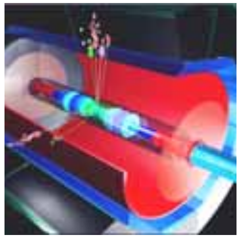
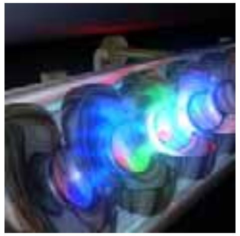
Advanced Accelerator Concepts

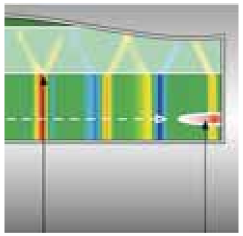
Rasmus Ischebeck, Paul Scherrer Institut



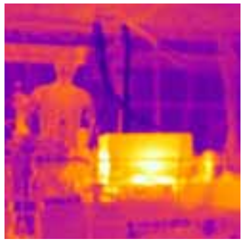
Accelerators for
Basic Research and Applications



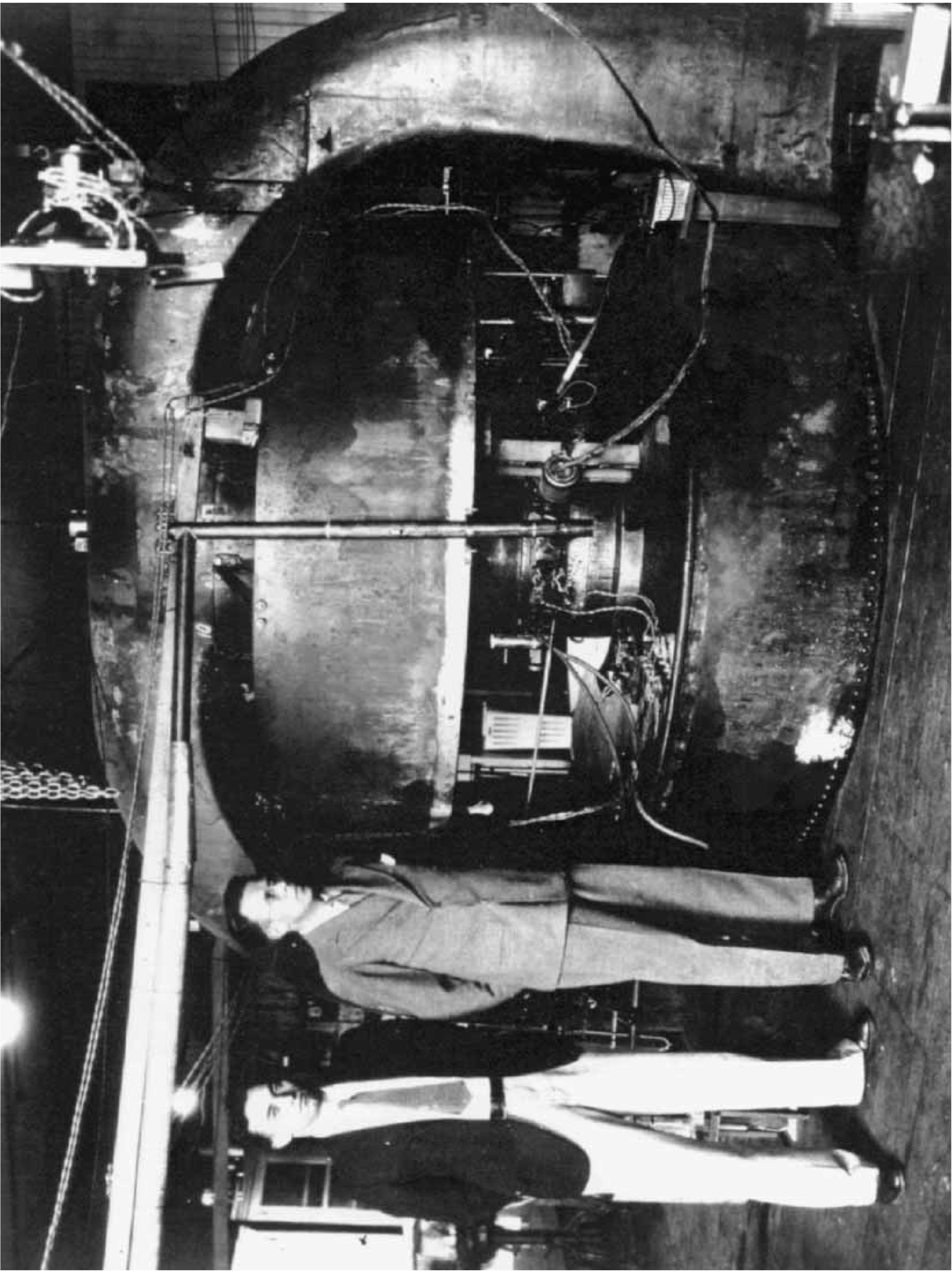
Present Technologies



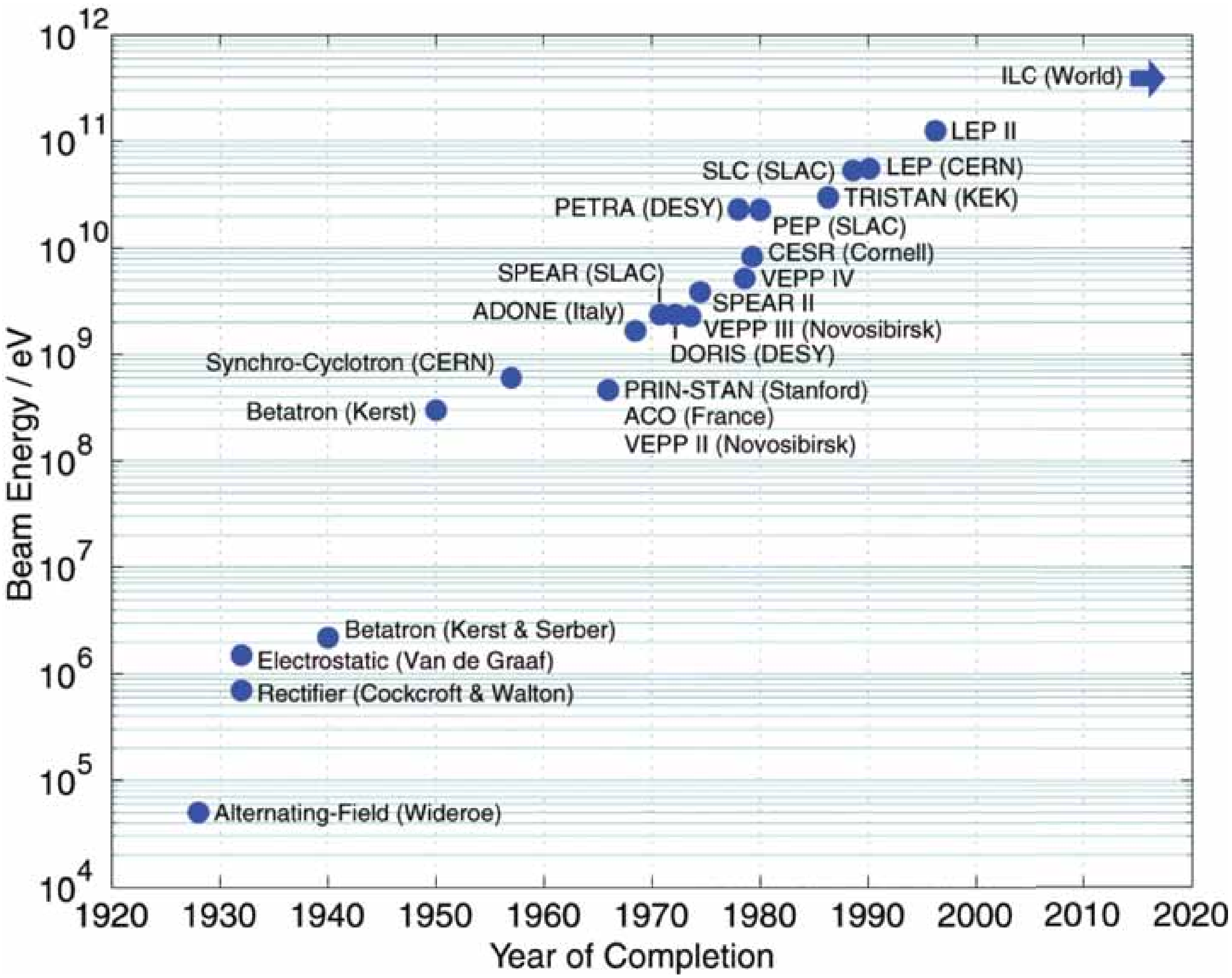
Dielectric Structures



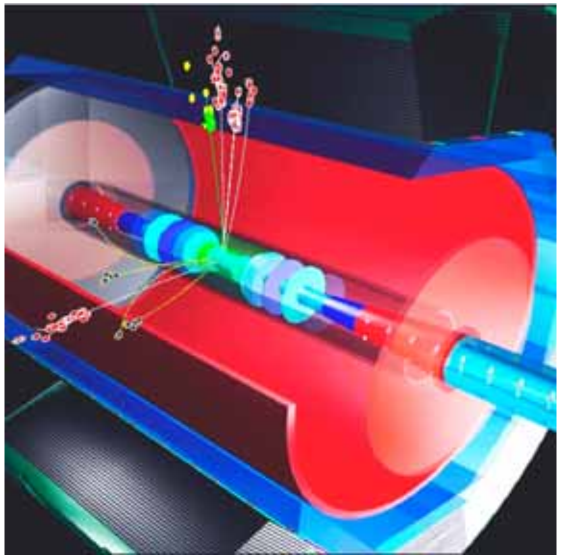
Plasma Wakefield Accelerators

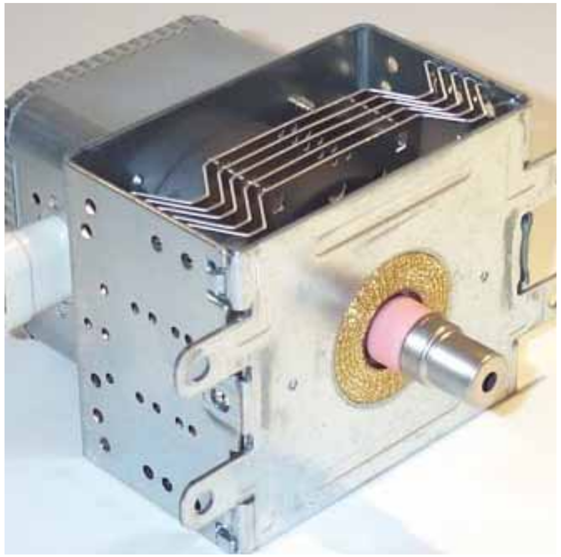


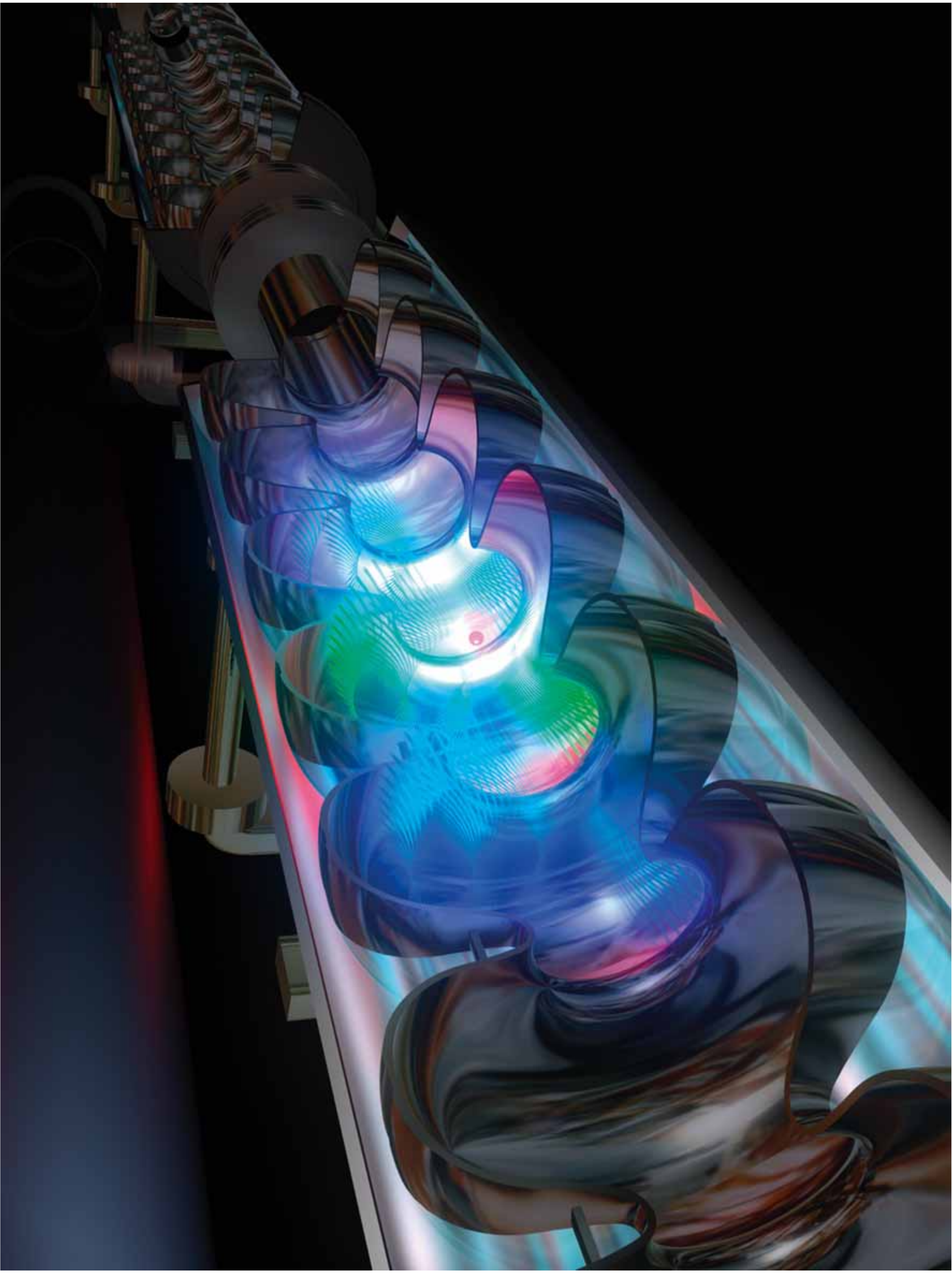
History of Electron Accelerators
Livingston Plot



Applications of Accelerators







Basic Requirements for Electron Accelerators beyond ILC

• Energy	$W \gtrsim 5\ldots10$ TeV	$W = E \bullet e \bullet L$ (Linac)
• Luminosity	$\mathcal{L} \gtrsim 10^{36}$ cm^{-2} s^{-1}	$\mathcal{L} = \dfrac{N^2 f}{4\pi\, \sigma_x \sigma_y}$
⇒ Beam power	$P \approx 100$ MW	$P = U \bullet I$
• Cost	$C \lesssim 5 \bullet 10^9$	

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

Luminosity

- Cross section for e^+e^- collisions goes as $1/E^2$
  - ⇒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
  - ⇒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

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: $3 \cdot 10^{10}$

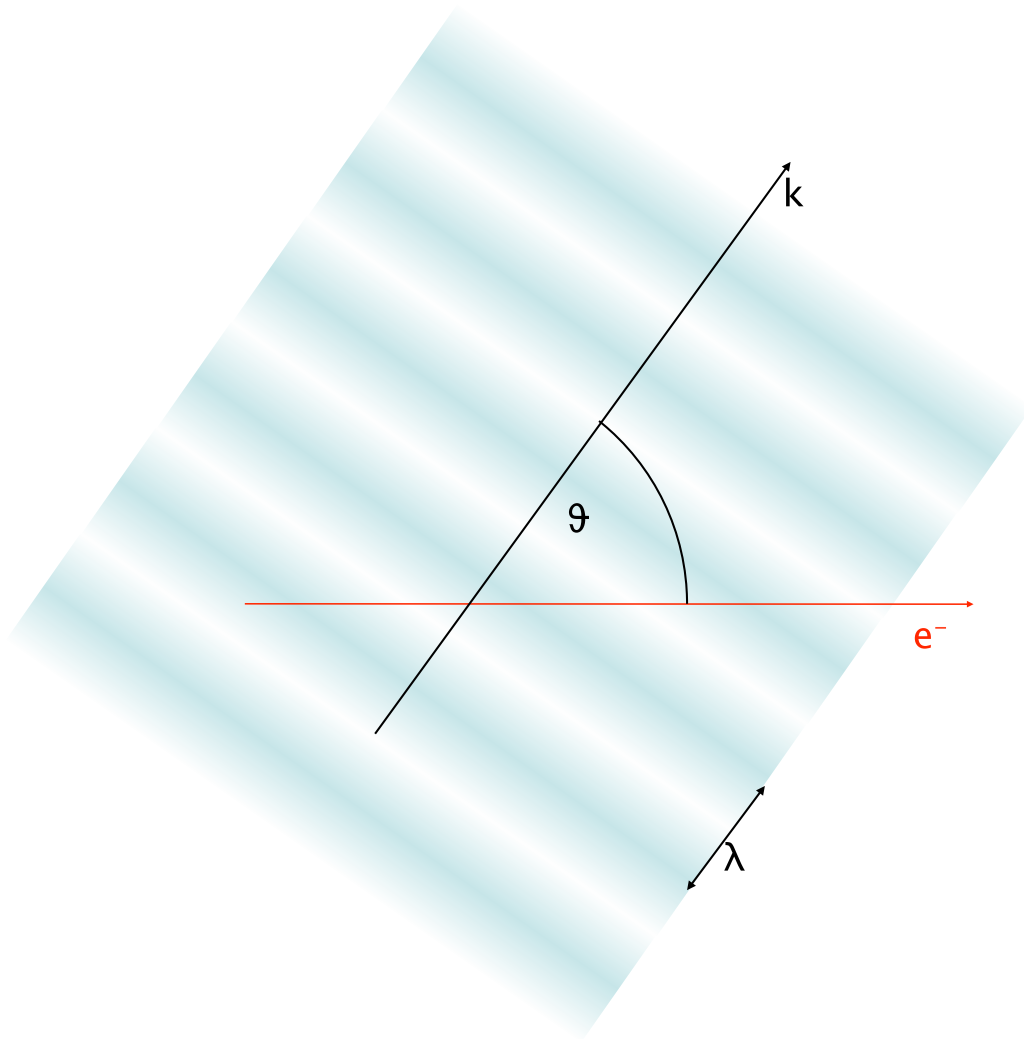
Therefore

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

How to Accelerate Charged Particles

Assume:

- an ultrarelativistic particle of charge e
- moving along the z axis
- accelerated by a plane electromagnetic wave that propagates at an angle ϑ to the z axis



How to Accelerate Charged Particles

Then:

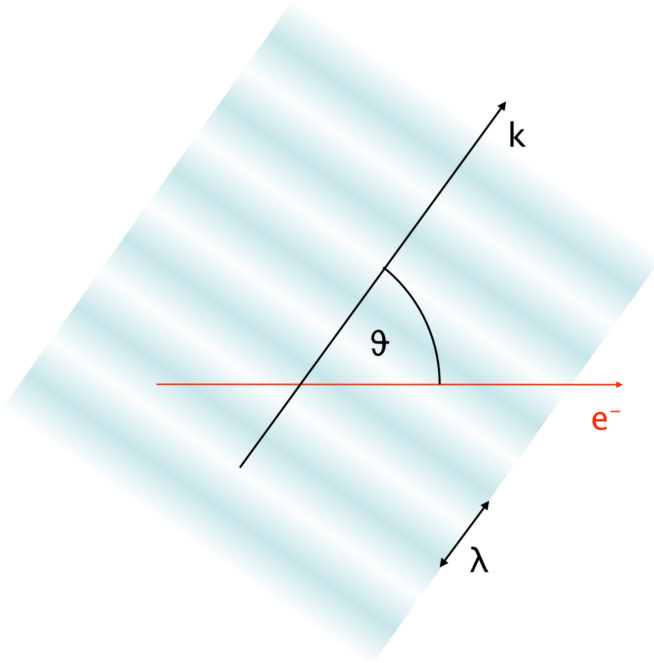
- Position of the electron

$$\vec{r}(t) = \begin{pmatrix} 0 \\ 0 \\ ct \end{pmatrix}$$

- Electric field

- Energy gradient

$$E_{\|} = \sin\vartheta \cos\left(\omega t - \frac{z}{2\pi\lambda\cos\vartheta}\right)$$



