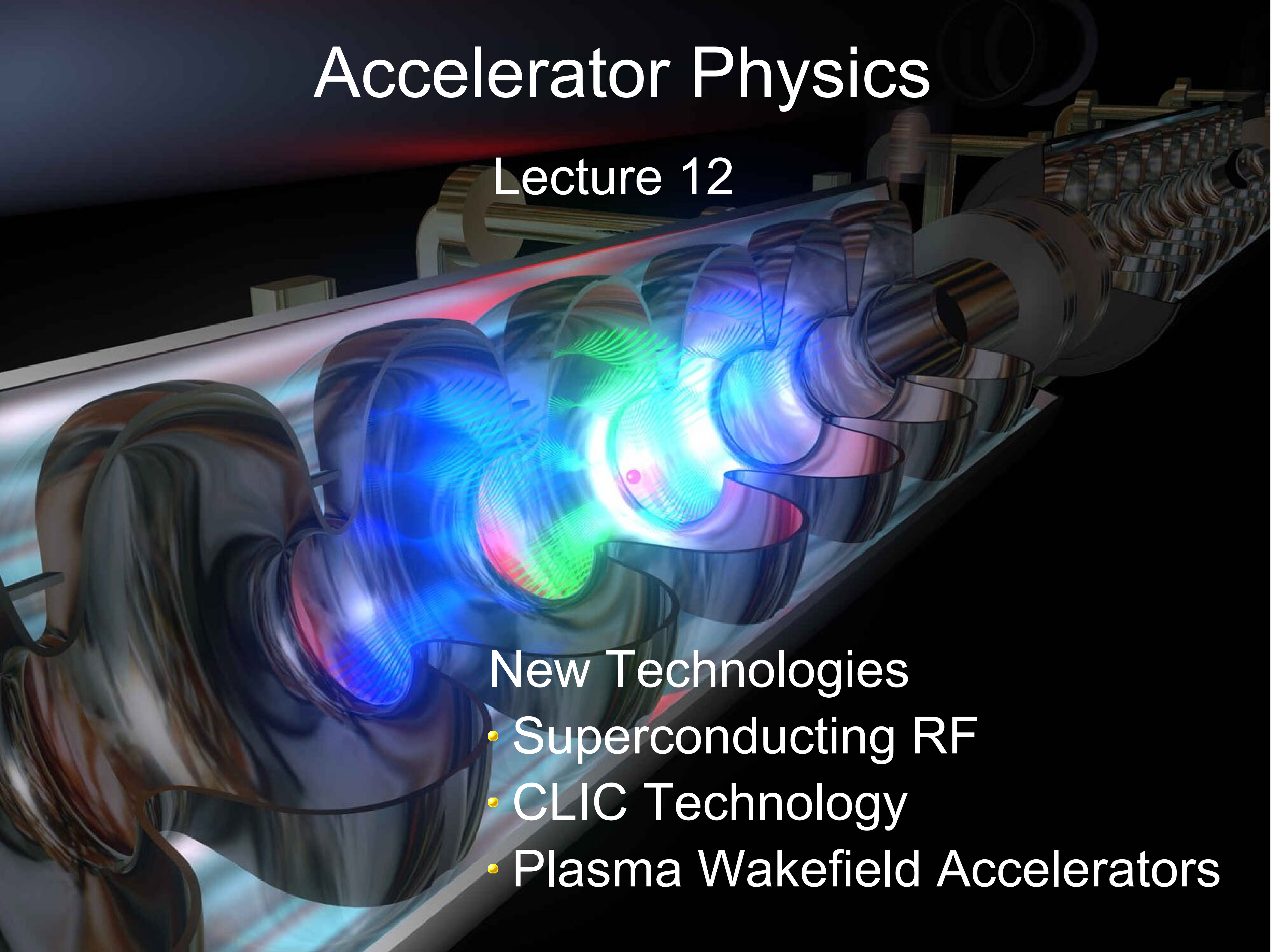
Accelerator Physics

Lecture 12



New Technologies

- Superconducting RF
- CLIC Technology
- Plasma Wakefield Accelerators

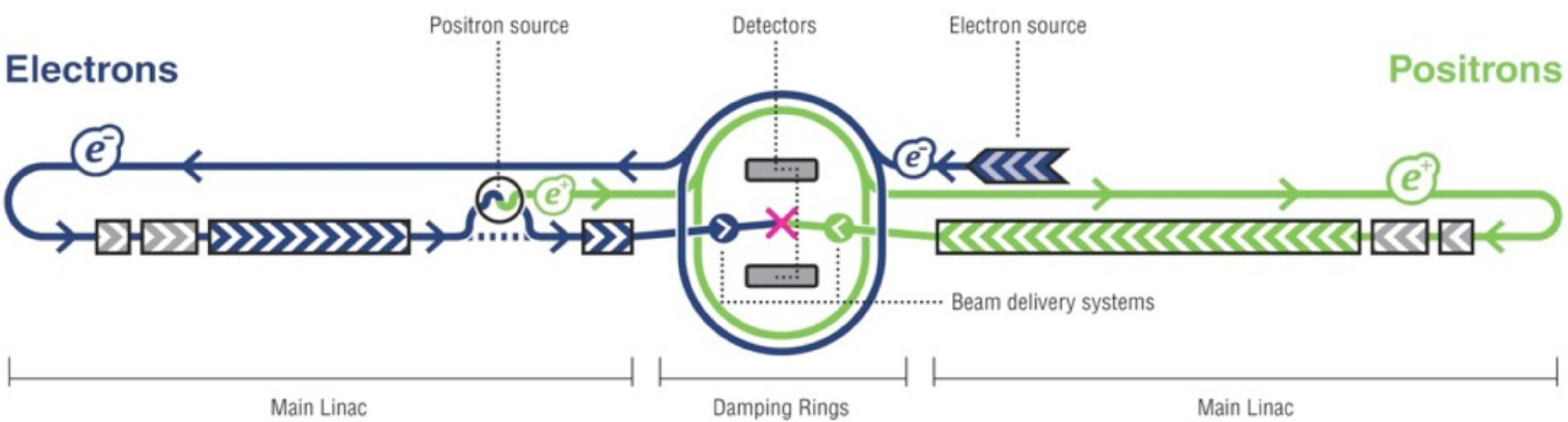
Electron-Positron High Energy Collider

LEP: P ~ 100 MW $\sqrt{s} = 200\,GeV$

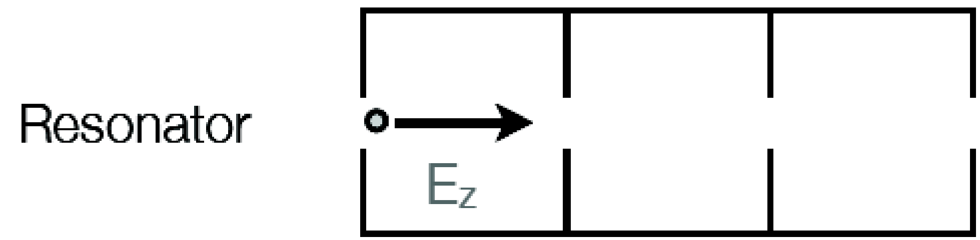
LEPX: P ~ 63 GW $\sqrt{s} = 1000\,GeV$

~63 nuclear plants!!!

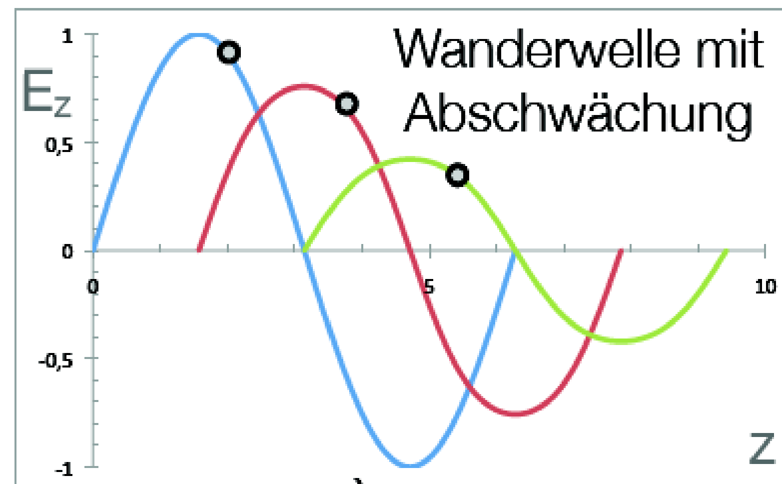
International Linear Collider (successor of the TESLA project)



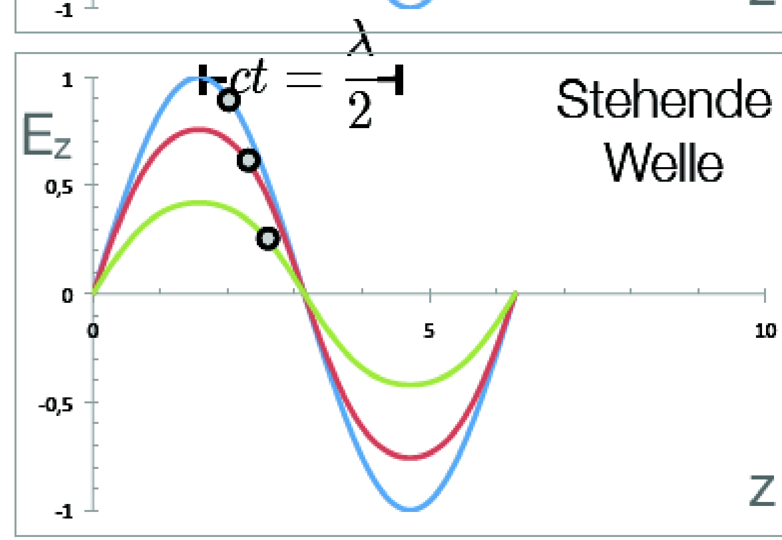
Konzepte der Hochfrequenzbeschleunigung



- Resonator erforderlich für
  - longitudinale Komponente E_z
  - Anpassung der Phasengeschwindigkeit
- Zwei Konzepte
  - **Wanderwelle** $$E_z = E_0 \cos(\phi)$$
    - Teilchenbündel entnimmt Energie und schwächt Amplitude der Welle



