Particle accelerators II: How to get protons in the LHC? (or electrons in the ILC)

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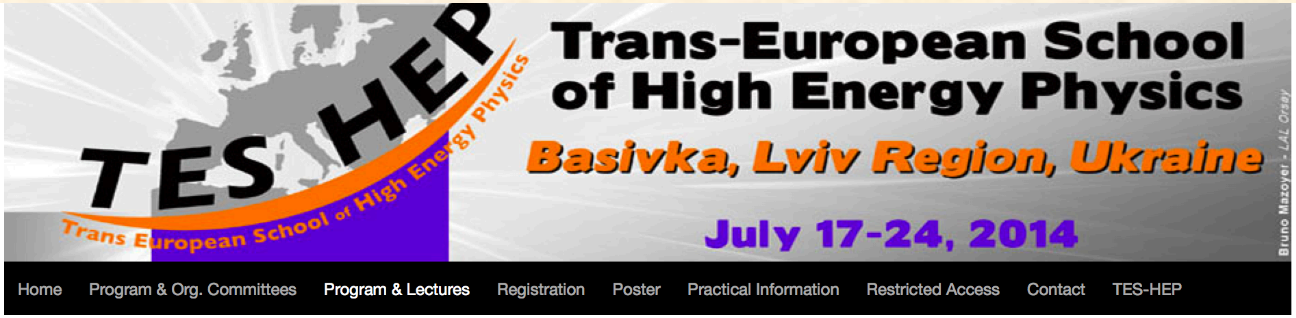
Slides are available online!

http://teschool14.lal.in2p3.fr/program-lectures/program/



Program

	Thursday July 17th	Friday July 18th	Saturday July 19th	Sunday July 20th	Monday July 21st	Tuesday July 22nd	Wednesday July 23rd	Thursday July 24th
09:00-10:00	Introduction	Standard Model & Beyond	Standard Model & Beyond	Standard Model & Beyond		Standard Model & Beyond	Standard Model & Beyond	Standard Model Precision tests
10:00-11:00	Standard Model & Beyond	Statistics	Statistics	Statistics	Excursion to Lviv	Standard Model Precision tests	Standard Model Precision tests	Standard Model Precision tests
11:00-11:30	Break	Break	Break	Break		Break	Break	Break
11:30-12:30	Accelerators	Accelerators	Accelerators	Instrumentation		Instrumentation	Instrumentation	Instrumentation
12:30-13:30	Neutrino Physics	Neutrino Physics	Neutrino Physics	Cosmology & Planck results		Cosmology & Planck results	Cosmology & Planck results	Instrumentation
13:30-15:00	Lunch	Lunch	Lunch	Lunch	Lunch	Lunch	Lunch	Lunch
15:00-16:00	Short course 1	Short course 2	Short course 3	TD Standard Model/Building detector in GEANT4	Satellite event: 90 years anniversary of G. Charpak birth	Instrumentation	Students presentations	Students presentations
16:00-17:00	Practical work presentation/ Students work with teachers on presentation	Practical work presentation/ Students work with teachers on presentation	Discussion session 1			Discussion session 2		
17:00-17:30	Break	Break	Break	Break		Break		
17:30-18:30	TP / Students work with teachers on presentation	TP / Students work with teachers on presentation	TD Standard Model/Building detector in GEANT4	Football		short course 4: Future challenges: projects vs. physics		
18:30-19:30	TP / Students work with teachers on presentation	TP / Students work with teachers on presentation						Summary

Answers to questions received

- Beam power:

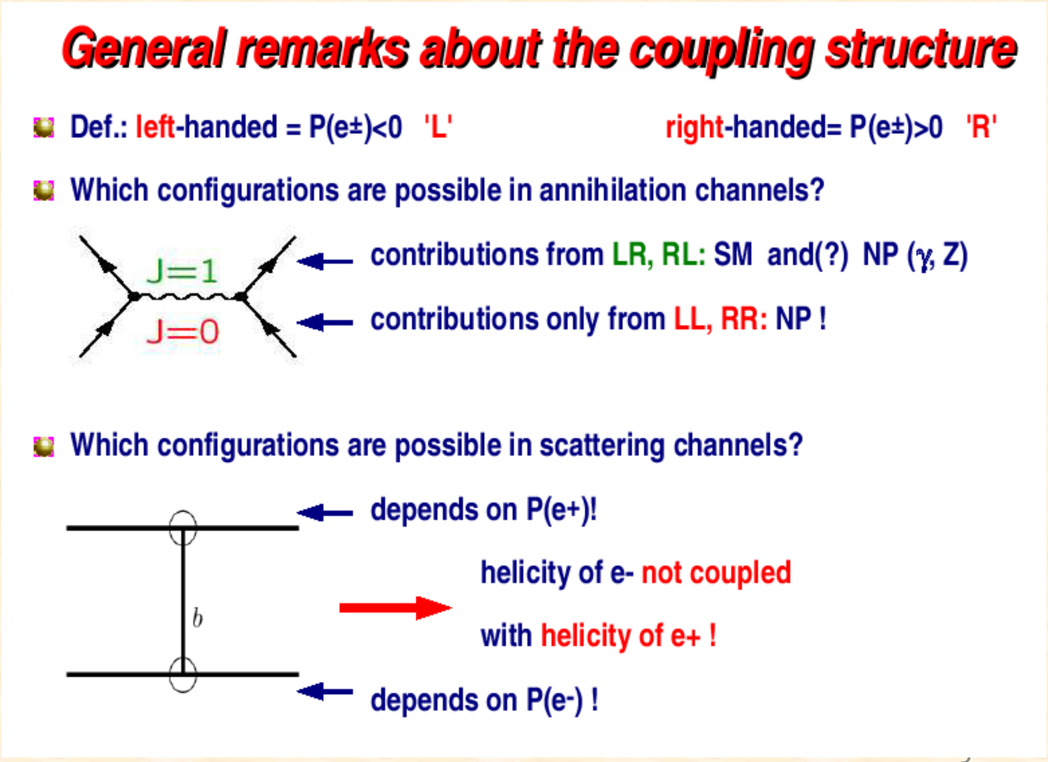
1 eV = 1.6 × 10^{-19} joule; Copper heat capacity: 0.385 J/g/K

10^{13} e- @100 keV => 0.1 J on 100g Cu => ~0.26K/shot

In the absence of cooling and with a high repetition rate this can quickly become a problem.

- Polarised beams:

http://www.ippp.dur.ac.uk/~gudrid/source/Physics-case.html



Feel free to ask me questions if you want more details on the material covered in the lecture!

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Lectures overview

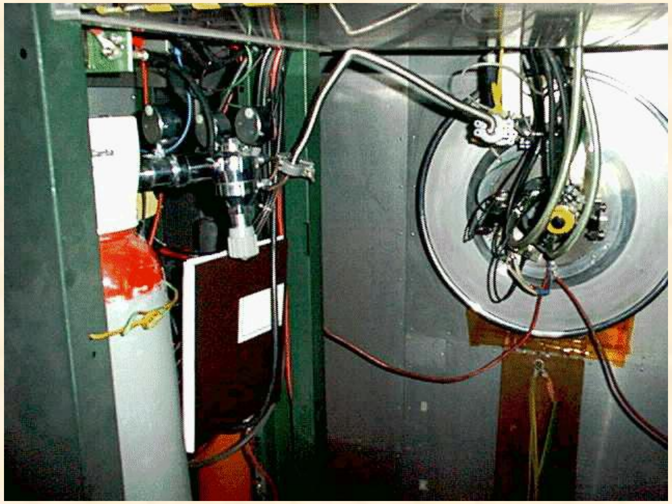
I. *How to produce protons (electrons) for the LHC (ILC)?*

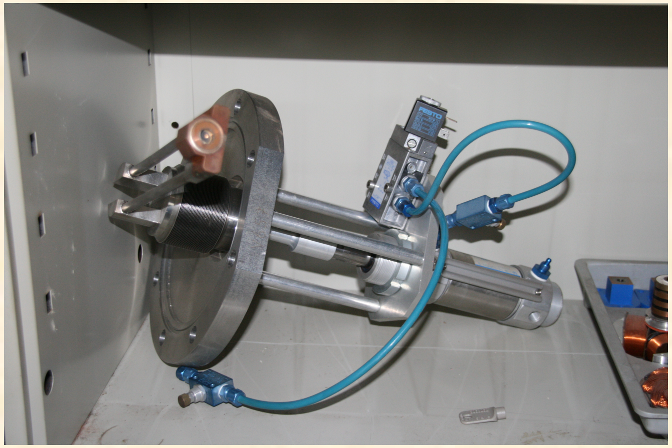
II. How to get protons in the LHC (or electrons in the ILC) ?
   - Magnets
   - Injection chain
   - Phase-space (emittance)
   - Beam dynamics
   - Beam-beam effects

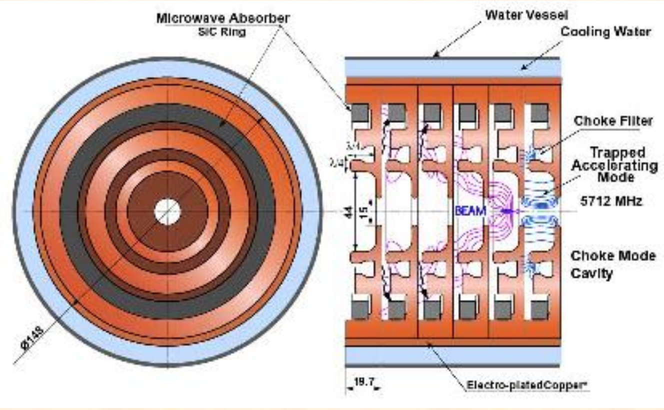
III. *How to "see" protons (electrons) in the LHC (ILC)? What can you do with a particle accelerator (apart from hunting the Higgs)?*

Where are we?

- Yesterday we have seen how ionization is used to produce electrons or ions.
- We saw that high energy particles can be used to create matter-antimatter pairs that are used in matter-antimatter colliders.
- Acceleration is done in most accelerators by sending RF waves in specially designed cavities. For protons and other ions the design of these cavities at low energy (non relativistic) can be tricky.
- Today we will see how to control these particles and how to keep them in the collider.







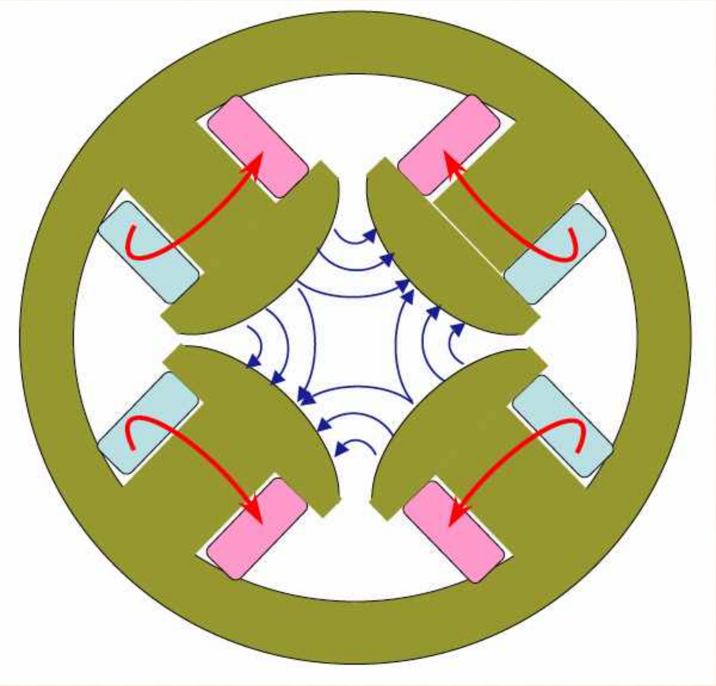
MAGNETS

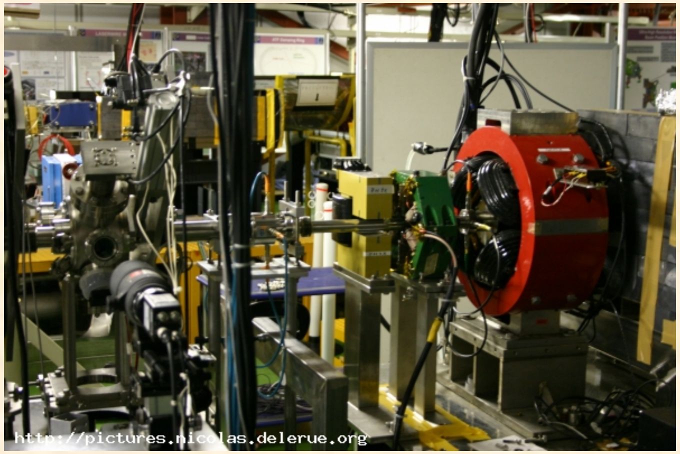
How to control where the particles go?

- Electric and magnetic fields can deflect charged particles.
- In an electric field the particles get accelerated.
- In magnetic field the direction of the particles is changed but not their energy.
  => it is preferable to use magnetic field (usually electromagnets) to control a beam.
- Magnets are also more efficient.

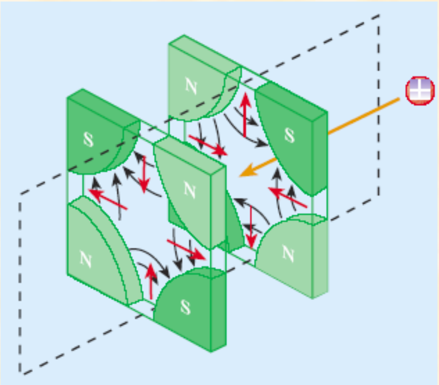
Beam focussing

- A regular magnet (dipole) will create a field that will bend the beam in one direction.
- To change the size of the beam a different type of magnets called quadrupoles need to be used.
- Quadrupoles create intense fields for off-axis particles but do not disturb particles on the axis.

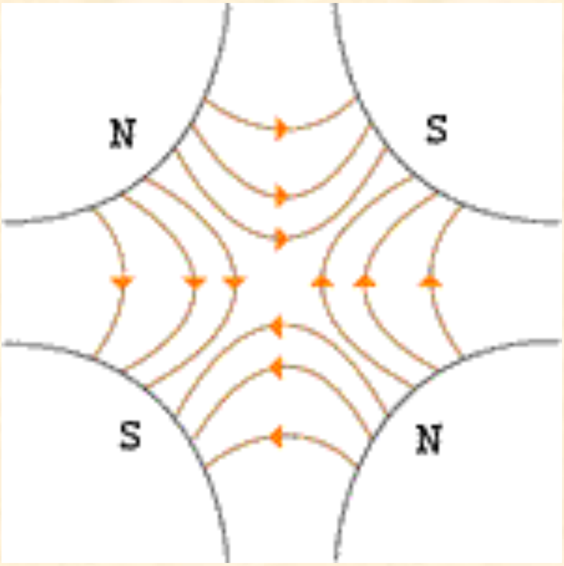




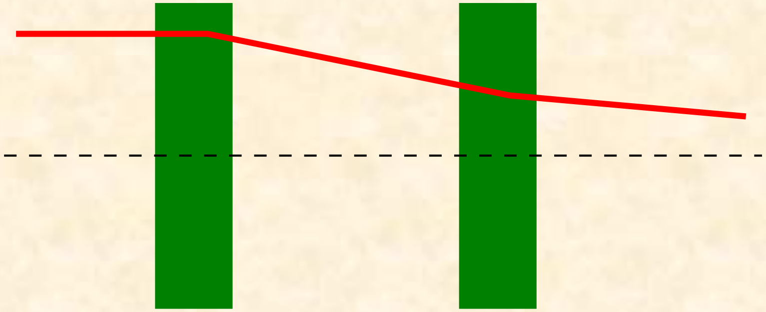
FODO cell



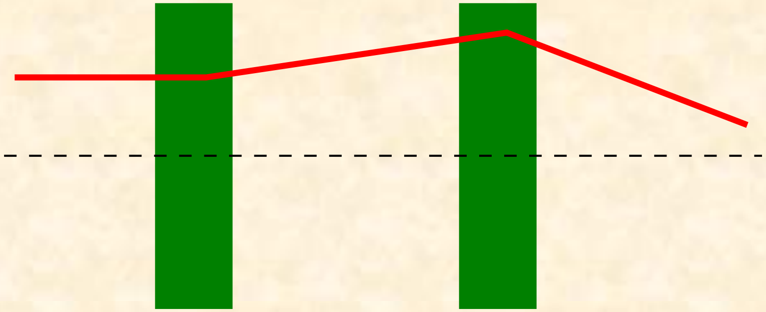
- A quadrupole will focus the beam in one plane but defocus it in the other plane.
- To have a net focussing effect, 2 quadrupoles are used, one focussing in one plane and the other one focussing in the other plane.



Focus Defocus

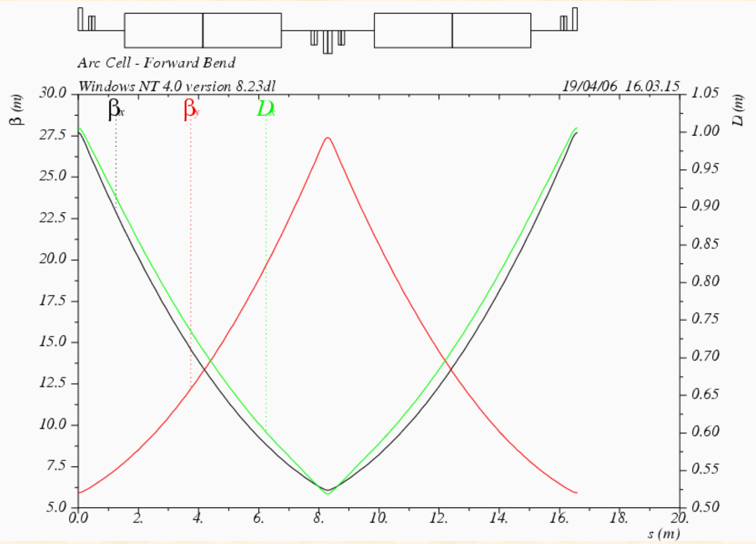


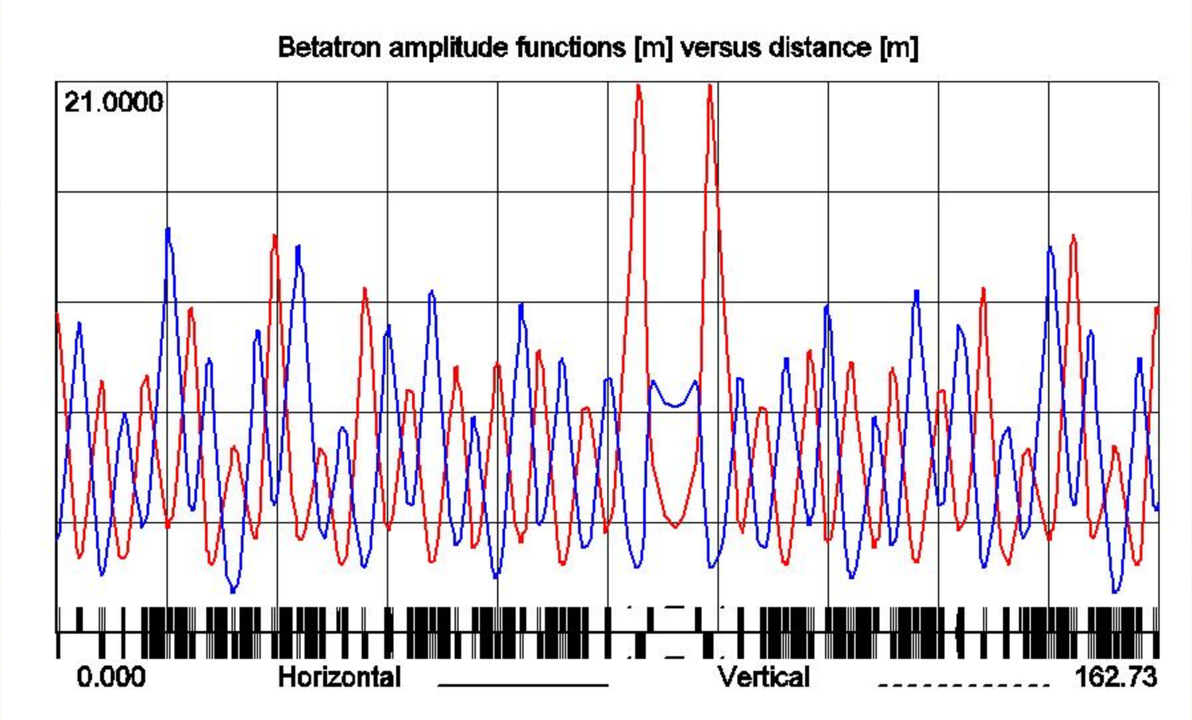
Defocus Focus

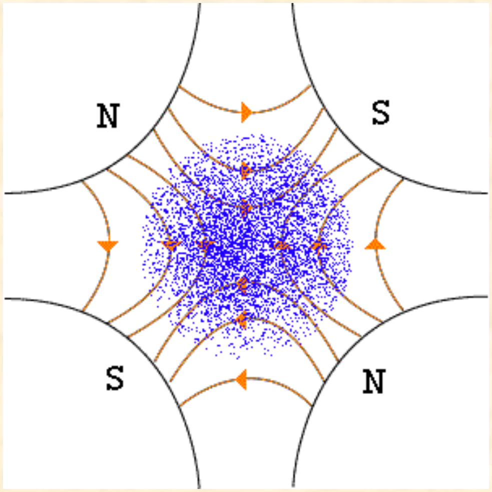


Accelerator lattice

- In an accelerator there is a large number of quadrupoles to keep the beam size under control.
- This is called the lattice of the accelerator.
- The magnet strength are characterised by a "beta" function.

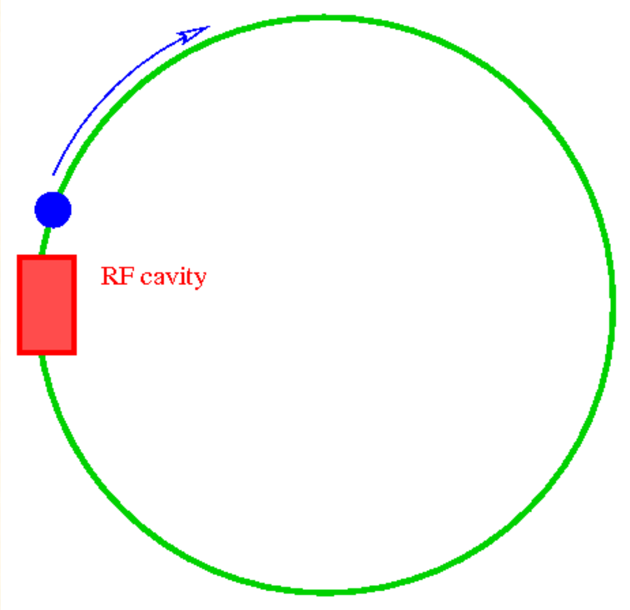






Synchrotrons

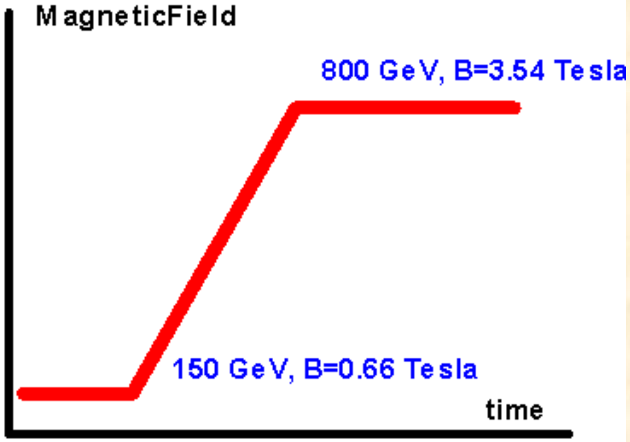
Dipole magnets can be used to make the particles follow a "circular" orbit.



⇒ re-use accelerating cavities.

⇒ As the particles gain energy the radius of curvature of their orbit in a constant field increases

⇒ The field of the dipoles has to be increased as the particles gain energy to keep a constant orbit. "Synchrotron"



Magnetic rigidity

- The bending power of a magnet depends on the beam energy.
- It is often useful to use the "magnetic rigidity" of a beam.
- One should note that rings often have straight section. So the magnetic radius of an accelerator is smaller than its geometrical radius.
- The LHC has a magnetic radius of 2804m.