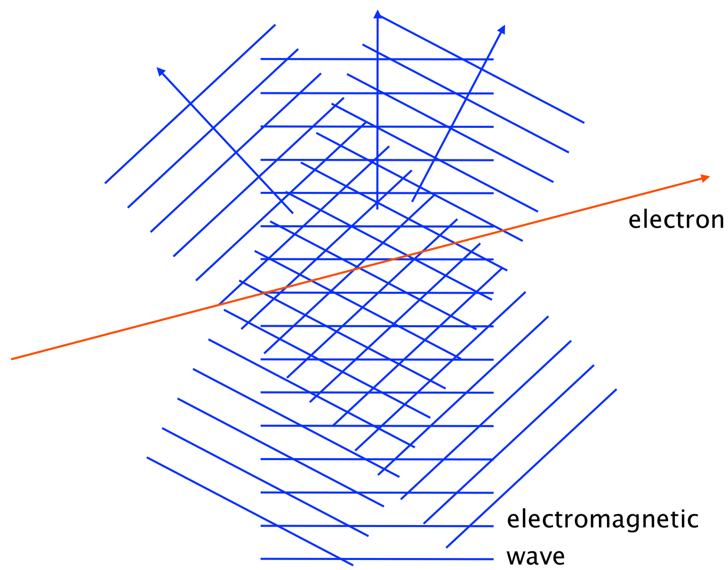
$$\frac{\Delta W}{L} = \frac{\int_L eE_{\|}dz}{L} = \frac{\int_L \sin\vartheta\cos(kz(1-\sec\vartheta))dz}{L}$$

$$= \frac{\sin\vartheta\sin(kL(1-\sec\vartheta))\frac{1}{k(1-\sec\vartheta)}}{L} \xrightarrow{L\to\infty} 0$$

Lawson Woodward Theorem

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

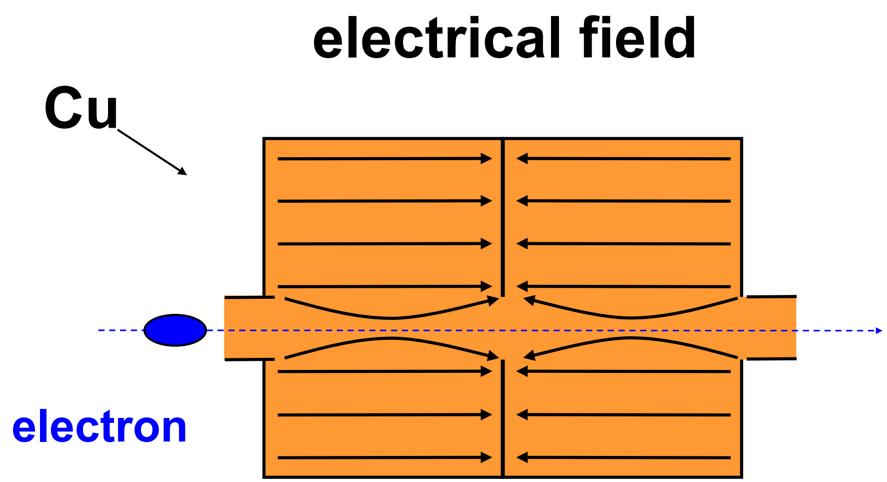
⇒ Need near–field structures



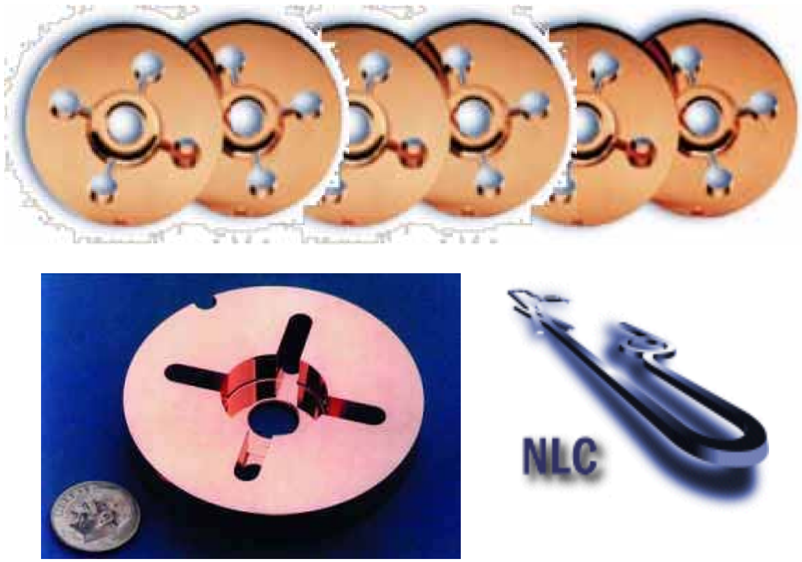
Woodward, J. IEE 93 (1947)
Lawson, IEEE Trans. Nucl. Sci. 26 (1979)
Palmer, Part. Accel. 11 (1980)

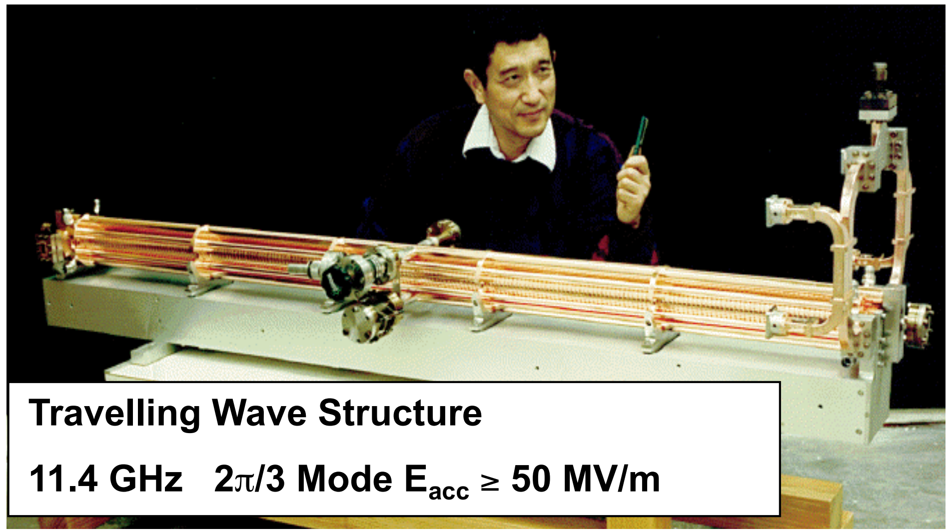
RF Acceleration

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



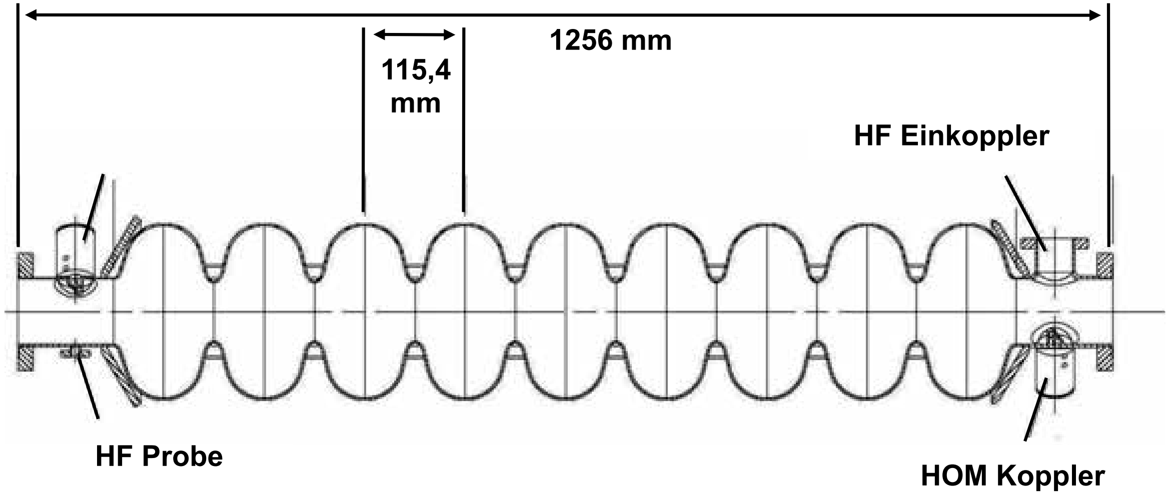
Resonating RF Cavity



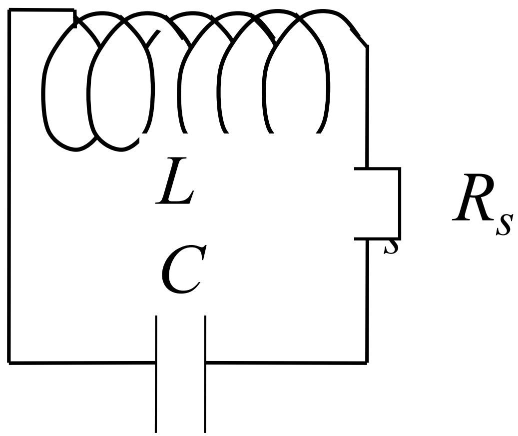


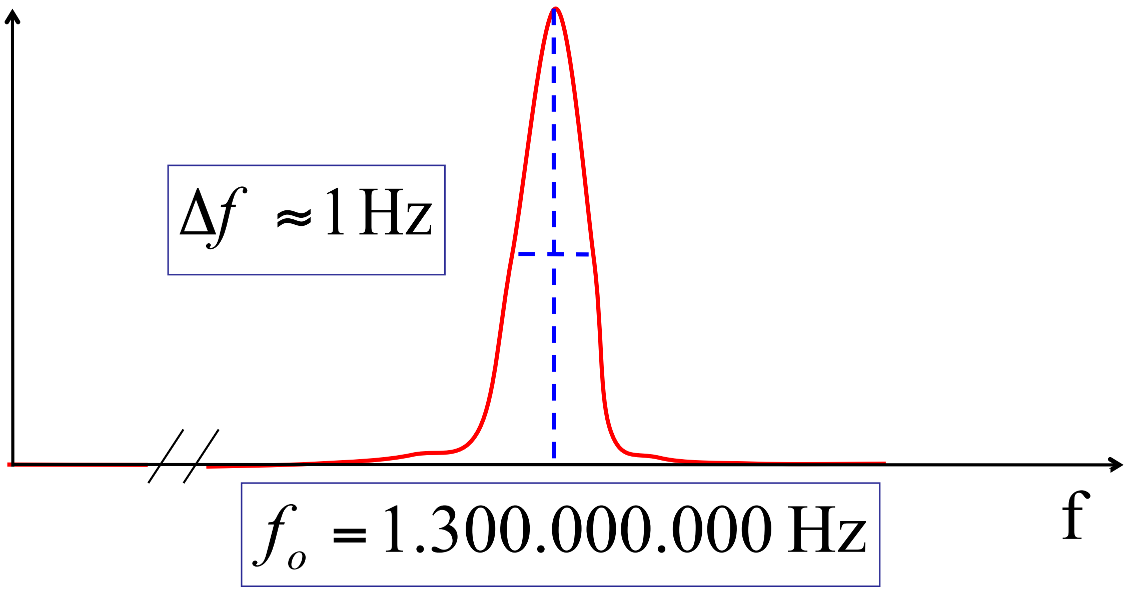
adapted from H. Weise

Superconducting RF



Resonant Circuit:





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

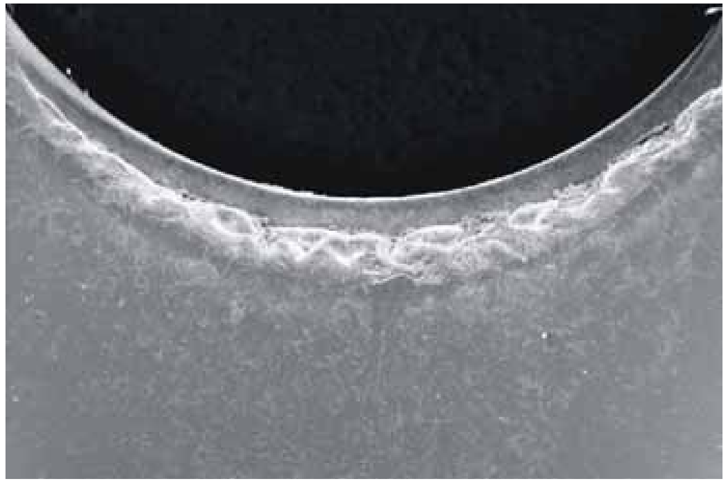
Quality factor: $Q_o = \dfrac{f}{\Delta f} = \dfrac{G}{R_s}$

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

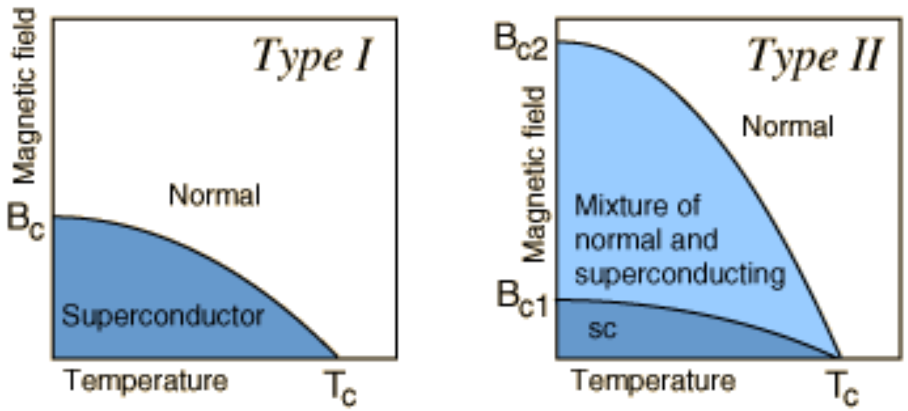
H. Weise

Limits to the Accelerating Field

- Normal-conducting accelerators
  - Breakdown on the surface

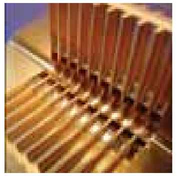
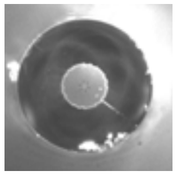
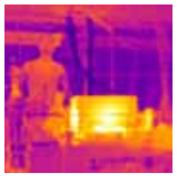


- Superconducting accelerators
  - Critical magnetic field



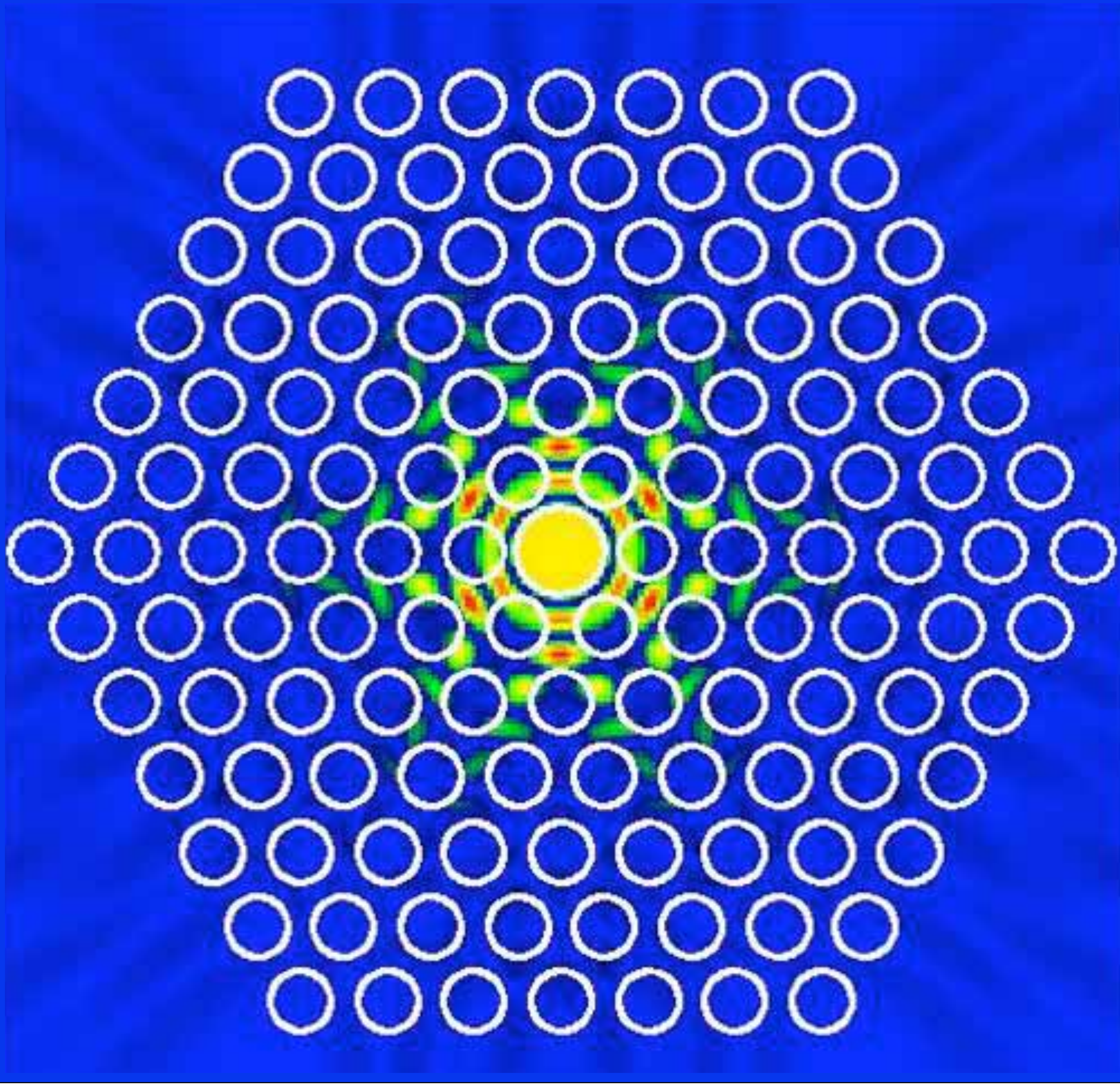
http://hyperphysics.phy-astr.gsu.edu/hbase/solids/scbc.html

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	$\geq 10^{11}$	laser	electron beams