  - **Stehende Welle** $$E_z = E_0 \sin(\omega t + \phi) \sin(kz) = E_0 \sin(kz + \phi) \sin(kz)$$
    - Teilchenbündel wird mit dem Mittelwert des Feldes beschleunigt; Feld selbst ziemlich unberührt



from E.Elsen

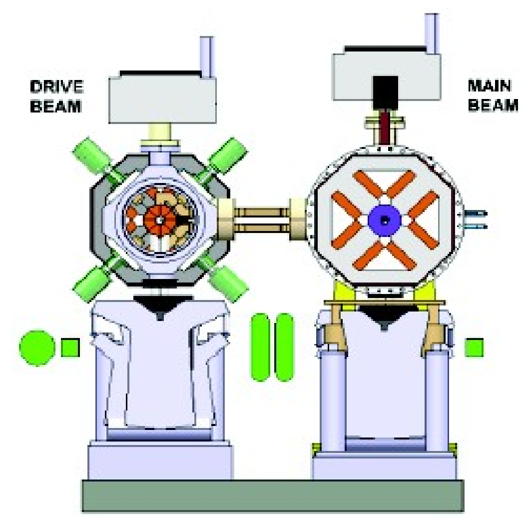
Hochfrequenzerzeugung

- Klystron
  - Geschwindigkeitsmodulation eines Elektronenstrahls durch ein äußeres Feld resultiert in Dichtemodulation des Elektronenstrahls
  - Elektrisches Feld wird ausgekoppelt

10 MW

Thales CPI Toshiba

- Wakefield
  - Das Feld einer räumlich begrenzten, bewegten Ladung wird in geeigneten resonanten Strukturen ausgekoppelt

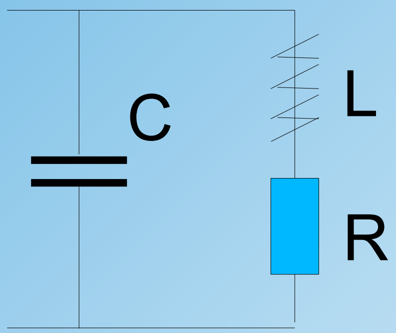


from E.Elsen

Cavity Basics

High frequency oscillator:

$$\left|Z^{-1}\right| = \left|\frac{1}{\frac{1}{i\omega C} + i\omega L + R}\right| = \frac{\omega/L}{\left(\left(\omega^2-\omega_0^2\right)^2+\omega^2\Gamma^2\right)^{1/2}}$$



cavity circuit
with series resistor

resoncance frequency:

$$\omega_0^2 = \frac{1}{LC}$$

bandwidth:

$$\Delta\omega = \Gamma = R/L$$

Quality factor:

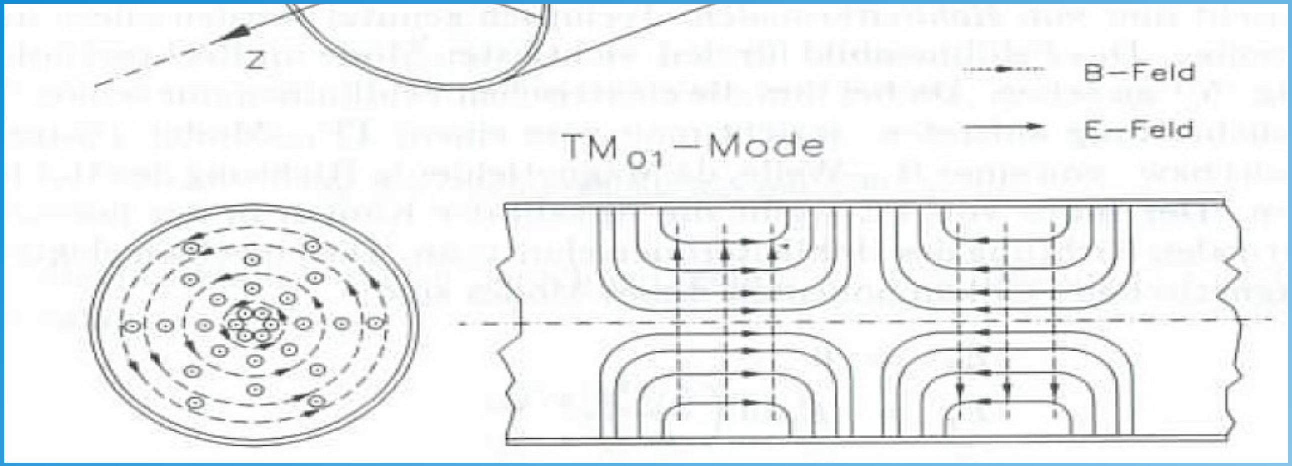
$$Q_0 = \frac{\omega_0}{\Delta\omega} = \frac{1}{R}\sqrt{\frac{L}{C}}$$

Ohmic resistor determines quality factor!

$10^4 - 10^5$ normal conducting

$> 10^9$ superconducting

Superconducting Cavity ILC (TESLA)

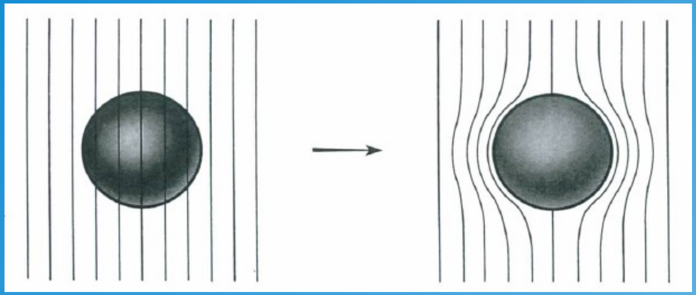


Advantage SC-RF:
no electrical resistance!
no power losses!

