Introduction to particle accelerators

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Exercises/questions….

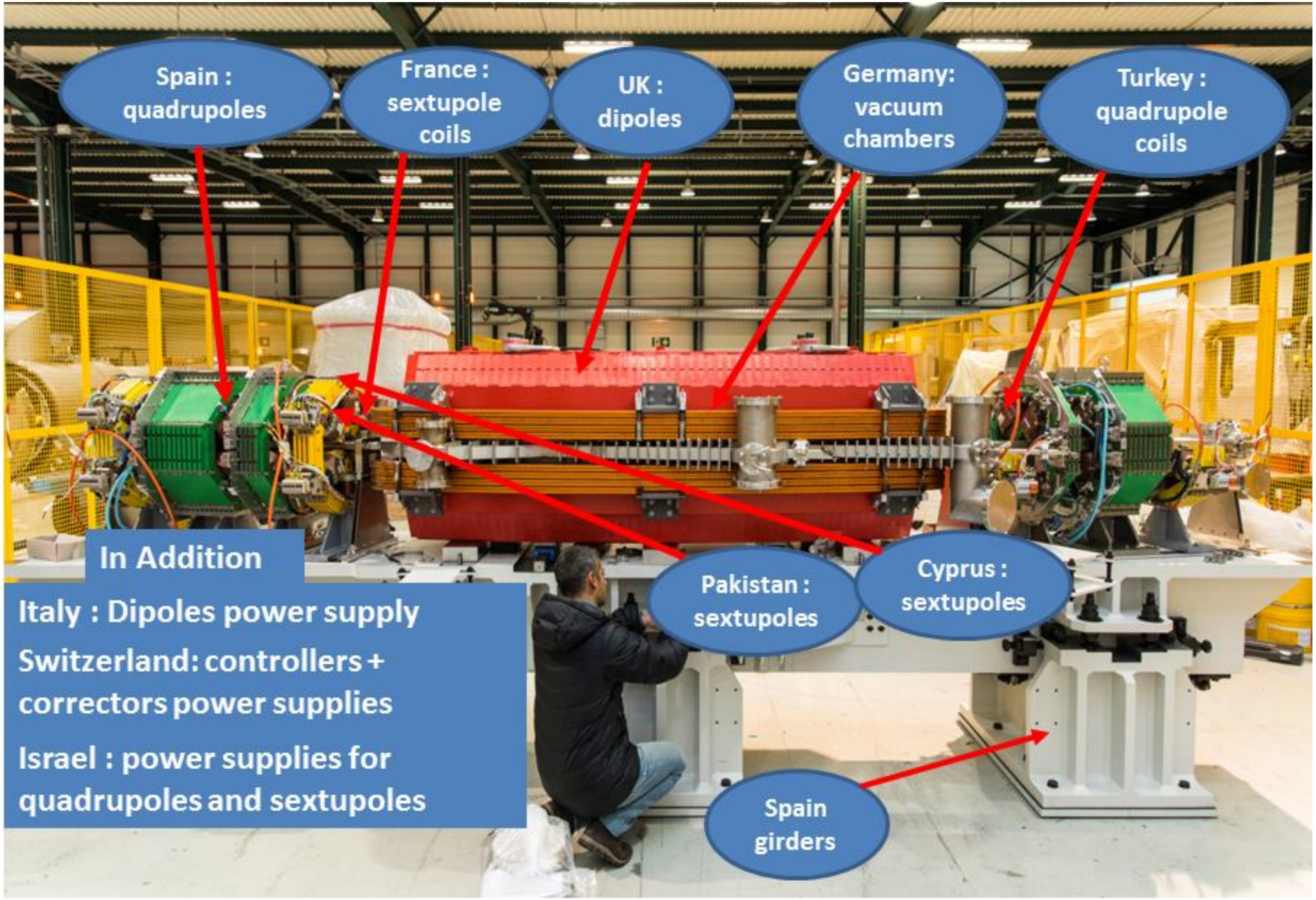
1) **During the LEP run (1996), two bottles of beer have been found inside the vacuum pipe.**

   In the LHC, neglecting the problem of finding a bottle that can fit in the aperture, **where would you place the bottle to minimise the emittance blow-up due to the multiple scattering** introduced by the glass (Consider the collision optics)? At one of the IPs? In one of the collimation sections? In one of the arcs? Motivate the solution

2) How many dipoles form the LHC lattice, knowing that at p=7 TeV each magnet has a field of B=8.33 T and a length of about L=14.2 m?

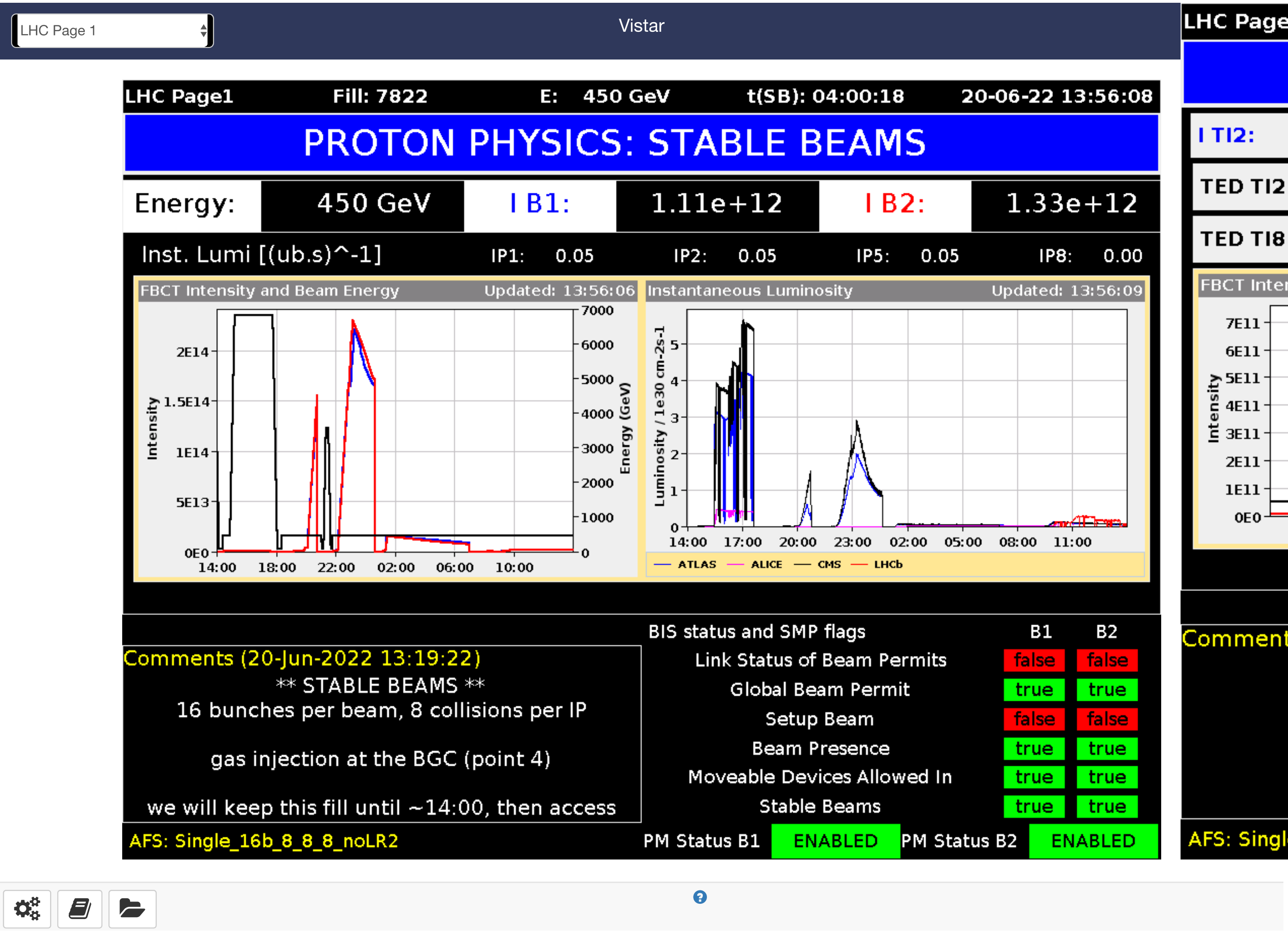
3) Compute the energy stored in the main dipoles at top energy, for an inductance of 98.7 mH and a current of 11850 A.

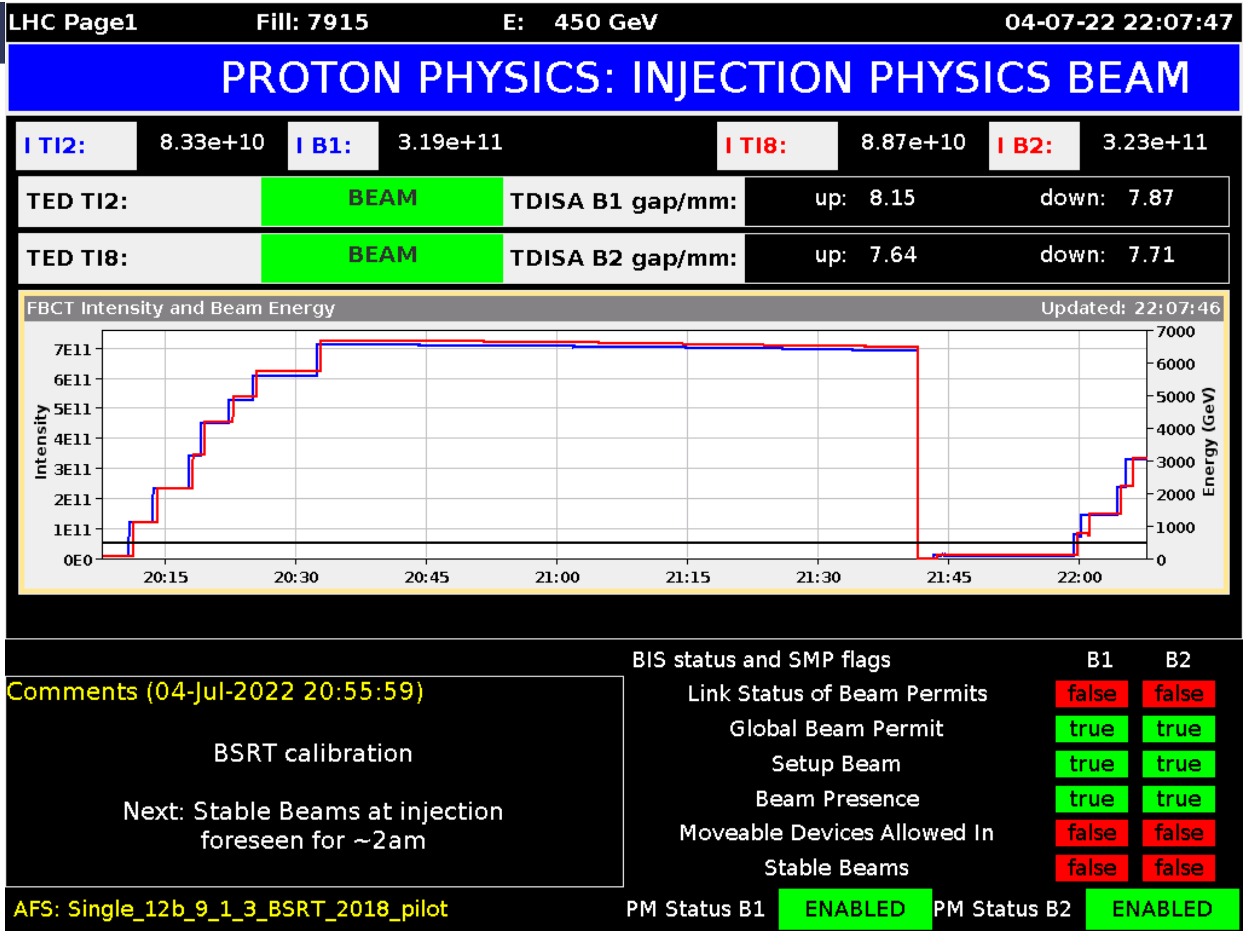
4) How many turns would take for a proton in the LHC to drop out of the LHC vertical aperture of 28 mm due gravitation ? The LHC revolution frequency is 11.245 kHz. Why it doesn't drop?


Spain : quadrupoles
France : sextupole coils
UK : dipoles
Germany: vacuum chambers
Turkey : quadrupole coils
In Addition
Italy : Dipoles power supply
Switzerland: controllers + correctors power supplies
Israel : power supplies for quadrupoles and sextupoles
Pakistan : sextupoles
Cyprus : sextupoles
Spain girders

What are we doing today ?

https://op-webtools.web.cern.ch/vistar/vistars.php

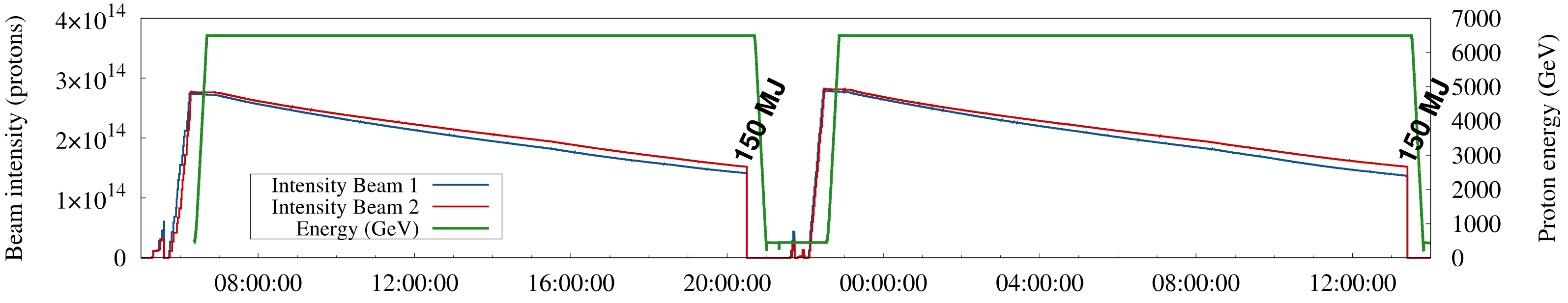

LHC Page 1
Vistar
LHC Page1 Fill: 7822 E: 450 GeV t(SB): 04:00:18 20-06-22 13:56:08
PROTON PHYSICS: STABLE BEAMS
Energy: 450 GeV
I B1: 1.11e+12
I B2: 1.33e+12
Inst. Lumi [(ub.s)^-1] IP1: 0.05 IP2: 0.05 IP5: 0.05 IP8: 0.00
FBCT Intensity and Beam Energy Updated: 13:56:06
Instantaneous Luminosity Updated: 13:56:09
Intensity
Energy (GeV)
Luminosity / 1e30 cm-2s-1
ATLAS ALICE CMS LHCb
BIS status and SMP flags B1 B2
Comments (20-Jun-2022 13:19:22)
** STABLE BEAMS **
16 bunches per beam, 8 collisions per IP
gas injection at the BGC (point 4)
we will keep this fill until ~14:00, then access
Link Status of Beam Permits false false
Global Beam Permit true true
Setup Beam false false
Beam Presence true true
Moveable Devices Allowed In true true
Stable Beams true true
AFS: Single_16b_8_8_8_noLR2
PM Status B1 ENABLED PM Status B2 ENABLED


LHC Page1 Fill: 7915 E: 450 GeV 04-07-22 22:07:47
PROTON PHYSICS: INJECTION PHYSICS BEAM
I TI2: 8.33e+10 I B1: 3.19e+11 I TI8: 8.87e+10 I B2: 3.23e+11
TED TI2: BEAM TDISA B1 gap/mm: up: 8.15 down: 7.87
TED TI8: BEAM TDISA B2 gap/mm: up: 7.64 down: 7.71
FBCT Intensity and Beam Energy Updated: 22:07:46
Intensity
Energy (GeV)
BIS status and SMP flags B1 B2
Comments (04-Jul-2022 20:55:59)
BSRT calibration
Next: Stable Beams at injection
foreseen for ~2am
Link Status of Beam Permits false false
Global Beam Permit true true
Setup Beam true true
Beam Presence true true
Moveable Devices Allowed In false false
Stable Beams false false
AFS: Single_12b_9_1_3_BSRT_2018_pilot
PM Status B1 ENABLED PM Status B2 ENABLED

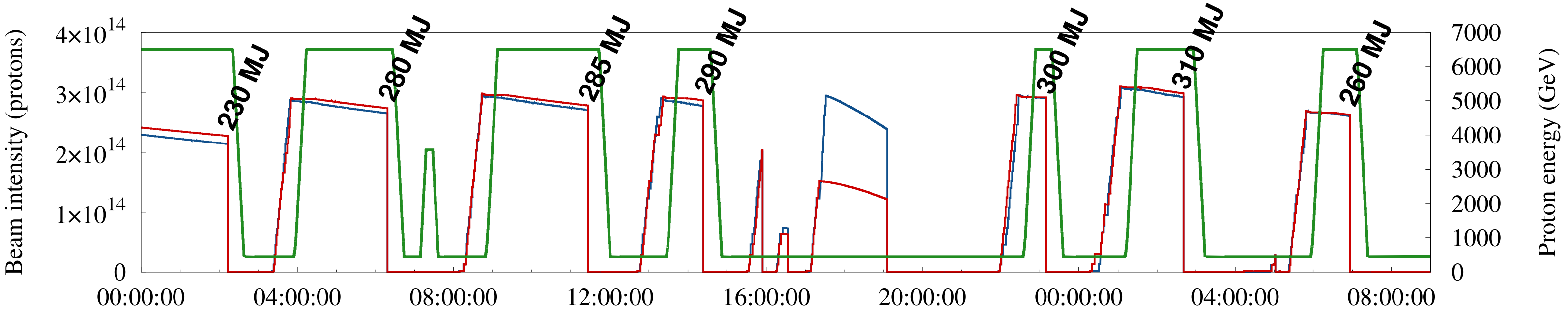
LHC cycles: typical days (good and bad ....)

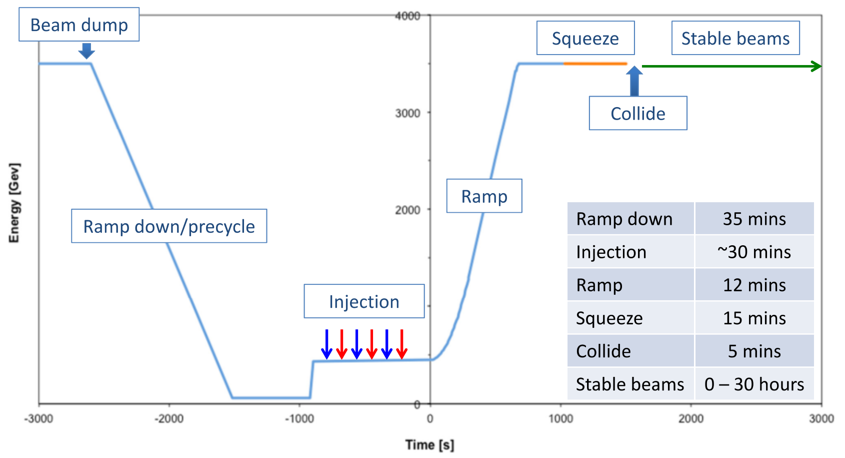
Dumped energy = ***proton energy*** × ***beam intensity*** *at the moment of beam extraction*

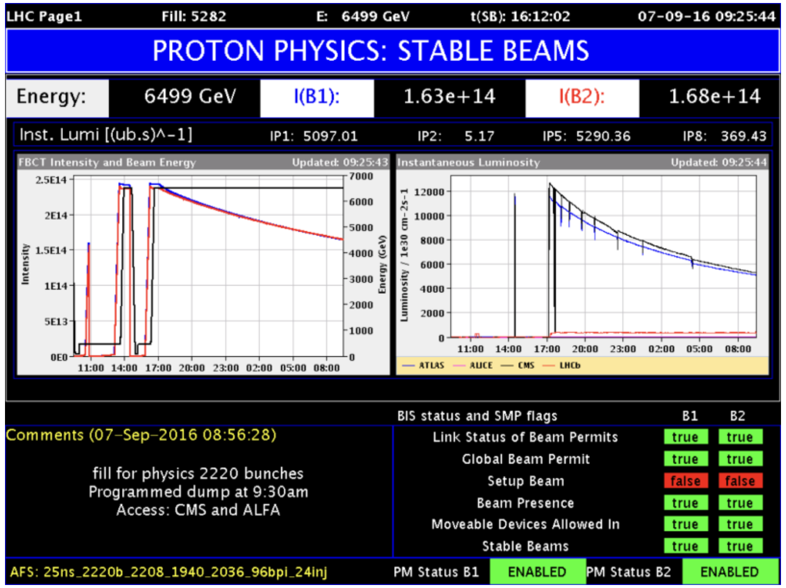
Good day:



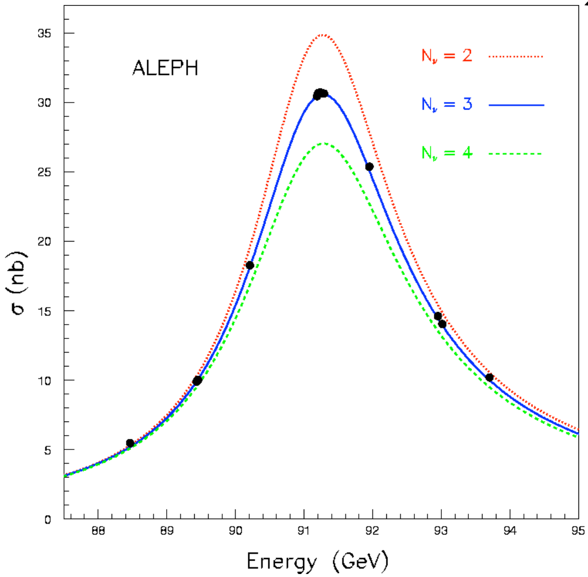
Bad day:

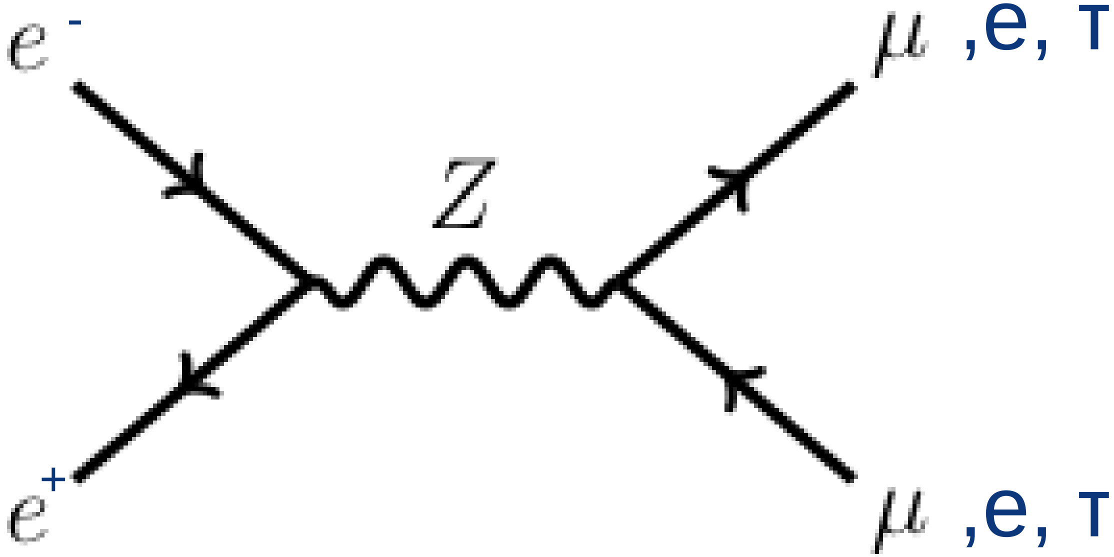




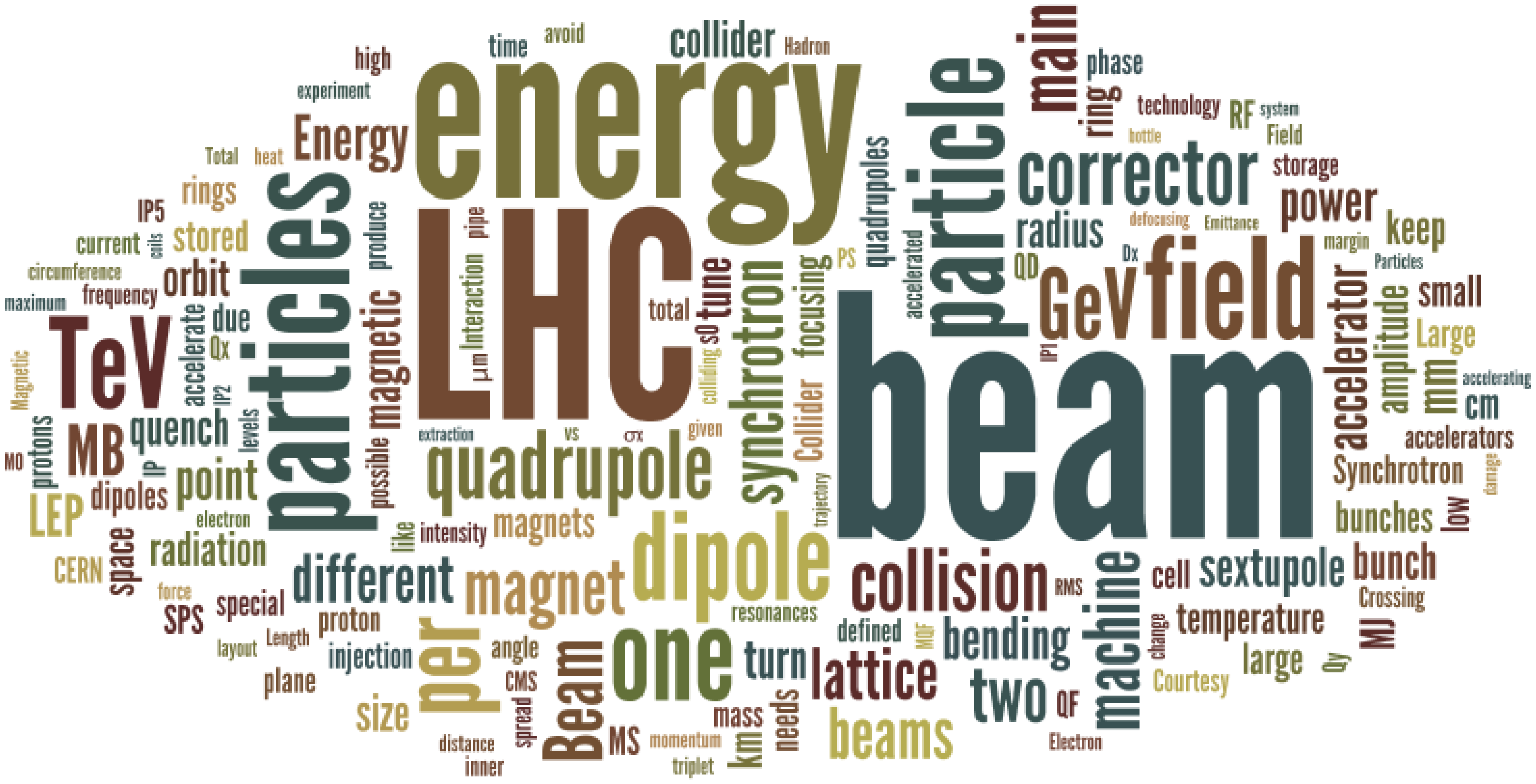


First question: what is the relationship between this, the moon, and a train?