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

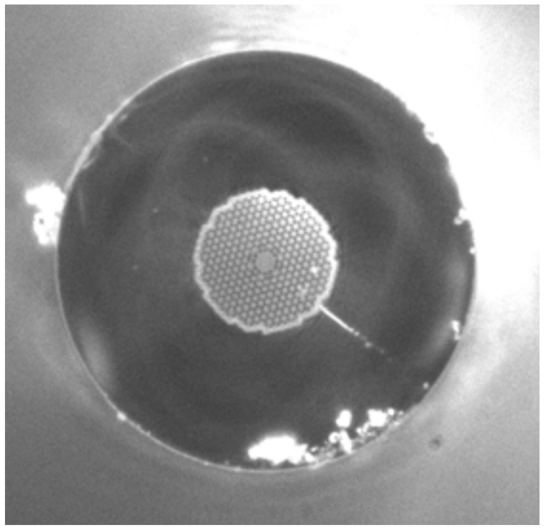
Dielectric Structures



Dielectric Accelerator Structures

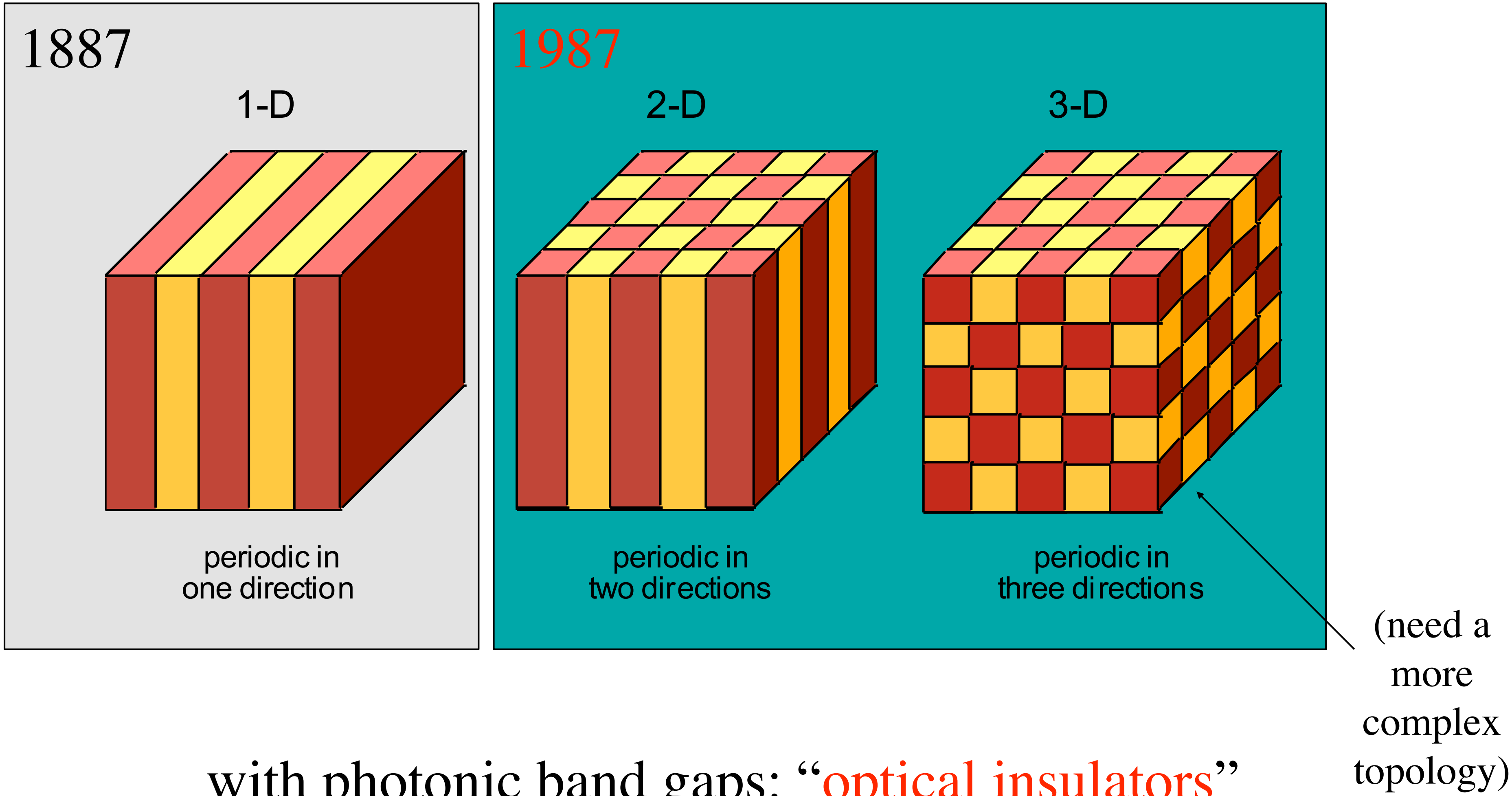
- Using much higher frequencies: THz to optical
- Using dielectrics (e.g. SiO_2)
- Advantages: higher damage threshold
  ⇒Higher accelerating fields, up to ~GV/m

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



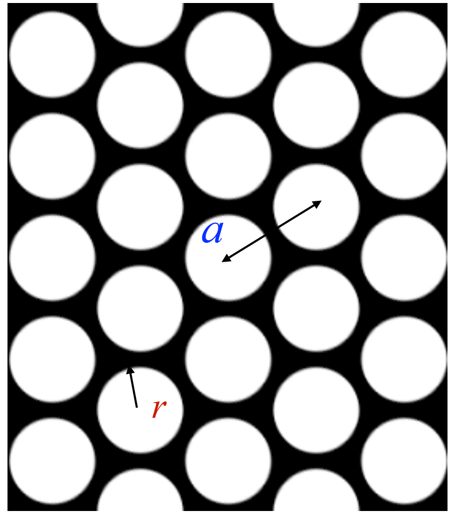
Photonic Crystals

periodic electromagnetic media



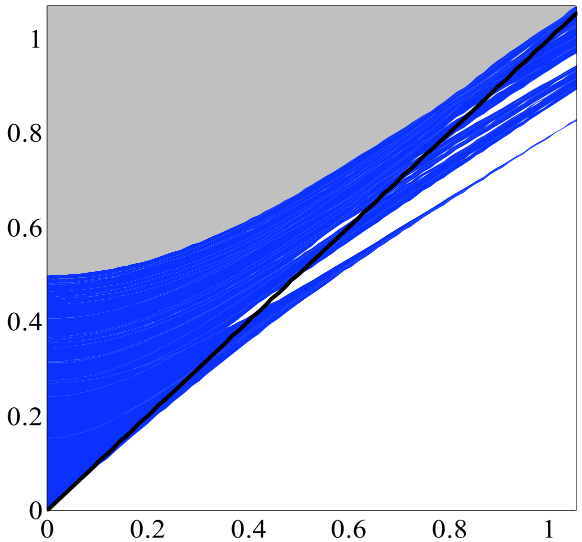
with photonic band gaps: "optical insulators"

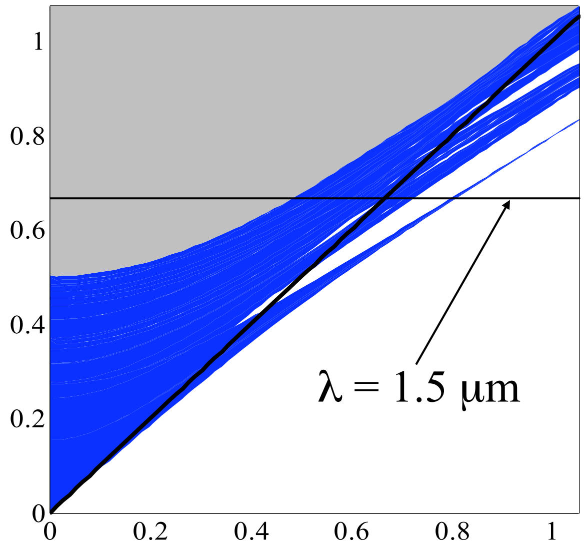
Band Gap maps

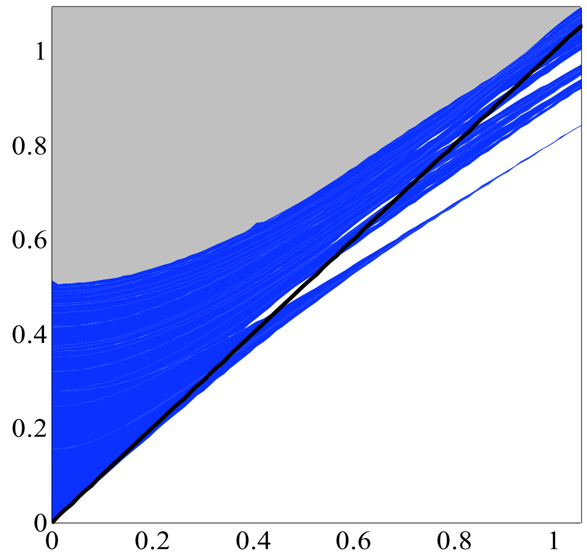


- Solutions of the wave equation

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



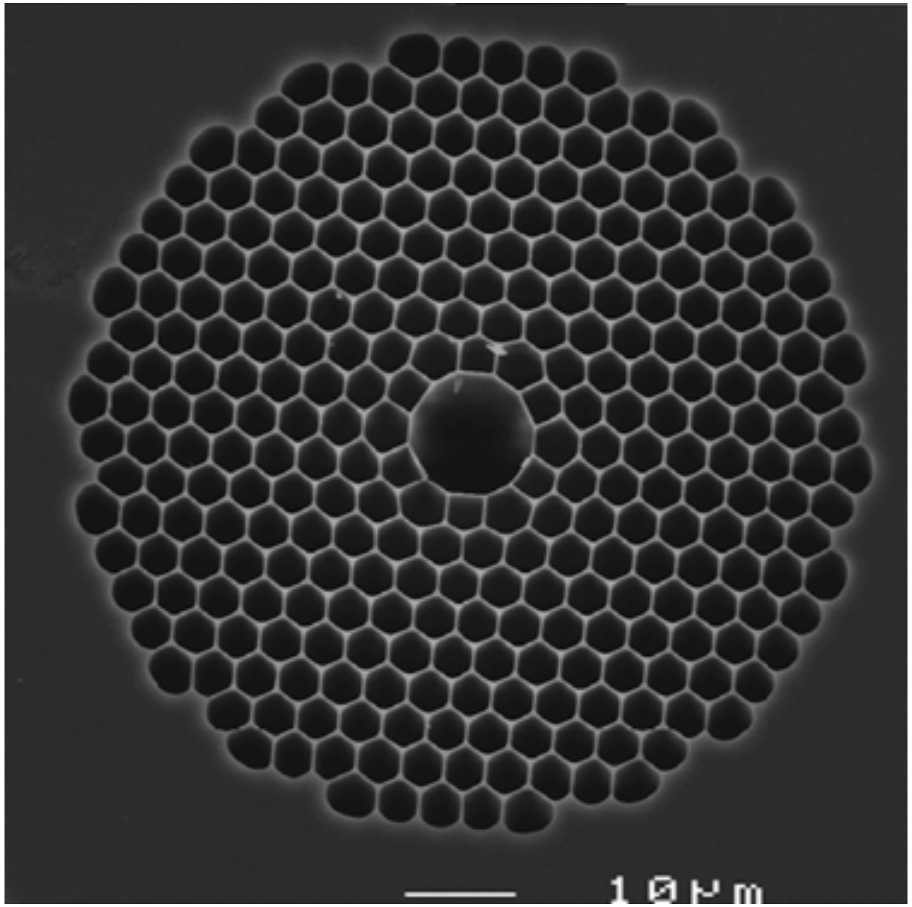


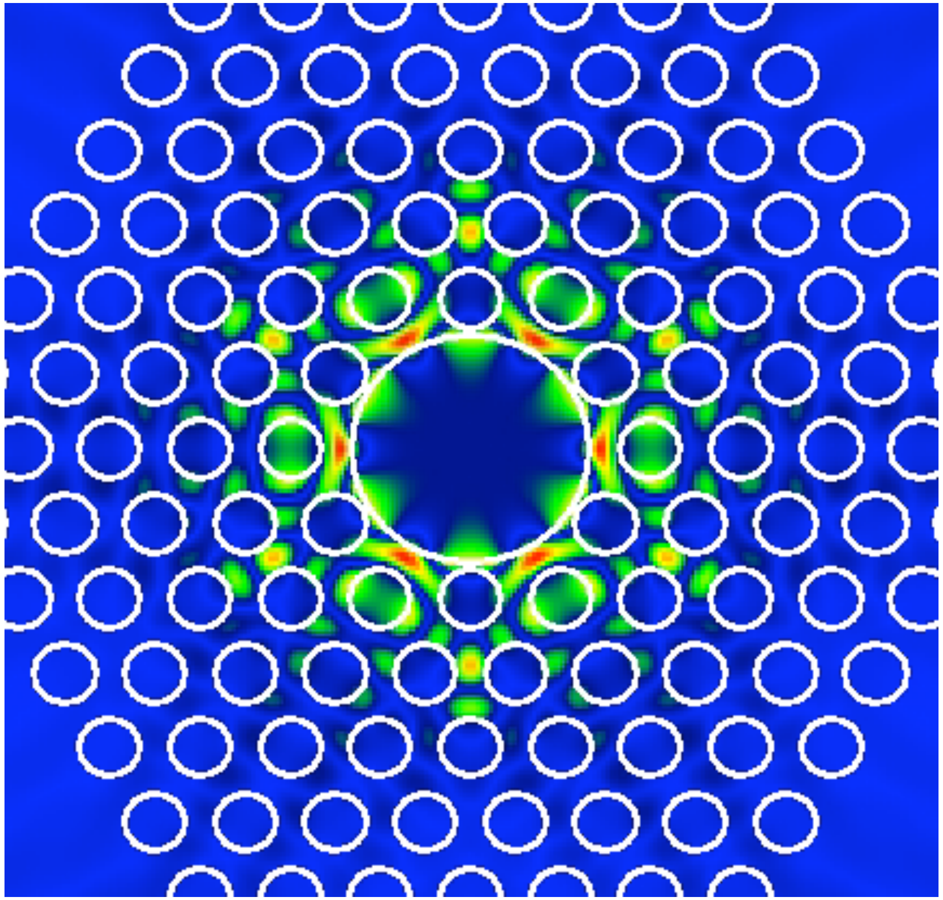


Ben Cowan

Dielectric Accelerator Structures

Photonic Band Gap Structures

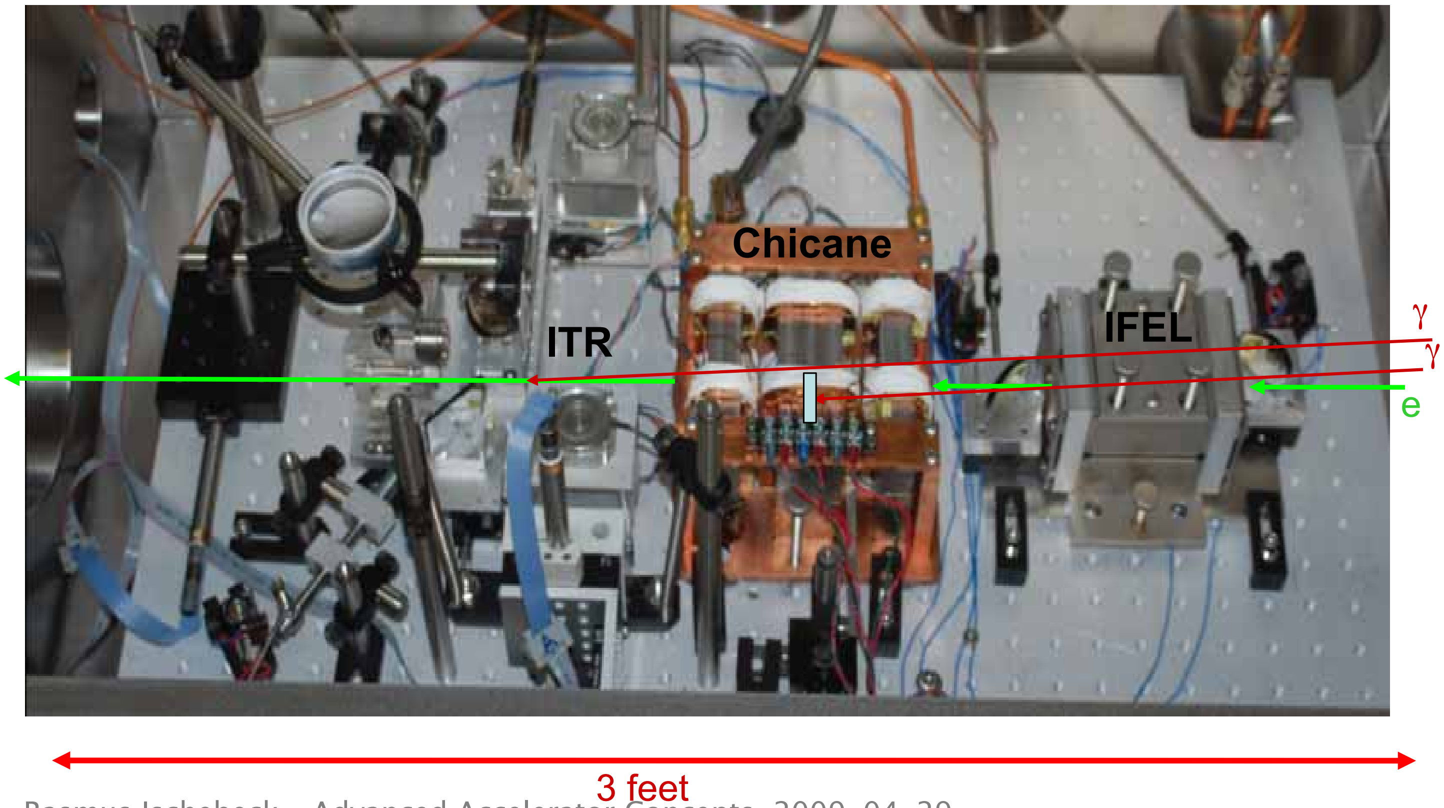


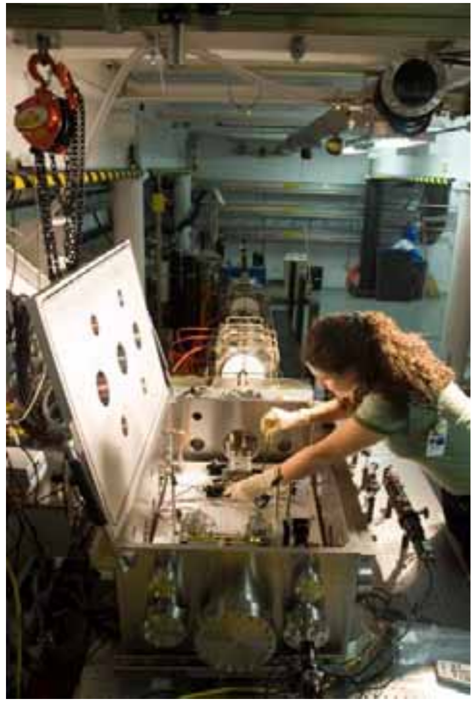


Chris Sramek

Setup of an Experiment

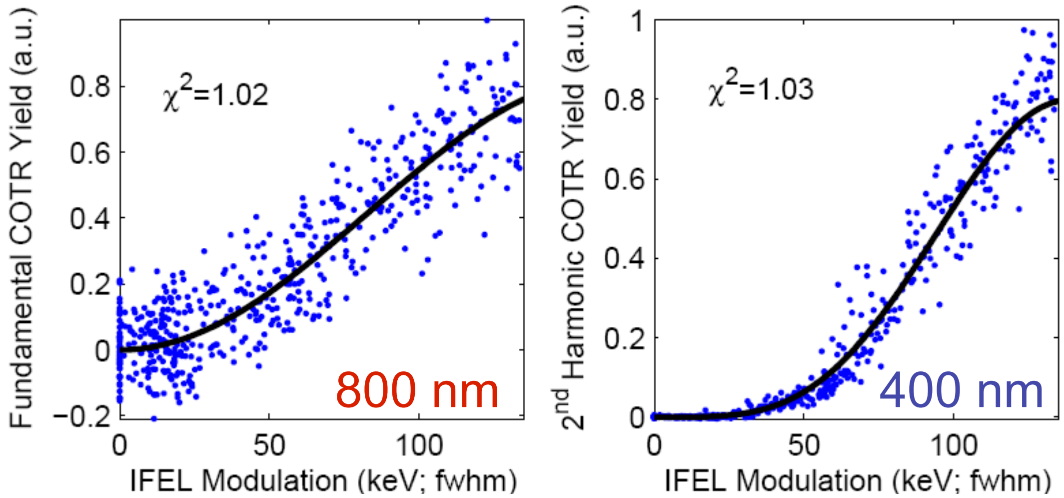
- Generation of 200 nm long electron bunches:
  - Energy modulation in IFEL
  - Pulse forming in chicane



