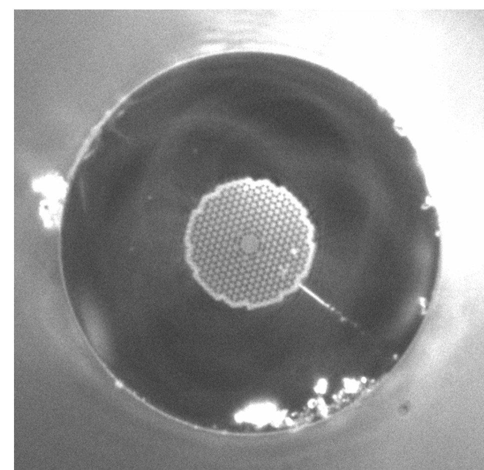
Laser Acceleration
The E-163 Experiment

- R. Siemann, R. Noble, E. Colby, J. Spencer, R. Ischebeck, M. Lincoln, B. Cowan, C. Sears, S. Tantawi, D. Walz, D.T. Palmer, N. Na, C.D. Barnes, M. Javanmarad, X.E. Lin, and Z. Zhang (SLAC)
- R. Byer, T.I. Smith, Y.C. Huang, T. Plettner, P. Lu, and J.A. Wisdom (Stanford)
- L. Schächter (Techion Israeli Institute of Technology)
- J. Rosenzweig (UCLA)

Dielectric Accelerator Structures

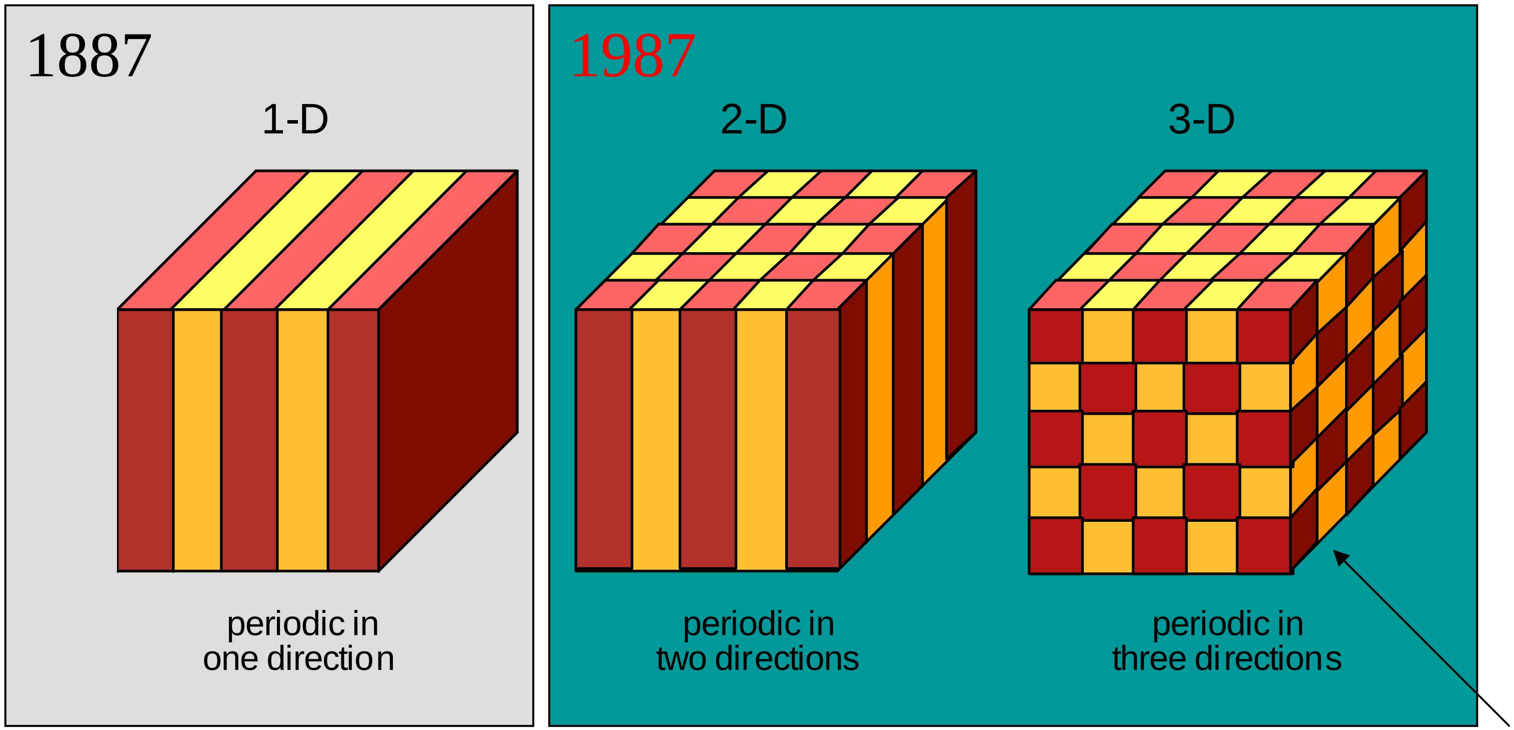
- Using much higher frequencies: THz to optical
- Using dielectrics (e.g. SiO_2)
- Advantages: higher damage threshold
  ⇒ Higher accelerating fields, up to ~GV/m

- Generate the electromagnetic field
  - Cherenkov radiation from an electron beam
  - Laser
- Confine the field
  - Photonic band gap



Photonic Crystals

periodic electromagnetic media



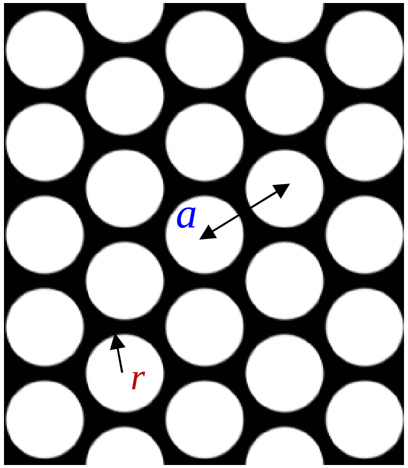
(need a more complex topology)

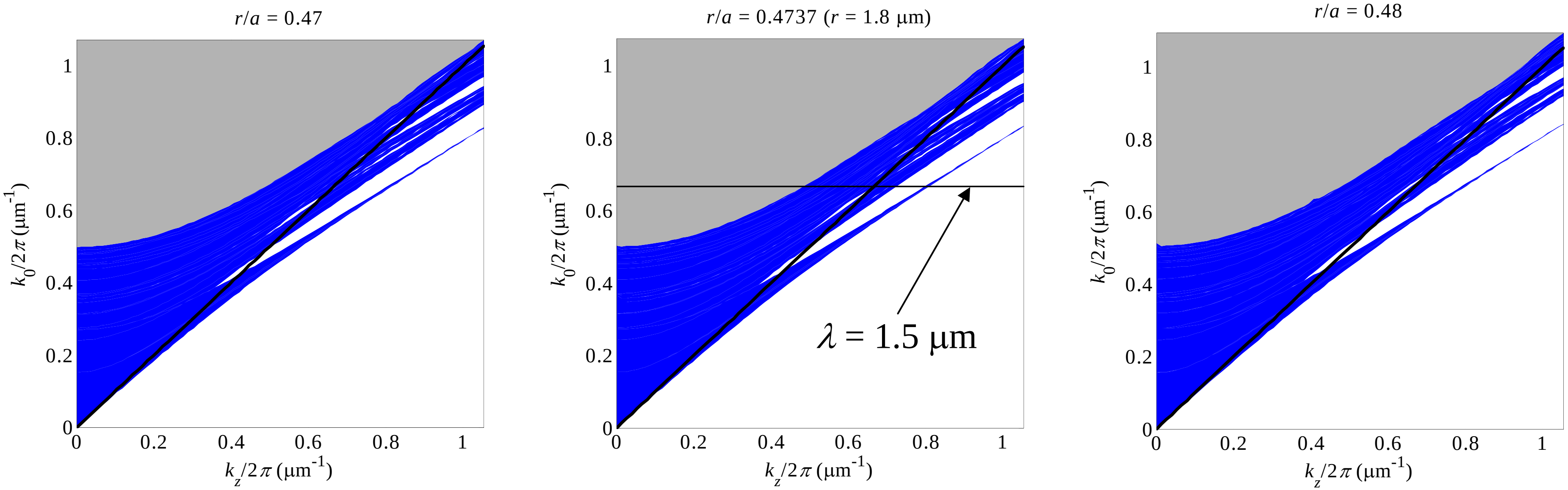
with photonic band gaps: "optical insulators"