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

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

$$B[T]\rho[m] = 3.34p[GeV/c]$$

$$B[T] = \frac{3.34 * 4000[GeV/c]}{2804[m]} = 4.8[T]$$

Quizz: Particles bending

- Inside a particle beam the energy of the particle is not exactly the same.
- Let's consider a 100 GeV relativistic beam with 1% energy spread in a dipole magnet.
- Will the particles with more energy have:
  (a) a larger radius of curvature than the others
  (b) the same radius of curvature
  (c) a smaller radius of curvature

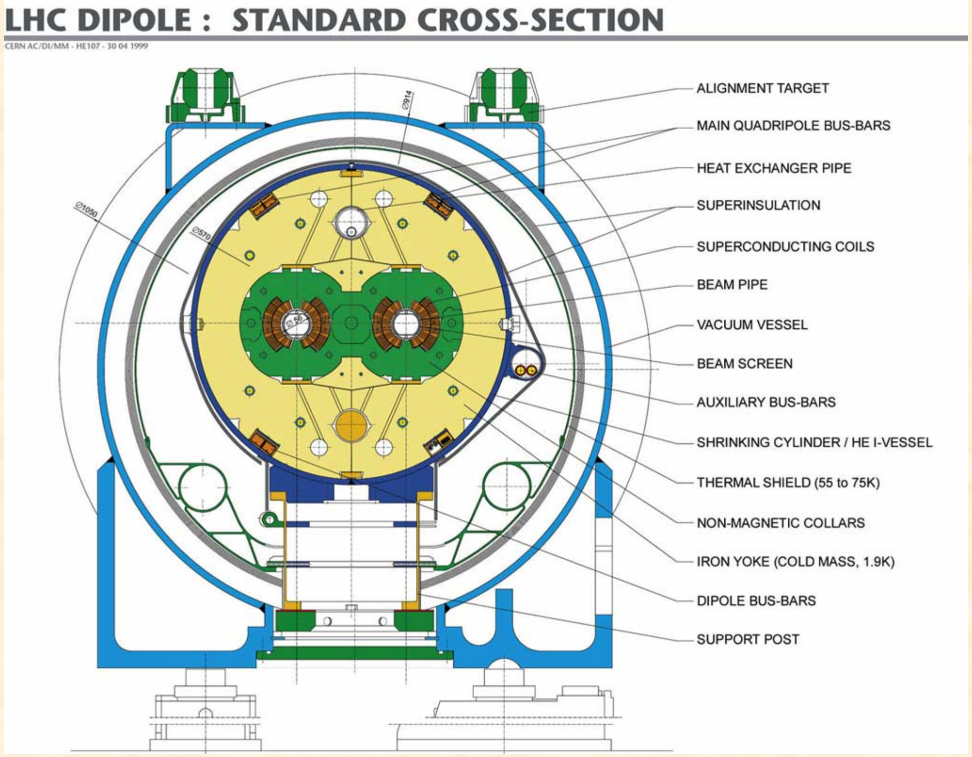
Answer (a)

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

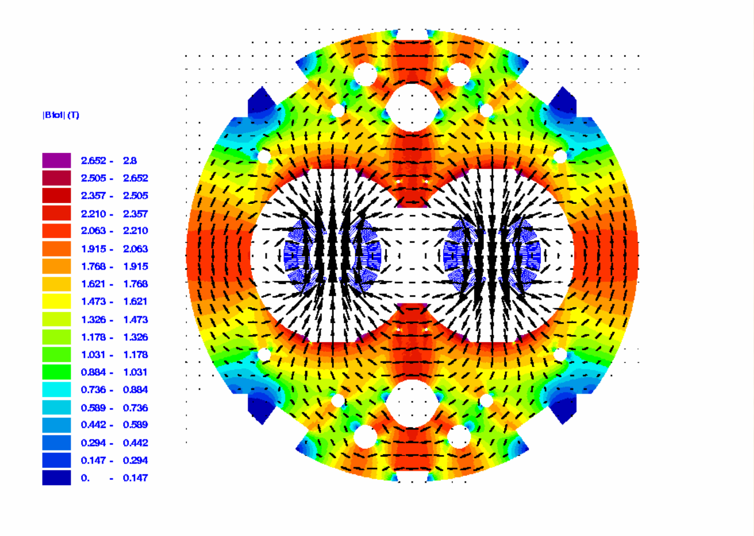
$$B[T]\rho[m] = 3.34p[GeV/c]$$

- All particles experience the same magnetic field (B).
- The all have (almost) the same speed (v ~ c)
- However the most energetic particle have a slightly higher mass
  => less transverse acceleration
  => larger radius of curvature.
- Particles with more energy are more « rigid ».

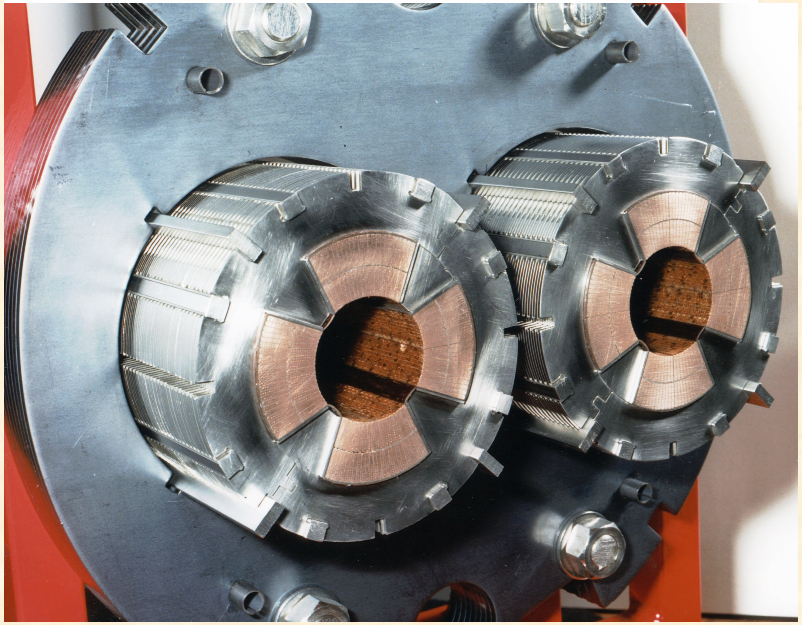
LHC Magnets



LHC DIPOLE : STANDARD CROSS-SECTION
CERN AC/DI/MM - HE107 - 30 04 1999
ALIGNMENT TARGET
MAIN QUADRIPOLE BUS-BARS
HEAT EXCHANGER PIPE
SUPERINSULATION
SUPERCONDUCTING COILS
BEAM PIPE
VACUUM VESSEL
BEAM SCREEN
AUXILIARY BUS-BARS
SHRINKING CYLINDER / HE I-VESSEL
THERMAL SHIELD (55 to 75K)
NON-MAGNETIC COLLARS
IRON YOKE (COLD MASS, 1.9K)
DIPOLE BUS-BARS
SUPPORT POST

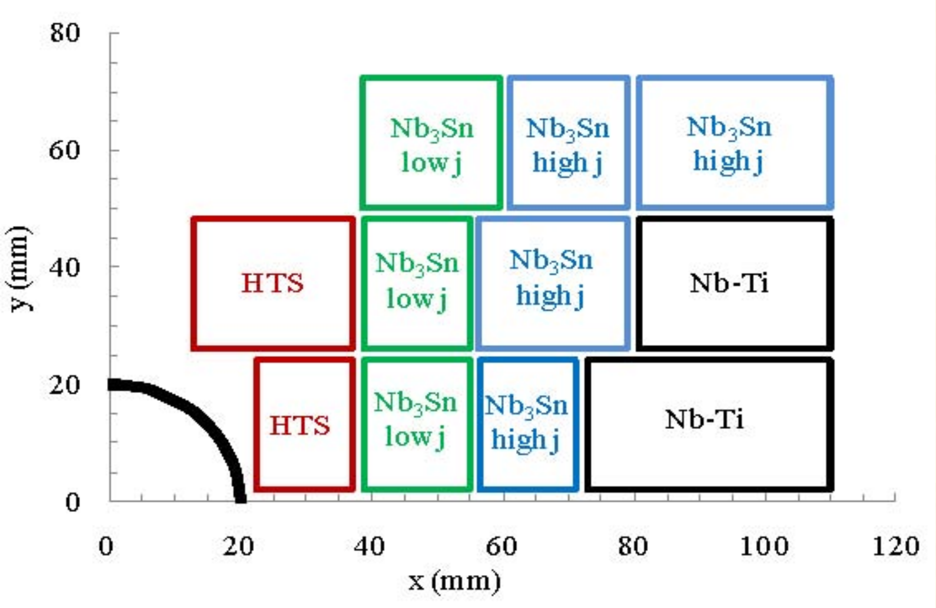


|Btot| (T)
2.652 - 2.8
2.505 - 2.652
2.357 - 2.505
2.210 - 2.357
2.063 - 2.210
1.915 - 2.063
1.768 - 1.915
1.621 - 1.768
1.473 - 1.621
1.326 - 1.473
1.178 - 1.326
1.031 - 1.178
0.884 - 1.031
0.736 - 0.884
0.589 - 0.736
0.442 - 0.589
0.294 - 0.442
0.147 - 0.294
0. - 0.147



More energy in the LHC?

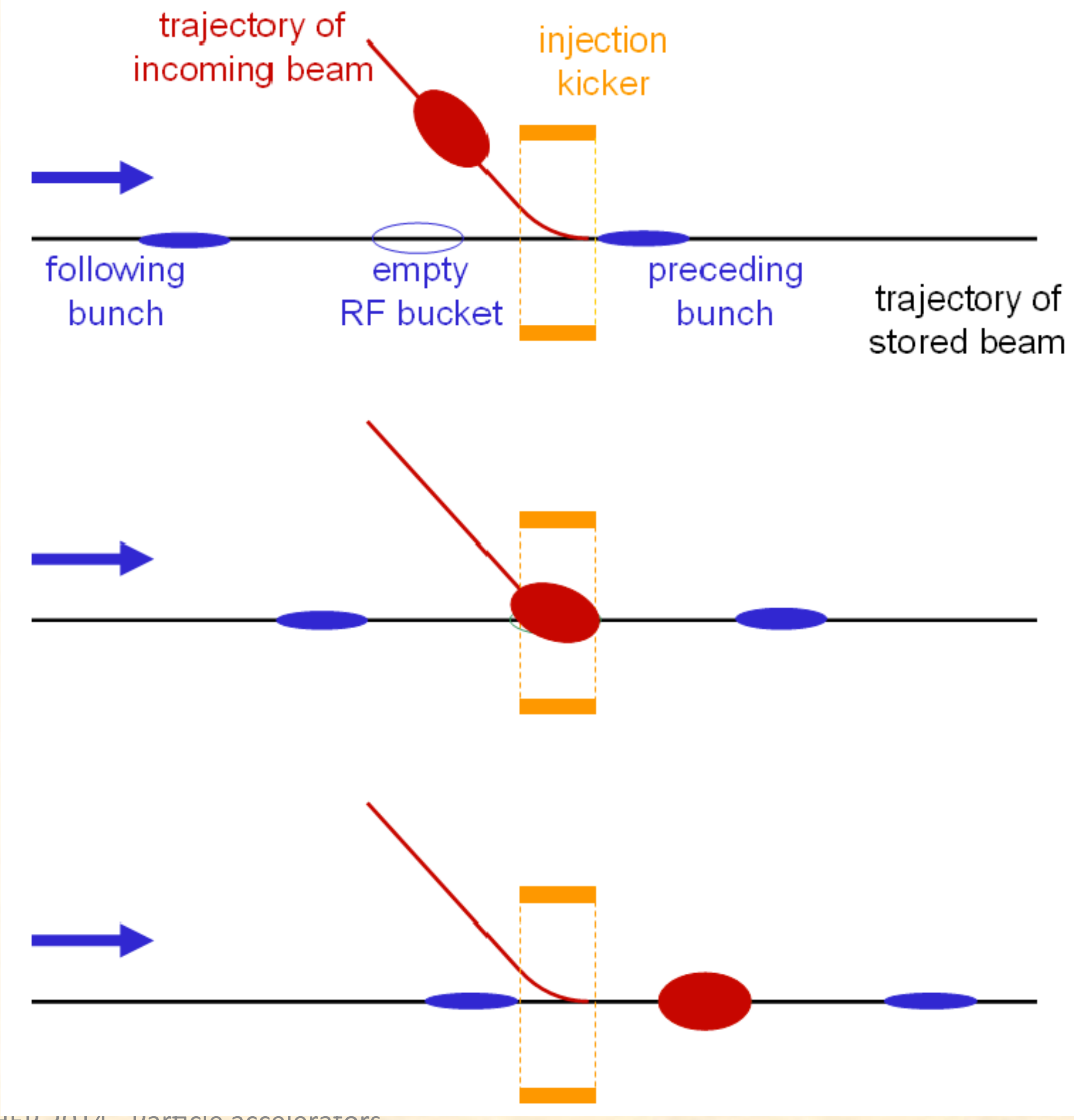
- The LHC magnets are near the state of the art.
- To significantly increase the energy of the LHC (beyond 14 TeV) one would need more powerful magnets
  => R&D in progress.



$$B[T] = \frac{3.34 * 4000[GeV/c]}{2804[m]} = 4.8[T]$$

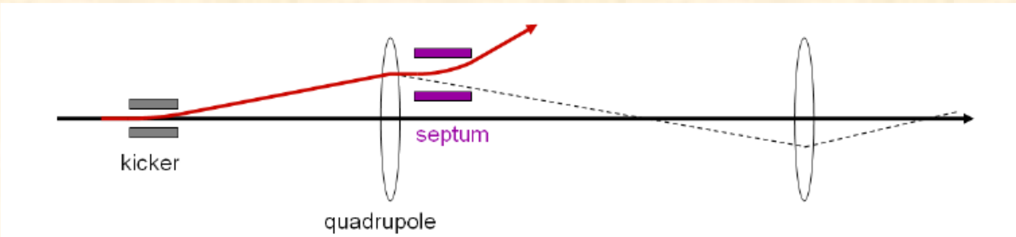
Beam injection/extraction

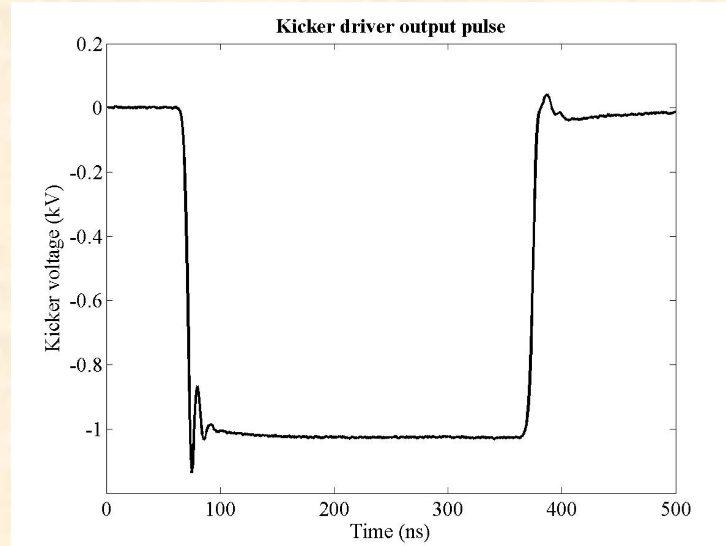
- Injecting (or extracting) particles from a ring is not easy.
- The particles must be inserted on the correct orbit.
- However the deflector must not affect the trajectory of other bunches in the ring (or of the same bunch after one turn).



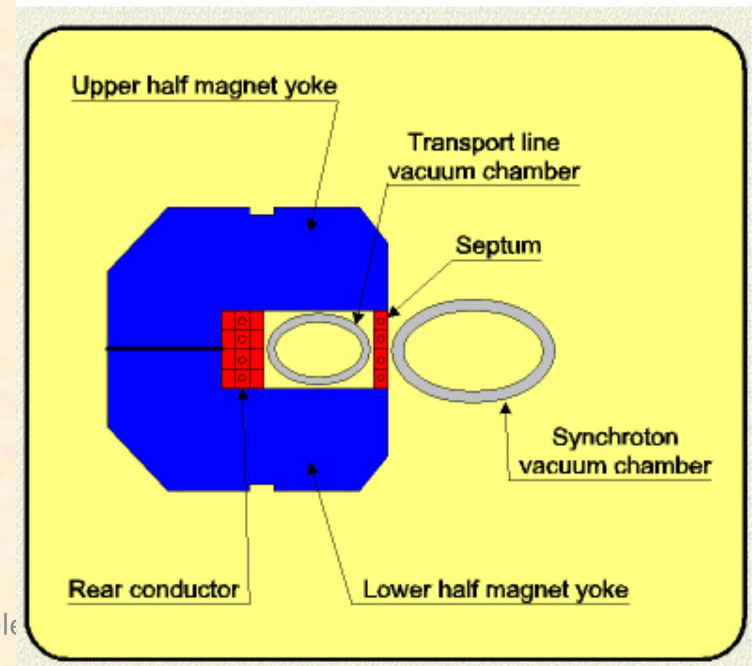
Courtesy of Andy Wolski

Septum magnets



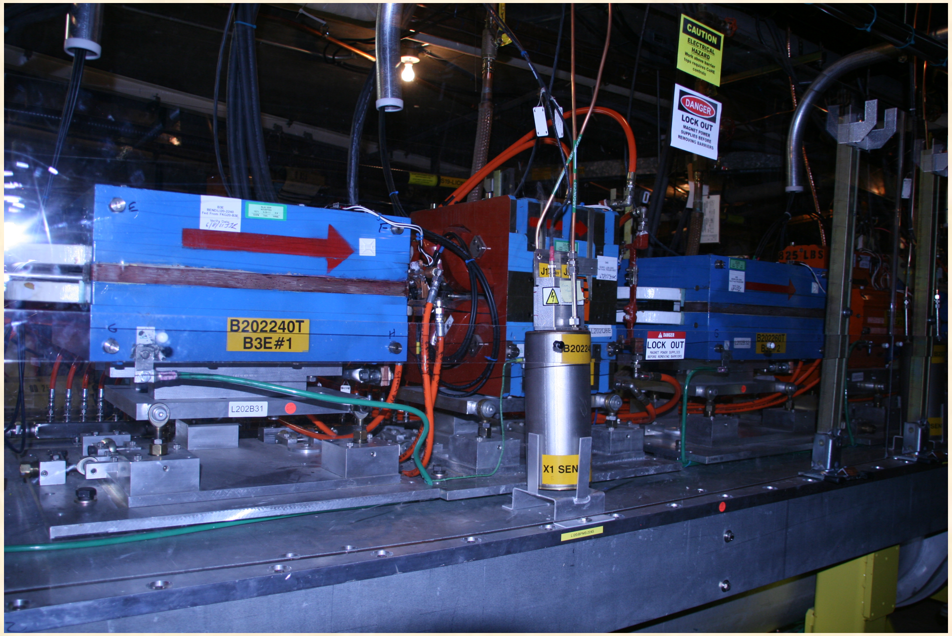


- Insertion/extraction are usually done by combining 2 types of deflectors:
  - Ultra fast kickers use an intense electric field to deflect the particles (but beware to ripples)
  - A septum magnet is used to separate neighbouring trajectories (thanks to a magnetic shield).



Magnets summary

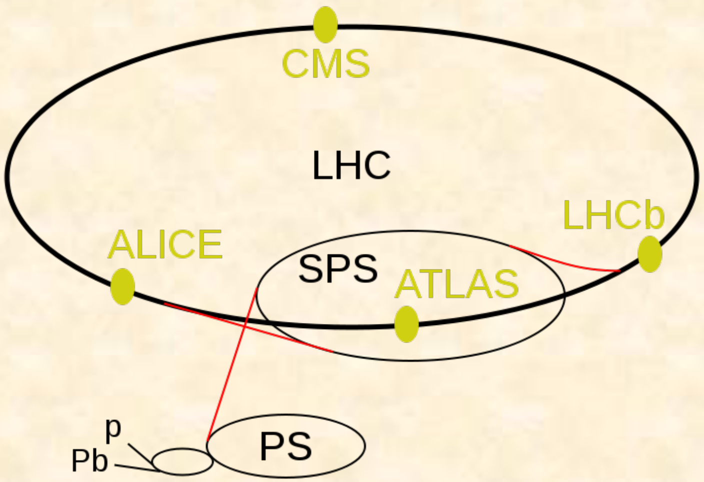
- Magnets are used to control particles in an accelerator.
- Dipole magnets are used to change the direction of the beam.
- Quadrupoles are used to control the focussing (size) of the beam.
- Septum magnets are used to inject extract the beam.
- In synchrotron (such as the LHC) the field of the magnets must be ramped when the energy of the particles increase.

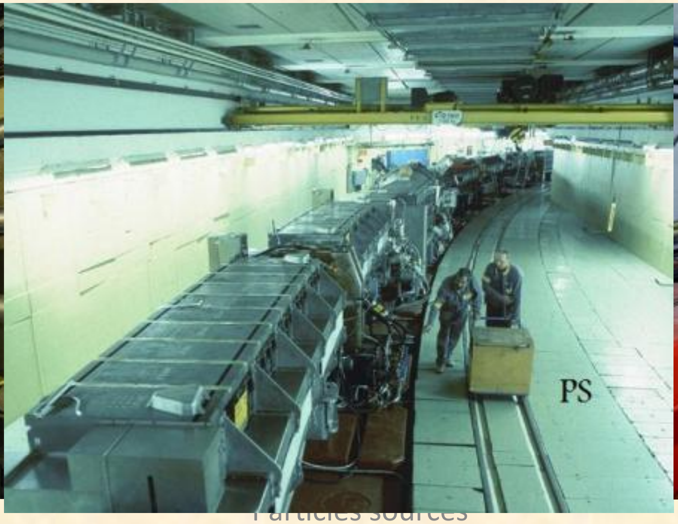


THE INJECTOR CHAIN

The injector chain

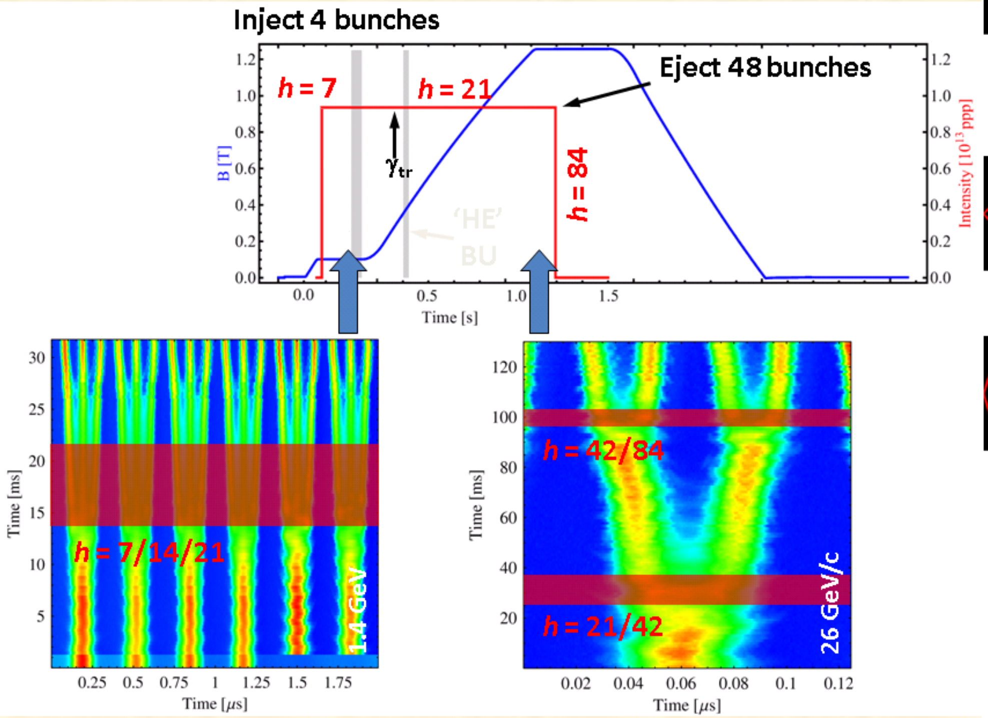
- Before reaching the LHC the particles go through several other rings.
- Each ring has a different aperture: low energy ring have a larger aperture (not good for magnetic field quality).
- Injecting directly from the source to the LHC would be like starting a car in 5^{th} gear.