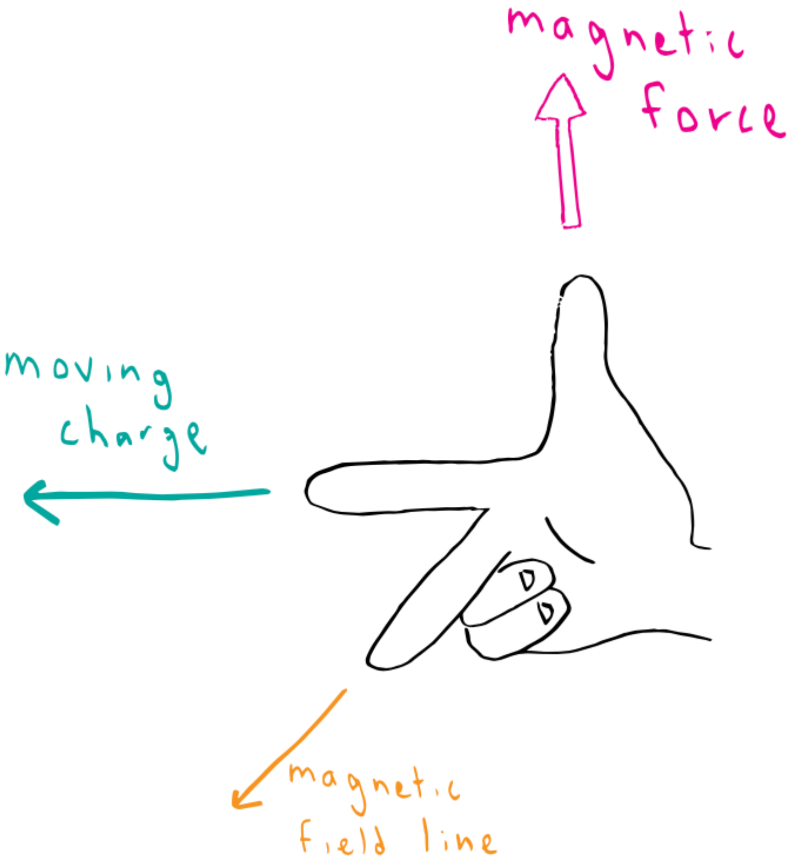


The agenda...



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

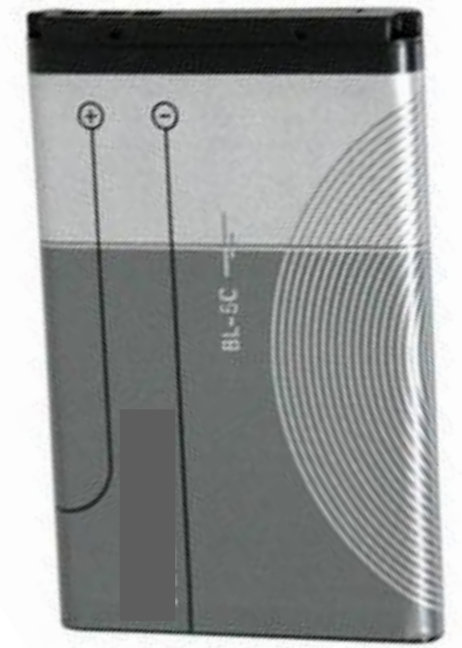
The “law” for these days : right hand rule



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

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

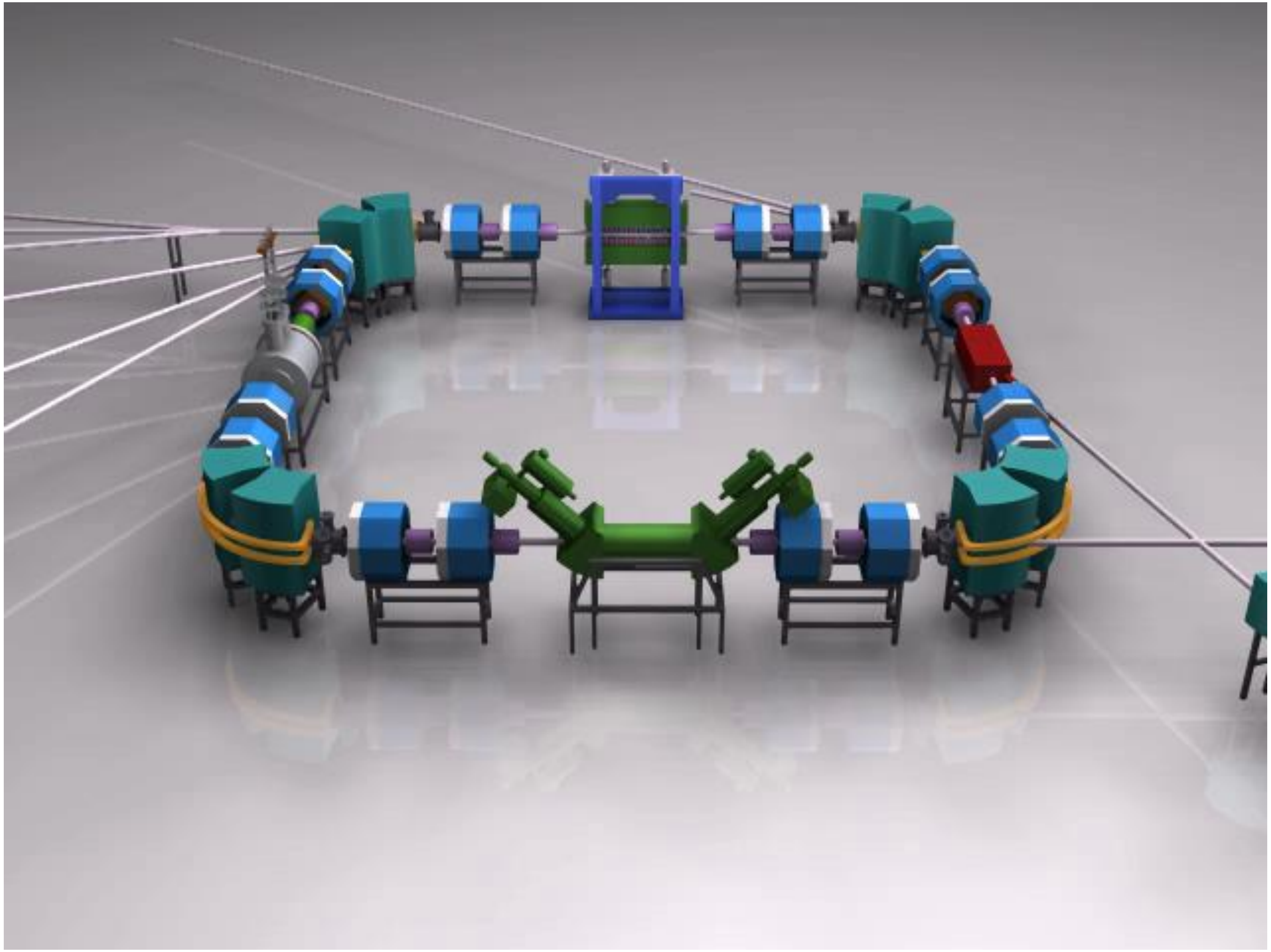
To accelerate an electron to an energy equivalent to a proton mass:

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 ....



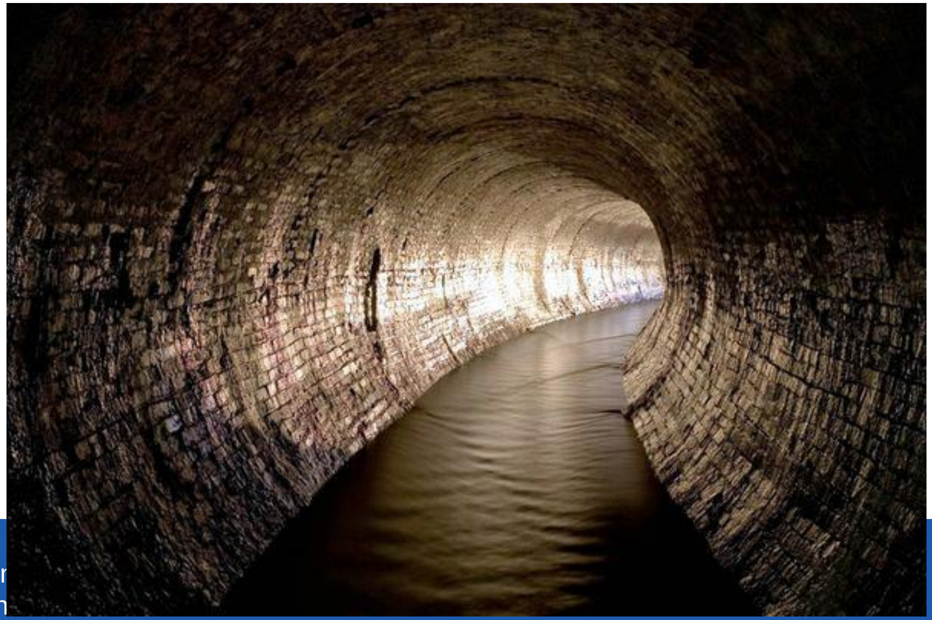
Electron Injection, Storage and Synchrotron Radiation Light Generation in the Storage Ring ASTRID. (Credit: Coldvision Studio/ISA)

Building Blocks of an accelerator

1) A particle source

2) An accelerating system

3) A series of guiding and storage devices

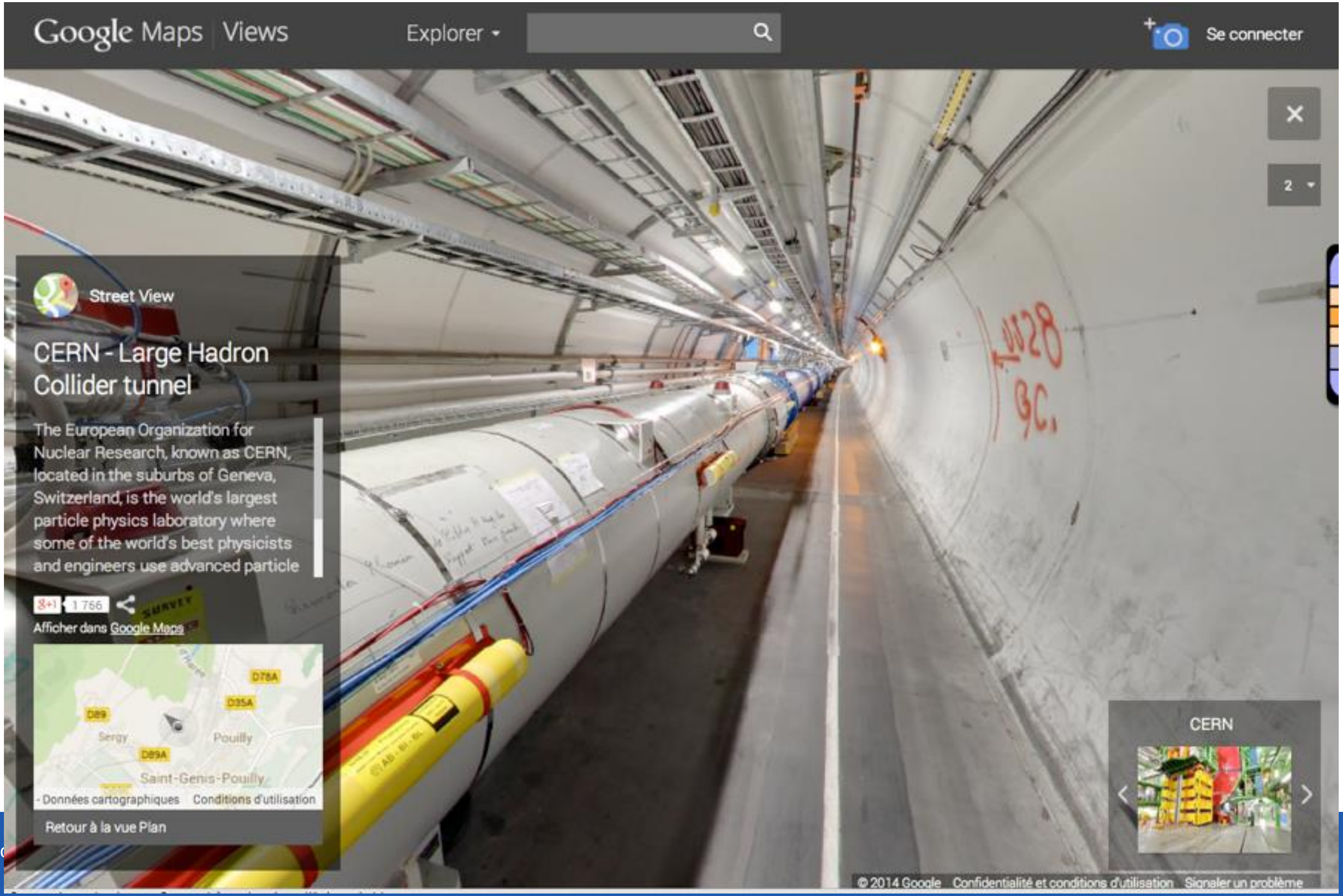


Everything under vacuum

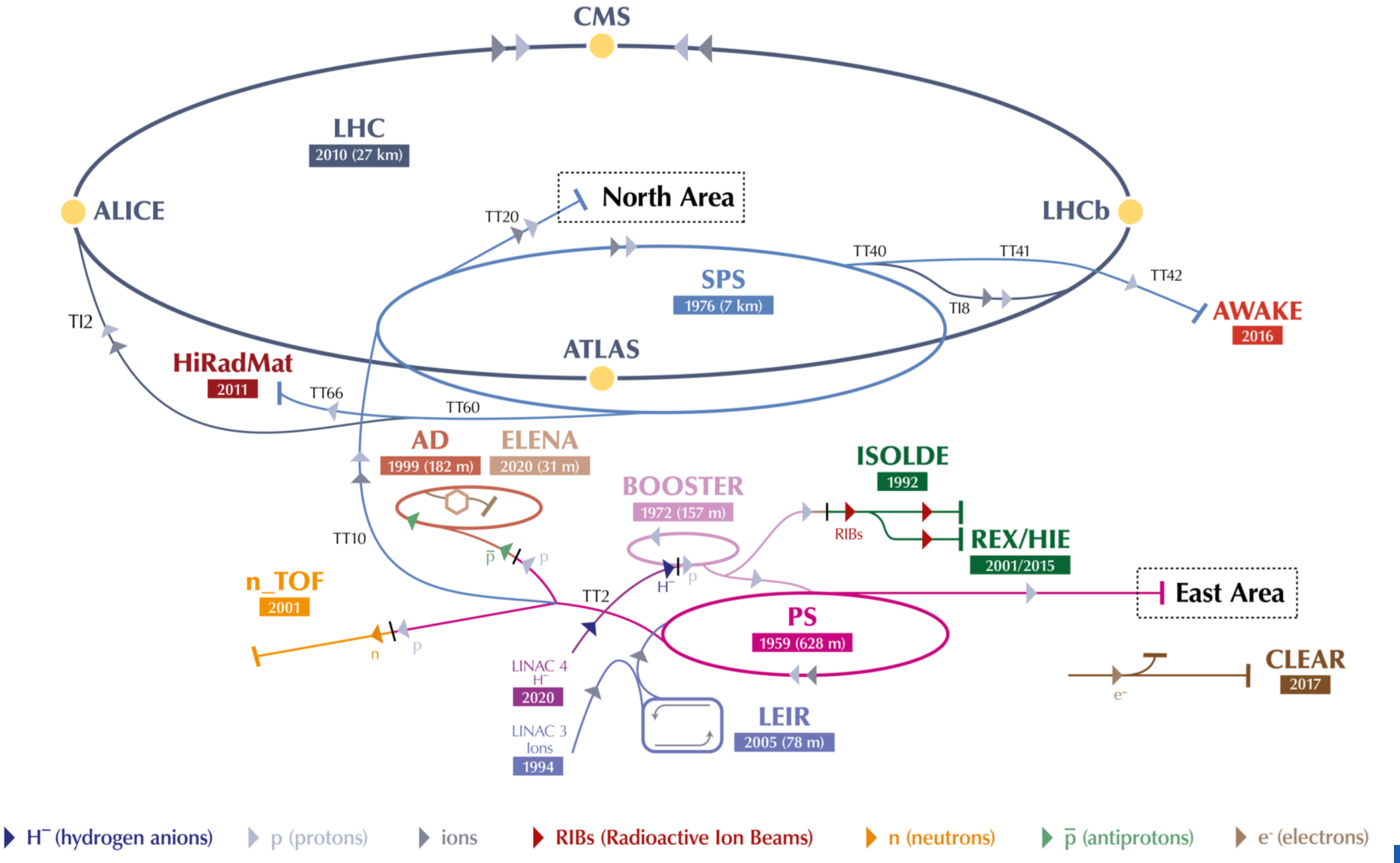
A Google view of high energy accelerators

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 ....

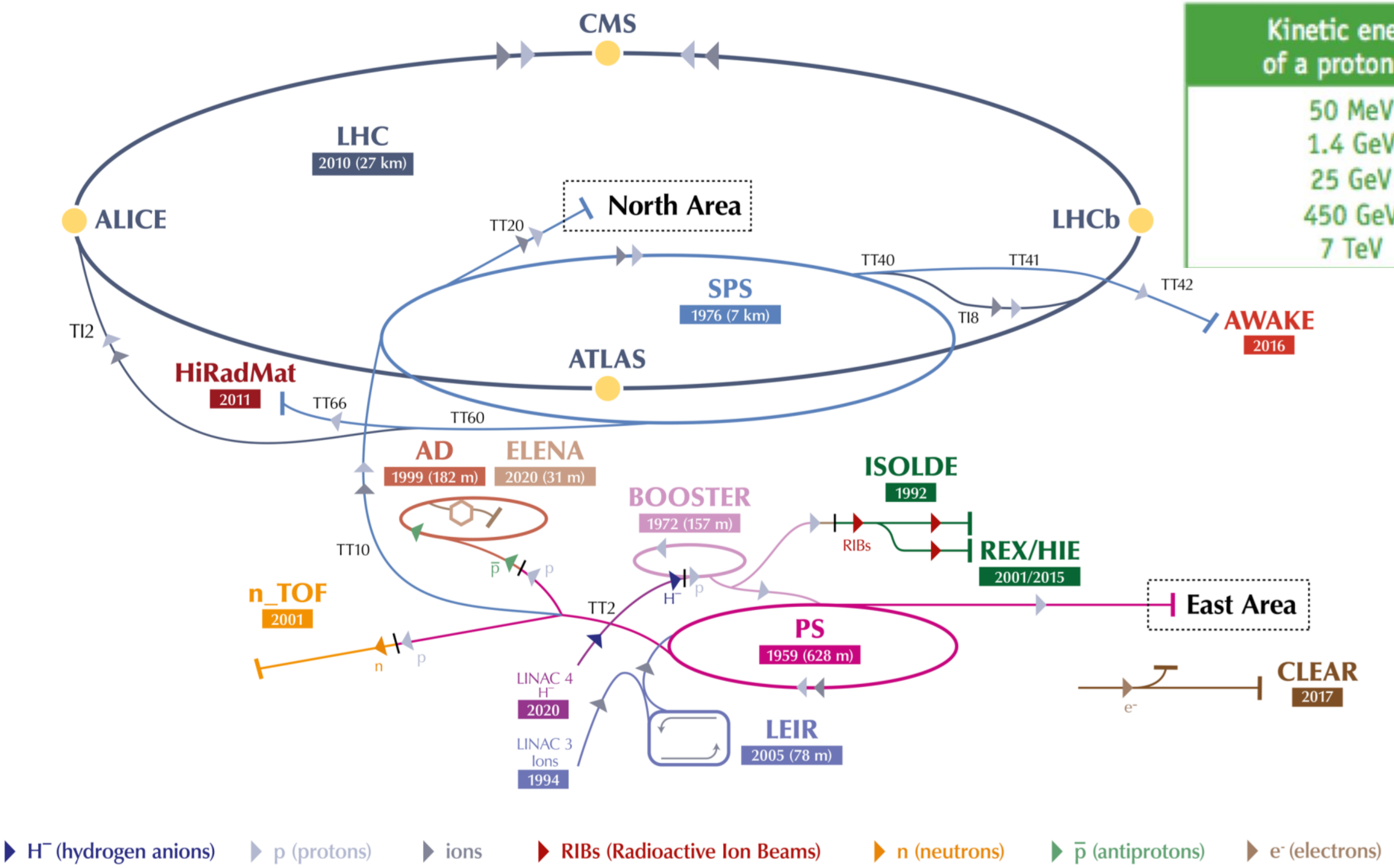


CERN accelerator complex overview



A view from the sky…

CERN accelerator complex as now

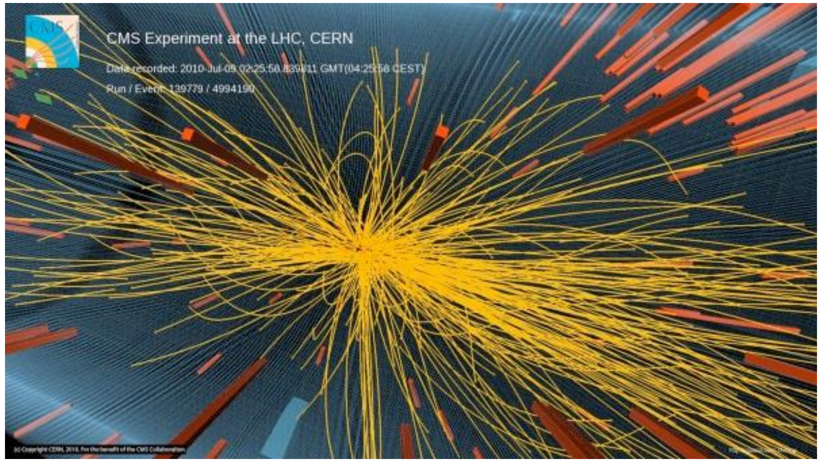


Kinetic energy of a proton (K)	Speed (%c)	Accelerator
50 MeV	31.4	Linac 2
1.4 GeV	91.6	PS Booster
25 GeV	99.93	PS
450 GeV	99.9998	SPS
7 TeV	99.9999991	LHC

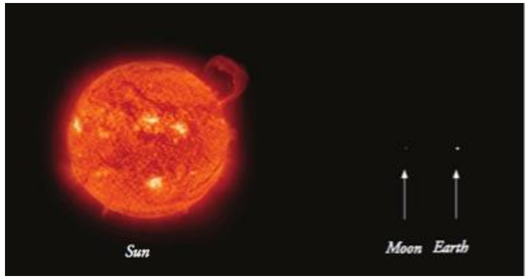
Basically accelerators brings you ...

from nearly a bottle of hydrogen

to a little bit before this



How much time(distance) does it take from the source to collisions ?
(assumption, protons travels always at the speed of light)



In the Linac 4, basically nothing.
In the **PSB,** a bit less than than 1.2 s.
In the **PS**, a bit less than 3.6 s
In the **SPS**, a bit less than 16.8 s
In the **LHC**, minimum 30 minutes

1 821.6 s → 546 480 000 km

about 3.7 time the distance Sun-Earth

How long does it takes a turn in the LHC ?

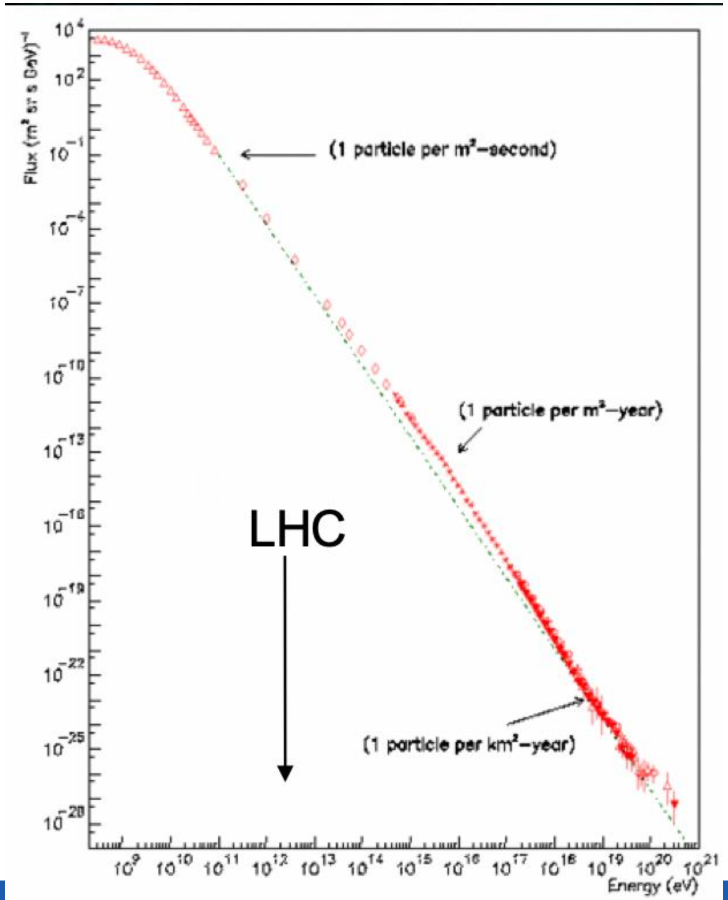
89 microseconds → 1 LHC turn

5 milliseconds – **a honey bee's wing flap** OR **~ 56 LHC turns**

The average human eye blink takes 350 milliseconds OR ~ 3930 LHC turn

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/cm^2/s** are traversing your body, about 10^5 LHC-equivalent experiment done by cosmic rays

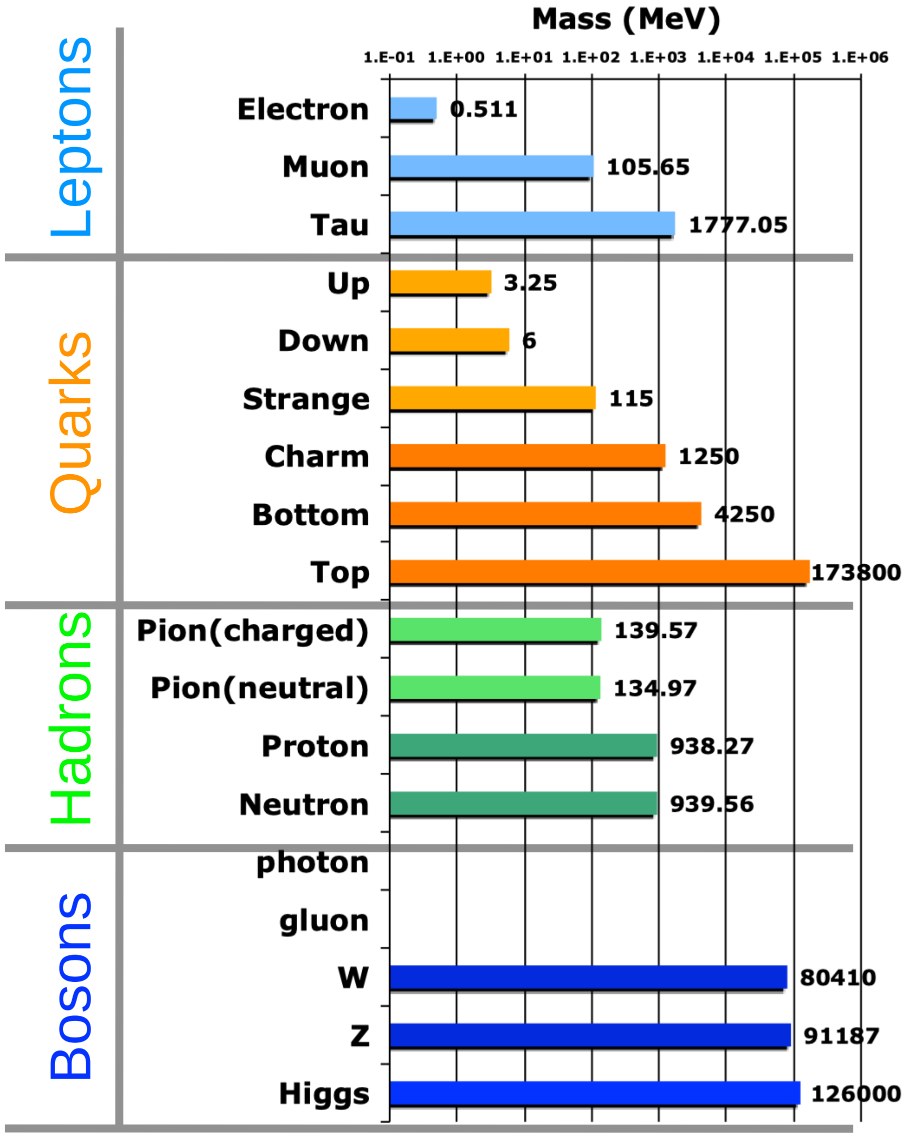
With a space distribution too dispersed for today's HEP physics!