Band Gap maps

- Solutions of the wave equation

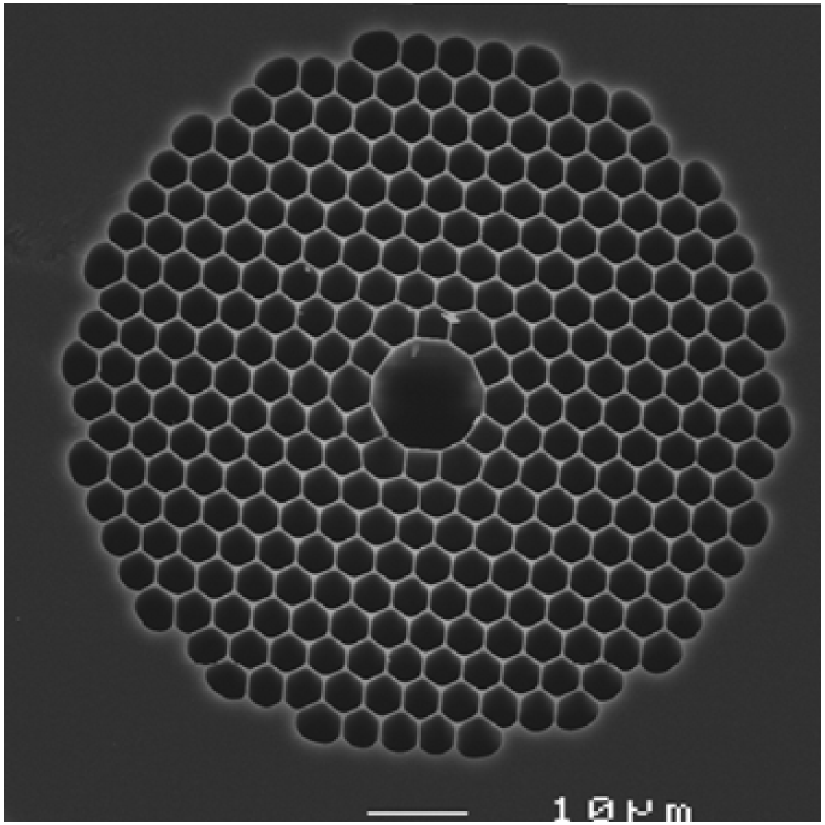
$$\vec{\nabla} \times \frac{1}{\varepsilon \varepsilon_0} \times \vec{H} = \left(\frac{\omega}{c}\right)^2 \vec{H}$$

