ACCELERAT .

. . . what else ?

. . . how ?

. . . and why ?

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Outline

- *"Particle accelerators 101"* – **short introduction**
- *"Recipe for acceleration"* – **how can we accelerate particles ?**
- *"Can we go larger ?"* – **future accelerator projects and novel acceleration methods**
- *"Beyond the bottle of hydrogen…"* – **what other particles do we accelerate ?**
- *"Accelerators outside CERN?"* – **applications of particle accelerators**

Acknowledgments

Ideas adopted from materials and lectures of

CERN Accelerator School (CAS)

and

Joint University Accelerator School (JUAS)

Knowledge to which I am forever grateful !

To remember going in . . .

Electromagnetism: **Lorentz force**

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

Electric fields – gain in energy

Magnetic fields – change of trajectory

Special relativity

$$\beta = \frac{v}{c}$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} = \frac{E_{total}}{E_{rest}}$$

At relativistic regime – increase of energy does not correspond to a change in velocity

Why particle accelerators?

In **high energy physics**

sub-atomic particle collisions at enormous energies are observed and measured

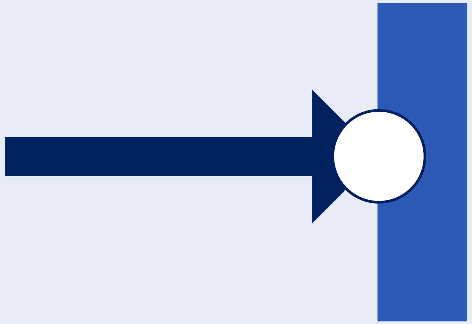
Collision energy → $E = mc^2$ → **Matter**

New particles

Particle accelerators

Since 1939 particle accelerators have contributed to **26 Nobel prizes**

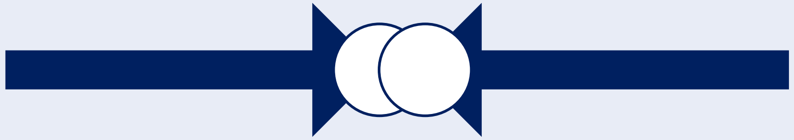
Particle colliders



Fixed target

$$E_{COM} = \sqrt{2E_1 m_{target} c^2}$$

- ➕ High rate of events
- ➖ Low energy reach



Collider

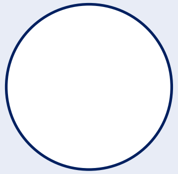
$$E_{COM} = E_1 + E_2$$

- ➕ High energy reach
- ➖ Low rate of events

In a fixed target experiment: $\mathbf{2\gamma E_1}$ compared to a collider!

But is it easy to collide 2 beams of sub-atomic particles?
We will see later !

What do we collide ?



Leptons

electrons and positrons

- Elementary particles – “what we accelerate - collides”
- Precisely defined energy at collision

Used for precision physics

Hadrons

protons

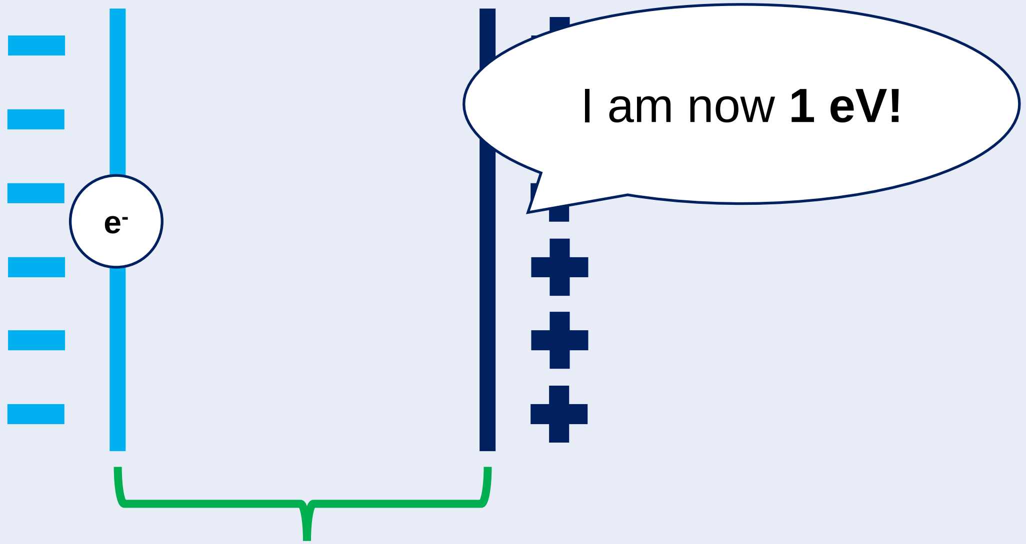
- Composite particles – constituent quarks collide
- Uncertainties for collision energy, not all of the energy used

Used for “new physics”

Record collision energy: **13.6 TeV**

How large is it?

Electronvolt – how much is it ?



1 V

How much is it?

One proton of 1 eV = **1.6 * 10^{-19} Joules**

One proton of 6.8 TeV = **1.1 * 10^{-6} Joules**

There are 1.15*10^{11} protons in a bunch of LHC

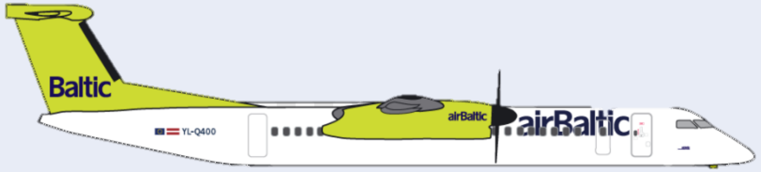
One LHC bunch = **1.25*10^{5} Joules**

It is all about energy density:

Apple and plane: **10^{5} - 10^{6} J/m^{3}**

LHC beam at interaction point: **10^{12} J/m^{3}**

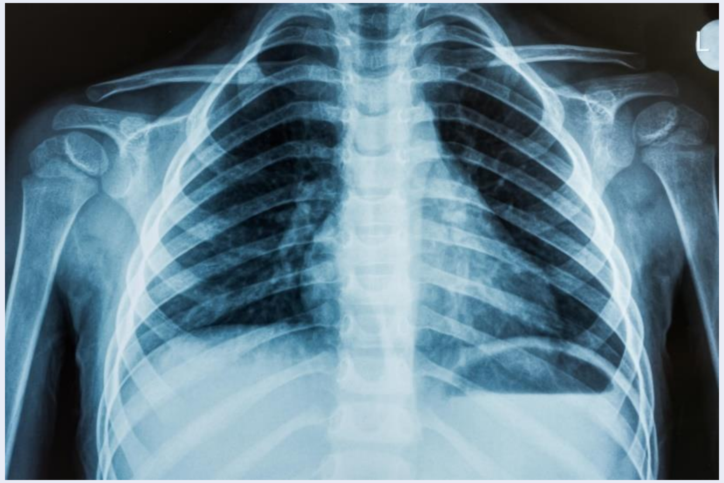
90 cal = 376.56 J



1*10^{10} J

Have we used a particle accelerator?

< 1 keV



120 keV

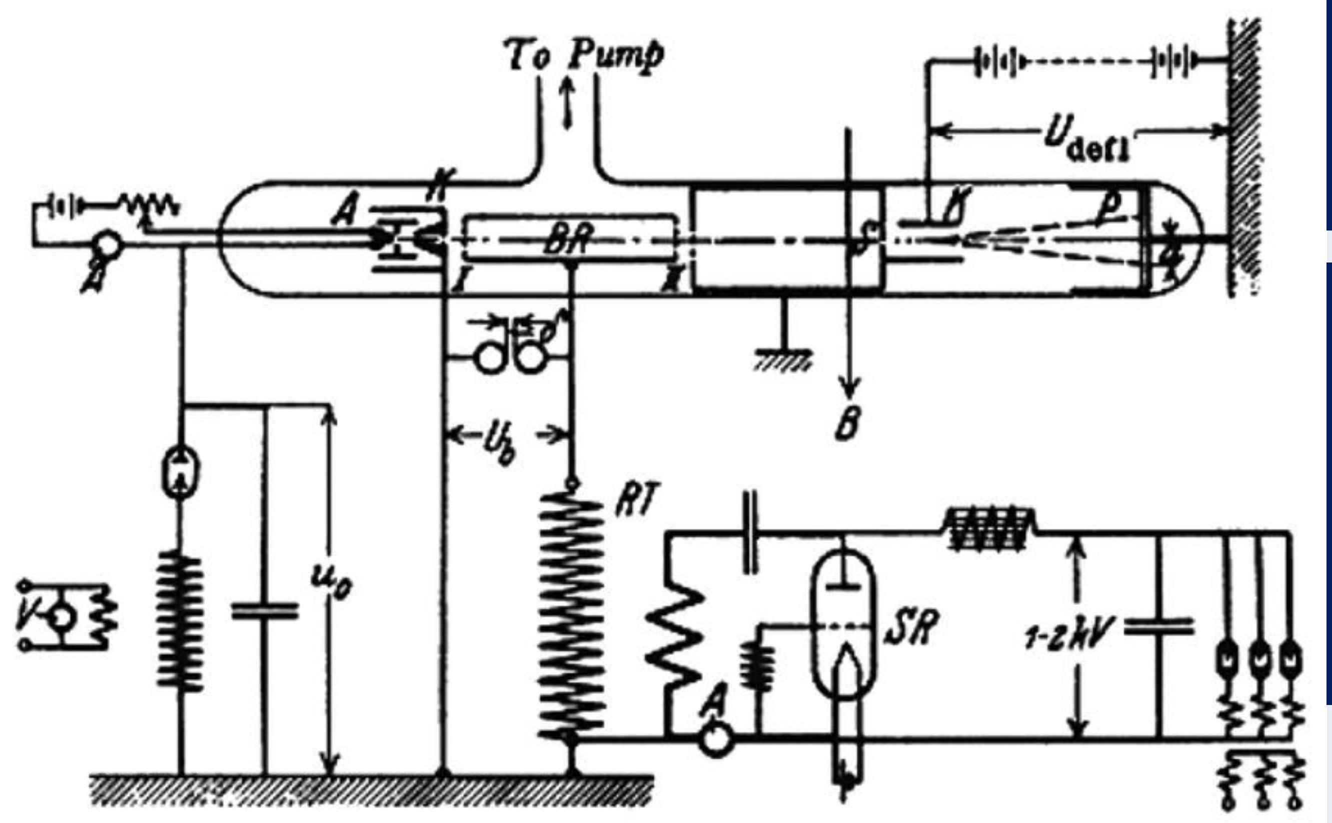
Electrostatic acceleration

Generally, we consider a particle accelerator as "particle accelerator" around **1 MeV**

So . . . we just apply 6.8 TV electric field? Well.. Not really!

