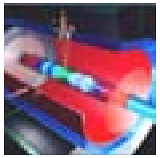
Advanced Accelerator Research

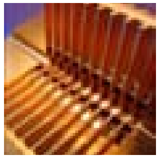
Rasmus Ischebeck, Stanford Linear Accelerator Center



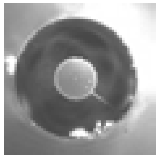
Accelerators for TeV-Energy electrons

Present Technologies

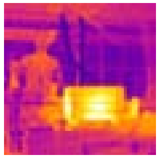
Advanced Accelerator Research



Metallic Cavities at Higher Frequencies



Dielectric Structures



Plasma-based Accelerators

Advanced Accelerator Research

explores new acceleration principles

- Extending RF to higher frequencies
- Dielectrics at optical* frequencies
- Plasma Wakefield Acceleration

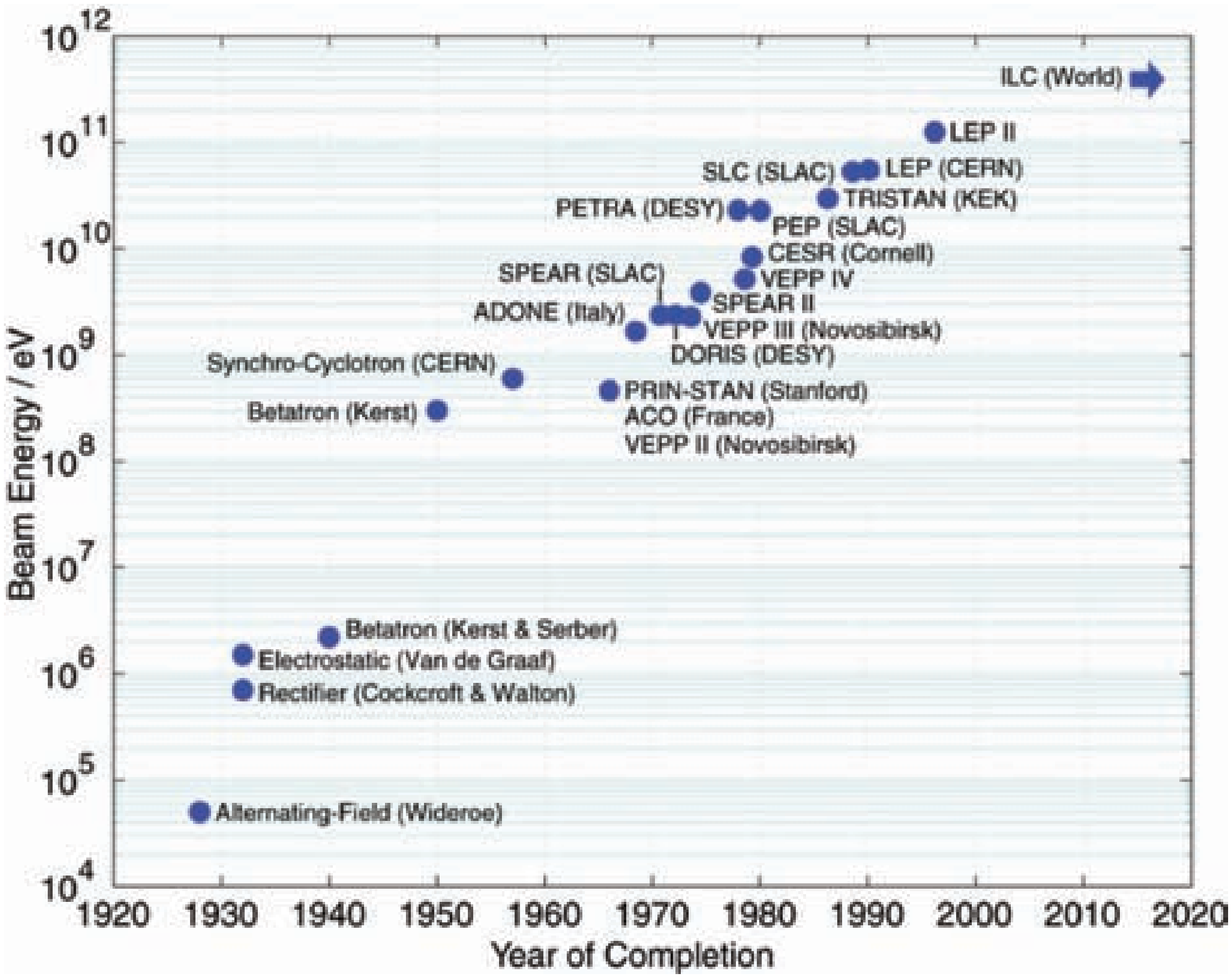
Accelerator Technology

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 $\mathfrak{L} \gtrsim 10^{36}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ $\mathfrak{L} = \dfrac{N^2 f}{4\pi\, \sigma_x \sigma_y}$

⇒ 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

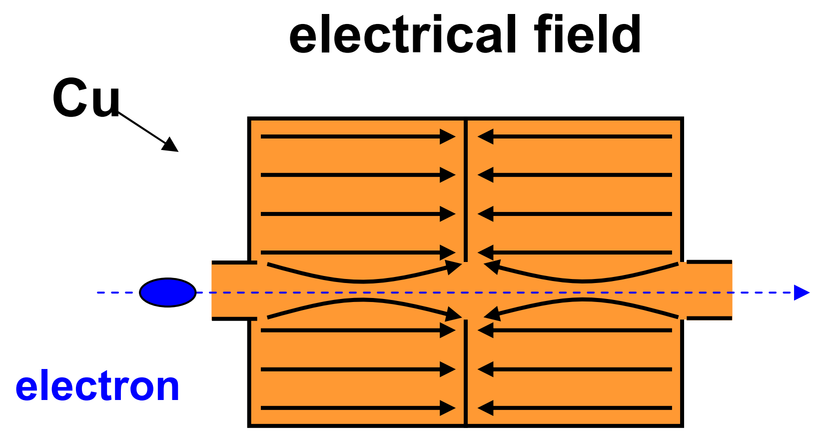
Luminosity

- Cross section for e^+e^- collisions goes as $1/E^2$
  - $\Rightarrow$ Need a luminosity of $\mathfrak{L} \gtrsim 10^{36}$ 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)

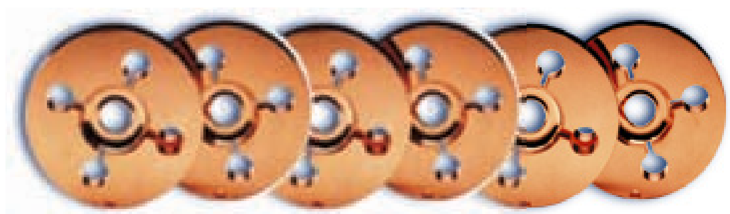
adapted from G. Dugan

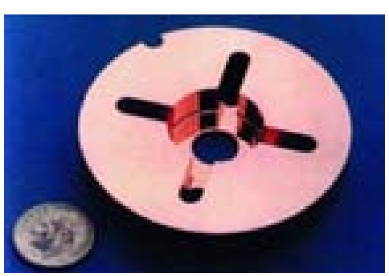
RF Acceleration

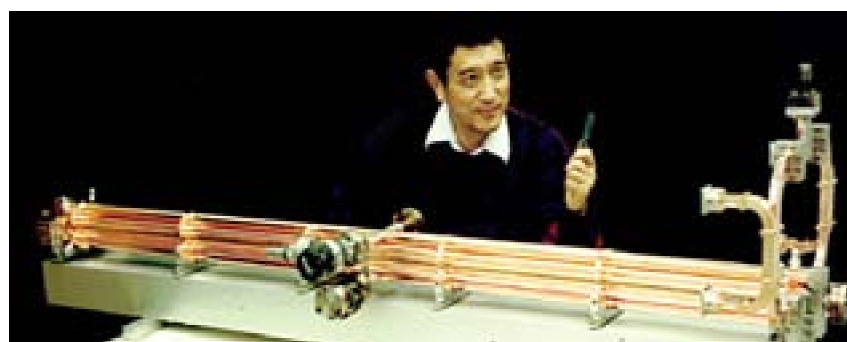
- Using a resonant cavity at radio frequencies (RF) (~GHz)
- Electromagnetic field provided by external source (e.g. klystron)



Resonating RF Cavity





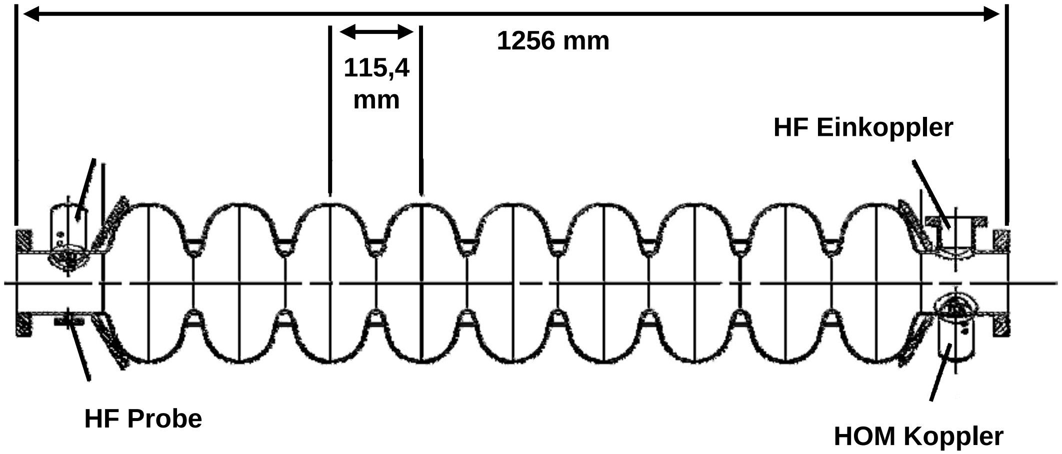


Travelling Wave Structure

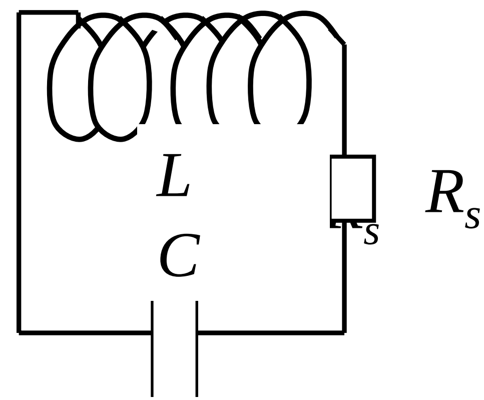
11.4 GHz $2\pi/3$ Mode $E_{acc} \geq 50$ MV/m