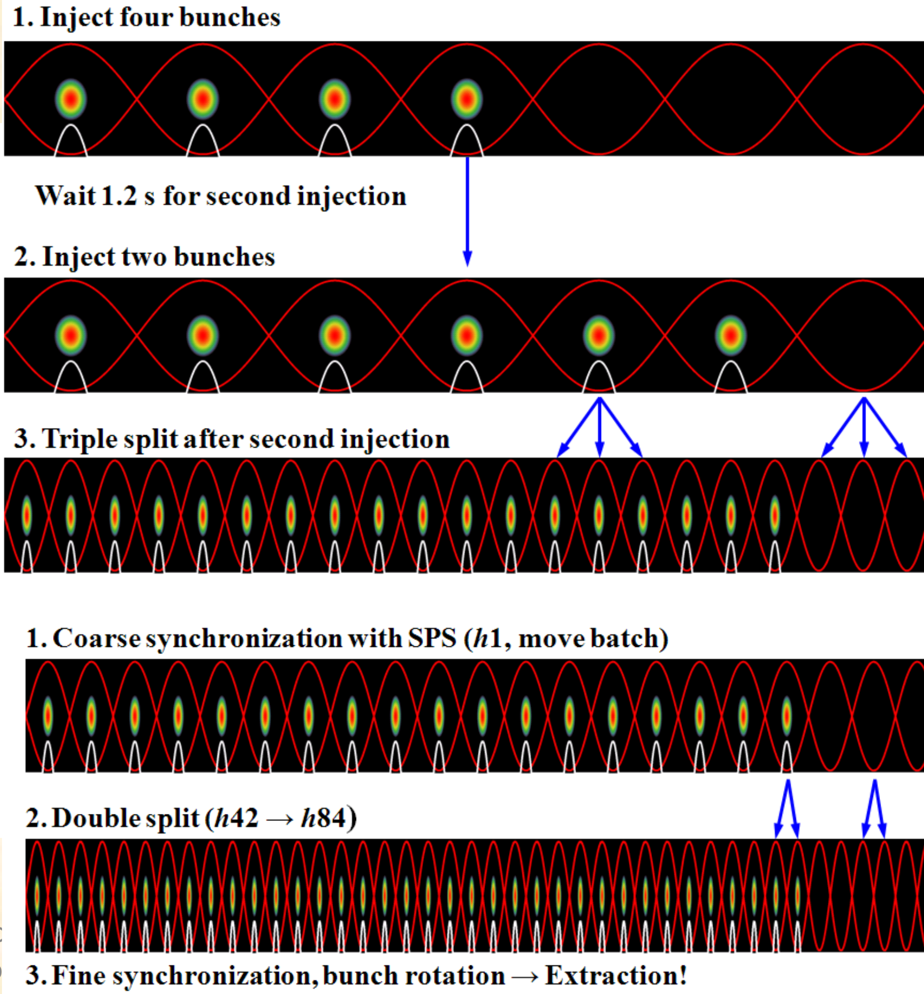




Protons bunch splitting

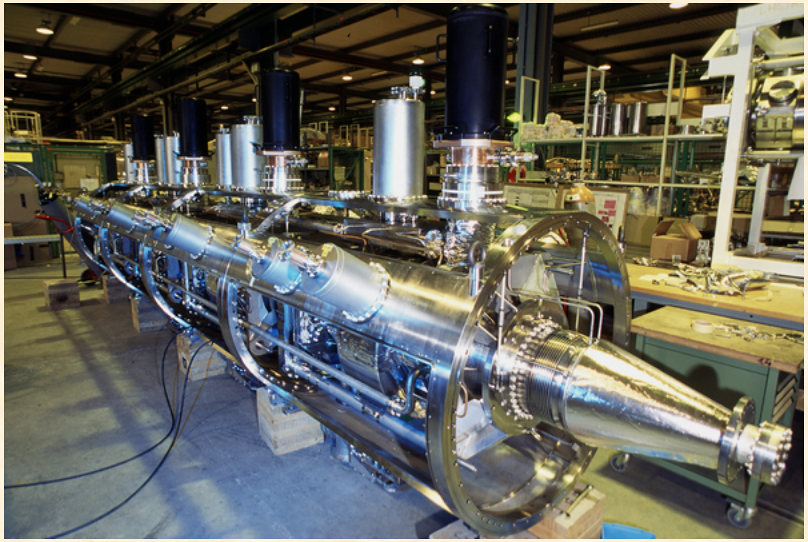
- In the pre-injectors the bunches coming from Linac 2 are adapted to the LHC bunch structure (frequency).
- The RF of the PS is used to split 8 proton bunches into 84 bunches!
- This is done by suddenly changing the RF frequency (don't try this at home).





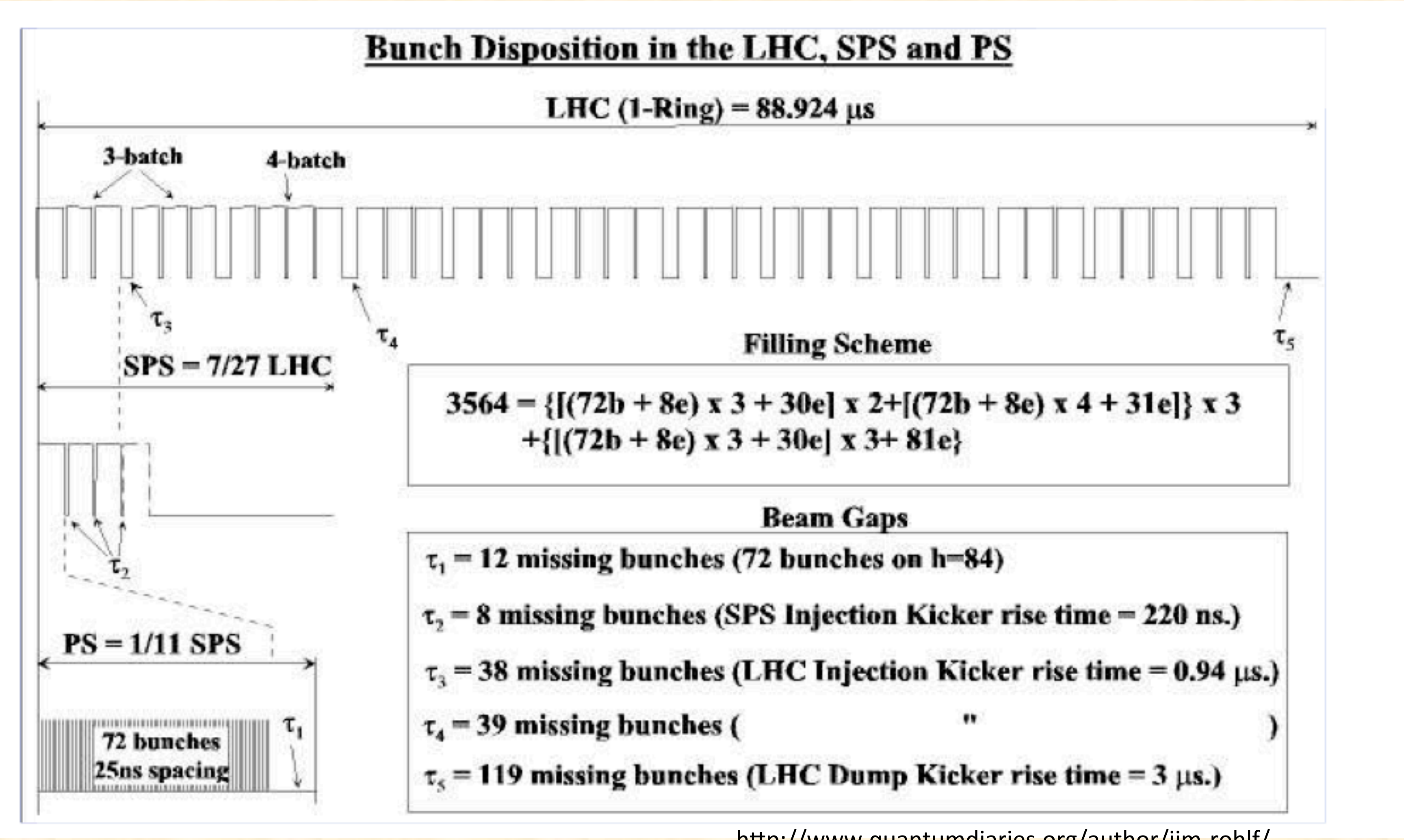
RF frequency

- The frequency of the RF cavity in the LHC is 400MHz.
- The SPS RF frequency is 200MHz
  => RF buckets are spaced by 5ns.
- However the system has been conceived with a 25ns spacing in mind.



LHC accelerating module
Source: CERN-AT-ACR-OP

LHC bunch structure



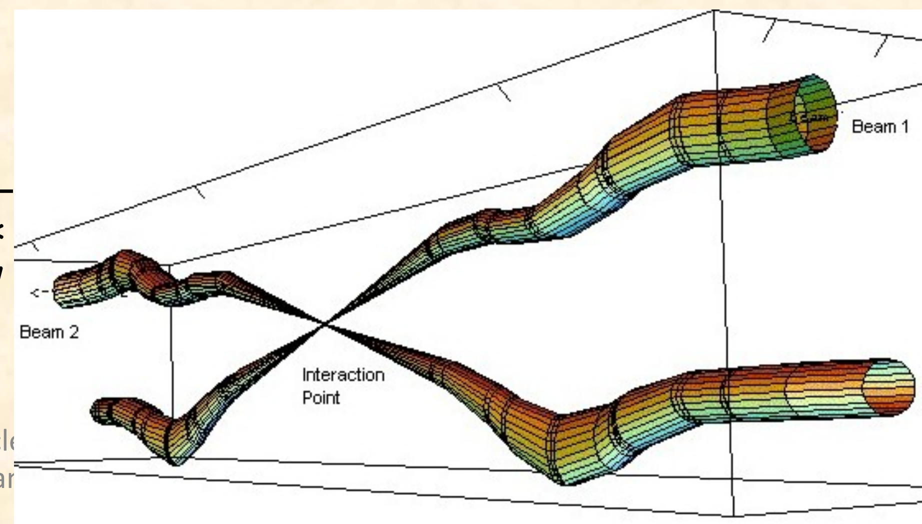
http://www.quantumdiaries.org/author/jim-rohlf/

EMITTANCE

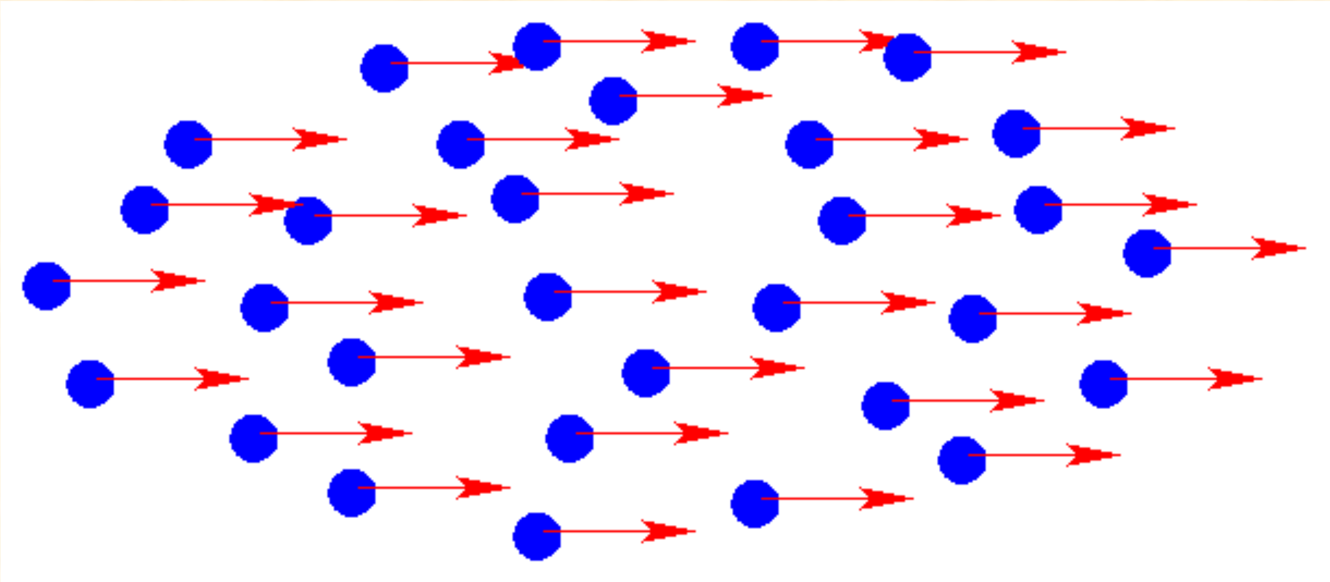
Luminosity

- The luminosity of a collider gives a measure of the number of collisions delivered.
- It is proportional to the collisions frequency and to the bunch charges.
- It is inversely proportional to the beam size.
- However because the beam size it the interaction point can not be measured, it is often written as a function of two other variables: the emittance and the beta function (magnetic properties of the beam).

$$\mathcal{L} = \frac{fN_1N_2}{4\sigma_x\sigma_y} = \frac{fN_1N_2}{4\pi\epsilon_x\beta_x^*\epsilon_y\beta_y^*}$$



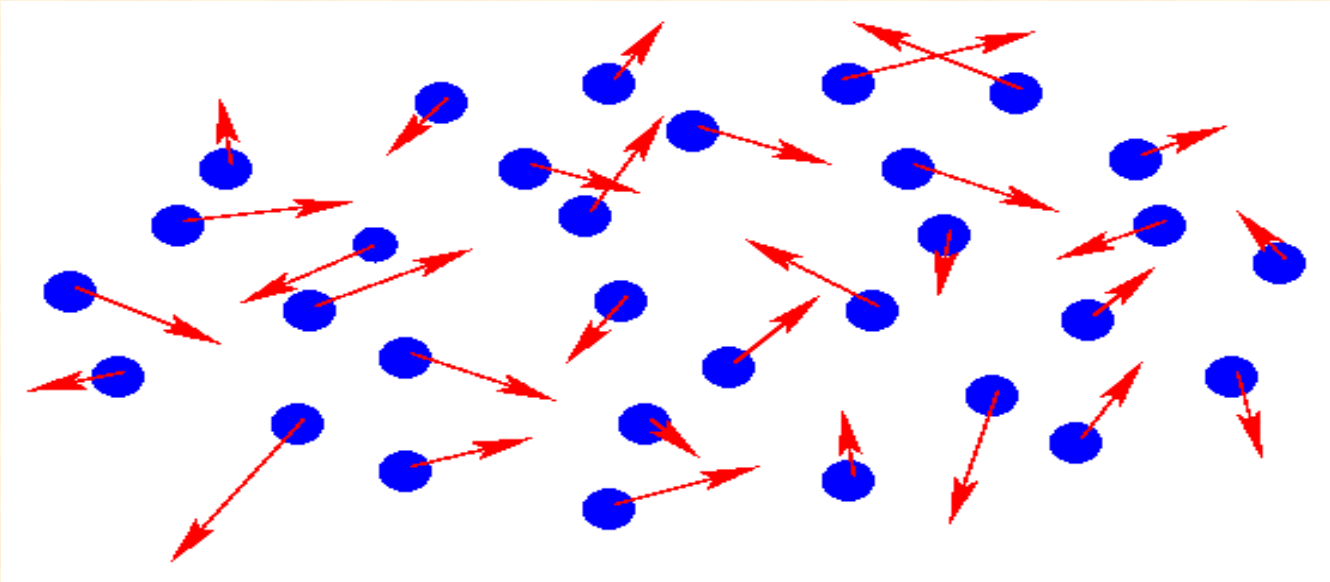
Let's look at a particle bunch



An observer in the laboratory frame looking at a particle bunch will only see particles travelling at the speed of light, apparently all in the same direction.

It is very different if one looks in the bunch's centre of mass frame...

Let's look at a particle bunch



In the centre of mass of the bunch, the particles do not look so well organised...

This should remind you other statistical systems that you have already studied: Gases!

Perfect gas law

- You have studied earlier that a perfect gas obeys the law: PV=nRT
- V is the volume term (V=xyz)
- P is a dynamic term: P, the pressure is proportional to the amount of scattering experienced by atoms as they travel in the volume. It is proportional to the momentum of the gas atoms (P~x'y'z').
- Hence it is possible to write that for gas atoms the product of their position by their momentum is expressed by their temperature *(times a constant).*
- We have seen that in the CoM particles look like a perfect gas. The product of their position by their momentum is called the “emittance” of the beam.

Liouville's theorem

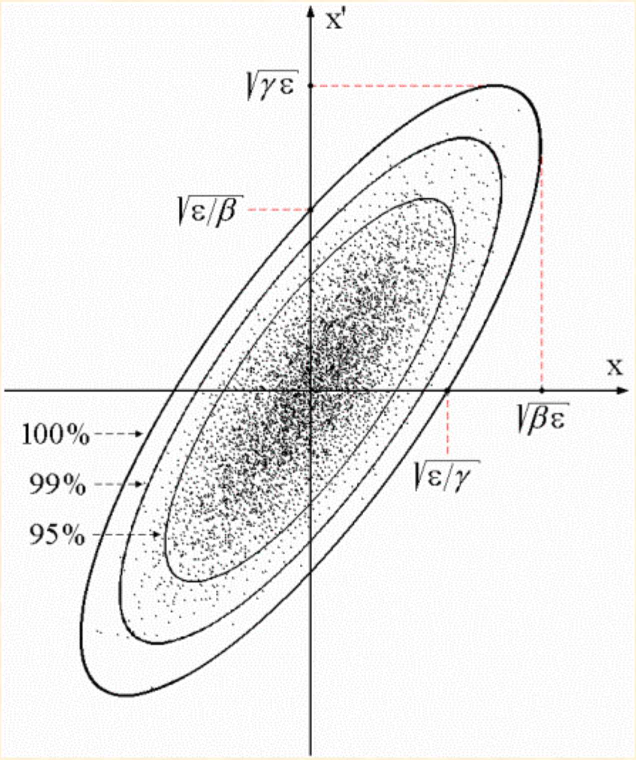
$$\frac{d\rho}{dt} = \frac{\partial\rho}{\partial t} + \sum_{i=1}^{d}\left(\frac{\partial\rho}{\partial q^i}\dot{q}^i + \frac{\partial\rho}{\partial p_i}\dot{p}_i\right) = 0.$$

- The volume occupied in the phase space by a system of particles is constant.
- This is a general physics theorem, not limited to accelerators.
- The application of external forces or the emission of radiation needs to be treated carefully.

Joseph Liouville
1809-1882
(source: wikipedia)

Emittance

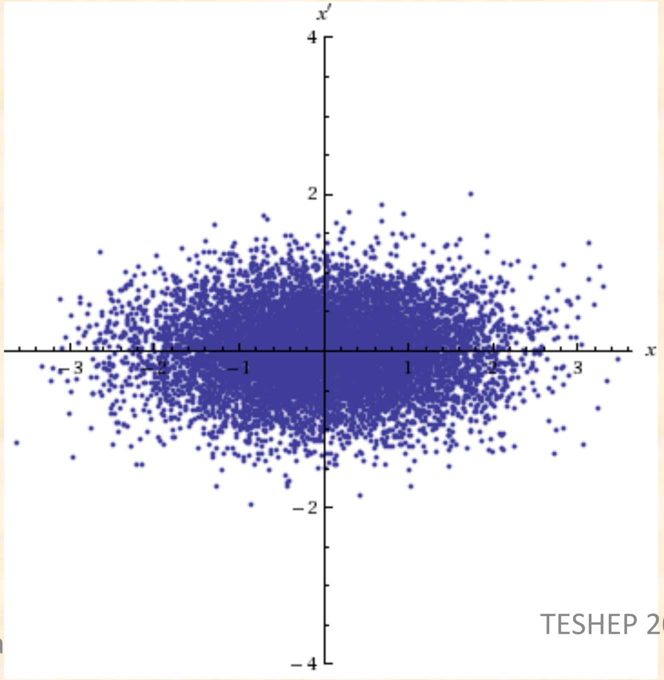
- We have defined the emittance as the volume occupied by the beam in the trace space.
- Liouville's theorem tells us that such volume must be constant.
- Hence the emittance of a beam is constant (unless external forces are applied).

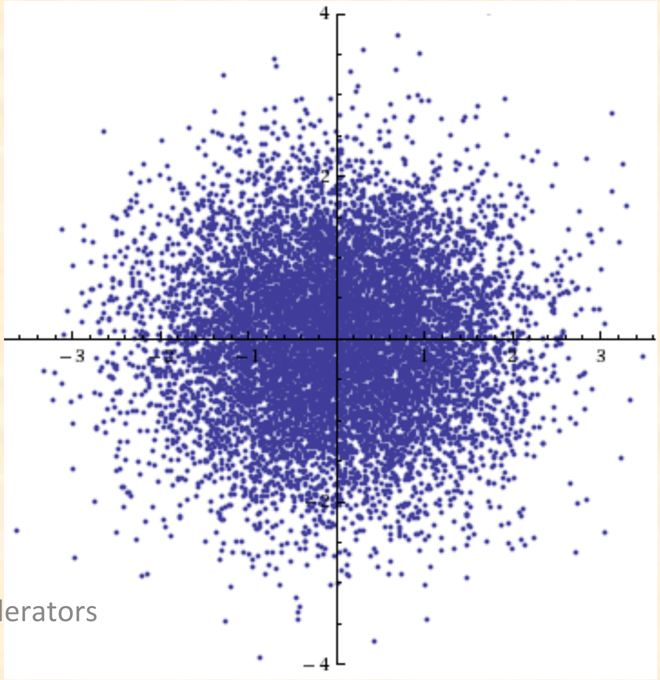


- The total volume occupied by the bunch in trace-space is usually dominated by a few far-outlying particles.
- Instead of giving the volume occupied by all the particles, it is common to give the volume occupied by 90% or 60% of the particles or to give the RMS emittance.

Emittance ellipse

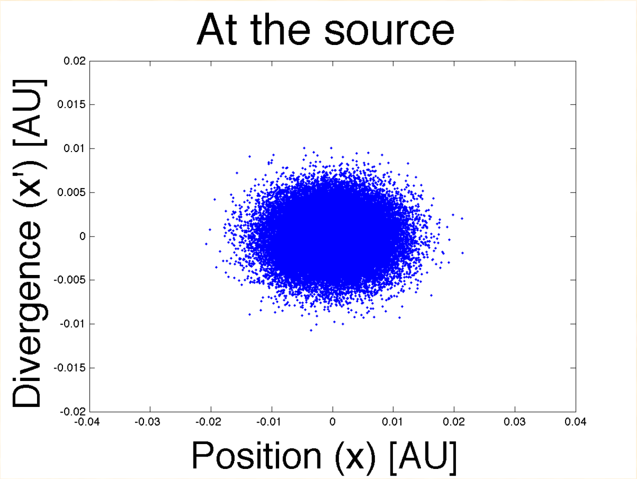
- A random Gaussian distribution of particles forms a straight ellipse.
- By choosing the right set of coordinates this ellipse can be transformed in a circle (do not forget that the two axis are orthogonal!).
- As the beam propagates, the shape of this ellipse will change.
- <u>At a waist</u> the emittance in a given plane is the product of the two ellipse axis.





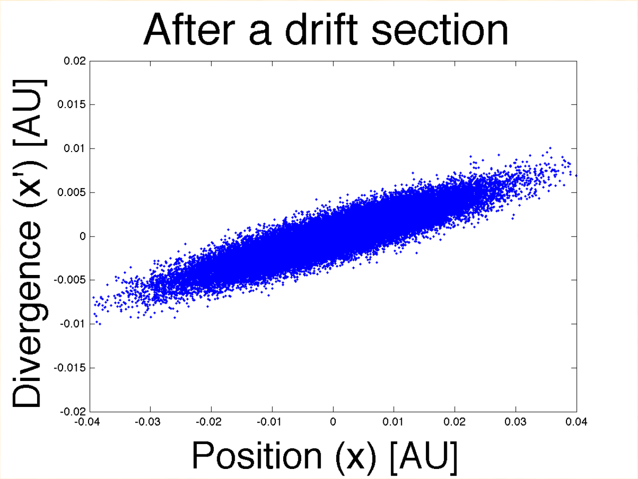
Beam drift

- When the beam "drifts" that is, propagates in space, over a length L with no external forces applied:
  - The momentum of the particles is constant
  - The position changes by the momentum times L.
- Hence, the emittance ellipse is sheared.



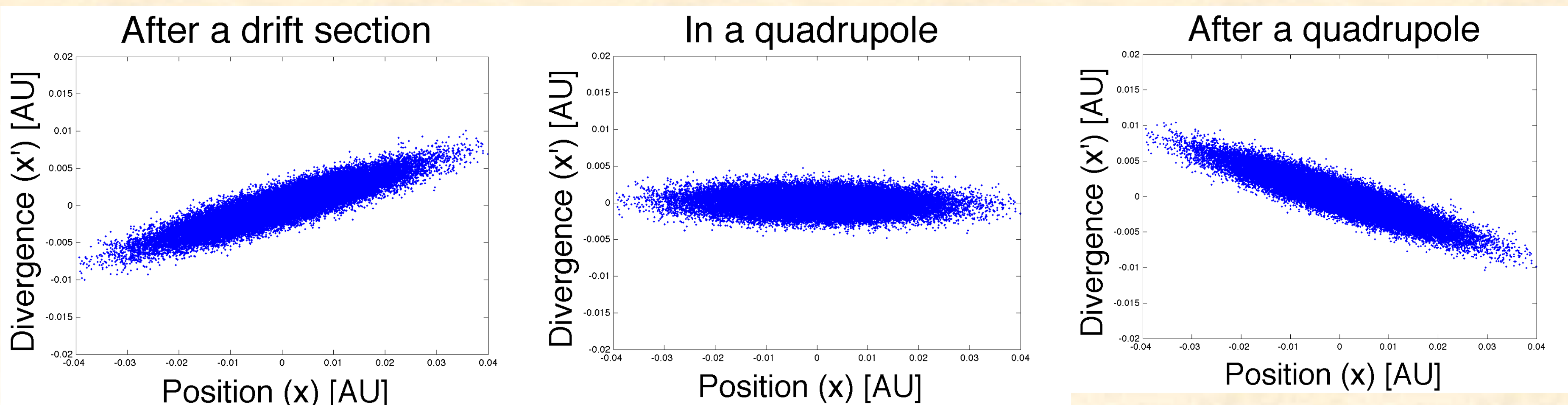
$$x'_2 = x'_1$$

$$x_2 = x_1 + Lx'_1$$



Focussing

- In a focussing section (typically a quadrupole), in the thin lens approximation:
  - The position of the particles is not affected
  - The momentums are reversed, hence a waist (at which all x'=0) is formed.
- The ellipse is unsheared and then sheared in the other direction

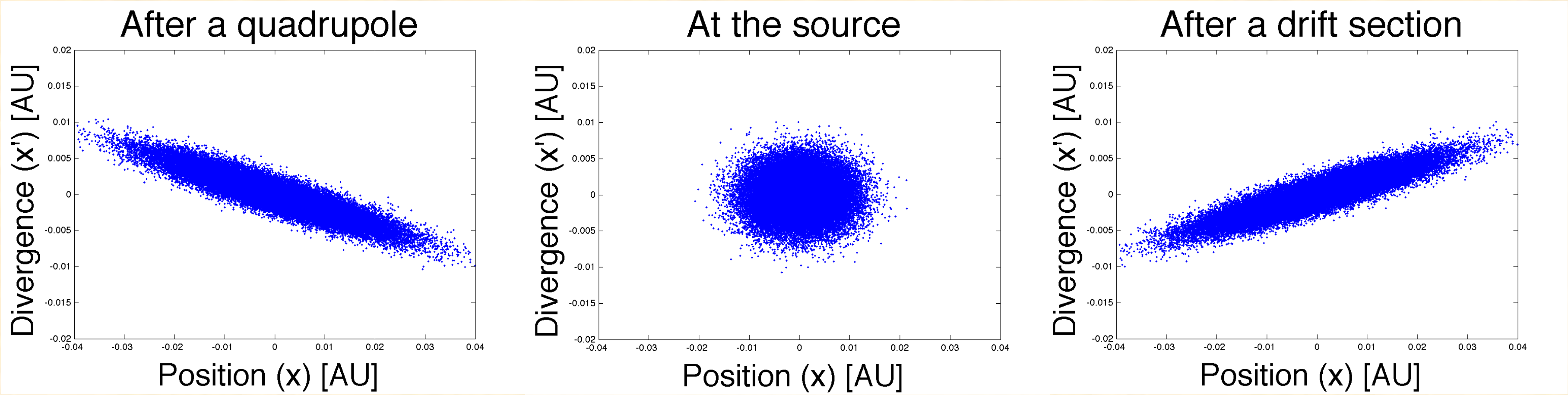


$$x_2 = x_1$$
$$x'_2 = 0$$

$$x'_3 = -x'_1$$
$$x_3 = x_1$$

Beam waist

- After the focussing section the beam will drift again, decreasing the shearing of the emittance ellipse.
- At some point the momentums will again average to 0, the beam will be forming a waist.
- At the waist the shearing of the emittance ellipse flips and starts increasing again.
- The beam size is the smallest at the waist.