In 1928 Rolf Wideröe's PhD thesis introduced the concept still used for modern particle accelerators

Radio-Frequency acceleration

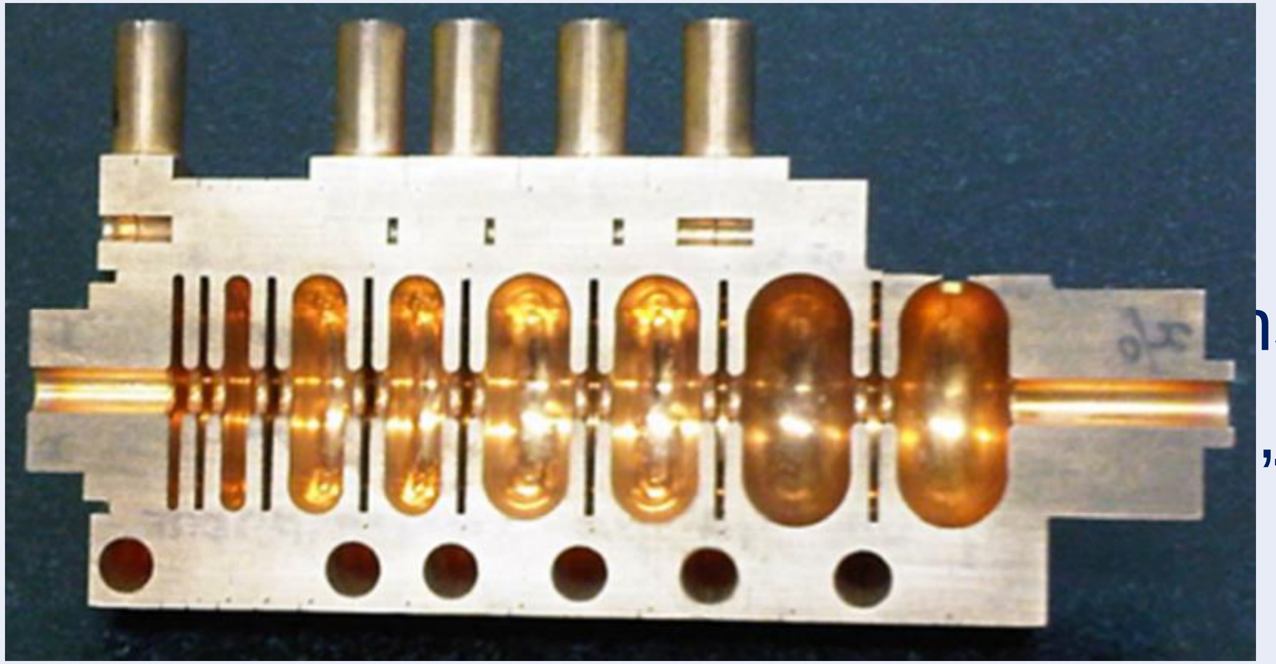


Time varying electric

The «trick» #1
particle beam must be bunched not continuous

The «trick» #2
sycnhronize the movement of the particle with the radiofrequency wave

Linear accelerators



Electrons – relativistic at low energies – same length

radiofrequencies

ns: **1.2 – 1000 GHz**

Protons, ions – non-relativistic – cavity length must account

, ions: **200 - 750 MHz**

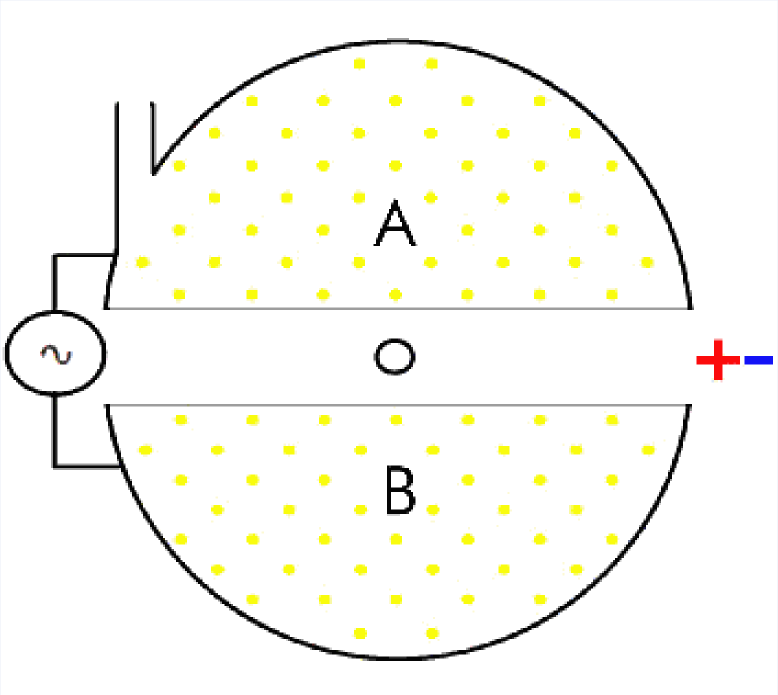
Radiofrequency cavities + radiofrequency generator = induced time-varying EM field

What are the limits?

Accelerating gradient – electrical breakdown

Increase energy – increase length of the structure

Going circular - cyclotron



What are the limits?

Maximum energy is limited by the diameter of machine

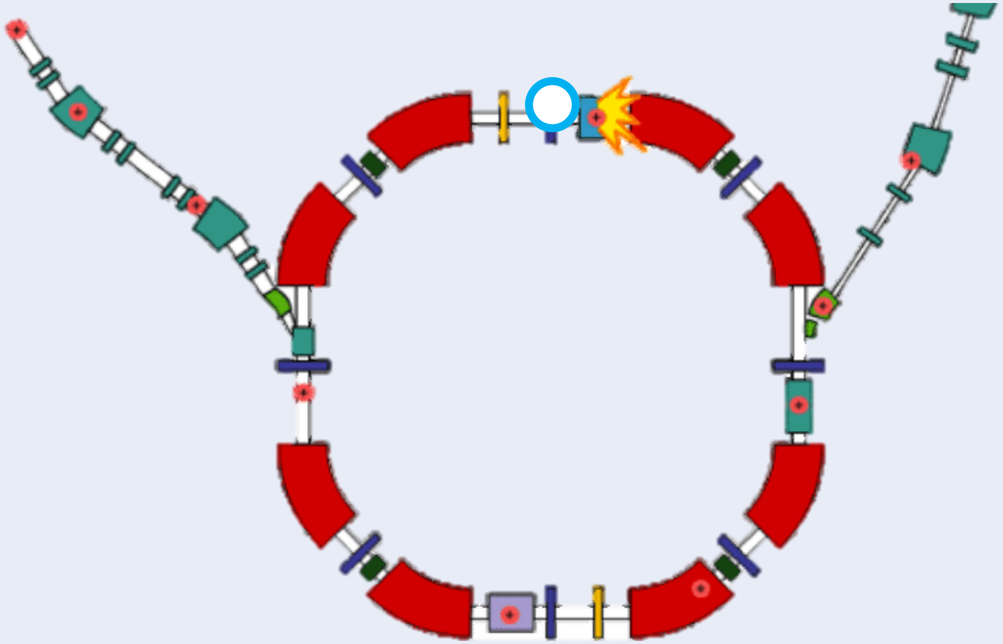
Acceleration with the basic concept works only in non-relativistic regime

How to regain the synchronicity?