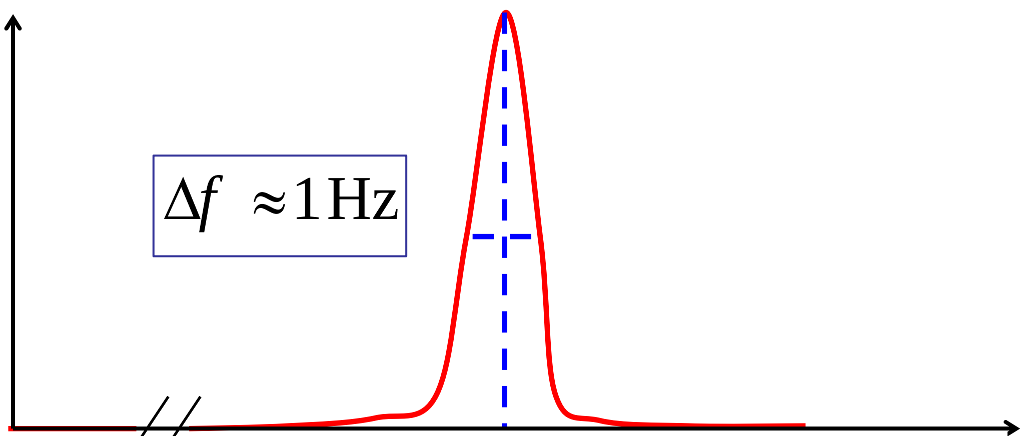
adapted from H. Weise

Superconducting RF



Resonant Circuit:





$$\Delta f \approx 1\,\mathrm{Hz}$$

$$f_o = 1.300.000.000\ \mathrm{Hz}$$

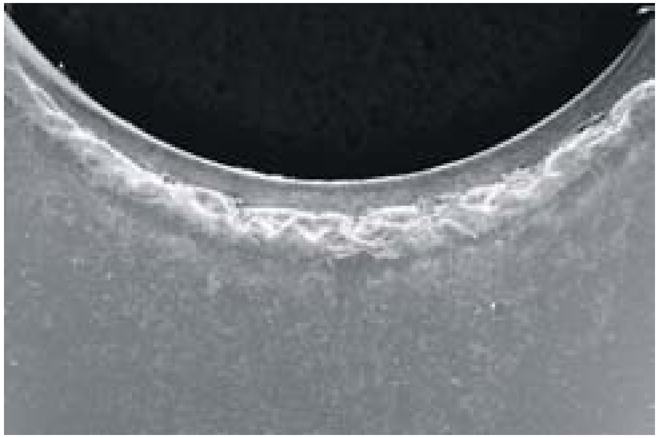
Frequency: $$f_o = \frac{1}{2\pi\sqrt{LC}}$$

Quality factor: $$Q_o = \frac{f}{\Delta f} = \frac{G}{R_s}$$

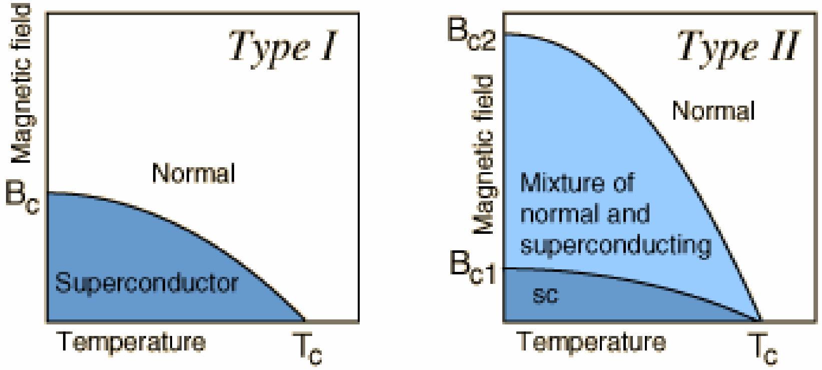
$$\Rightarrow \mathbf{Q_0 \approx 10^{9} - 10^{10}}$$

Limits to the Accelerating Field

- Normal-conducting accelerators
  - Breakdown on the surface



- Superconducting accelerators
  - Critical magnetic field



http://hyperphysics.phy-astr.gsu.edu/hbase/solids/scbc.html

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 by a factor 10 (without increasing the cost by the same factor)
- Explore alternative acceleration techniques

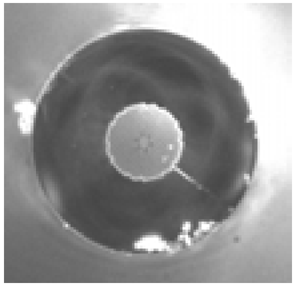
Advanced Accelerator Research

- Extending RF to higher frequencies
- Dielectrics at optical* frequencies
- Plasma Wakefield Acceleration
- Direct laser acceleration (inverse transition radiation)
- Inverse free electron lasers
- Laser-plasma acceleration of protons
- Particle acceleration by stimulated emission of radiation
- Muon collider

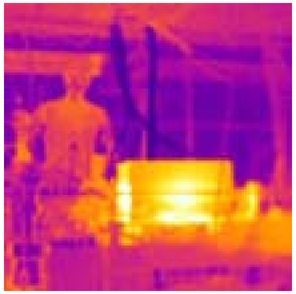
*actually infrared

Advanced Acceleration Schemes

Extending RF to Higher Frequencies



Dielectrics at Optical Frequencies



Plasma Wakefield Acceleration

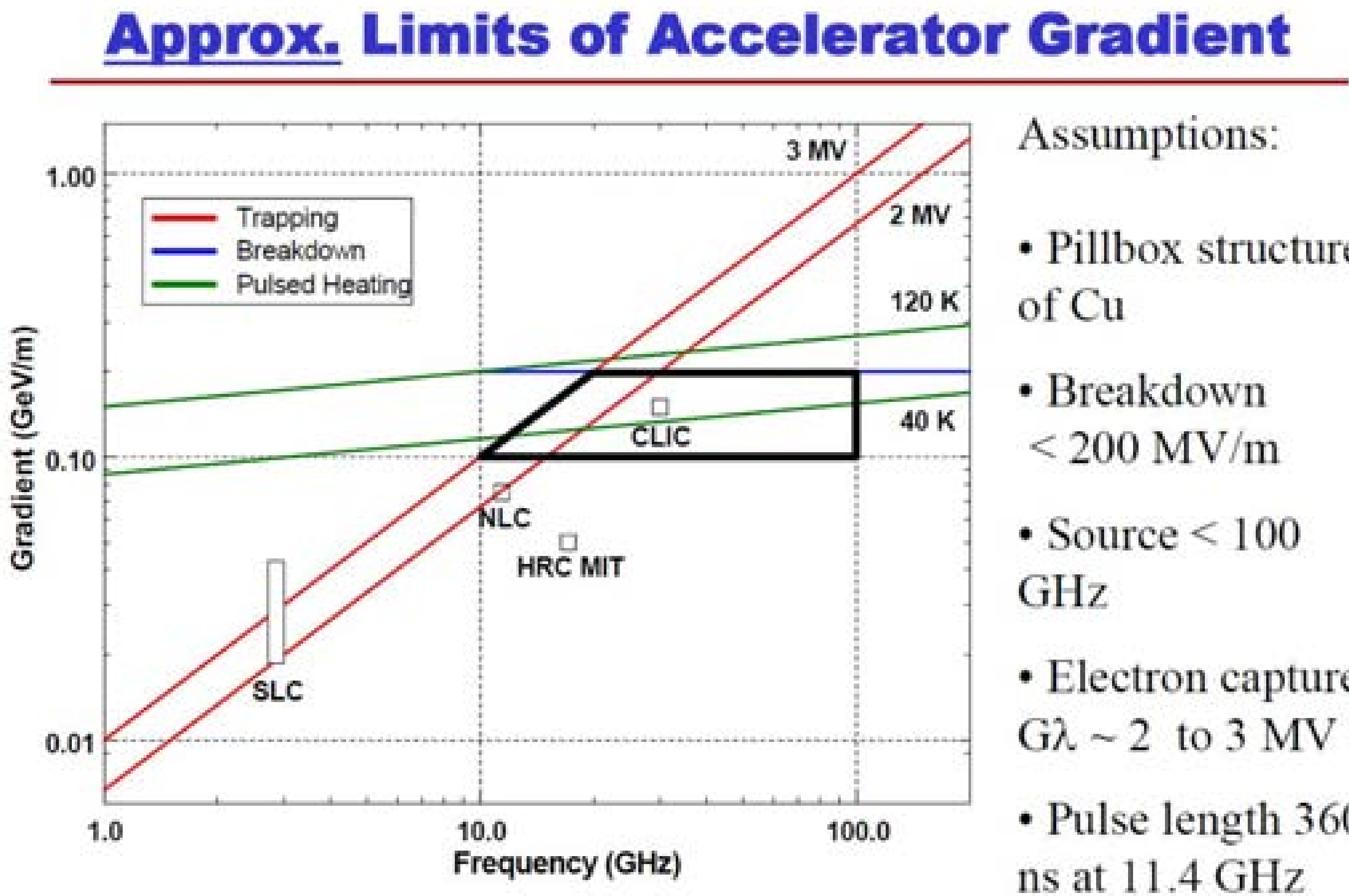
Advanced Acceleration Schemes

Extending RF to Higher Frequencies

Dielectrics at Optical Frequencies

Plasma Wakefield Acceleration

Frequency Dependence of Fields



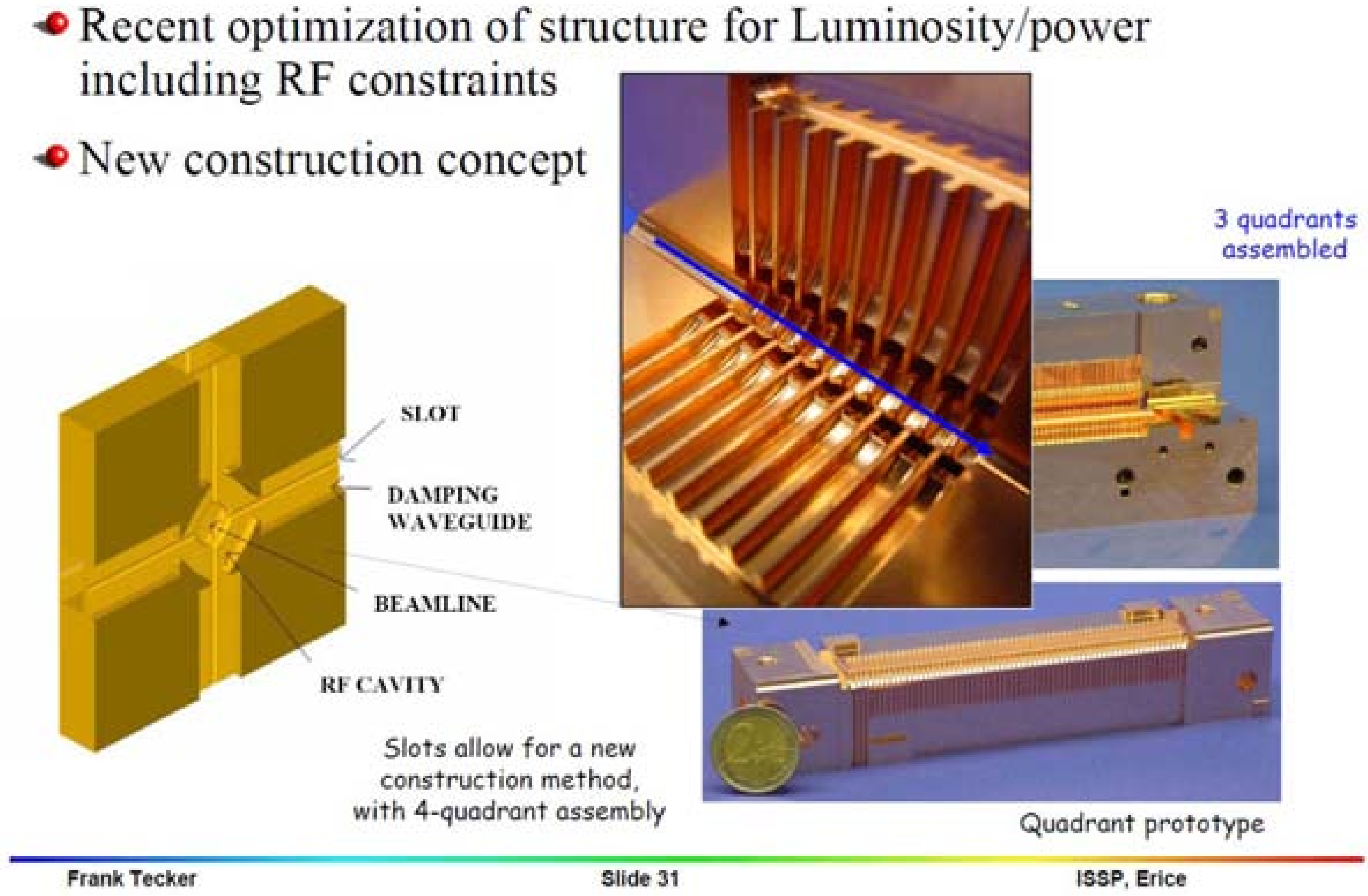
Assumptions:

- Pillbox structure of Cu
- Breakdown < 200 MV/m
- Source < 100 GHz
- Electron capture $G\lambda \sim 2$ to 3 MV ?
- Pulse length 360 ns at 11.4 GHz

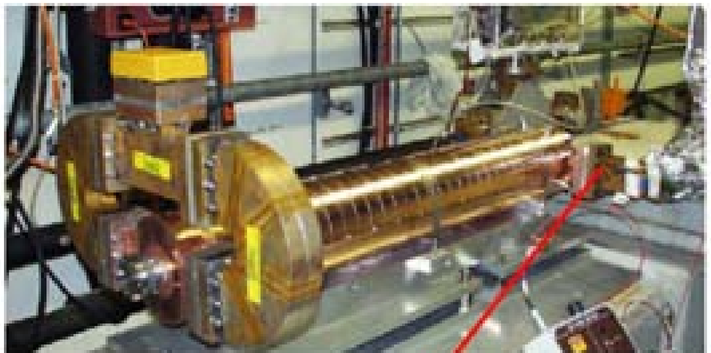
Limits are approximate!