Normalised emittance

- When the beam is accelerated its emittance decrease proportionally.
- It is convenient to define the normalised emittance of a beam: it is the volume of phase space occupied by the beam multiplied by gamma.
- The actual volume of phase space occupied by the beam is called the geometric emittance.
- The normalised emittance of a beam is constant under acceleration.

$$\in_N = \gamma \in_{Geometric}$$

Quizz: Gun emittance

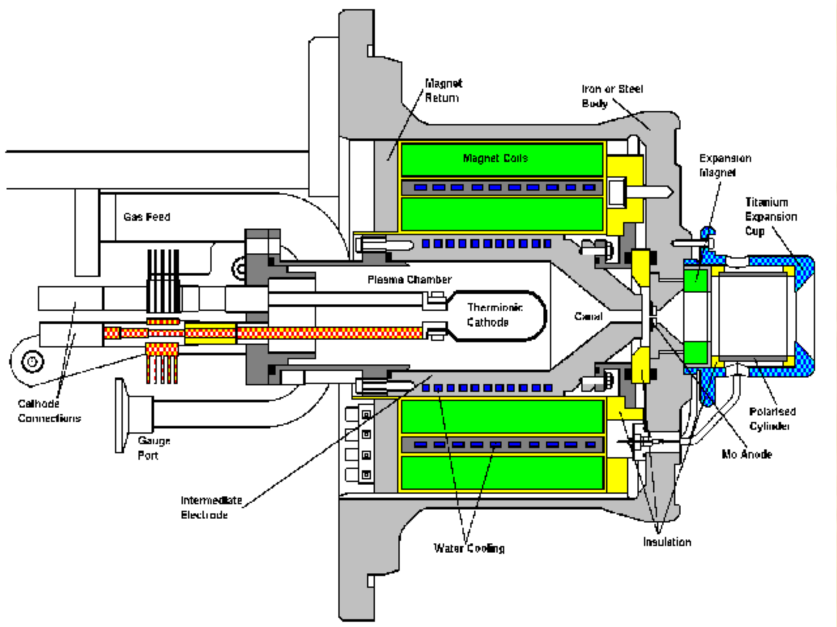
- A particle gun emits particles with a x divergence of 0.5mrad.
- It is fitted with an exit collimator with a hole with a dimension of 1mm in x.
- What is the geometrical x-emittance of the bunch produced by this gun?

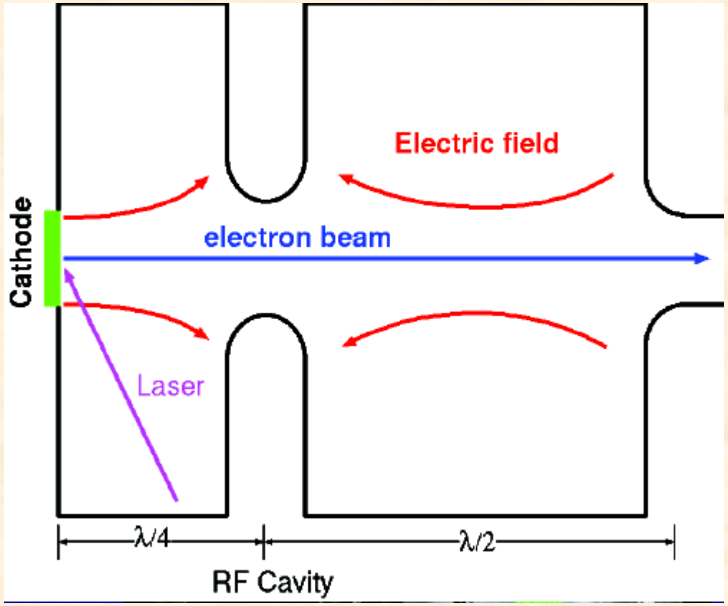
(A) 5mm.mrad

(B) 1mm. rad

(C) 500m.nrad

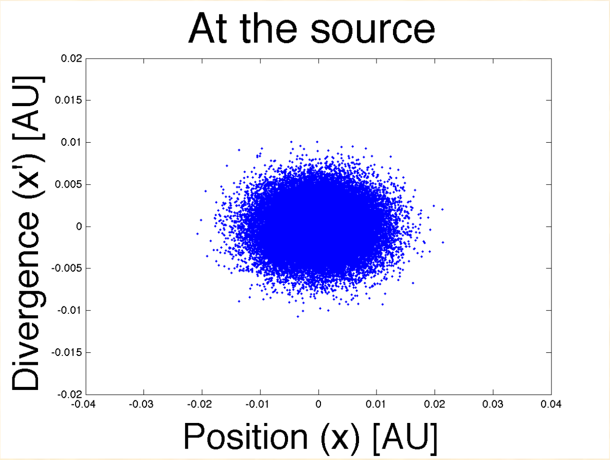
(D) 50mm.urad

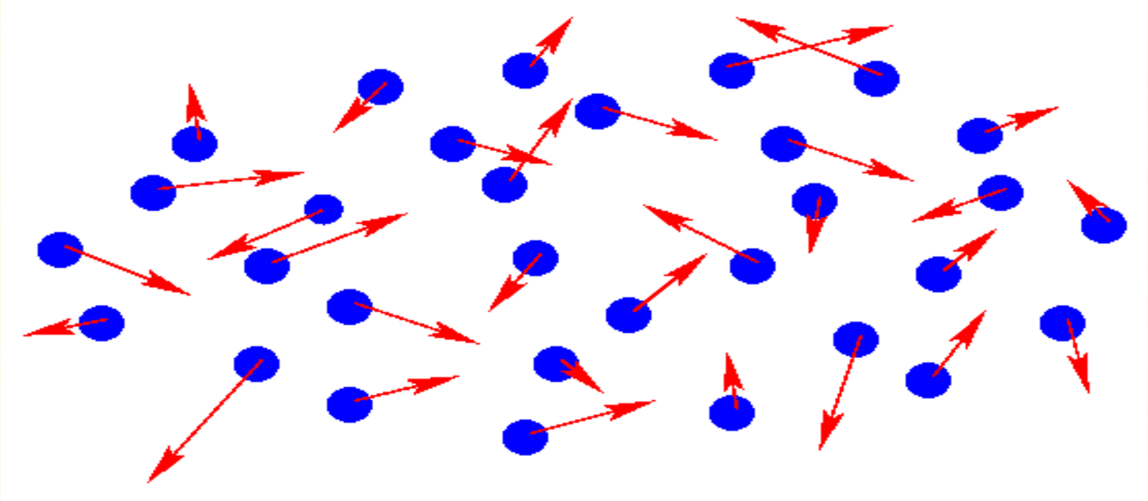


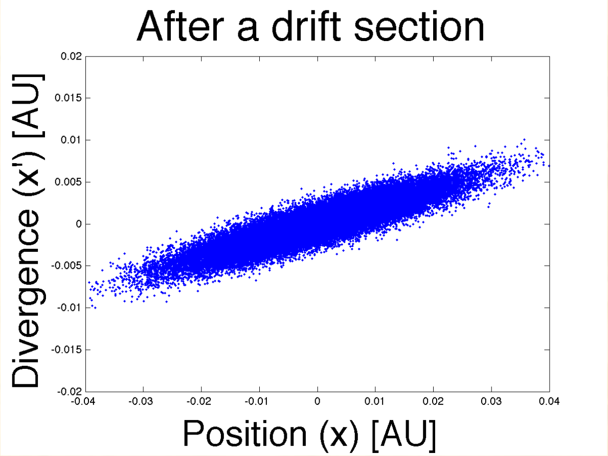


Answer (c)

- The x-emittance at a waist is given by x*x'.
- Here we have x=1mm, x'=0.5mm
- That is:
  0.5 mm.mrad or 500mm.urad or 500m.nrad.



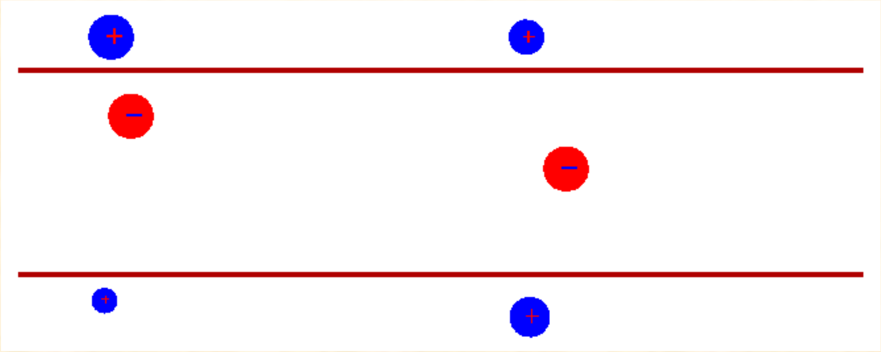


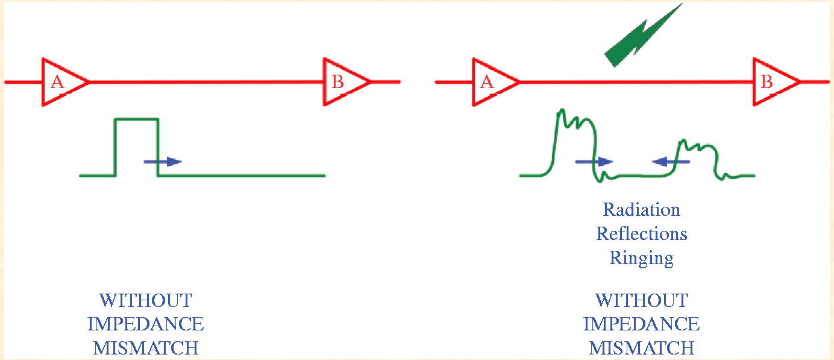


BEAM DYNAMICS

Impedance matching

- Charged particles travelling near a conductor induce image charges (induced current).
- In a electronic circuit an impedance mismatch will result in a reduced transmission at the interface.
- The same is true in an accelerator: an impedance mismatch is likely to induce a reflective wave at the interface.
- This will induce a loss of power and an emittance increase.
- In a synchrotron the impedance of all beam pipe elements is carefully controlled.
- This is less important in a transfer line where the beam passes only once.





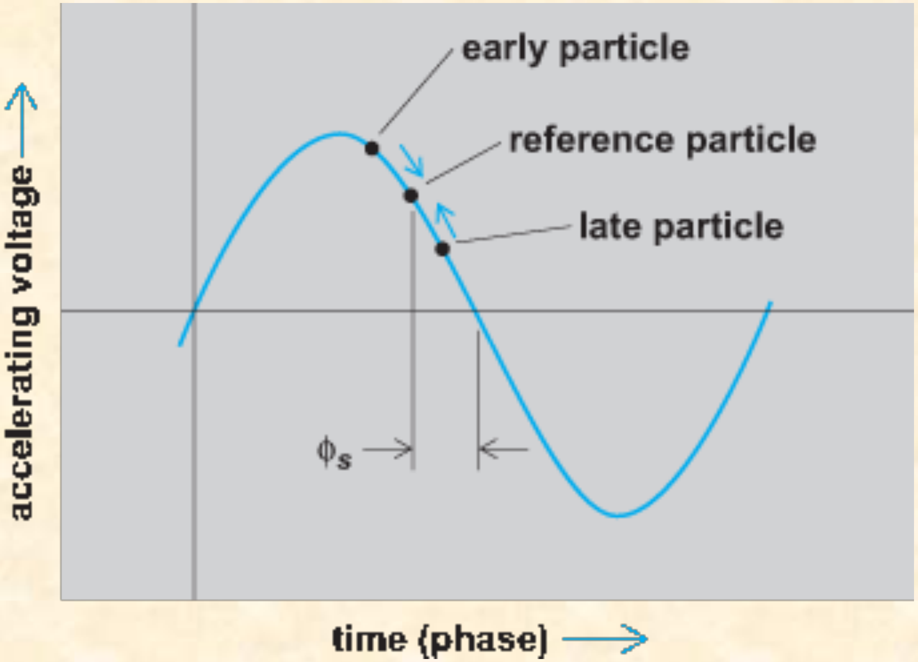
Wake field issues

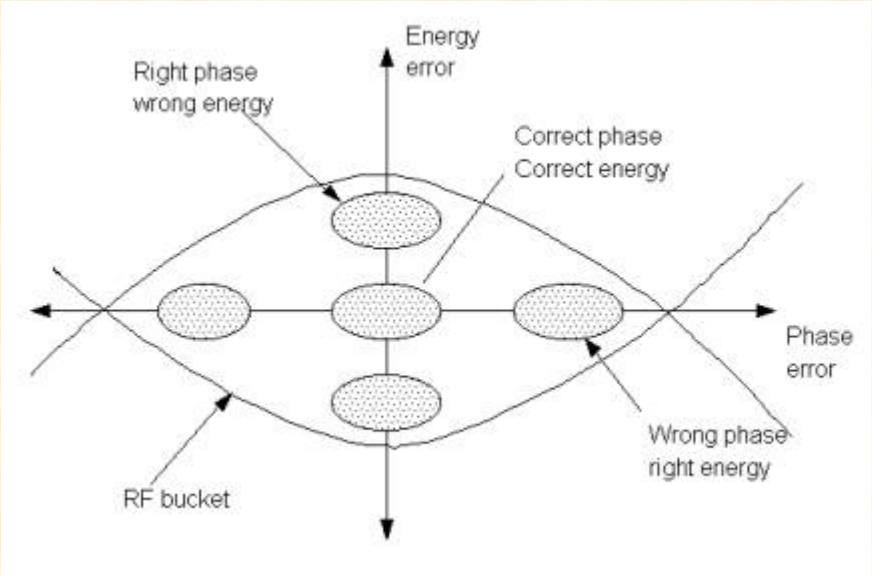
- Electrons produce an electromagnetic wave behind them.
- This can be compared the to wake of a boat and is called wake field.
- Imagine what would happen if there was a second surfer on the picture below...
- How good is the wake for the walls of the canal?
  It is not good for the beam pipe either!

Source: Reuters

Longitudinal dynamics

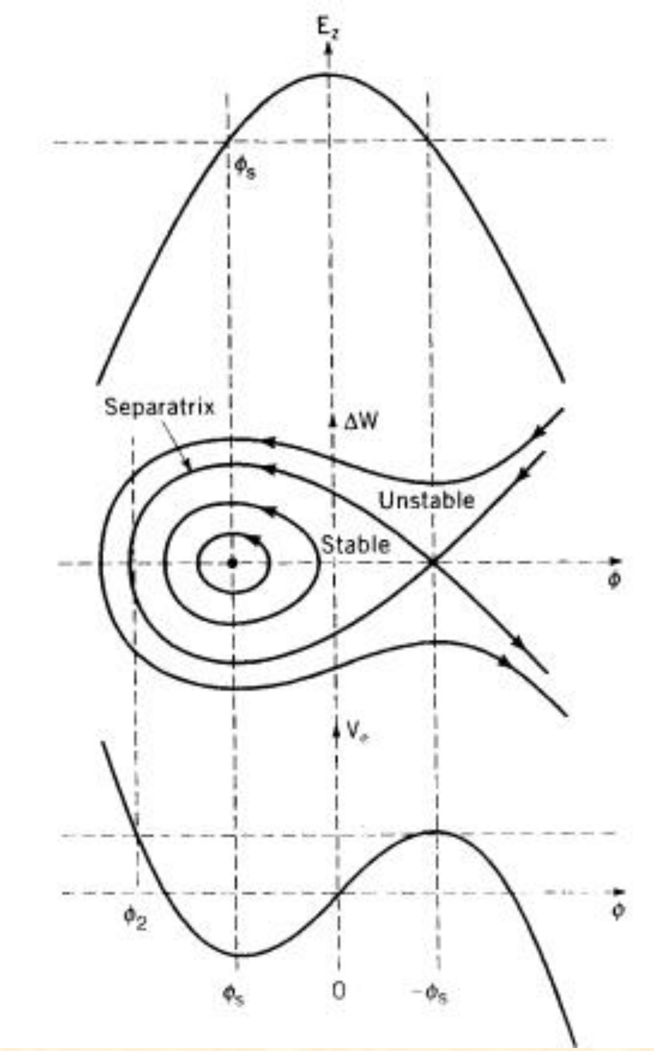
- As there is a relation between momentum and orbit, the particles that do not have the correct momentum will experience a phase slippage.
- This will in turn induce a change in their energy.
- In fact all the particles "rotate" in all planes around the reference orbit.





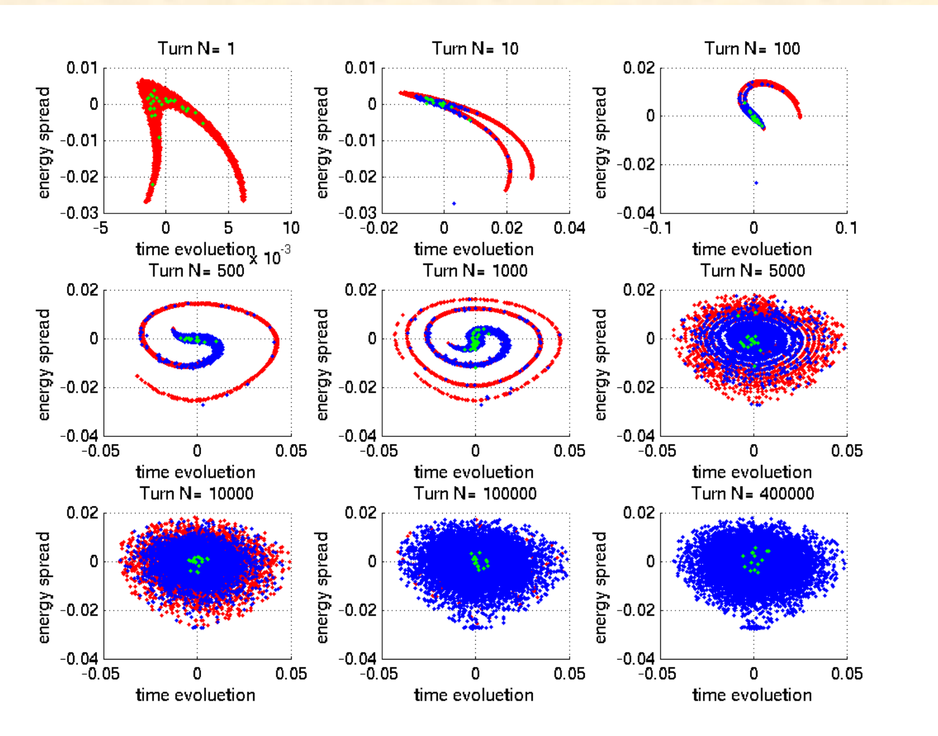
Longitudinal dynamics (2)

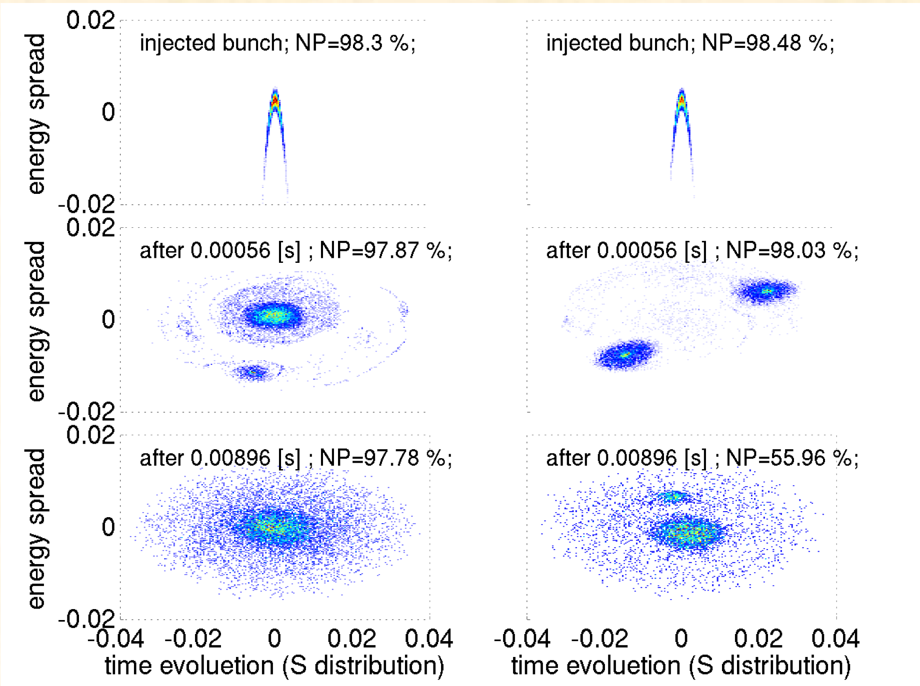
- Only a certain area of the phase vs energy plan is stable.
- Particles outside this stable area will drift away and eventually get lost.
- The position and size of this area will depend on the RF cavity voltage, the energy lost per turn (SR) and momentum compaction factor.



Longitudinal dynamics (3)

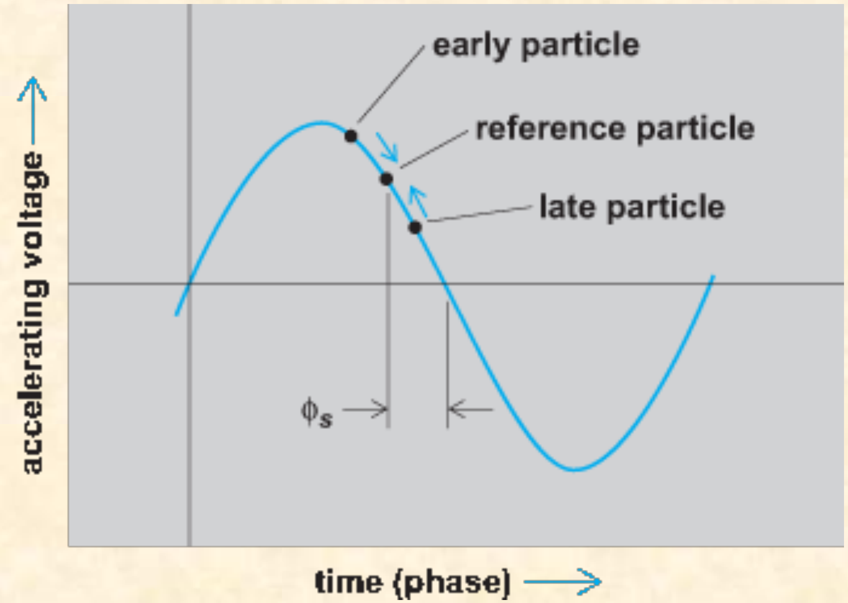
- Longitudinal dynamics can be critical in some rings.