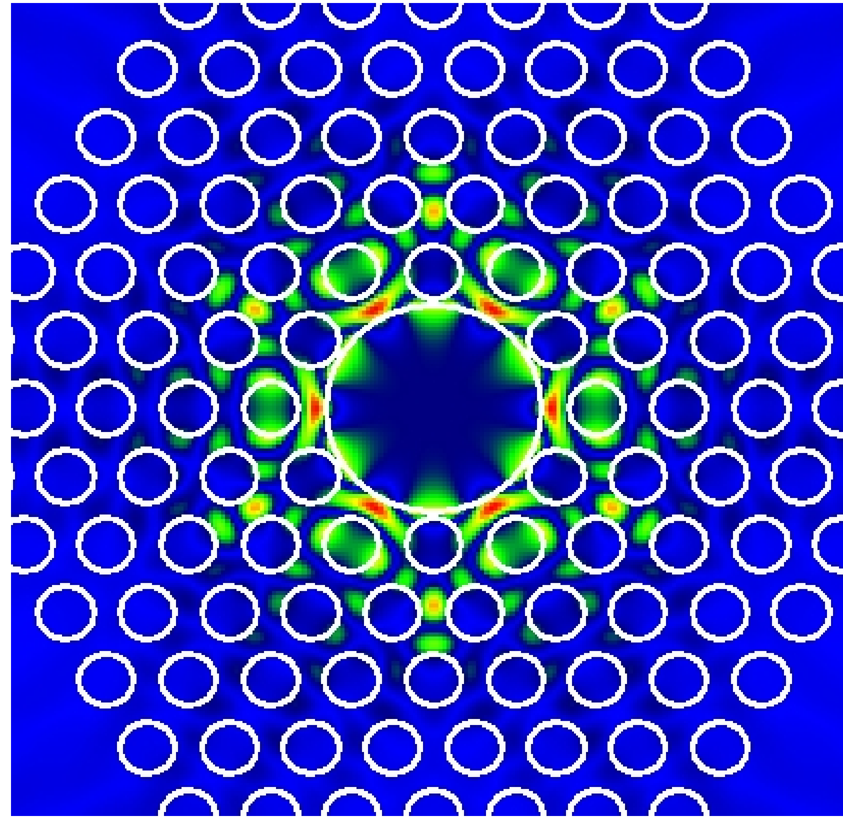




Ben Cowan

Photonic Band Gap Structures

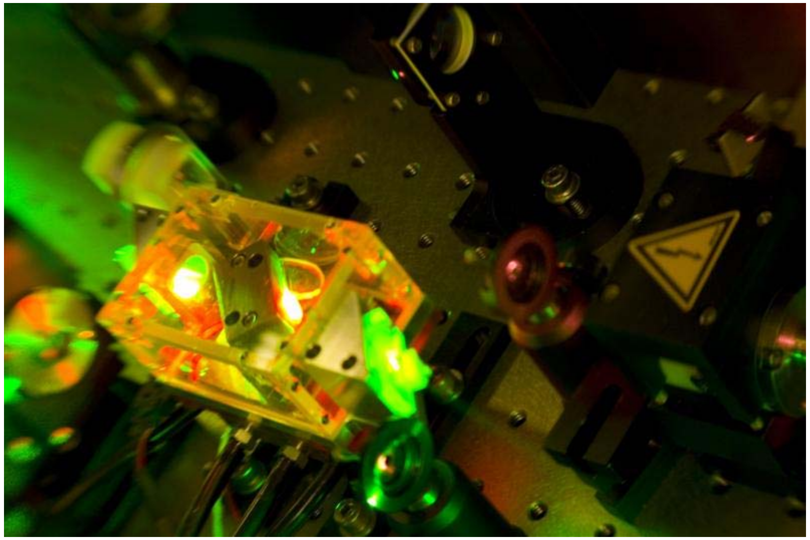




Laser Acceleration

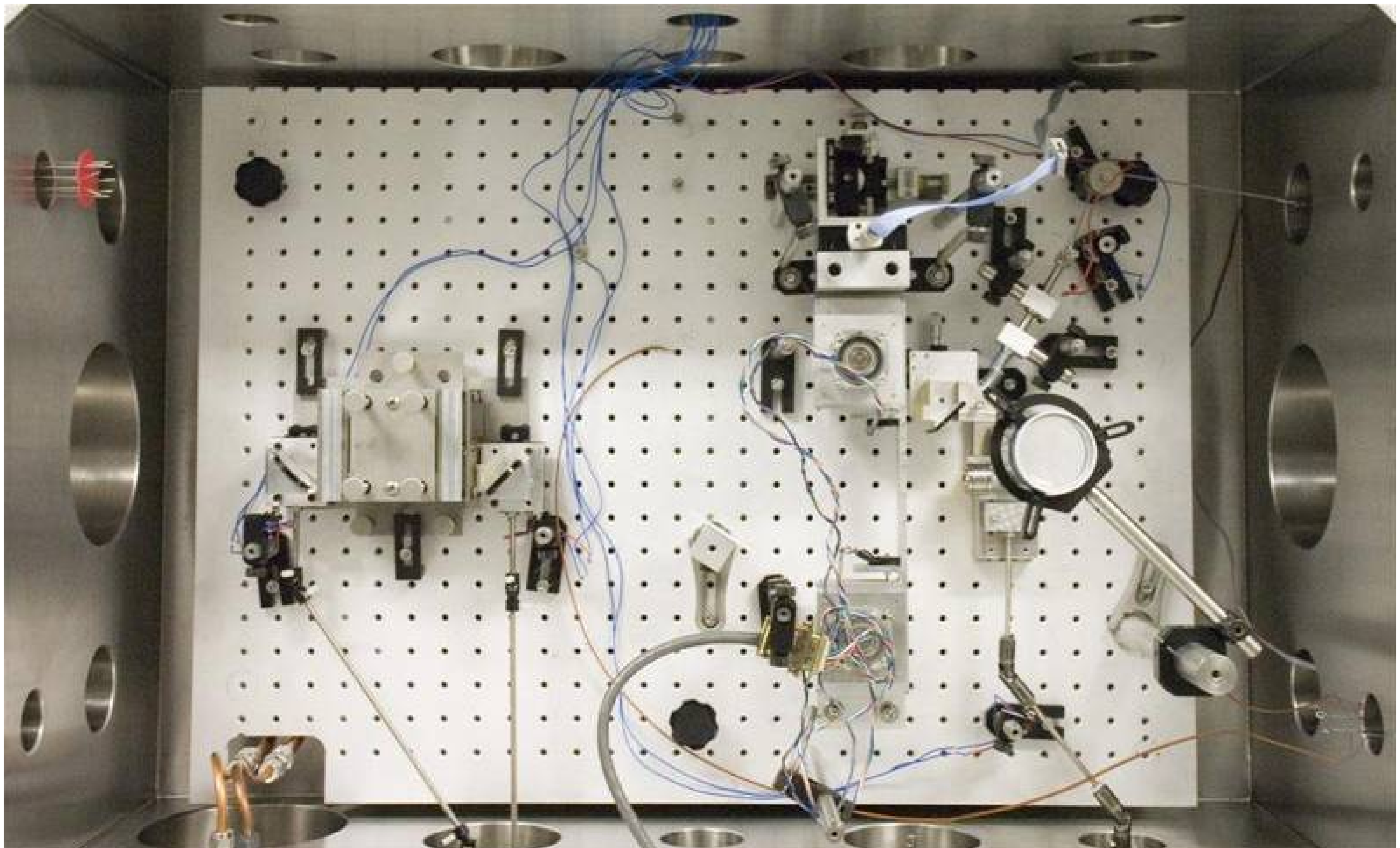
First Experiments

- Establish interaction between laser and electron beam



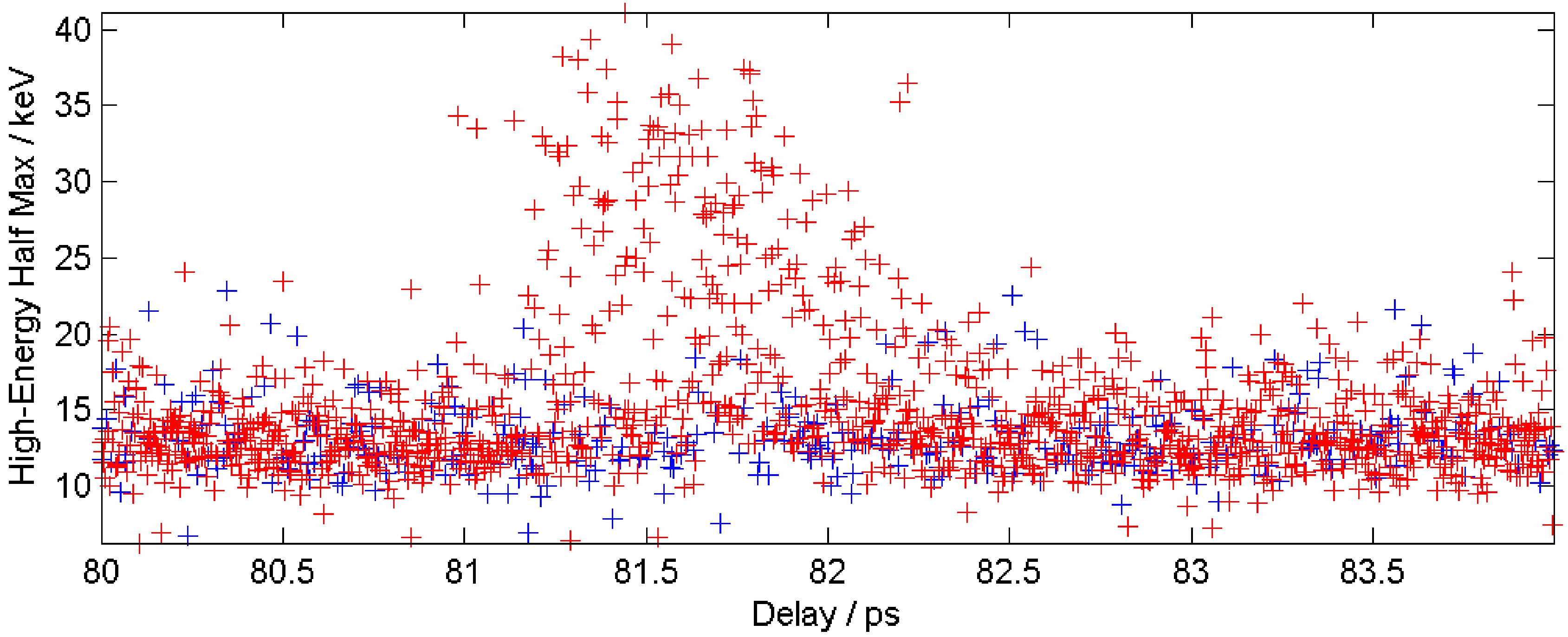
First Experiments

- Inverse free electron laser
- Inverse transition radiation



Inverse Transition Radiation

- Scanning the laser timing with respect to the electron beam



Above the Damage Threshold, indeed

- For the inverse transition radiation experiment, we have used various tape surfaces
  - reflective
  - absorbent
  - scattering

Laser Acceleration
Next Steps

- Net acceleration by combining IFEL, chicane and ITR
- Fabricate suitable structures
  - Side-coupled
  - Photonic bandgap fiber
- Measure spectrum emitted from structures
- Accelerate particles

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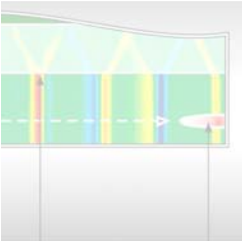
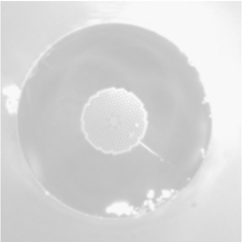
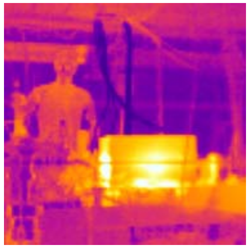


Electron beam driven Dielectric Structures



Laser-driven Dielectric Structures

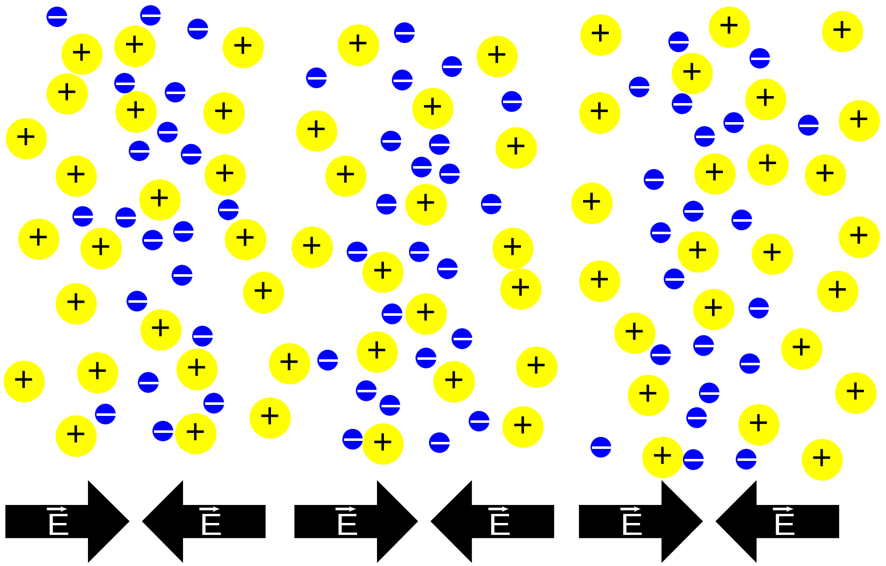


Plasma Wakefield Accelerators

Plasma Wakefield Acceleration
The E-167 Experiment

- M. Berry, I. Blumenfeld, F.-J. Decker, P. Emma, M.J. Hogan*, R. Ischebeck, R.H. Iverson, N. Kirby, P. Krejcik, R.H. Siemann, and D. Walz (SLAC)
- C.E. Clayton, C. Huang, D. Johnson, C. Joshi*, W. Lu, K.A. Marsh, W.B. Mori, and M. Zhou (UCLA)
- S. Deng, T. Katsouleas, P. Muggli* and E. Oz (USC)

Plasma Wakes – Theory



- Unlike electromagnetic waves in vacuum, plasma wakes can have a longitudinal electric field
- *Tajima & Dawson, PRL, 43, 267(1979)*
- Linear plasma wake:

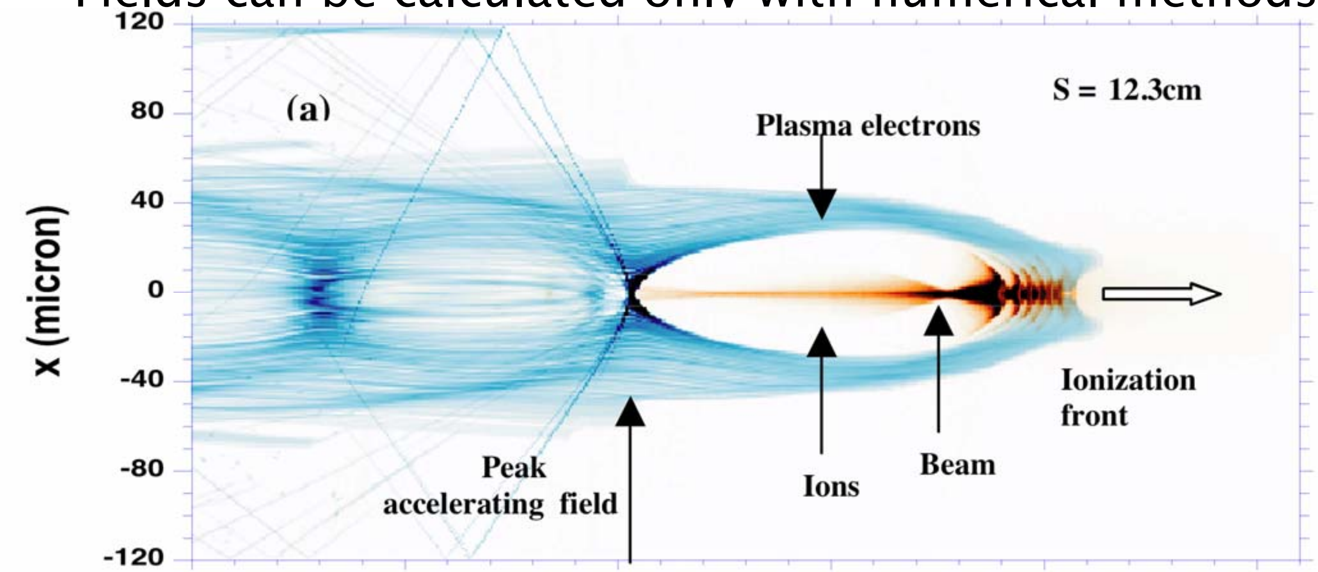
$$\lambda_p \approx \sqrt{\frac{10^{15}\mathrm{cm}^{-3}}{n_p}} \quad \mathrm{mm}$$

  - Limit:

$$E_0 = \frac{4\pi\,\varepsilon_0\,c\,m_e}{e}\omega_p \quad \approx \sqrt{\frac{n_p}{\mathrm{cm}^{-3}}} \quad \frac{\mathrm{V}}{\mathrm{cm}}$$

Plasma Wakes - Theory

- Above this limit: non-linear wakes, “Blow-out regime”
- Fields can be calculated only with numerical methods

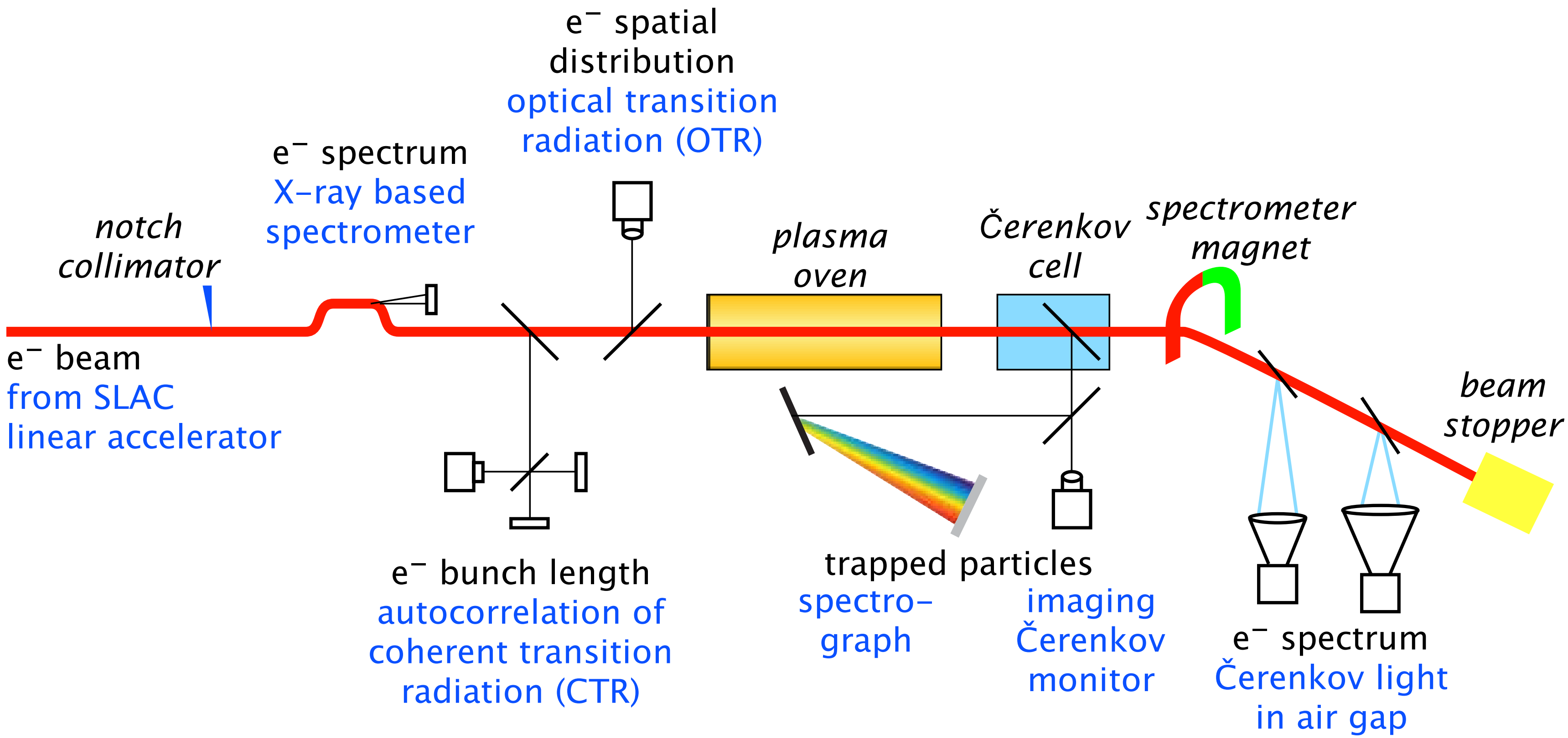


- Typical wavelength: 50 μm
- Accelerating fields up to 50 GV/m

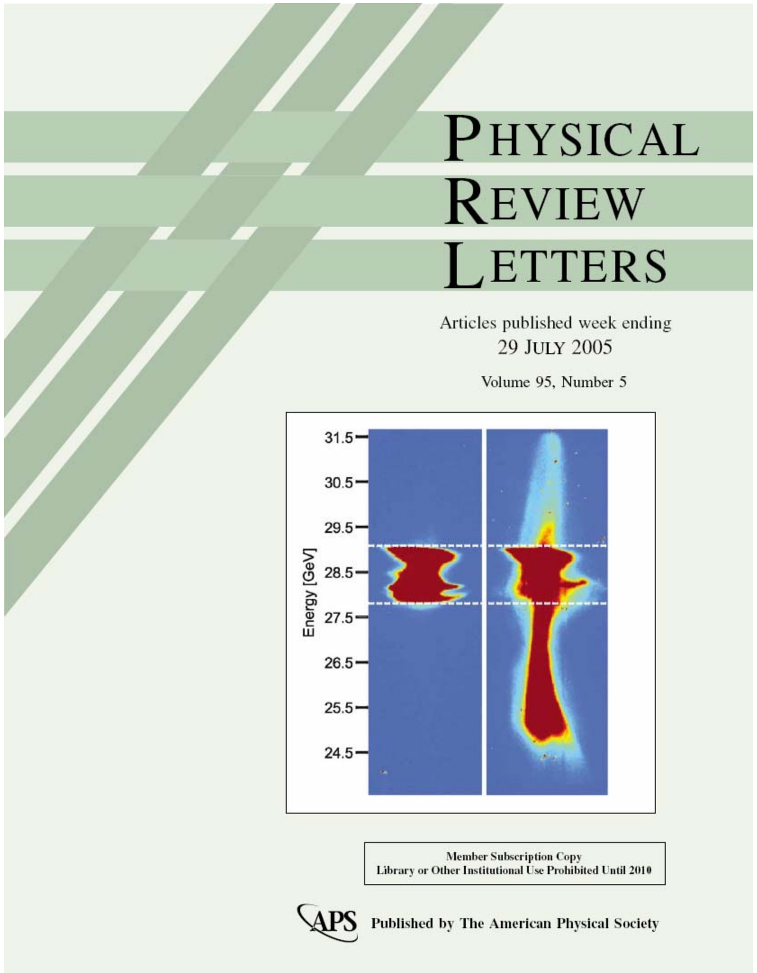
Drive the Plasma Wake

- Typical drive beam power: $\sim 10^{15}$ W = 1 TW
- Power density: $\sim 10^{24}$ W/m^2 =1 YW/m^2
- Drive the plasma wake:
  - Photons
  - Electrons

