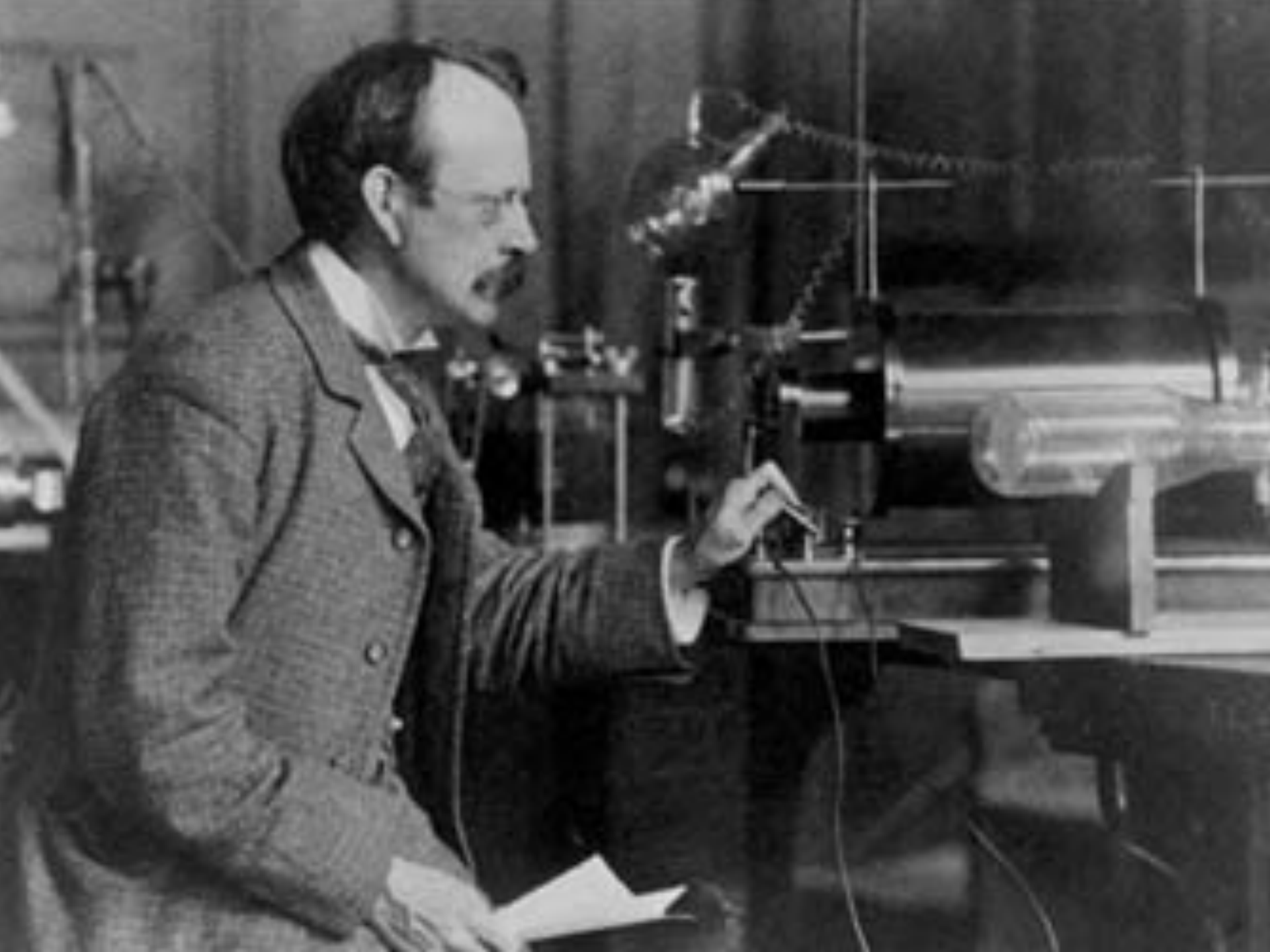
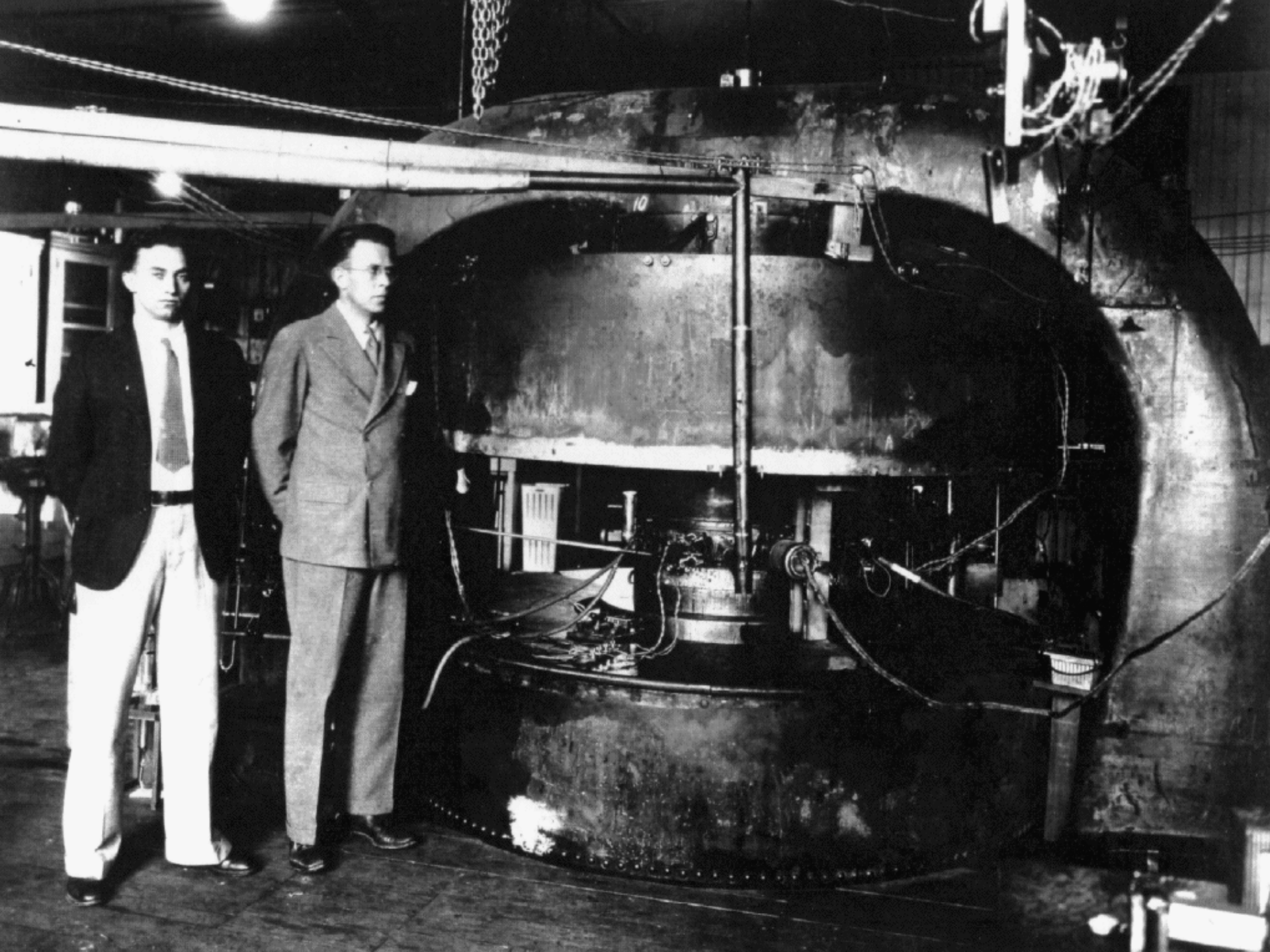
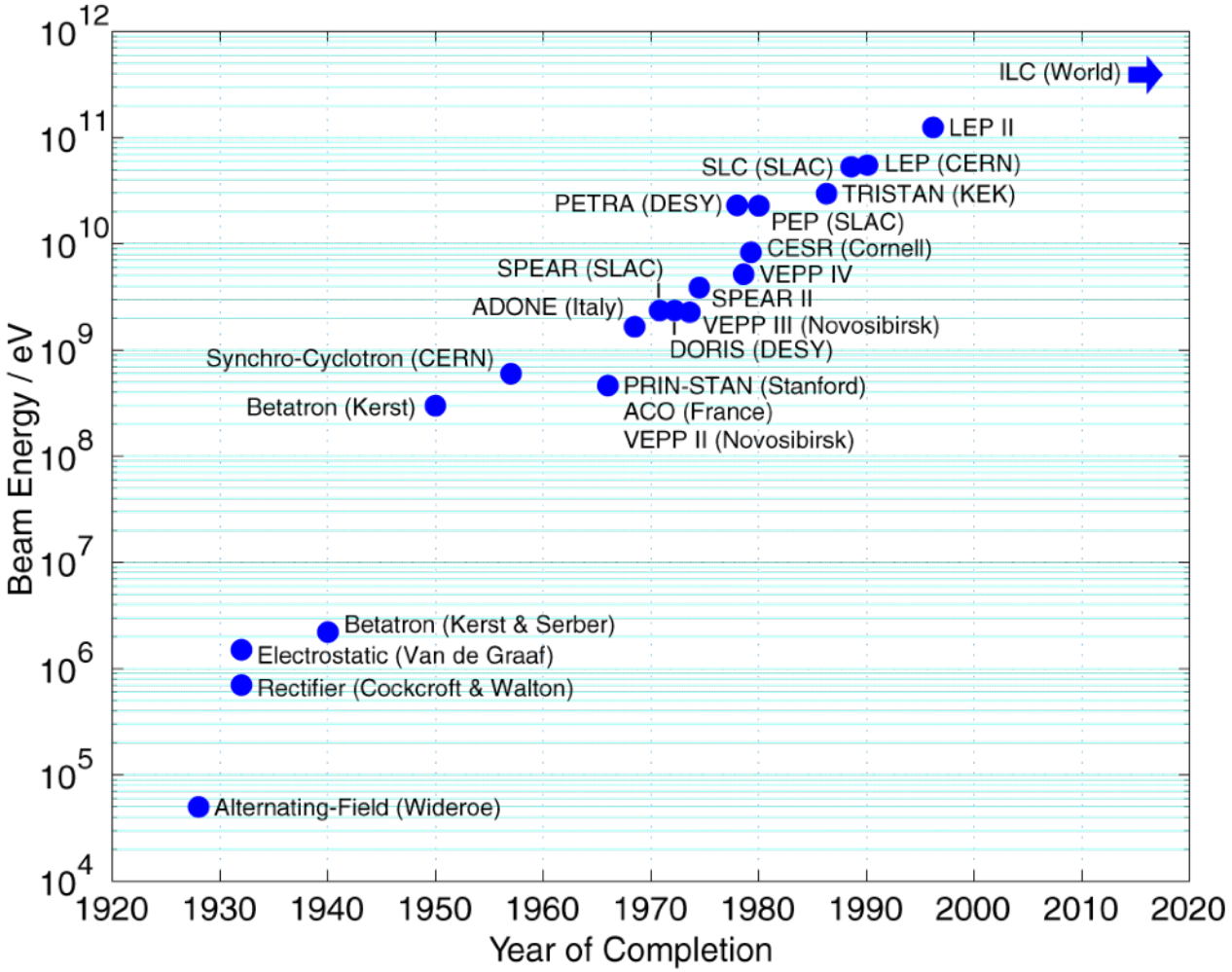
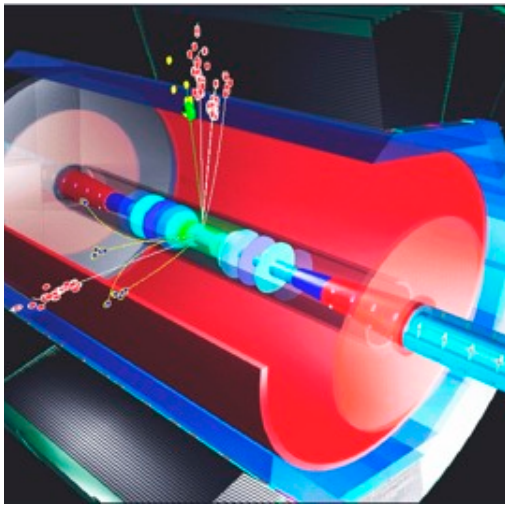


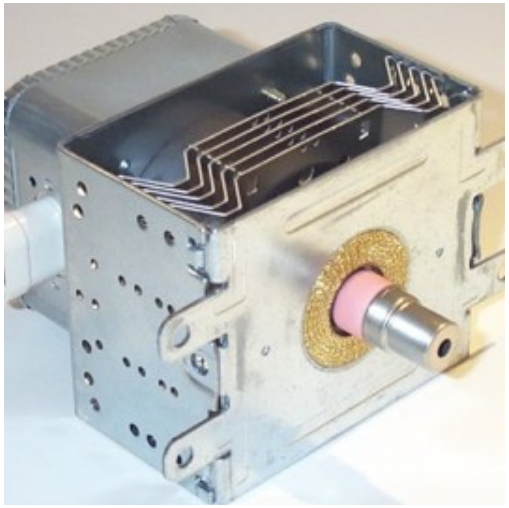


History of Electron Accelerators: Livingston Plot



Applications of Accelerators

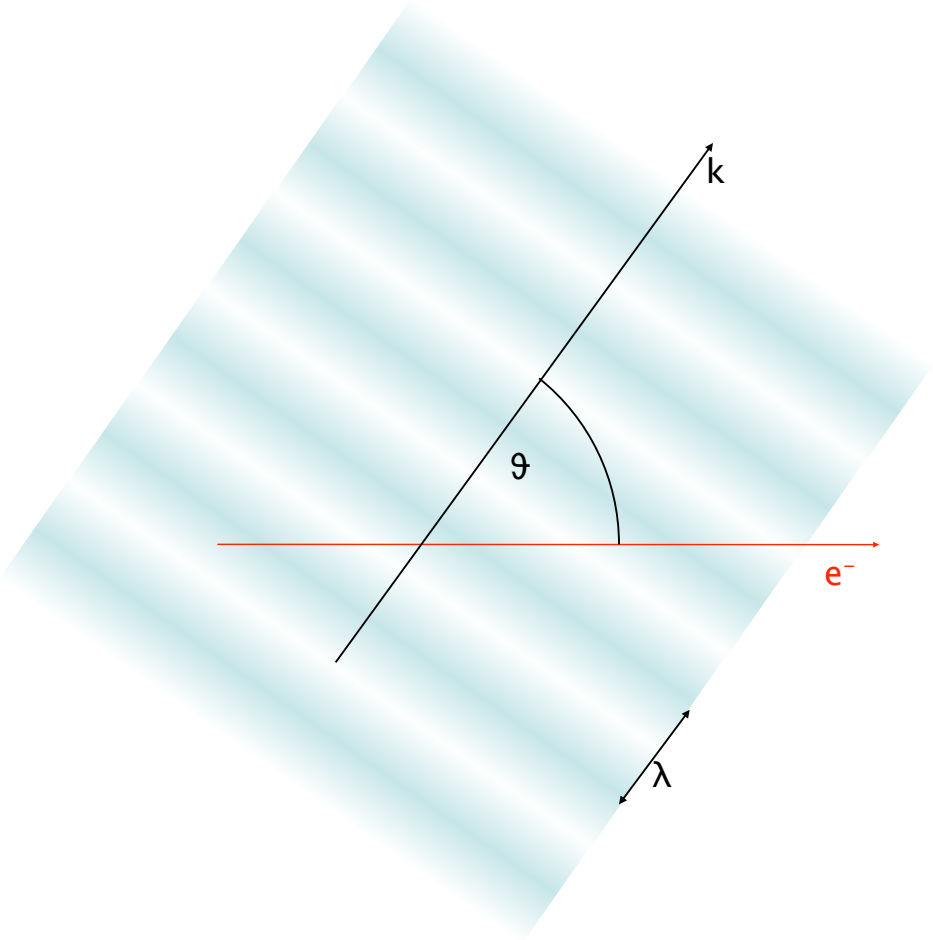




How to Accelerate Charged Particles

Assume:

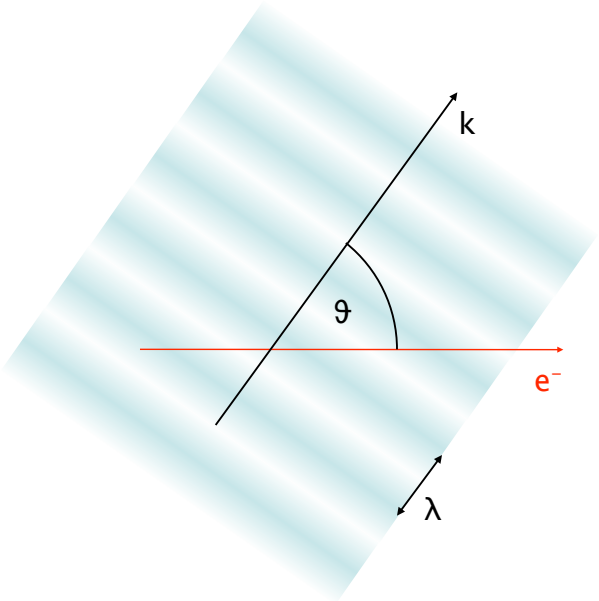
- an ultrarelativistic particle of charge e
- moving along the z axis
- accelerated by a plane electromagnetic wave that propagates at an angle ϑ to the z axis