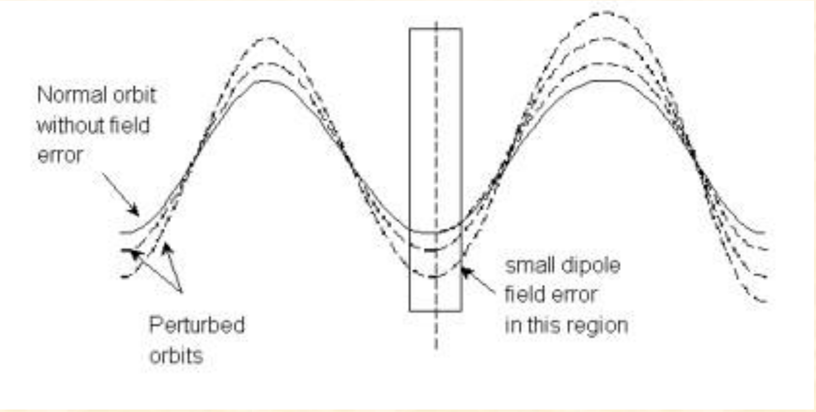




Betatron oscillations

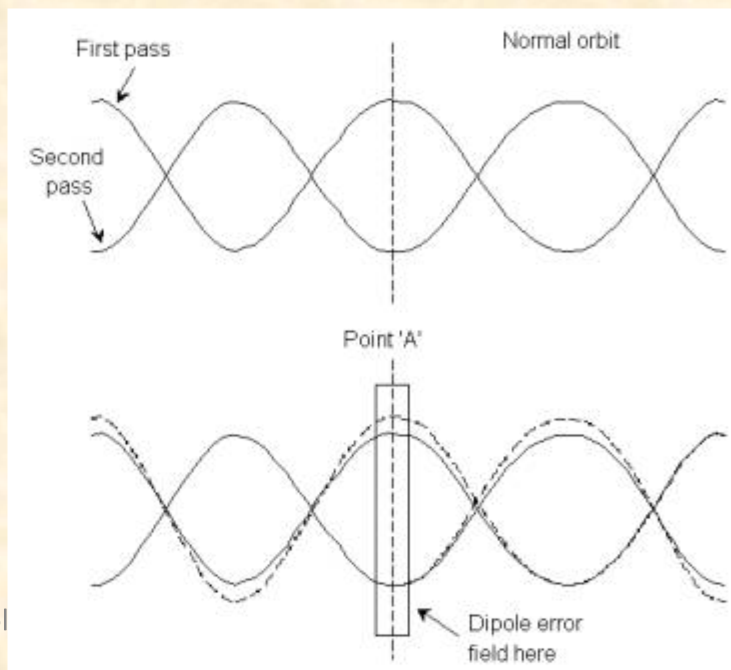
- The rotation of the particles around the reference orbit is “betatron oscillation” (x and y)
- If the particles perform an integer number of betatron oscillations in one turn, they come back at the same position turn after turn.
- After a large number of turns (millions…) what was initially a very small error can lead to large orbit changes and eventually to the loss of the beam.
  => avoid integer betatron oscillations…
- 1M turn@LHC = 100s.

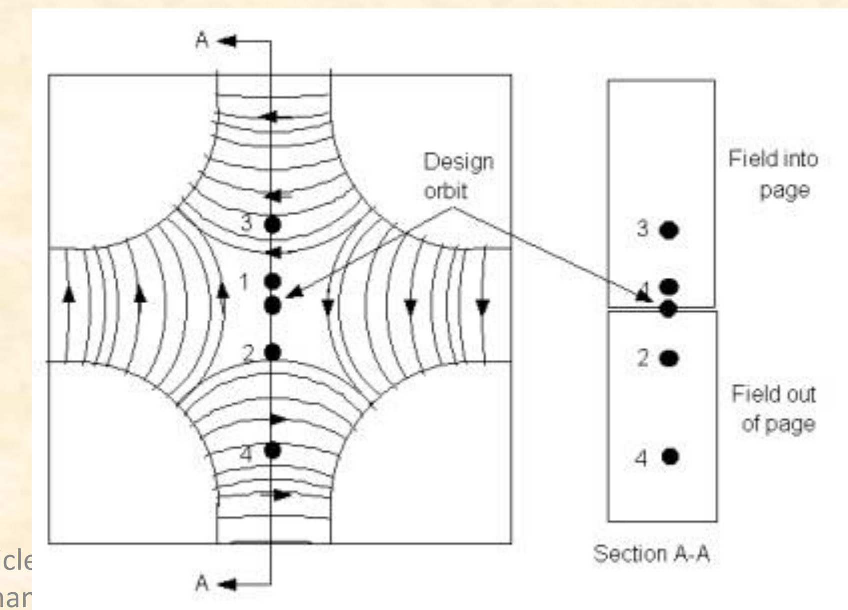




Half-integer betatron oscillations

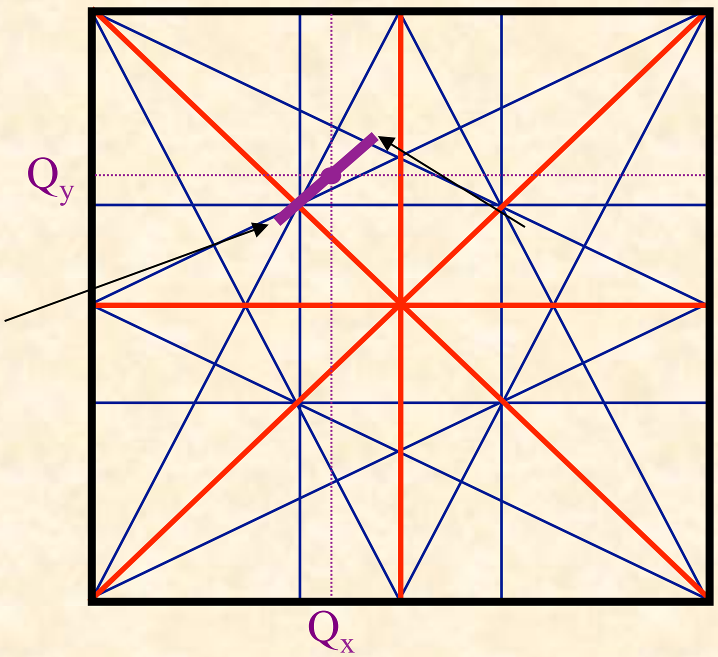
- Using an optic with an half-integer number of oscillations avoids first order problems.
- However a similar effect may accumulate every other turn…





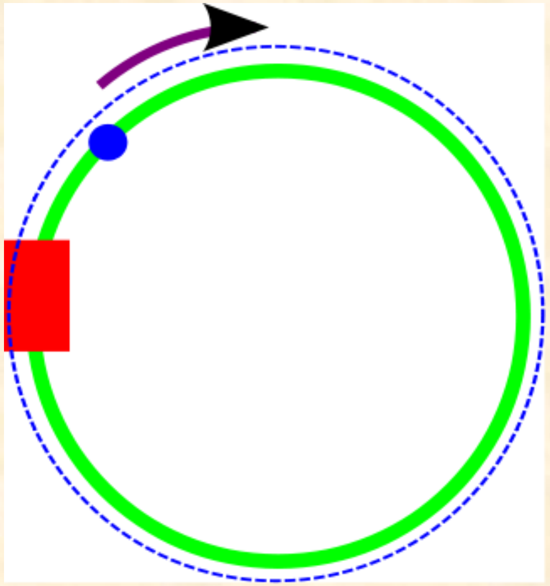
Tune

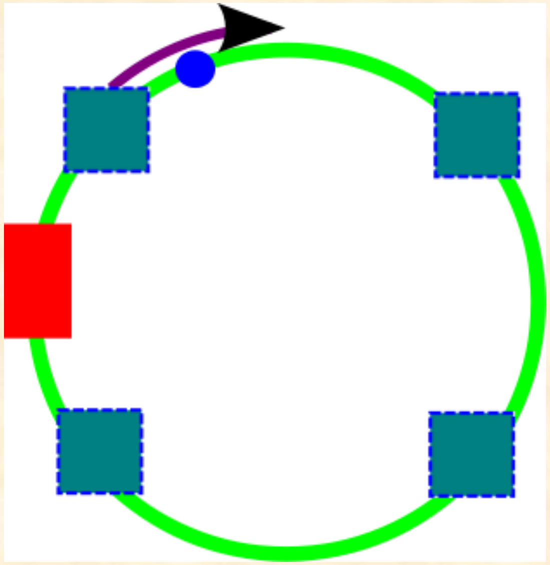
- To avoid cumulative effects in the accelerator over a large number of turns all rational numbers should be avoid for betatron oscillations in both planes
=> choose an irrational number!
- Choosing an incorrect tune can significantly increase the particle loss rate.



Quizz

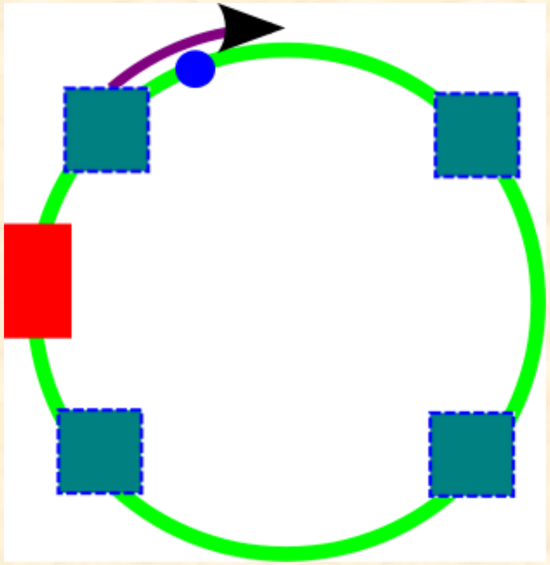
- We have seen that particles with a higher energy will be less deflected by the dipole magnets so they will have a larger orbit.
- How is this result changed if there are 4 quadrupoles in the ring?
  (a) they will have a larger orbit
  (b) they will have a narrower orbit
  (c) their orbit will be similar
  (d) Can not tell





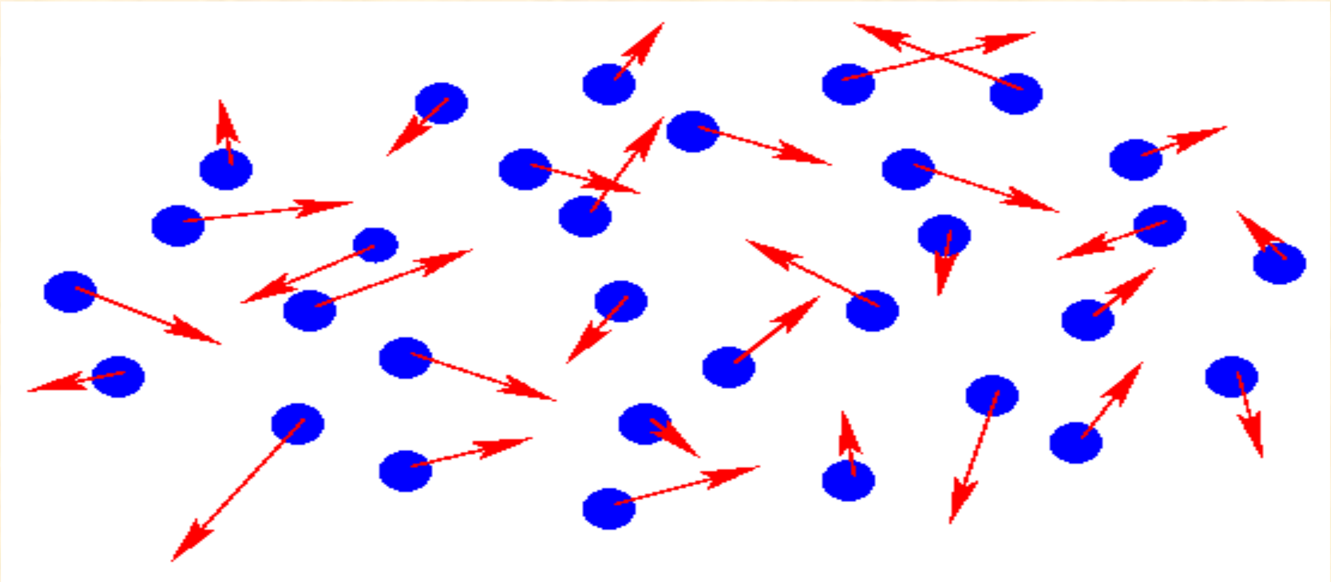
Answer (2d): Can not tell

- To know which particles have a larger orbit and which particles have a smaller orbit the lattice must be taken into account.
- A parameter called momentum compaction factor gives the relation between momentum and orbit radius.
- It is dependant on the beam optics.



$$\frac{\Delta r}{r} = \alpha p \frac{\Delta p}{p}$$

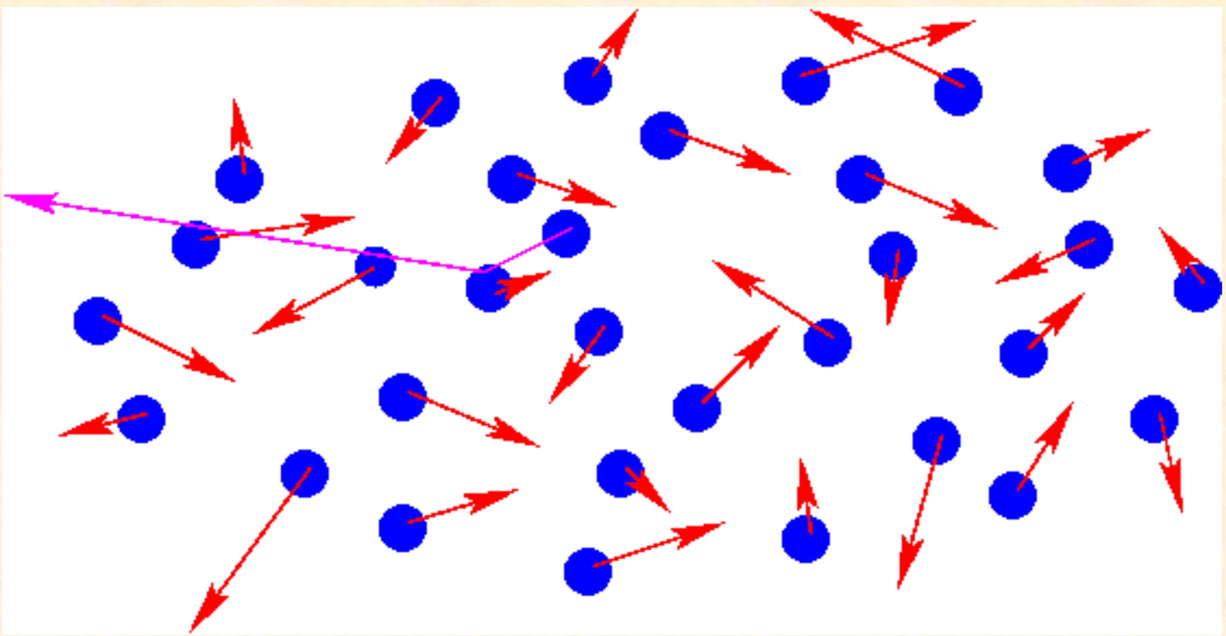
Intra-beam scattering



- We have seen that inside the beam the particles behave somewhat like a gas.
- Coulomb collisions do occur between the particles.
- These collisions lead to a momentum transfer between the particles and thus an emittance coupling and emittance growth.
- Beams with a larger emittance will experience more IBS.

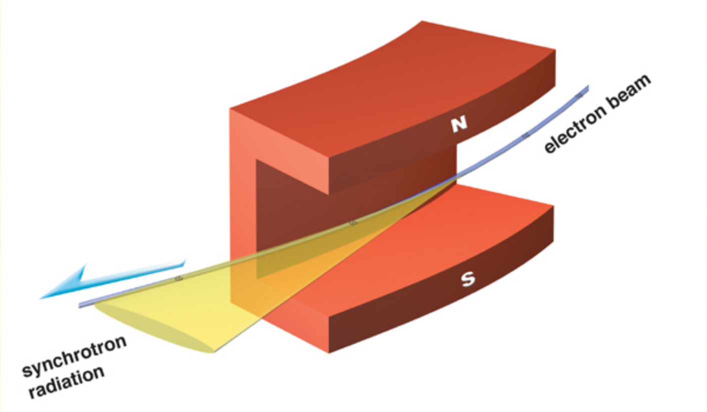
Touschek effect

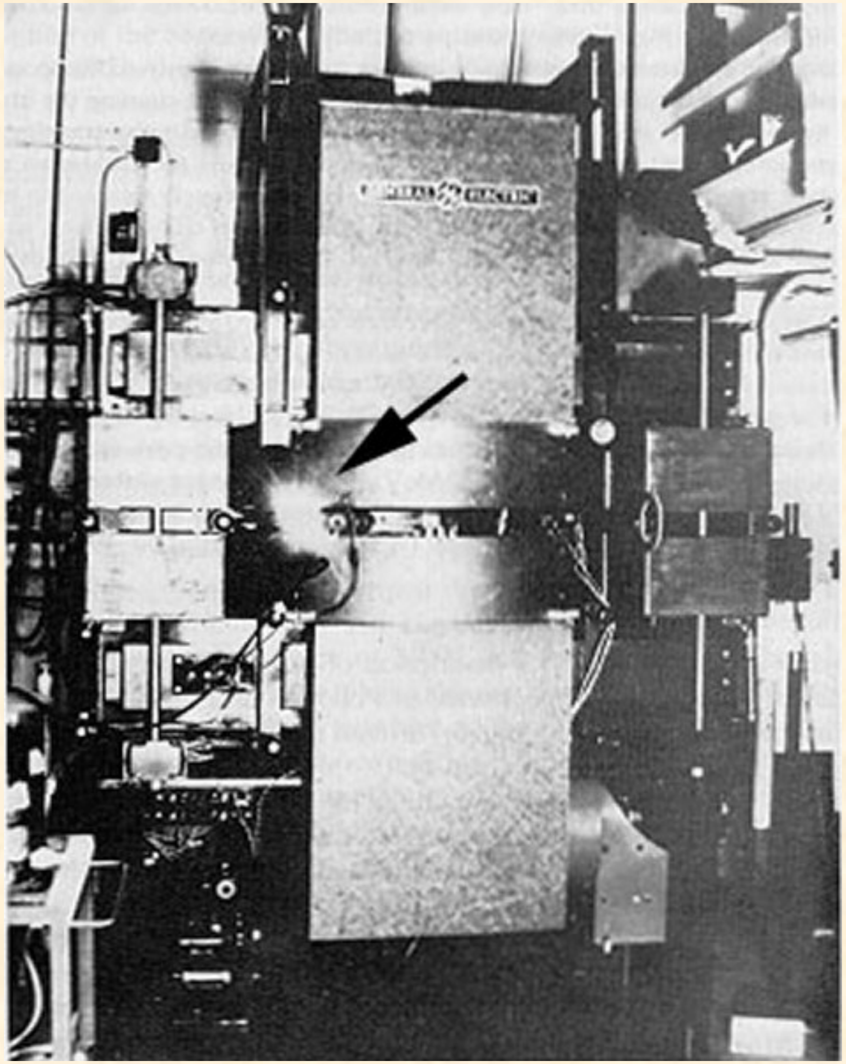
- In addition to Coulomb scattering, hard scattering can also occur.
- In most cases this will lead to one particle being pushed out of the acceptable beam orbit and thus being lost soon after.
- Touschek scattering occurs in high current beams.



Synchrotron radiation

- Any charged relativistic particle that is accelerated or decelerated emits radiation (cf Maxwell).
- When this is a transverse acceleration as in a dipole magnet this radiation is called synchrotron radiation.



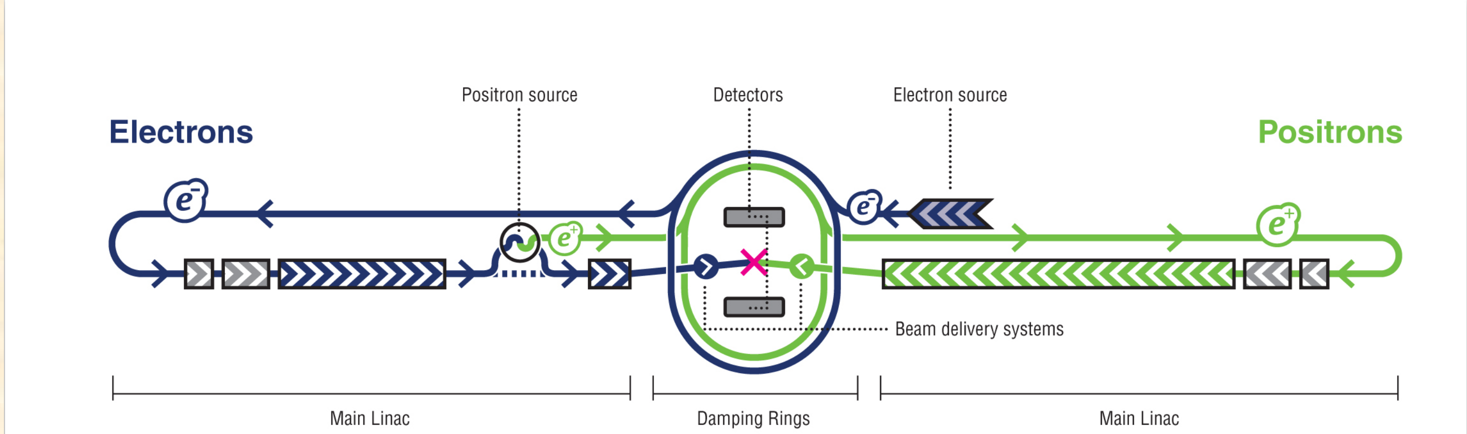


Discovery of Synchrotron radiation in 1946

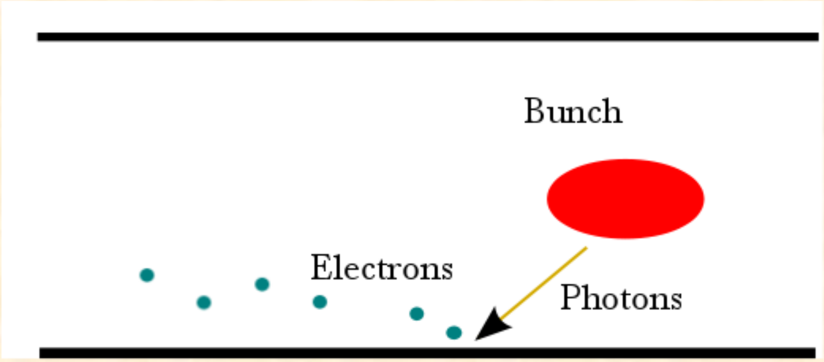
Source: wikipedia

Radiation damping

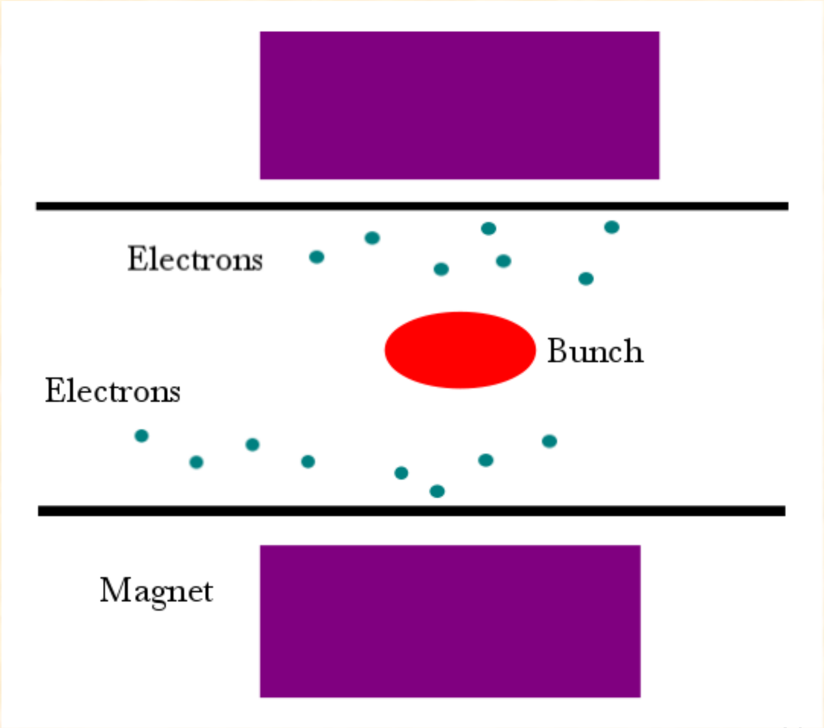
- The energy lost due to synchrotron radiation emission has to be compensated by a RF cavity that tops-up the energy of the beam at each turn.
- This additional acceleration at each turns results in a decrease of the beam transverse emittance.
- By storing a beam in a ring for several milliseconds it is possible to significantly reduce its transverse emittance.
- The reduction of emittance in a ring due to SR emission is called “radiation damping”.
- As the radiation is emitted in the plane of the accelerator, radiation damping is faster in the direction orthogonal to the accelerator. => very flat beams