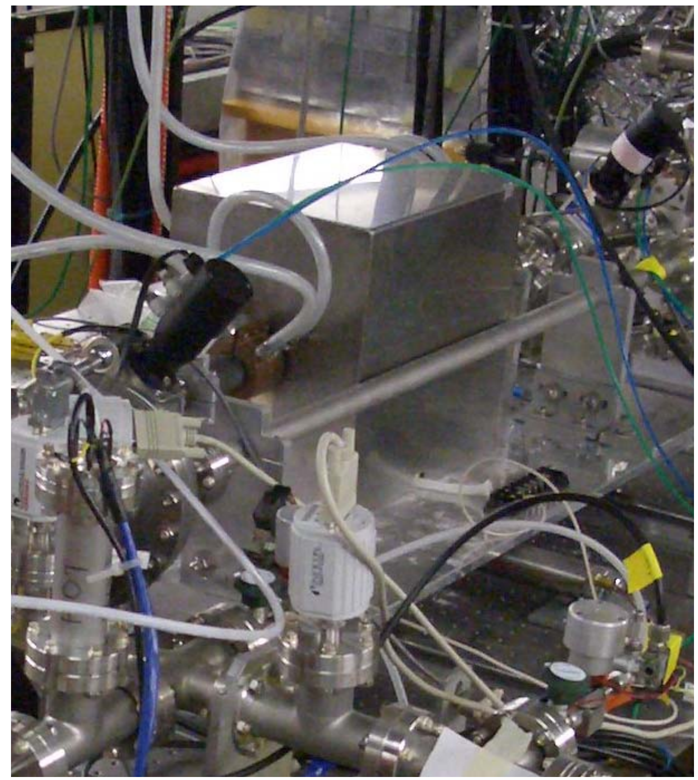
Plasma Wakefield Acceleration at SLAC Experimental Setup



