Introduction to accelerators

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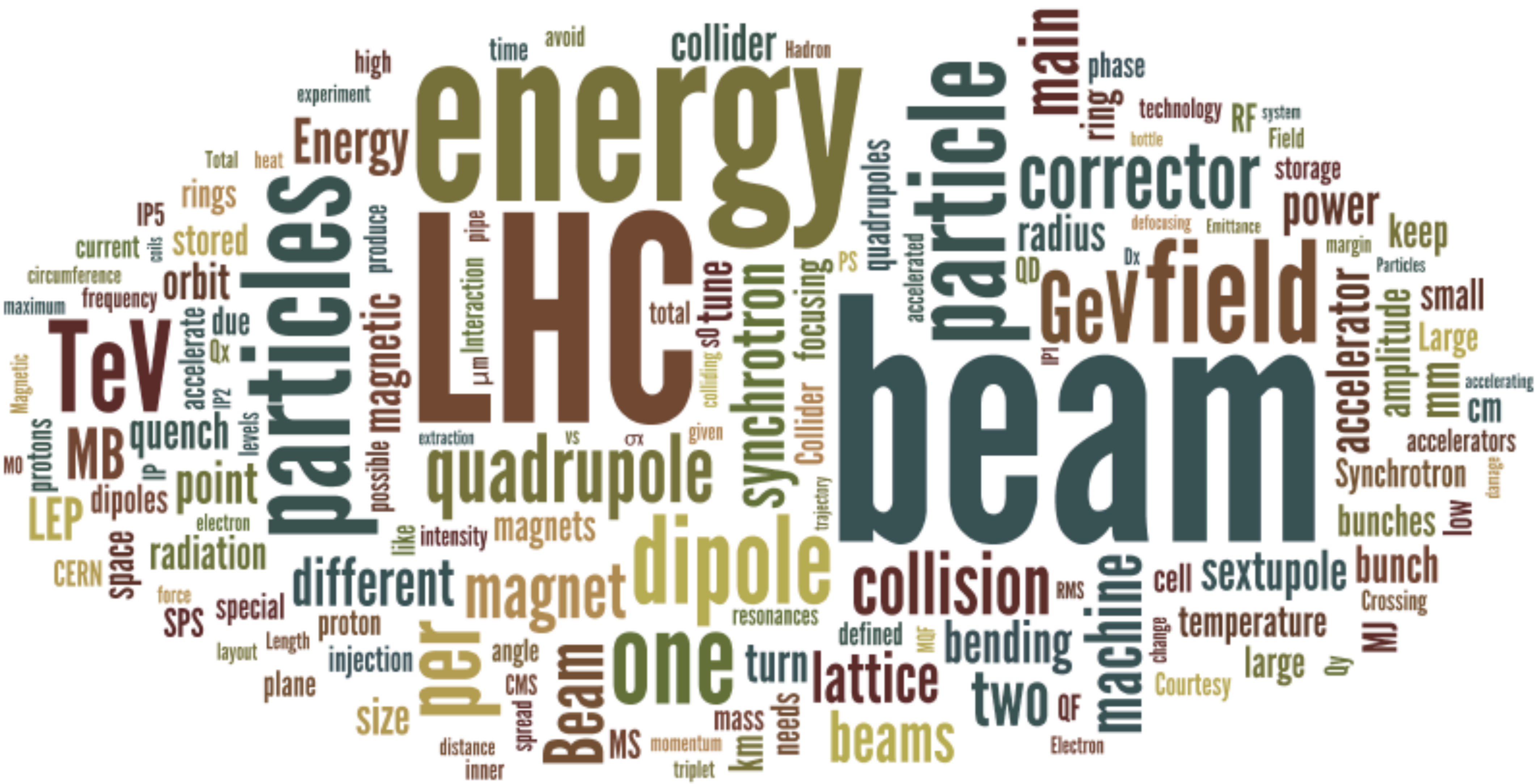
The agenda...


energy
LHC
beam
particle
particles
corrector
field
GeV
TeV
dipole
quadrupole
one
collision
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main
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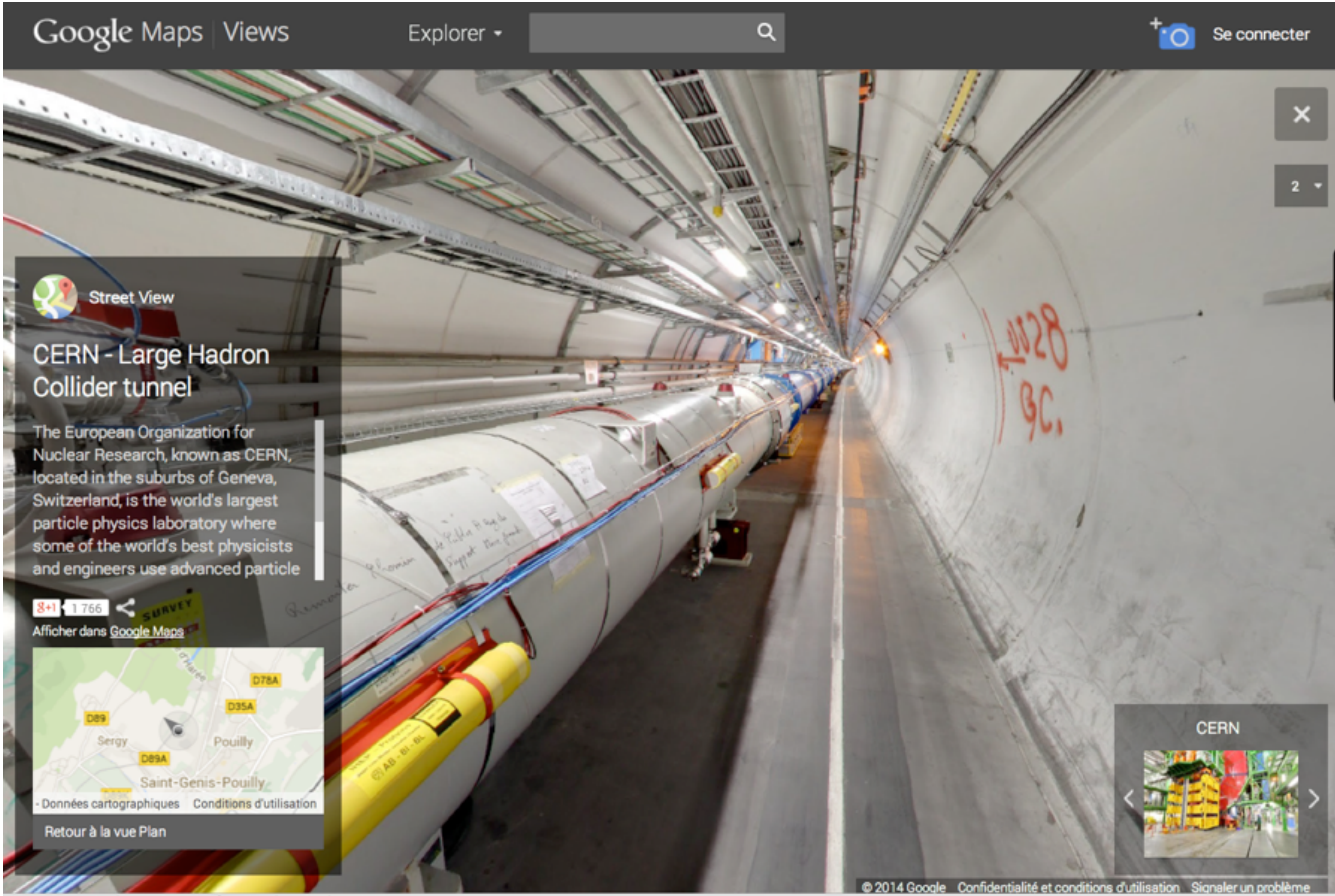
lattice
machine
two
Beam
per
different
beams
bending
power
accelerator
collider
Energy
radius
sextupole
bunch
bunches
turn
magnetic
quench
point
orbit
MB
radiation
stored
rings
LEP
dipoles
magnets
temperature
large
keep
small
amplitude
mm
Large
cm
accelerators
Synchrotron
storage
technology
phase
ring
RF
Field
system
bottle
defocusing
Emittance
margin
Dx
Particles
quadrupoles
accelerated
focusing
tune
total
Collider
QD
PS
IP1
accelerating
damage
low
Crossing
MJ
Qy
Courtesy
cell
RMS
change
MQF
QF
Electron
defined
resonances
given
colliding
trajectory
needs
km
mass
momentum
triplet
MS
spread
CMS
angle
size
injection
proton
plane
layout
Length
special
SPS
CERN
force
space
electron
intensity
like
possible
extraction
vs
σx
μm
Interaction
pipe
produce
due
accelerate
Qx
IP2
levels
IP
protons
MO
Magnetic
maximum
circumference
frequency
current
coils
IP5
Total
heat
experiment
high
time
avoid
Hadron
distance
inner
s0

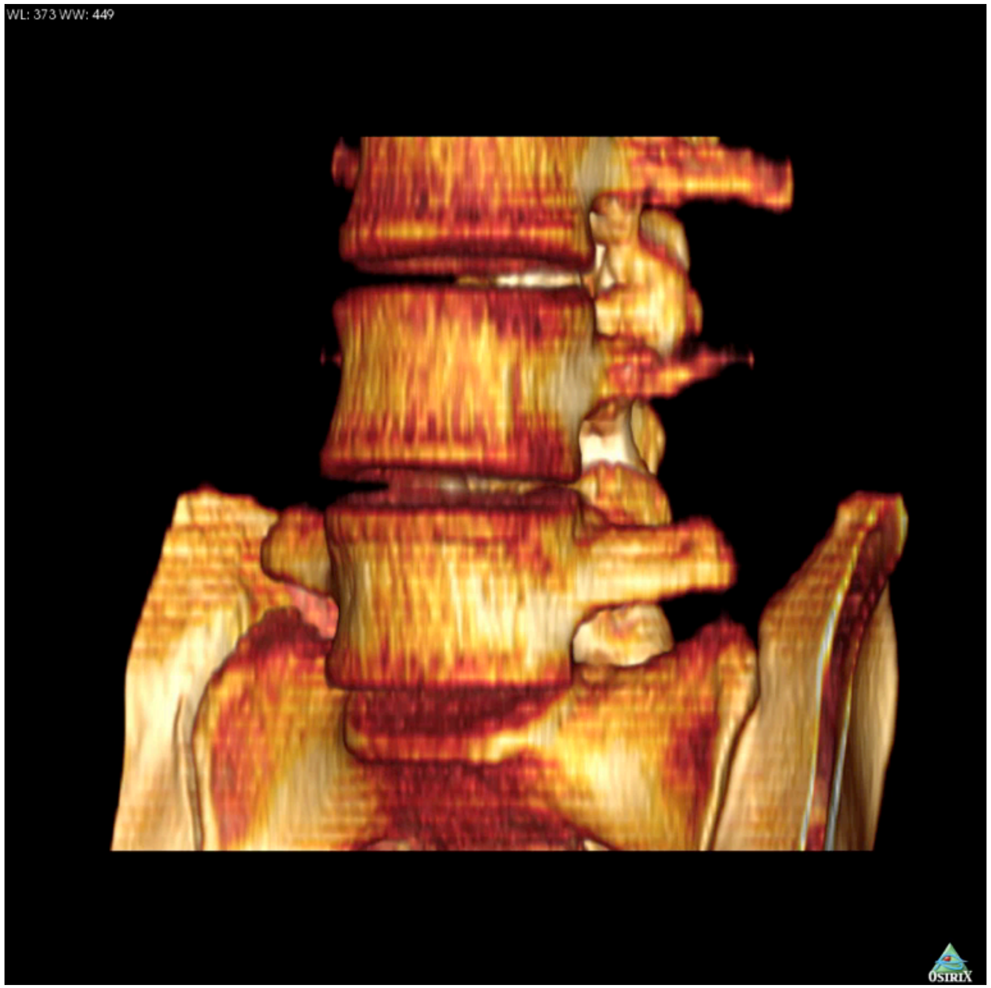
A Google view of high energy accelerators

https://maps.google.com/maps/ms?ie=UTF8&hl=en&t=h&msa=0&msid=100574363331995850370.000495f3c601139ebb21e&ll=31.052934,0&spn=163.748232,181.054688&z=2

Where we are going to go ....



Medical imagery



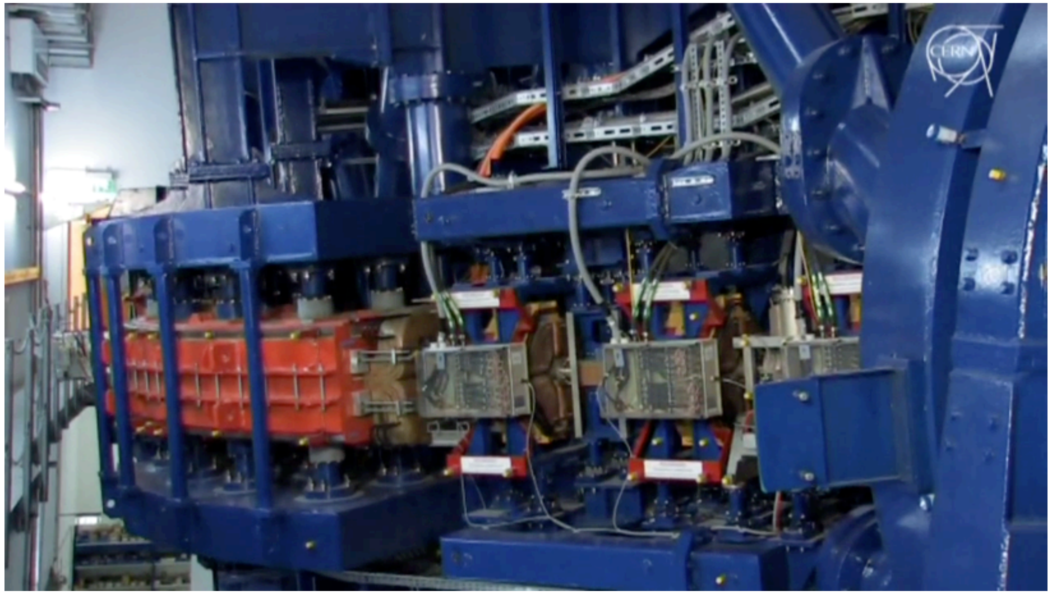
A CT (computerized tomography) scanner,
or CAT (computerized axial tomography).

x-ray machine plus detector, both rotating around the patient

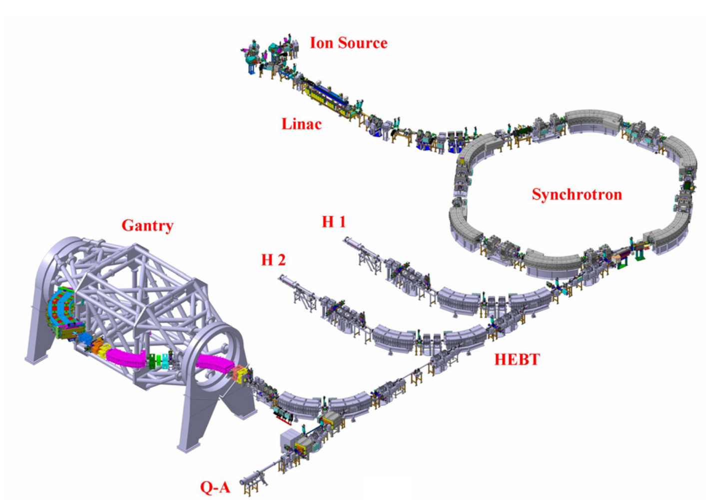
Kind of low energy particle physics fix target experiment

Image reconstruction similar to what we do for beam property diagnosis

Accelerators for cancer therapy

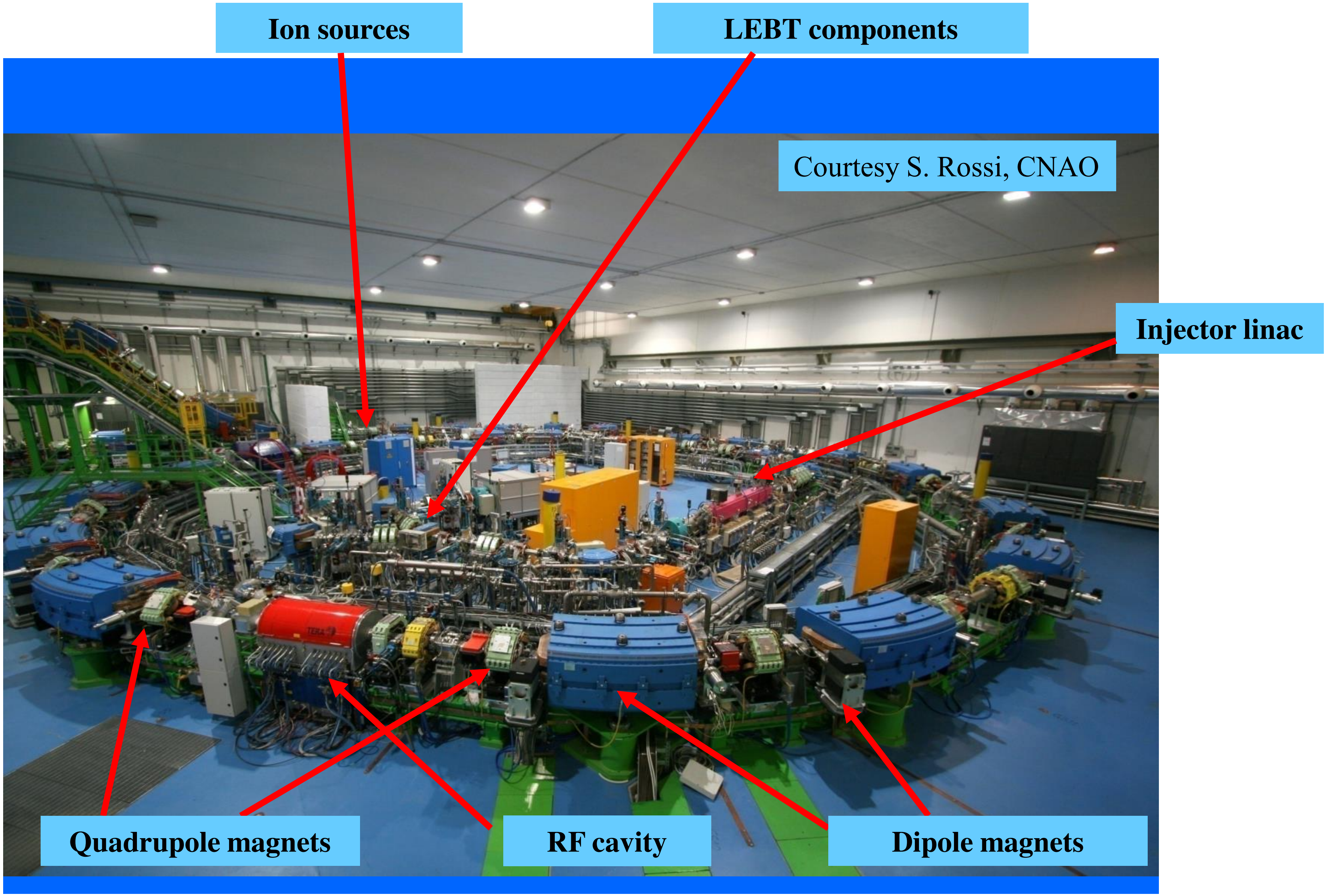


THE HEIDELBERG ION THERAPY (HIT)

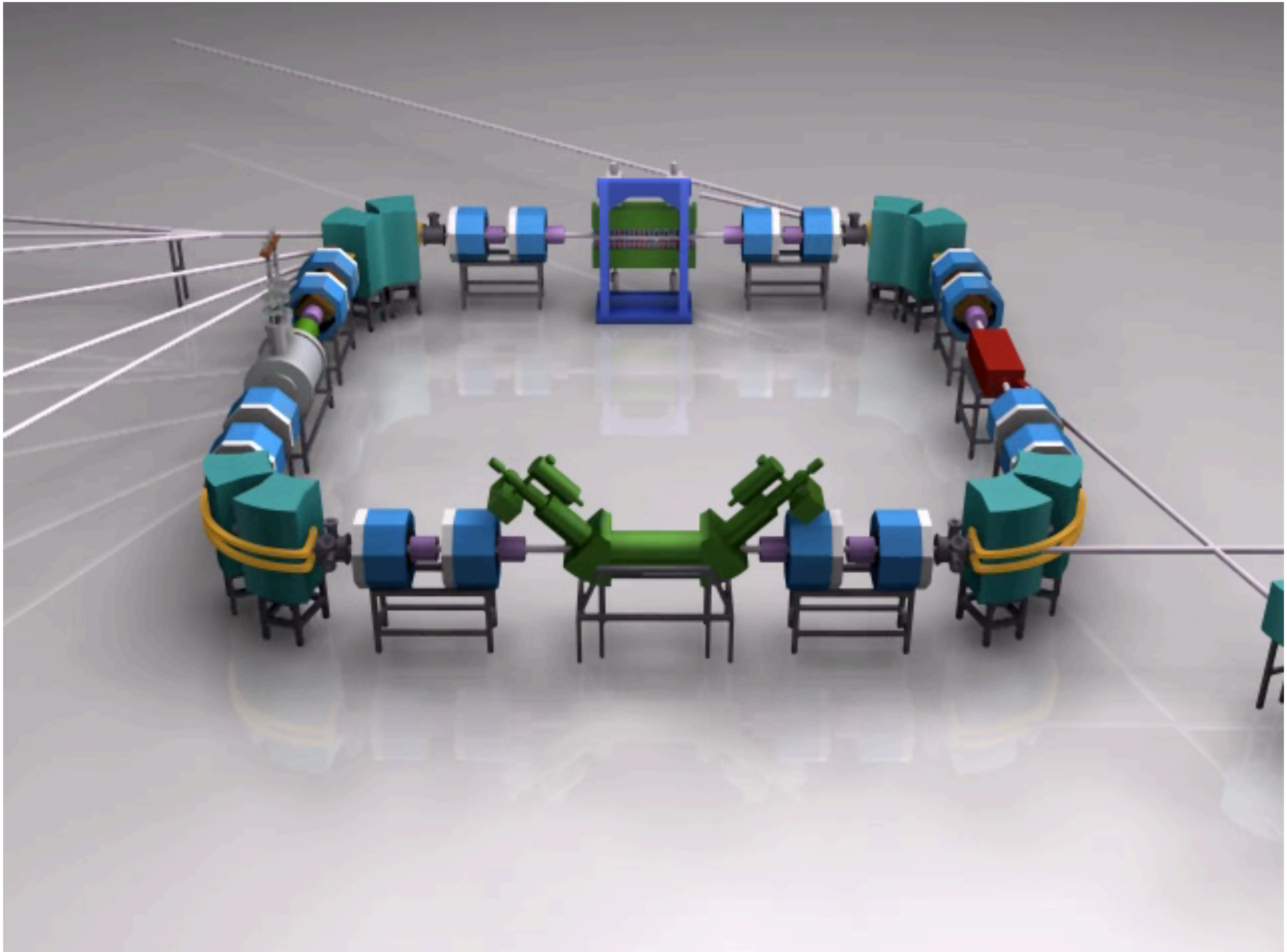


CNAO = Centro Nazionale di Adroterapia at Pavia

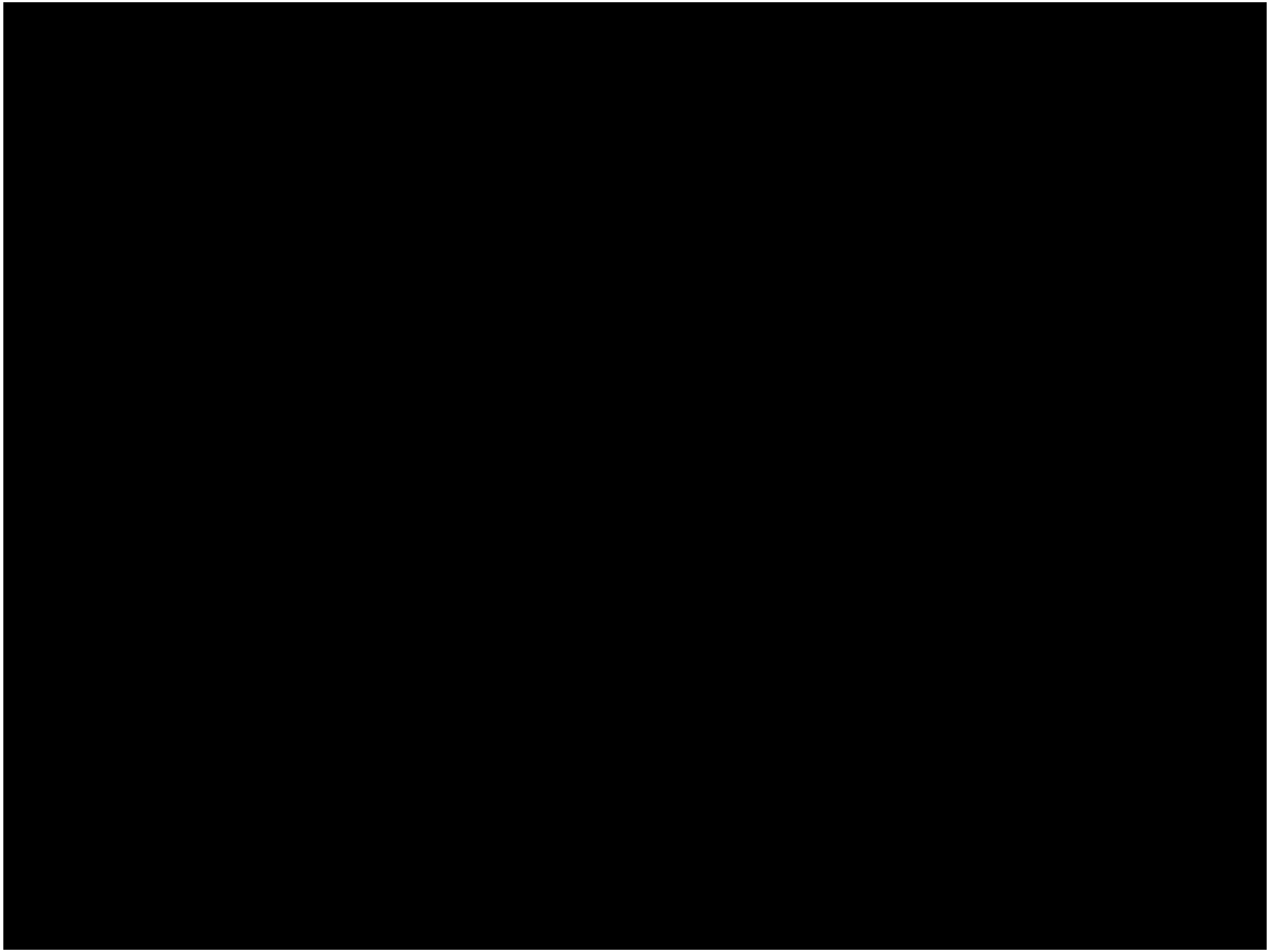
National Centre for Oncological Hadrontherapy, CNAO, Pavia, Italy



بيروت
Zahle
زحلة
Baalbek
بعلبك
Yabrud
يبرود
Beit Al Dine
بيت الدين
Ad Dumayr
الضمير
Damascus
دمشق
Rachaiya
راشيا
Sidon District
صيدا
Al-Qisa
قيسا
Sour
صور
Nabatieh
النبطية
Jdaydet Artooz
جديدة عرطوز
Qana
قانا
Nahariya
Safed
Nawa
نوى
Izraa
ازرع
Acre
Karmiel
Haifa
Kiryat Ata
Tiberias
As Suwayda
السويداء
Nesher
Nazareth
Daraa
درعا
Zihron Ya'akov
Afula
Irbid
اربد
Umm al-Fahm
Hadera
Al Hosn
الحصن
Al Mafraq
المفرق
Jenin
Netanya
Jarash
جرش
Tel Aviv-Yafo
Amman
عمان
Or Yehuda
Al-Bireh
Rishon LeTsiyon
Jerusalem
Madaba
Ashkelon
Beit Shemesh
Al Jiza
الجيزة
Gaza
Kiryat Gat
Suwaqa Al Gharbiya
سواقة الغربية
Yata
Rahat
Khan Yunis
Dahriya
Be'er Sheva
Arad
Karak
Arish
Rafa
Google
Map data ©2015 Basarsoft, Google, Mapa GISrael, ORION-ME Imagery ©2015 TerraMetrics
Terms of Use



Electron Injection, Storage and Synchrotron Radiation Light Generation in the Storage Ring ASTRID. (Credit: Coldvision Studio/ISA)



SSRL – Stanford Synchrotron Radiation Lightsource

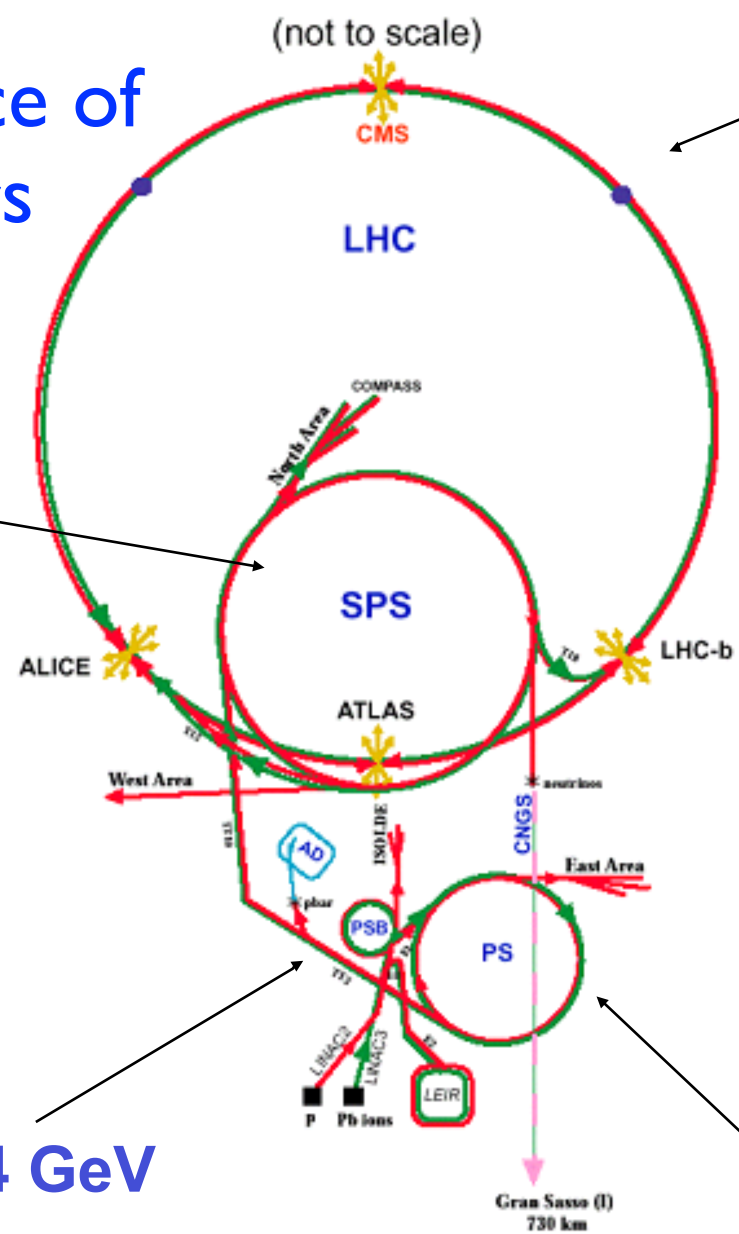
- **Protein Crystallography at SLAC**
  (Credit: Juna Kurihara/SLAC)

CERN accelerator complex overview

Chain/sequence of accelerators

450 GeV /c – 7 TeV /c

26 - 450 GeV/c



- protons
- antiprotons
- ions
- neutrinos to Gran Sasso (I)