Electron cloud effect



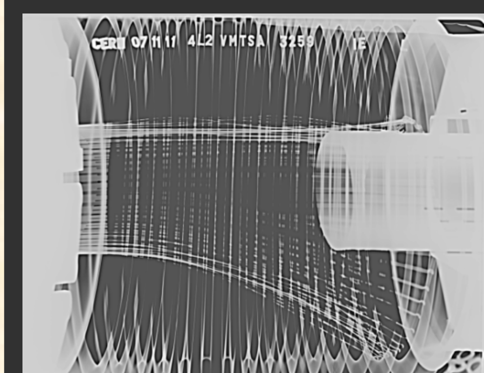
- Radiation from a bunch can extract electrons (and ions) from the beam pipe and from residual gas in the vacuum.
- These electrons fall back and get re-absorbed with a certain time constant.
- However if the bunch frequency is too high these electrons (and ions) will accumulate in the beam pipe and shield the beam from the magnetic elements.
- Special coatings, beam pipe geometries and bunch repetition patterns can mitigate this problem to some extent.
- This is one of the main limitations to increasing the



some issues in LHC 2011-12 operation

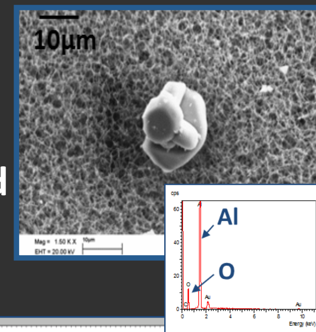
Beam induced heating

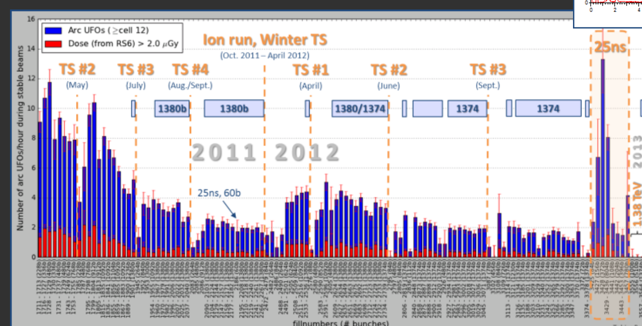
- Local non-conformities (design, installation)
  - injection protection devices
  - sync. Light mirrors
  - vacuum assemblies

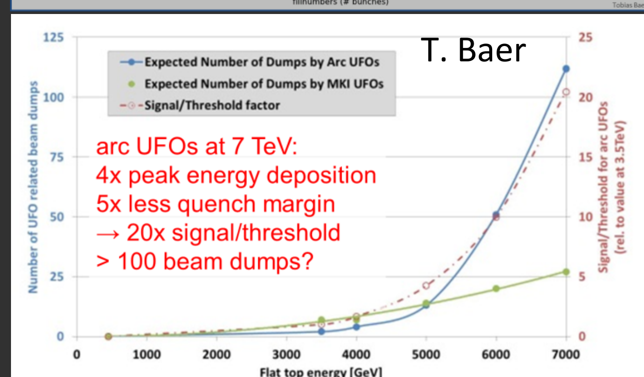


UFOs

- 20 dumps in 2012
- time scale 50-200 µs
- conditioning observed
- worry about 6.5 TeV and 25 ns spacing

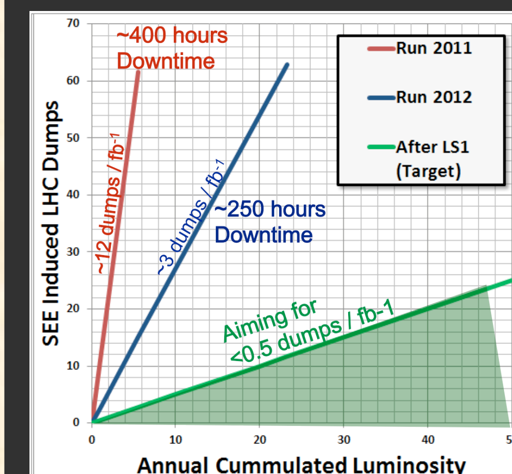






Radiation to electronics

- concerted program of mitigation measures (shielding, relocation…)
- premature dump rate down from 12/ fb^{-1} in 2011 to 3/ fb^{-1} in 2012



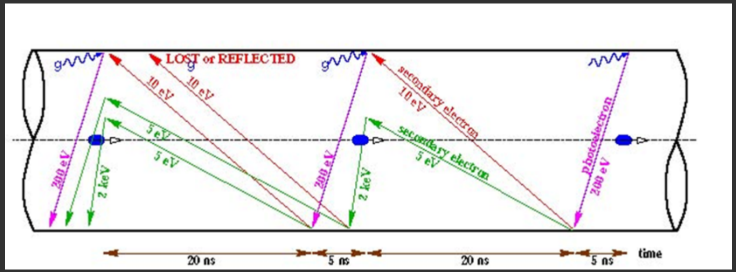
Courtesy of F. Zimmerman

another issue in LHC 2011-12 operation

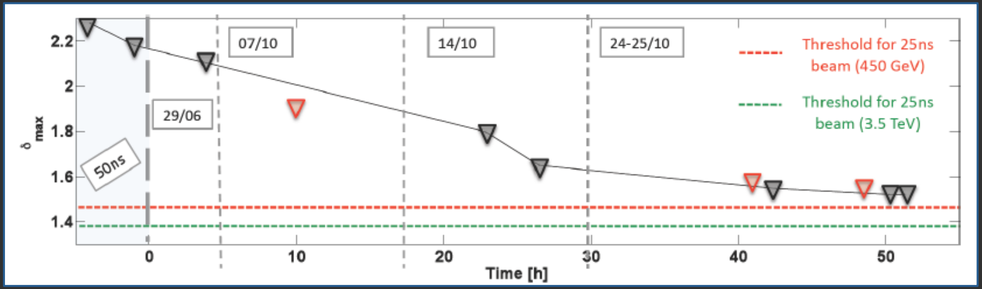
Electron cloud

Courtesy of F. Zimmerman

- **beam induced multipactoring process, depending on secondary emission yield**
- **LHC strategy based on surface conditioning (scrubbing runs)**
- **worry about 25 ns (more conditioning needed) and 6.5 TeV (photoelectrons)**



25-ns scrubbing in 2011 – decrease of SEY



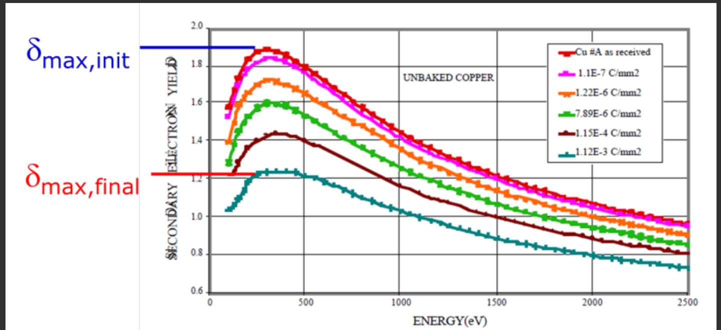
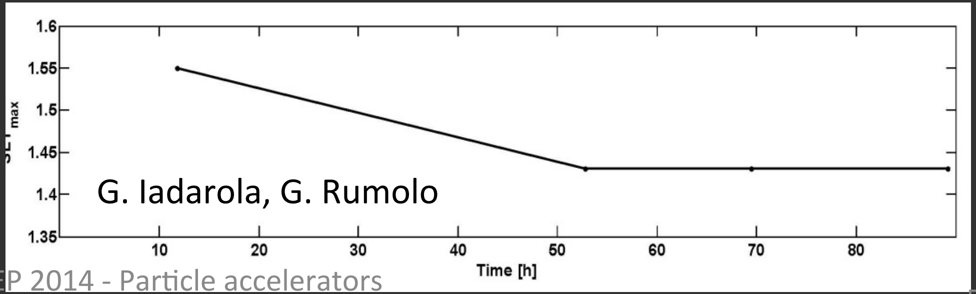
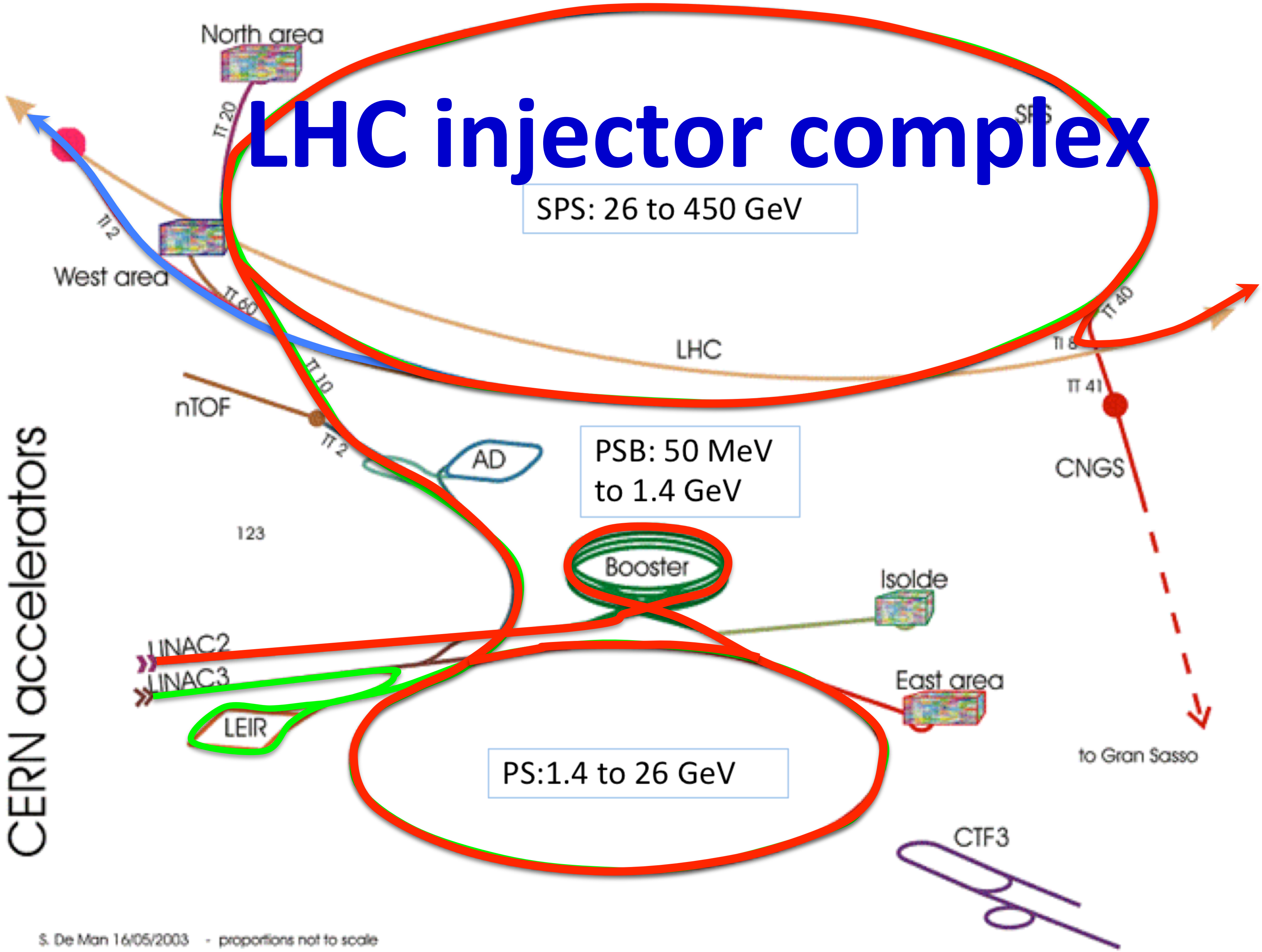


Figure 12: Variation of the S.E.Y. of copper with the incident electron dose

25-ns scrubbing in 2012 – conditioning stop?



LHC injector complex

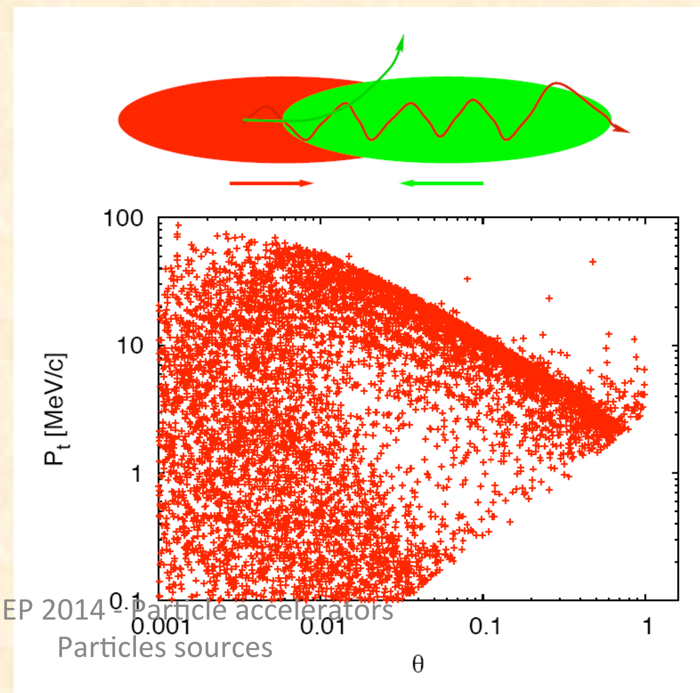


M. Lamont

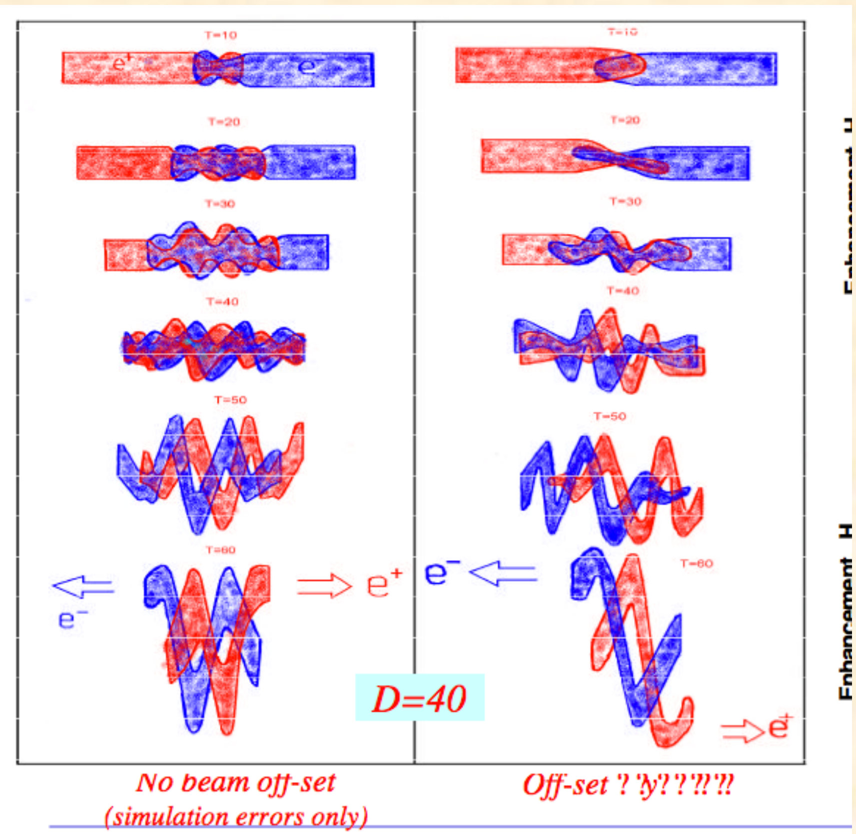
BEAM-BEAM EFFECTS

Beam beam effects (1)

- In a collider the two beams feel each other's electric field well before and well after colliding.
- Given that the particles come very close to each other, this lead to very intense forces.
- These forces lead to significant disruption of the beam.



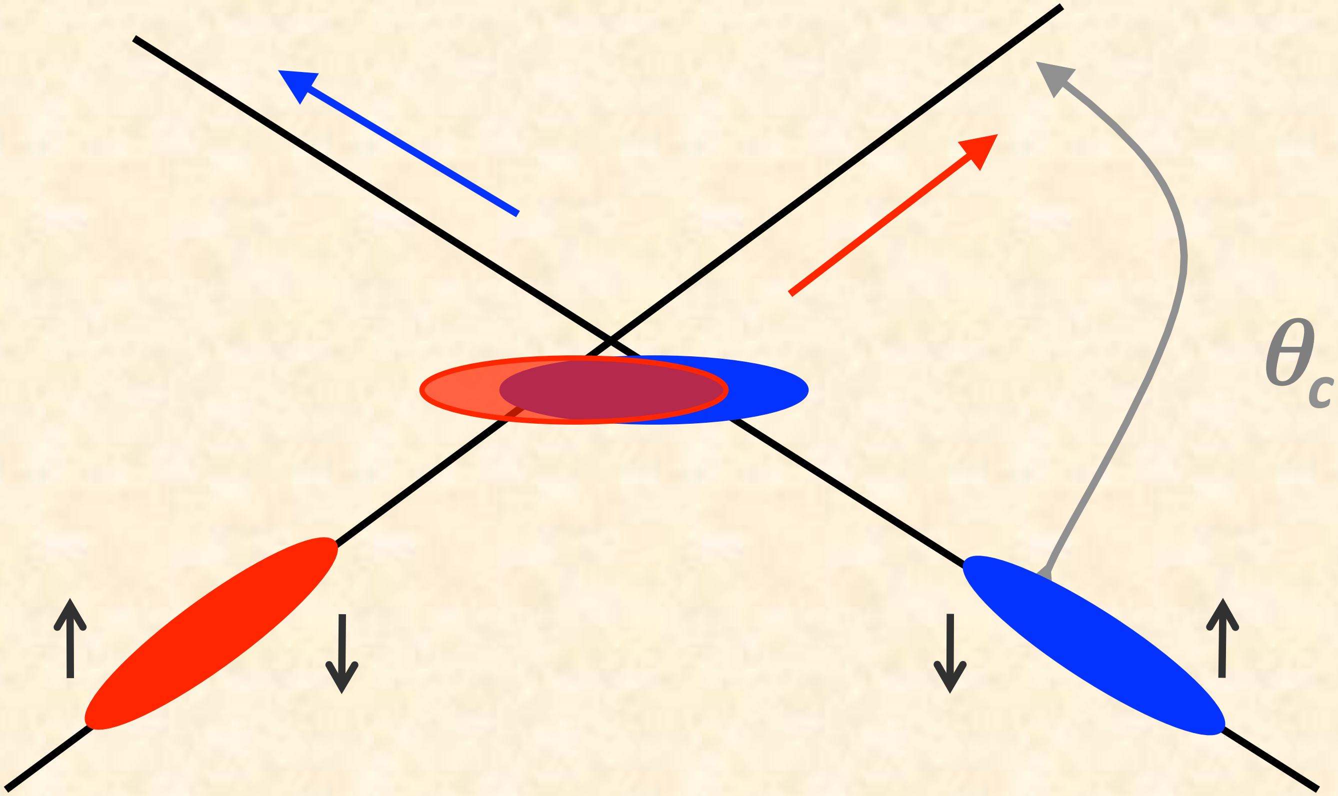
Beam beam effect (2)



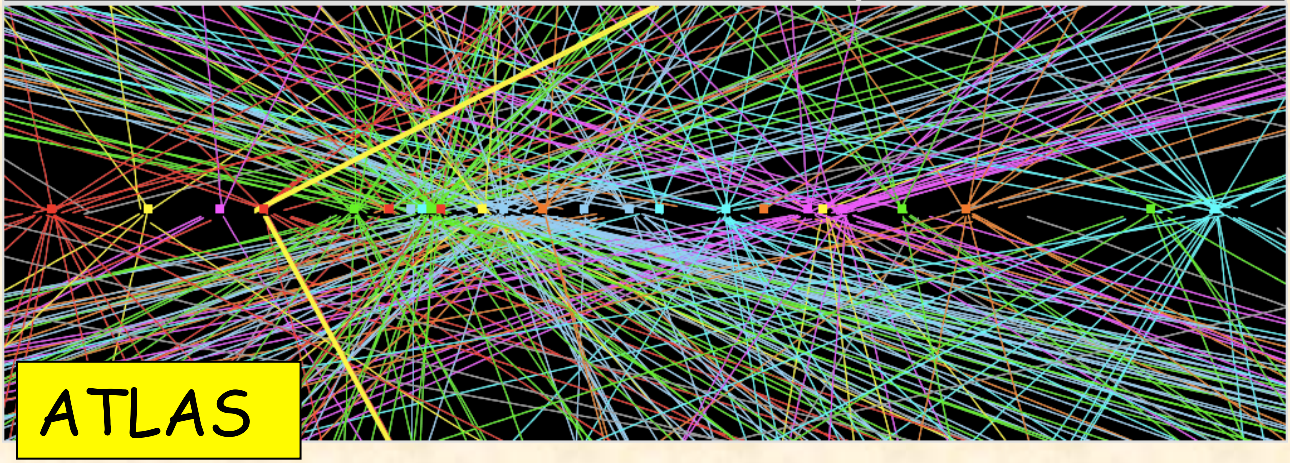
Courtesy of N. Solyak

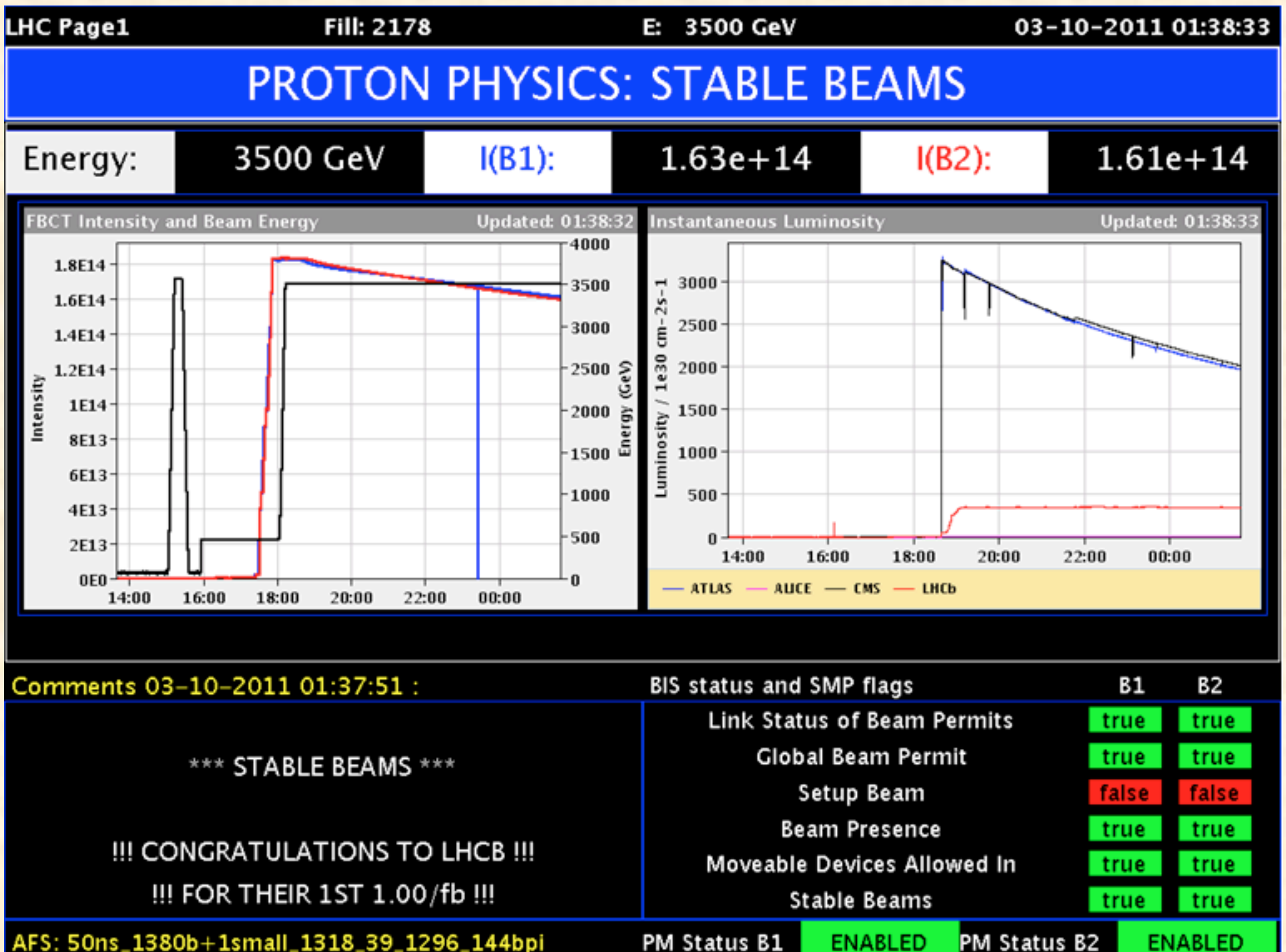
- At the interaction point the two beams self-focus onto each other.
- If the self focussing is too strong this can lead to a large emittance growth.
- If the two beam are not perfectly aligned this will also lead to large transverse deflection.
- This is a strong limitation on the size of the beams and therefore the luminosity, especially in a ring.

The future: crab crossing (?)