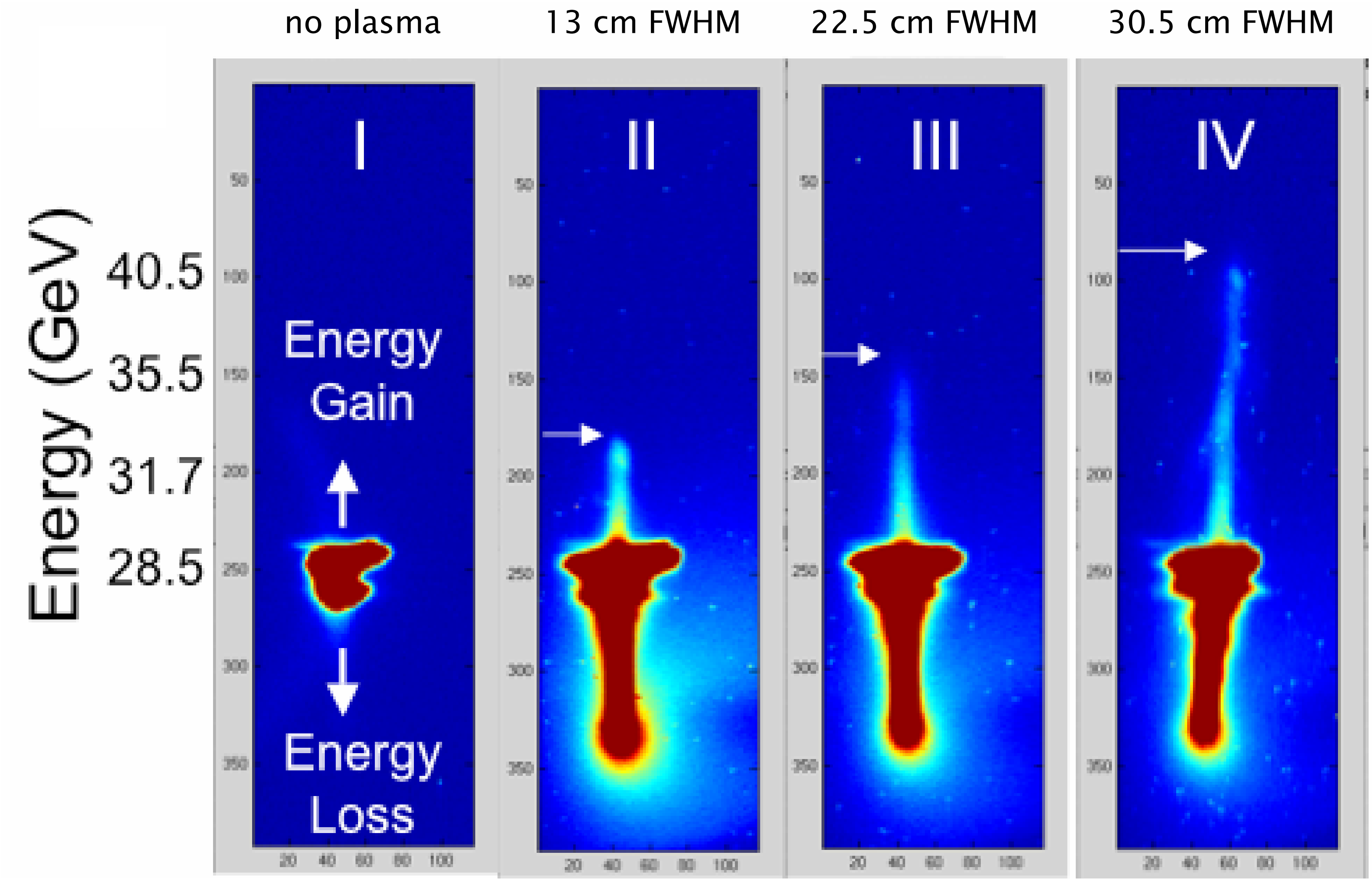
Previous Results



More than 3 GeV energy gain
in 10 cm plasma length

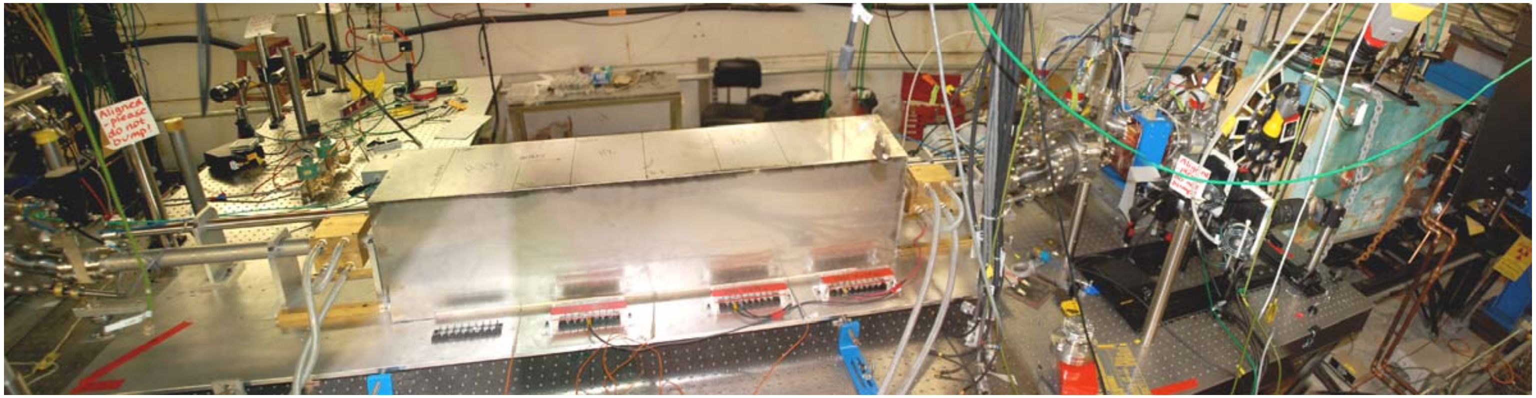


Increasing the Plasma Length to 30.5 cm

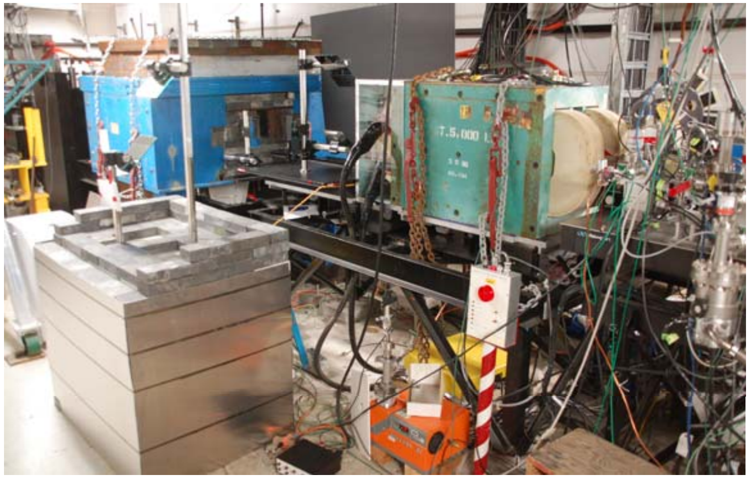


Patric Muggli

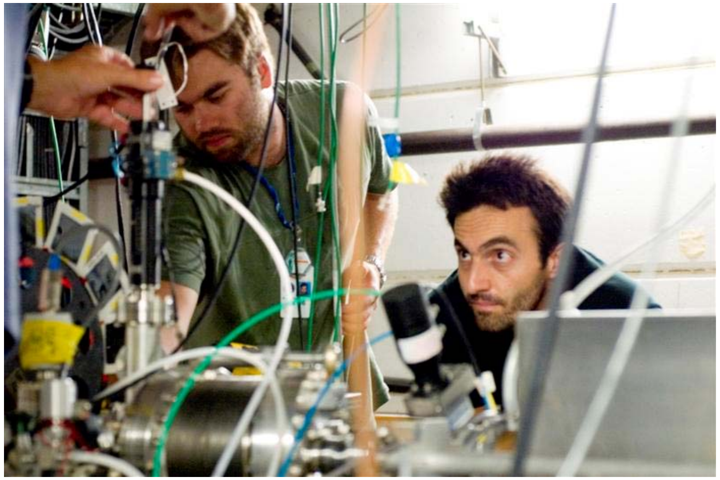
Changes to the Experimental Setup



Longer plasma oven



New spectrometer

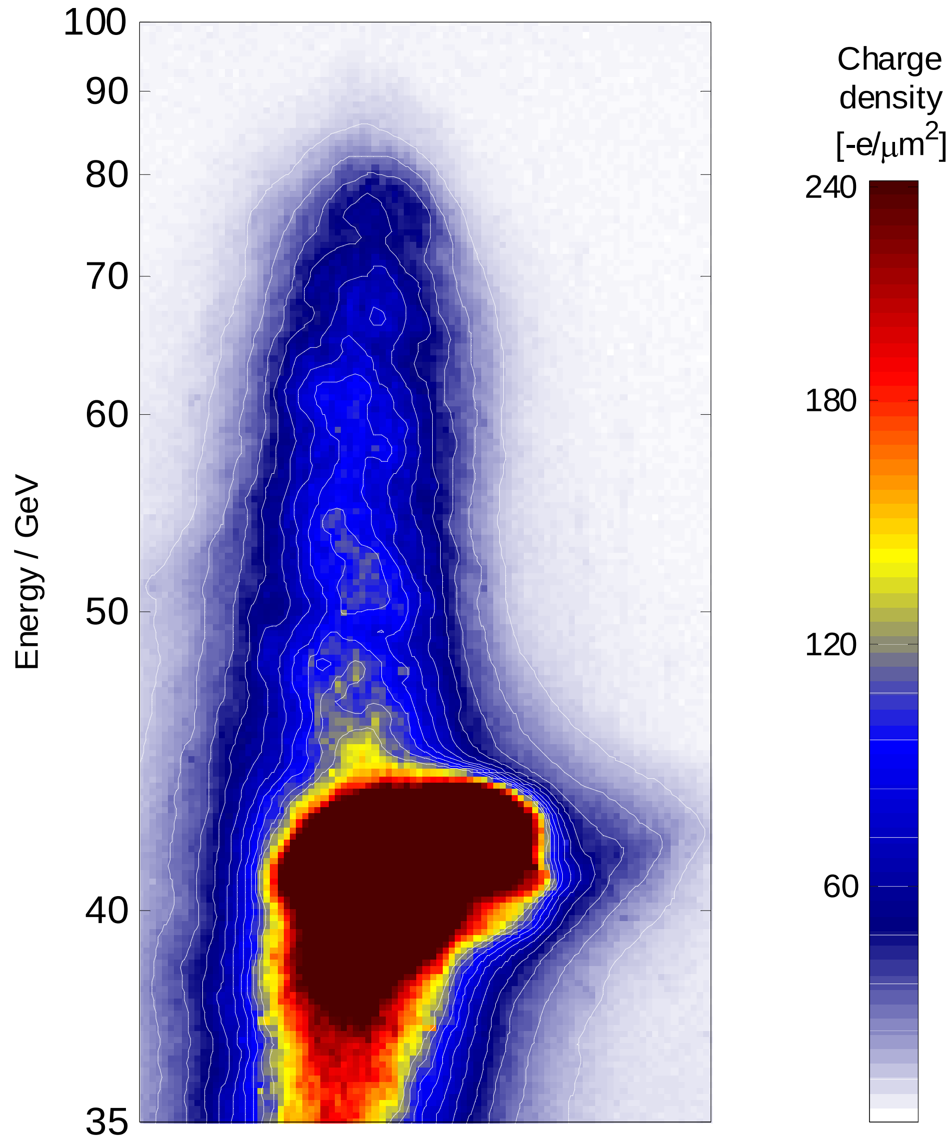


Diagnostics for low-energy particles

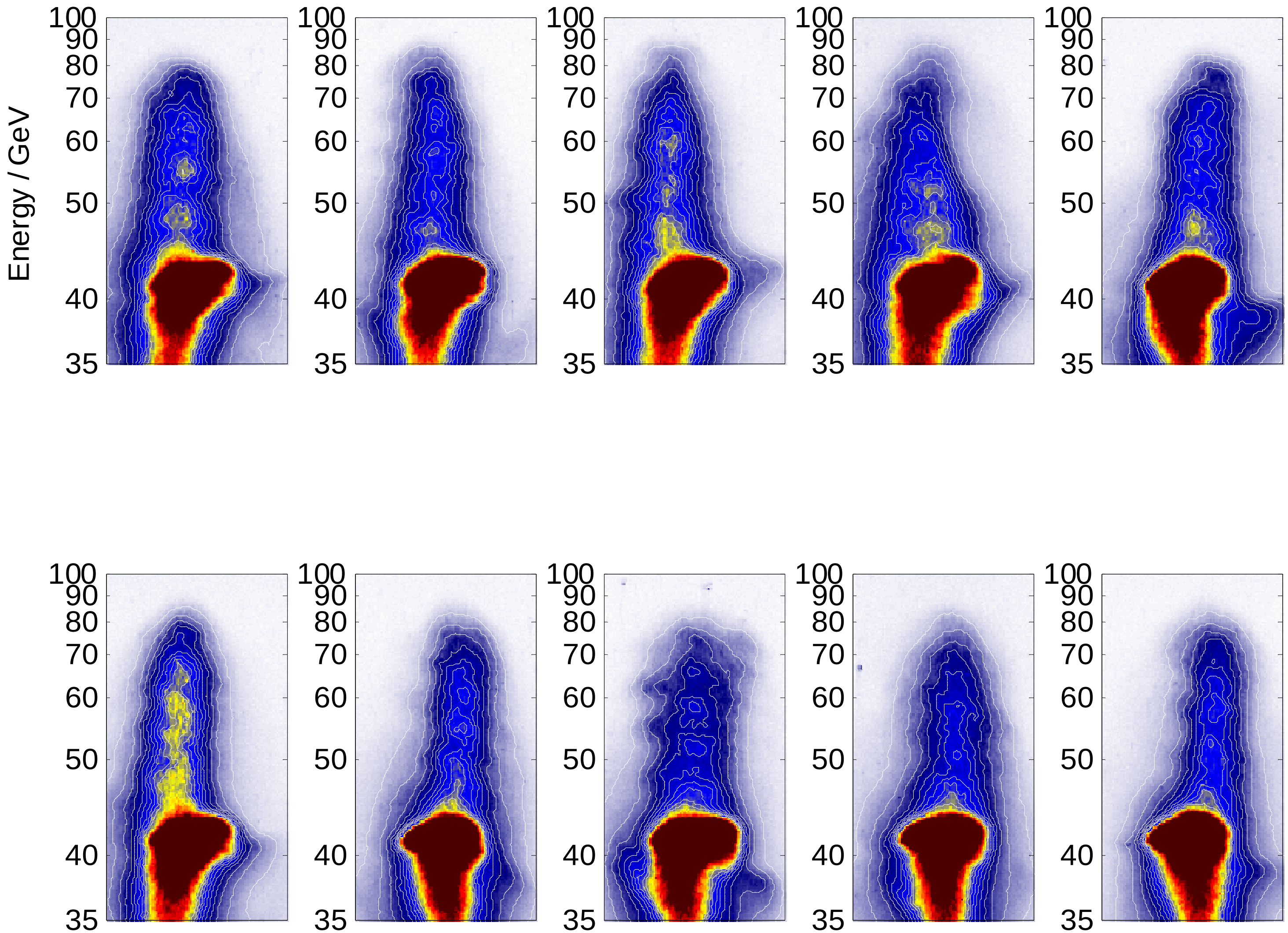
Increased the energy in the drive beam

Energy Doubling

- Plasma length: 85 cm
- Density: $2.7 \cdot 10^{23}\ m^{-3}$
- Incoming energy: 42 GeV
- Peak energy: 85 ± 7 GeV