R. Temkin

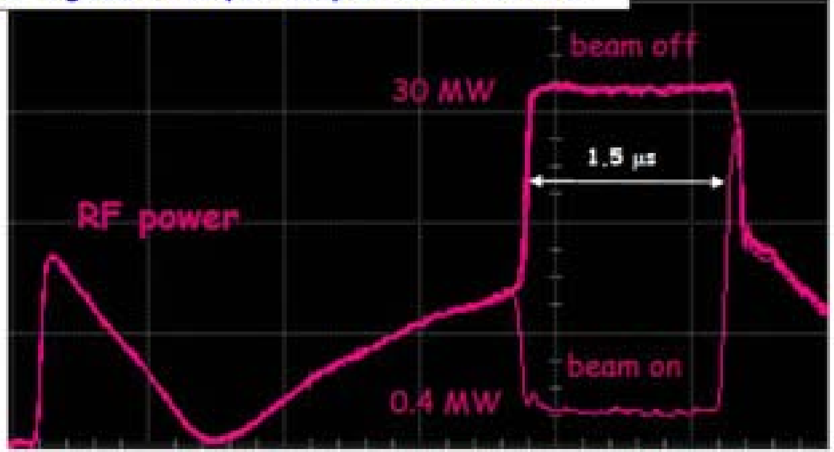
Extending RF to Higher Frequencies



Extending RF to Higher Frequencies



RF signals / output coupler of structure

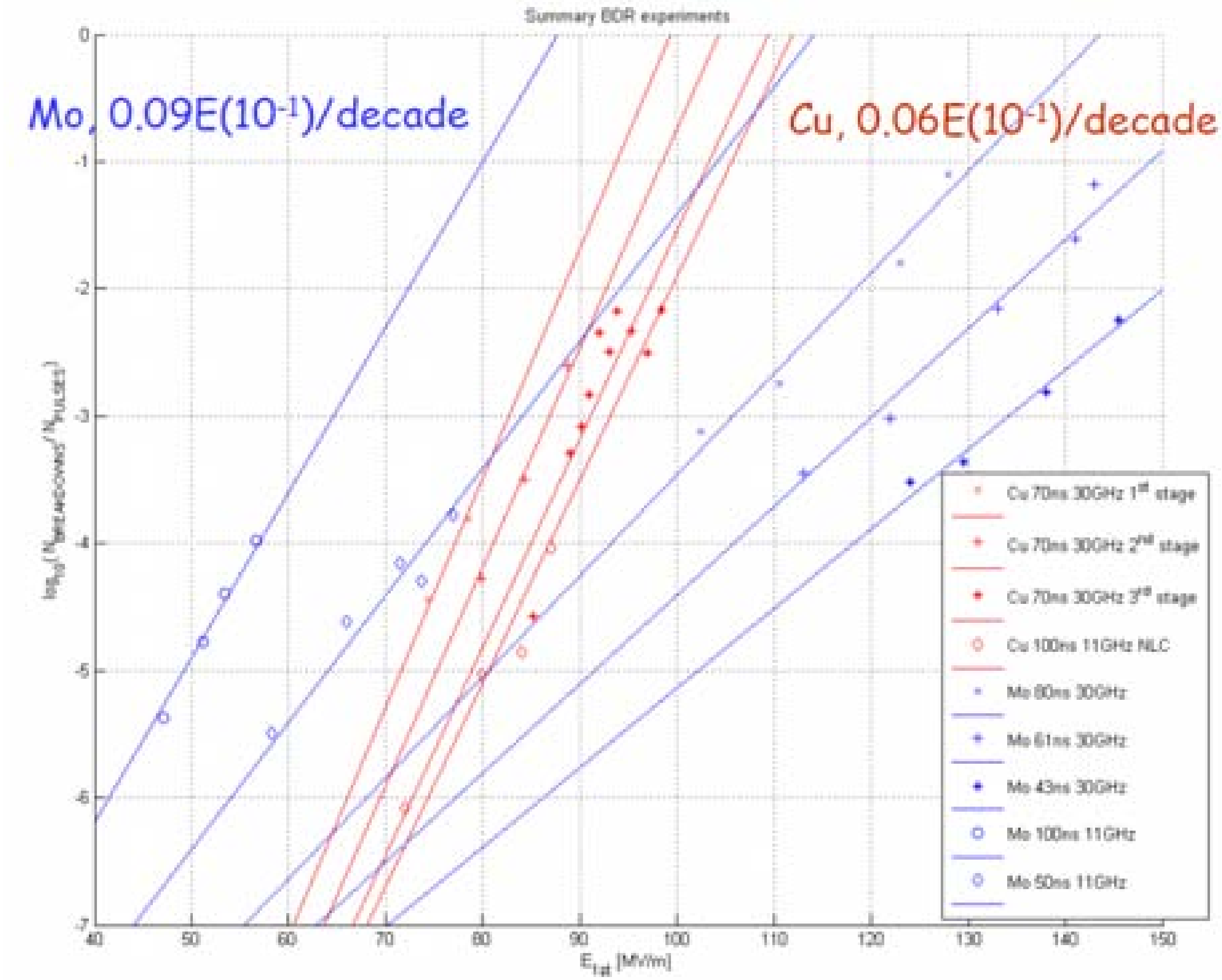


Dipole modes suppressed by slotted iris damping (first dipole's Q factor < 20) and HOM frequency detuning

Beam current	4 A
Beam pulse length	1.5 µs
Power input/structure	35 MW
Ohmic losses (beam on)	1.6 MW
RF power to load (beam on)	0.4 MW
RF-to-beam efficiency	~ 94%

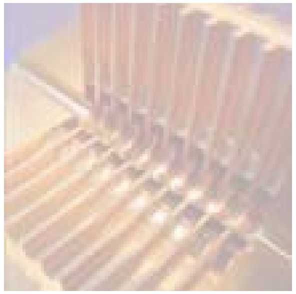
Frank Tecker   Slide 35   ISSP, Erice

Material Dependence of Breakdown Probability

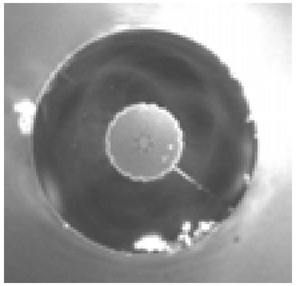


W. Wuensch

Advanced Acceleration Schemes



Extending RF to Higher Frequencies



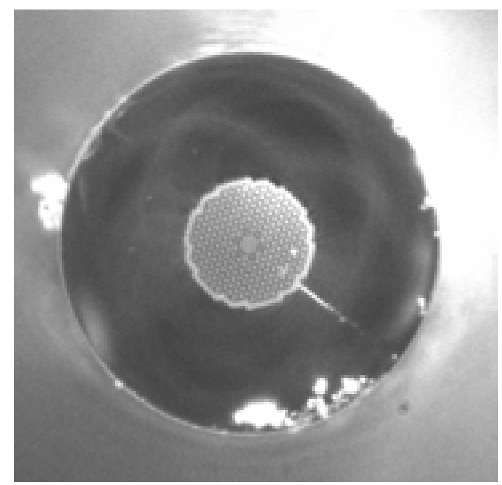
Dielectrics at Optical Frequencies

Plasma Wakefield Acceleration

Dielectric Accelerator Structures

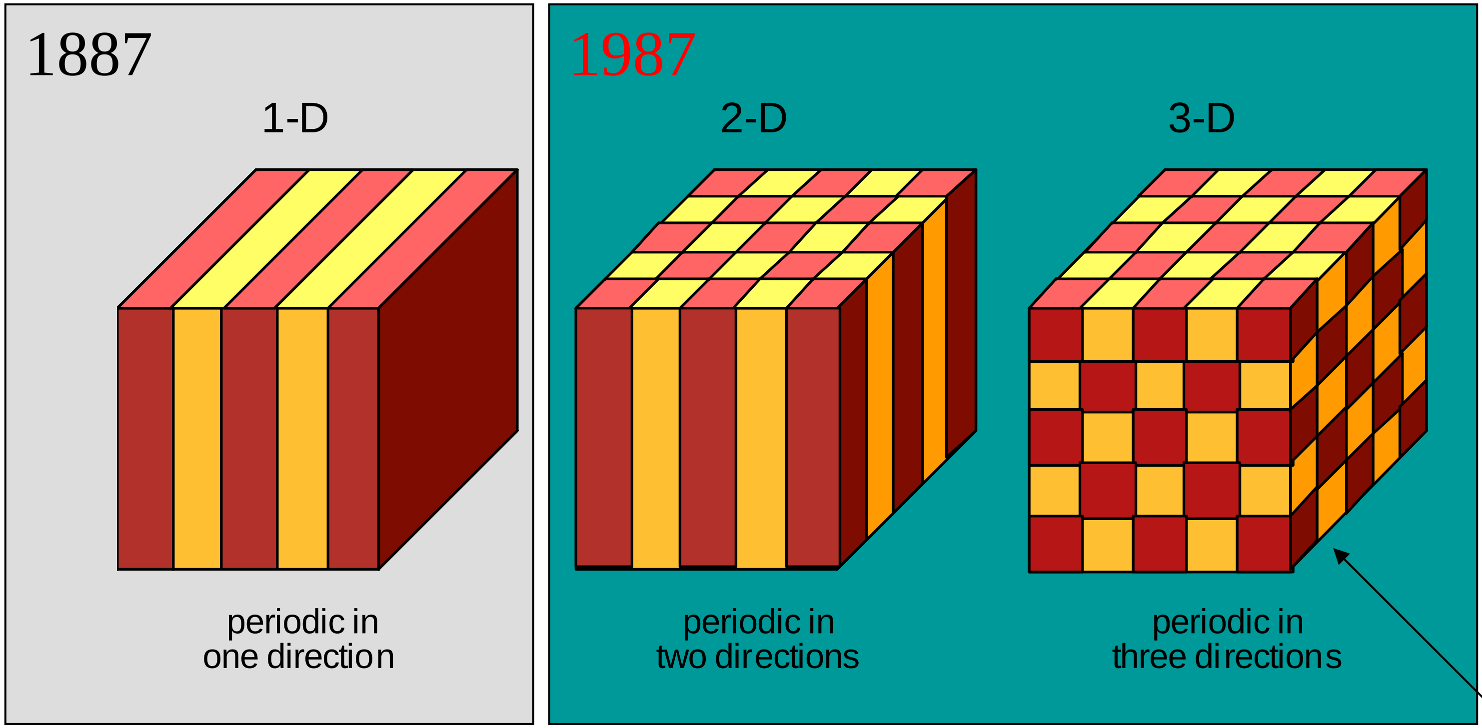
- Using much higher frequencies: THz to optical
- Using dielectrics (e.g. SiO_2)
- Advantages: higher damage threshold