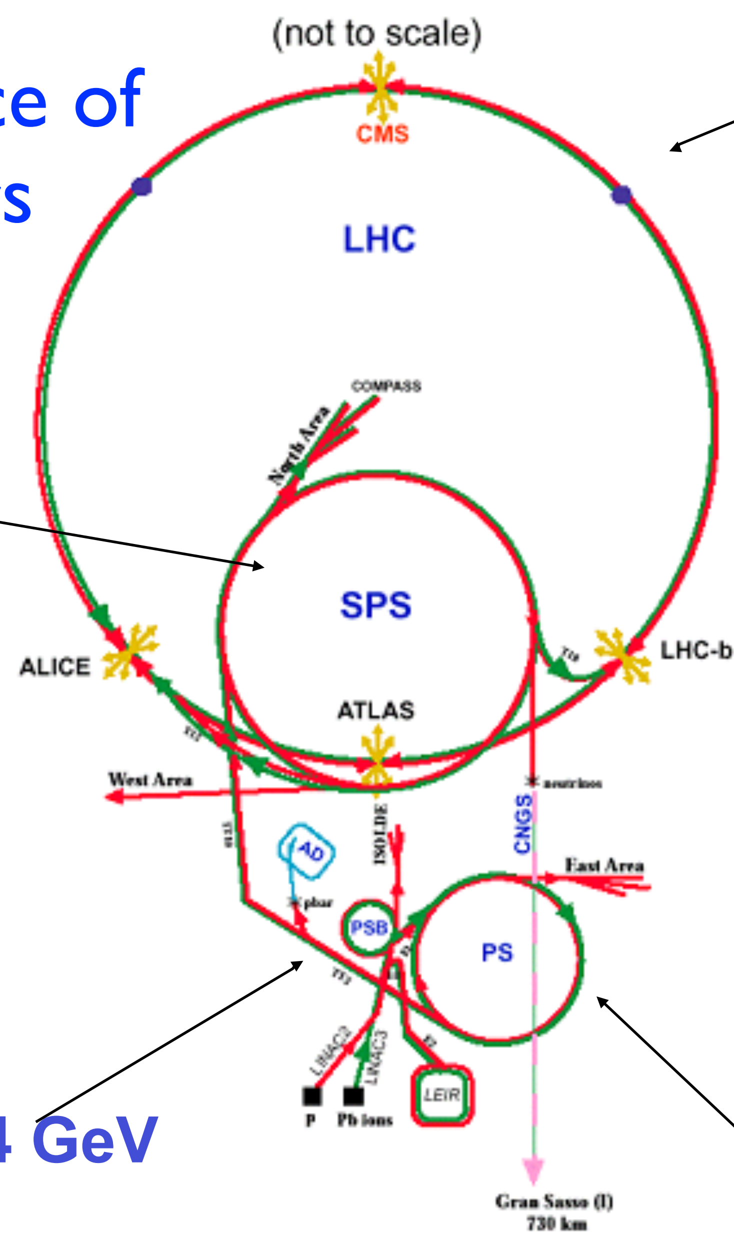
LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

50 MeV – 1.4 GeV

1.4 GeV – 26 GeV/c

CERN accelerator complex overview

Chain/sequence of accelerators



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450 GeV/c – 7 TeV/c

C ~ 27 km

26 - 450 GeV/c

C ~ 6 km

1.4 GeV – 26 GeV/c

C ~ 630 m

50 MeV – 1.4 GeV

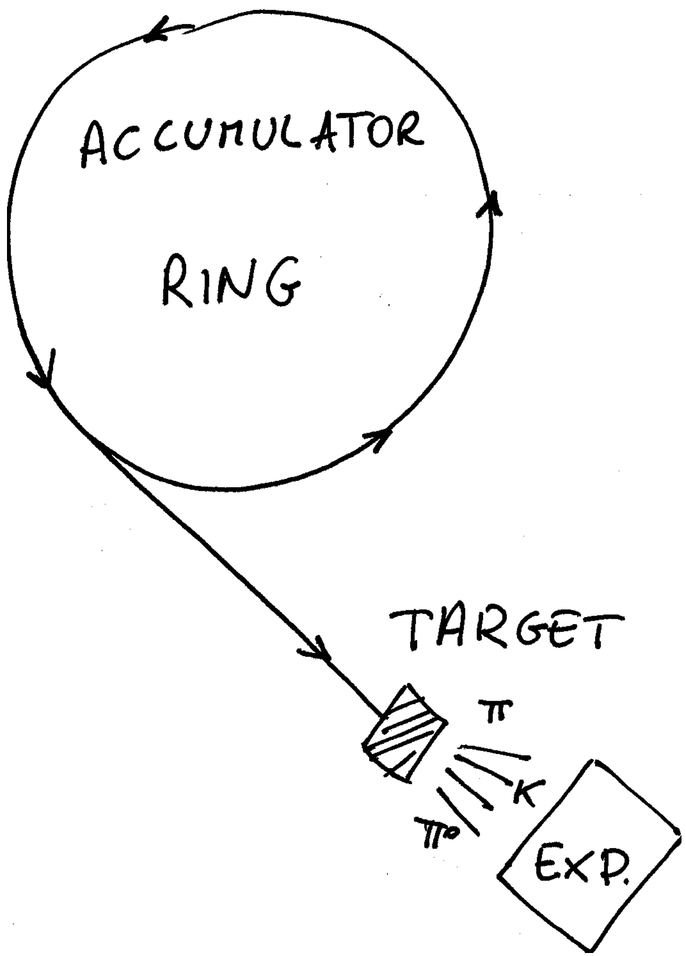
C ~ 157 m

Questions:

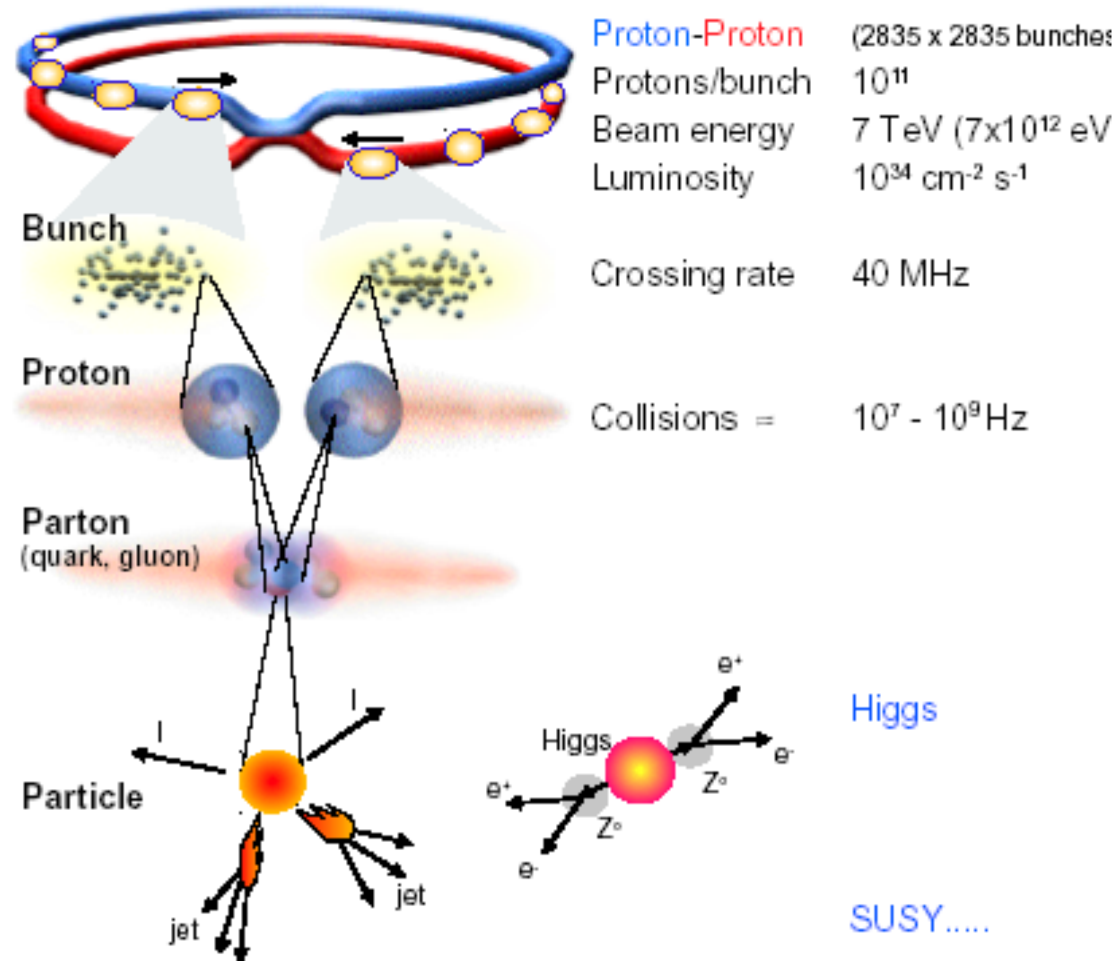
- why so many accelerators and not just the LHC?
- why rings of increasing circumference?
- why rings and linear accelerators?
- how particles go from one machine to the other?

Different approaches: fixed target vs collider

Fixed target

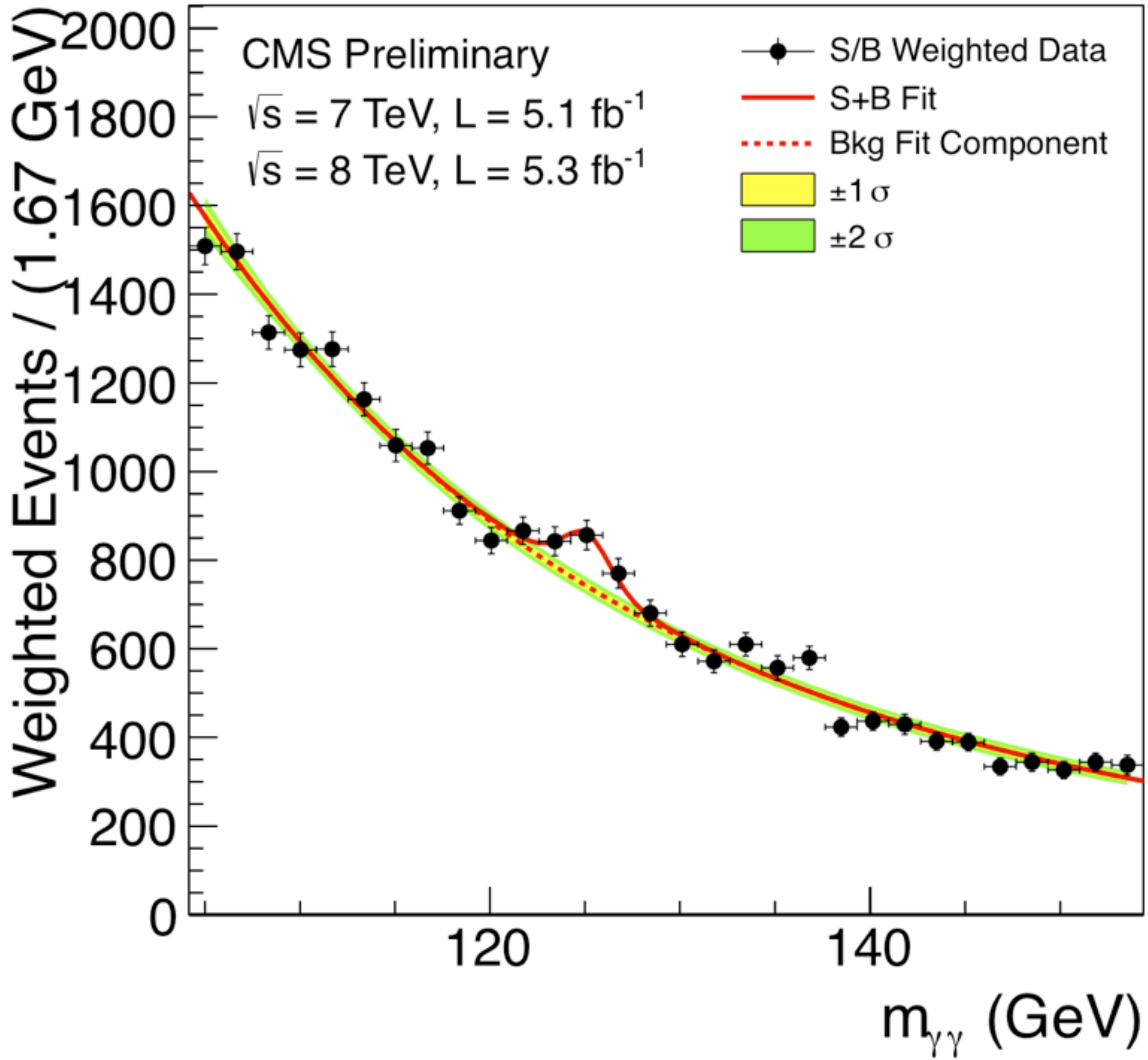


Storage ring/collider



$$E_{CM} = \sqrt{2\left(E_{beam}mc^2 + m^2c^4\right)} \quad << \quad E_{CM} = 2\left(E_{beam} + mc^2\right)$$

This usually is defined as $\sqrt{s}$


CMS Preliminary
√s = 7 TeV, L = 5.1 fb-1
√s = 8 TeV, L = 5.3 fb-1
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
Weighted Events / (1.67 GeV)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
120
140
mγγ (GeV)

SPEECH DELIVERED BY PROFESSOR NIELS BOHR

ON THE OCCASION OF THE INAUGURATION OF THE CERN PROTON SYNCHROTRON

ON 5 FEBRUARY, 1960

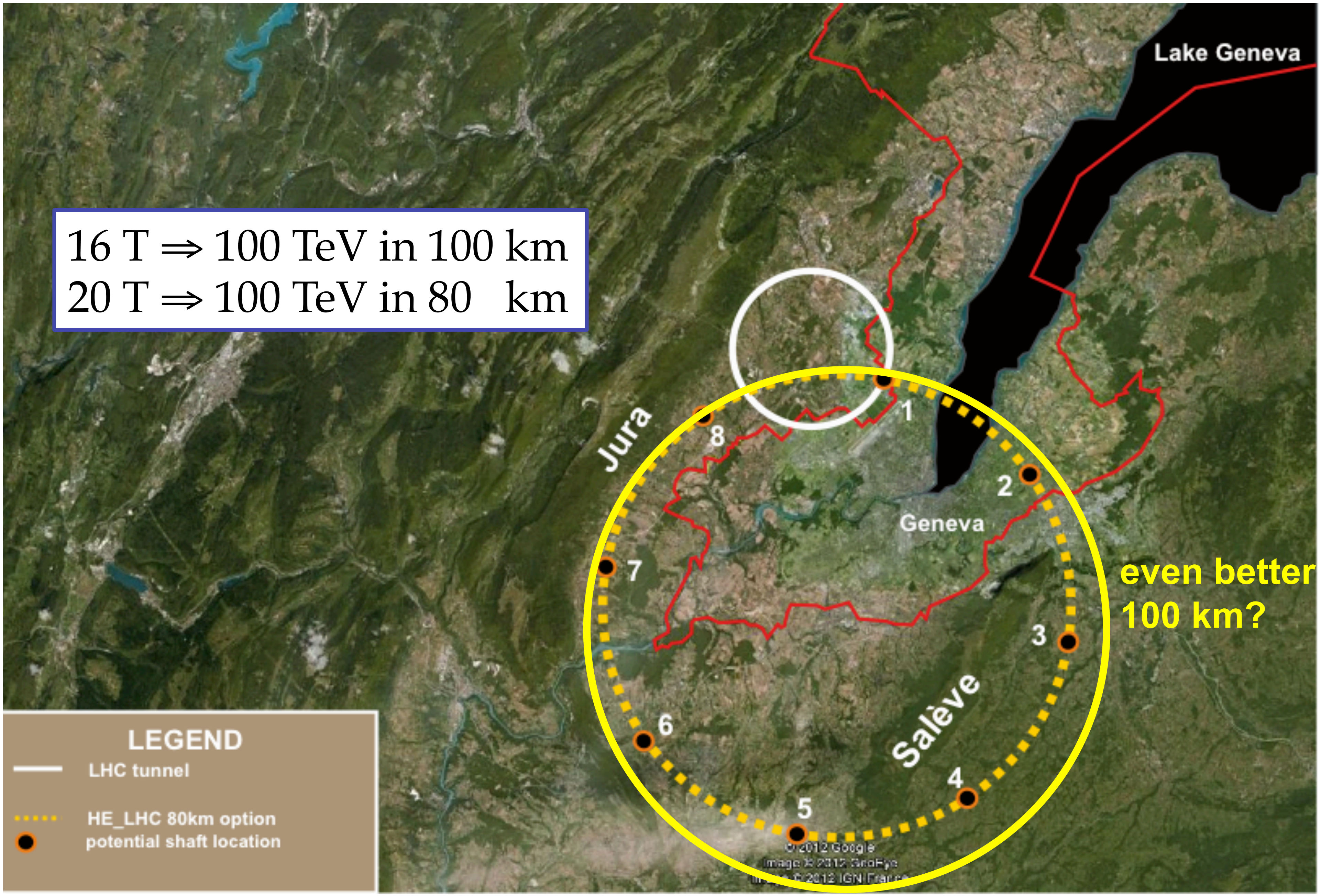
Press Release PR/56
12 February, 1960

It may perhaps seem odd that apparatus as big and as complex as our gigantic proton synchrotron is needed for the investigation of the smallest objects we know about. However, just as the wave features of light propagation make huge telescopes necessary for the measurement of small angles between rays from distant stars, so the very character of the laws governing the properties of the many new elementary particles which have been discovered in recent years, and especially their transmutations in violent collisions, can only be studied by using atomic particles accelerated to immense energies. Actually we are here confronted with most challenging problems at the border of physical knowledge, the exploration of which promises to give us a deeper understanding of the laws responsible for the very existence and stability of matter.

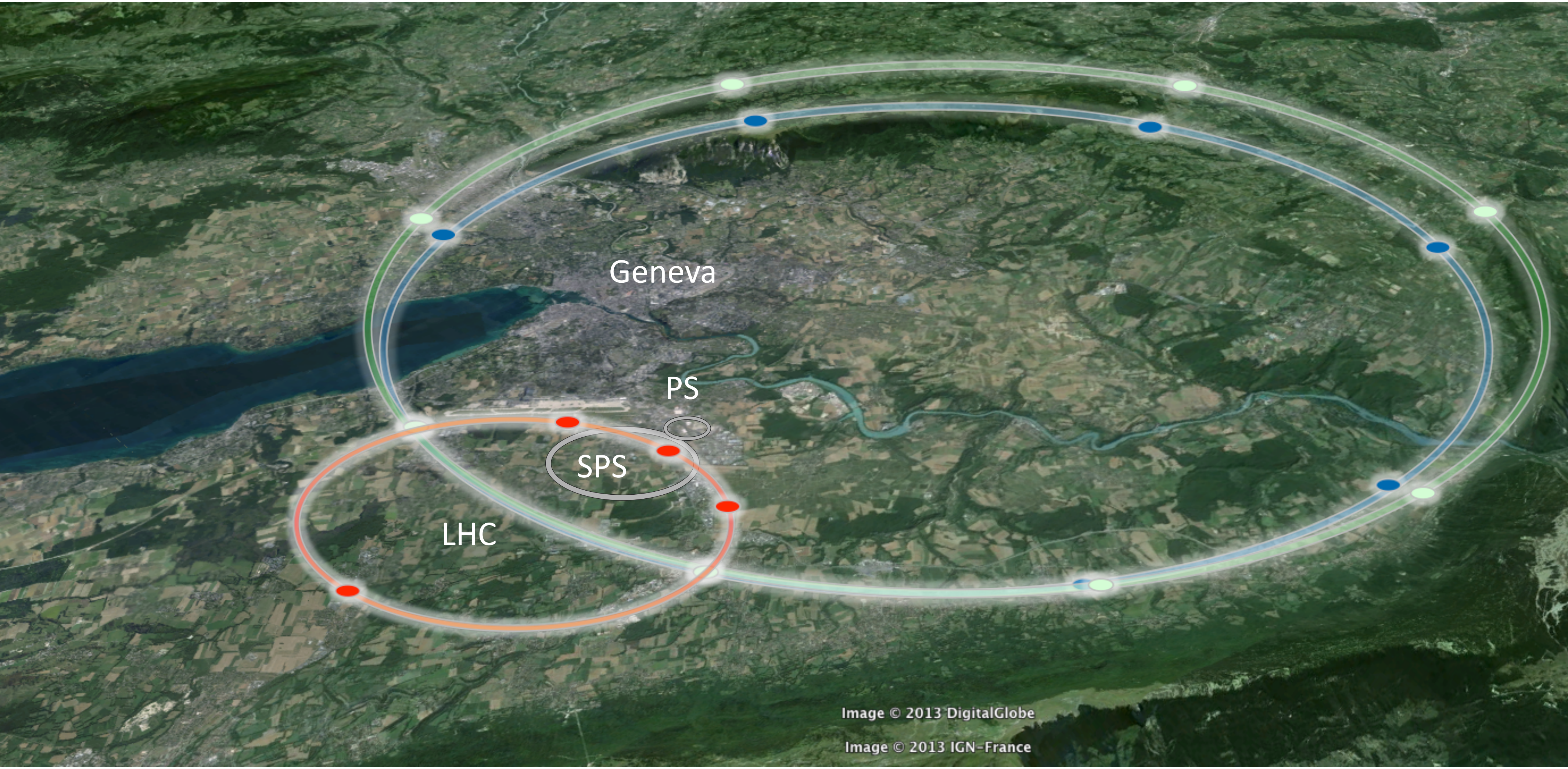
All the ingredients are there: we need high energy particles produced by large accelerators to study the matter constituents and their interactions laws. This also true for the LHC.

Small detail... Bohr was not completely right, the “new” elementary particles are not elementary but mesons, namely formed by quarks

What's the future ?



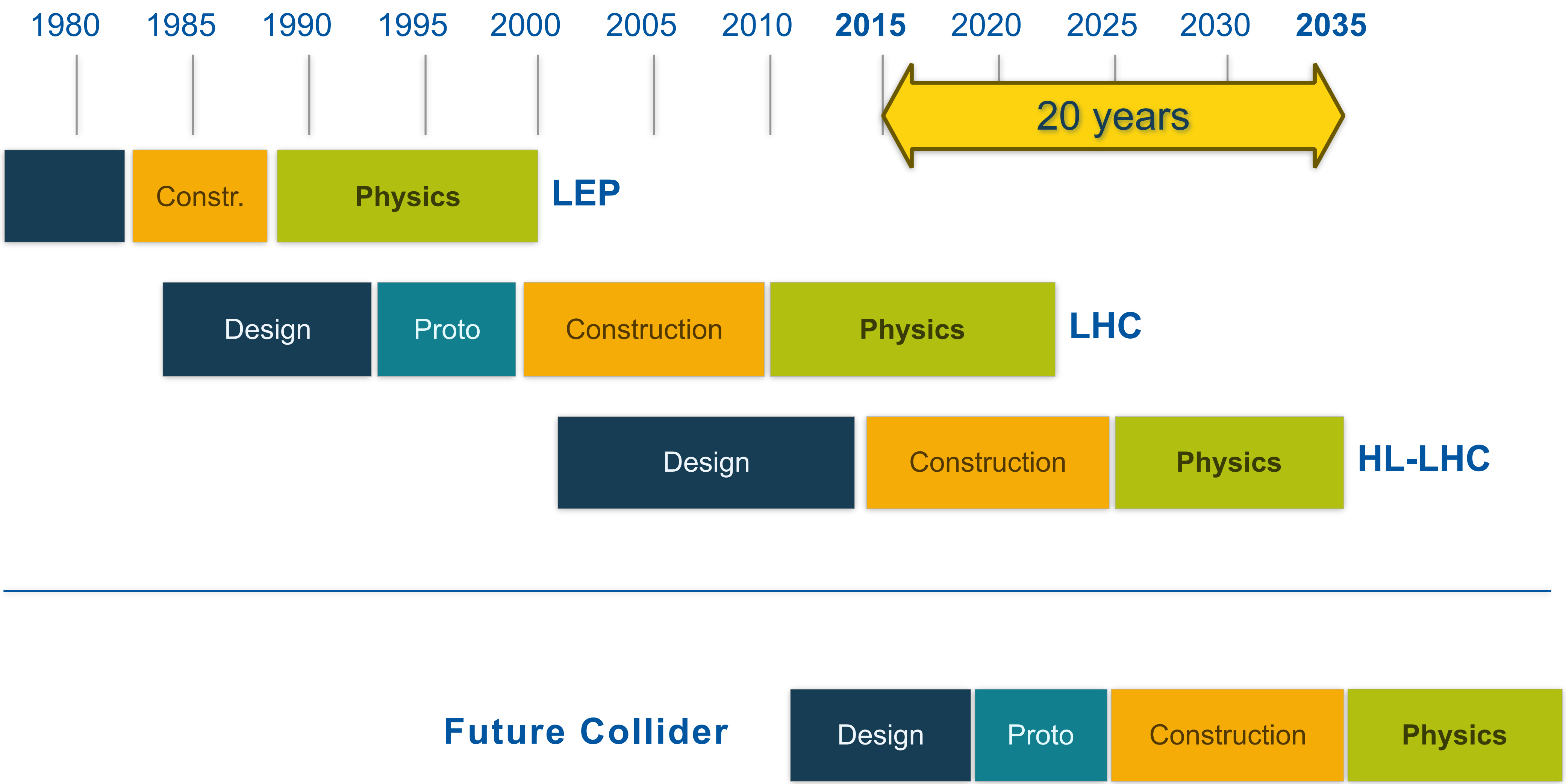
FCC-hh: 100 TeV *pp* collider



LHC	"HE-LHC"	FCC-hh (alternative)	FCC-hh (baseline)
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.m.)	33 TeV (c.m.)	100 TeV (c.m.)	100 TeV (c.m.)

L. Bottura
B. Strauss

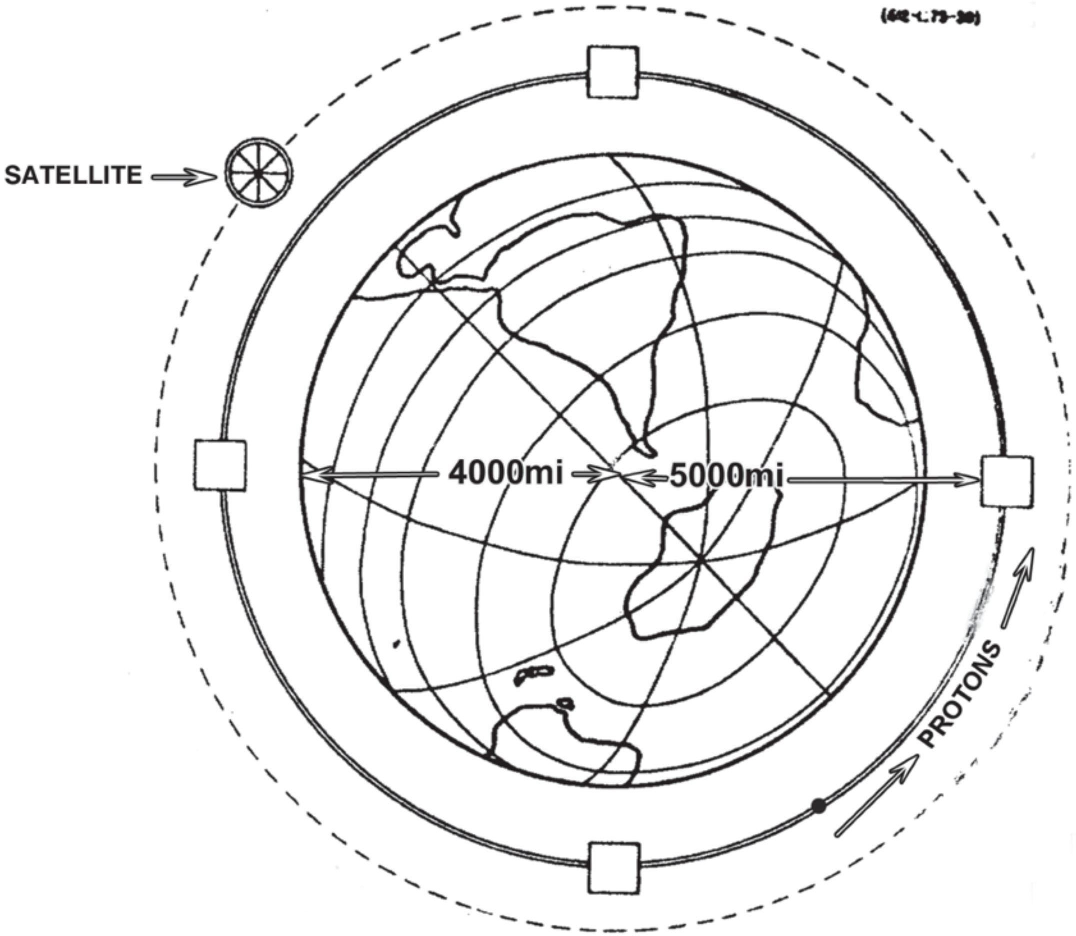
CERN Circular Colliders + FCC

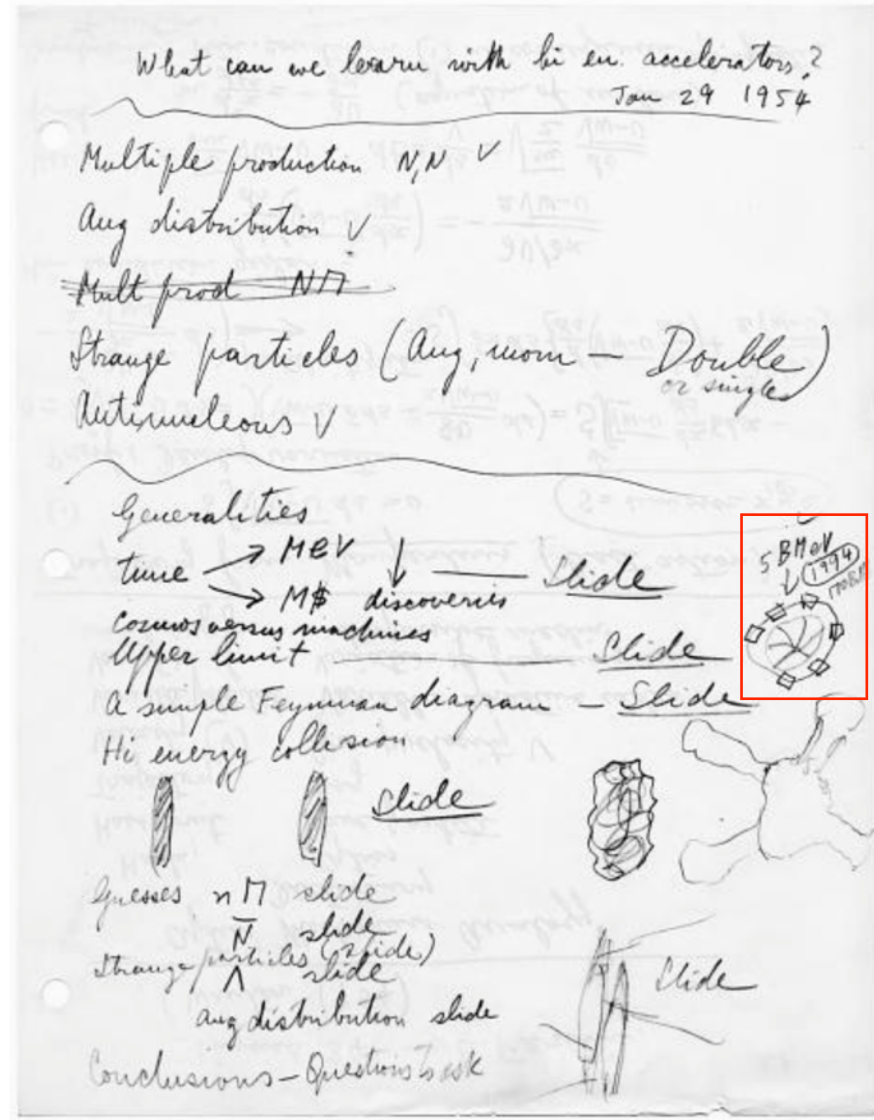


from F. Zimmermann

… or back to the future

5000 TeV
B=2 T
R = 8000 km

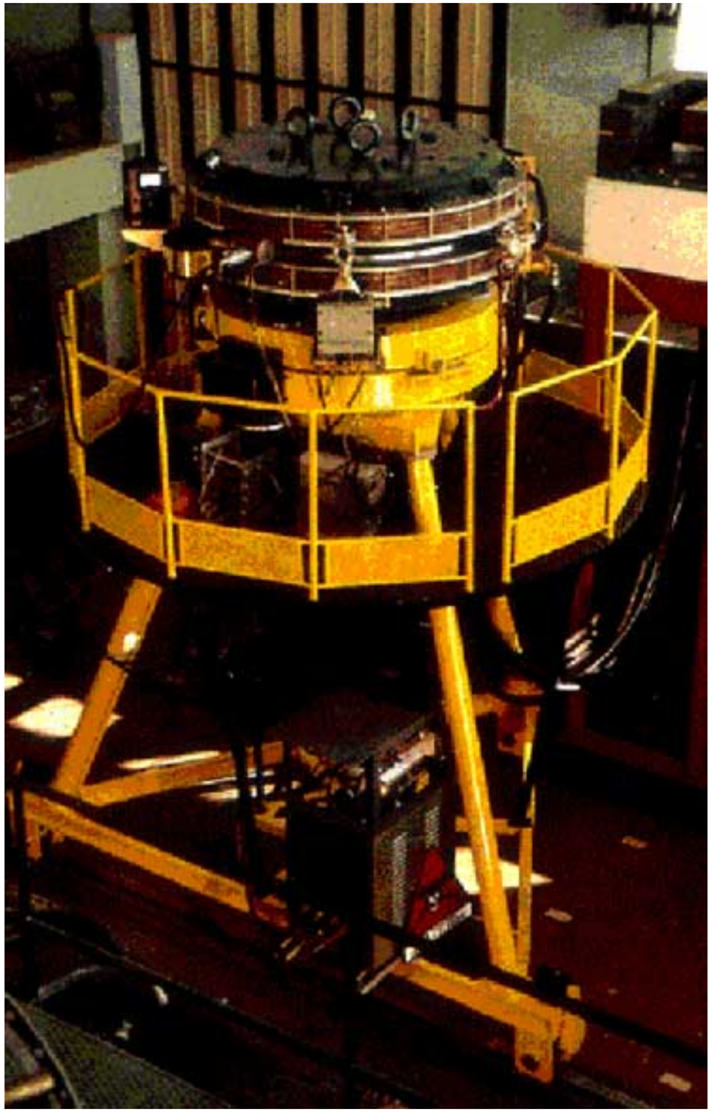




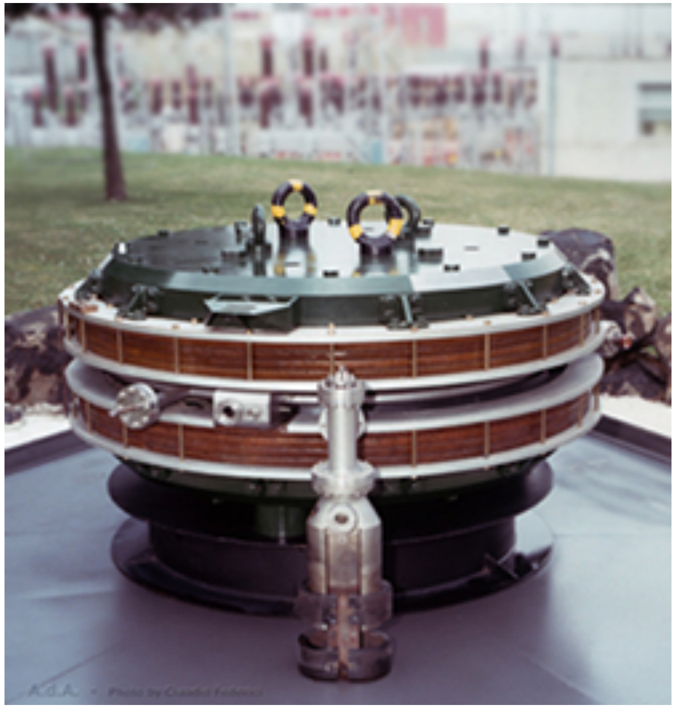
Images courtesy of the Special Collections Research Center, University of Chicago Library and Cronin J (ed.) Fermi Remembered (University of Chicago Press, 2004)

