The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

SMR/1847-2

Summer School on Particle Physics

11 - 22 June 2007

LHC Accelerators and Experiments (part I)

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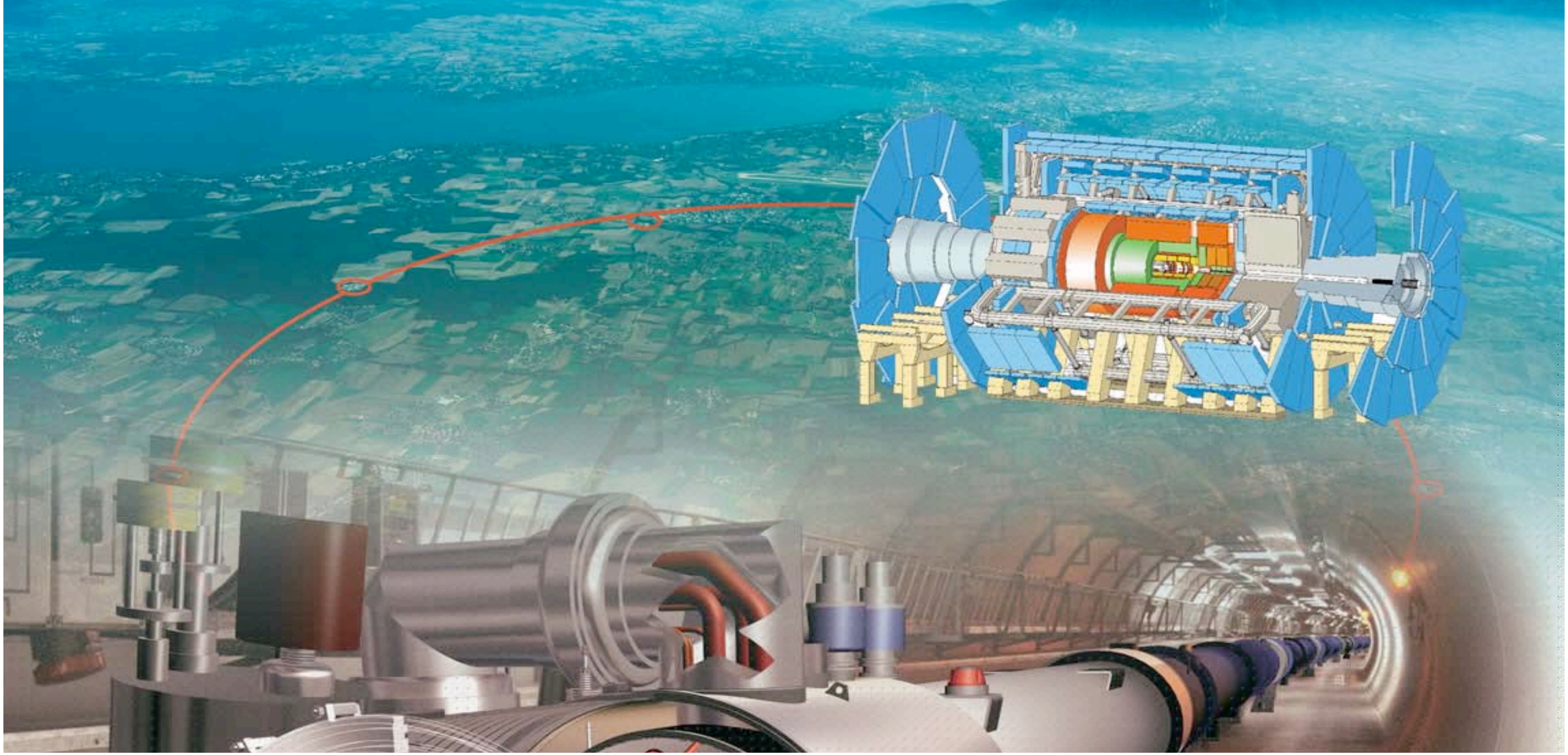
ICTP

Marzio Nessi

Trieste, 11-13th June 2007



ICTP-2007 The LHC project

Part I : motivation, the LHC accelerator

Part II : experimental goals, ATLAS and CMS detectors

Part III : LHCb and Alice experiments,
luminosity measurements,
early discovery potential

- *These will be a set of experimental lectures, with the goal of giving you an impression of the complexity and challenges of this project*
- *My deep involvement in the design and construction of the ATLAS detector will bias me towards it as a show case … sorry!*

Table of Content (Part I)

- ✓ The TeV region
- ✓ The LHC program
- ✓ Motivation
- ✓ Challenge

- ✓ The LHC accelerator
- ✓ LHC machine construction status
- ✓ LHC machine start up / commissioning plans

The TeV scale

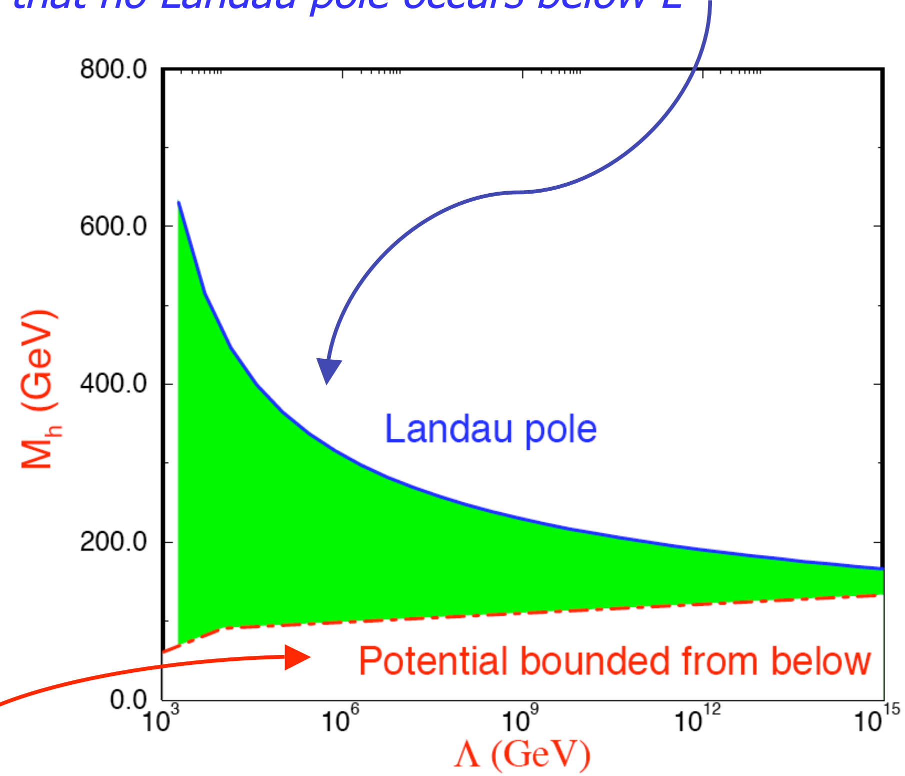
- ✓ Standard Model in perfect agreement with all *confirmed* accelerator data
- ✓ Consistency with precision electroweak data (LEP et al) only if there is a Higgs boson
- ✓ Agreement seems to require *a relatively light Higgs boson*
- ✓ Raises many unanswered questions: *mass? flavour? unification?*

We expect something at the TeV scale:

SM Higgs mass is highly restricted by requirements of theoretical consistency

If SM valid up to Planck scale, only a small range of allowed Higgs masses!

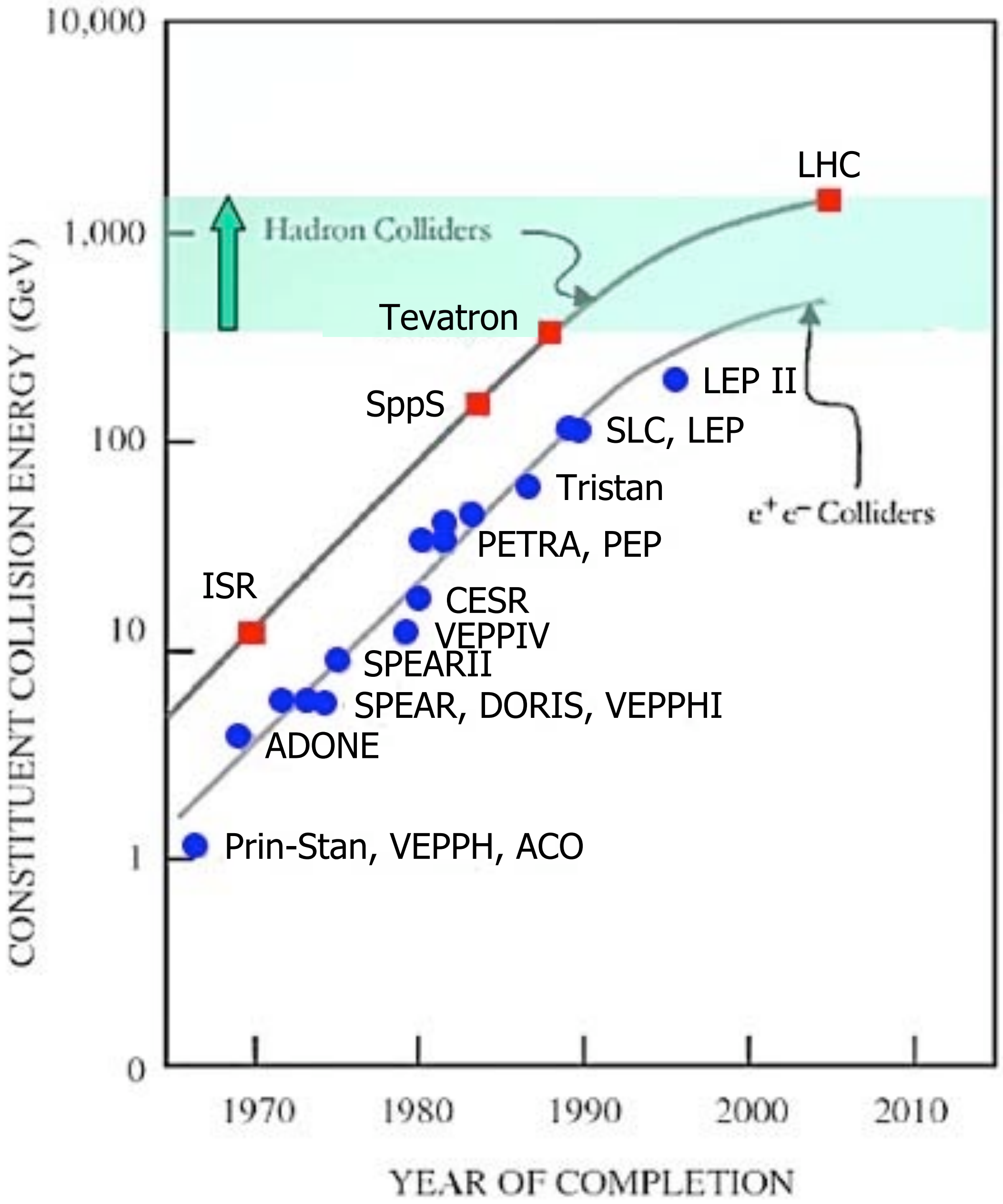
The upper limit for m_H is obtained by requiring that no Landau pole occurs below L



$\lambda(\Lambda)$ >0 needed for the vacuum to be stable (i.e.for a state of minimum energy to exist)

$m_H \leq 180$ GeV for $\Lambda \sim M_{GUT}$
$m_H \leq 600 - 800$ GeV for $\Lambda \sim \mathcal{O}$(TeV)

Accelerators technology



mid ‘80 the question was raised on how to reach collision constituents energies at the TeV scale

e-e+ colliders with LEPII have reached the limit of their possibilities (Synchrotron radiation) :

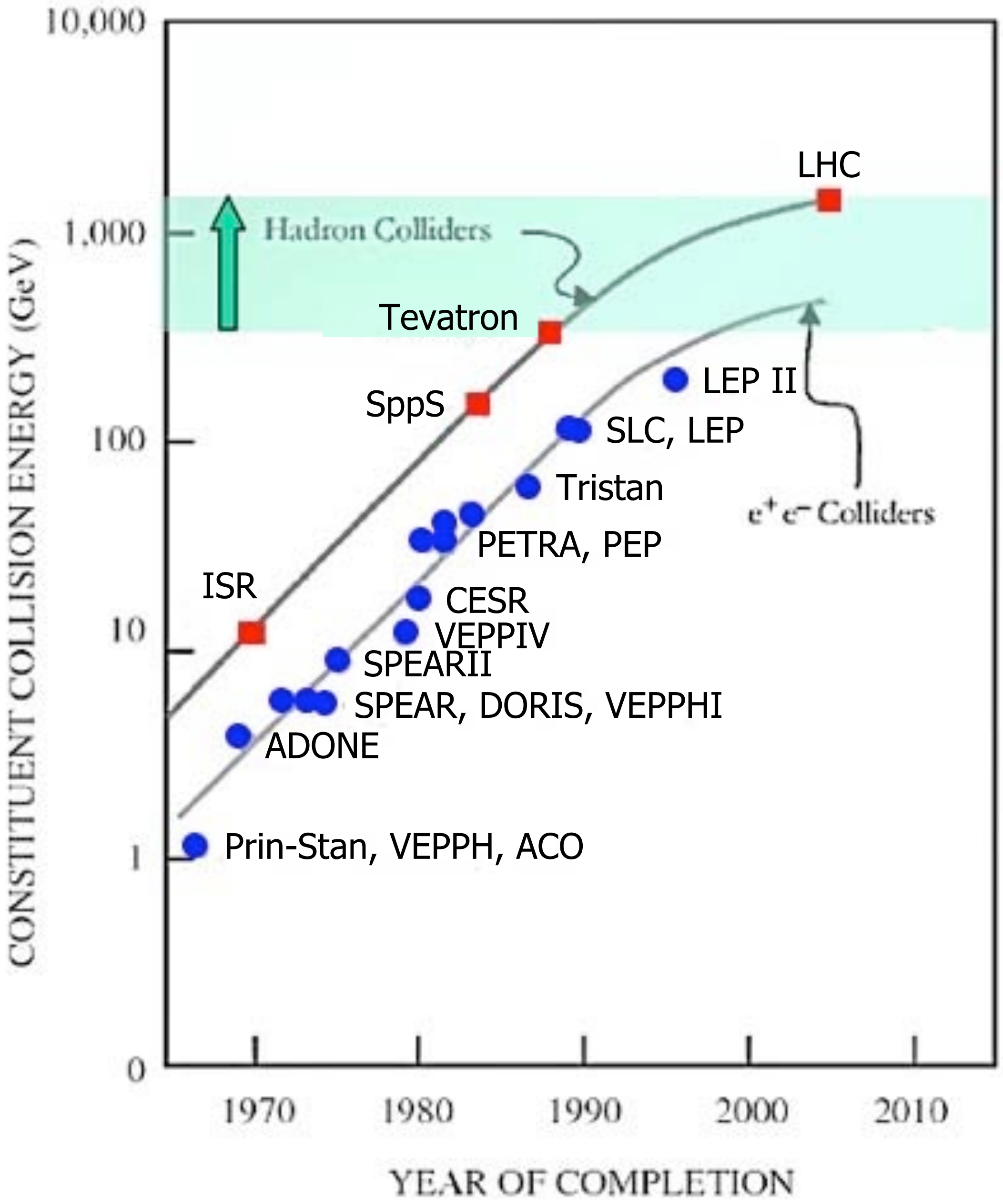
$$E_{loss} / turn \; (KeV) = 88.5 * E^4 (GeV) / R (m)$$

~ 0.3 GeV at LEPII (100 GeV)
impossible at 1TeV

TeV linear colliders are technologically not ready (ILC & CLIC R&D few years still to go)

TeV muon colliders are still an option, beam intensities and beam lifetime a challenge

Accelerators technology



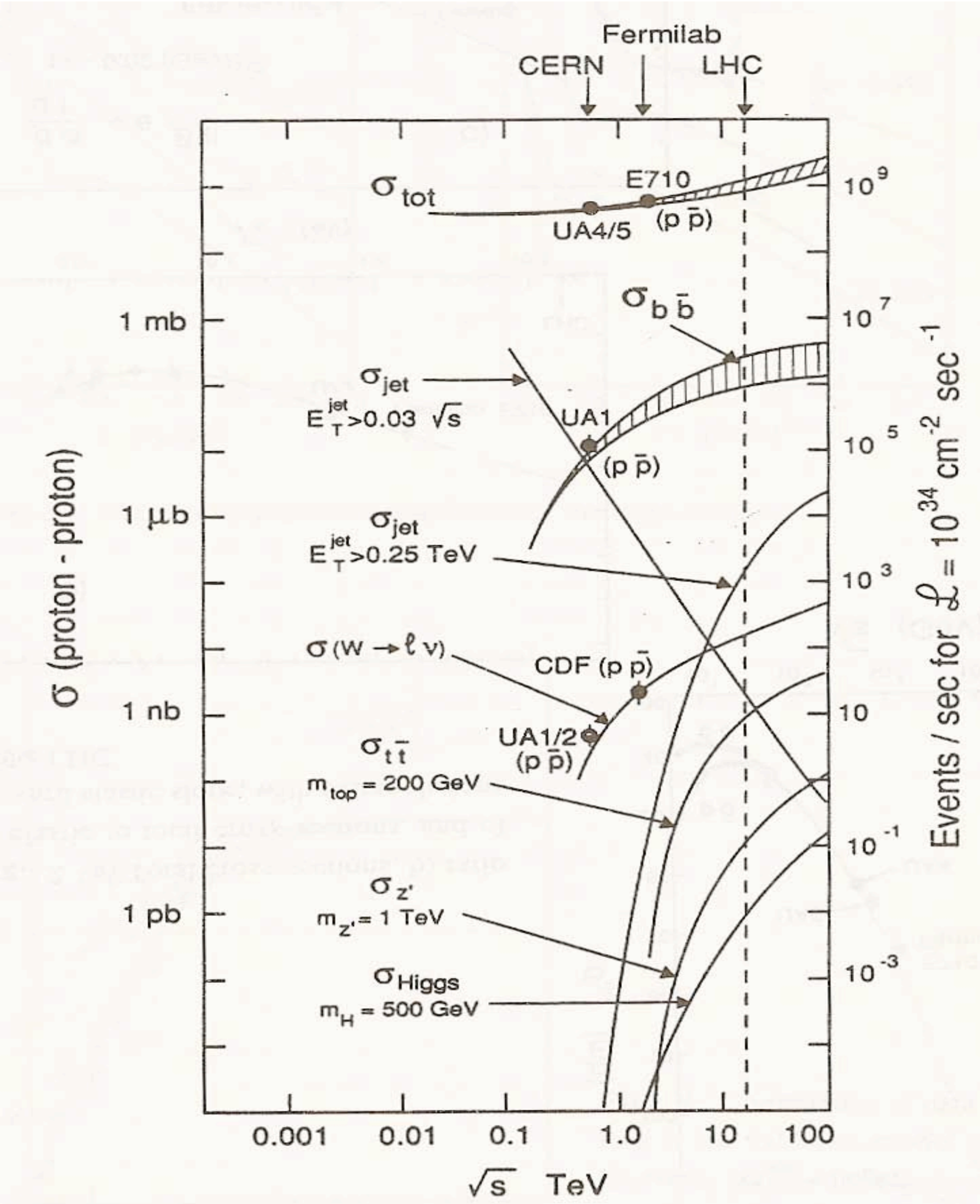
Hadron colliders are a natural choice for an exploration machine at the TeV scale. It just requires bending magnets working at high B field value

4-5 Tesla technology became available at the Tevatron ('87) and later at HERA. 8-9 Tesla are technologically possible going to superfluid Helium (II): 4.5K to 1.9K

The LEP tunnel was the natural choice. SSC was proposed in the US and then abandoned.

