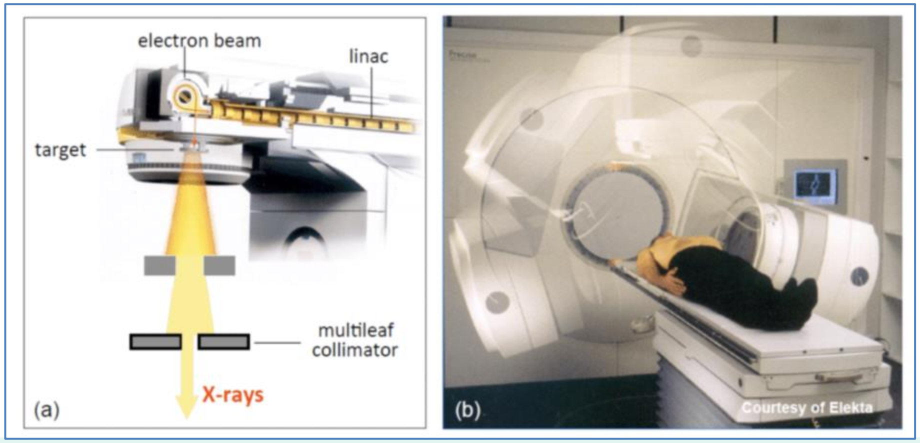
Particle accelerators

Part II: applications outside particle physics

Norwegian Teachers at CERN
February 19-20, 2024

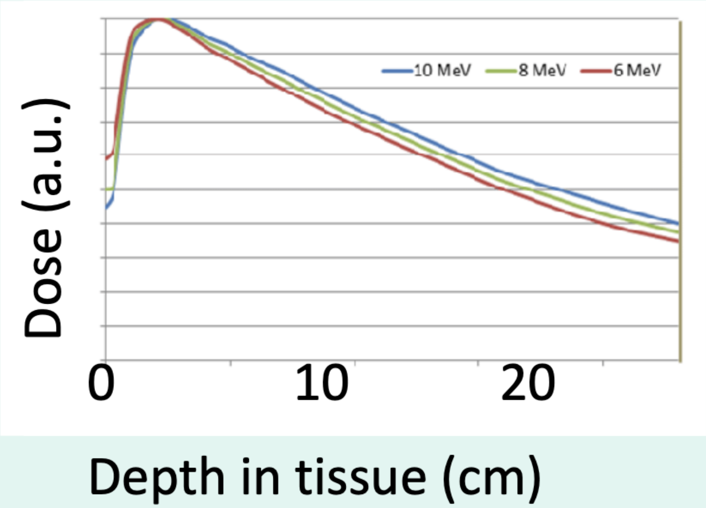
Prof. Erik Adli
Department of Physics, University of Oslo, Norway
Erik.Adli@fys.uio.no

Particle therapy (protons, ions, e^-…)

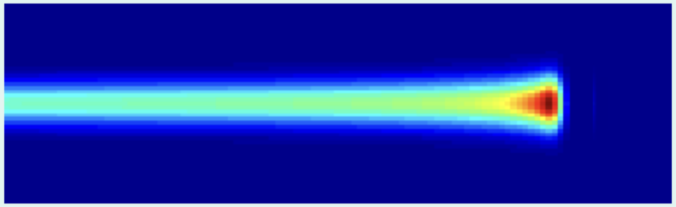


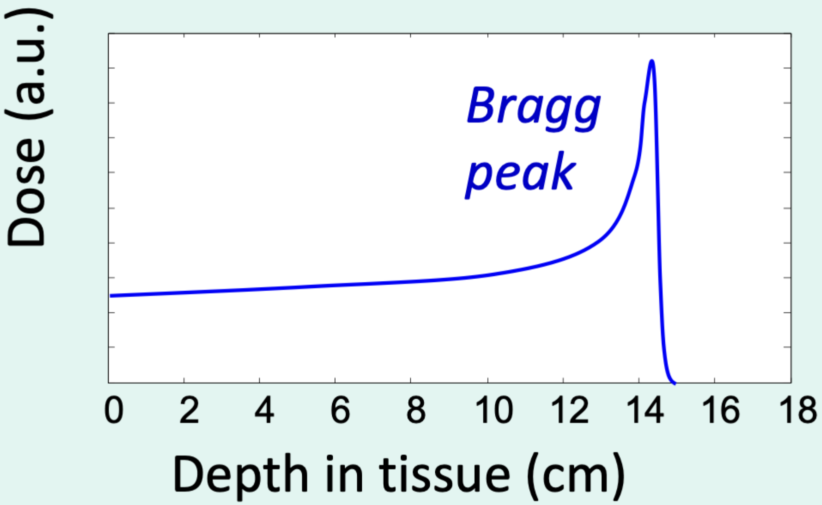
Courtesy of Elekta

X-rays



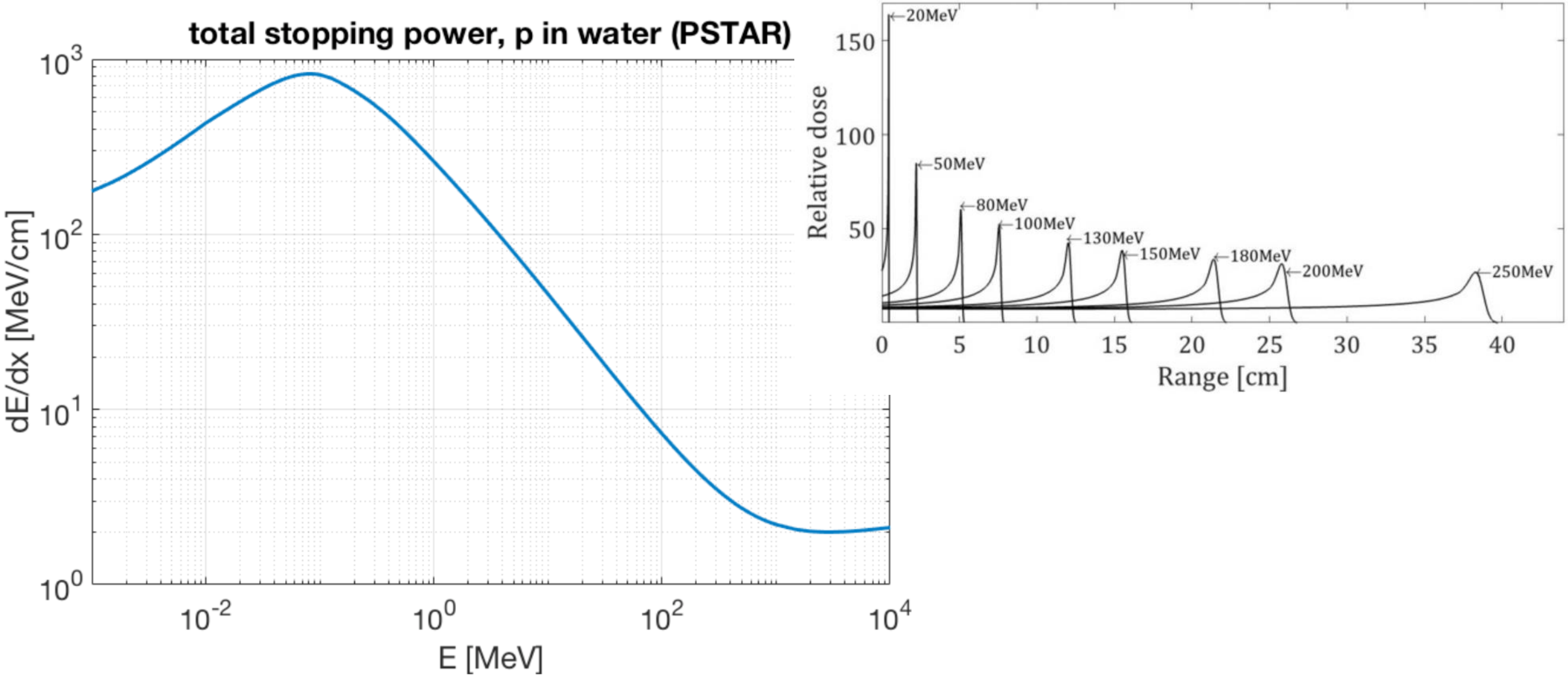
Protons



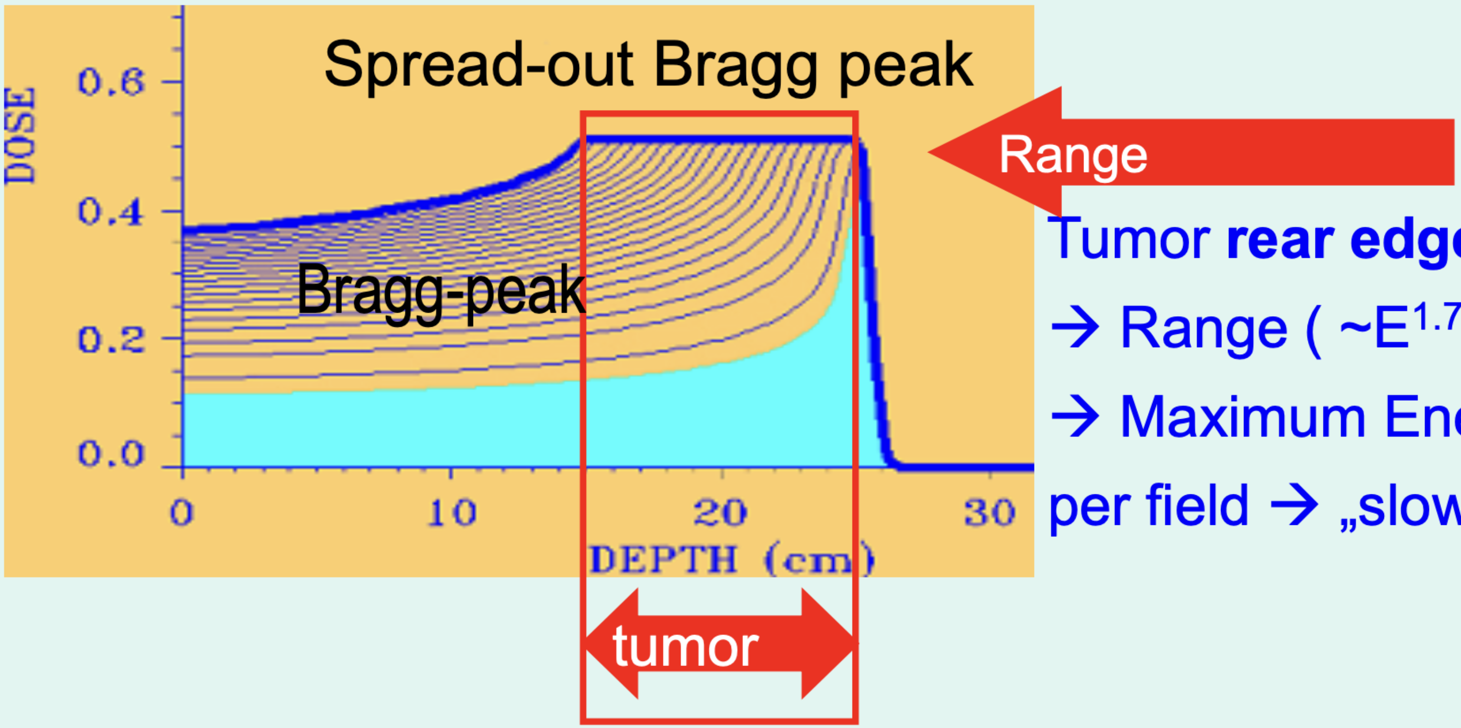


Energy loss of heavy charges particles – Bethe-Bloch

$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \gamma^2 \beta^2}{I^2} T^{\max} - \beta^2 - \frac{\delta}{2} \right]$$



Stopping power of protons in water according to PSTAR



Tumor **rear edge**

→ Range ($\sim E^{1.7}$)

→ Maximum Energy in field

per field → „slow“ (sec)

