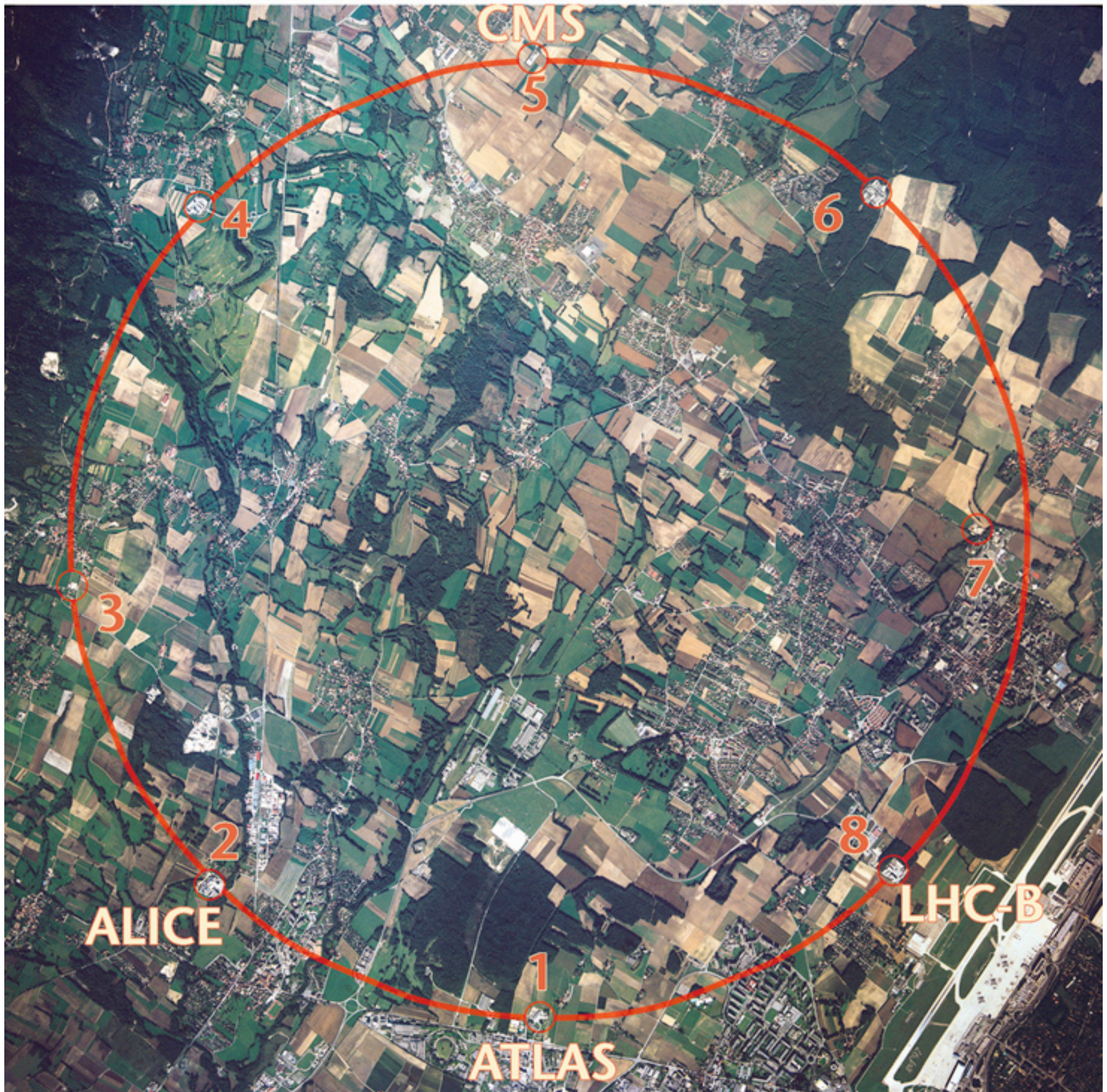
The LHC

LHC

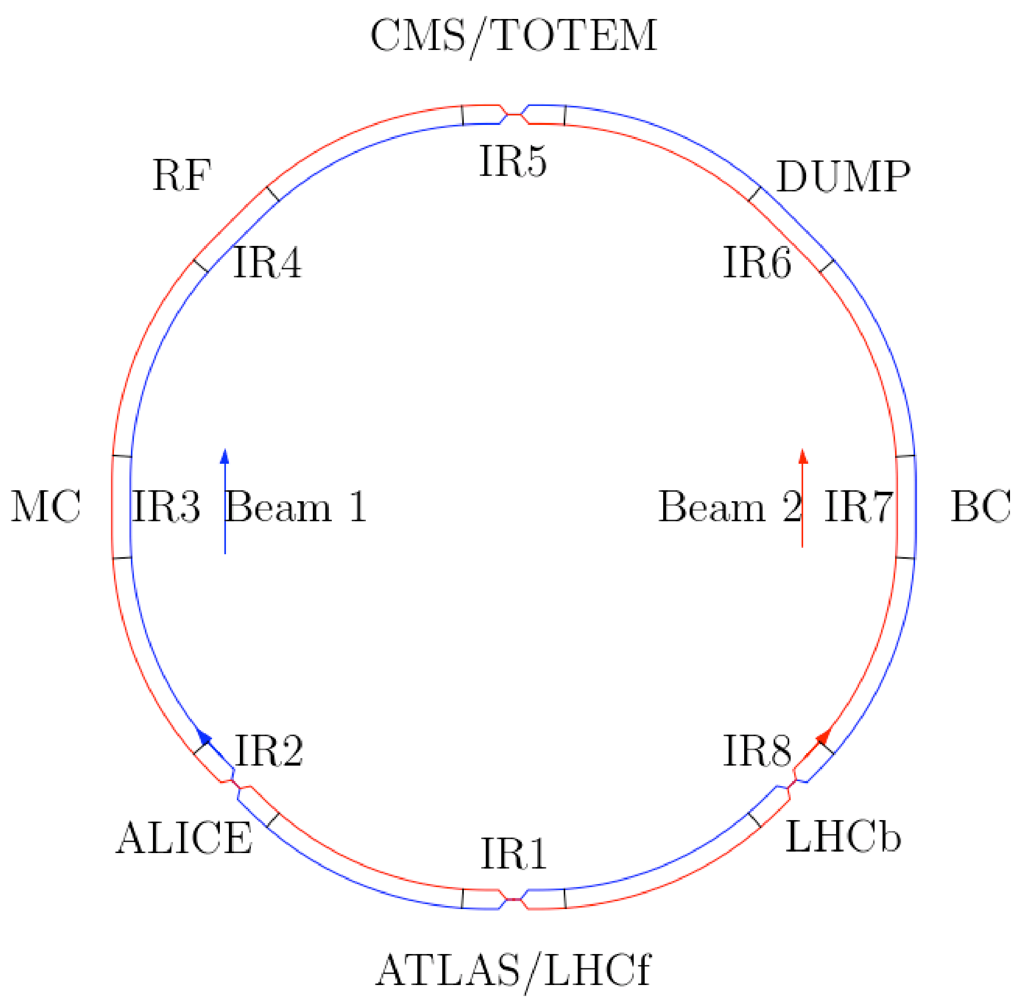
CERN

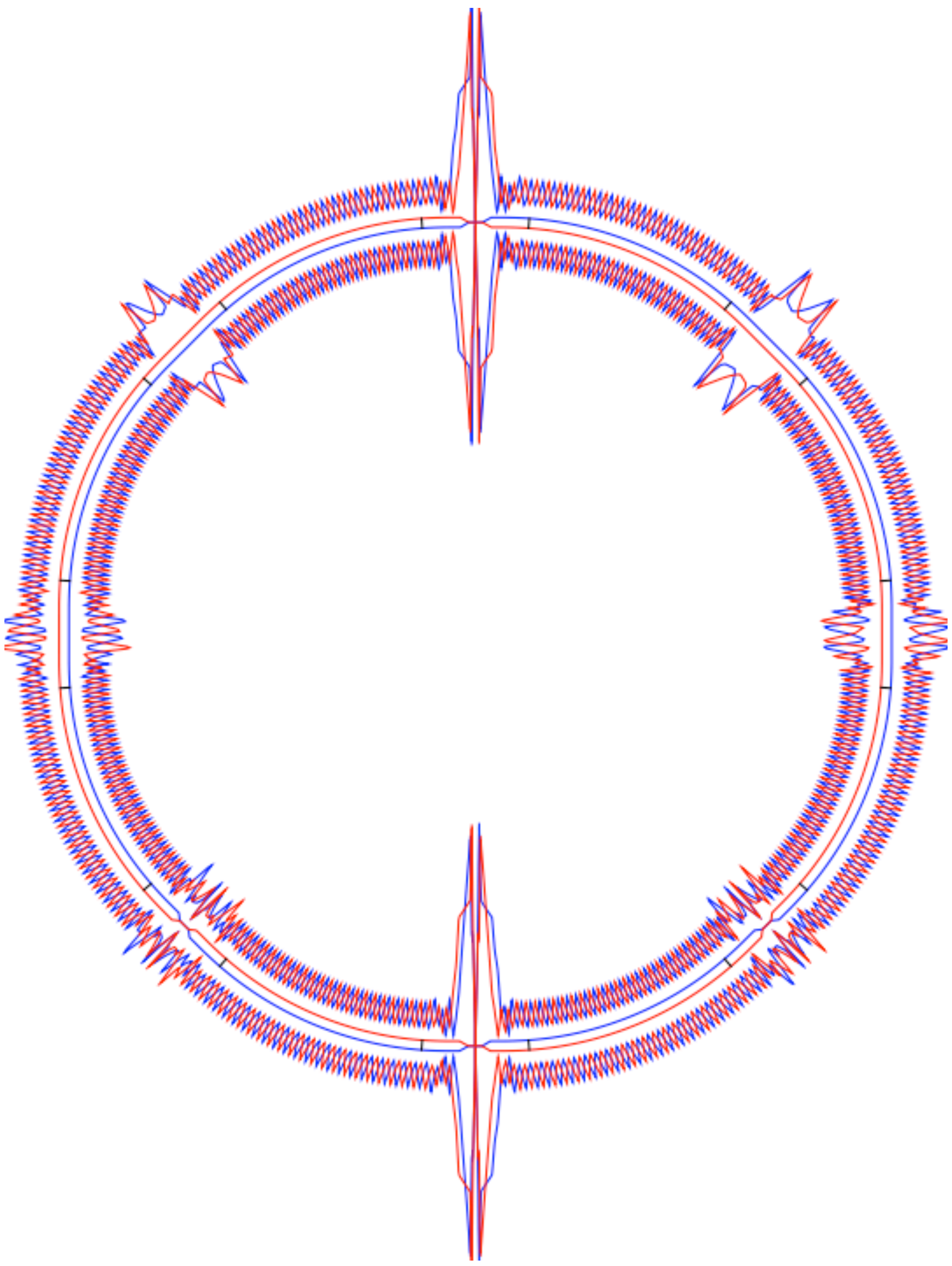
THE LARGE HADRON COLLIDER



LE GRAND COLLISIONNEUR DE HADRONS

The LHC optics in one slide





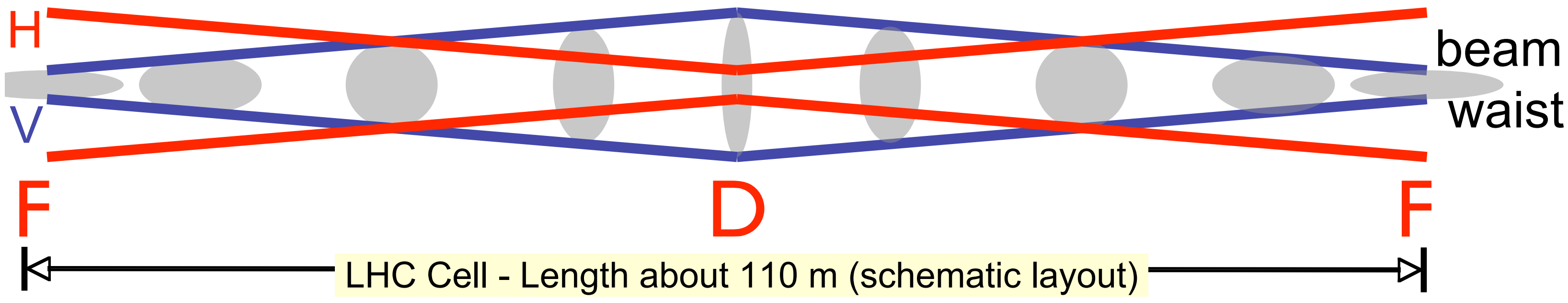
Magnets for the LHC, total budget, every magnet has a role in the optics design

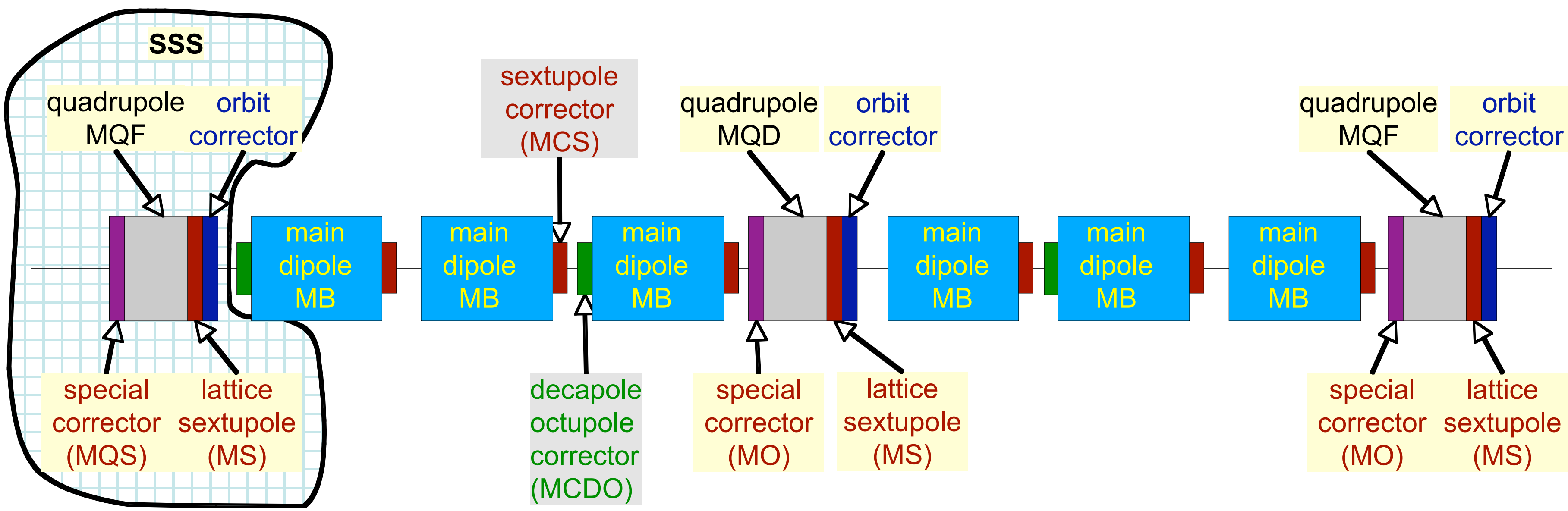
Name	Quantity	Purpose
MB	1232	Main dipoles
MQ	400	Main lattice quadrupoles
MSCB	376	Combined chromaticity/ closed orbit correctors
MCS	2464	Dipole spool sextupole for persistent currents at injection
MCDO	1232	Dipole spool octupole/decapole for persistent currents
MO	336	Landau octupole for instability control
MQT	256	Trim quad for lattice correction
MCB	266	Orbit correction dipoles
MQM	100	Dispersion suppressor quadrupoles
MQY	20	Enlarged aperture quadrupoles

In total 6628 cold magnets ...

LHC optics, ARC lattice

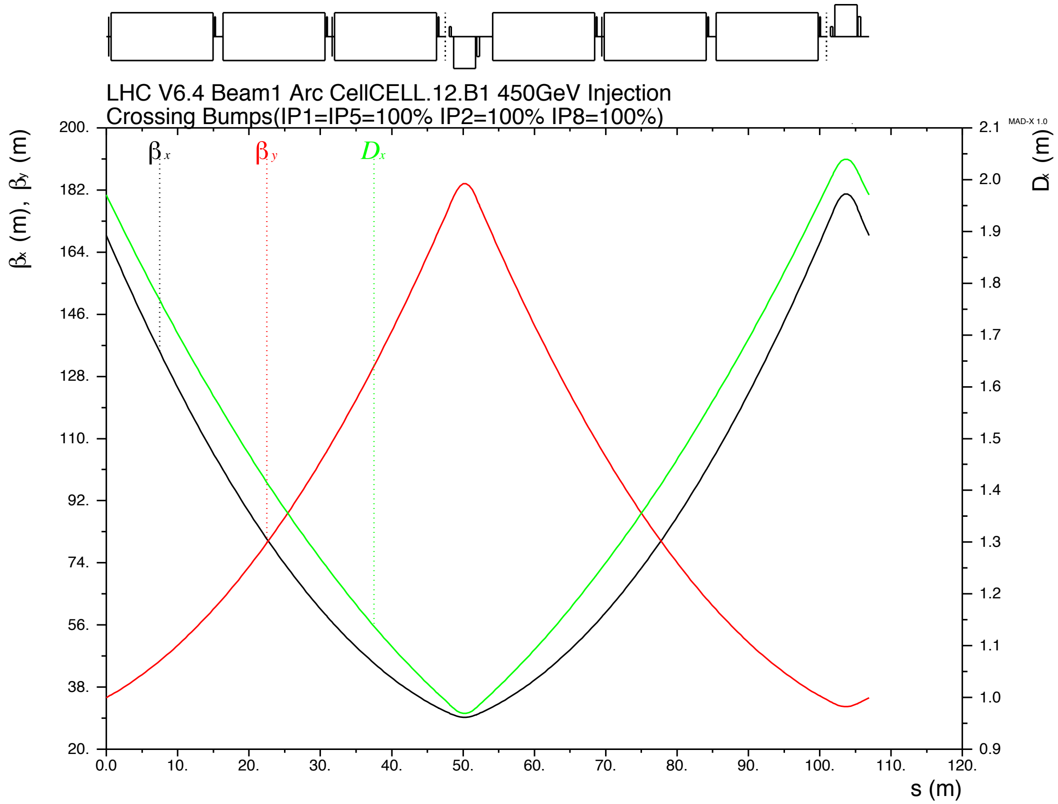
Classical FODO cell with about 90^0 phase advance per cell
(F=focusing, O=drift, D=defocusing)

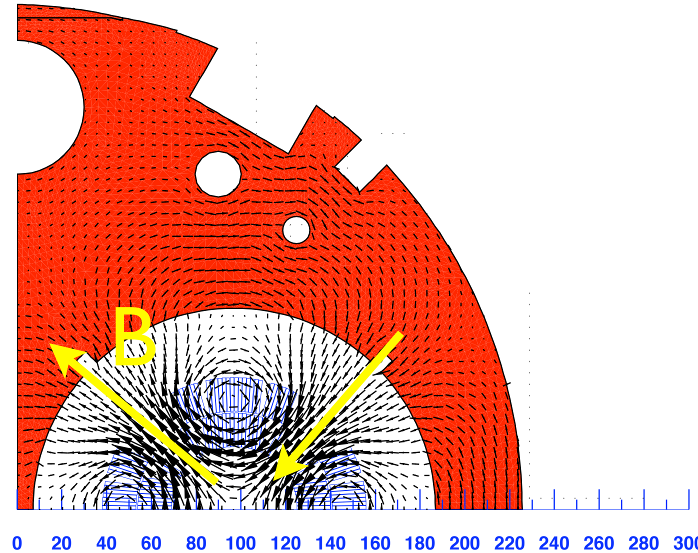


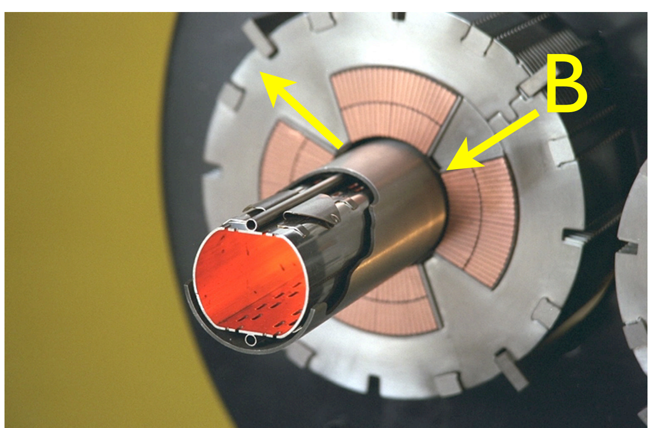


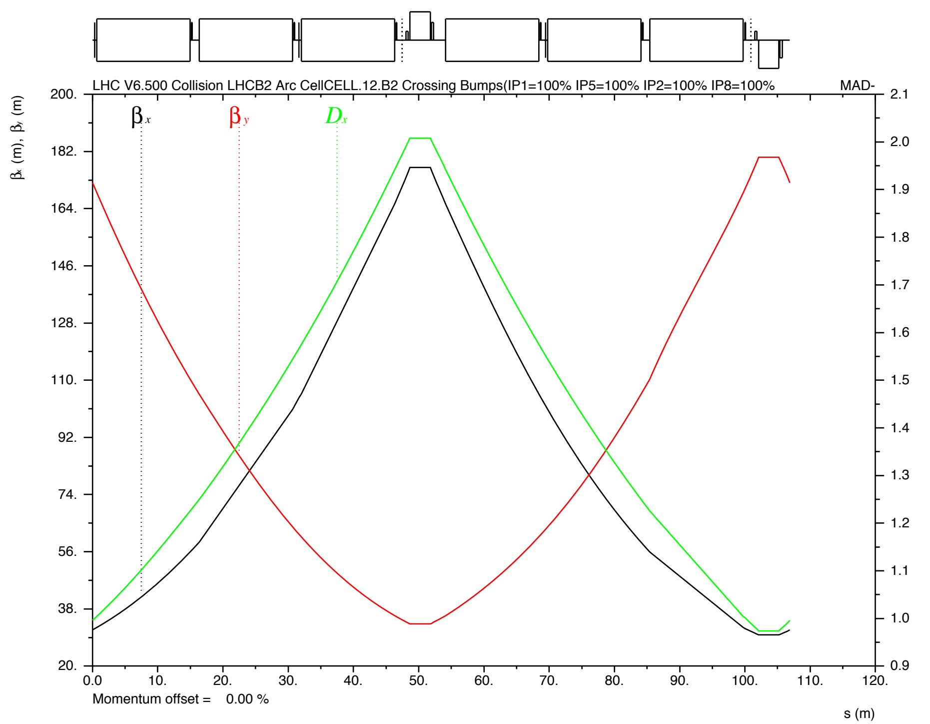
2-in-1 design true also for the optics:
a quadrupole F for beam 1 (circulating clockwise) is D for beam 2 circulating anticlockwise