Then:

- Position of the electron

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



- Electric field

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

- Energy gradient

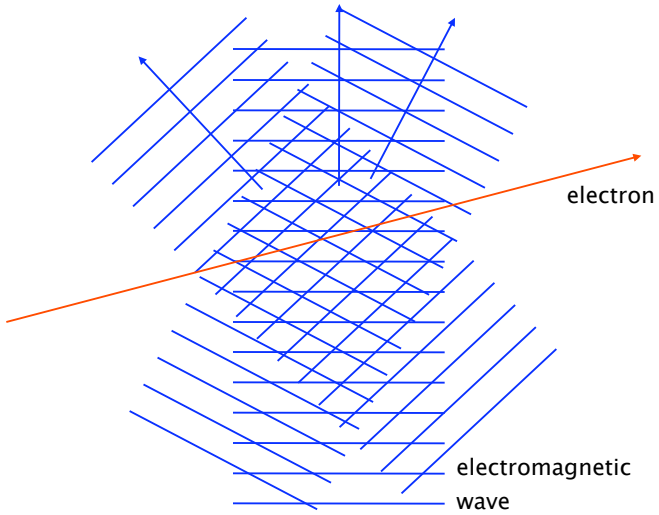
$$\frac{\Delta W}{L} = \frac{\int_L eE_{\parallel} dz}{L} = \frac{\int_L \sin\vartheta \cos(kz(1-\sec\vartheta))dz}{L}$$

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

Lawson Woodward Theorem

- Every wave in far field can be written as a superposition of plane waves
- The Lawson-Woodward Theorem states:
  - the total acceleration
    - of ultrarelativistic particles
    - by far-field electromagnetic waves
  - is zero

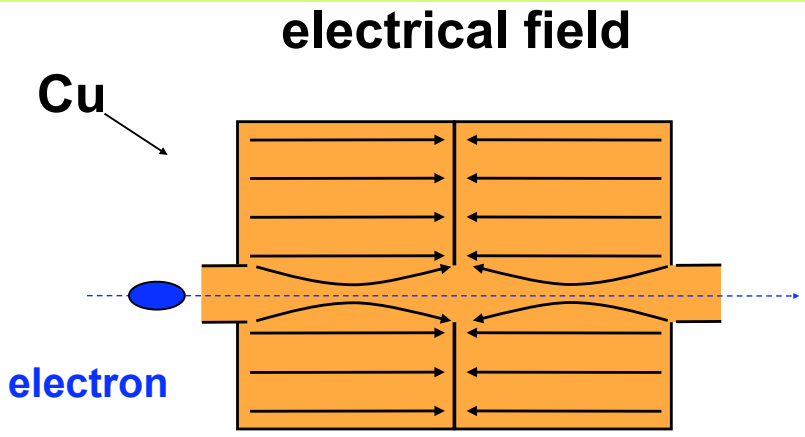
⇒ Need near-field structures



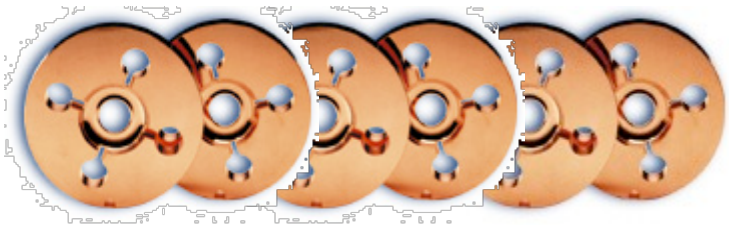
Woodward, J. IEE 93 (1947)
Lawson, IEEE Trans. Nucl. Sci. 26 (1979)
Palmer, Part. Accel. 11 (1980)

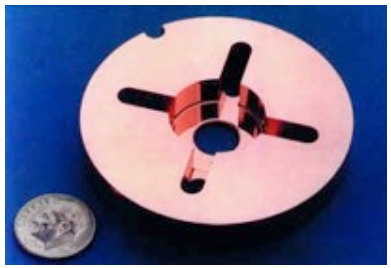
RF Acceleration

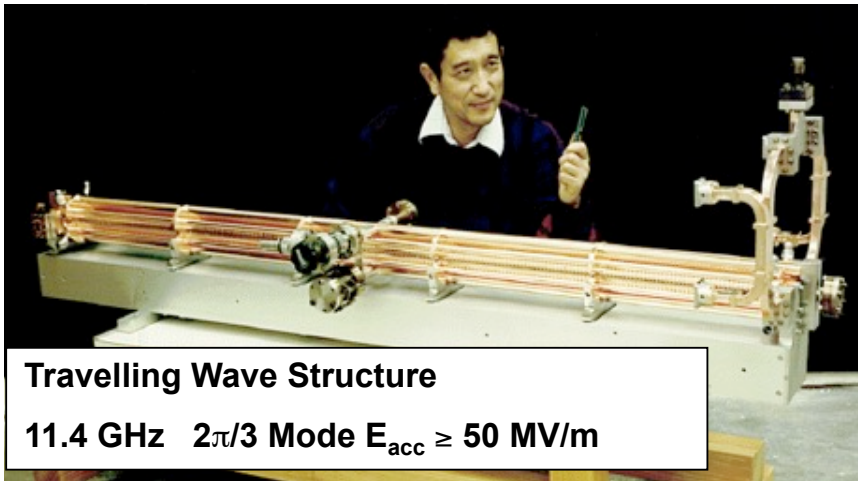
- Using a resonant cavity at radio frequencies (RF) (~GHz)
- Electromagnetic field provided by external source (e.g. klystron)



Resonating RF Cavity

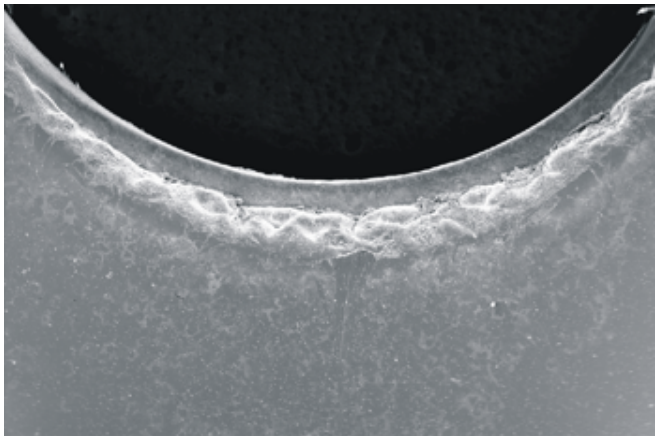




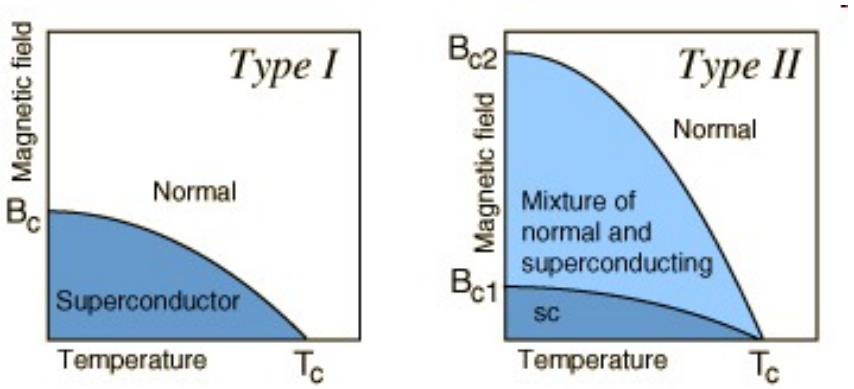


Limits to the Accelerating Field

- Normal-conducting accelerators
  - Breakdown on the surface

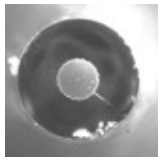
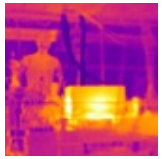


- Superconducting accelerators
  - Critical magnetic field



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

Metallic Structures

> Transformation of far-field into accelerating field

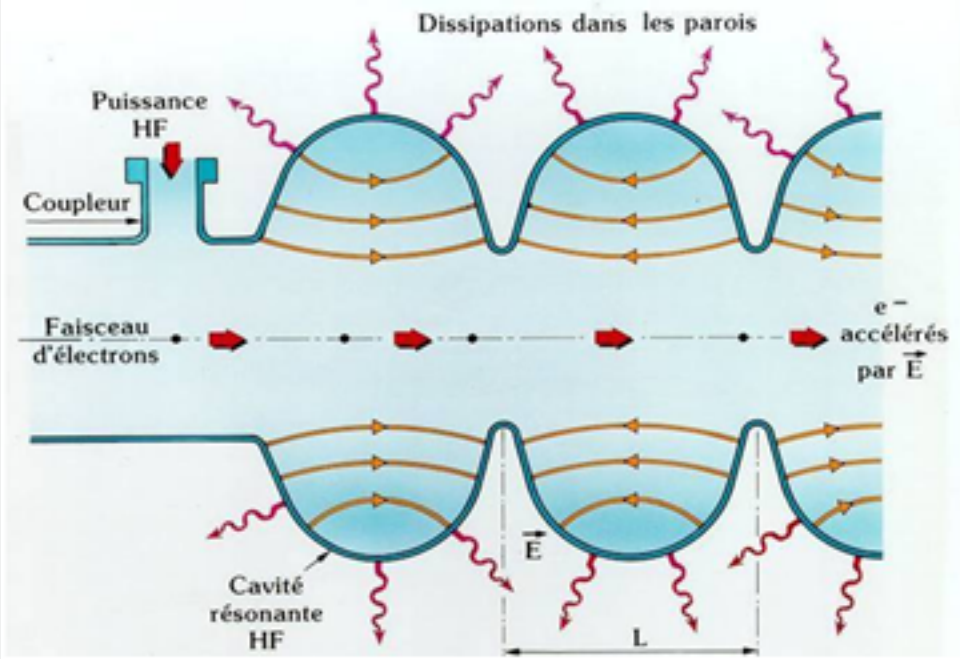
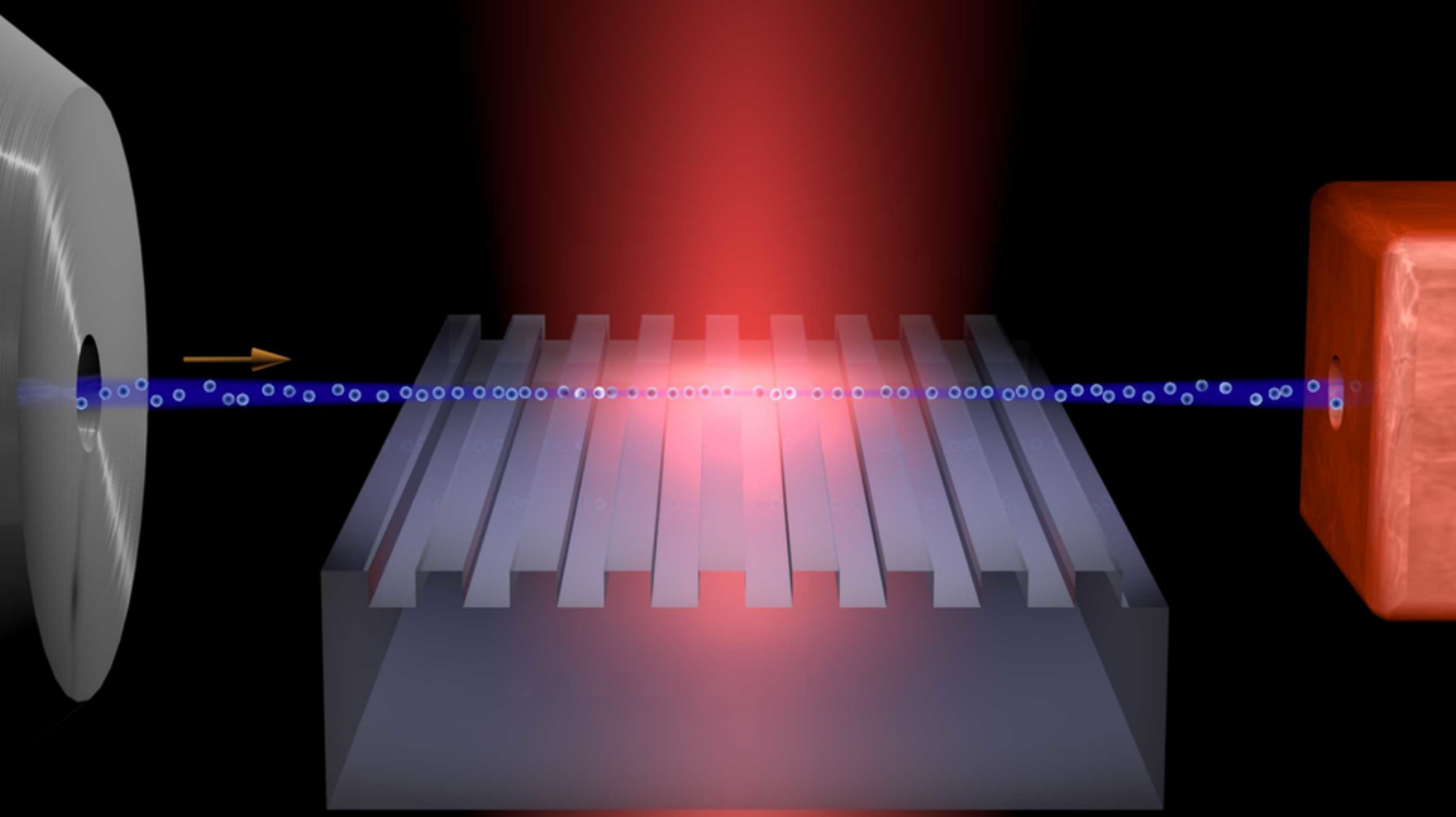


Figure 1 Schéma de la distribution du champ électrique dans une cavité résonante

Laser-Based Acceleration



Laser Acceleration (1961)

Koichi Shimoda, Applied Optics 1 (1), 33 (1961)

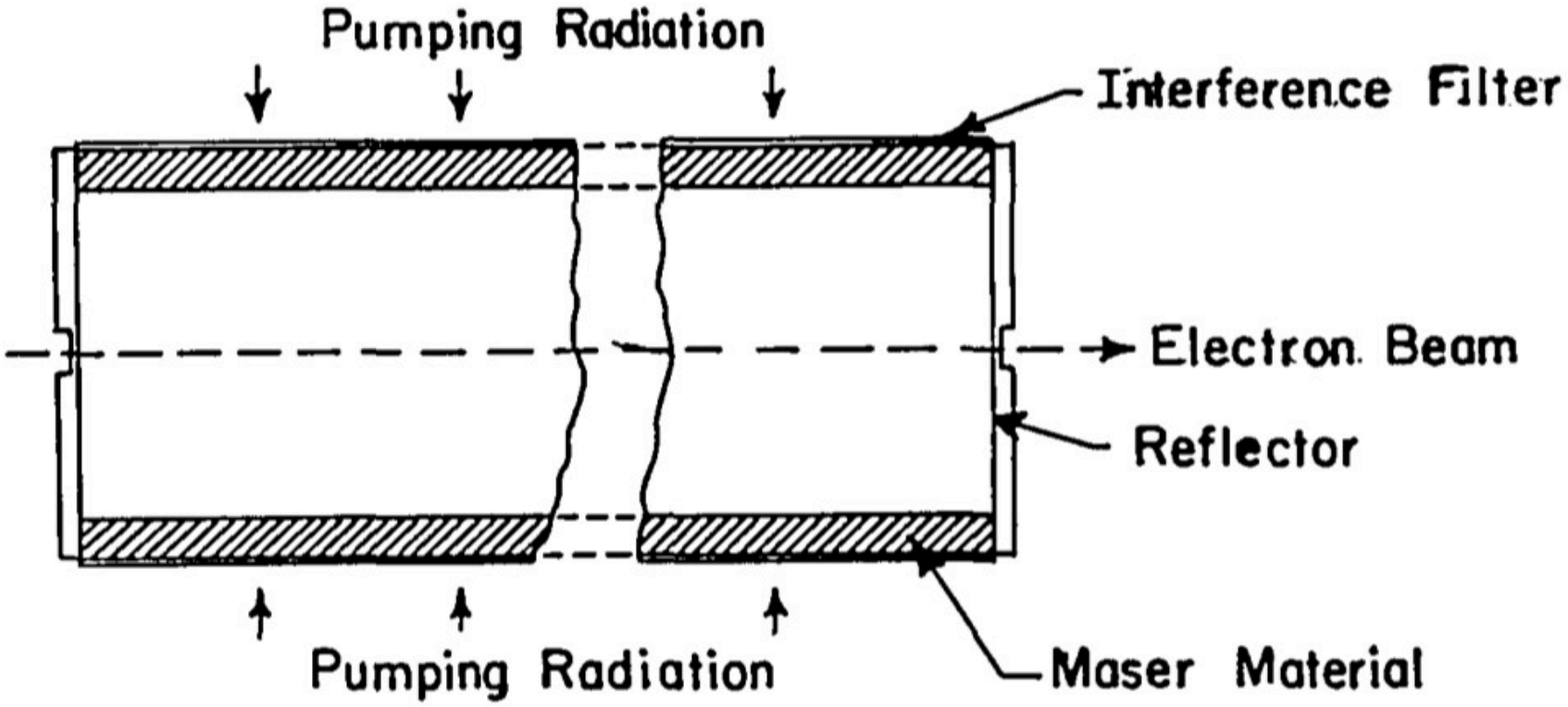
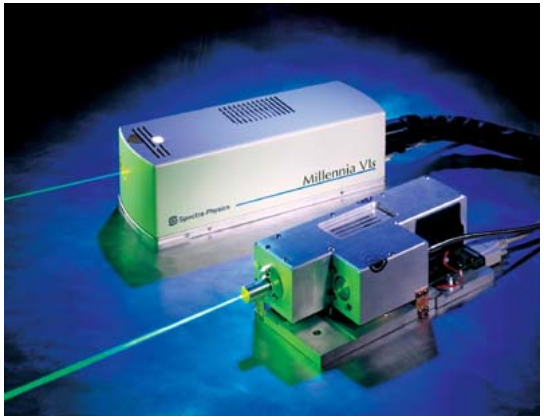


Fig. 1. Schematic diagram of an electron linear accelerator by optical maser.