Tumor **thickness**

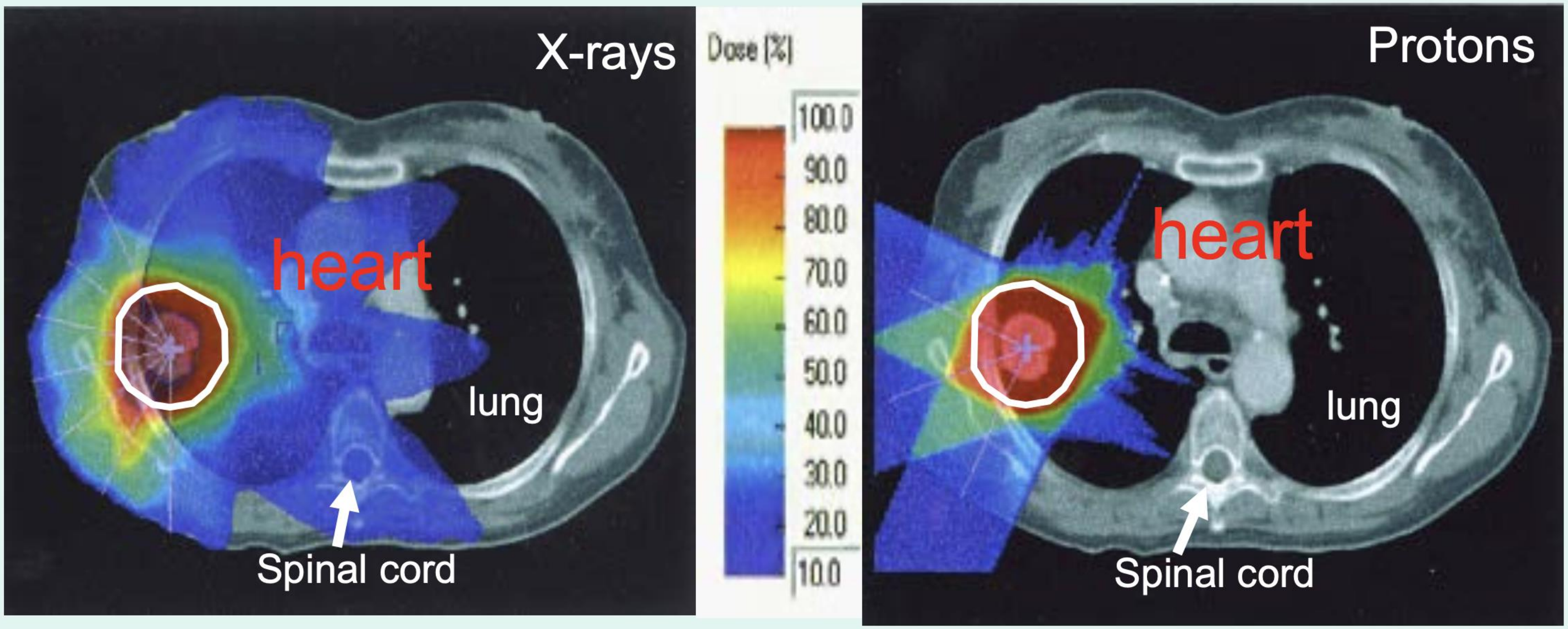
→ spread-out Bragg peak

→ energy modulation

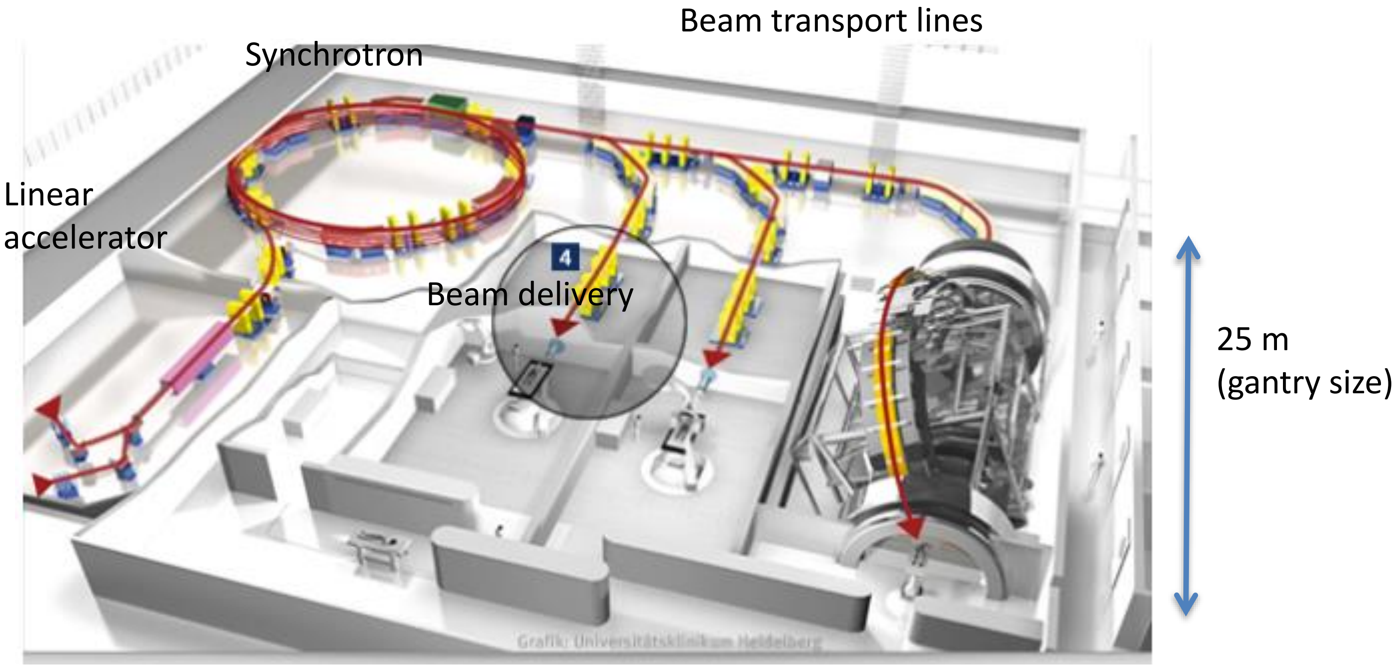
During trmt → „fast“ (<0.1-0.2 sec)

X-ray beams (IMRT) from 7 directions

Proton beams from 3 directions



pictures: Medaustron



Beam transport lines

Synchrotron

Linear accelerator

Beam delivery

25 m (gantry size)

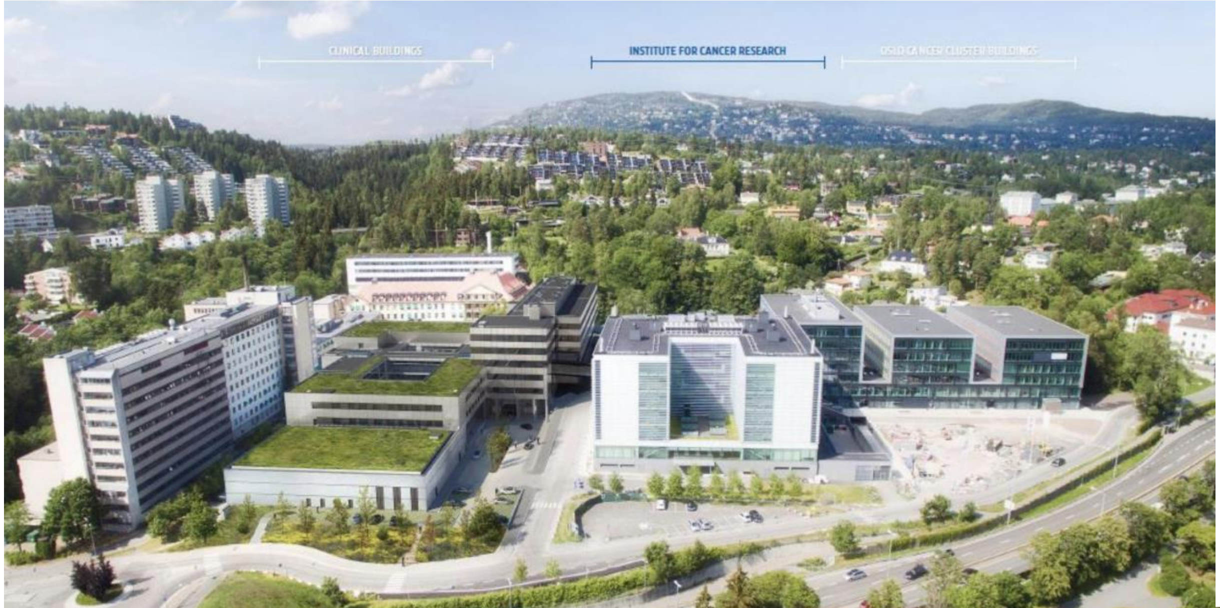
Heidelberg Ion-Beam Therapy Center (HIT)

Accelerator challenges:

- **Stable and precise beam delivery**
- **Strong bending and focusing fields**
- **Higher accelerating gradients, MV/m**

Can particle accelerator R&D drive size and cost down?

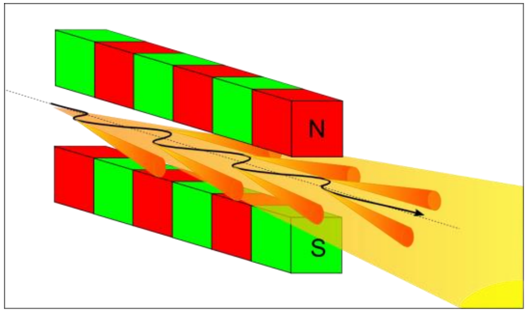
Proton therapy in Norway (2025 ->)



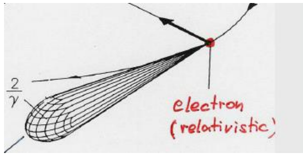
The Radium Hospital site after completion of new clinical buildings and the new proton therapy centre Q1 2024 (new buildings with green/

Veidekke ASA: Construction job at the proton centre in Bergen - Veidekke ASA

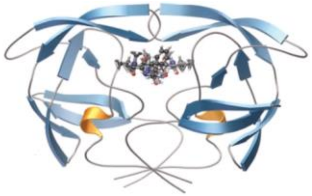
Photon Sources



- **Synchrotron radiation** emitted from accelerated charged particles can produce very intense radiation at X-ray frequencies
- The last decades, vast increase in the use of synchrony radiation **for photon science**. Some uses: material sciences; life sciences; earth sciences.

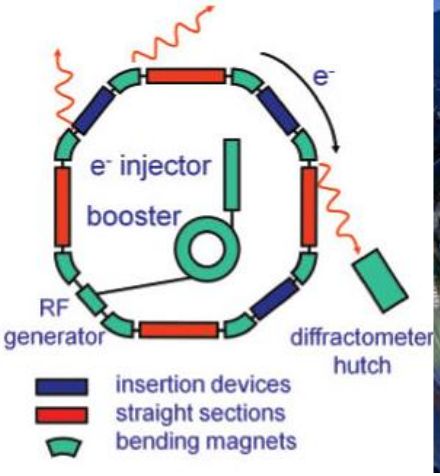


Radiation from ultra-relativistic electrons: forward direction.



Structure of a protein of HIV-1, as studied in light sources

ESRF, Grenoble



Accelerator challenges:
- **High-brightness, high-frequency photons.**
- **Coherent, narrow-band, short duration photon radiation, from charged particle beams**

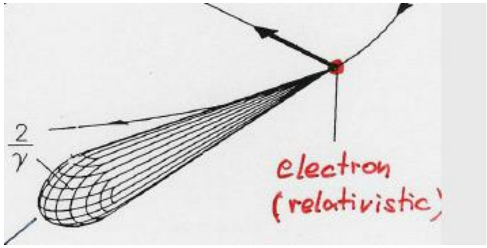
Synchotron light source: **GeV e- beams**

Synchrotron radiation - revisited

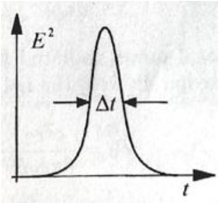
SR power

$$P_S = \frac{e^2 c}{6\pi\varepsilon_0} \frac{\gamma^2}{(m_0 c^2)^2} (\frac{dp}{dt})^2 = \frac{e^2 c}{6\pi\varepsilon_0} \frac{1}{(m_0 c^2)^4} \frac{E^4}{R^2}$$