Stability

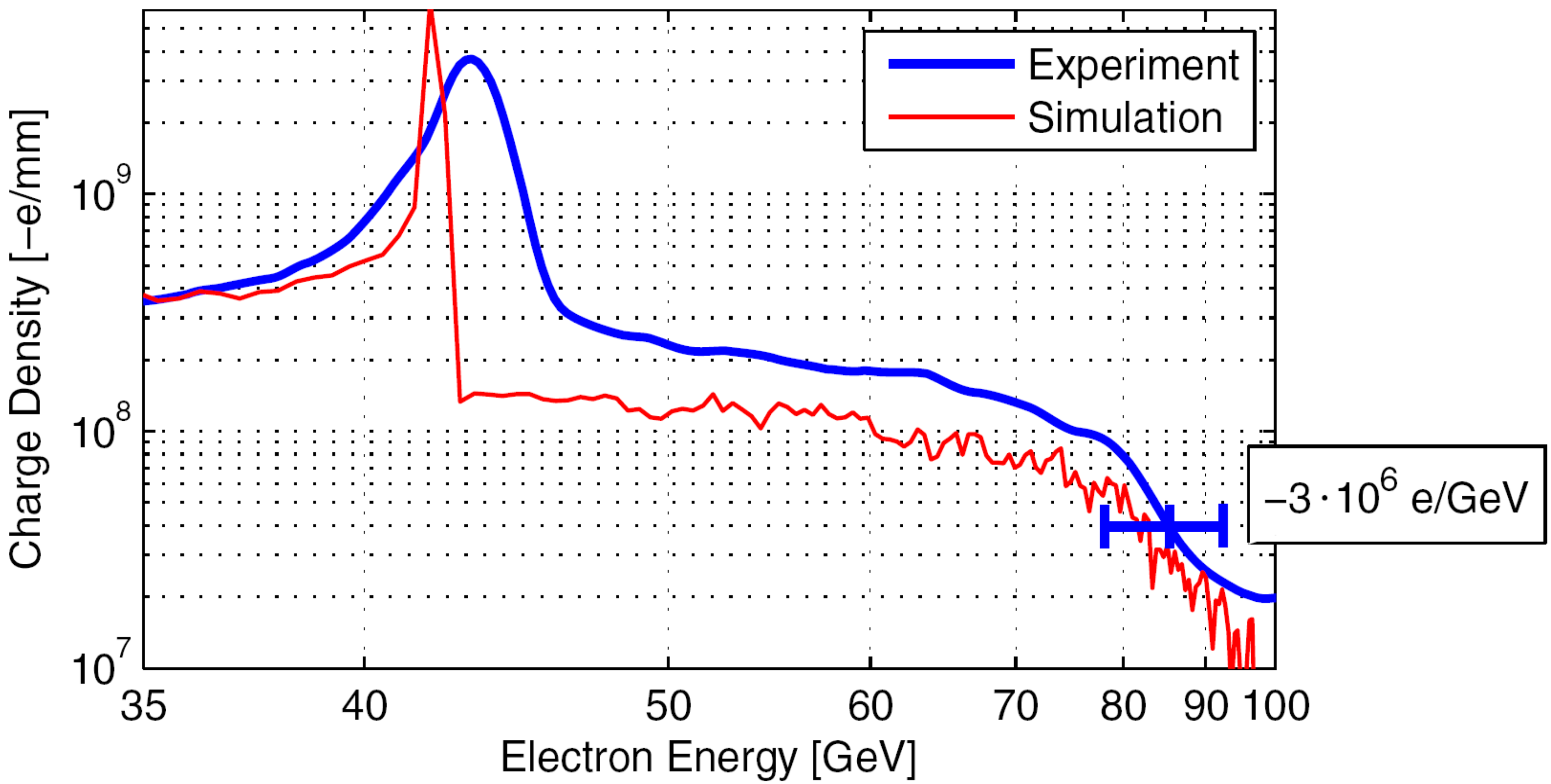


Simulations

- Particle-In-Cell codes:
  - full PIC code: approximately 132,000 CPU hours for 85 cm plasma
  - QuickPIC: quasi-static approximation, 2760 CPU hours

- Simulation of
  - ⇒ field ionization
  - ⇒ motion of beam and plasma electrons
  - ⇒ wake formation
  - ⇒ acceleration
  - ⇒ energy spectrum