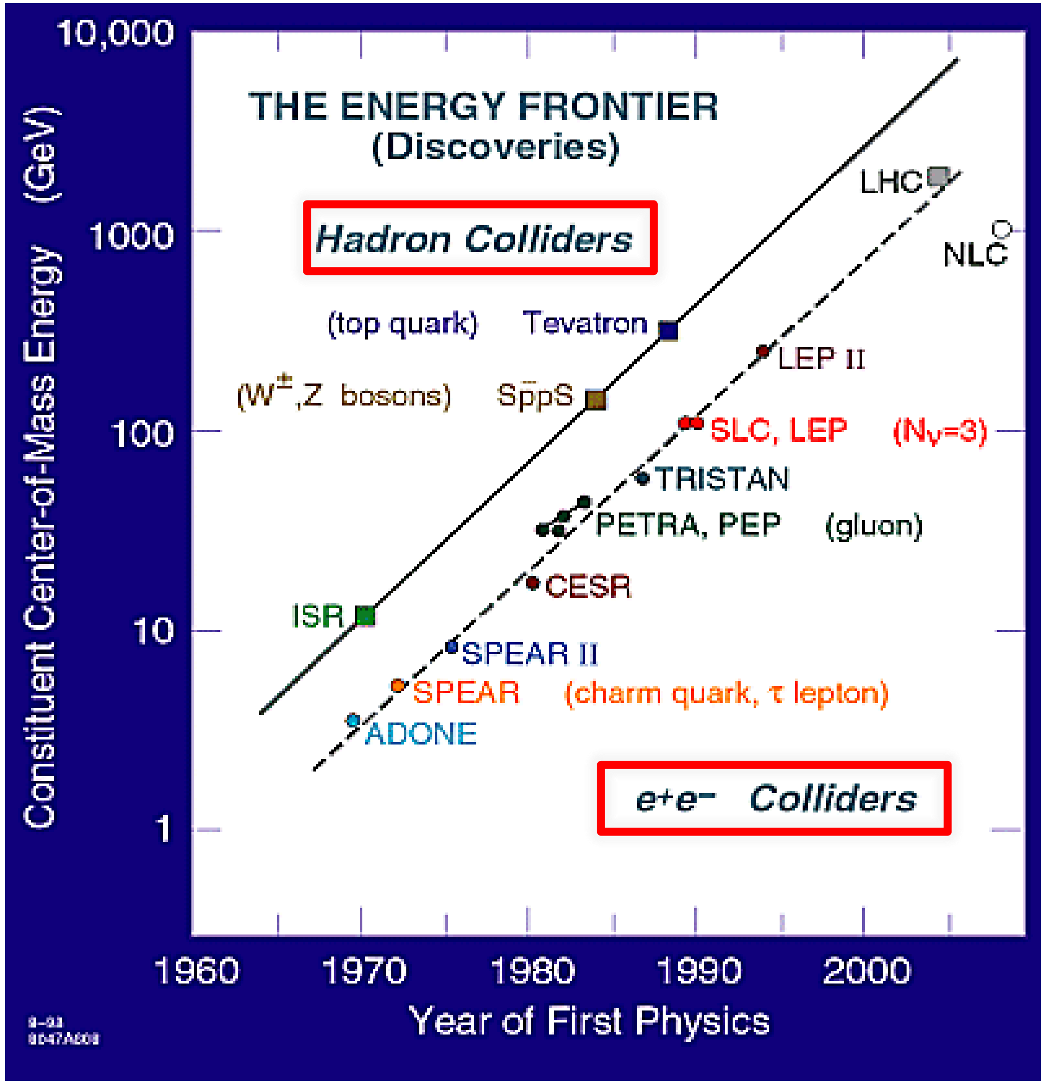
Cloud chamber, from YOUTUBE

To accelerate particles, nature can count on exceptional phenomena

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

History/Energy line vs discovery potentials

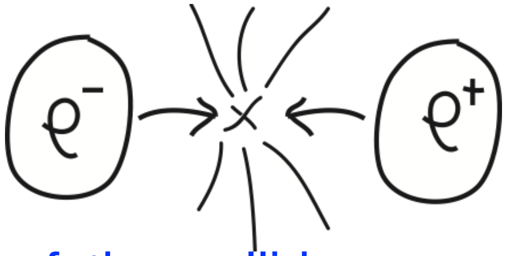




Different particle species used in the different collider: Why?

The right particle for the right 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

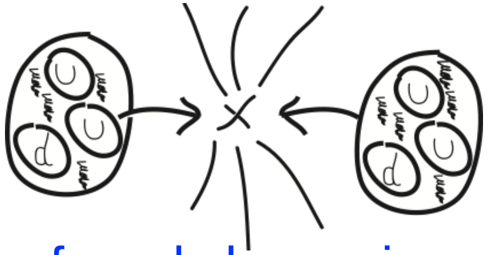
Ecoll= Eb1+ Eb2= 2Eb = 200 GeV (LEP)

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

Precision measurement (LEP)

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

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)

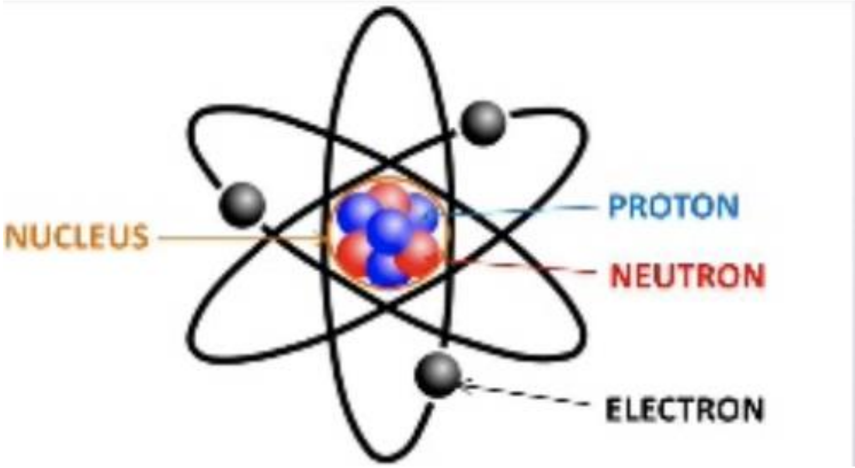
Pros: with a single energy possible to scan different processes at different energies.

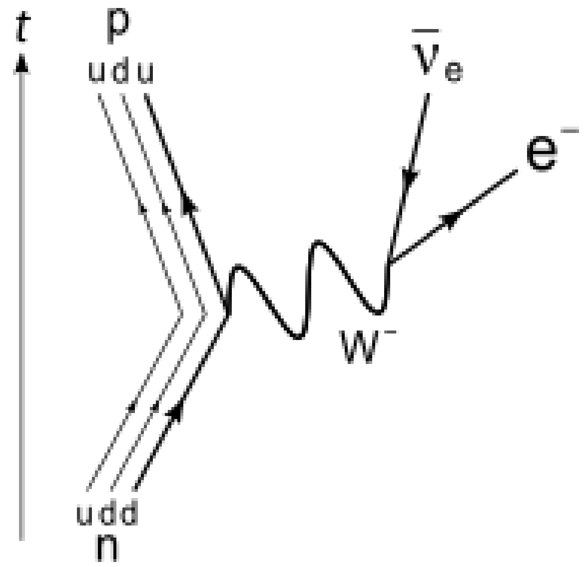
Discovery machine (LHC)

Cons: the energy available for the collision is lower than the accelerator energy

What is the LHC ? H = HADRON

- Protons are hadrons because are made of quarks

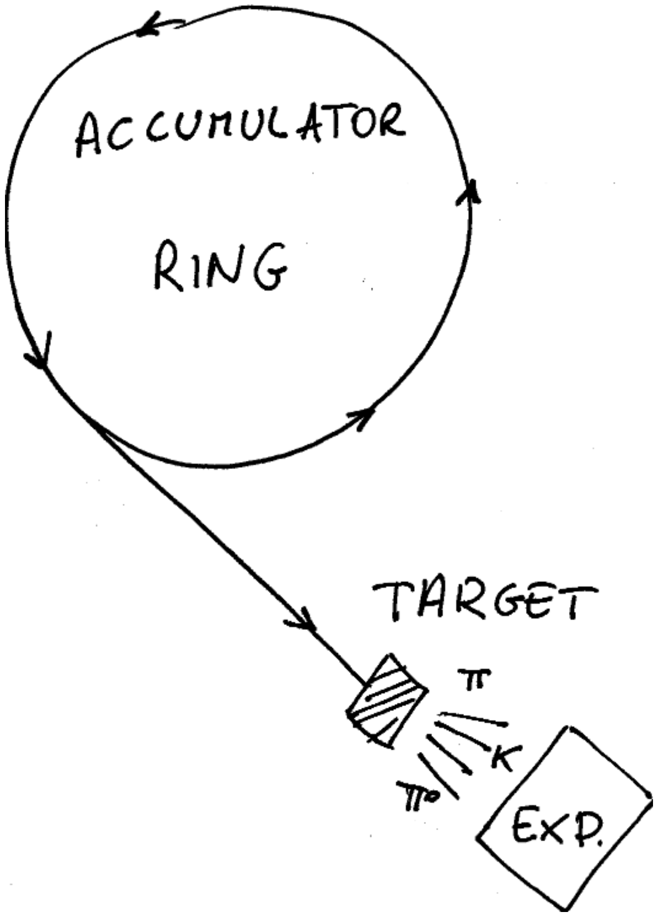




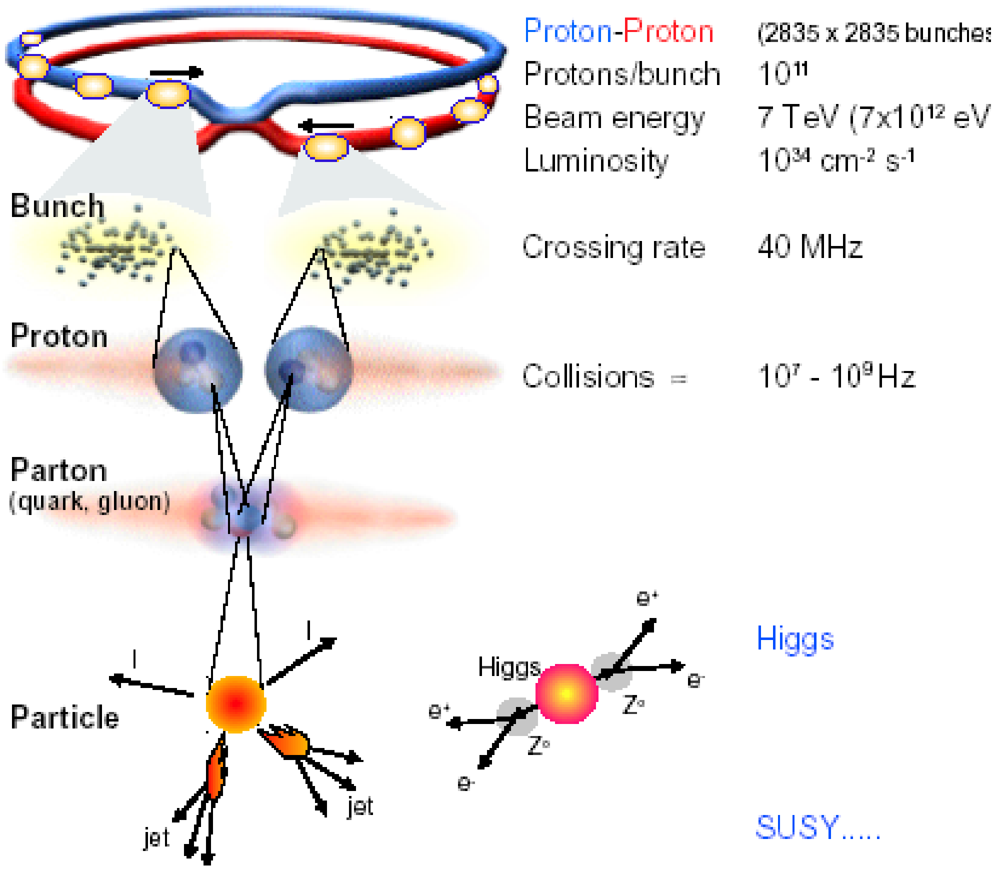
How many quarks in a proton?

Different approaches: fixed target vs collider

Fixed target



Storage ring/collider



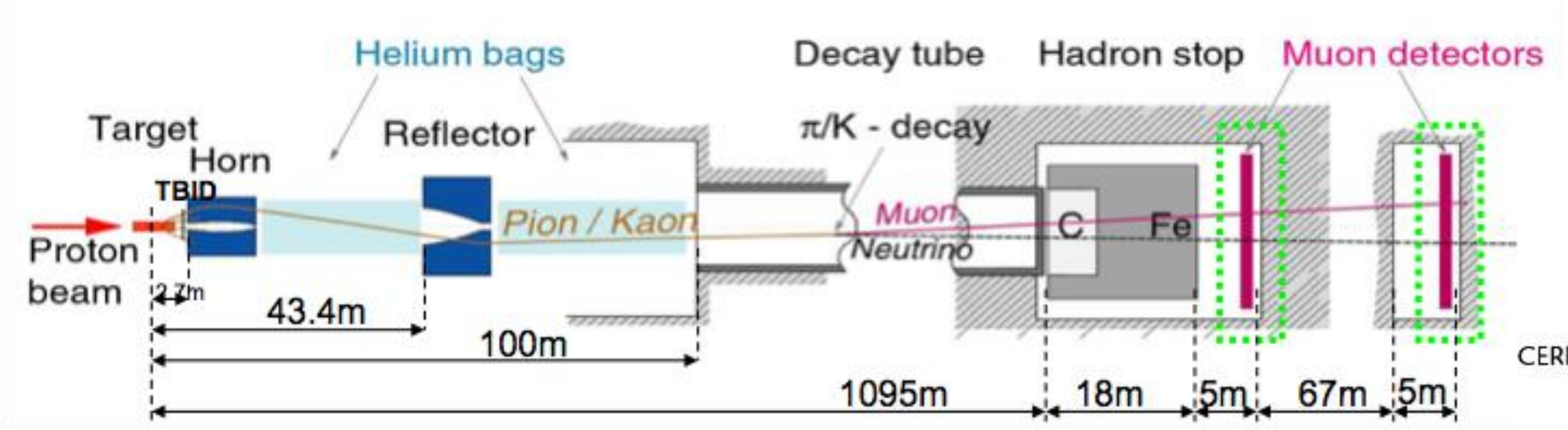
$$E_{CM} = \sqrt{2\left(E_{beam}mc^2 + m^2c^4\right)}$$

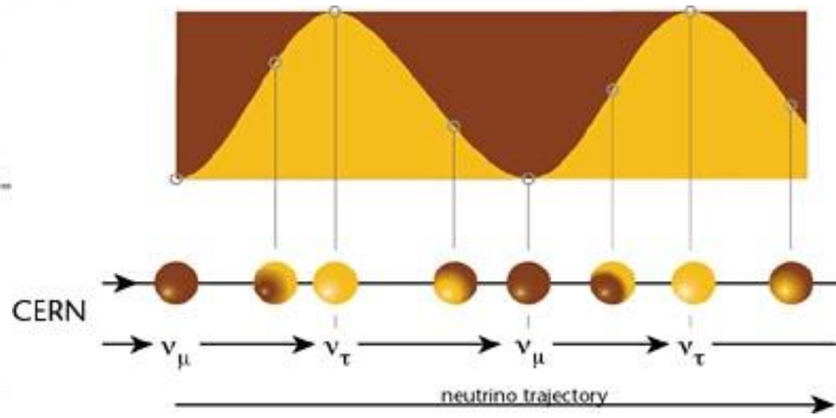
<<

$$E_{CM} = 2\left(E_{beam} + mc^2\right)$$

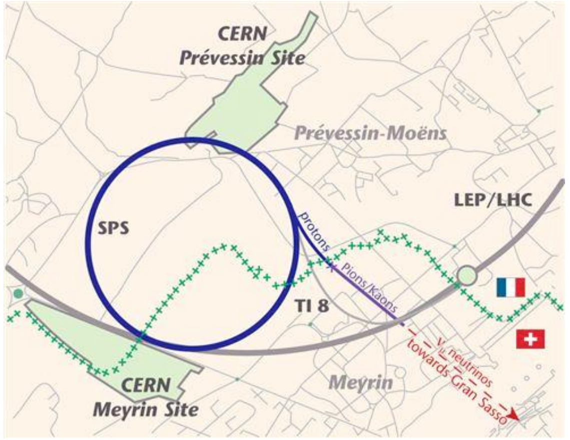
This usually is defined as √s

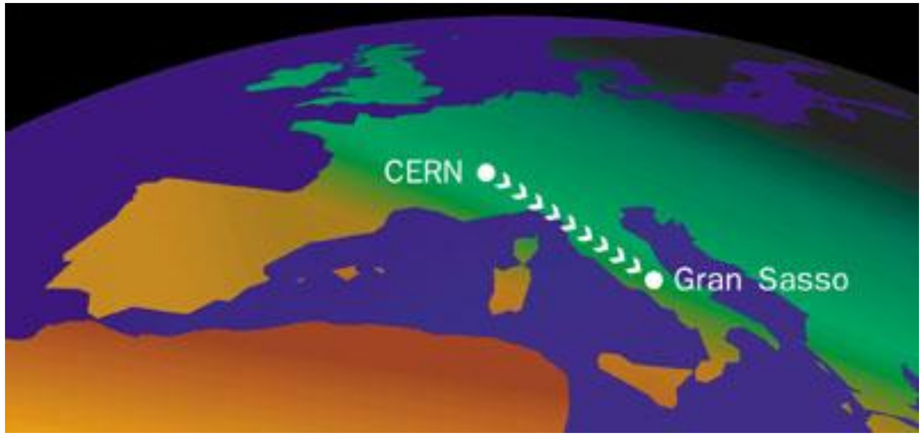
CNGS, conventional man-made neutrino beam

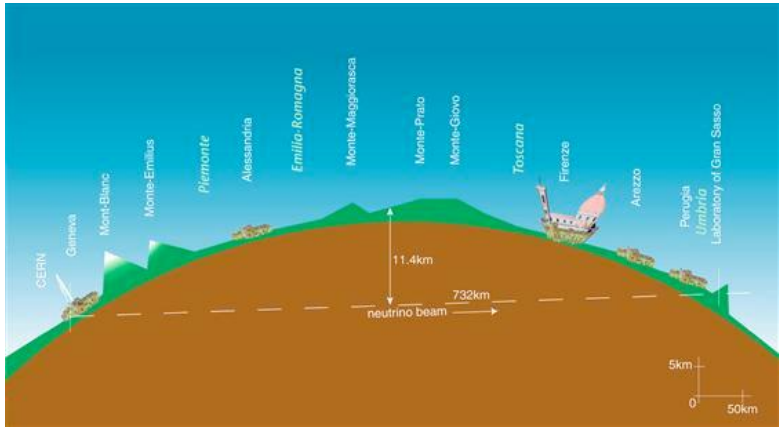




CERN to Grans Sasso





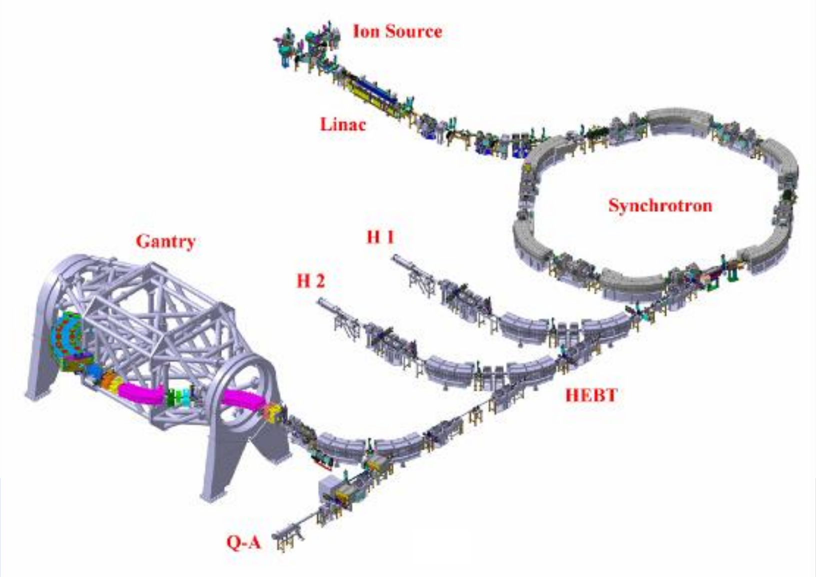


CNGS looked for ν_τ appearance in a beam of ν_μ

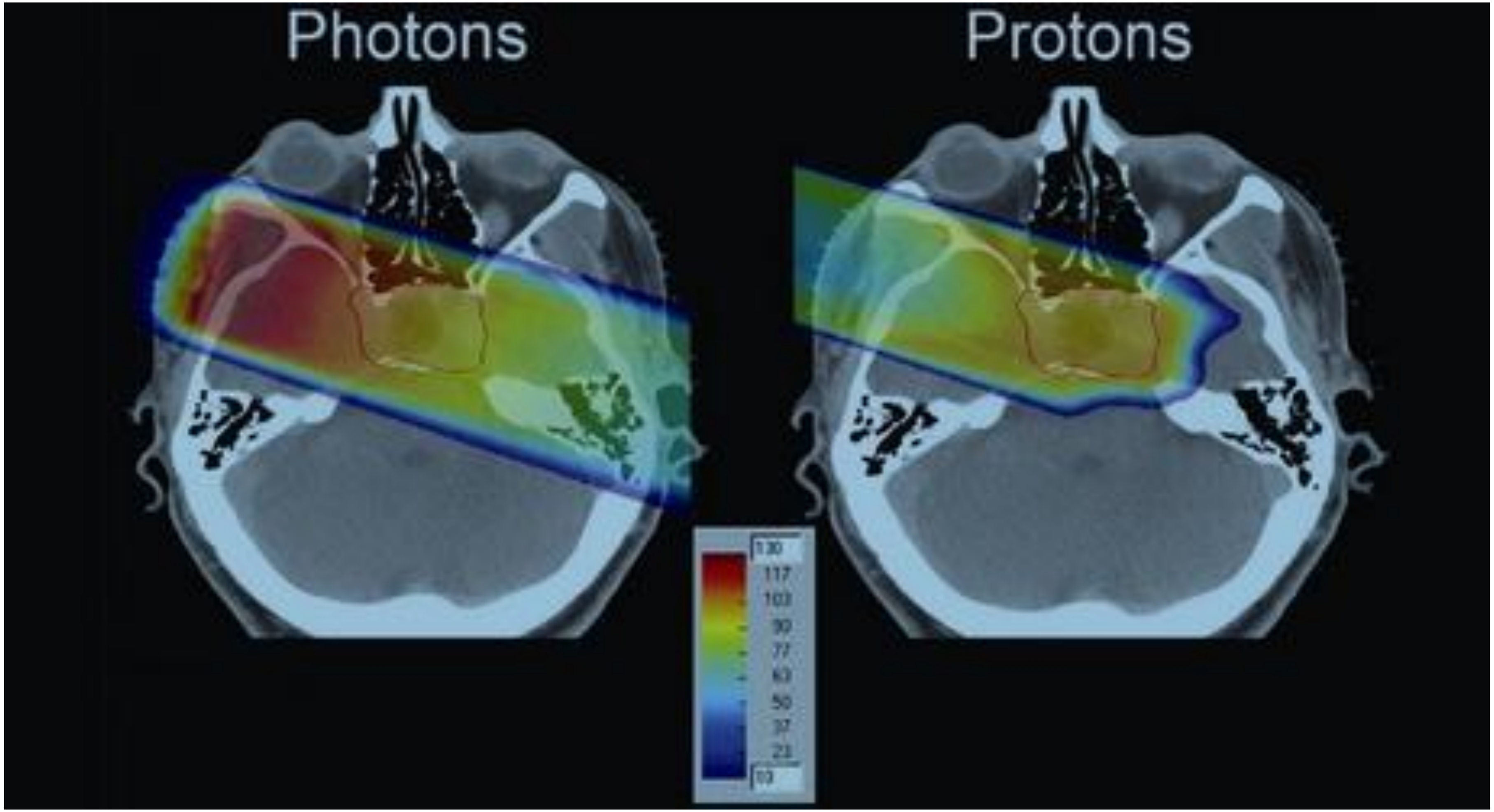
The beam was sent from the SPS at 400 GeV/c on the C target. **It was “only” a 450 kW beam**