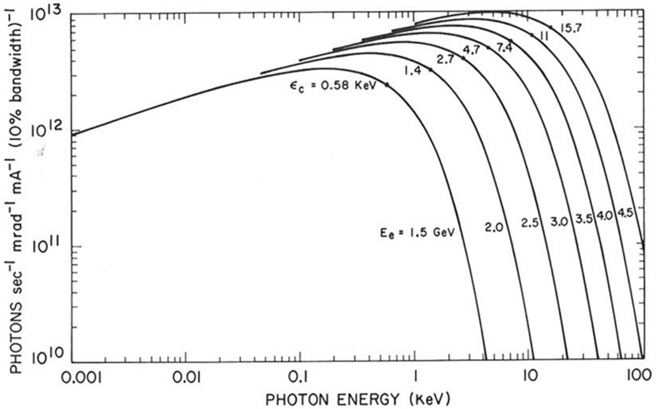
SR opening angle

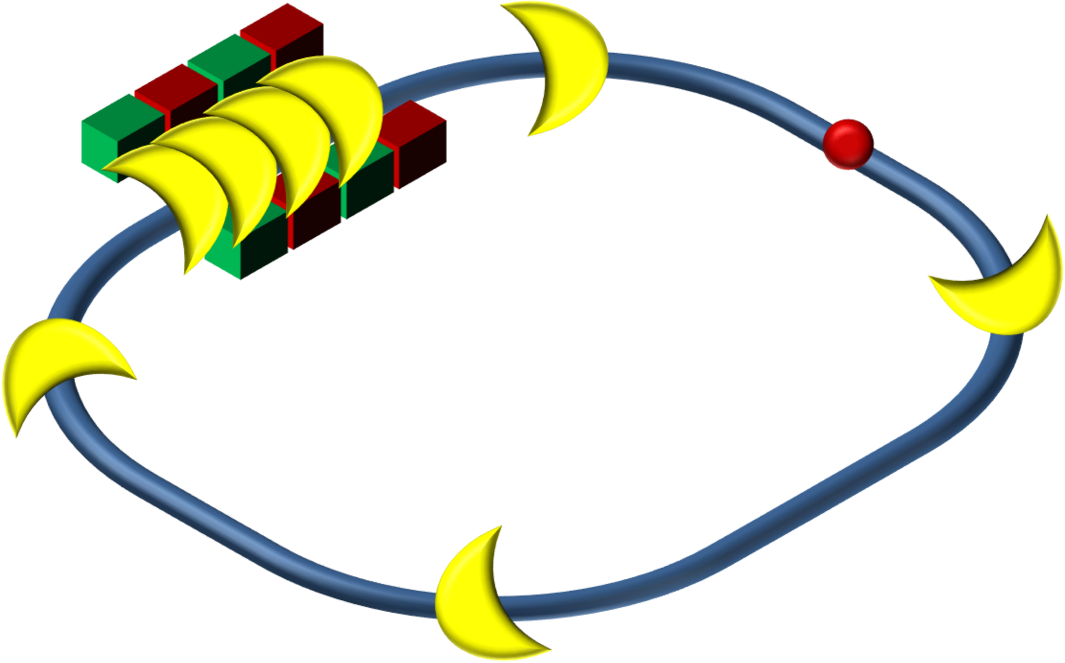


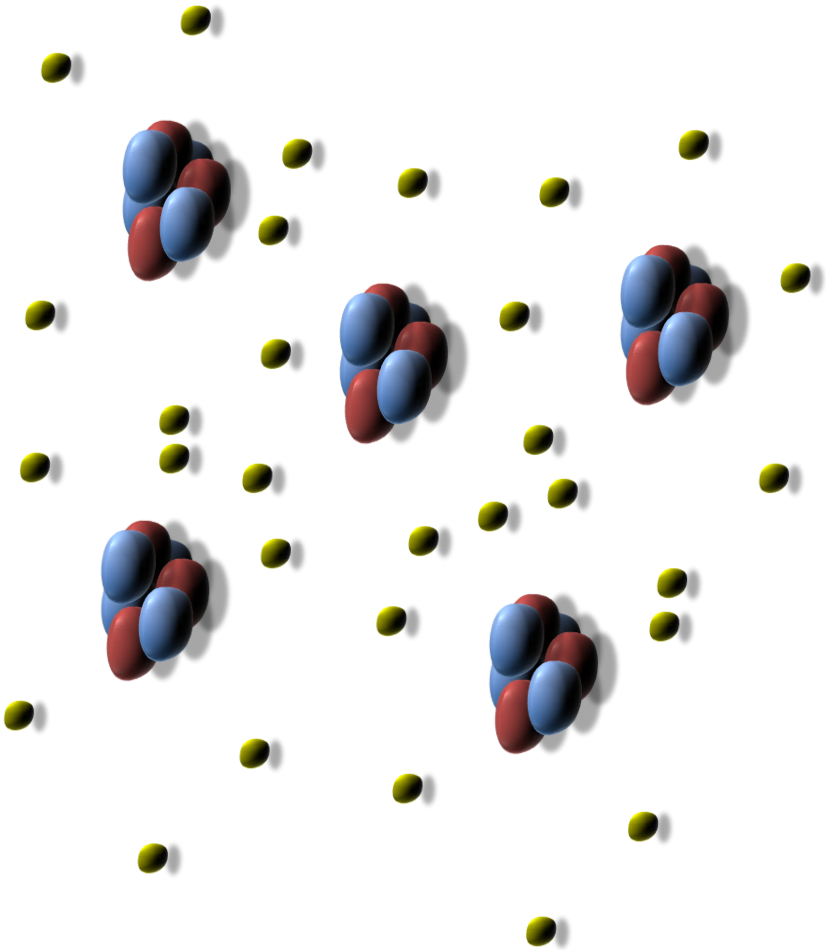
SR spectrum



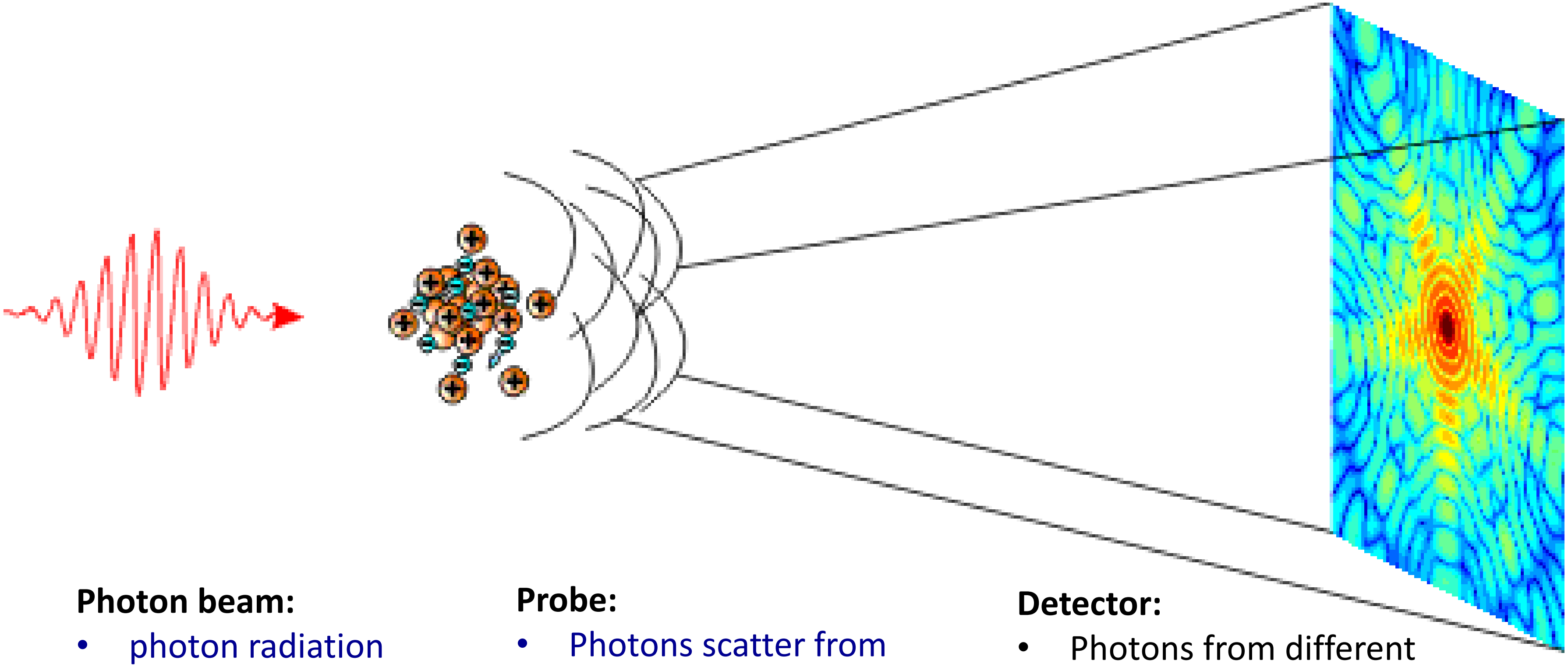
$$\omega_c = \frac{3c\gamma^3}{2R}$$







Diffraction imaging



Photon beam:

- photon radiation has wave fronts that can interfere.
- Wavelength on the order of the probe.

Probe:

- Photons scatter from electron cloud.
- Scattered light is a spherical wave starting at the interaction point.

Detector:

- Photons from different scattering point have different phases, and create interference pattern.
- Image is the Fourier transform of probe.

Reconstruction:

- Inverse Fourier transform
- But no phase information (phase problem)

Diffraction imaging example

Pharmacological development are nowadays still based to a good extent on trial and error.

nature

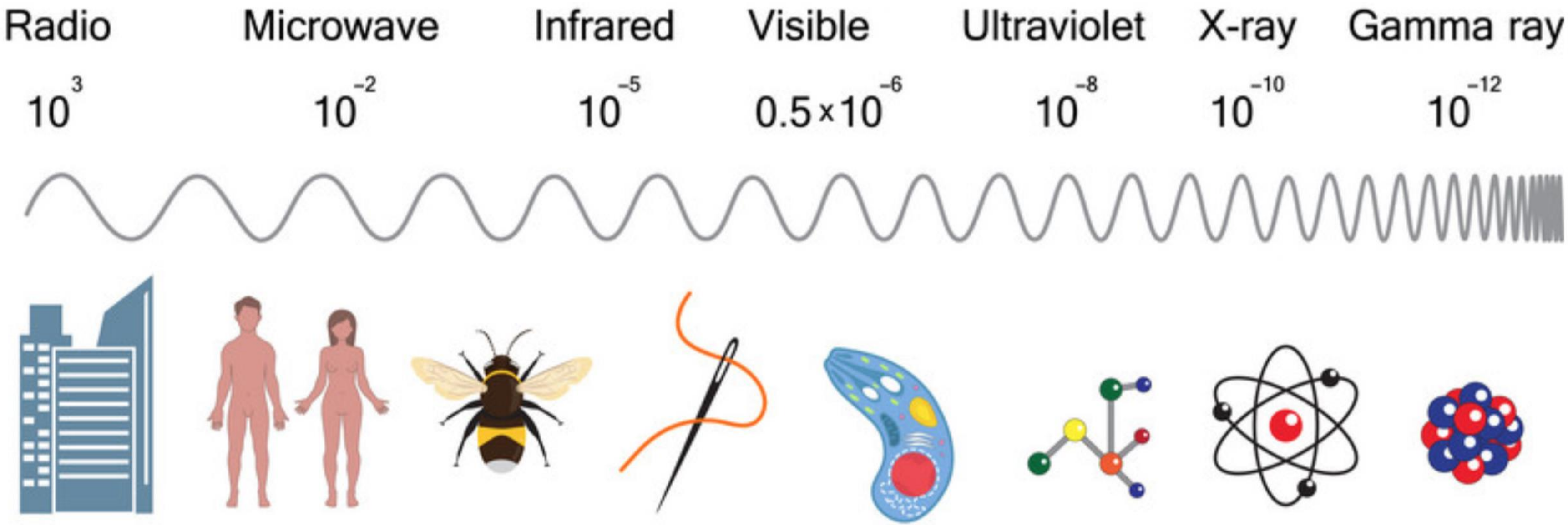
Viagra target

Crystal structure of phosphodiesterase 5

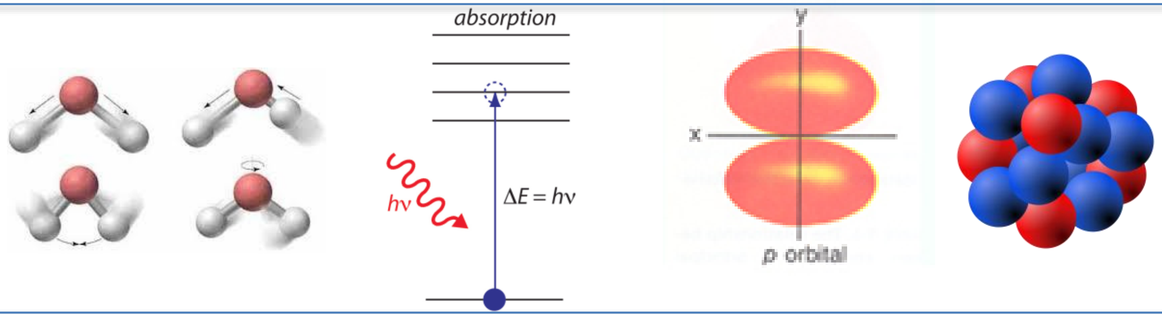
- The action of Viagra was understood only 2003.
- The drug was created for the first time in 1989.

- Tamiflu (anti-flu) was the first medicament that was specifically tailored.
- Knowledge about the atomic structure of the virus was used (Synchrotron Light Source).
- This helps to make drug research more systematic and efficient.