Varying magnetic field strength with radius – **isochronous cyclotron**

Gradually lower the RF frequency - **synchrocyclotron**

Everything in sync - synchrotron

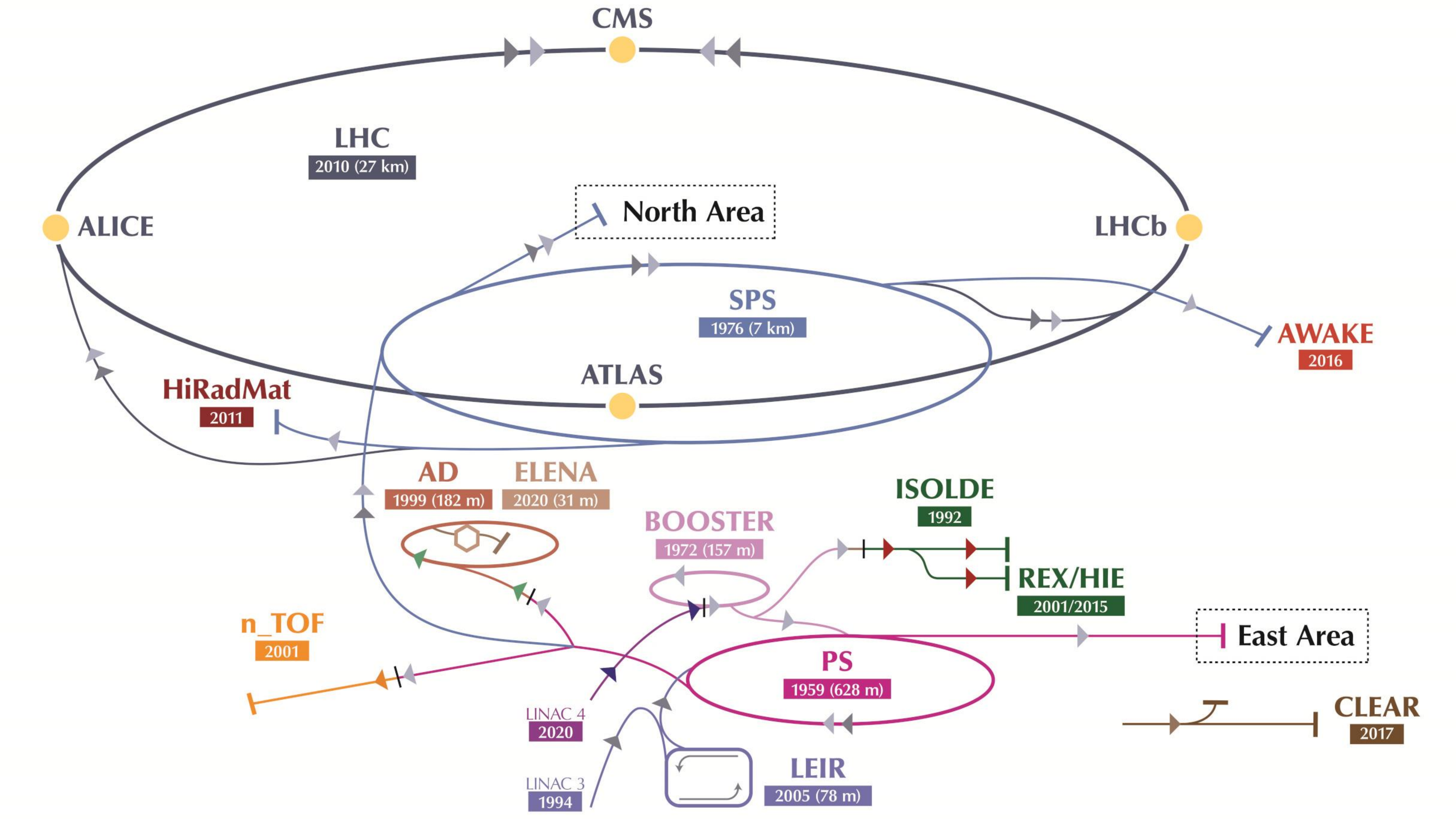


What are the limits?

Limits coming from technological capabilities – *discussed later*

Synchronization rule for acceleration:
Keep a constant trajectory :
Ramping magnetic field strength and adapting RF frequency

The accelerator complex of CERN



Lorentz force and centrifugal force

Lorentz force = Centrifugal force

$$F = qvB$$

$$F = \frac{mv^2}{R}$$

Beam rigidity

One of the main parameters describing the technical requirements for a synchrotron

$$p\left[\frac{GeV}{c}\right] = 0.3 * B * \rho$$

How big should my synchrotron be?

In the case of LHC . . .

$B\rho = 6800 / 0.3 = 22667$ T*m

If we would want a … 10 km ring?

6.5 km – for dipole magnets

$\rho = 1035$ m

We would need 21.9 Tesla dipole magnets – not really feasible

Optimum parameters

- Circumference of **27 km**
- Bending radius of **2803 m**
- Dipole magnets of **8.3 T**

Design of close to 7 TeV

LHC – what do we need?

RF system

8 cavities @ **400 MHz**

Magnets

1232 dipole SC magnets

Quadrupoles – focusing

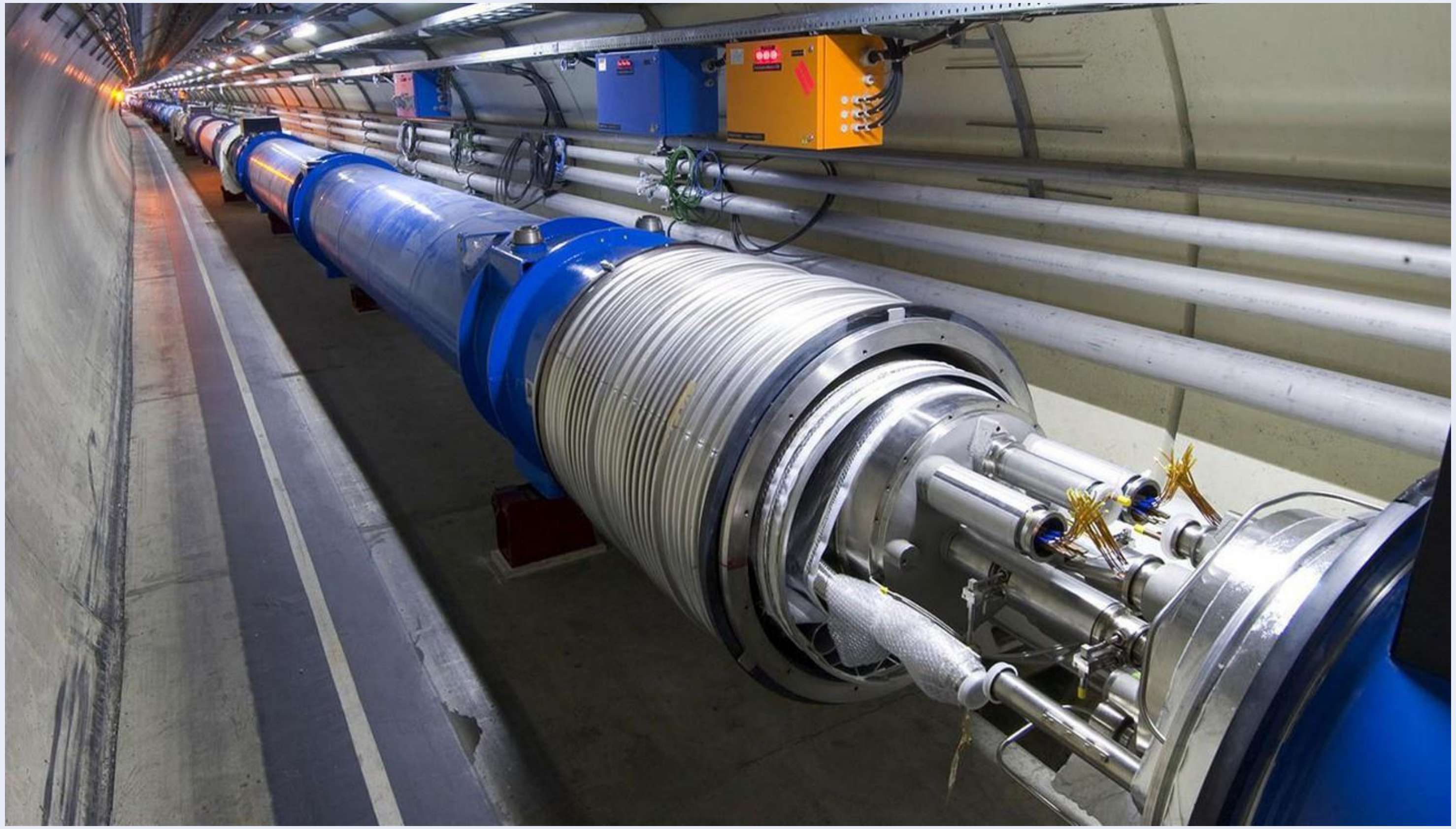
Sextupoles – chromaticity

Up to dodecapoles . . .

Corrector magnets

Support systems

Instrumentation (sensors), vacuum, cryogenics, mechanical support etc.



True engineering marvel

Does the moon affect LHC?

With the enormous size of LHC . . .

Even when 100 m underground, the central orbit trajectory is affected:

- **by the gravitational pull of the Moon –** the miniscule changes in gravity around the circumference
- seasonal changes- rain, snow and temperature of the earth
- ground tides

All these impacts are registered and corrected

What are the prerequisites for acceleration?

- particles **must be electrically charged**
- **sufficient vacuum** to limit the interaction with the environment
- particles **must be stable or decay slowly enough**

For LHC everything starts here . . .

Each day **just 2 nanograms are accelerated**

1 gram of hydrogen would take a million years to accelerate

. . . and then collisions! Right ???

When fully injected . . .

- $1.15*10^{11}$ protons per a bunch
- 2808 bunches rotating
- 11245 revolutions per second

Per single bunch crossing – **just 20 collisions**

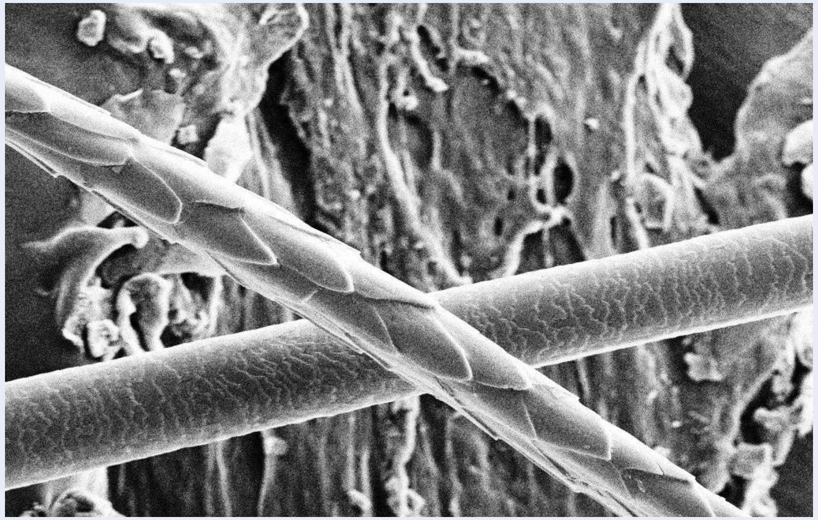
Though per second – **close to 1 billion events**

Protons stored for 12 hours travel **about 10^{10} to 10^{11} kilometers**

8 times back and forth from Sun to Pluto

At the point of interaction . . .

beams are squeezed **to 20 µm**



Size of a hair of a cat !