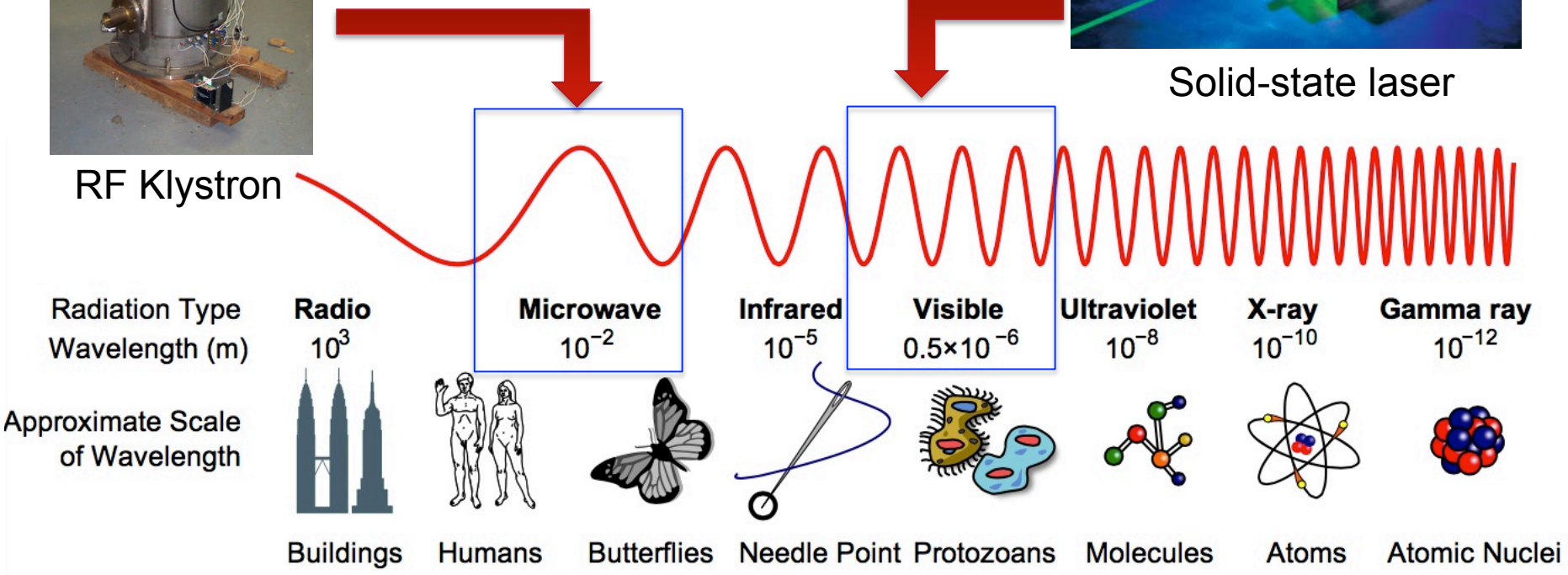
Laser as a source of electromagnetic fields

RF Klystron

1. Smaller/less expensive than RF.
2. Energy efficient (near 50%).
3. High repetition rate (1 to 100 MHz).
4. Large electric fields (GV/m).



Solid-state laser



Dielectric Accelerator Structures

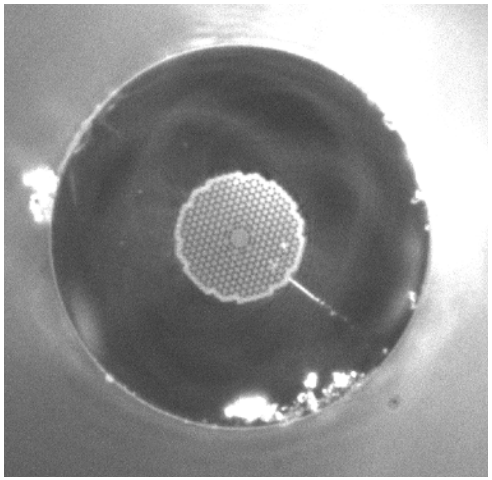
> Using much higher frequencies: THz to optical

> Using dielectrics (e.g. SiO_2)

> Advantages: higher damage threshold
  ⇒ Higher accelerating fields, up to ~GV/m

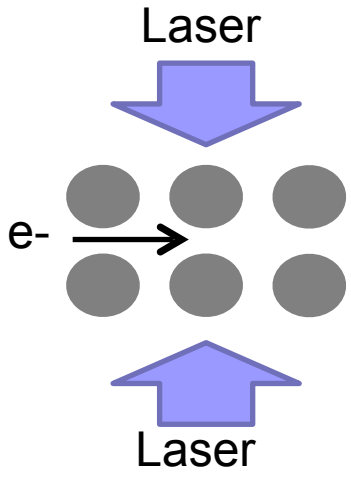
> Generate the electromagnetic field
  > Cherenkov radiation from an electron beam
  > Laser