Arc cell at injection for beam 1 and beam 2



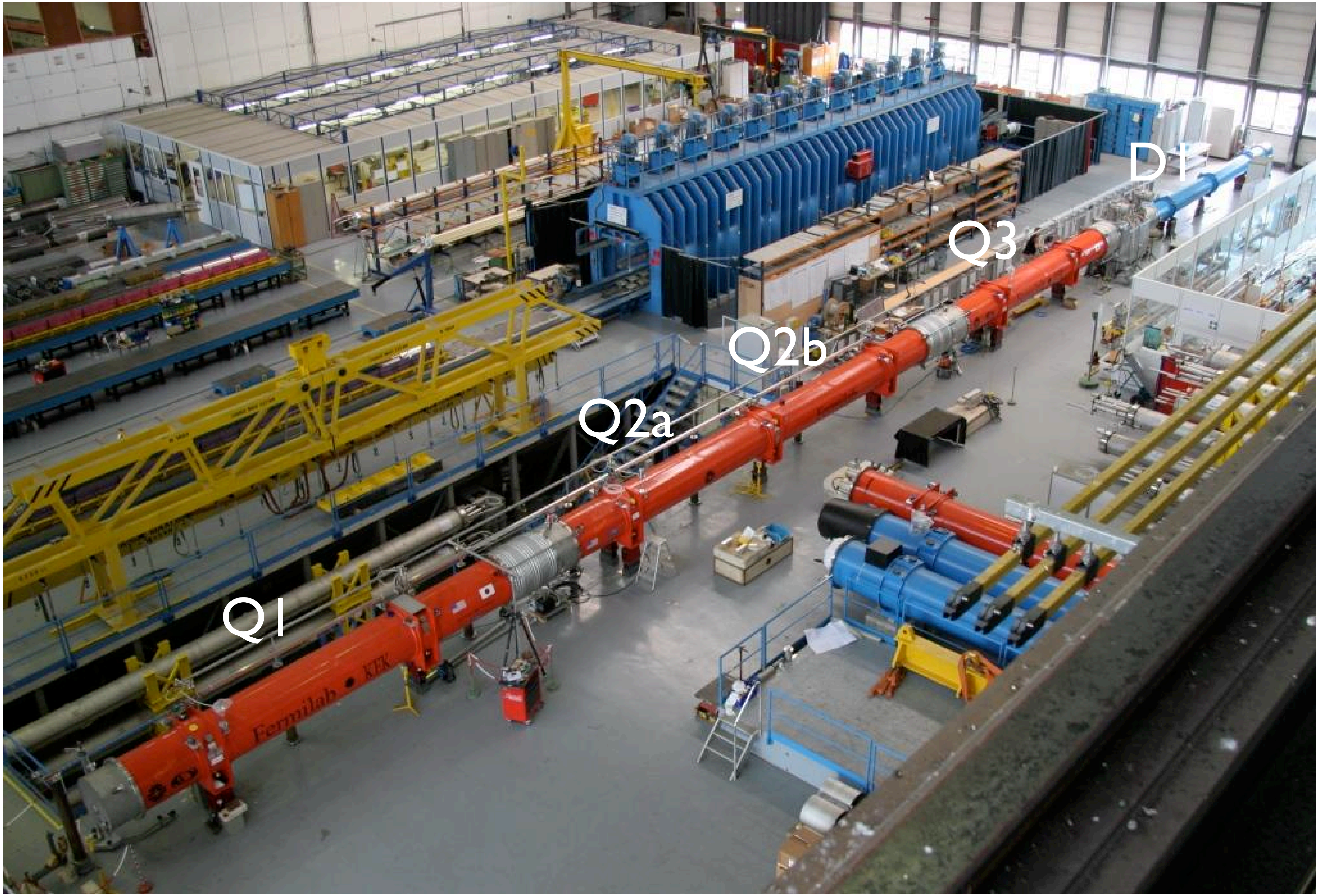






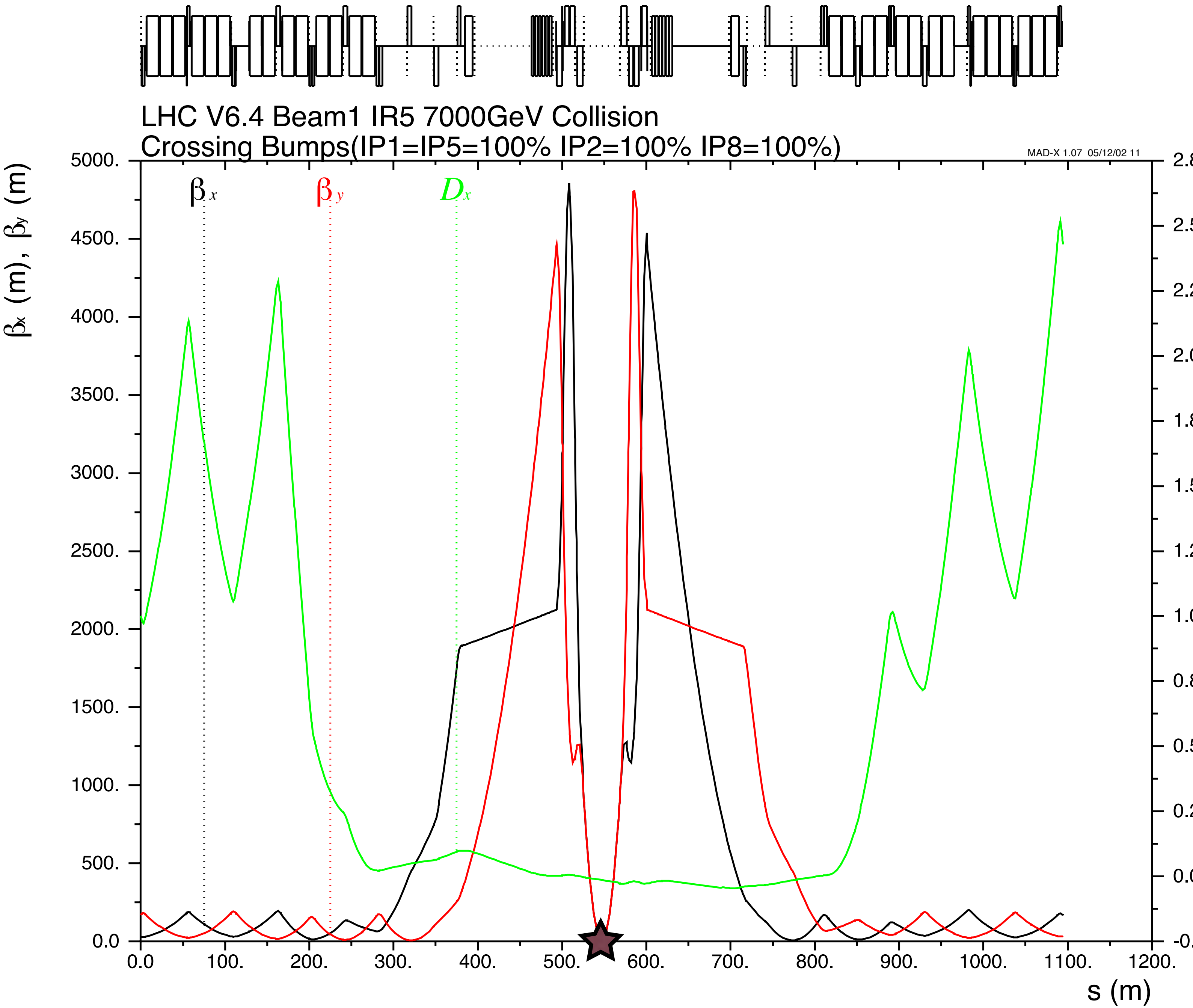
One LHC test CELL on surface

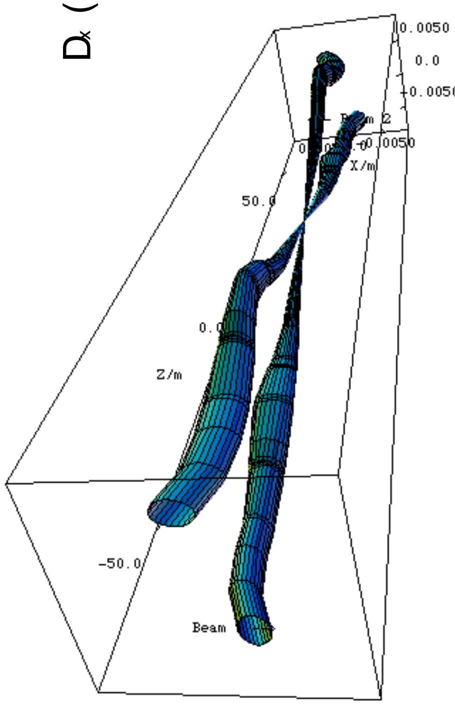
Triplets before lowering in the tunnel



Optics at collision IP1- ATLAS, only beam 1

$$x_{MAX} = \sqrt{\epsilon\beta}$$





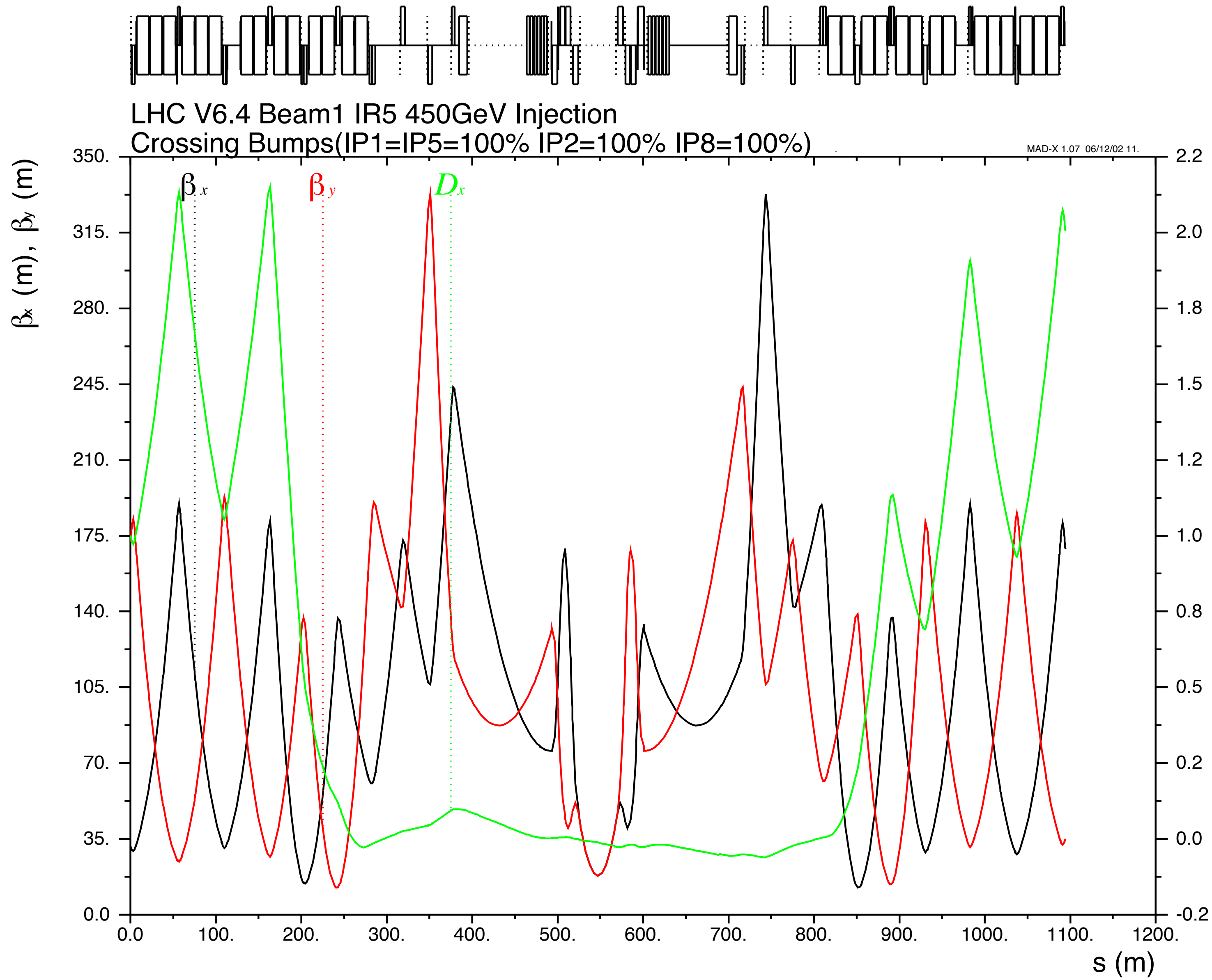
Bmax in the triplets⇒ 5 Km

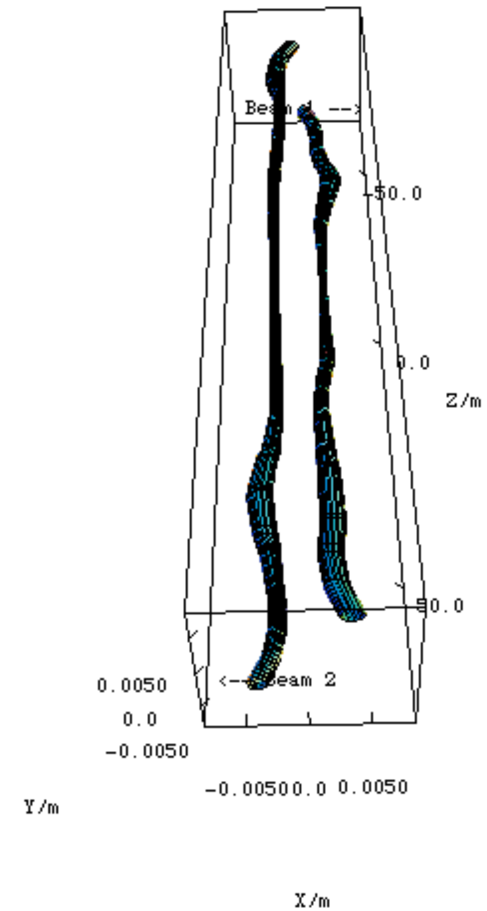
Bmin in the IPs = 0.55 m

Zero dispersion

Vertical crossing

Injection optics and during accelleration IP1- ATLAS, only beam 1





Bmax outside triplets

Bmin in the IPs = 11 m

Zero dispersion

Vertical separation

The importance of field quality

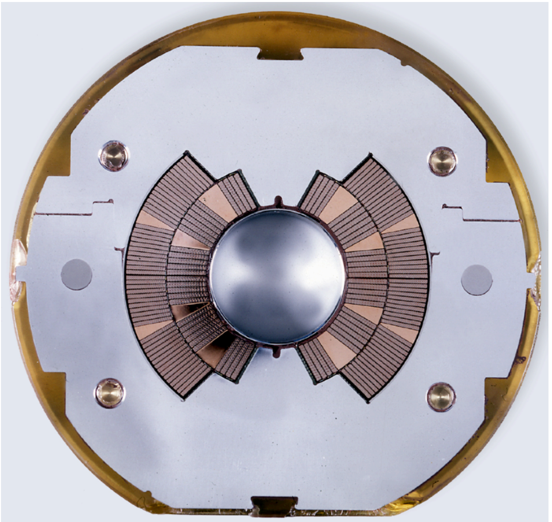
Field quality, i.e. multipole components in the main field dominated by SC geometry, not by the IRON as in normal conducting magnets.

As example, sextupolar component generated by the main dipoles. Let consider 3 units, meaning 3 10^{-4} times the 8.33 T fields. This is the target to have enough margin to correct the chromaticity using lattice correctors.

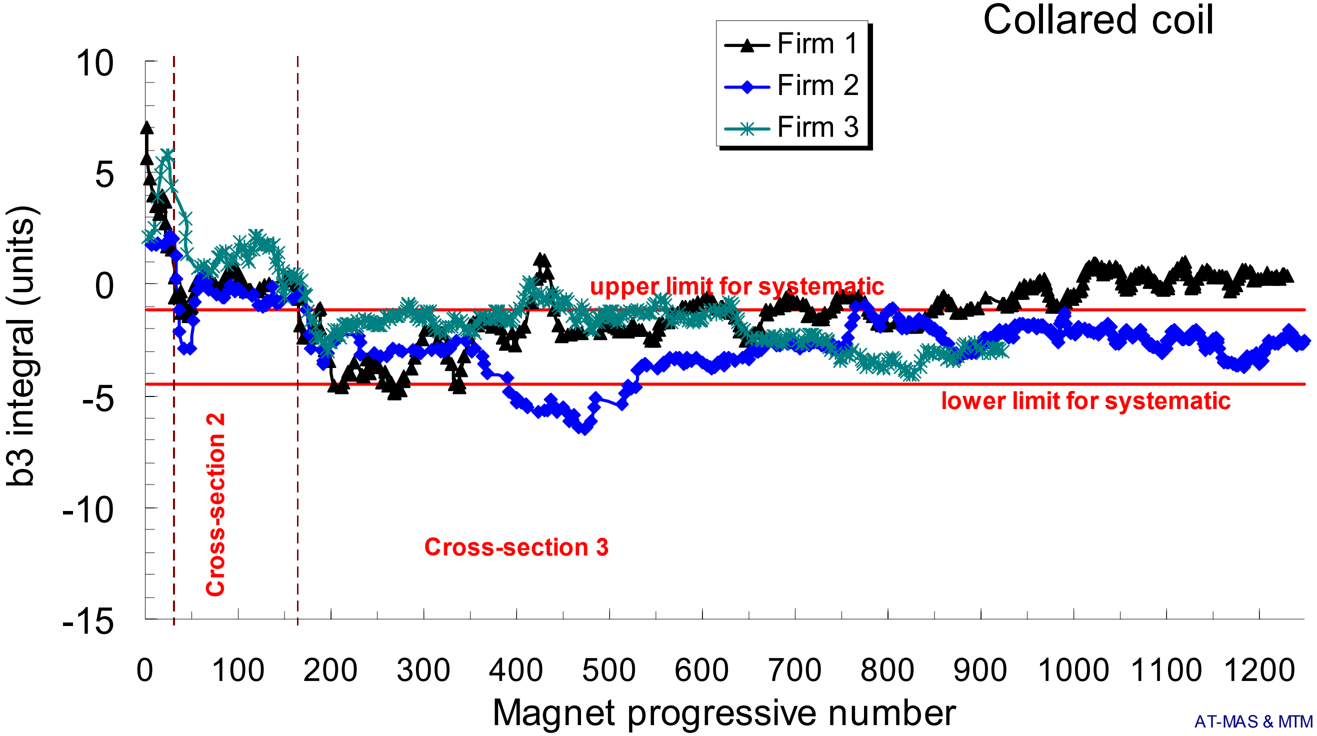
Multipoles measured up to b14 and a14 (b2 quadrupole, b3 sextupole ...)

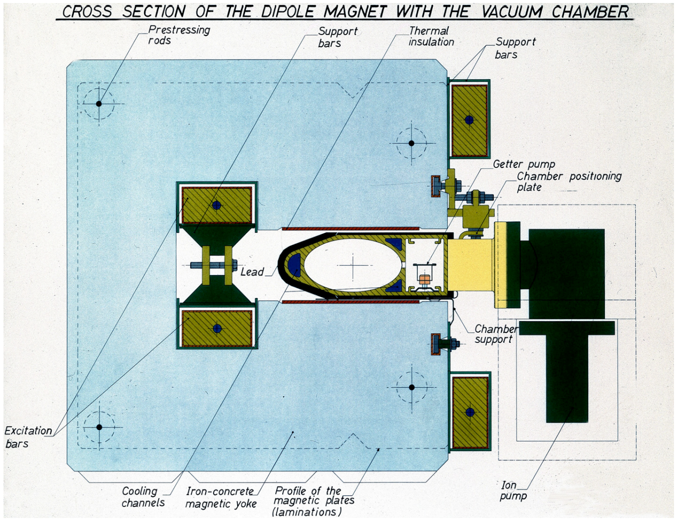
For the LHC Rr=17 mm, about 2/3 of the aperture

$$B_y + iB_x = B_{ref} \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_r} \right)^{n-1}$$

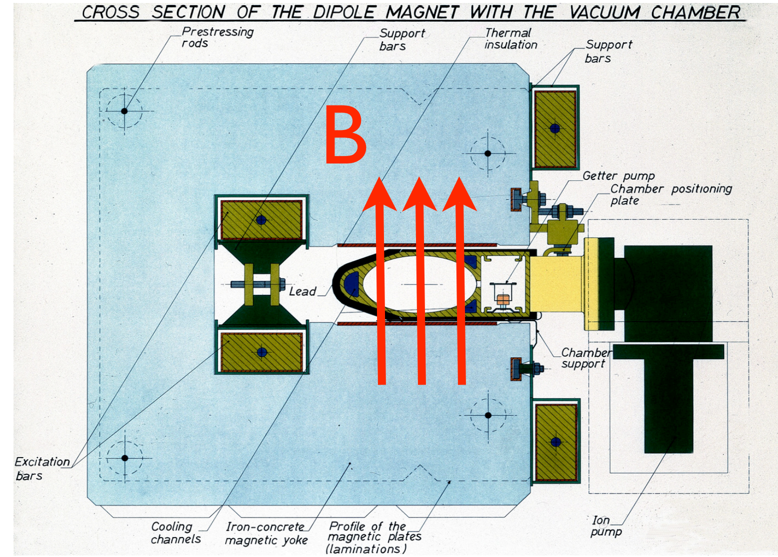


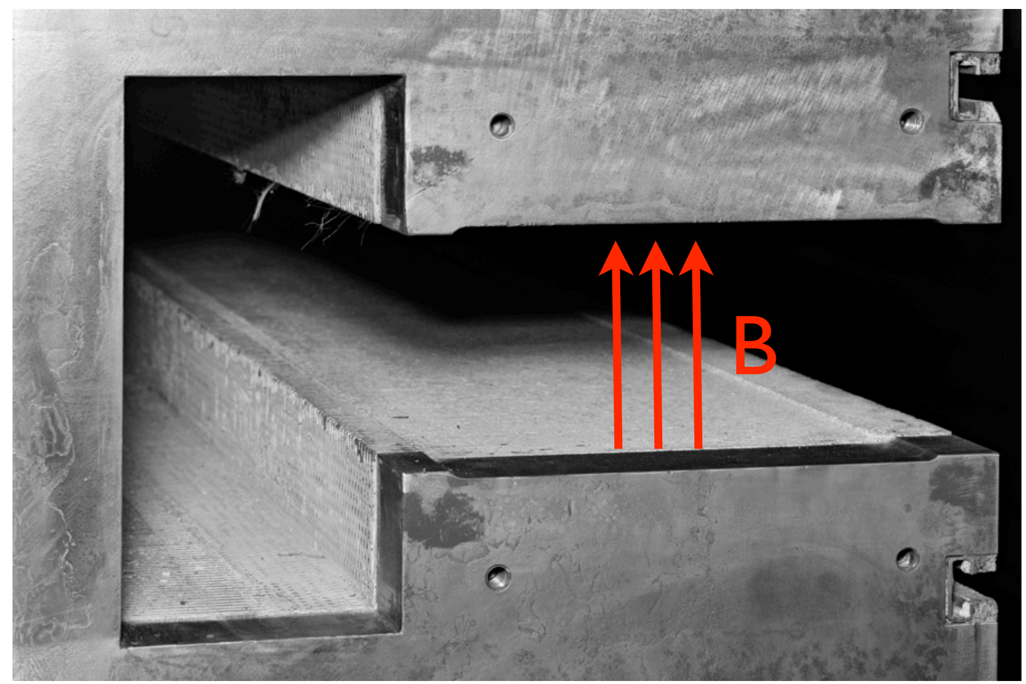
Collared coil



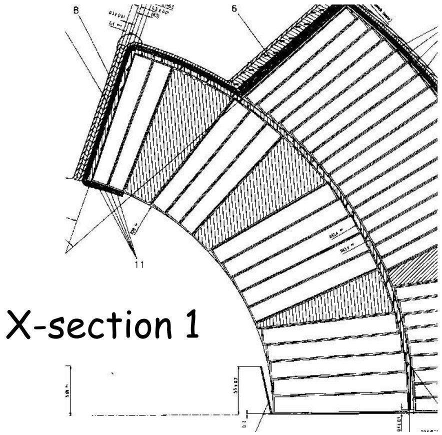


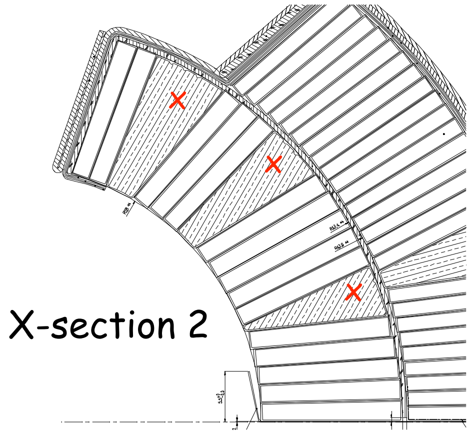
From LEP to the LHC, iron-concrete yoke ...





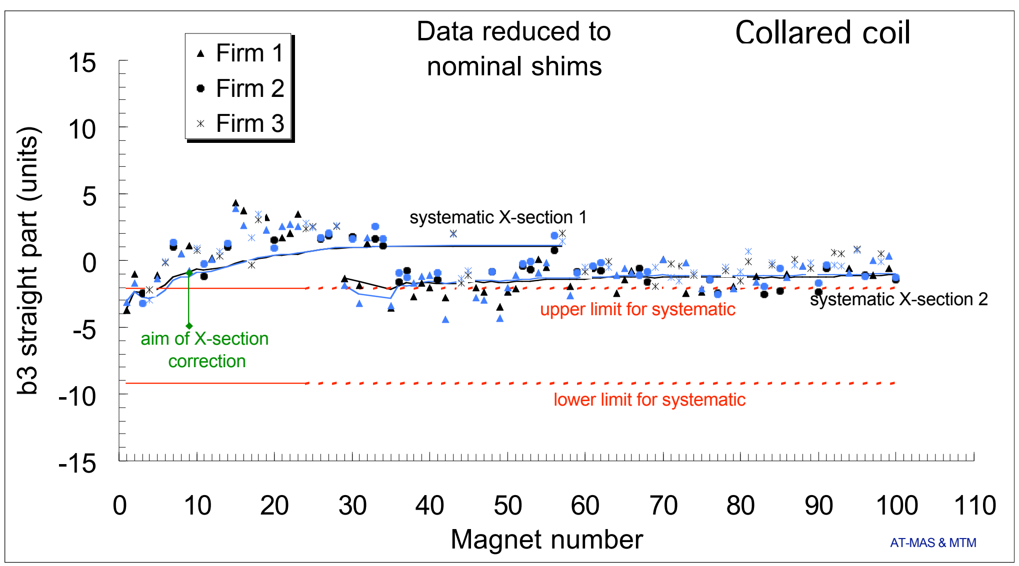
Magnet design important for field quality and machine performances

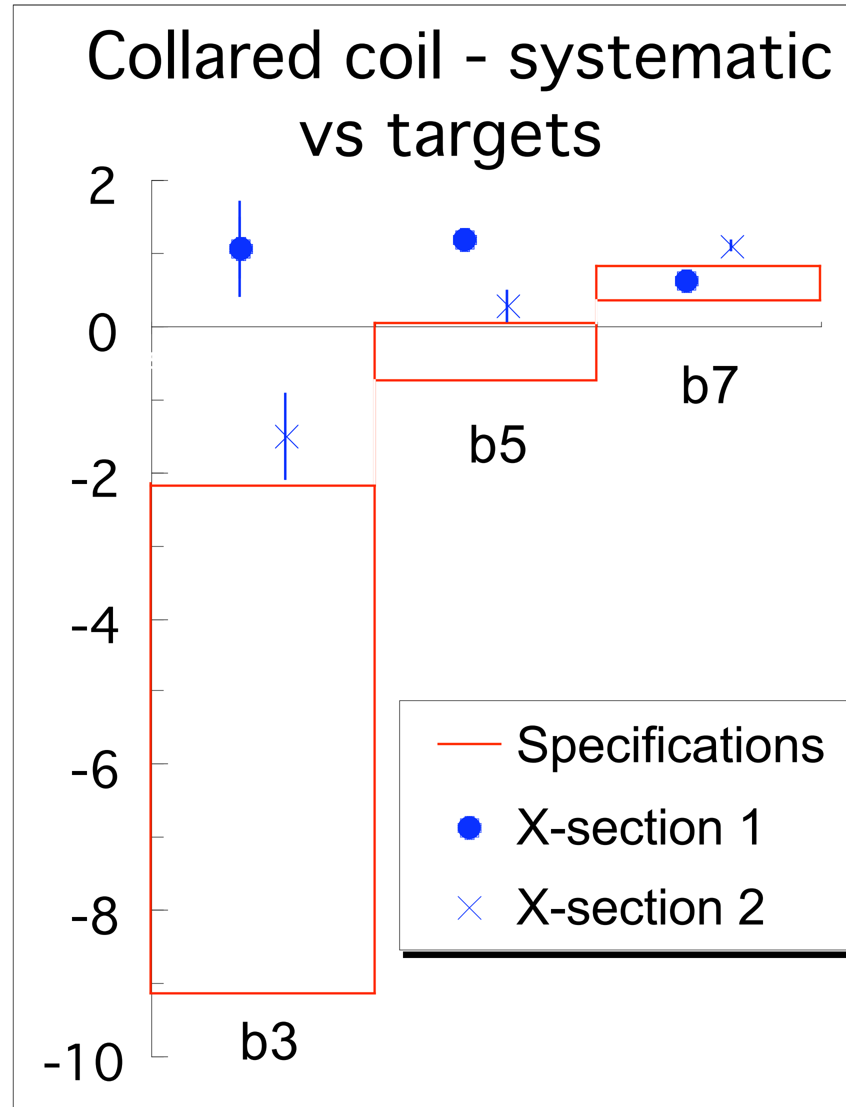




Aim of the change:

Δb_3=-4.0 Δb_5=-1.35 Δb_7=0.17 and $\Delta b1$=0



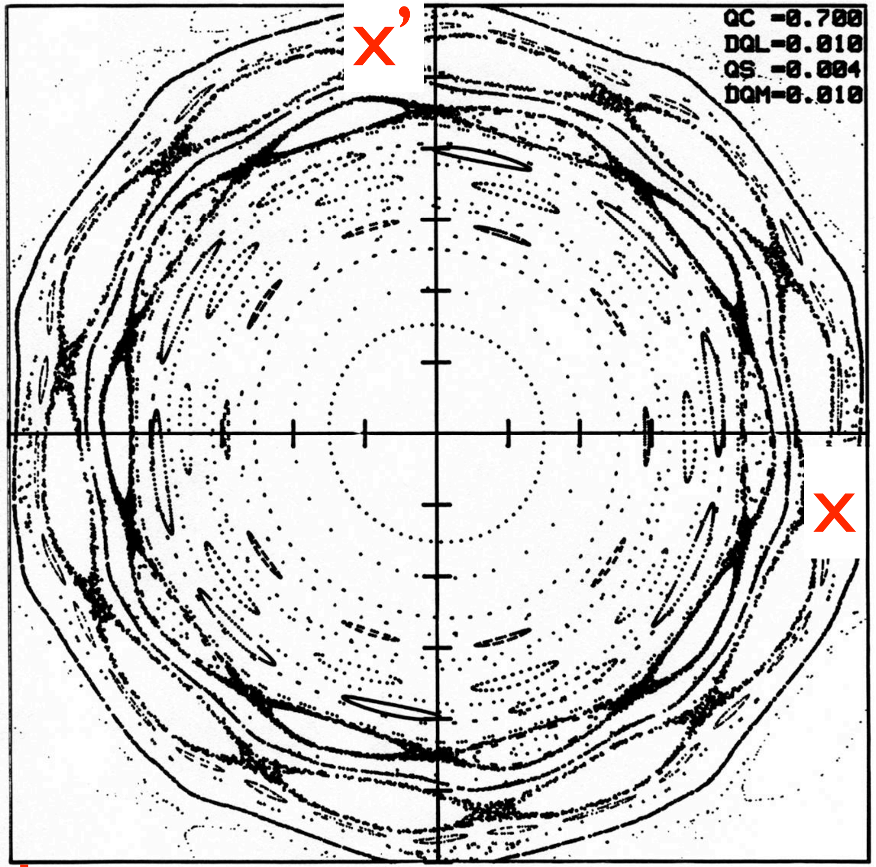


Dynamical Aperture

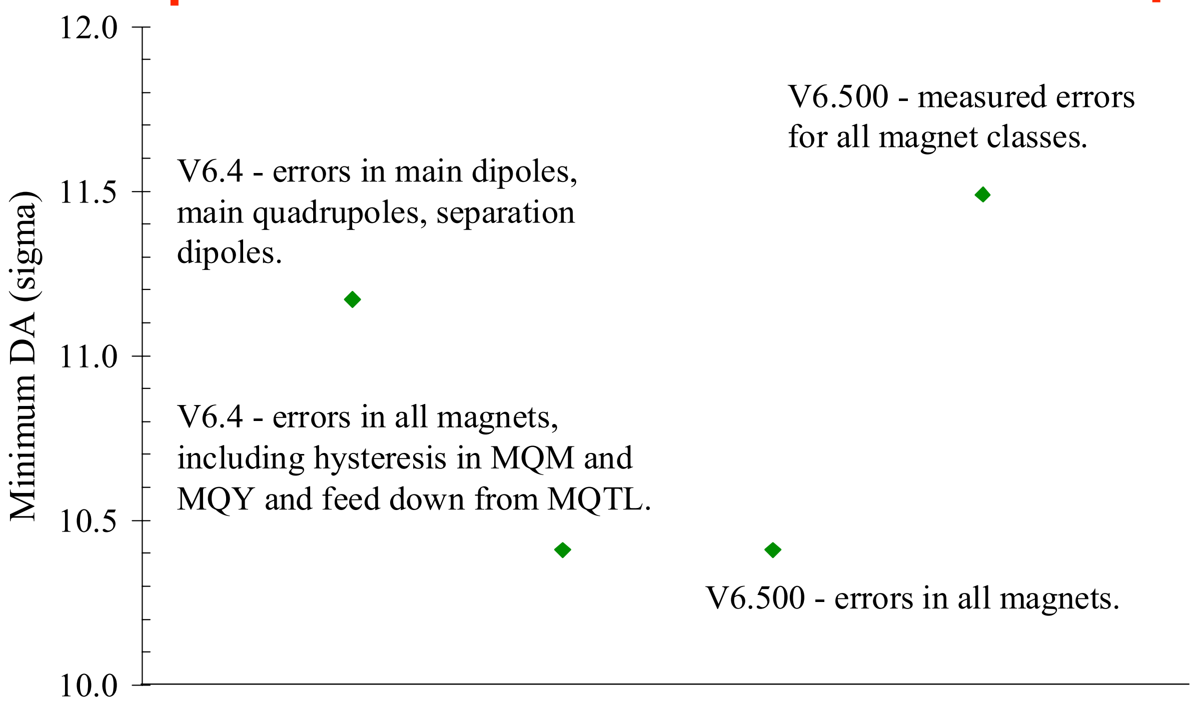
Dynamic aperture (DA) is largest region of phase space where stable motion occurs.
Computed by particle tracking simulating different sets of machine imperfection due to:

(A) machine alignement/mechanical aperture

(B) multipoles generated by the magnets itself

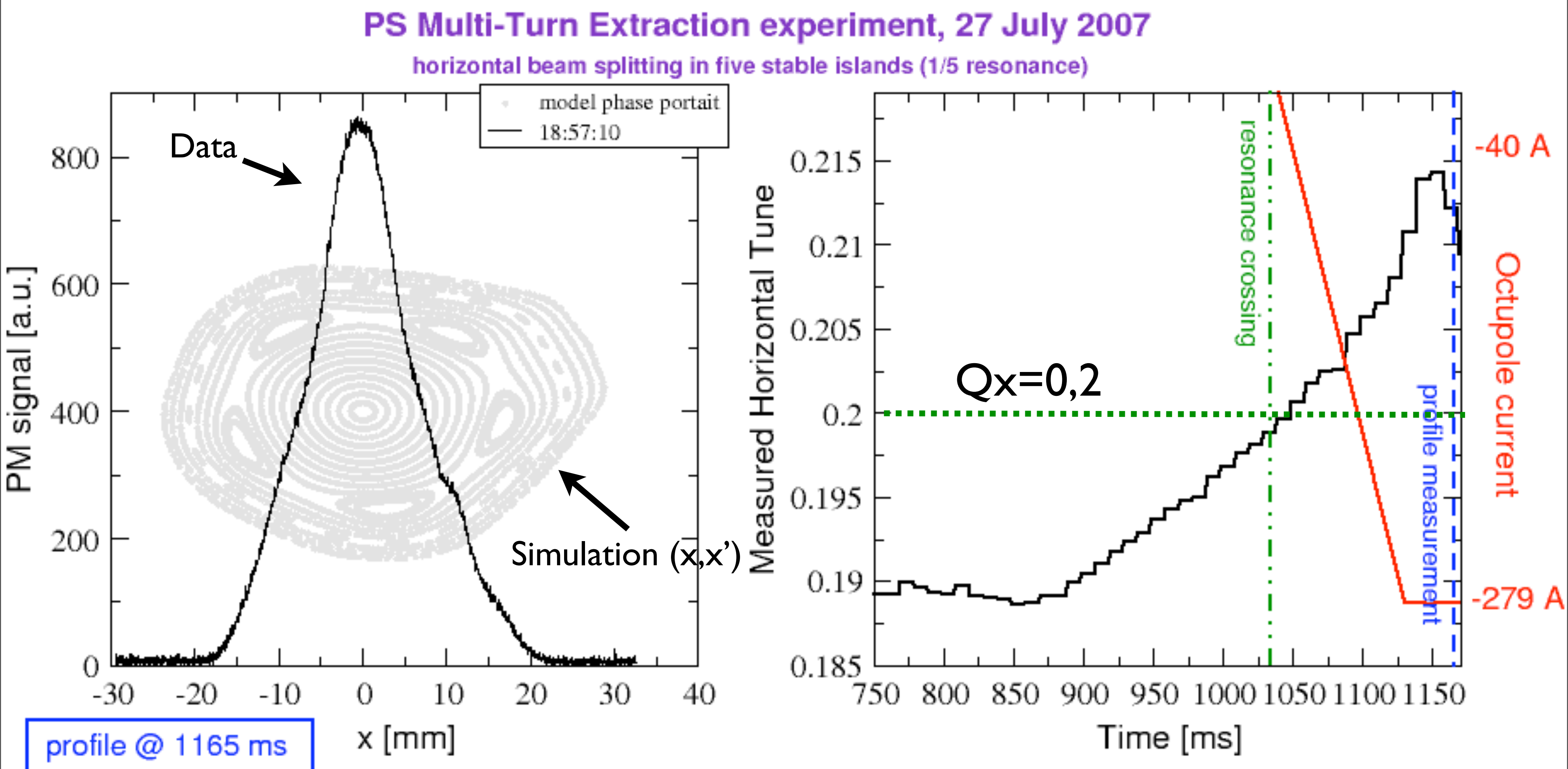


Dynamic aperture for different LHC "realisation"



In the transverse phase space, one cannot really see an ellipse which describes the normal betatronic phase space in a FODO lattice. Islands and chaotic (both in mathematical sense as in how it looks like) motion appear due to fields that vary with amplitudes (x) ⇒ Multipoles

In fact, if can control properly the non-linearities you can even split up the beam



Experiment done in the PS at 14 GeV/c (not @ the LHC) to show the splitting in *5 islands* of the beam by using sextupoles and octupoles and crossing the *1/5 resonance, i.e. Qx=0,2*

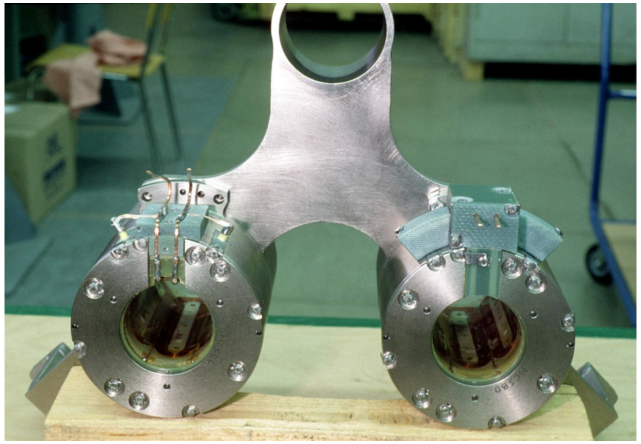
If this not done not under controlled conditions, losses appear ⇒ Resonance crossing in the LHC

If one can produce multibeams, one can for sure produce tails in a nice gaussian beam profile...

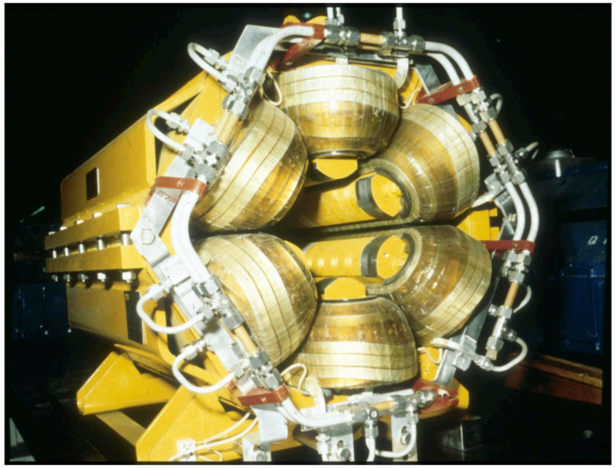
Two zoo of the multipoles and orbit correctors

Name	Quantity	Purpose
MB	1232	Main dipoles
MQ	400	Main lattice quadrupoles
MSCB	376	Combined chromaticity/ closed orbit correctors
MCS	2464	Dipole spool sextupole for persistent currents at injection
MCDO	1232	Dipole spool octupole/decapole for persistent currents
MO	336	Landau octupole for instability control
MQT	256	Trim quad for lattice correction
MCB	266	Orbit correction dipoles
MQM	100	Dispersion suppressor quadrupoles
MQY	20	Enlarged aperture quadrupoles

LHC sextupole



LEP sextupole



Working point choice

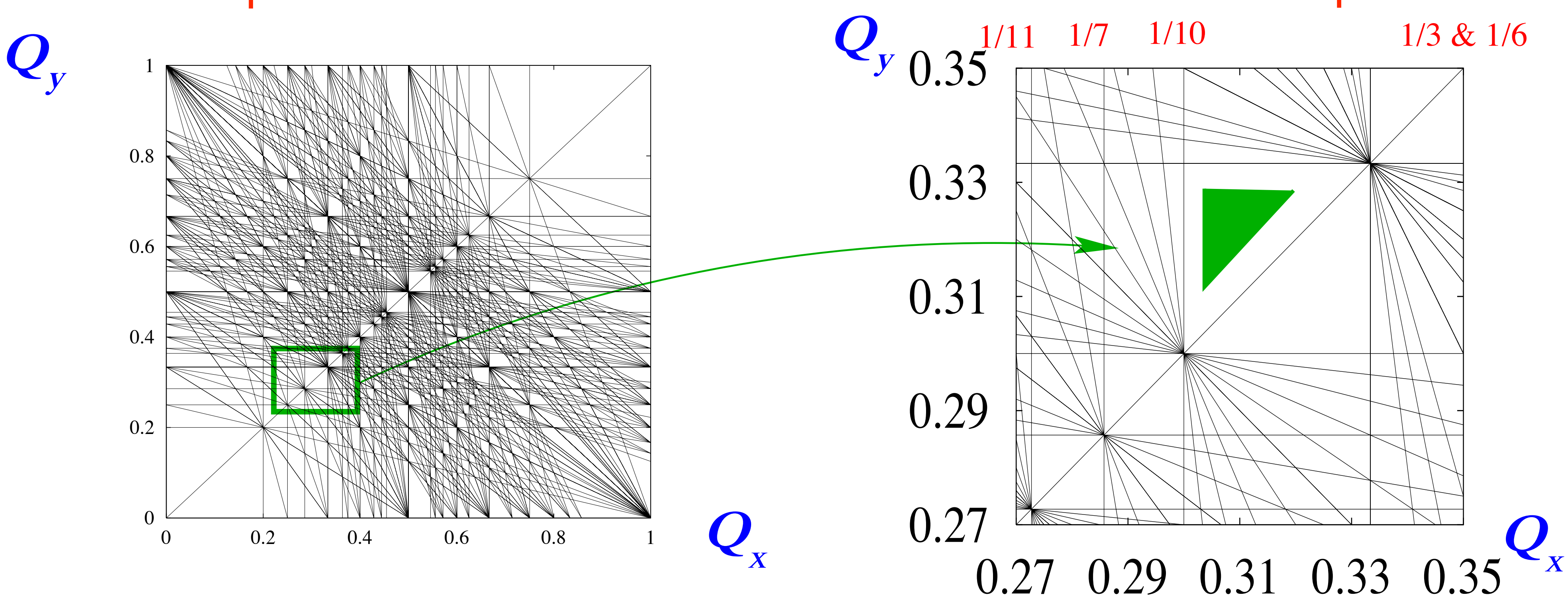
Tune: number of betatron oscillations in the x-x' (Qx) or y-y' (Qy) plane per machine turn.
An integer number in Qx or Qy correspond to a 2π rotation in the phase space. Not interesting in term of resonance instabilities.
Usually fractional tune is quoted, meaning what rest of the tune after subtracting the integer part.

From previous experience (Hera, Tevatron)
Avoid resonances n+m < 12

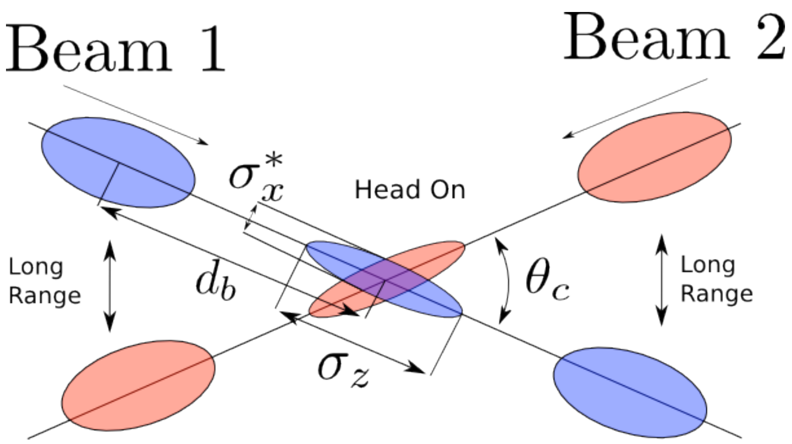
Working point → Qx and Qy.
LHC working point:
Q_x=64.28, Q_y=59.31

Choose region of (Qx,Qy) with enough free space from resonances

Resonances: nQx + mQy = p "n+m" → resonance order→



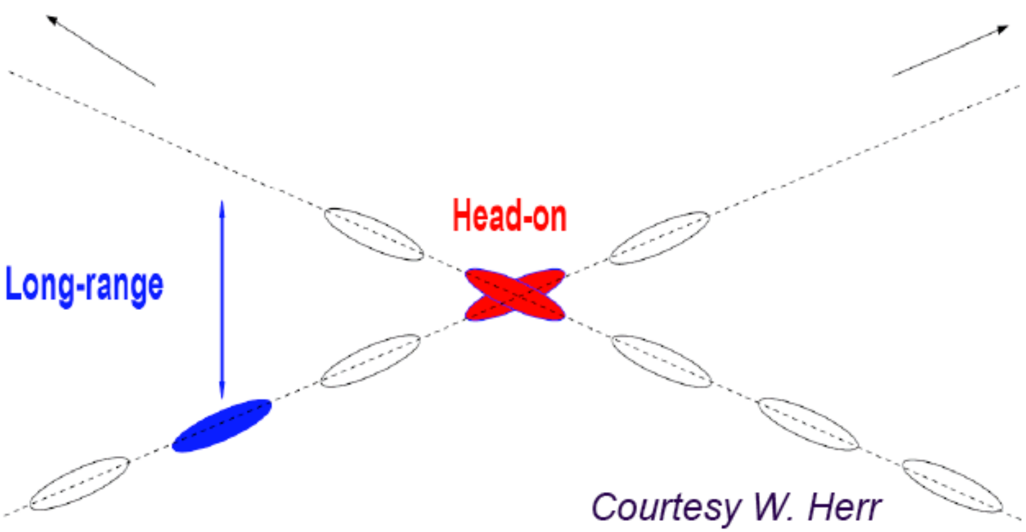
Beam-Beam interaction



The two beams travels one near the other at the IP

The electromagnetic field generated by one beam is felt by other ⇒ Beam-Beam

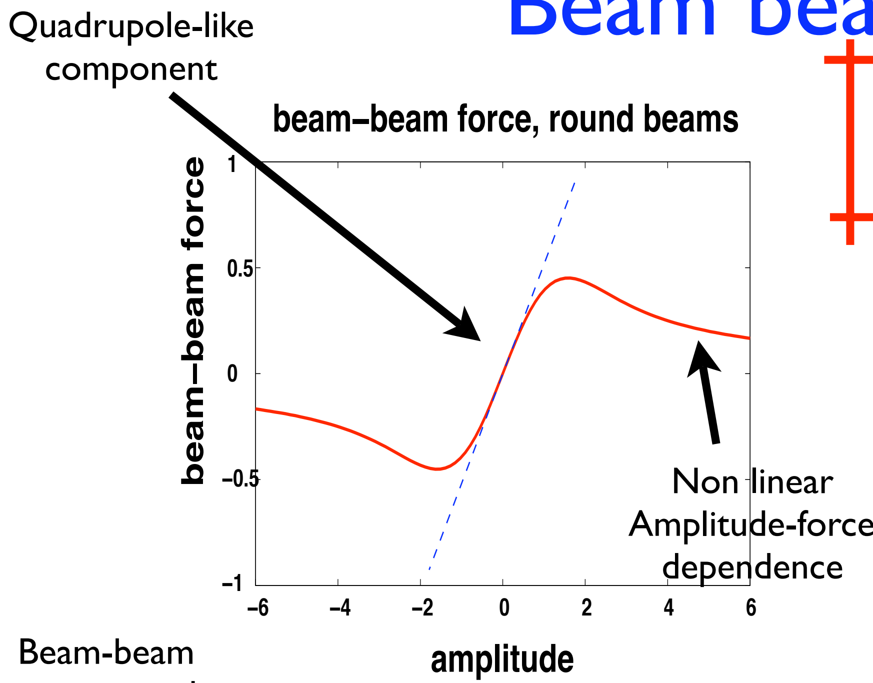
Three classes of beam-beam effects:
A)Long range
B) Packman bunches
C) Head-on



Packman bunches are the bunches of one beam that at the IP don't see a correspondant bunch of the other beam.

As a results, for them the tune, orbit and chromaticity will be different from the other bunches ....

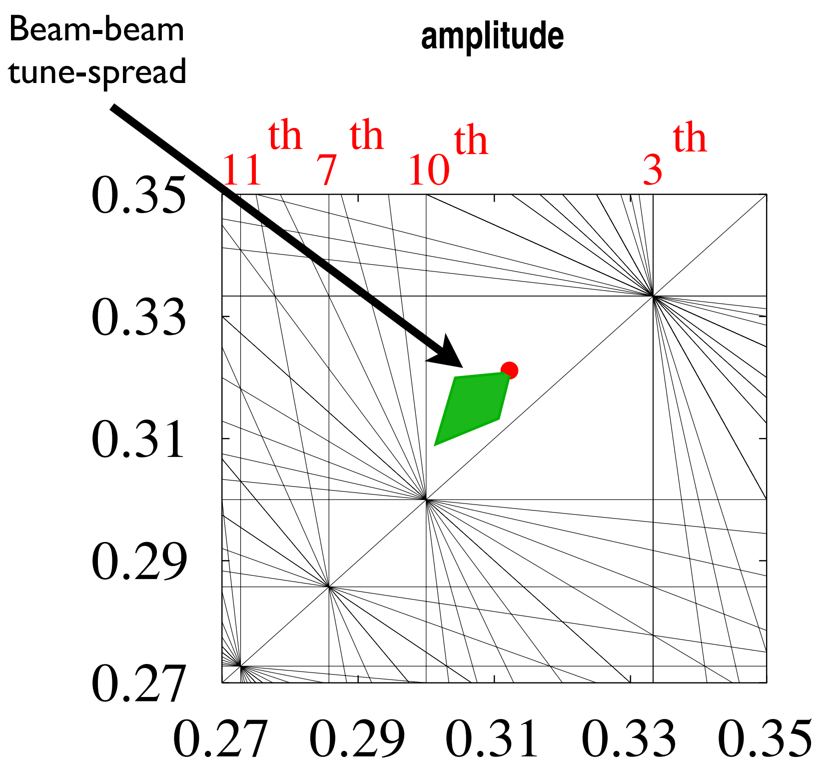
Beam beam tune spread

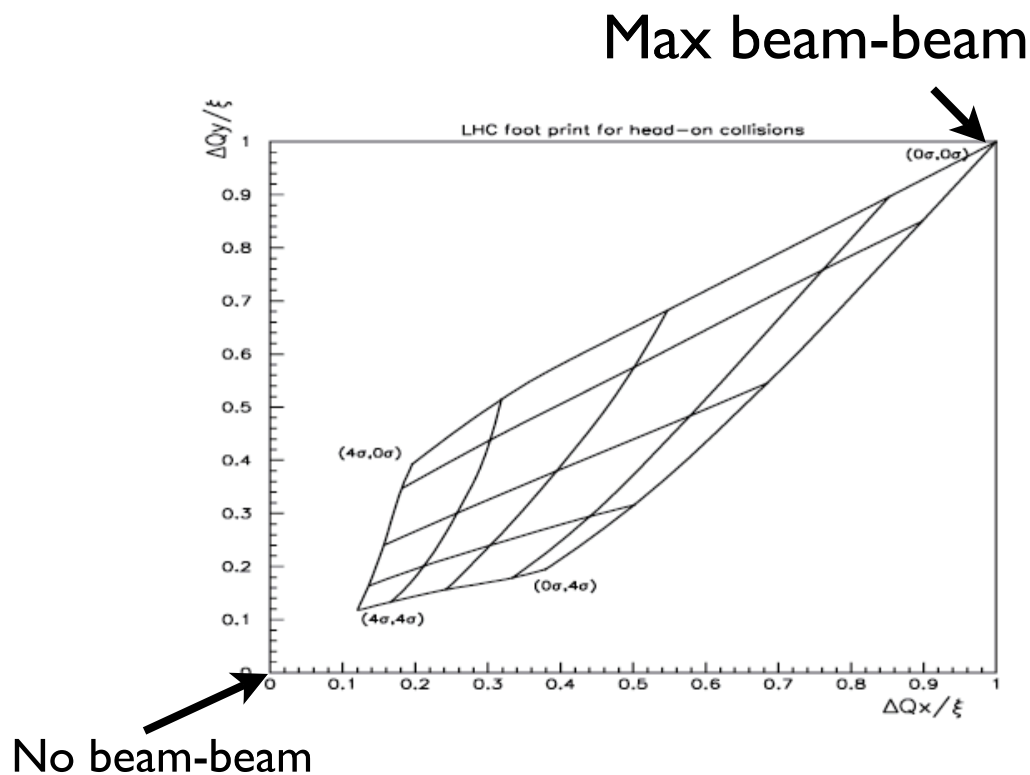


Max beam-beam tune shift ⇒ not more than 0.015 to avoid crossing resonances

$$\Delta Q = \frac{N_2 \cdot r_p}{4\pi \cdot \gamma \cdot \epsilon} = \xi_{beam-beam}$$

So N_2=intensity per bunch should be small and ε=emittance should be big, *exactly the opposite to have large Luminosity*. An optimum has to be chosen



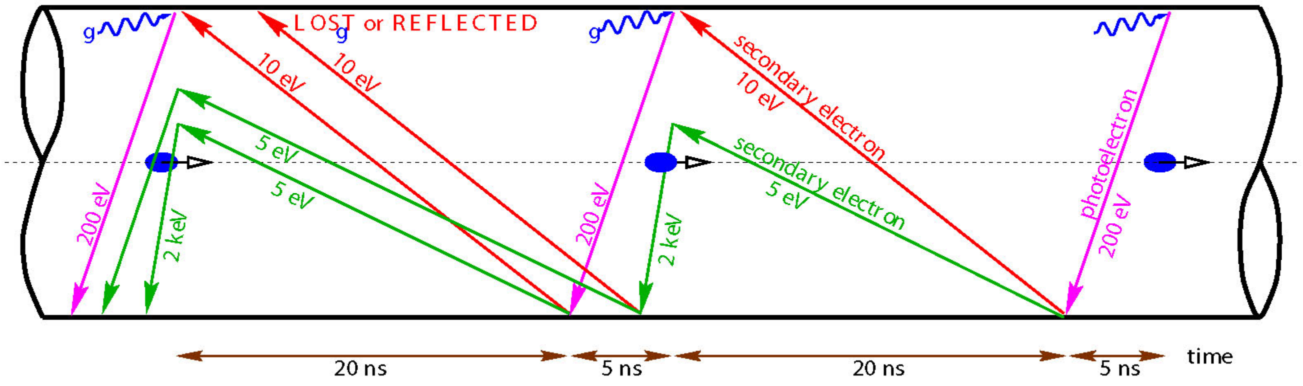


Electron clouds

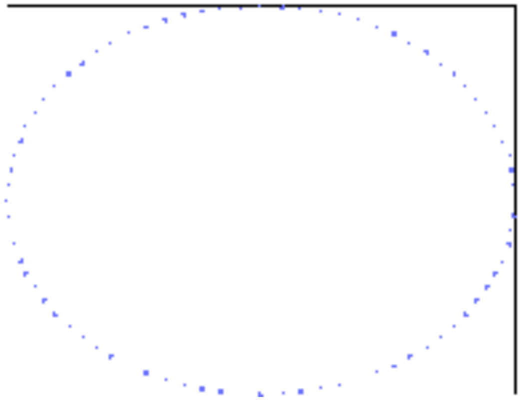
Electron cloud in the vacuum beam pipe can be created by "avalanche" process :

1. few primary e⁻ generated by as photoelectrons, from residual gas ionization, extract by Synchrotron radiation
2. p+ bunches accelerate e⁻ (this depends from the bunch separation, i.e. 25 nsec in the LHC)
3. e⁻ impact on the wall and extract secondary e⁻

and so on ... and the cloud can generate:
a) heating of the beam pipe ⇒ magnet heating b) beam instabilities