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



Photonic Crystals

periodic electromagnetic media



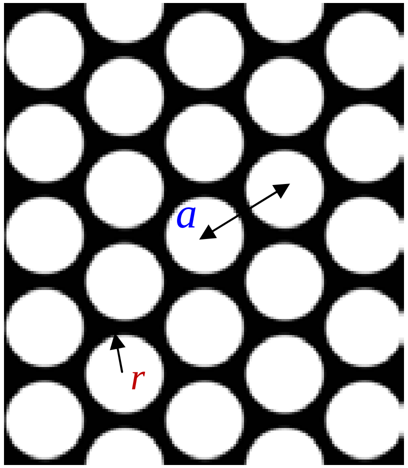
(need a more complex topology)

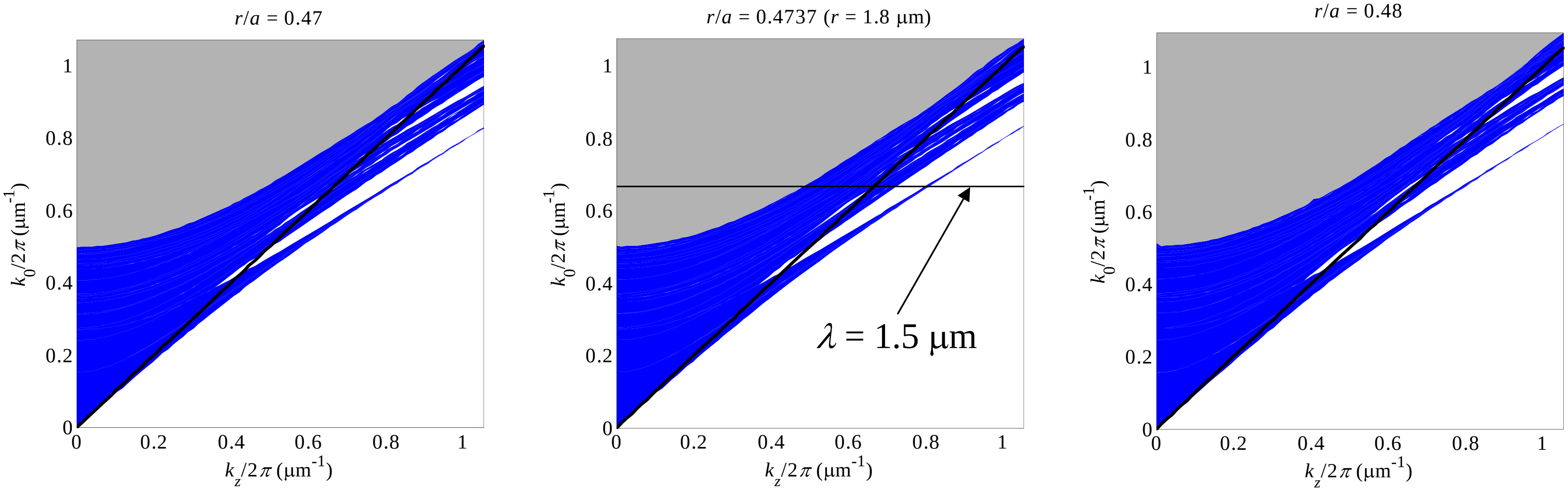
with photonic band gaps: "optical insulators"

Band Gap maps

- Solutions of the wave equation

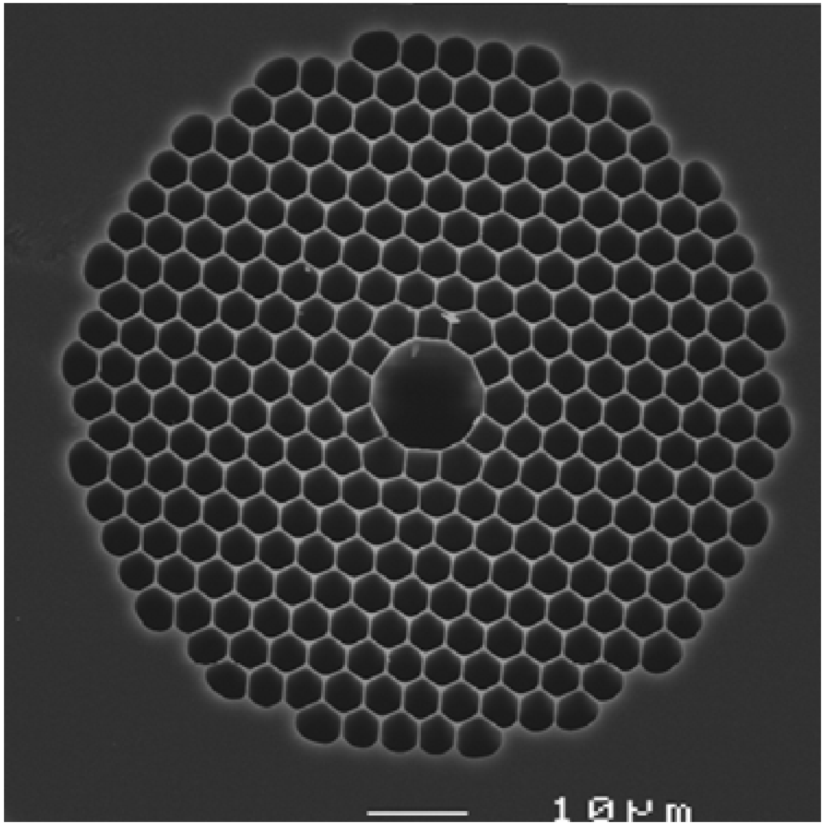
$$\vec{\nabla} \times \frac{1}{\varepsilon\varepsilon_0} \times \vec{H} = \left(\frac{\omega}{c}\right)^2 \vec{H}$$