f = 1.3 GHz

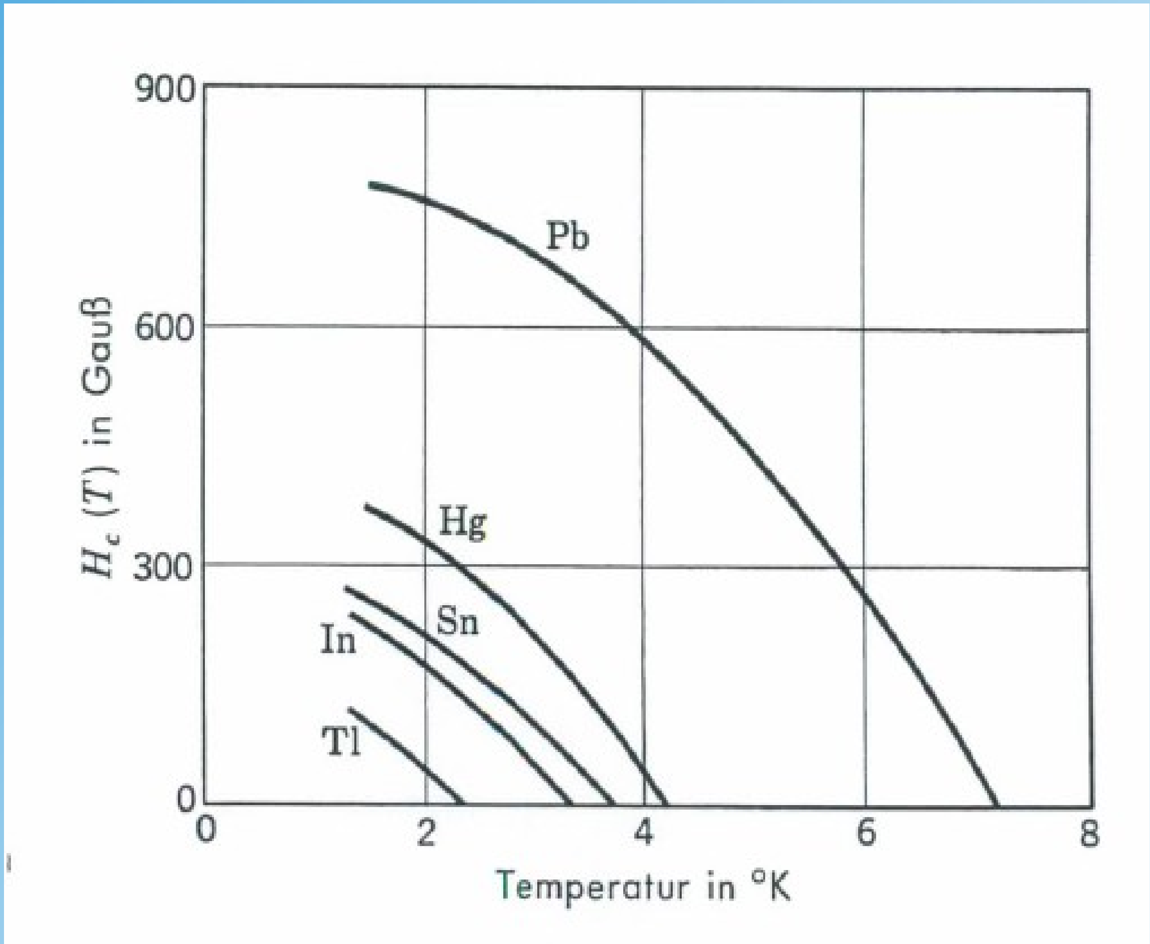
Niobium

Superconductor



Meißner-Ochsenfeld Effect

Superconductor of first kind



<u>Limitation:</u>

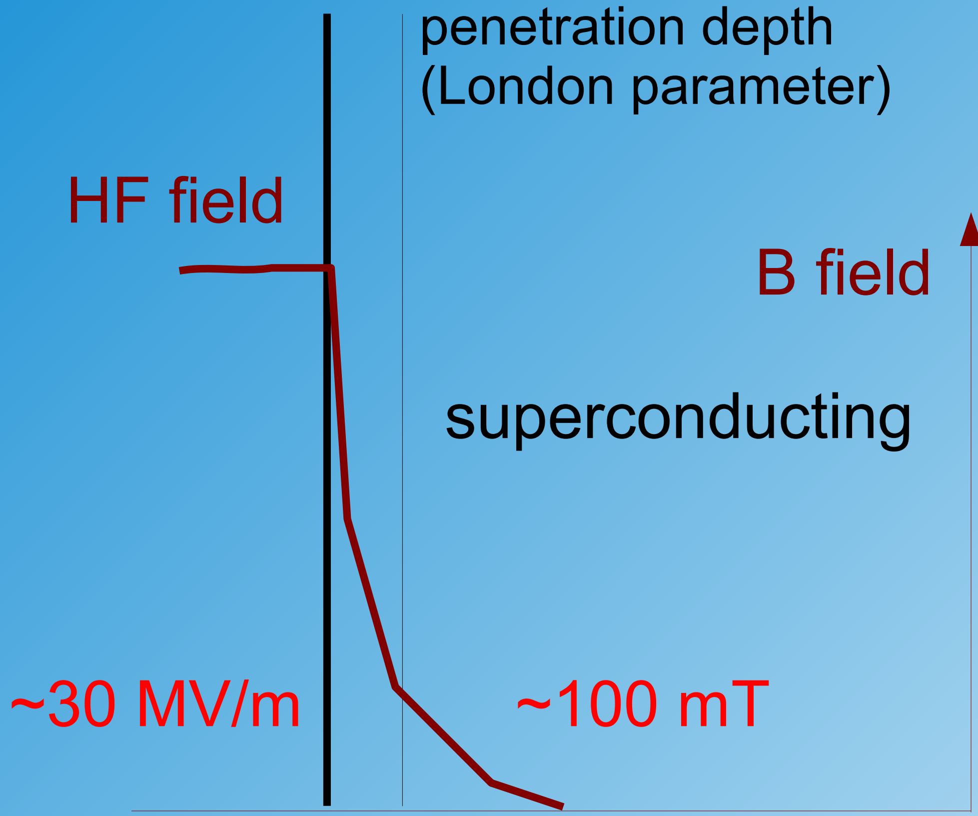
critical magnetic field H_c

$$H_c(T) \approx H_c(0)(1 - T^2/T_c^2)$$

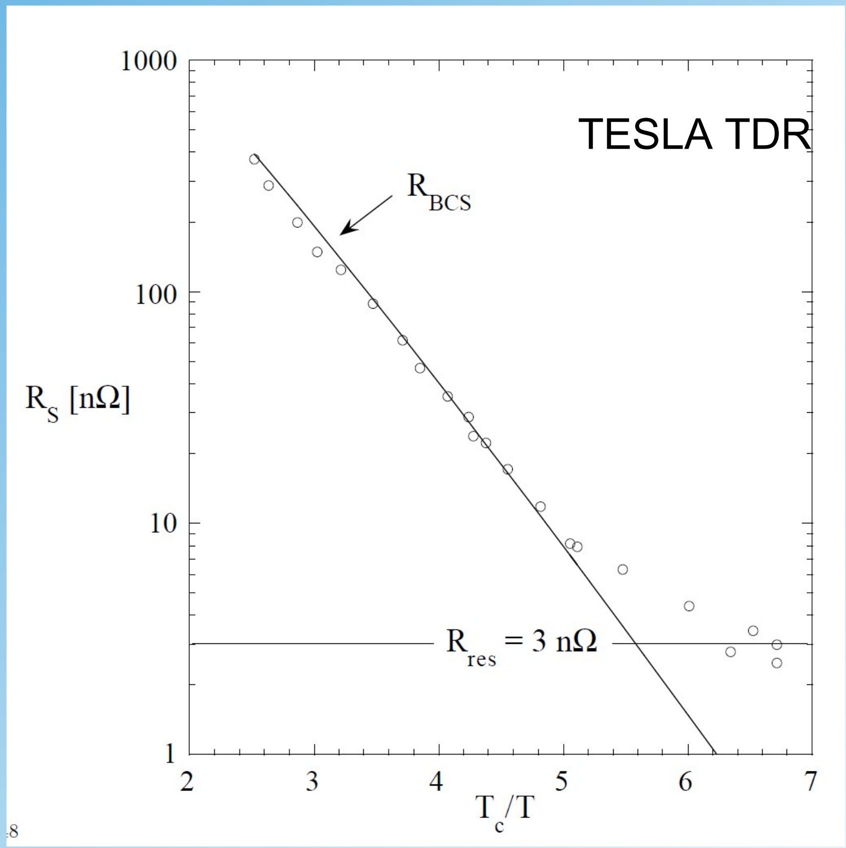
need low temperatures!

TESLA Cavity

A superconductor in a HF field has a surface resistance R_S



R_s surface resistance



Superheating:
for a short time (HF) magnetic field may exceed critical temperature!

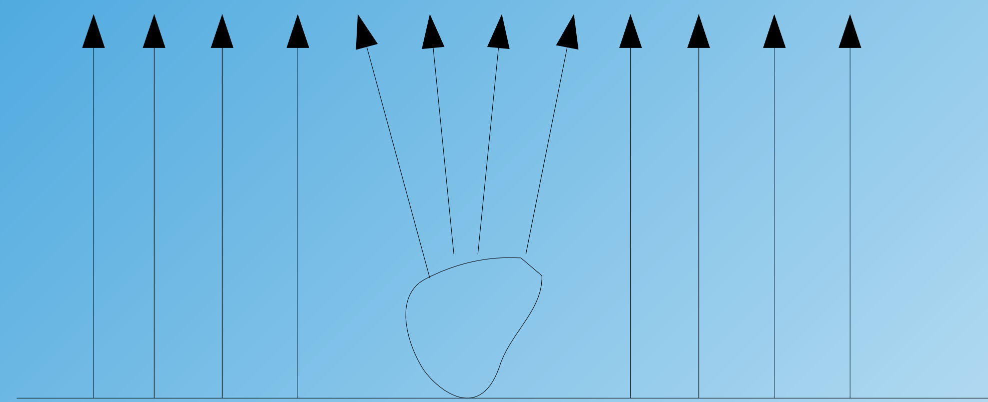
Superconducting Cavity

Technical problems

- thermal instabilities
- field emissions

caused by

- weld splatters
- cracks
- dust



strong em. field → heating

maximum acceleration field 35-40 MV/m

Therefore very clean surface required

→ electro-polishing

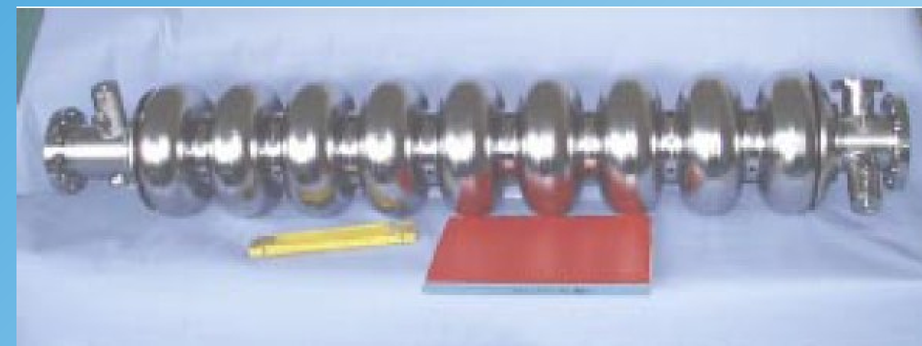
Fabrication

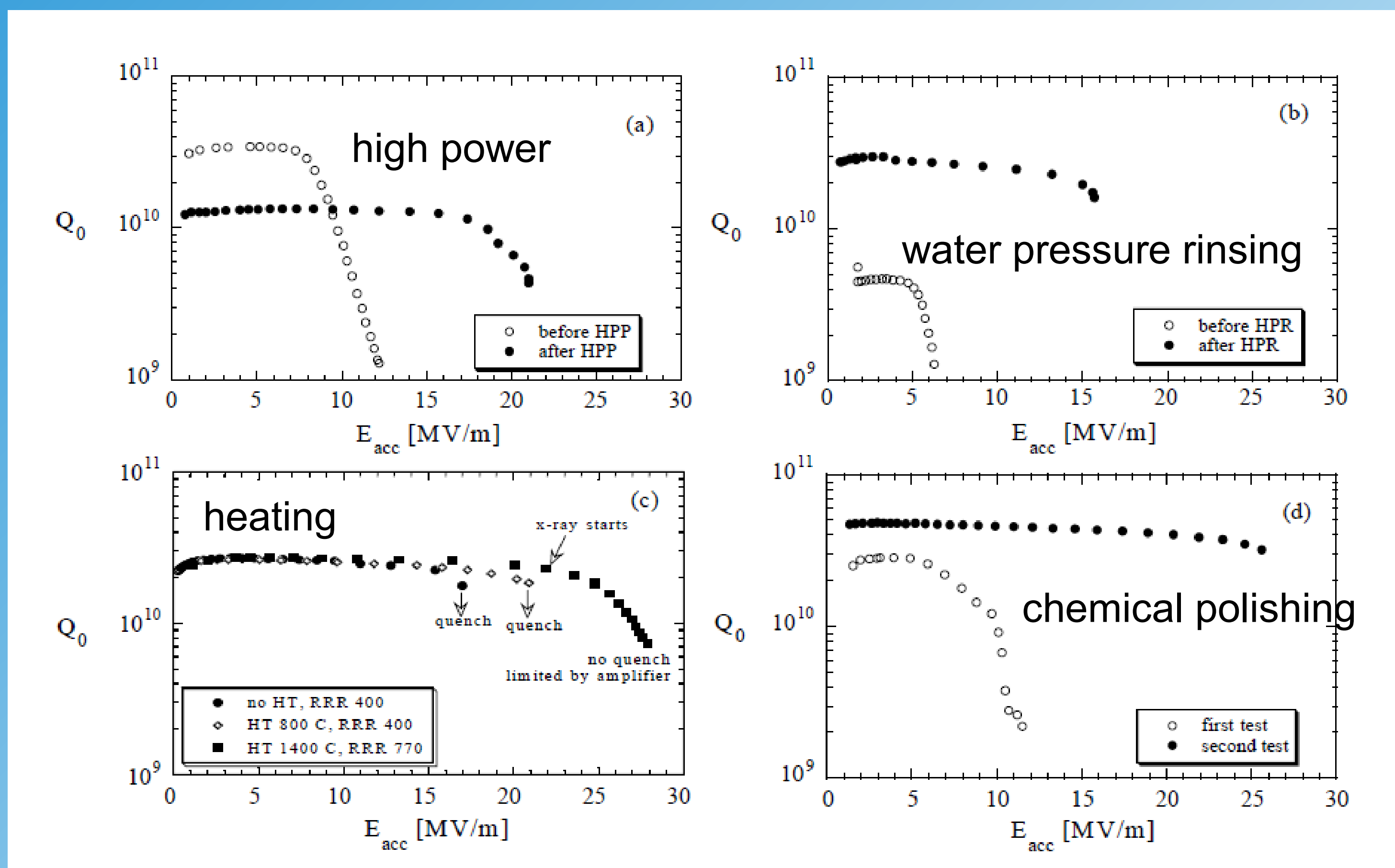
Material niobium   Tc=9.2 K

single-crystal (no welding)

small impurities!