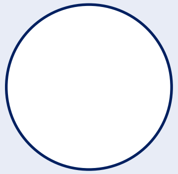
What are the limits for accelerators?

Hadron accelerators

Beam rigidity

Either larger circumference or greatly increased magnetic field strength

ADVANCES IN SUPERCONDUCTING MAGNET TECHNOLOGY



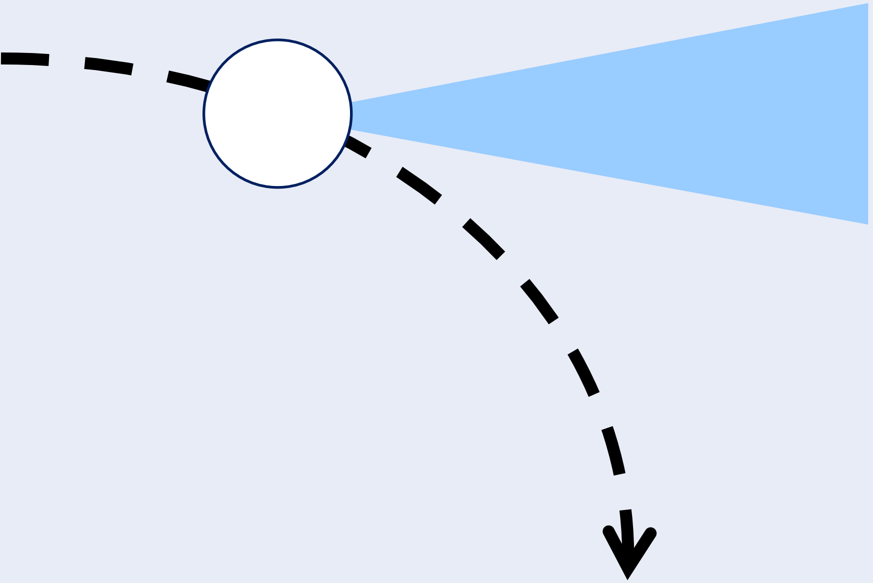
Lepton accelerators

RF power

In circular machines – electrons emit **synchrotron radiation** – energy loss

ADVANCES IN RF TECHNOLOGY OR GOING LINEAR

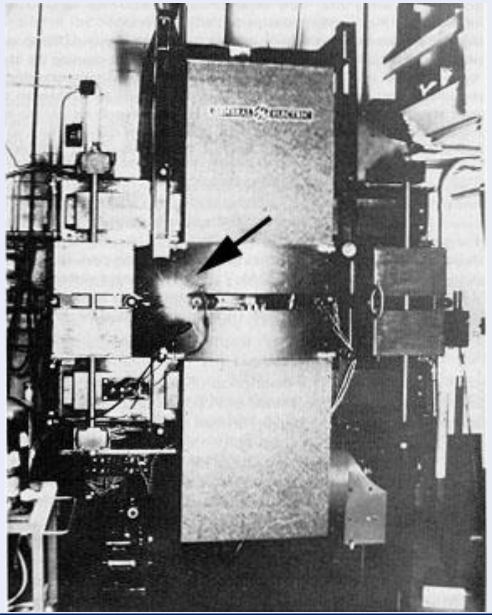
Synchrotron radiation – e^- limit



When the trajectory of a charged particle is bent – electromagnetic radiation is emitted, so-called, **synchrotron radiation**

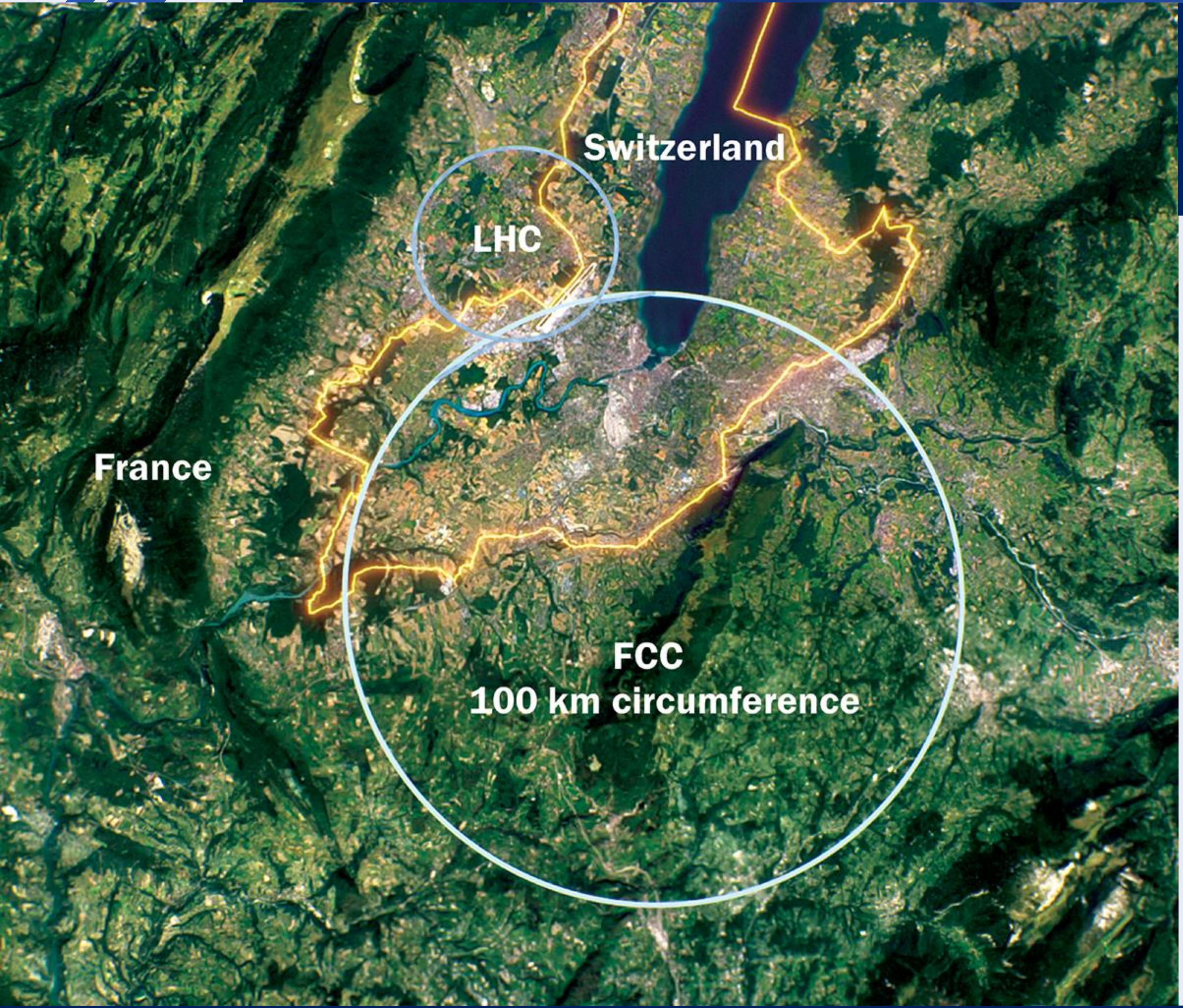
For lepton rings – energy loss that must be compensated

How to mitigate: larger circumference or heavier particles



Is it.. all bad or it could be useful ?