By E. Fermi: “Preliminary design...8000 km, 20.000 gauss” for 1994

The first electron-positron 250 MeV collider/storage ring, AdA (1960), built and operated at Frascati



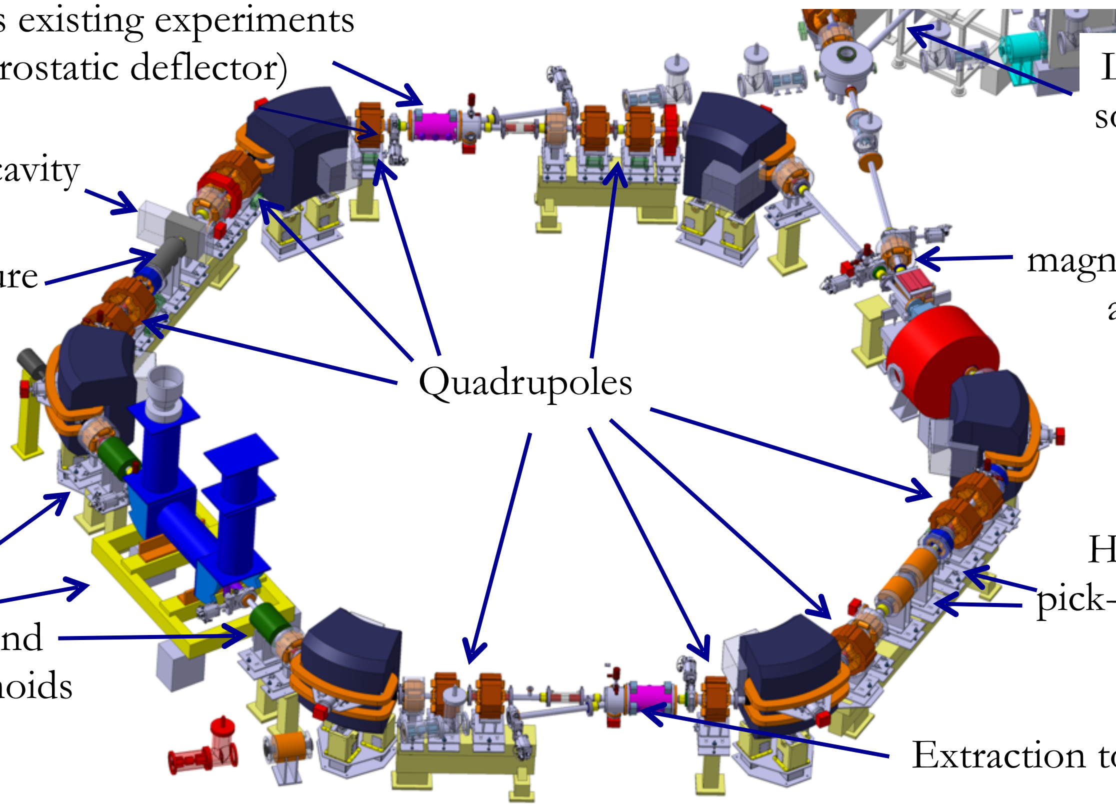
First collisions in 1963
Not for producing HEP data
but to bring better understanding
of beam dynamics



AdA = Anello di Accumulazione

https://cas.web.cern.ch/cas/Baden/PDF/Bernardini.pdf

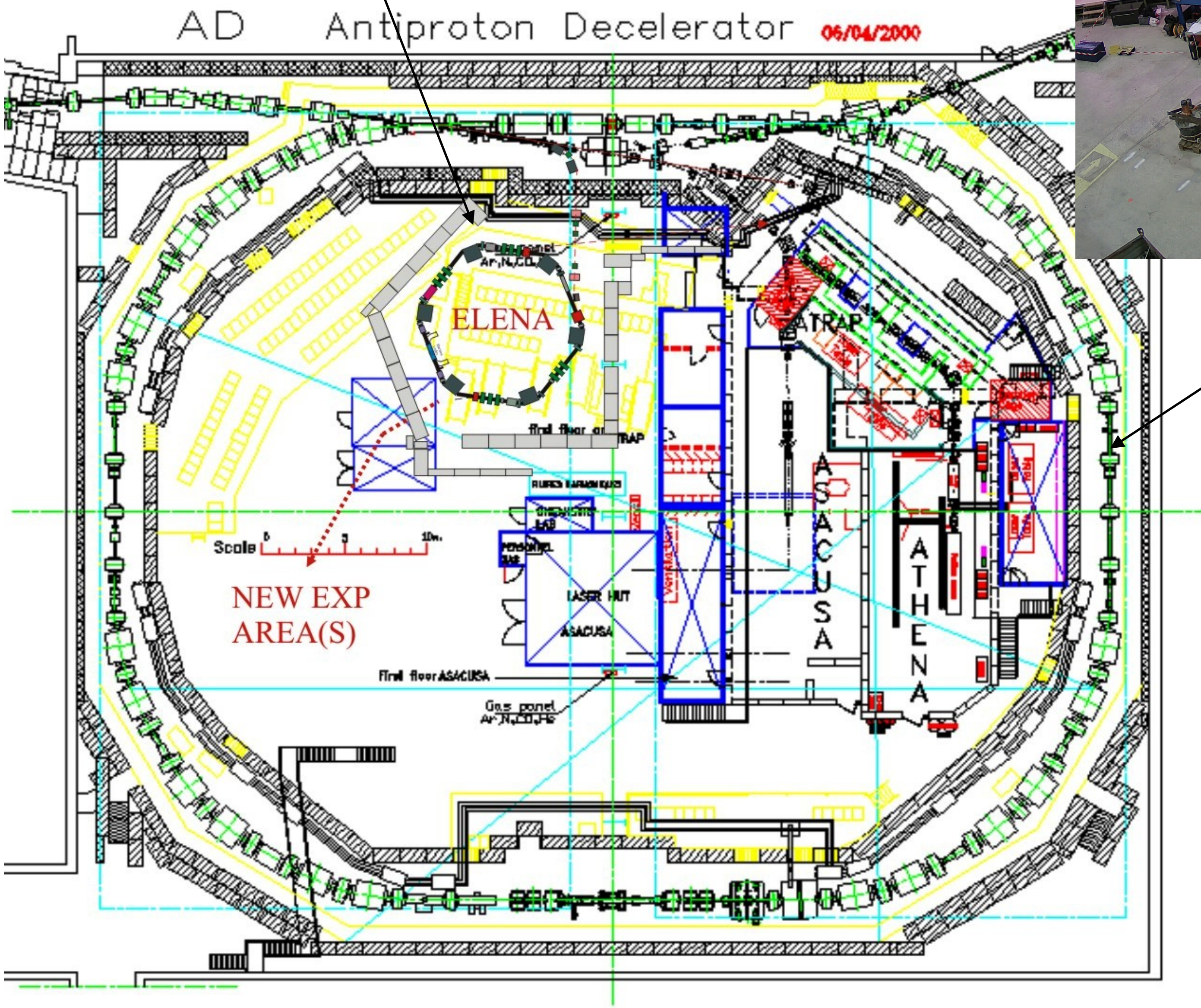
But in reality this is the next new machine… ELENA



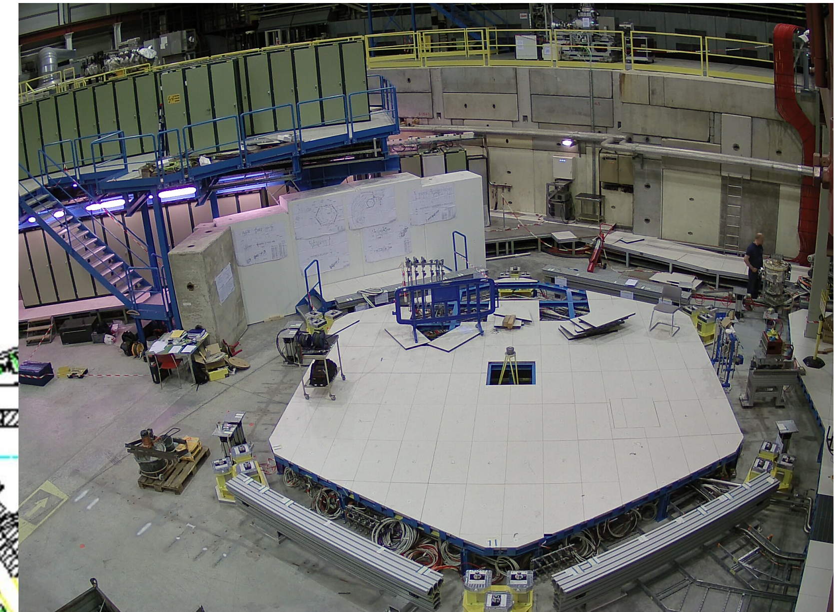
- **Deceleration of antiprotons from 5.3 MeV to 100 keV** to improve efficiency of antimatter experiments
- **Circumference 30.4 m**
  - Fits in available space in AD hall and allows installing all equipment without particular efforts
  - Lowest average field (beam rigidity over average radius) Bρ/R = 94 G (smaller than for AD 115 G)

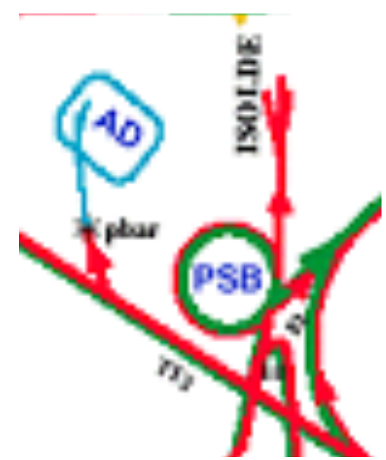
ELENA in AD hall

ELENA



AD





Interlude: a brief recall of energy scales

- WARNING: for purists or non-experts: Energy, Masses and Momentum have different units, which turn to be the same since c (speed of light) is considered equal to one.
  - Energy[GeV], Momentum [GeV/c], Masses [GeV/c^2]
    (Remember golden rule, $E=mc^2$ has to be true also for units...)
- Just an as a rule of thumb: **0.511 MeV/c^2** (electron mass) corresponds to about **9.109 10^{-31} kg**

An Example about energy scales: my cellular phone battery.

Voltage: 3.7 V
Height: 4.5 cm
proton mass ~ 1 GeV
To accelerate an electron to an energy equivalent to a proton mass:

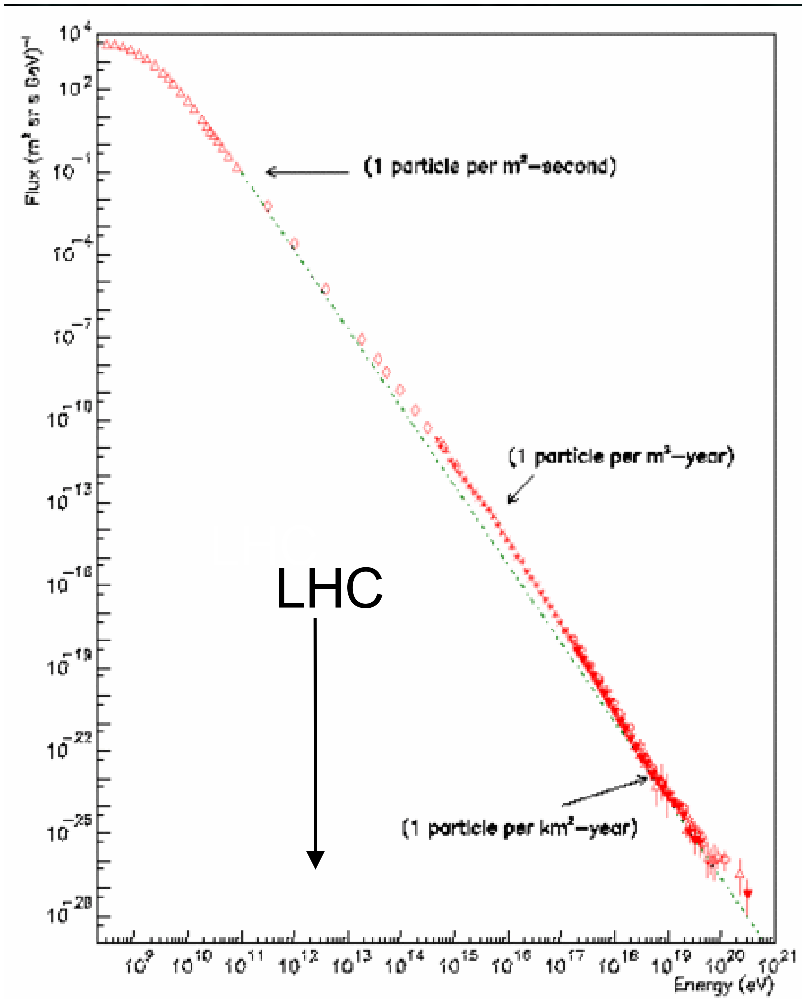
1 GeV/3.7 eV = 270 270 270 batteries
270 270 270 batteries * 0.045 m ~ 12 000 000 m

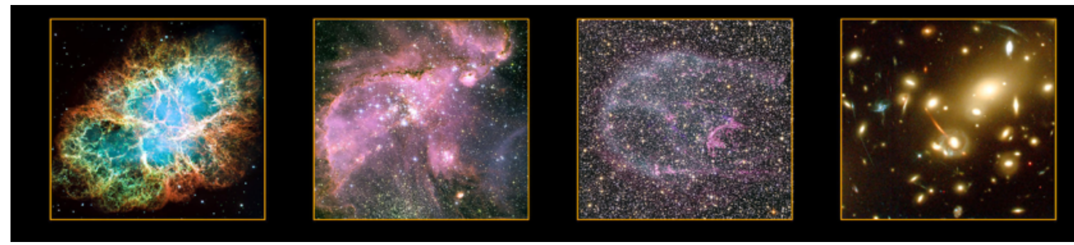
12 000 000 m ~ THE EARTH DIAMETER

Obviously one has to find a smarter way to accelerate particles to high energies instead of piling up cellular phone batteries ....

Why particle accelerators ?

- *Why accelerators?:* need to produce under <u>controlled conditions</u> HIGH INTENSITY, at a CHOSEN ENERGY particle beams of GIVEN PARTICLE SPECIES to do an EXPERIMENT
- An experiment consists of studying the results of colliding particles either onto a fixed target or with another particle beam.





The cosmos accelerates already particles more than the TeV

While I am speaking about **66 10^9 particles/cm²/s** are traversing your body, about 10^5 LHC-equivalent experiment done by cosmic rays

With a space distribution too dispersed for today's HEP physics!

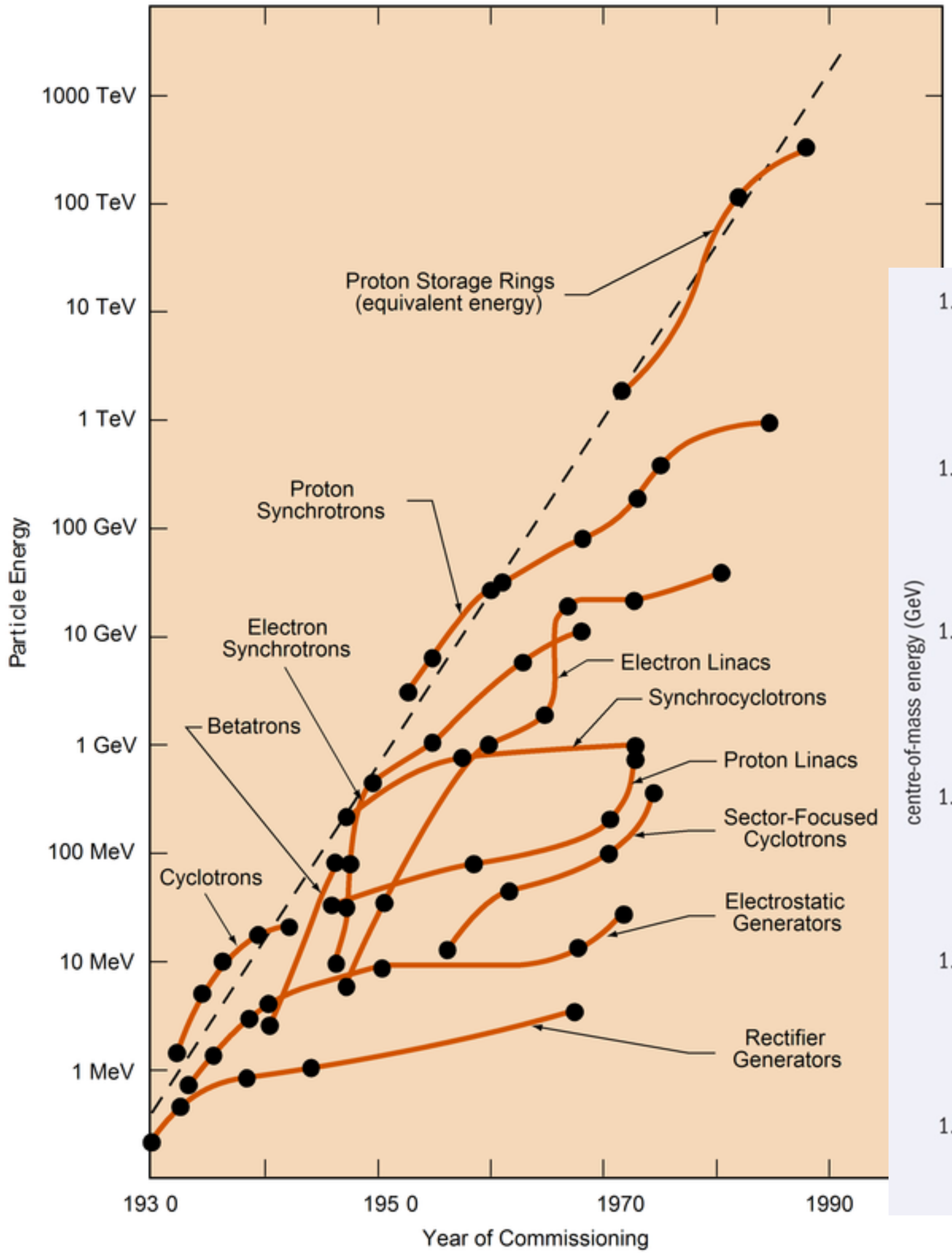
Cloud chamber, from YOUTUBE

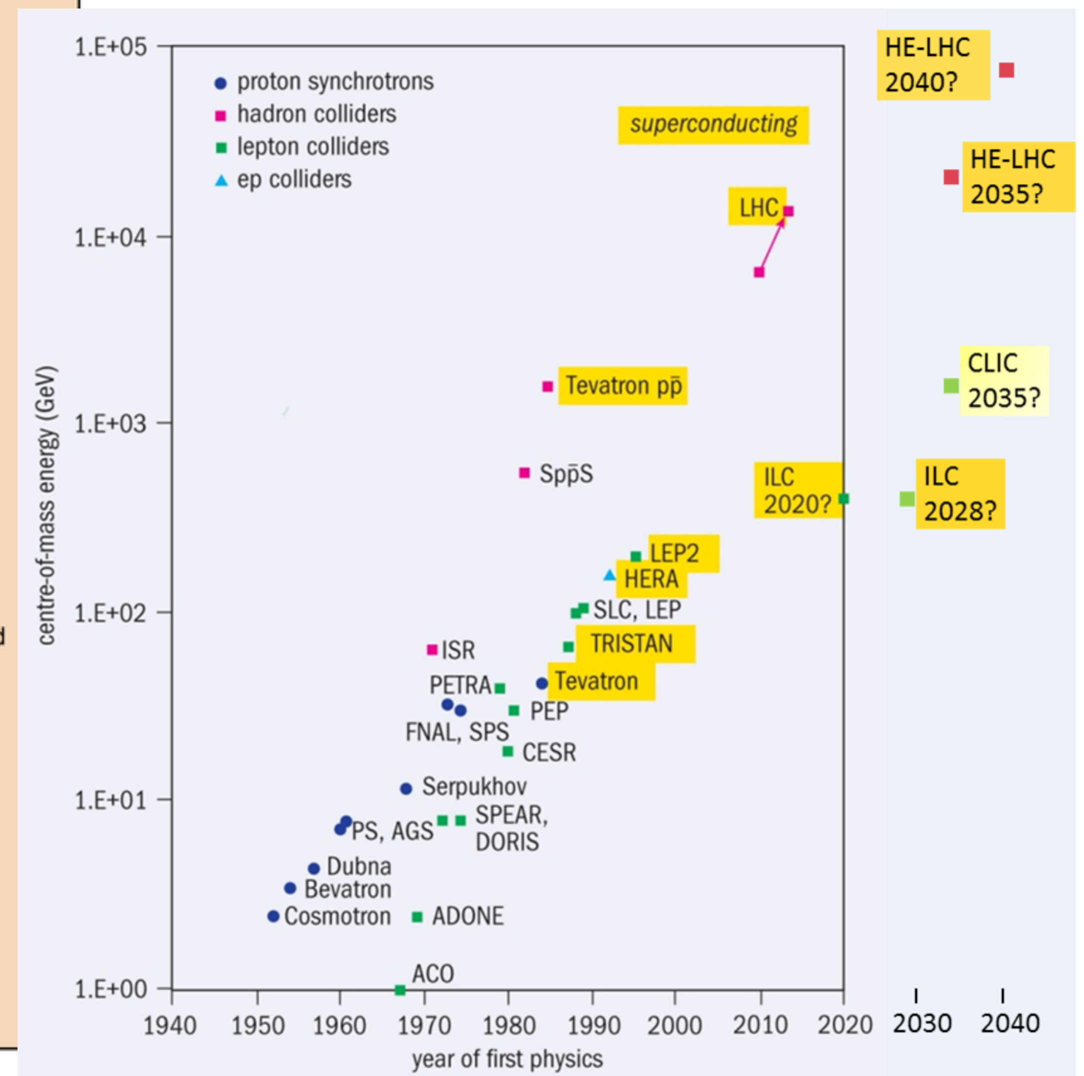
To accelerate particles, nature can count on exceptional phenomena

Like supernova explosions…

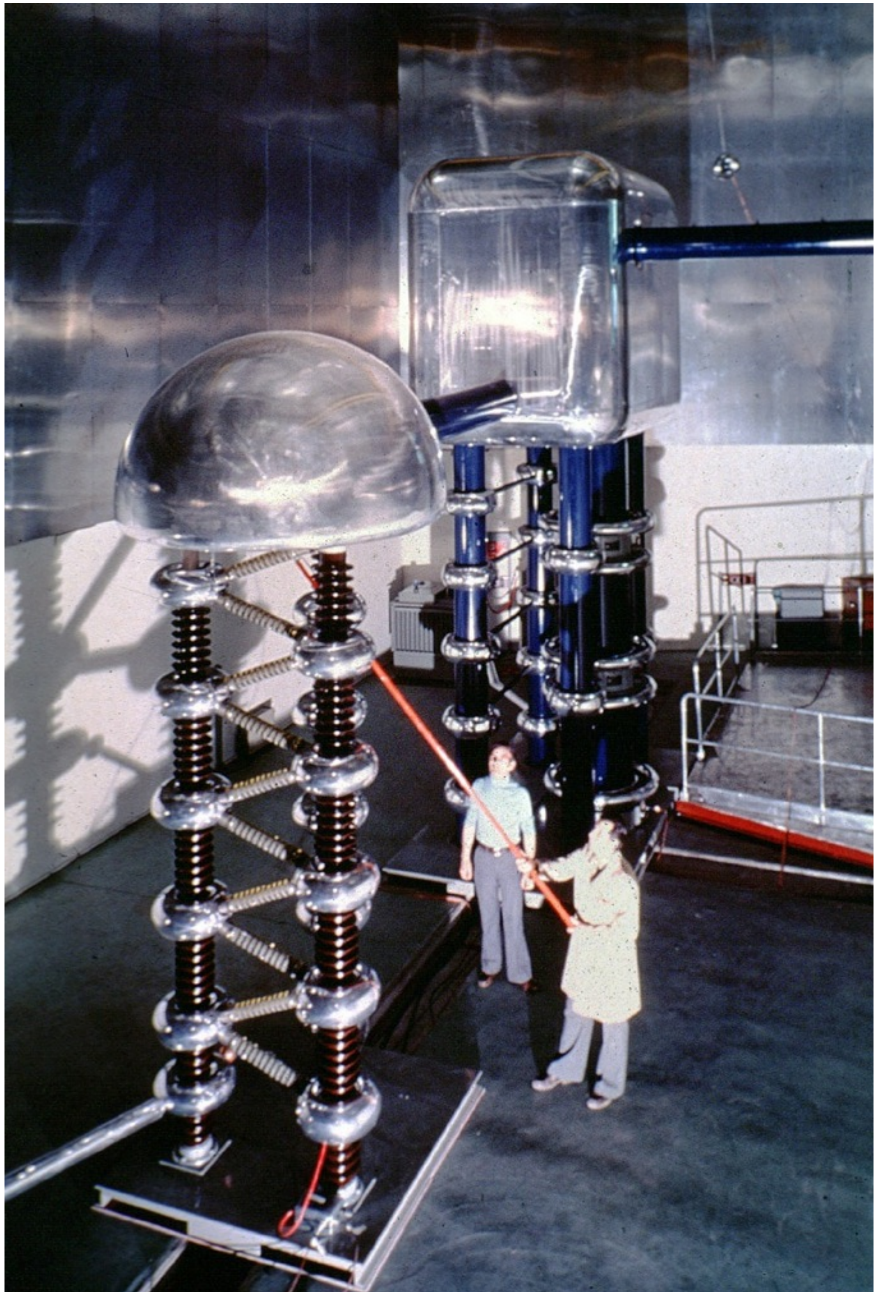
http://www.youtube.com/watch?v=dkg5-qXJfRU

Accelerators timeline: history of man-made accelerators

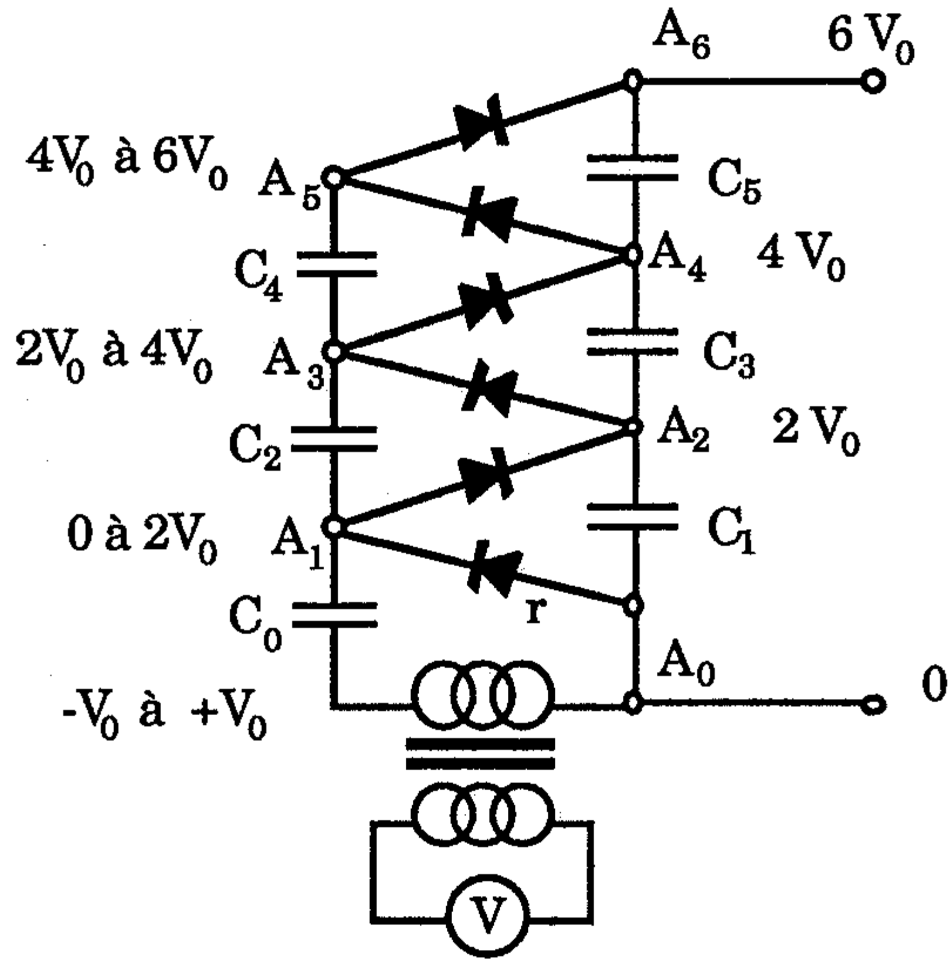




Cockroft-Walton. Old CERN proton pre-injector



High voltage unit composed by a multiple rectifier system

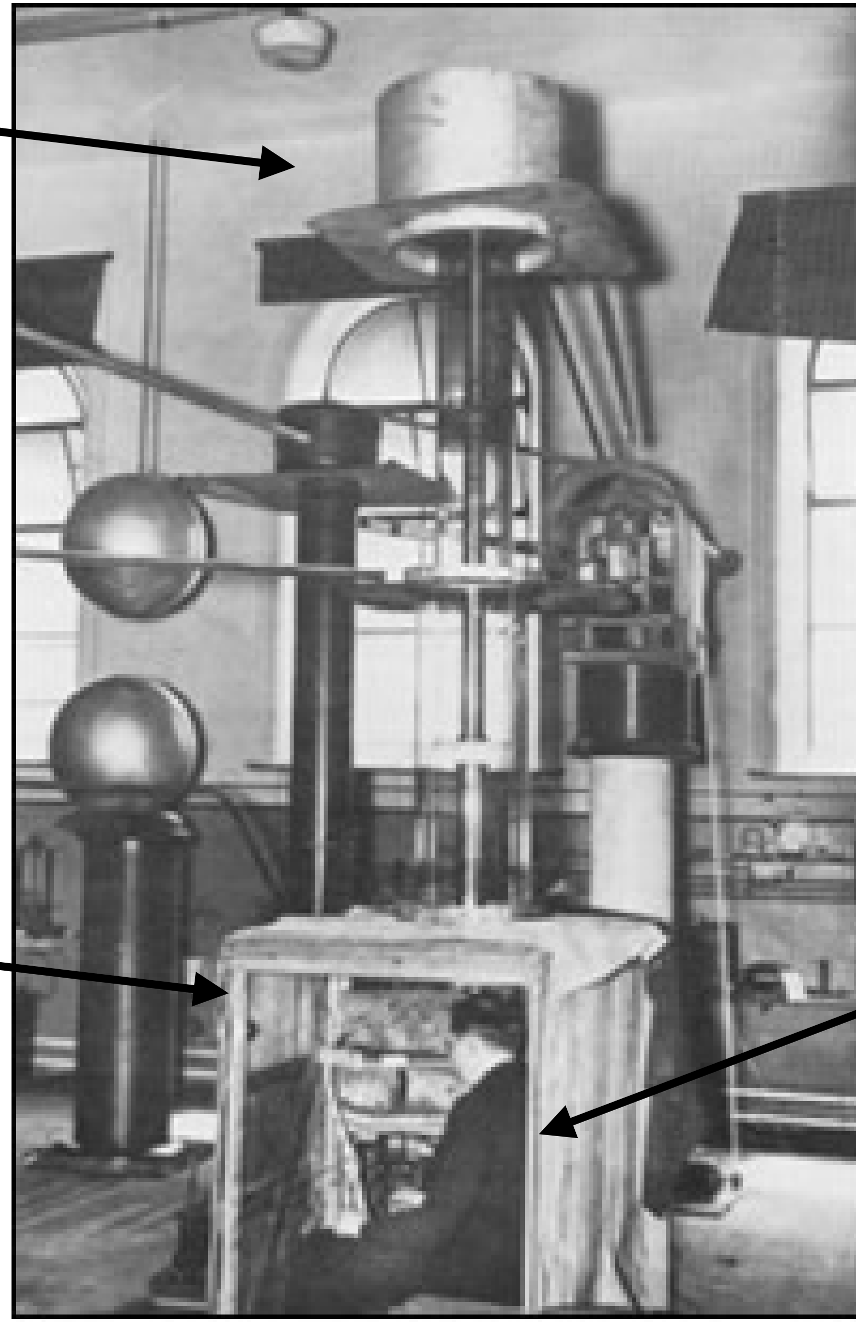


CERN: 750 kV

Accelerator

Experimental
Hall

Walton

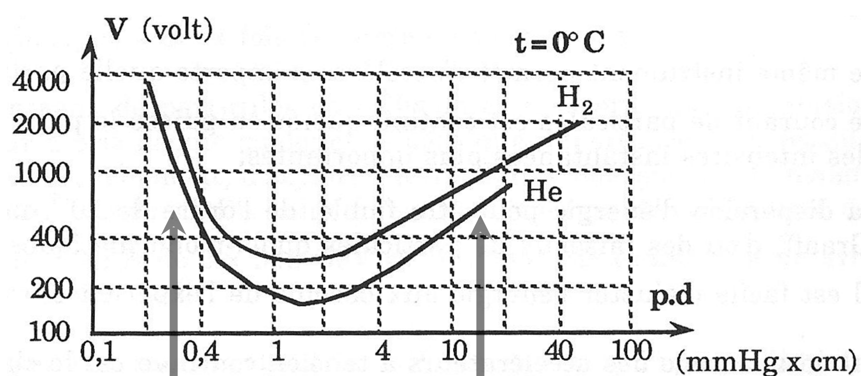


Walton and the machine used to "split the atom"