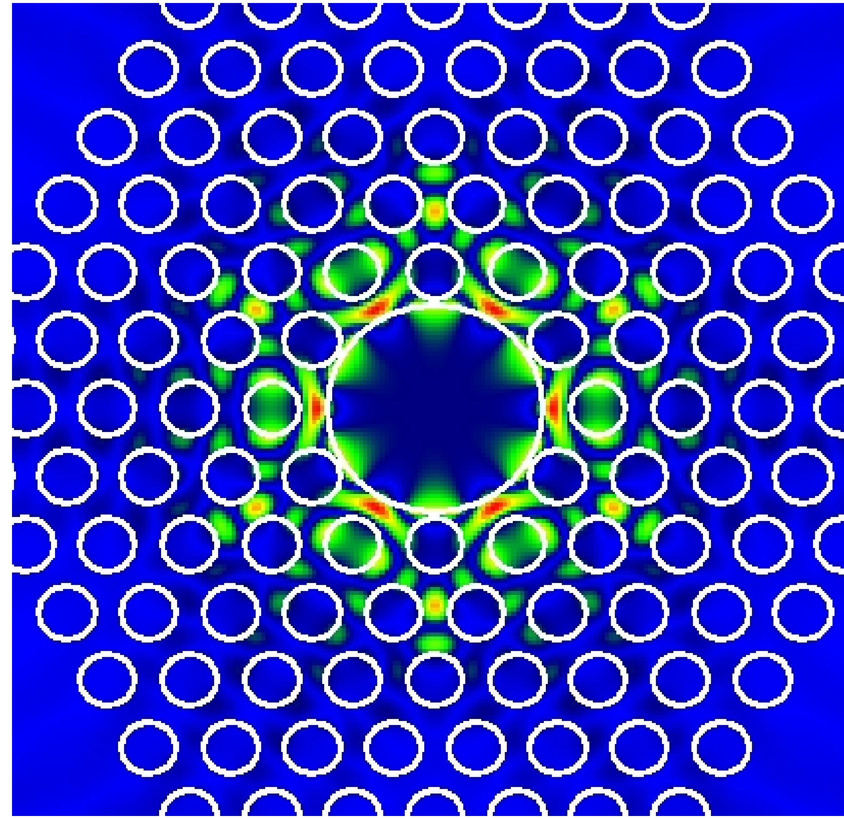




Ben Cowan

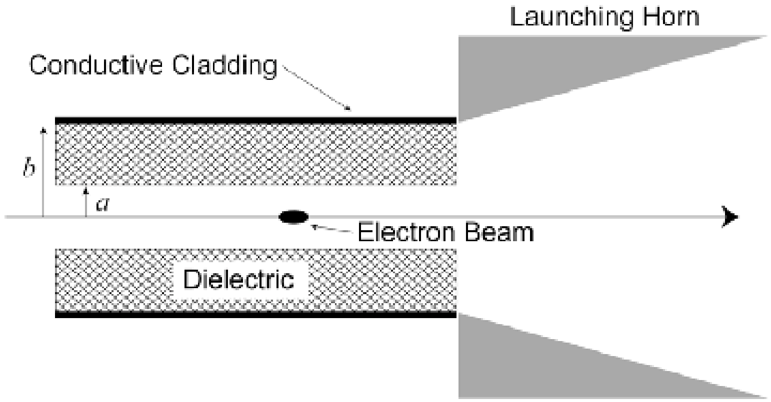
Photonic Band Gap Structures



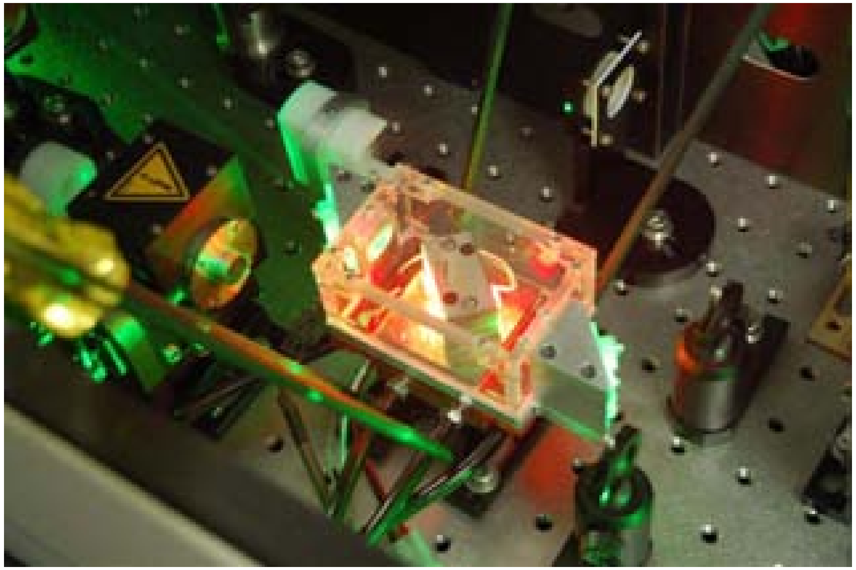


Generation of the Accelerating Field

- Coherent Cherenkov radiation from a high-current electron beam

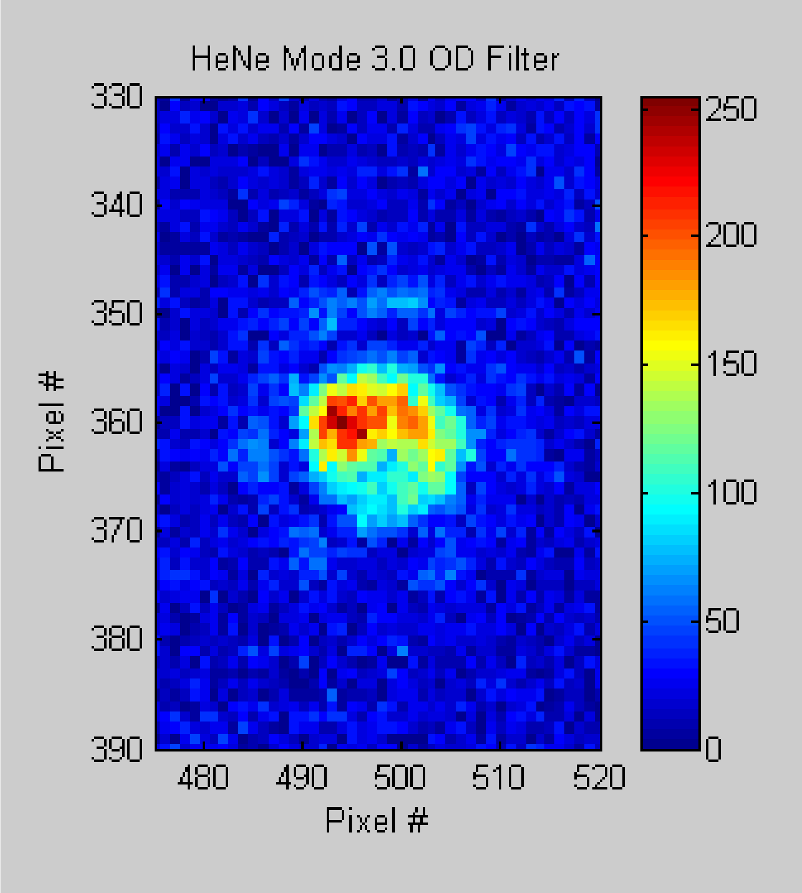


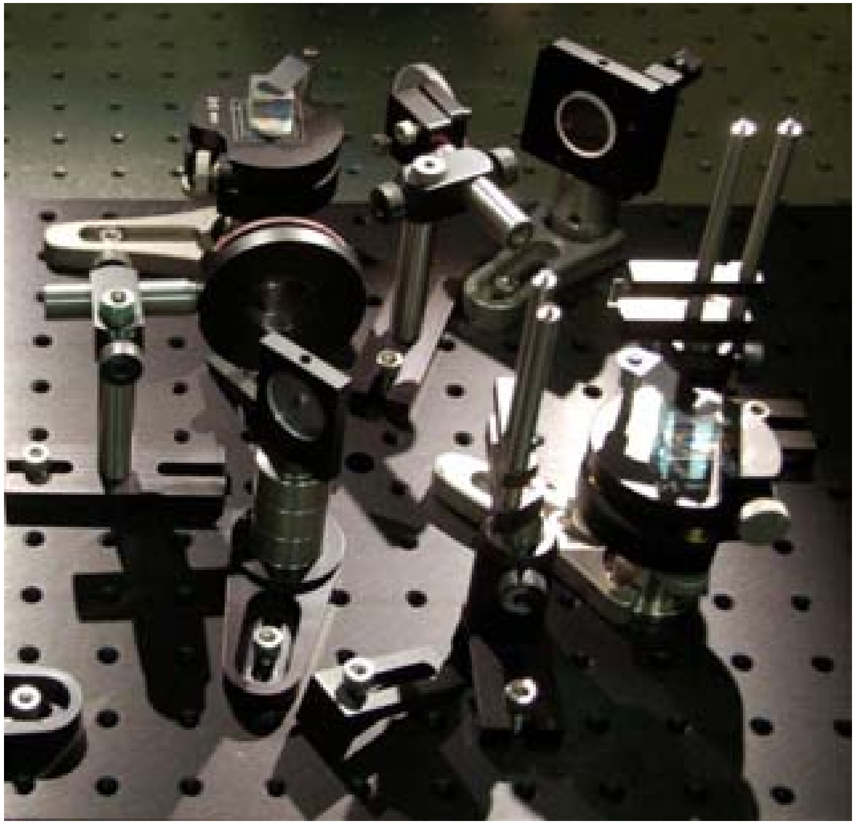
- Laser



Dielectric Accelerator Structures

Mode Profile

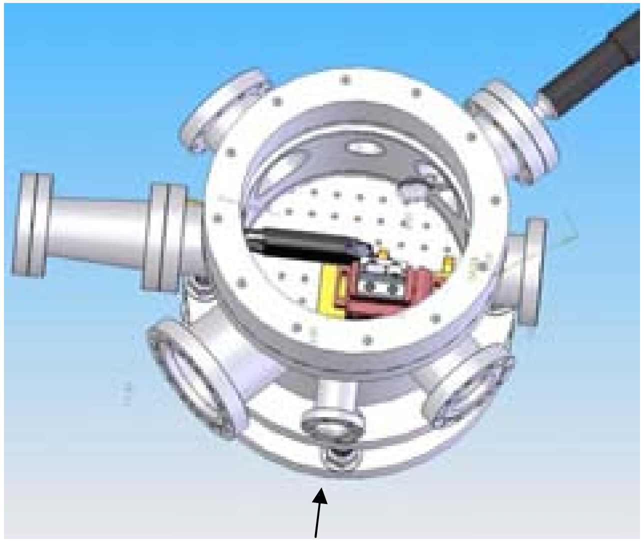


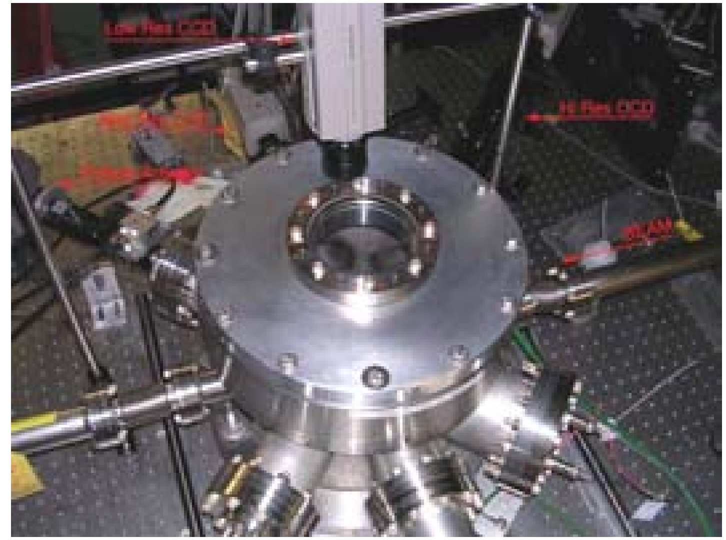


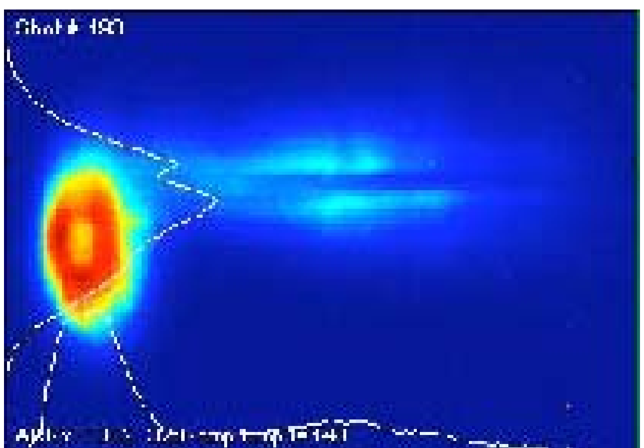
Melissa Lincoln, Patrick Lu

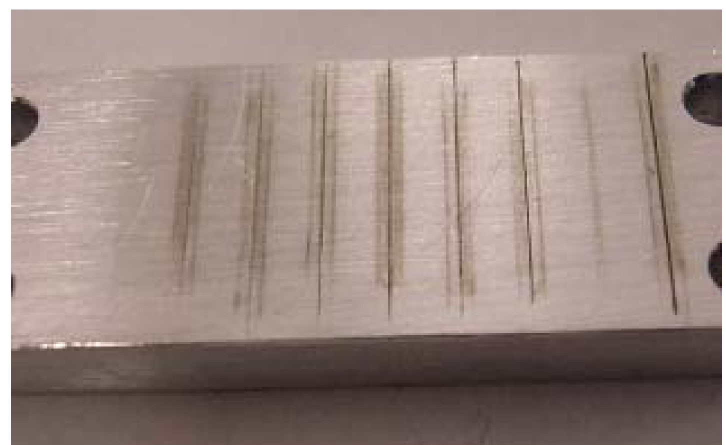
Dielectric Accelerator Structures: Proof-of-Principle Experiments

Cherenkov Wakefield Experiment

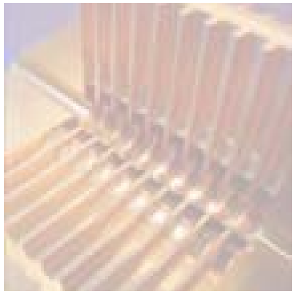






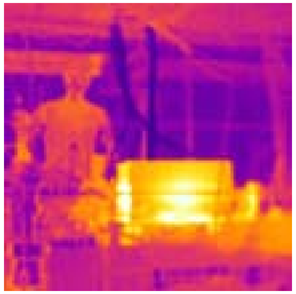


Advanced Acceleration Schemes



Extending RF to Higher Frequencies

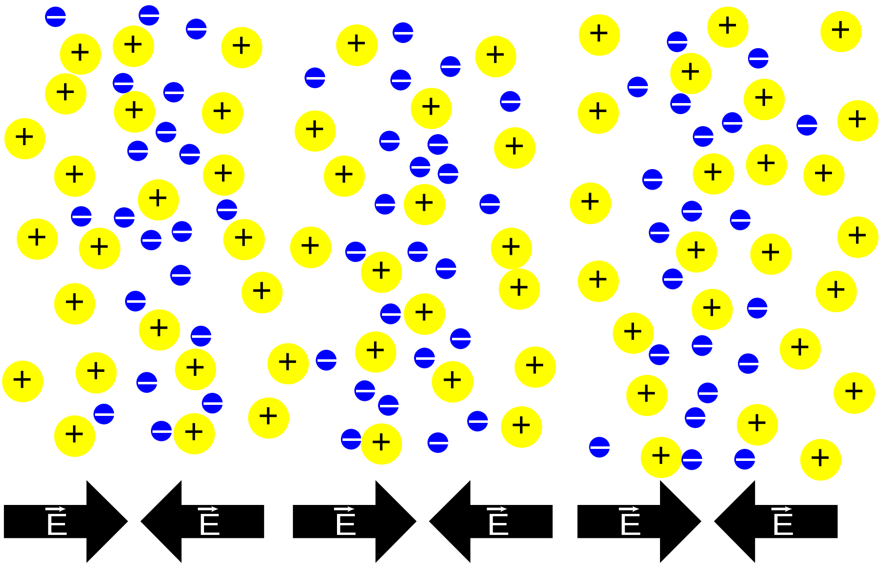
Dielectrics at Optical Freuqencies



Plasma Wakefield Acceleration

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:

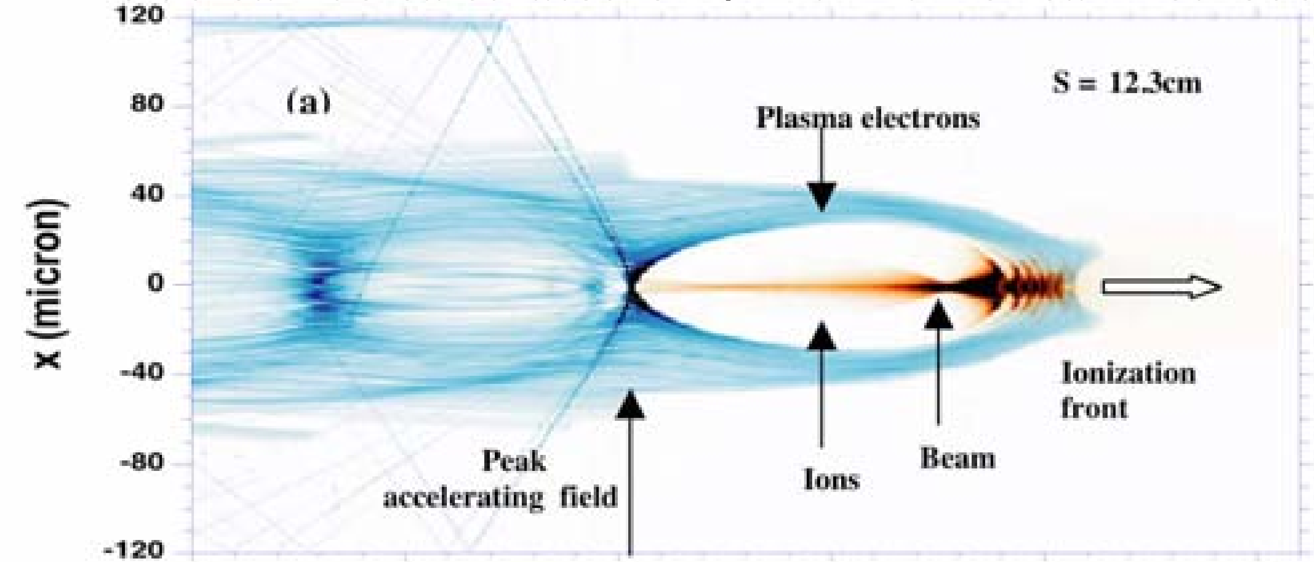
$$\lambda_p \approx \sqrt{\frac{10^{15}\mathrm{cm}^{-3}}{n_p}} \quad \mathrm{mm}$$