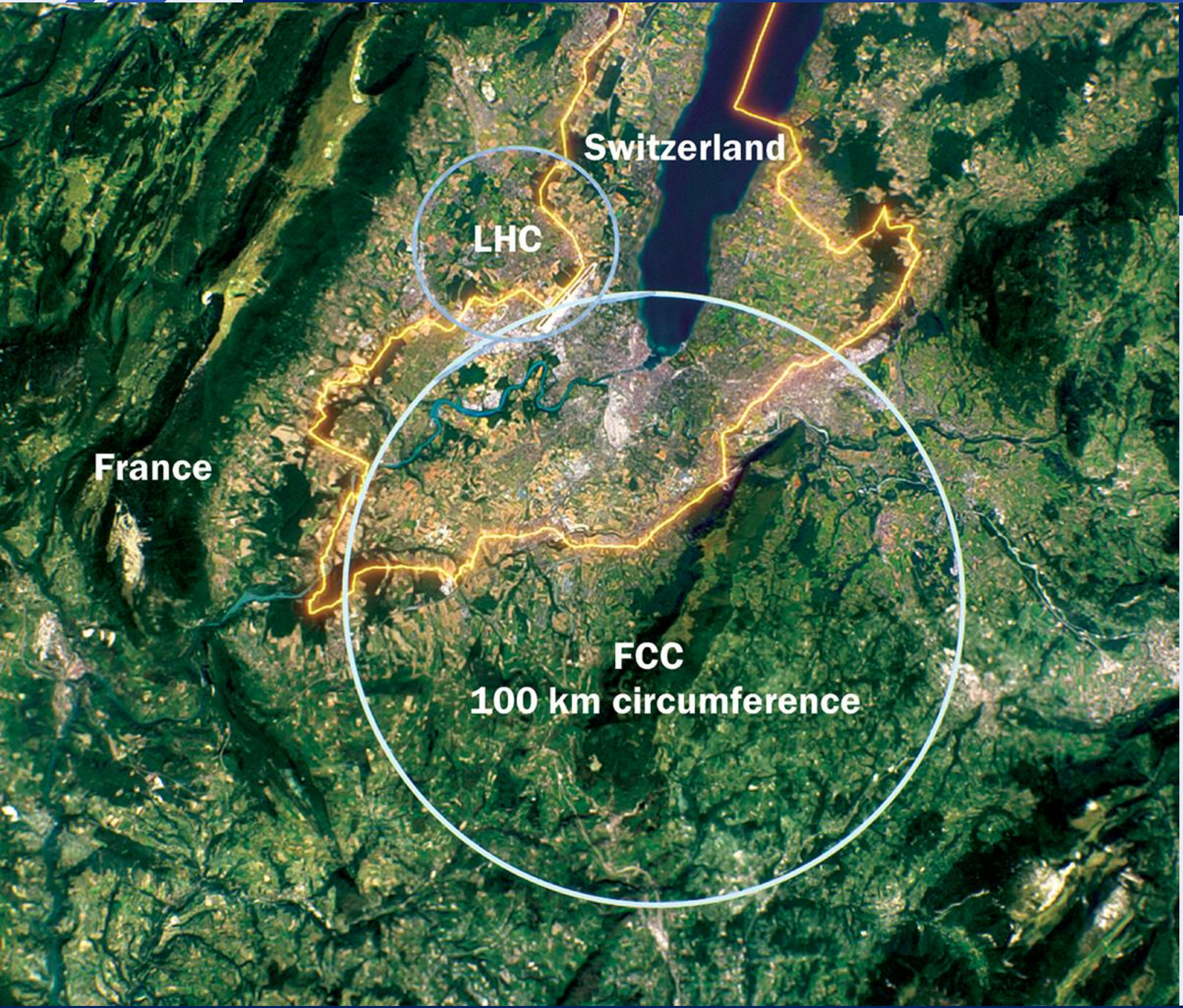
Future accelerator projects: FCCe^+e^-



Future Circular Collider

- Circumference of **close to 100 km**
- First iteration – **electron and positron collisions**
- **Precision measurements** of Z and W bosons, Higss boson and top quark

Future accelerator projects: **FCChh**

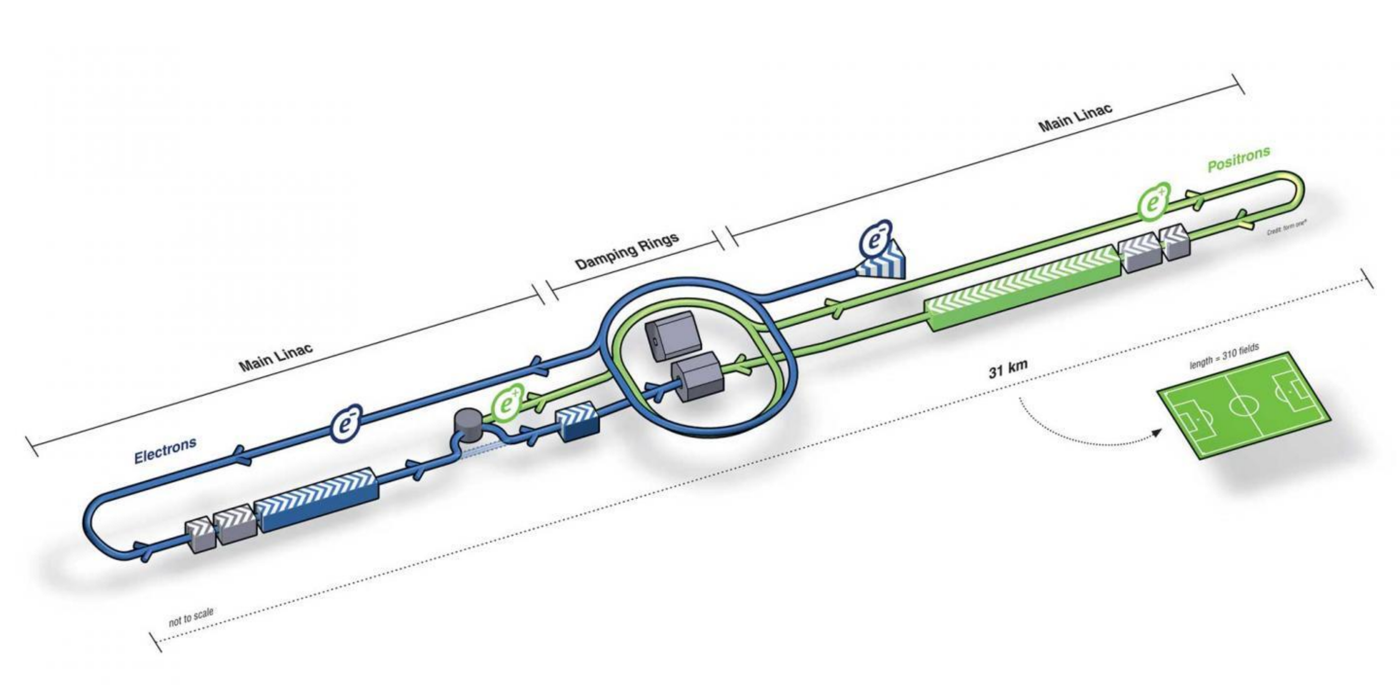


Future Circular Collider

- For proton-proton collisions **16 Tesla superconducting magnets** must be developed
- A **100 TeV** centre-of-mass could be reached

Future accelerator projects: **CLIC, ILC**

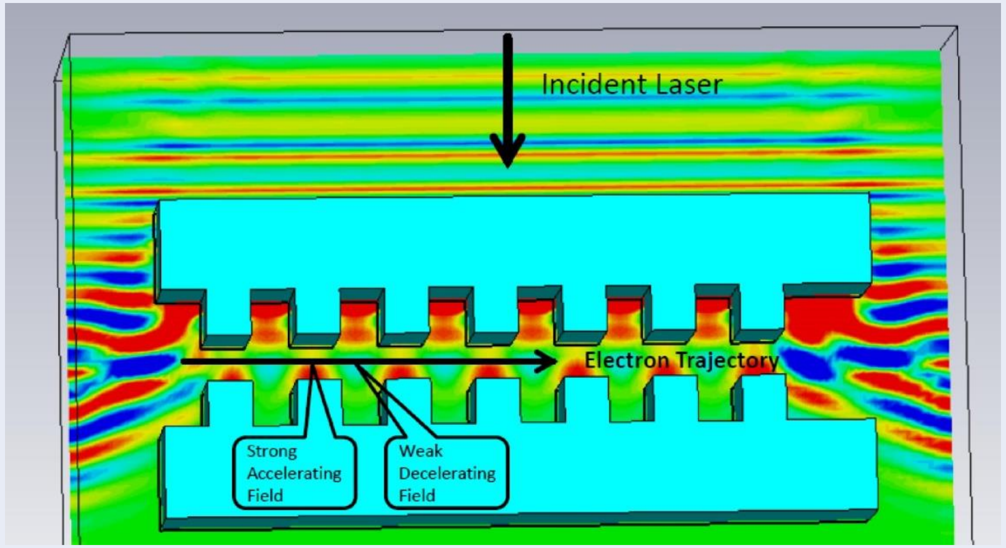
Up to 3 TeV with 50 km length



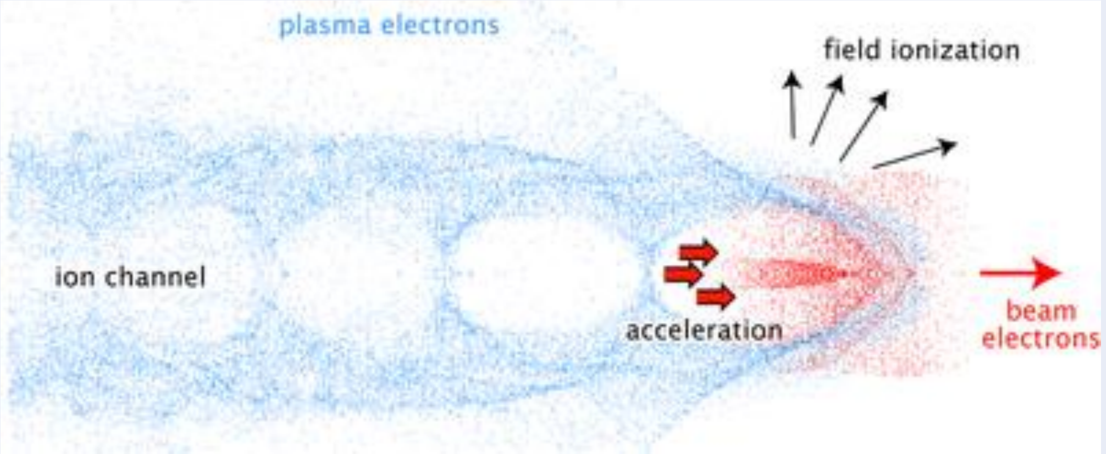
Up to 250 GeV with 20 km length

Is there more than RF?