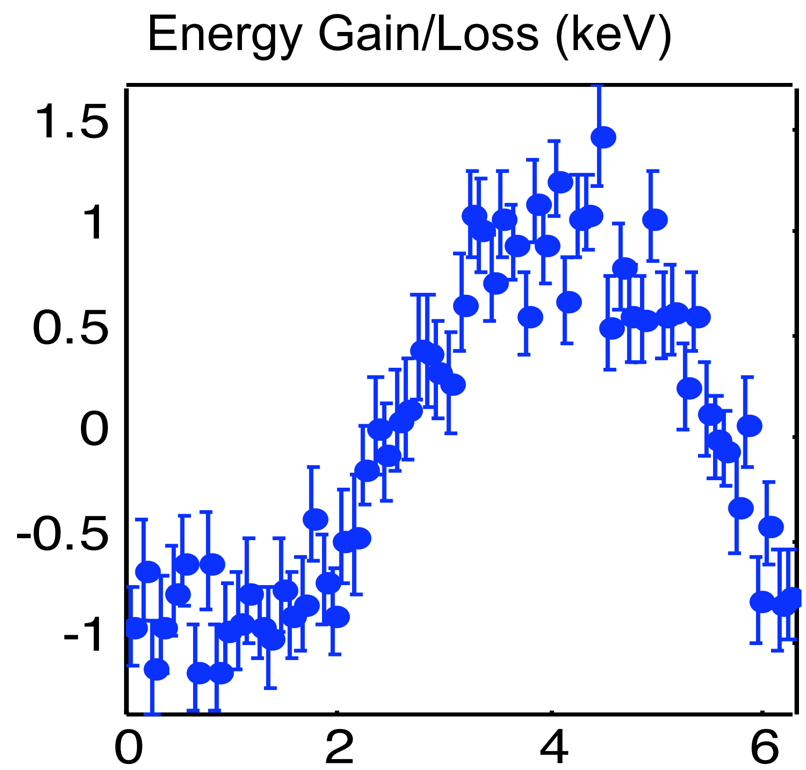


Results

Generation of attosecond pulses



Acceleration

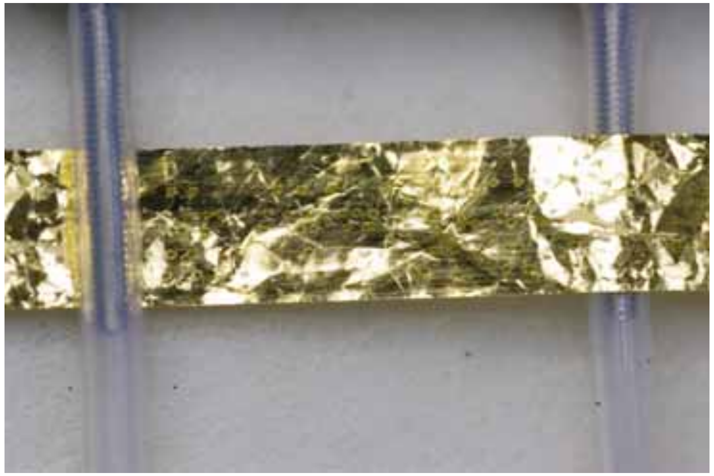


Chris Sears,
Eric Colby

Acceleration on Metallic Surfaces

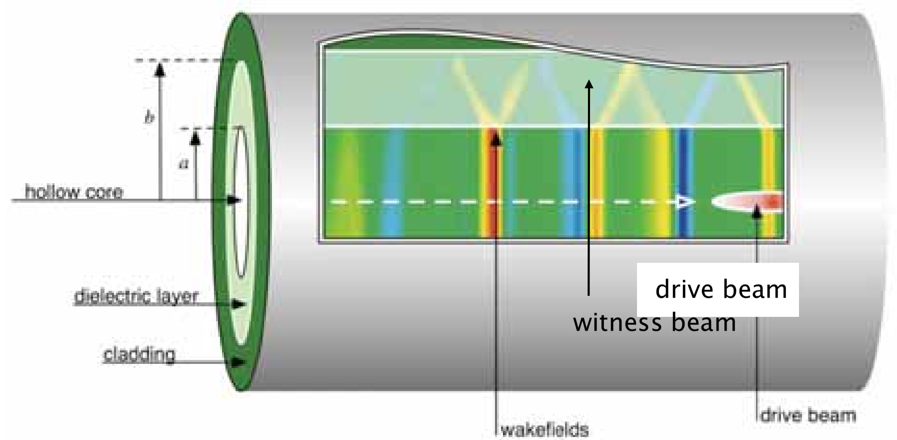
- Inverse transition radiation on a metallic surface

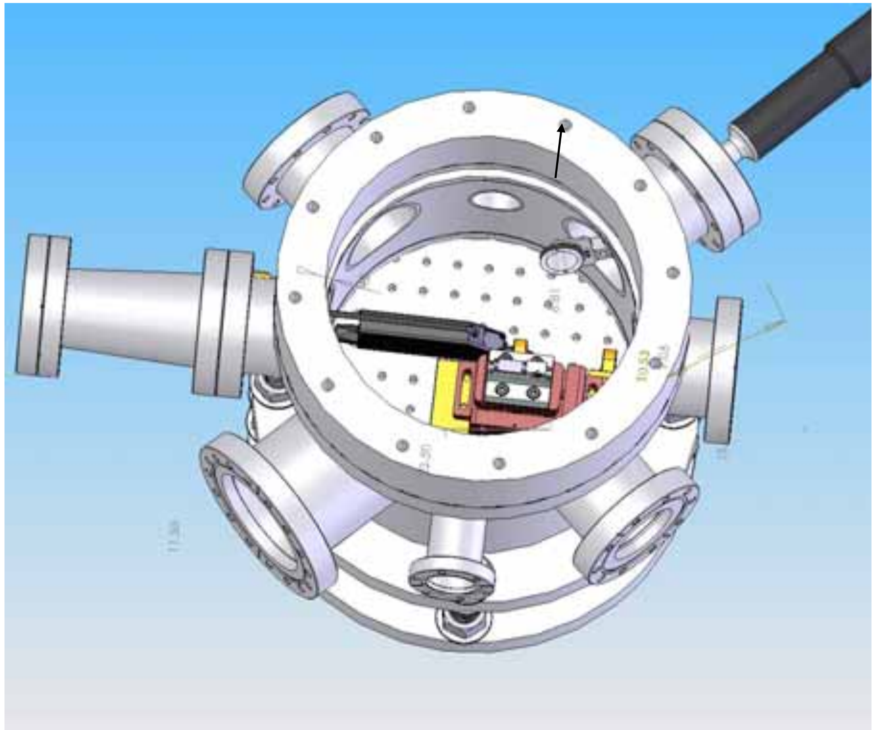
Above the damage threshold, indeed!

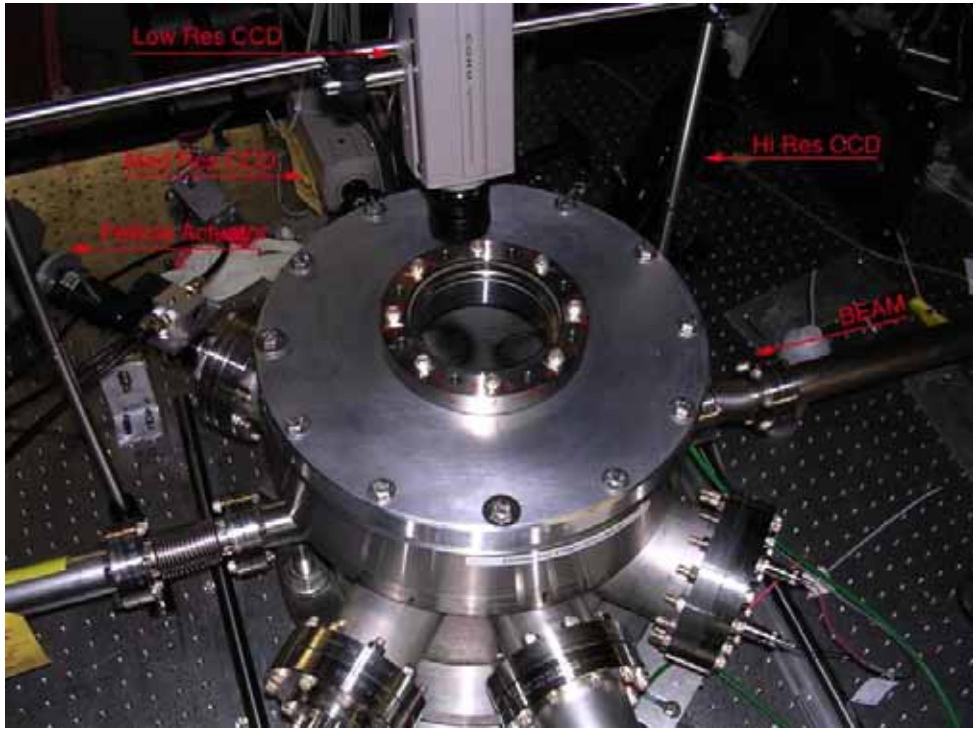


Dielektric Structures

Generation of the accelerating field by an electron beam





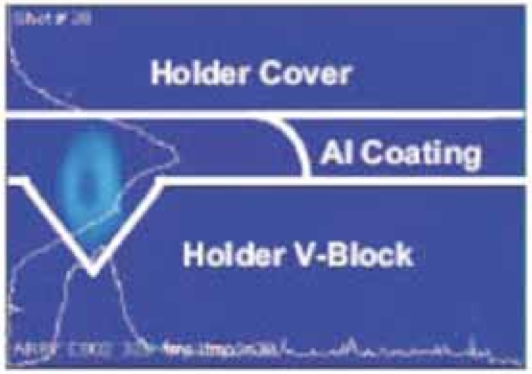


Hristo Badakov, Gil Travish

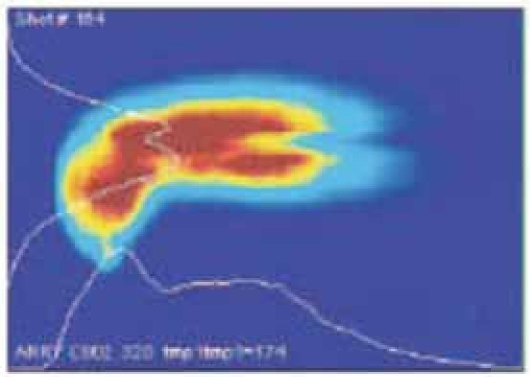
Studies on the Maximum Fields

Emission of Cherenkov light

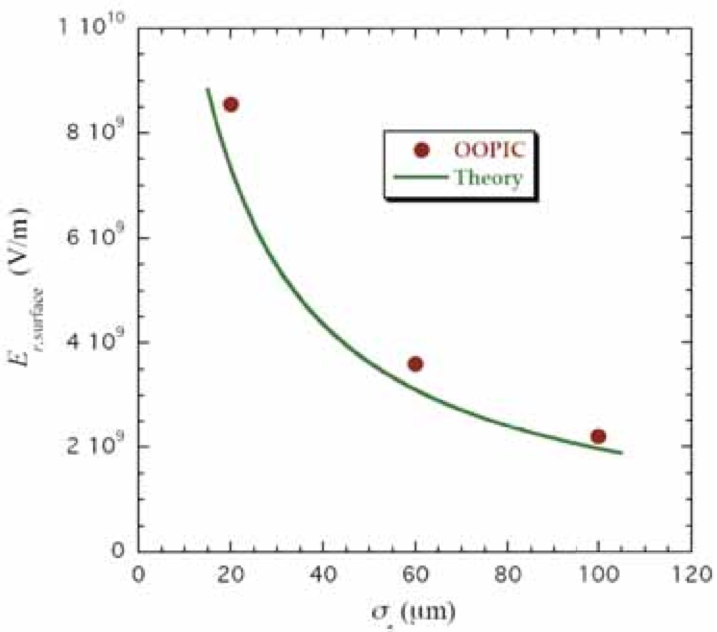
100 μm pulse length

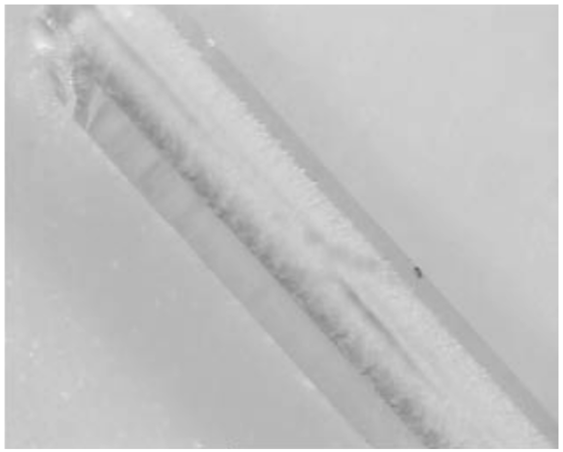


20 μm pulse length

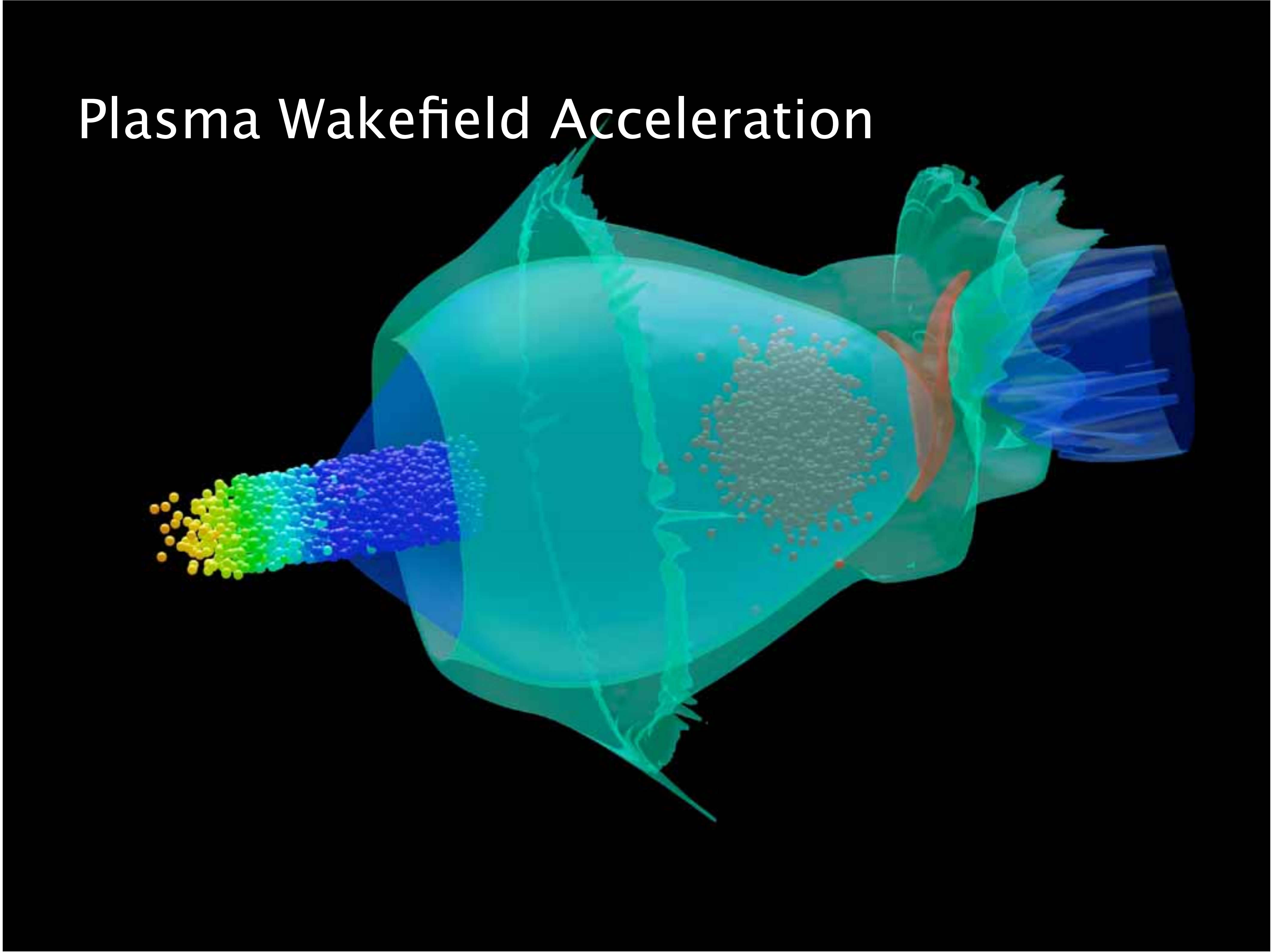


Calculated surface fields



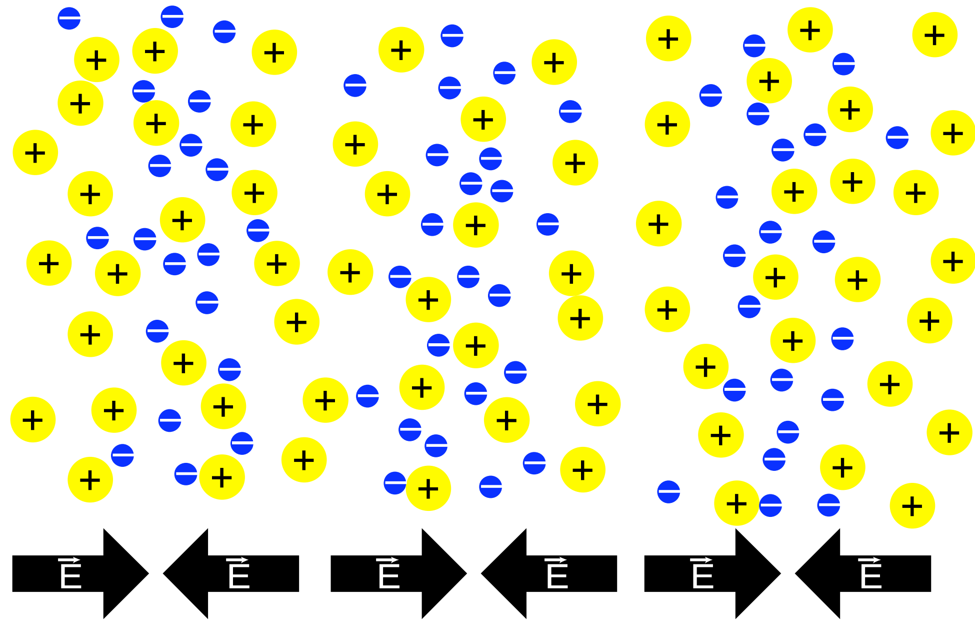


Cracks in the dielectric


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:

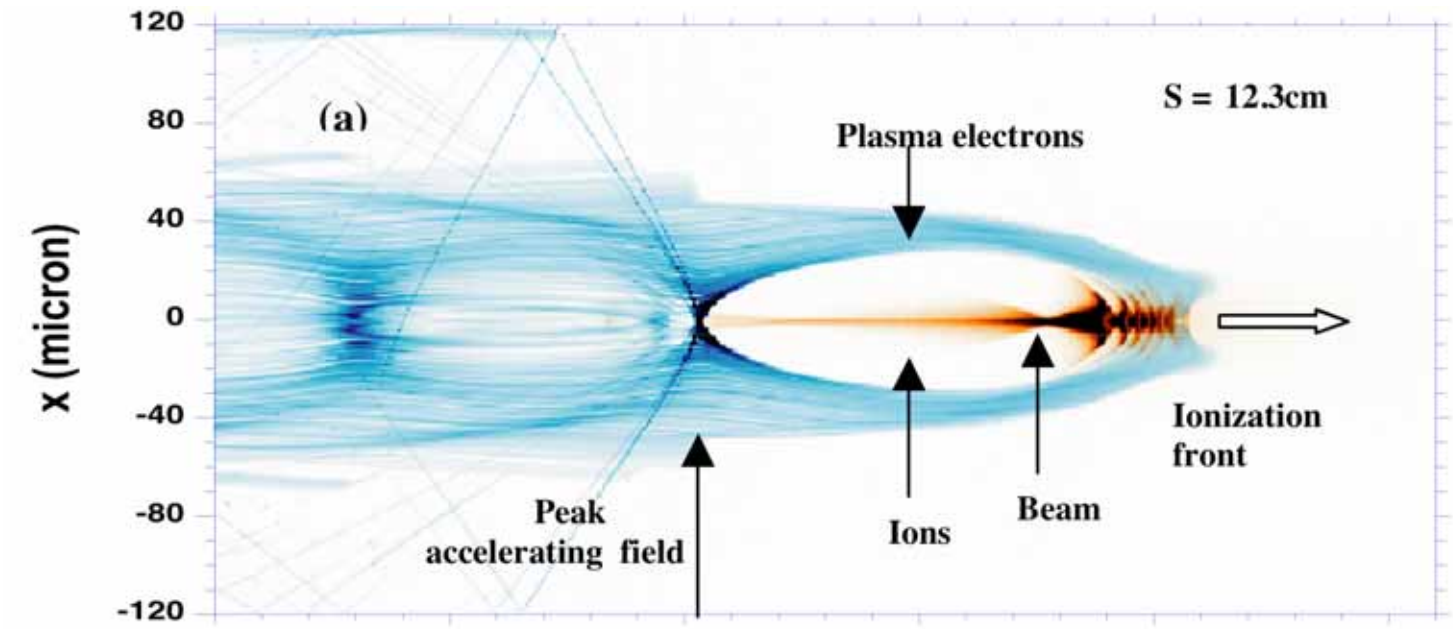
  - Limit:

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

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

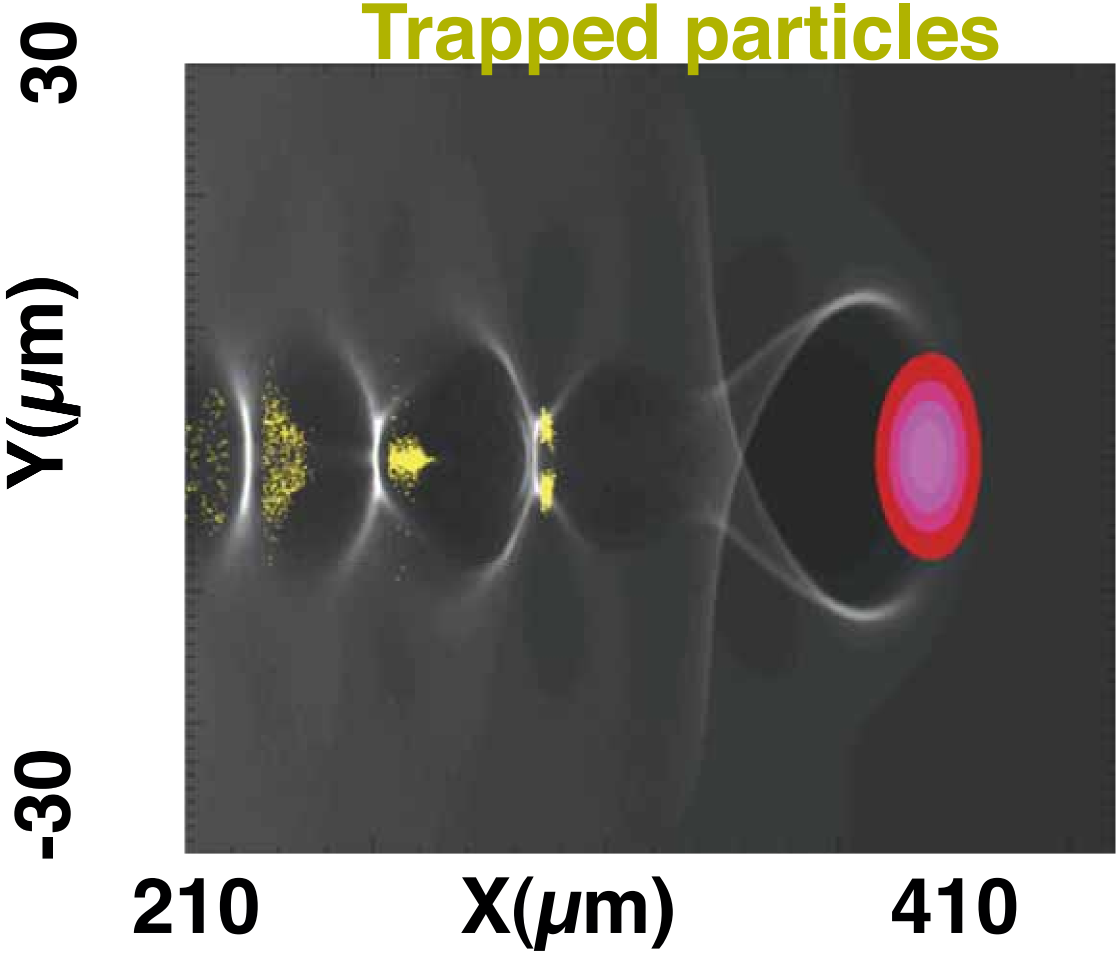
Plasma Wakes – Theory

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



Trapping of Plasma Electrons

Laser ($I>0.2I_0$), density,
Trapped particles



Cameron Geddes

Drive the Plasma Wake

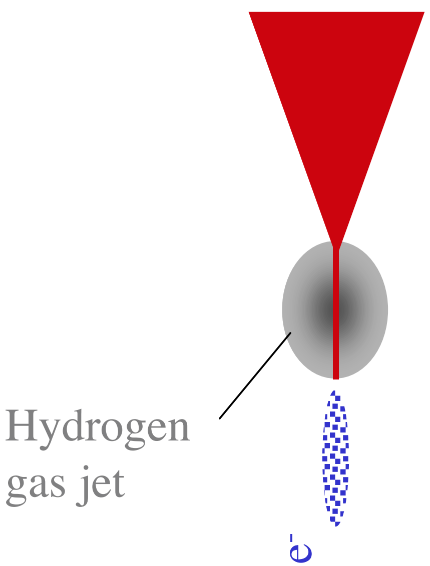
- Typical drive beam power: $\sim 10^{15}$ W = 1 TW
- Power density: $\sim 10^{24}$ W/m^2 =1 YW/m^2
- Drive the plasma wake:
  - Photons
  - Electrons

Laser-Driven Plasma Wakefield Acceleration – State of the Art 2003

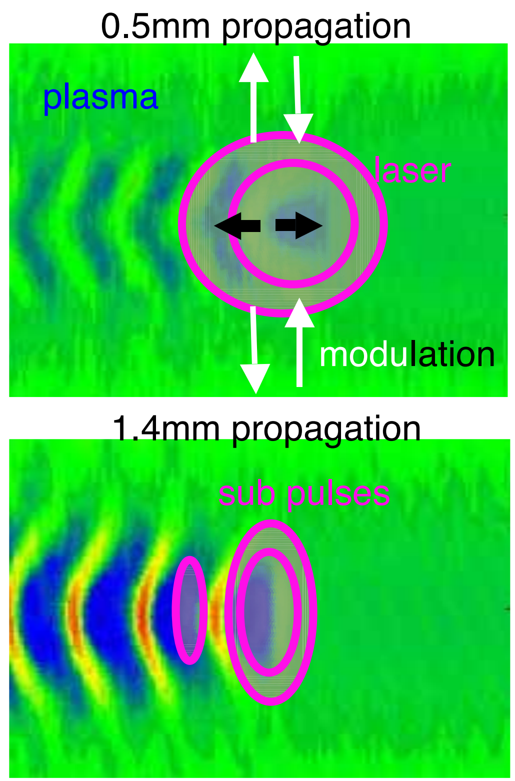
Tightly focused laser ionized gas jet & drove wake

Drive beam

10 TW, 500mJ 50fs, 10^{19}W/cm^2

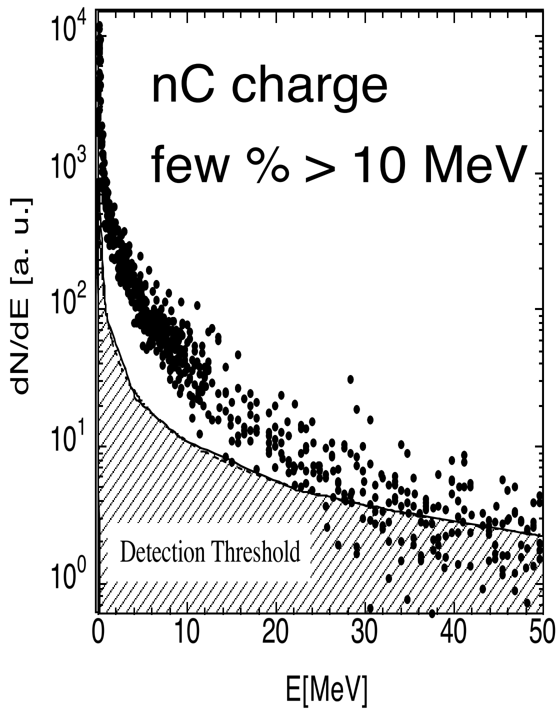


Laser self modulation to plasma period drives wake to trapping



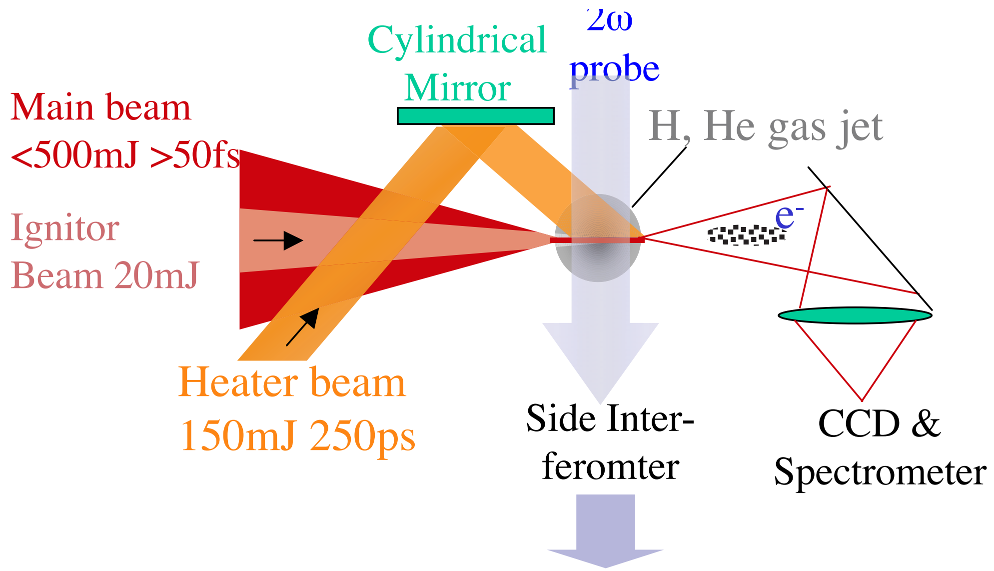
Enlarged wake

Acceleration to 50 MeV in ~1 mm



Cameron Geddes

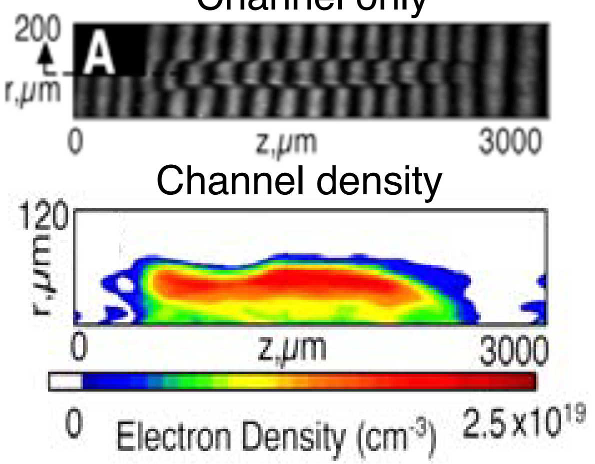
Hydrodynamic Plasma Channels



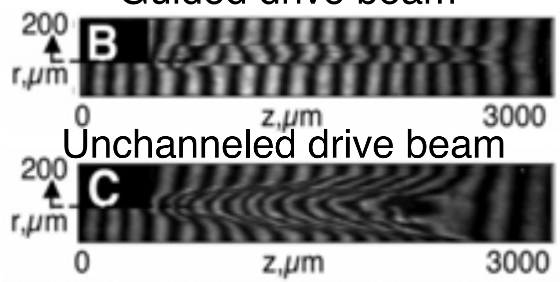
Plasma ionized by ignitor
heated by heater