  - 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

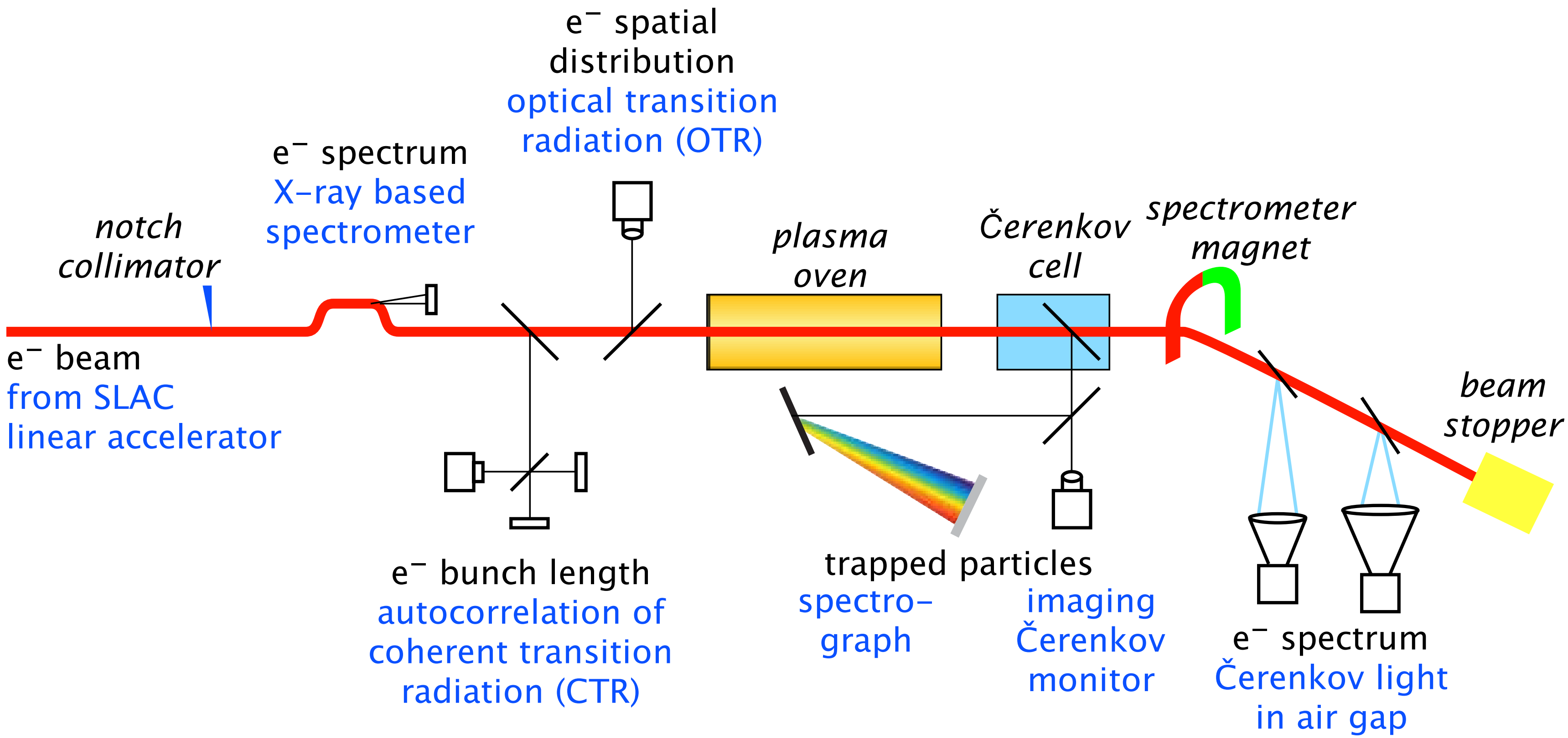


- Typical wavelength: 50 μm
- Accelerating fields up to 50 GV/m

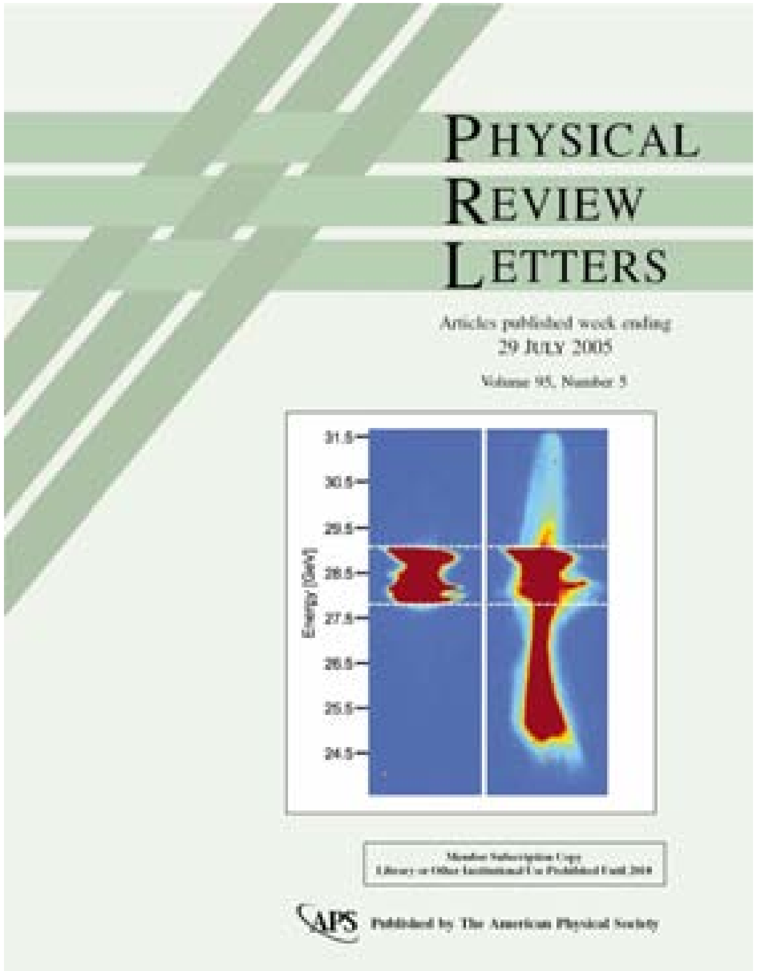
Drive the Plasma Wake

- 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

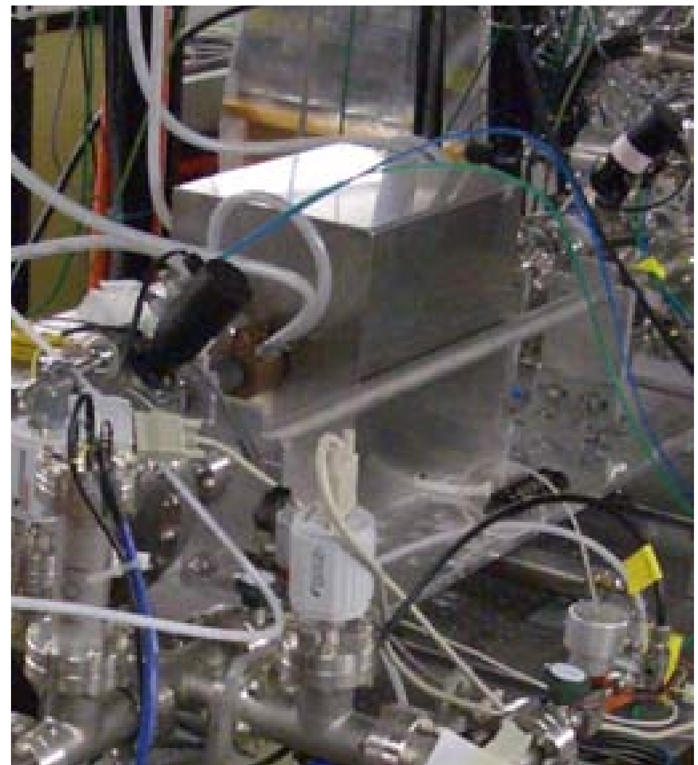
Experimental Setup



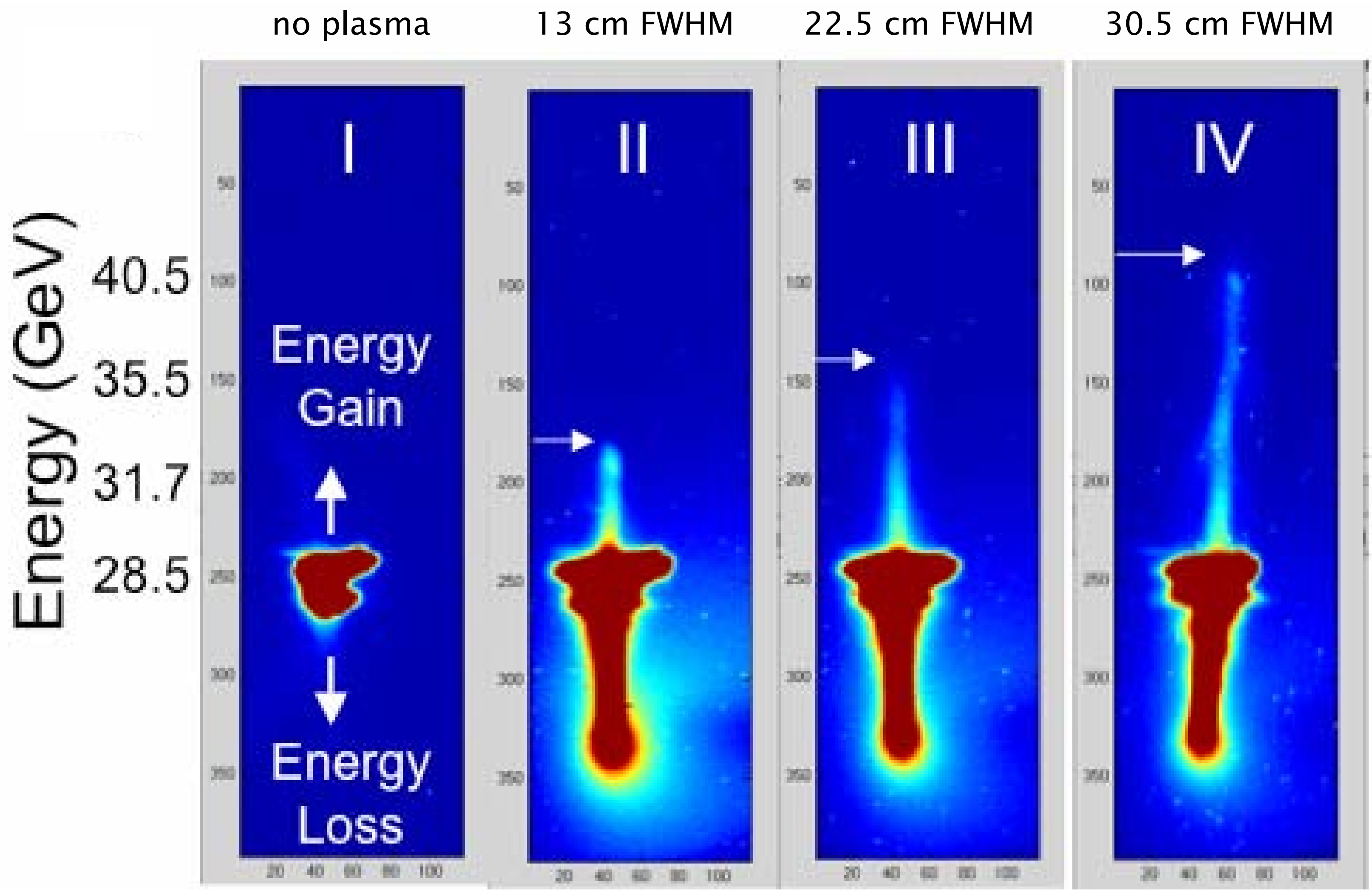
Previous Results



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

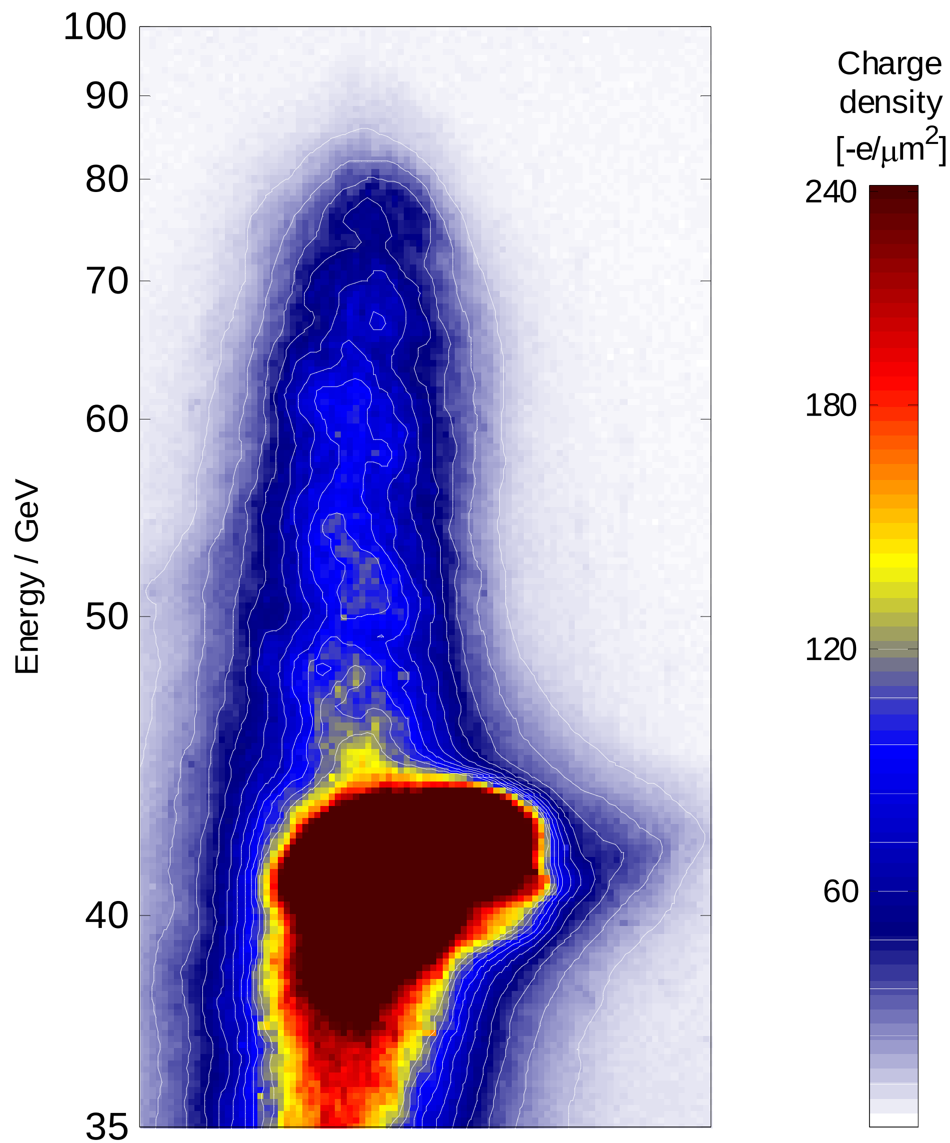
New spectrometer

Diagnostics for low-energy particles

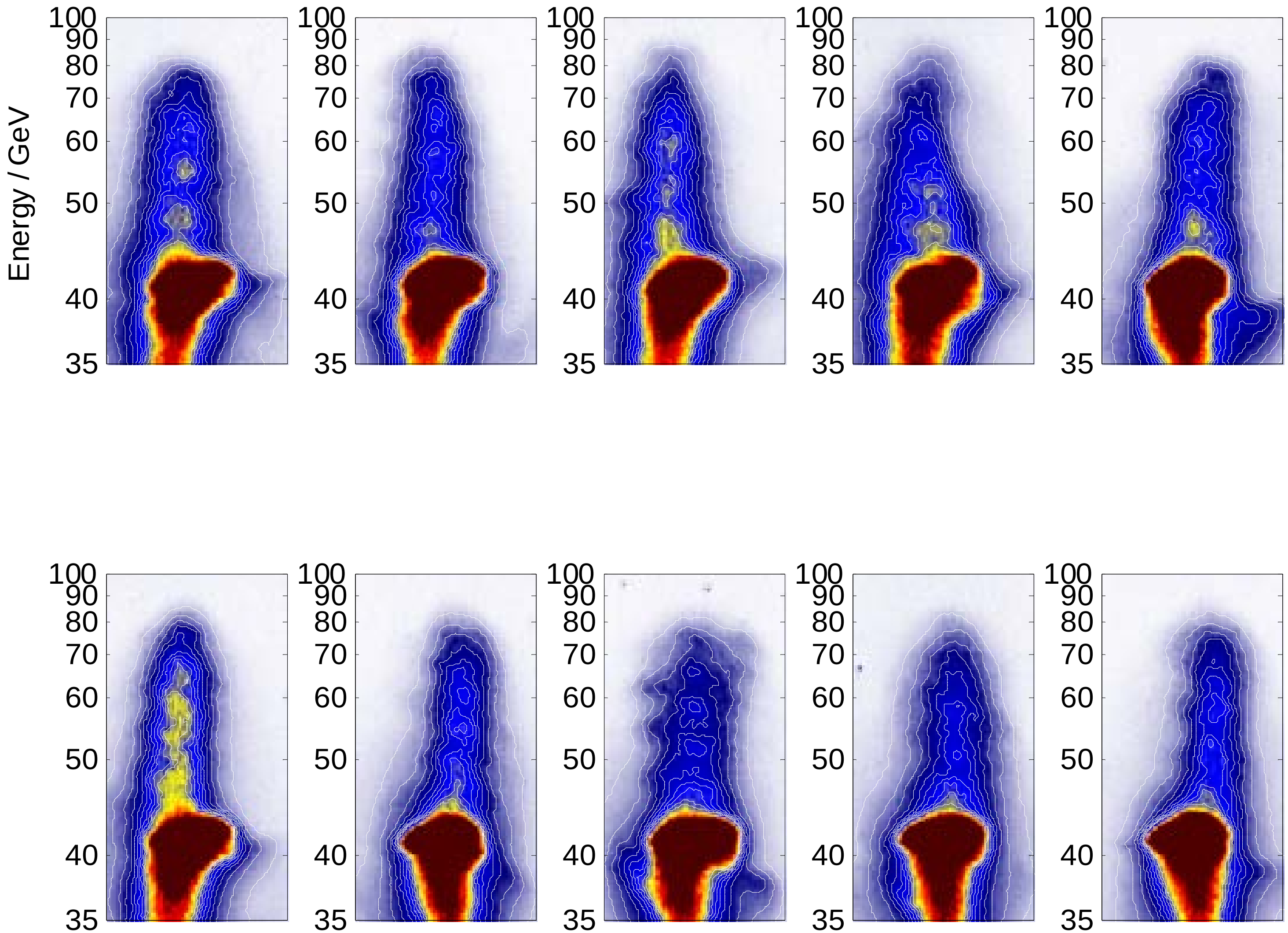
Increased the energy in the drive beam