Dielectric acceleration



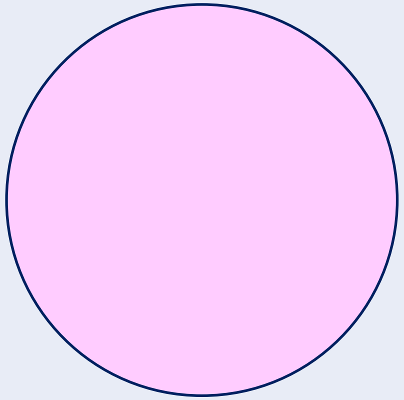
Laser plasma acceleration



Although a lot of challenges to overcome
Accelerating gradients of 1 GeV / m could be achieved

Future accelerators: **Muon Collider**

e⁻ x 200

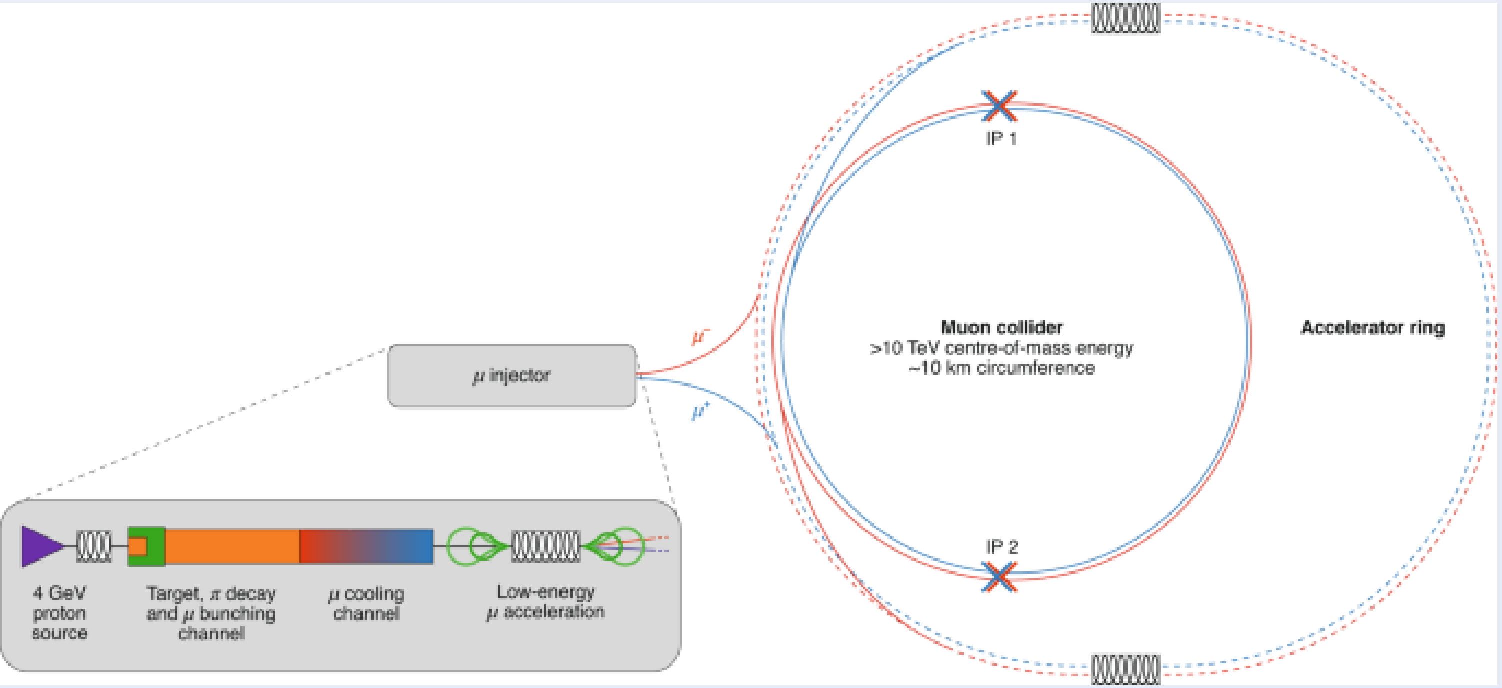


Muon

Synchrotron radiation losses reduced – possibility for **circular lepton collider**

BUT

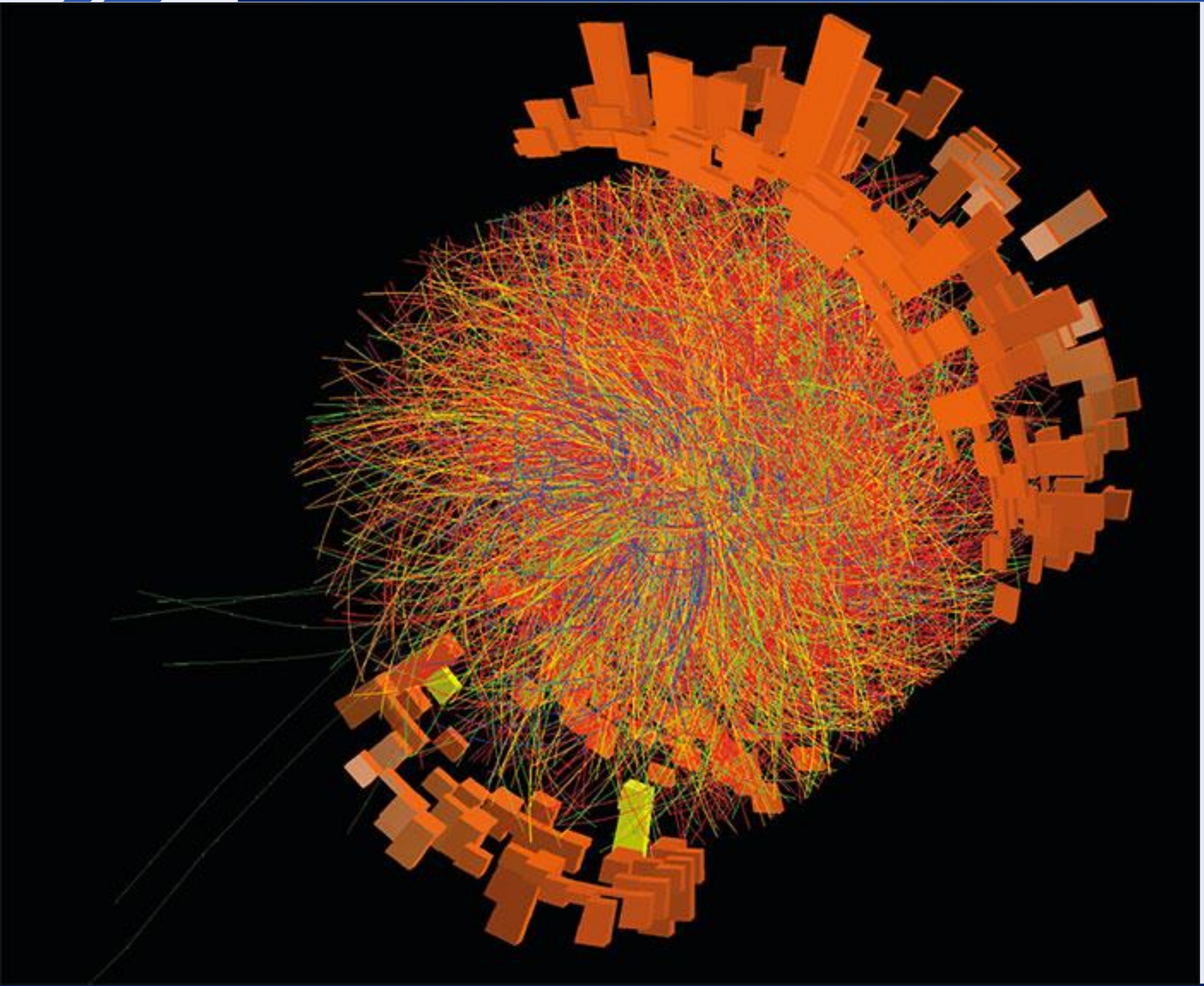
muon lifetime is 2.2 µs



Due to **time dilation** at higher energy – **500 µs**

Challenging, but actively researched

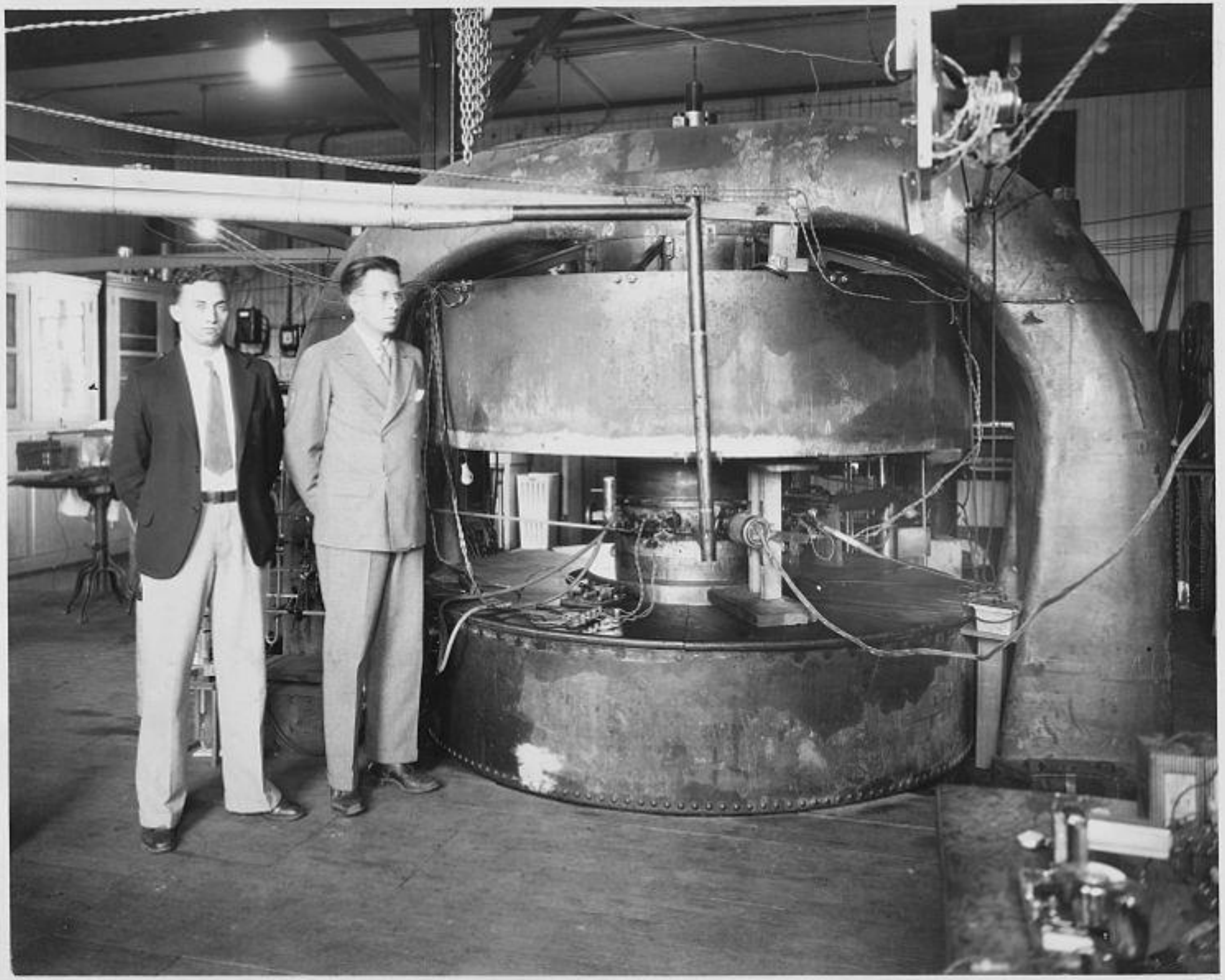
What other particles we accelerate?