Expansion shock yields
guiding profile

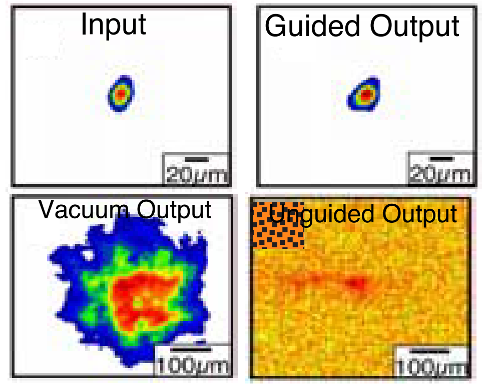
<u>Channel profile</u>



<u>No channel leakage</u>



<u>Guiding over > 10 ZR ~ 2mm relativistic intensity</u>

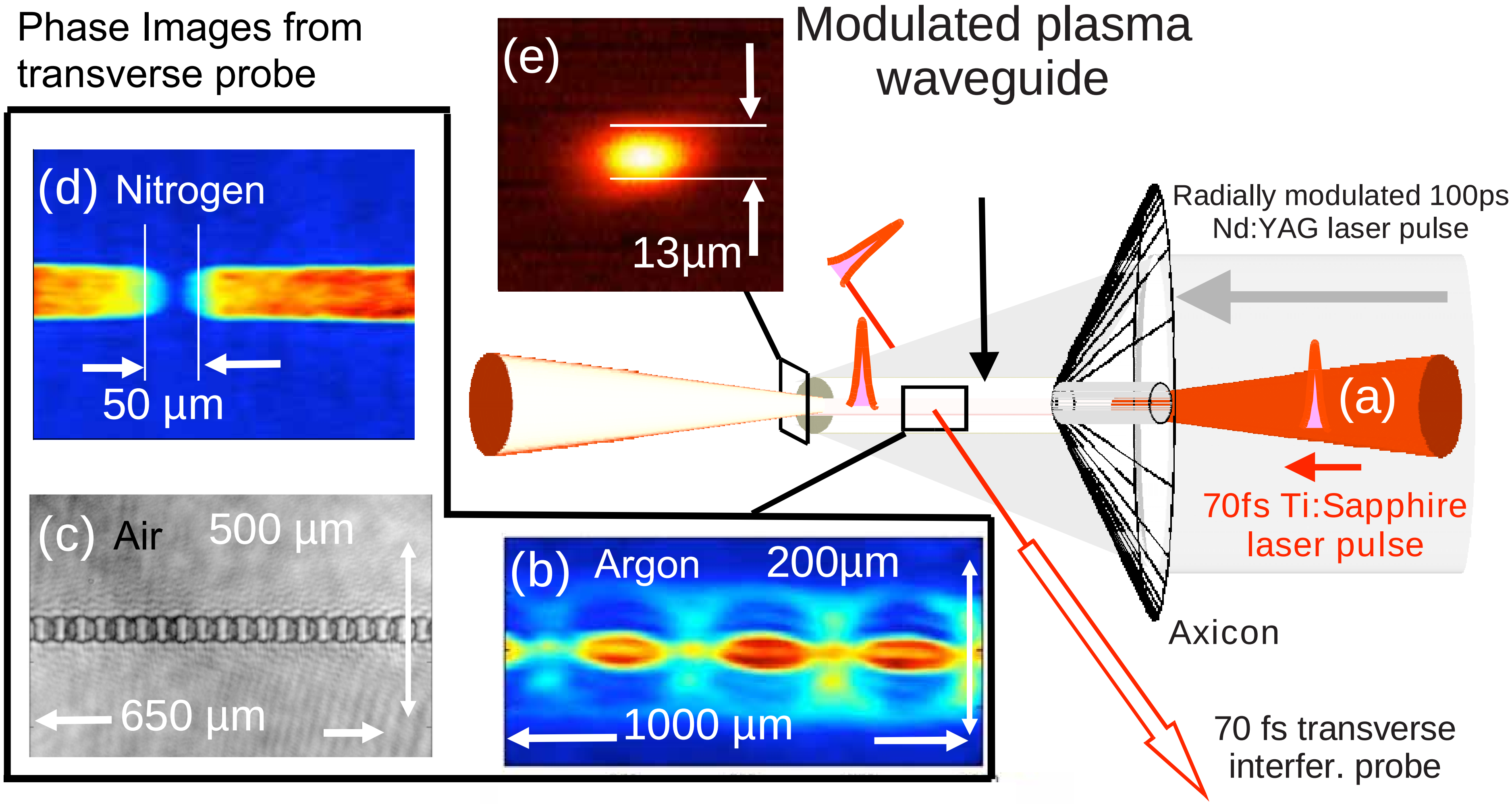


High quality guiding up to 4TW

C.G.R. Geddes et al, PRL, 2005

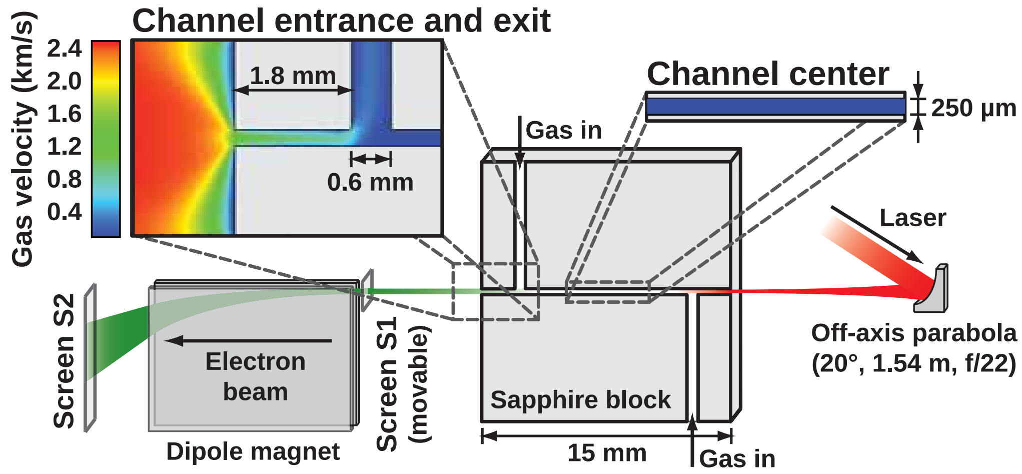
Cameron Geddes

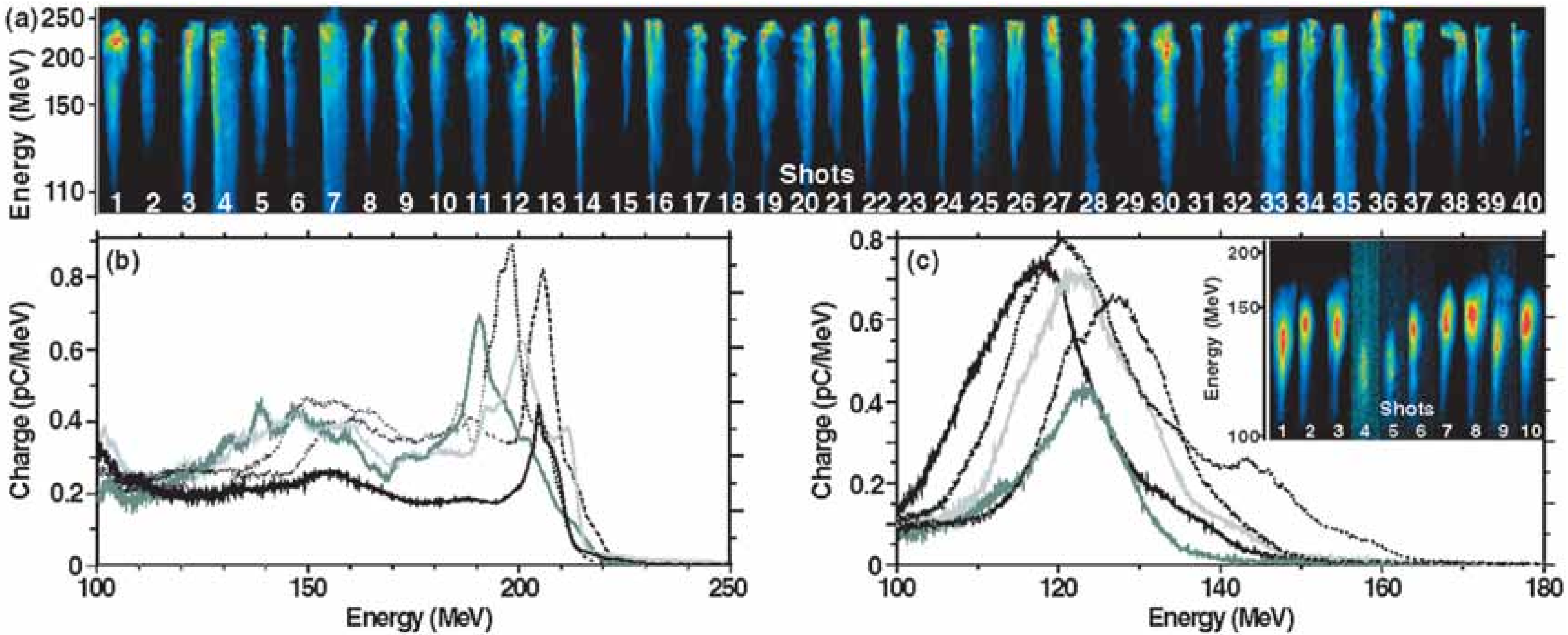
Plasma Waveguides



Andrew York

Plasma Acceleration in Capillaries

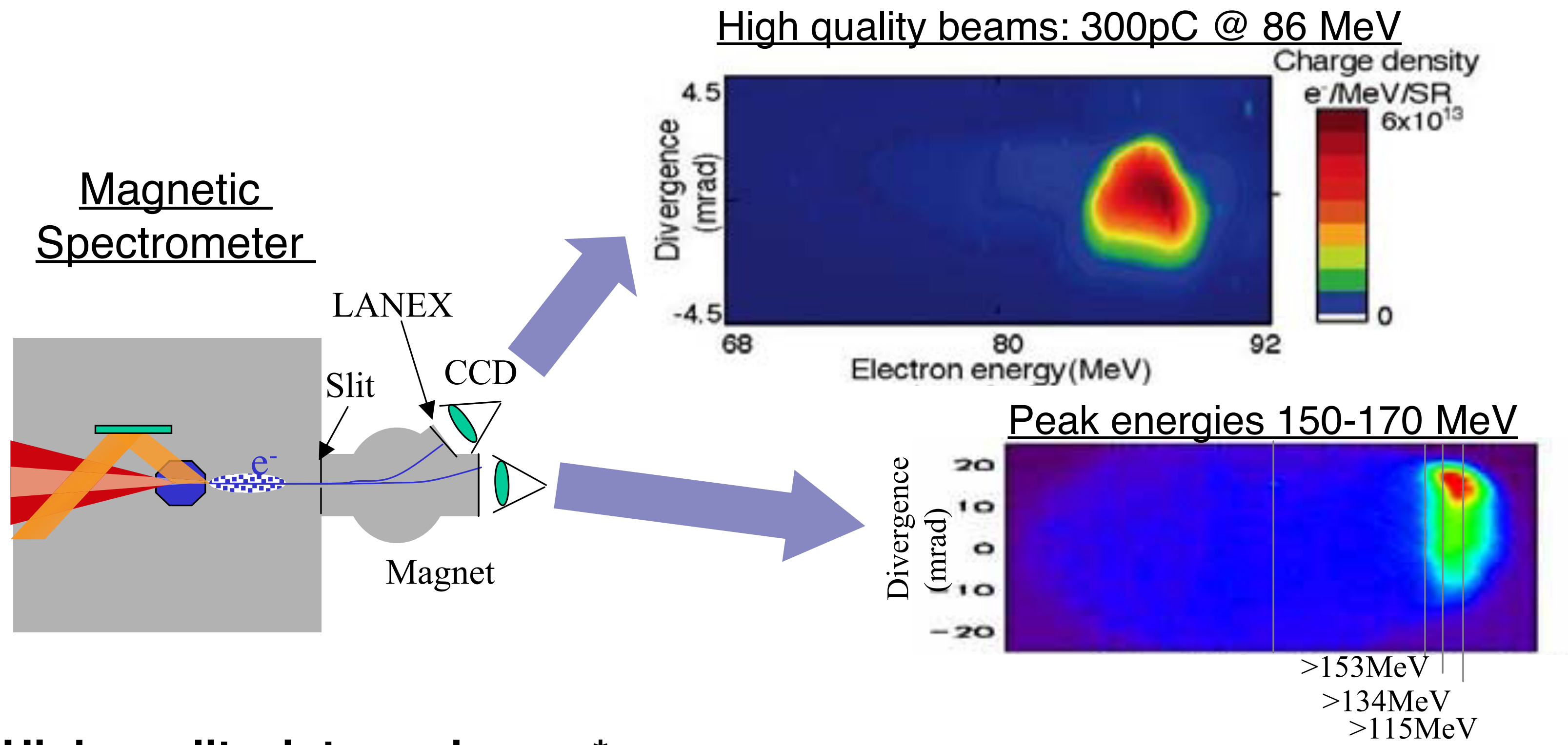




Jens Osterhoff,
Stefan Karsch

“Monoenergetic” Particle Bunches

Laser = 9TW, 50 fs, Z_R=200μm **Plasma = 1.8e19cm^{-3}, 1.7mm**



High quality, intense beams*

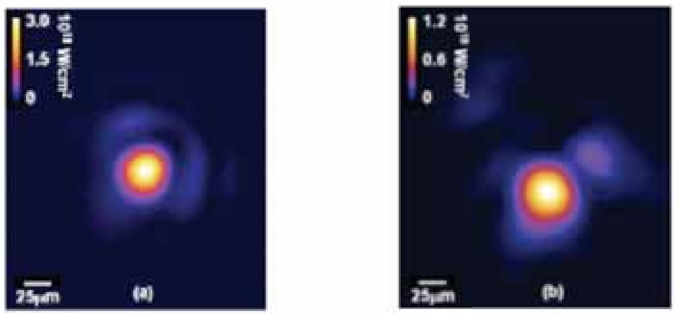
2e9 electrons — Divergence 3mrad

Energy Spread<4MeV — Normalized Geometric Emittance 2π mm-mrad

Cameron Geddes

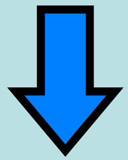
Particle Energies up to 1 GeV

Waveguide:
Guiding of 40 TW laser pulses:
- in capillary discharge waveguide
- over 33 mm of plasma

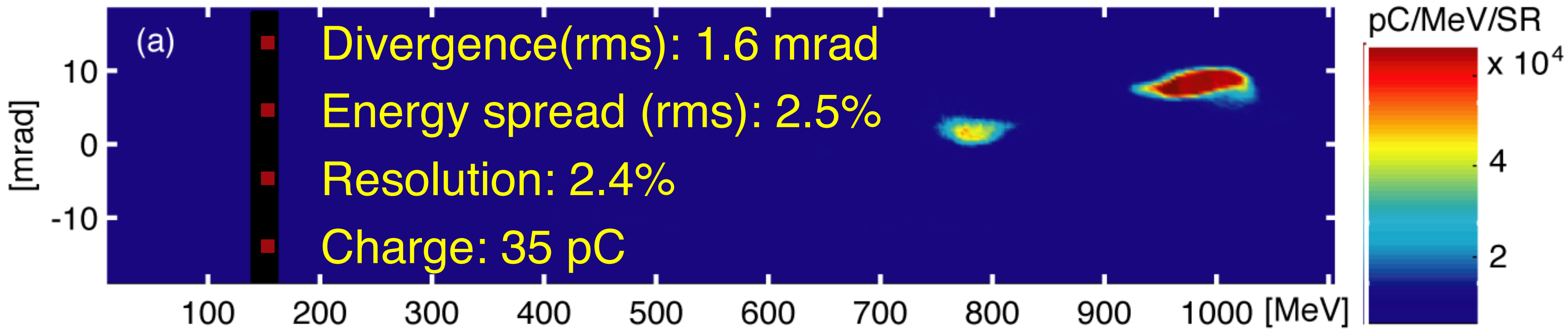


Input spot   Exit spot

- a_0 ~ 1.46 (40 TW, 37 fs)
- n_e ~ 4x10^{18} cm^{-3}, P_{crit} ~ 7 TW

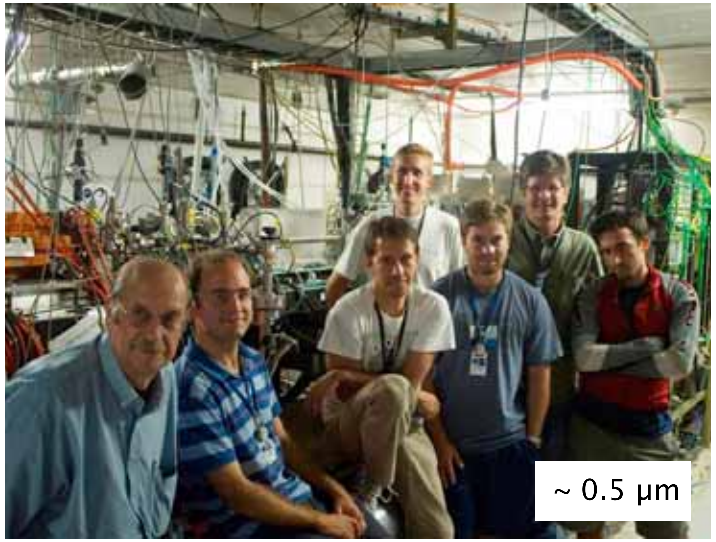


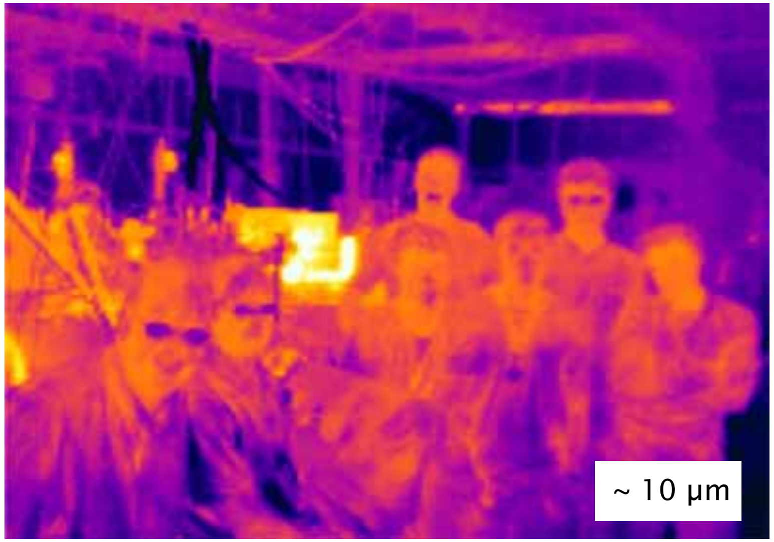
1 GeV BEAM



Cameron Geddes

Plasma Wakefield Acceleration with Electron Bunches



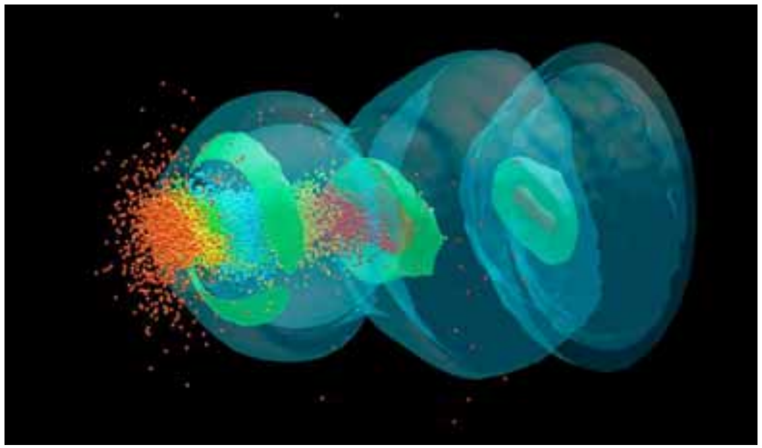


Energy source: electron beam

- 42 GeV particle energy
- 3.2 nC bunch charge
- Beam power: $\sim 10^{15}$ W = 1 TW
- Power density: $\sim 10^{24}$ W/m^2 =1 YW/m^2

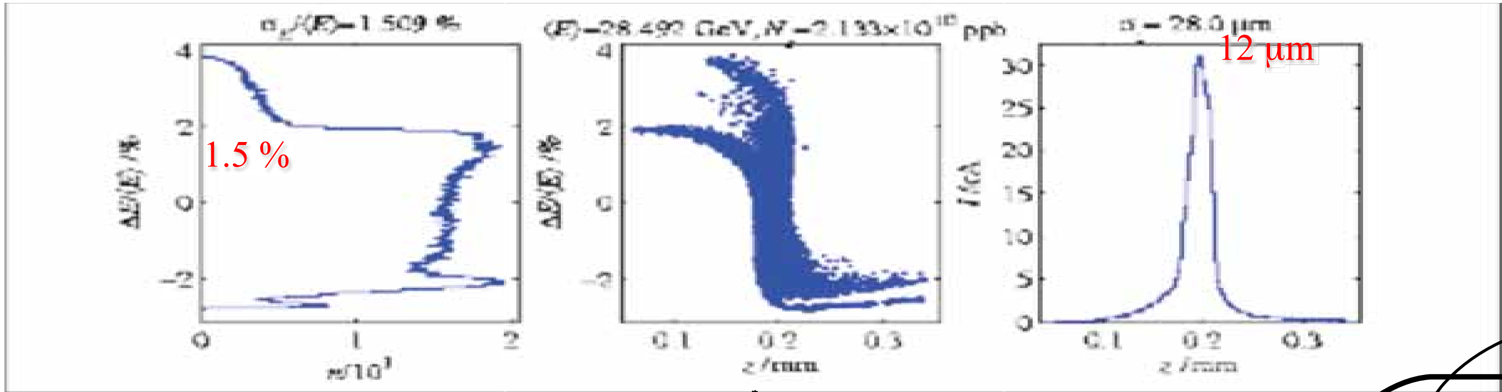
Plasma source: Lithium oven

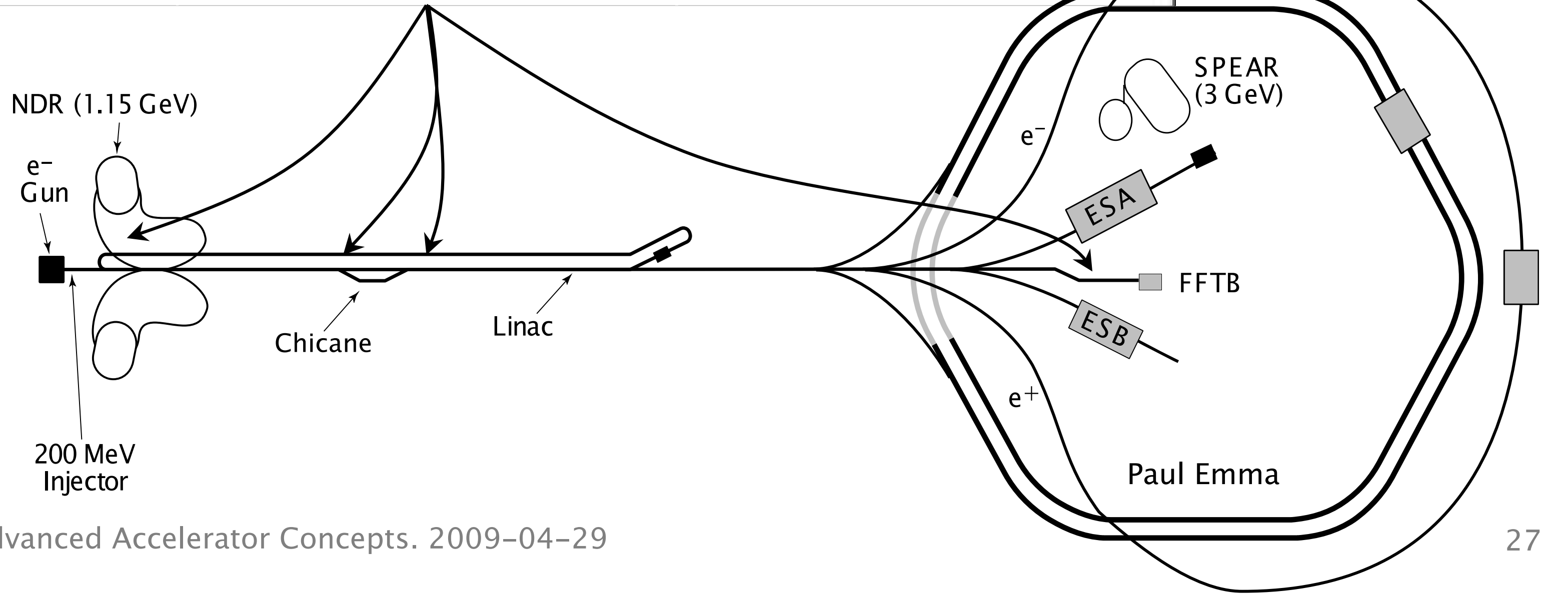
- Particle density: $\sim 10^{23}$ / m^3



Plasma Wakefield Acceleration at SLAC

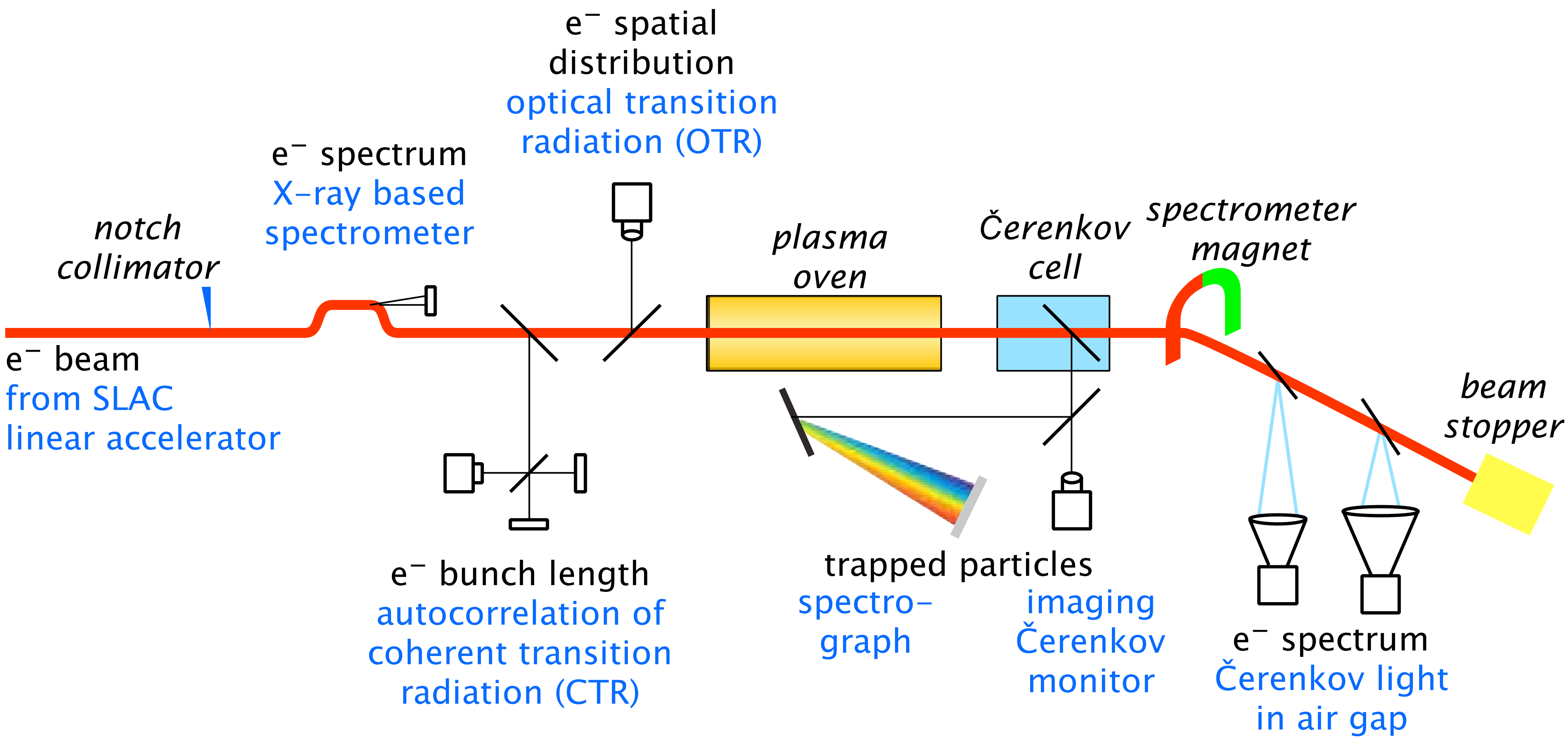
Acceleration, compression and focussing of bunches to reach a peak power density of 5 YW/m²