Energy Doubling

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



Stability

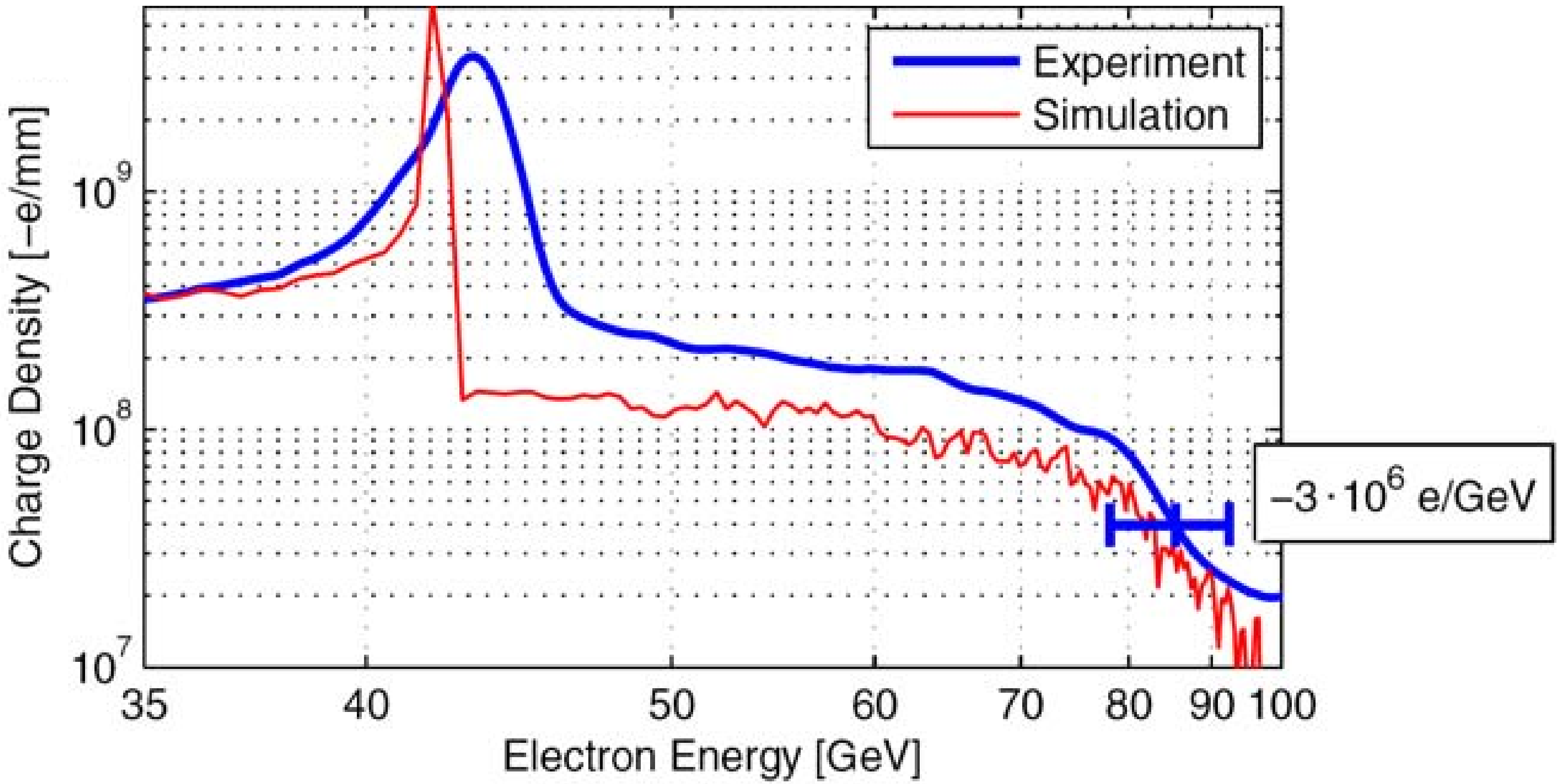


Simulations

- 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

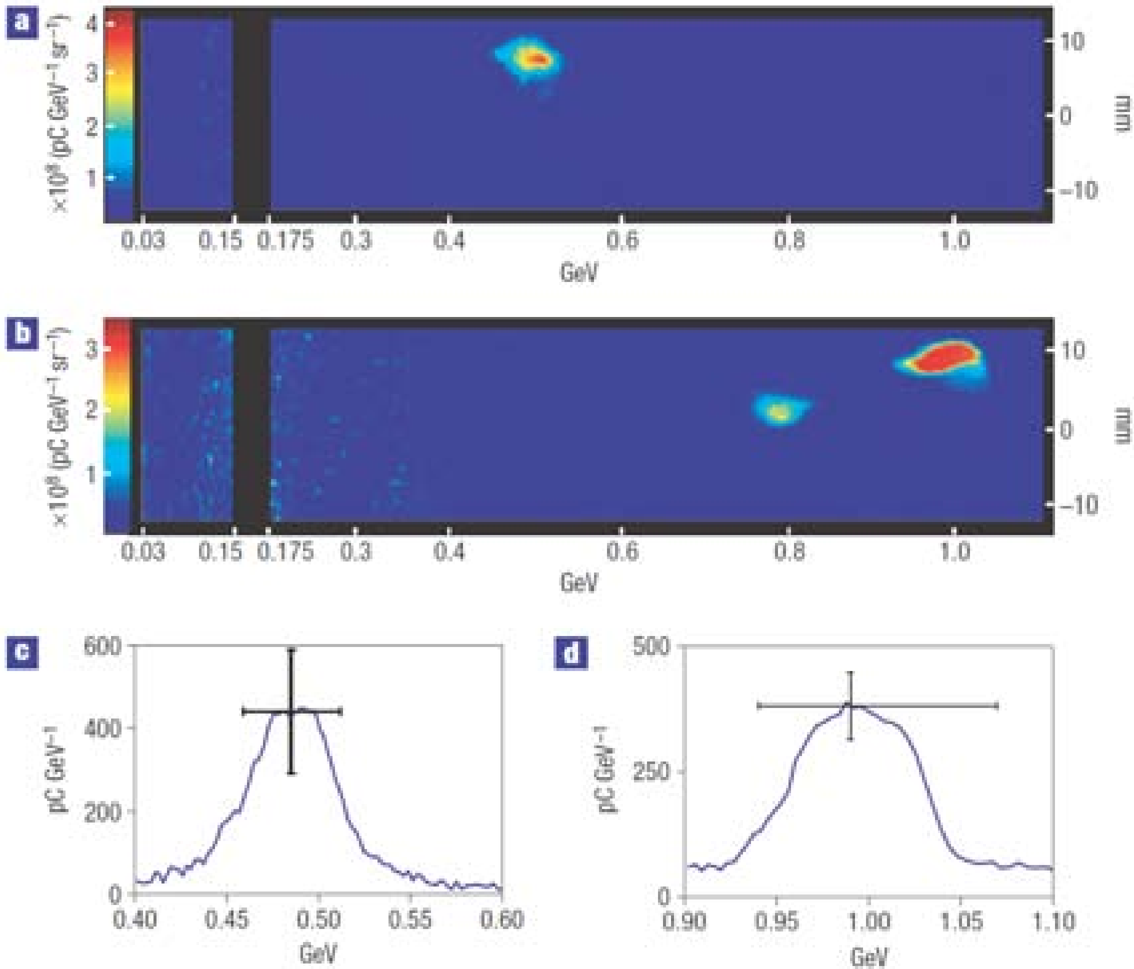


Plasma Wakefield Acceleration

There is still Work to Do…

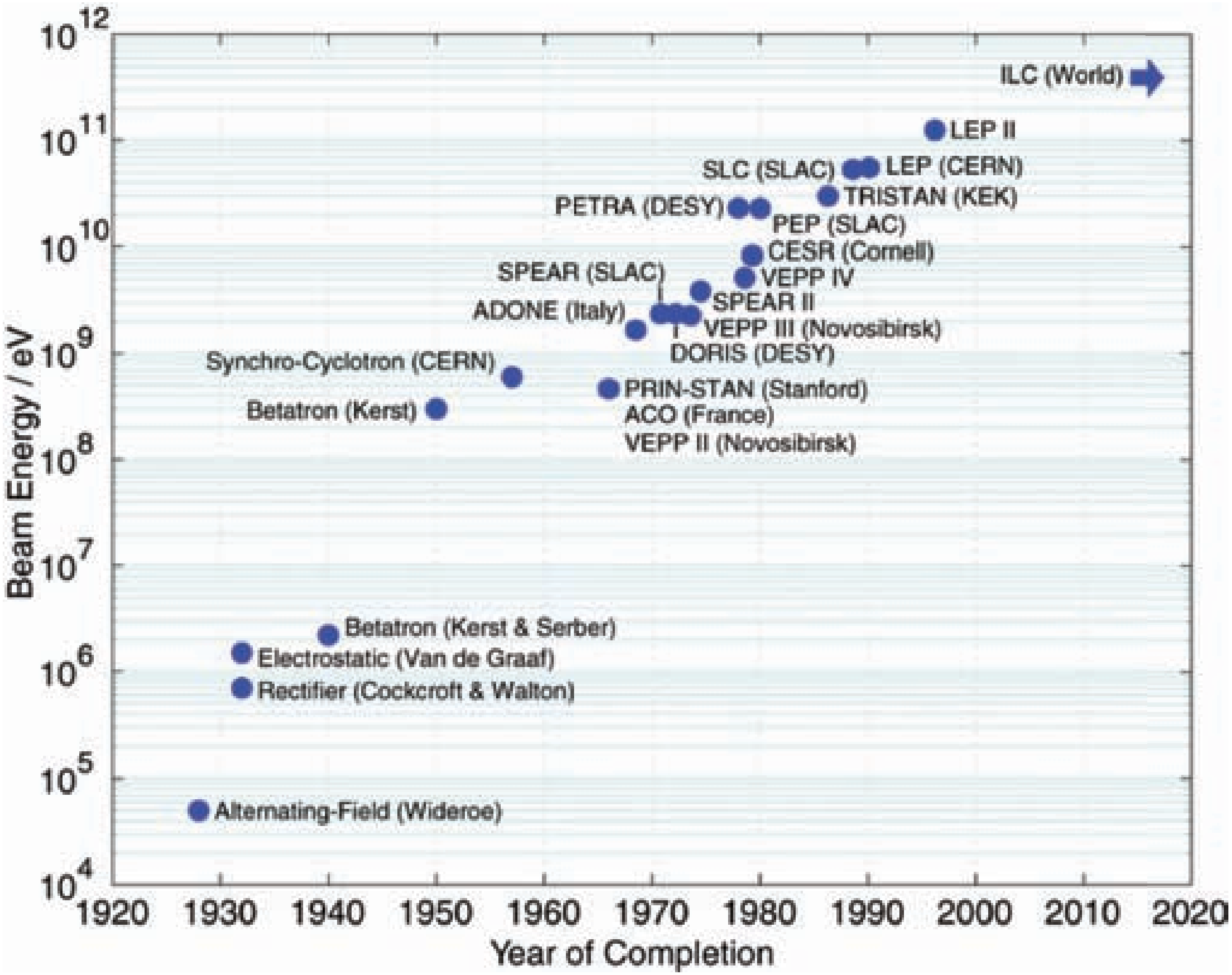
- Understand (and exploit) self-injection
- Scaling to higher energies
  - Hose instability effect
  - Ion motion
- Acceleration of positrons

Self-Injected Particles
Laser-Driven Plasma Wake

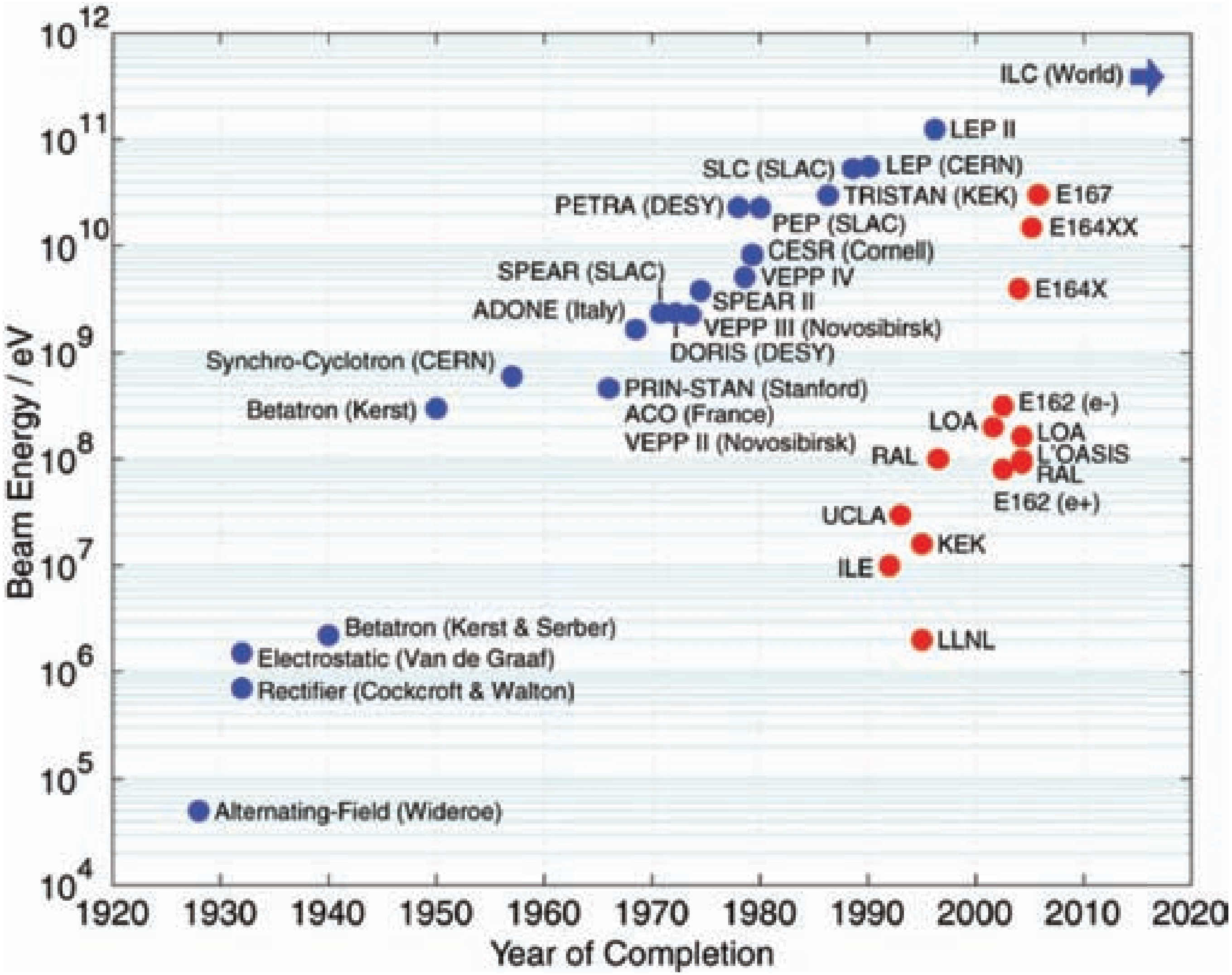


W. P. Leemans

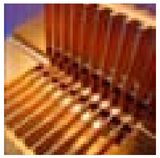
Livingston Plot



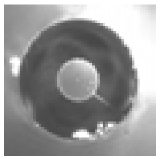
An Unfair Comparison



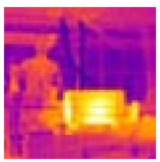
Summary: Advanced Accelerator Research



Extending RF to Higher Frequencies



Dielectrics at Optical Frequencies



Plasma Wakefield Acceleration

- Direct laser acceleration (inverse transition radiation)
- Inverse free electron lasers
- Laser-plasma acceleration of protons
- Particle acceleration by stimulated emission of radiation
- Muon collider

Accelerator research is more than just engineering

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)
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