At 7 TeV in the LEP tunnel the energy loss per turn, per p is marginal (8 KeV), but now this energy will go into the superconducting magnets and might become a problem (KW which might quench the magnets or create beam instabilities)

TeV production rates



Whatever accelerator might cover the TeV scale, it must produce a high enough event rate to be statistically significant

$$N_{rate} = \sigma * \text{Luminosity} * BR$$

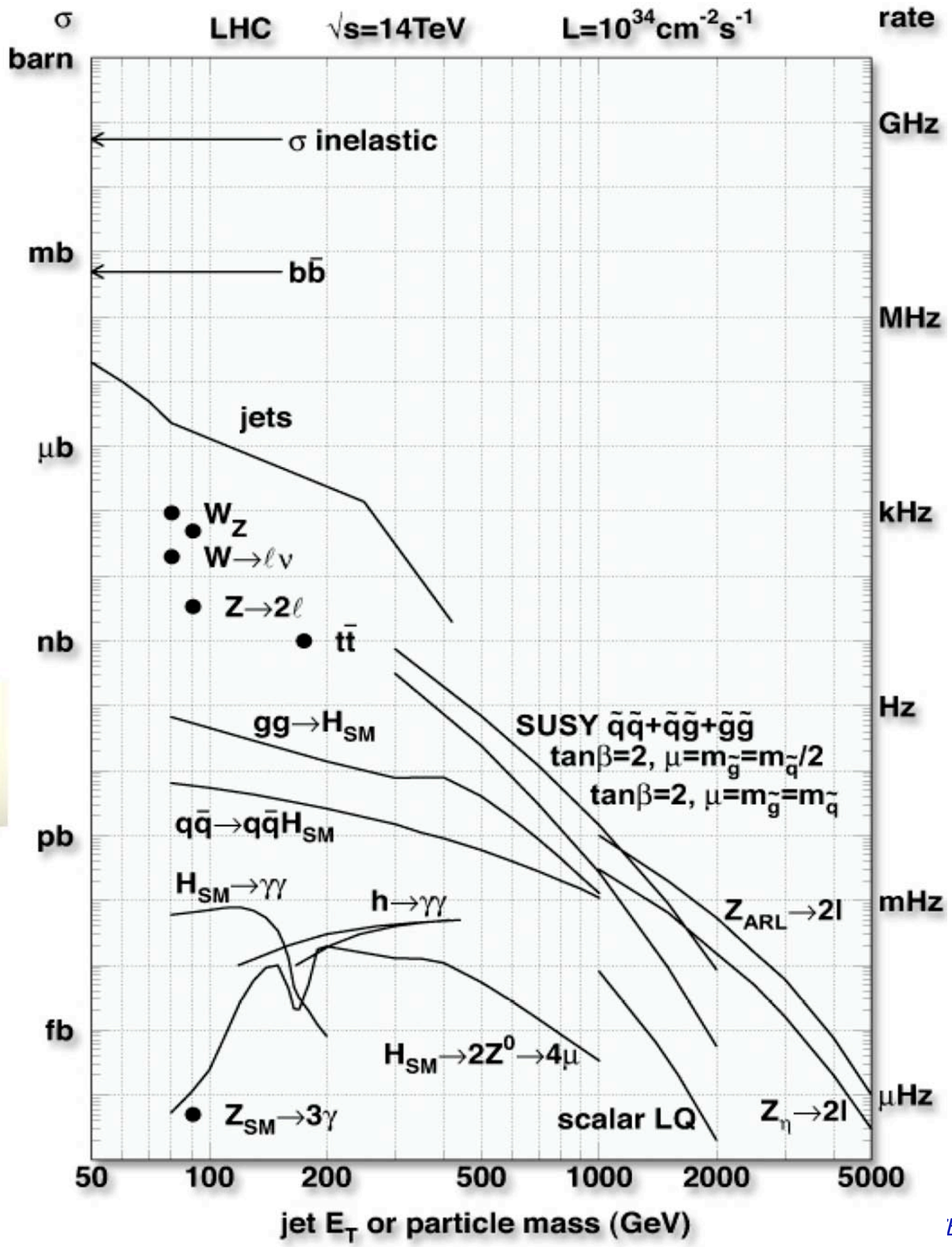
Higgs showcase: m=500 GeV, σ ~ pb, BR(to 4 μ)~10^{-3}

N~few/day -> L=10^{34} cm^{-2} sec^{-1}

Beam Energy needed to produce new massive particles such as the Higgs boson --> **TeV**

Beam Intensity needed because some of the processes that one would like to study are very rare (e.g. small σ·*B* for decay modes visible above background) --> ***L=10^{34} cm^{-2} sec^{-1}***

TeV production rates



Already at $L=10^{33}$

Process	Events/s	Events/year	present facilities (total statistics)
W→ eν	15	10^8	10^4 LEP / 10^7 Tev
Z→ ee	1.5	10^7	10^7 LEP
$t\bar{t}$	0.8	10^7	10^5 Tevatron
$b\bar{b}$	10^5	10^{12}	10^8 Belle/BaBar
$\tilde{g}\tilde{g}$ (m=1 TeV)	0.001	10^4	—
H (m=0.8 TeV)	0.001	10^4	—
QCD jets p_T > 200 GeV	10^2	10^9	10^7

LHC will be a production factory for all known physics, with 3-5 orders of magnitude more rate than in previous facilities

For new physics the mass scale it will cover, might reach 4-5 TeV, if enough integrated luminosity will be collected > 100 fb^{-1}

LHC physics mission

- *Discover or exclude the Higgs in the mass region up to 1 TeV. Measure the Higgs properties*
- *Discover Supersymmetric particles, if existing, up to 2-3 TeV mass*
- *Discover Extra Space Dimensions at the TeV scale, explore black holes*
- *Search for new phenomena (strong EWSB, new gauge bosons, Little Higgs model, Split Supersymmetry, Compositness,…)*
- *Study CP violation in the B sector, high statistics B Physics*
- *Precision measurements on m_{top}, m_W, anomalous couplings,…*
- *Study new super relativistic Heavy Ions Collision, look for quark gluon plasma*
- *QCD and diffractive forward physics in a new regime*

Explore new physics at a new energy frontier

The LHC collider

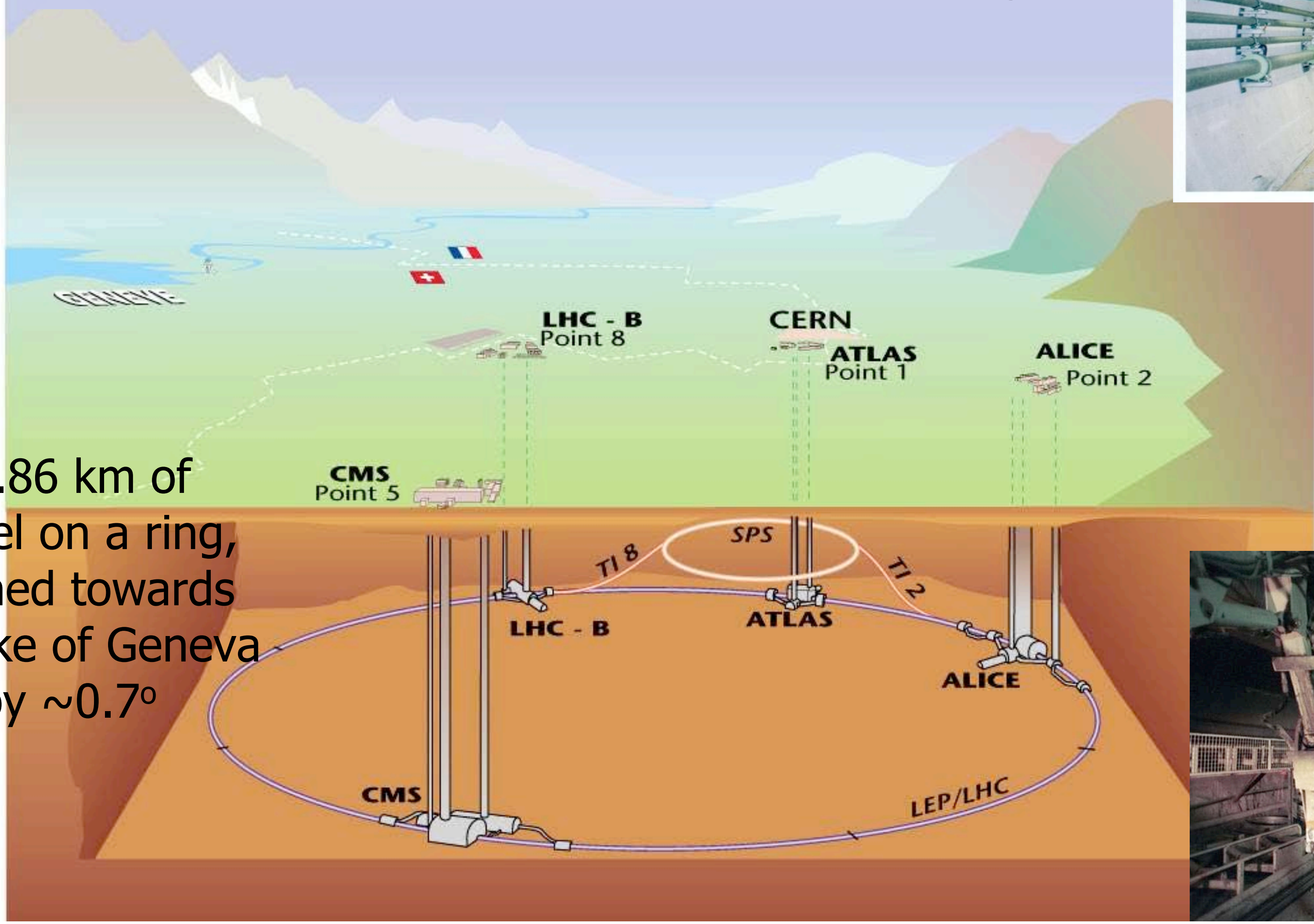
p (7 TeV) + p (7 TeV)

1982 : First studies for the LHC project
1983 : Z0 detected at SPS proton antiproton collider
1989 : Start of LEP operation
1994 : Approval of the LHC by the CERN Council
1996 : Final decision construction
1996 : LEP operation at 100 GeV
2000 : End of LEP operation
2002 : LEP equipment removed
2003 : Start of the LHC installation
2005 : Start hardware commissioning
2007 : End of the installation effort

2008 : Commissioning with beams at 7 TeV

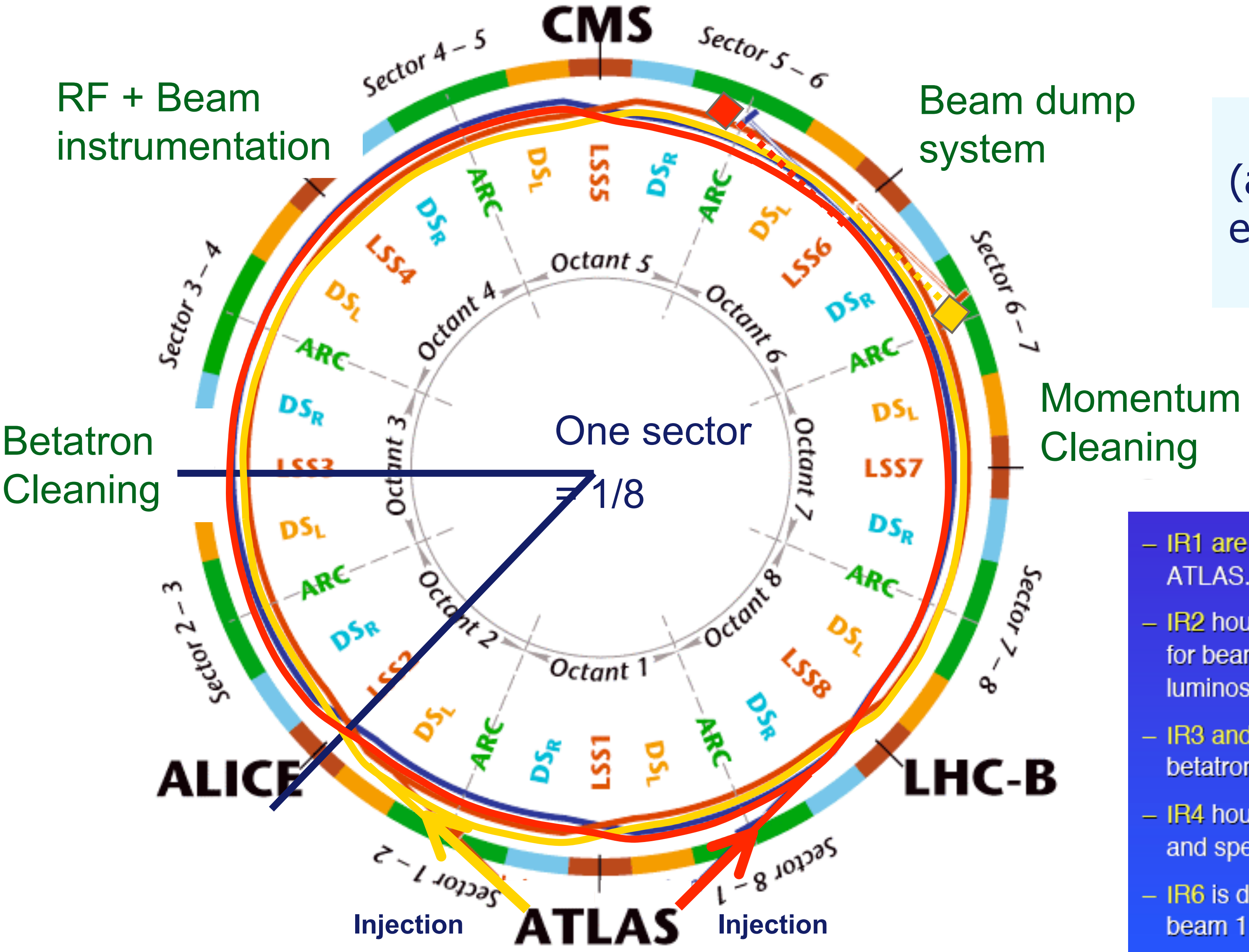
The LHC collider (I)

LHC placed in the LEP tunnel (50-100 m underground)



26.86 km of tunnel on a ring, inclined towards the lake of Geneva by ~0.7º

The LHC collider (II)

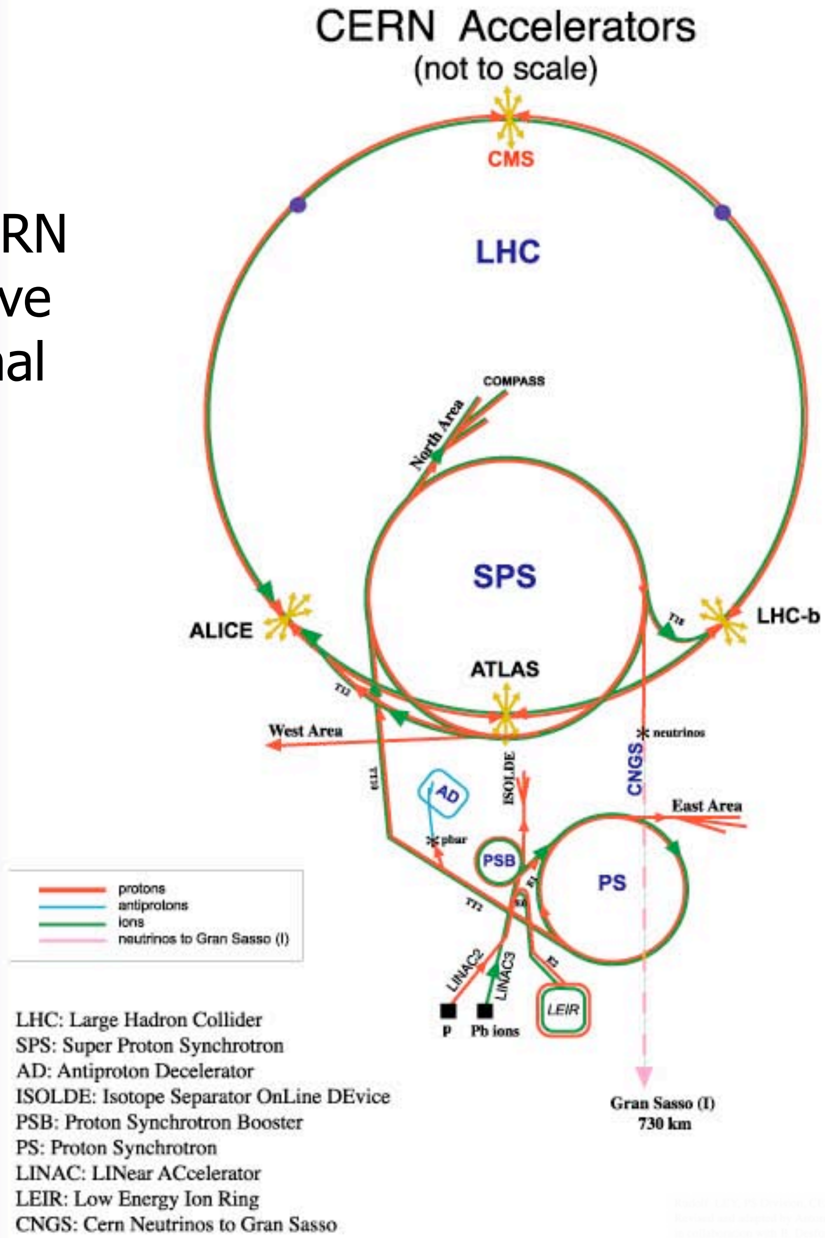


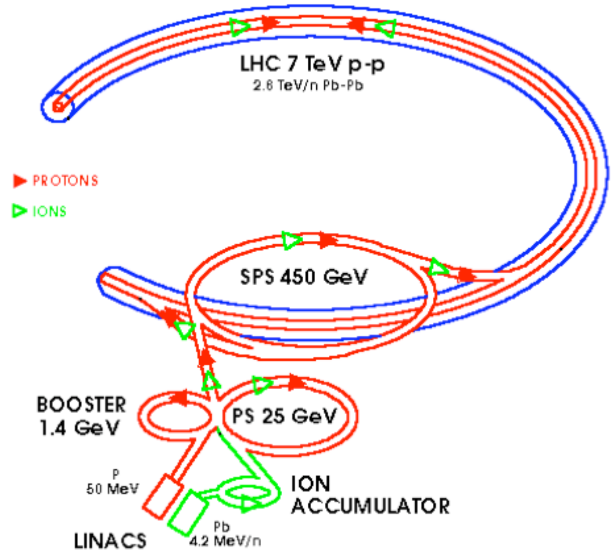
LHC: eight arcs (approximatly circular) and eight long straight sections (about 700 m long)

- IR1 are IR5 high luminosity insertions. IR1: ATLAS. IR5: CMS and TOTEM.
- IR2 houses ALICE experiment (ions) and injection for beam 1. Flexible optics for controlling luminosity.
- IR3 and IR7 are dedicated to momentum and betatron collimation.
- IR4 houses the RF system for beam acceleration and special beam instrumentation.
- IR6 is dedicated to the beam dump for both of beam 1 and beam 2.
- IR8 houses LHCb experiment (low luminosity) and injection for beam 2. Off center collisions.

The LHC collider (III)

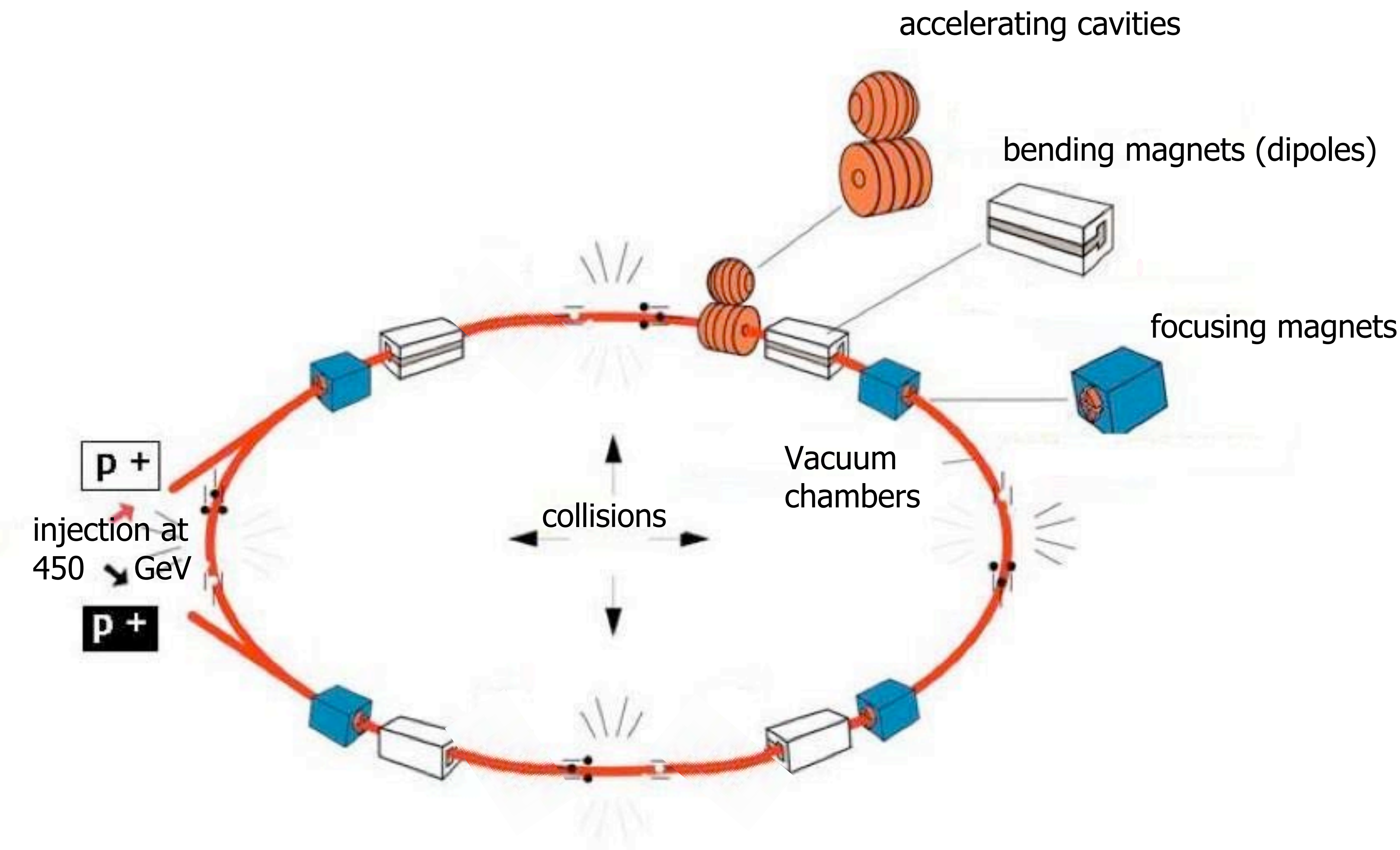
50 years of CERN history still alive and operational





the deeper you go, younger is the accelerator facility

The LHC collider basic layout



Beam transport

How to get protons on a circle ? **dipole magnets (B vertical)**

How to get the final energy? **RF cavities (E Field)**

Why to focus the beams ?