Main limitation

Main limitation:
electric discharge due to too high Voltage.
Maximum limit: 1 MV

Limit set by Paschen law:
the breaking Voltage between two parallel electrodes depends only on the pressure of the gas between the electrodes and their distance



Low pressure: gas not too dense, long mean average path of electrons

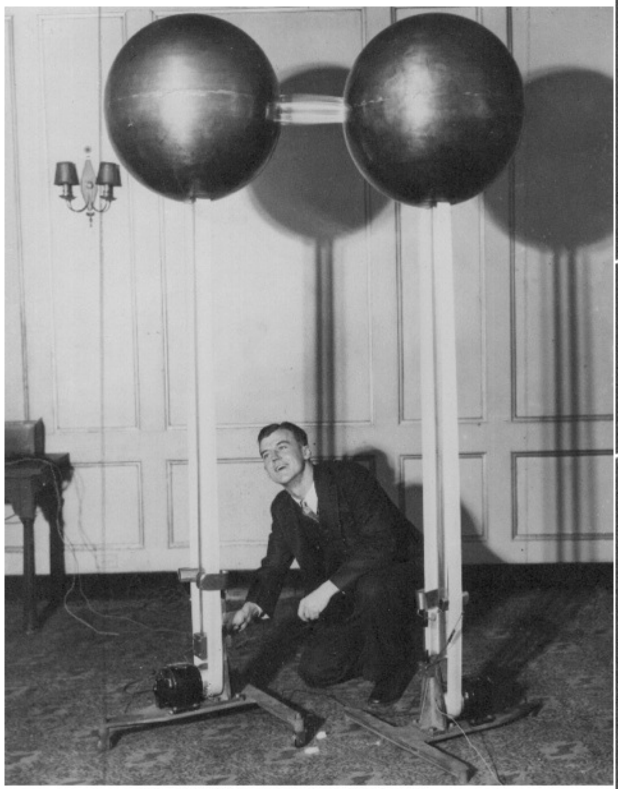
High pressure: dense gas, large Voltage needed for gas ionisation

Van De Graaf electrostatic generator (1928)

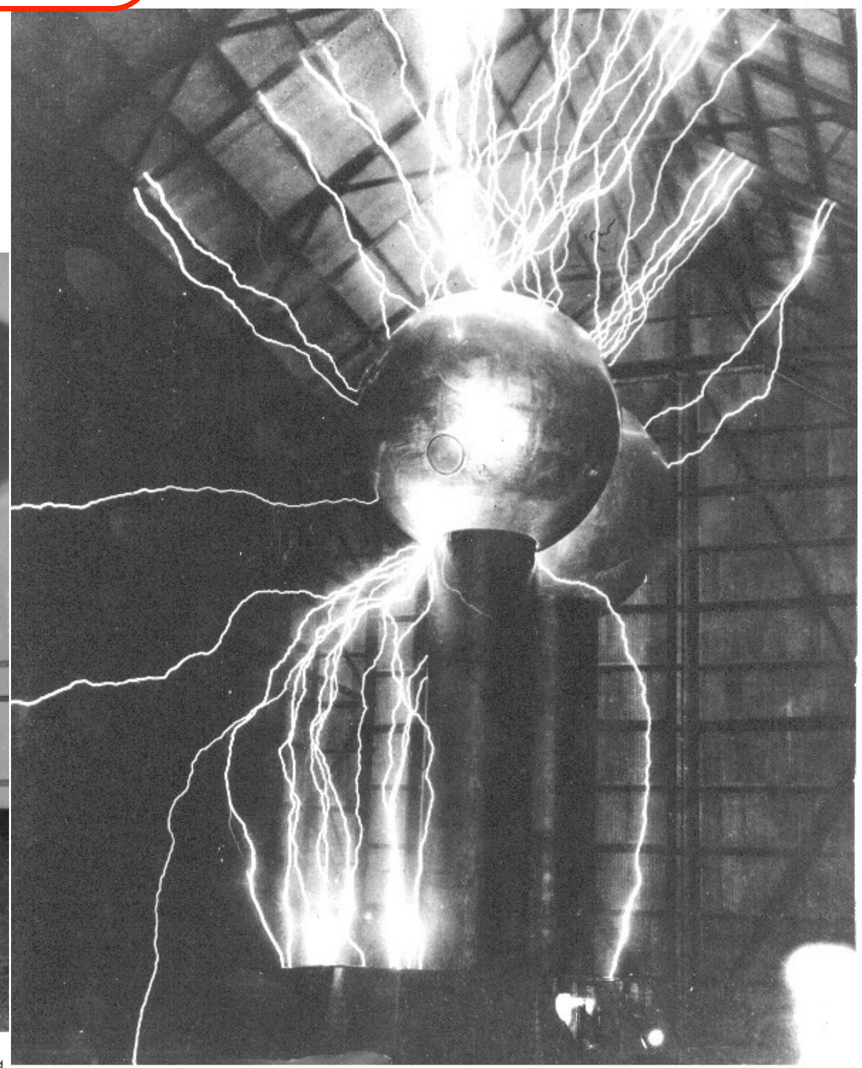
A rotating belt charges a top terminal up to the maximum voltage before sparking.

Maximum accelerating Voltage: 10 MV

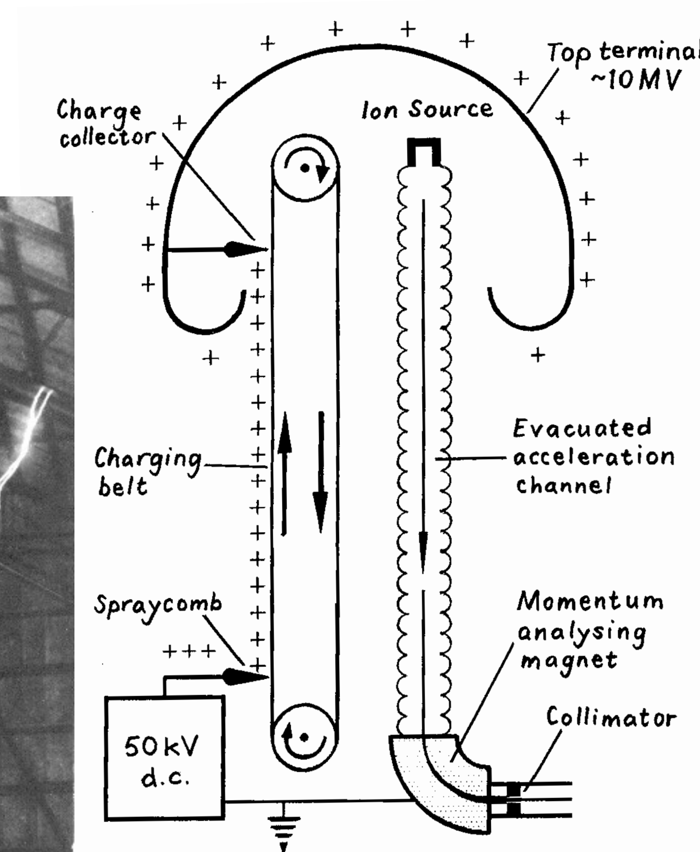
Typical speed: 20 m/s
Hight: 0.5 m
Top terminal: 1 MV - 10 MV



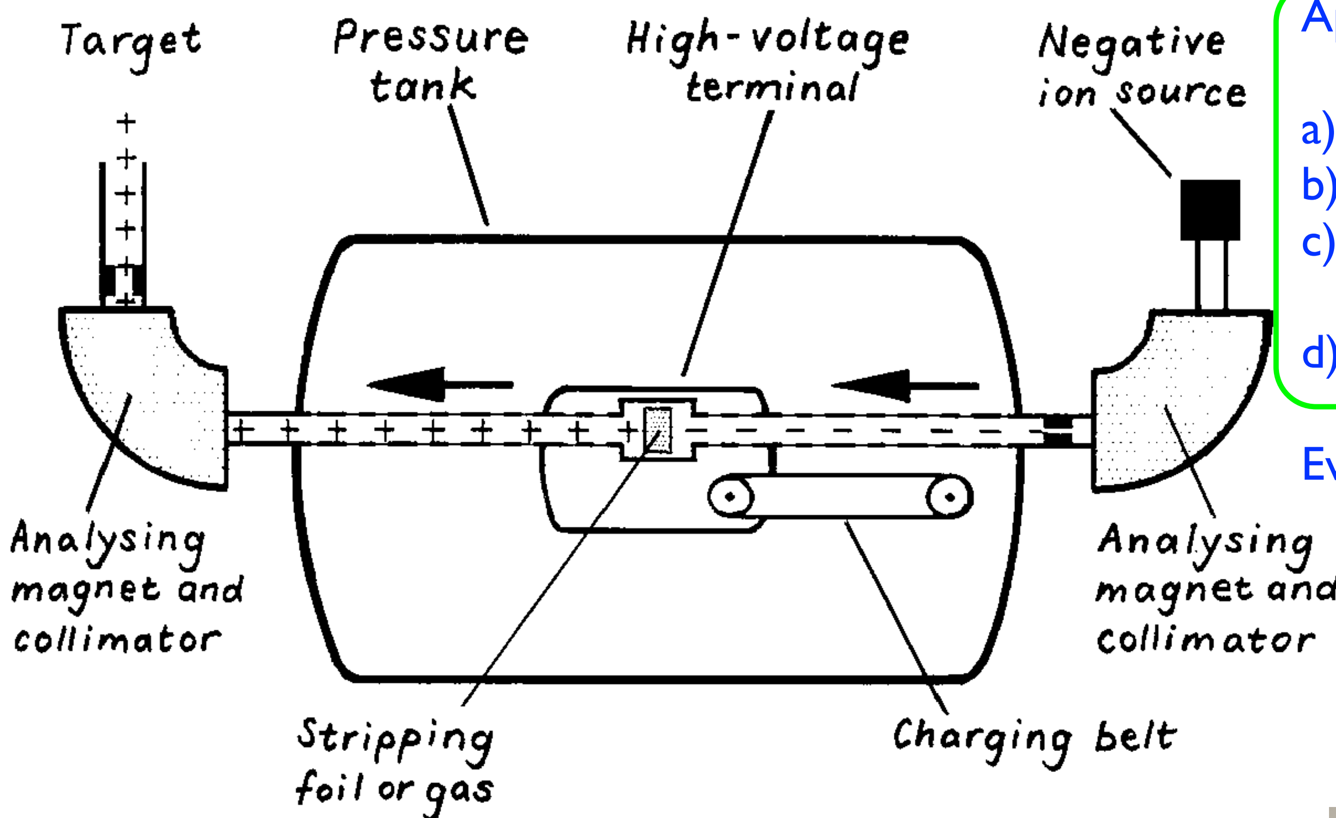
R. J. VAN DE GRAAFF WITH FIRST GENERATOR



AT ROUND HILL SPARKING TO HANGAR (LONG EXPOSURE)



Tandem



Application of Van der Graaf generator

a) Source of negative ions (150 keV)
b) Van Der Graff column (25 MV)
c) Stripping foil
change in charge
d) Further re-acceleration

Everything in a pressurized vacuum tank

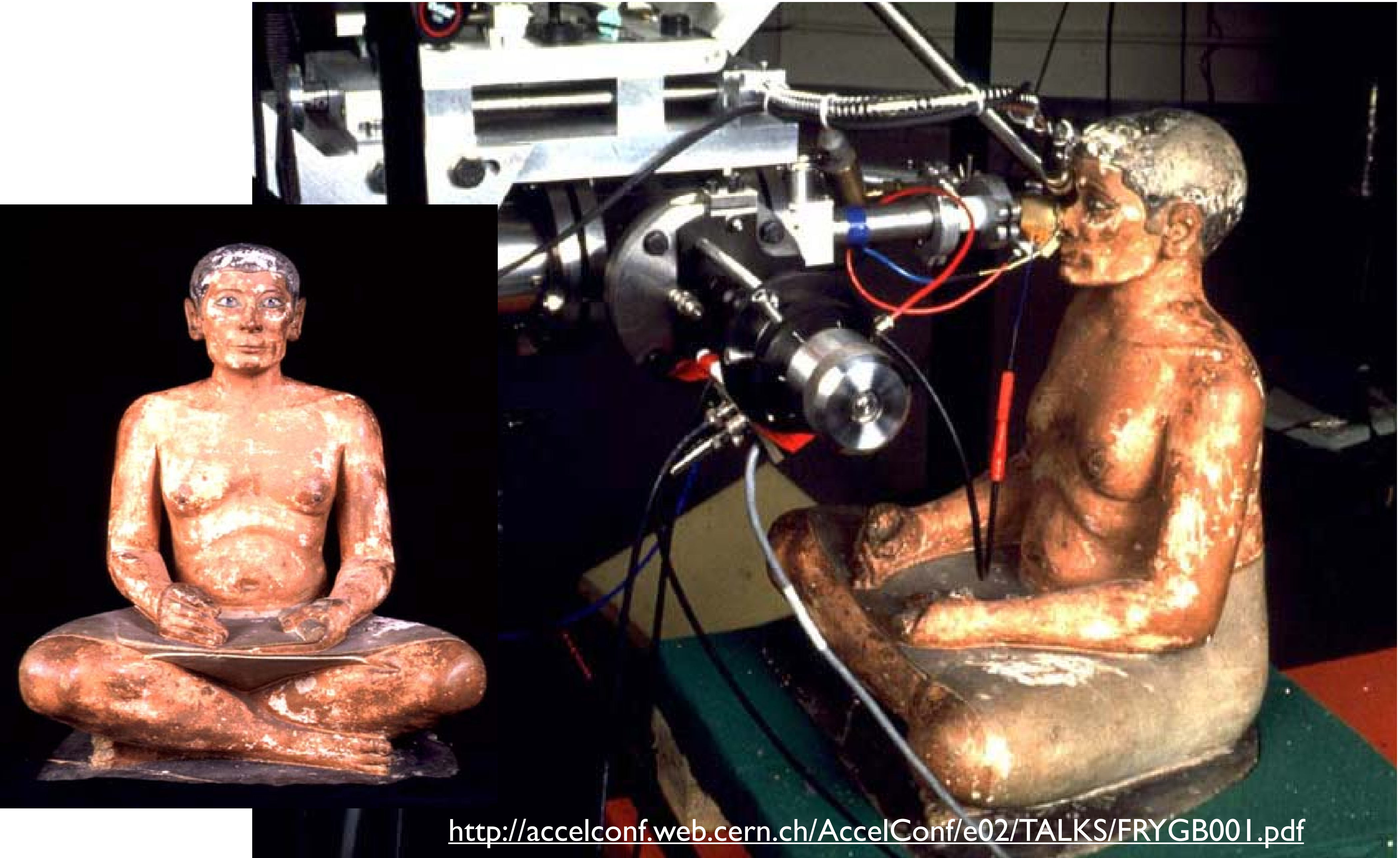
Since negative and positive multicharge states are used, different energies can be obtained

Current applications:

a) Low energy injector for Ions
Still in use at Brookeven (US) as injector for Cu and Au ions

b) Compact system for "other uses"
Dating of samples at Louvre.

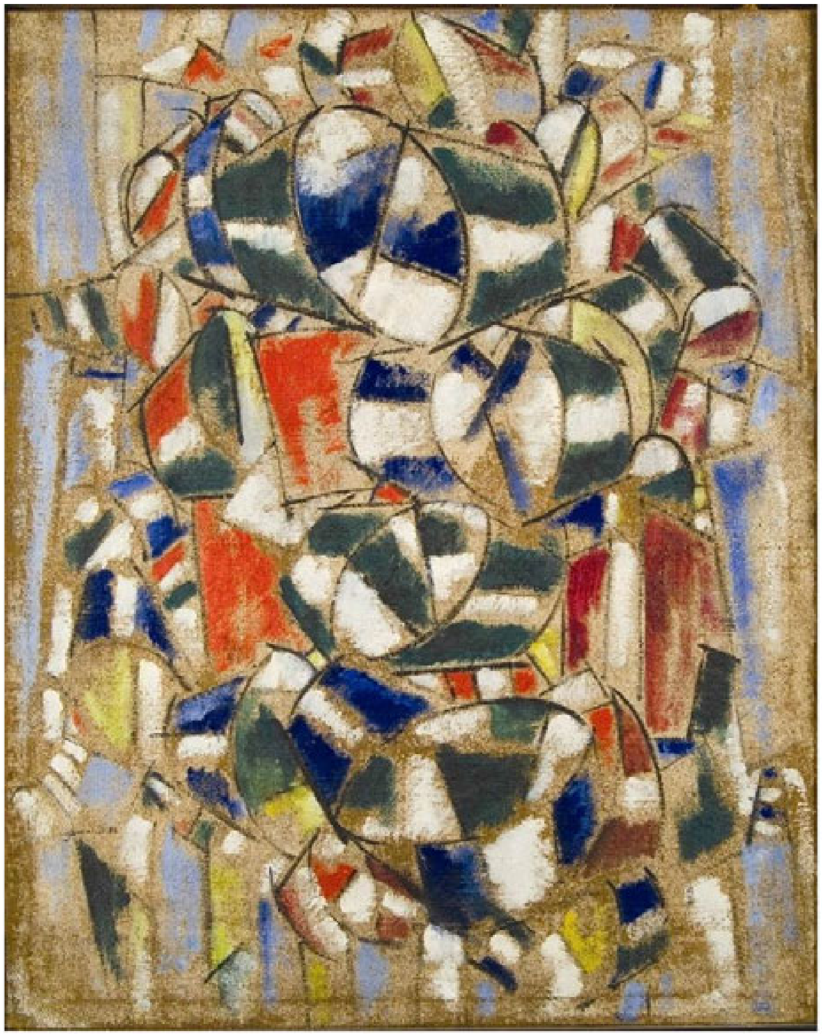
Application of Louvre Tandem: composition of scribe eyes



http://accelconf.web.cern.ch/AccelConf/e02/TALKS/FRYGB001.pdf

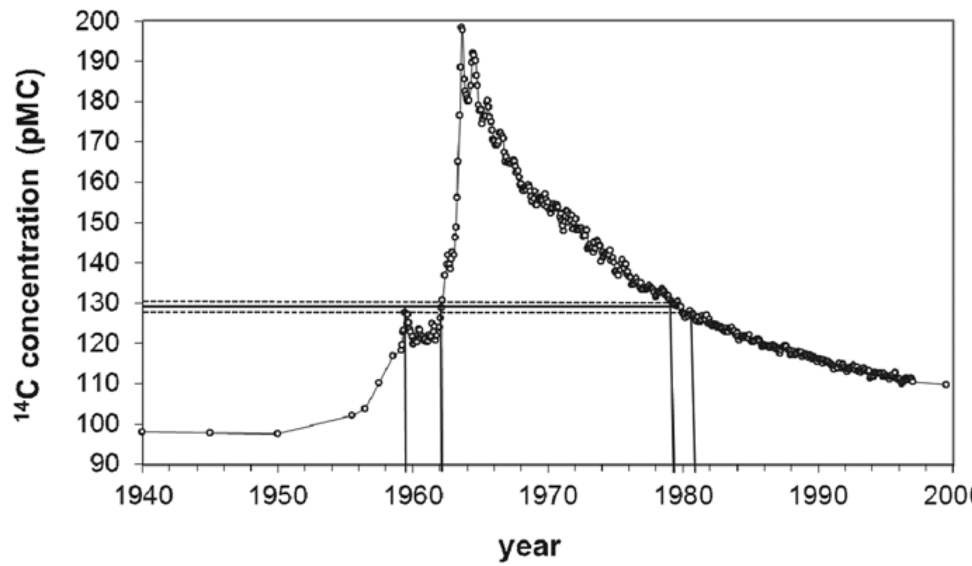
Discovering forgeries of modern art by the 14C Bomb Peak

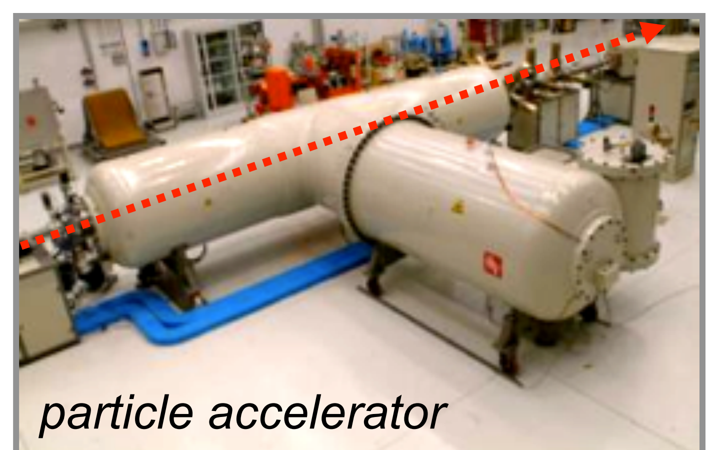
Eur. Phys. J. Plus (2014) **129**: 6
DOI 10.1140/epjp/i2014-14006-6



Contraste de formes, Fernard Leger (?)
Peggy Guggenheim Collection, Venice.

Accelerator Mass Spectrometry (AMS)
to measure rare isotopes abundance with
3MV Tandetron accelerator of INFN-LABEC in
Florence.





… by the way, one can also date French wine with isotopes

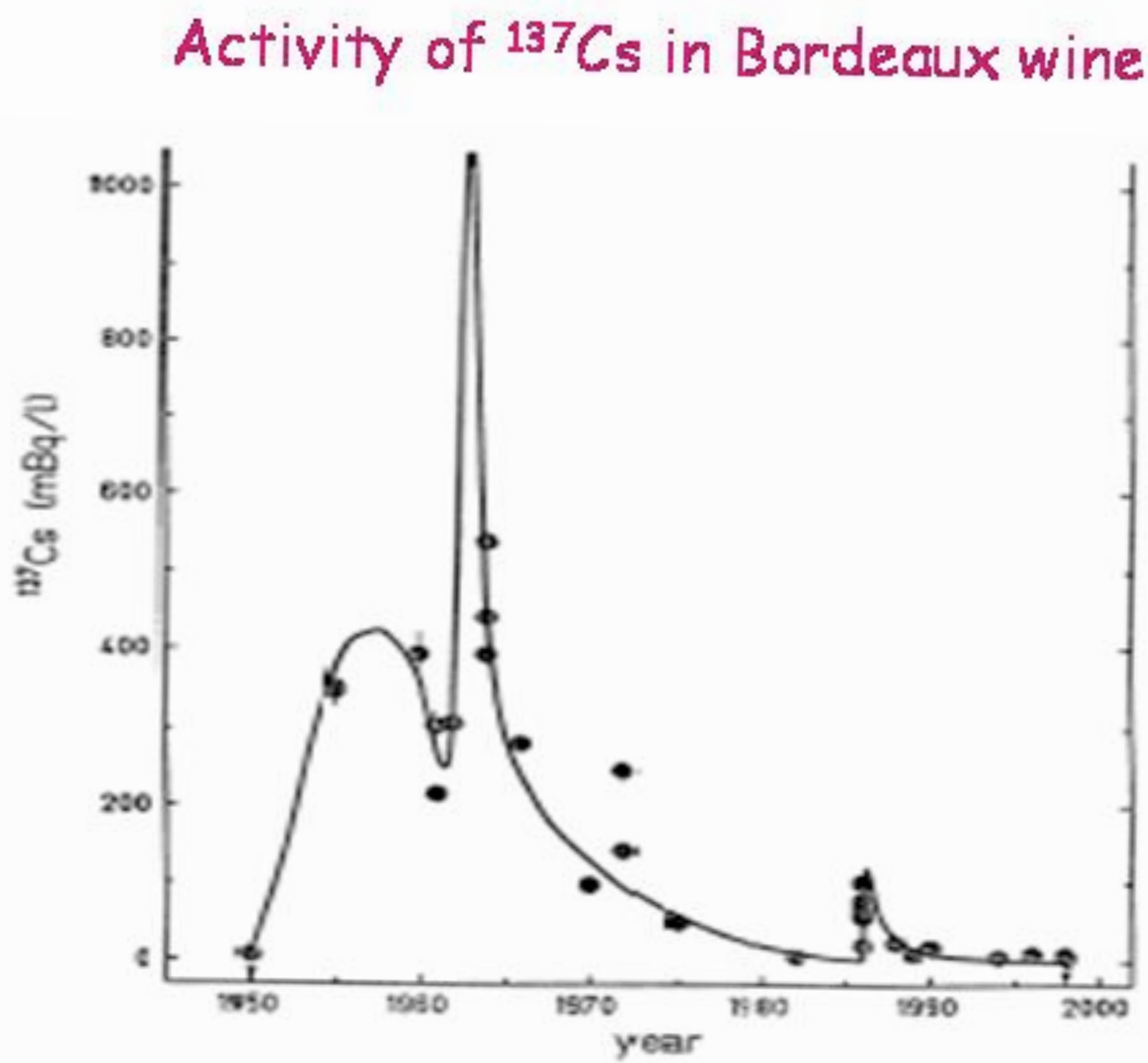
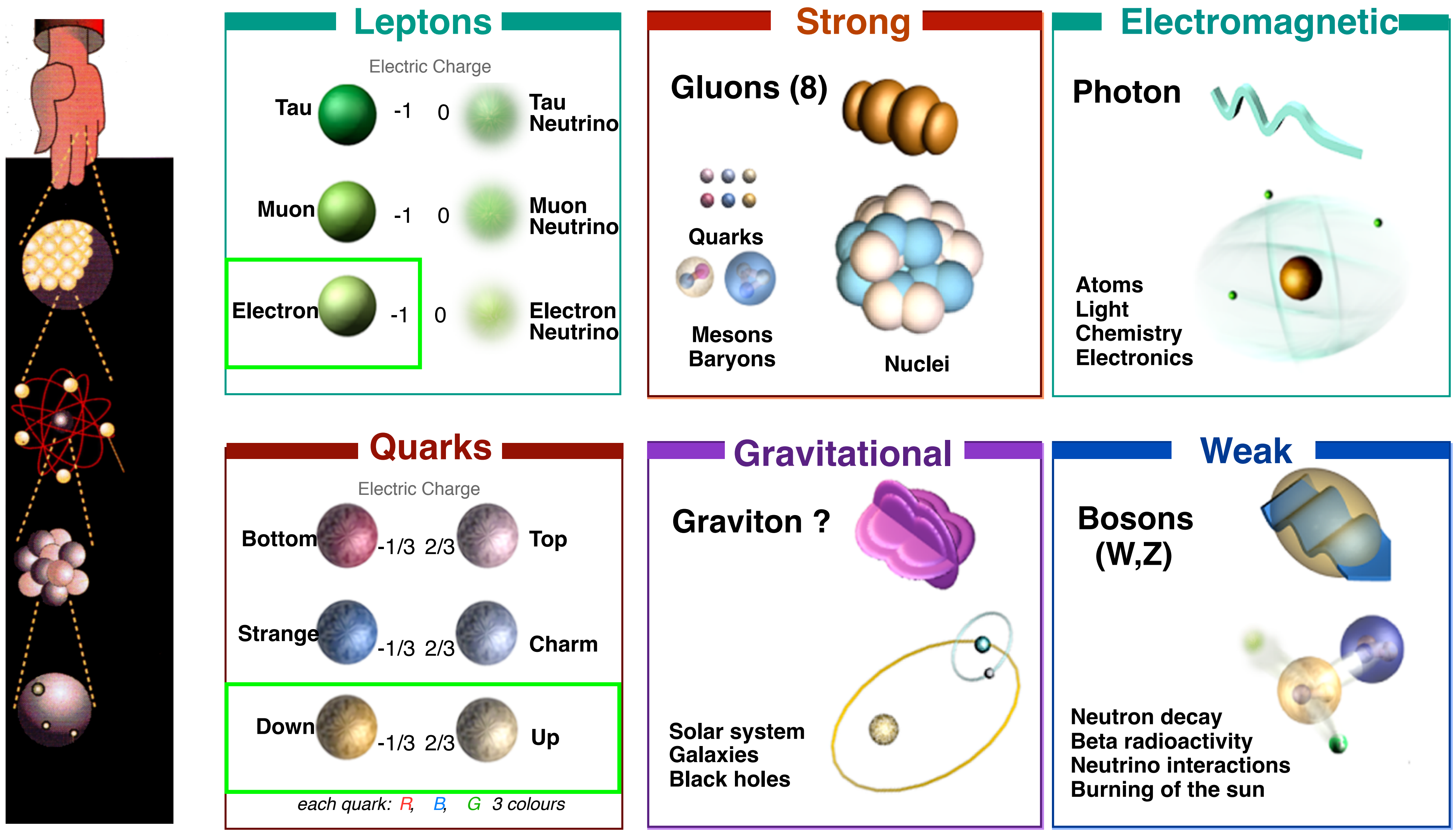


Figure 1. *Cesium activity in the Bordeaux wine as a function of the millésime.*

Matter constituents and interaction laws, the actors of our play



The particle drawings are simple artistic representations

We need **enough energy** to produce directly the different particles, **at least their mass**

We need **enough intensity** (i.e. particle interactions) **to produce enough particles**

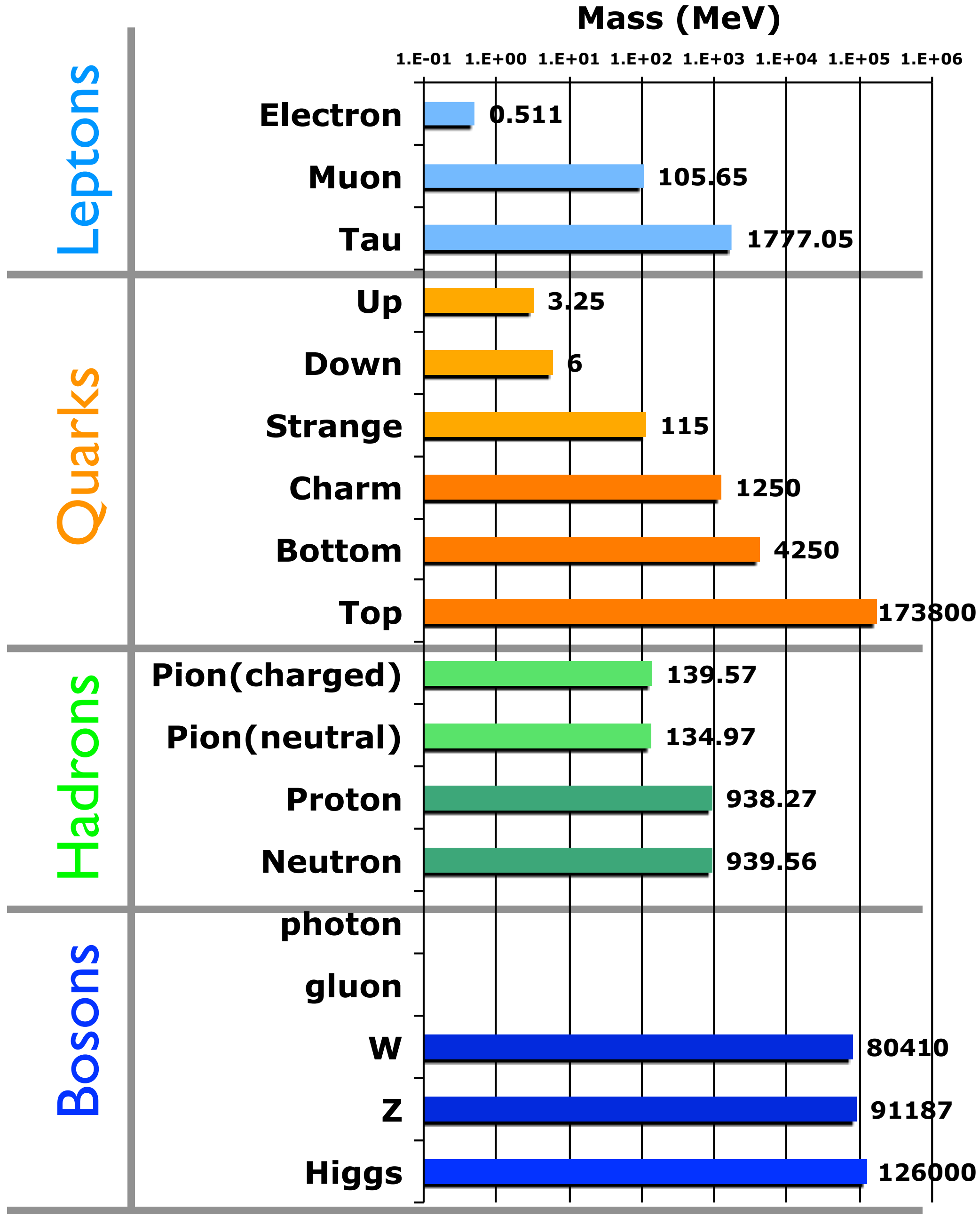
Synergy between accelerators and particle physics

- First prove that the ***antiproton life time has to be comparable to the one of the protons*** (from CPT theorem) came from the ICE storage ring in 1978 (ICE does not exists anymore...)
  - Antiproton lifetime before ICE experiment: 1.2 10^-4 s
  - About 240 antiprotons stored for 85 h, the final intensity of about 80 antiprotons due to Coulomb scatting on residual gas.
    - Estimated final lifetime: about 32 h in the rest frame.