> Confine the field
  > Photonic band gap

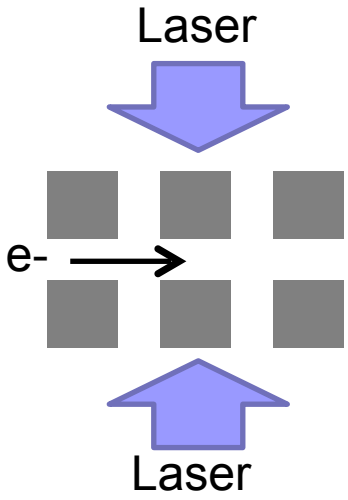


Planar Structures

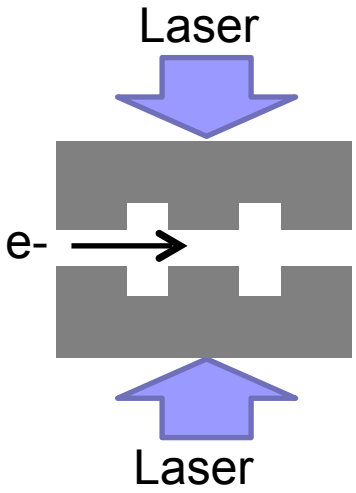
Elliptical Pillars



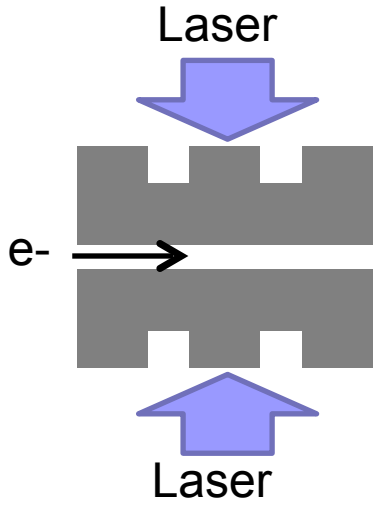
Rectangular Pillars



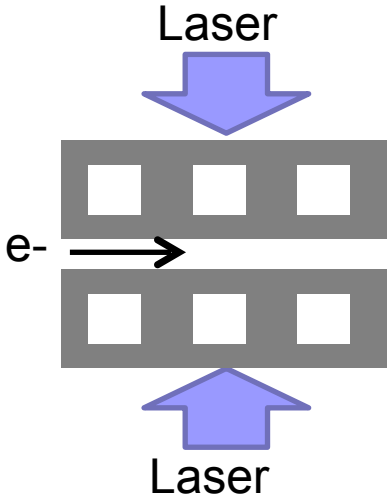
Double Slab Grating



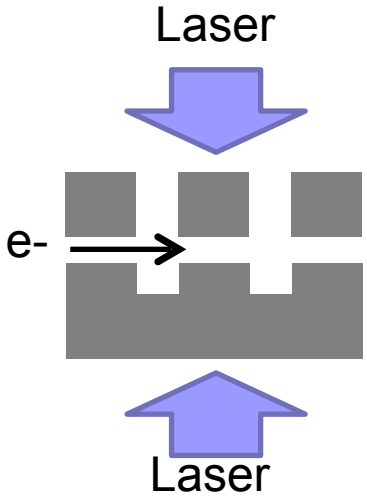
Reverse Slab Grating



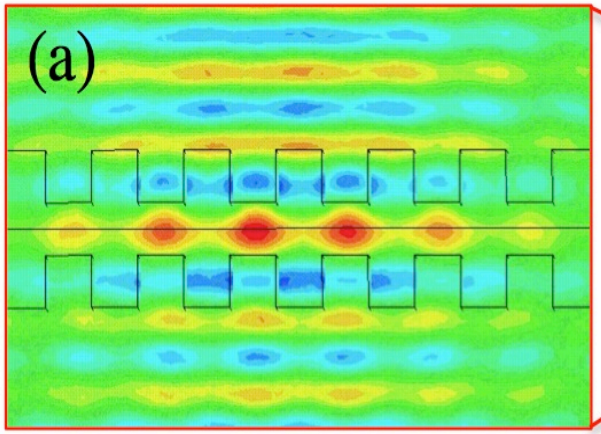
Buried Grating

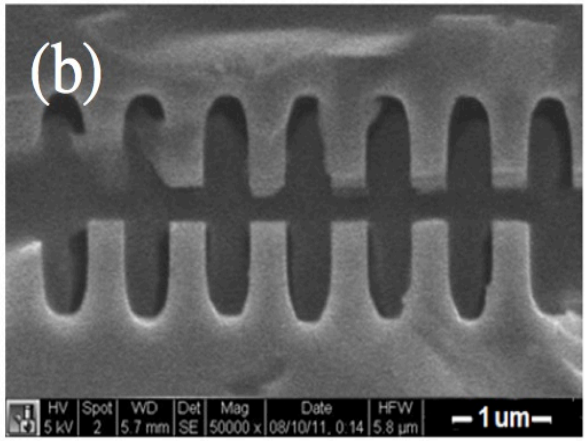


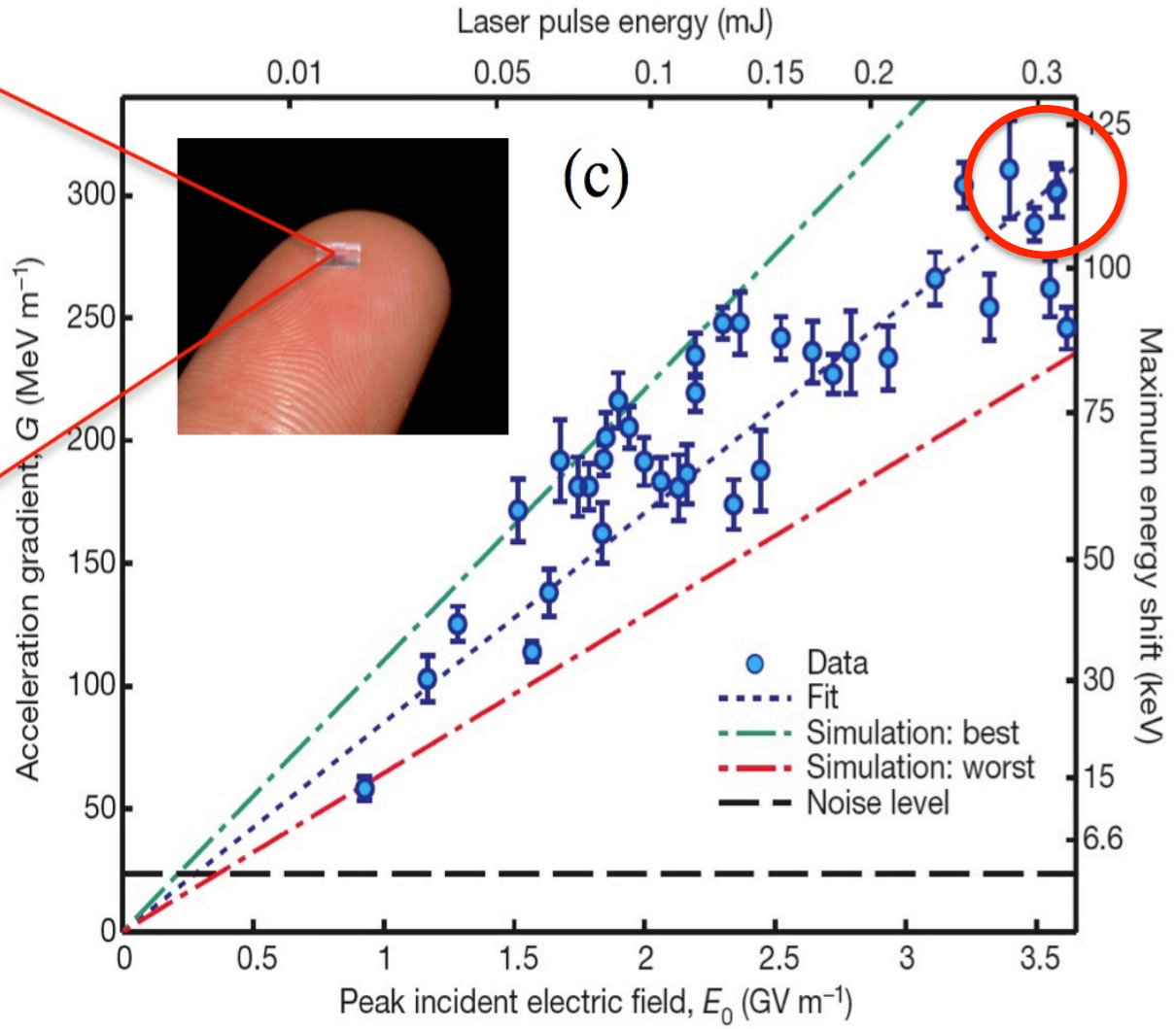
Asymmetric Grating



Planar Structures: Measurements

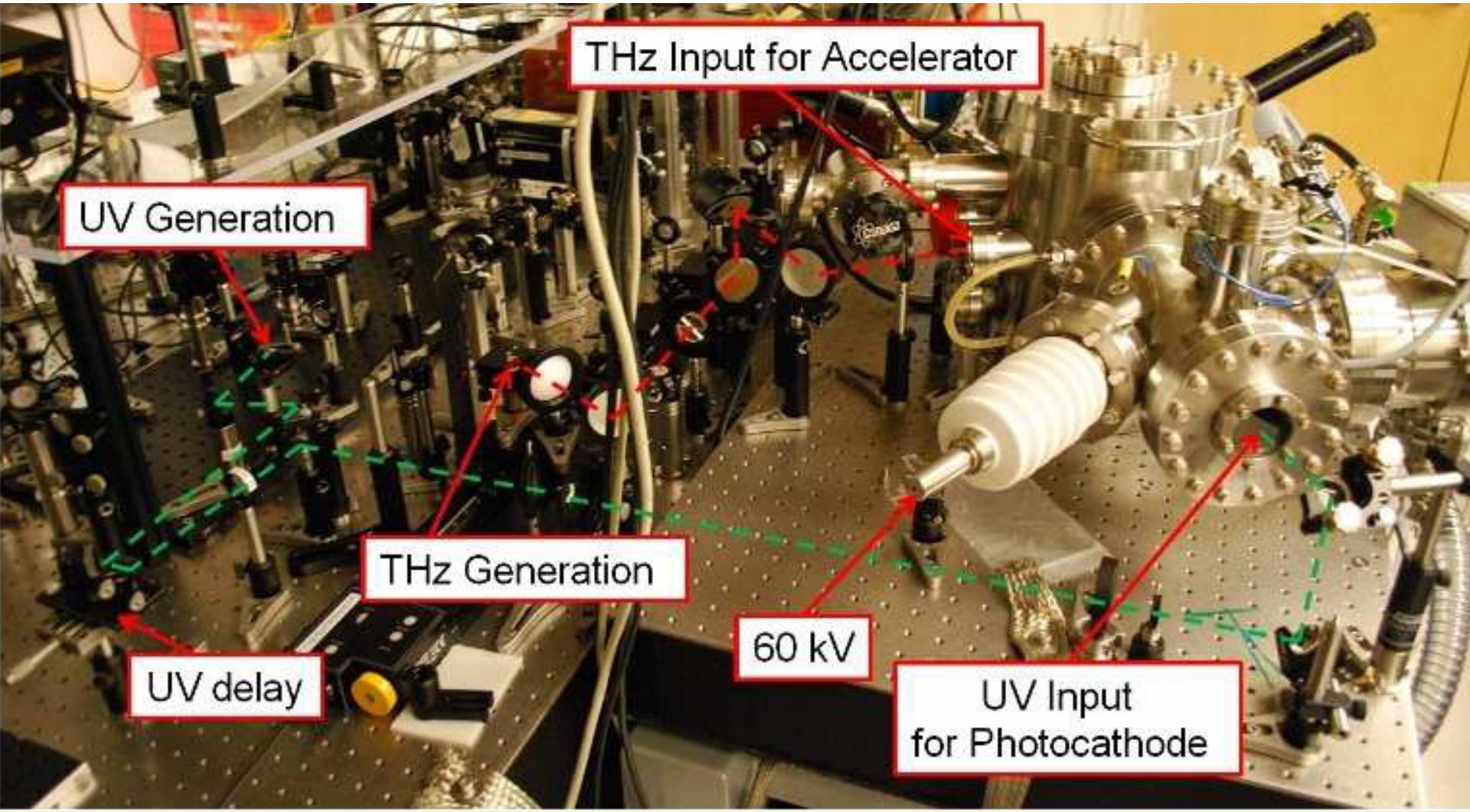






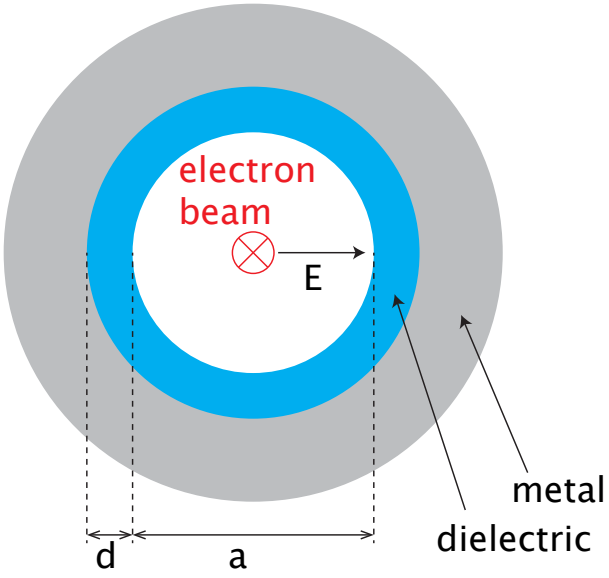
Circular Structures

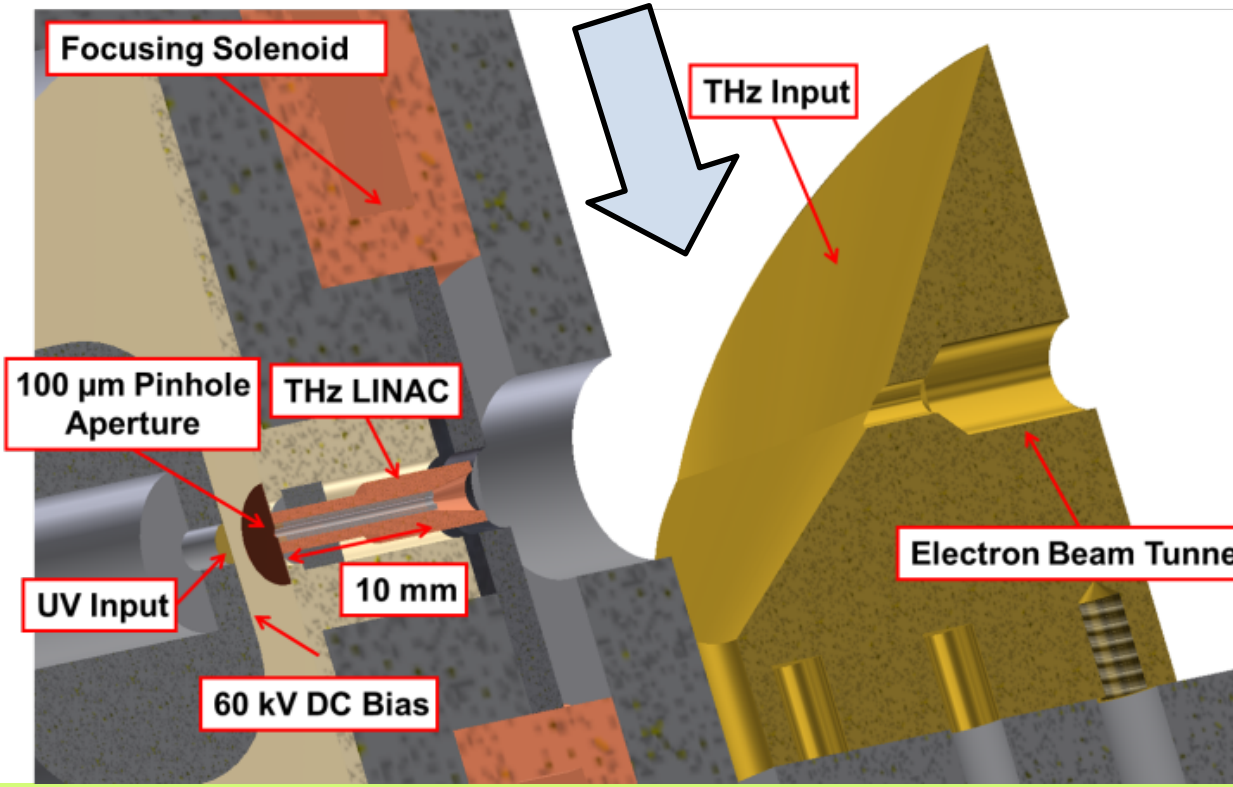
> Experiment at MIT



Circular Structures

> Structure geometry:





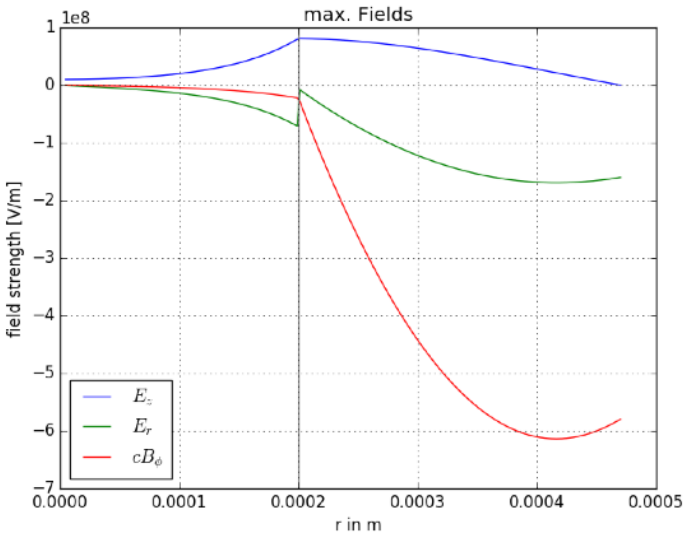
Circular Structures: Modeling

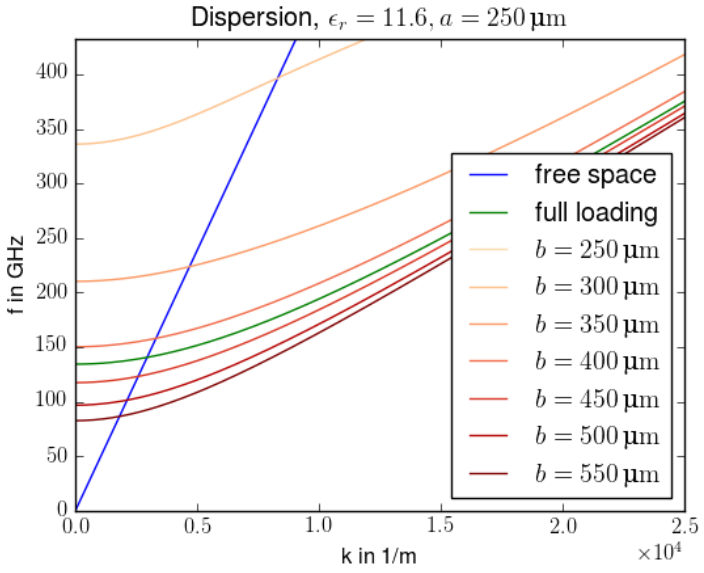
> Analytical solution for the electromagnetic fields:

$$E_z = \begin{cases} E_1 J_0(\gamma_1 r) e^{i(kz-\omega t)}, & r < a \\ E_2 \left(J_0(\gamma_2 r) - \frac{J_0(\gamma_2 b)}{Y_0(\gamma_2 b)} Y_0(\gamma_2 r) \right) e^{i(kz-\omega t)}, & a < r < b \end{cases}$$

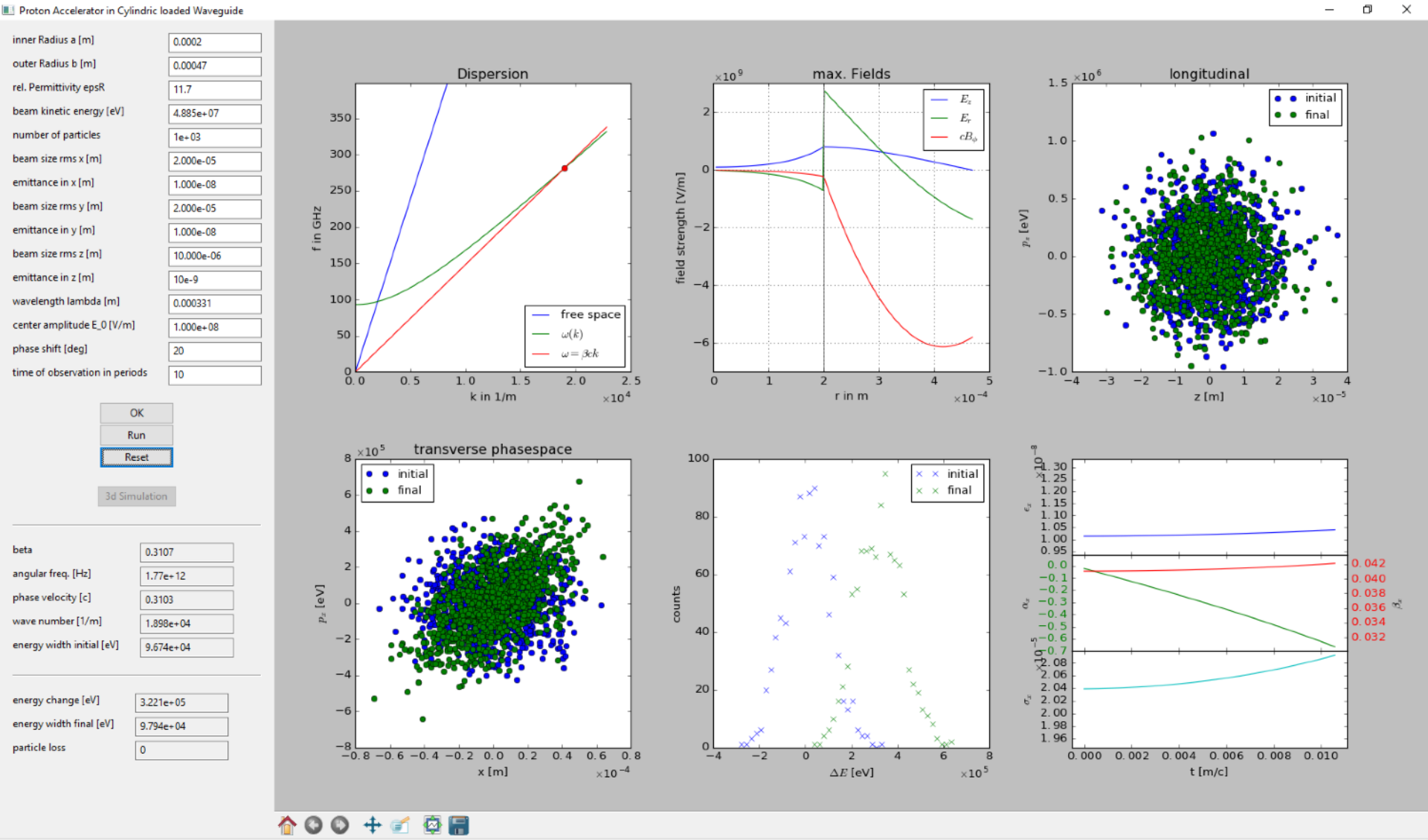
$$E_r = \begin{cases} i\frac{k}{\gamma_1} E_1 J_0'(\gamma_1 r) e^{i(kz-\omega t)}, & r < a \\ i\frac{k}{\gamma_2} E_2 \left(J_0'(\gamma_2 r) - \frac{J_0(\gamma_2 b)}{Y_0(\gamma_2 b)} Y_0'(\gamma_2 r) \right) e^{i(kz-\omega t)}, & a < r < b \end{cases}$$

$$B_\phi = \begin{cases} i\frac{\omega}{\gamma_1 c^2} E_1 J_0'(\gamma_1 r) e^{i(kz-\omega t)}, & r < a \\ i\frac{\omega}{\gamma_2 c^2} \epsilon_r E_2 \left(J_0'(\gamma_2 r) - \frac{J_0(\gamma_2 b)}{Y_0(\gamma_2 b)} Y_0'(\gamma_2 r) \right) e^{i(kz-\omega t)}, & a < r < b \end{cases}$$