- Increases luminosity without increasing charge.
- RF crab cavity deflects head and tail in opposite direction so that collision is effectively "head on" for luminosity and tune shift
- bunch centroids still cross at an angle (easy separation)
- 1st proposed in 1988, used in operation at KEKB since 2007



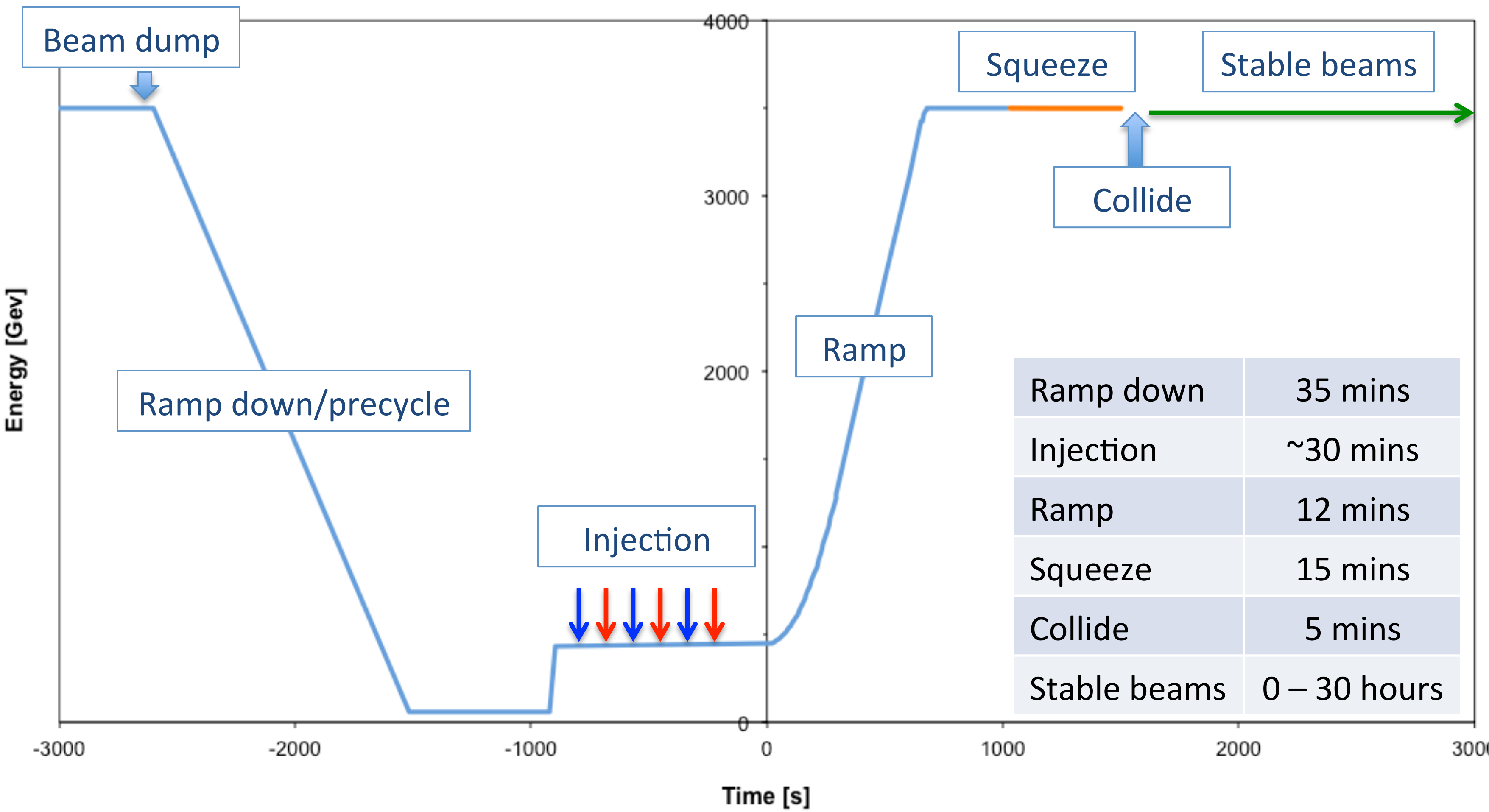


Luminosity issues

More luminosity,
=> more collisions per turn
=> pile-up.

Not everybody want more instantaneous luminosity. Eg: LHCb

Operational cycle at LHC



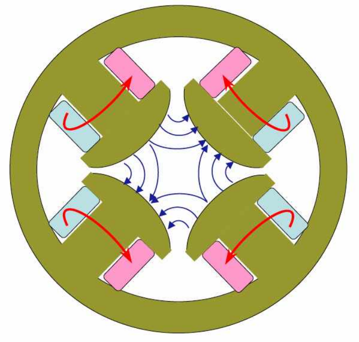
Ramp down	35 mins
Injection	~30 mins
Ramp	12 mins
Squeeze	15 mins
Collide	5 mins
Stable beams	0 – 30 hours

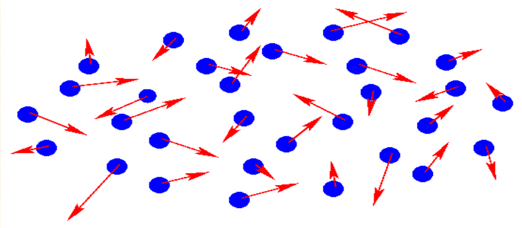
Turn around 2 to 3 hours on a good day

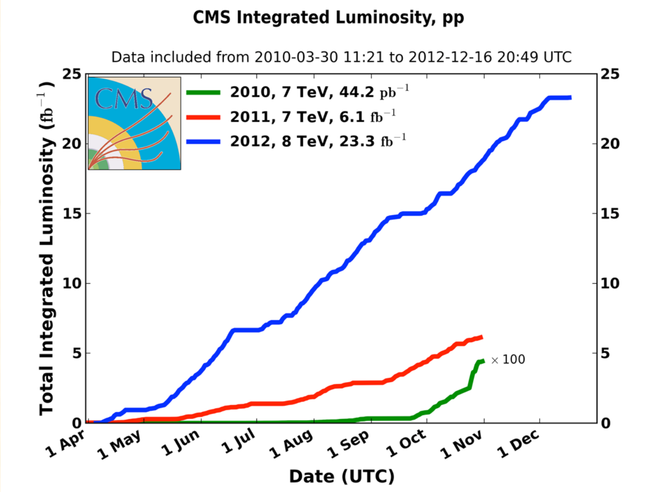
M. Lamont, IPAC'13

Summary

- Today we have seen how to control the particles trajectory.
- We have also seen that the dynamics of the particles in the accelerator is very complicated.
- Bunches too close from each other will damage each other by their wakefields or by electron cloud effect.
- Bunches compressed too much will blow up due to IBS, Touschek effect, space charge effect or beam-beam effect during the collisions...
- Despite these difficulties the luminosity of the LHC is steadily increasing!
- Tomorrow we will see how to produce the particles to inject in the LHC.

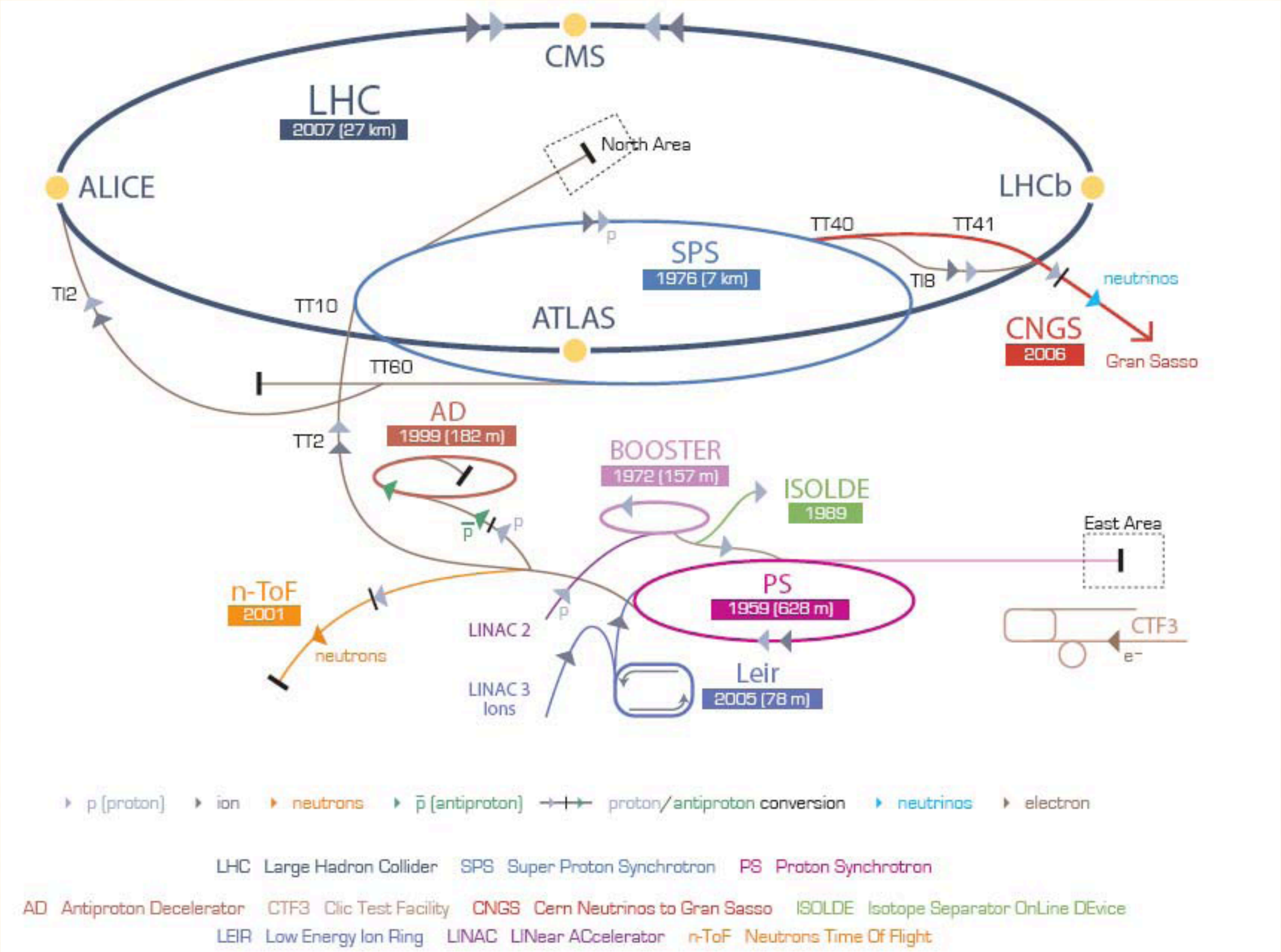


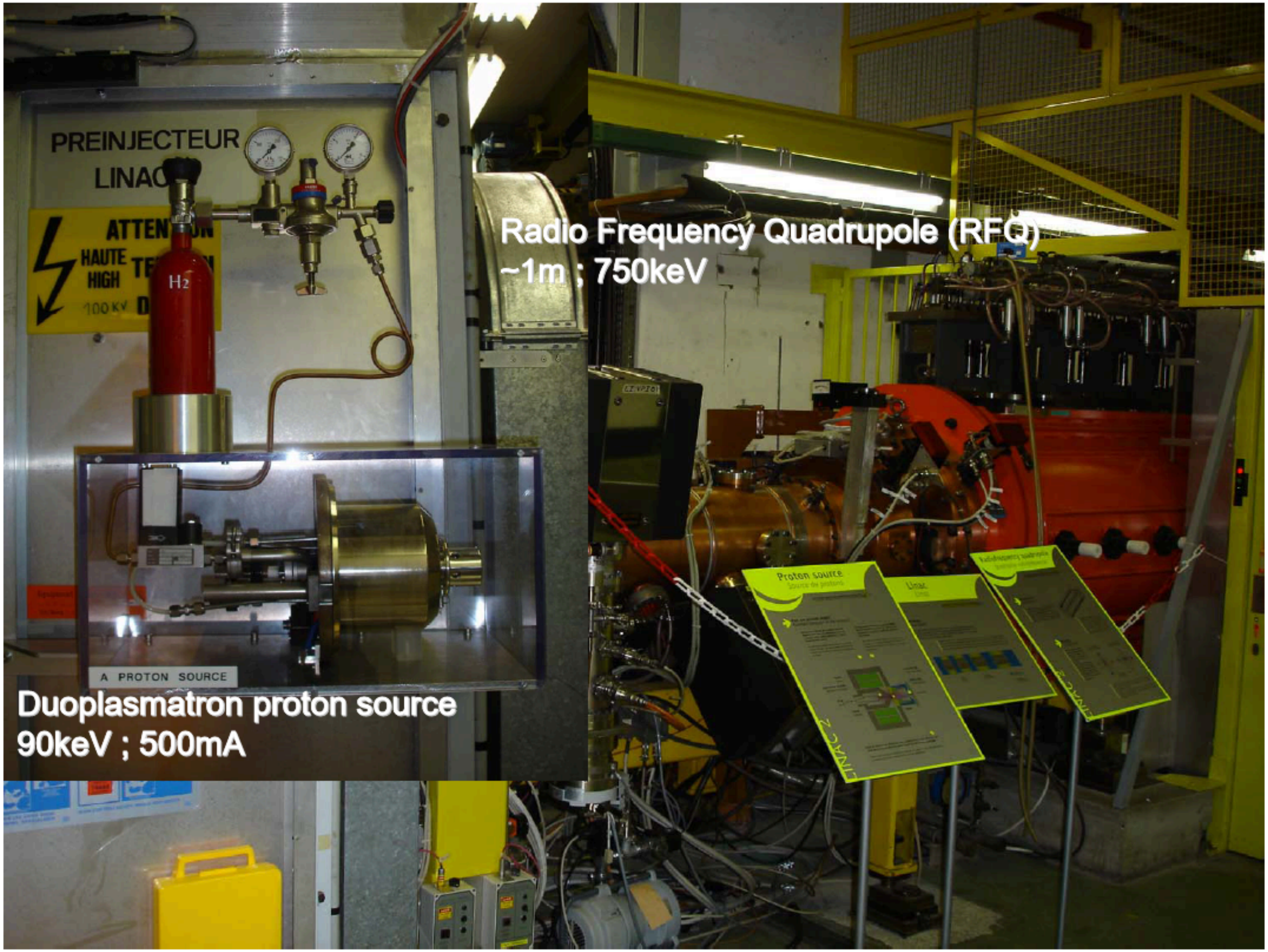


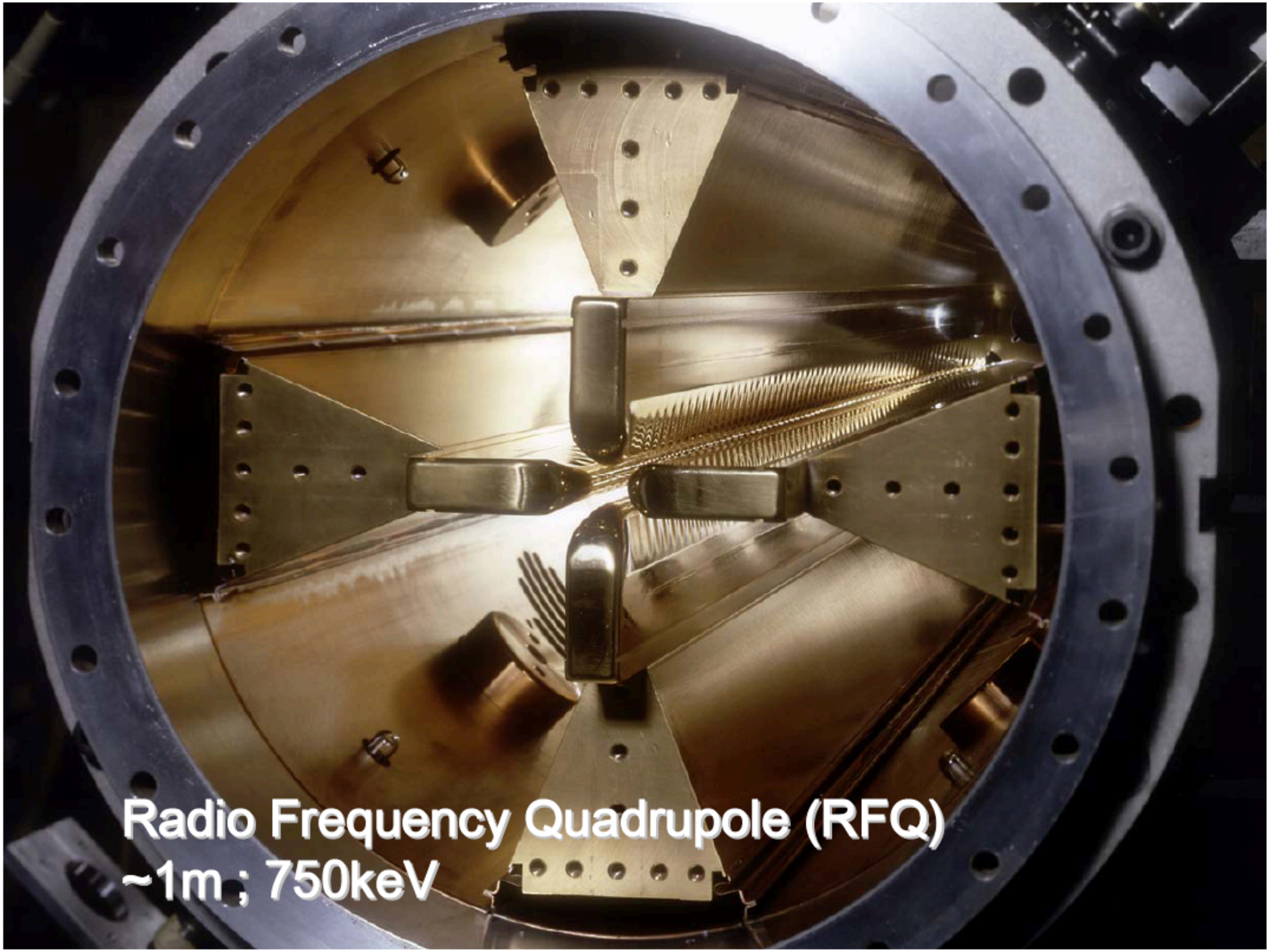


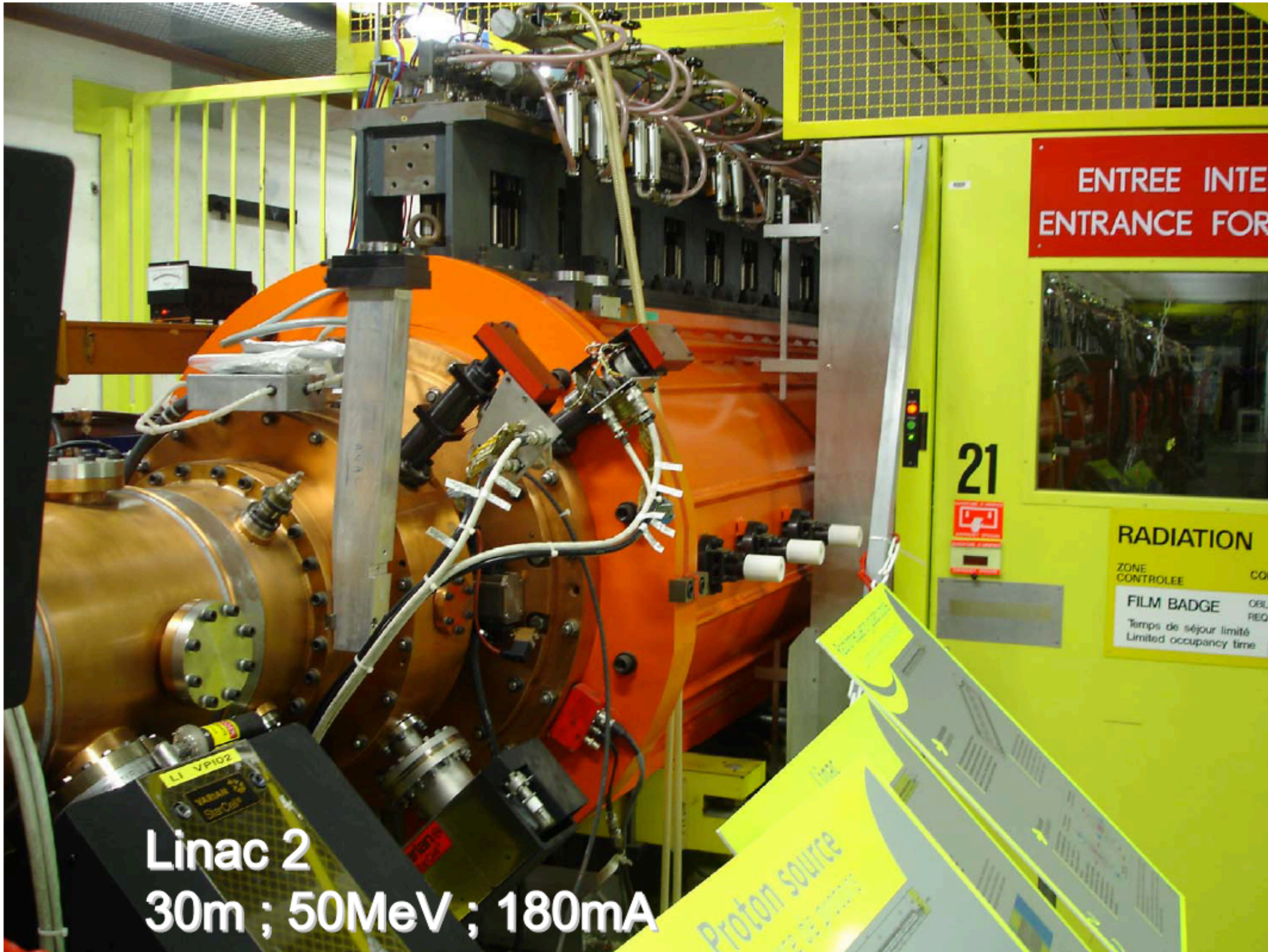
THE JOURNEY OF A PROTON FROM THE SOURCE TO THE LHC

(Courtesy of D.Manglunki - BE/OP/CERN)

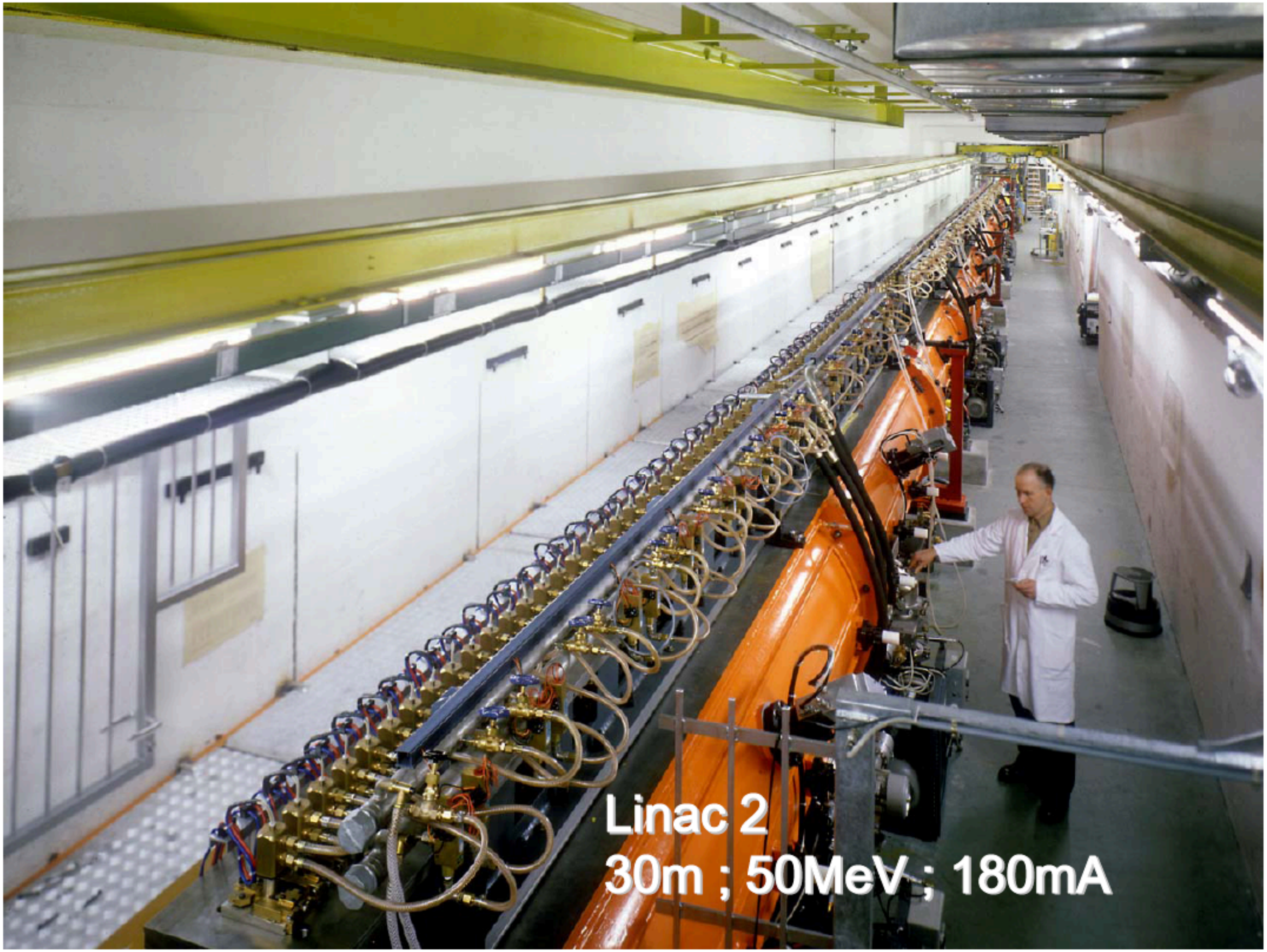

CMS
LHC
2007 (27 km)
North Area
ALICE
LHCb
TT40
TT41
SPS
1976 (7 km)
TI8
neutrinos
TI2
TT10
ATLAS
CNGS
2006
Gran Sasso
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
n-ToF
2001
PS
1959 (628 m)
LINAC 2
CTF3
neutrons
e⁻
LINAC 3
Ions
Leir
2005 (78 m)
p (proton)
ion
neutrons
p̄ (antiproton)
proton/antiproton conversion
neutrinos
electron
LHC Large Hadron Collider
SPS Super Proton Synchrotron
PS Proton Synchrotron
AD Antiproton Decelerator
CTF3 Clic Test Facility
CNGS Cern Neutrinos to Gran Sasso
ISOLDE Isotope Separator OnLine DEvice
LEIR Low Energy Ion Ring
LINAC LINear ACcelerator
n-ToF Neutrons Time Of Flight