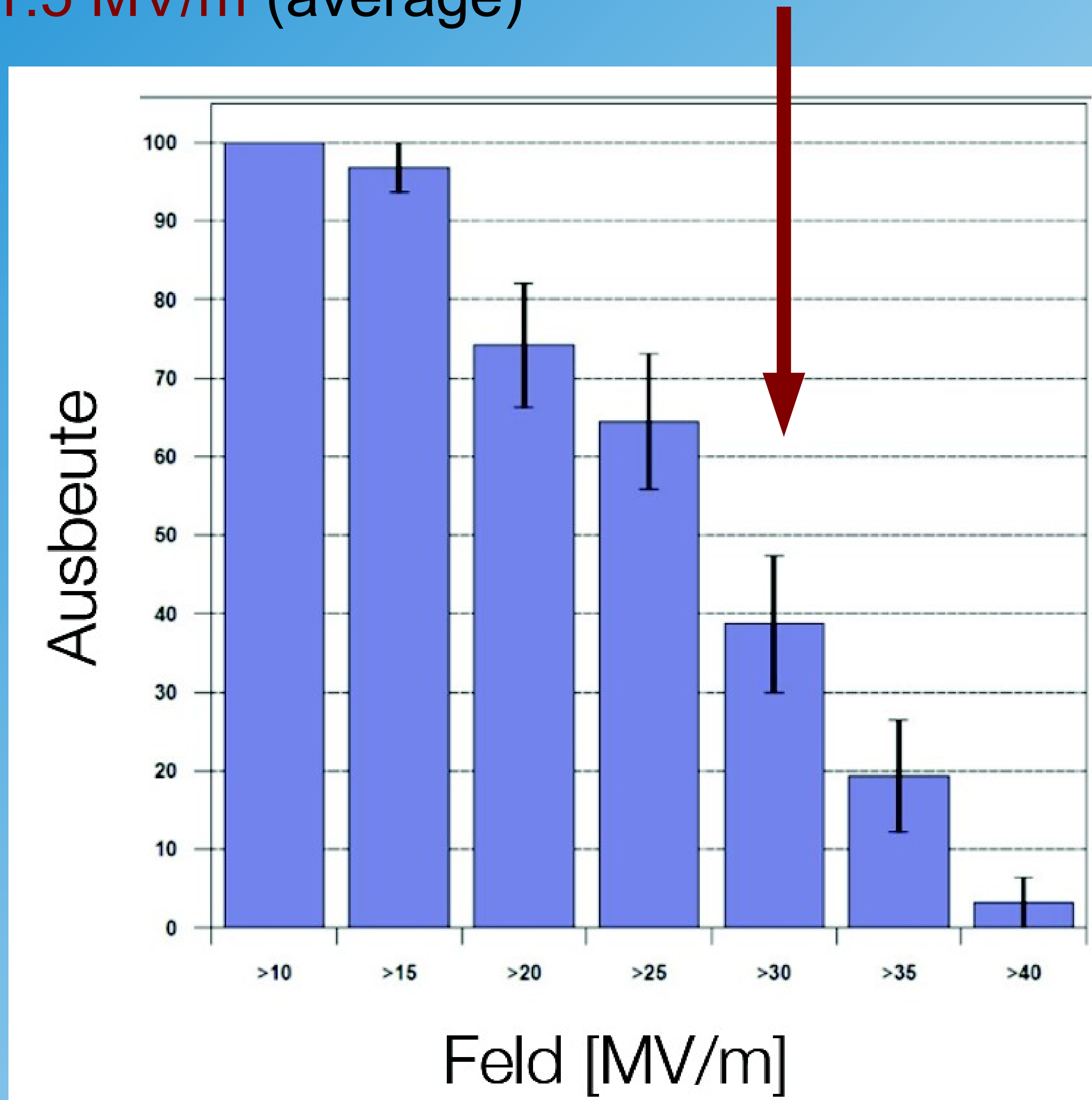
careful processing:





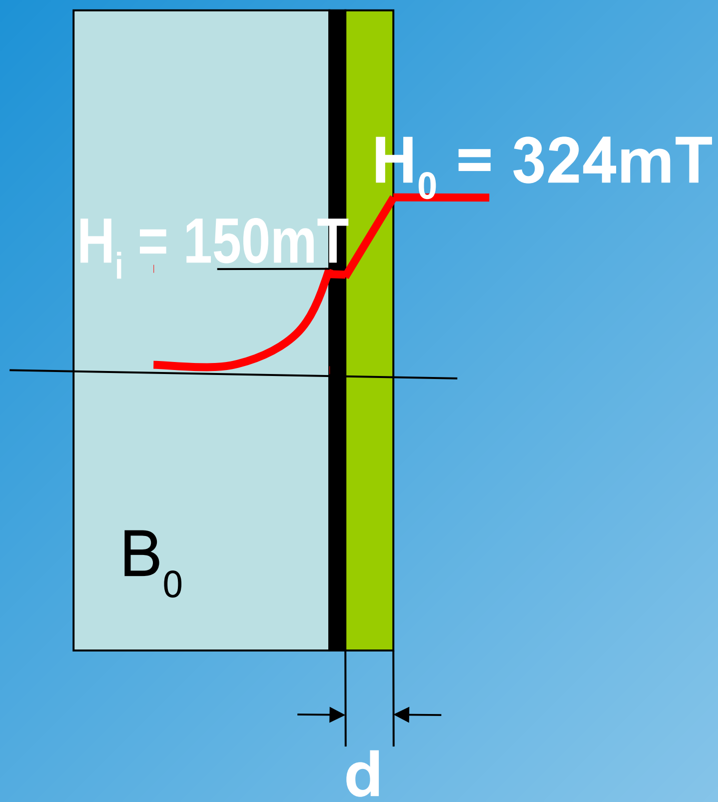
Yield of Cavities

ILC goal: 31.5 MV/m (average)



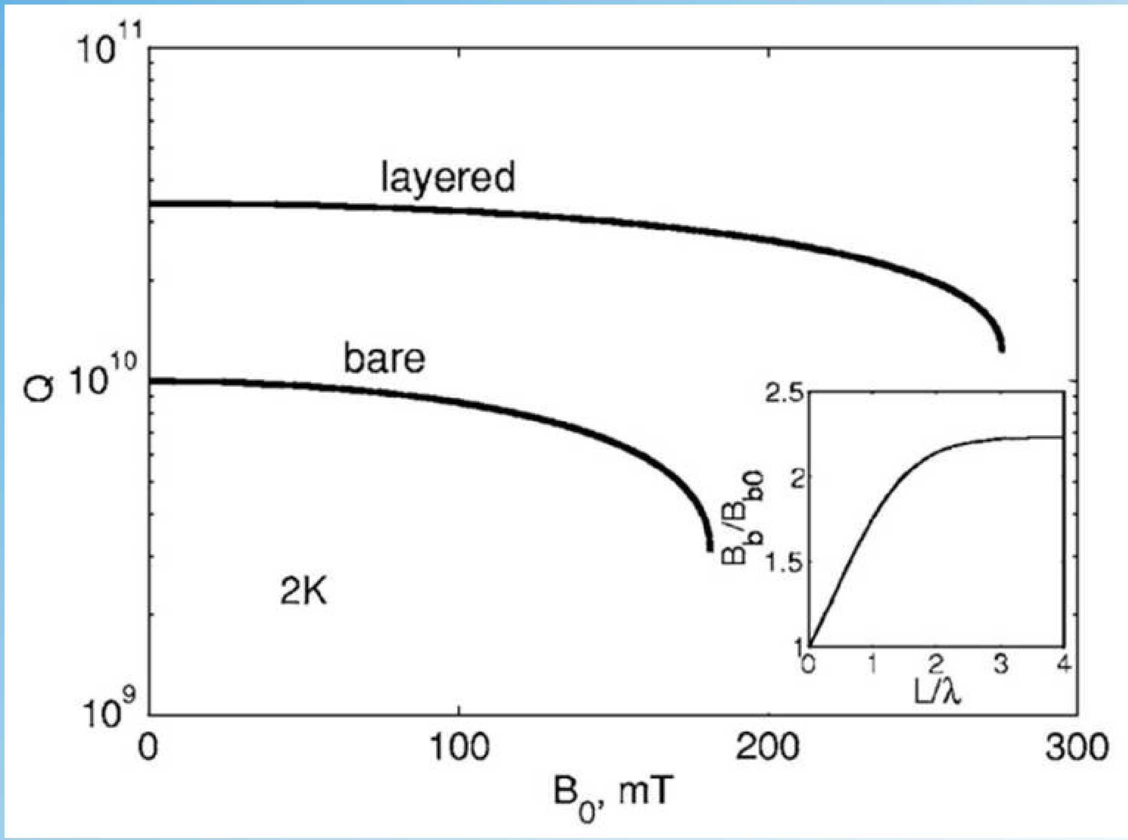
Future Ideas

Coating of surface



thin layer

coating reduces magnetic field
in superconducter and
surface resistance (A. Gurevich)