Tool to Calculate Beam Propagation



Circular Structures: Measurements

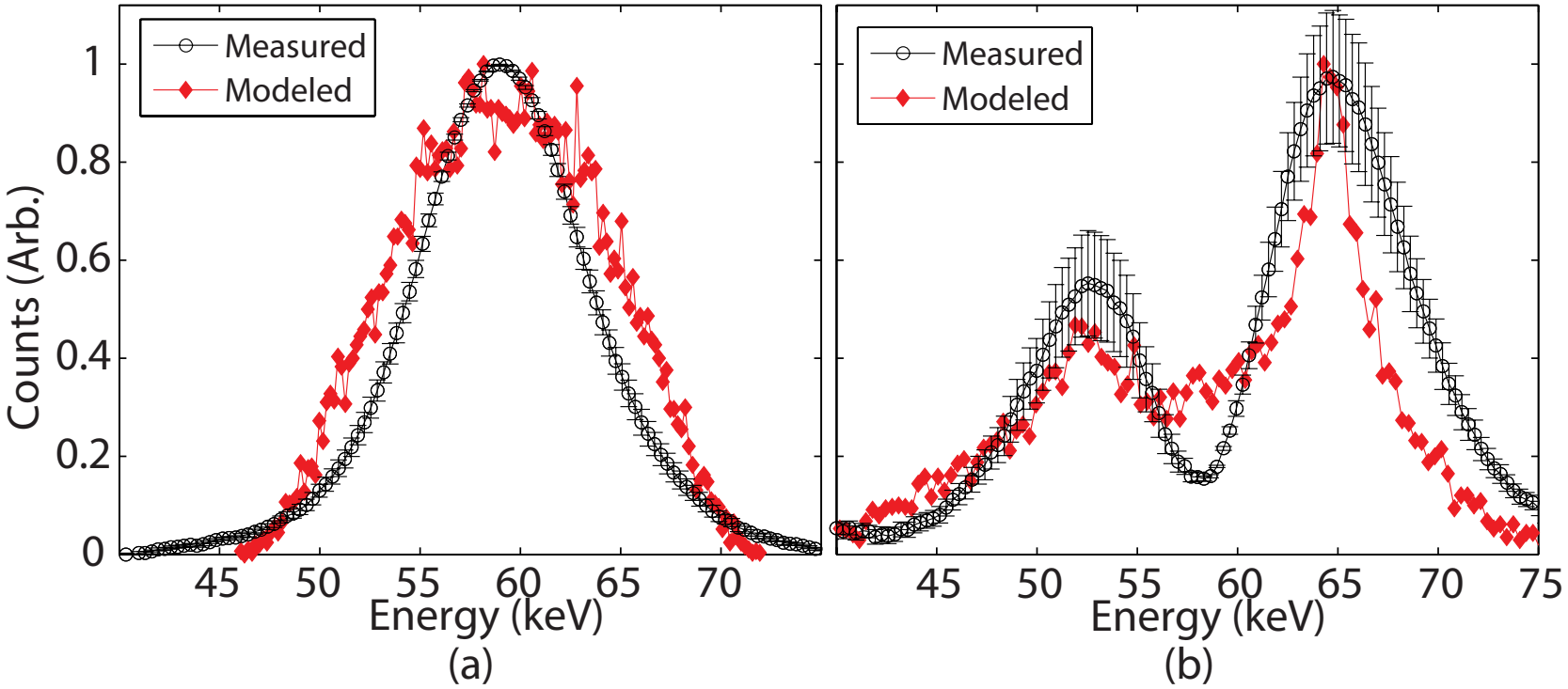
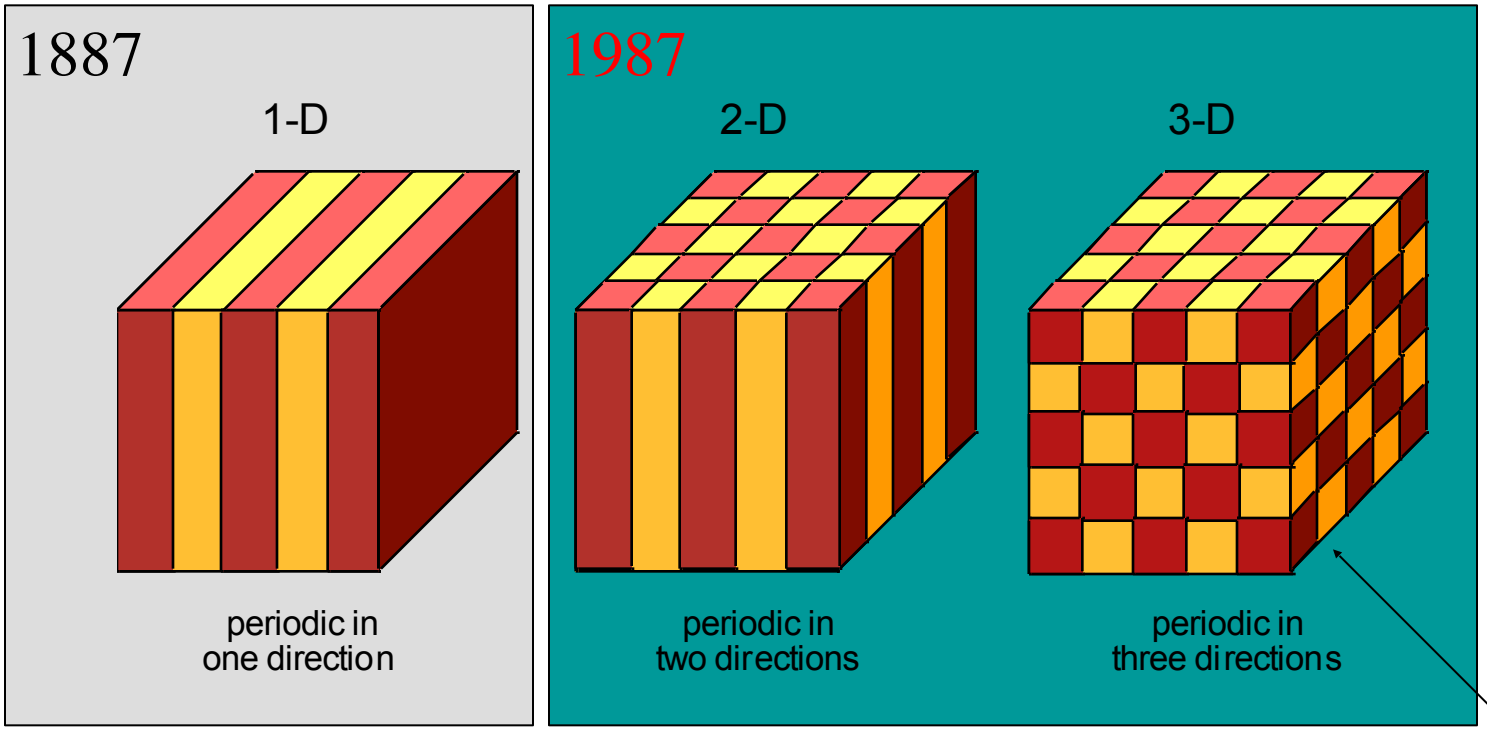


Figure 4: Measured (black) and modeled (red) energy spectrum with THz (a) off and (b) on at a gun voltage of 59 kV.

Towards 3-Dimensional Structures: Photonic Crystals

periodic electromagnetic media

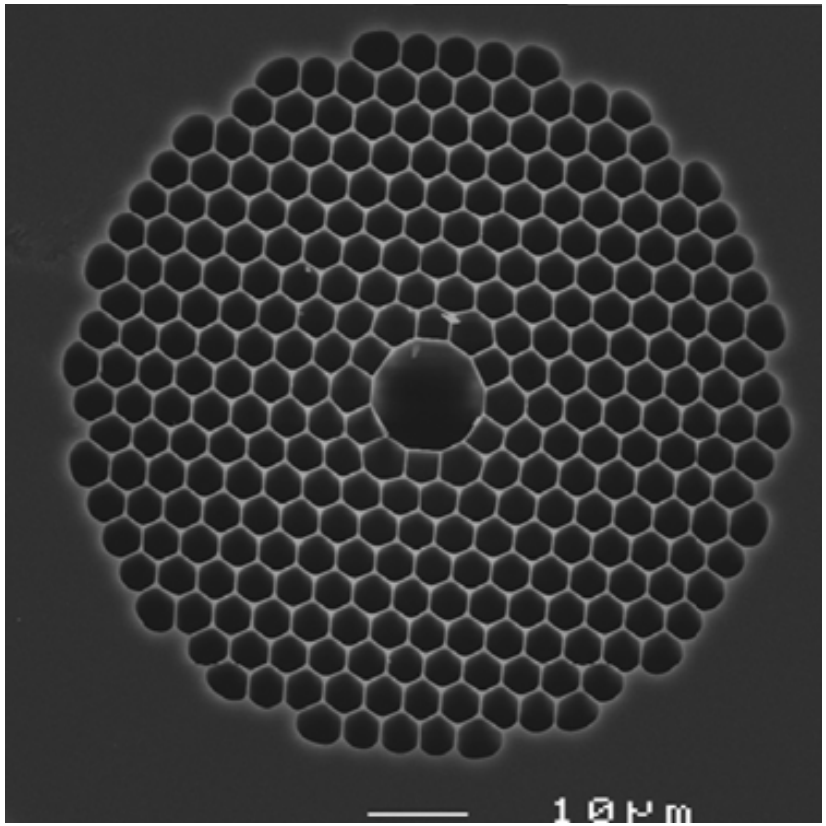


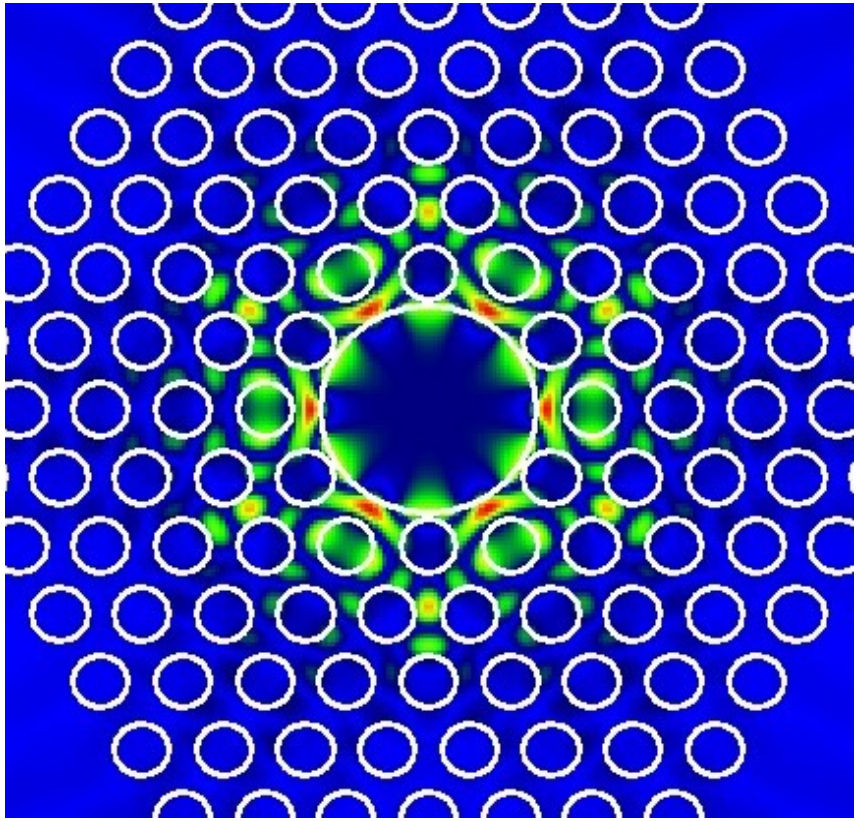
(need a more complex topology)

with photonic band gaps: "optical insulators"

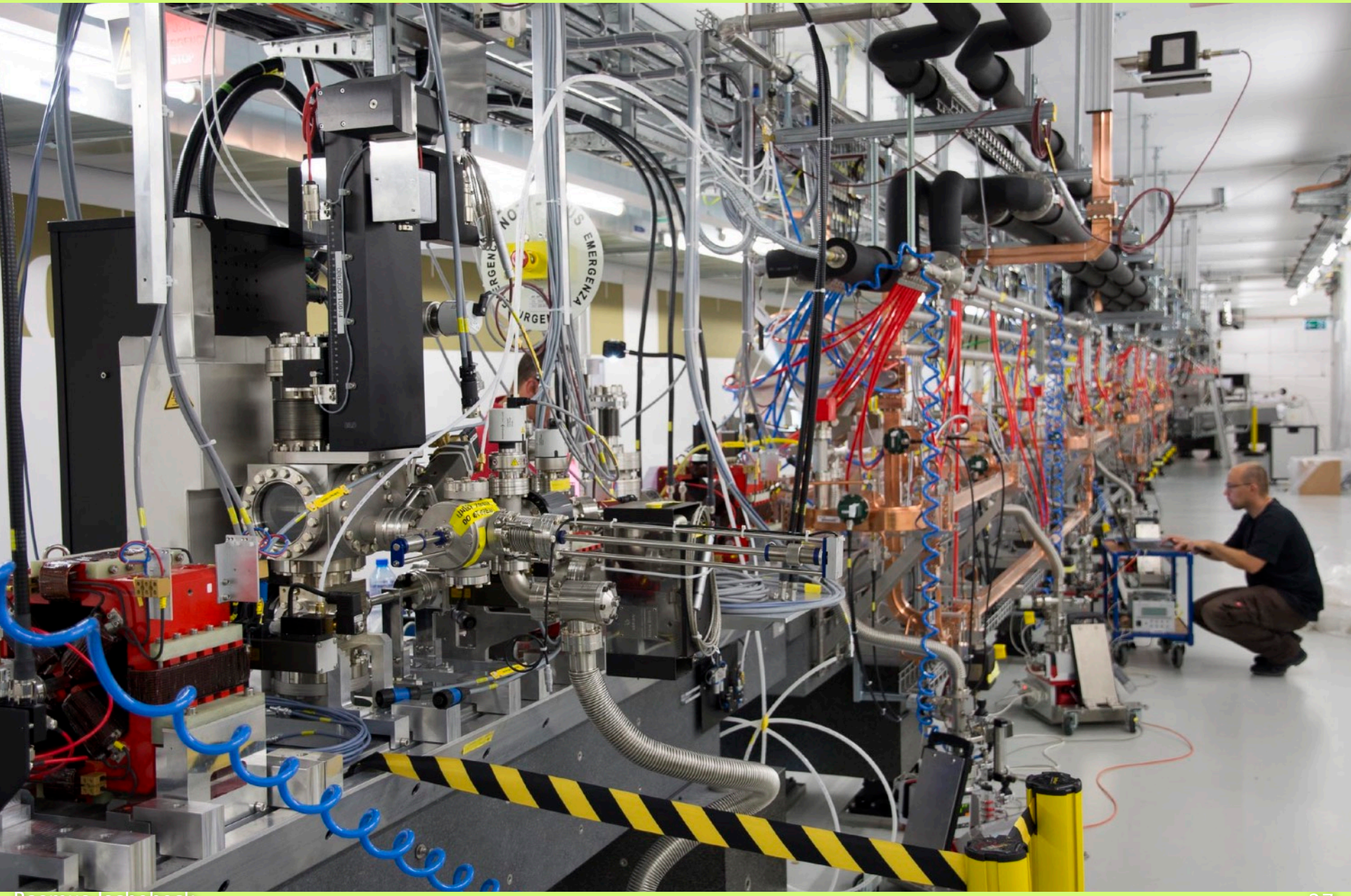
Steven G. Johnson

Photonic Band Gap Structures



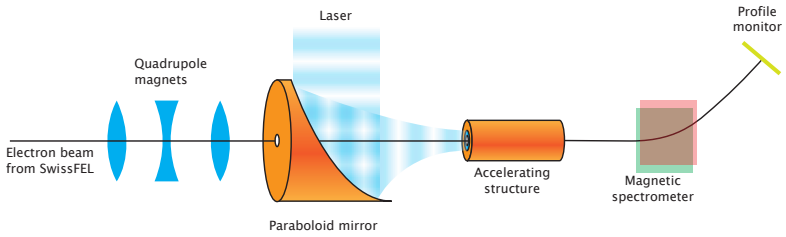


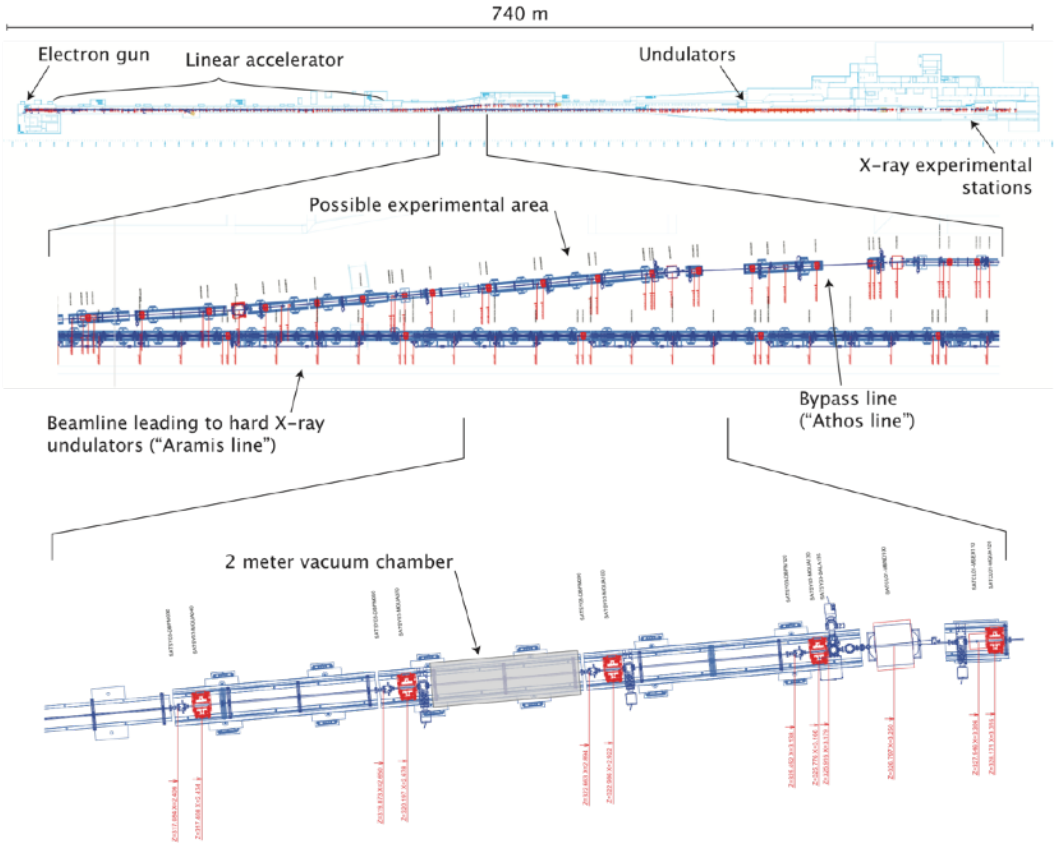
Installation of a Test Chamber in SwissFEL