Comparison to Simulations



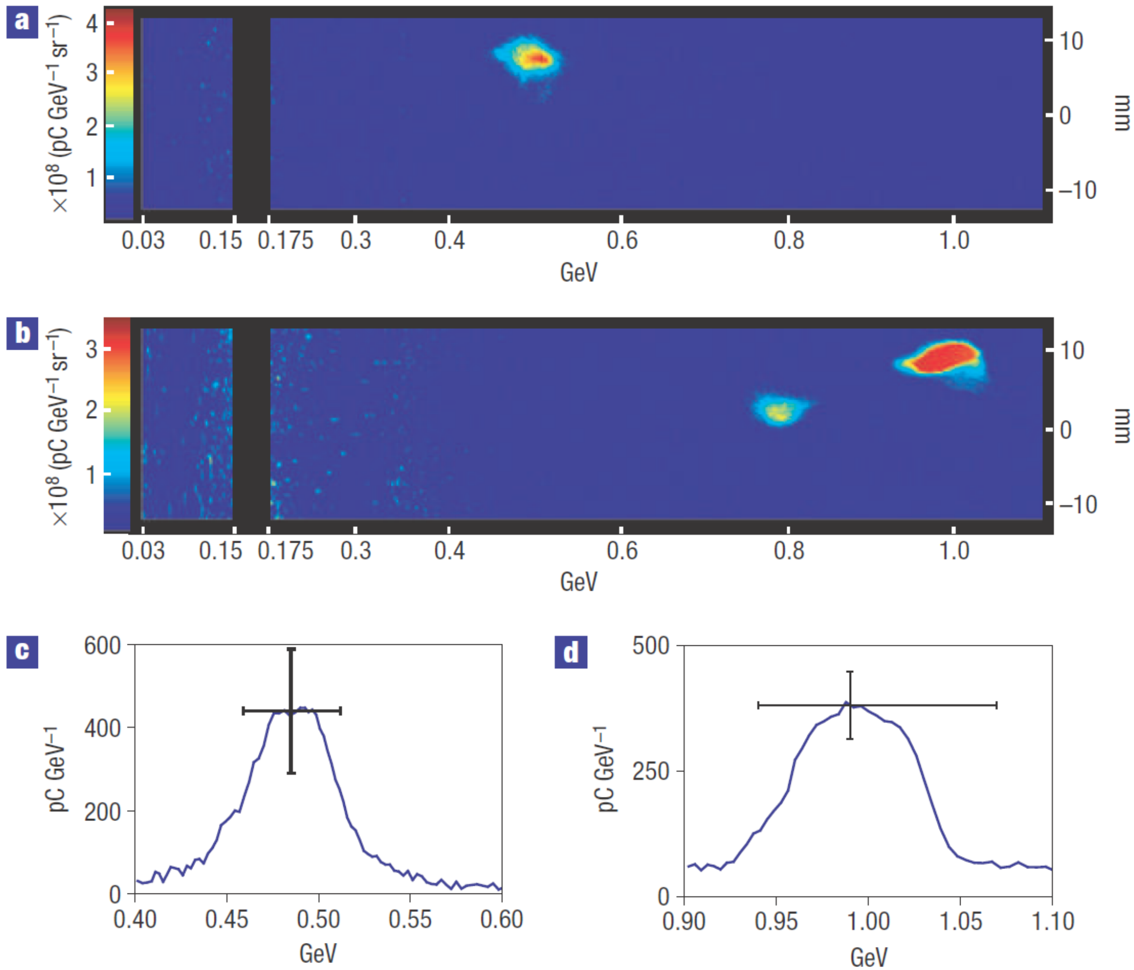
There is still Work to Do…

- Understand (and exploit) self-injection

- Scaling to higher energies
    - Hose instability effect
    - Ion motion

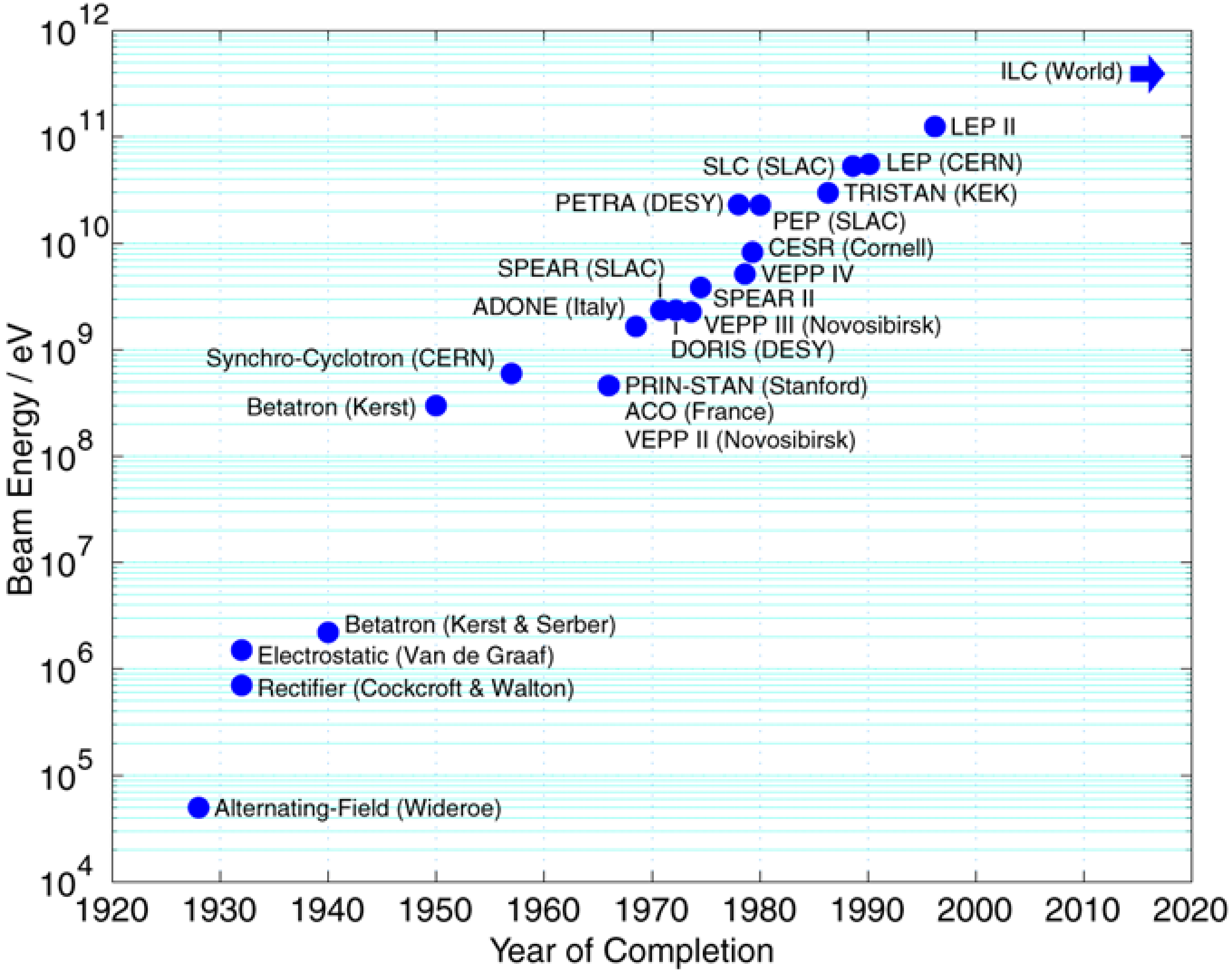
- Acceleration of positrons

Self-Injected Particles Laser-Driven Plasma Wake

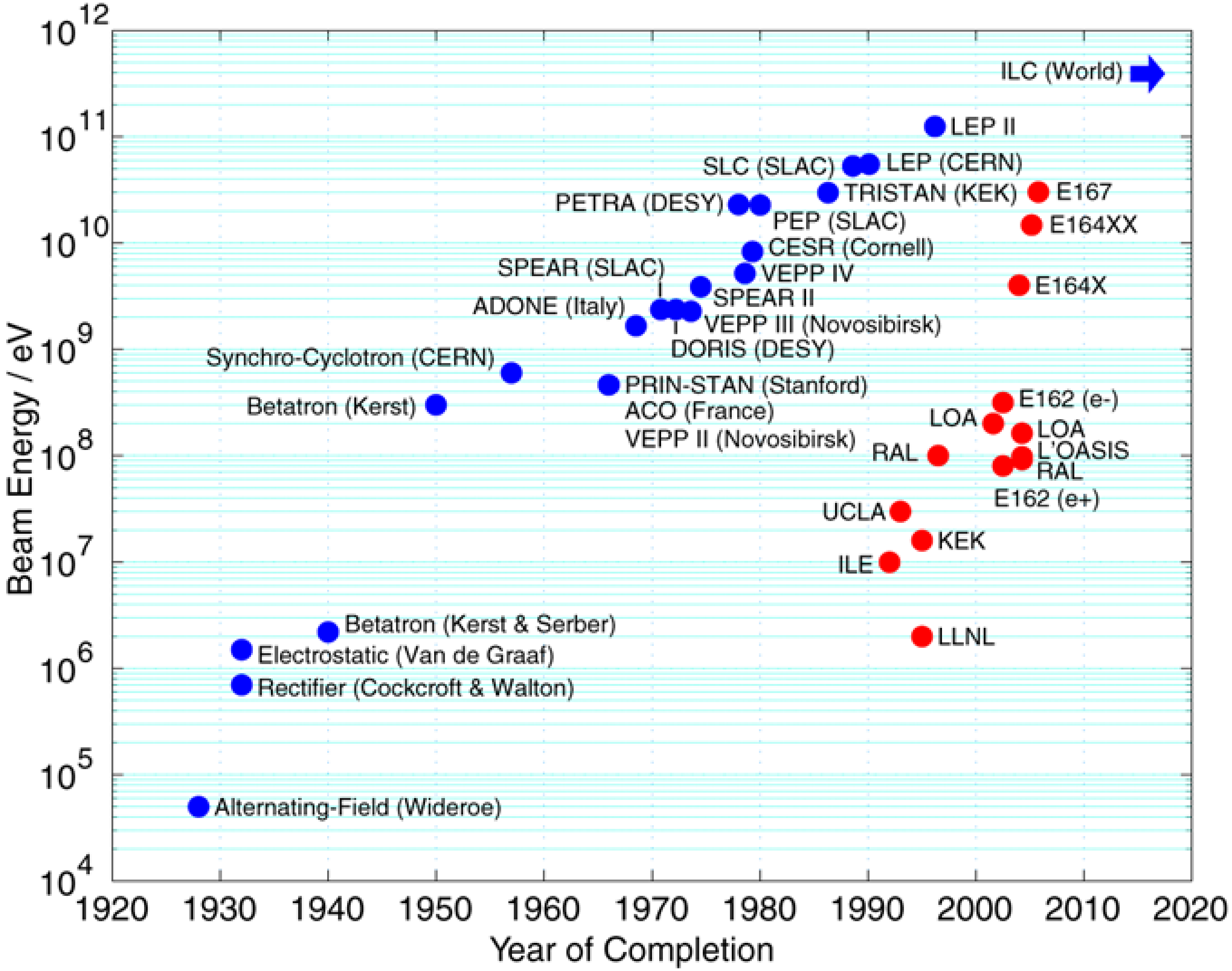


W. P. Leemans

Livingston Plot

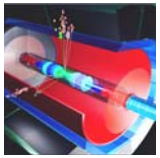


An Unfair Comparison



Accelerators Beyond LHC and ILC

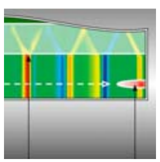
Rasmus Ischebeck, Stanford Linear Accelerator Center



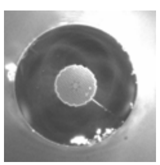
Accelerators for TeV-Energy electrons

Present Technologies

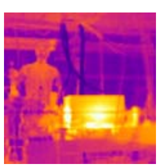
Advanced Accelerator Research at SLAC



Electron beam driven Dielectric Structures



Laser-driven Dielectric Structures



Plasma Wakefield Accelerators

Accelerator research is more than just engineering

STANFORD LINEAR ACCELERATOR CENTER

There is More to Accelerating Structures than the Accelerating Field

- Power sources
- Beam loading
- Emittance preservation
    - Non-linear transverse forces
    - Wakefields

There is Much More to an Accelerator than Accelerating Structures

- Particle sources (injectors)
- Bend magnets for storage rings
- Focusing, beam dynamics
- Detectors

Thank You!

- The E-167 Collaboration
    - M. Berry, I. Blumenfeld, F.-J. Decker, P. Emma, M.J. Hogan*, R. Ischebeck, R.H. Iverson, N. Kirby, P. Krejcik, R.H. Siemann, and D. Walz (SLAC)
    - C.E. Clayton, C. Huang, D. Johnson, C. Joshi*, W. Lu, K.A. Marsh, W.B. Mori, and M. Zhou (UCLA)
    - S. Deng, T. Katsouleas, P. Muggli* and E. Oz (USC)

- The E-163 Collaboration
    - R. Siemann, R. Noble, E. Colby, J. Spencer, R. Ischebeck, M. Lincoln, B. Cowan, C. Sears, S. Tantawi, D. Walz, D.T. Palmer, N. Na, C.D. Barnes, M. Javanmarad, X.E. Lin, and Z. Zhang (SLAC)
    - R. Byer, T.I. Smith, Y.C. Huang, T. Plettner, P. Lu, and J.A. Wisdom (Stanford)
    - L. Schächter (Techion Israeli Institute of Technology)
    - J. Rosenzweig (UCLA)

- The GigaWake Dielectric Accelerator Experiment
    - M.C. Thompson, H. Badakov, J. Rosenzweig, and G. Travish (UCLA)
    - M.J. Hogan, R. Ischebeck, N. Kirby, R. Siemann, and D. Walz (SLAC)
    - P. Muggli (USC)
    - A. Scott (UCSB)
    - R. Yoder (Manhattan College)

- Special thanks to
    - H. Weise, F. Tecker, D. Sutter, N. Kirby, E. Oz

- Work supported by Department of Energy contracts DE-AC02-76SF00515 (SLAC), DE-FG03-92ER40745, DE-FG03-98DP00211, DE-FG03-92ER40727, DE-AC-0376SF0098, DE-AC02-76SF00515 and National Science Foundation grants No. ECS-9632735, DMS-9722121 and PHY-0078715.