Photon science:
Photon interaction with matter



Excited processes



High power sources

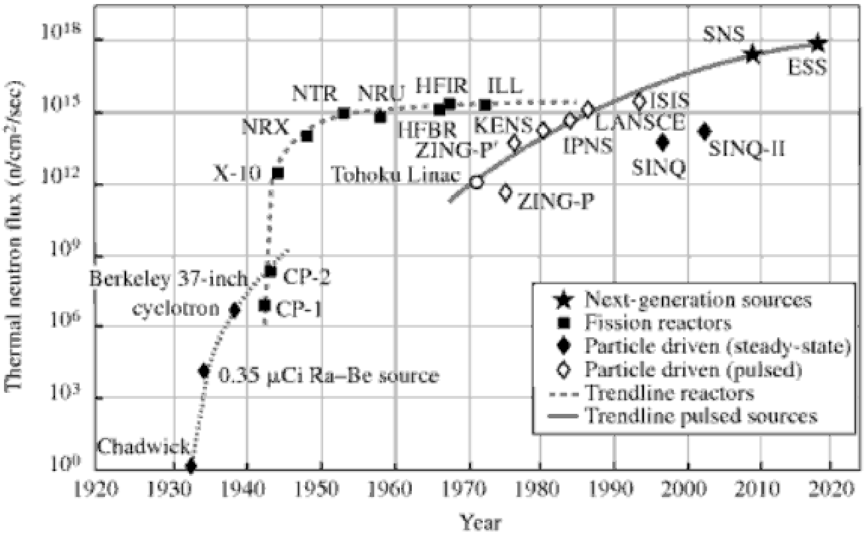
FELs

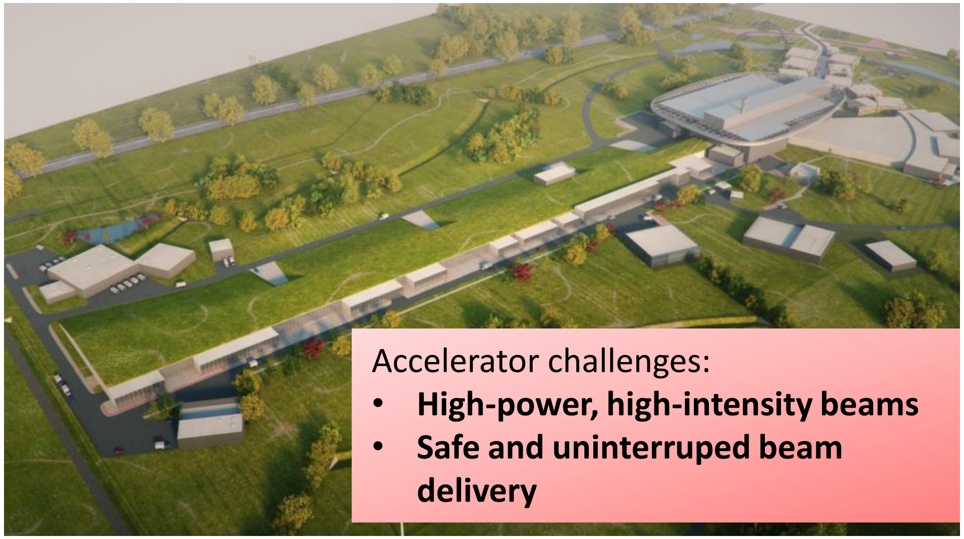
Lasers

XFELs

Synchr. light sources

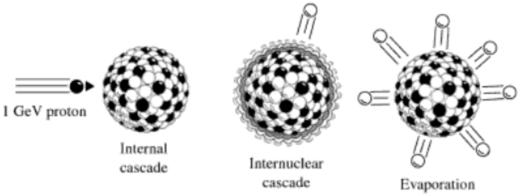
Neutron spallation sources, ADS

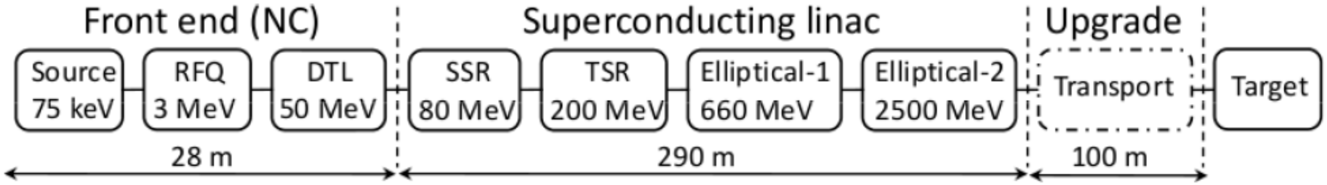




Accelerator challenges:

- **High-power, high-intensity beams**
- **Safe and uninterruped beam delivery**





Front end (NC)

Source 75 keV — RFQ 3 MeV — DTL 50 MeV

28 m

Superconducting linac

SSR 80 MeV — TSR 200 MeV — Elliptical-1 660 MeV — Elliptical-2 2500 MeV

290 m

Upgrade

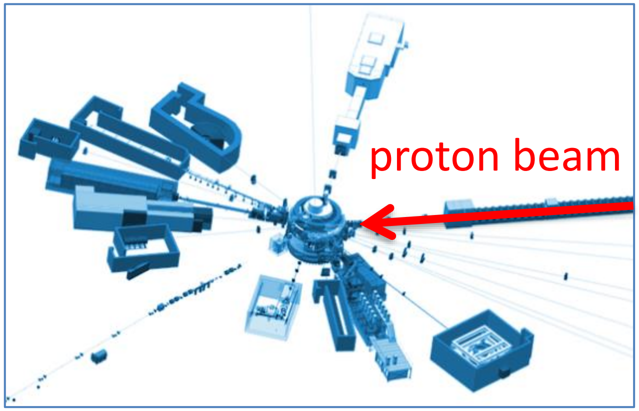
Transport

100 m

Target

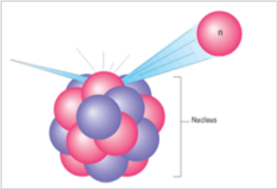
Neutron spallation sources: intense flux of protons at high energies.
Lund, Sweden: building Europe’s first neutron spallation source, the **European Spallation Source**, using superconducting technology.

Neutron science gives new information on microscopic scales



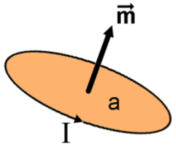
Charge neutral

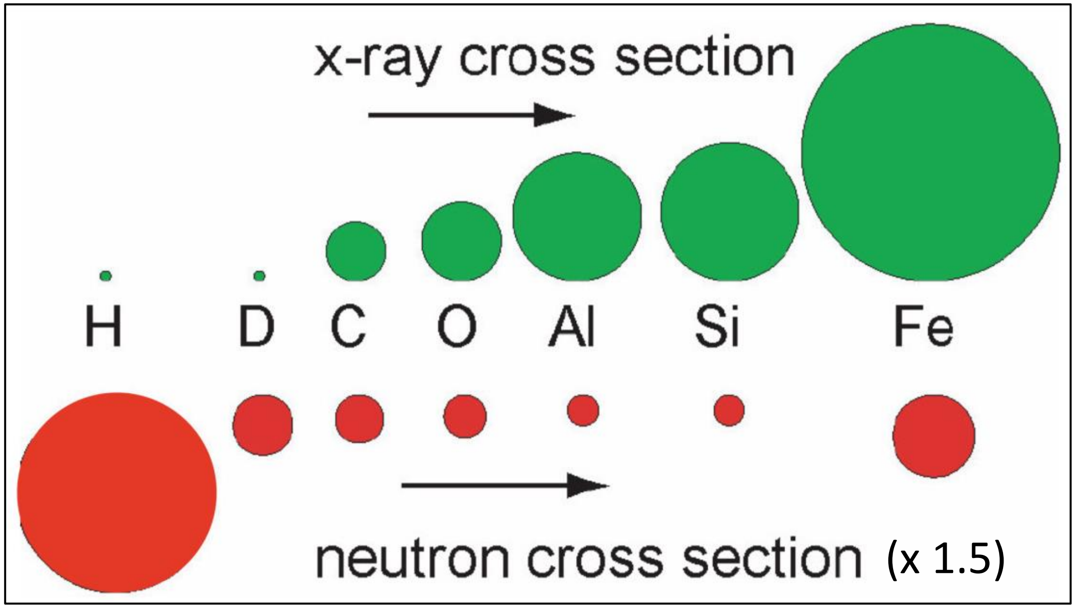
Nuclear interactions



Mass

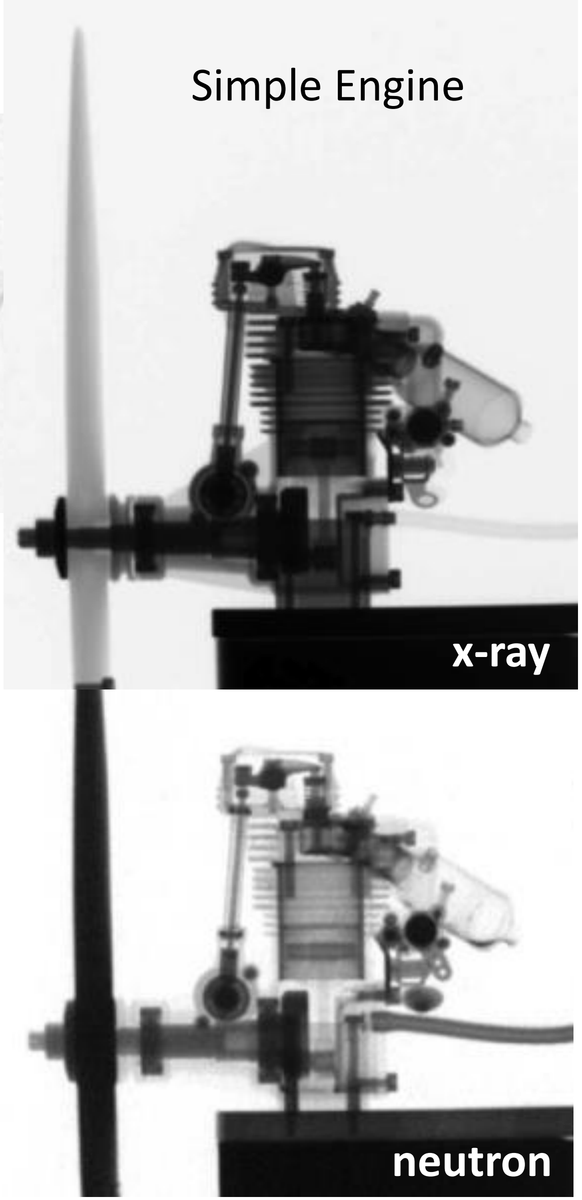
Magnetic moment



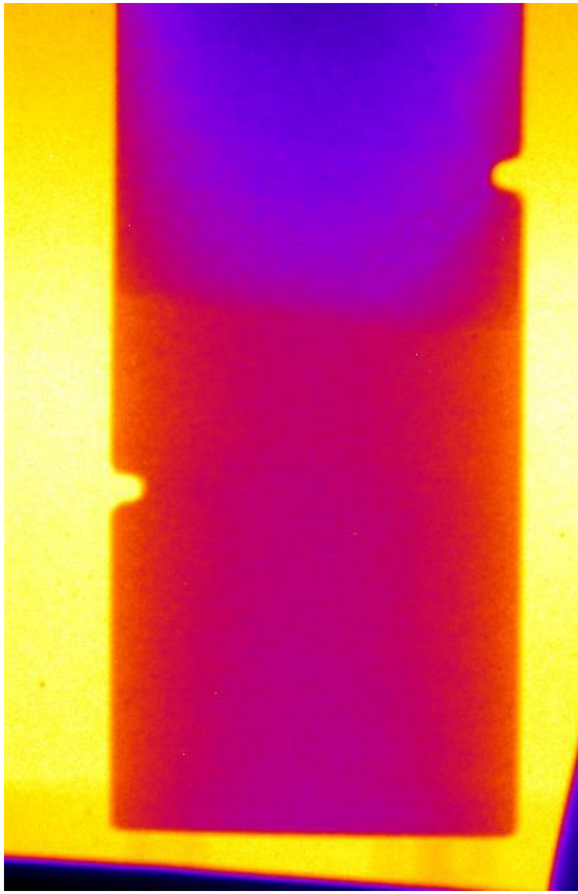


Example: neutrons see the light elements

Courtesy of the NIAG group, PSI, Switzerland.