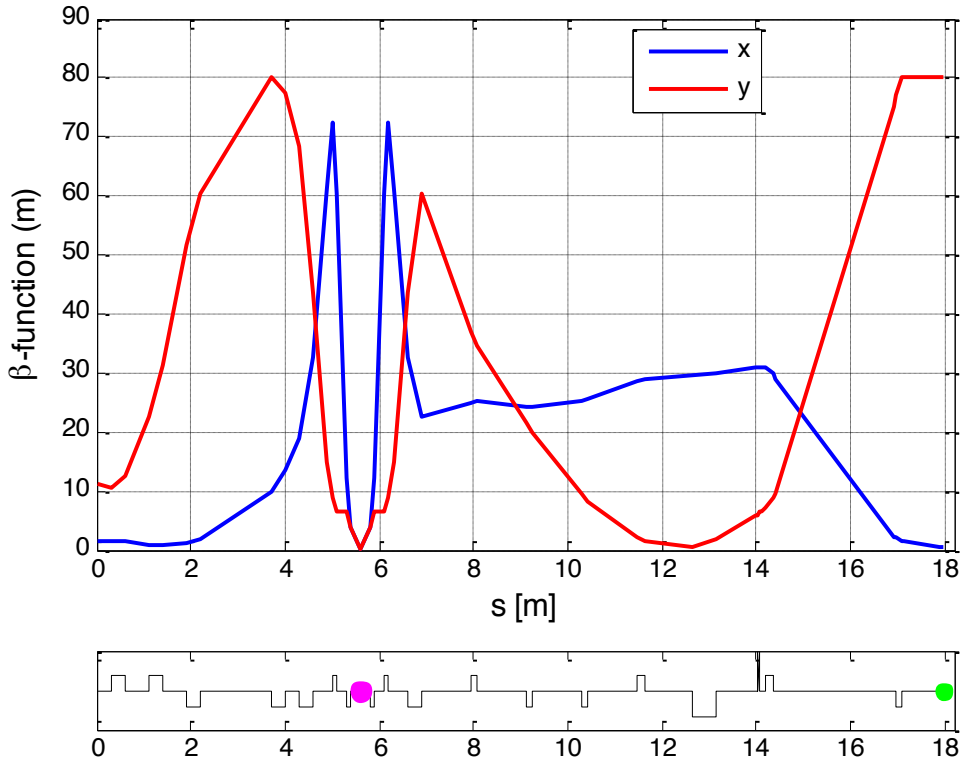
Planned Experimental Setup in SwissFEL

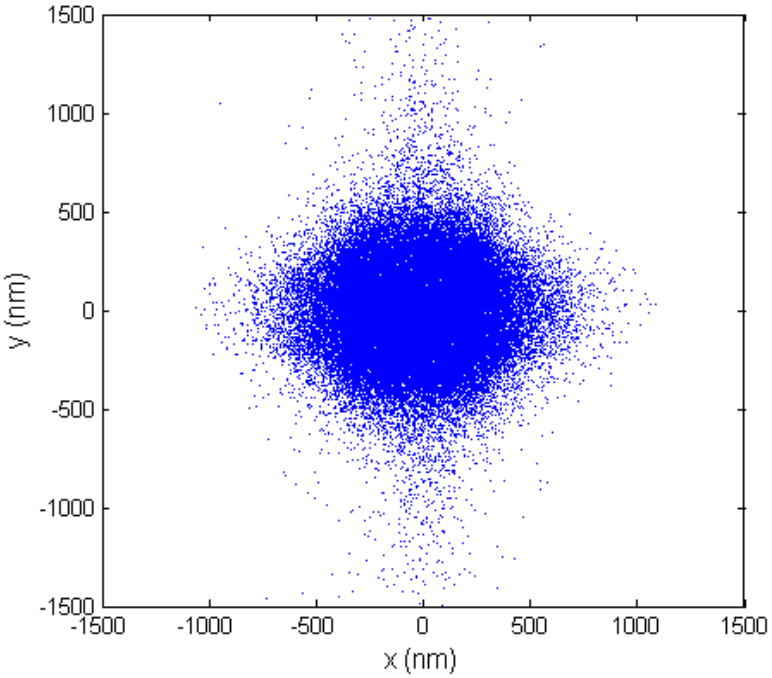
> Goal: Acceleration by 1 MeV





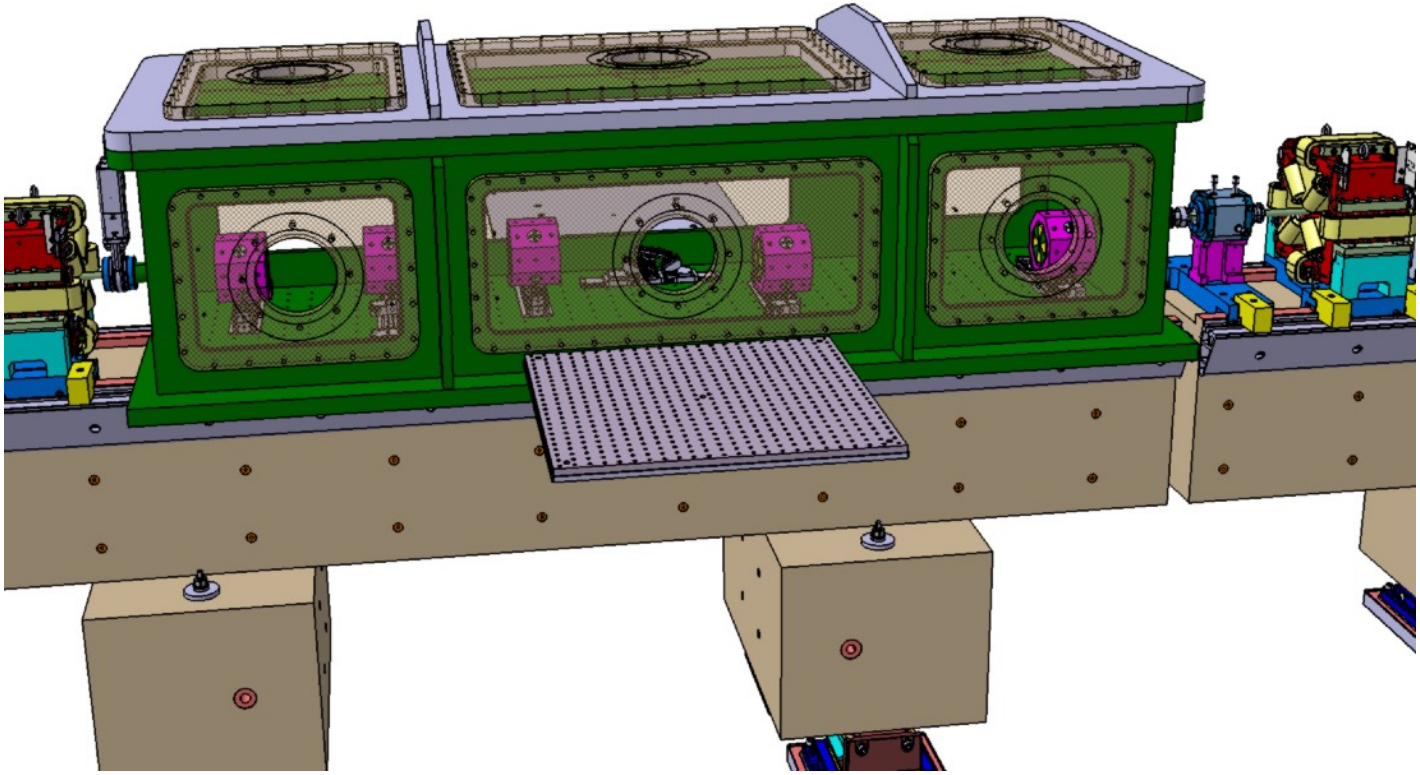
Focusing of the Electron Beam



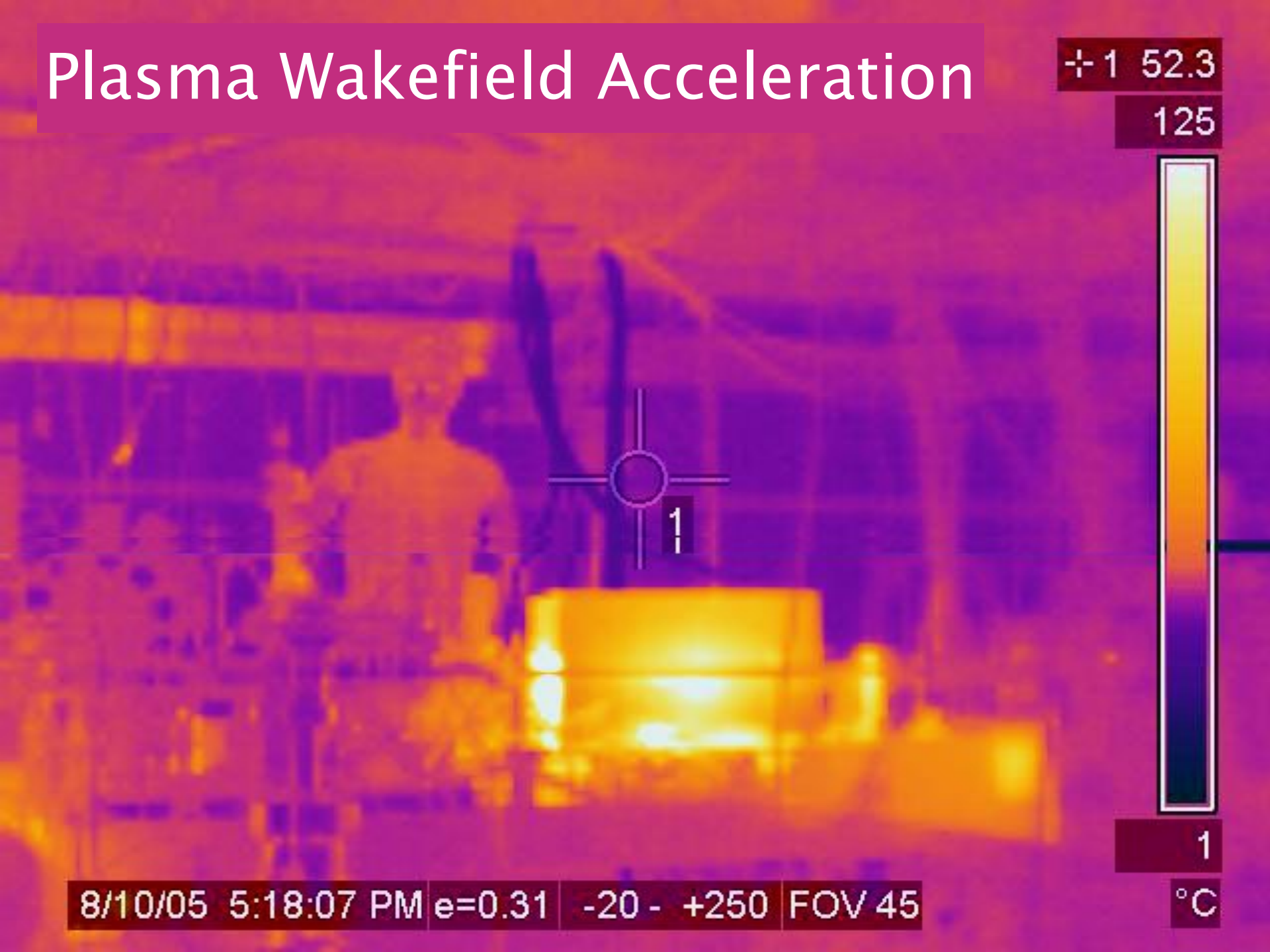


Design of Interaction Chamber

> Design in progress…



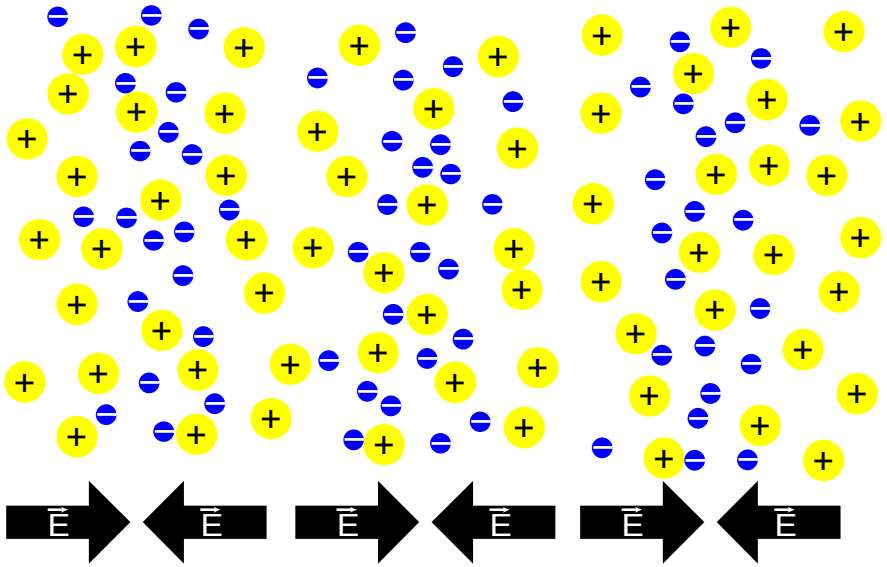
Plasma Wakefield Acceleration



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:

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

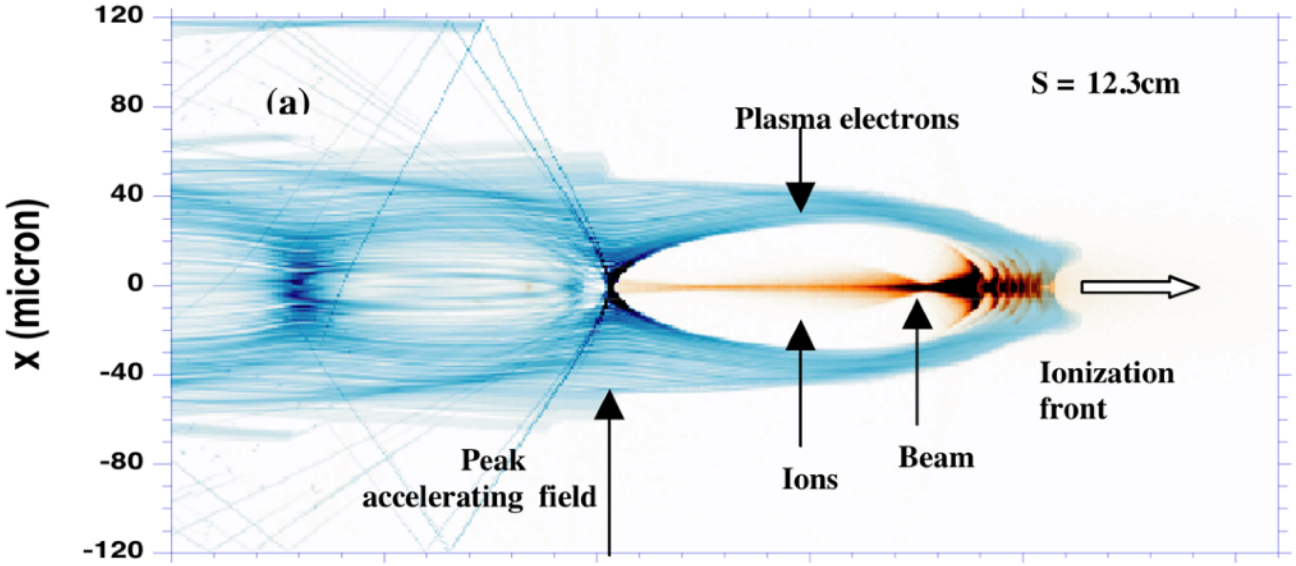
> Limit:

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

Plasma Wakes – Theory

> Above this limit: non-linear wakes, “Blow-out regime”

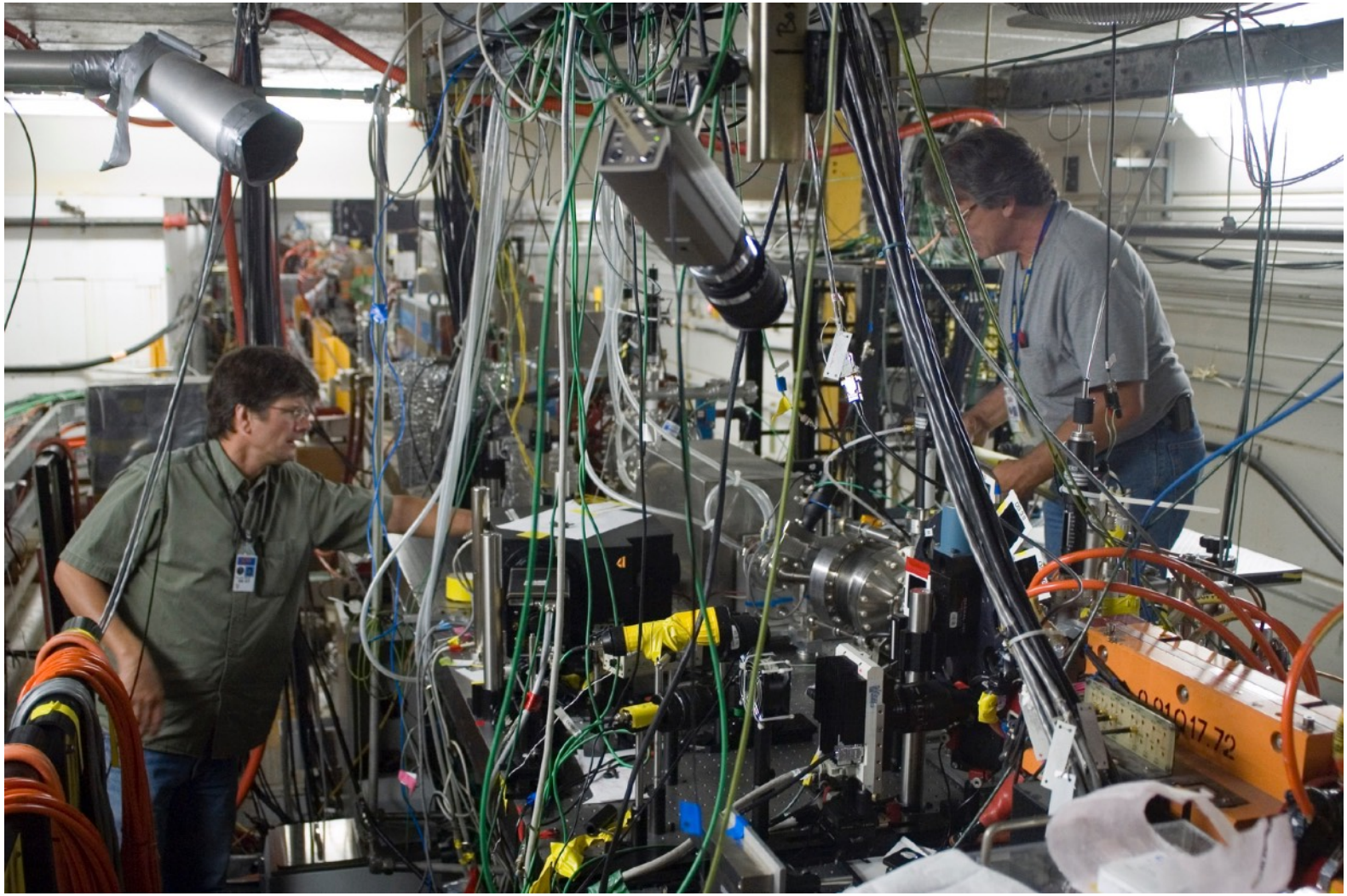
> Fields can be calculated only with numerical methods