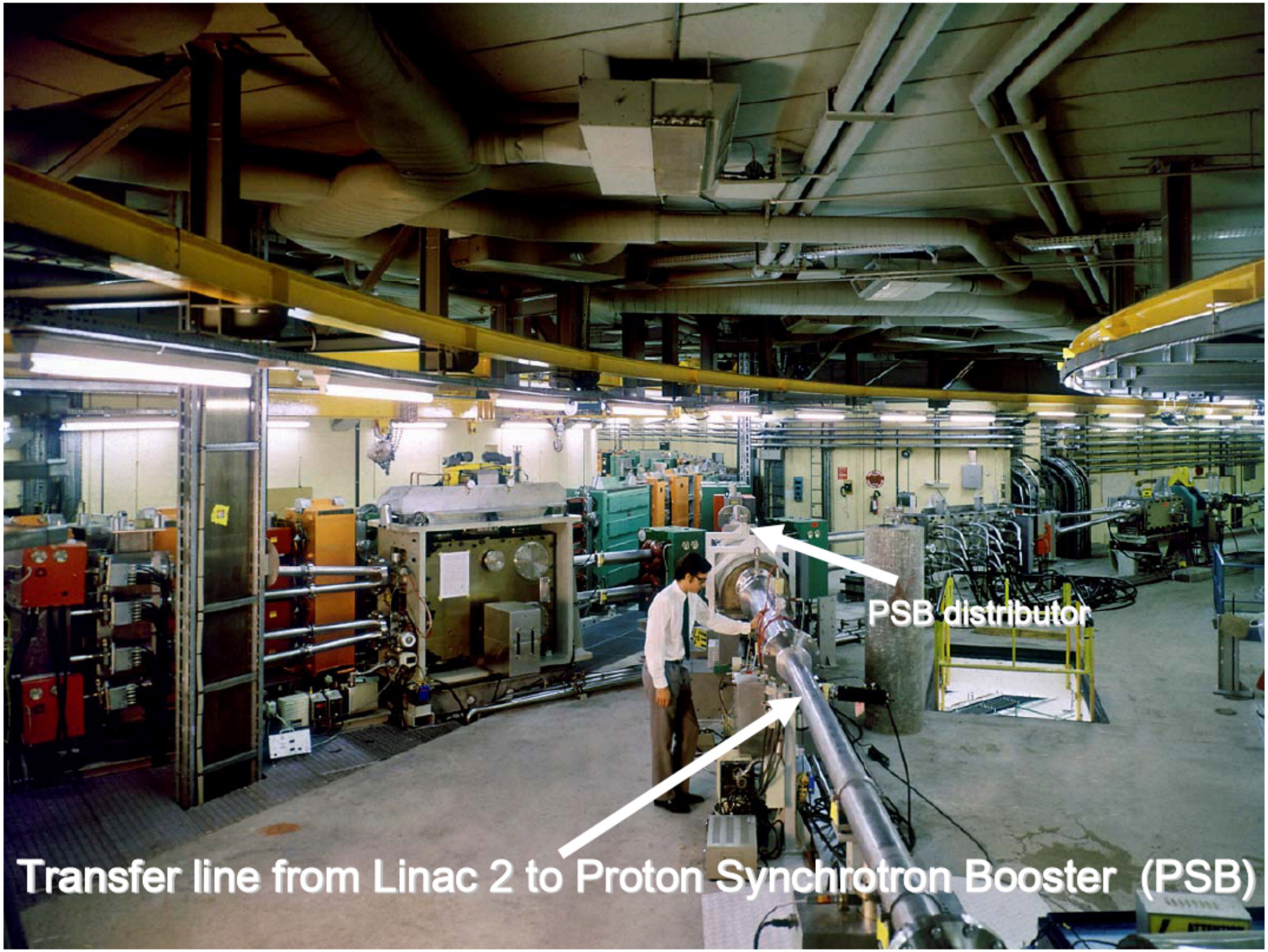

Radio Frequency Quadrupole (RFQ)
~1m ; 750keV
Duoplasmatron proton source
90keV ; 500mA
PREINJECTEUR
LINAC
A PROTON SOURCE
H2
HAUTE
HIGH
100 KV
Proton source
Linac
LINAC 2

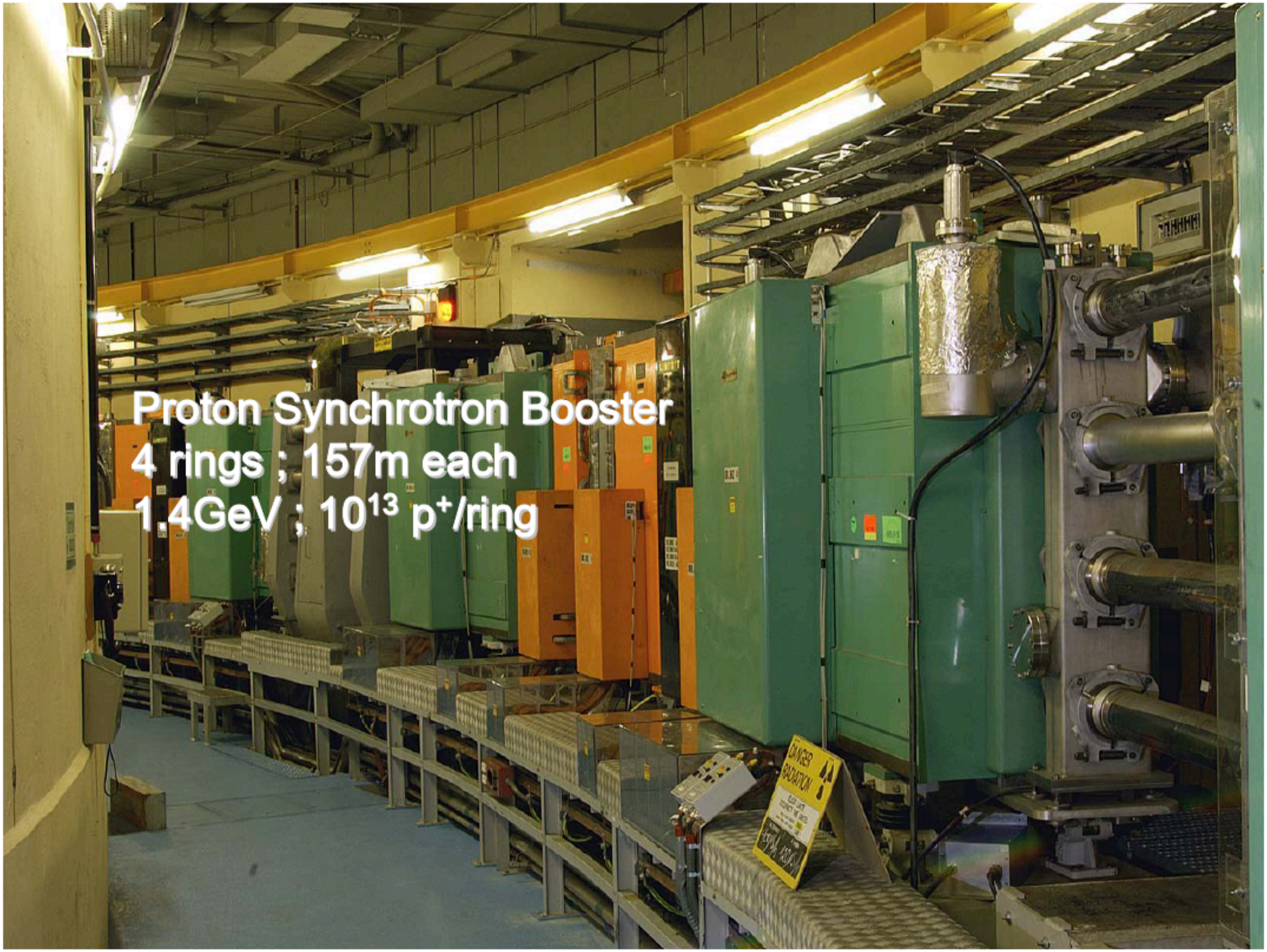

Radio Frequency Quadrupole (RFQ)
~1m ; 750keV

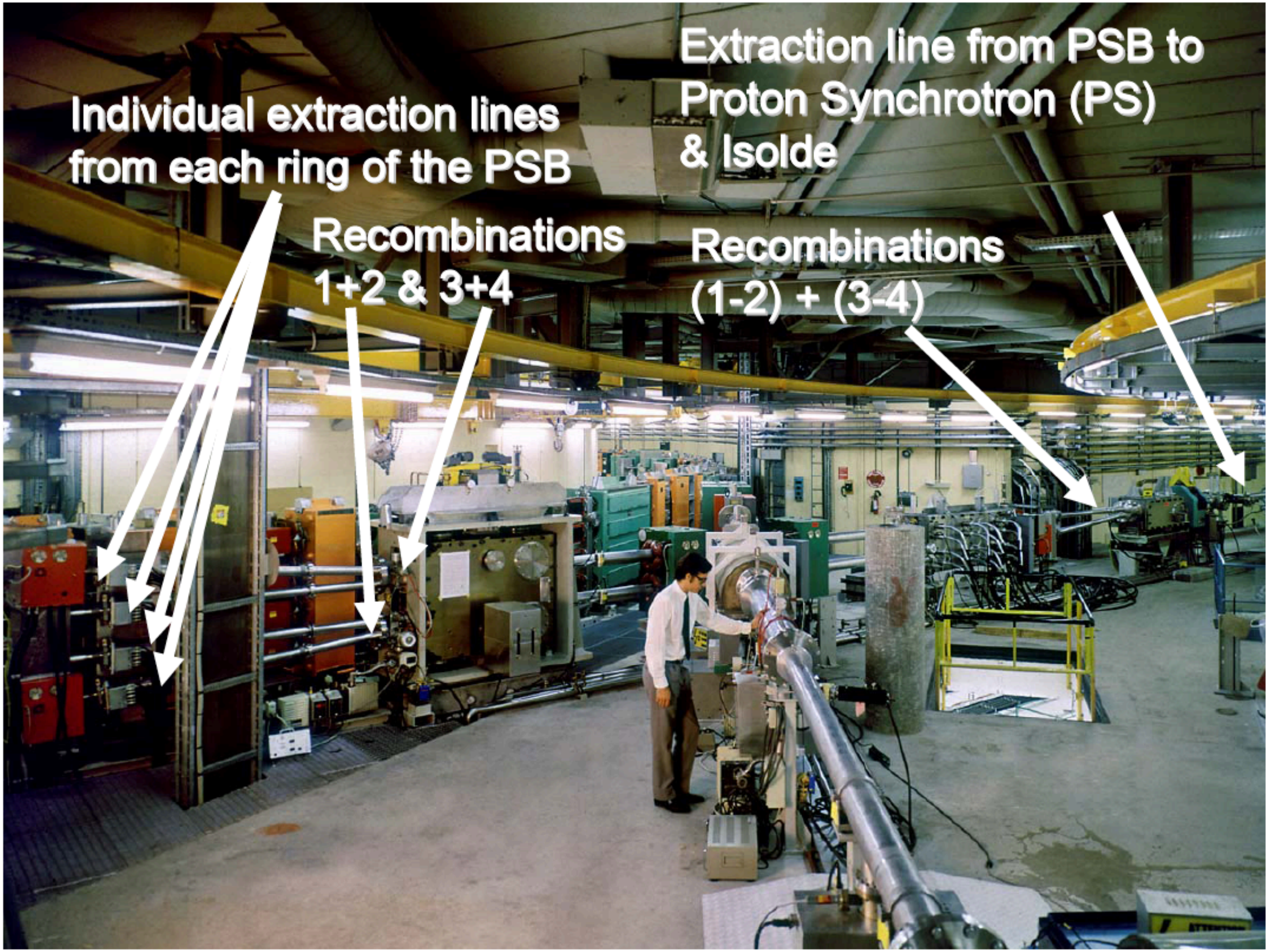


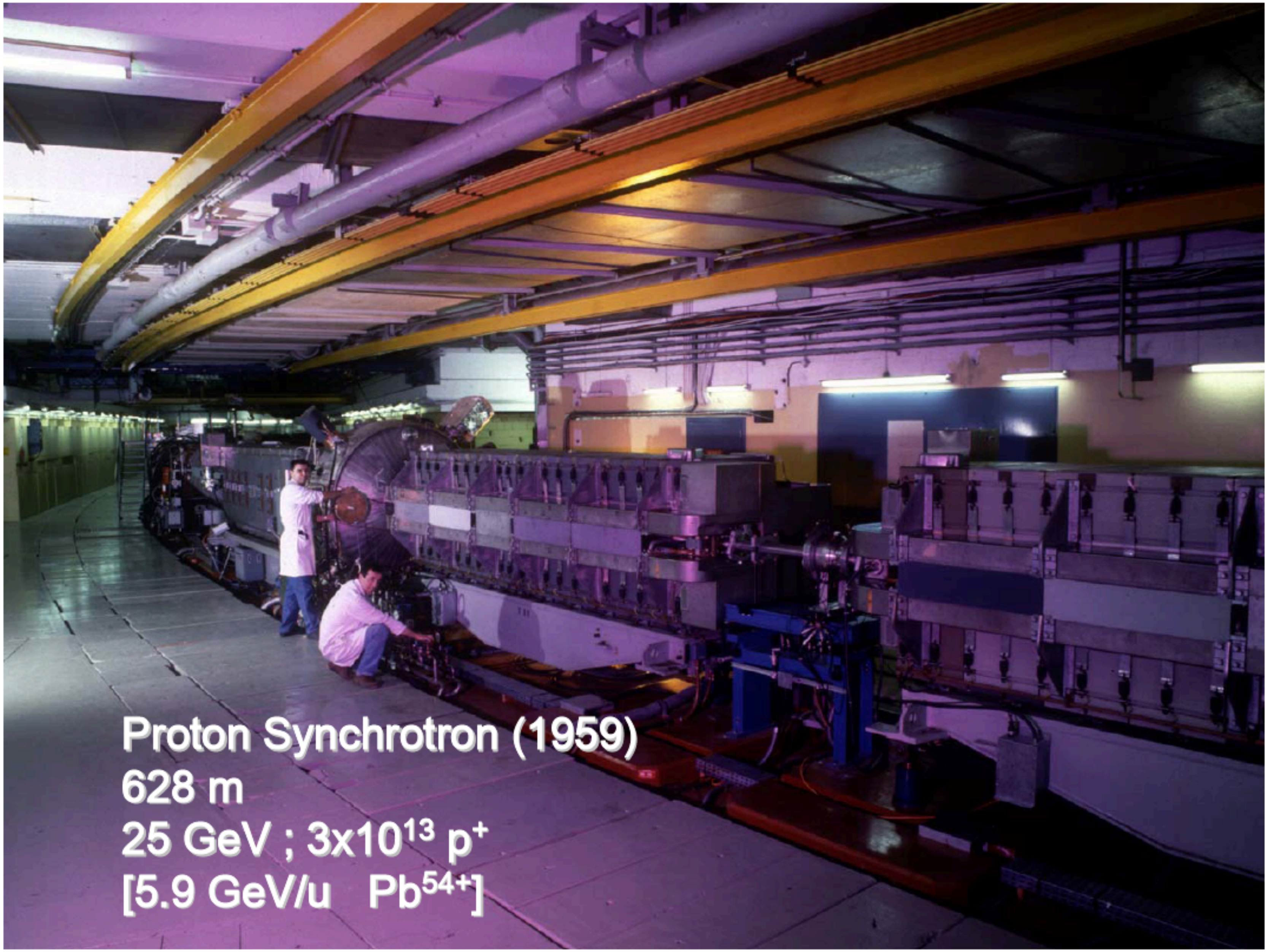
Linac 2
30m ; 50MeV ; 180mA

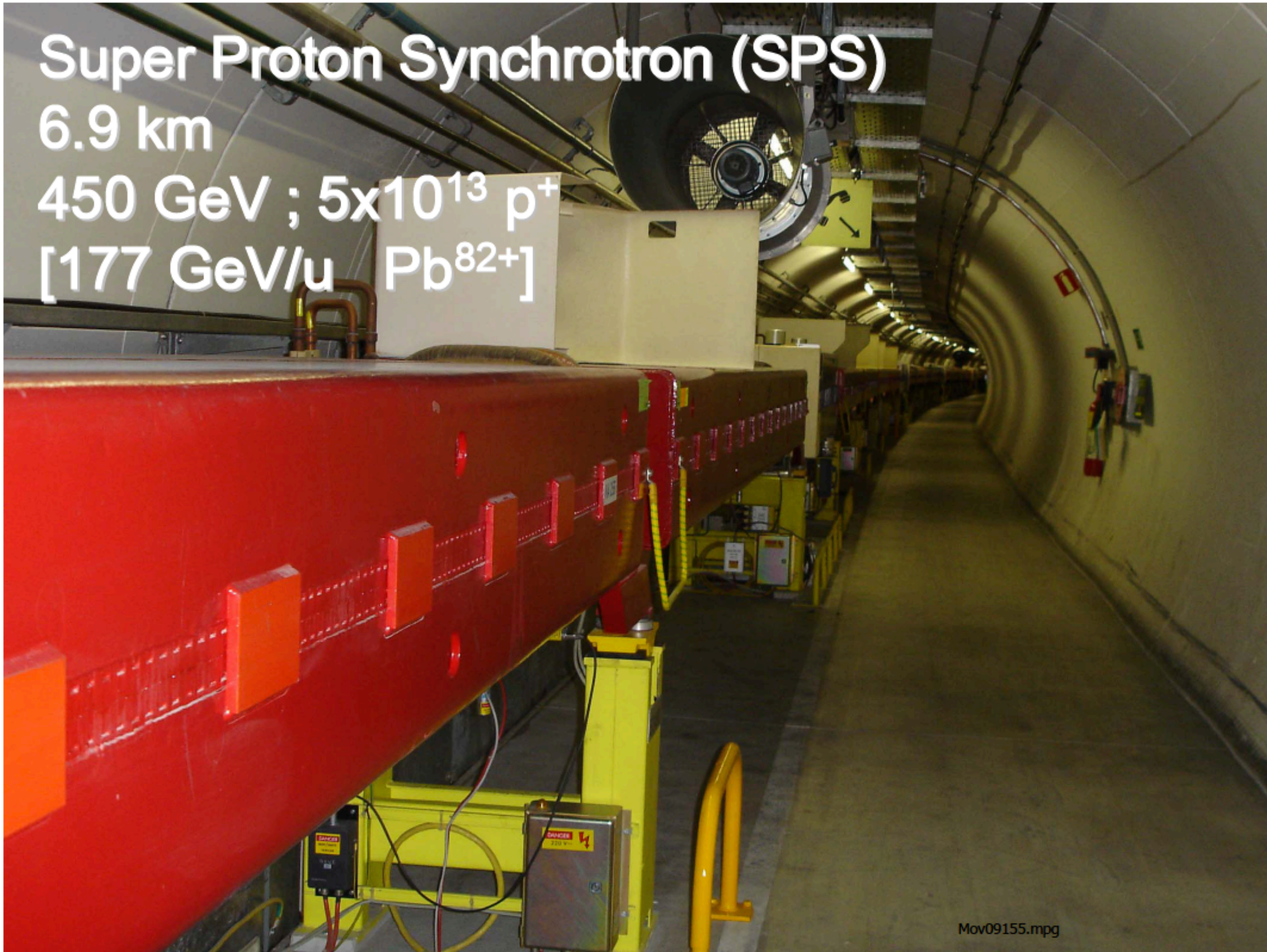

Linac 2
30m ; 50MeV ; 180mA


PSB distributor
Transfer line from Linac 2 to Proton Synchrotron Booster (PSB)

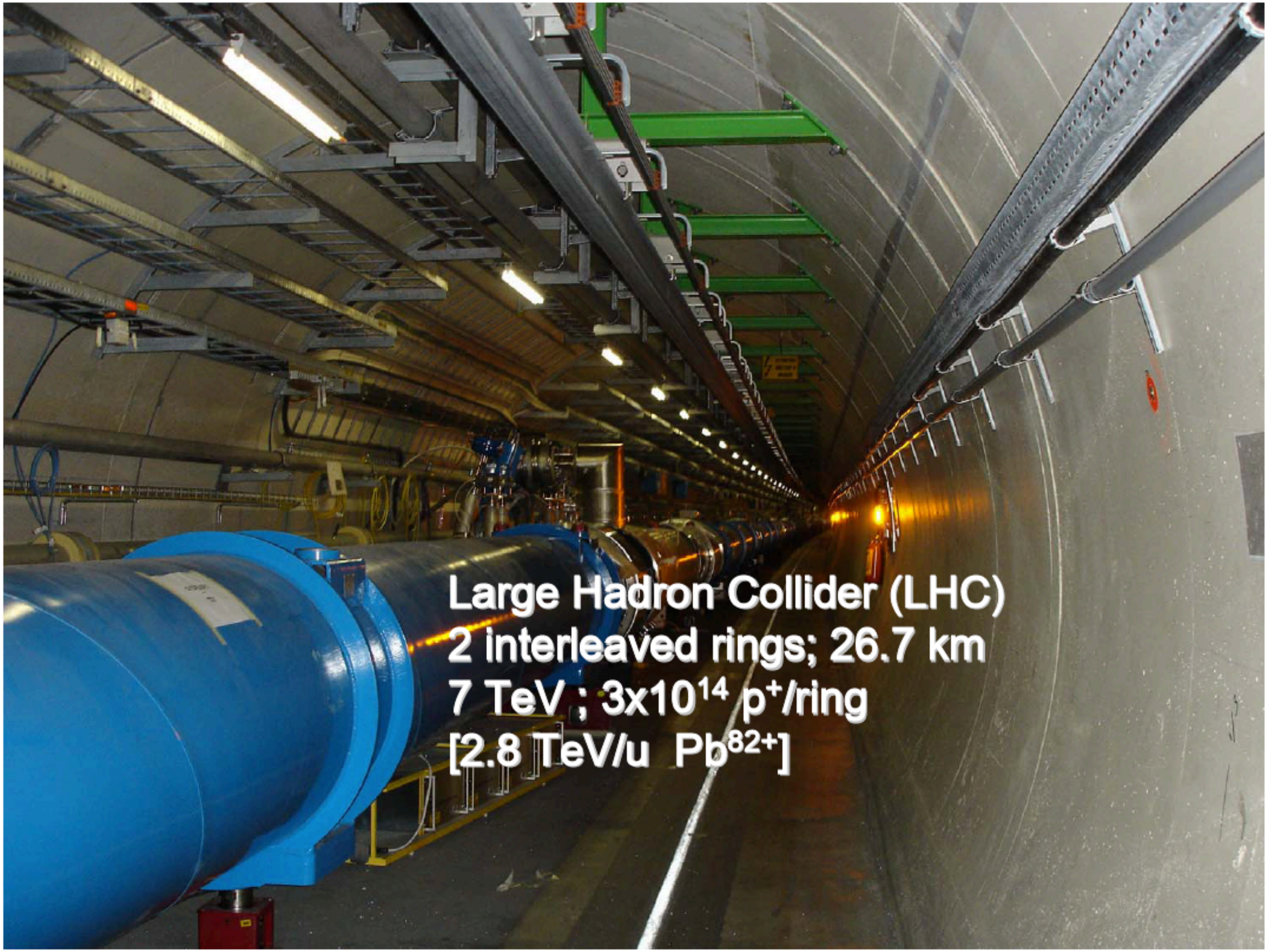

Proton Synchrotron Booster
4 rings ; 157m each
1.4GeV ; 10^{13} p^{+}/ring


Extraction line from PSB to
Proton Synchrotron (PS)
& Isolde
Individual extraction lines
from each ring of the PSB
Recombinations
1+2 & 3+4
Recombinations
(1-2) + (3-4)


Proton Synchrotron (1959)
628 m
25 GeV ; 3x10^{13} p^{+}
[5.9 GeV/u Pb^{54+}]


Super Proton Synchrotron (SPS)
6.9 km
450 GeV ; 5×10^{13} p^+
[177 GeV/u Pb^{82+}]
Mov09155.mpg

TI8 counter-clockwise transfer line from SPS to LHC


Large Hadron Collider (LHC)
2 interleaved rings; 26.7 km
7 TeV ; 3x10^14 p+/ring
[2.8 TeV/u Pb82+]