✓ Particles with different injection parameters (angle, position) separate over time

Assuming an angle difference of 10^{-6} rad, two particles would separate by 1 m after 10^6 m. At the LHC, with a length of 26860 m, this would be the case after 50 turns (5 ms !)

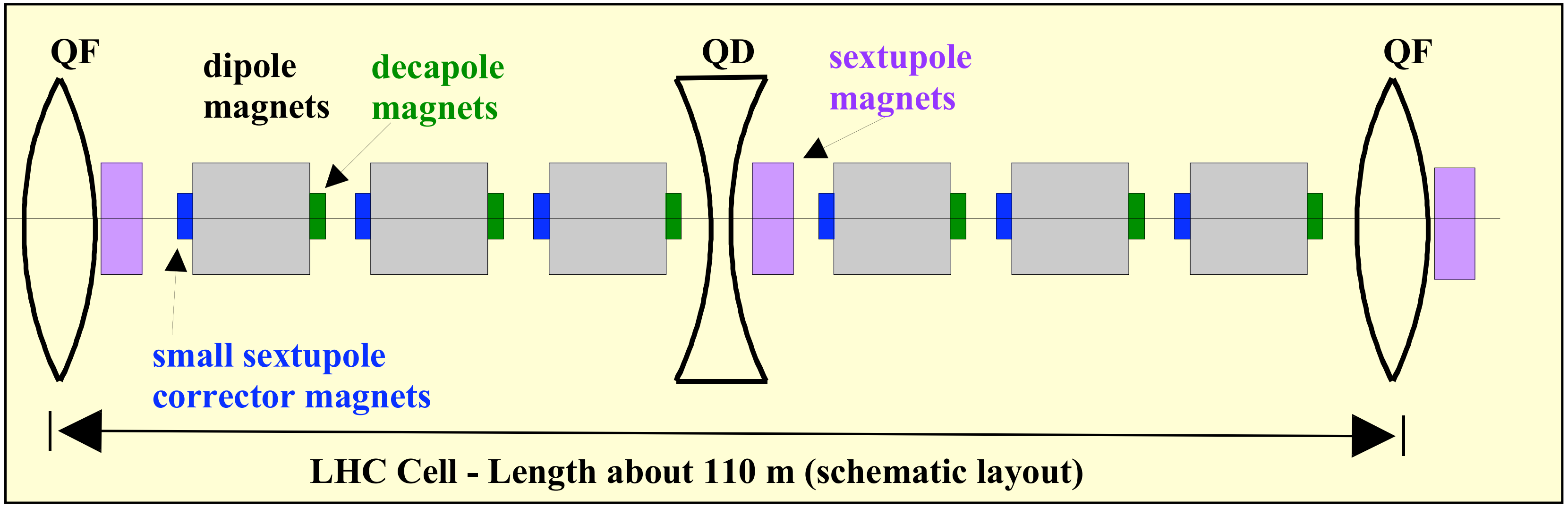
✓ Particles would „drop“ due to gravitation

✓ The beam size must be well controlled

At the collision point the beam size must be tiny to maximize luminosity

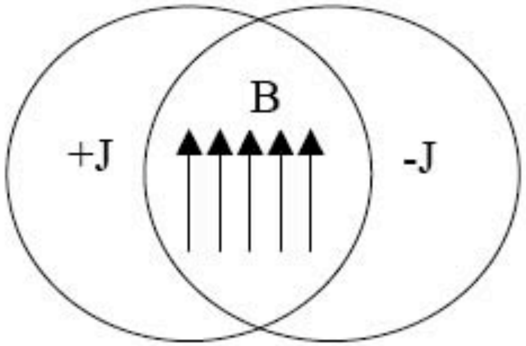
✓ Particles with (slightly) different energies should stay together

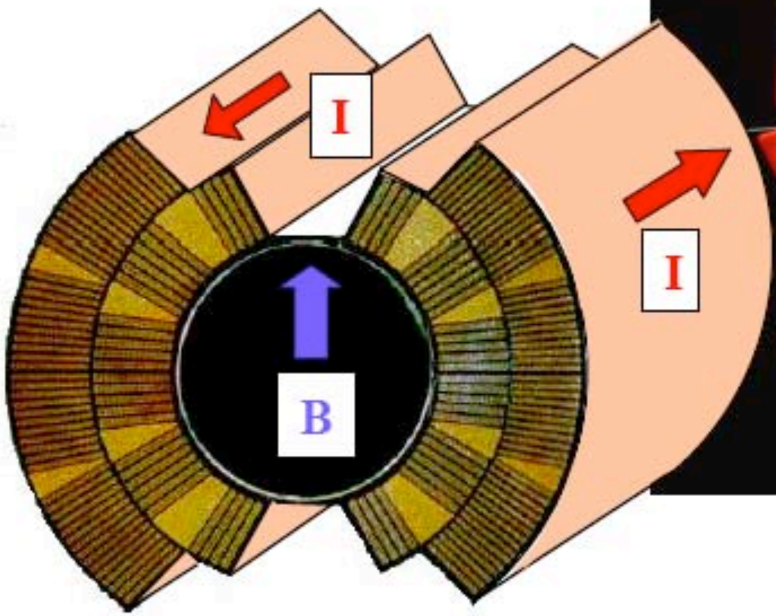
Beam transport (LHC arcs)

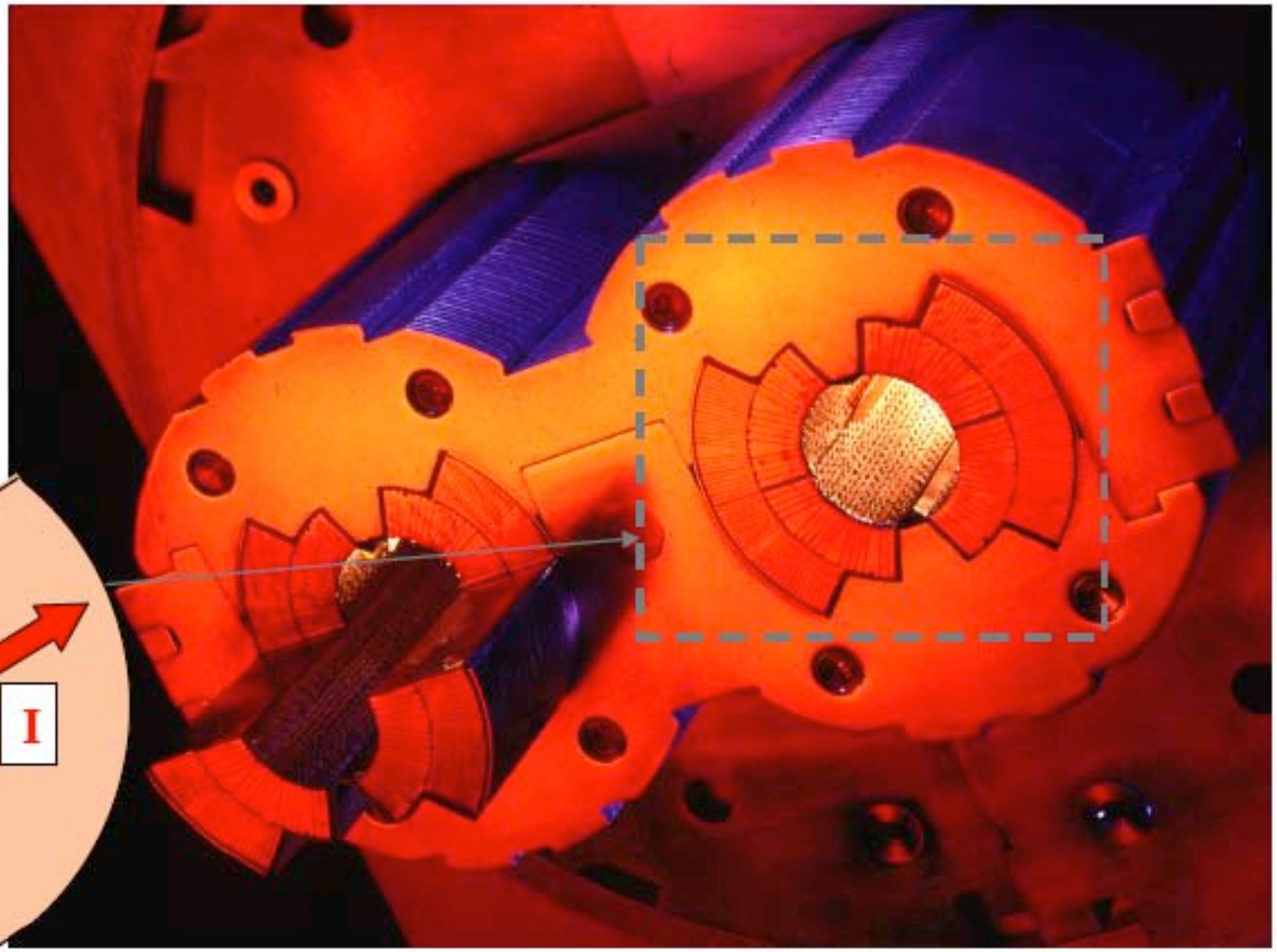


- *Dipole- and Quadrupole magnets*
  - Particle trajectory stable for particles with nominal momentum
- *Sextupole magnets*
  - To correct the trajectories for off-momentum particles
  - Particle trajectories stable for small amplitudes (about 10 mm)
- *Multipole-corrector magnets*
  - Sextupole - and decapole corrector magnets at end of dipoles
  - Particle trajectories can become unstable after many turns (even after 10^6 turns)

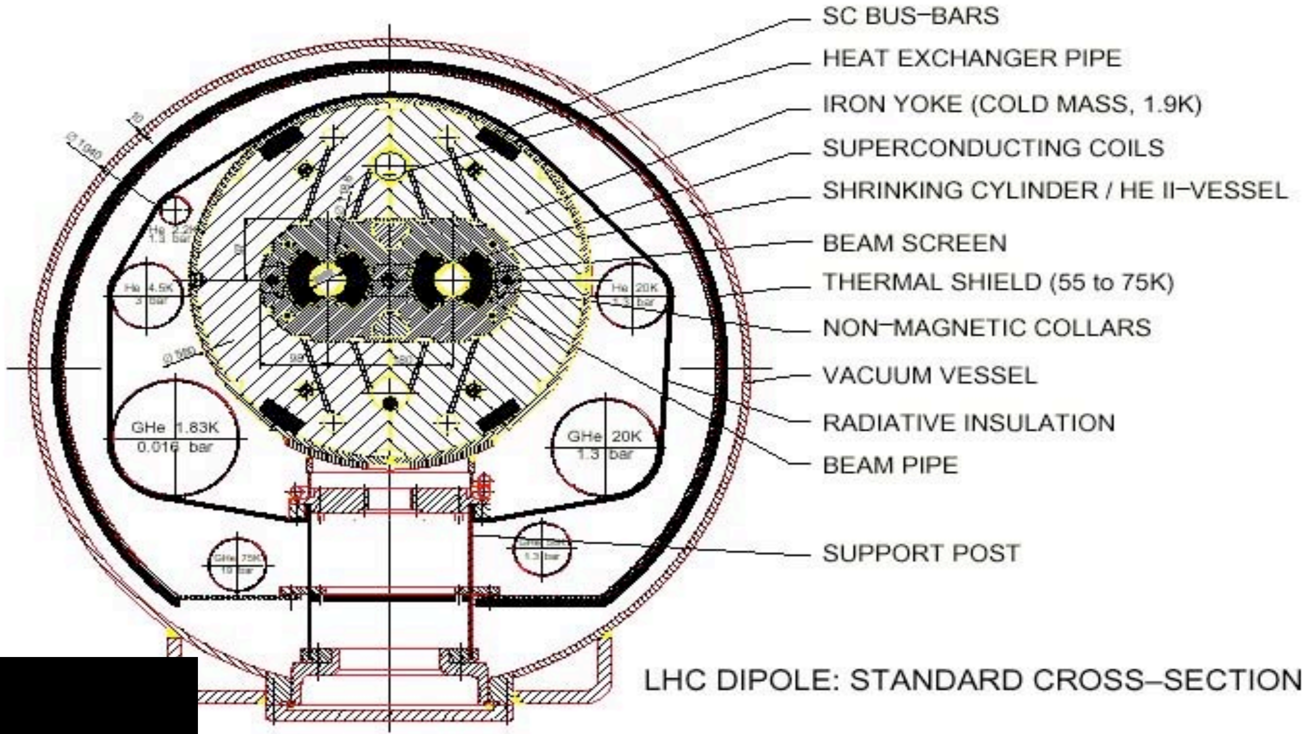
The cryodipoles

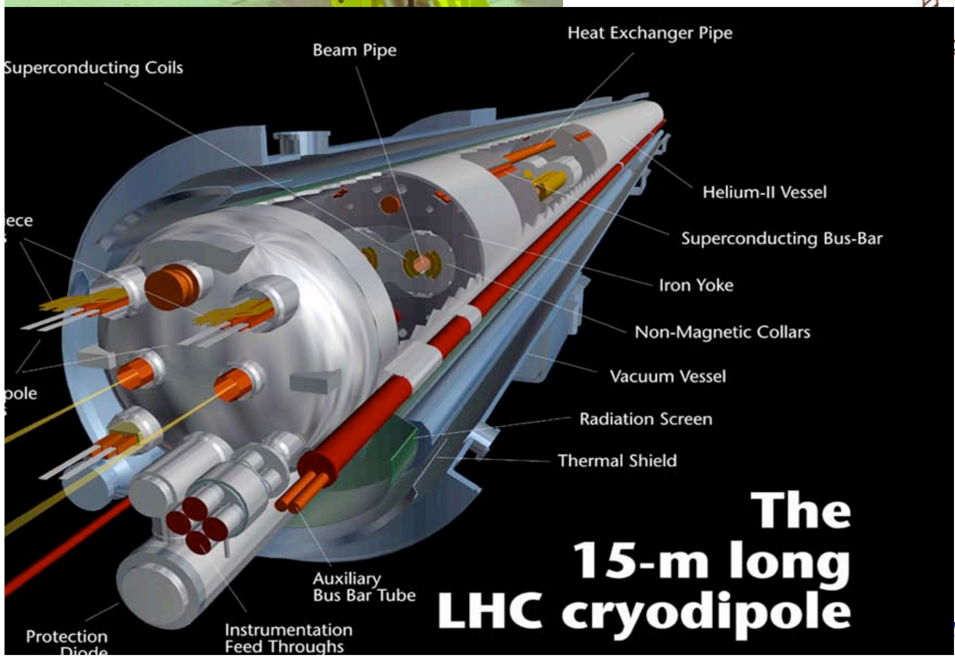




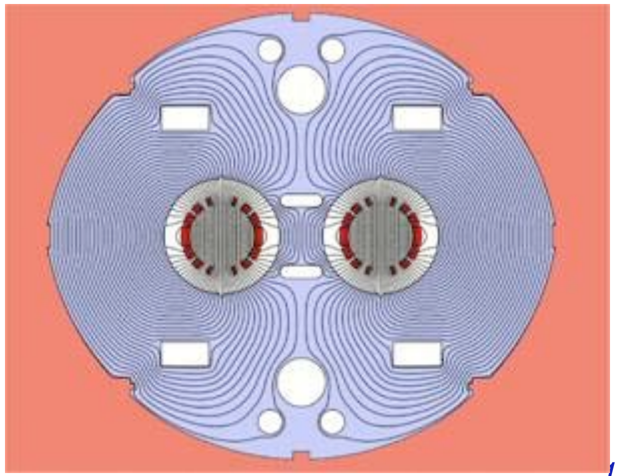


The cryodipoles (1232 pieces)

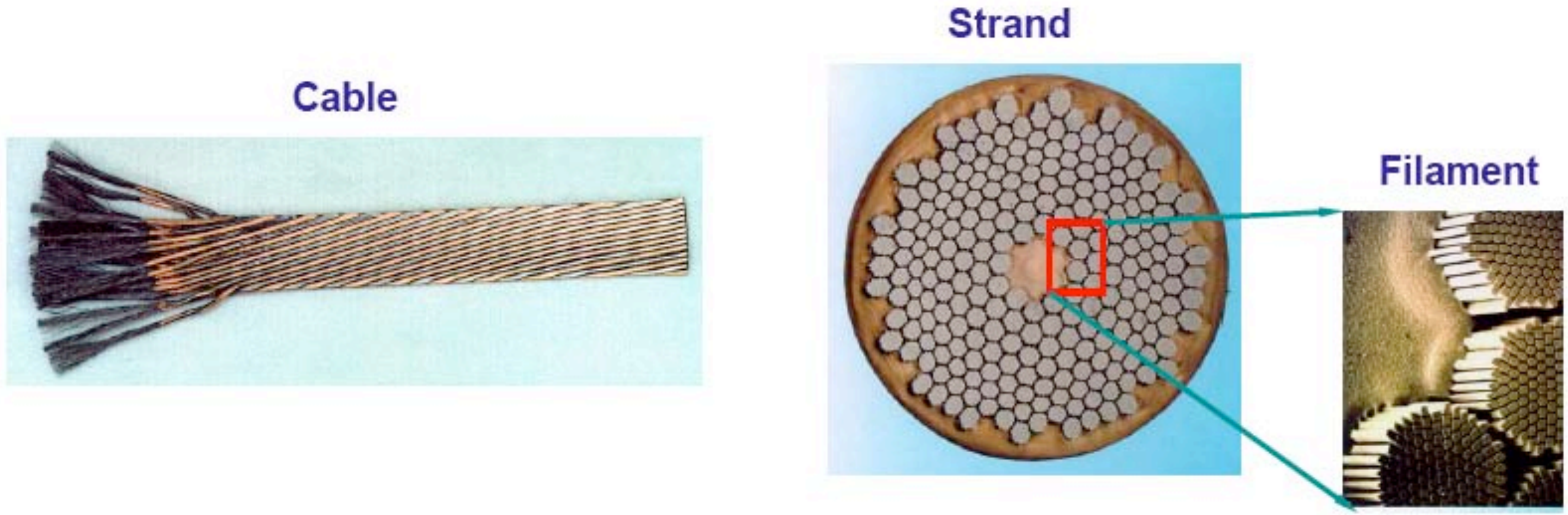




- ✓ *1.9 K*
- ✓ *8.33T @ 11.6KA*
- ✓ *15m, 34 tons*
- ✓ *1232 dipoles*
- ✓ *3700 correction magnets*



Niobium Titanium Rutherford cable



Total superconducting cable required 1200 tons which translate to about 7600 km of cable

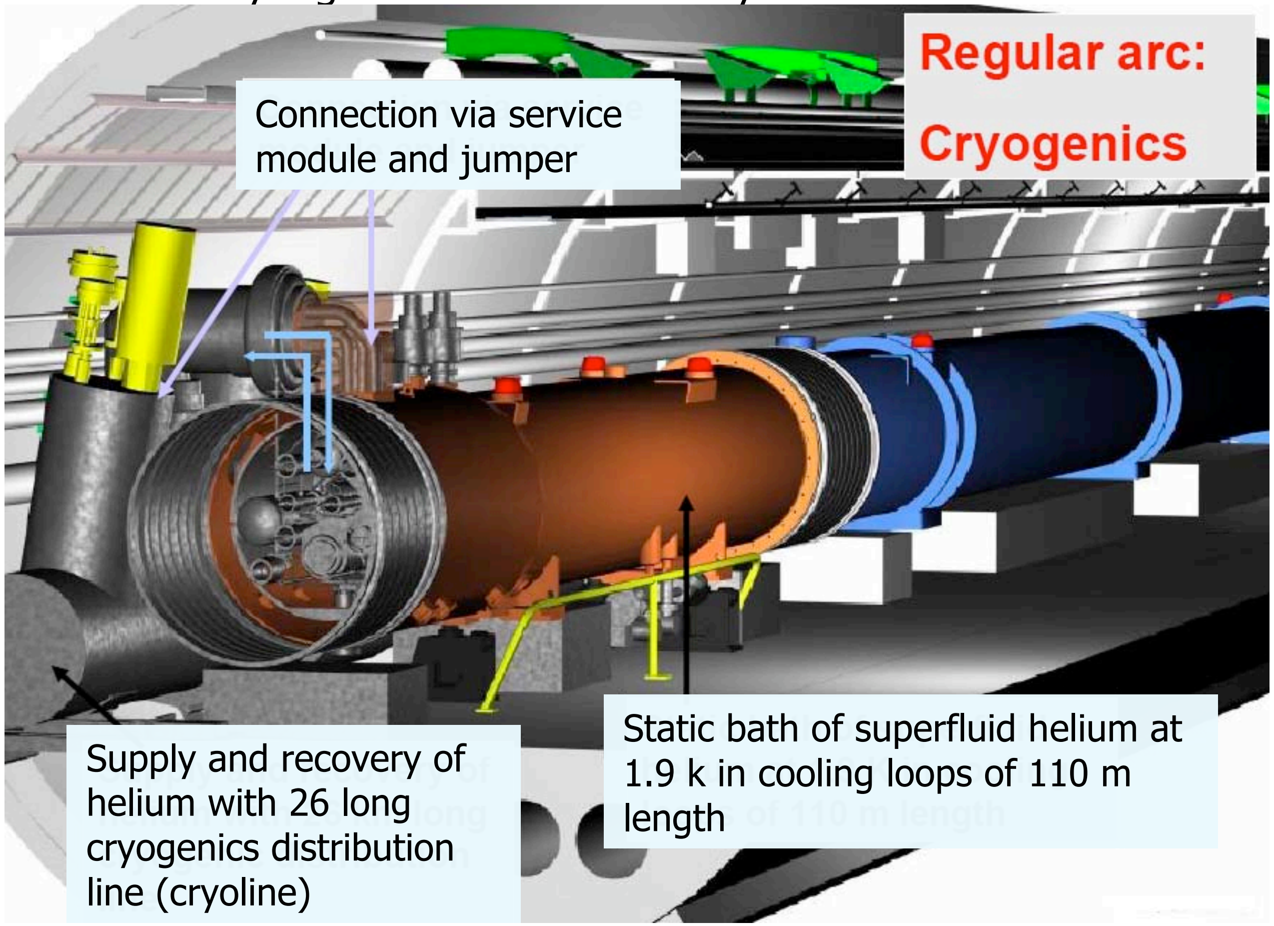
The cable is made up of strands which are made out of filaments. The total length of filaments would allow to go 5 times to the sun and back with enough length left over for a few trips to the moon

The cryoplant

The LHC dipoles use niobium-titanium (NbTi) cables, which become superconducting below a temperature of 10 K (-263.2 °C). In fact the LHC will operate at the still lower temperature of 1.9 K. A current of 11 700 A flows in the dipoles, to create the high magnetic field of 8.3 T.