Heavy-ion programme at CERN:

- Lead ions (Pb-Pb, Pb-p)
- Xenon ions (Xe-Xe)
- Argon ions (Ar-p)
- Oxygen ions (O-p)

What other particles we accelerate?



Lawrence Berkley National Laboratory

- Deuterons
- Helium ions
- Carbon ions
- Oxygen ions
- Neon ions
- Silicon ions
- Argon ions

Cyclotron could accelerate up to Uranium

For collisions or something else?

Accelerator - scientific instrument?

Particle accelerators have contributed to **26 Nobel prizes**

Particle physics laboratories around the world:

- CERN
- DESY
- SLAC
- Brookhaven
- Fermilab
- KEK
- IHEP
- ….

$= < 1\ \%$

How many accelerators are there ?

There are around 35 000 particle accelerators around the world

Where are the other accelerators used ?

Particle accelerators in the Baltics?

Scan the QR code or go to **menti.com**

and **use code**

2245 5867

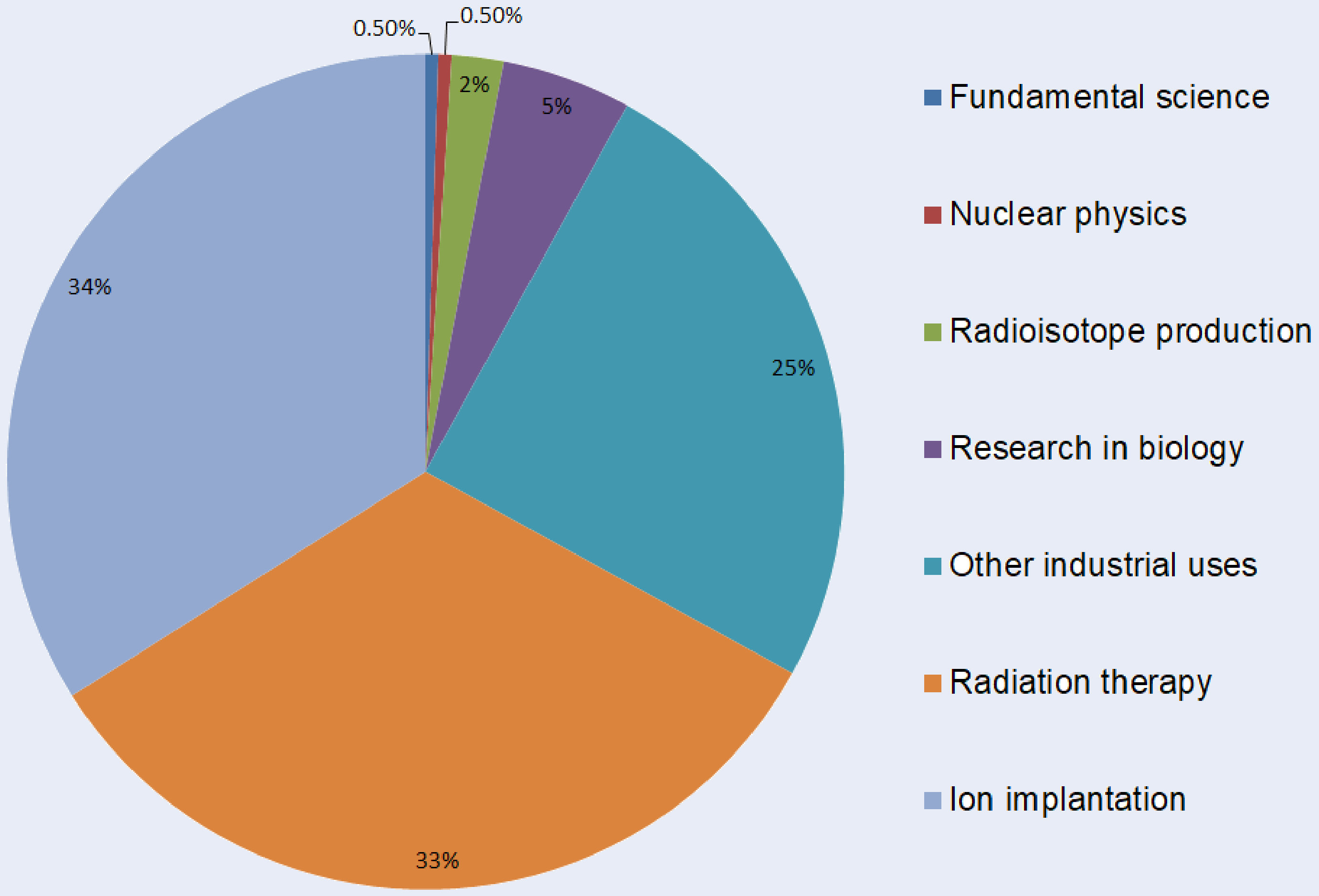
Are there accelerators in Baltics ?

We have

28 electron linear accelerators

and **1 cyclotron**

Where are accelerators used?



Majority is used in medicine and industry

The many uses of accelerators

"A beam of the **right particles** with the **right energy** at the **right intensity**

can shrink a tumour, produce cleaner energy, spot suspicious cargo, make a better radial tire, clean up dirty drinking water, map a protein, study a nuclear explosion, design a new drug, make a heat-resistant automotive cable, diagnose a disease, reduce nuclear waste, detect an art forgery, implant ions in a semiconductor, prospect for oil, date an archaeological find, package a Thanksgiving turkey or…
…discover the secrets of the universe."

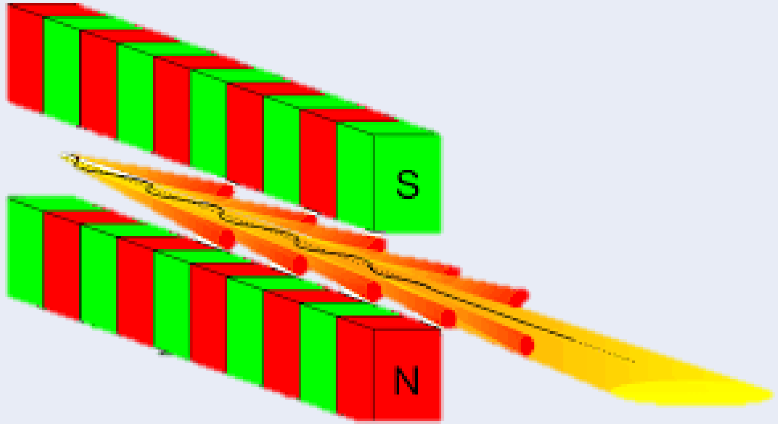
-Accelerators for Americas Future Report, pp. 4, DoE, USA, 2011

(Applications of Accelerators by Dr. Suzie Sheehy, CERN Accelerator School 2021)

Remember synchrotron light ?

One man's trash is another man's treasure

Dedicated synchrotron light sources are built to provide high brilliance (intensity) X-ray beams, introducing new technologies as wigglers, undulators and free-electron lasers



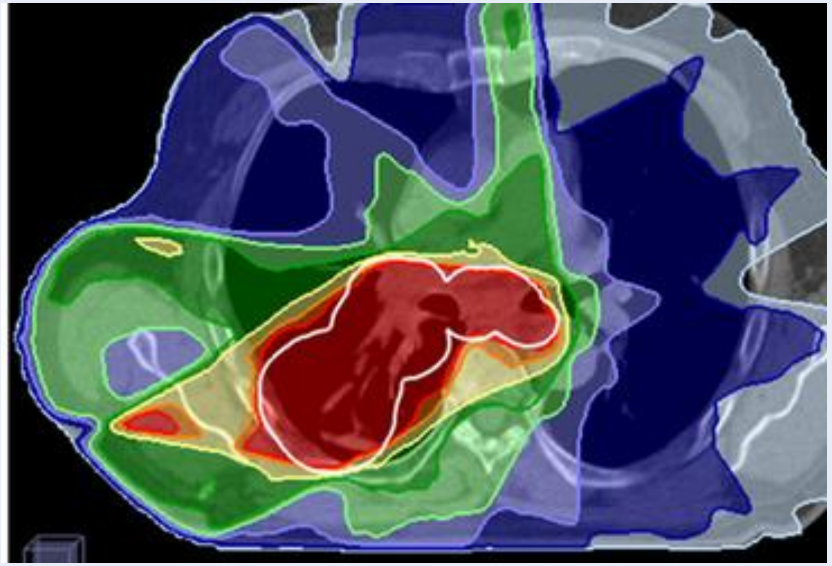
Material science, solid state physics, protein crystallography, structural biology, archaeology . . .