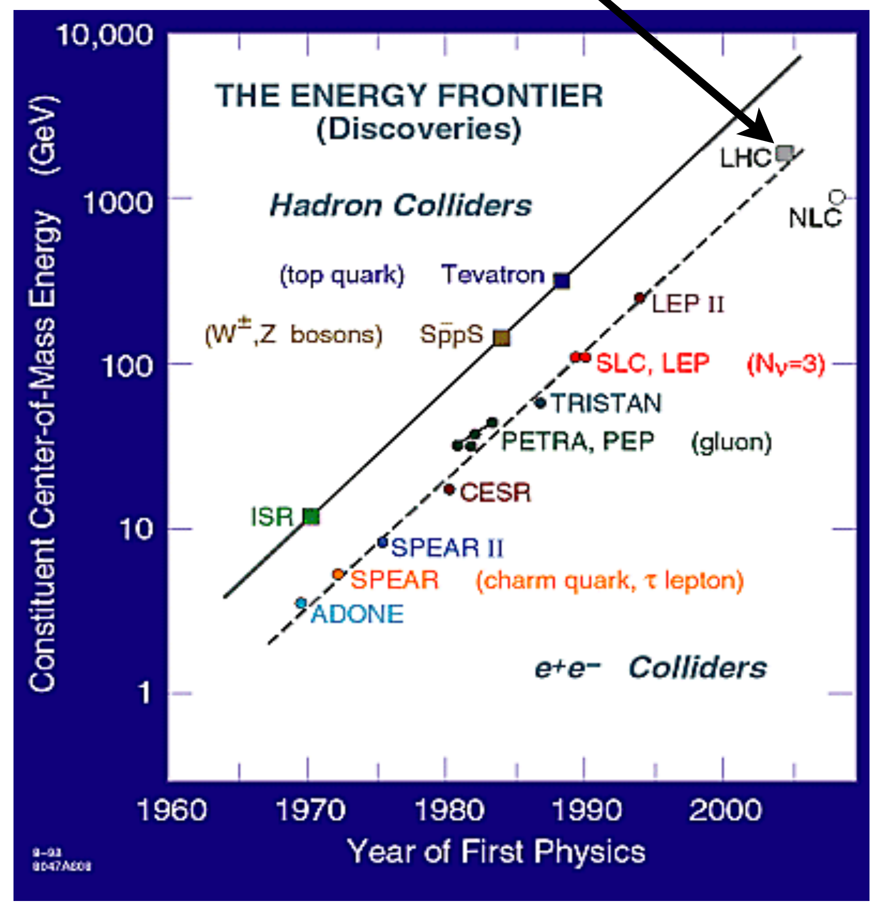
- This experiment also opened the era of the p-$\bar{p}$ collider which required storage time of about 24 h.

See Phys. Lett. 78B, 1 pag.174, you will find 2 nobel prices in the author list

History/Energy line vs discovery



Higgs and super-symmetry ?
Or something else maybe

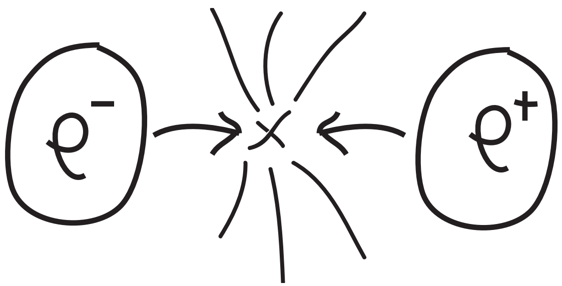


Constant increase in energy to discover heavier and heavier particles or very rare processes

Obs: you can notice different particle species used in the different colliders electron-positrons and hadron colliders (either p-$\bar{p}$ as Tevratron, p-p as LHC)

The proper particle for the proper scope

Electrons (and positrons) are (so far) point like particles: no internal structure



The energy of the collider, namely two times the energy of the beam colliding is totally transferred into the collision

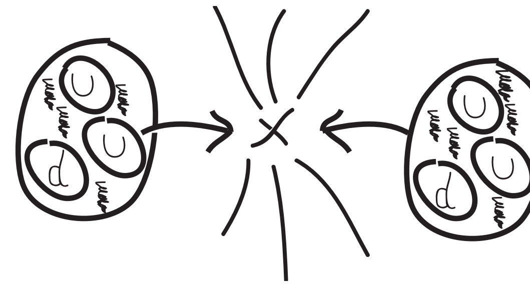
Ecoll= Eb1+ Eb2= 2Eb = 200 GeV (LEP)

<u>Pros</u>: the energy can be precisely tuned to scan for example, a mass region.

Precision measurement (LEP)

<u>Cons</u>: above a certain energy is no more possible to use electrons because of too high <u>synchrotron radiation</u>

Protons (and antiprotons) are formed by quarks (uud) kept together by gluons



The energy of each beam is carried by the proton constituents, and it is not the entire proton which collides, but one of his constituent

Ecoll (about 2 TeV at LHC) < 2 Eb (14 TeV)

<u>Pros</u>: with a single energy possible to scan different processes at different energies.

Discovery machine (LHC)

<u>Cons:</u> the energy available for the collision is lower than the accelerator energy

Synchrotron radiation

Radiation emitted by charged particles accelerated longitudinally and/or transversally

Power radiated per particle goes like:

4th power of the energy
(2nd power)$^{-1}$ of the bending radius
(4th power)$^{-1}$ of the particle mass

$$P = \frac{2c \times E^4 \times r_0}{3\rho^2 \left(m_0 \times c^2\right)^3}$$

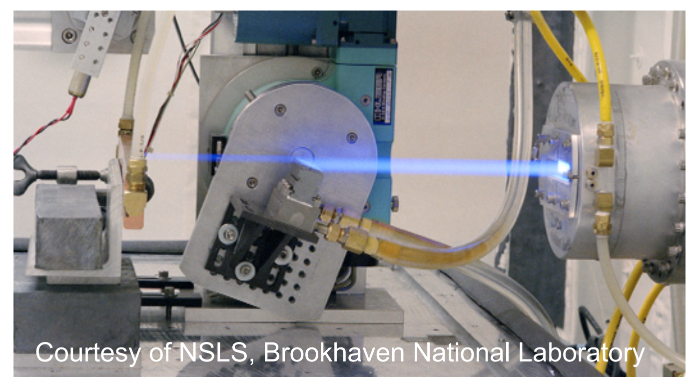
$r_0 = \dfrac{q^2}{4\pi\varepsilon_0 m_0 c^2}$ particle classical radius

ρ particle bending radius

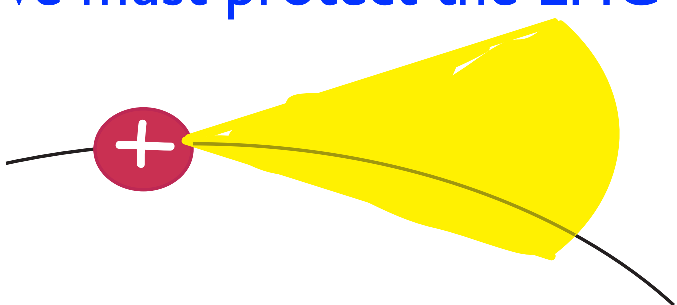
Energy lost per turn per particle due to synchrotron radiation:

e- ≈ some GeV (LEP)

p ≈ some keV (LHC)

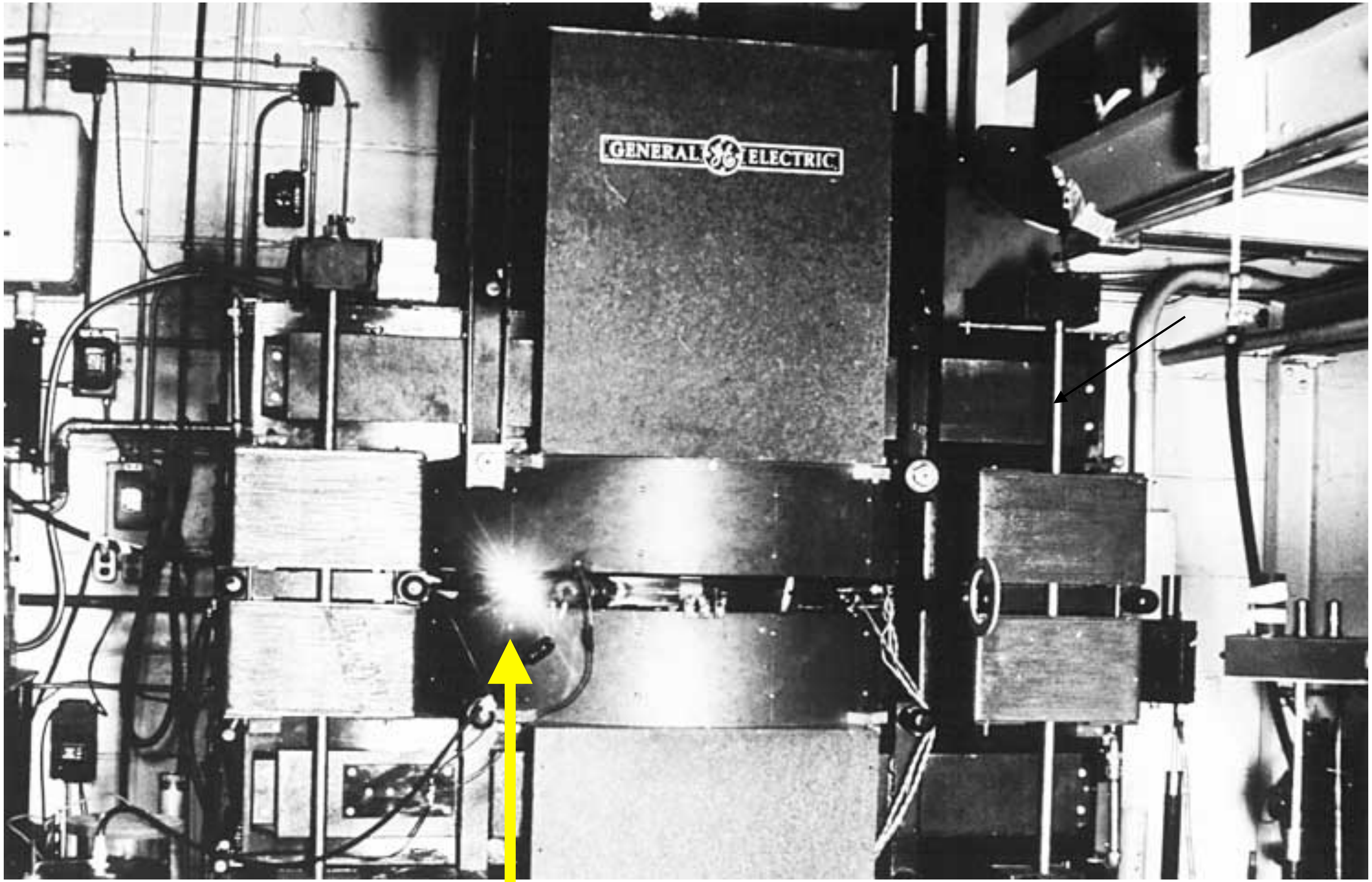


We must protect the LHC coils even if energy per turn is so low



Power lost per m in dipole: <u>some W</u>
Total radiated power per ring: <u>some kW</u>

300 MeV electron synchroton at the General Electric Co. at Schenectady, late 1940s.



synchroton light

Building Blocks of an accelerator

1) A particle source

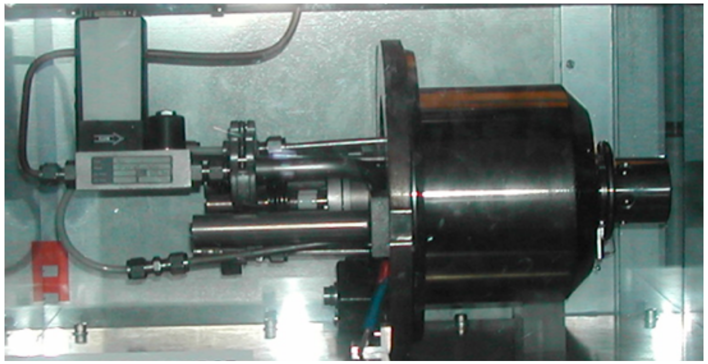
2) An accelerating system

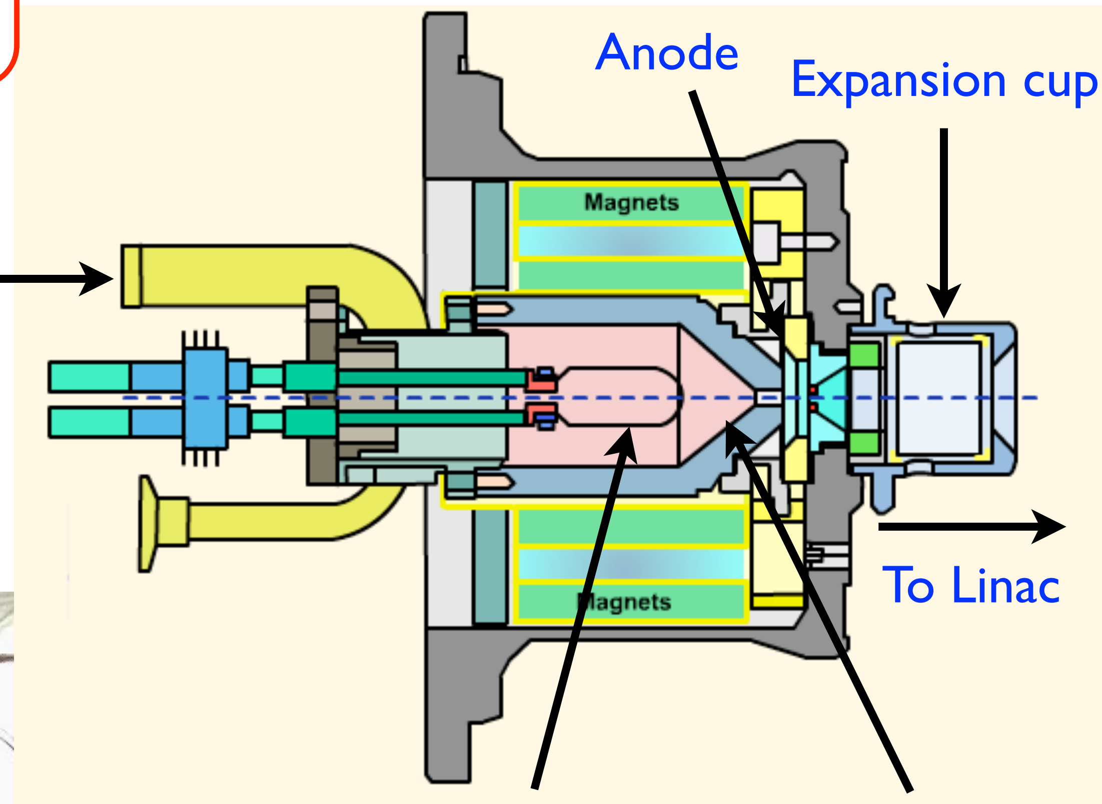
3) A series of guiding and storage devices

Everything under vacuum

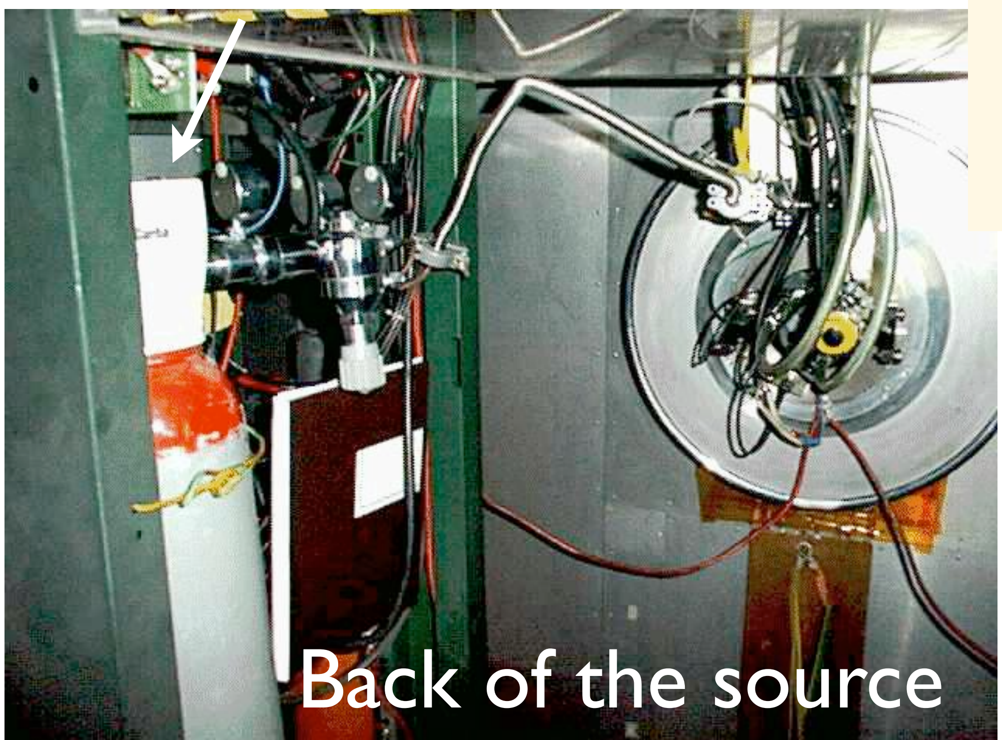
How to get protons: duoplasmatron source

Protons are produced by the ionization of H_2 plasma enhanced by an electron beam





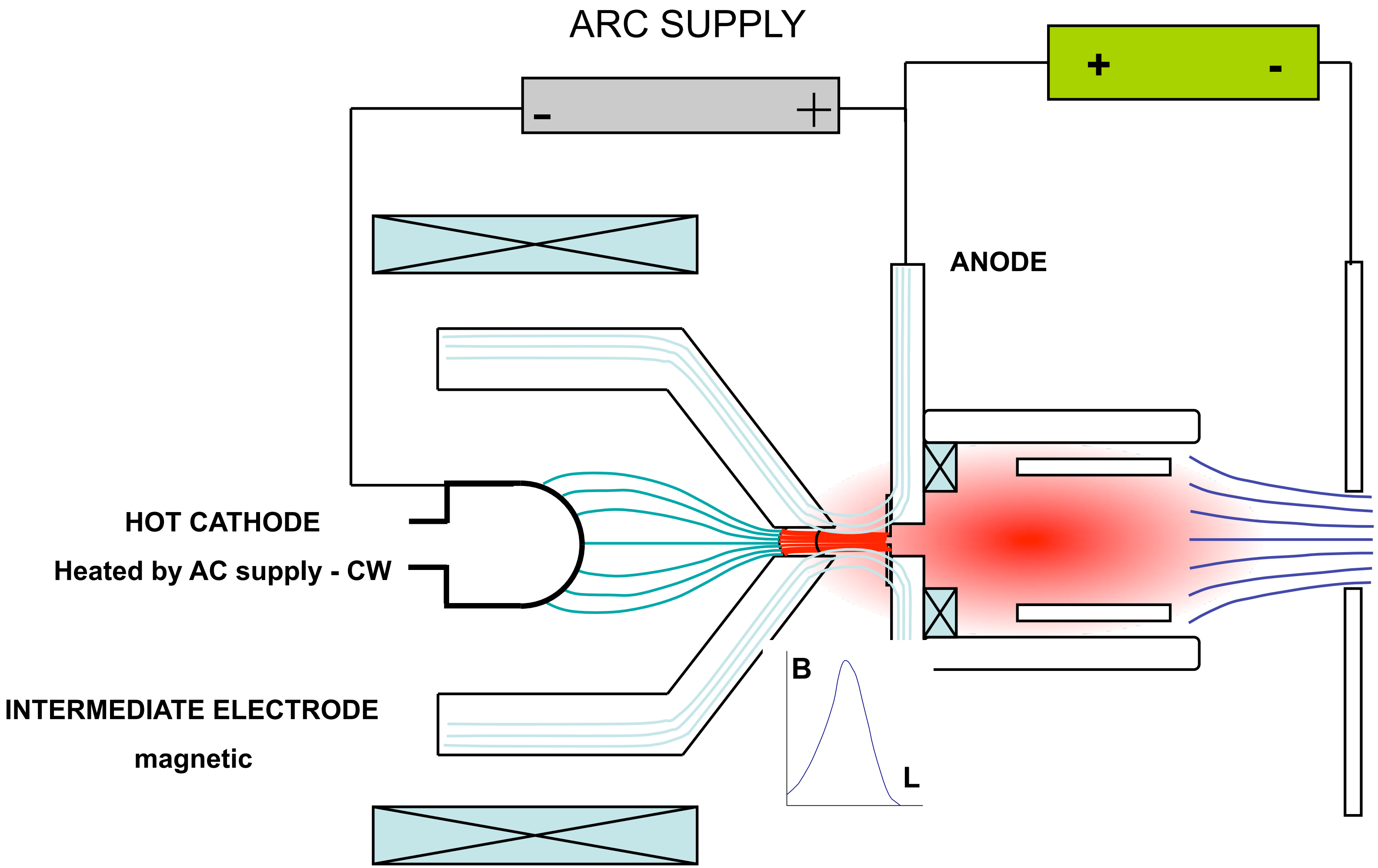
Hydrogen supply (one lasts for 6 months)



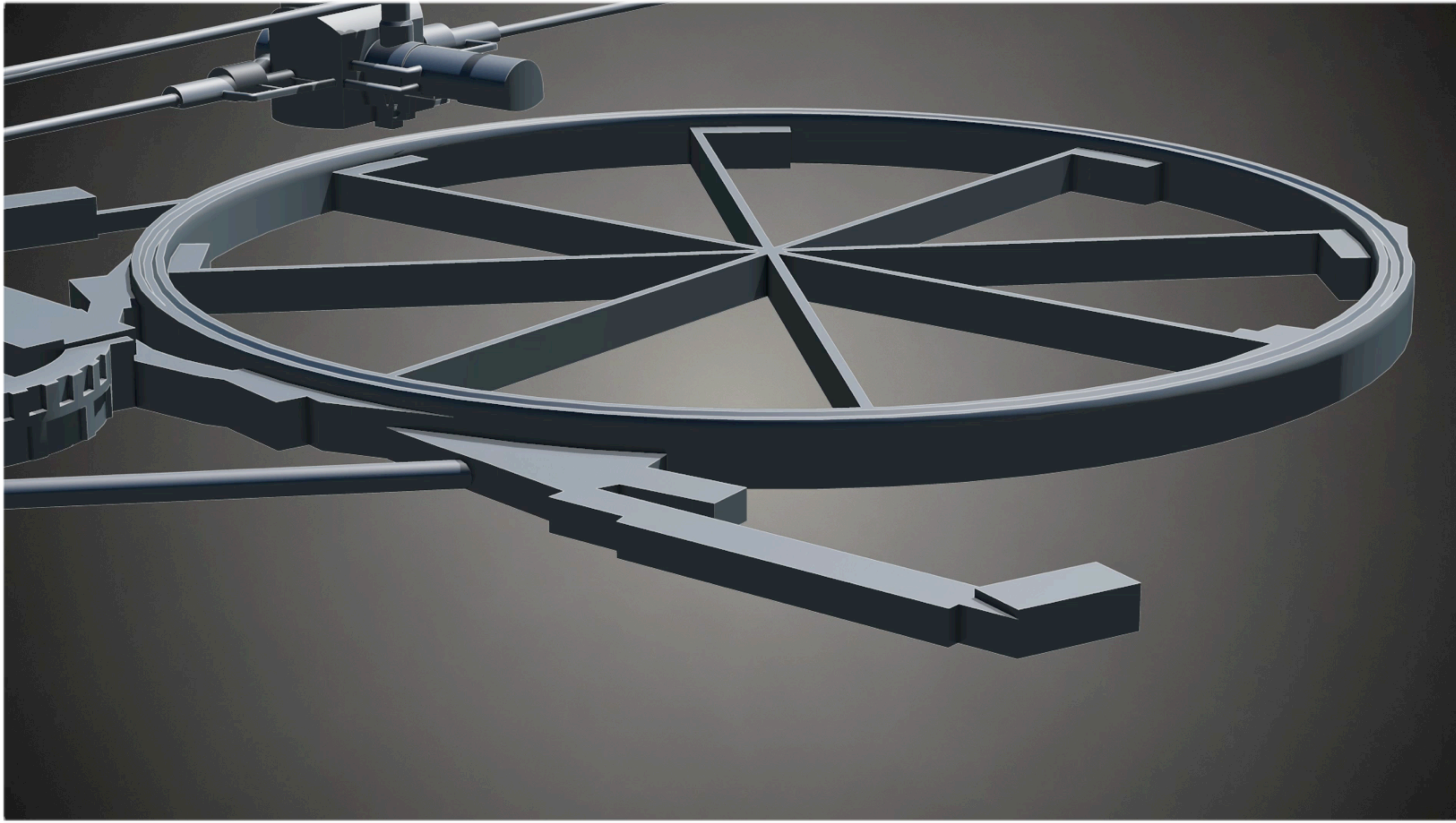
Proton exiting from the about 1 mm^2 hole have a speed of 1.4 % c, $v \approx 4000$ km/s

The SPACE SHUTTLE goes only up to 8 km/s

Source electrical scheme



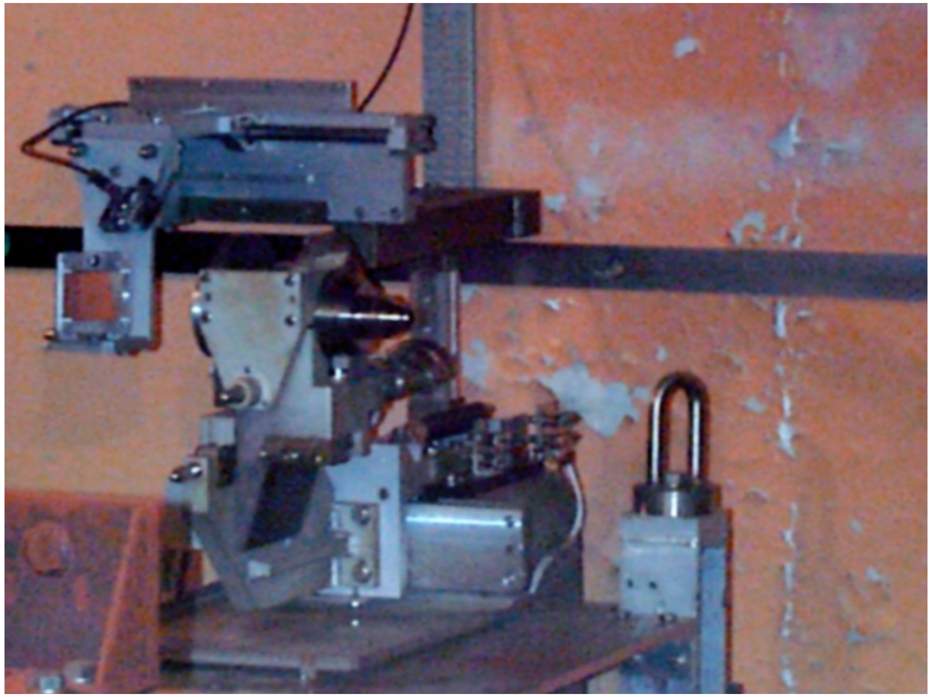
Courtesy R. Scrivens

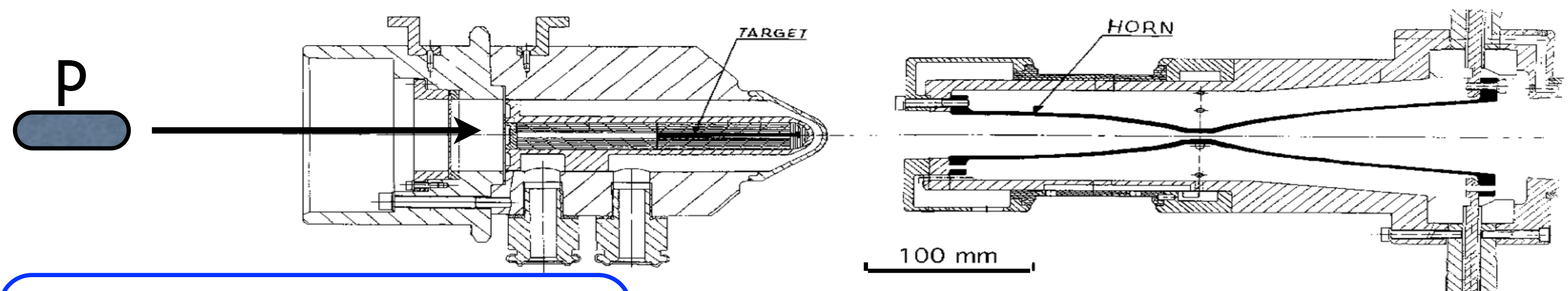


http://cern60.web.cern.ch/fr/exhibitions/duoplasmatron

Cern Control Center: first LHC day

How to get antiprotons





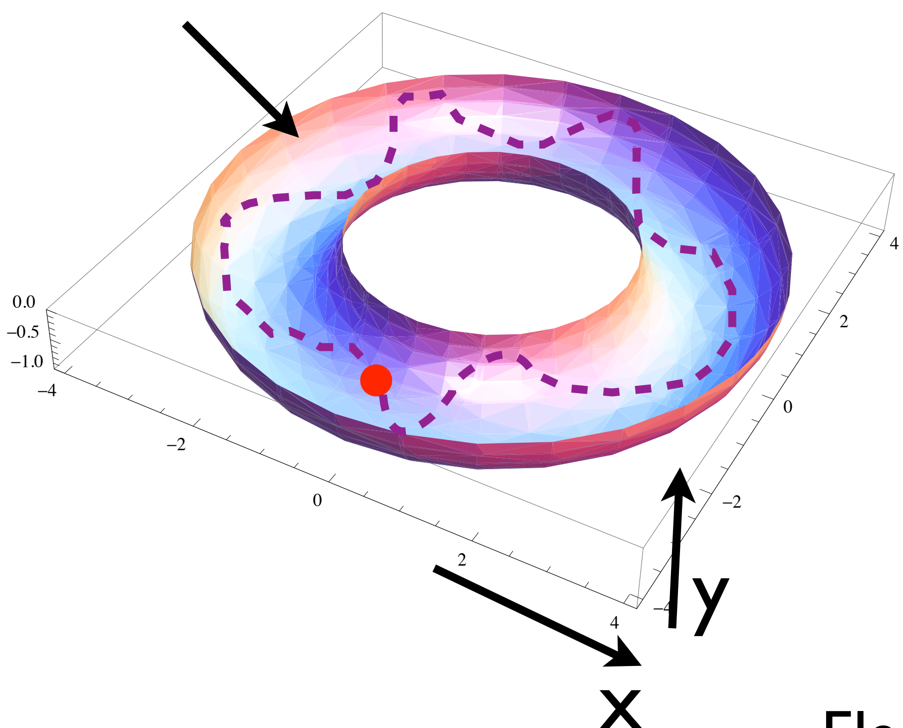
Starting from high energy p and with a very low efficiency

$$p + p \rightarrow p + p + p + \bar{p}$$

10^{13} p to have about 10^{7} antiprotons

How an accelerator works ?