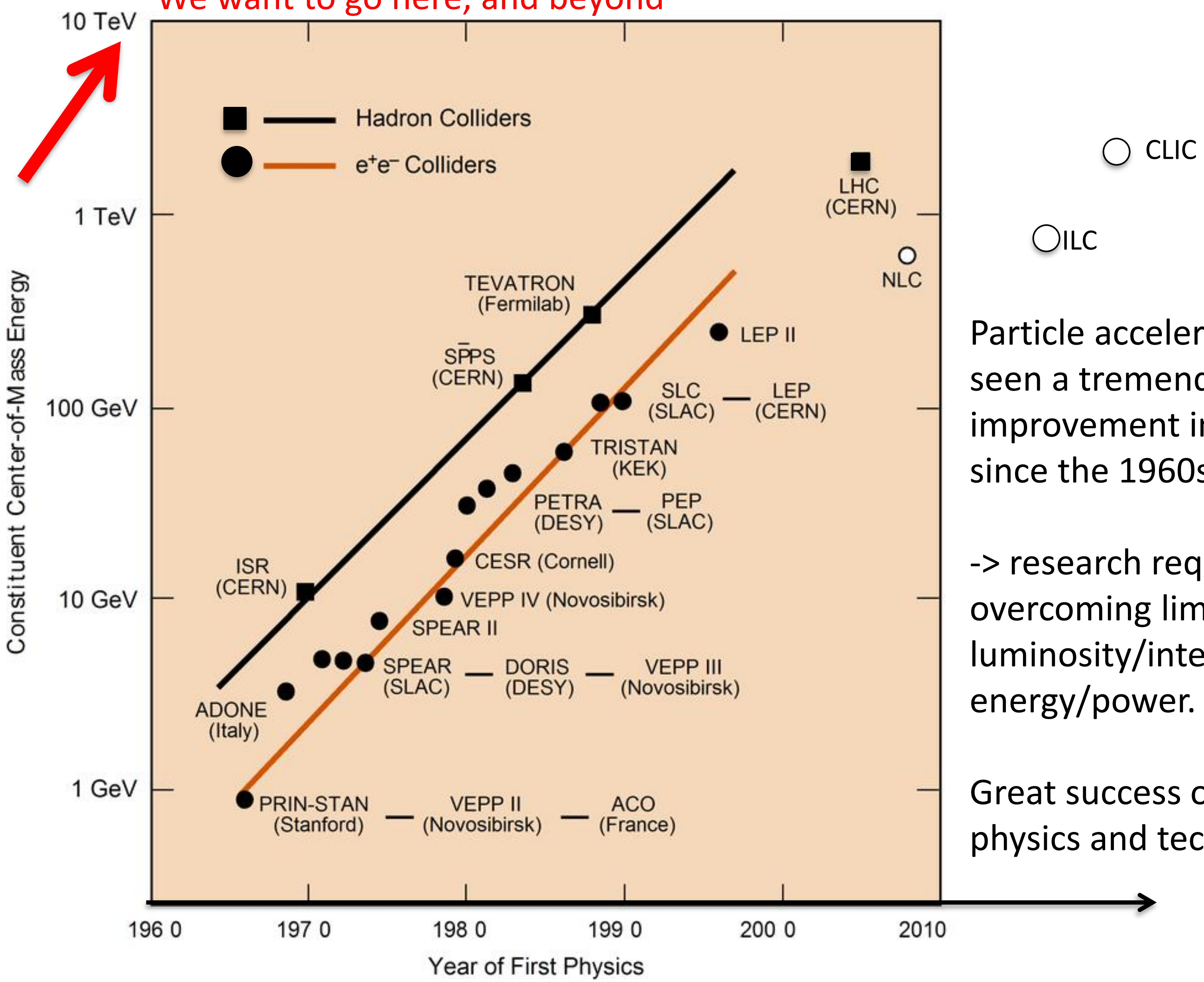
Co2 sequestration
Fracking



Courtesy of S. Hall, Lund Univ.

Advanced accelerator R&D:
Better and smaller accelerators?

Particle collider Livingstone plot


We want to go here, and beyond

Particle accelerators have seen a tremendous improvement in performance since the 1960s.

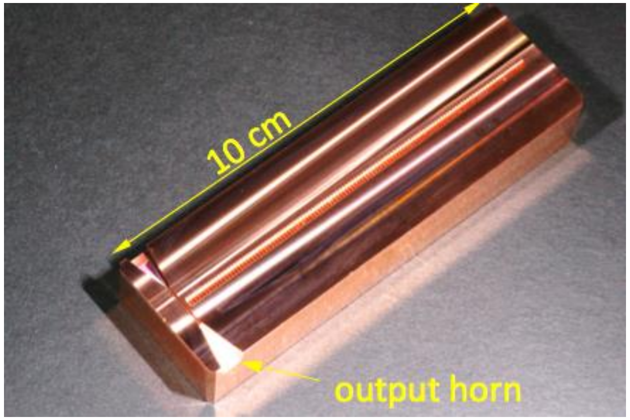
-> research required to overcoming limits in luminosity/intensity and energy/power.

Great success of accelerator physics and technology.

Novel accelerator research

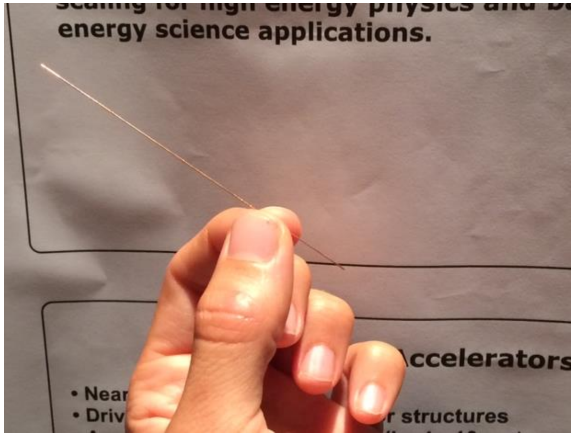
Cutting edge accelerator physics research, with the objective of **overcoming limitations** of conventional accelerator technology.

Very high frequency normal conducting rf structures (~100 GHz to ~THz)



116 GHz structure (SLAC)

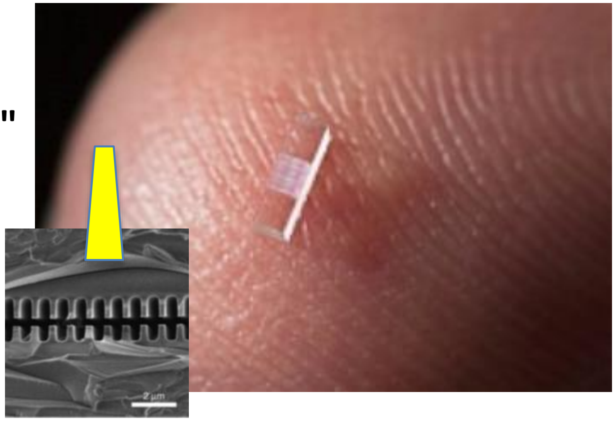
Dielectric structures



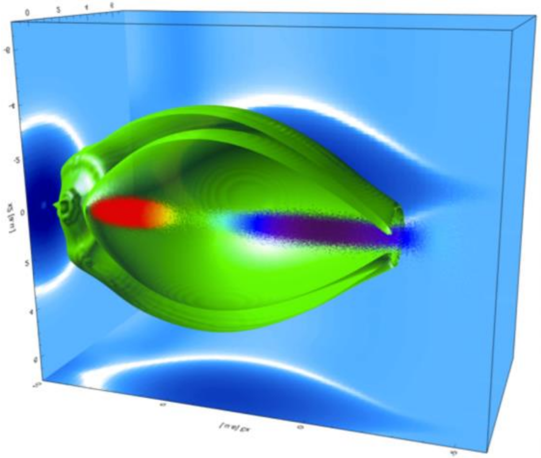
SiO_2

~1.0 THz, 1-10GV/m

Laser based acceleration "DLA"
Several 100 MV/m demonstrated (SLAC)



Feed of laser beam into Si structure



Plasma wakefield acceleration

The topic here.

Novel accelerator concepts: **muon collider**

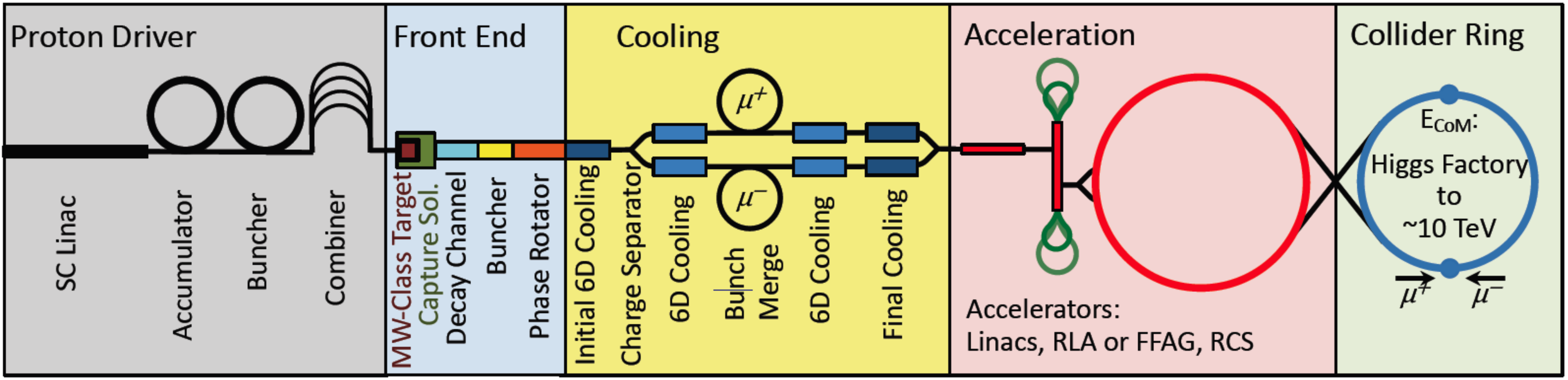
Promising concept, many hurdles to overcome before use in a collider.

Muon collider pros and cons

Negligible synchrotron radiation

Main challenge: $\tau_\mu = 2.2\ \mu s$

- Produce sufficiently dense muon beams
- Rapid acceleration
- Mitigate radiation hazards



Protons on target
hadronic showers,
Pions decay into muons

Muon are captured,
bunched and then cooled.

Rapid acceleration
to collision energy

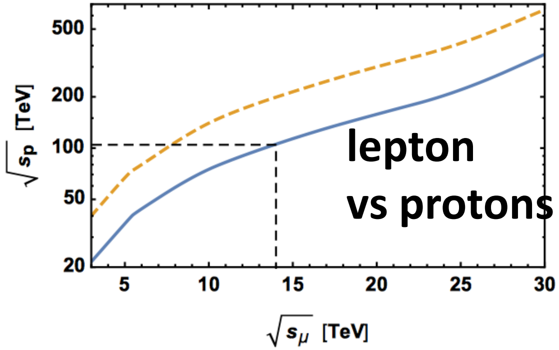
Collision

Precision, plus discovery potential!

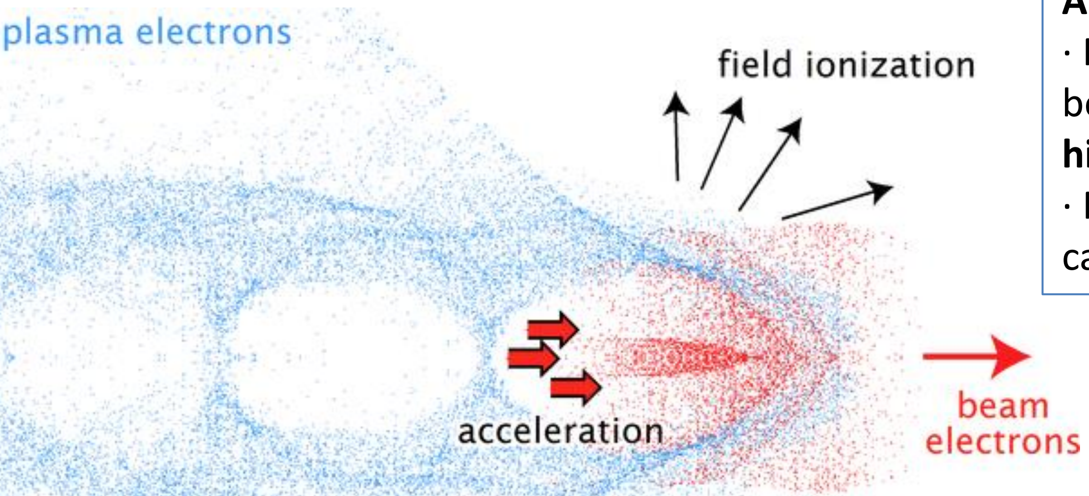
3 TeV ~ LHC

14 TeV ~ FCC-hh;

30 TeV ~ "amazing"



Novel accelerator concepts: **plasma acceleration**



Principle: *drive a wave in plasma with particle or laser beams*

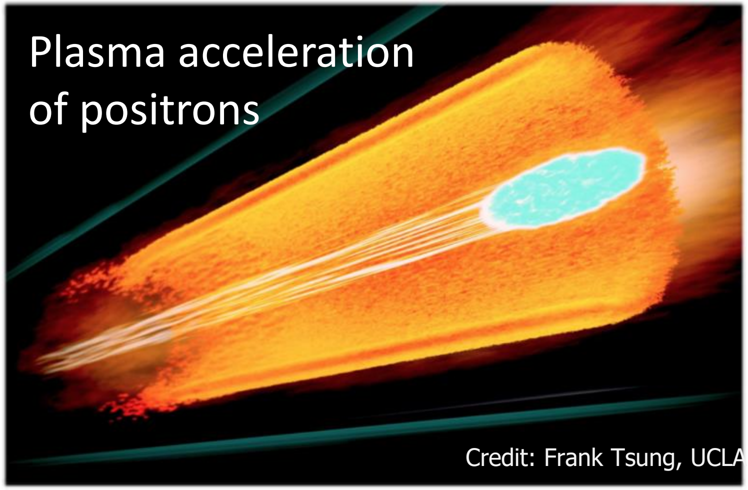
RF cavities: limited by metal surface break down