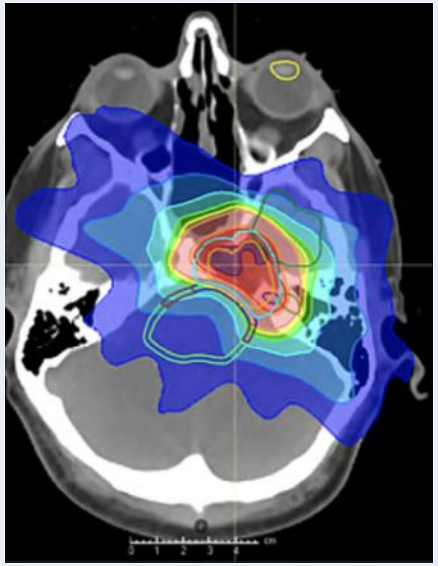
Medical applications: **Radiotherapy**

A compact **6 to 20 MeV electron** accelerator

Production of **bremsstrahlung photons** for deep-seated tumor treatment

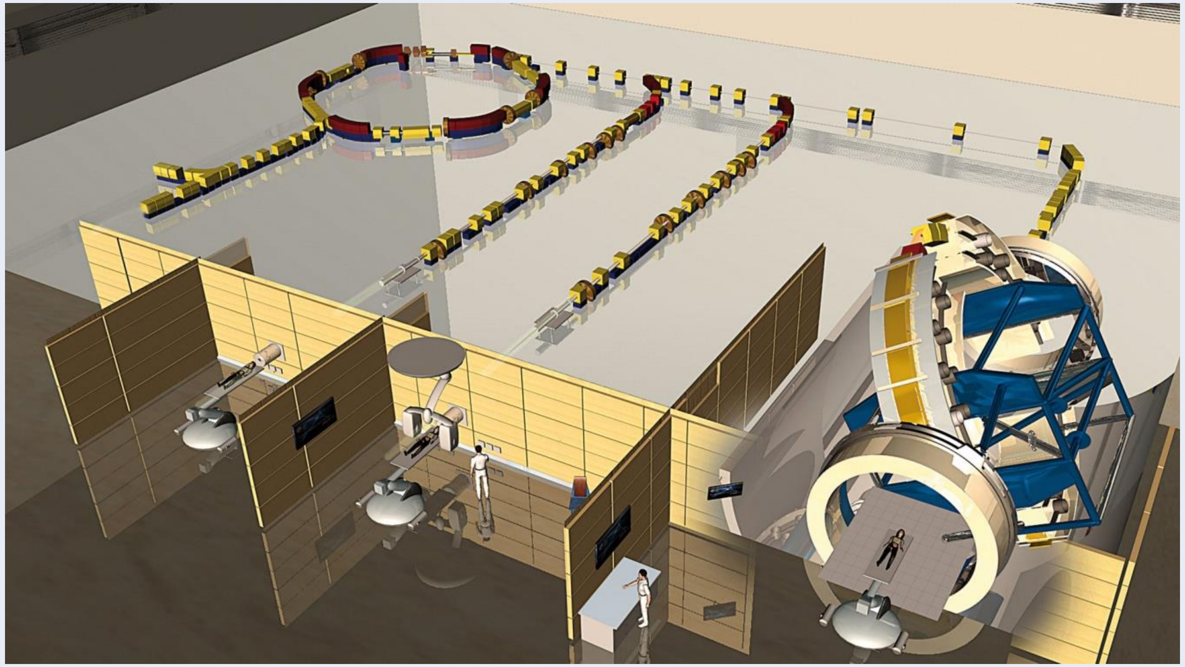
Ionizing radiation damages cellular DNA of cancer, limiting the spread and destroying it





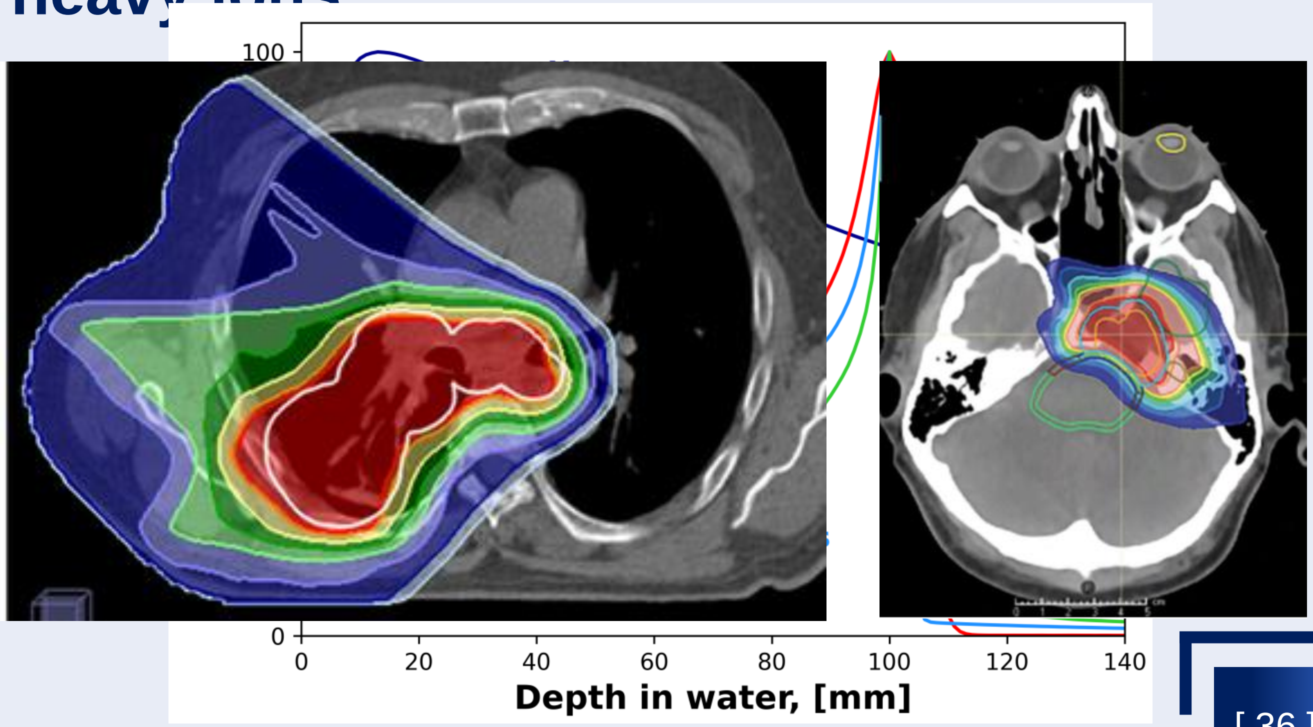
Medical applications: **Particle therapy**

Let's downscale LHC about 415 times and limit proton energy to 220 MeV

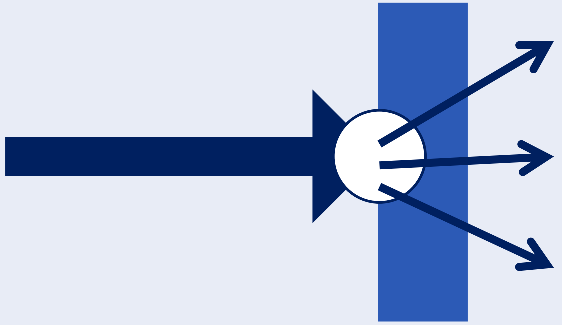


Proton and ion therapy is a promising cancer treatment modality due to favourable dose deposition characteristics – **Bragg peak**

Protons and ions ionize matter more densely – **increased biological effect, possible to treat otherwise resistant tumors with heavy ions**



Medical applications: **Radioisotopes**



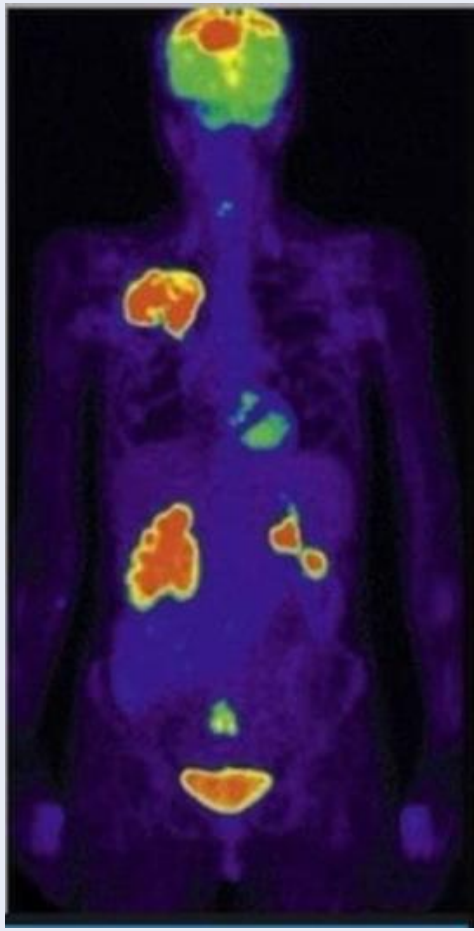
Relatively low energy proton (deuteron, alpha) beams imping on a target can produce radioactive isotopes in nuclear reactions. Isotopes can be extracted and by joining with a specific biological molecules – **radiopharmaceuticals for nuclear medicine**

Diagnostics

Positron emission tomography (PET) and single photon emission computed tomography (SPECT) – **cancer diagnostics**

Therapy

Biologically **targeted cancer therapy** – emission of electrons ($beta^-$), alpha particles or Auger electrons locally



Take - away

- The very basics of particle acceleration – Lorentz force from highschool
- Particle accelerators encompass a broad field of disciplines both in physics and engineering
- Particle accelerator scientific developments are moving forward with a lot of bright and prospective future projects

A magnificent instrument to do marvelous things

Take - away

«Physics is beautiful and useful»

/Ugo Amaldi,

founder of Hadron Therapy project and TERA organization

Thank you so much for your attention!