Accelerator



Goal: *keep enough* ***CHARGED*** *particles confined in a well defined volume to accelerate them for a sufficiently long time* ***(ms - hours)***

How ? Lorentz Force!

$$\overline{F(t)} = q\left(\overline{E(t)} + \overline{v(t)} \otimes \overline{B(t)}\right)$$

Electric field accelerates particles

Particles of different energy (speed) behave differently

Magnetic field confines particles on a given trajectory

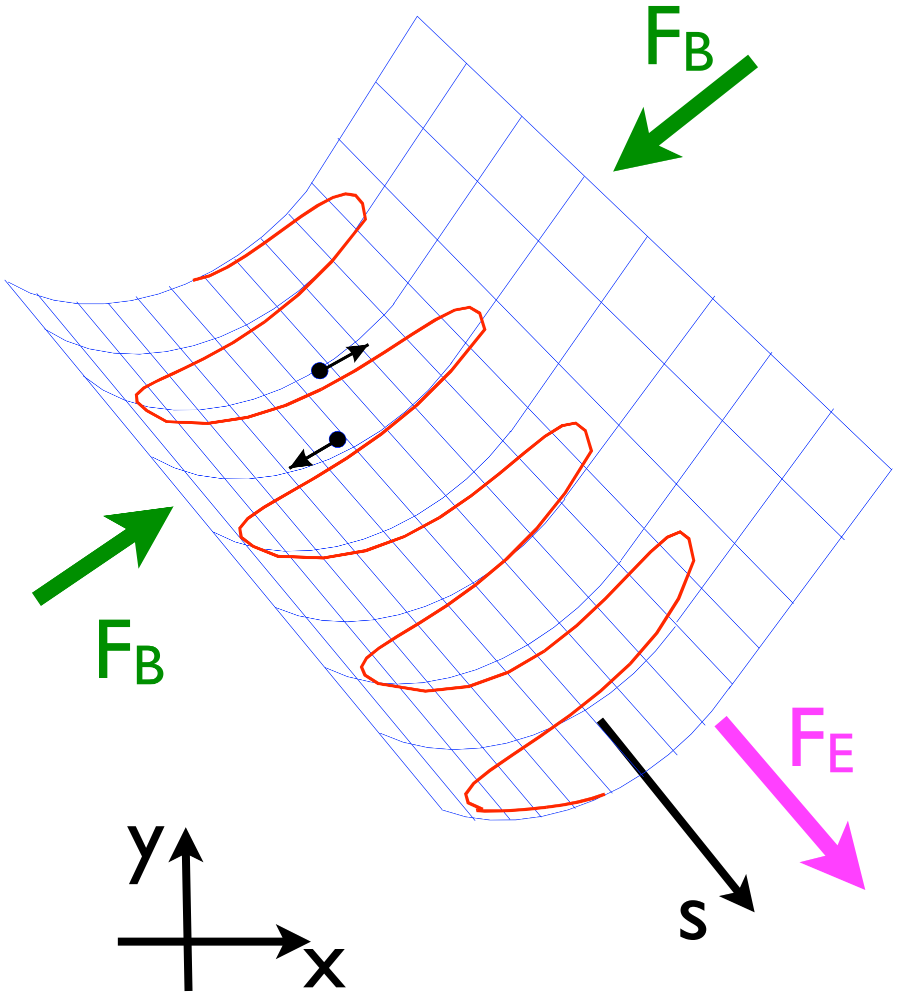
An ***accelerator*** *is formed by a sequence (called* ***lattice****) of:*

a) Magnets → Magnetic Field

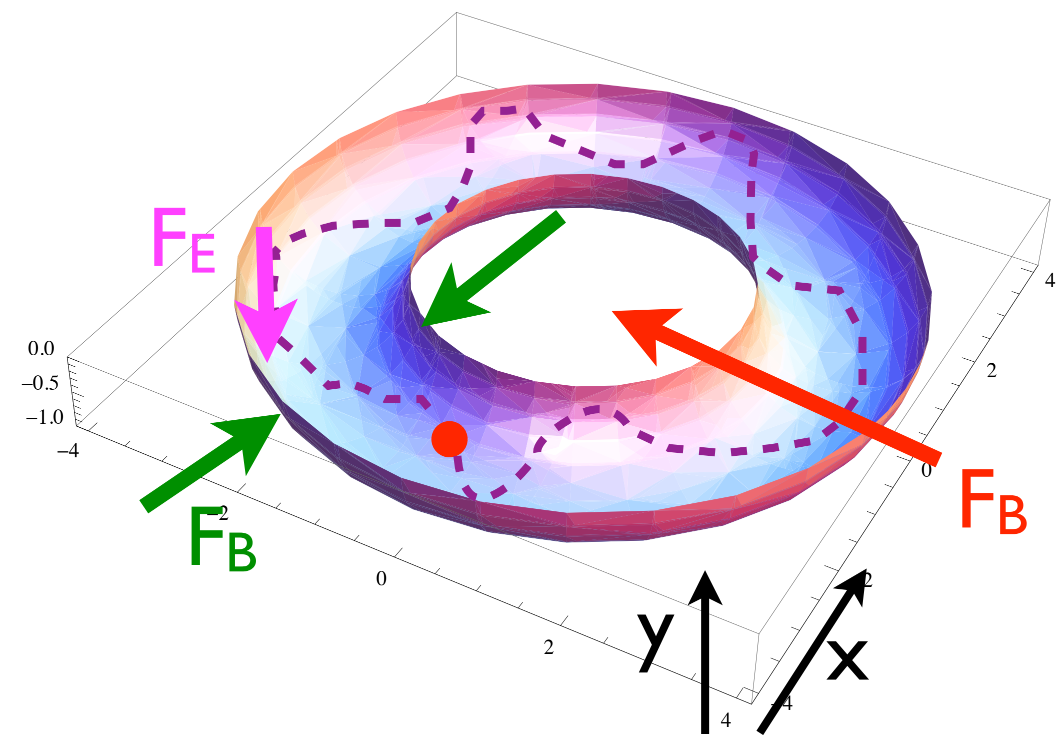
b) Accelerating Cavity → Electric Field

$$\overline{F(t)} = q\Big(\underbrace{\overline{E(t)}}_{F_E} + \underbrace{\overline{v(t)} \otimes \overline{B(t)}}_{F_B}\Big)$$

Linear Accelerator



Circular Accelerator



Cyclotron

Particle source located in a vertical B field near the center of the ring

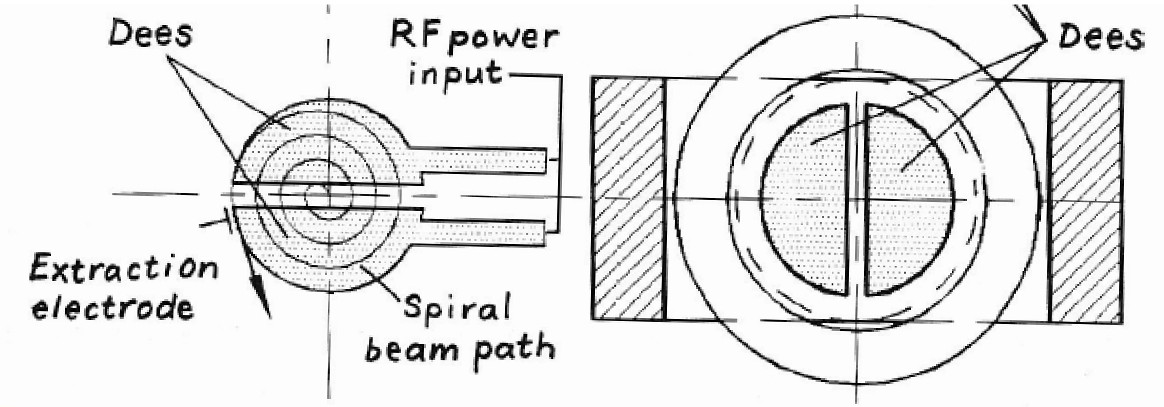
Electrical (E) RF field generated between two gaps with a fixed frequency

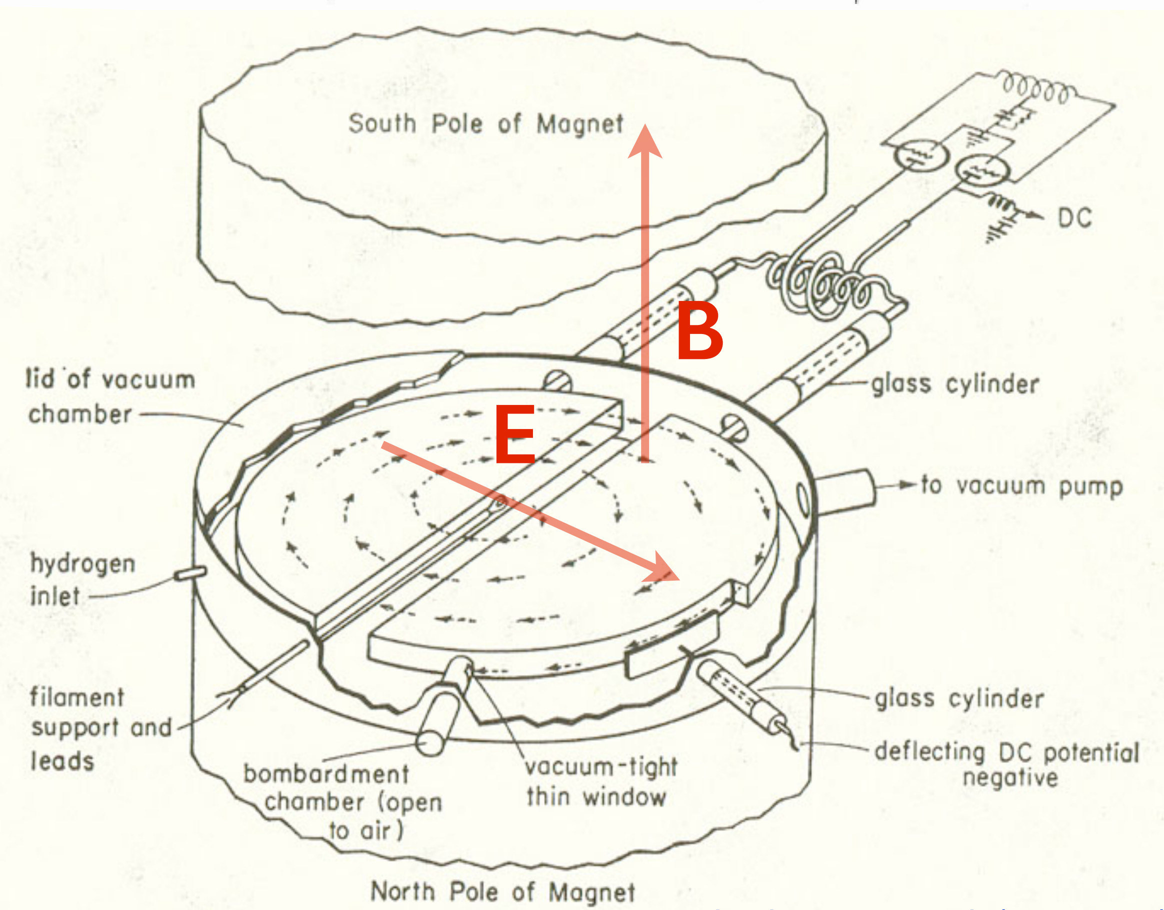
Particles spiral while accelerated by E field every time they go through the gap

$$Ep = \frac{1}{2}\frac{e^2}{m_0}B^2R_{max}^2$$

Max energy for protons: 20 MeV

Main limitations:
1) not working for relativistic particles, either high energy or electrons
2) B field at large radius not vertical





www.physics.rutgers.edu/ cyclotron/

Invented by Lawrence, got the Noble prize in 1939

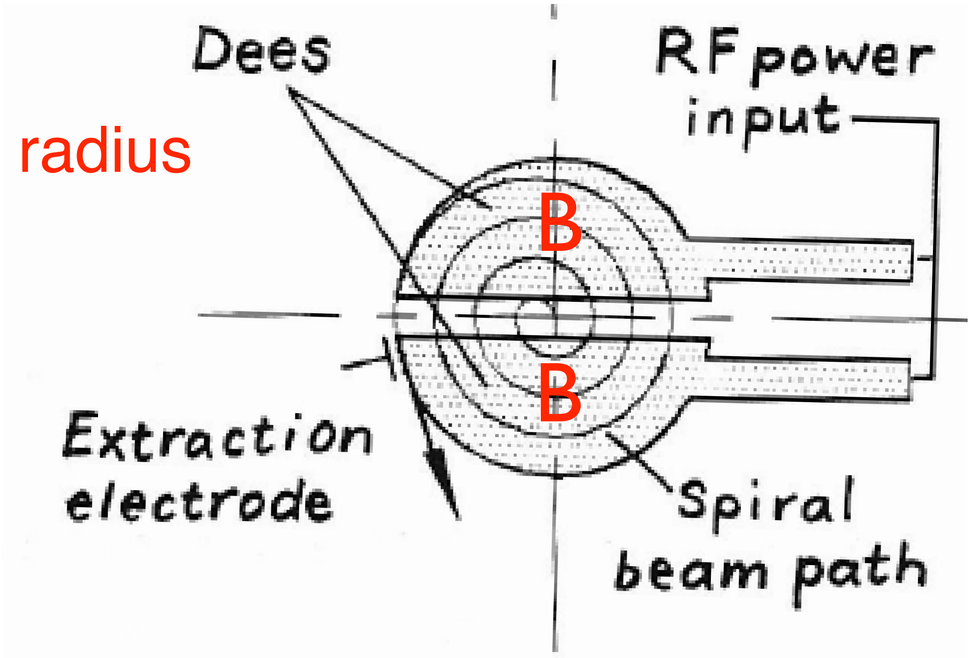
Cyclotron in few formulas

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \longrightarrow F_L = q\, v\, B \longrightarrow$$ Vertical B
No E

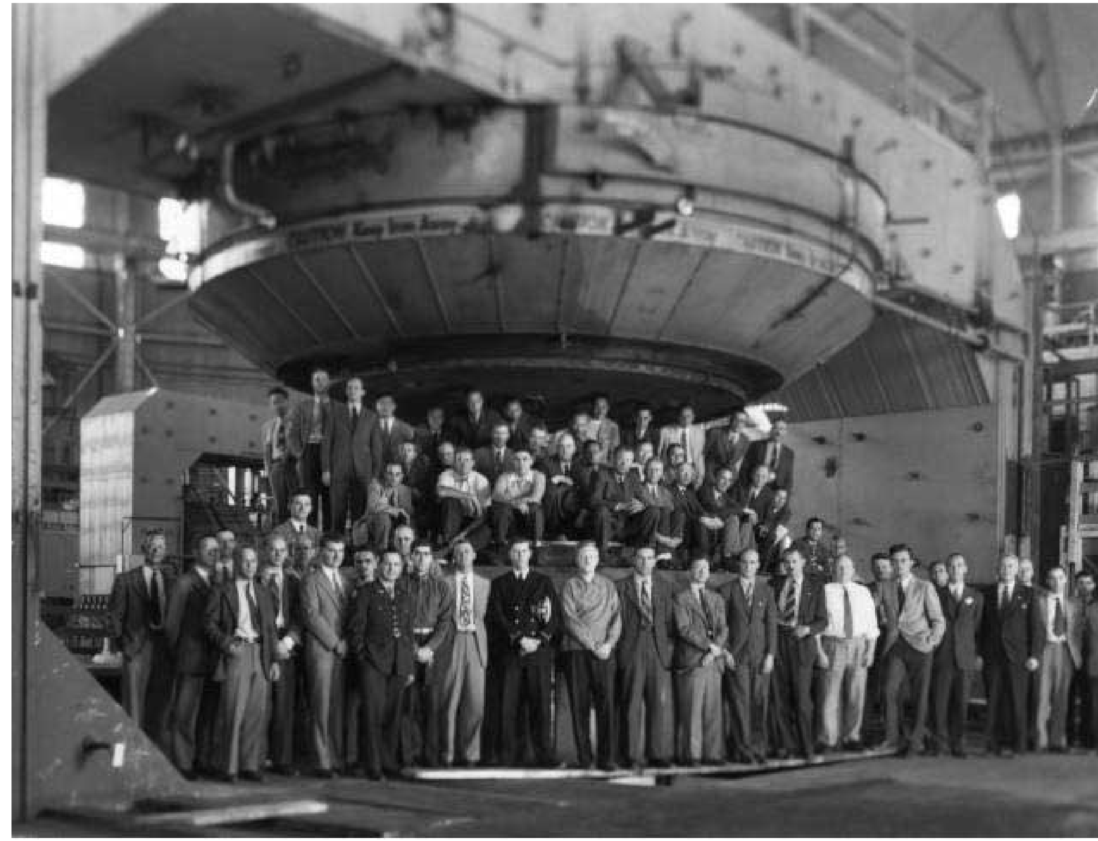
$$F_c = m\frac{v^2}{r} \longrightarrow$$ centrifugal force

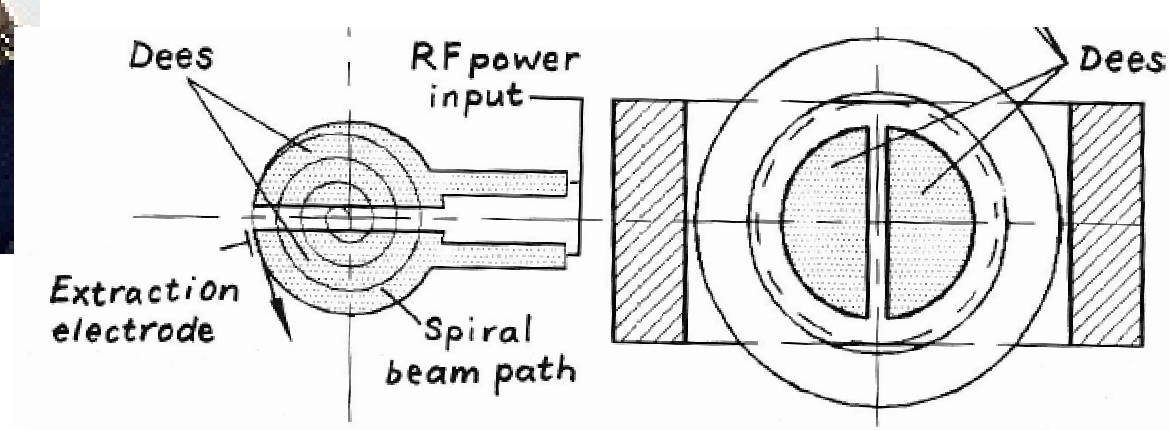
$$F_L = F_c \longrightarrow \omega = \frac{v}{r} = \frac{qB}{m} \longrightarrow$$ revolution period

Revolution period independent of the radius
Particle always synchronous with RF
R increases with v for a fixed B

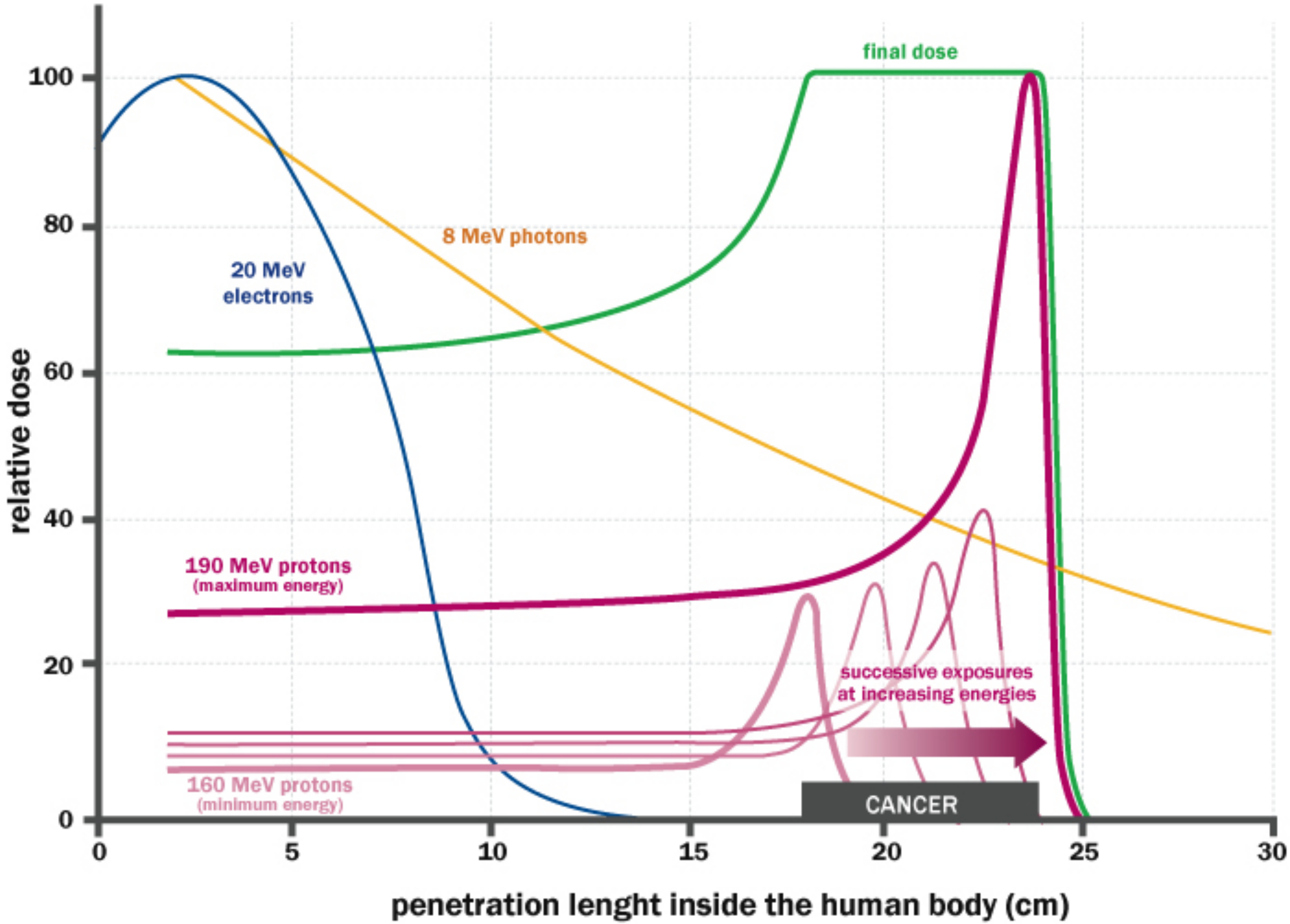


The first cyclotron and the Berkeley one

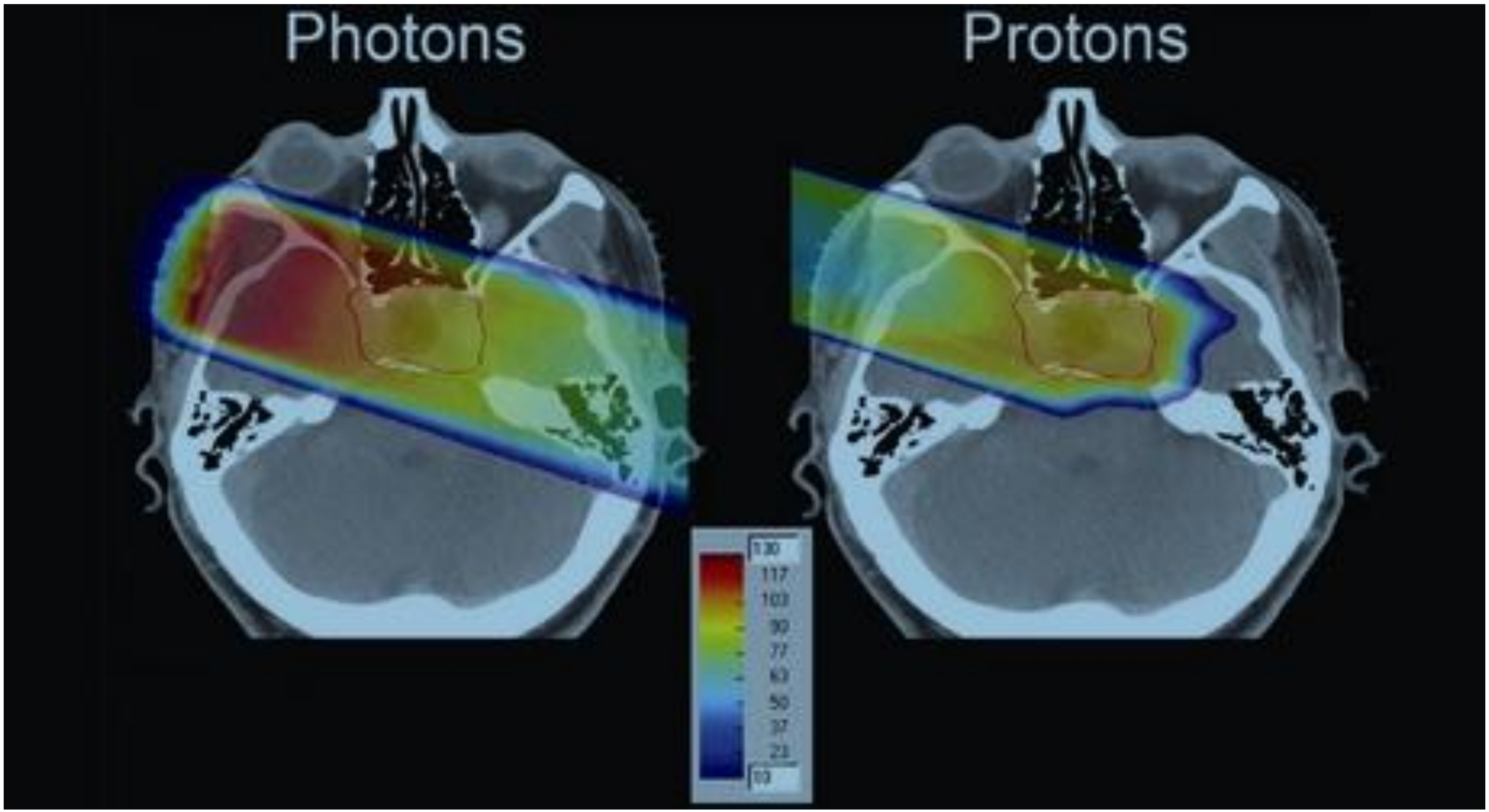




Cyclotron application: cancer therapy



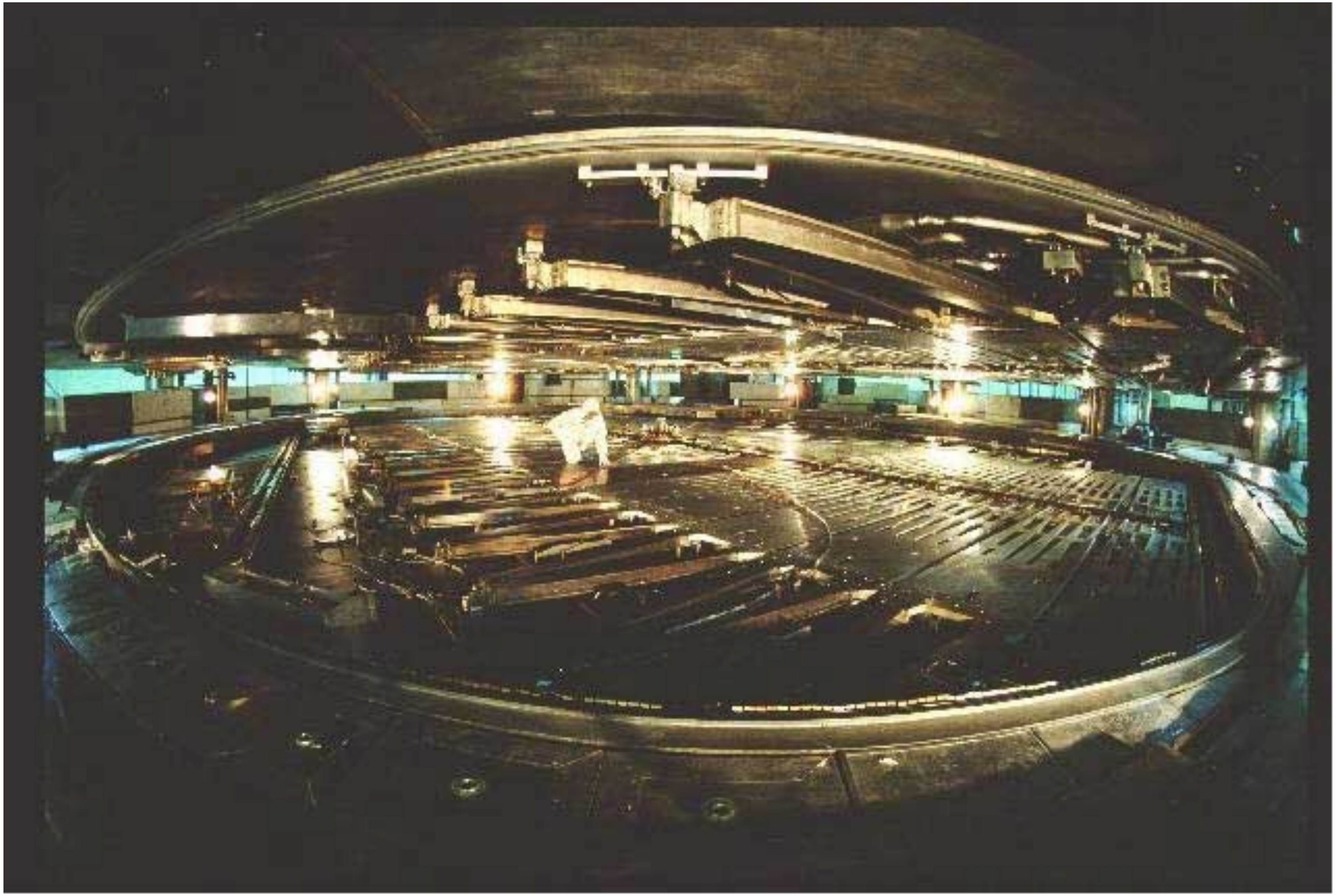
Cyclotron application: cancer therapy, photons vs protons



https://kce.fgov.be/publication/report/hadron-therapy-in-children-–-an-update-of-the-scientific-evidence-for-15-paediatr#.VehXyIuNeDs

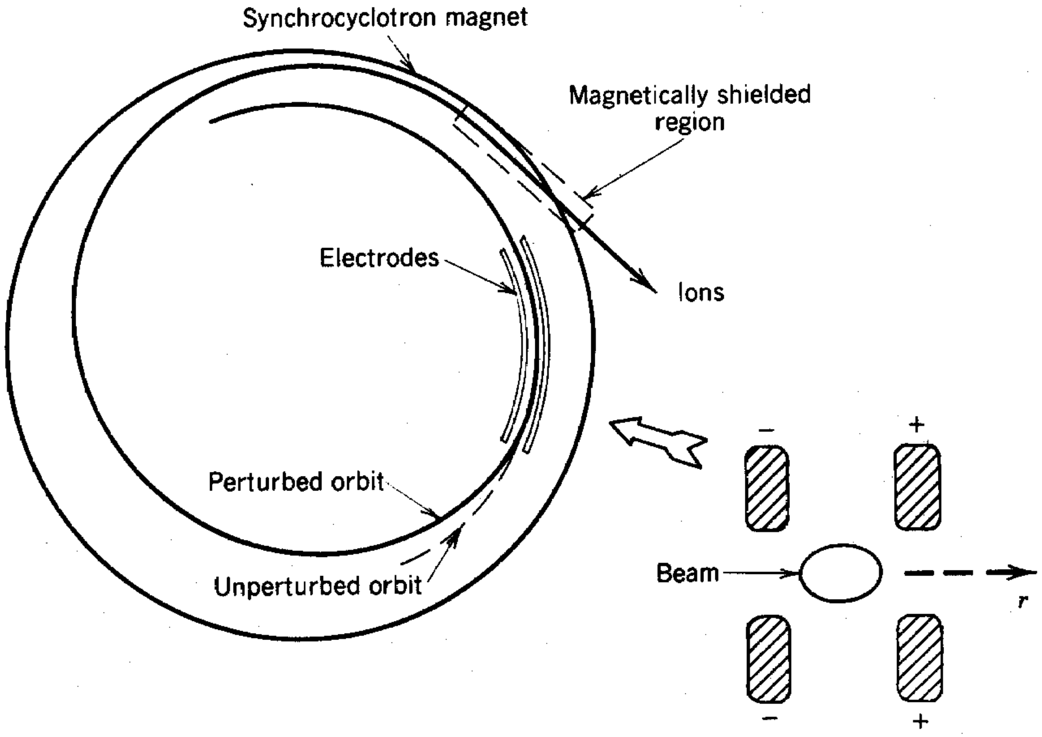
TRIUMF cyclotron - 520 MeV

Used for rare isotope acceleration



Synchrocyclotron

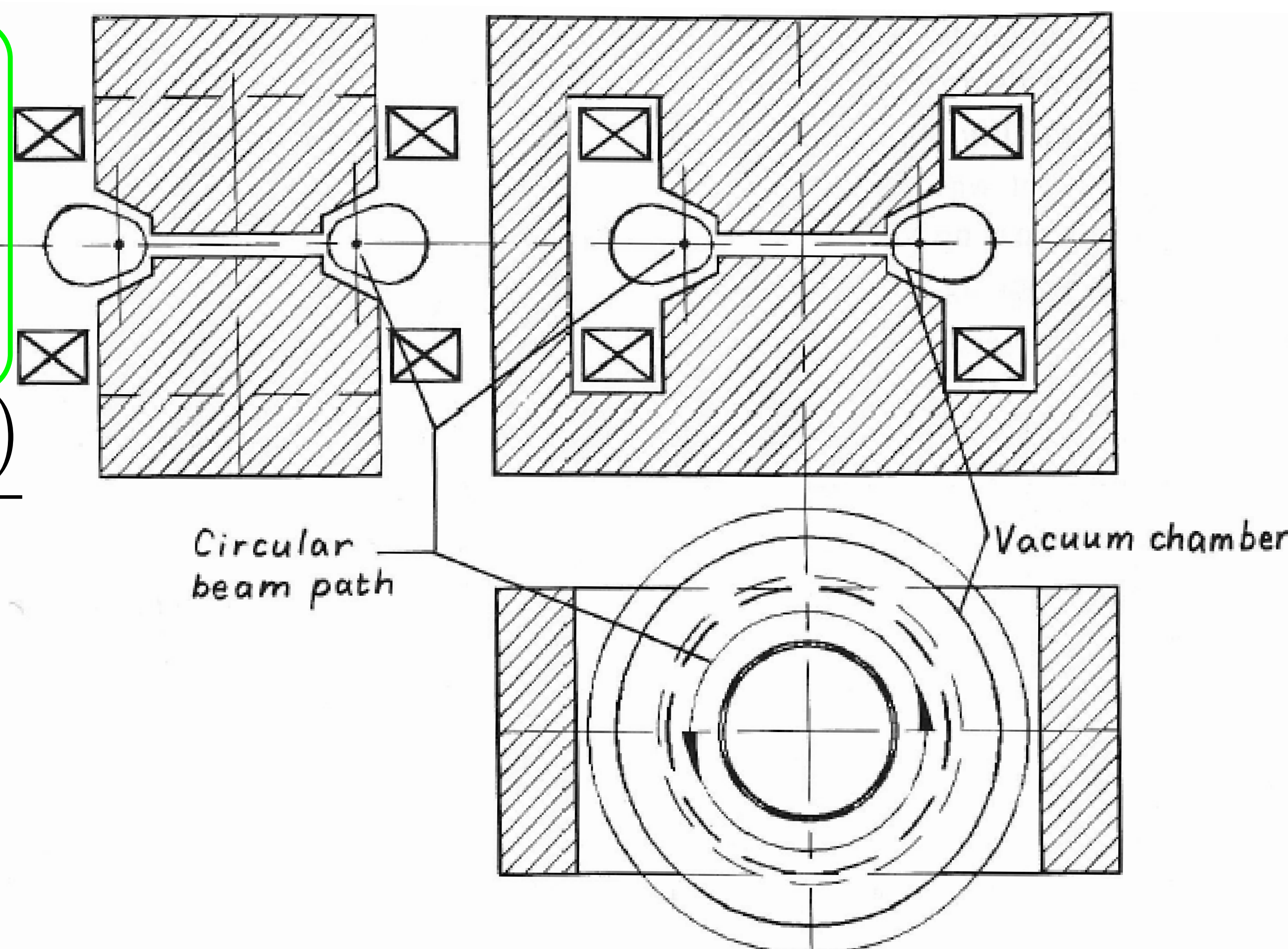
Synchrocyclotrons have a constant magnetic field with geometry similar to the uniform-field cyclotron. The main difference is that the rf frequency is varied to maintain particle synchronization into the relativistic regime.