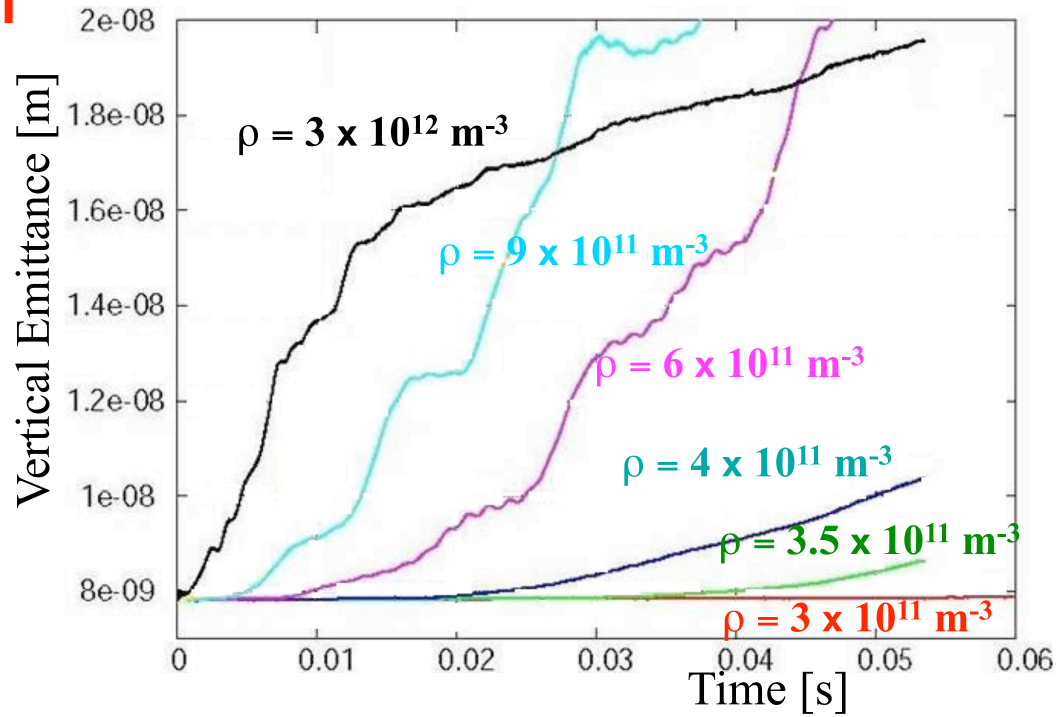
(Courtesy F.Ruggiero)



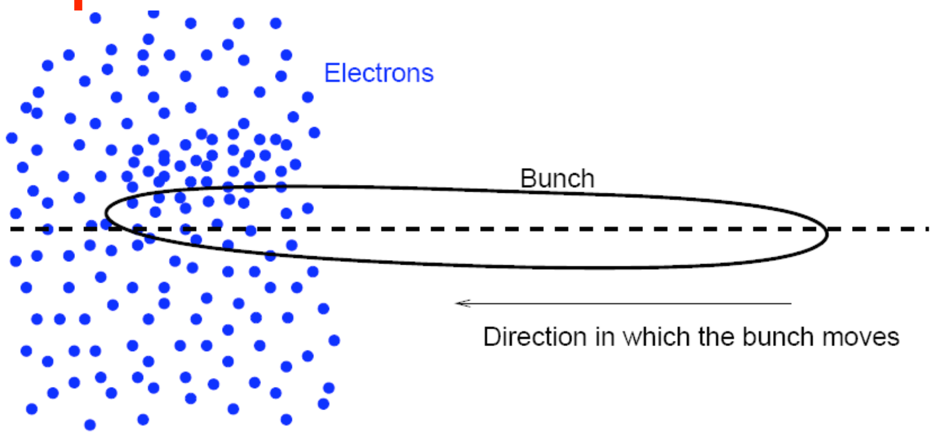
Animation from O. Brüning simulation
→ 10 subsequent bunch passages
Color describes the formation of the electron cloud

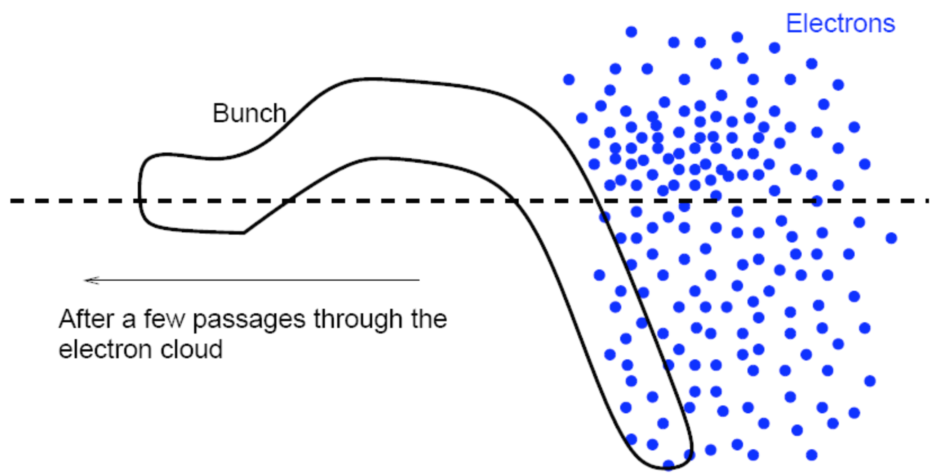
Electron clouds issues on beam

1. Bunch passage, electrons accumulated near beam centroid
2. If there is offset between head and tail:
   - → tail feels transverse electric field created by head
   - → tail become unstable
3. Particles mix longitudinally
   - → also head can become unstable (above threshold)



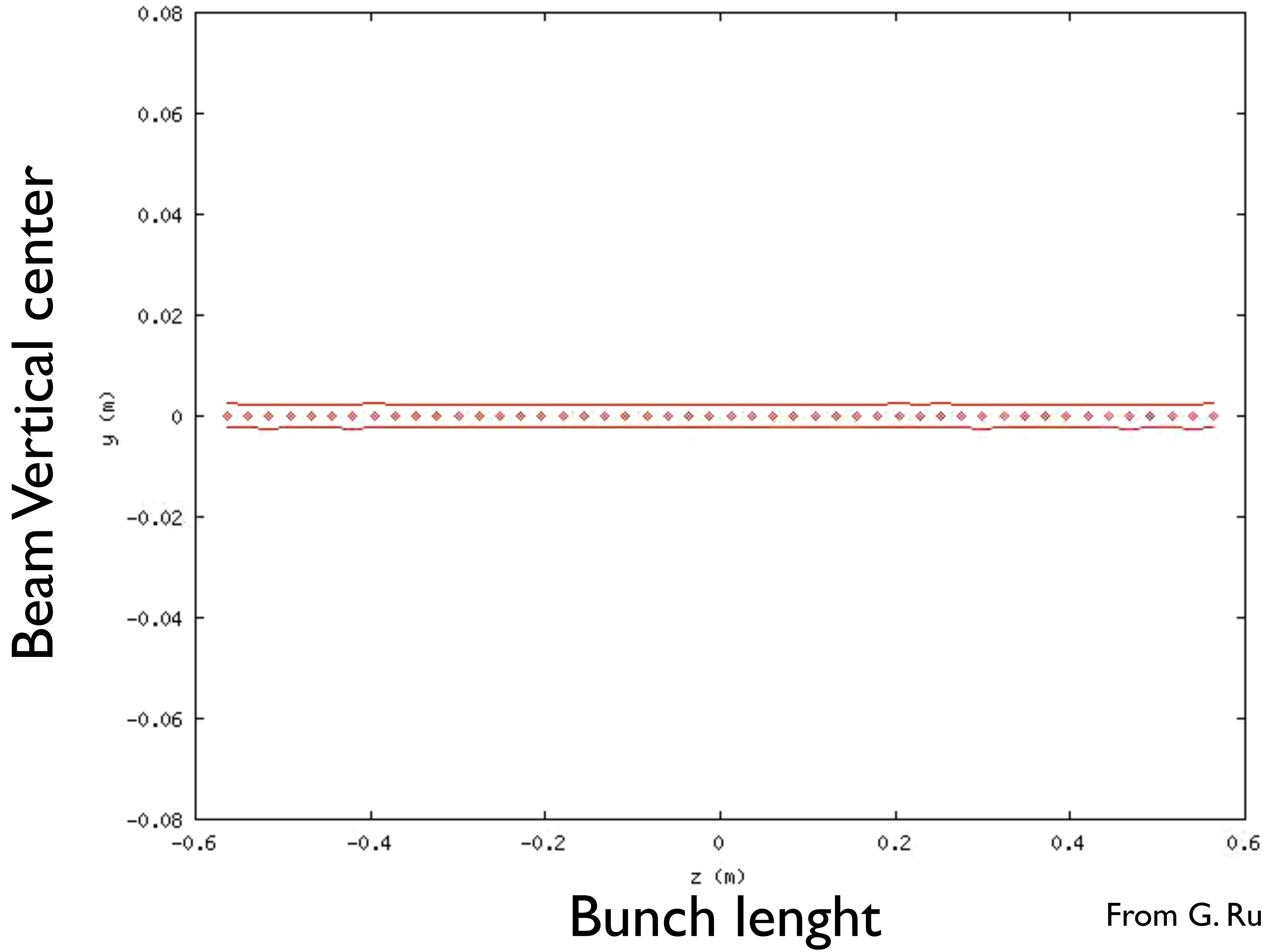
Vertical emittance vs. time, for different EC densities @ LHC injection





From E. Benedetto

Simulation of SPS experiment, 500 turn



From G. Rumolo

How to alleviate the effect ?

Three hardware fixes are used to suppress/alleviate electron-cloud build-up:

(a) A saw tooth chamber in the arcs (a series of 30-μm high steps spaced at a distance of 500 μm in the longitudinal direction) to reduce the photon reflectivity.
(b) Shielding the pumping holes inside the arc beam screen so as to prevent multipacting electrons from reaching the cold bore of the dipole magnet.
(c) Coating the warm regions by a special Non Evaporable Getter (NEG) material, TiZrV, with low secondary emission yield.

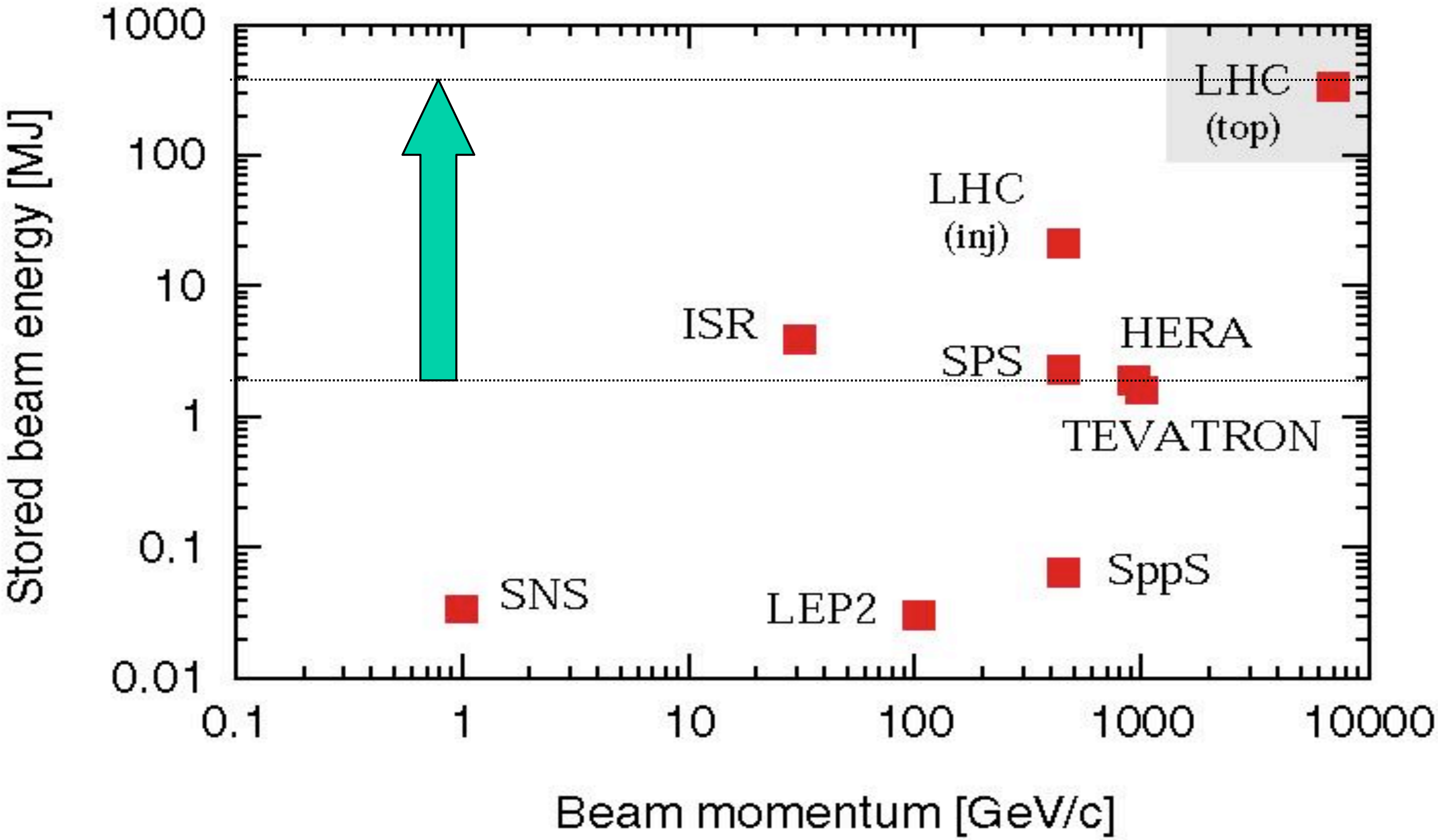
Three beam related fixes are used to suppress/alleviate electron-cloud build-up:

(a) Conditioning of the arc chamber surface by the cloud itself (beam scrubbing), which will ultimately provide a low secondary emission yield. This is done by circulating high intensity beam for long time, accepting losses and instabilities but cleaning the surfaces.

(b) Changing the chromaticity working point to use longitudinal motion to "diluite" the effect of the electron cloud.

(c) Changing the bunch spacing from 25 ns to 75 ns. This cause a Luminosity reduction ...

LHC: the issue of stored beam energy



Why do we have to protect the machine ?

Why do we have to protect the machine ?

Total stored beam energy at top energy (7 TeV), nominal beam, 334 MJ (or 120 kg TNT)
Nominal LHC parameters: $1.15\ 10^{11}$ protons per bunch
2808 bunches
0.5 A beam current

British aircraft carrier:
HMS Illustrious and Invincible weigh 20,000 tons all-up and fighting which is 2×10^7 kg.
Or the USS Harry S. Truman (Nimitz-class) - 88,000 tons.

Energy of nominal LHC beam = 334 MJ or 3.34×10^8 J

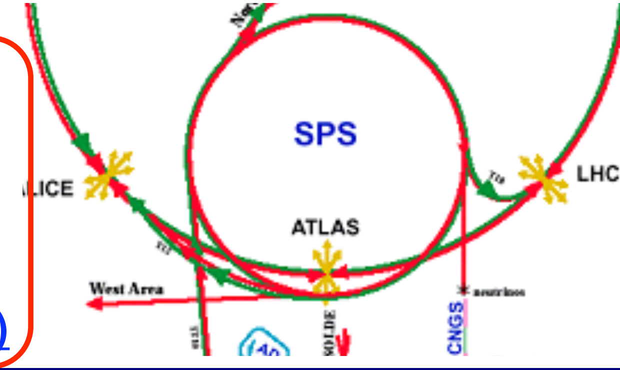
which corresponds to the aircraft carrier navigating
at v=5.8 m/s or 11.2 knots (or around 5.3 knots if you're an American aircraft carrier)

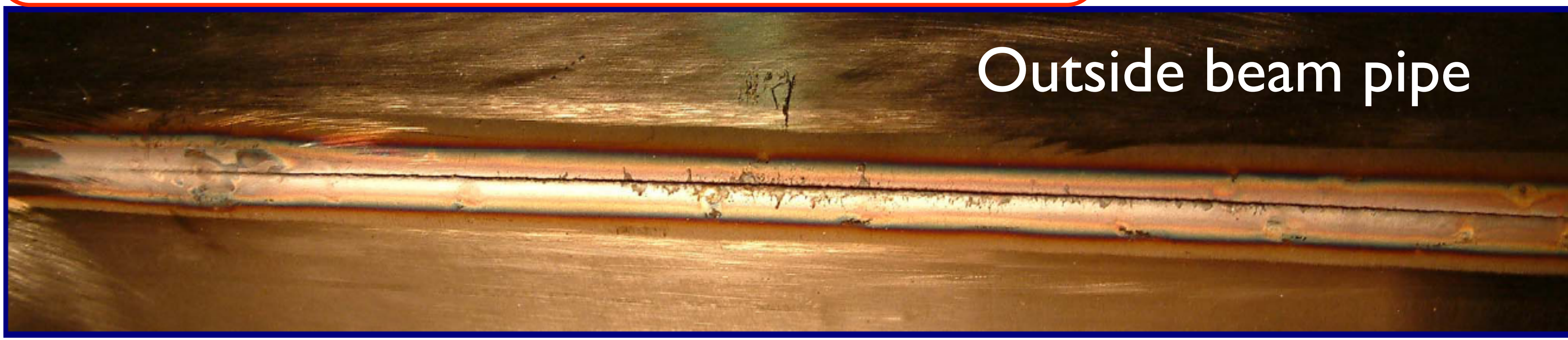
So, what if something goes wrong?

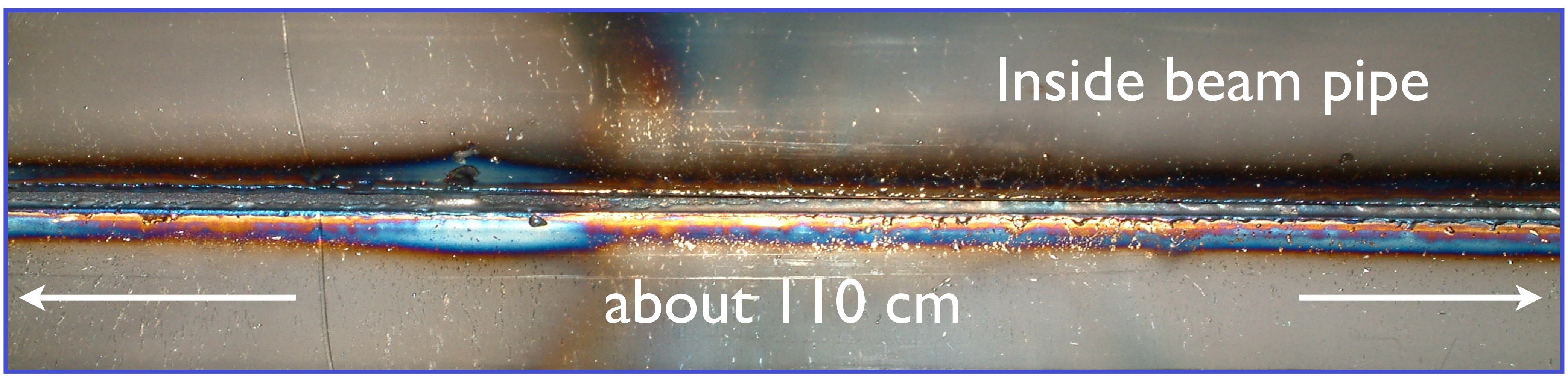
What is needed to intercept particles at large transverse amplitude or with the wrong energy to avoid quenching a magnet?

3 years ago something went wrong during a test ...

LHC extraction from the SPS
450 GeV/c, 288 bunches
Transverse beam size 0.7 mm (1 σ)
1.15×10^{11} p+ per bunch, for total intensity of 3.3×10^{13} p+
Total beam energy is 2.4 MJ, lost in extraction test (LHC 334 MJ)





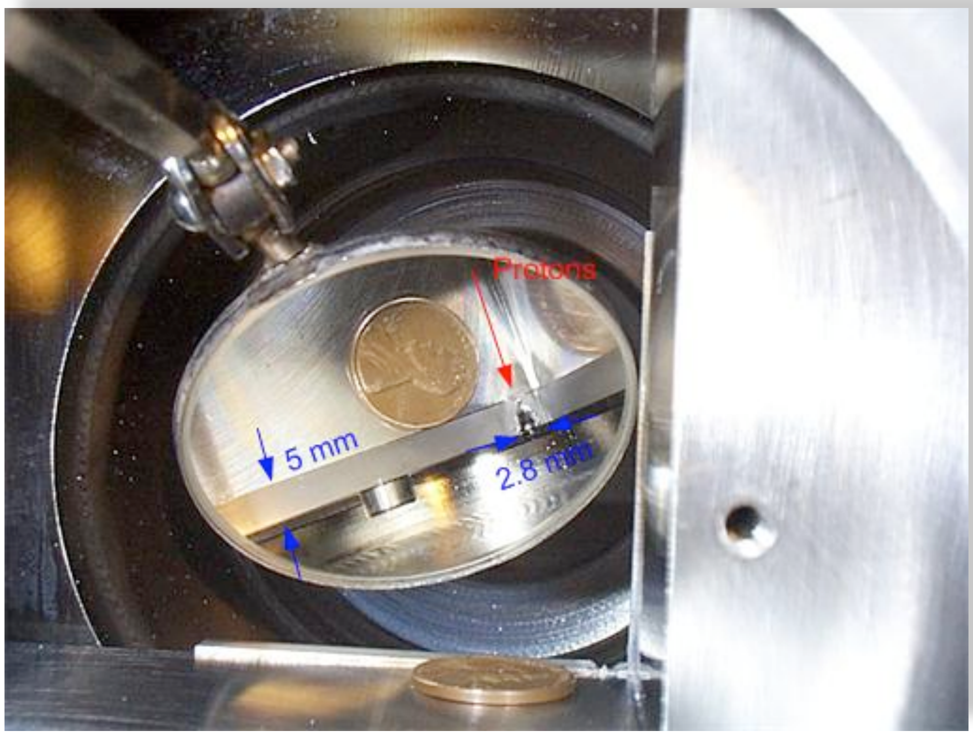


B.Goddard CERN AB/BT

Tevatron accident in 2003 (courtesy of N. Mokhov)

Accident caused by uncontrolled movement of beam detectors
(Roman Pots) which caused a secondary particle shower
magnet quench → no beam dump → damage on approximatively 550 turns

Tungsten collimator. Tmelting = 3400 °C



1.5 m long stainless steel collimator

Experiment simulating beam-losses

Controlled SPS experiment

$8*10^{12}$ protons ⇒ 0.1% full LHC power

Clear damage

Beam size σx/y = 1.1 mm/0.6 mm

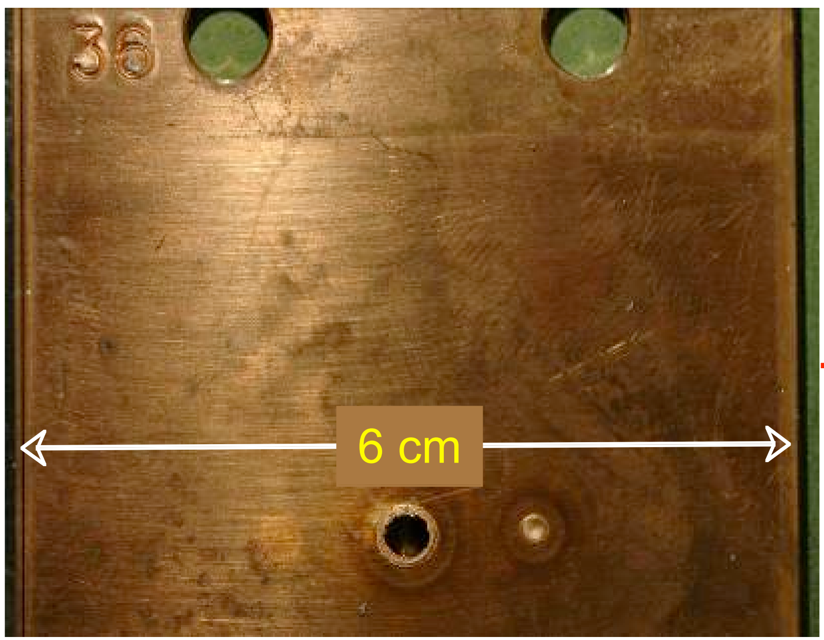
$2*10^{12}$ protons ⇒ below damage limit

0.1 % of the full LHC beams

Aim of the experiment:

1. test on different material the possible damage cause by beam-loss

2. test the codes used for predict possible damages in the real machine



From V. Kain

Collimation system for machine protection

Two sections in LHC dedicated to beam cleaning:

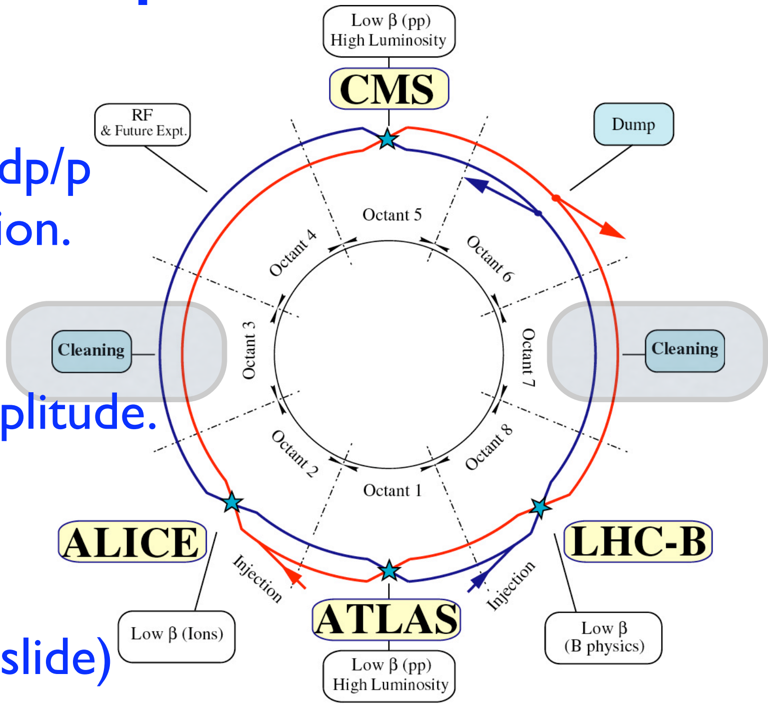
IR3 momentum cleaning → remove particles with too large dp/p (> ±10^{-3}) thanks to large dispersion.

$$\Delta x = D\frac{\Delta p}{p}$$

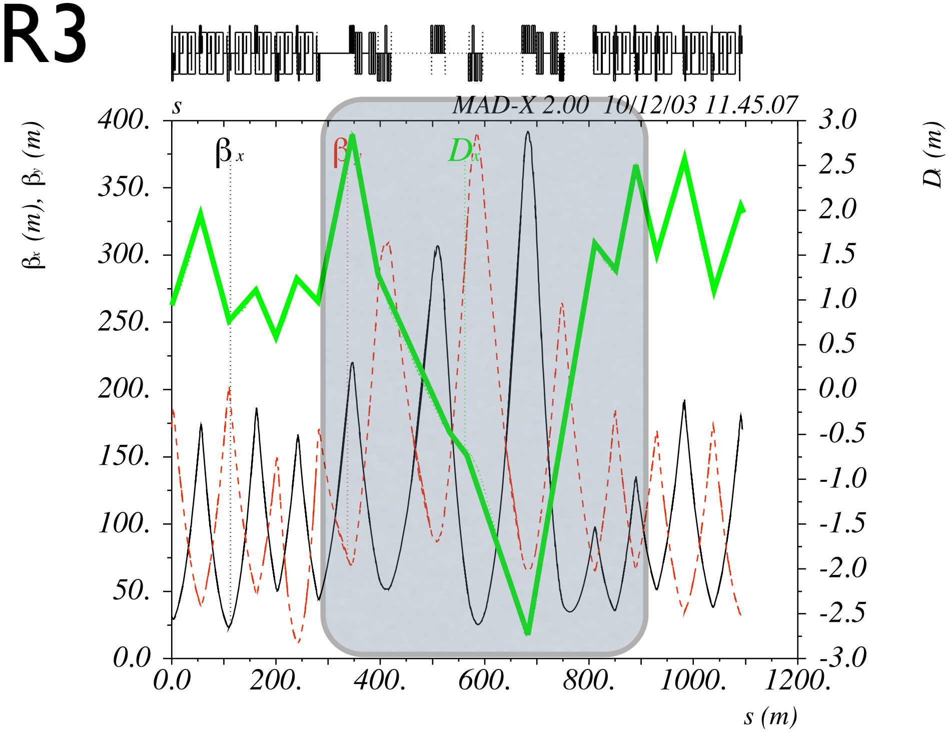
IR7 betatron cleaning → remove particles at too large amplitude. Dispersion as small as possible.