Alternative: high fields inside plasmas:

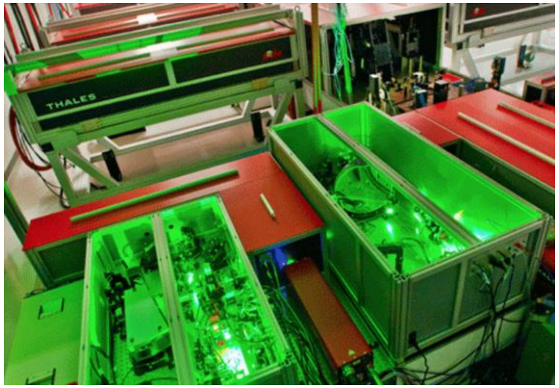
- Plasmas of a large range of densities can easily be produced. Fields scale with density. **Very high fields can be generated**.
- Plasmas are already broken down. The plasma can **sustain the very high fields.**

Typical numbers :

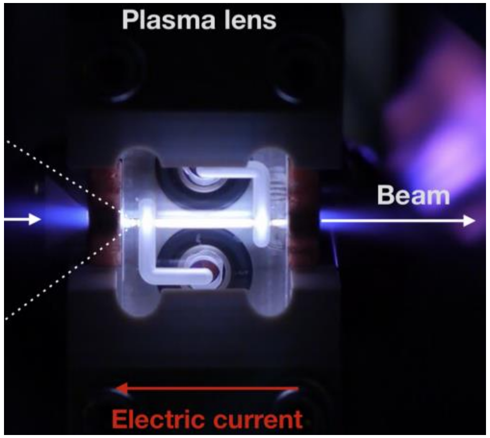
Plasma density ~ **10^{16-18}/cm^3**
Field scale: 10-100 GV/m
Length scale : $\lambda_p/2\pi$=**10-100 μm**



Credit: Frank Tsung, UCLA



TW-PW laser technology



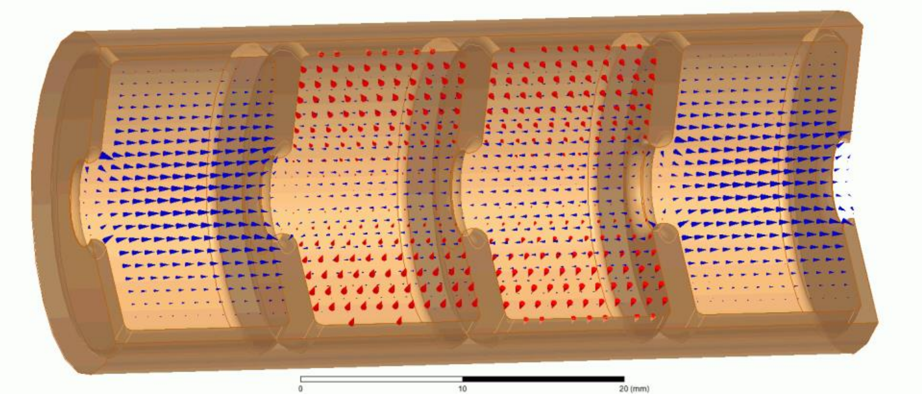
Plasma lenses for particle beams

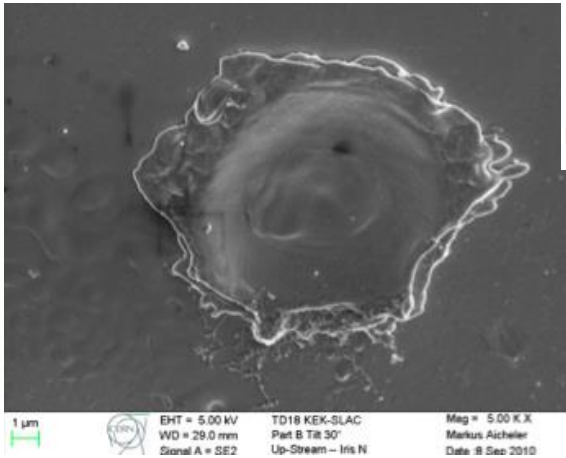
Great experimental progress recent years:
50 GV/m accelerating fields, positron acceleration, AWAKE...

Breakdown limits and plasma

In **metallic structures** : break down of the surfaces, creating electric discharge. Field cannot be sustained. **Current practical limit (CLIC): order of 100 MV/m gradients**..

***Break down of field** limits the gradient.*





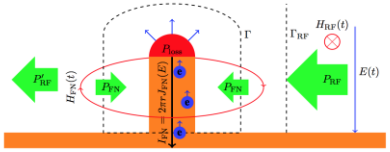
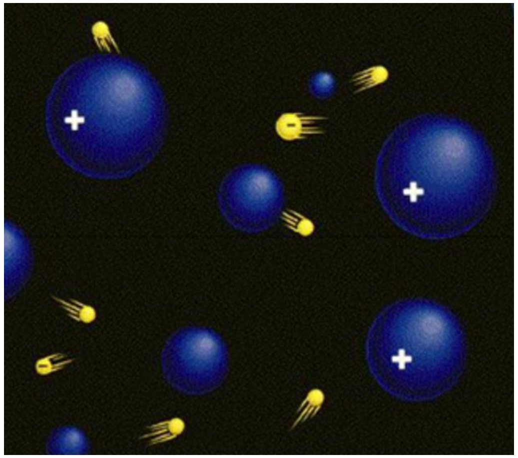


Figure 4.3.: Power flows around a field emitter tip in an RF cavity.

Alternative to high fields in vacuum: high fields in plasmas:

collection of free ions and electrons.

- Plasmas of a large range of densities can be produced. Fields scales with density. **Very high fields can be generated**.
- Material is already broken down. The plasma can **sustain the very high fields.**



Gauss law : estimate fields in a plasma wave

Assume that the **plasma electrons are pushed out** of a small volume of neutral plasma, with plasma density $n_0 = n_e = n_{ion}$:

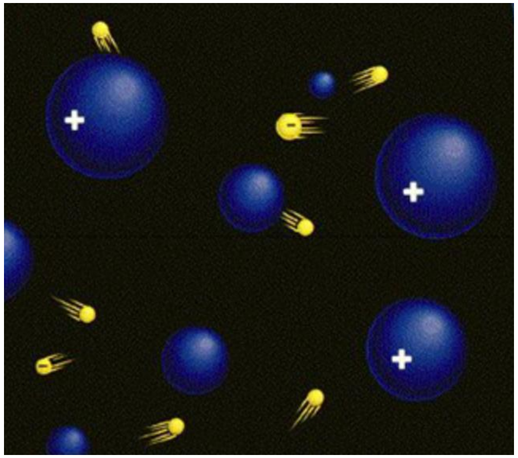
Scale of electrical fields (1D) :

Gauss' law:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \sim \frac{e n_{\mathrm{ions}}}{\varepsilon_0} \sim \frac{e n_0}{\varepsilon_0}$$

Plasma electron frequency :

$$\omega_p = \sqrt{\frac{n_0 e^2}{m_e \varepsilon_0}}$$



Assume wave solutions:

$$\mathbf{E} \sim \mathbf{E_0} \exp(-i\omega_p / cz)$$

Apply Gauss' law:

$$\frac{e n_0}{\varepsilon_0} = E_0 \frac{\omega_p}{c} \Rightarrow \boxed{E_{WB} = \frac{e c n_0}{\varepsilon \omega_{0p}}} \sim \sqrt{n_0}$$

Field scale, E_{WB} "wave breaking field"

Typical plasma density, available by many types of plasma source :

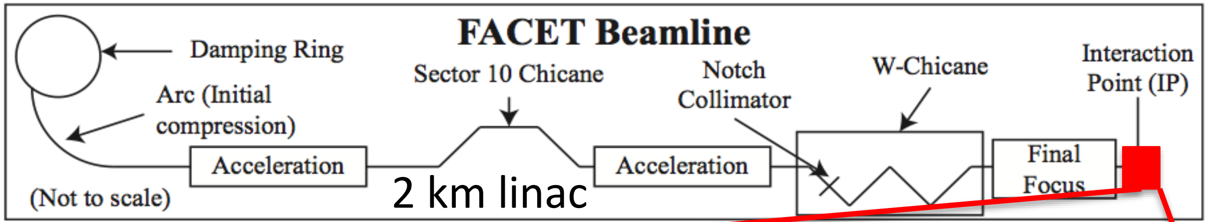
n_0 = 1e17/cm3 : **E_{WB} = 30 GV/m**

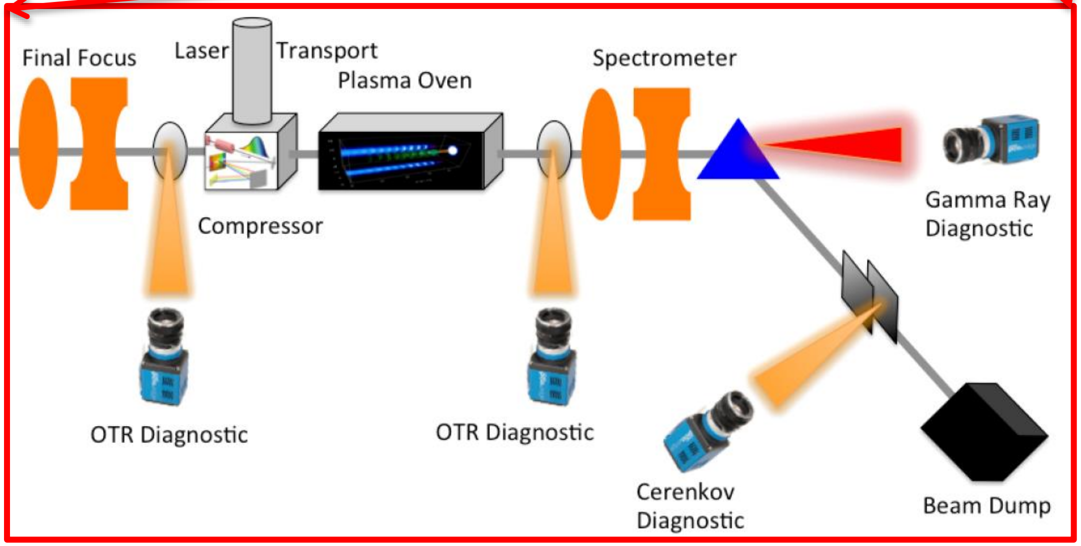
Development of novel accelerators

Currently a large experimental R&D effort to develop novel accelerators based on plasma and other technologies :

1. Meter scale plasmas ✓
1. High gradients ✓
1. Low energy spread ✓
1. High efficiency ✓
1. Multi GeV e^+ PWFA ✓
1. Emittance preservation

Development of novel accelerators

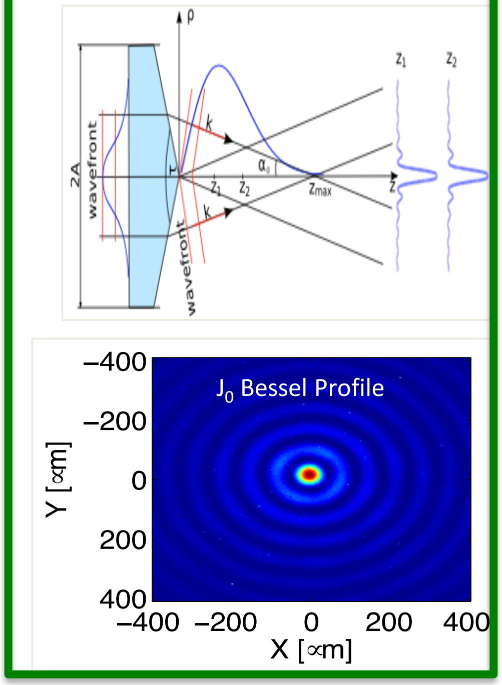




Electron, or
Positron bunch

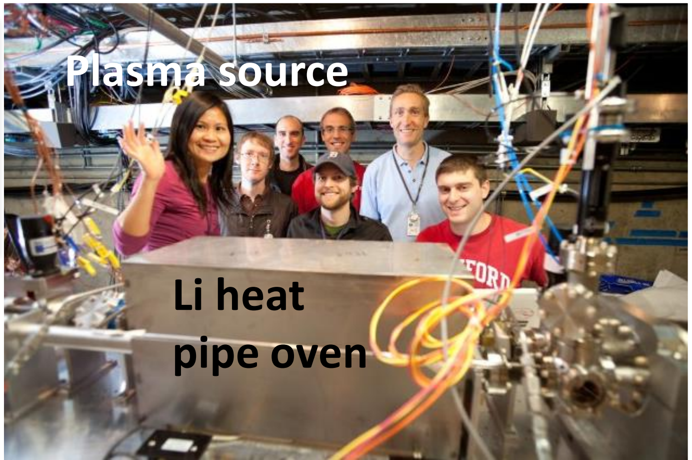
E = 20 GeV
Q = 3 nC
$\sigma_{z,min}$ = 20 um
$\sigma_{r,min}$ = 20 um
ε_n ~ 100 um