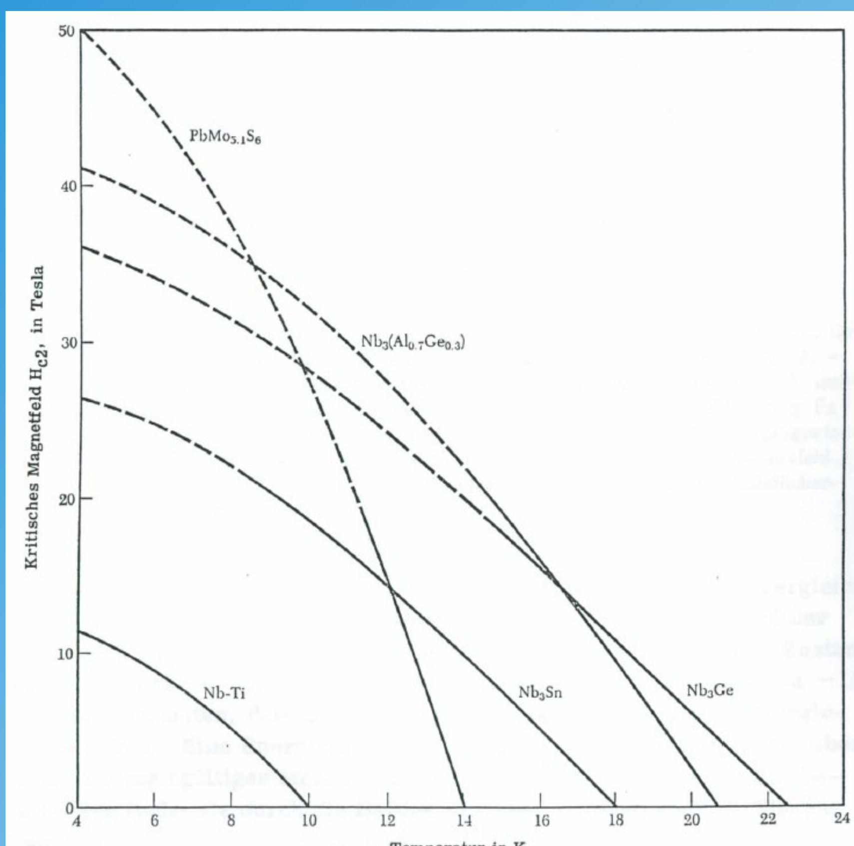
figures from Elmar Vogel (DESY)

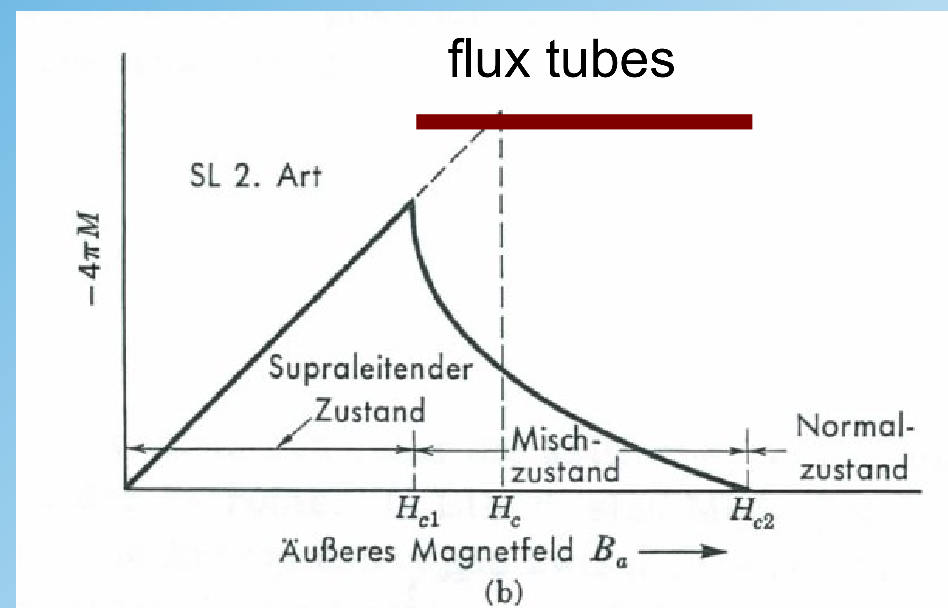
Superconducting Materials

Task: Find superconductor with high H_C

Problem:

Most “high temperature” superconductors are of second kind (incomplete Meißner effect → flux tubes)





HF: walking flux tubes absorb energy!

→ **need SC of 1st kind!**

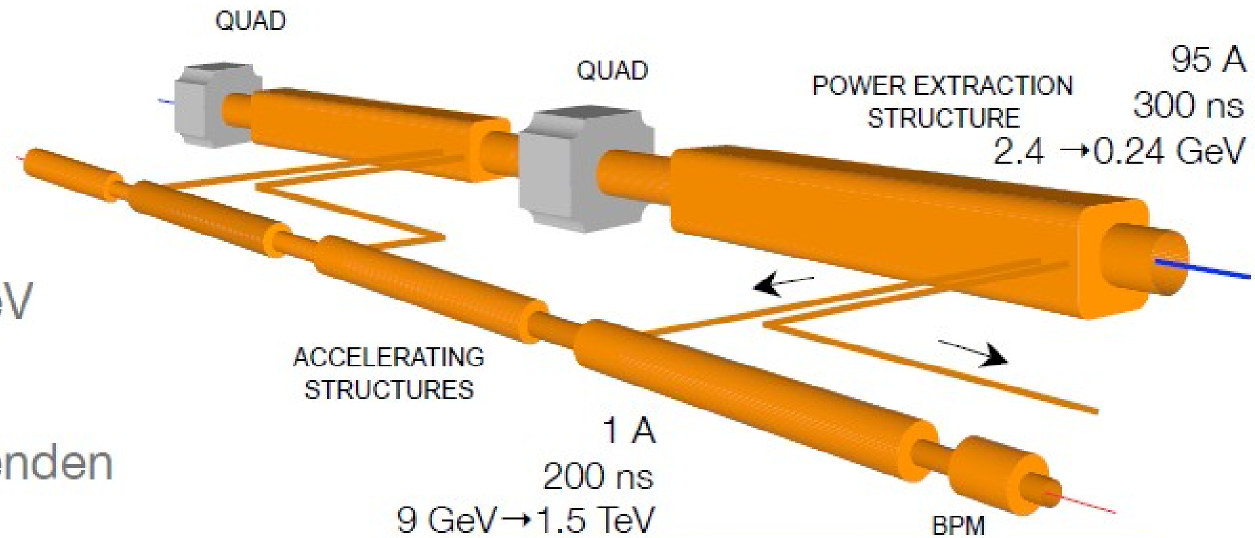
CLIC

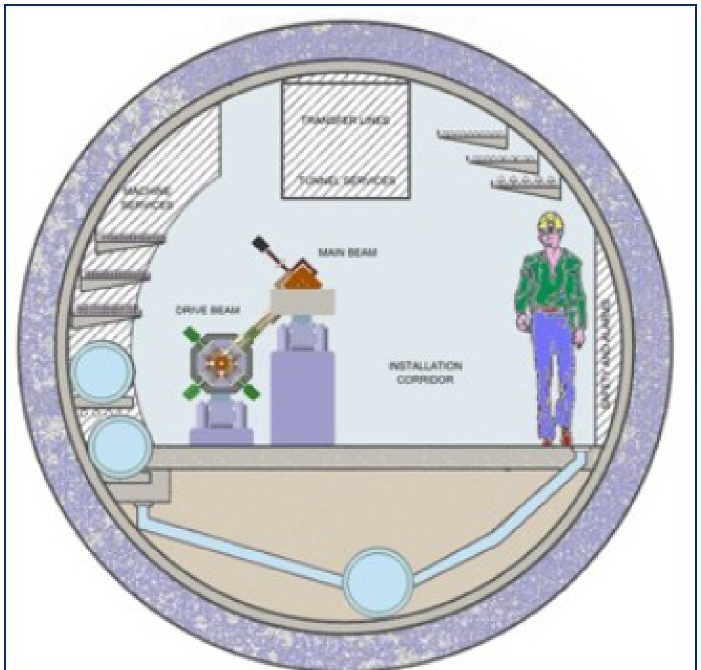
The wakefield accelerator

heavy boat → fast runner

CLIC Prinzipien

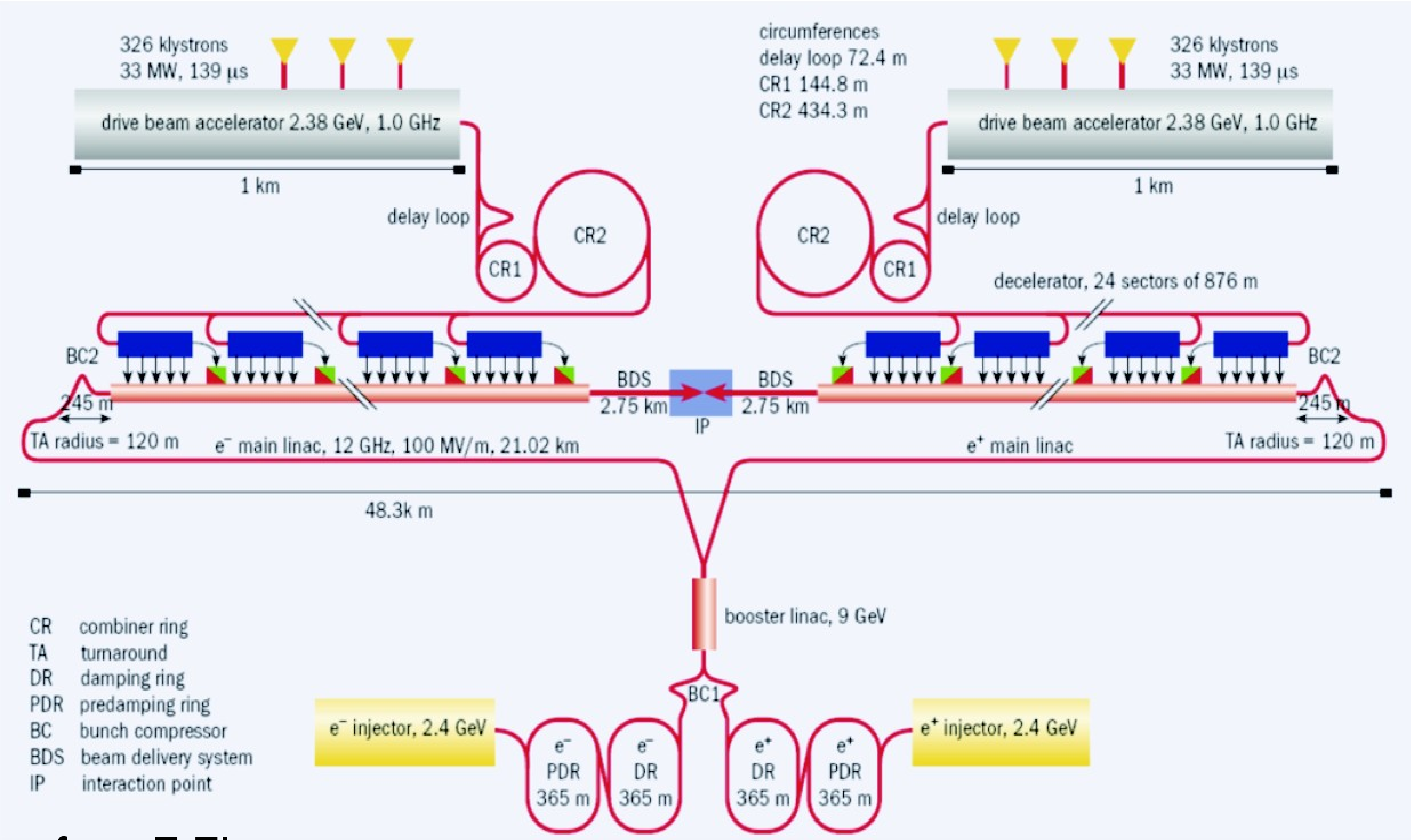
- Hoher Gradient >100 MV/m
  - Kompakter Collider;
    Gesamtlänge < 50 km für 3 TeV
  - Beschleunigung in normalleitenden Strukturen @ 12 GHz
- Beschleunigungsfeld von einem parallel laufenden Hochstromstrahl ausgekoppelt.
  - Elektrisches Feld nur bei Bedarf erzeugt
  - Hochstromstrahl wird sehr effizient generiert