Accelerators for cancer therapy

THE HEIDELBERG ION THERAPY (HIT)



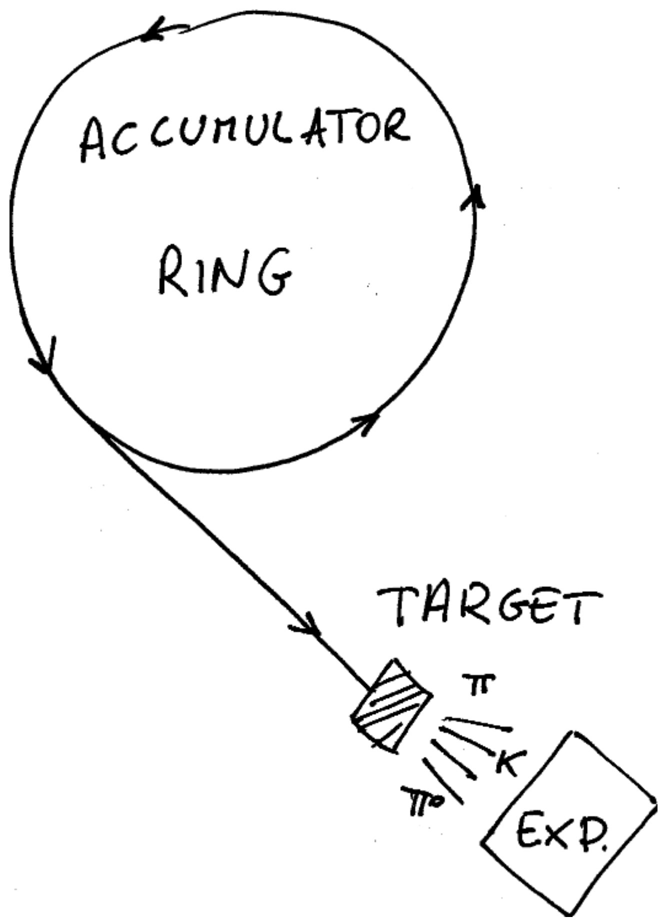
Cyclotron application: cancer therapy, photons vs protons



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

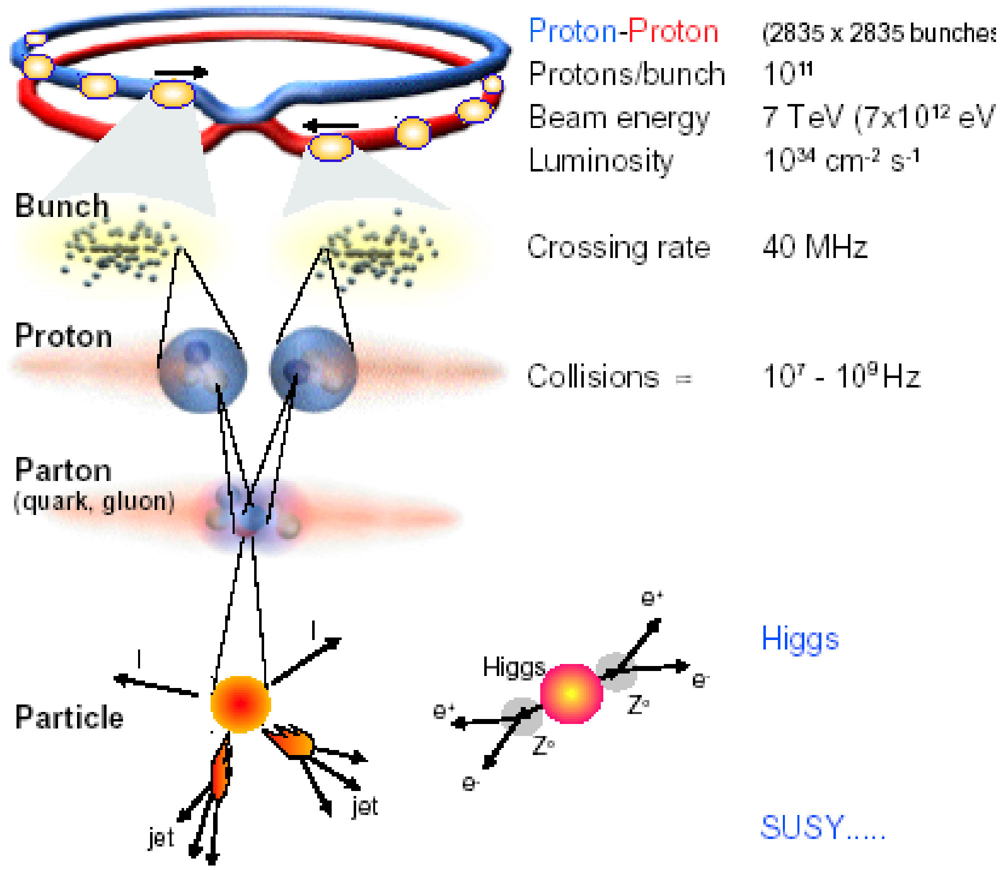
Different approaches: fixed target vs collider

Fixed target



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

Storage ring/collider



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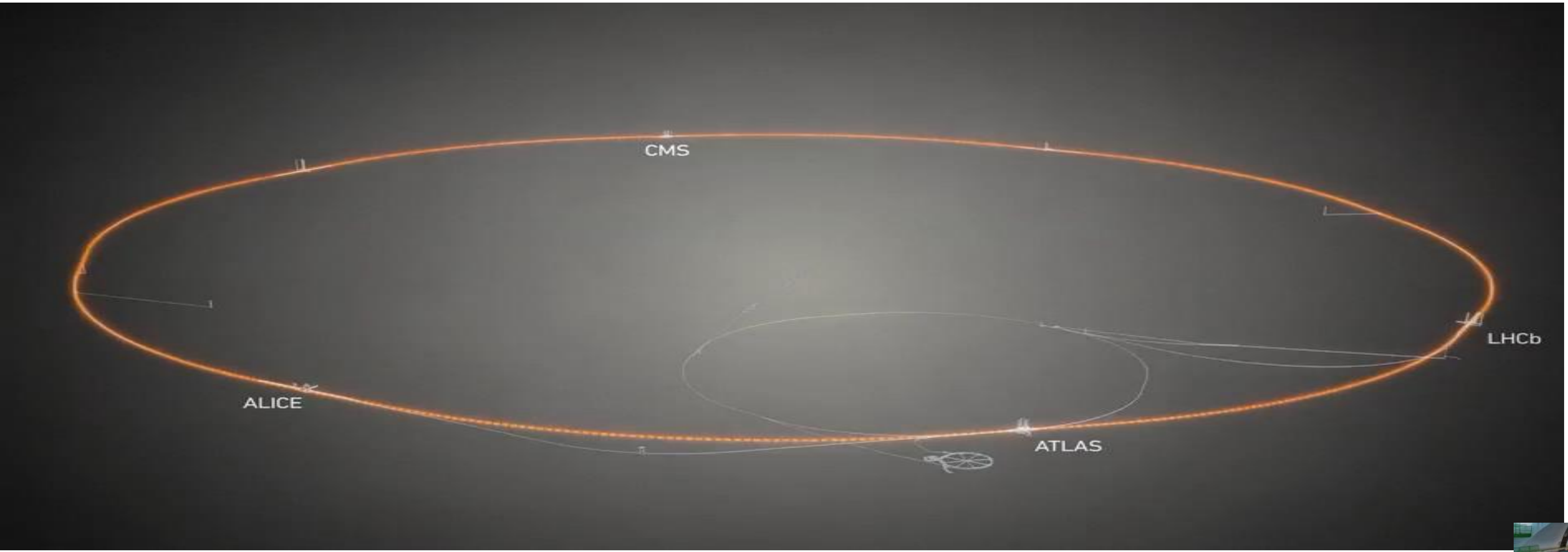
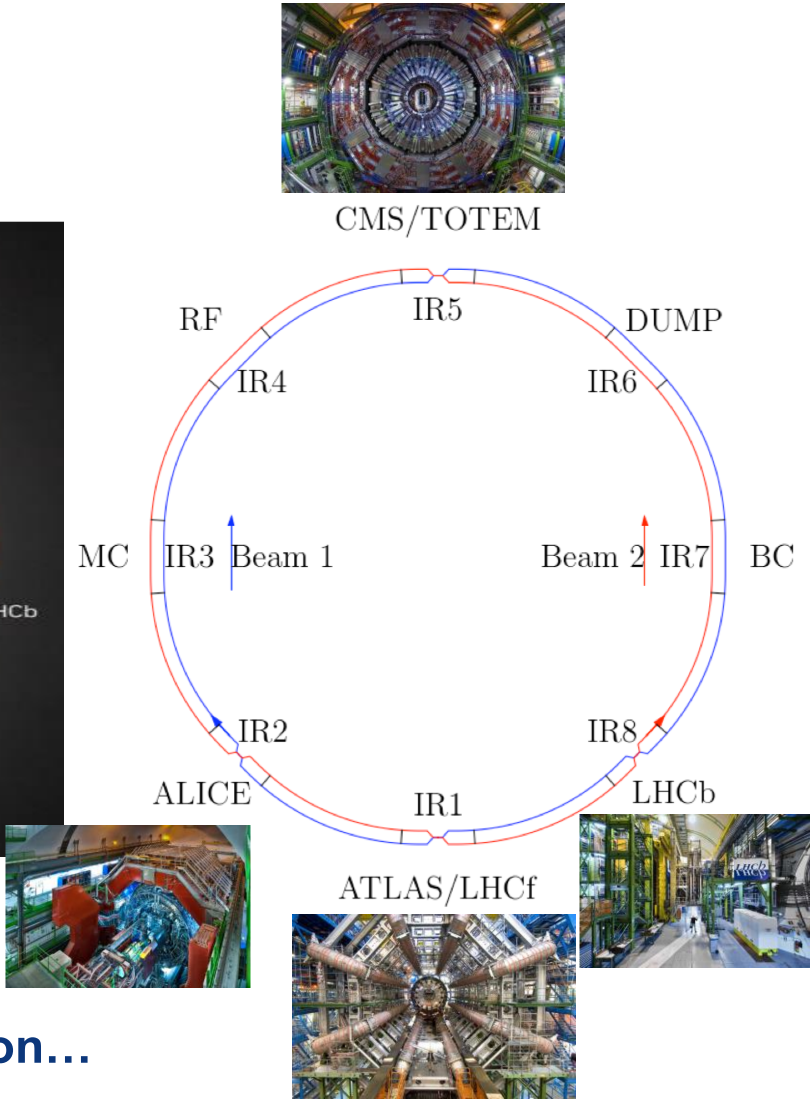
$$E_{CM} = 2\left(E_{beam} + mc^2\right)$$

This usually is defined as √s

Collider: LHC with 4 collision points (IP)





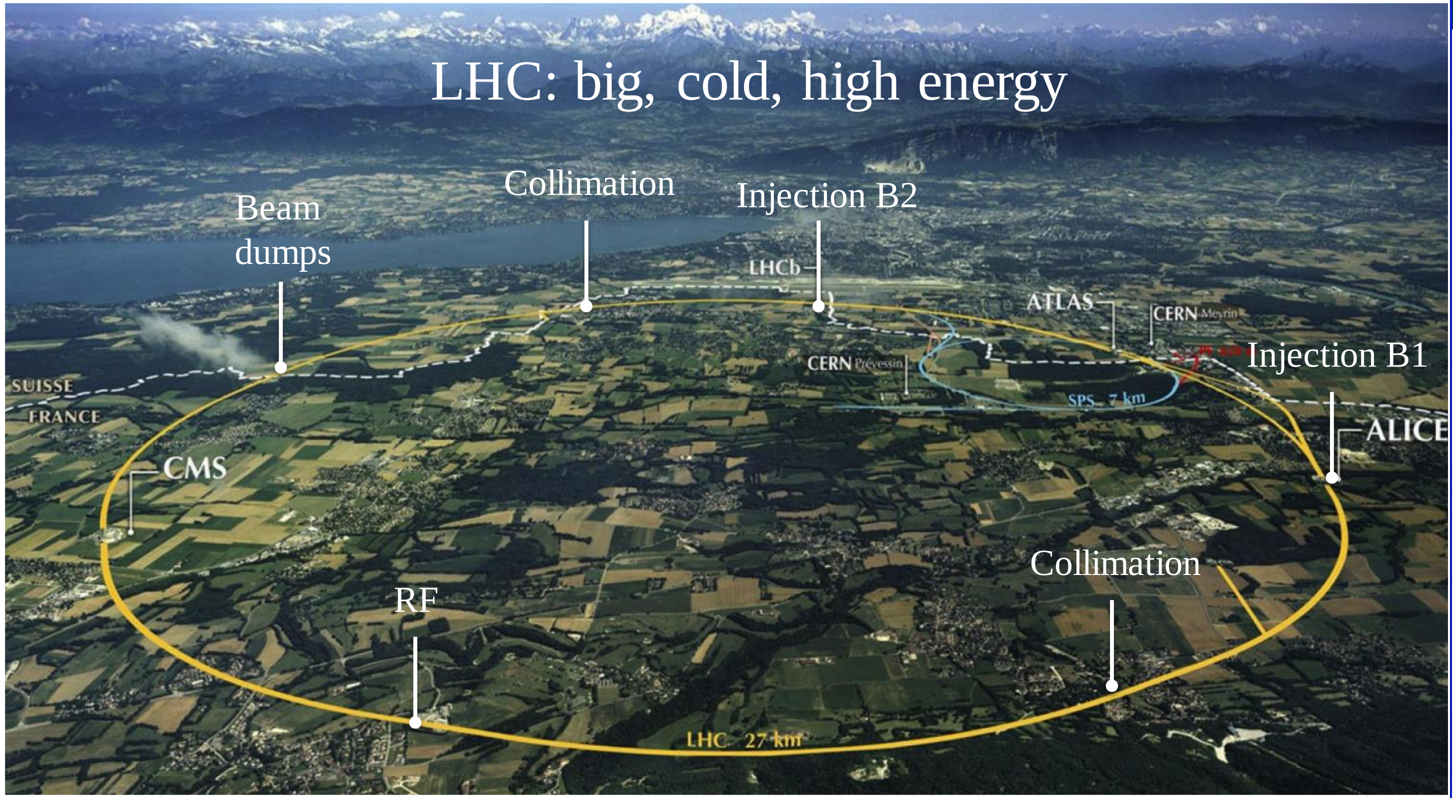
4 main experiments → Alice, ATLAS, CMS, LHb

Where the beam size is reduced to a minimum → important for later on…

The Large Hadron Collider : the LHC

The largest machine and scientific instrument ever built by mankind

…. For the moment….

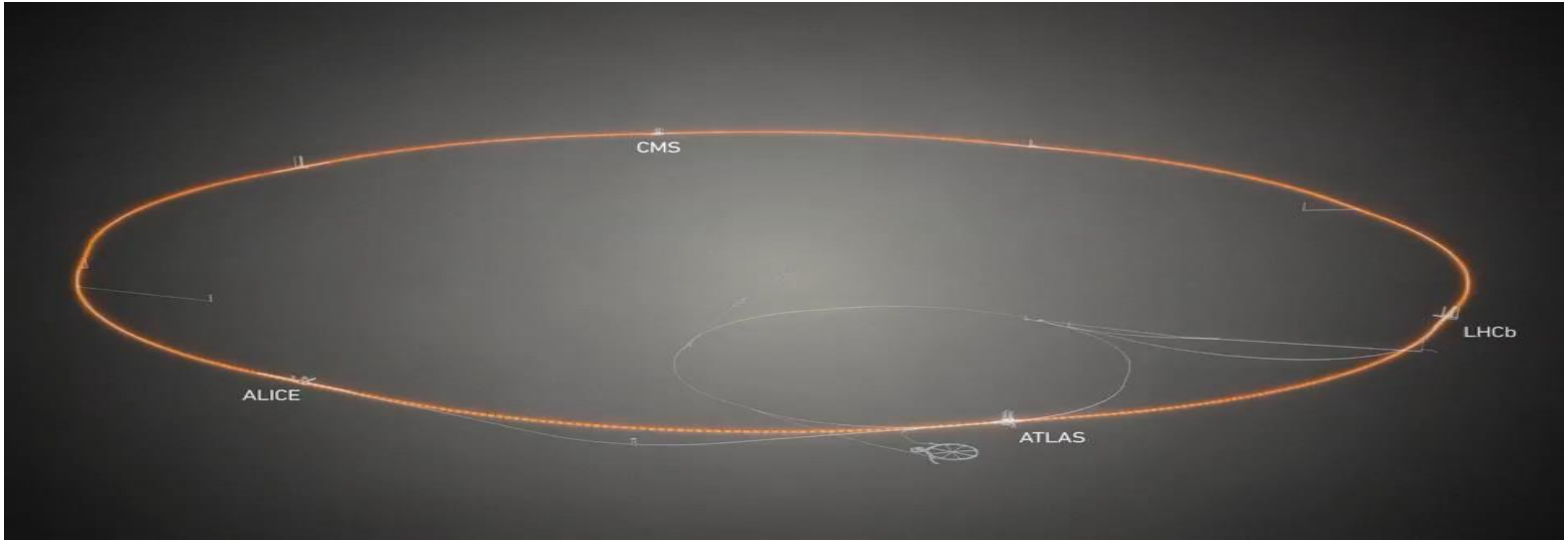


Quantity	**Number**
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Nominal energy, protons	6.5 TeV (6.8 TeV)
Nominal energy, protons collisions	13 TeV (13.6 TeV)
No. of protons	Some 10^{14}
Number of turns per second	11245
Number of collisions per second	1 billion

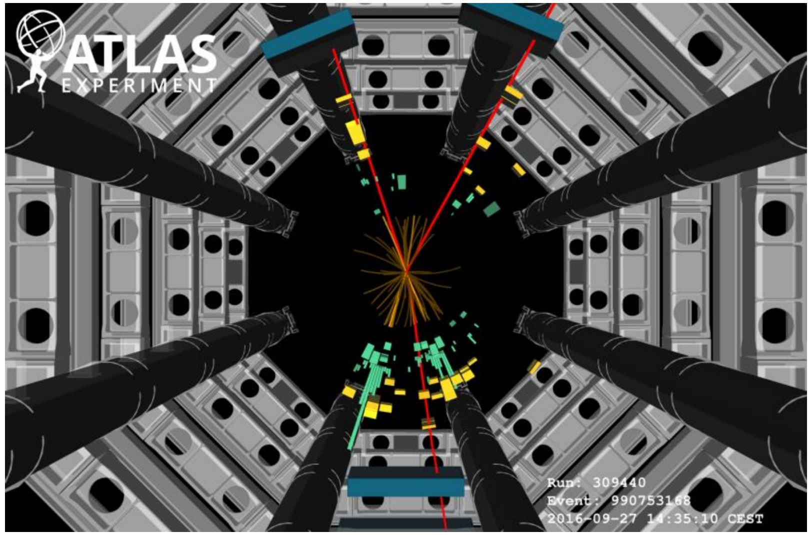
Why the LHC is so complicated?

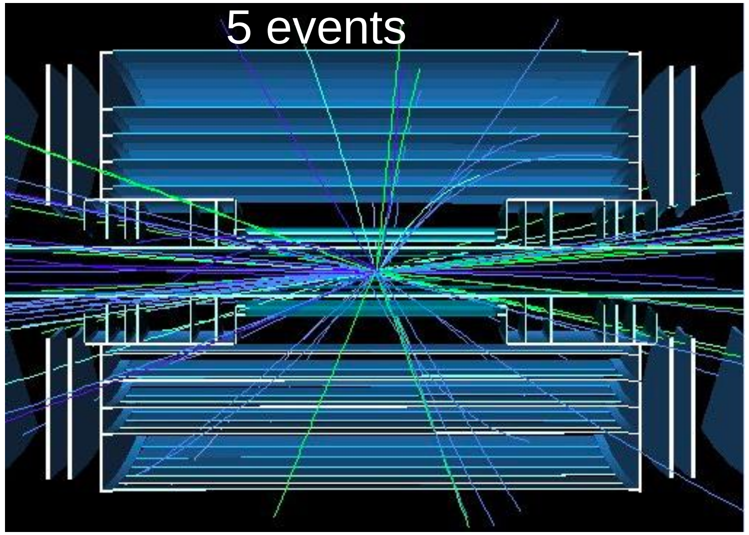
One has to control **~2000 needles travelling at the speed of light** with the **energy sufficient to melt 2.5 tons of copper** in such a way that they **meet each and every single second about 11000 times.**

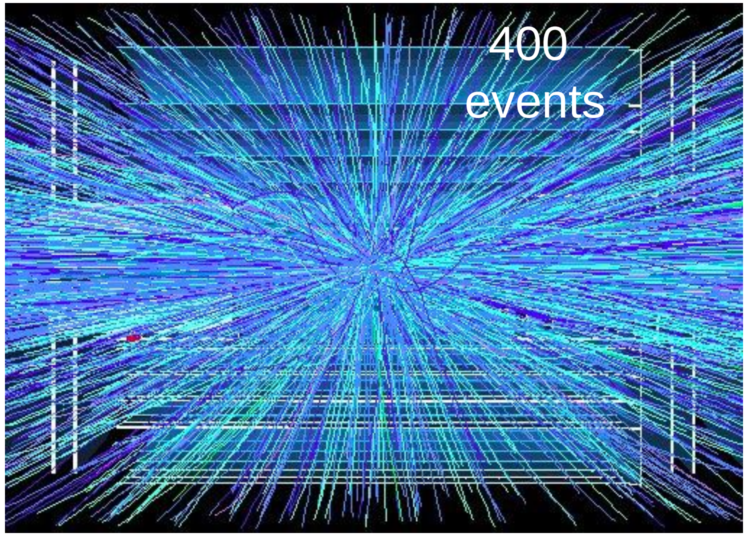
While leaving at a temperature which is cooler that the empty space and 100 m underground.

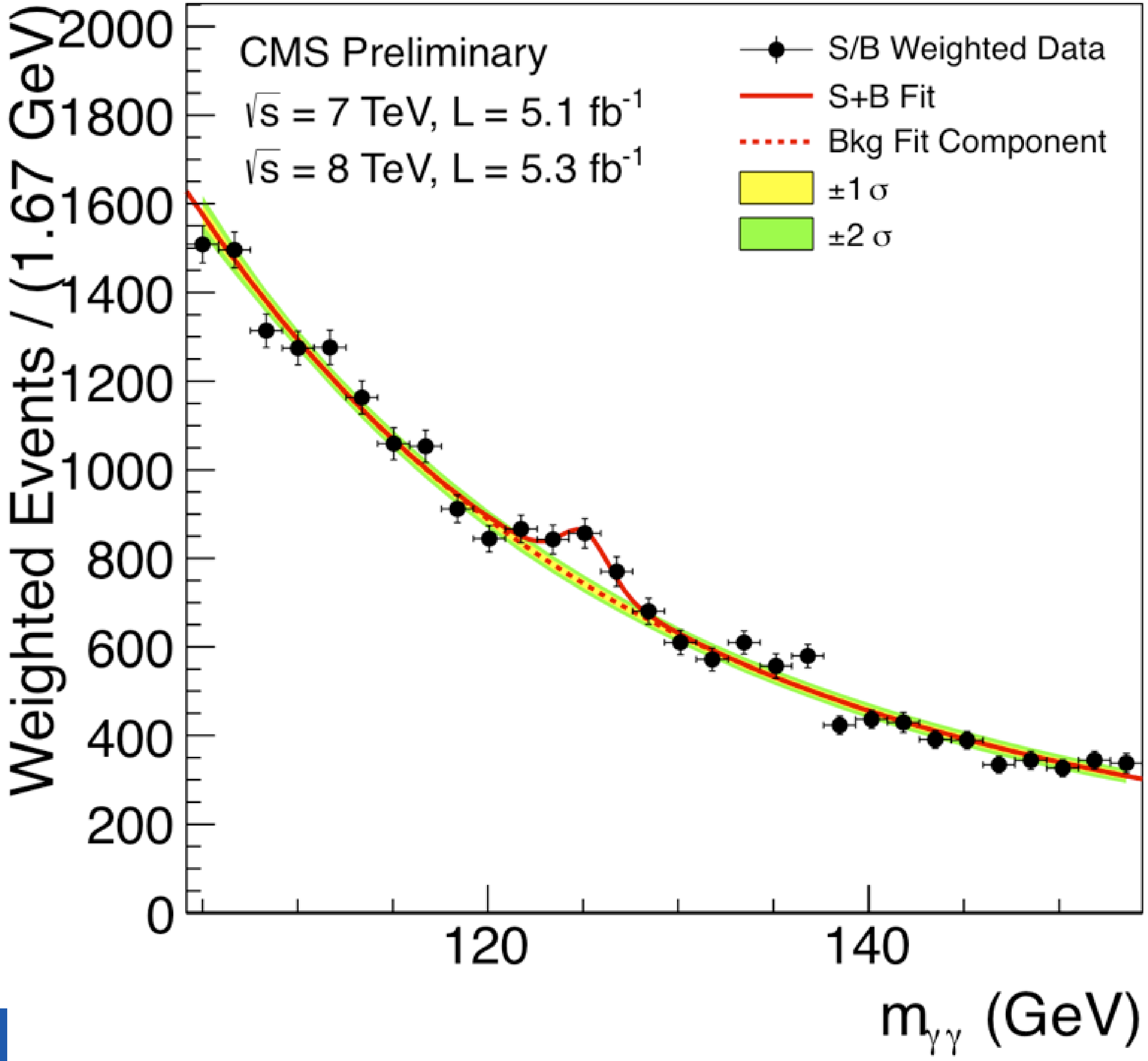


A collider event ….









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)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
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

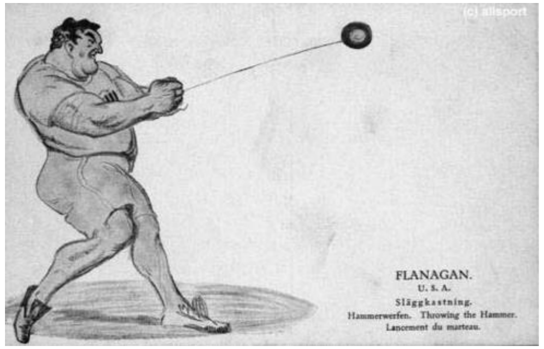
It may perhaps seem odd that apparatus as big and as complex as our gigantic proton synchrotron is needed for the investigation of the smallest objects we know about. However, just as the wave features of light propagation make huge telescopes necessary for the measurement of small angles between rays 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.