At atmospheric pressure helium gas liquefies at around 4.2 K (-269°C), but when it is cooled further it undergoes a second phase change at about 2.17 K (-271°C) to its 'superfluid' state. Among many remarkable properties, superfluid helium has a very high thermal conductivity.

- ✓ ~12 tons of liquid He / sector
- ✓ 120 MW of installed electrical power
- ✓ 144 KW of refrigeration power (He)
- ✓ large cryoplant (He, N_2)
- ✓ 1260 tons of N_2 to cool down a sector



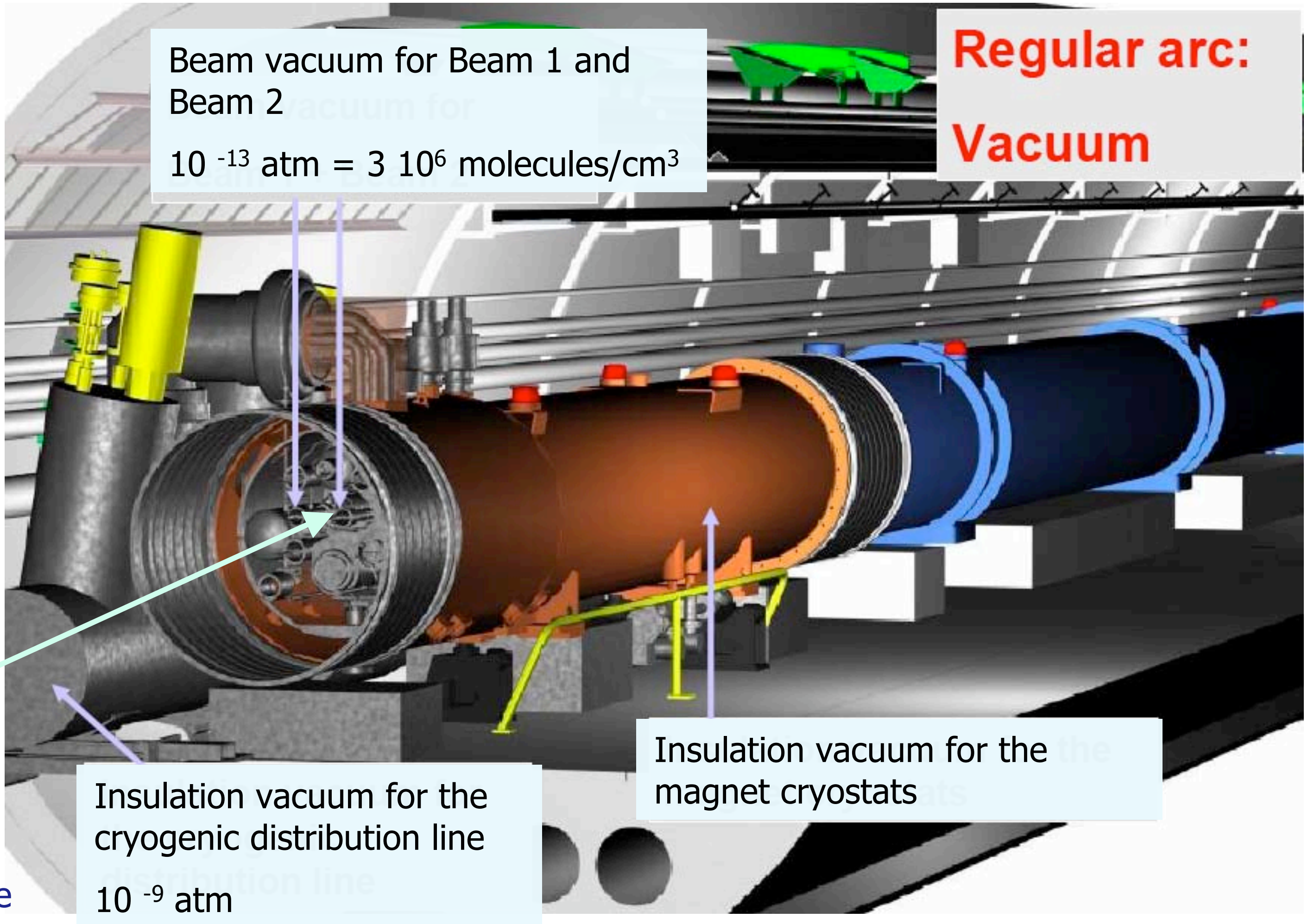
The vacuum plant

- *requirement < 10^{15} H_2/m^3*
  for 100h beam lifetime
- *over 27 km*
- *large amount of*
  isolation vacuum
  ~ 6500 m^3

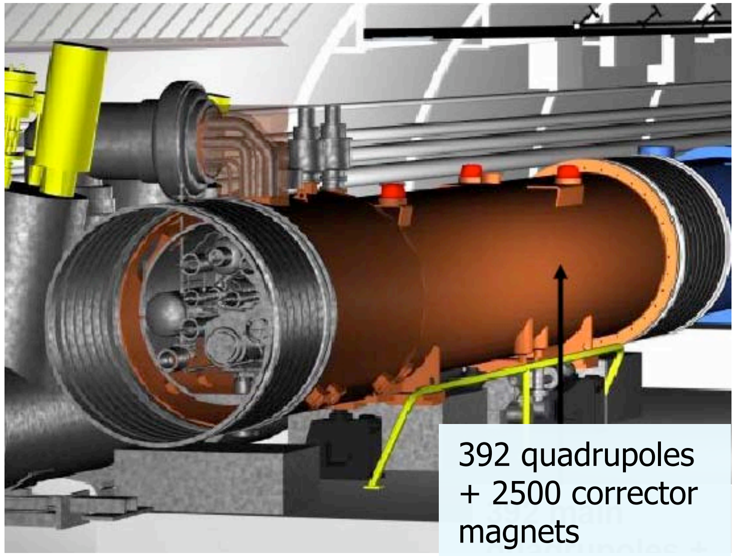
The cold bore tubes of the dipole magnets are seamless non-magnetic austenitic steel tubes 15.6 m long. The insulated cold bore tubes are placed in the aperture of the coils and form part of the inner wall of the helium vessel that contains the active part of the magnet.

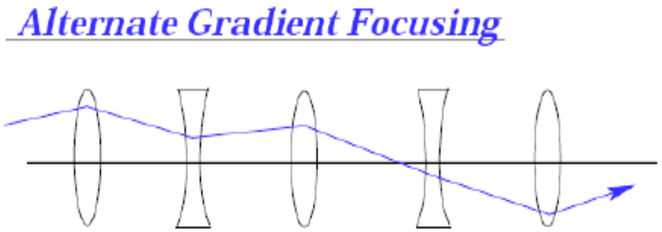
Permanent pumping is done with a limited number of sputter ion pumps (every 28m) and NEG (TiZrV) coating

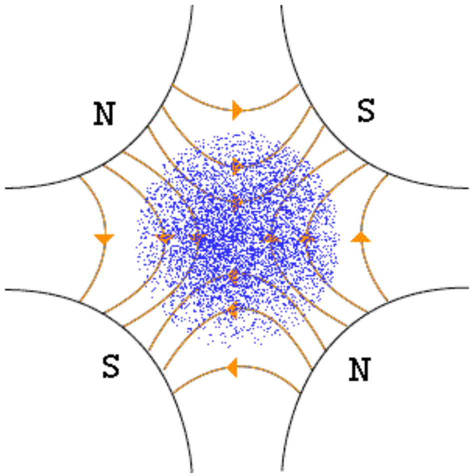
The vacuum lifetime is dominated by the nuclear scattering of protons on the on the residual gas



The focusing magnets (392 quadrupoles)



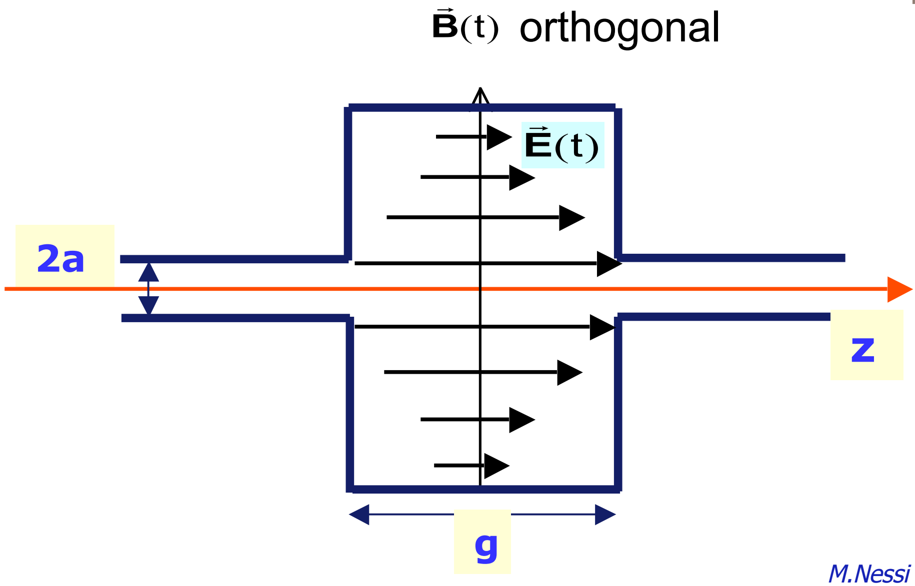


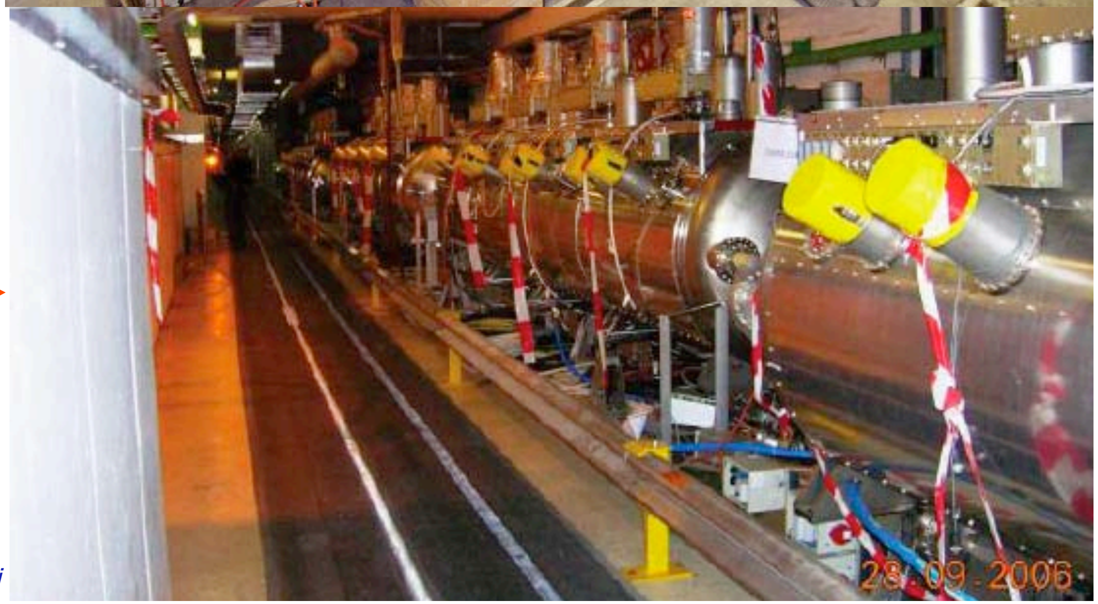


Nominal current: 11,870 A
(corresponds to a field gradient of
223 T/m)

The RF accelerating cavities (8 pieces)

The main role of the LHC cavities is to keep the 2808 proton bunches tightly bunched to ensure high luminosity at the collision points. They also deliver radiofrequency (RF) power to the beam during acceleration to the top energy. Superconducting cavities with small energy losses and large stored energy are the best solution. The LHC uses eight cavities per beam, each delivering 2 MV (an accelerating field of 5 MV/m) at 400 MHz. The cavities will operate at 4.5 K. They are grouped in fours in cryomodules, with two cryomodules per beam, and installed in a long straight section of the machine where the interbeam distance is increased from the normal 195 mm to 420 mm

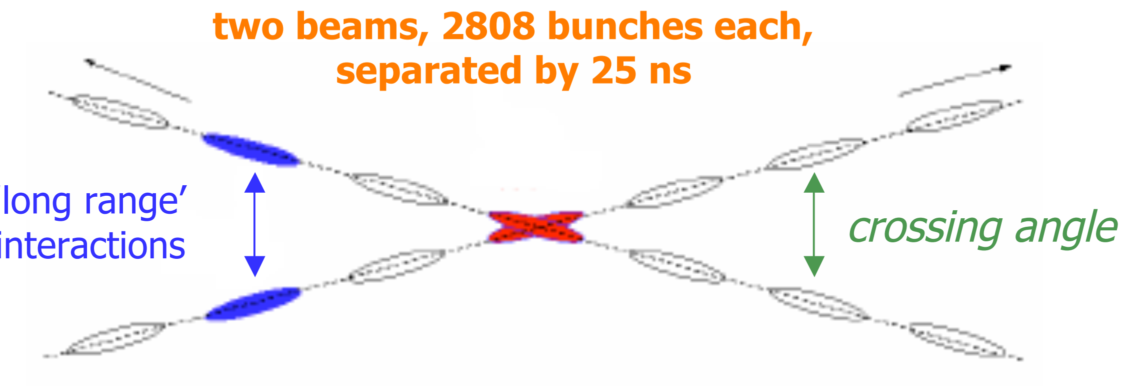




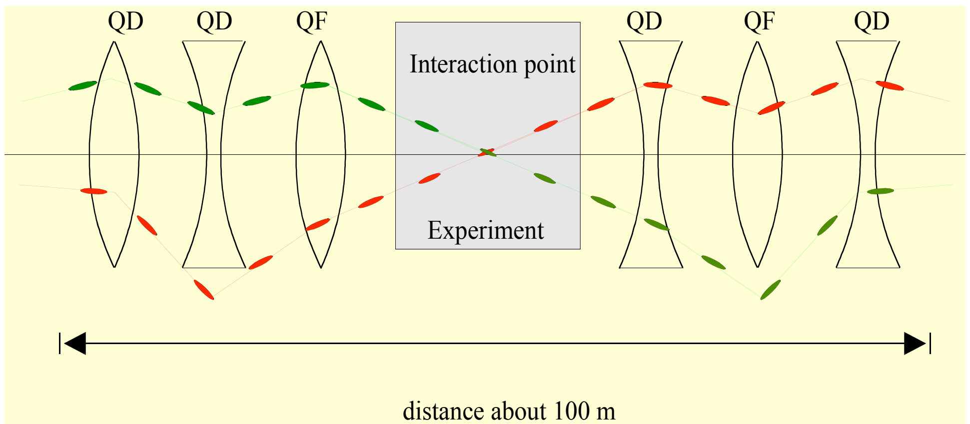
M.Nessi

LHC collides bunches with a crossing angle

To avoid unwanted parasitic encounters, the LHC beams cross at an angle of 300 microradian (full angle). The spacing between two bunches is 25 ns. Before the two beams enter separate beam pipes, they travel in the same vacuum chamber where parasitic 'long range' collisions can occur



Beam size at IP 16 μm, in arcs about 0.3 mm



Interaction Region quadrupoles with gradient of 250 T/m and 70 mm aperture

M.Nessi - CERN

Production rate proportional to Luminosity

Production rate:

$$N_{ev/sec} = L * \sigma$$

$$L = \frac{N^2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} \cdot F \leftarrow F = 1 \Big/ \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sqrt{\varepsilon_n \beta^*}}\right)^2}$$

- Number of protons per bunch: N
- Number of bunches: k_b
- Relativistic Lorentz factor: γ
- Full crossing angle: θ_c
- Bunch length: σ_z
- Normalized emittance: ε_n
- Beta function at the IP: β^*

$\varepsilon_n \beta^*$: beam size or rather overlap integral at IP

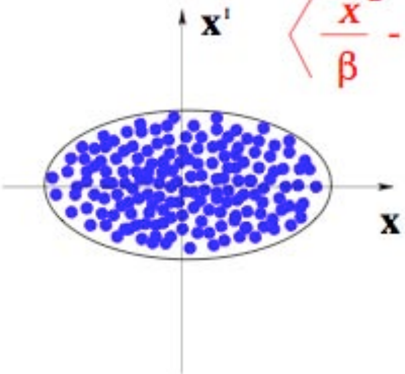
crossing angle correction: F

N= 1.15 10^{11} p/bunch, f=11.2455 kHz,
σ=17μm, β=.55, F=0.8

1 bunch --> L= 3.45 10^{30} cm^{-2} sec^{-1}

2808 bunches --> L= 0.97 10^{34} cm^{-2} sec^{-1}

- ***beam ensemble:***



$$\left\langle \frac{x^2}{\beta} - \beta' \cdot x \cdot x' + \beta \cdot x'^2 \right\rangle = \varepsilon$$

$$\varepsilon = \frac{area}{\pi}$$

→ ε ***describes the beam quality***

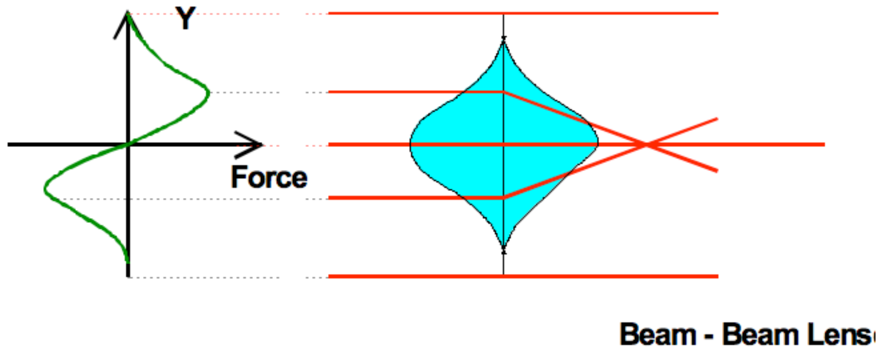
→ $\sigma = \sqrt{\varepsilon \cdot \beta}$ ***describes the beam size***