> Typical wavelength: 50 μm

> Accelerating fields up to 50 GV/m

Plasma Wakes – Reality



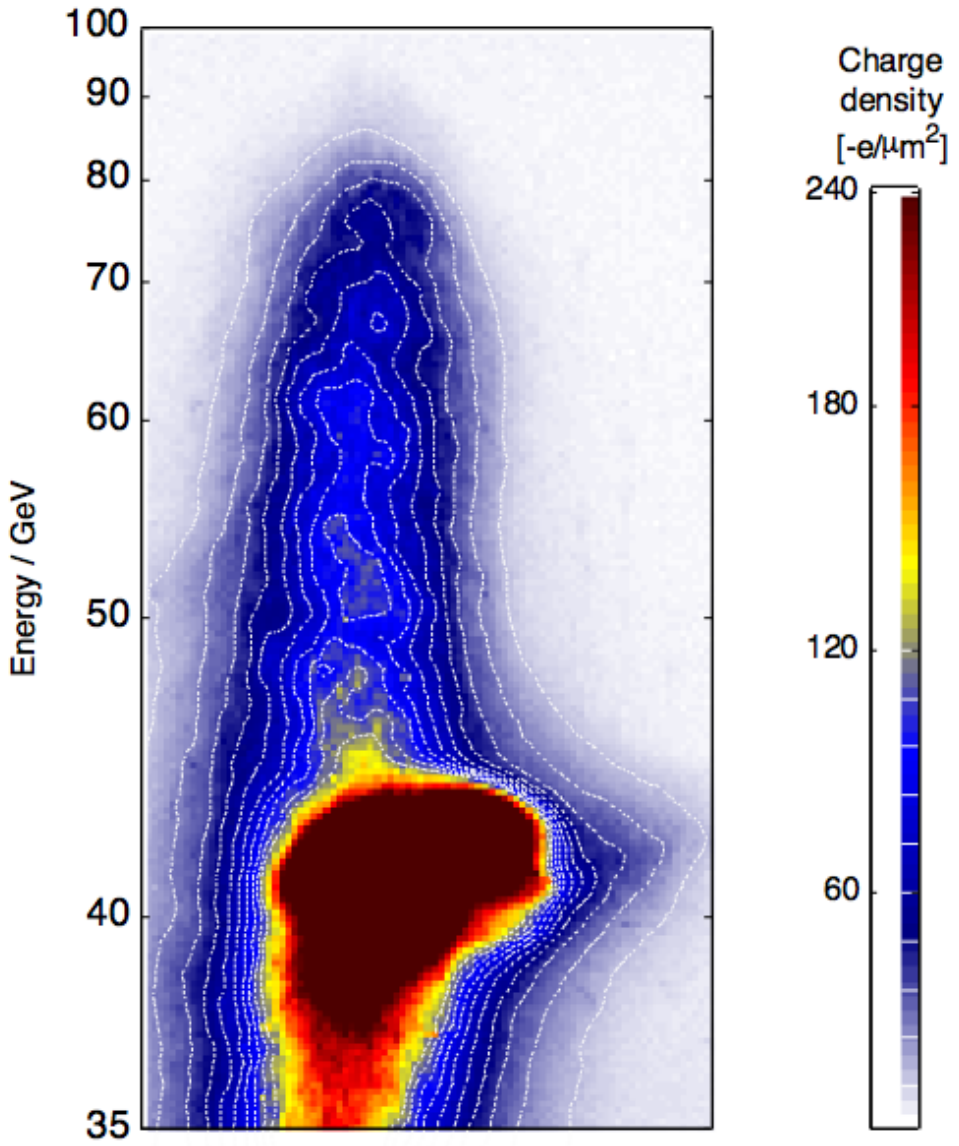
Energy Doubling

> Plasma length: 85 cm

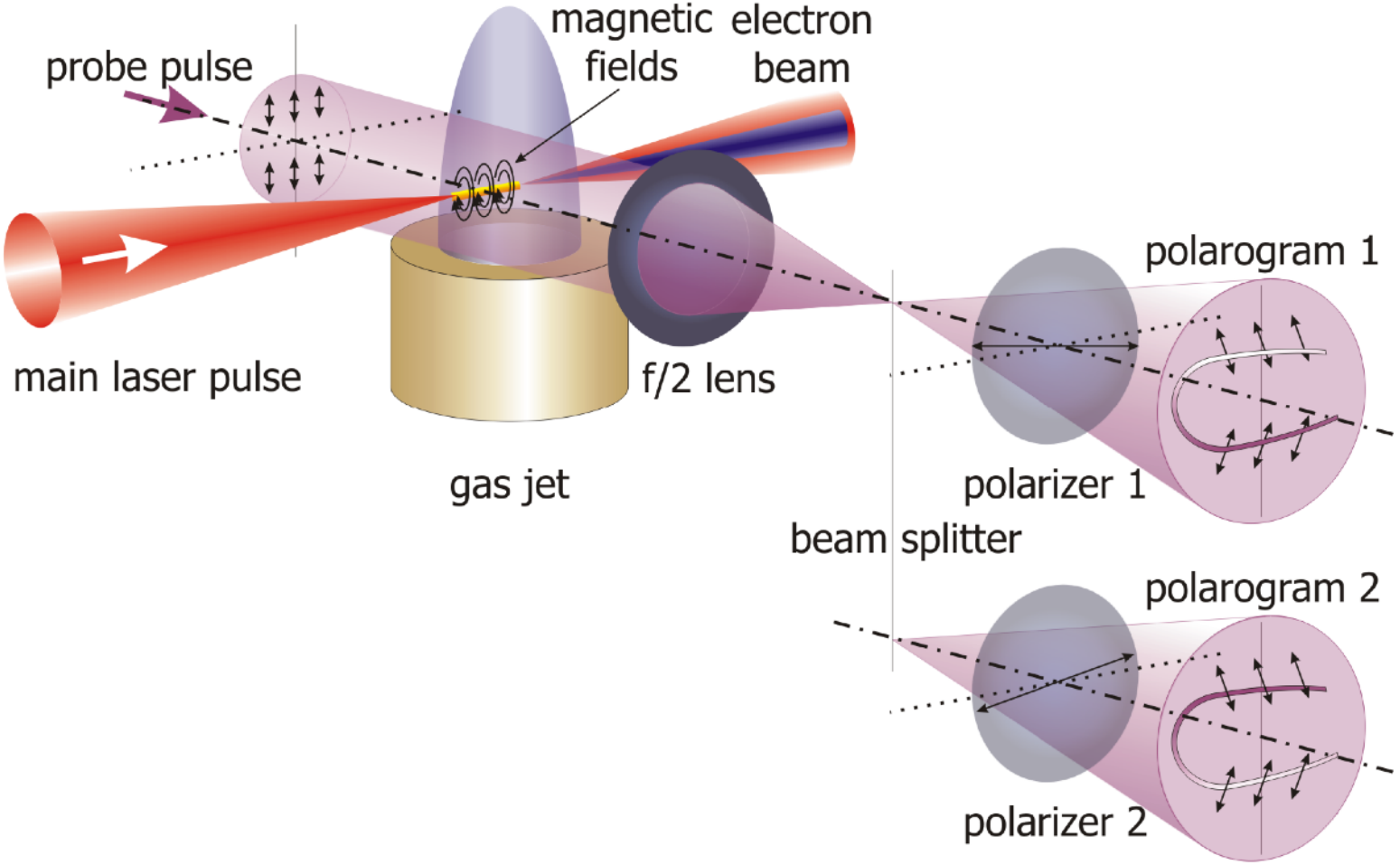
> Density: $2.7 \bullet 10^{23}\ m^{-3}$