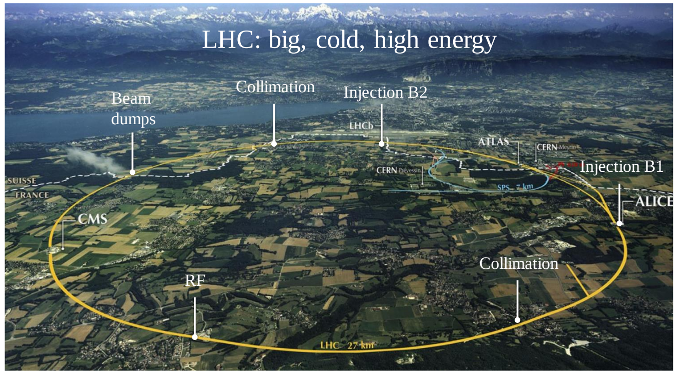
All the ingredients are there: we need high energy particles produced by large accelerators to study the matter constituents and their interactions laws. This also true for the LHC.

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

What is the LHC ? L = LARGE → 27 km

Large: high energy needs large bending radius due to the maximum magnetic field existing technology can produce 26.7 km circumference





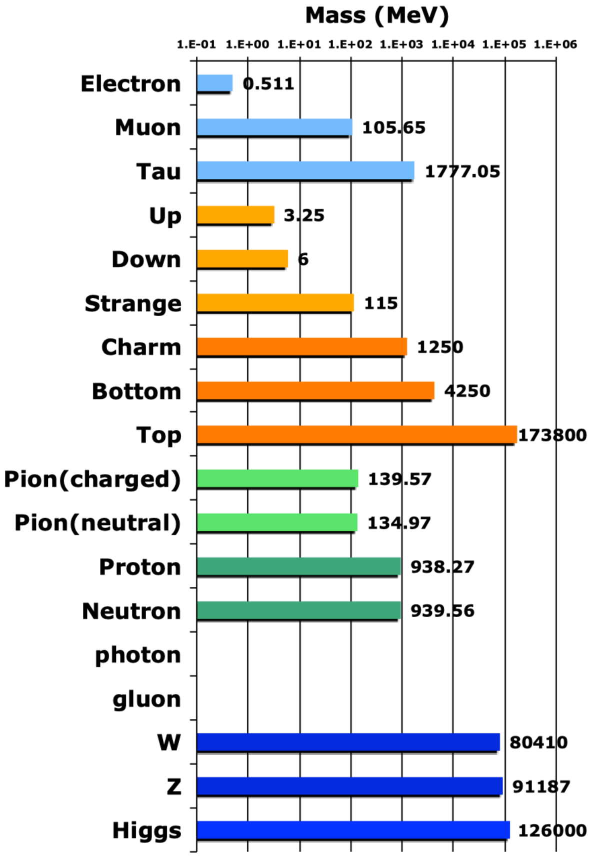
Something related to the **force to keep particles on track**

$$k = \frac{1}{\rho} = \frac{e}{p}B = \frac{e\mu_0}{p}\frac{nI}{h}$$

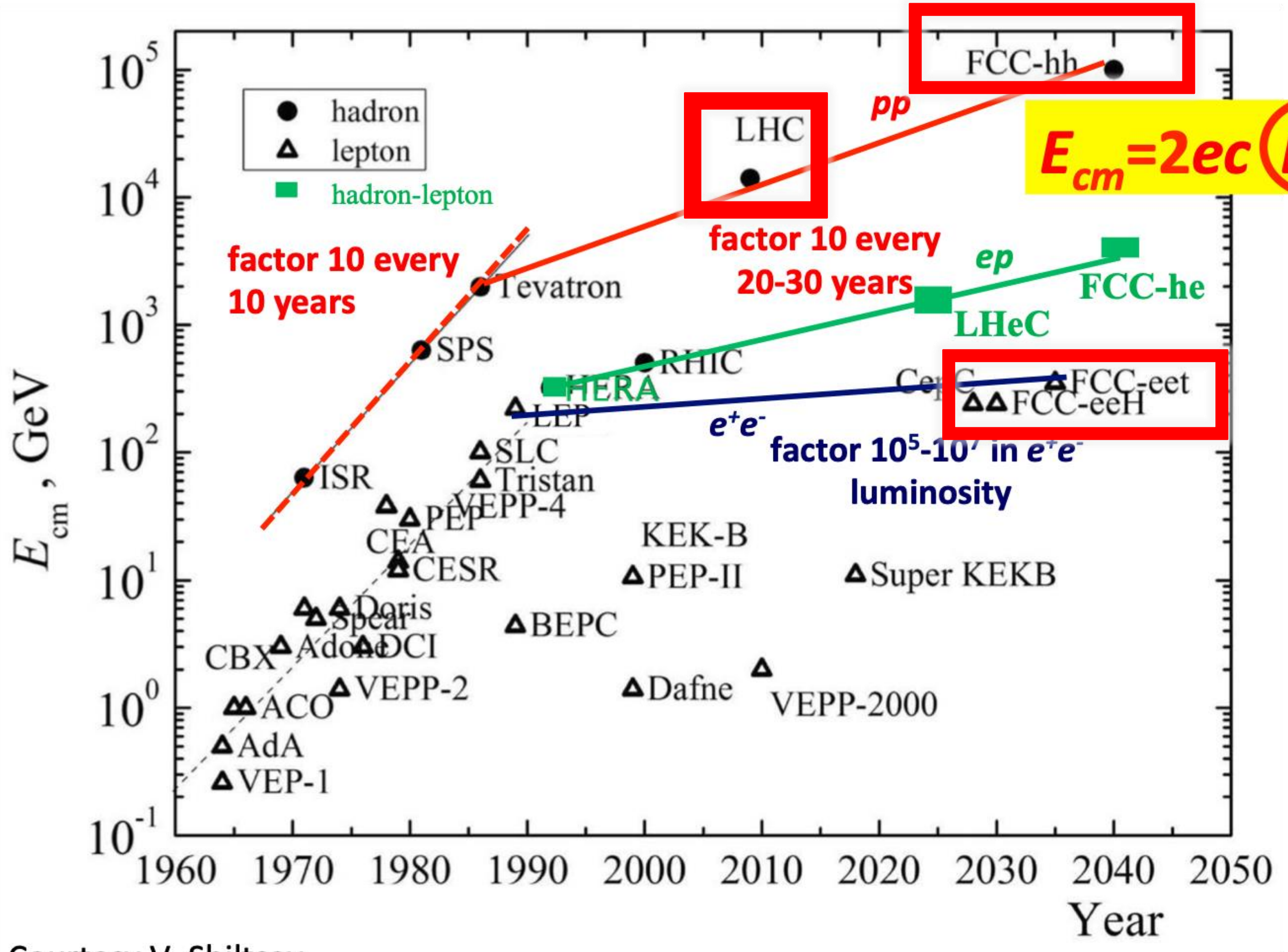
Magnetic Field
Limited by technology

Radius: limited by cost,
and by the radius of the Earth...

Energy : given by the physics
This will depend on the mass of the particles we want to discover



What’s next: LARGE?

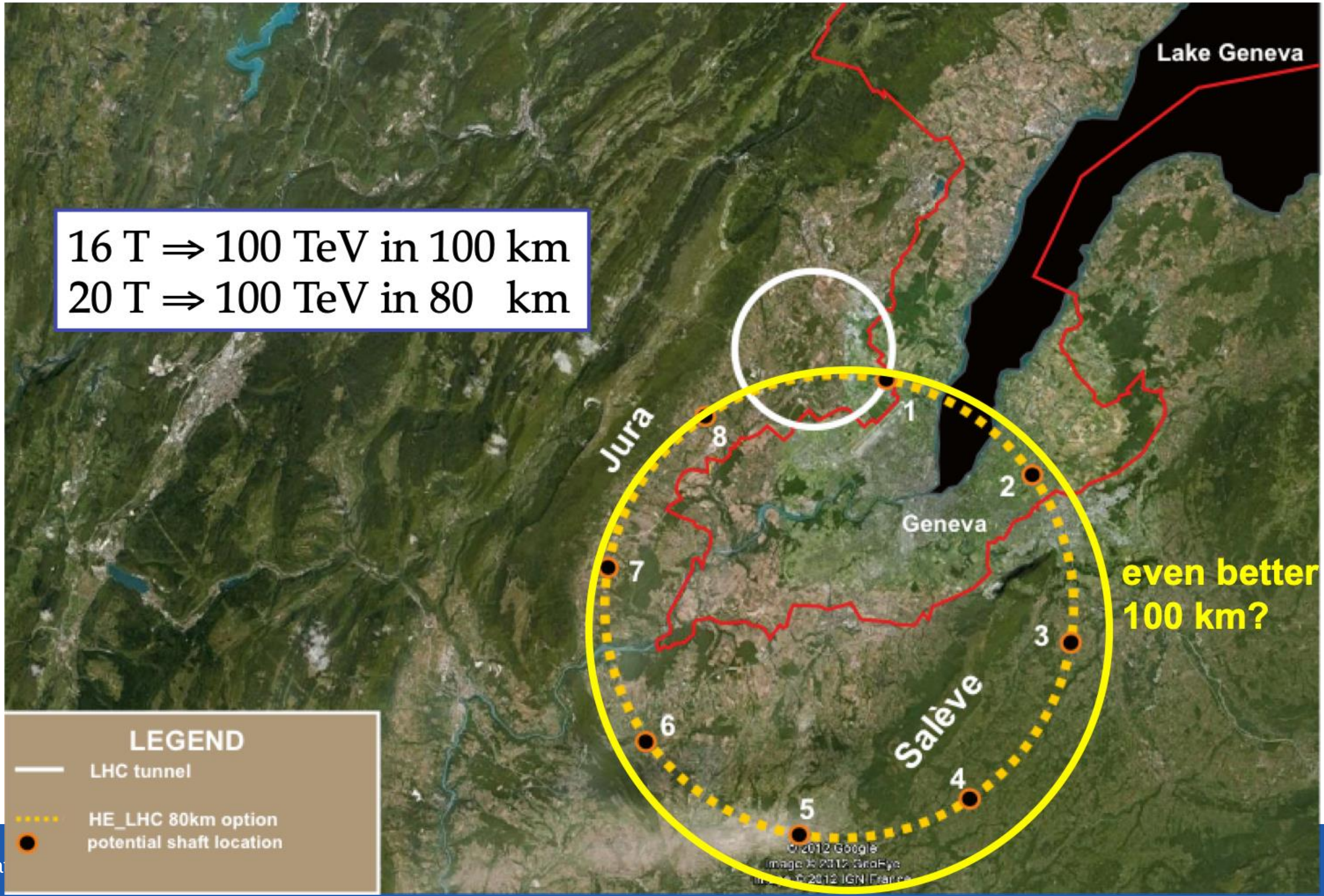


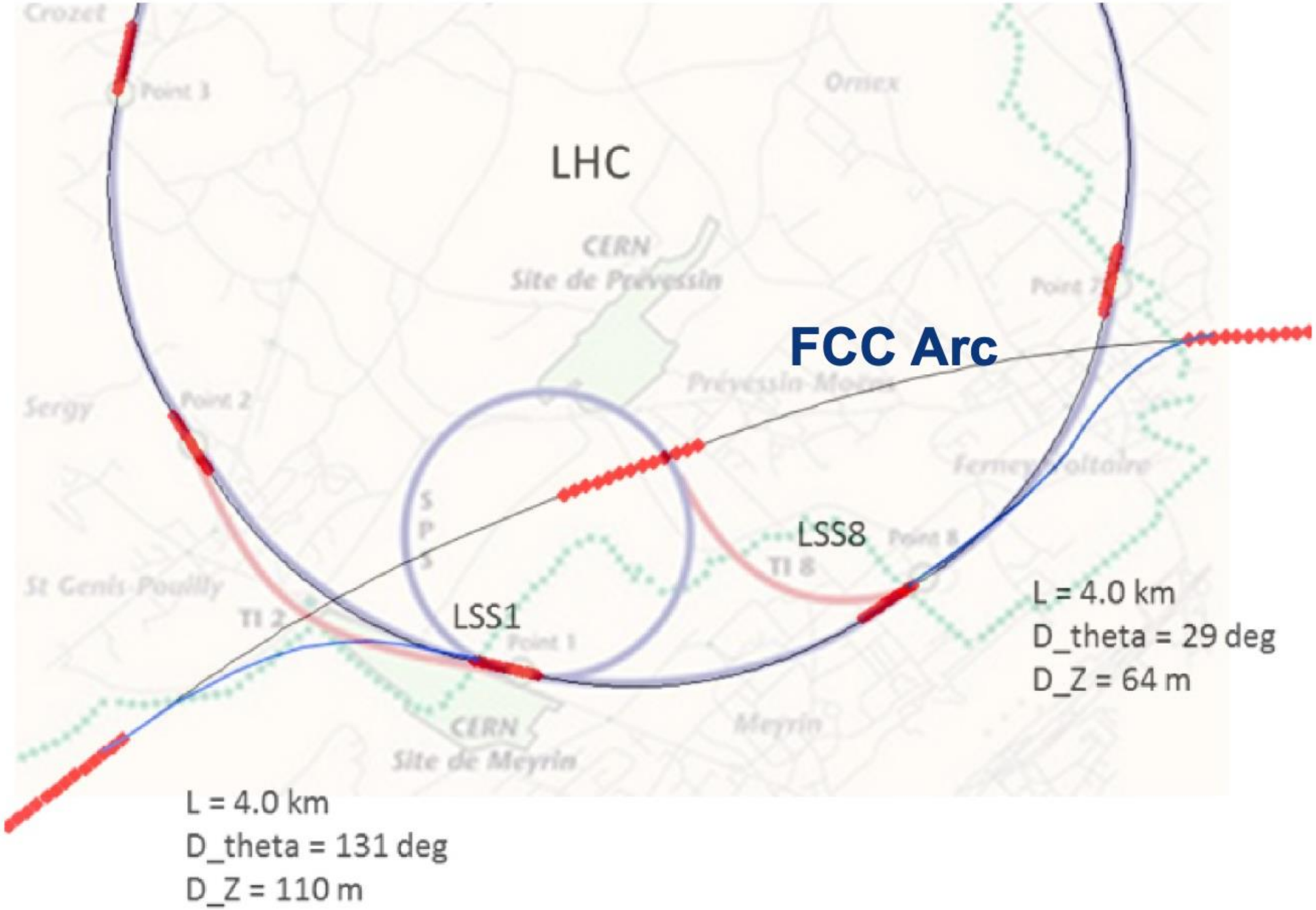
$$E_{cm}=2ec\,B\rho$$

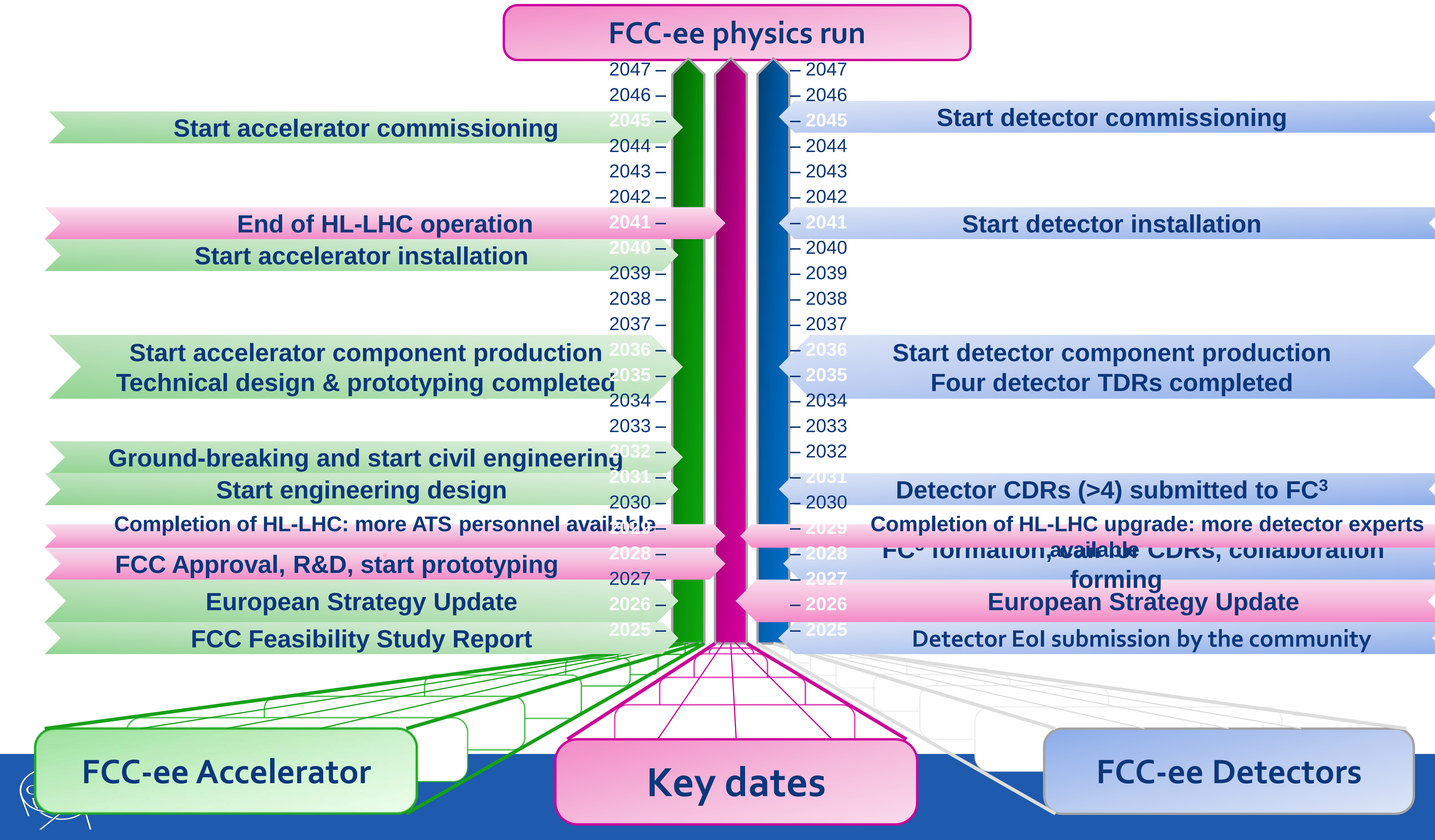
$$k=\frac{1}{\rho}=\frac{e}{p}B$$

Courtesy V. Shiltsev

What's the future ? Going bigger ….



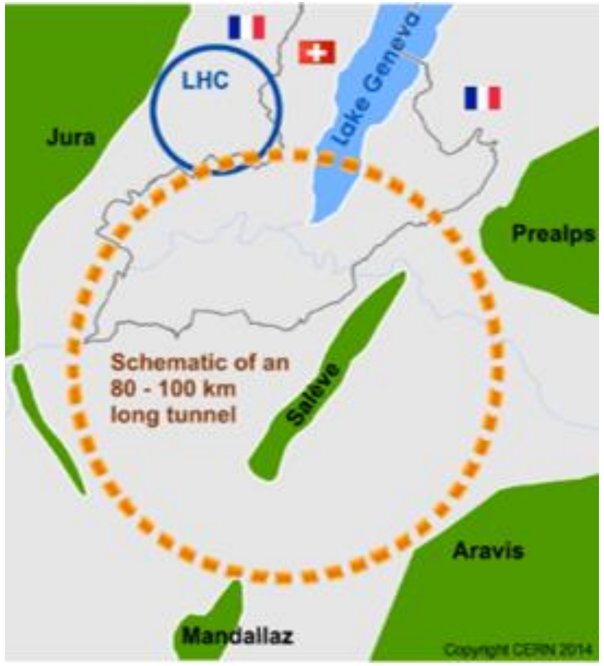

LHC
FCC Arc
LSS8
LSS1
L = 4.0 km
D_theta = 29 deg
D_Z = 64 m
L = 4.0 km
D_theta = 131 deg
D_Z = 110 m
CERN
Site de Prévessin
CERN
Site de Meyrin
Crozet
Ornex
Sergy
St Genis-Pouilly
Meyrin
Point 1
Point 2
Point 3
Point 7
Point 8
TI 2
TI 8
SPS

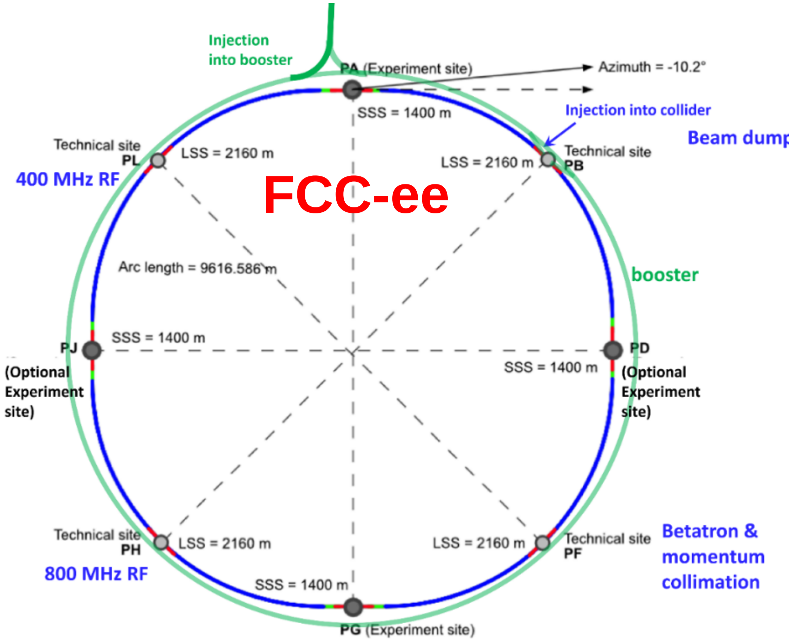

FCC-ee physics run
Start accelerator commissioning
End of HL-LHC operation
Start accelerator installation
Start accelerator component production
Technical design & prototyping completed
Ground-breaking and start civil engineering
Start engineering design
Completion of HL-LHC: more ATS personnel available
FCC Approval, R&D, start prototyping
European Strategy Update
FCC Feasibility Study Report
2047
2046
2045
2044
2043
2042
2041
2040
2039
2038
2037
2036
2035
2034
2033
2032
2031
2030
2029
2028
2027
2026
2025
Start detector commissioning
Start detector installation
Start detector component production
Four detector TDRs completed
Detector CDRs (>4) submitted to FC³
Completion of HL-LHC upgrade: more detector experts available
FC³ formation, call for CDRs, collaboration forming
European Strategy Update
Detector EoI submission by the community
FCC-ee Accelerator
Key dates
FCC-ee Detectors

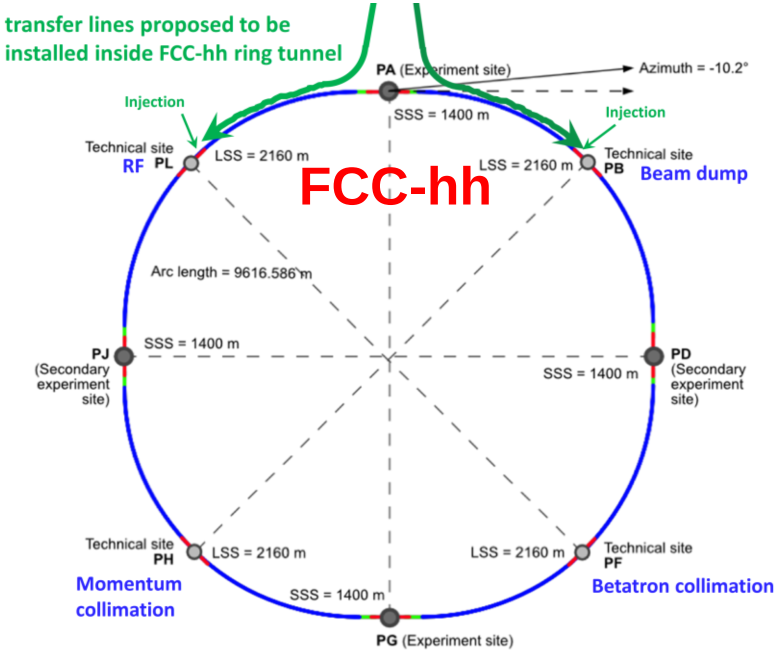
The FCC integrated program inspired by successful LEP – LHC programs at CERN

comprehensive long-term program maximizing physics opportunities

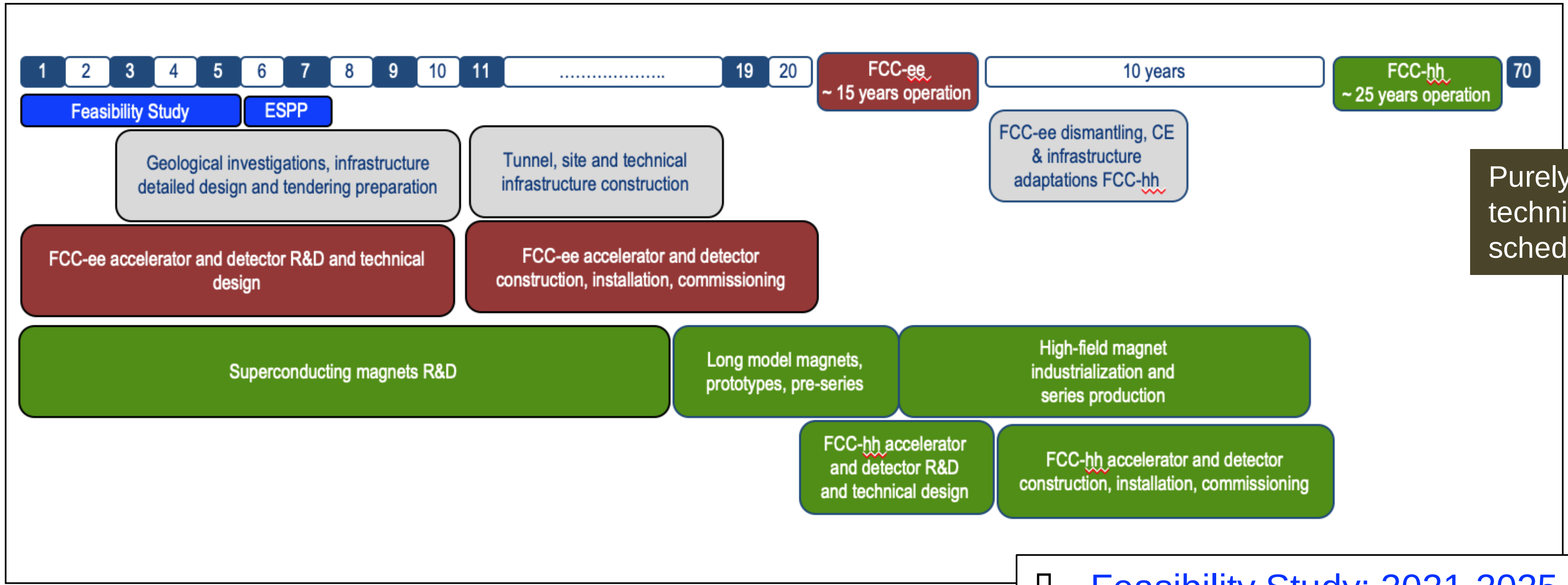
- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- complementary physics
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after completion of the HL-LHC program