Beams : moving charges

- ✓ A beam is a collection of charges
- ✓ It represents an electromagnetic potential for other charges

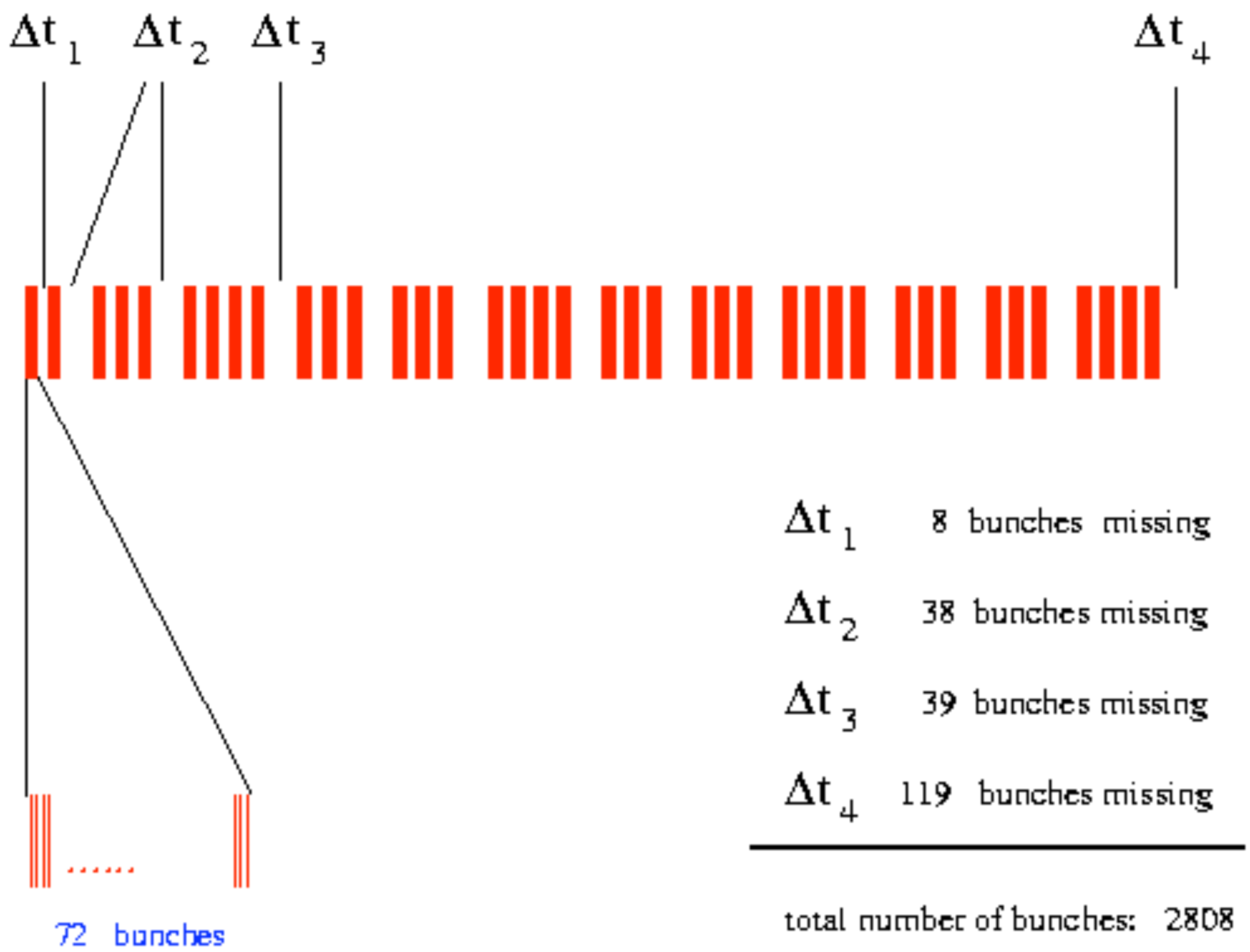
  - → *Forces on itself (space charges) and on opposing beam (beam-beam effects)*
  - → *Main limit for present and future colliders*
  - → *Important for high density and small beams = high luminosity*
  - → *Beam induced quenches (when 10^{-7} of beam hits magnet at 7 TeV)*

Beam beam interactions



Beams structure

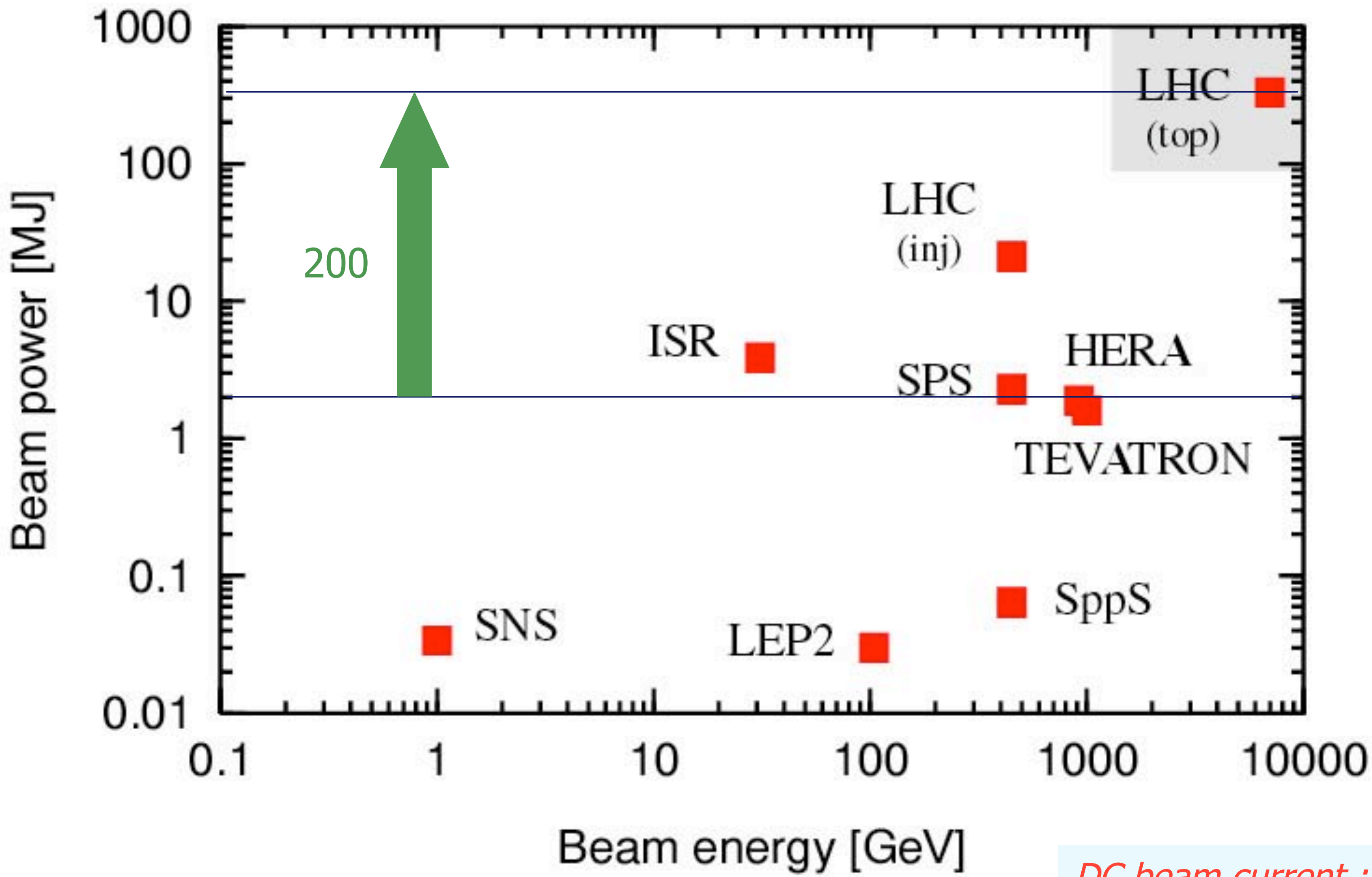
- ✓ bunch filling not continuous
- ✓ holes for injection, extraction and dump ….
- ✓ 2808 of 3564 possible bunches -> 1756 holes
- ✓ holes meet holes at the IP
- ✓ …. but not always … the one misses some long range interaction (PACMAN bunches)



LHC parameters

Beam energy:	**7 TeV**
➔ limited by maximum dipole field	
➔ **extension by factor 7 beyond TEVATRON**	
Bunch intensity:	**1.15×10^{11} p**
➔ limited by beam-beam effects	
Normalized emittance:	**3.75 μm**
➔ limited by injectors and main dipole aperture (keep smaller or equal)	
Beam size at IP ($\beta^* = 0.5$ m):	**16 μm**
➔ limited by triplet magnet aperture	
Crossing angle:	**300 μrad**
➔ limited by triplet magnet aperture	
Number of bunches:	**2808**
➔ limited by stored beam energy	
➔ **extension in stored energy by factor ~200**	
Nominal luminosity:	**10^{34} cm^{-2}s^{-1}**
➔ **extension by factor 100 beyond TEVATRON**	

Stored beam energy



DC beam current : 0.56 A
Stored energy per beam : 350 MJ

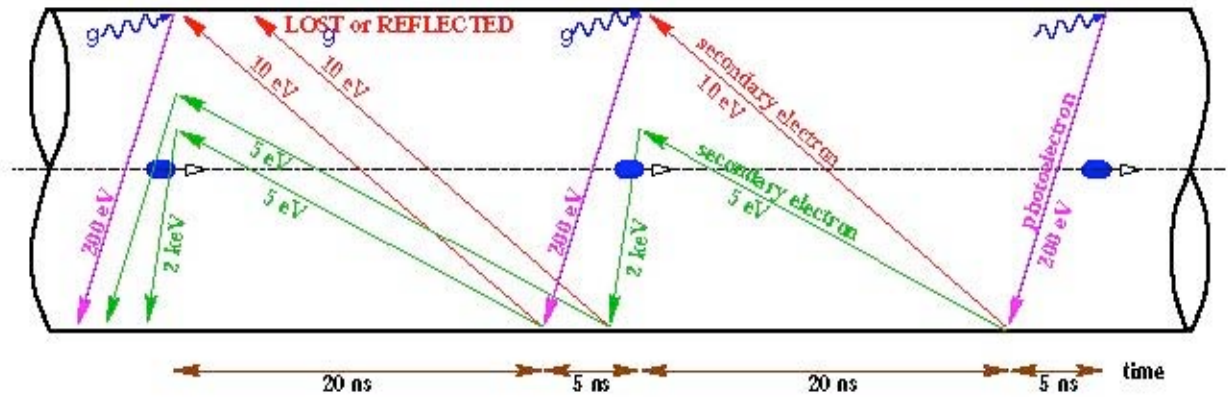
Beam stored energy (350 MJ/beam)

British aircraft carrier at 12 knots

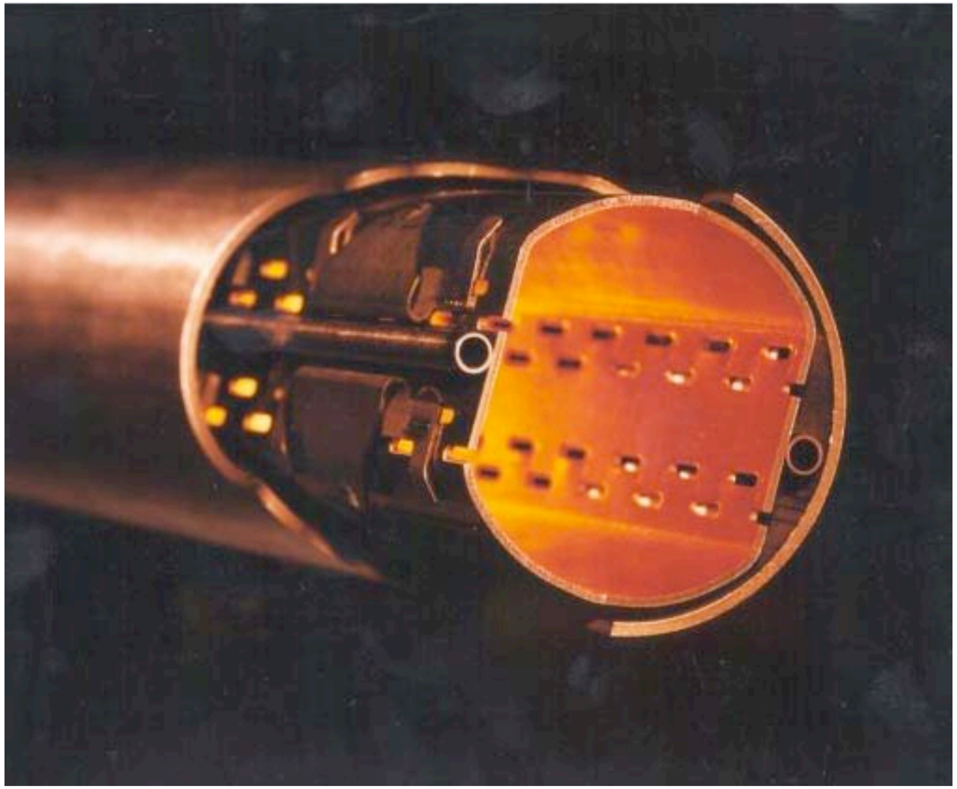
Electron clouds

Synchrotron radiation from proton bunches creates photoelectrons at the beam screen wall. These photoelectrons are pulled toward the positively charged proton bunch. When they hit the opposite wall, they generate secondary electrons which can in turn be accelerated by the next bunch.

Depending on several assumptions about surface reflectivity, photoelectron and secondary electron yield, this mechanism can lead to the fast build-up of an electron cloud with potential implications for beam stability and heat load on the beam screen.



Electron clouds strategy



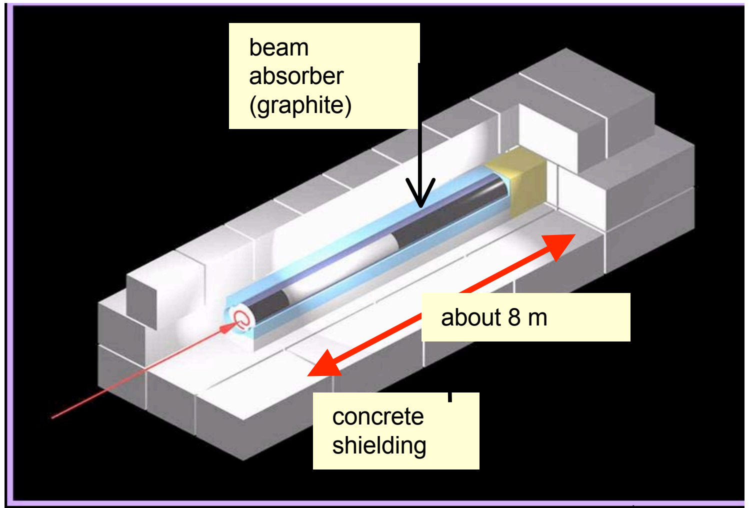
1) warm sections (20% of circumference) **coated by TiZrV getter** developed at CERN; low secondary emission; if cloud occurs, ionization by electrons (high cross section ~400 Mbarn) aids in pumping & pressure will even improve

*2) outer wall of beam screen (at 4-20 K, inside 1.9-K cold bore) will have a **sawtooth surface** (30 mm over 500 mm) to reduce photon reflectivity to ~2% so that photoelectrons are only emitted from outer wall & confined by dipole field*

3) pumping slots in beam screen are **shielded** to prevent electron impact on cold magnet bore

*4) rely on **surface conditioning** ('scrubbing'); commissioning strategy; as a last resort doubling or tripling bunch spacing suppresses e-cloud heat load*

Beam dump system in IR6



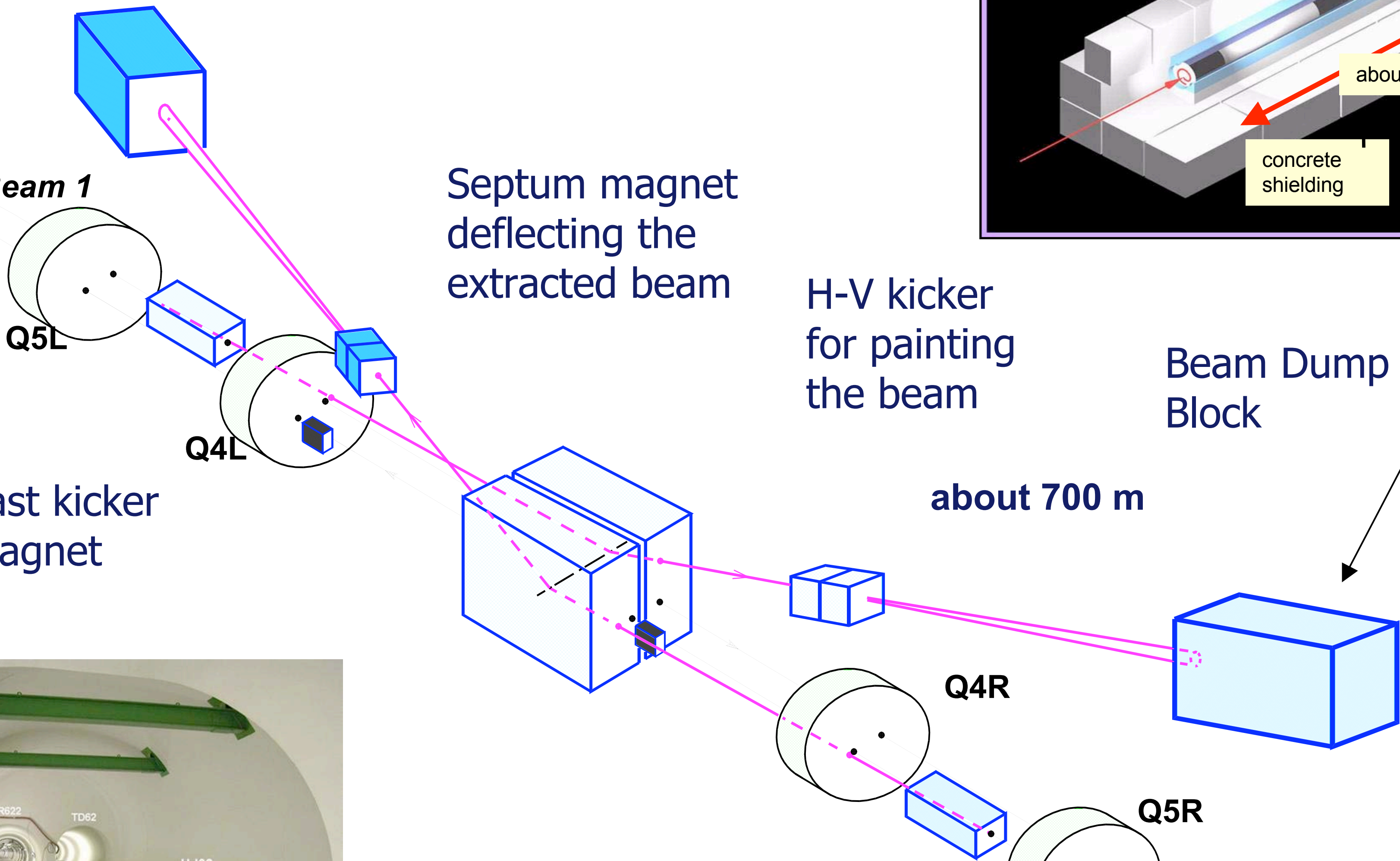
Septum magnet deflecting the extracted beam