$$x_{MAX} = \sqrt{\epsilon\beta}$$

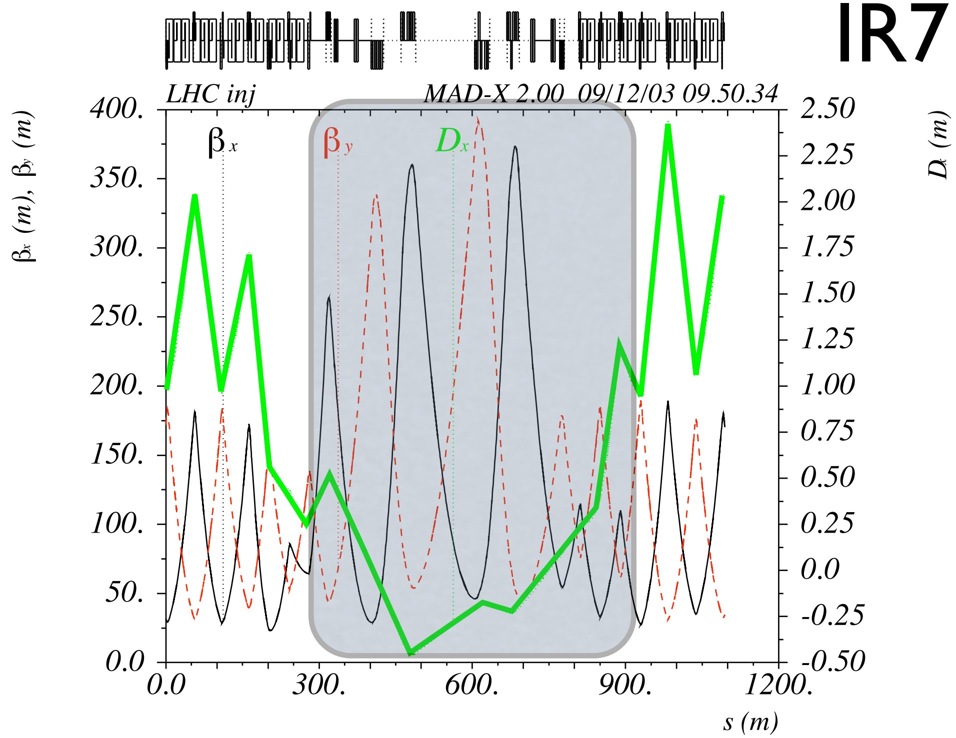
Done by intercepting particle with 2 stage collimation (next slide)



IR3

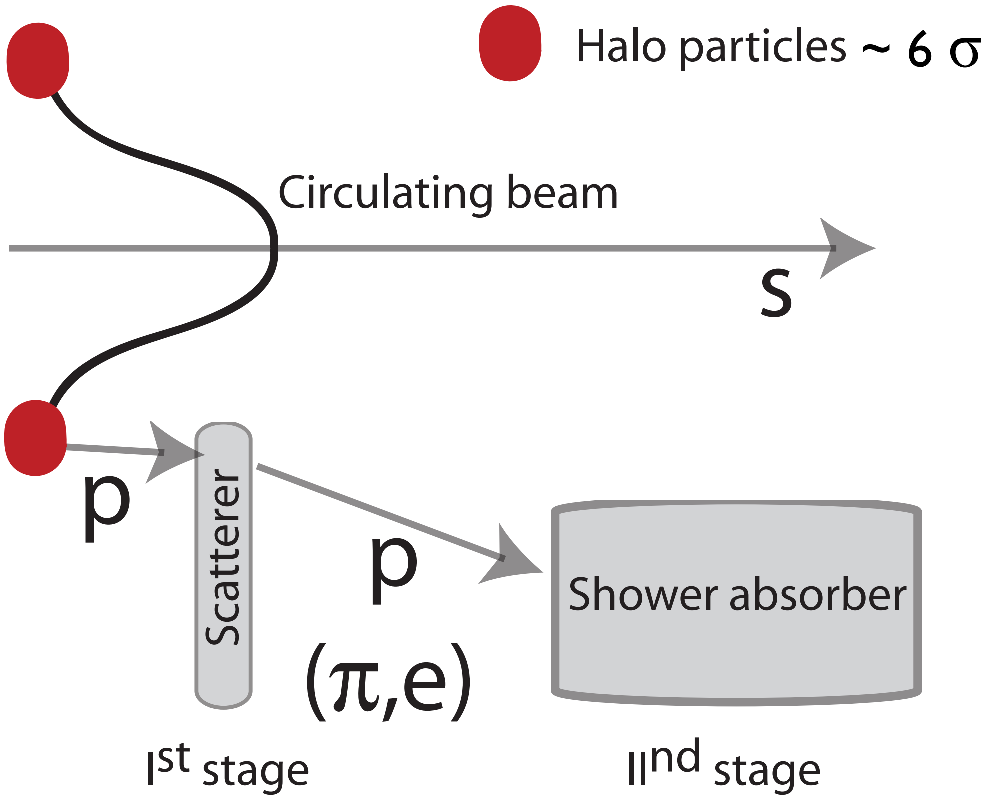


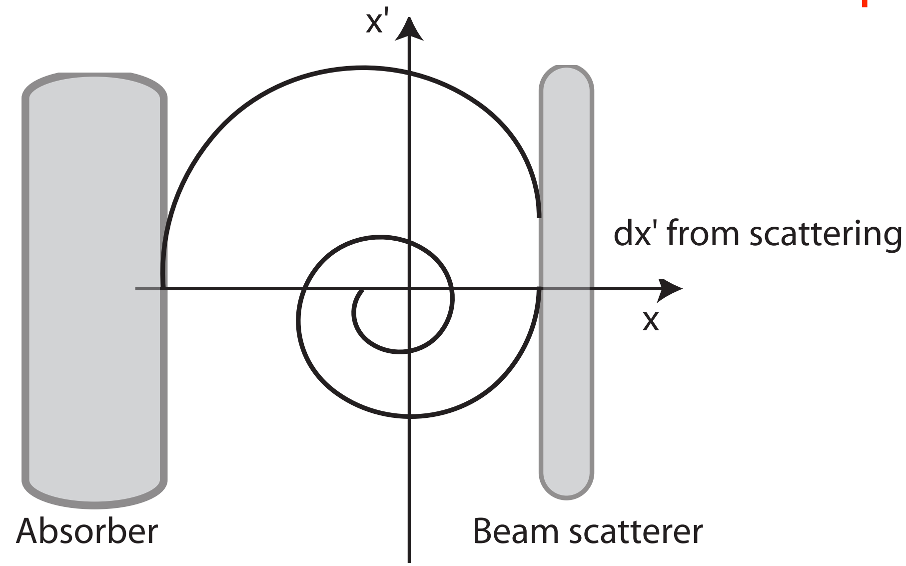
IR7

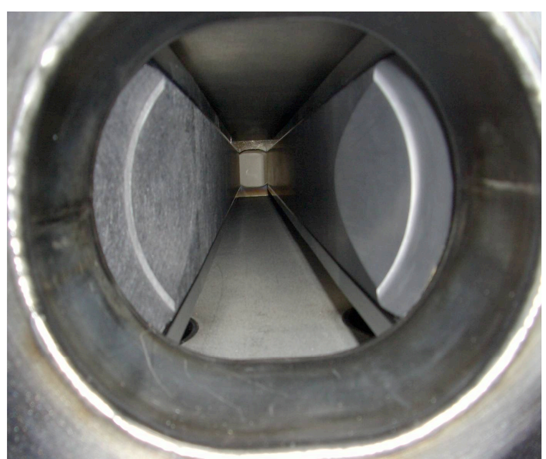


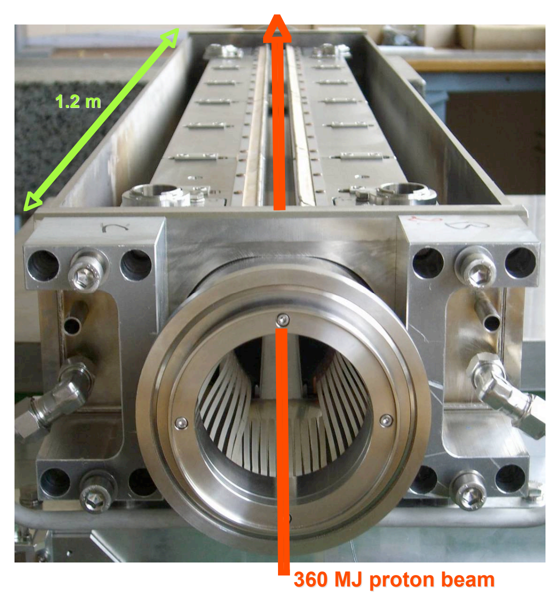
2 stage collimation

A) Low Z material scatters halo particles
B) High Z and low Z catch the primary or secondaries
C) In total, 95 % of the energy is spread over 250 m, with a very low energy density, and not in a cold region.









Movable collimators, they to be robust

Materials chosen:
Metals where possible
or C-C fibers

Robustness required,
listen to 10^{13} p on a
C-C Jaw

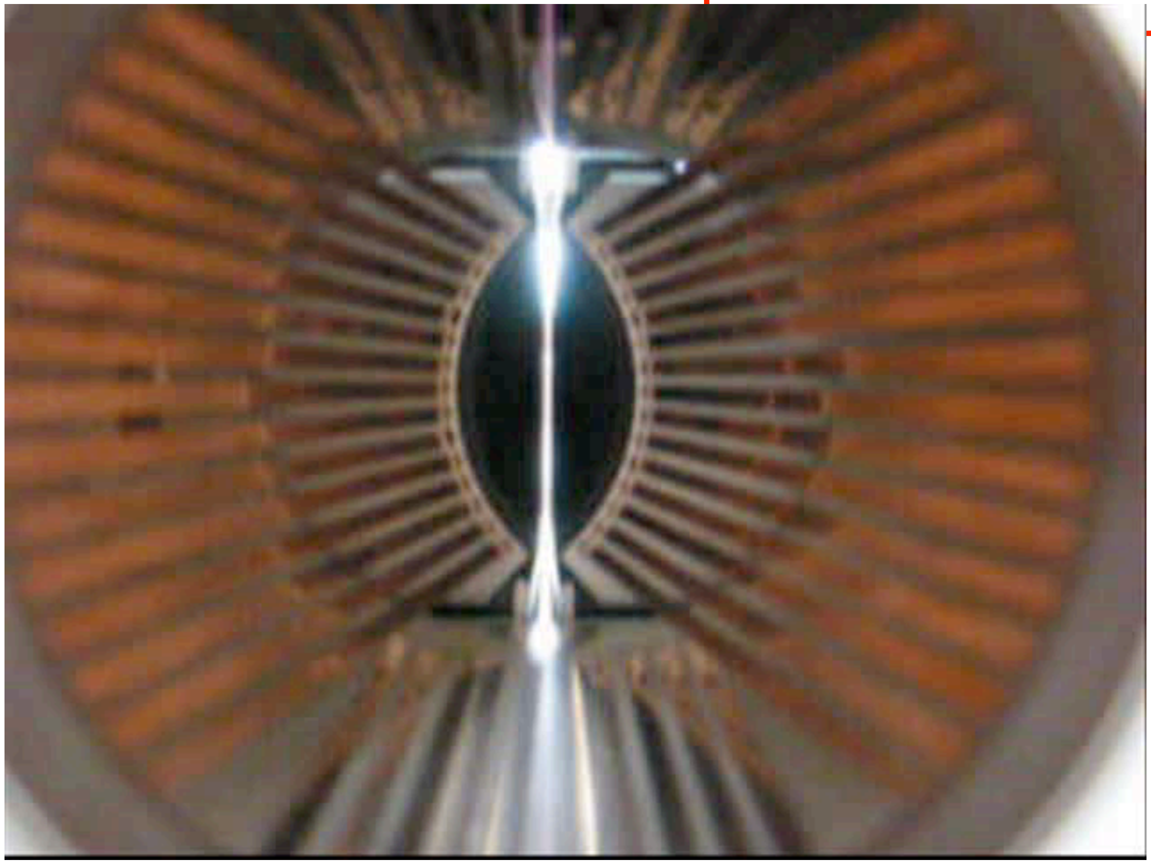
SPS experiment:

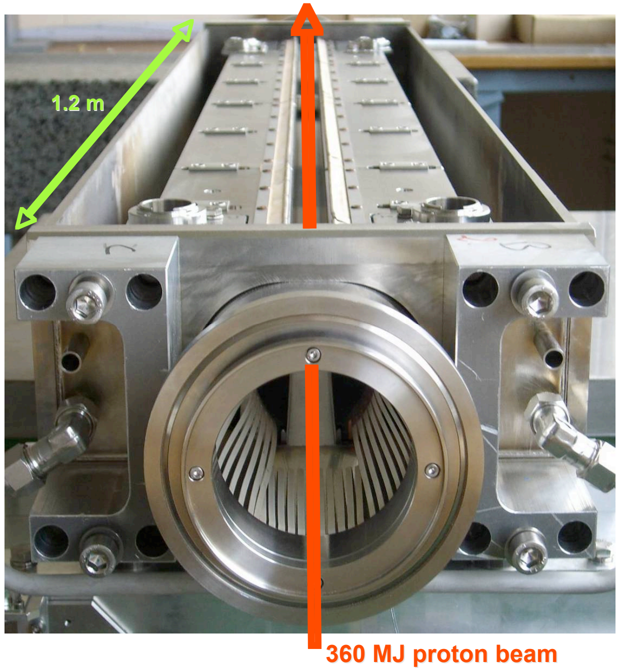
a) 1.5e13 protons, 450 GeV, 0.7*1.2 mm^2 (rms) on CC jaw

b) 3e13 protons , 450 GeV, 0.7*1.2 mm^2 (rms) on CC jaw ⇒ full design CASE

equivalent to about 1/2 kg of TNT

from S. Redaelli





Movable collimators, they to be robust

Materials chosen:
Metals where possible
or C-C fibers

Robustness required,
listen to 10^{13} p on a
C-C Jaw

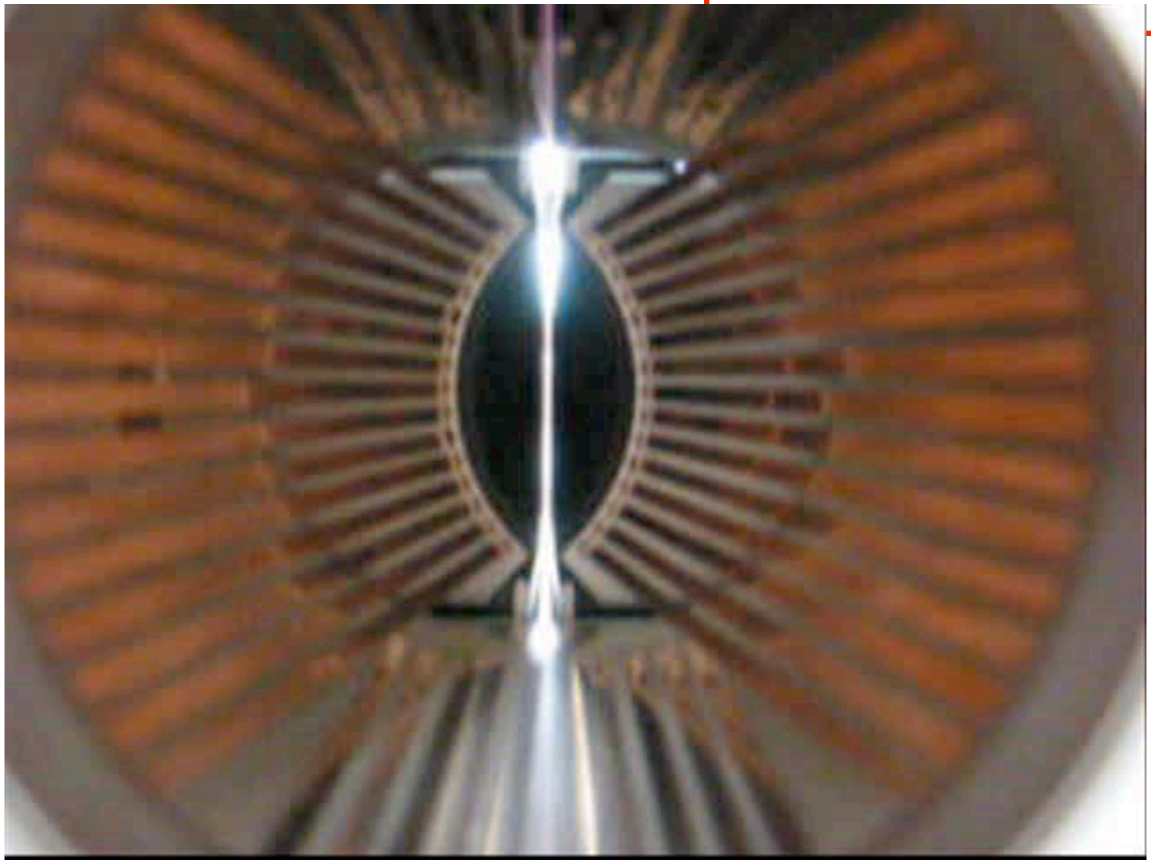
SPS experiment:

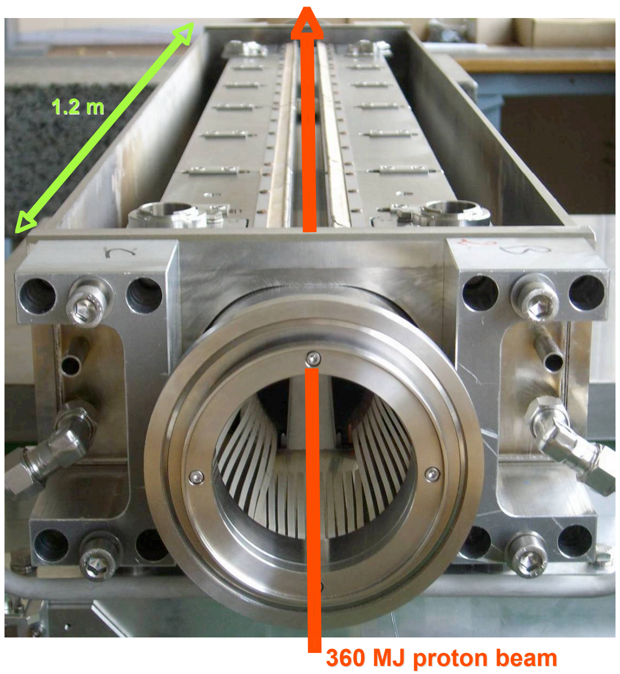
a) 1.5e13 protons, 450 GeV, 0.7*1.2 mm^2 (rms) on CC jaw

b) 3e13 protons , 450 GeV, 0.7*1.2 mm^2 (rms) on CC jaw ⇒ full design CASE

equivalent to about 1/2 kg of TNT

from S. Redaelli





Movable collimators, they to be robust

Materials chosen:
Metals where possible
or C-C fibers

Robustness required,
listen to 10^{13} p on a
C-C Jaw

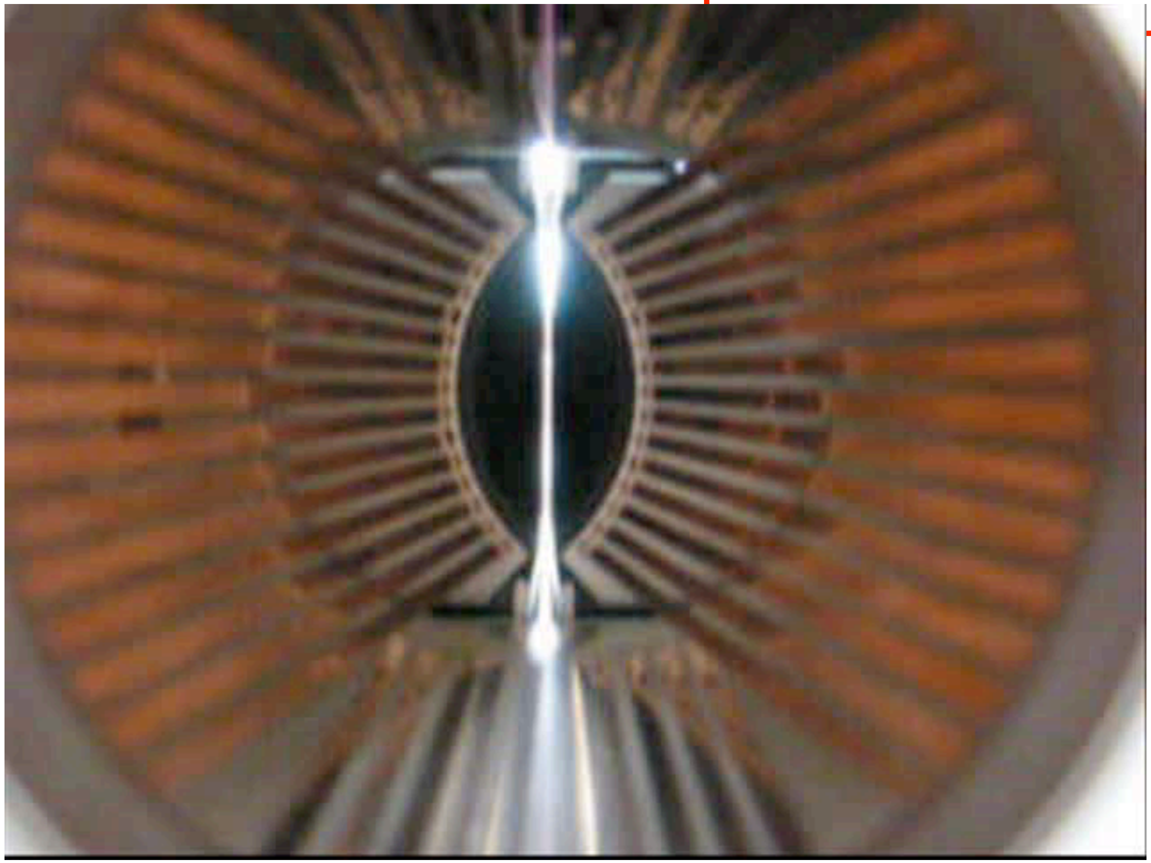
SPS experiment:

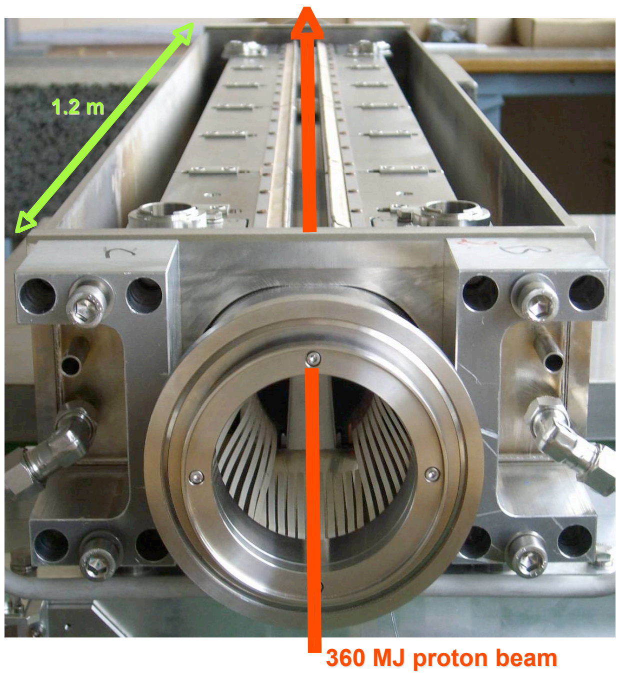
a) 1.5e13 protons, 450 GeV, 0.7*1.2 mm^2 (rms) on CC jaw