2020 - 2040 | **2045 - 2060** | **2070 - 2090++**

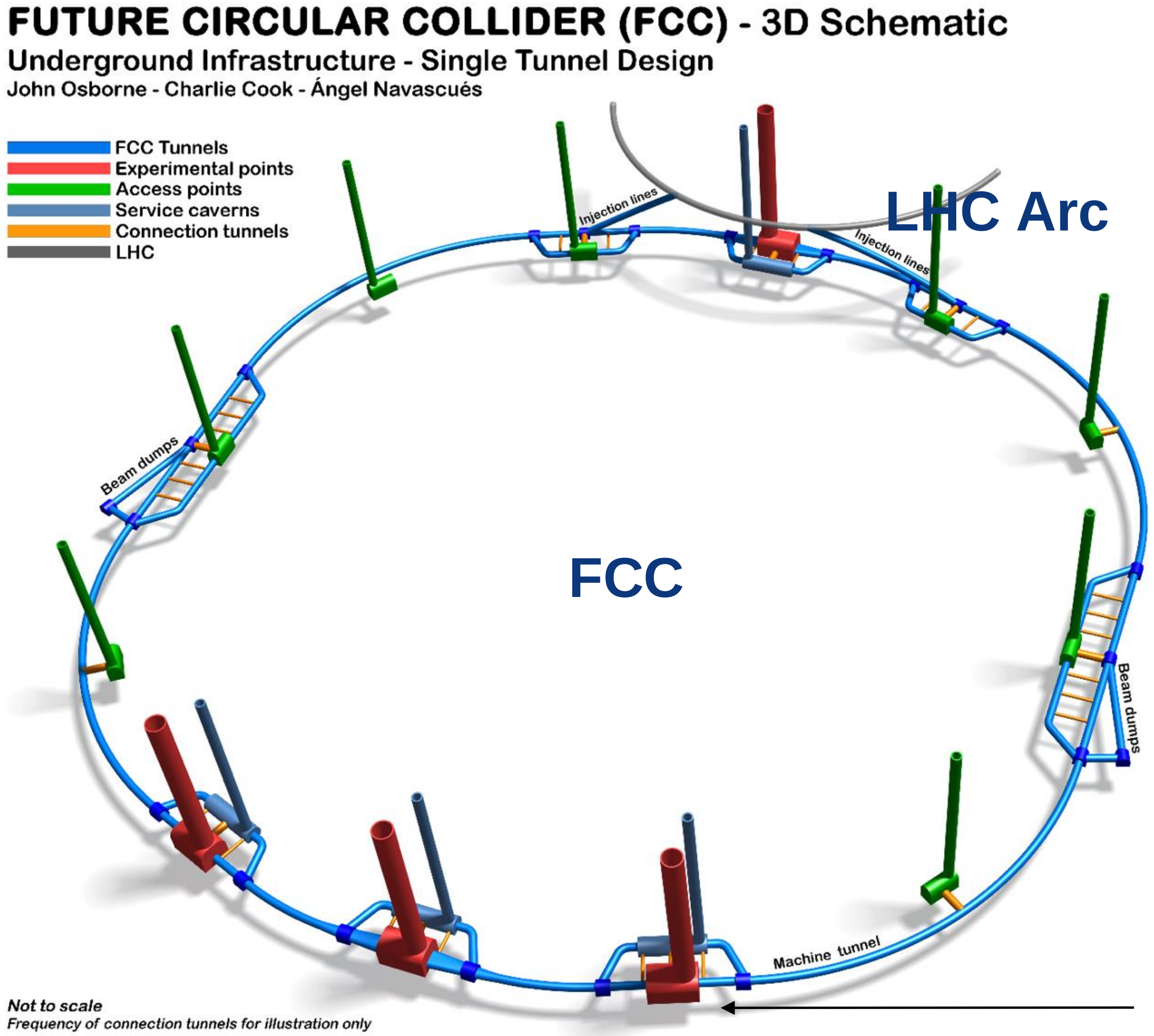


Purely technical schedule

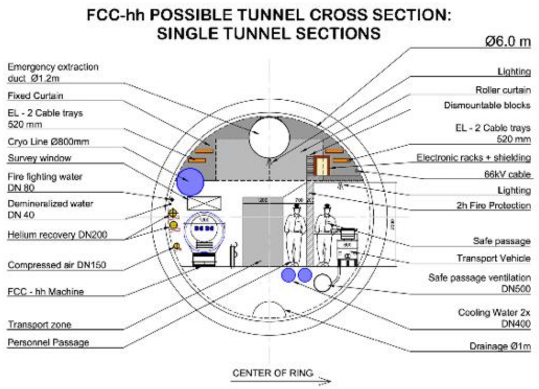
	√s	L /IP ($cm^{-2} s^{-1}$)	Int. L /IP(ab^{-1})	Comments
e^+e^- FCC-ee	~90 GeV Z 160 WW 240 H ~365 top	230 $\times 10^{34}$ 28 8.5 1.5	75 5 2.5 0.8	2-4 experiments Total ~ 15 years of operation
pp FCC-hh	100 TeV	5 x 10^{34} 30	20-30	2+2 experiments Total ~ 25 years of operation
PbPb FCC-hh	$\sqrt{s_{NN}}$ = 39TeV	3 x 10^{29}	100 nb^{-1}/run	1 run = 1 month operation
ep Fcc-eh	3.5 TeV	1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb Fcc-eh	$\sqrt{s_{eN}}$ = 2.2 TeV	0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb

- Feasibility Study: 2021-2025
- If project approved before end of decade → construction can start beginning 2030s
- FCC-ee operation ~2045-2060
- FCC-hh operation ~2070-2090++

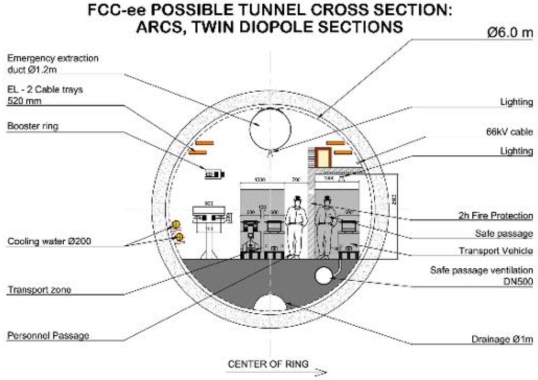
From : F. Giannotti – FCC week – Paris 2022



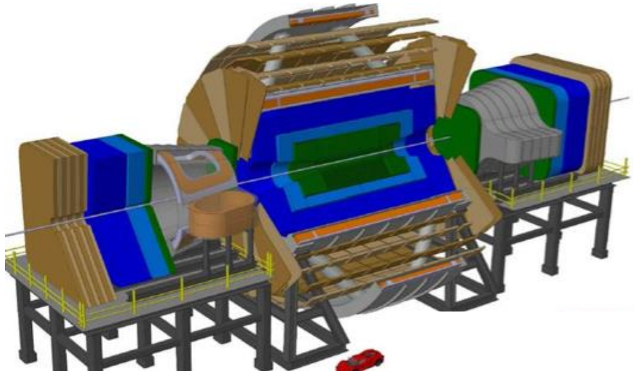
FUTURE CIRCULAR COLLIDER (FCC) - 3D Schematic
Underground Infrastructure - Single Tunnel Design
John Osborne - Charlie Cook - Ángel Navascués
FCC Tunnels
Experimental points
Access points
Service caverns
Connection tunnels
LHC
Injection lines
Injection lines
Beam dumps
Beam dumps
Machine tunnel
Not to scale
Frequency of connection tunnels for illustration only
LHC Arc
FCC



FCC-hh POSSIBLE TUNNEL CROSS SECTION:
SINGLE TUNNEL SECTIONS
Ø6.0 m
Emergency extraction duct Ø1.2m
Fixed Curtain
EL - 2 Cable trays 520 mm
Cryo Line Ø800mm
Survey window
Fire fighting water DN 80
Demineralized water DN 40
Helium recovery DN200
Compressed air DN150
FCC - hh Machine
Transport zone
Personnel Passage
Lighting
Roller curtain
Dismountable blocks
EL - 2 Cable trays 520 mm
Electronic racks + shielding
66kV cable
Lighting
2h Fire Protection
Safe passage
Transport Vehicle
Safe passage ventilation DN500
Cooling Water 2x DN400
Drainage Ø1m
CENTER OF RING



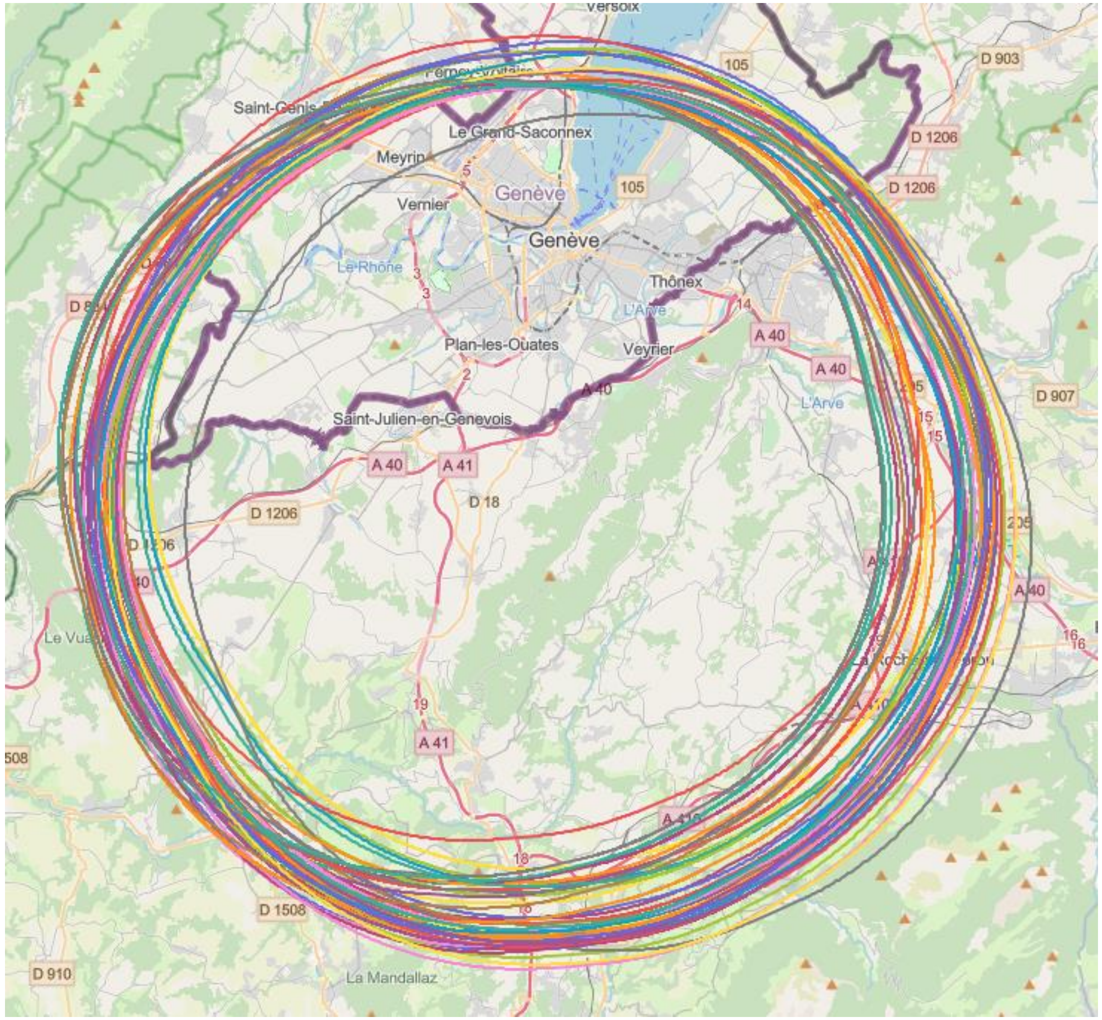
FCC-ee POSSIBLE TUNNEL CROSS SECTION:
ARCS, TWIN DIPOLE SECTIONS
Ø6.0 m
Emergency extraction duct Ø1.2m
EL - 2 Cable trays 520 mm
Booster ring
Cooling water Ø200
Transport zone
Personnel Passage
Lighting
66kV cable
Lighting
2h Fire Protection
Safe passage
Transport Vehicle
Safe passage ventilation DN500
Drainage Ø1m
CENTER OF RING

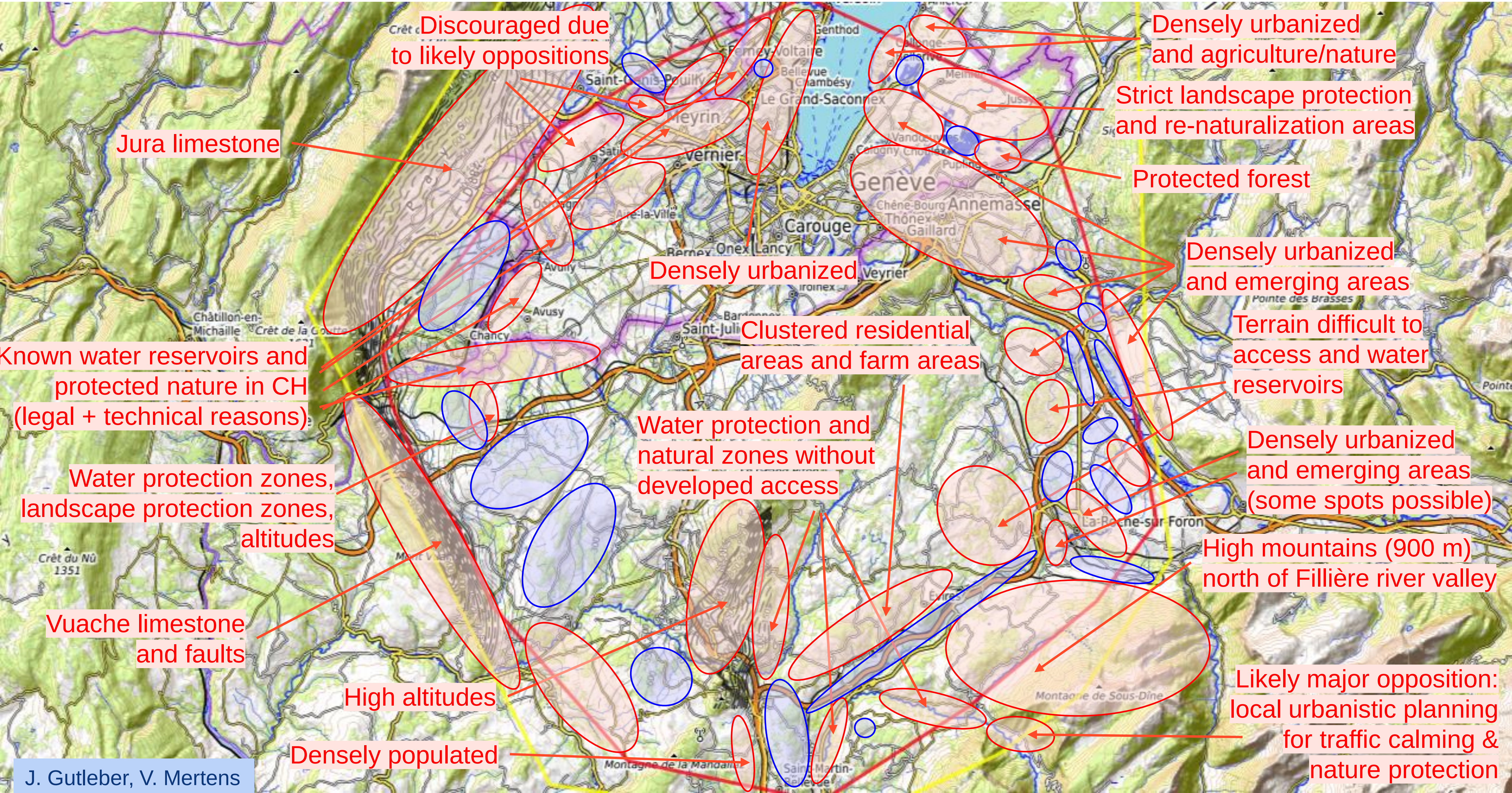


Detector

Implementation studies with host states

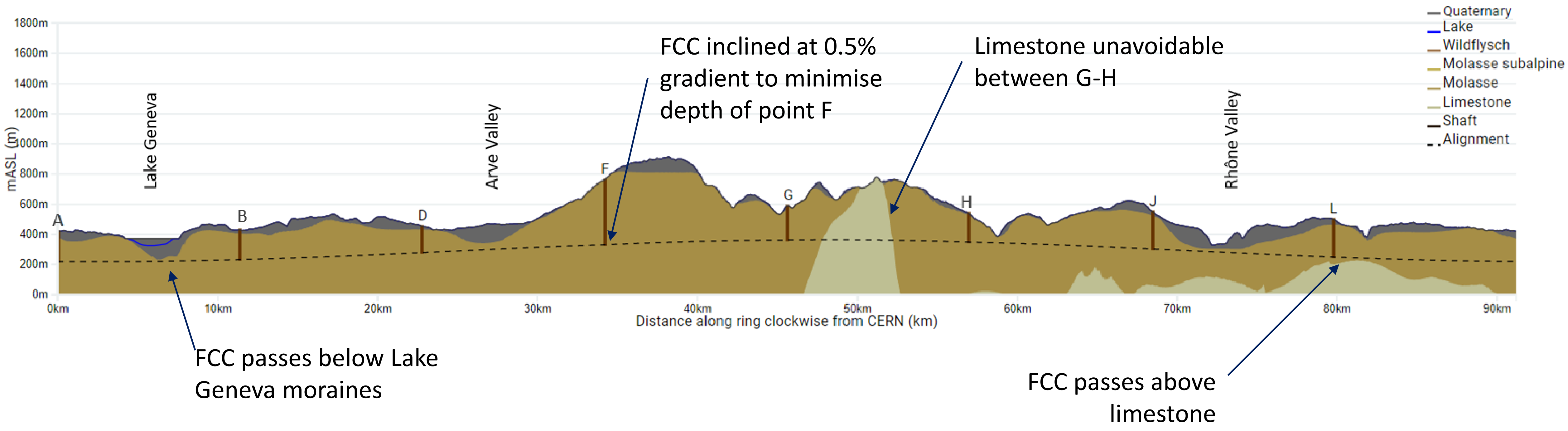
- layout & placement optimisation across both host states, Switzerland and France;
- following "avoid-reduce-compensate" directive of European & French regulatory frameworks;
- diverse requirements and constraints:
  - **technical feasibility of civil engineering** and subsurface geological constraints
  - **territorial constraints on surface** and subsurface
  - **nature, accessibility**, technical infrastructure, resource needs & constraints
  - **optimum machine performance and efficiency**
  - economic factors including benefits for, and synergies, with the **regional developments**
  - …
- collaborative effort: FCC technical experts, consulting companies, government-notified bodies





J. Gutleber, V. Mertens

FCC Long Section – PA31-1.0

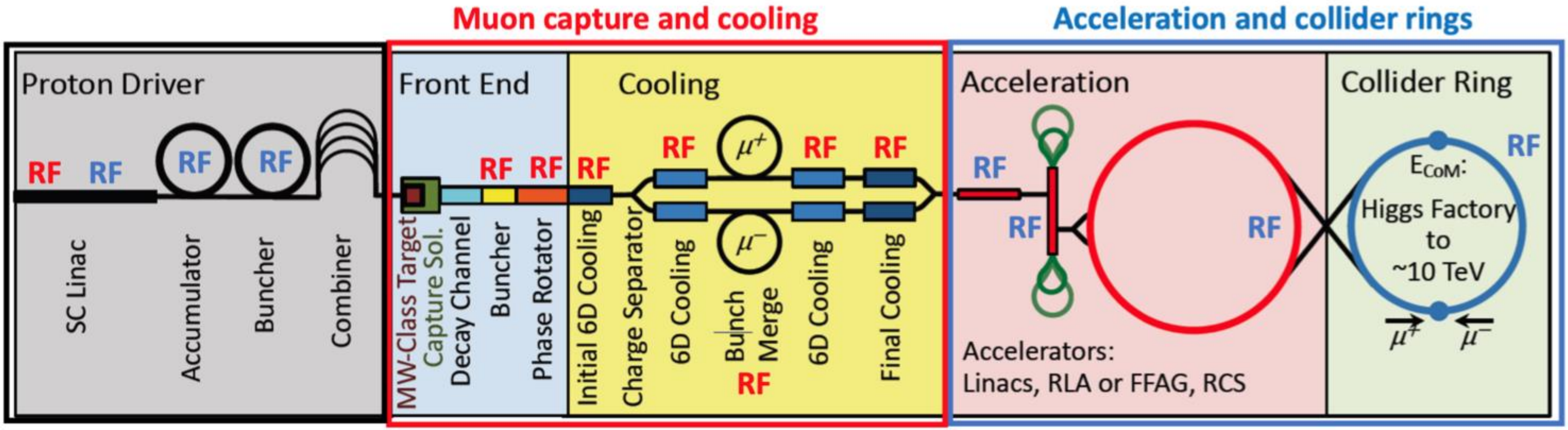


- **Shaft depth:**

A: 202 m B: 200 m D: 177 m F: 399 m G: 228 m H: 139 m J: 251 m L: 253 m

John Osborne

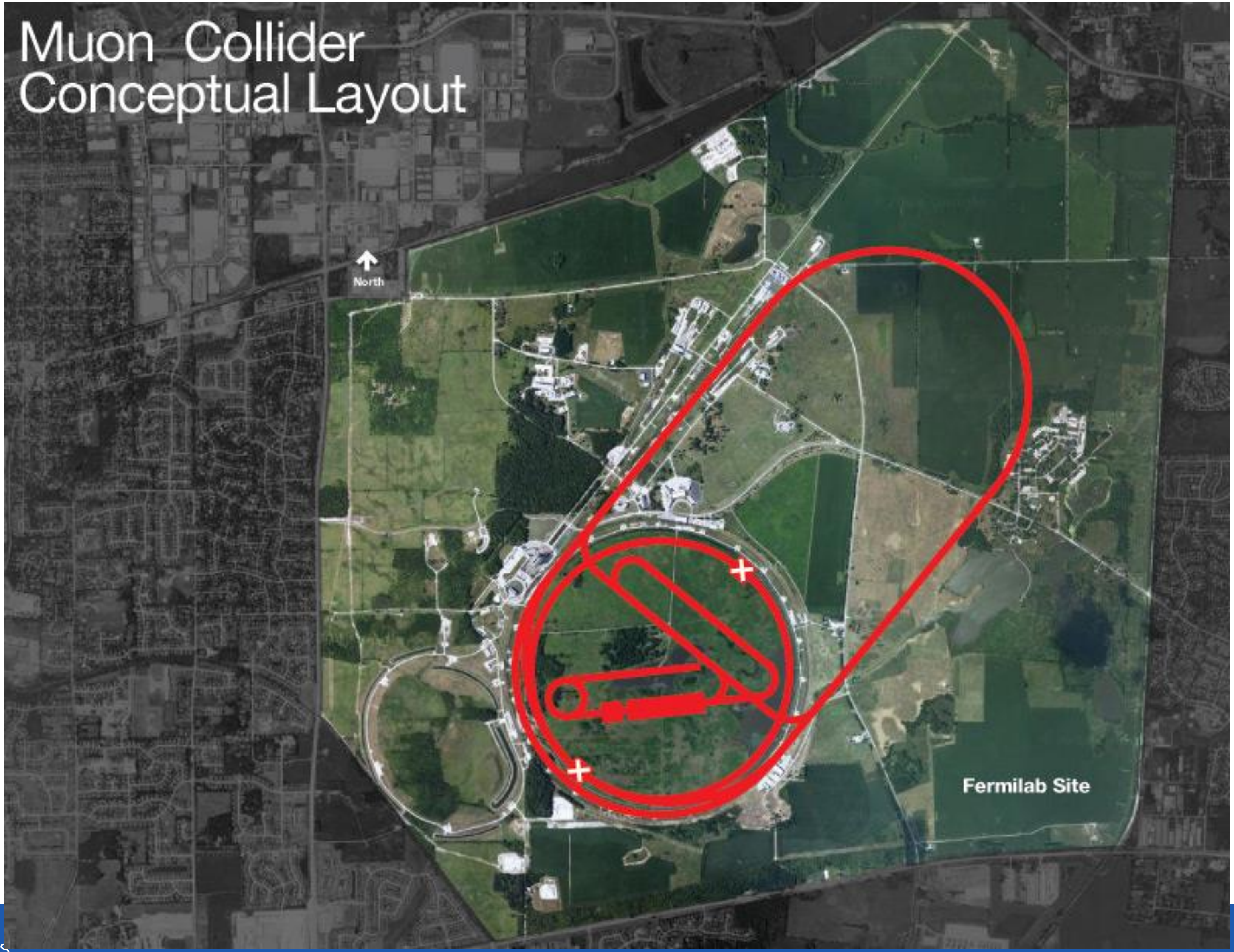
An alternative: the muon collider



Are muons stable particles?

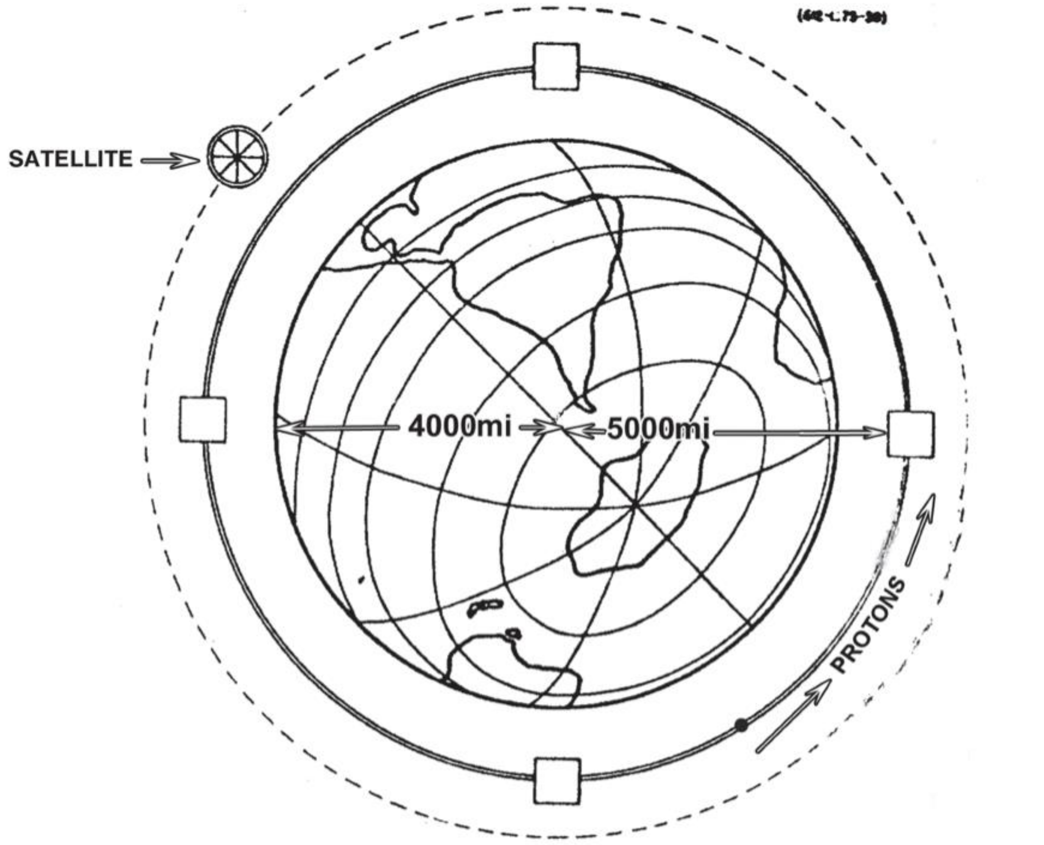
Courtesy of A. Grudiev et al.