from E.Elsen

CLIC Layout für 3 TeV



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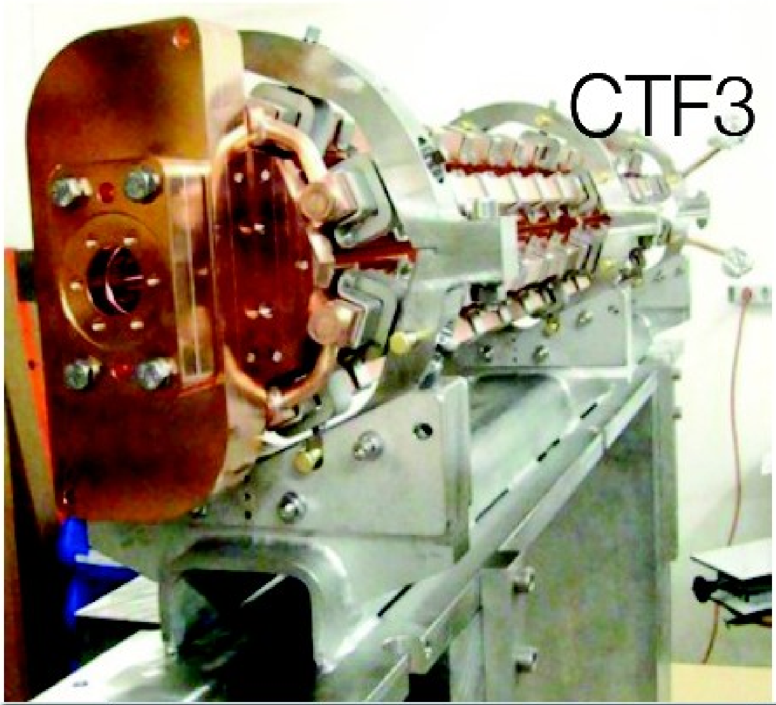
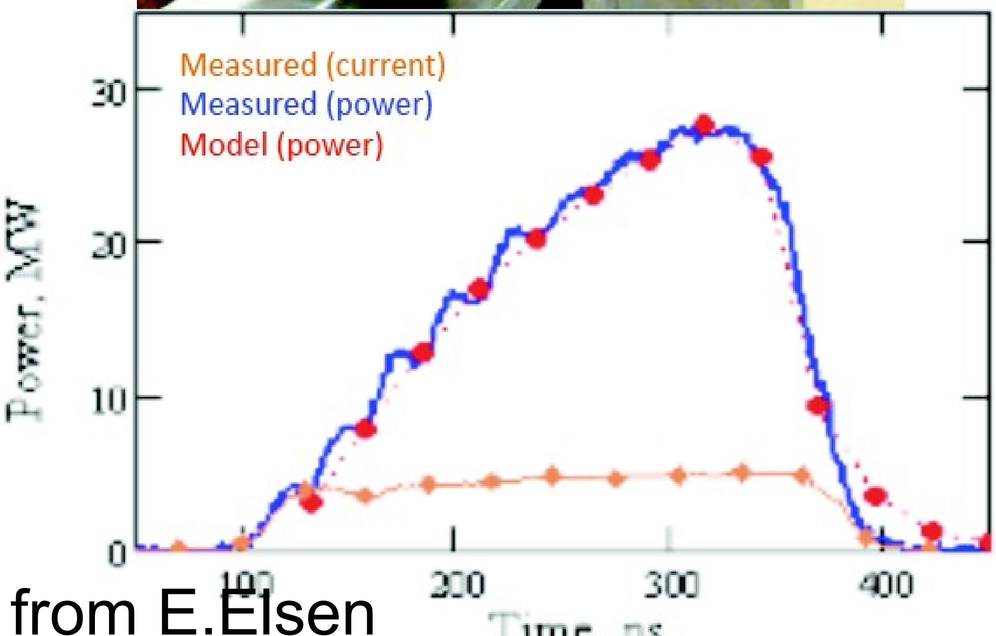
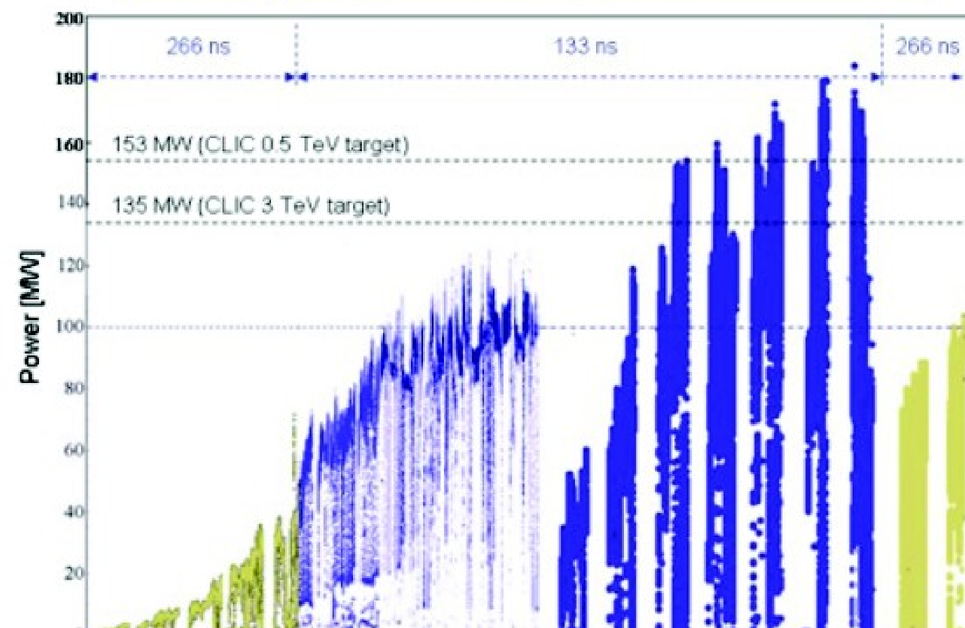
Power Extraction and Transfer Structure (PETS)







from E.Elsen

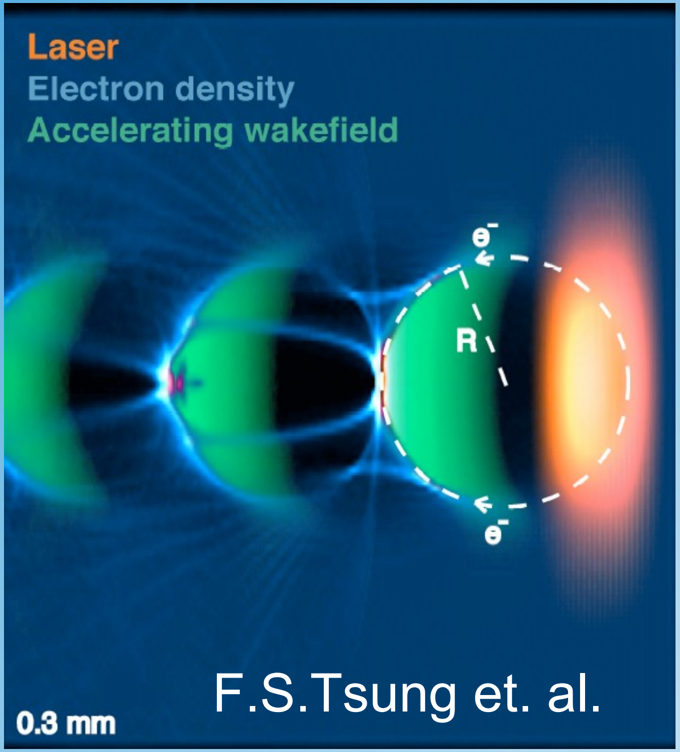
Plasma Wakefield Accelerators

A revolutionary technology...