H-V kicker for painting the beam

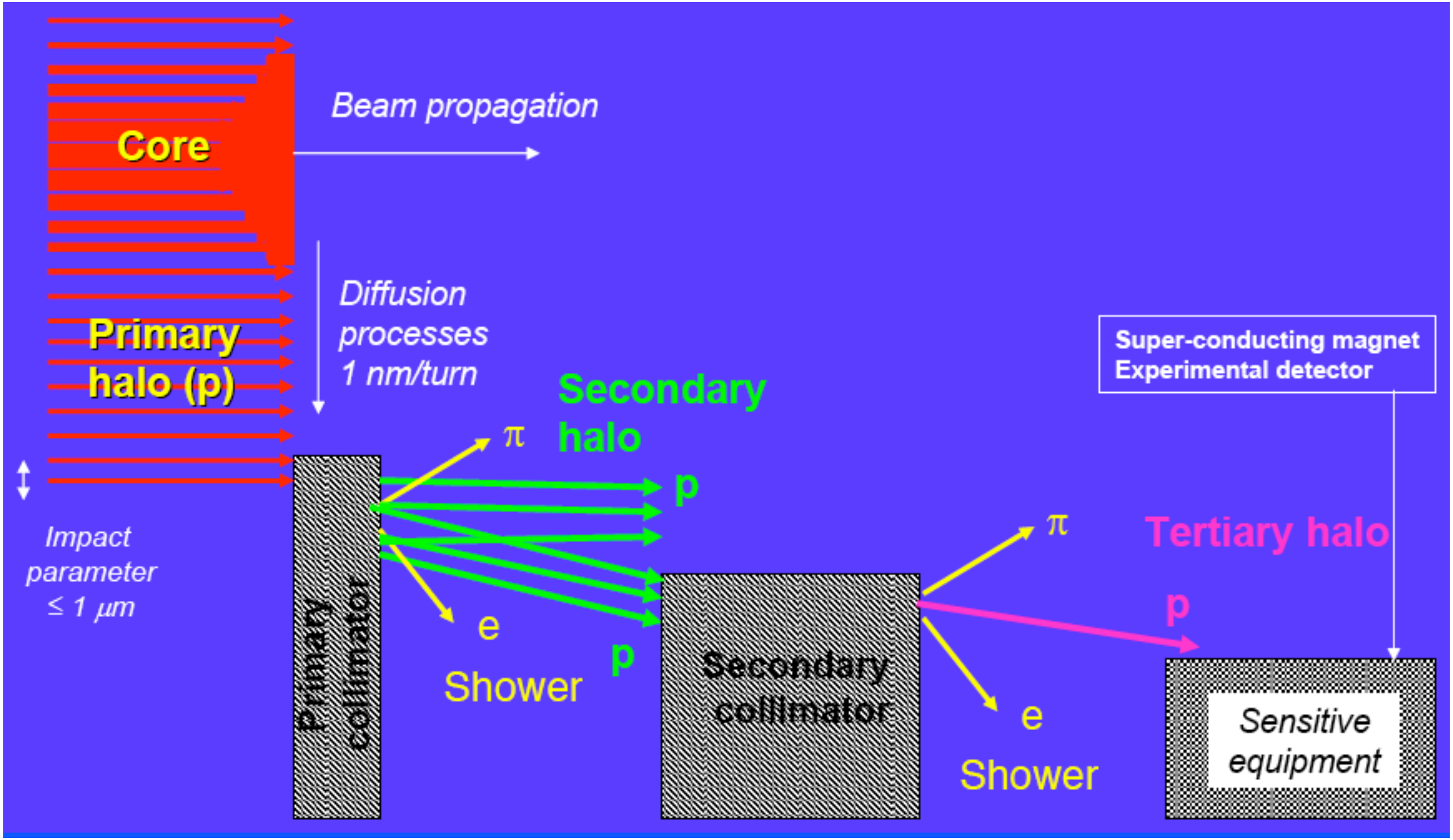
Beam Dump Block

Fast kicker magnet

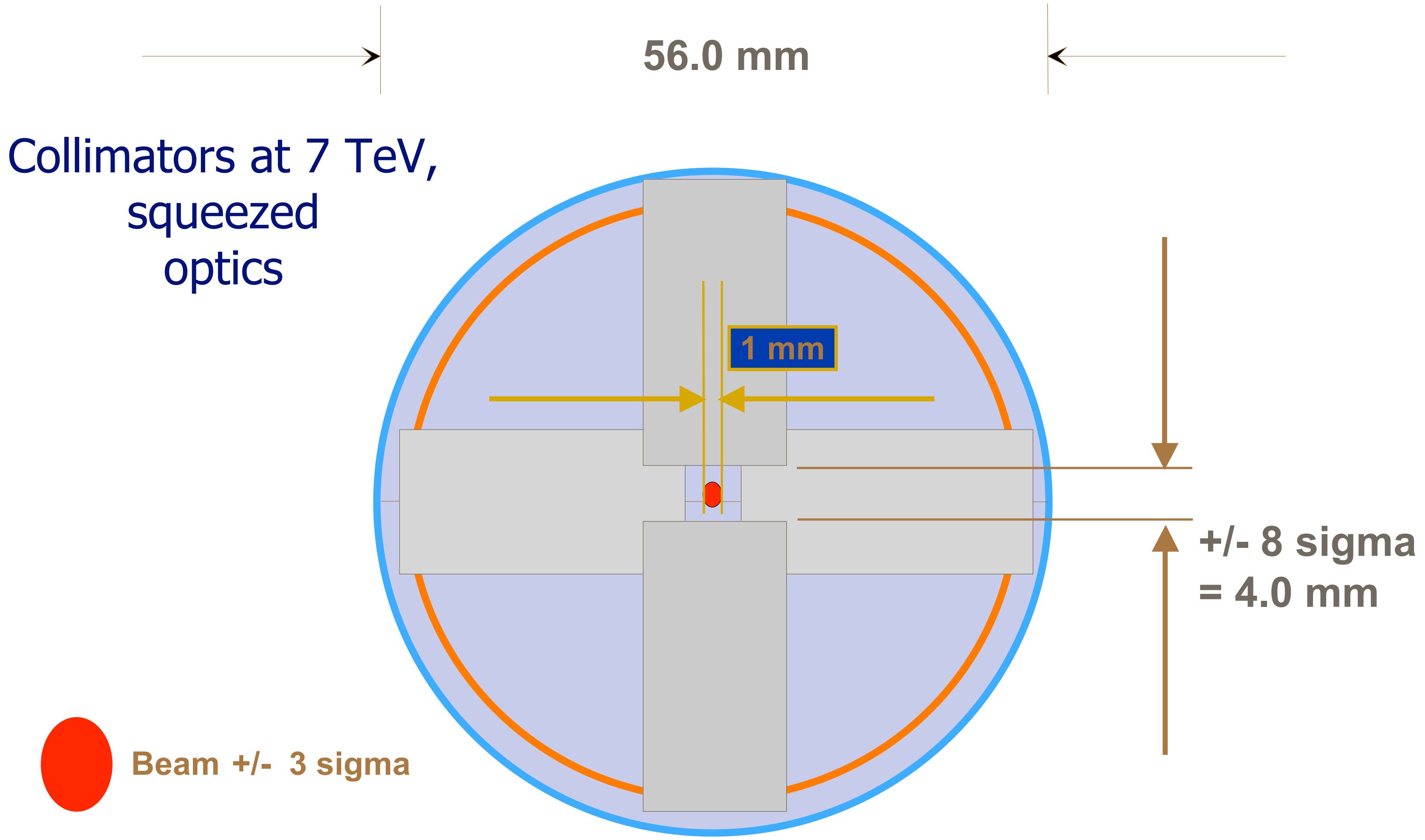
about 700 m



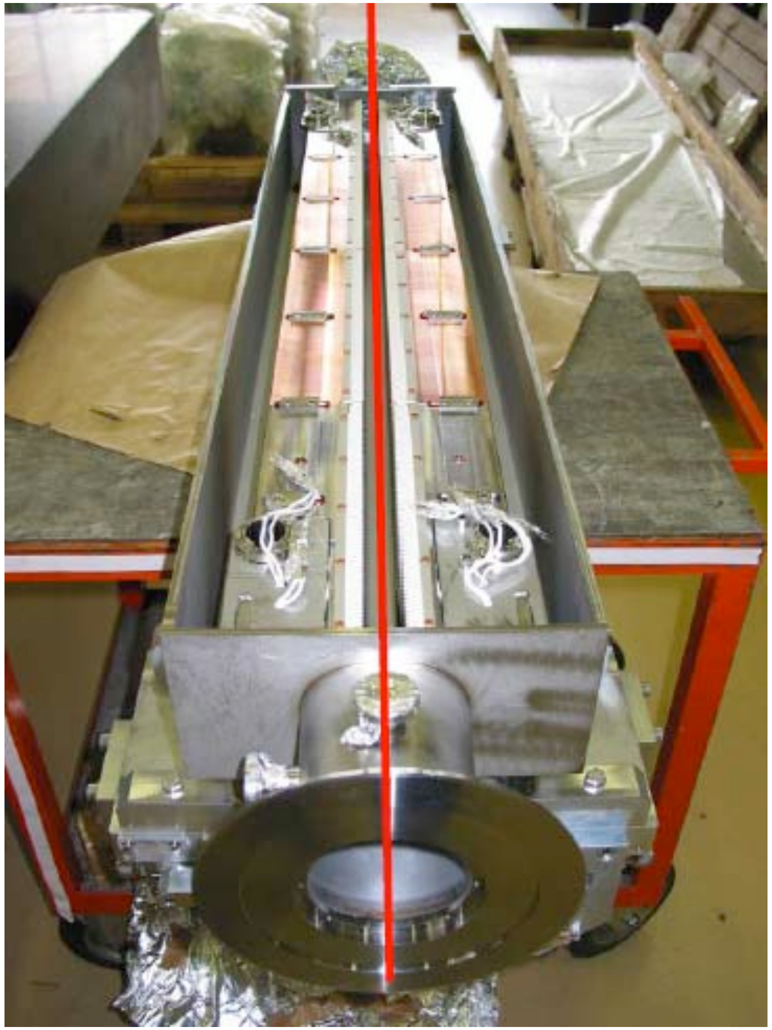
Beam protection (IR3 and IR7)



Beam must always touch collimators first !



Beam protection



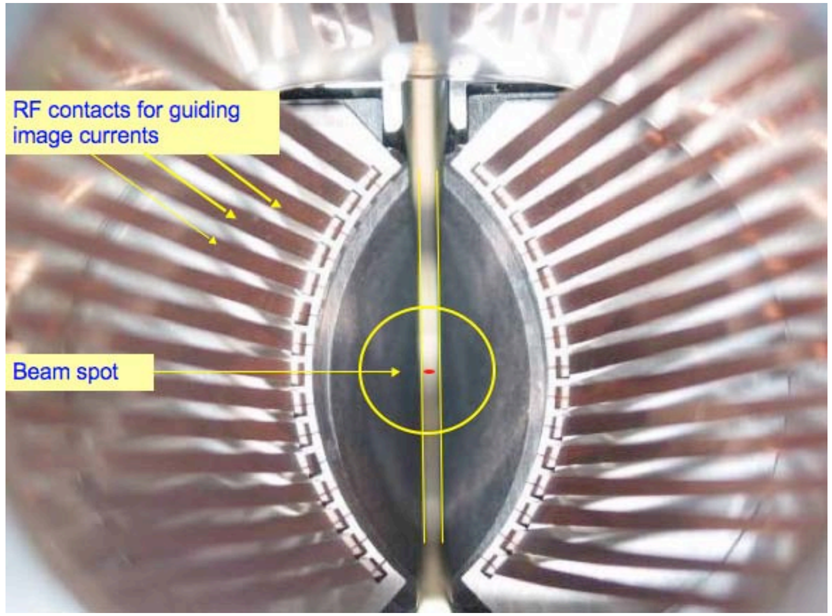
A tiny fraction of the beam is sufficient to quench a magnet

Very efficient beam cleaning is required

- ✓ *Sophisticated beam cleaning with about 50 collimators, each with two jaws, in total about 90 collimators and beam absorbers*
- ✓ *Collimators are close to the beam (full gap as small as 2.2 mm, for 7 TeV with fully squeezed beams), particles will always touch collimators first !*

Designed for maximum robustness:

Advanced Carbon Composite material for the jaws with water cooling!

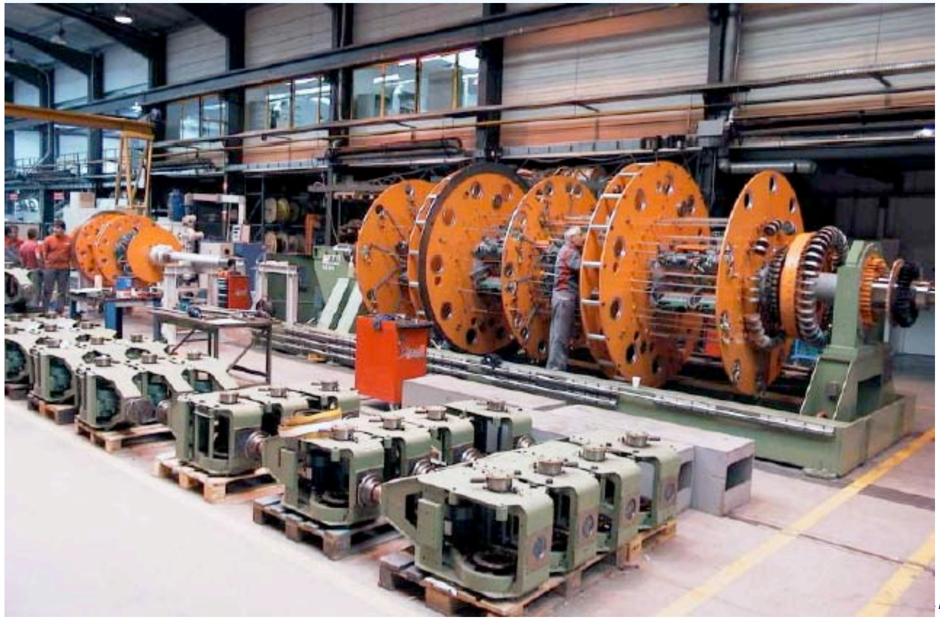


Many successes

Dipoles construction ....some problems....

- In January 2002, [redacted] declared a case of "force majeure", flooding of the premises of a subcontractor. Billet assembly dropped to half speed, concentrating on inner cable on CERN's demand. This resulted in no delivery of outer cable from [redacted] in the months June – August. The situation will now improve.
- In June, the cabling machine at [redacted] had a major breakdown. This machine is being repaired and should become fully operational early November. A second cabling machine is being manufactured and will become fully operational early next year. In the meantime we are accumulating strands.

example of problems occurred

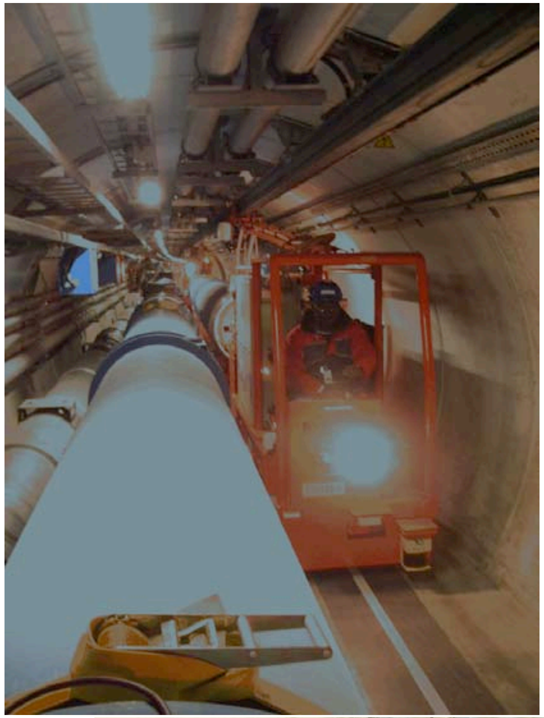


- Coil production and collaring is now fully industrial. Additional winding and curing tooling is being commissioned.
- Production startup for cold mass assembly has been slower than foreseen (commissioning of automatic welding presses, training of additional staff ~50 per firm, motivation).
- Production will now ramp up in all 3 firms.
  - ~40 dipoles by end of year
  - First octant complete September 2003

example of problems occurred

Dipoles installation

First cryodipole lowered on 7 March 2005



Transport in the tunnel with an optical guided vehicle, about 1600 magnets transported for up to 20 km at 3 km/hour

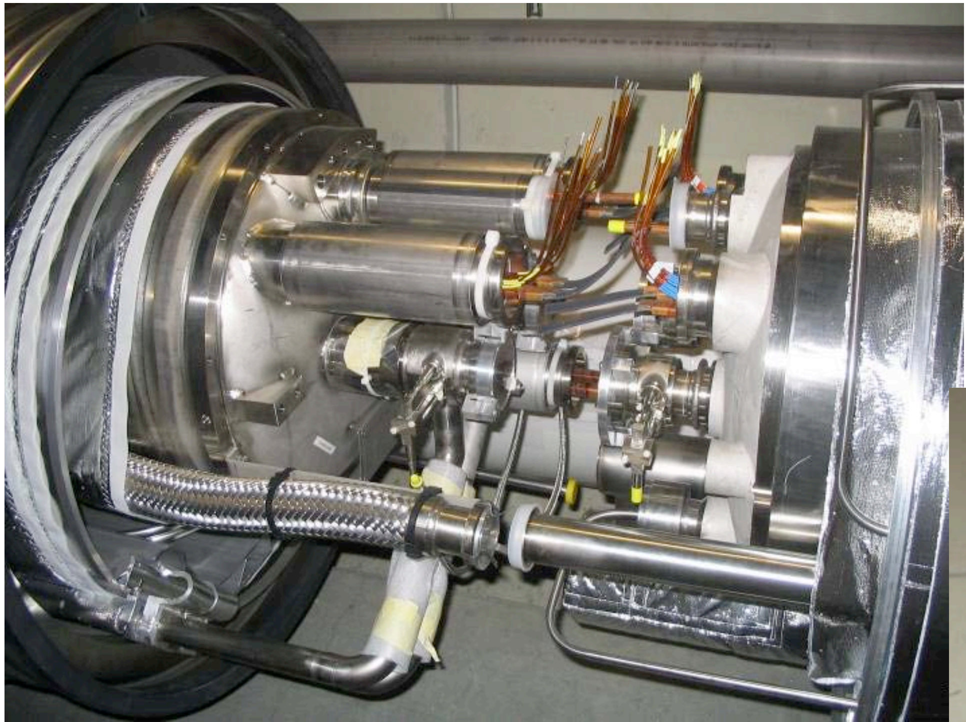
Last cryodipole lowered on 16 April 2007

Transfer on jacks

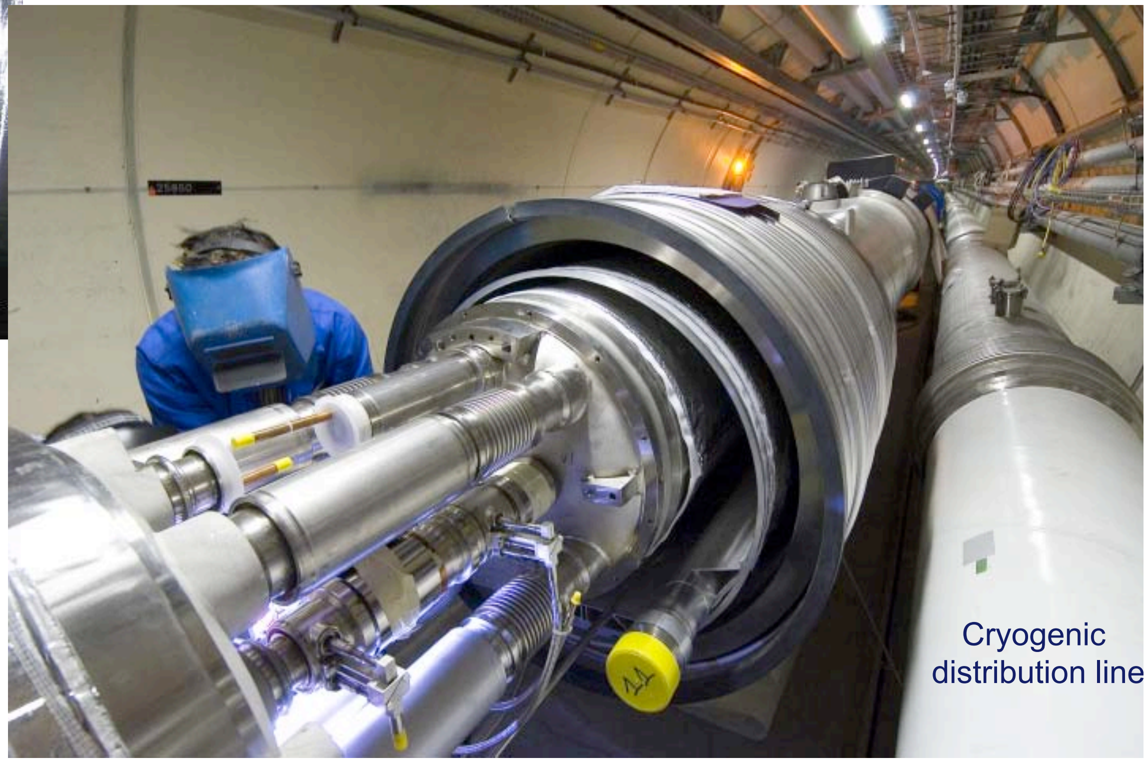
Dipoles interconnection

Vacuum, bellows, RF contacts plus leak checks
Cryogenics, thermal shield, heat exchanger
Bus bars
- superconducting splices x 10,000 (induction welding)

Corrector circuits
- splices x 50,000 (ultrasonic welding)