Muon collider proposal at Fermilab (US)

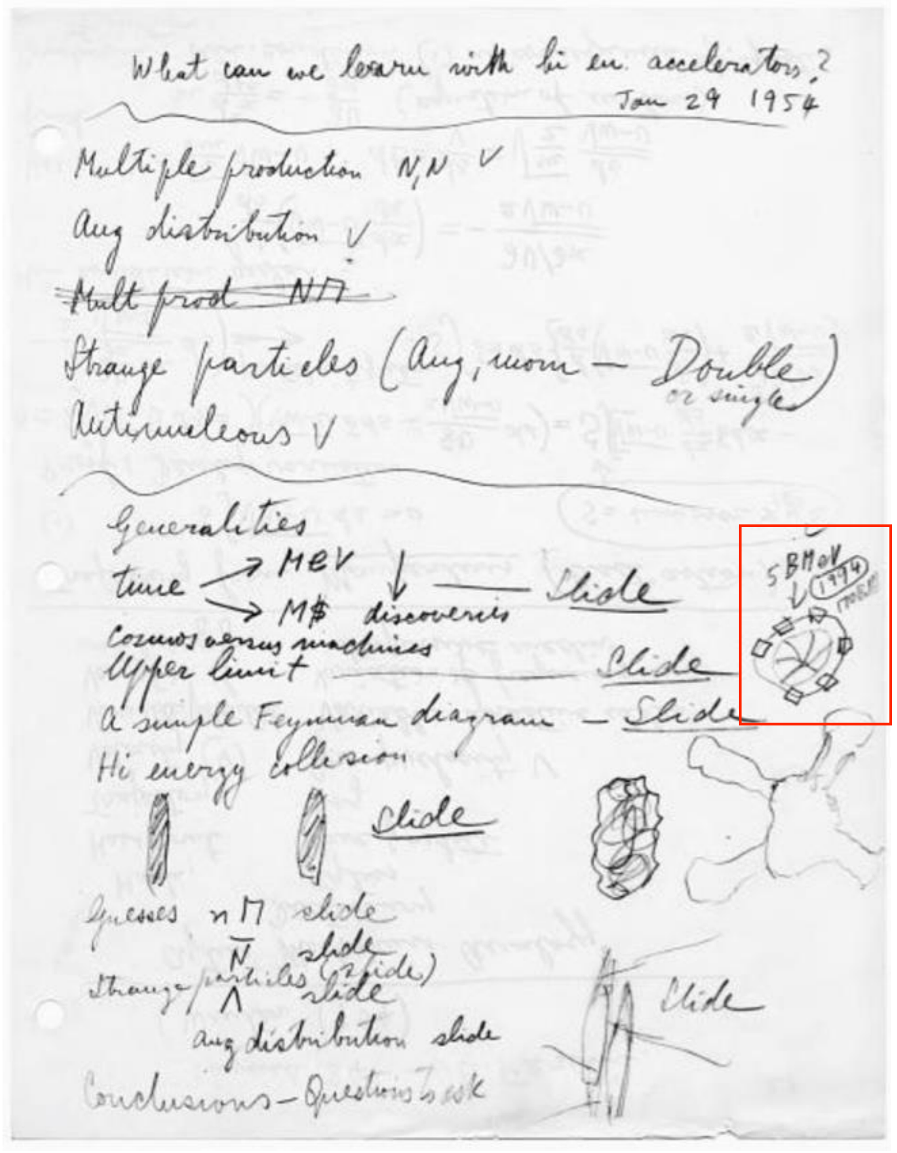


… or back to the future

5000 TeV
B=2 T R = 8000 km



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



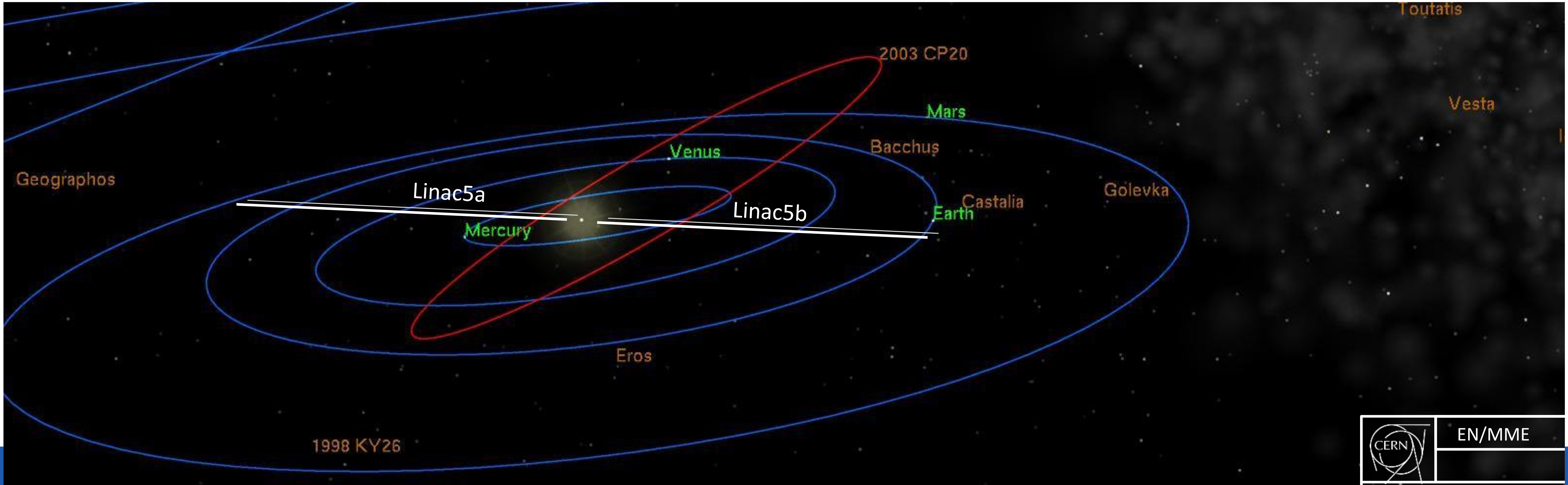
Images courtesy of the Special Collections Research Center, University of Chicago Library and Cronin J (ed.) Fermi Remembered (University of Chicago Press, 2004)

From: B. Goddard

Where is the limit?

Ultimate physical limits?

- Maximum voltage gradient: limited by spontaneous e+e- pair production in vacuum to *Scwinger critical field* of 10^{18} V/m
  - Assume a comfortable engineering margin: take 10^{17} V/m
- Linac length to reach Planck scale: ~10^{11} m (per Linac)
- Earth-sun distance: 149’000’000 km = 1.5 x 10^{11} m
- So: Linear collider at scale of earth orbit, at 10% of vacuum critical field gradient
- Circular colliders are out: with 1’000 T bend field, takes a 10 light year diameter to reach 10^{28} eV. Beam revolution period is 31 years….

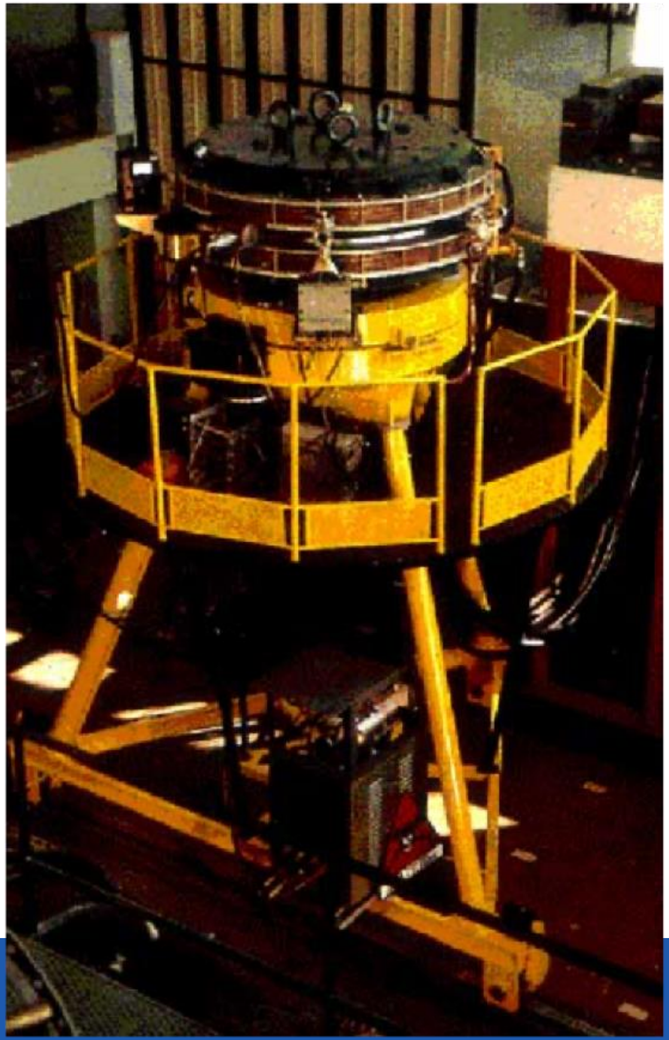


Beam loss control will be important: a single proton at 1e28 eV = 1’600 MJ

A bit of hystory

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

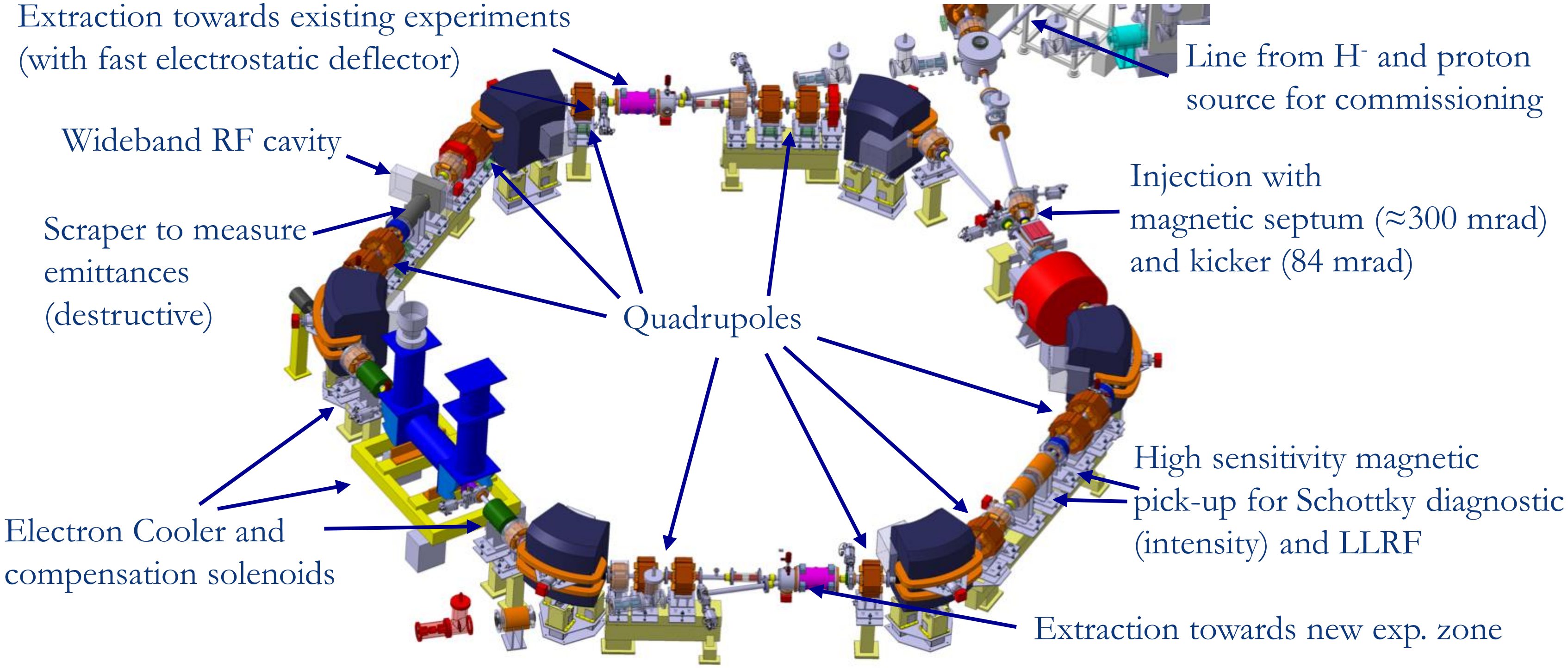
AdA = Anello di Accumulazione



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

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

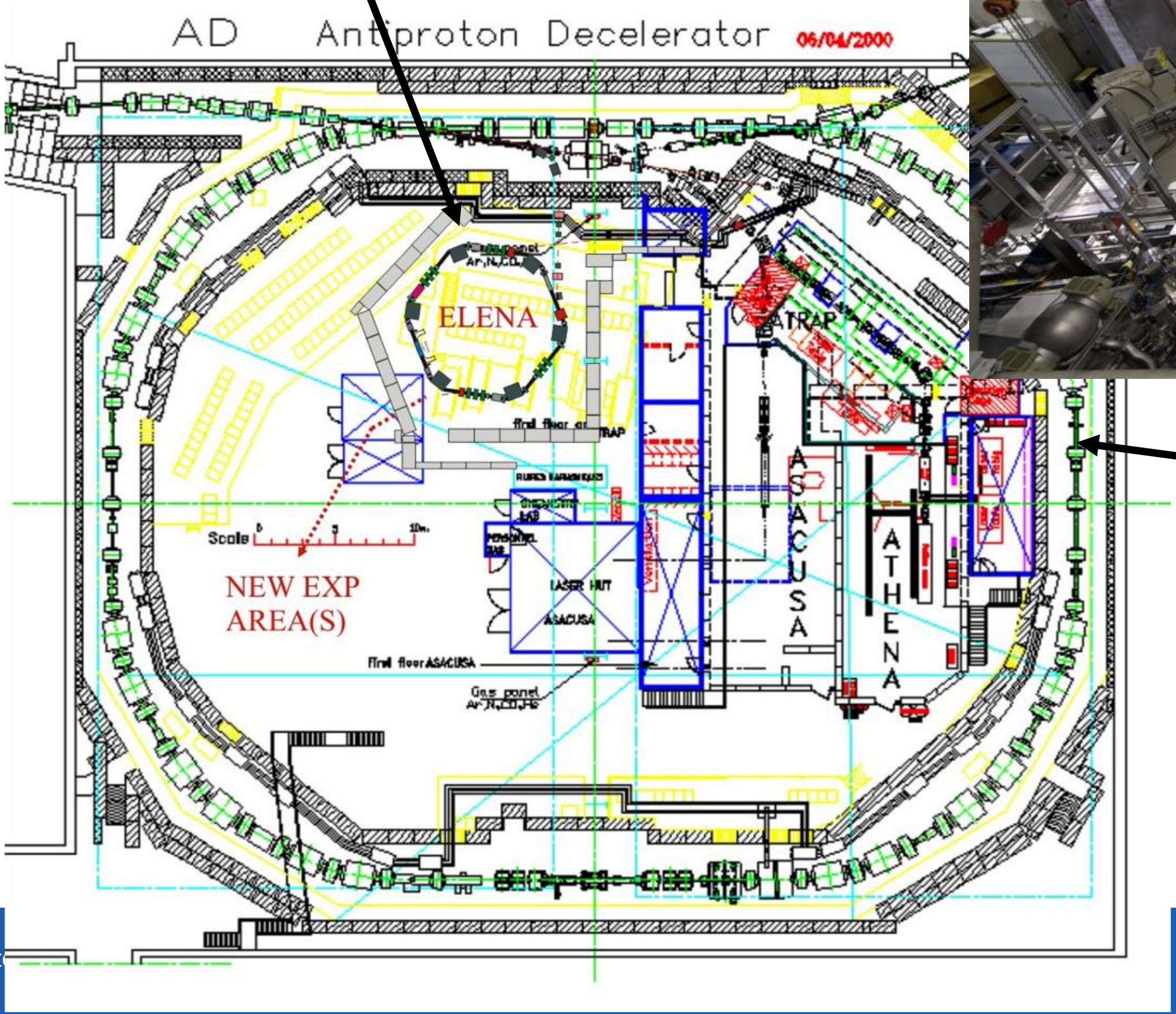
The most recent CERN (de)celerator… ELENA

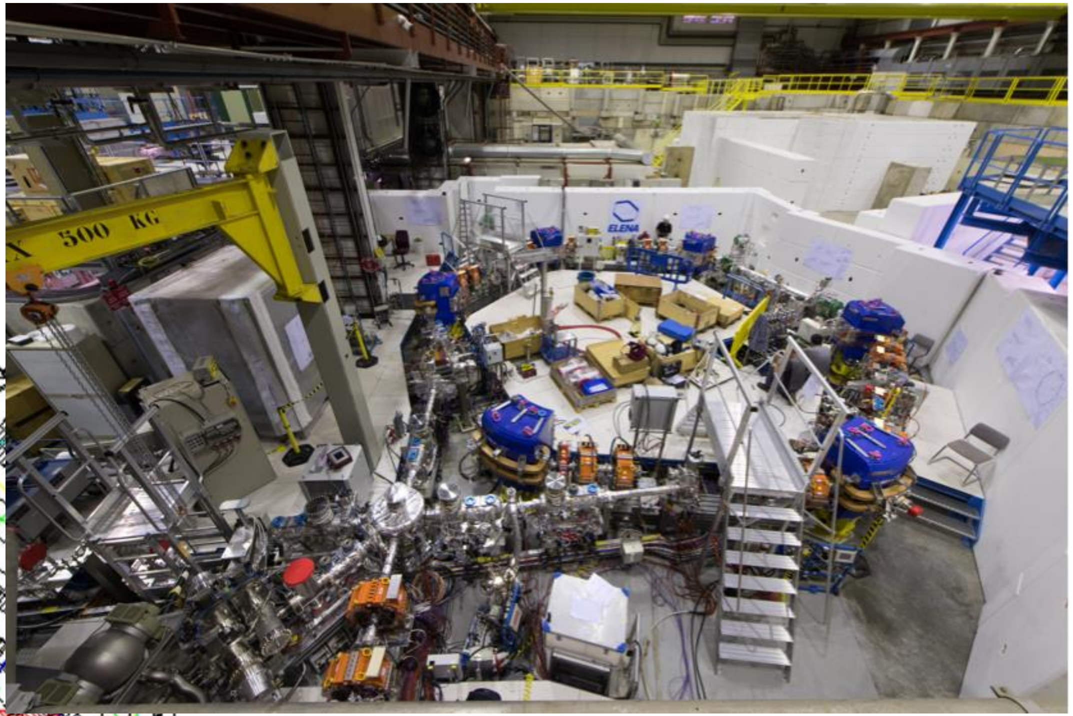


- **Deceleration of antiprotons from 5.3 MeV to 100 keV** to improve efficiency of antimatter experiments
- **Circumference 30.4 m**
  - Fits in available space in AD hall and allows installing all equipment without particular efforts
  - Lowest average field (beam rigidity over average radius) Bρ/R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

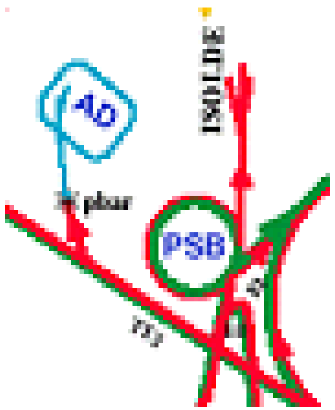
ELENA in AD hall

ELENA





AD



Influence of environmental magnetic fields

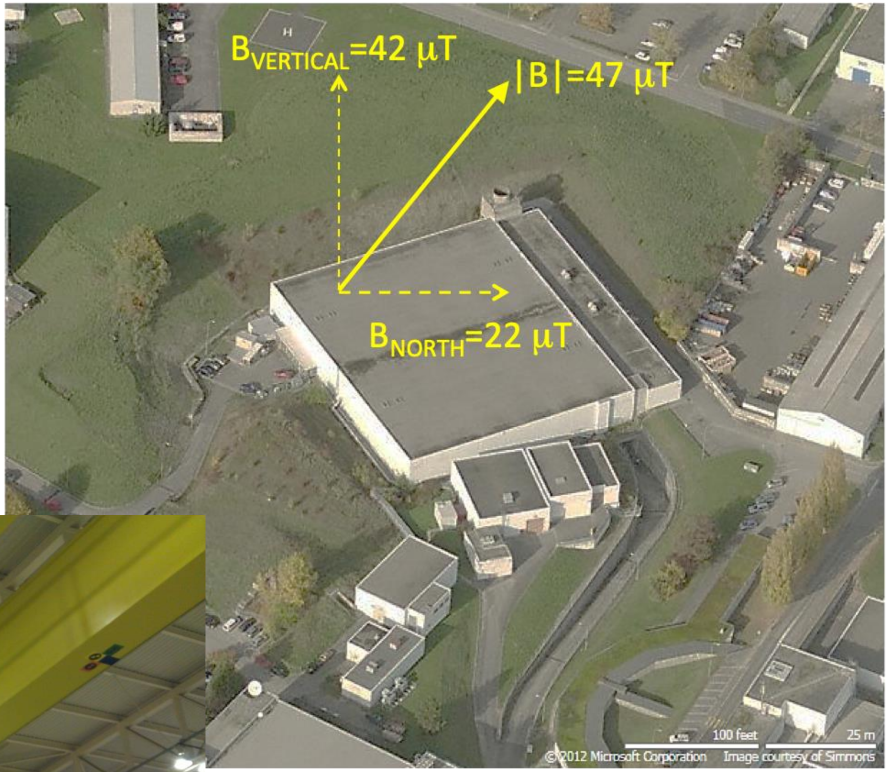
General tolerance for the background field 0.1 G i.e. 10 µT (~1 mm/m deflection @ 100 keV)
Lowest field at extraction : 94 G

Field sources:
- geomagnetic field
- DC and AC currents: power lines, busbars …
- remanent magnetization in steel components (typical in welded/cold worked parts)
- electrical machinery (motors, pumps …)

Field decays with distance from source *r* as $1/r^n$

Steel structures (beams, scaffolding, rebars in concrete etc.) may both shield or amplify locally the field according to the geometry, material properties, magnetic history ……

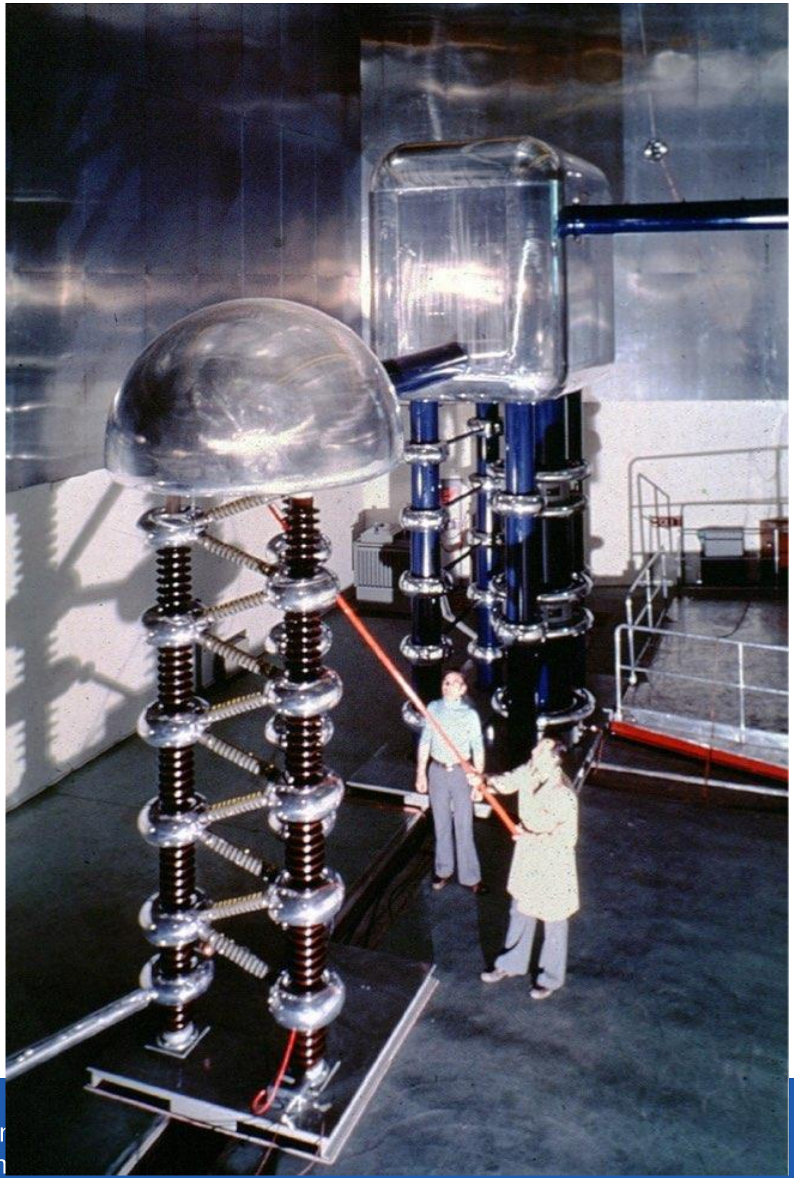
Magnetic field measured at 1.3 m from the floor as the crane passes overhead ± 2.5 µT $B_{vertical}$ fluctuation correlated with the position of the beam.