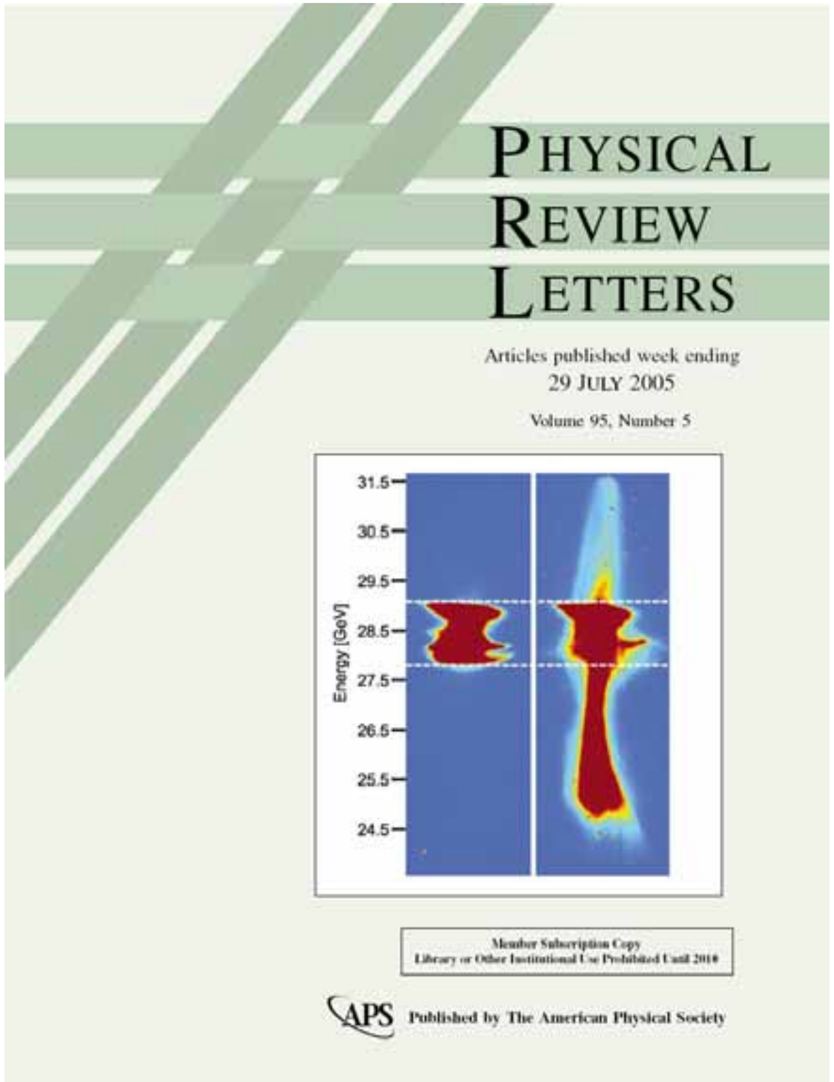


P. Emma et al., PAC (2005)

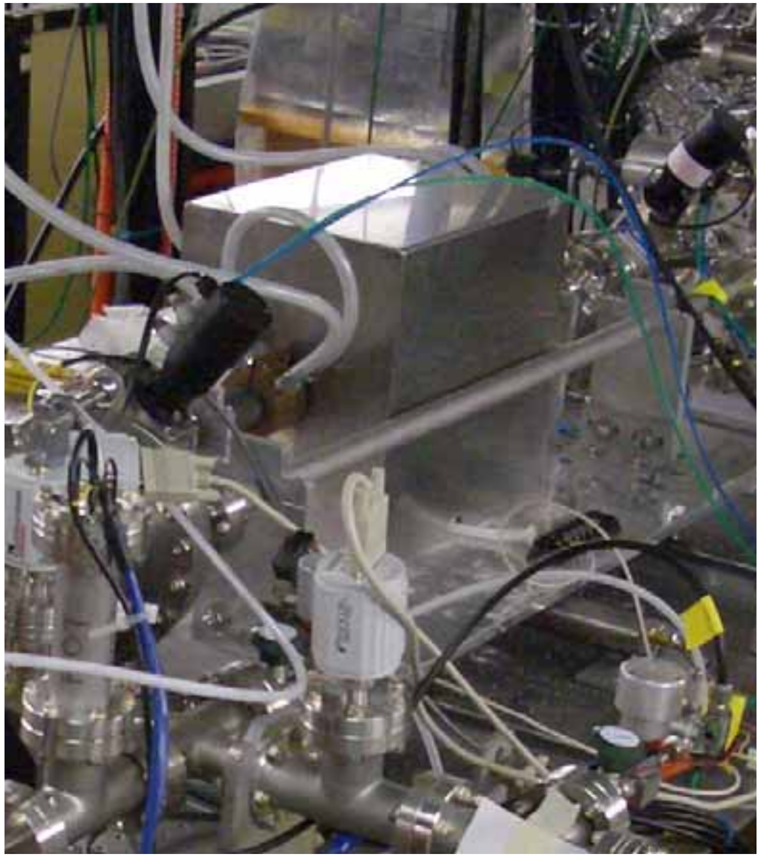
Experimental Setup



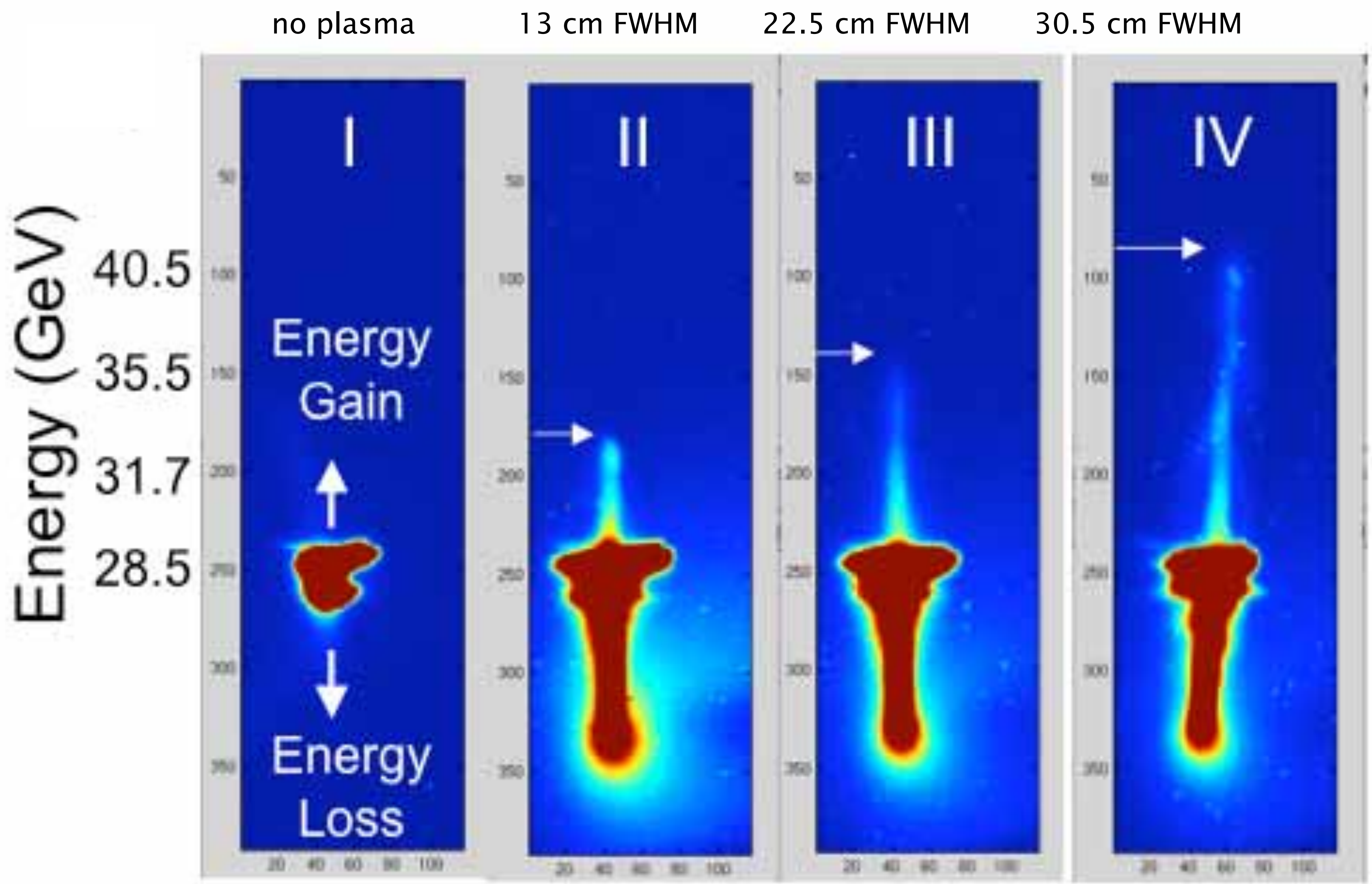
First Results



More than 3 GeV energy gain in 10 cm plasma length

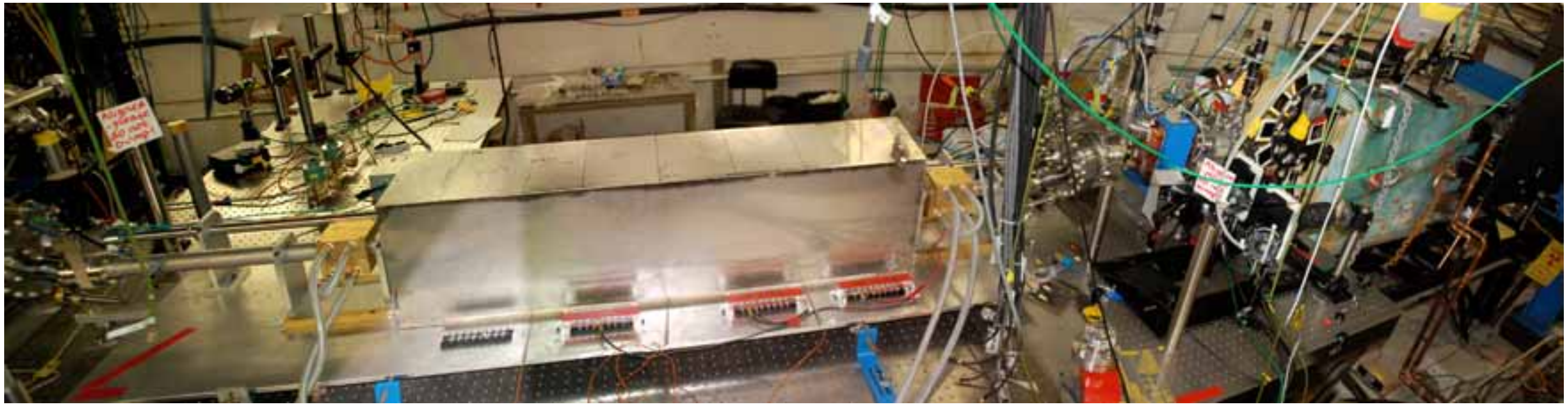


Increasing the Plasma Length to 30.5 cm



Patric Muggli

1 m Long Plasma



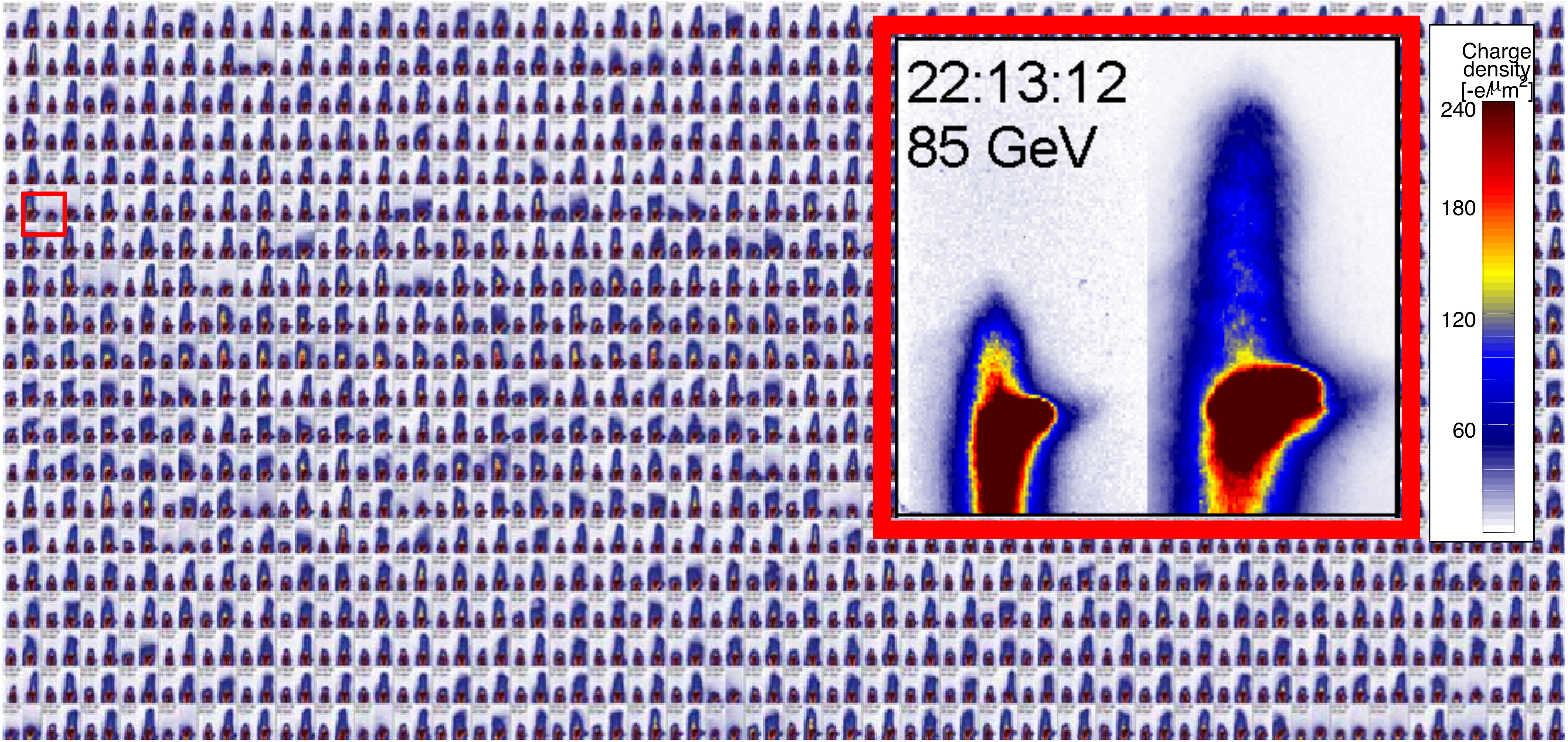
Longer plasma oven

New spectrometer

Diagnostics for low-energy particles

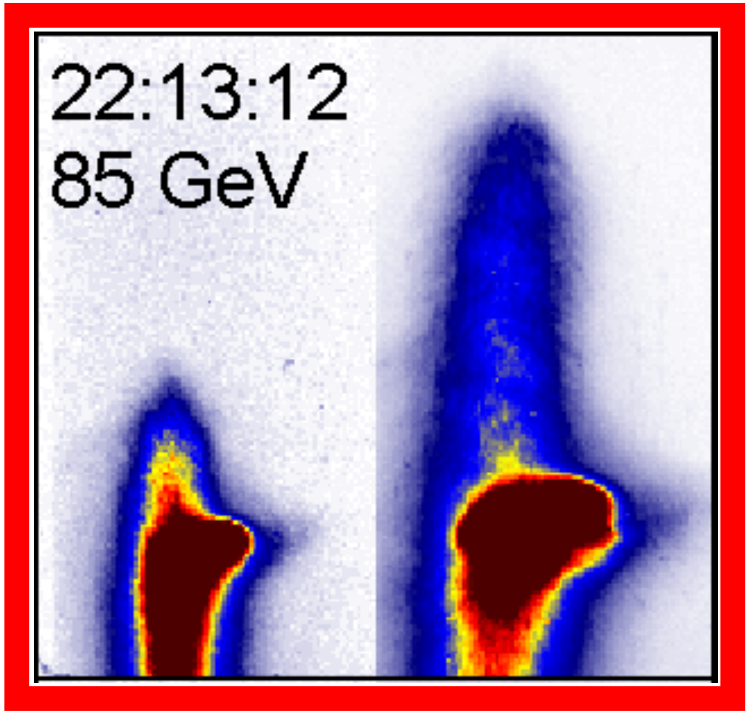
Increased the energy in the drive beam

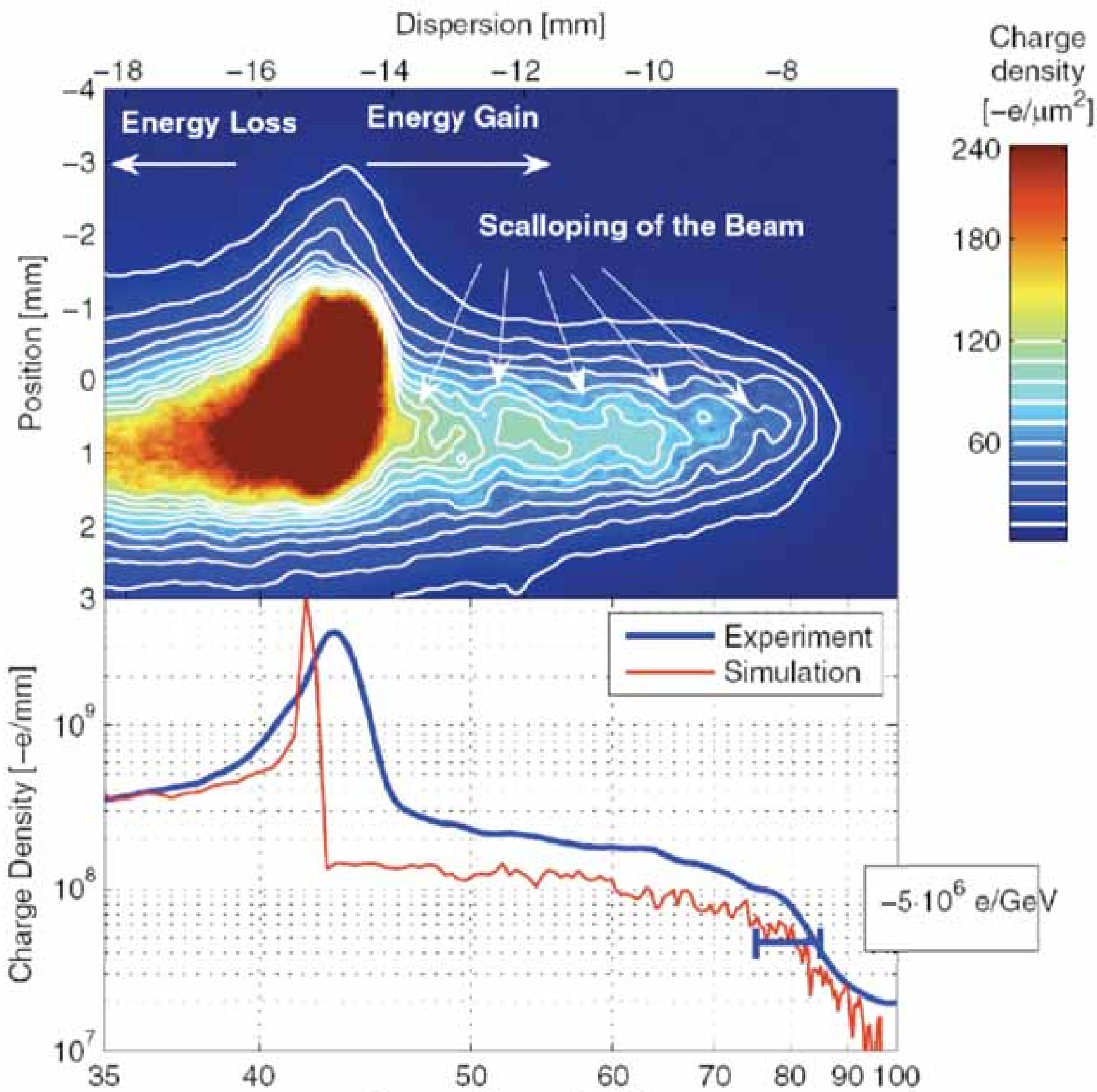
Images from both Spectrometer Planes 800 Consecutive Events



Energy Doubling

- Plasma length: 85 cm
- Density: $2{,}7 \bullet 10^{17}\ \mathrm{cm}^{-3}$
- Entrance energy: 42 GeV
- Peak energy: 85 GeV