Plasma Wakefield Accelerators

Driving Beams:

- Laser
- electron beam
- proton beam



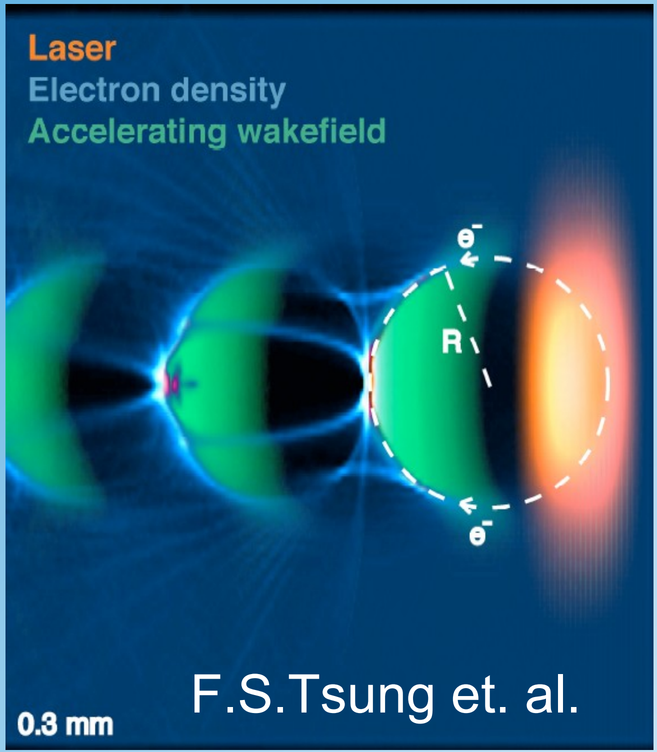
E.g.: Proton Driven Plasma Wakefield Accerator:

Use 7 TeV LHC proton beam to transfer energy to an electron beam of 7 TeV or even higher, fantastic!

Acceleration in Plasma

<u>Principle:</u>

- Plasma is created either by using strong Lasers or by heating
- A (second) laser or a particle beam creates strong electric fields which lead to charge density fluctutations in the plasma
- The mobility of ions is given by its mass → electrons move
- Charge density fluctutation create strong fields which can be used for acceleration



electrical field:

$$E_{field} = c\sqrt{\frac{m_e \rho}{\epsilon_0}}$$

density fluctutation (← ρ)

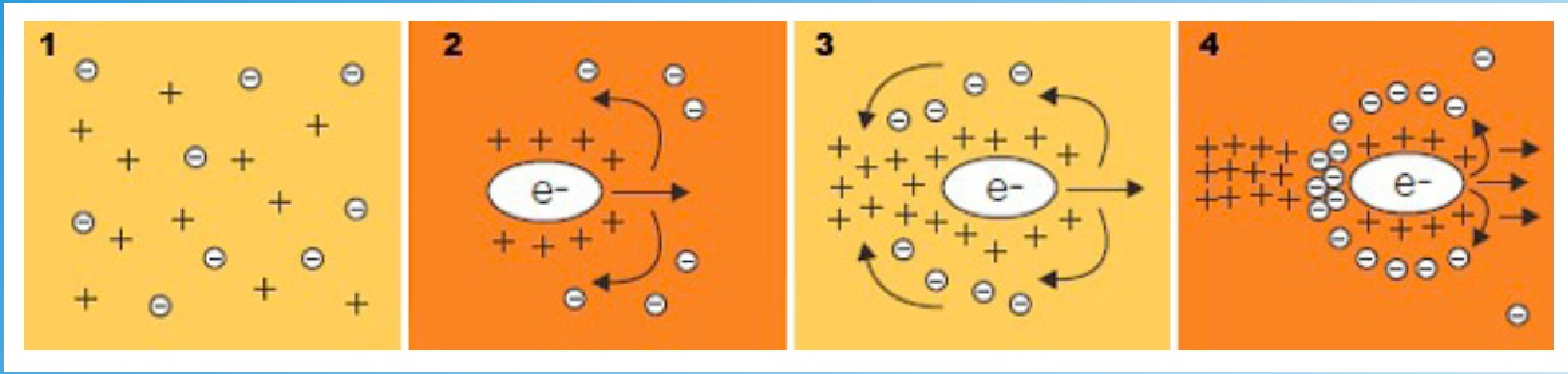
Plasma frequency:

$$\omega_p = c\sqrt{\frac{n_p e^2}{\epsilon_0 m_e}}$$

n_p = plasma density

Plasma Wakefield by Electron Beam

Sketch:



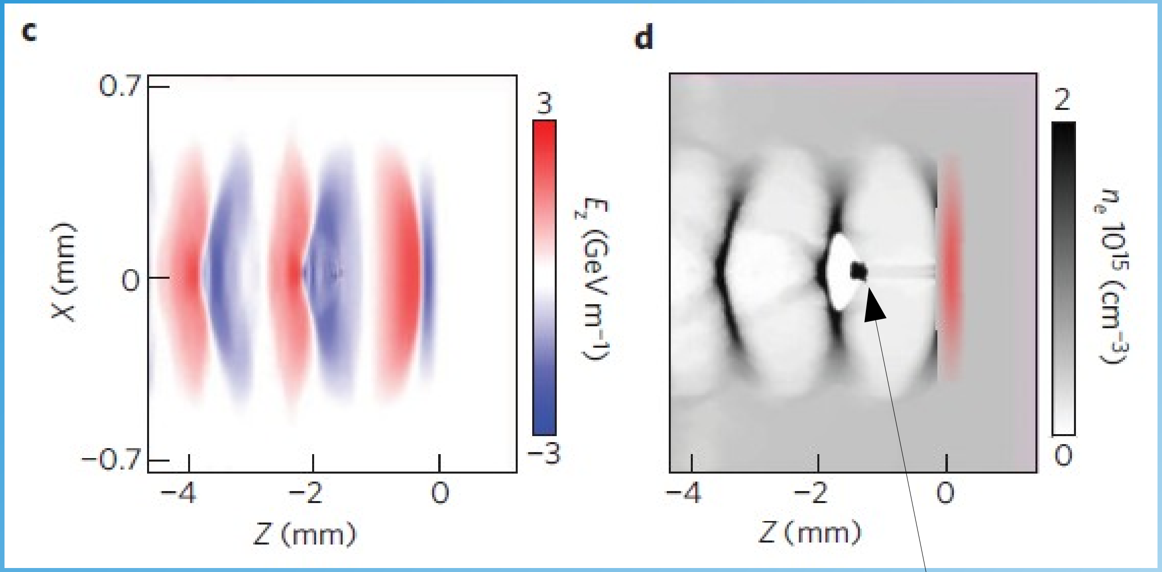
Proton Driven Plasma Wakefield

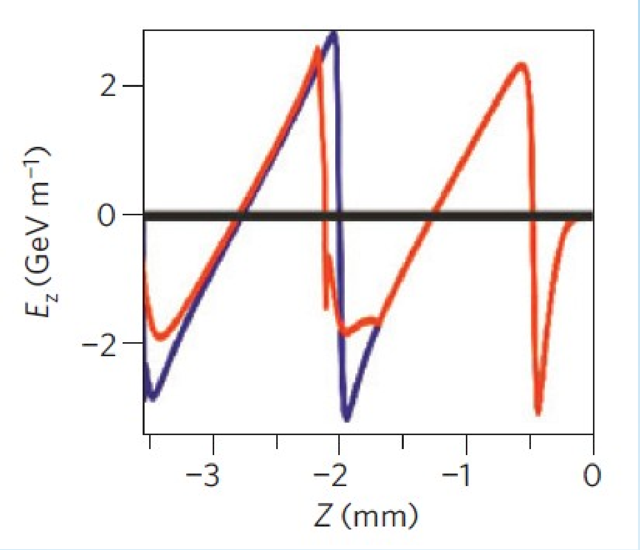
Simulation (A.Caldwell et. al.):

electrical field

density fluctutation

long. E-field

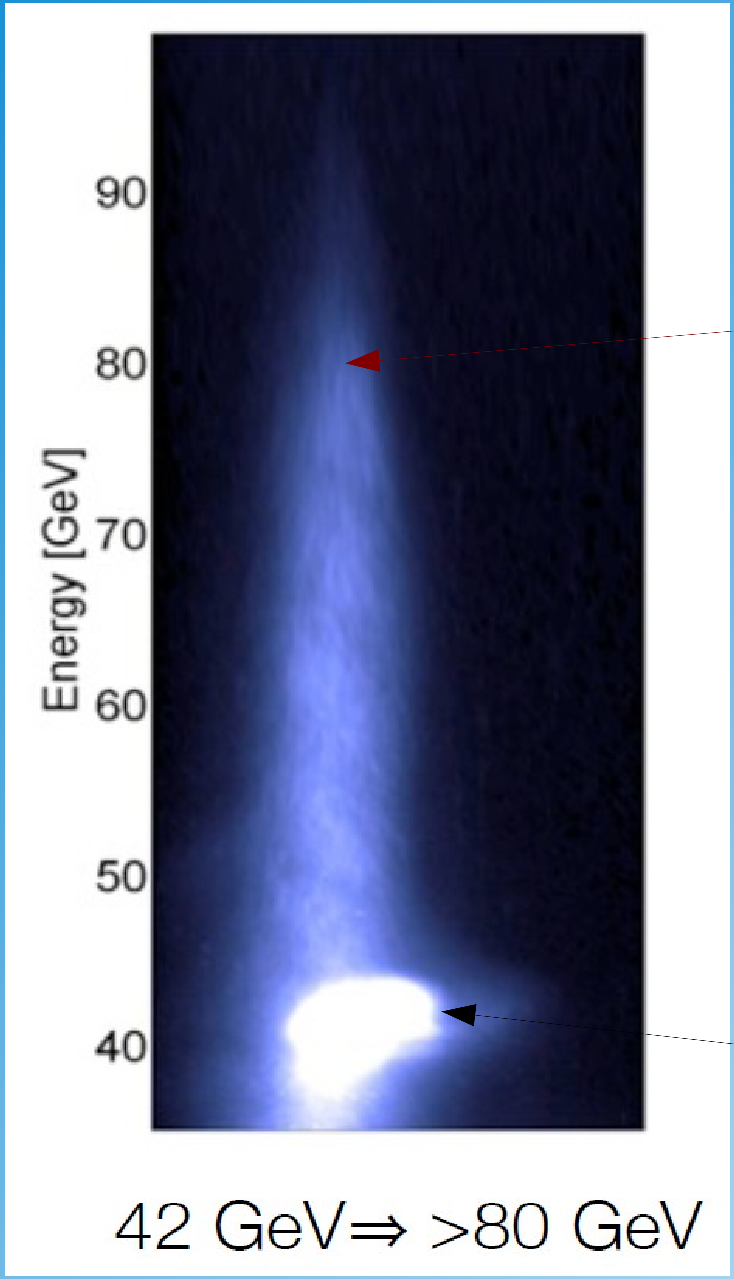




witness bunch!