b) 3e13 protons , 450 GeV, 0.7*1.2 mm^2 (rms) on CC jaw ⇒ full design CASE

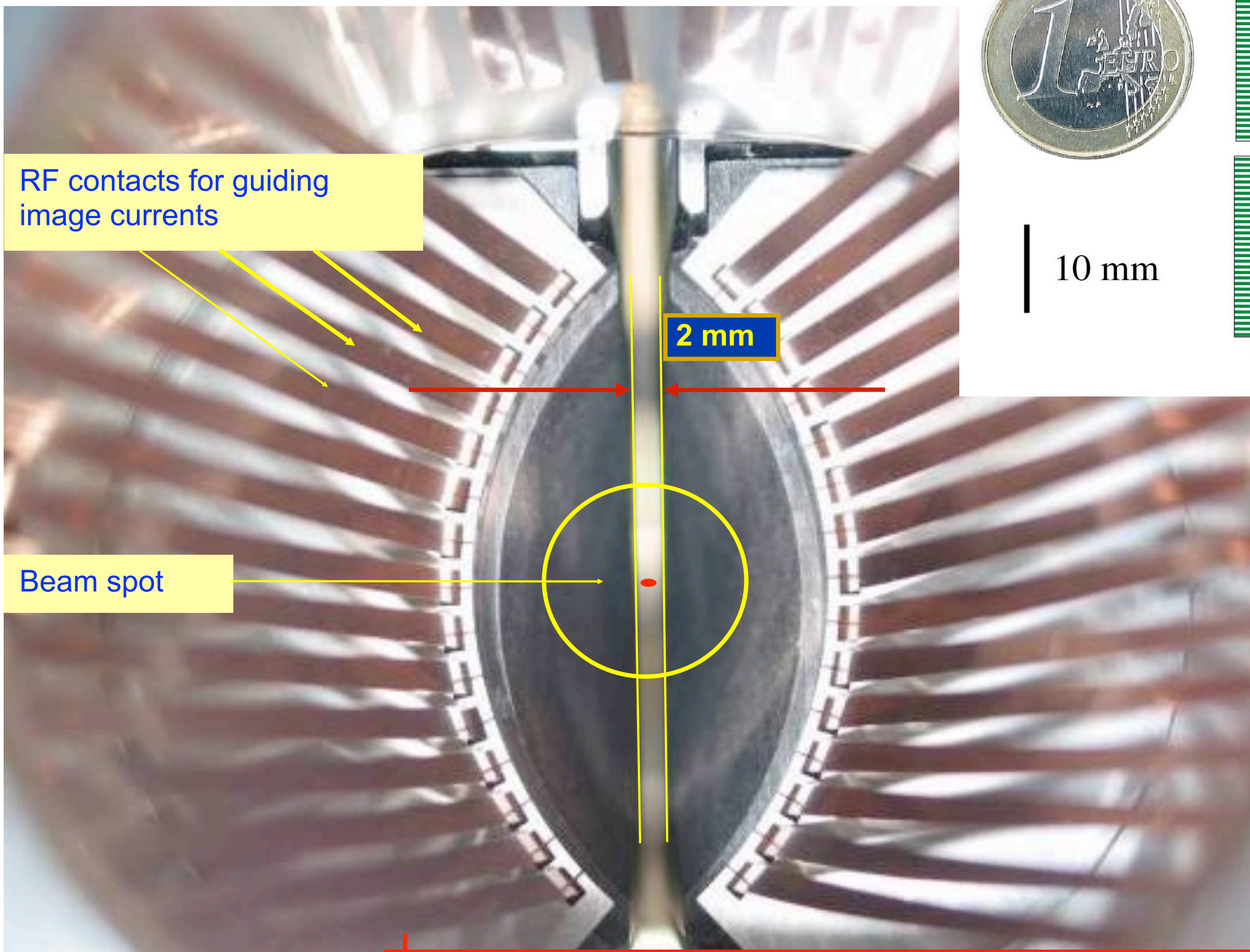
equivalent to about 1/2 kg of TNT

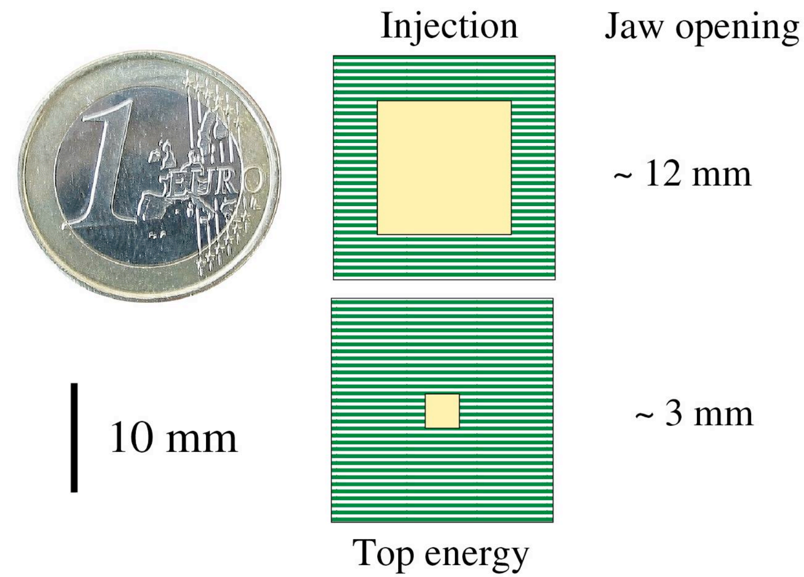
from S. Redaelli





At 7 TeV, beam really small, 3σ diam. ~ 1. 2 mm





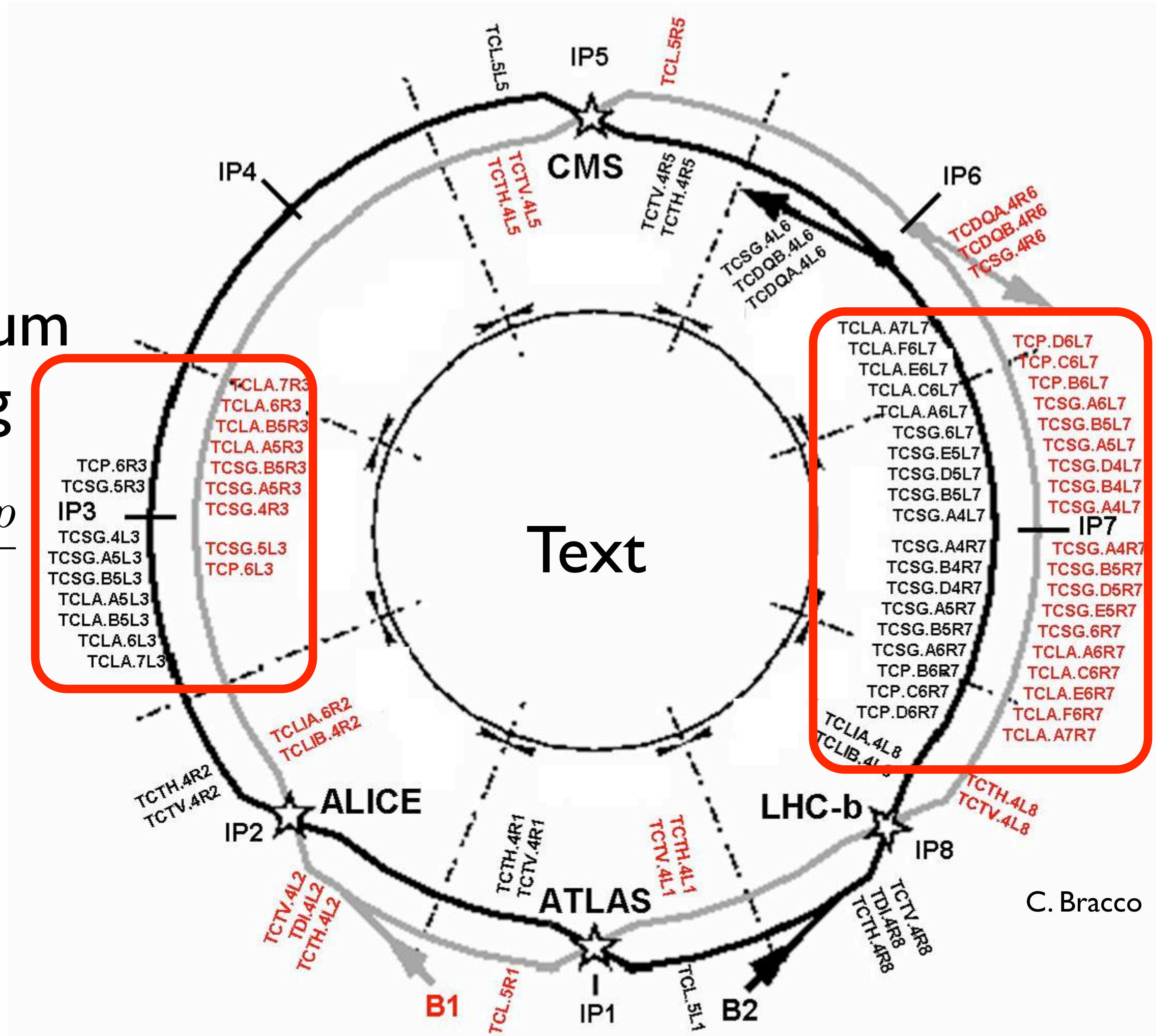
Precision required for collimator movements about 25 μm

Collimation inventory for Phase I - medium luminosity

Momentum cleaning

$$\Delta x = D\frac{\Delta p}{p}$$

$$\Delta x = D\frac{\Delta p}{p}$$



C. Bracco

Betatron cleaning

$$x_{max} = \sqrt{\varepsilon\beta}$$

$$x_{MAX} = \sqrt{\epsilon\beta}$$

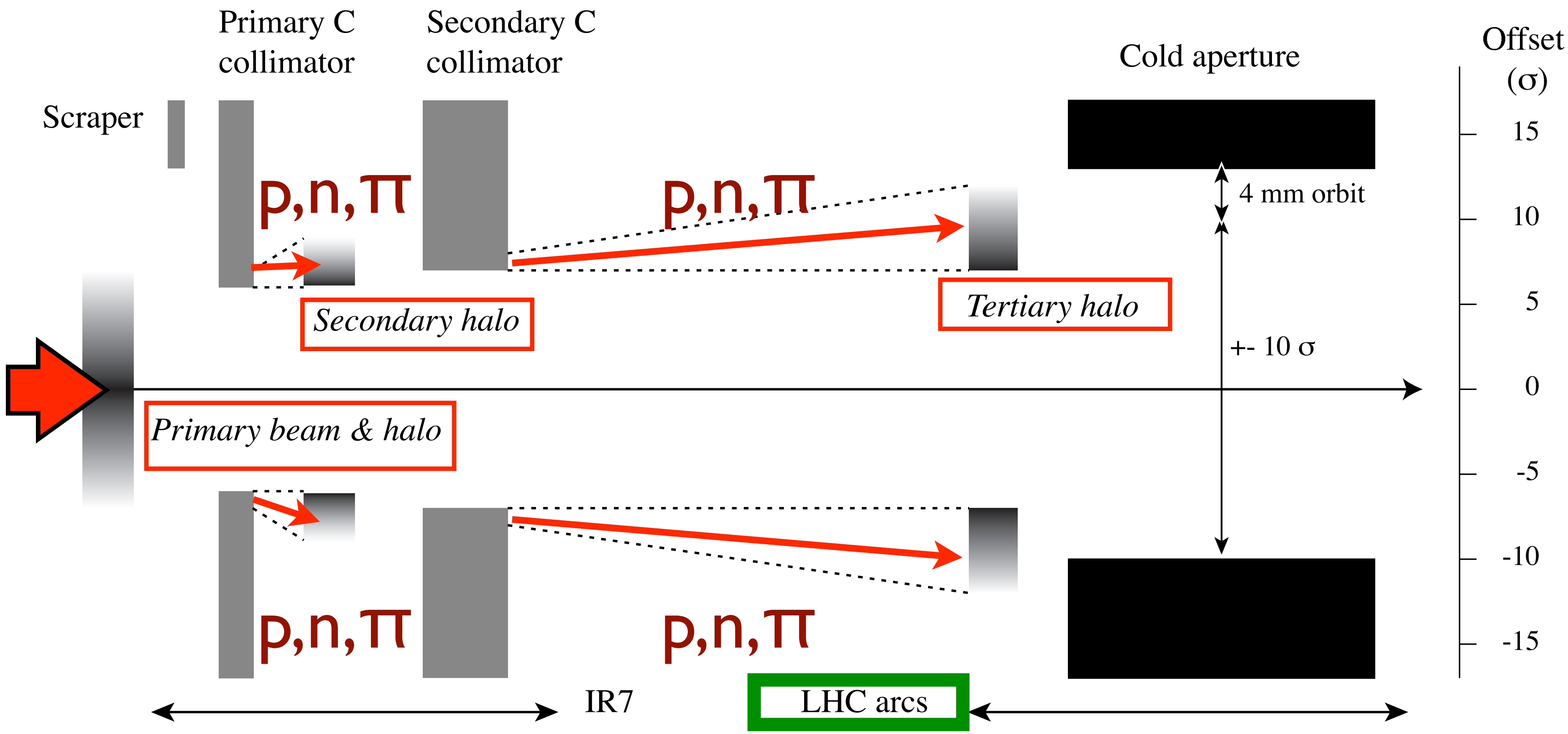
About 88 collimators with the aim to be always the first aperture restriction encountered by the beam, with a 99.998 cleaning efficiency:

a) during a slow beam drift towards large amplitudes, some 10 turns

b) in case of a fast failure, like a misfire of the extraction/injection fast magnets

Collimator in the tunnel during installation

2 - 3 stage collimation scheme at injection

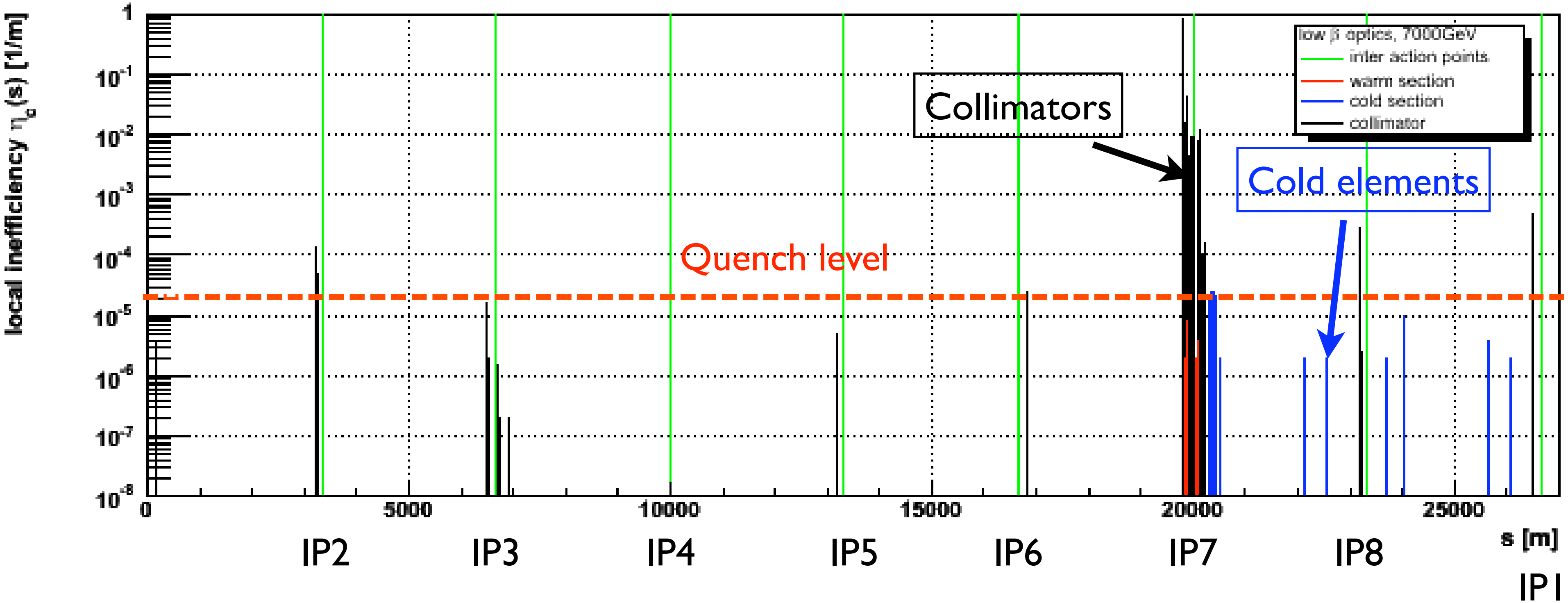


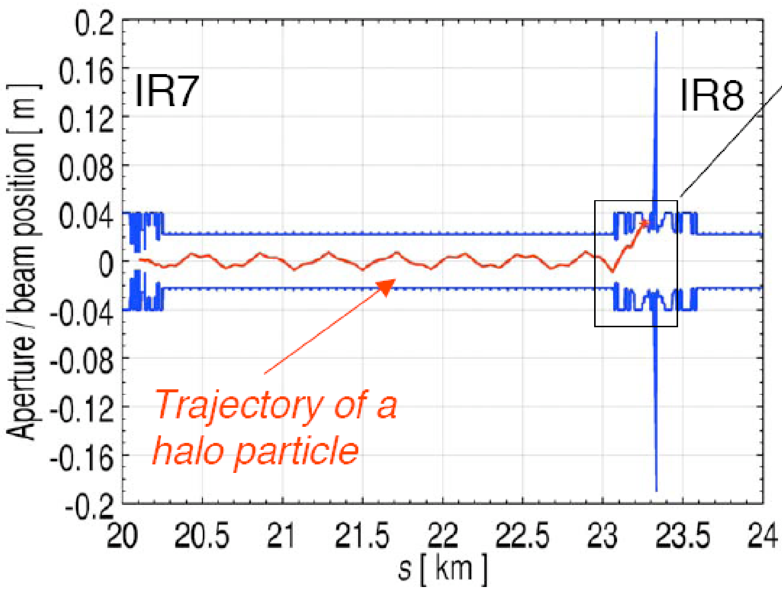
Aim @ **injection**:
protect the **LHC arcs** from too high energy deposition ⇒ QUENCH

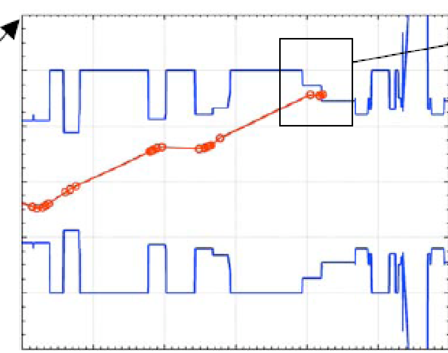
Two stage collimation system intercepts the secondaries produced in the collimation section, or by other losses, to reach the ARC with a too large energy density.
Beam is large in the ARC due to the low energy plus about 4 mm orbit oscillation/uncertainty

Loss-map around the ring

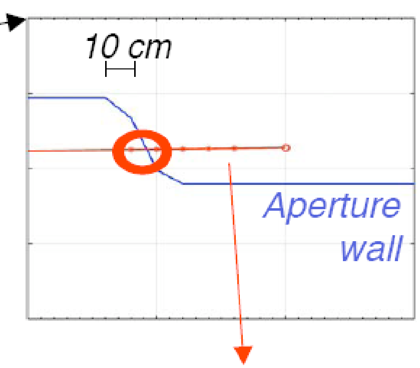
Collimation inefficiency at collision vs ring position and magnet type







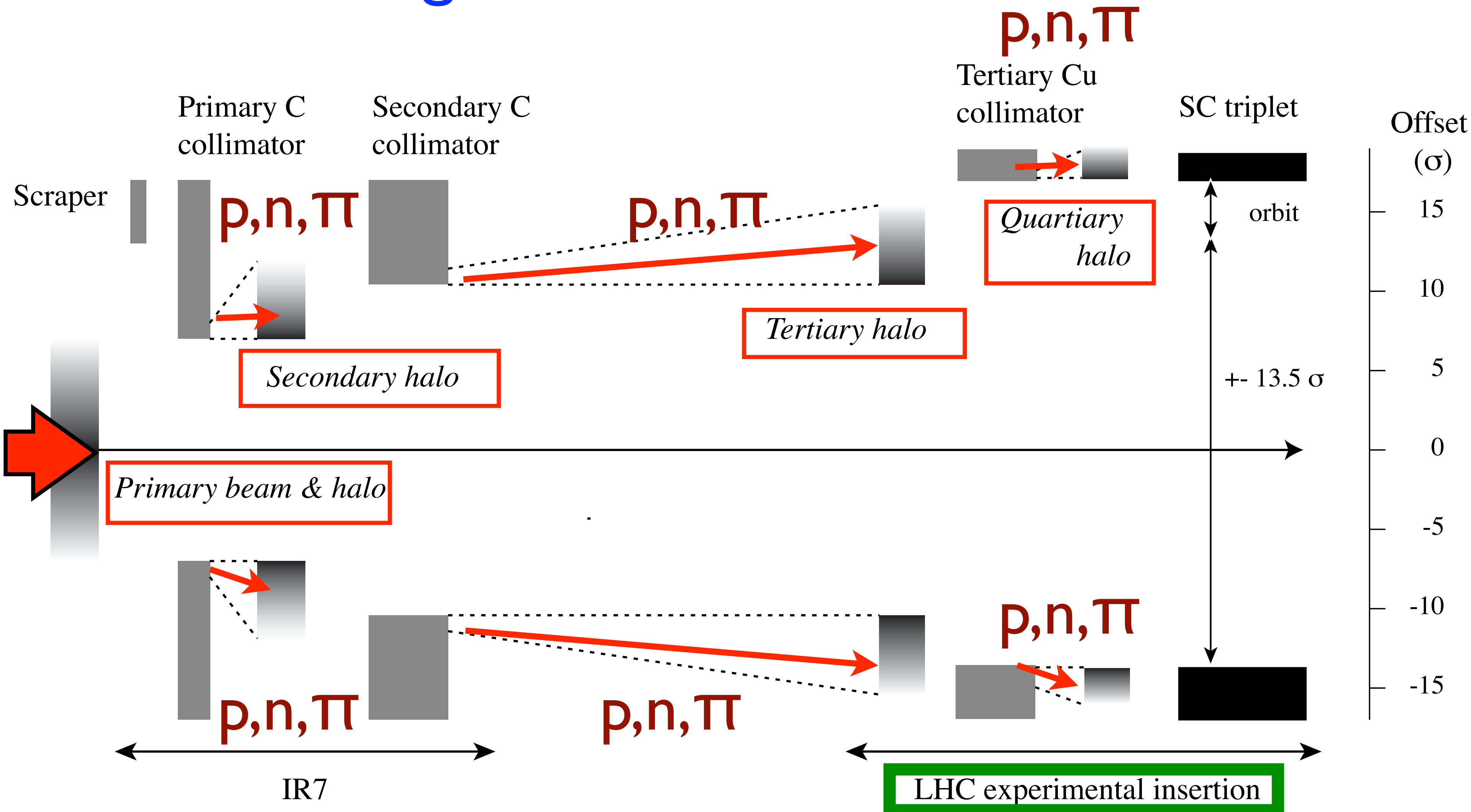
Magnets locations (*thin lenses*): ***Δs* ≤ 100m**



Interpolation: ***Δs*=10 cm**
(**270'000** points!)

Collimation Team

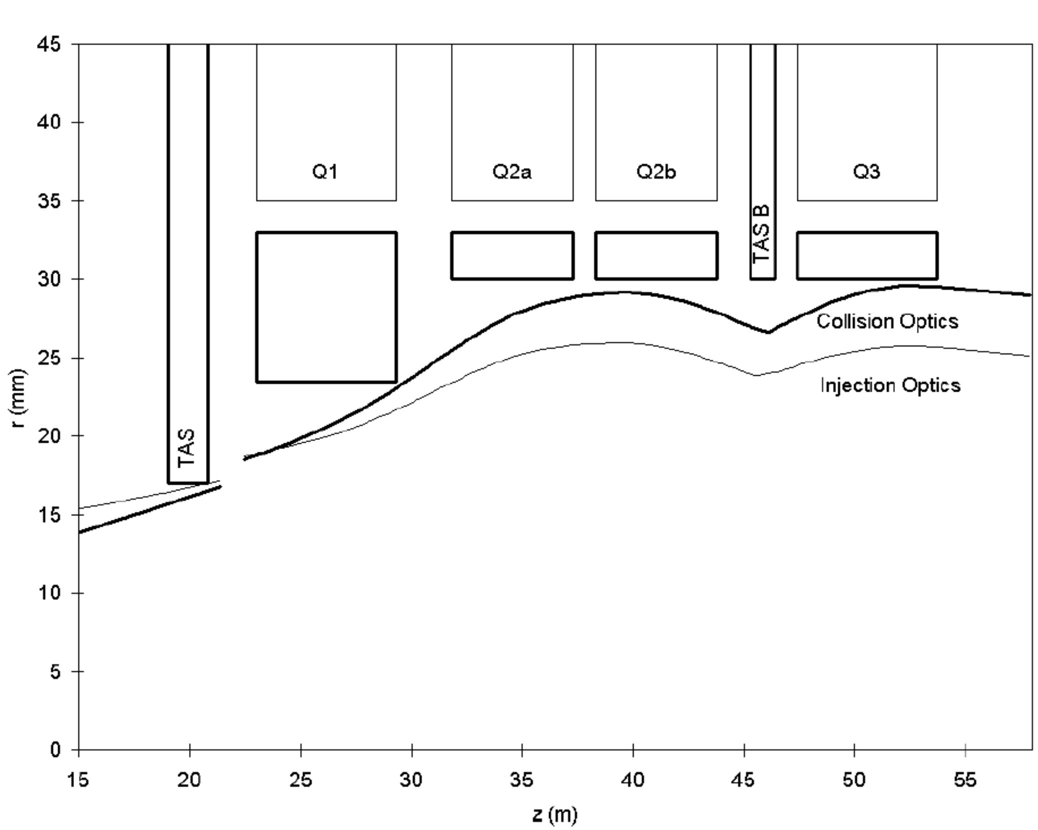
2 - 3 stage collimation scheme at collision

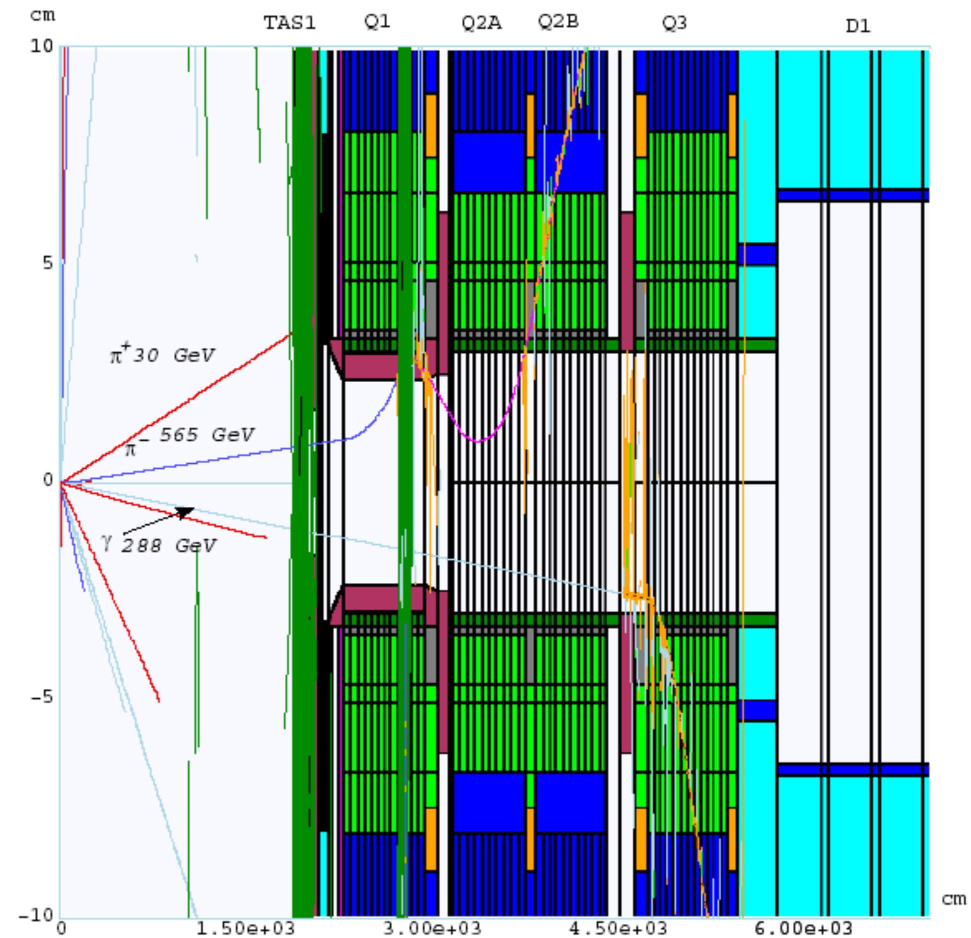


Aim @ ***collision***:
 protect the **LHC insertions** from too high energy deposition ⇒ QUENCH

Two stage collimation system leaves to limits the secondaries produced in the collimation section, or by other losses, to reach the Superconducting triplets for the final focusing.