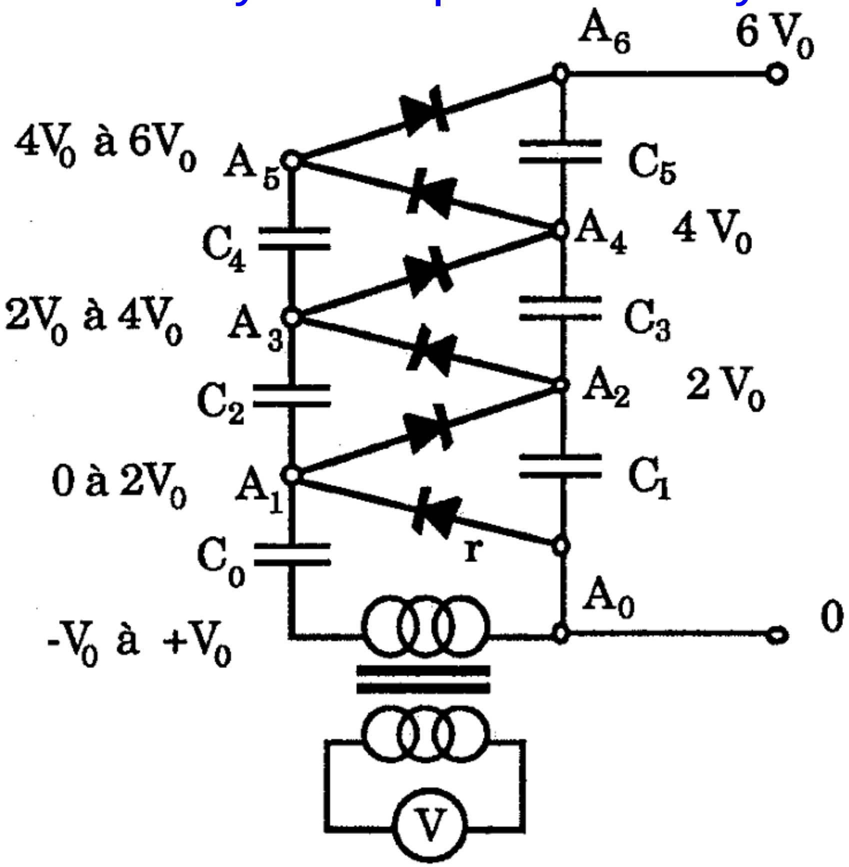
Daily and yearly change < 1%

From M. Buzio

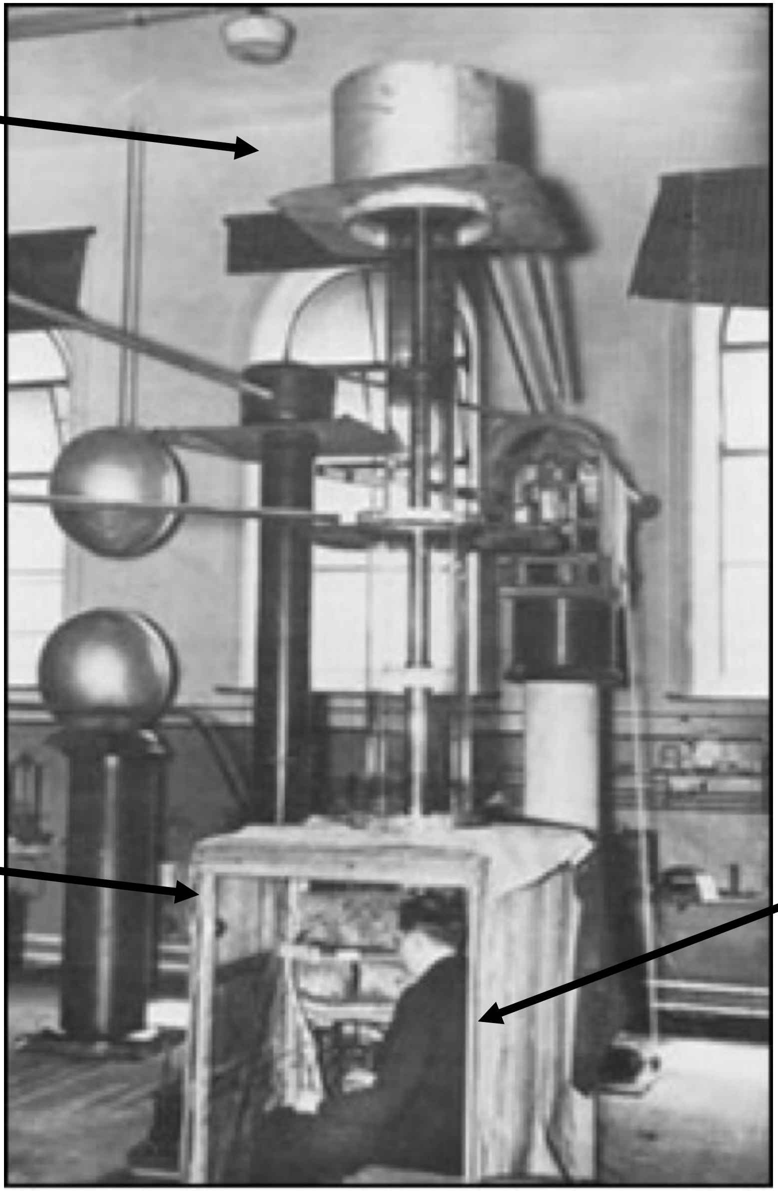
Cockroft-Walton. Old CERN proton pre-injector



High voltage unit composed by a multiple rectifier system



CERN: 750 kV



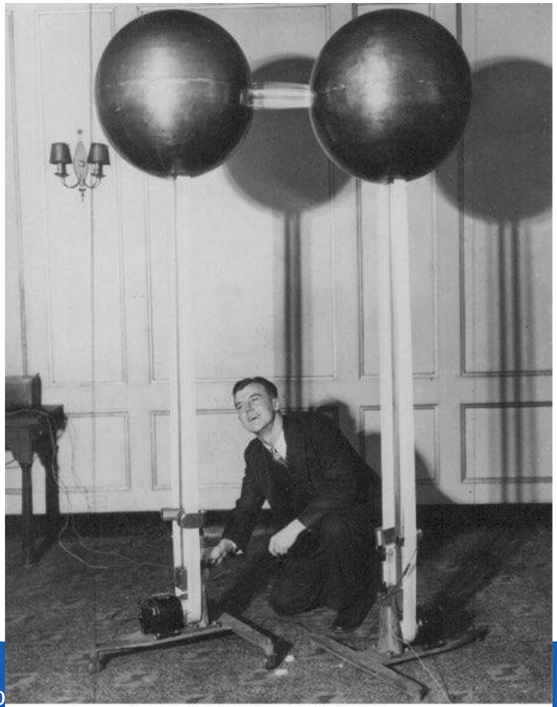
Walton and the machine used to "split the atom"

Van De Graaf electrostatic generator (1928)

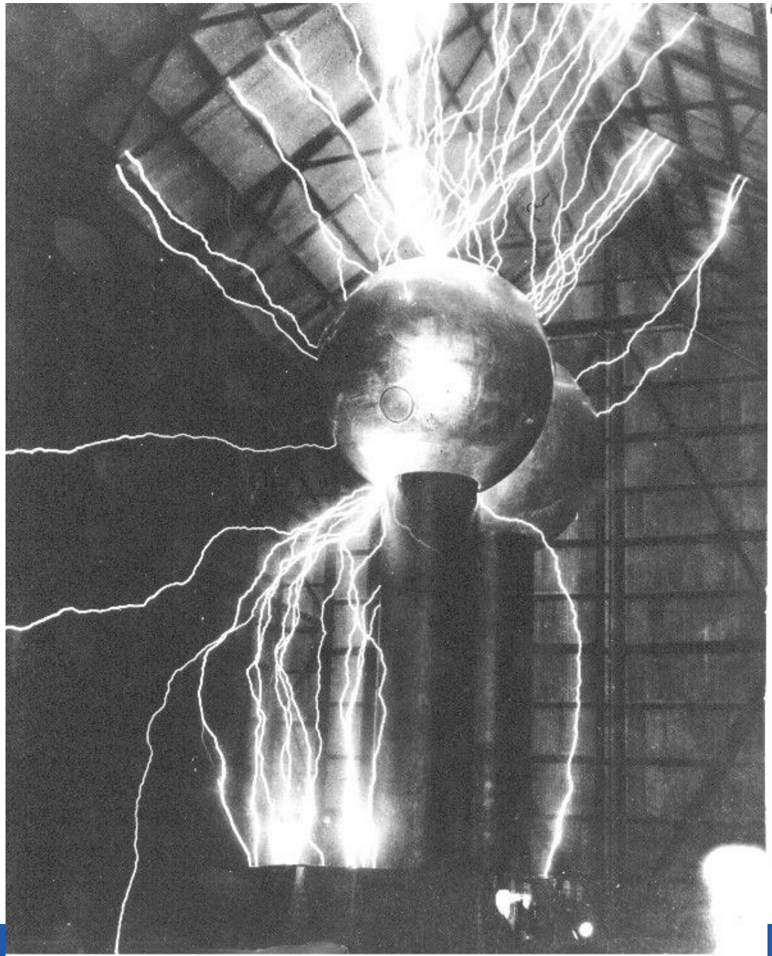
A rotating belt charges a top terminal up to the maximum voltage before sparking.

Maximum accelerating Voltage: 10 MV

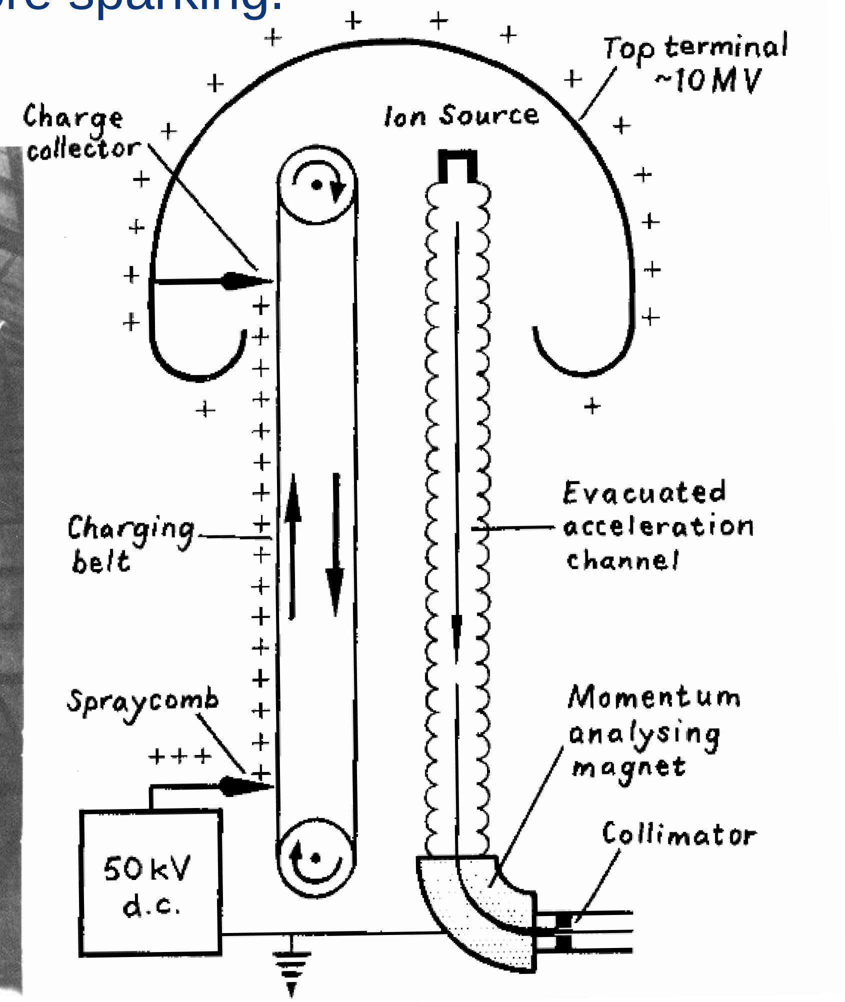
Typical speed: 20 m/s
Hight: 0.5 m
Top terminal: 1 MV - 10 MV



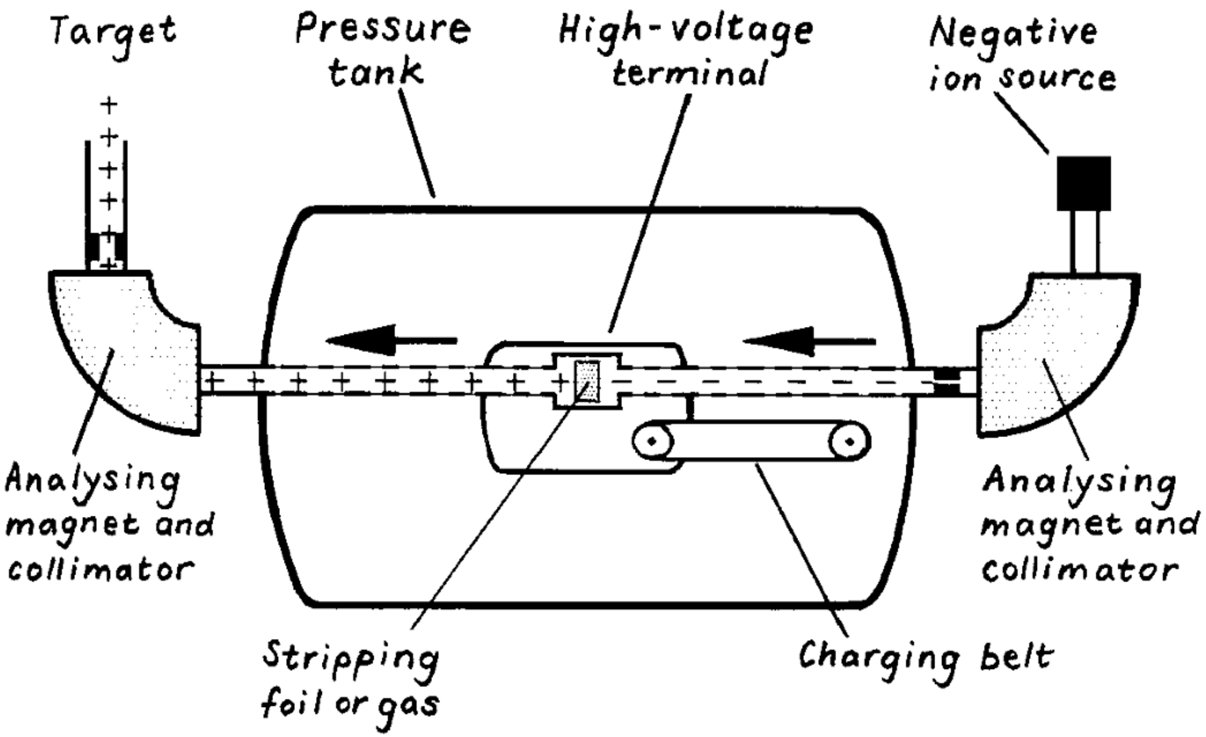
R. J. VAN DE GRAAFF WITH FIRST GENERATOR



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

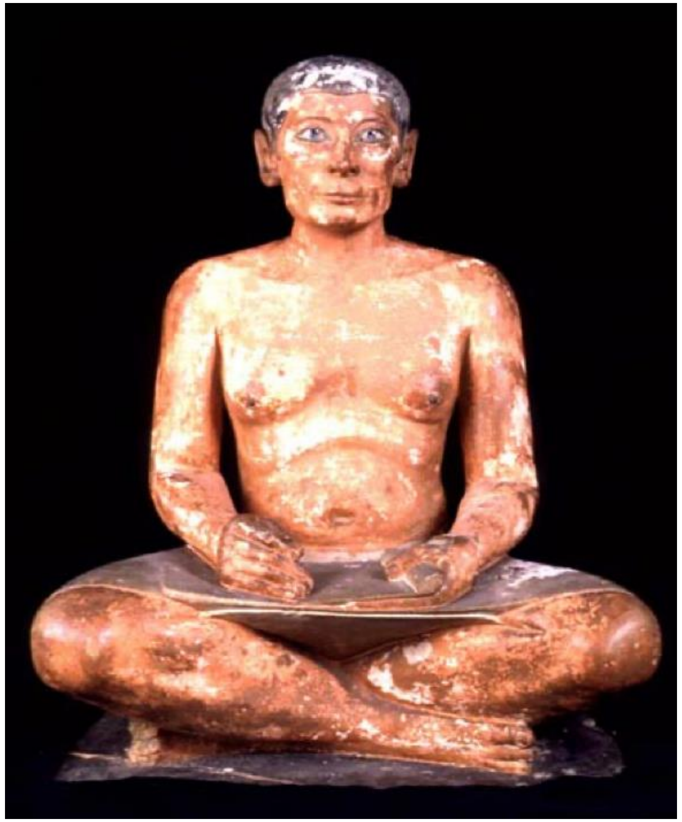
Since negative and positive multicharge states are used, different energies can be obtained

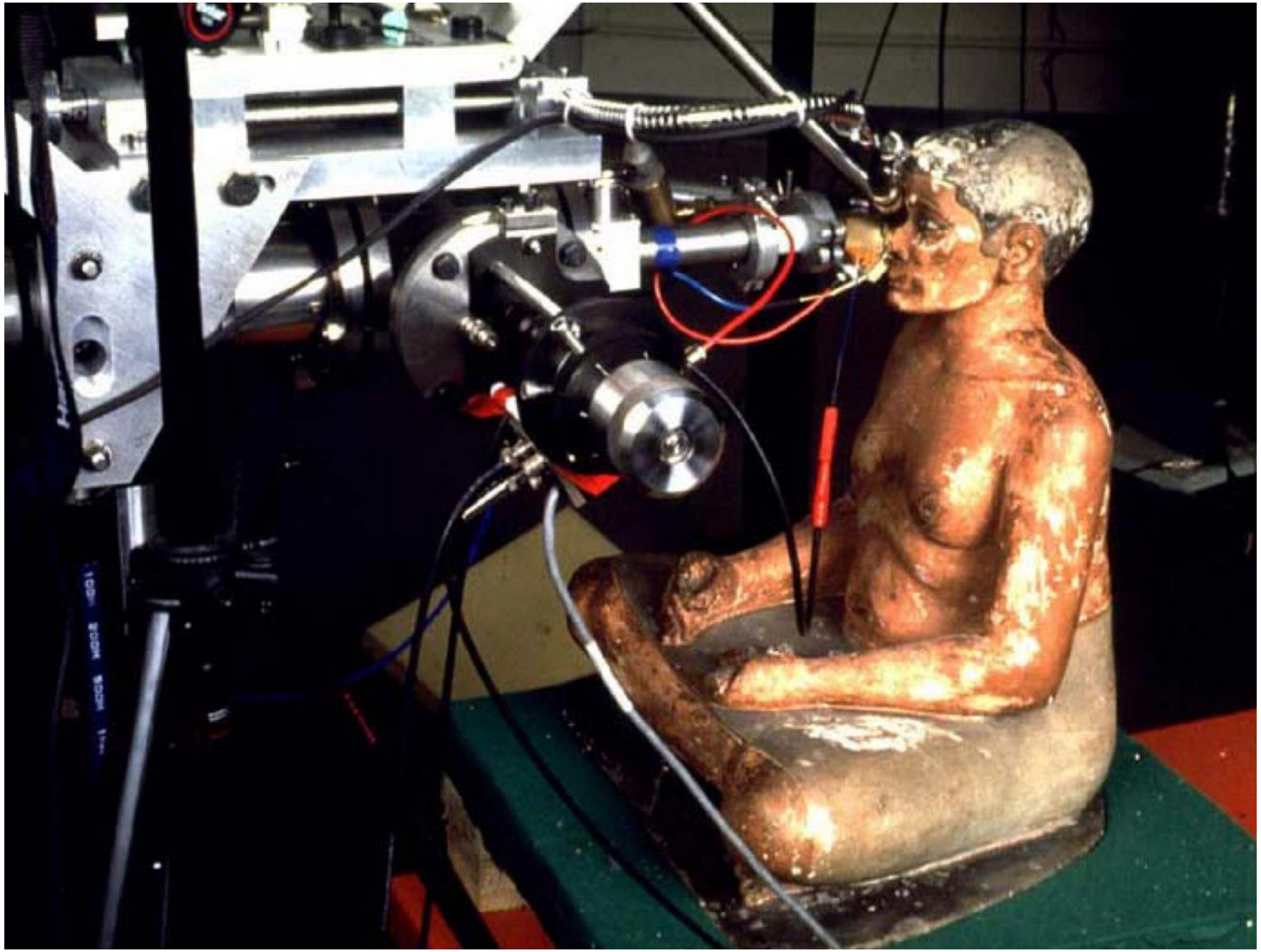
Current applications:

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



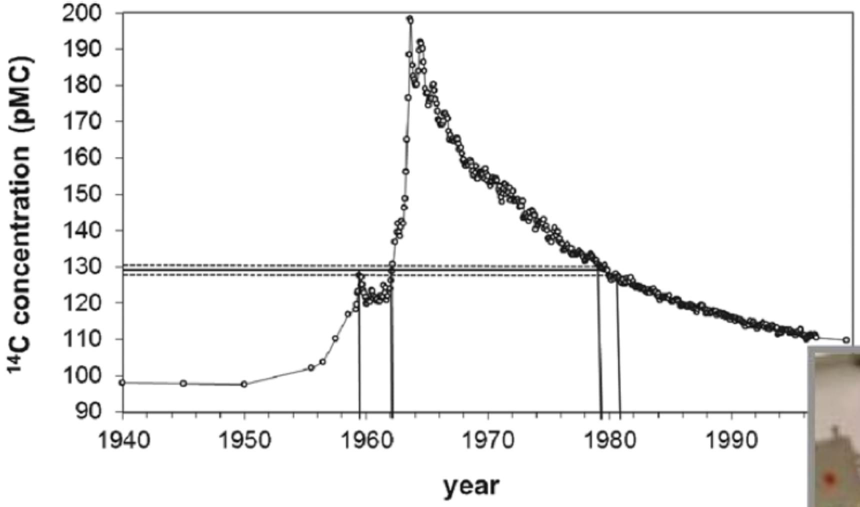


http://accelconf.web.cern.ch/AccelConf/e02/TALKS/FRYGB001.pdf

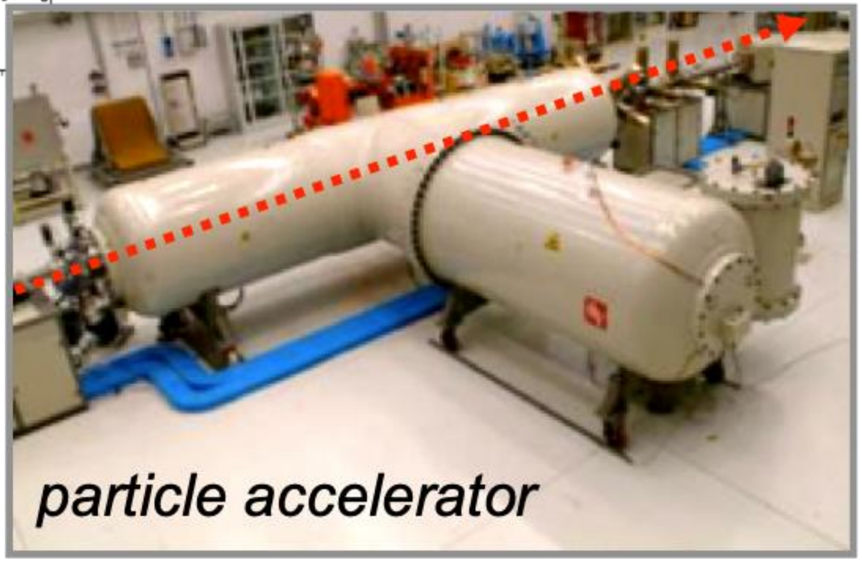
Discovering forgeries of modern art by the 14C Bomb Peak

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.



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



Synchrotron (1952, 3 GeV, BNL)

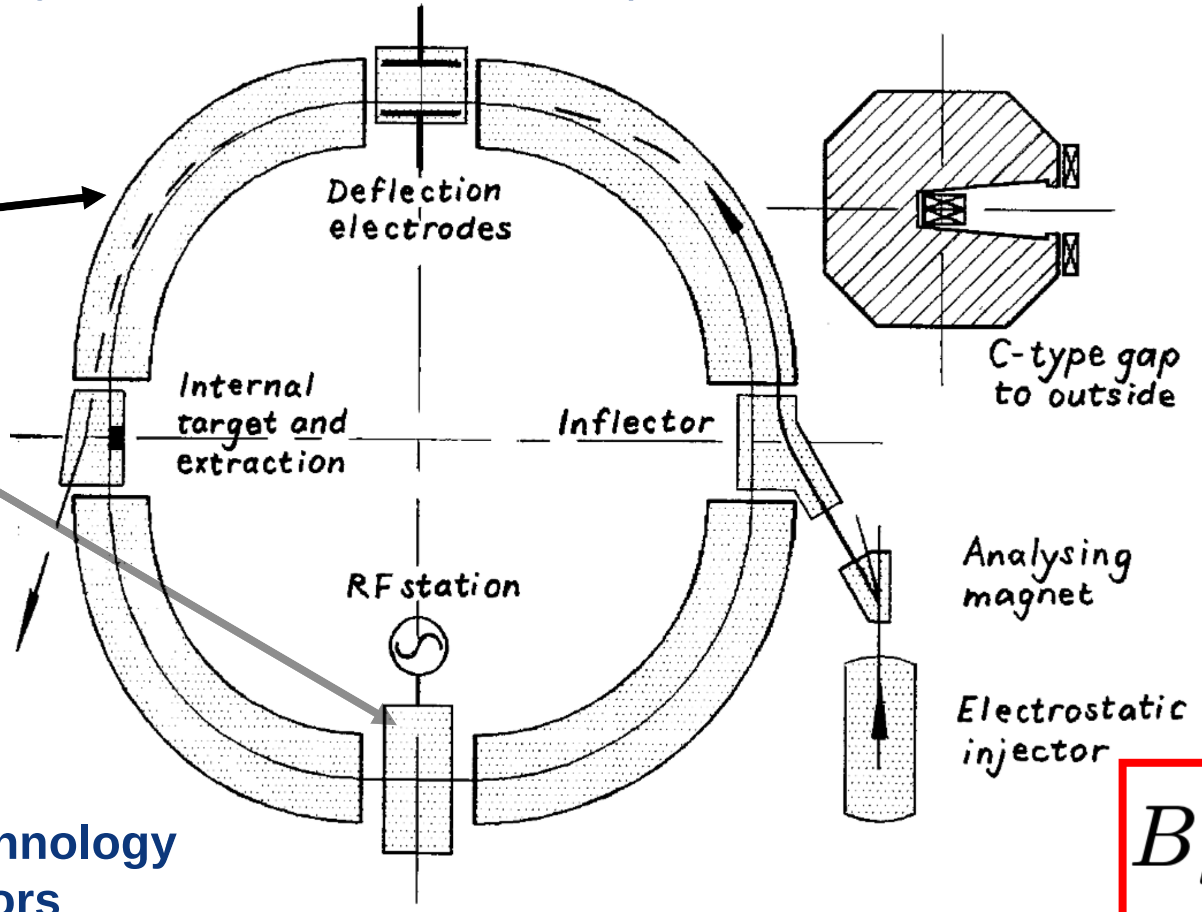
New concept of circular accelerator. The magnetic field of the bending magnet varies with time.
As particles accelerate, the B field is increased proportionally.
The frequency of the accelerating cavity, used to accelerate the particles, has also to change.

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:

$$B\rho = \frac{p}{e}$$

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.