2 GeV/m !!!!

SLAC Result with Electron Beam:



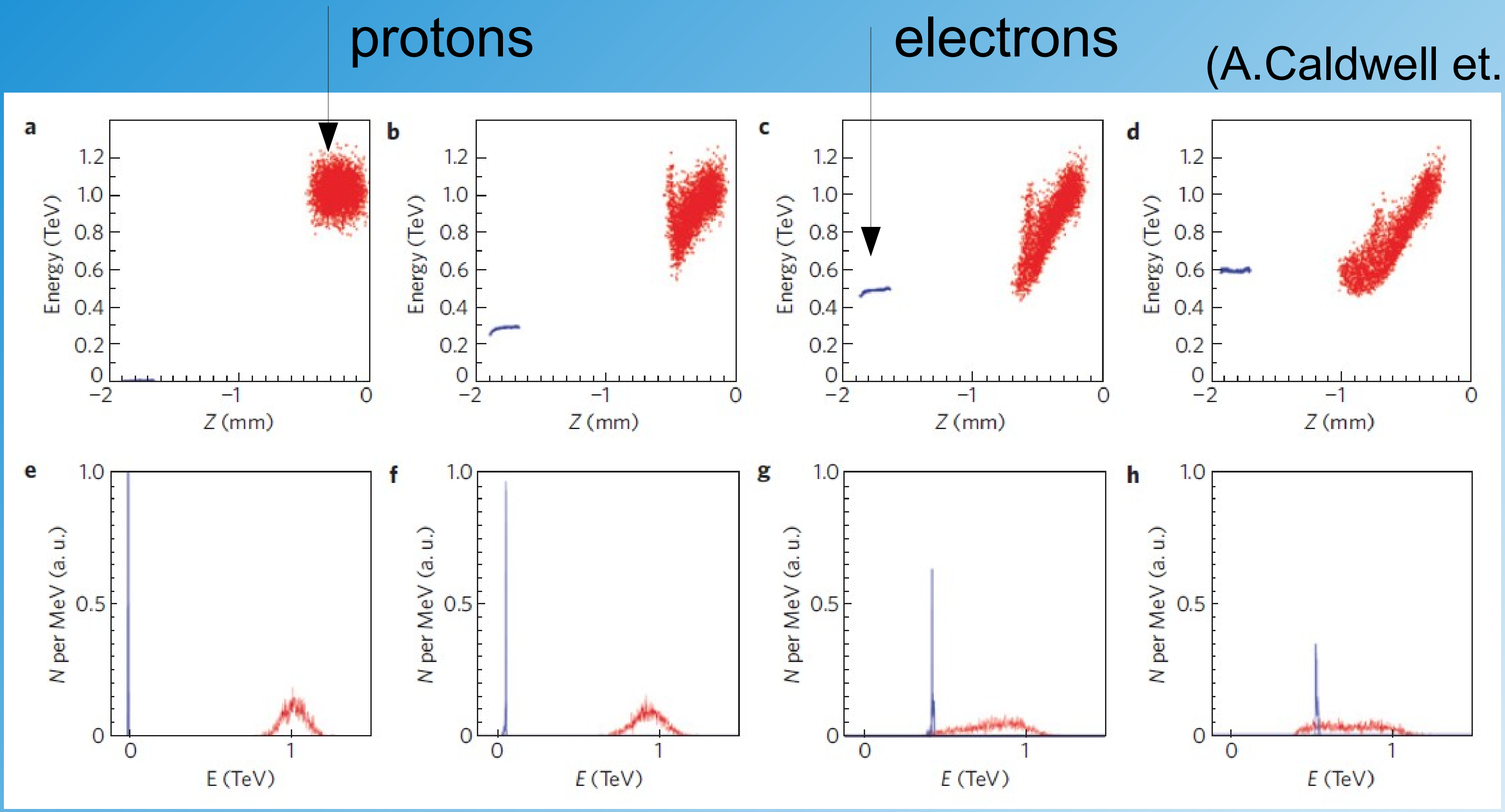
accelerated electrons

energy more than doubled in plasma !

driving beam

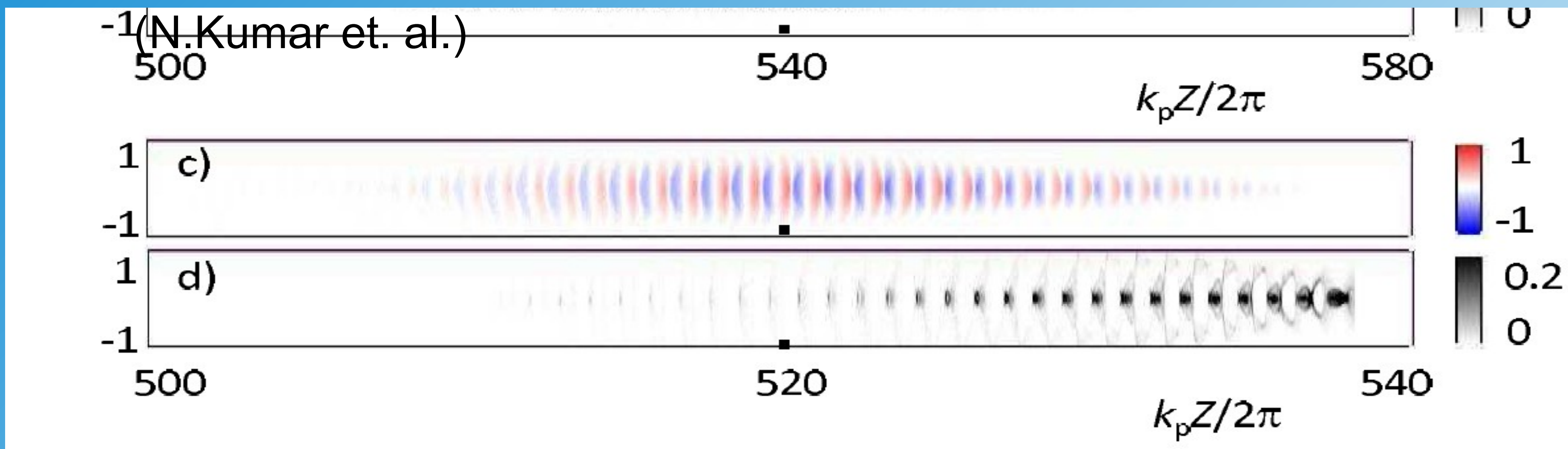
Simulation of 1 TeV Proton Beam

(A.Caldwell et. al.)



- Could be experimentally studied at SPS (E=450 GeV)
- However, proton bunches are usuall long ~ 10cm

Microbunching and Self Modulation of Proton Beams



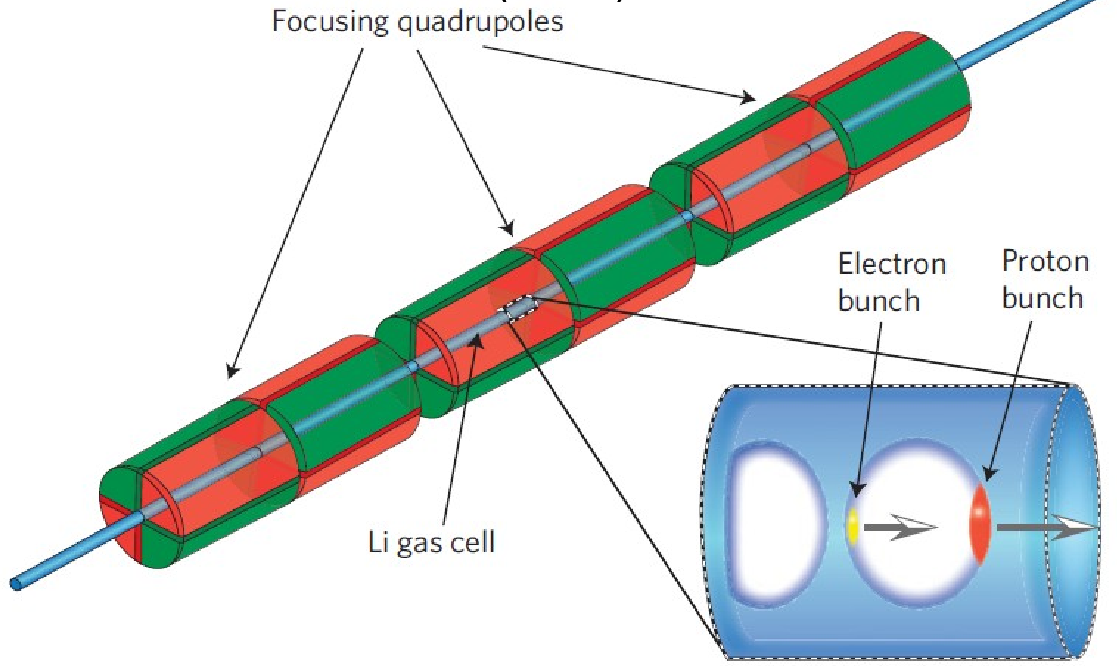
red/**blue** electrical field **black** plasma density

plasma is also modulated using long proton bunches!

→ Self Modulation

The Future: Proton Driven Plasma Accelerator at LHC?

A.Caldwell et al. Nature (2009)



$$E = 240(\mathrm{MV\,m^{-1}})\left(\frac{N}{4\times 10^{10}}\right)\left(\frac{0.6}{\sigma_z(\mathrm{mm})}\right)^2$$

$$R = \frac{E_{\mathrm{max}}^{\mathrm{witness}}}{E_{\mathrm{max}}^{\mathrm{drive}}} \leq 2 - \frac{N_{\mathrm{witness}}}{N_{\mathrm{drive}}}$$

1km linear TeV accelerators with large acceleration gradients are possible, in principle!

AWAKE Collaboration @ CERN