> Incoming energy: 42 GeV

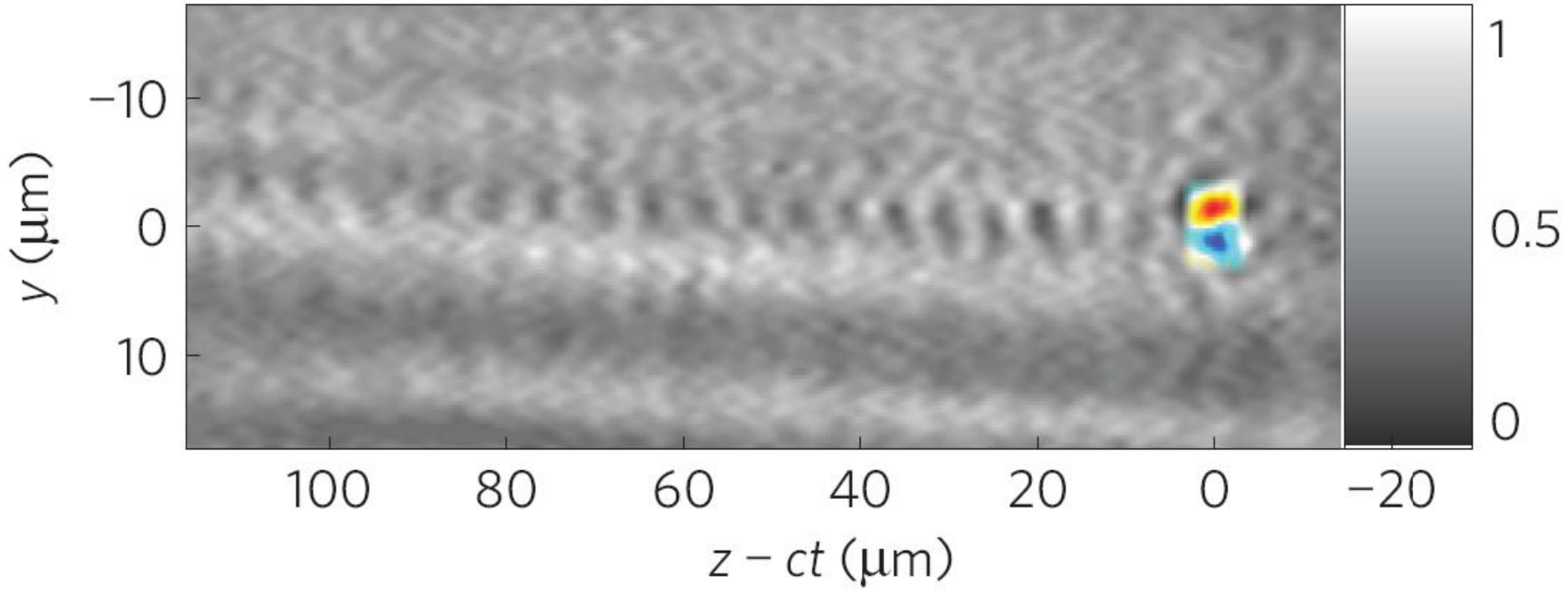
> Peak energy: 85±7 GeV



Measurement of Electromagnetic Fields



Measured Electromagnetic Fields



Recent Experiments at PSI

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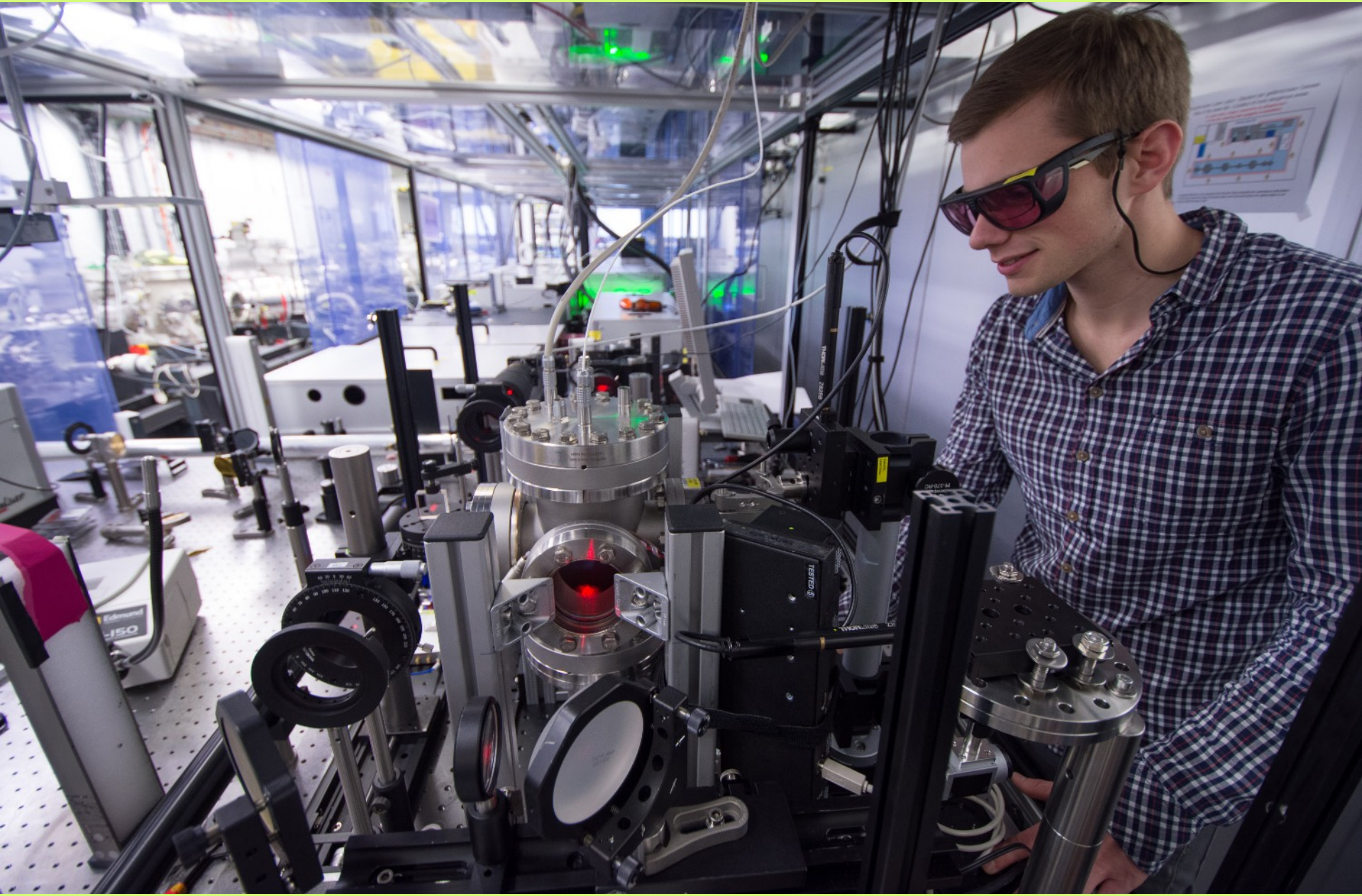
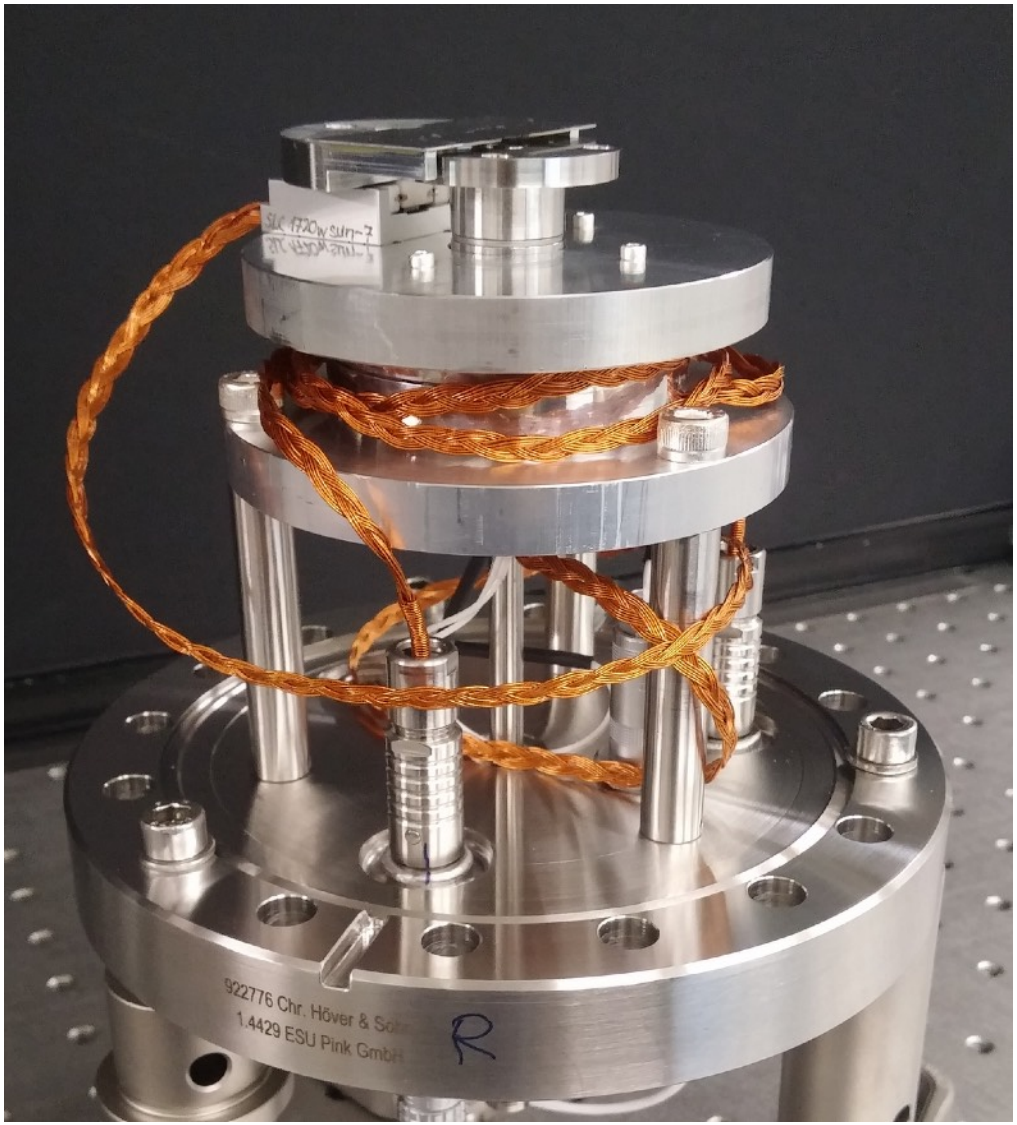
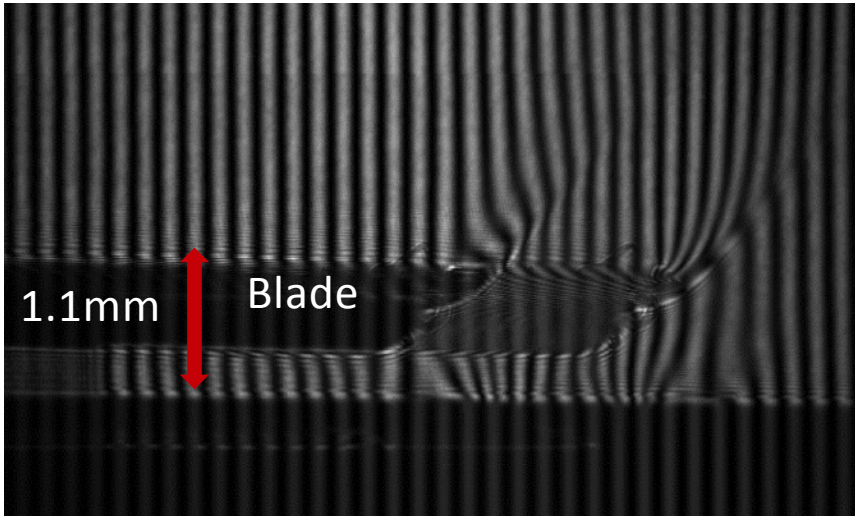
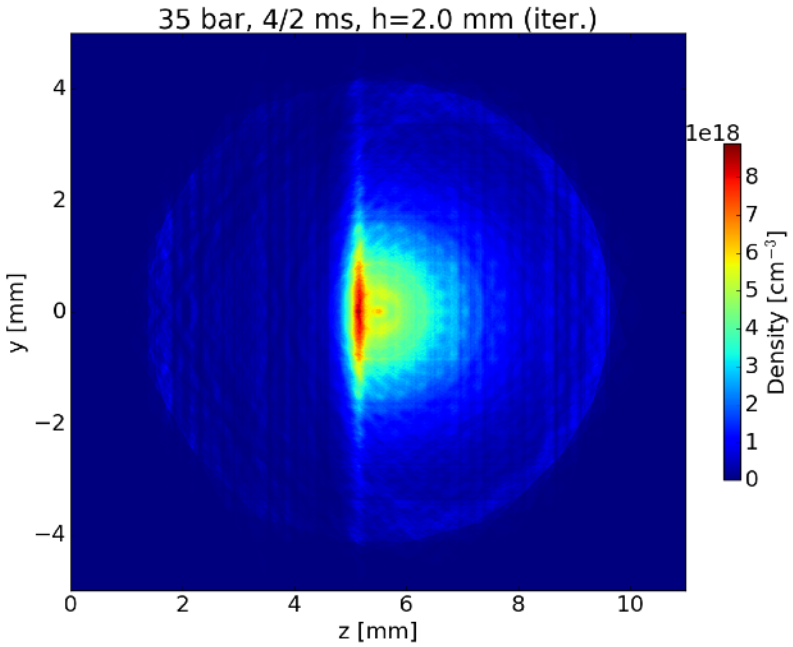


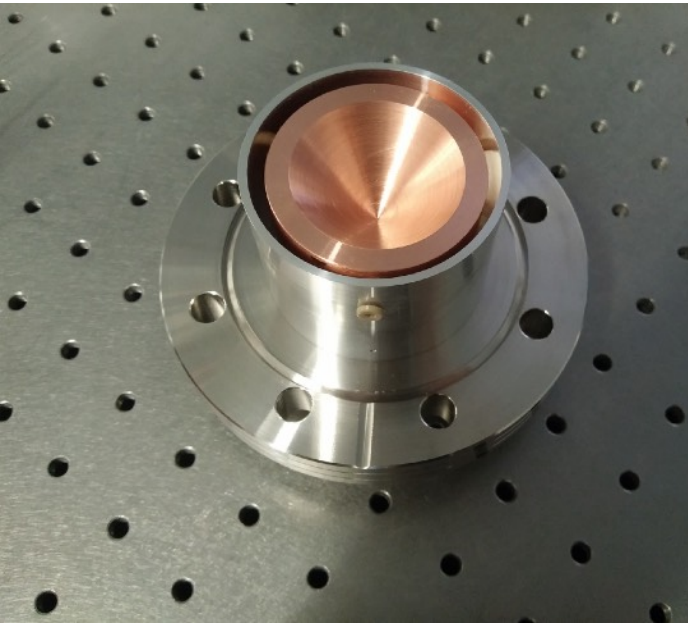
Generation of a Density Ramp

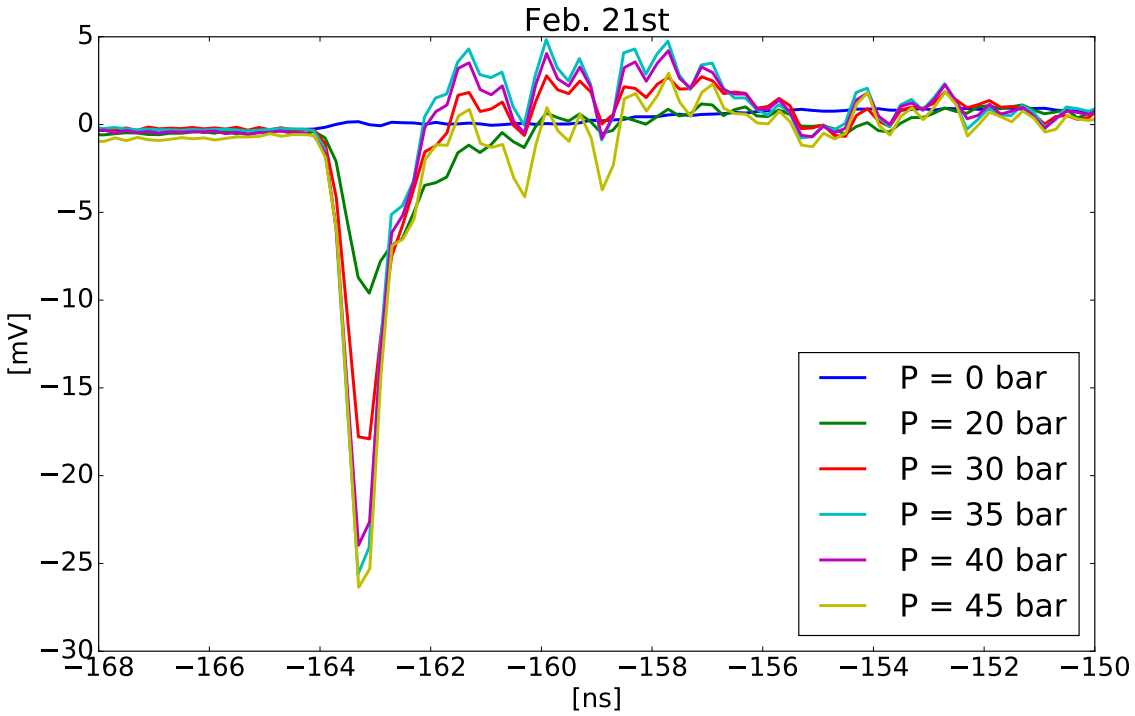




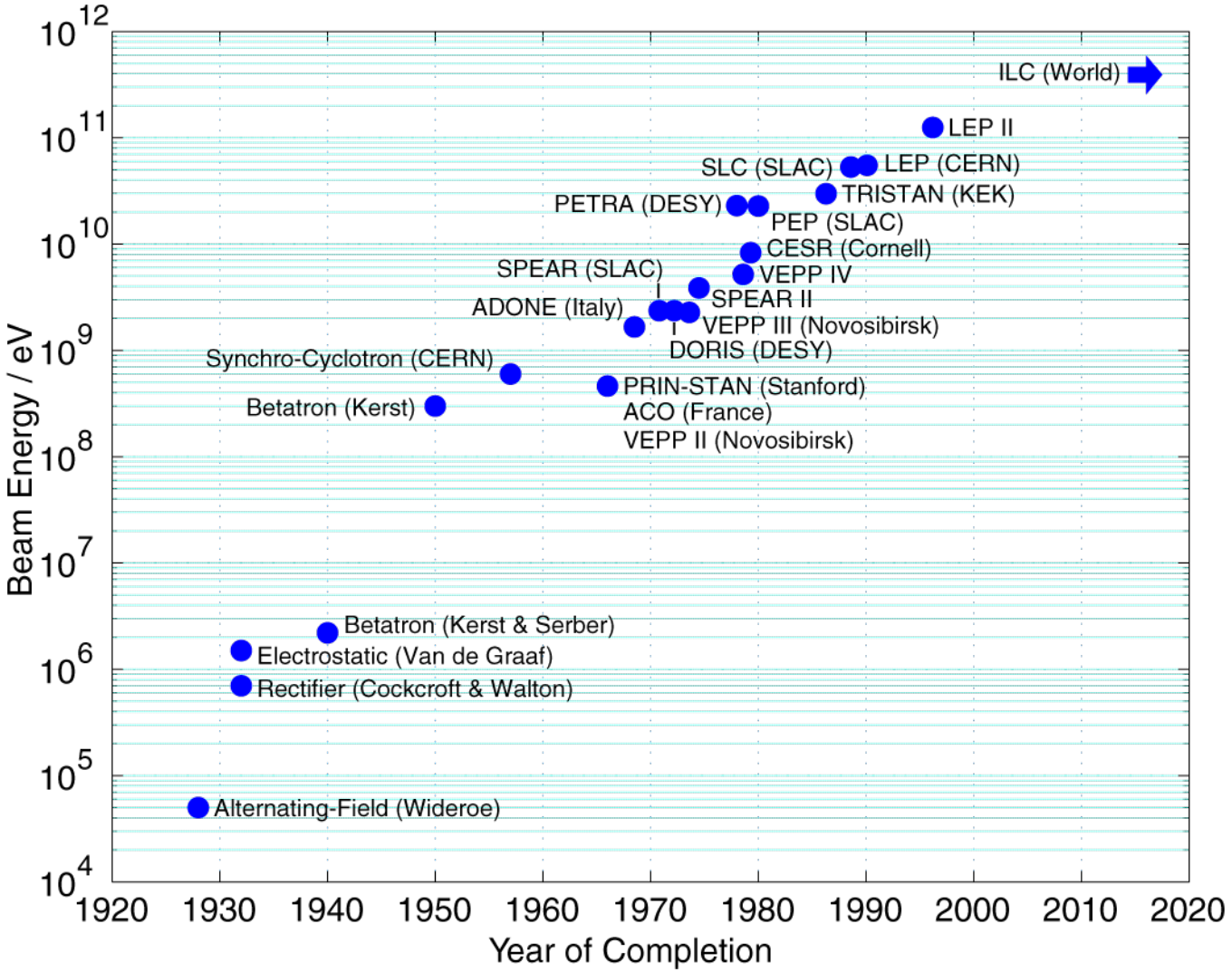


Charge Measurement

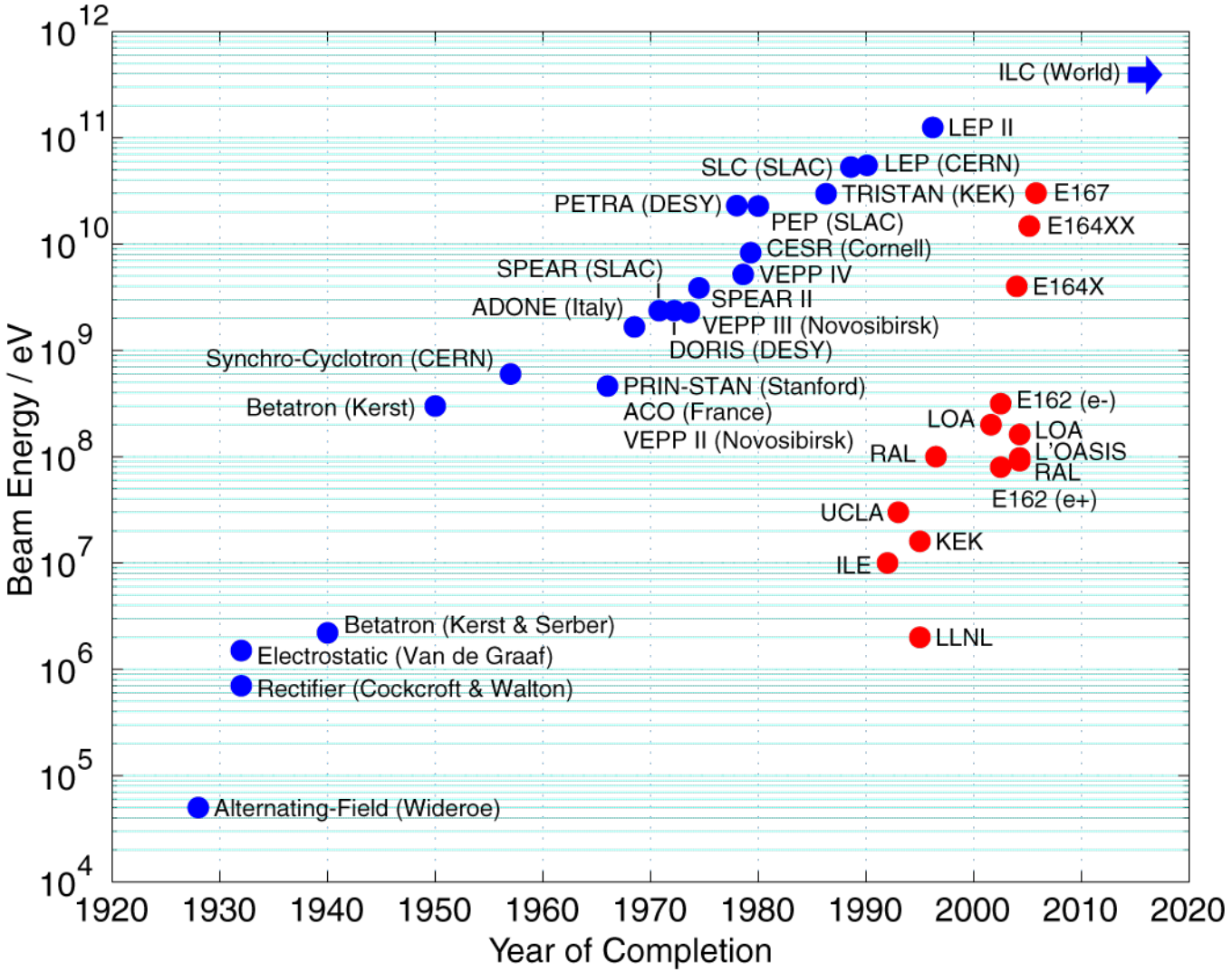




Livingston Plot



An Unfair Comparison



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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

Instrumentation and Acceleration Research at PSI

- Special Thanks to:
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  - Nick Sauerwein

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