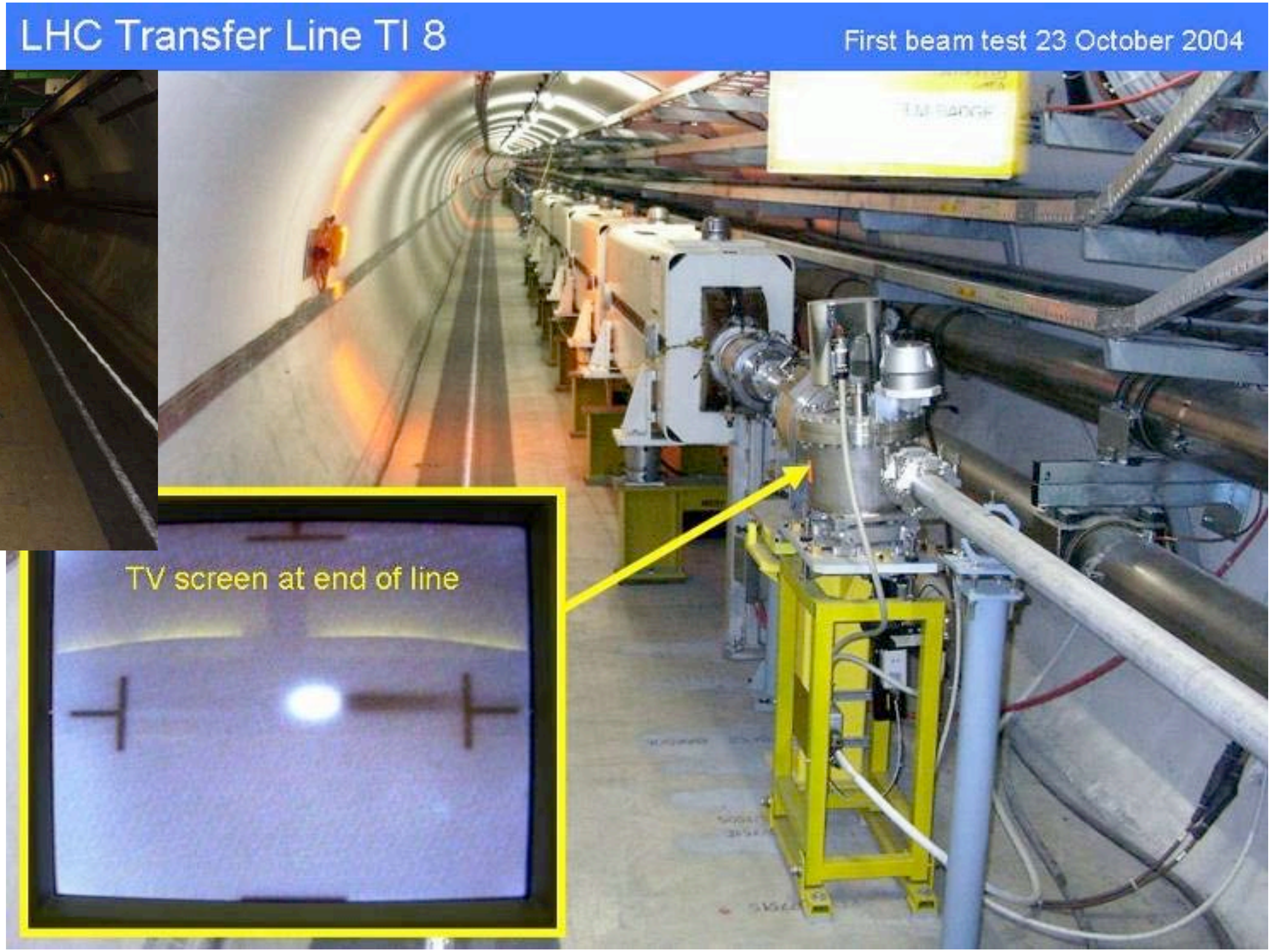
Preparation of interconnect



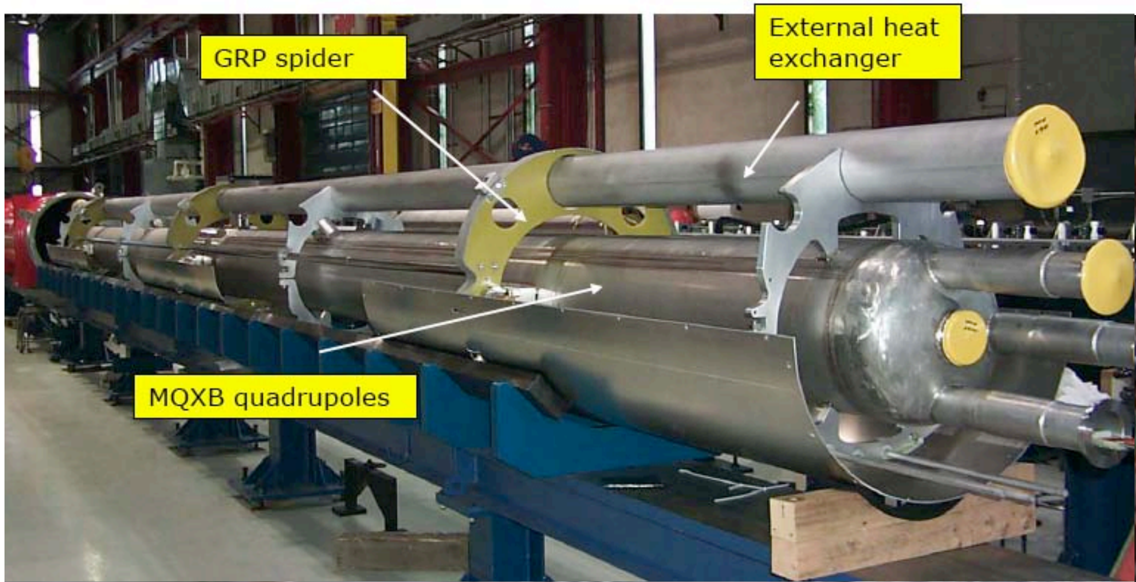
Interconnection of beam tubes

Electrical tests

Transfer line tests (October 2004)



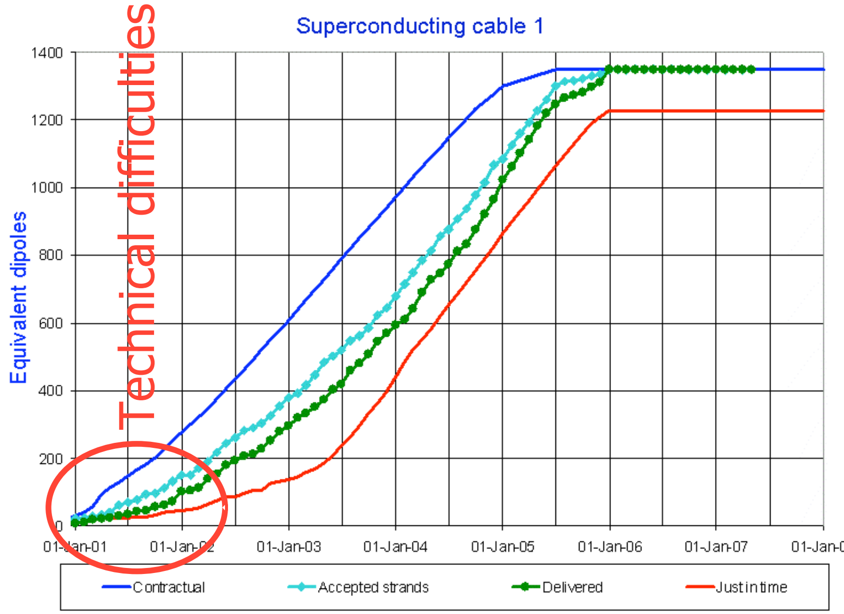
Low beta triplets (today on the critical path)