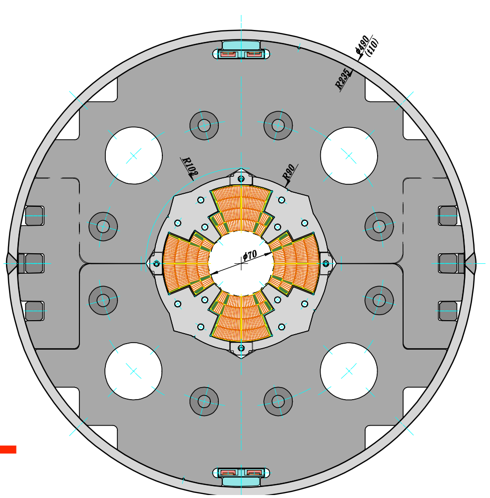
IP optics injection ⇒ collision, protecting the IPs

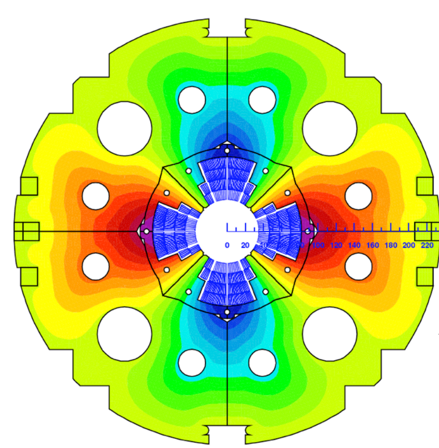


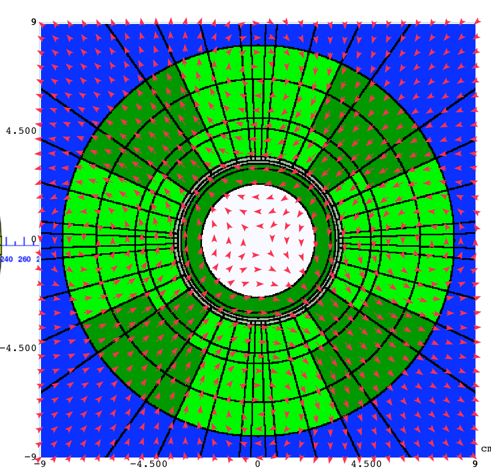


Typical study case:

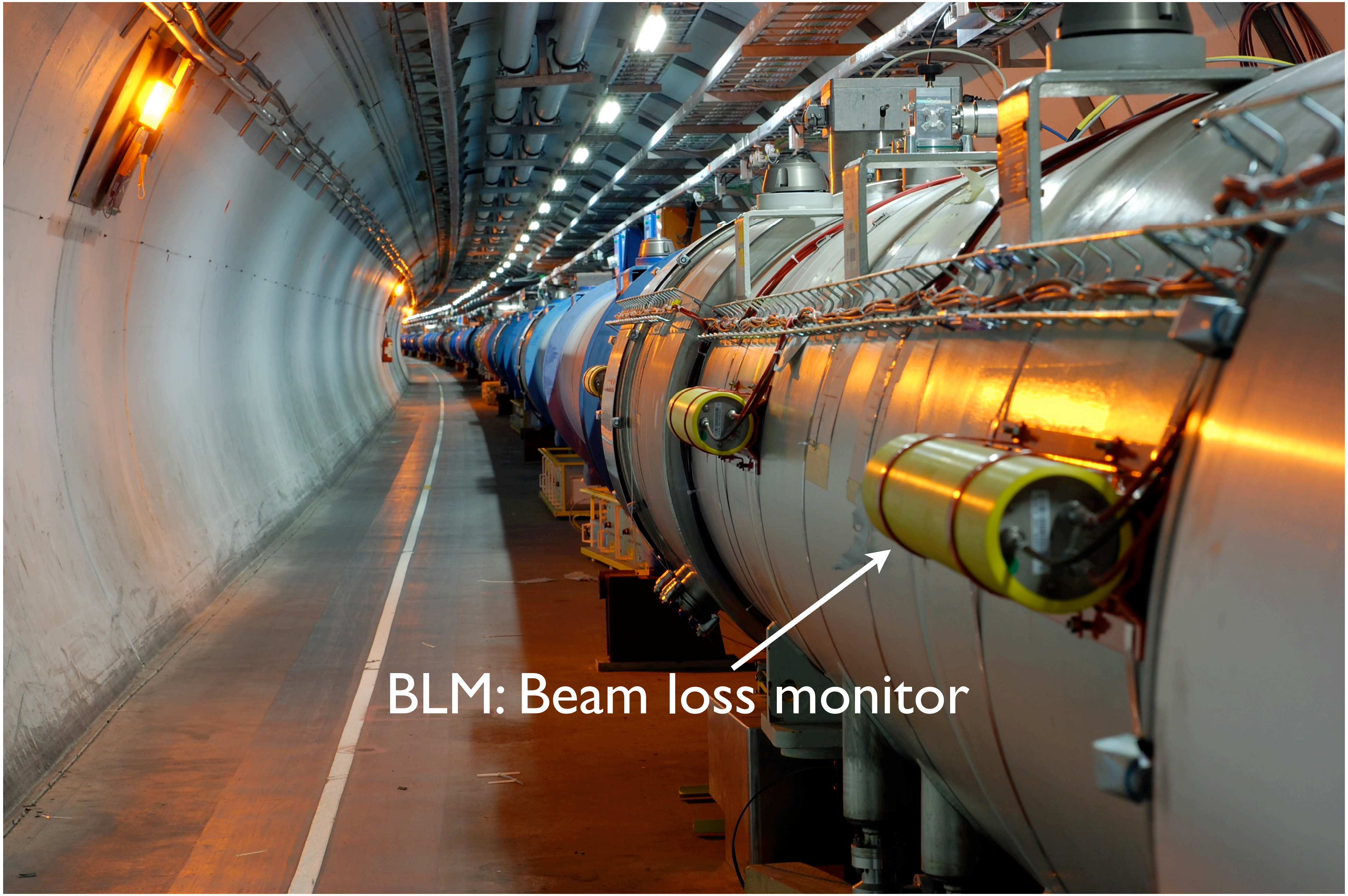
a) Optics model
b) Implementation of geometry in Monte-Carlo environment
c) Includes field-maps for precise tracking
d) Compute energy deposition







How to detect losses: BLMs installed in the tunnel

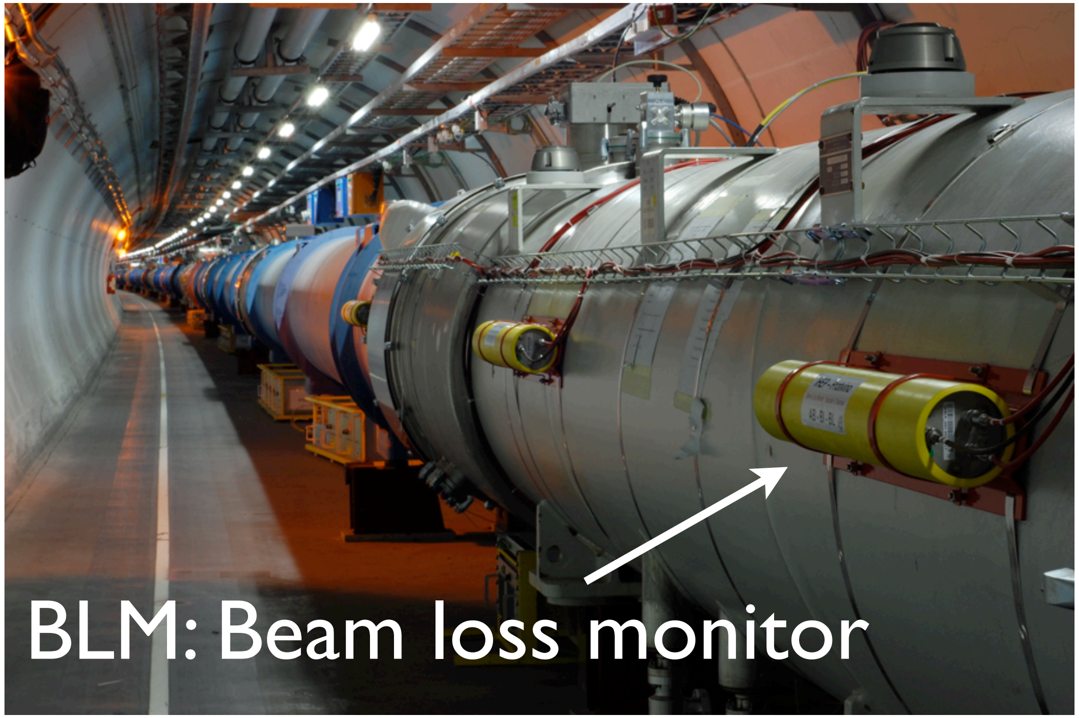


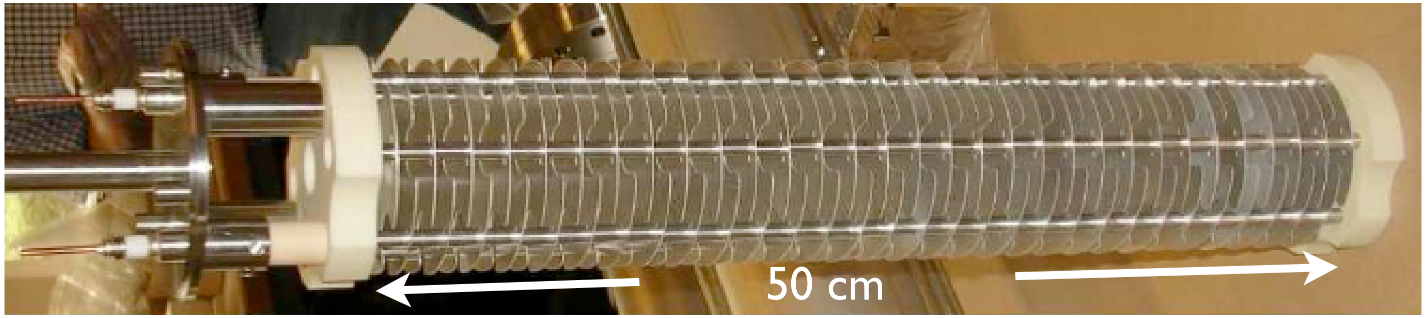
Beam Loss Monitor (BLM) system: the angel watching over the LHC

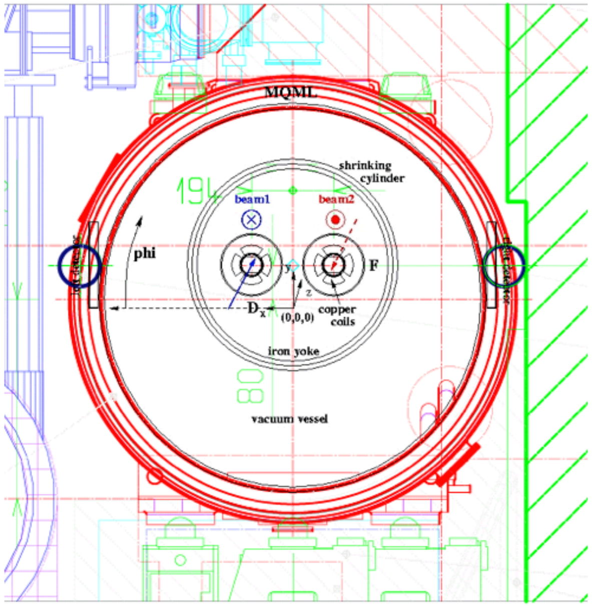
About **3600** chambers monitors continuously proton losses.

If **ONE** of the **few thousands** pre-programmed thresholds of protons losses is passed ⇒ **EXTRACTION**

Ionization chamber:
- N_2 gas at 100 mbar over-pressure
- Length 50 cm
- Sensitive volume 1.5 l
- Ion collection time 85 μs (1 turn, 89 μs)
- 6 every lattice quadrupole plus in particularly hot zone (cleaning insertions, near the IPs)



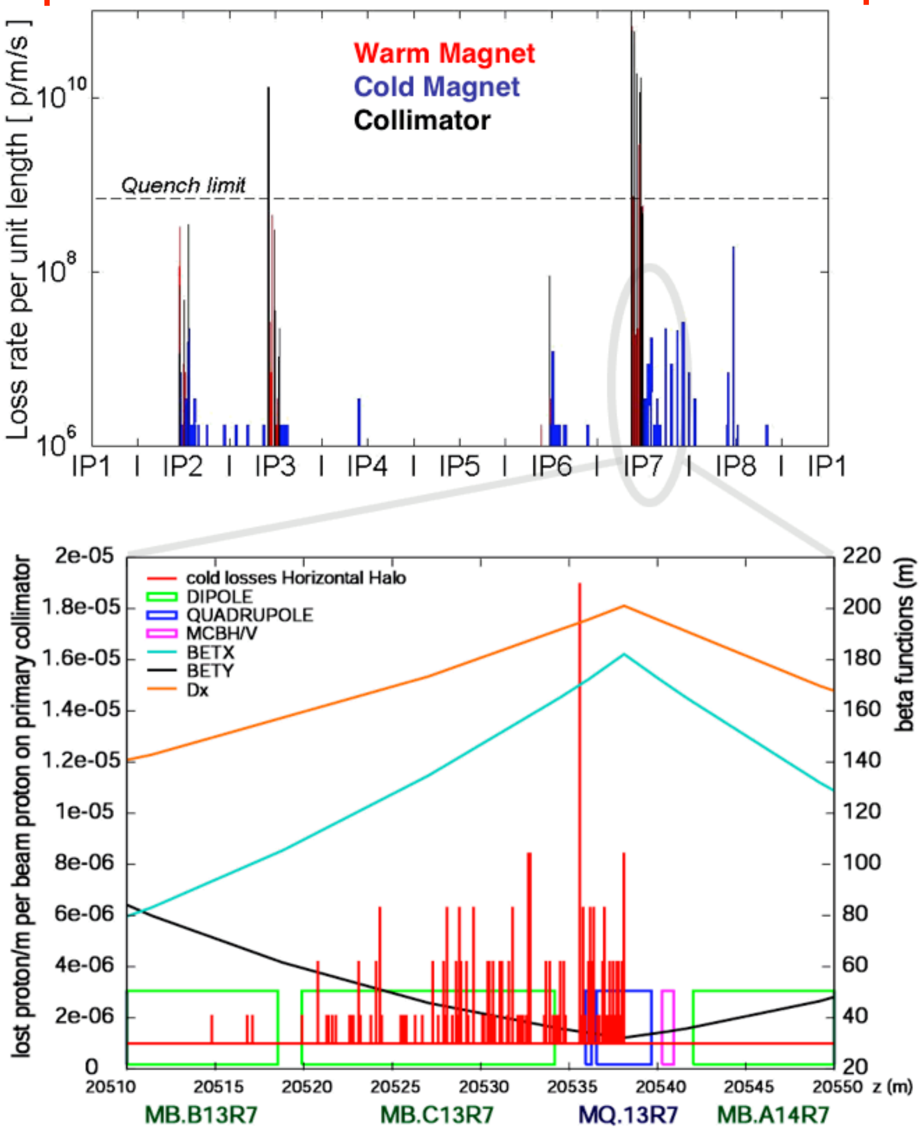


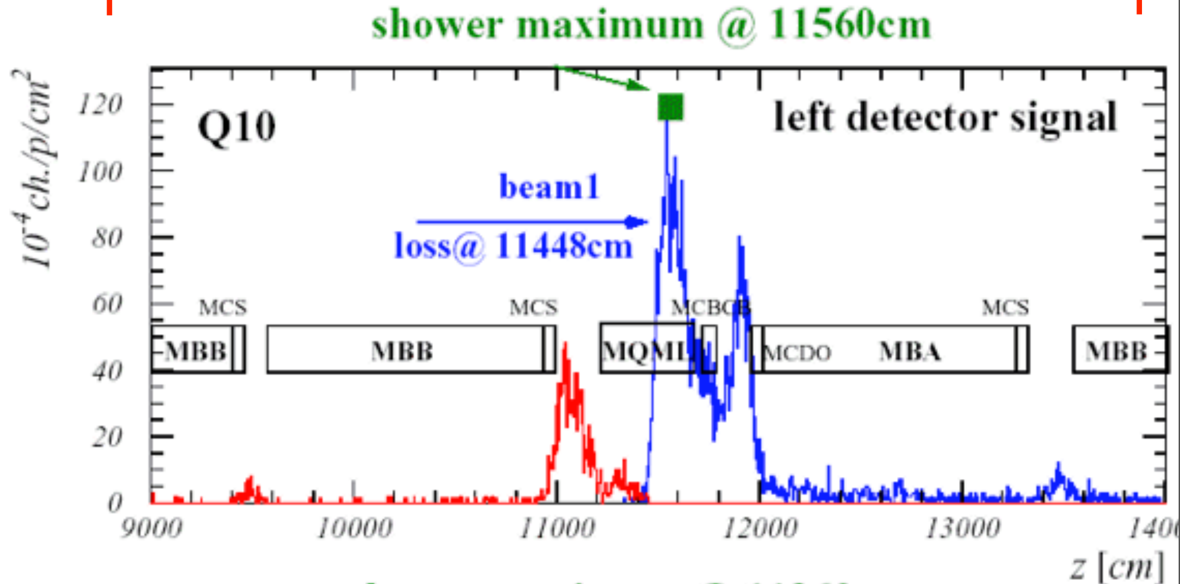


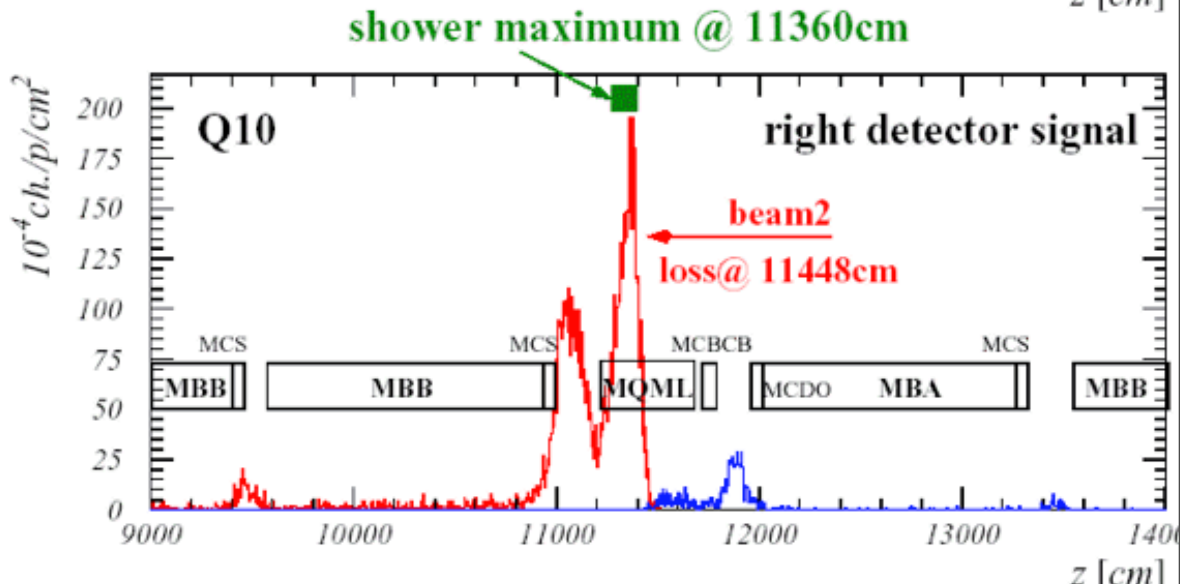
BLMs position vs losses

1st) Loss pattern determination:
Large Bx and Dx horizontal loss

2nd) Loss hadronic shower simulation
to determine where max energy deposition occurs

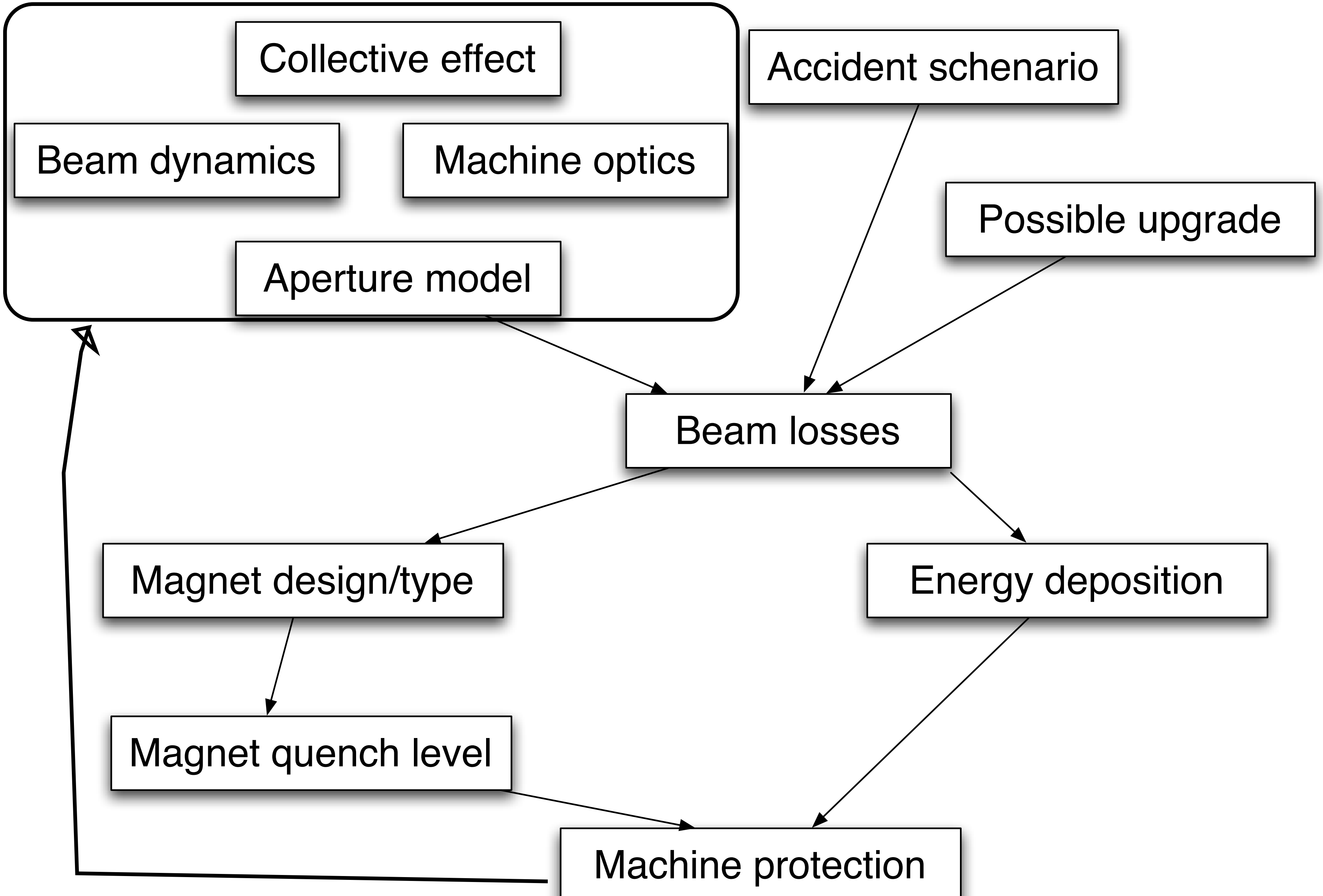






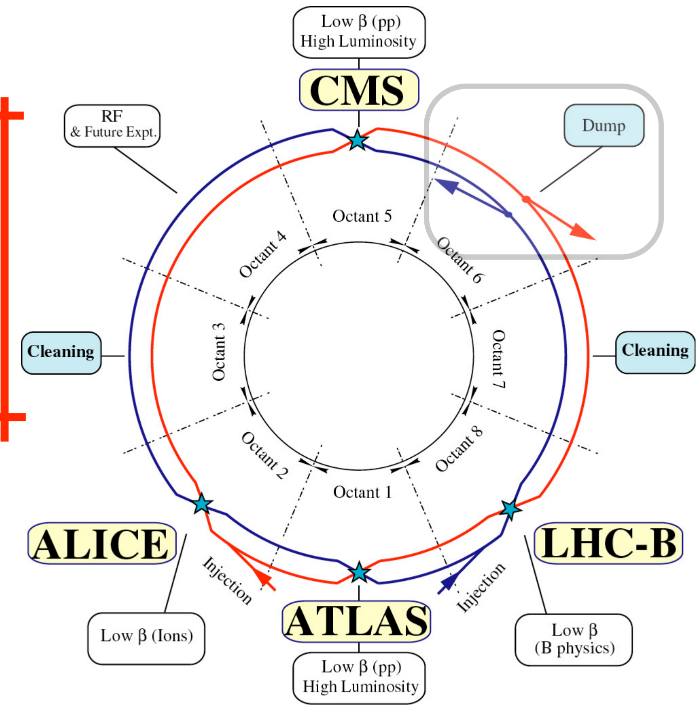
This is in the ARC⇒COLD region !

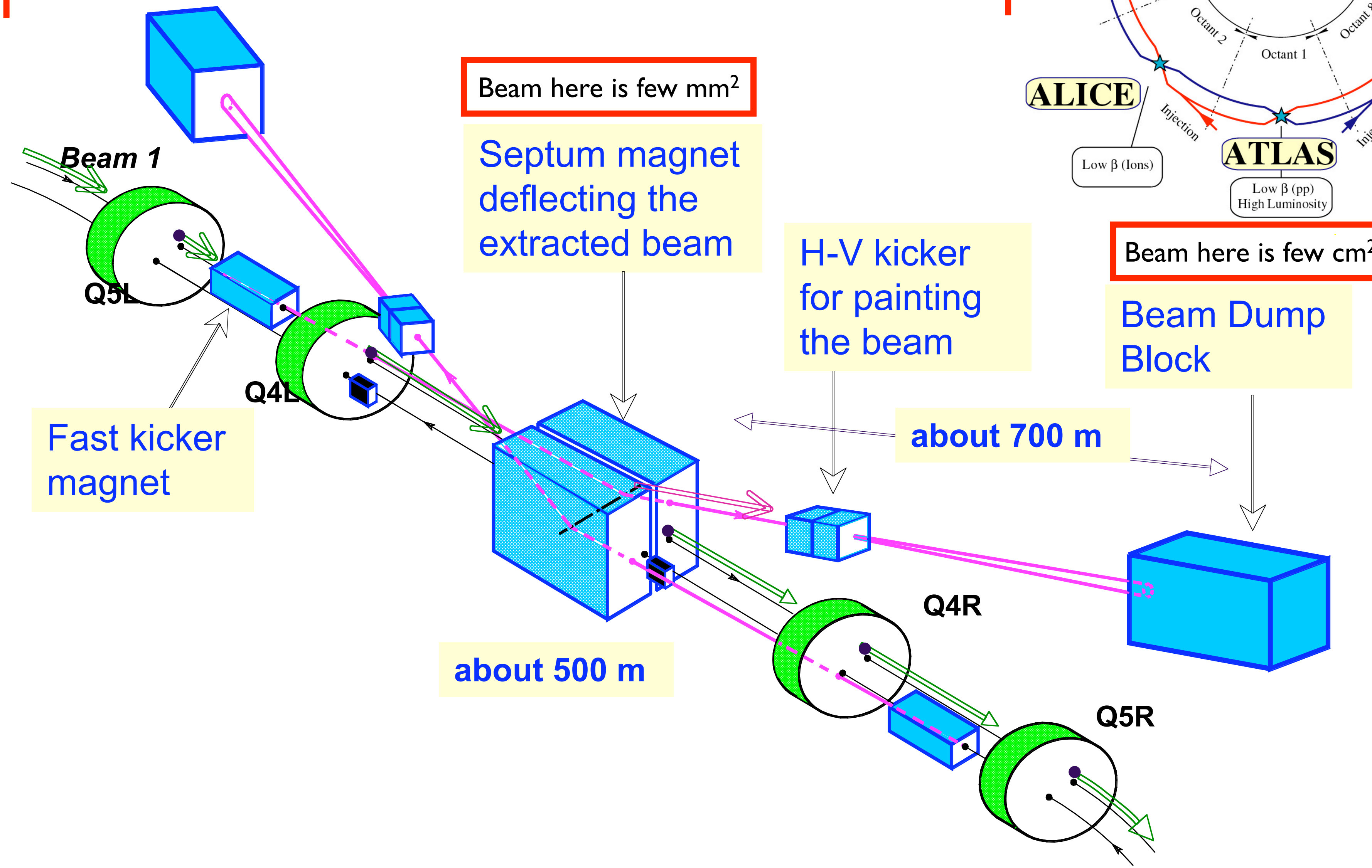
Typical study case, all the pieces together



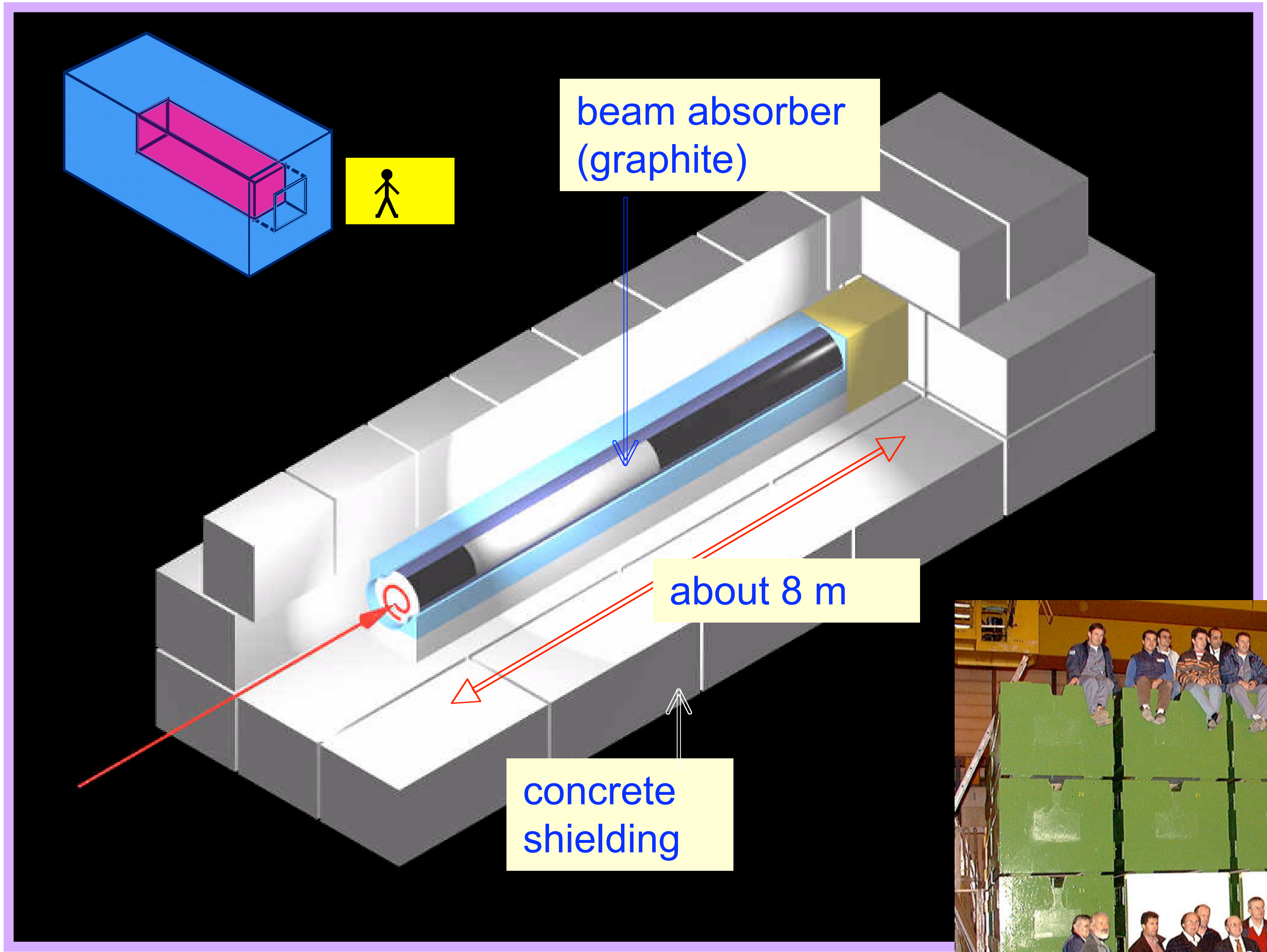
Beam extraction, emergency or not...