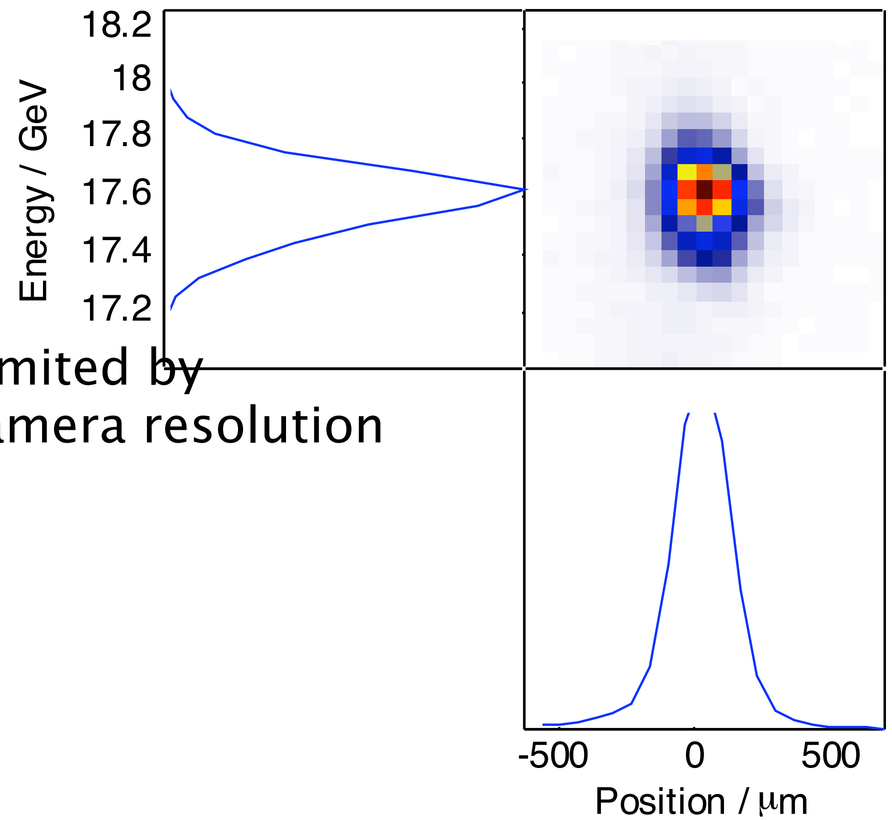


I. Blumenfeld et al., Nature 445, p. 741 (2007)

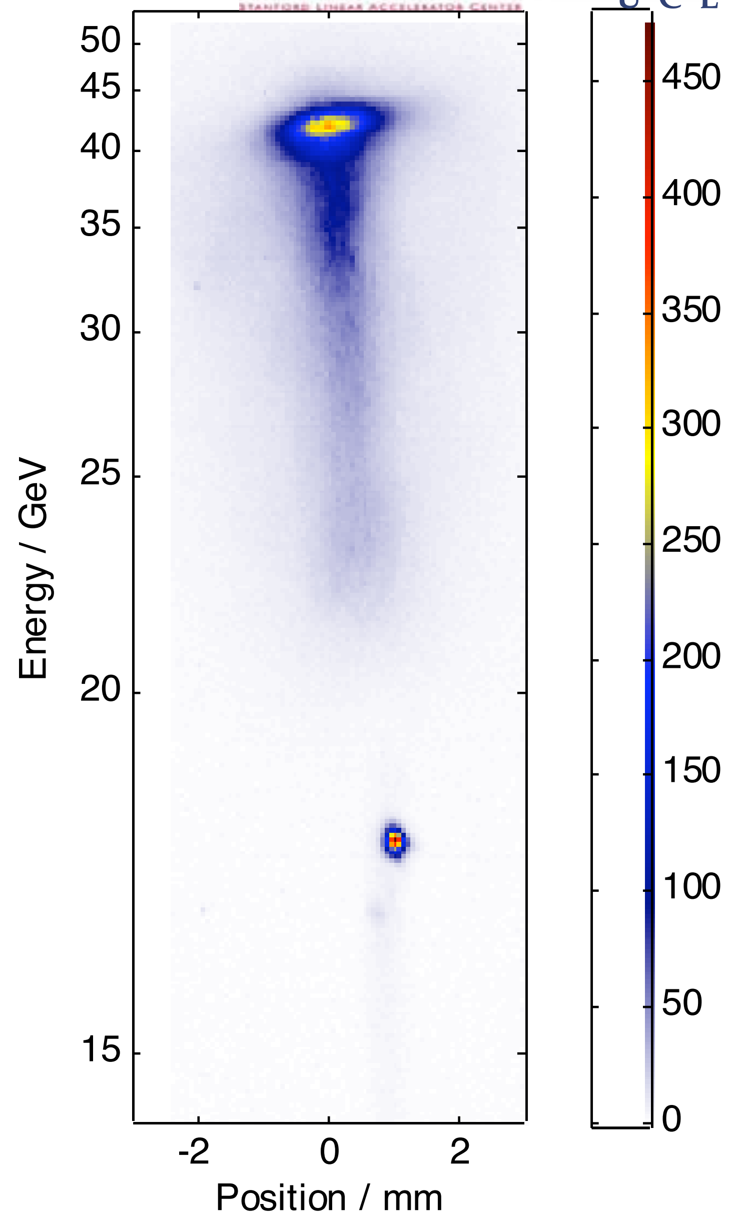
Trapping of Plasma Electrons

- Very small angle of emission at the plasma exit:

  $\langle \dot{x}^2 \rangle \lessapprox 33\,\mu\text{rad}$

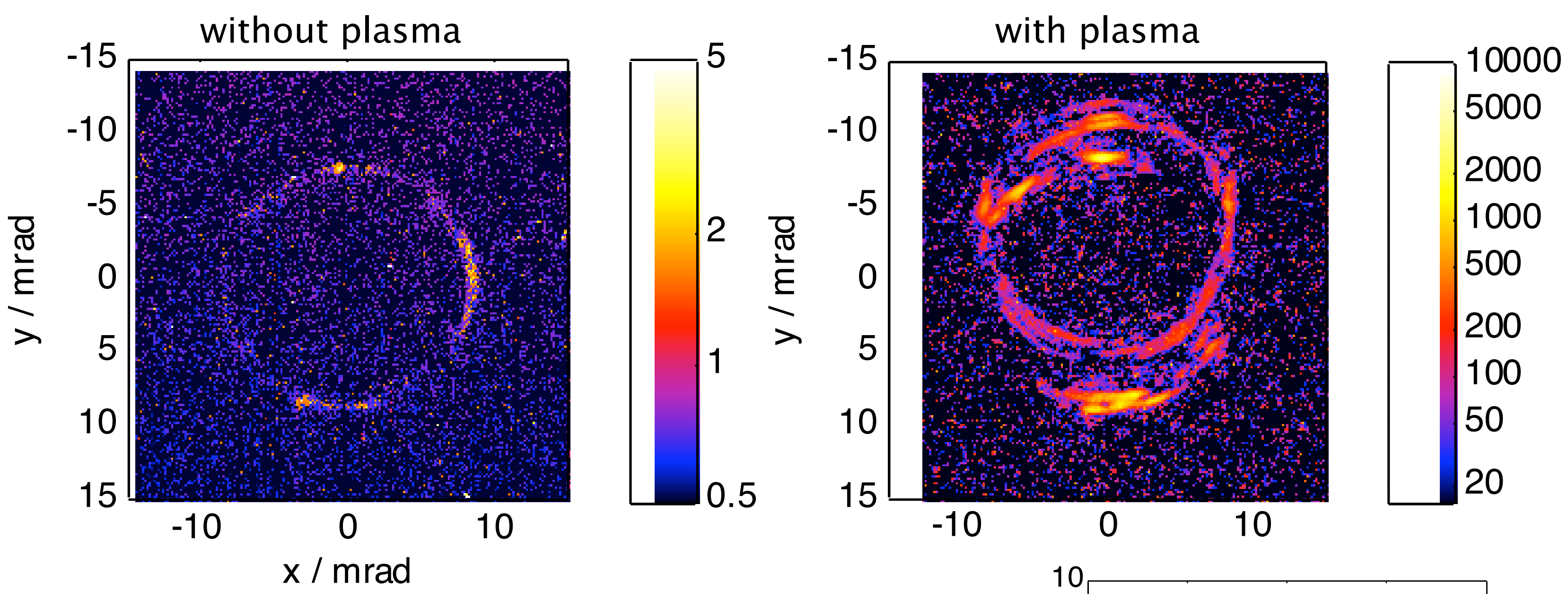


- Limited by camera resolution



Trapping of Plasma Electrons (Short Plasma)

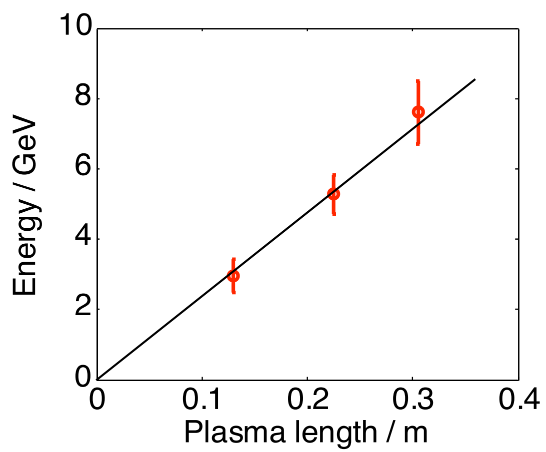
- Imaging the angle of Čerenkov radiation
- Light intensity is increased by more than three orders of magnitude



- Particle energy E is proportional to plasma length L:

$$E \approx 25\,\mathrm{GV/m} \cdot L$$

N. Kirby et al., AIP Conf Proc 877 (2006)



Neil Kirby

There is More to Accelerating Structures than the Accelerating Field

- Power sources
- Beam loading
- Emittance preservation

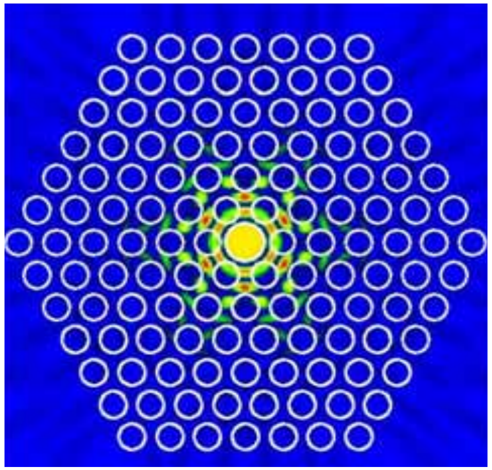
There is Much More to an Accelerator than Accelerating Structures

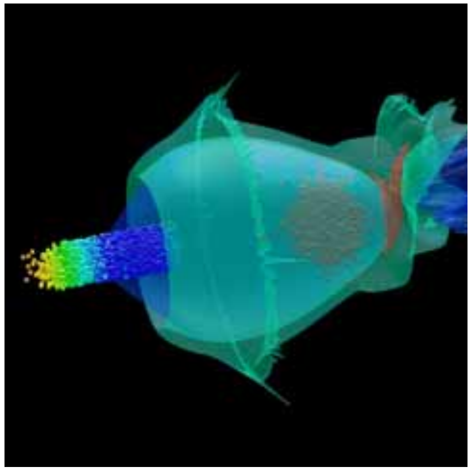
- Particle sources (injectors)
- Bend magnets for storage rings
- Focusing, beam dynamics
- Detectors

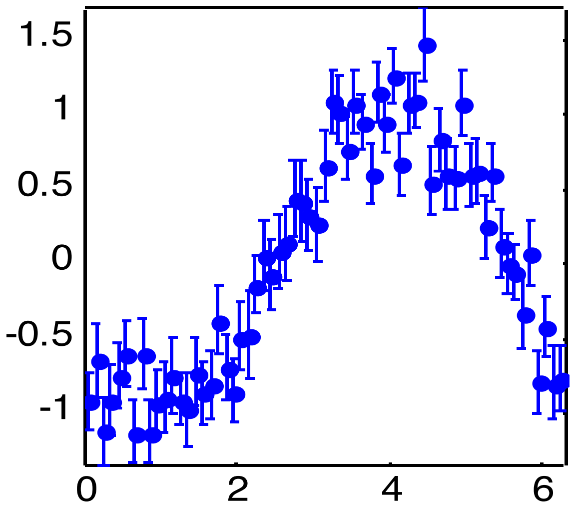
Demonstrated Once does not mean Available for Users

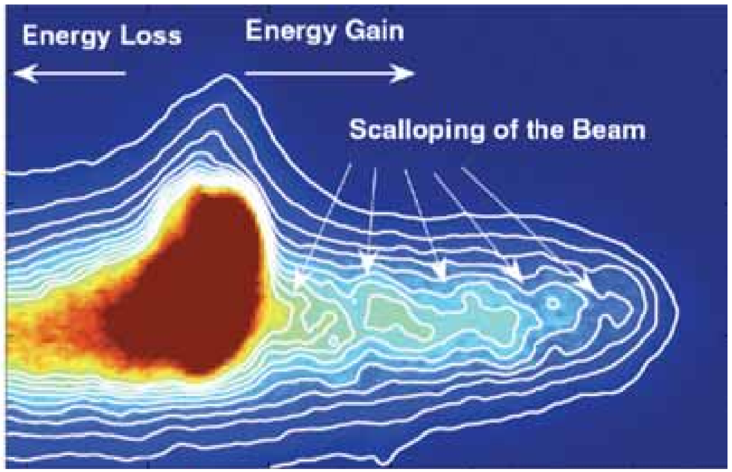
But

- Future particle accelerators cannot be built with today's technologies

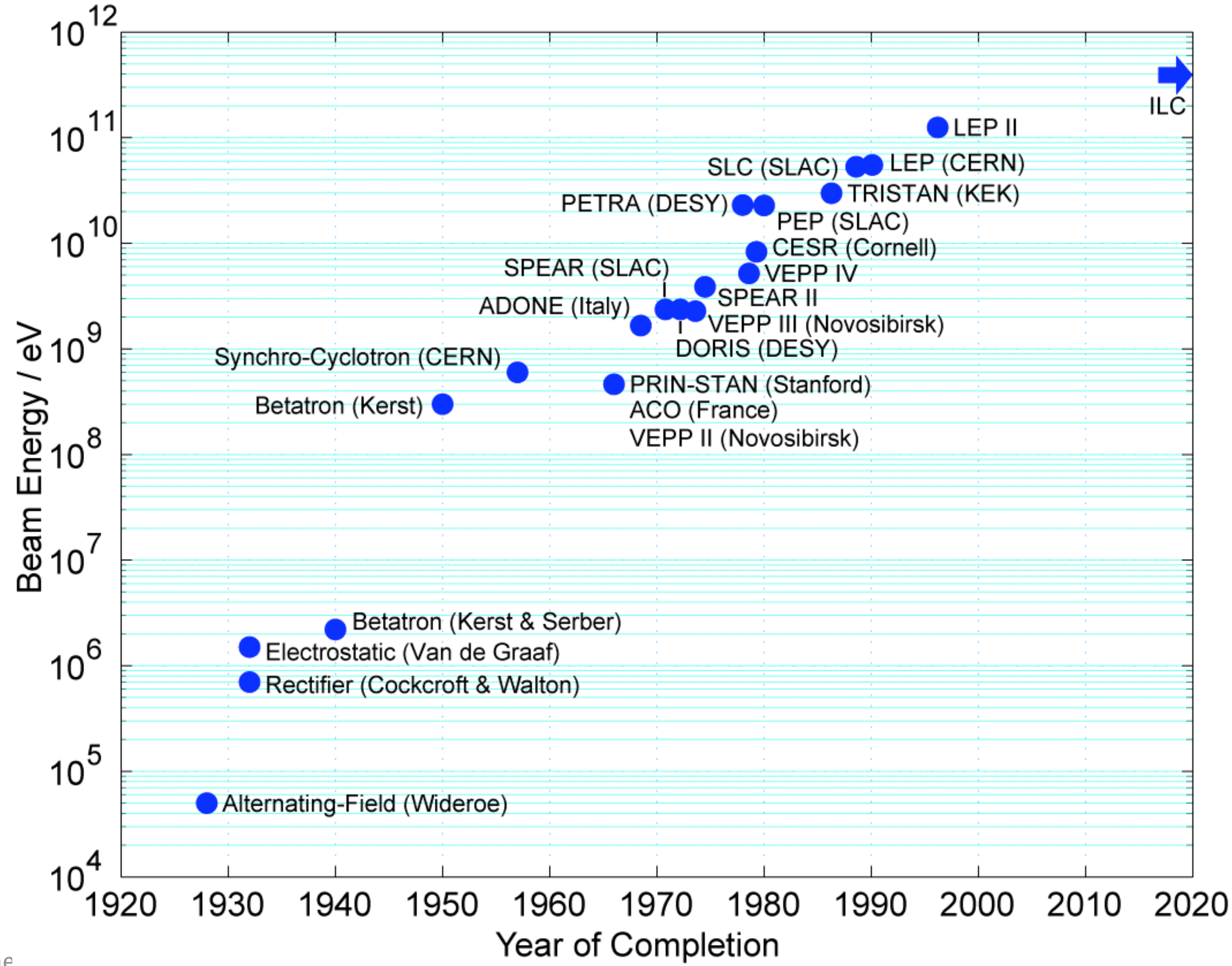




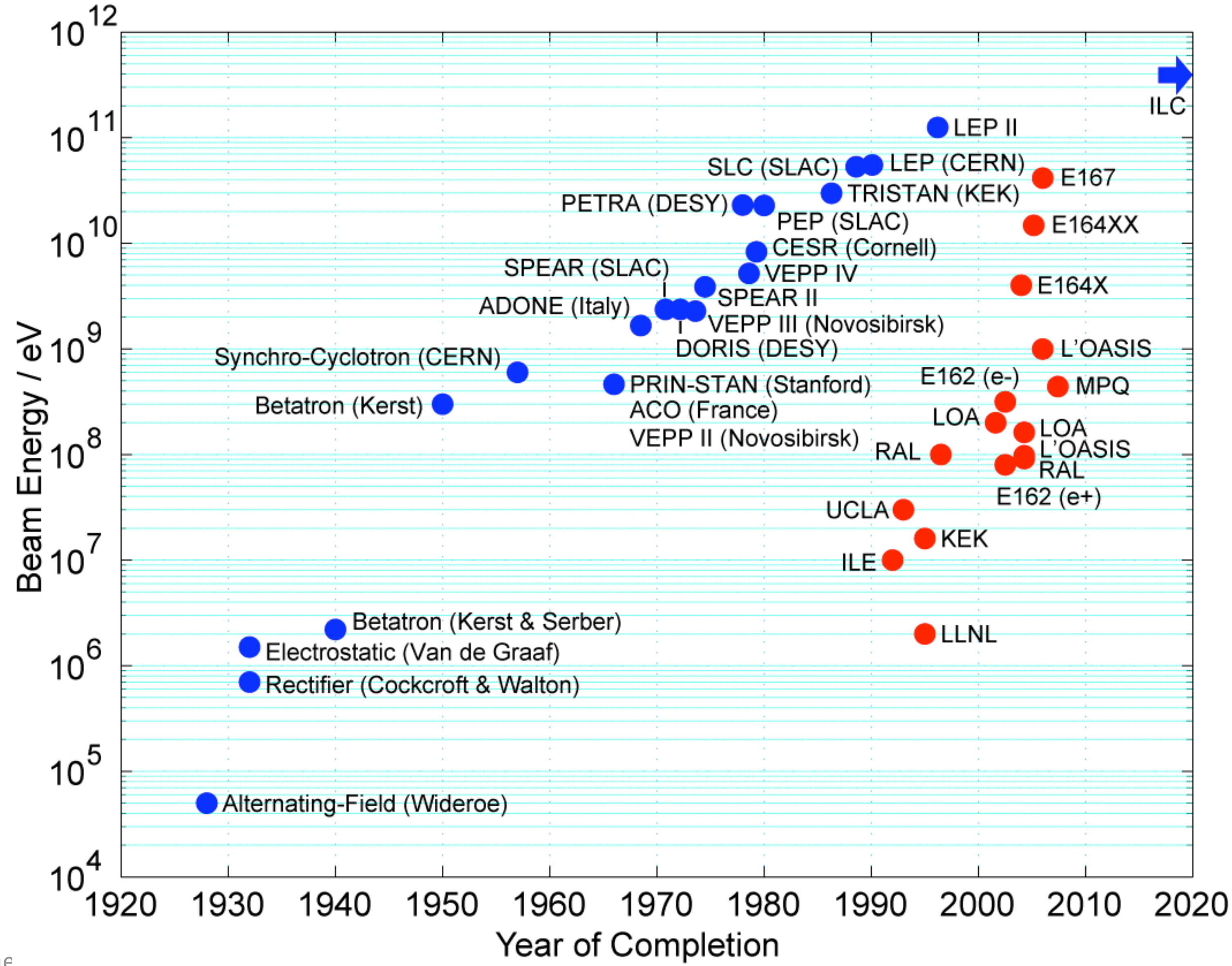




Livingston Plot



An Unfair Comparison



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  - S. Deng, T. Katsouleas, P. Muggli* and E. Oz (USC)

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http://people.web.psi.ch/ischebeck