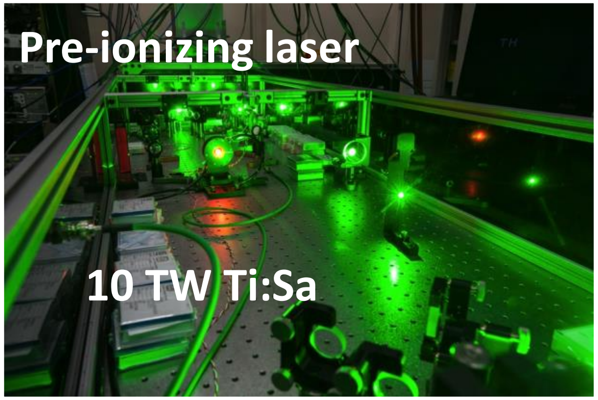
Laser axicon focusing



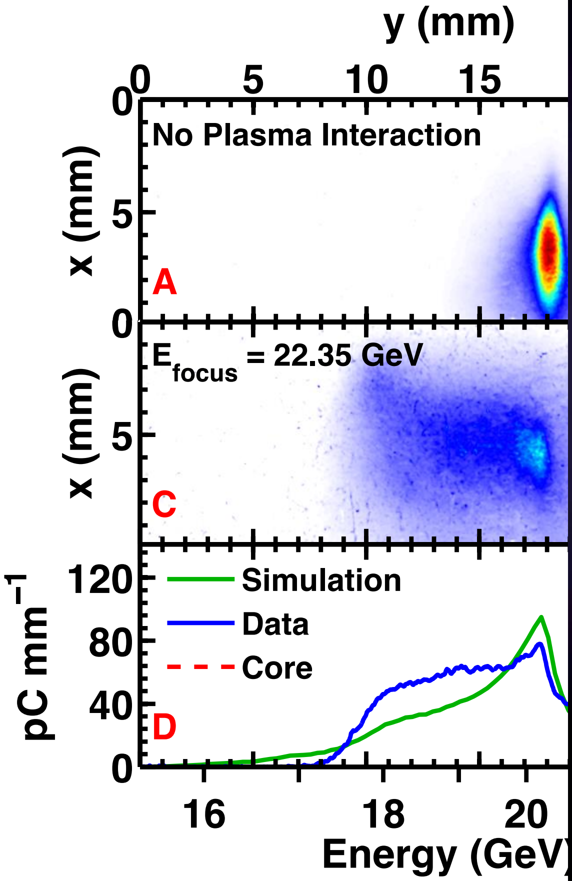
Plasma
densities, n_0,
10^{16}-10^{17}cm^{-3}

~ 1 m length





FACET two-bunch results



2013

FULL SPEED AHEAD

Plasma wakefield machines — the particle accelerators of the future? PAGES 40 & 92

CENTRAL EUROPE
LIFE AFTER THE WALL
Science 25 years after the collapse of communism
PAGE 22

ENVIRONMENTAL SCIENCE
CASH, CONFLICT, CONSERVATION
To protect the planet, stop the infighting and fudging
PAGES 27, 28 & 32

INTERACTIVE NOTEBOOKS
SHARE AND SHARE ALIKE
IPython allows on-the-run analysis
PAGE 151

NATURE.COM/NATURE
6 November 2014 £10
Vol. 515, No. 7525

n in

d Li

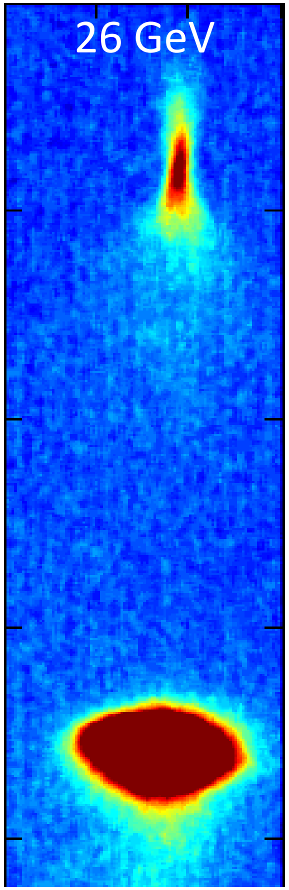
-

sfer

3%).

in

1.3 m plasma



2014

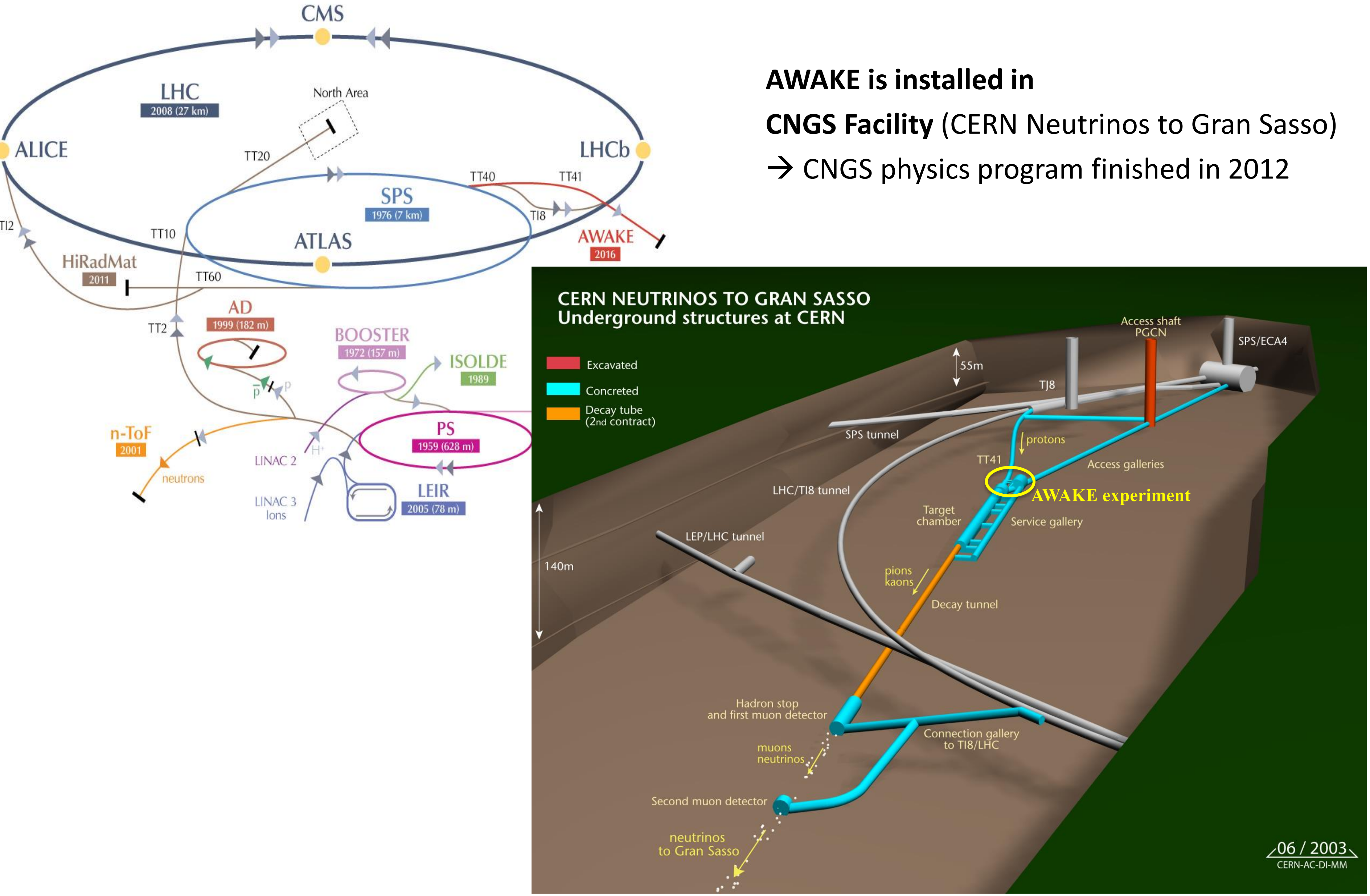
M. Litos *et al.*, Nature **515**, 92 (2014)

AWAKE: proton driven plasma wakefield at CERN

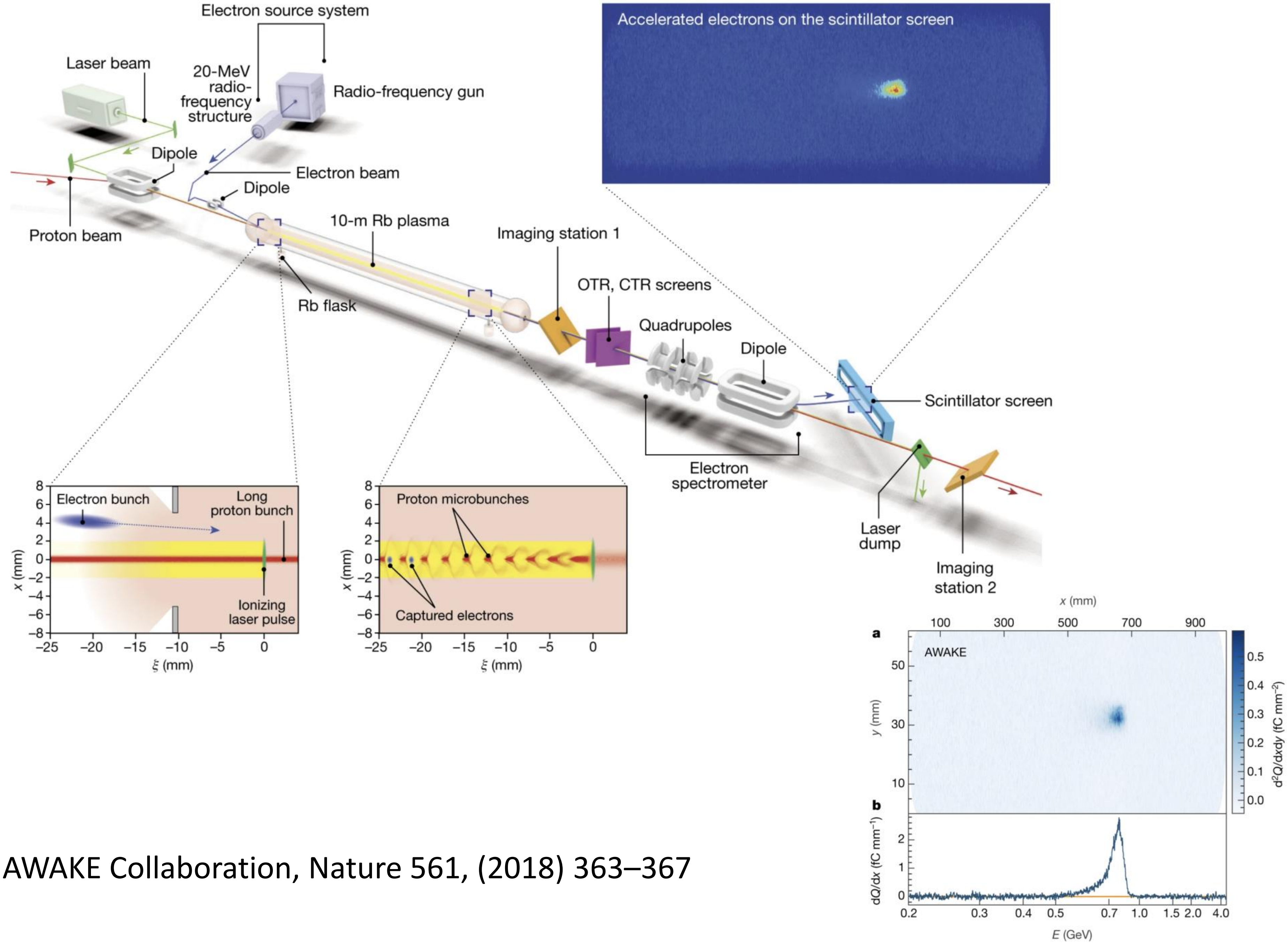
AWAKE is installed in

CNGS Facility (CERN Neutrinos to Gran Sasso)