At the end of every “fill”, when too low luminosity, or when BLM system triggers, both beams extracted on an external beam dump, in one turn. Beam dump built to absorbe full power at full energy.





Scheme of one of the beam absorbers



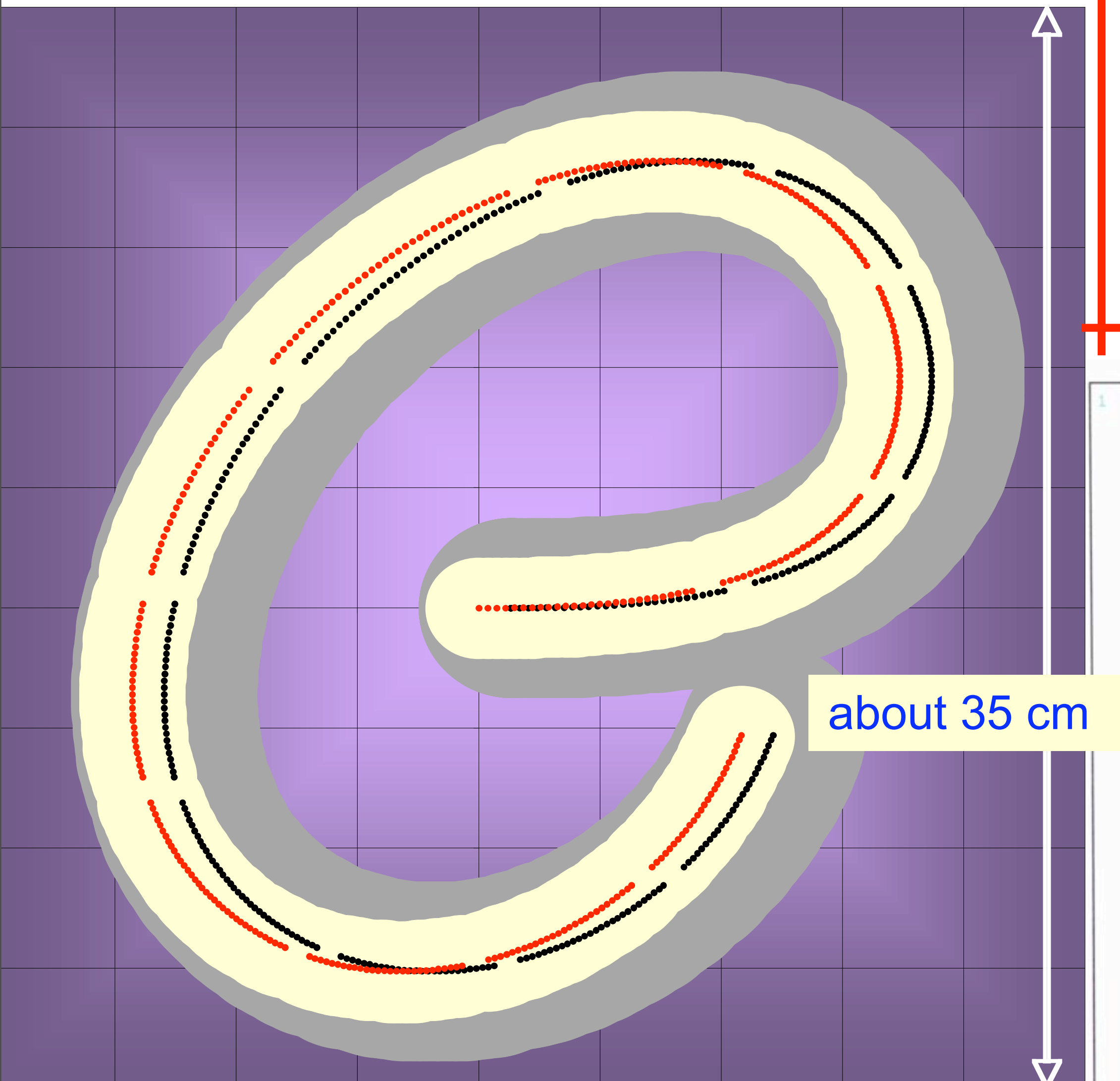
L.Bruno

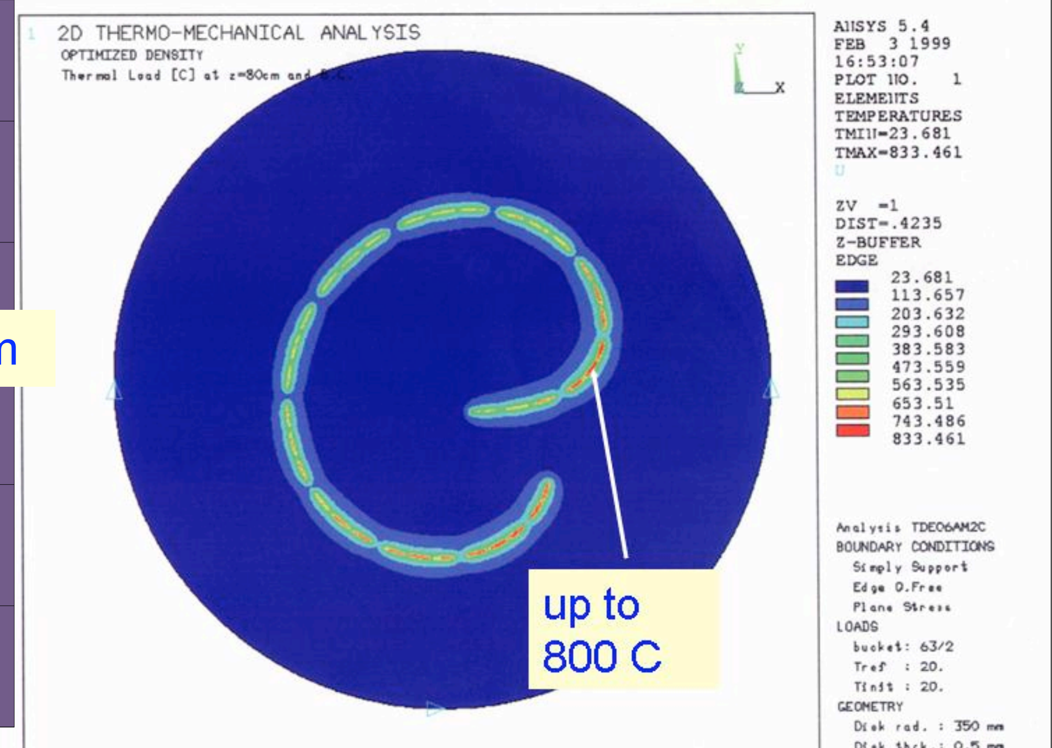
Spot size on the beam dump

To reduce energy deposition peak, proton swept by fast kickers to for a spiral on the transverse face of the dump.

Beam impact in less than 0.1 ms

Even like this, maximum temperature rise about 800 C.





L.Bruno: Thermo-Mechanical Analysis with ANSYS

Beam commissioning planning

I. Pilot physics run
- First collisions
- 43 bunches, no crossing angle, no squeeze, moderate intensities
- Expected performance ~ 10^{31} cm^{-2} s^{-1} at ~1 event/crossing
- Push performance (156 bunches, partial squeeze in 1 and 5, push intensity)
- Performance limit 10^{32} cm^{-2} s^{-1} (event pileup)

II. 75ns operation
- Establish multi-bunch operation, moderate intensities
- Relaxed machine parameters (squeeze and crossing angle)
- Expected performance ~ 10^{32} cm^{-2} s^{-1} at ~1 event/crossing
- Push squeeze and crossing angle
- Performance limit 10^{33} cm^{-2} s^{-1} (event pileup)

III. 25ns operation I
- Nominal crossing angle
- Push squeeze
- Increase intensity to 50% nominal
- Performance limit $2\ 10^{33}$ cm^{-2} s^{-1}

IV. 25ns operation II
- Push towards nominal performance

Courtesy R. Bailey - CERN

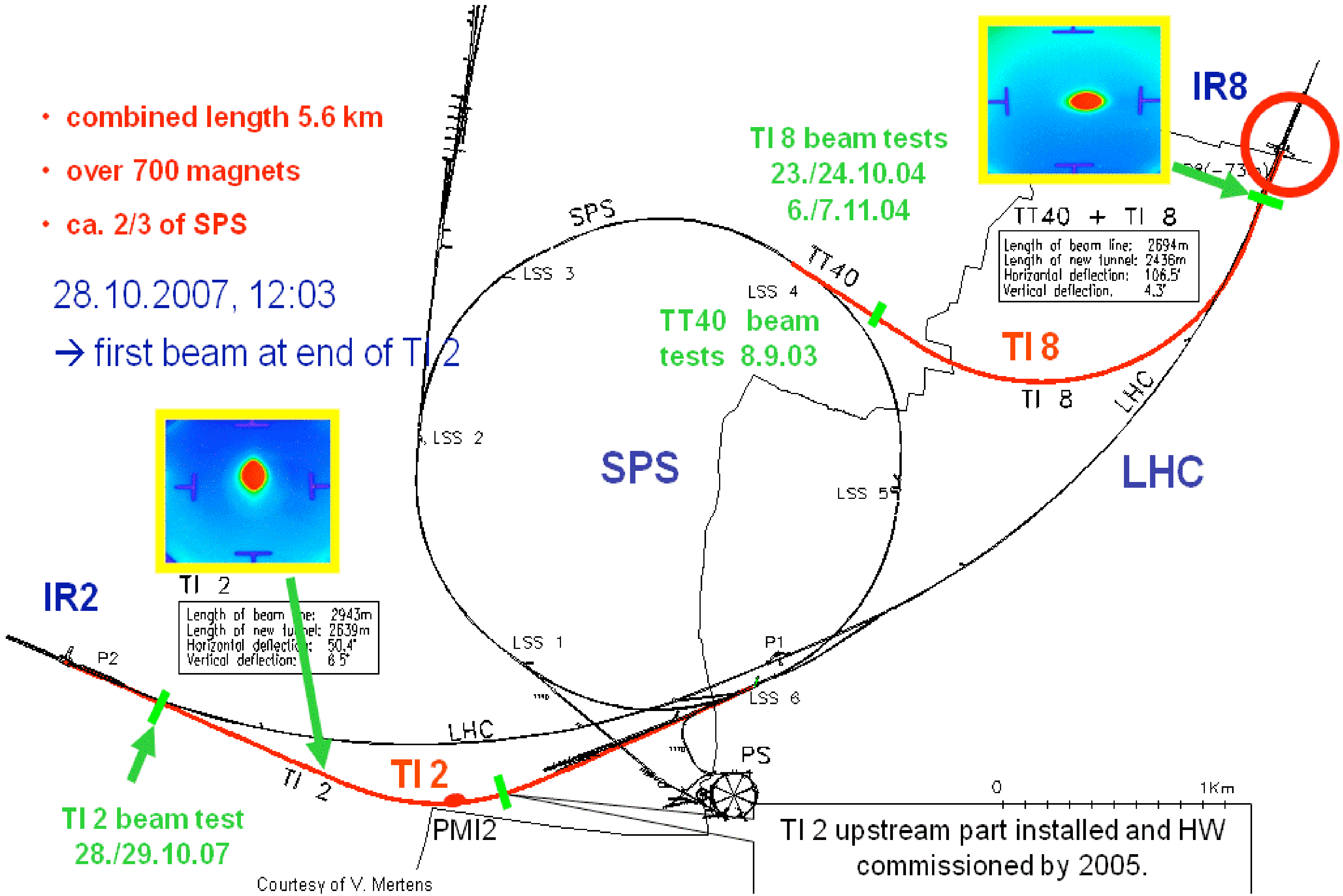
And then the upgrade ... with Nobel price for Higgs discovery ...

Beam at the end of injection lines

- combined length 5.6 km
- over 700 magnets
- ca. 2/3 of SPS

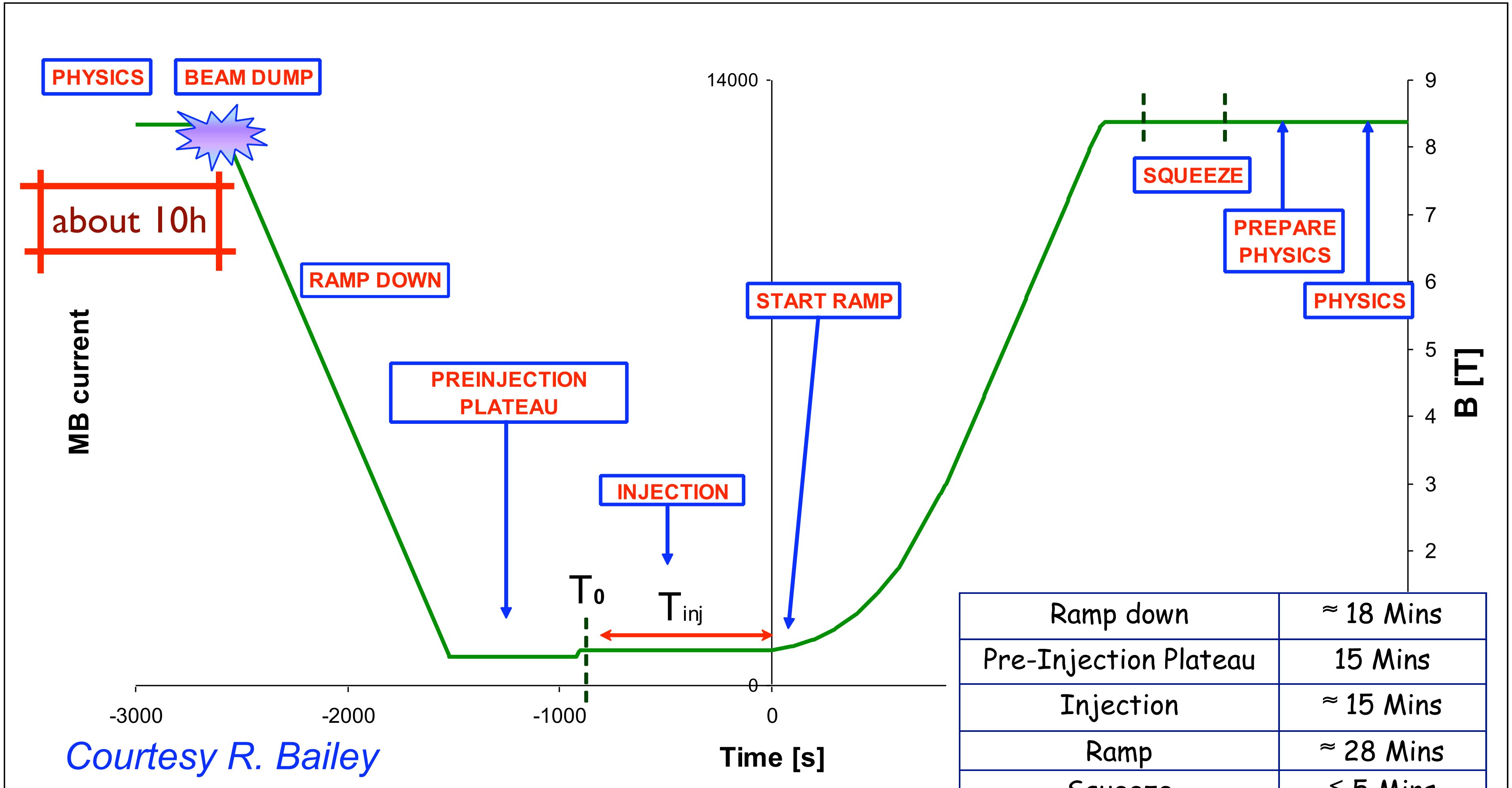
28.10.2007, 12:03

→ first beam at end of TI 2



... beam knocking at the heaven doors,
which is still not cold enough, but it will be soon

Operational cycle



Ramp down	≈ 18 Mins
Pre-Injection Plateau	15 Mins
Injection	≈ 15 Mins
Ramp	≈ 28 Mins
Squeeze	< 5 Mins
Prepare Physics	≈ 10 Mins
Physics	10 - 20 Hrs

From previous experience, at least 6 attempts before a good physics fill

Few words on the future ....

First things to mention, the LHC is not yet running ...
We will have exciting days commissioning the machine
Pushing it to the nominal parameters and beyond...

For this, an UPGRADE study is already ongoing to increase the Luminosity

Upgrade 0 $\Rightarrow$ energy increase by pushing the dipole field at the maximum of 9 T

Upgrade 1 $\Rightarrow$ re-design of the interaction region, by changing the triplets magnets

but this would require to understand/re-design the collimation system,
understand the collective effect which might limit the luminosity, the effect which can limit the luminosity lifetime...
.... and so on ....

and this is an ongoing research

We are a lot, but your possible contribution is more the welcome.
LHC is one of the most complicated apparatus ever built by mankind...

Conclusion/future..

- As last transparency, what about the future.
- The “after LHC” is going to be a LINEAR COLLIDER with leptons:
    - see next lectures...
- Thanks for your attention.

References I

[0] 2005 Summer Student Lectures of O. Bruning,
[http://agenda.cern.ch/askArchive.php?base=agenda&categ=a054021&id=a054021/transparencies]

[1] M. Martini, An Introduction to Transverse Beam Dynamics in Accelerators, CERN/PS 96-11 (PA), 1996,
[http://doc.cern.ch/archive/electronic/cern/preprints/ps/ps-96-011.pdf]

[2] L. Rinolfi, Longitudinal Beam Dynamics (Application to synchrotron), CERN/PS 2000-008 (LP), 2000,
[http://doc.cern.ch/archive/electronic/cern/preprints/ps/ps-2000-008.pdf]

[3] Theoretical Aspects of the Behaviour of Beams in Accelerators and Storage Rings: International School of Particle Accelerators of the 'Ettore Majorana' Centre for Scientific Culture, 10–22 November 1976, Erice, Italy, M.H. Blewett (ed.), CERN report 77-13 (1977)
[http://preprints.cern.ch/cgi-bin/setlink?base=cernrep&categ=Yellow_Report&id=77-13]

[4] CERN Accelerator Schools [http://cas.web.cern.ch/cas/]

[5] K. Schindl, Space Charge, CERN-PS-99-012-DI, 1999
[http://doc.cern.ch/archive/electronic/cern/preprints/ps/ps-99-012.pdf]

[6] A.W. Chao, Physics of Collective Beam Instabilities in High Energy Accelerators, New York: Wiley, 371 p, 1993
[http://www.slac.stanford.edu/~achao/wileybook.html]

[7] Web site on LHC Beam-Beam Studies [http://wwwslap.cern.ch/collective/zwe/lhcbb/]

[8] Web site on Electron Cloud Effects in the LHC [http://ab-abp-rlc.web.cern.ch/ab-abp-rlc-ecloud/]

[9] LHC design report [http://lhc.web.cern.ch/lhc/]

References II

[10] A.I. Drozhdin, N.V. Mokhov, D.A. Still, R.V. Samulyak "Beam-Induced Damage to the Tevatron Collimators: Analysis and Dynamic Modeling of Beam Loss, Energy Deposition and Ablation", Fermilab-FN-751 (2004).

[11] Wiedemann, Particle accelerator physics I, Springer

[12] P. Germain CERN 89-07

[13] Wangler, RF accelerators, from CERN Library

[14] CMS web page [http://cmsinfo.cern.ch/outreach/CMSdocuments/CMSdocuments.html]

[15] E. Bravin et al. , The Influence of Train Leakage Currents on the LEP Dipole Field, CERN-SL-97-047-BI [http://preprints.cern.ch/cgi-bin/setlink?base=preprint&categ=cern&id=SL-97-047]

[16] L. Arnaudon et al., Effects of terrestrial tides on LEP bean energy CERN SL 94-07 (BI)

[17] R. Assman, Collimation project web page [http://lhc-collimation-project.web.cern.ch/lhc-collimation-project/]

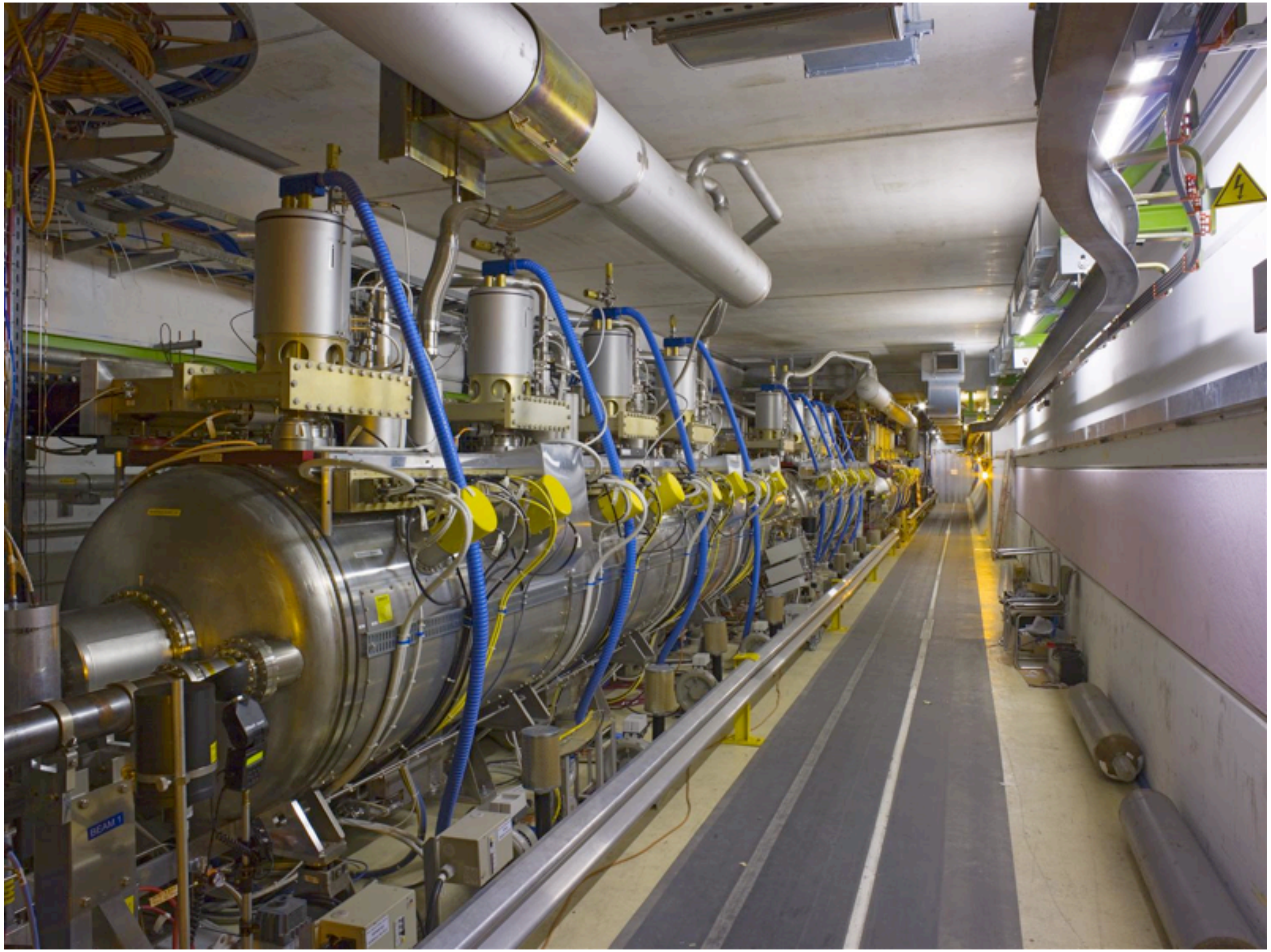
[18] Mess, K H; Schmüser, P; Wolff, Superconducting accelerator magnets, 1996 Singapore, World Sci.

[19] Simone Gilardoni, CERN, 1211 Geneva 23, Switzerland. +41 22 767 1823

RF system

LHC RF frequency 400 MHz

Revolution frequency 11246 Hz



Multiple summary for Main Dipoles