Betatron (invented by Wideroe in 1923)

Accelerating field generated by the variation in time of the magnetic flux which couples with the “current” flowing in the vacuum chamber, the beam, to accelerate.

$$eE_\varphi = \frac{e}{c} R \frac{dB(R)}{dt}$$



Large betatron built:

R = 1.23 m

Bmax= 8.1 kG

pmax= 300 MeV/c

Main limitation:
1) iron saturation

Kerst built the first one in 1940 for electrons up to 2.3 MeV
Betatron transverse oscillations first introduced in 1941
Betatron named for beta rays, namely electrons

Betatron in few formulas

$$\boxed{\oint \vec{E}\,ds} = -\frac{d}{dt}\phi \longrightarrow \text{Ampere's law}$$

$$\boxed{\phi = \int_A \vec{B}\,ds} \longrightarrow \text{Magnetic flux with A surface}$$

$$E = -\frac{1}{2\pi\,r}\frac{d}{dt}\phi = \frac{1}{2\pi\,r}\pi\,r^2\frac{d}{dt}B = -\frac{r}{2}\frac{d}{dt}B$$

Betatron

Betatron from wikipedia

Betatron used for xray generation

Synchrotron (1952, 3 GeV, BNL)

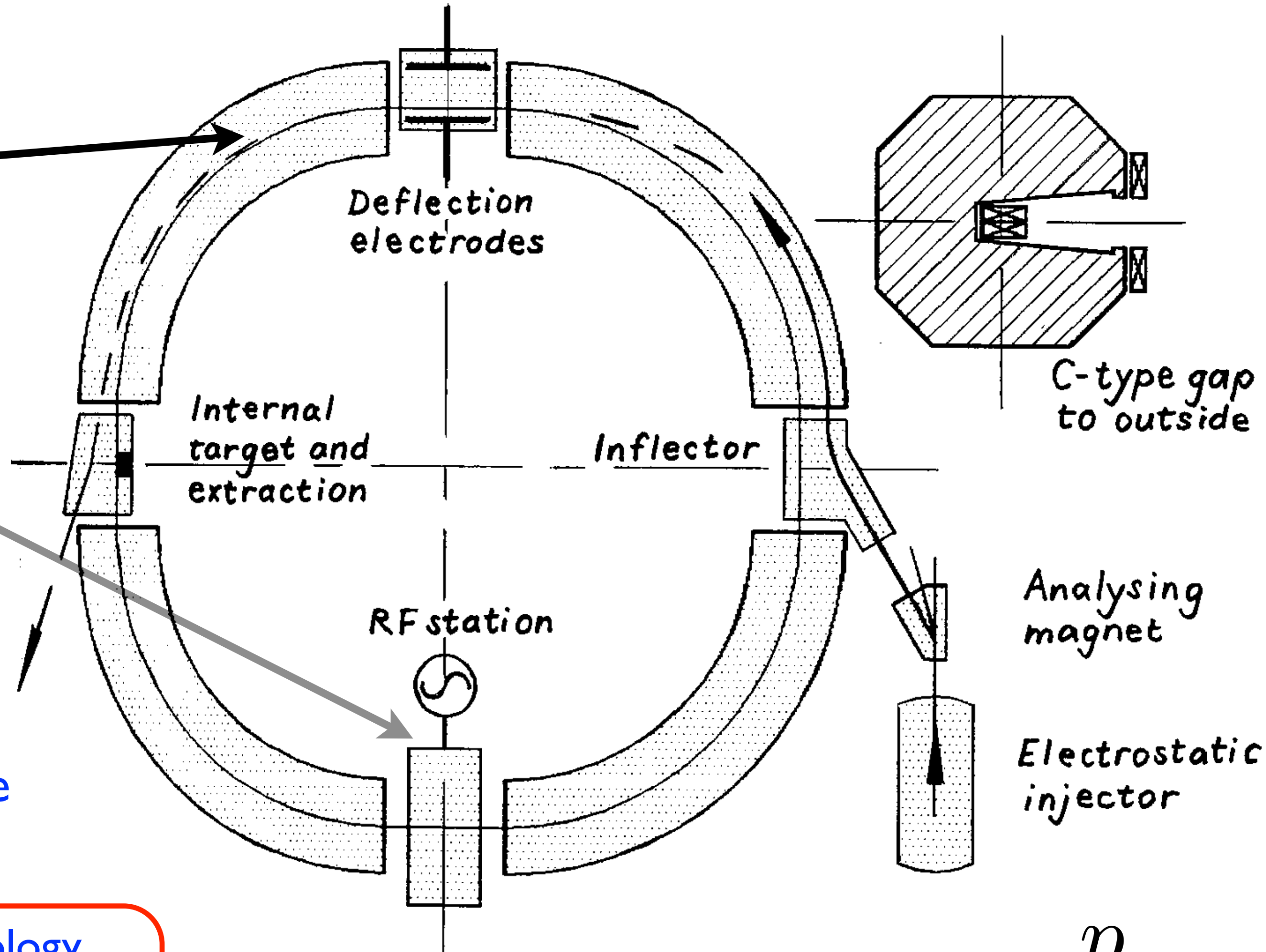
New concept of circular accelerator. The magnetic field of the bending magnet varies with time.
As particles accelerate, the B field is increased proportionally.
The frequency of the accelerating cavity, used to accelerate the particles, has also to change.

B = B(t) magnetic field from the bending magnets

p = p(t) particle momentum varies by the RF cavity

e electric charge

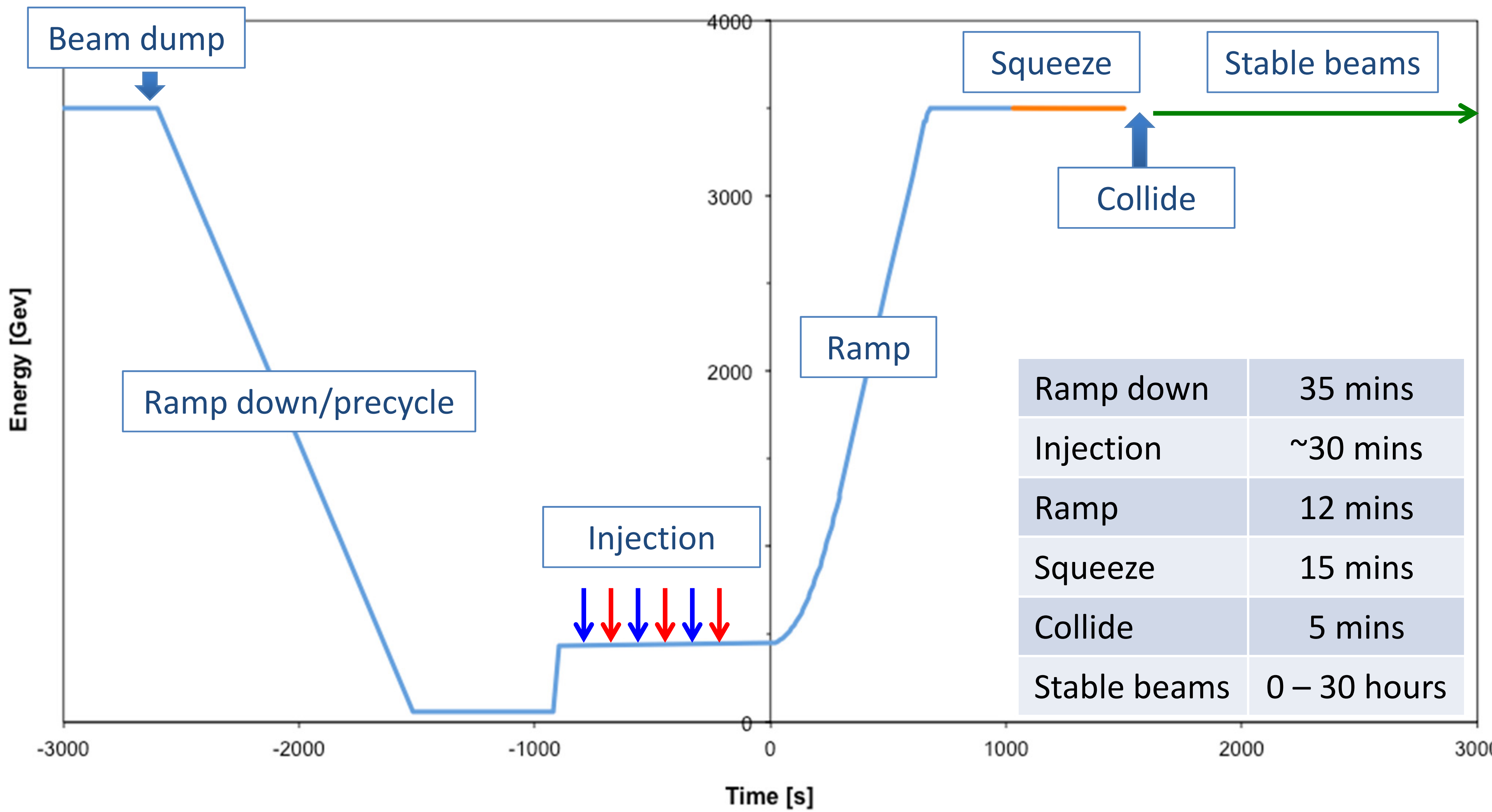
ρ constant radius of curvature



Bending strength limited by used technology to max ~ 1 T for room temperature conductors

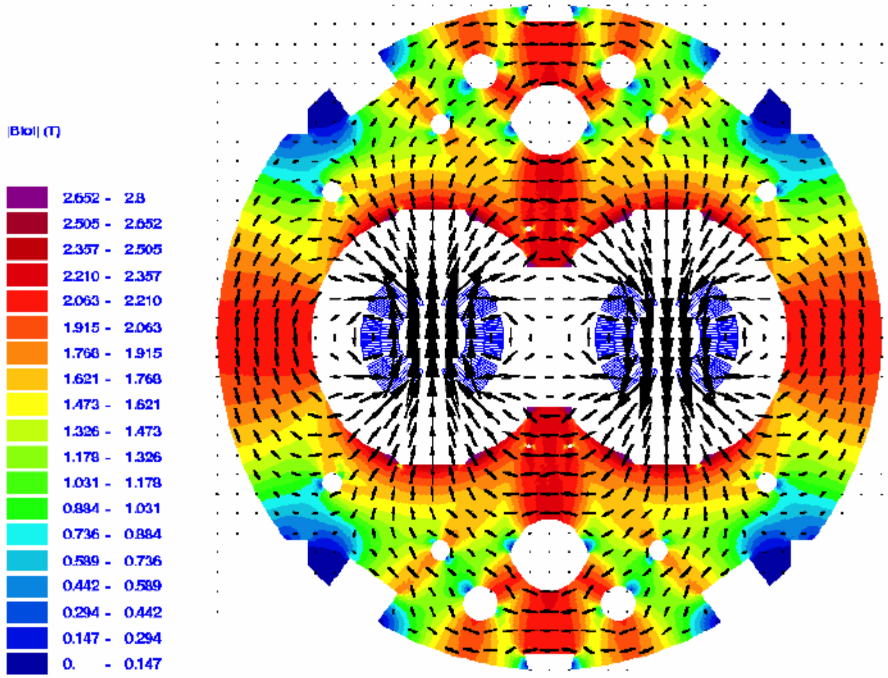
Particle rigidity: $B\rho = \frac{p}{e}$

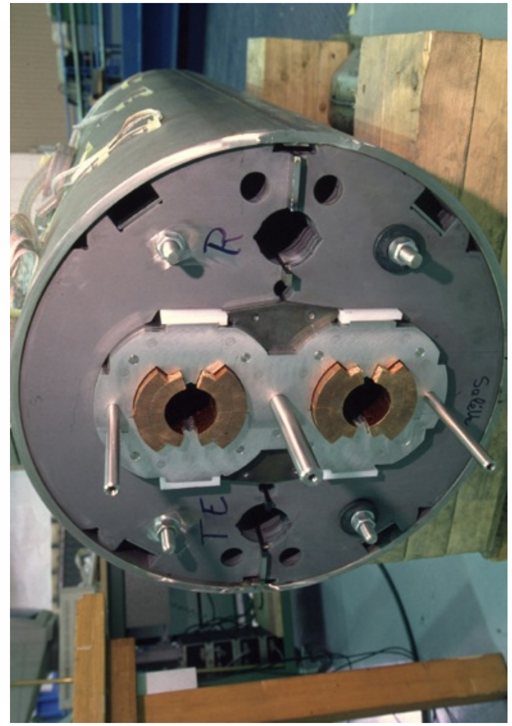
Typical LHC Operational cycle

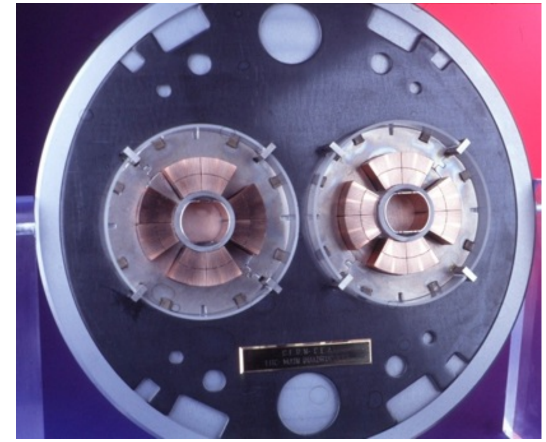


Ramp down	35 mins
Injection	~30 mins
Ramp	12 mins
Squeeze	15 mins
Collide	5 mins
Stable beams	0 – 30 hours

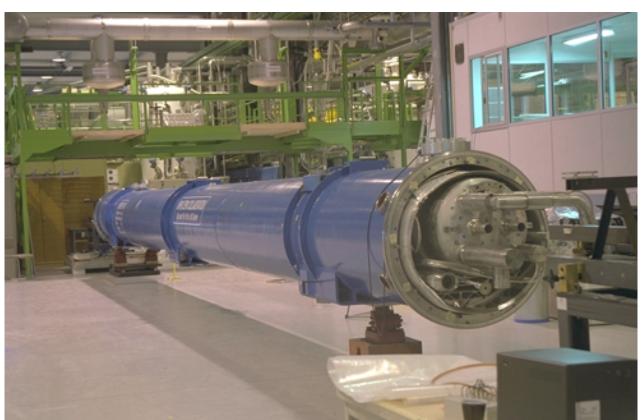
Two-in-one magnet design

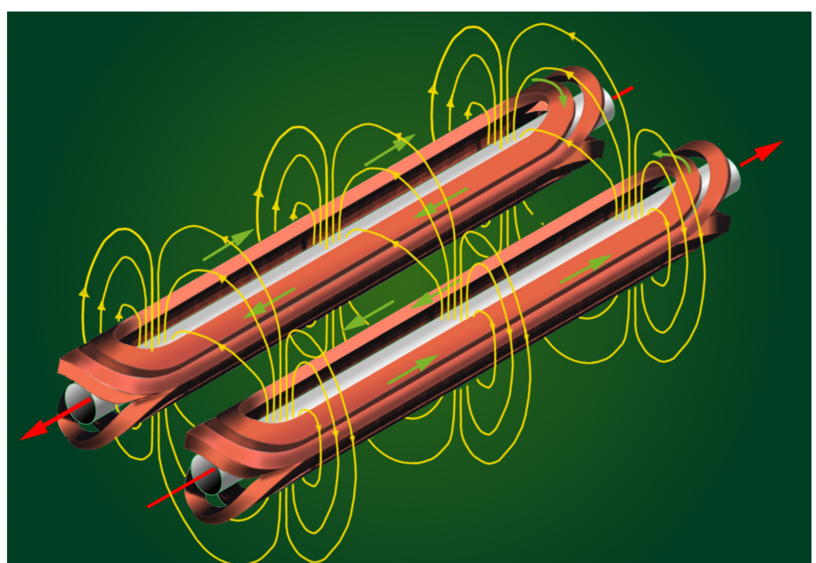




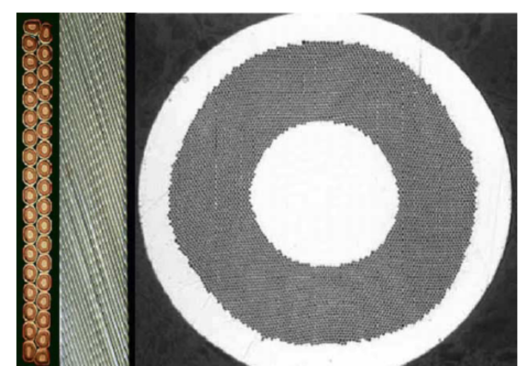


The LHC is <u>one ring</u> where <u>two accelerators</u> are coupled by the magnetic elements.

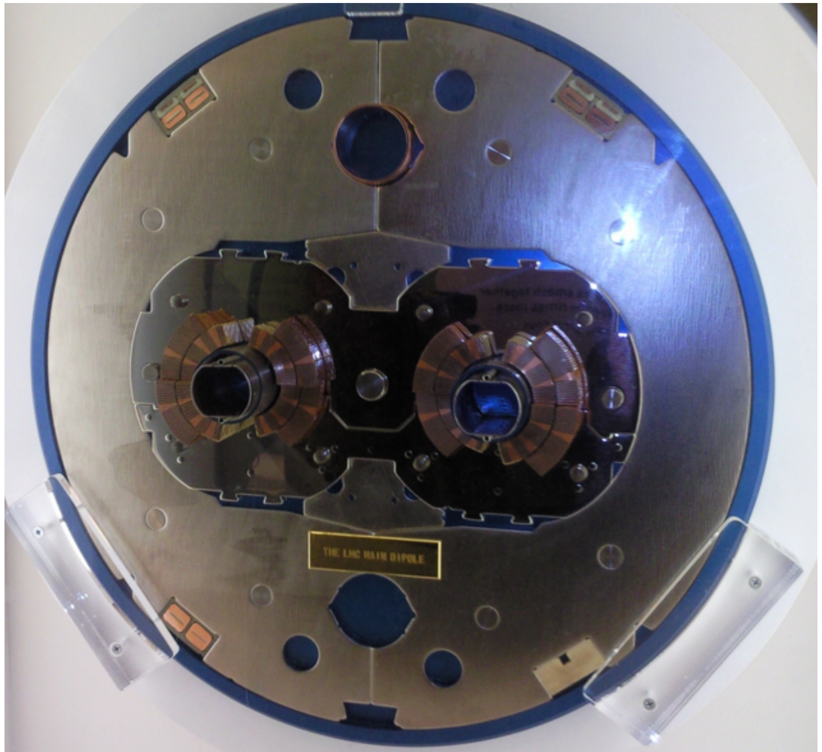


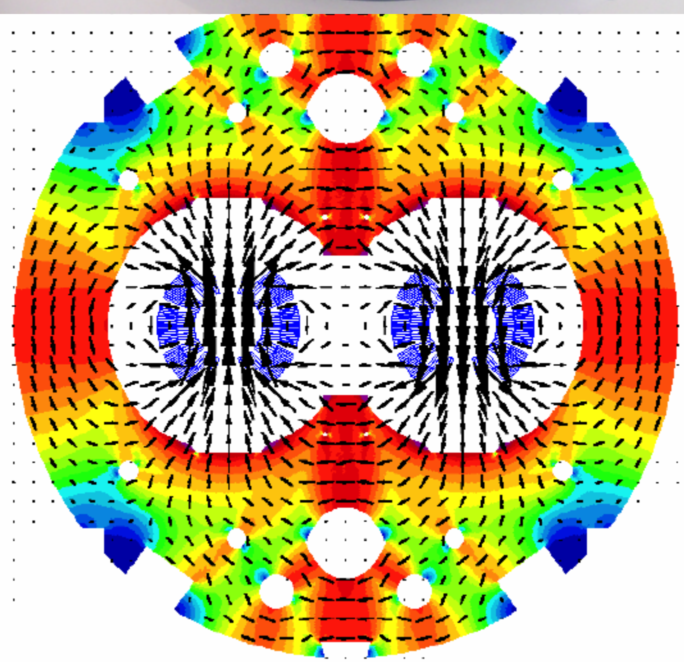


Nb -Ti superconducting cable in a Cu matrix

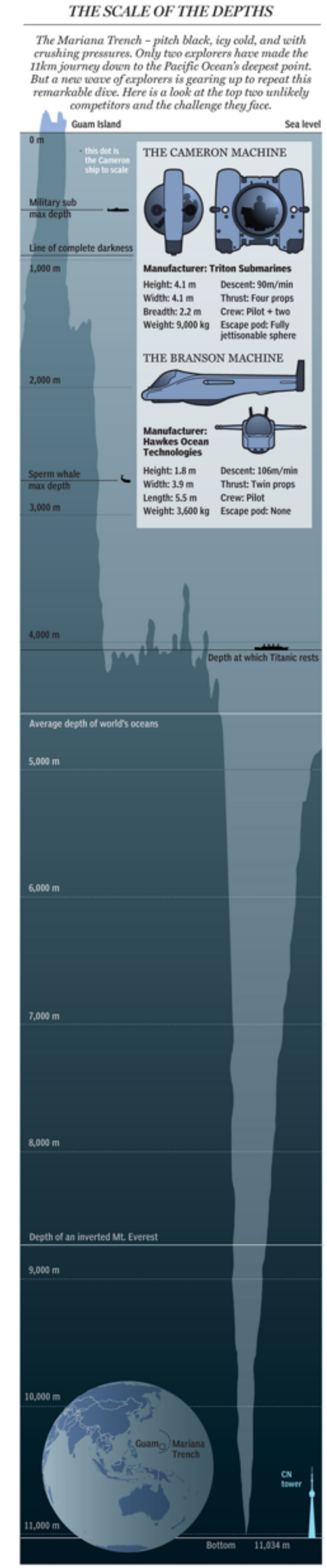


Pressure on conductors ~ 110 MPa

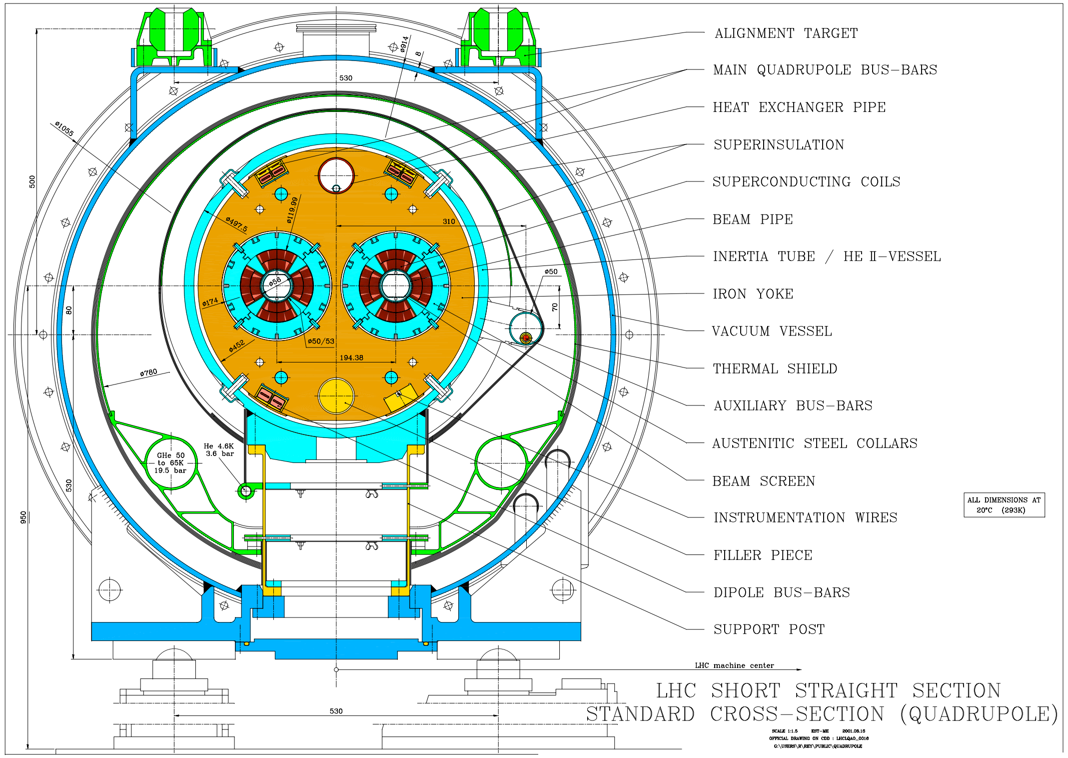




About same pressure at the bottom of Mariana trench: 11 000 m of water



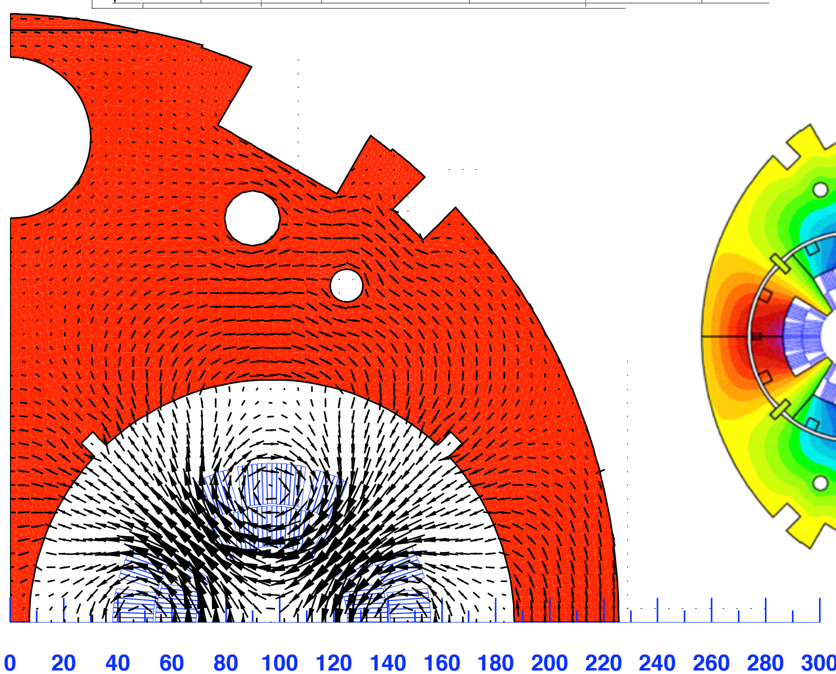
Quadrupoles are also two-in one

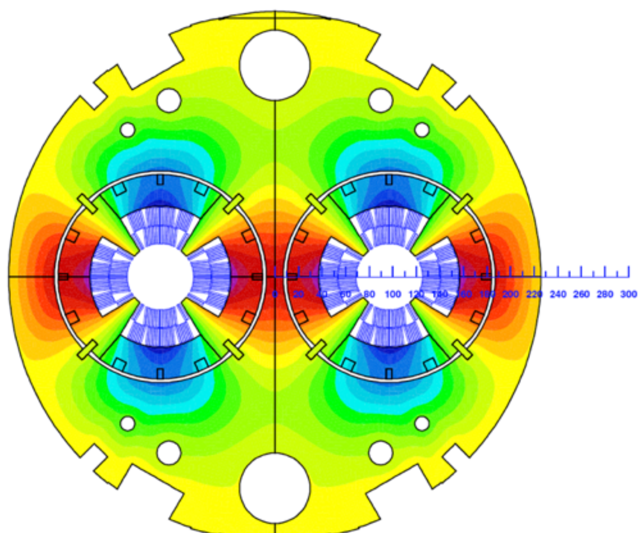


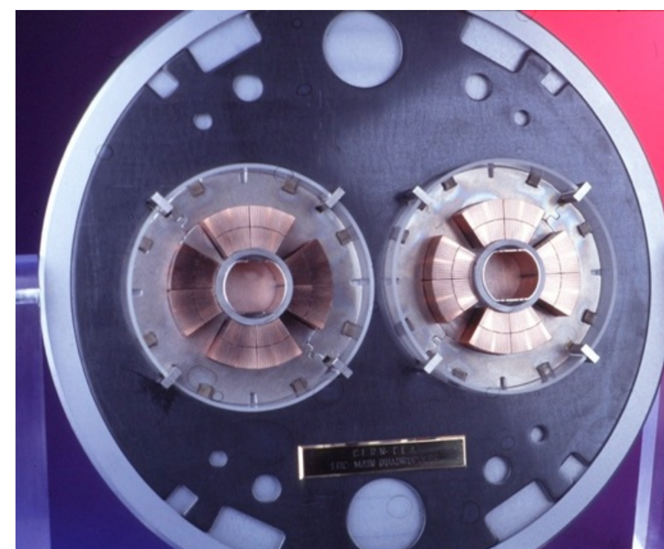
At 7 TeV:

I_{max} = 11850 A
Field=225 T/m

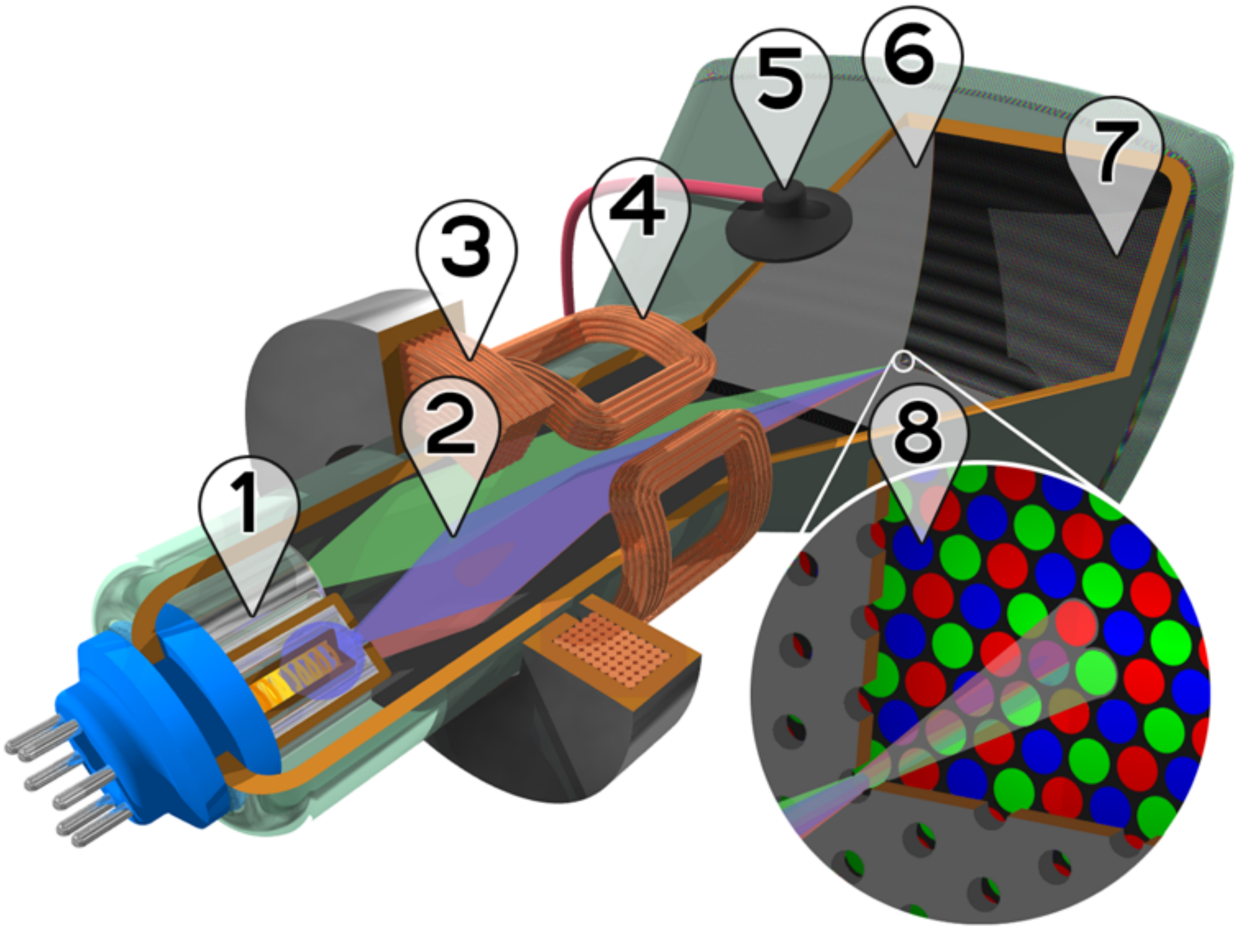
Weight = 6.5 Tons
Length =3.1 m







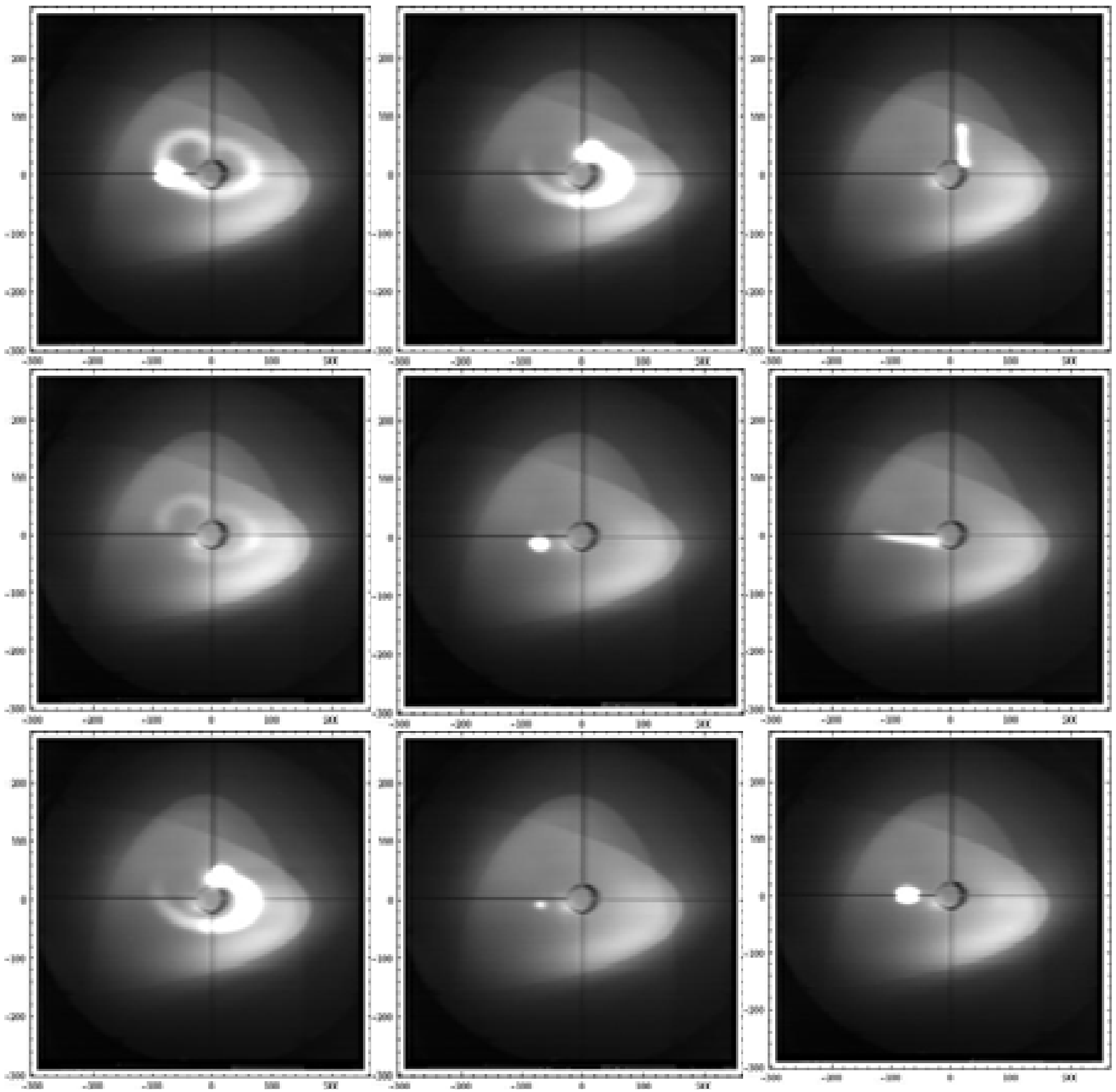
Summary: an accelerator that you know very well

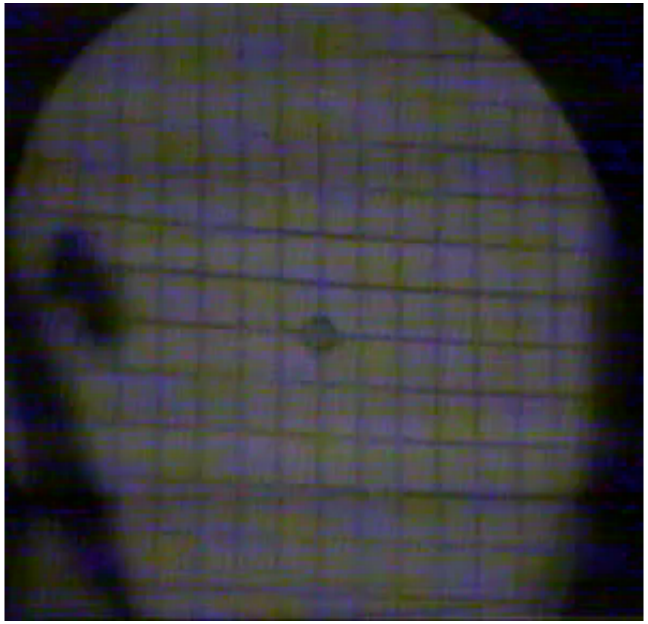


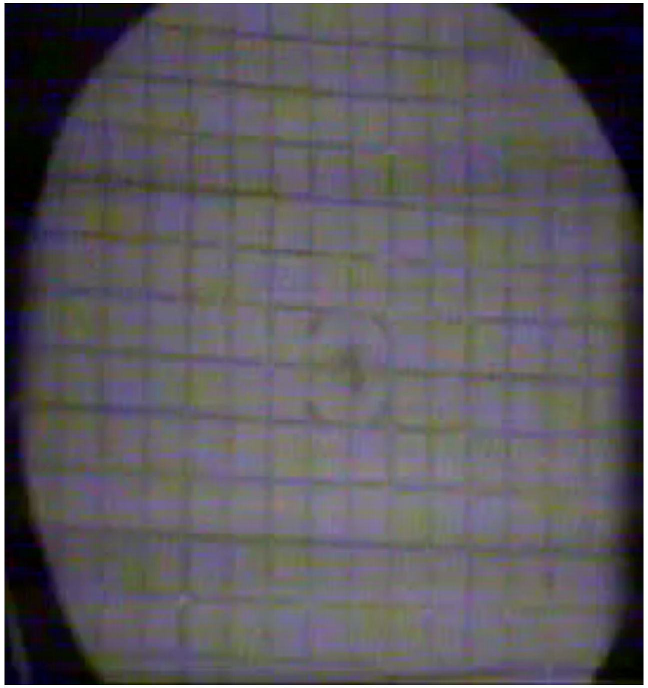
1. Three Electron guns (for red, green, and blue phosphor dots)
2. Electron beams
3. Focusing coils
4. Deflection coils
5. Anode connection
6. Mask for separating beams for red, green, and blue part of displayed image
7. Phosphor layer with red, green, and blue zones
8. Close-up of the phosphor-coated inner side of the screen

From Wikipedia

Real beam images



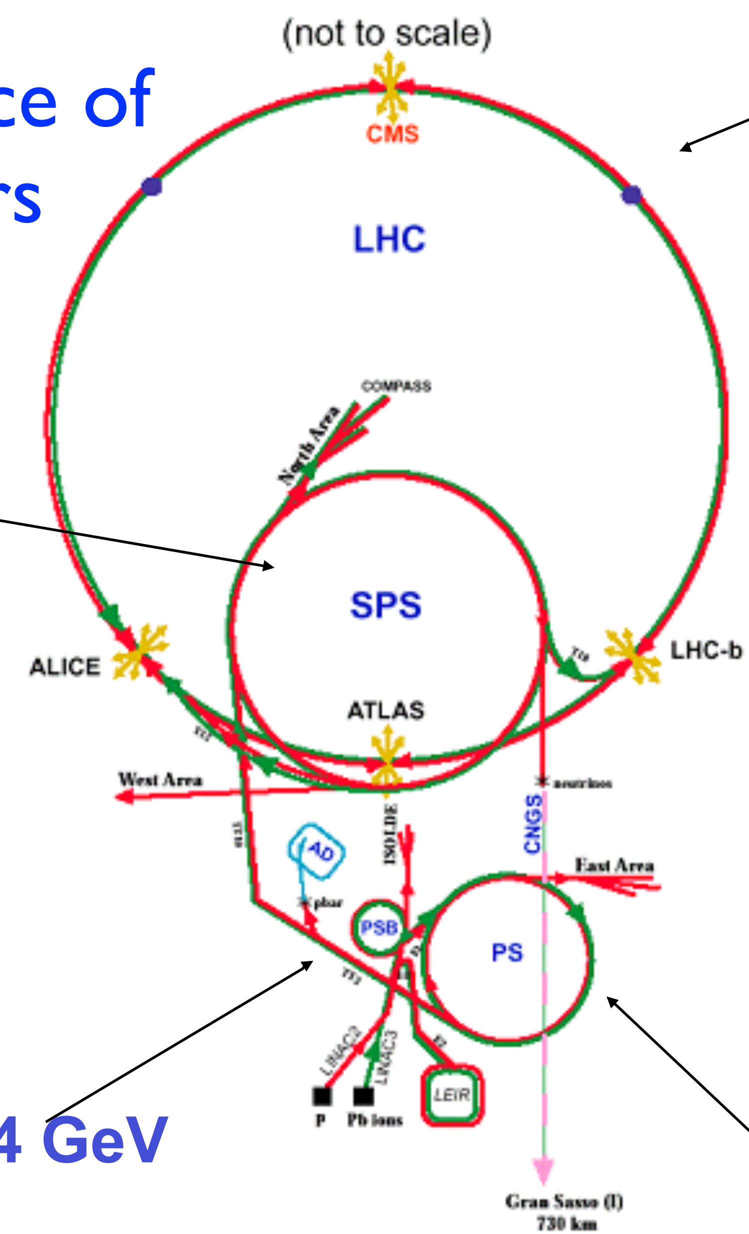




Courtesy of B. Goddard

CERN accelerator complex overview

Chain/sequence of accelerators



450 GeV/c – 7 TeV/c

C ~ 27 km

Questions:

- why so many accelerators and not just the LHC?

- why rings of increasing circumference?

- why rings and linear accelerators?

- how particles go from one machine to the other?

26 - 450 GeV/c

C ~ 6 km

LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

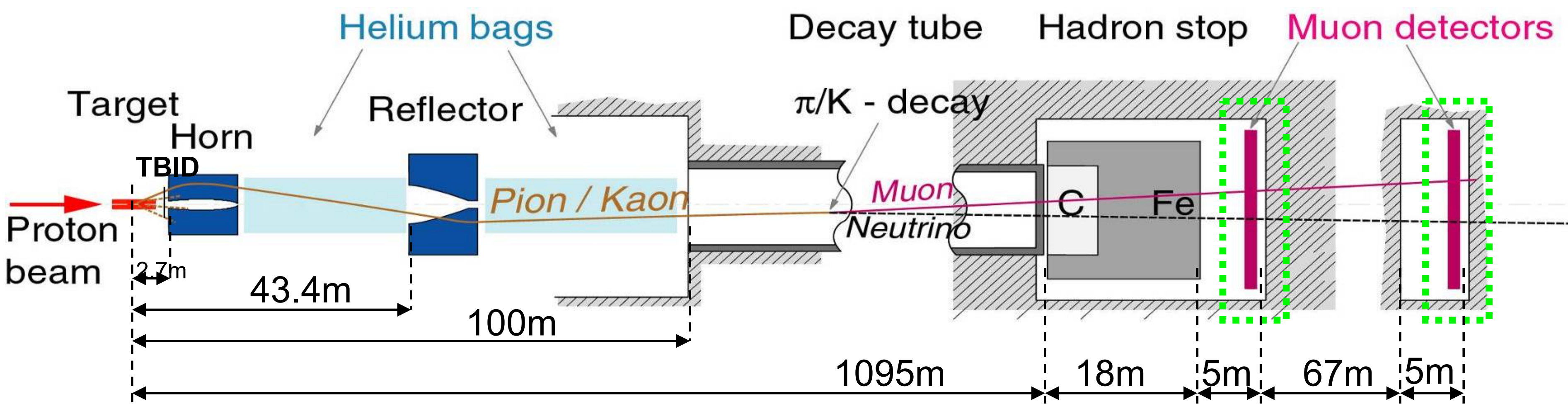
1.4 GeV – 26 GeV/c

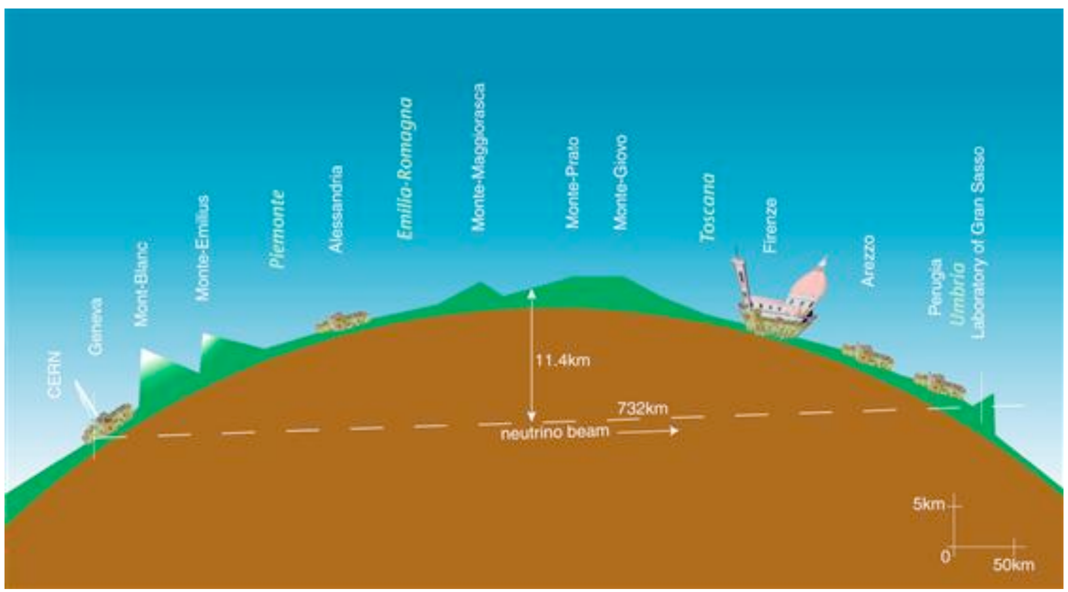
C ~ 630 m

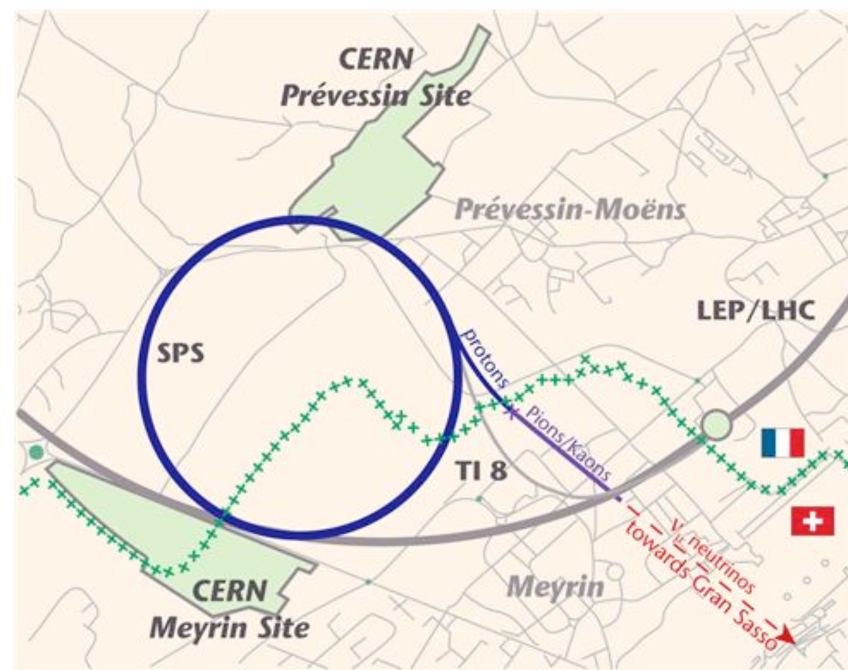
50 MeV – 1.4 GeV

C ~ 157 m

CNGS, conventional neutrino beam



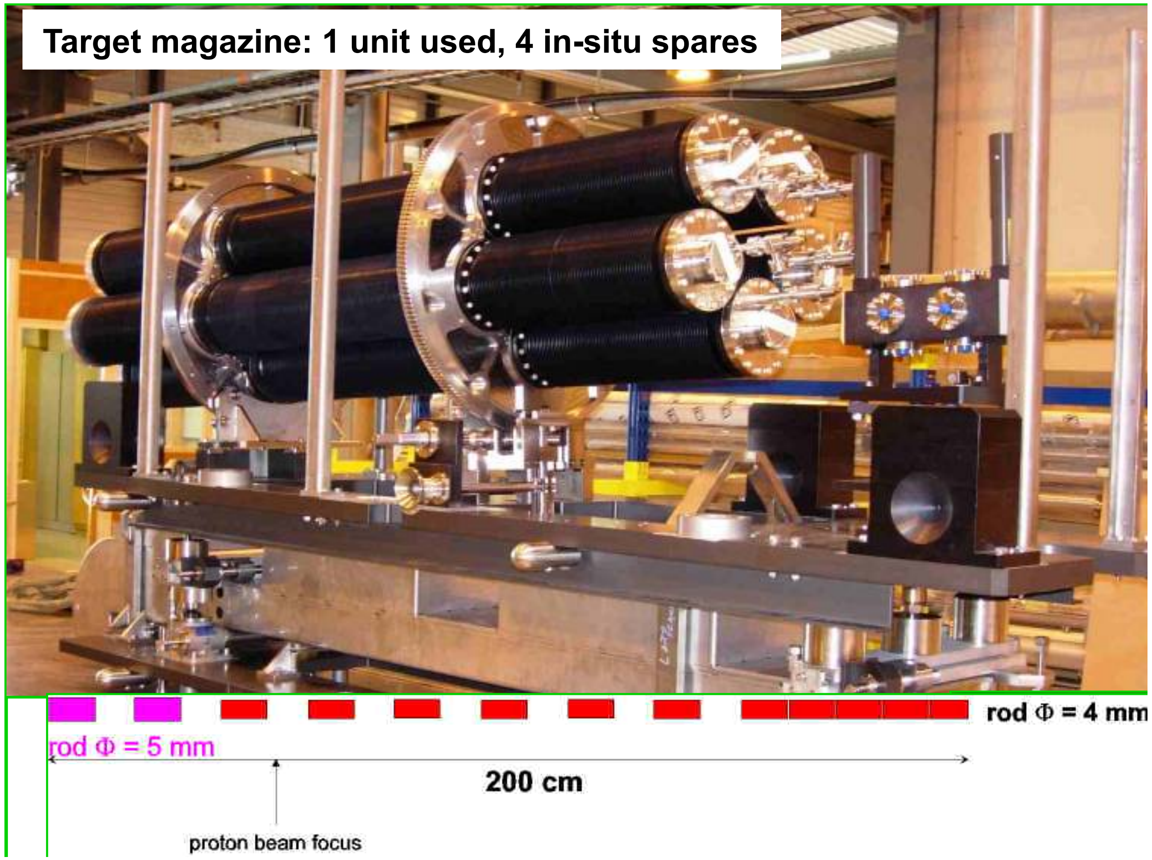


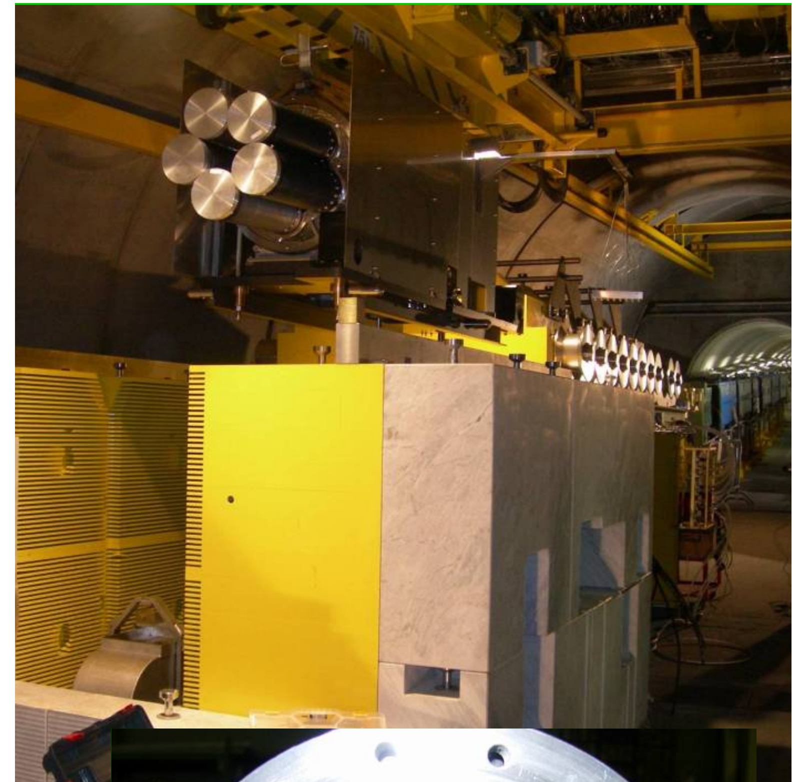


CNGS looks for ν_τ appearance in a beam of ν_μ

The beam is sent from the SPS at 400 GeV/c on the C target. **It is “only” a 450 kW beam**

CNGS target station



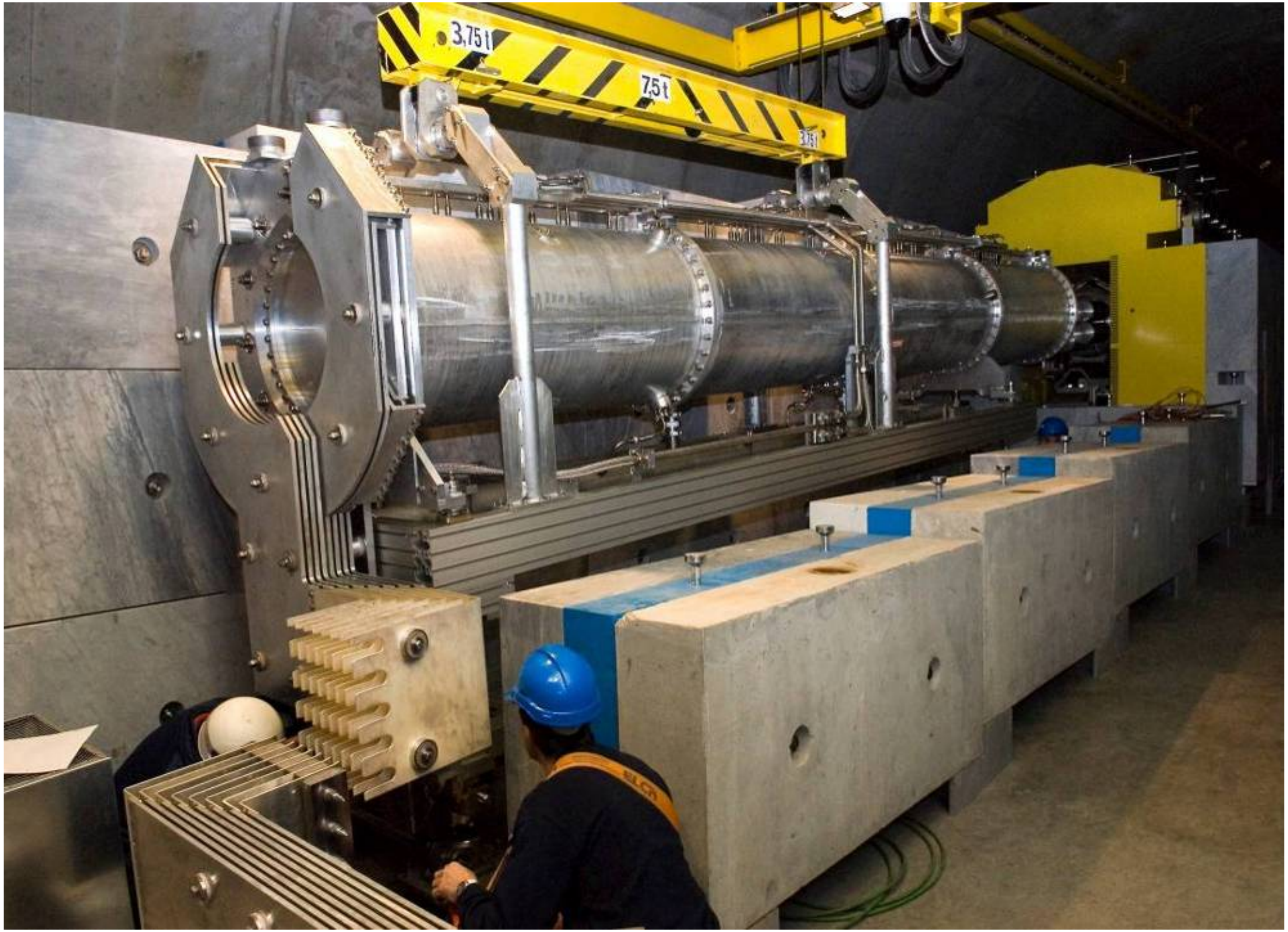


Highly radioactive area.

Everything has to be built to be remotely handled

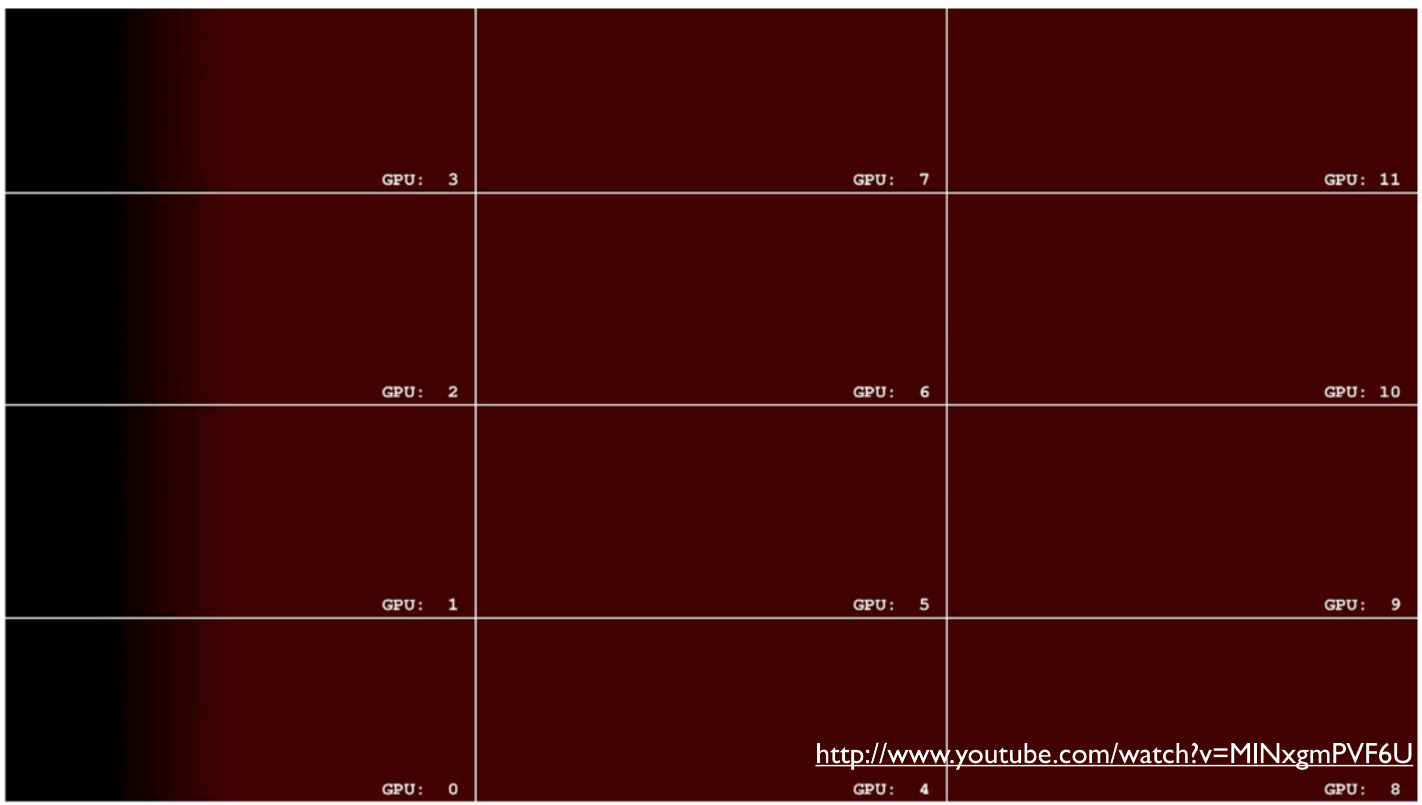
For CNGS, 5 target in situ. One is used, the other four in case of failure. So far... no failures....

CNGS horn



The future (personal view, pretty long term...)

- **Laser plasma acceleration : some GeVs per meter ....**



... that's not for tomorrow... yet… thanks for you attention