→ CNGS physics program finished in 2012



AWAKE: successful Acceleration of electrons in a proton driven plasma

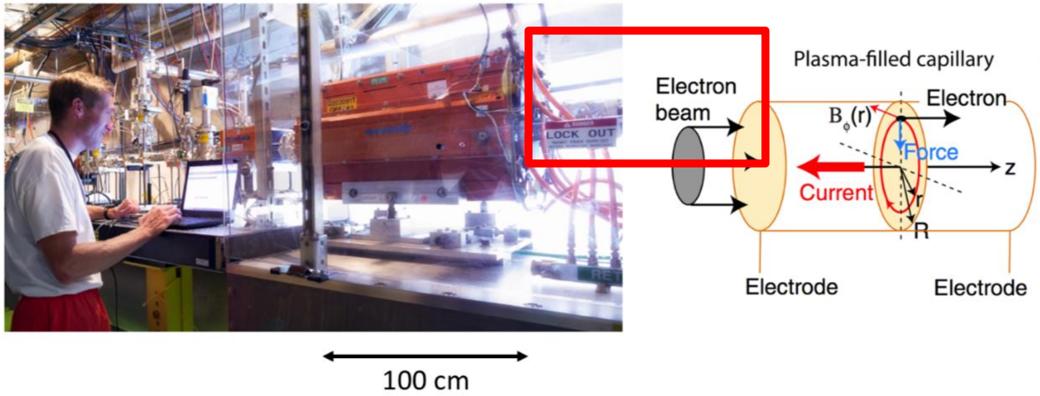


AWAKE Collaboration, Nature 561, (2018) 363–367

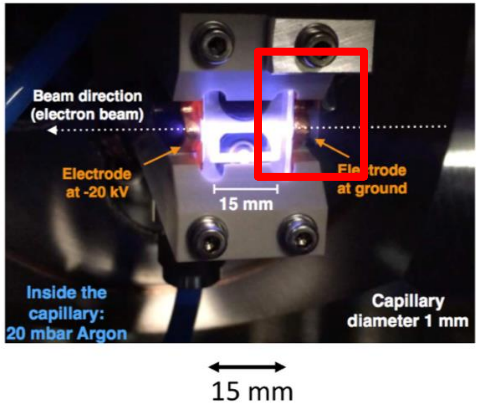
Compact focusing: The CERN-Oslo plasma lens

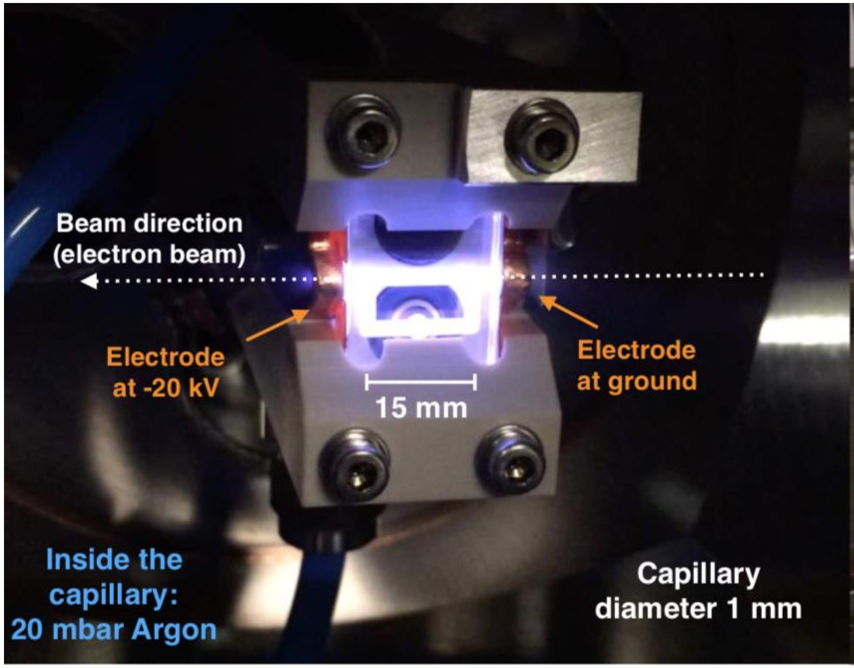
a) Normal conducting magnetic focusing quadrupole at the FACET high energy test facility

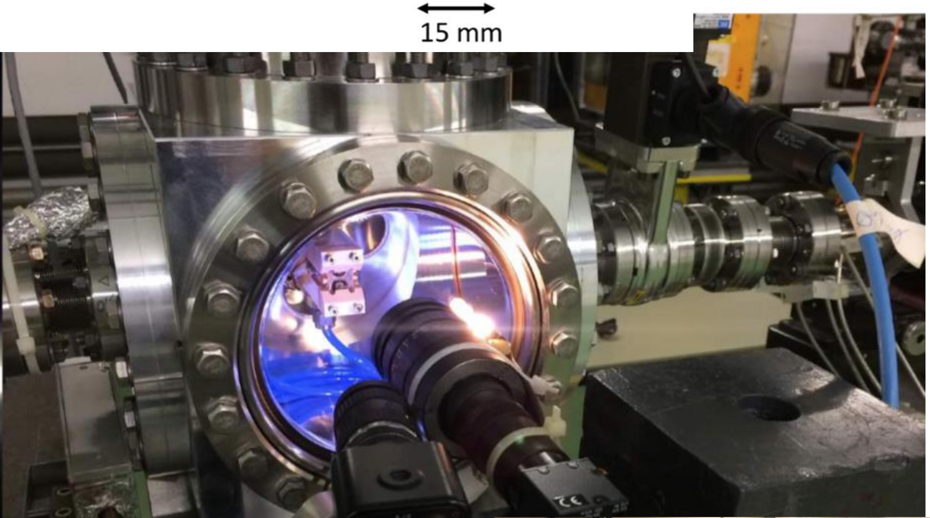
c) Principle of an active plasma lens



b) The Oslo active plasma lens focusing device

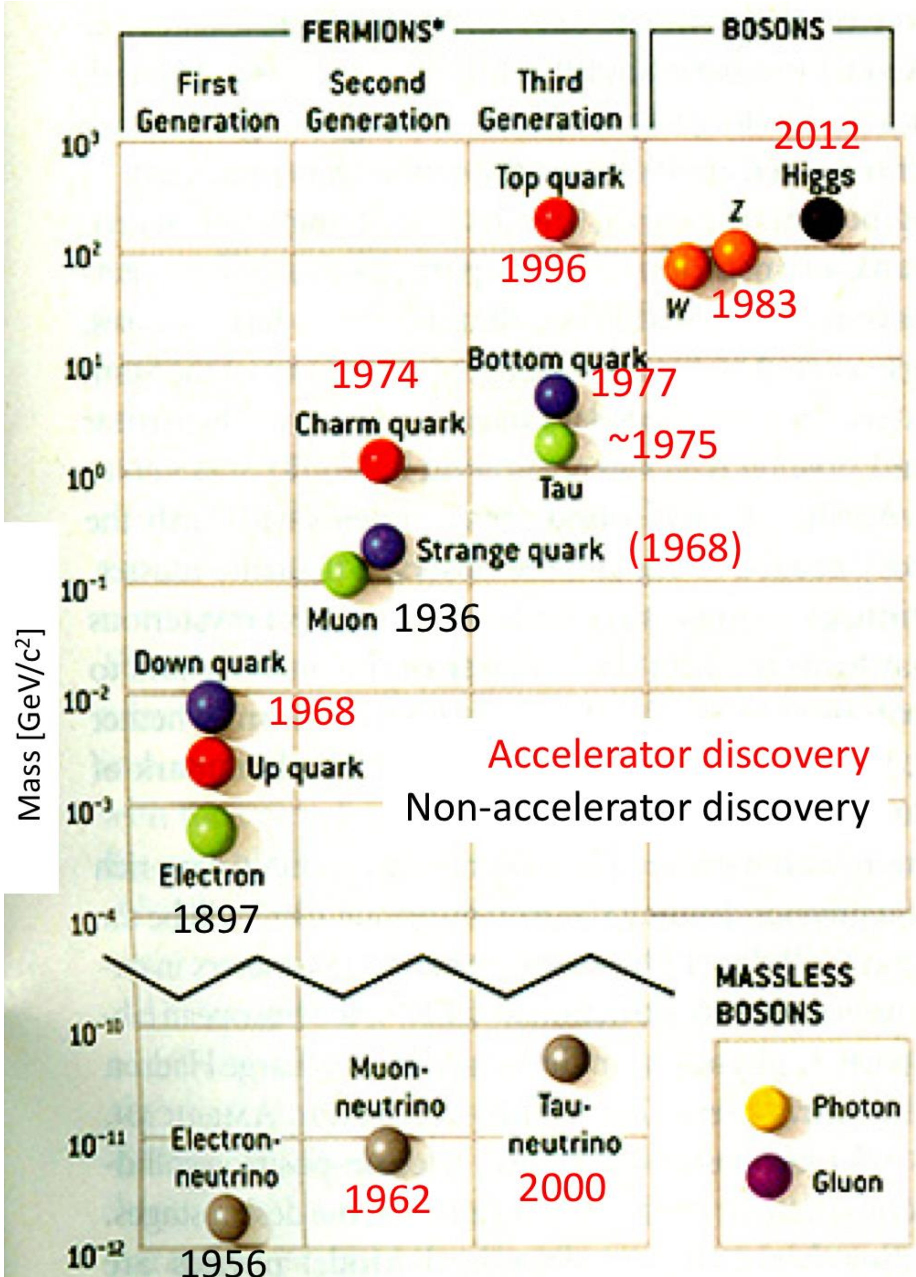




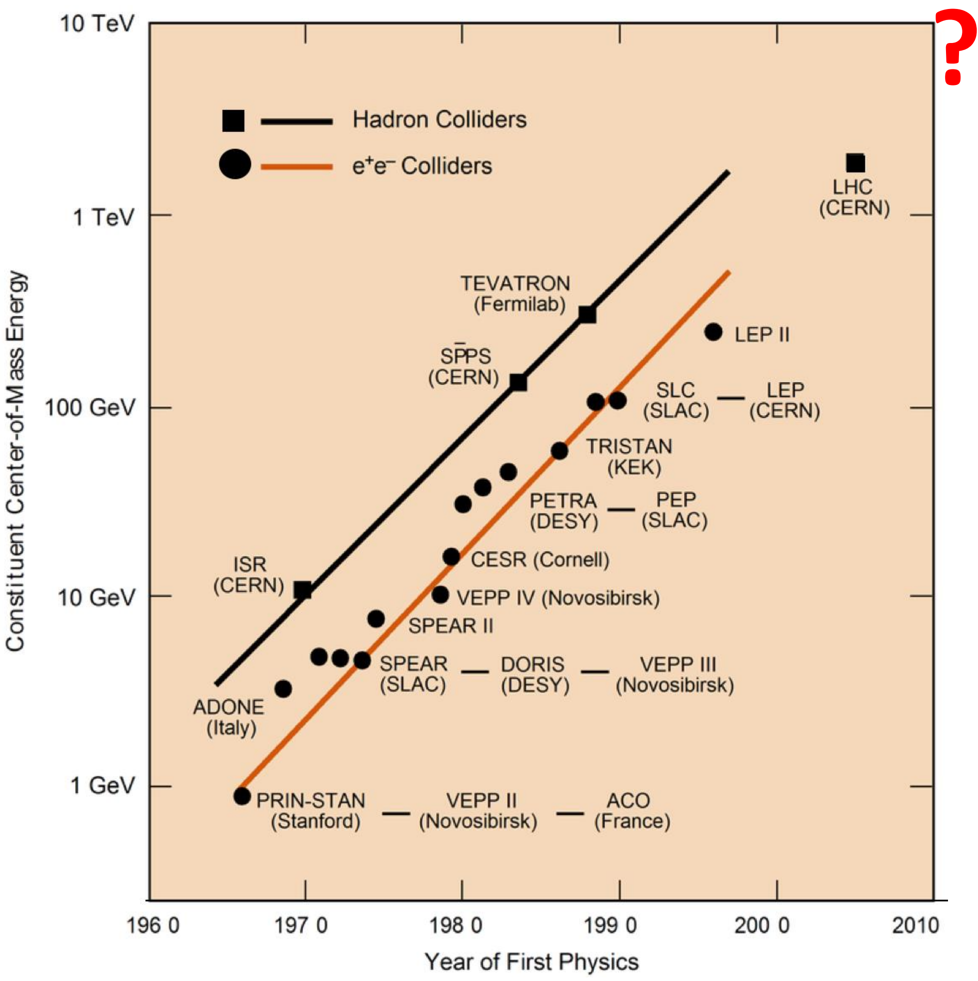


- An experiment to test the operation and characteristics of an active plasma lens.

The role of particle accelerators



The last particle predicted by the standard model, discovered at the LHC in 2012.



Several **Nobel prizes** for accelerator technology,
and > 20 Nobel prizes where accelerators where used.