Problems found during final pressure tests in situ

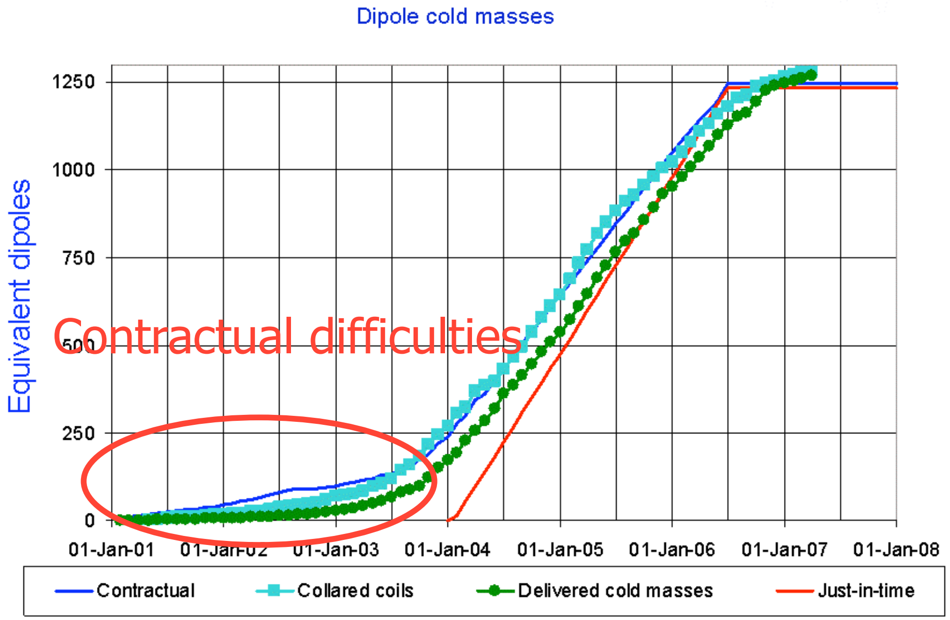
LHC Progress Dashboard

Accelerator Technology Department



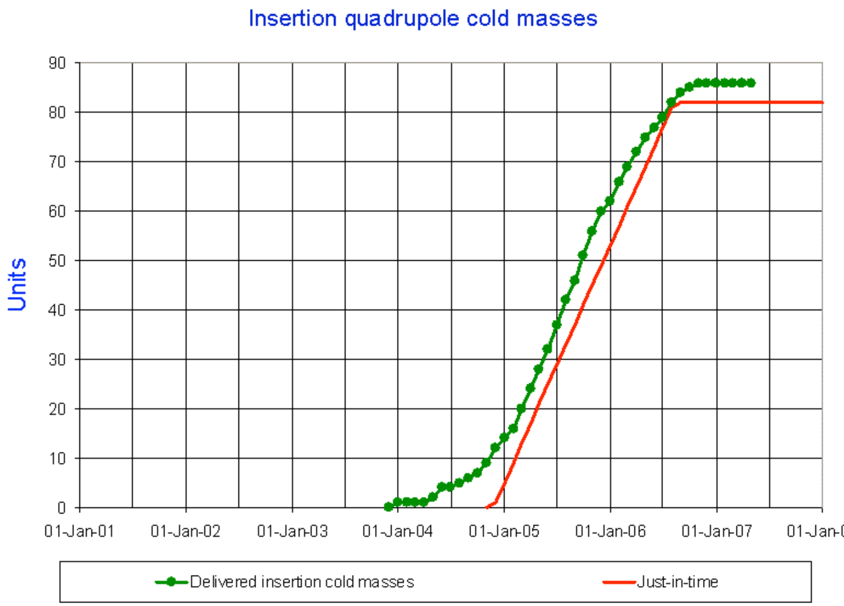
LHC Progress Dashboard

Accelerator Technology Department



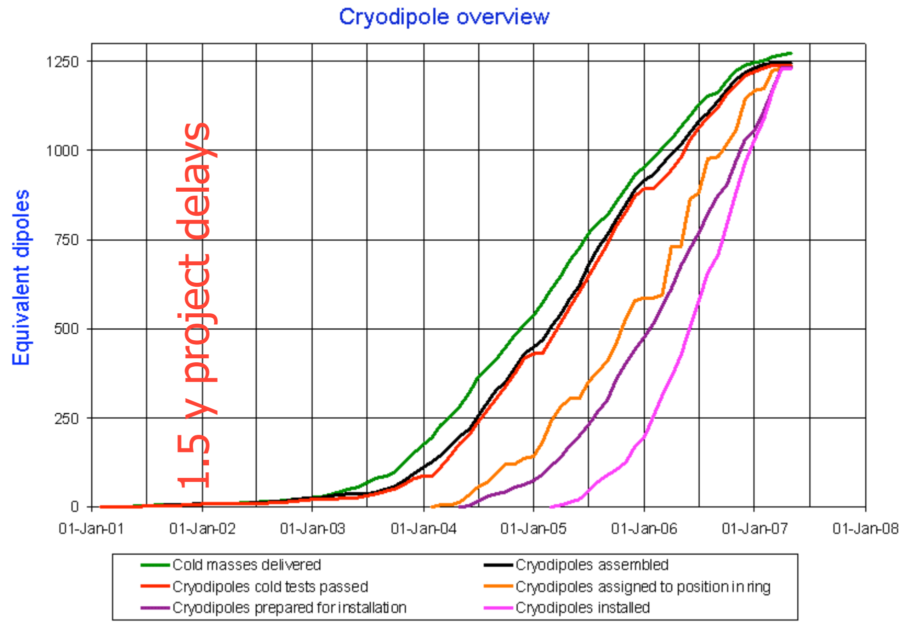
LHC Progress Dashboard

Accelerator Technology Department

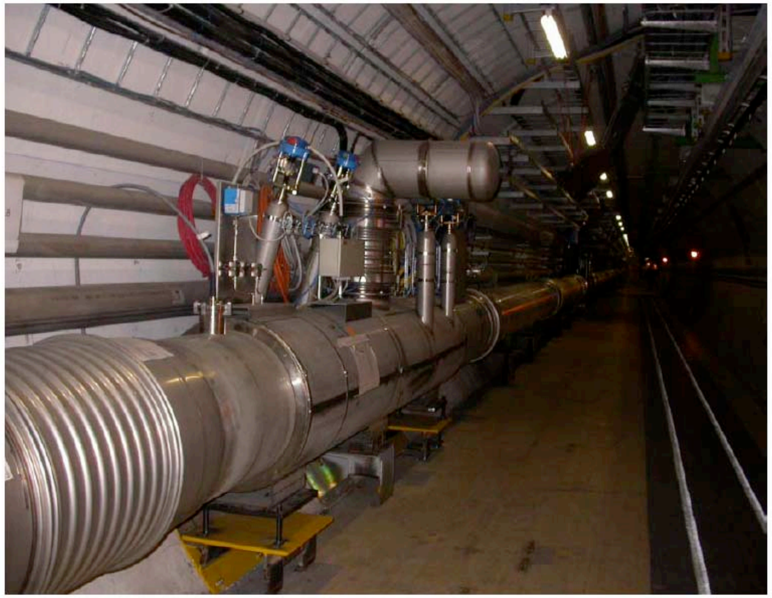


LHC Progress Dashboard

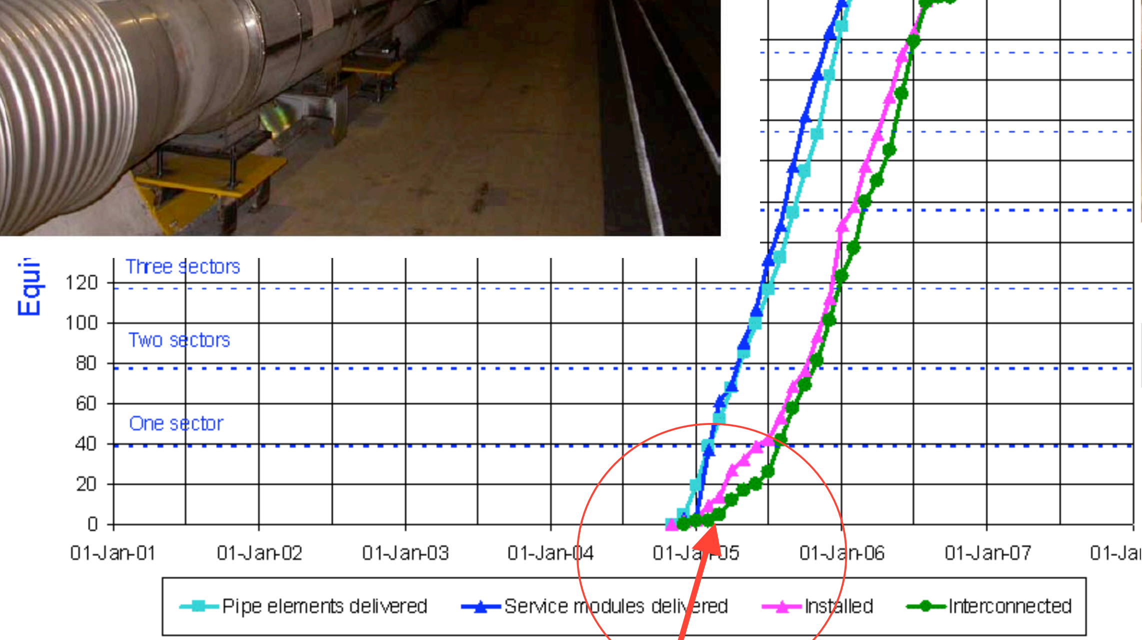
Accelerator Technology Department



Cryogenics transfer lines



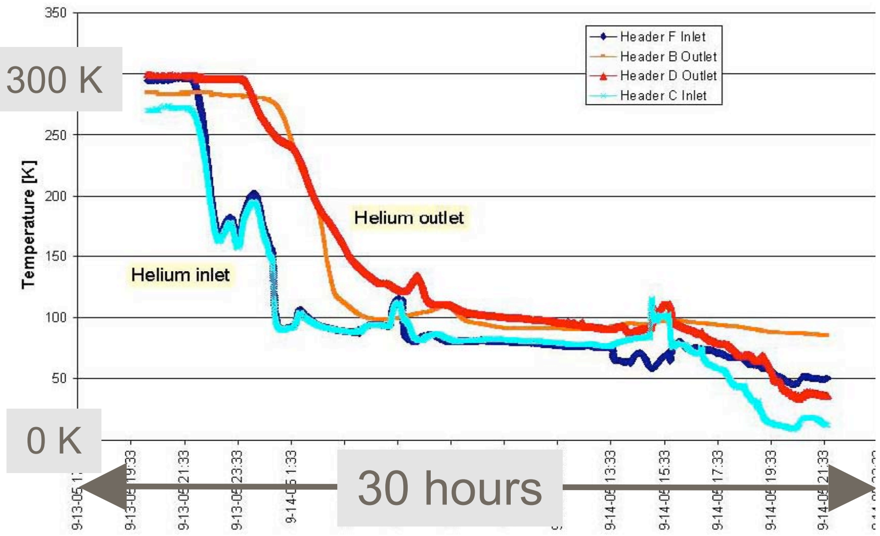
QRL repairs



Updated 30 April 2007 Data provided by G. Riddone AT-ACR

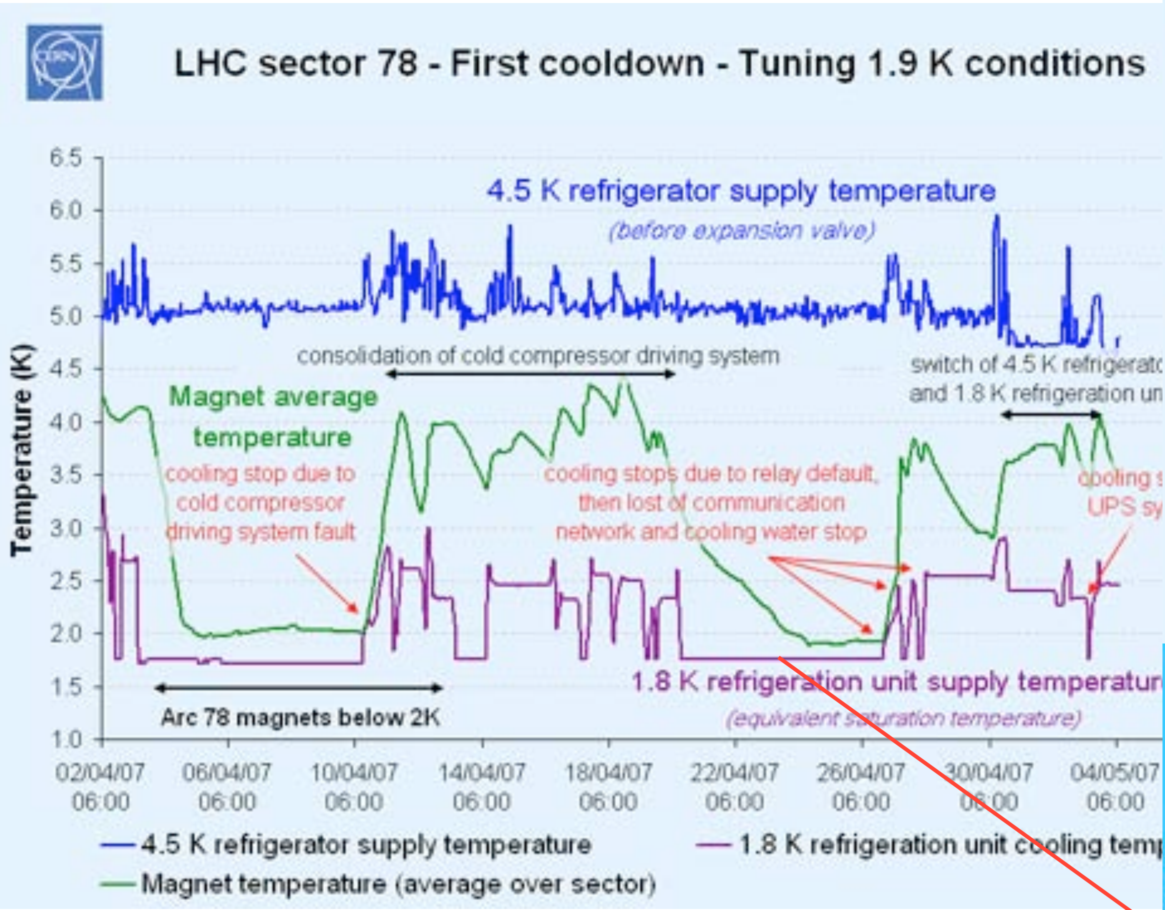
QRL crisis

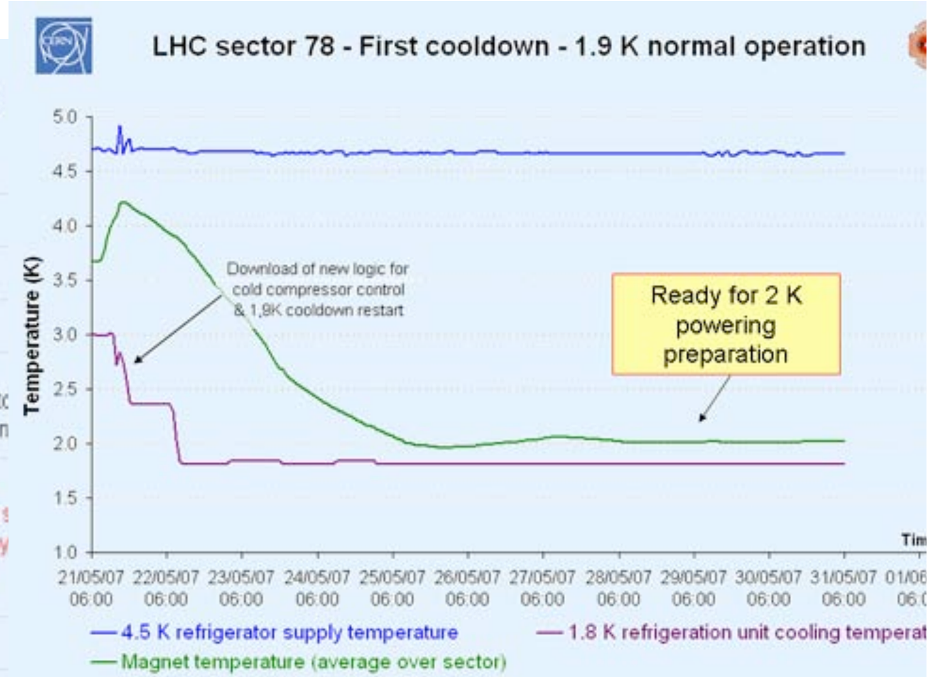
Temperatures in the 600-m QRL sub-sector

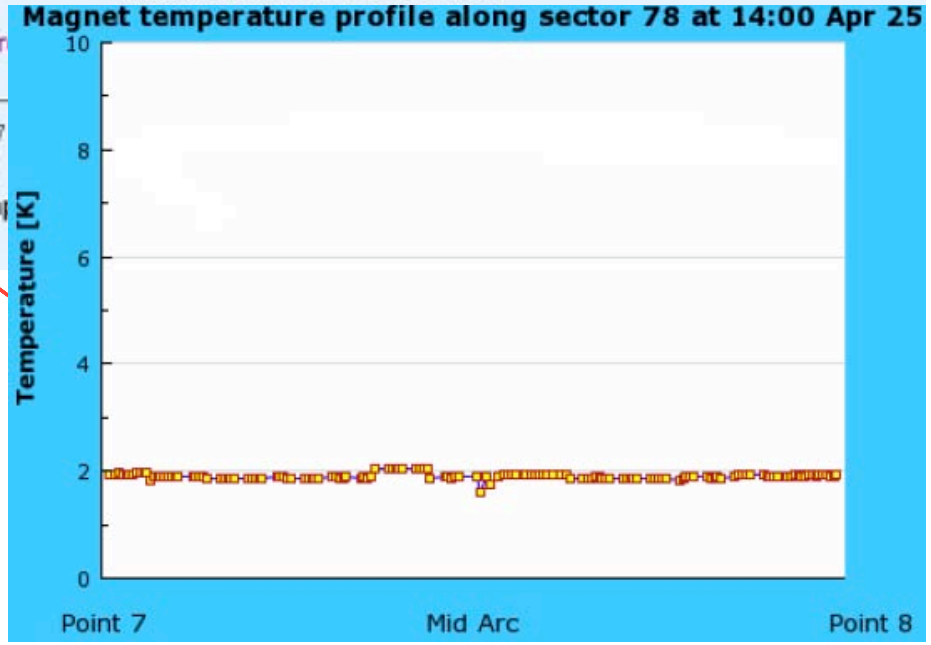


AT/ACR - 2005.09.14

First sector cooldown (April 2007)



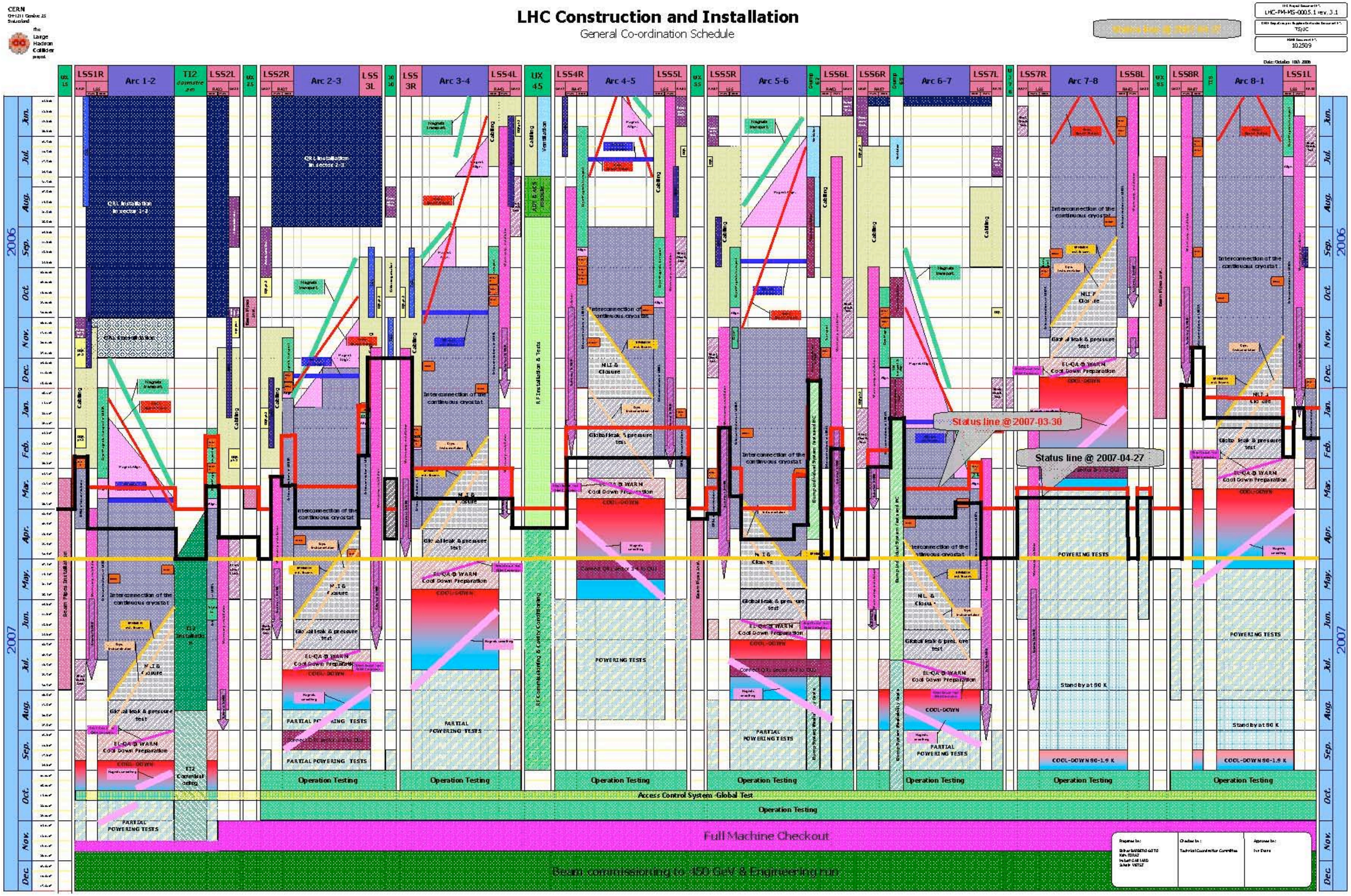




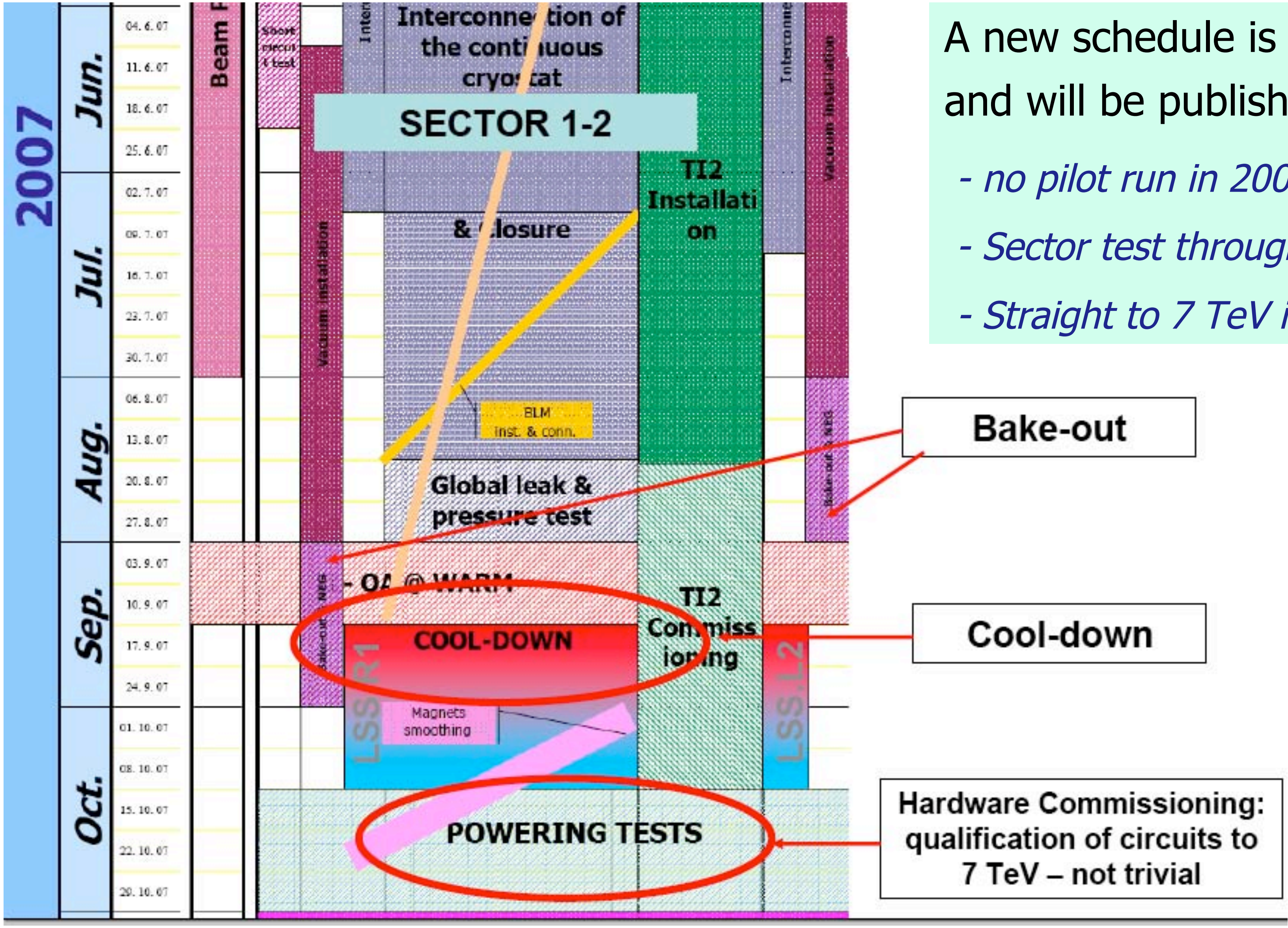
One sector, 3.3 km and 154 dipoles cooled at 1.9K

Main control room operational (CCC)

The LHC installation schedule (last 15 months)



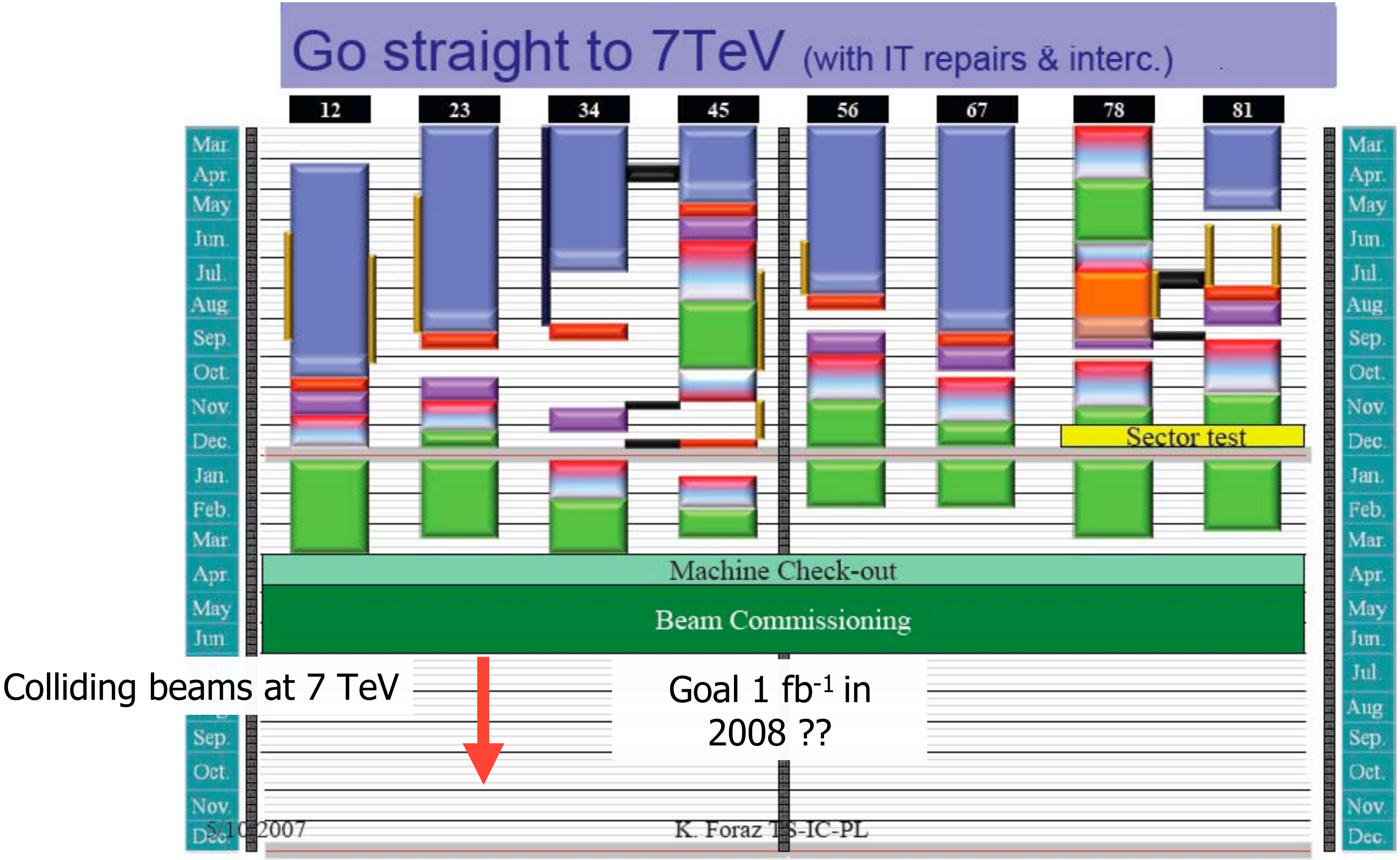
The LHC installation schedule (last 15 months)



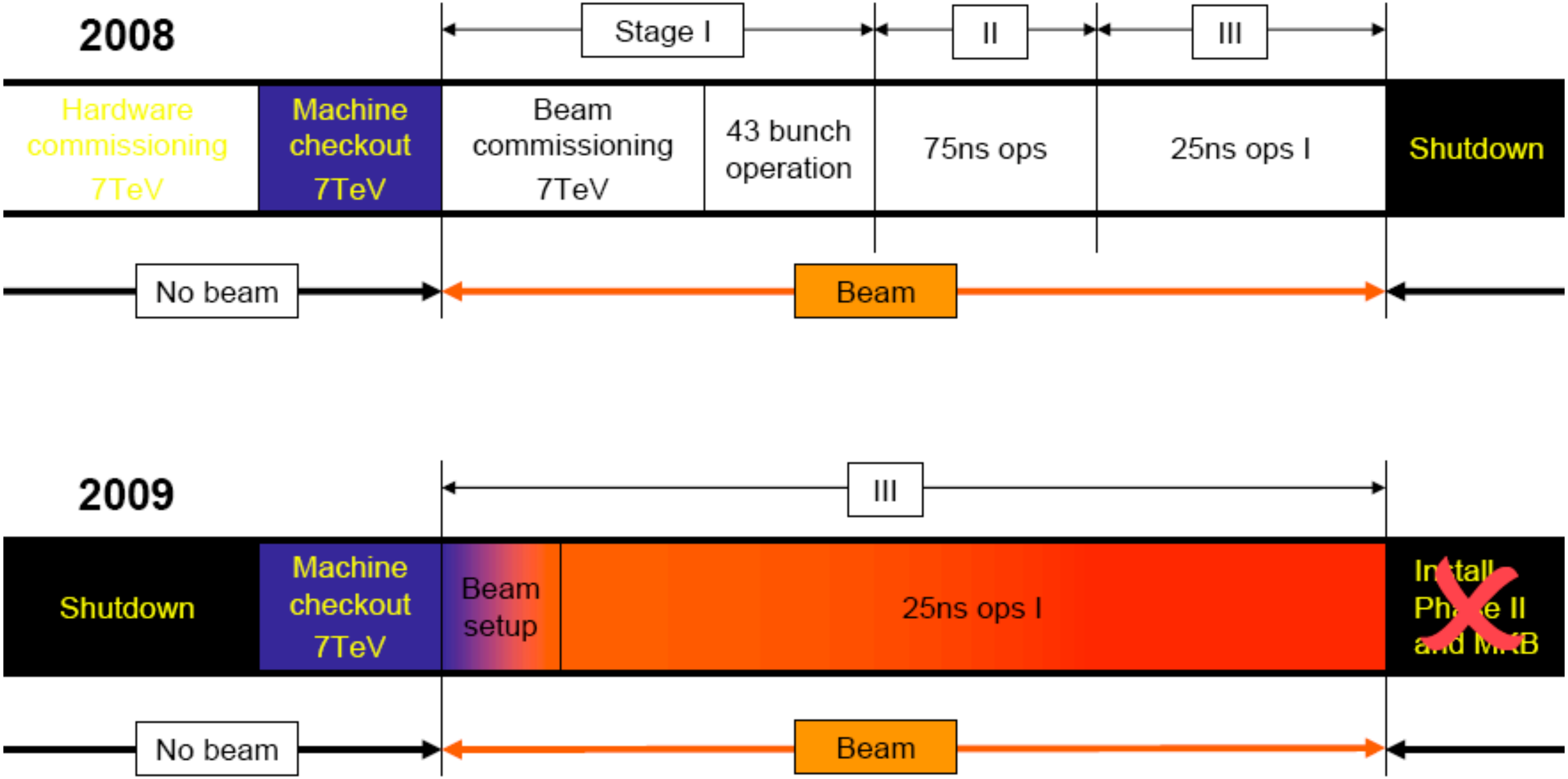
A new schedule is being prepared and will be published soon :

- *no pilot run in 2007 at 450 GeV*
- *Sector test through LHCb Dec '07*
- *Straight to 7 TeV in 2008*

The LHC installation schedule (new draft)



Staged commissioning plan for 7TeV



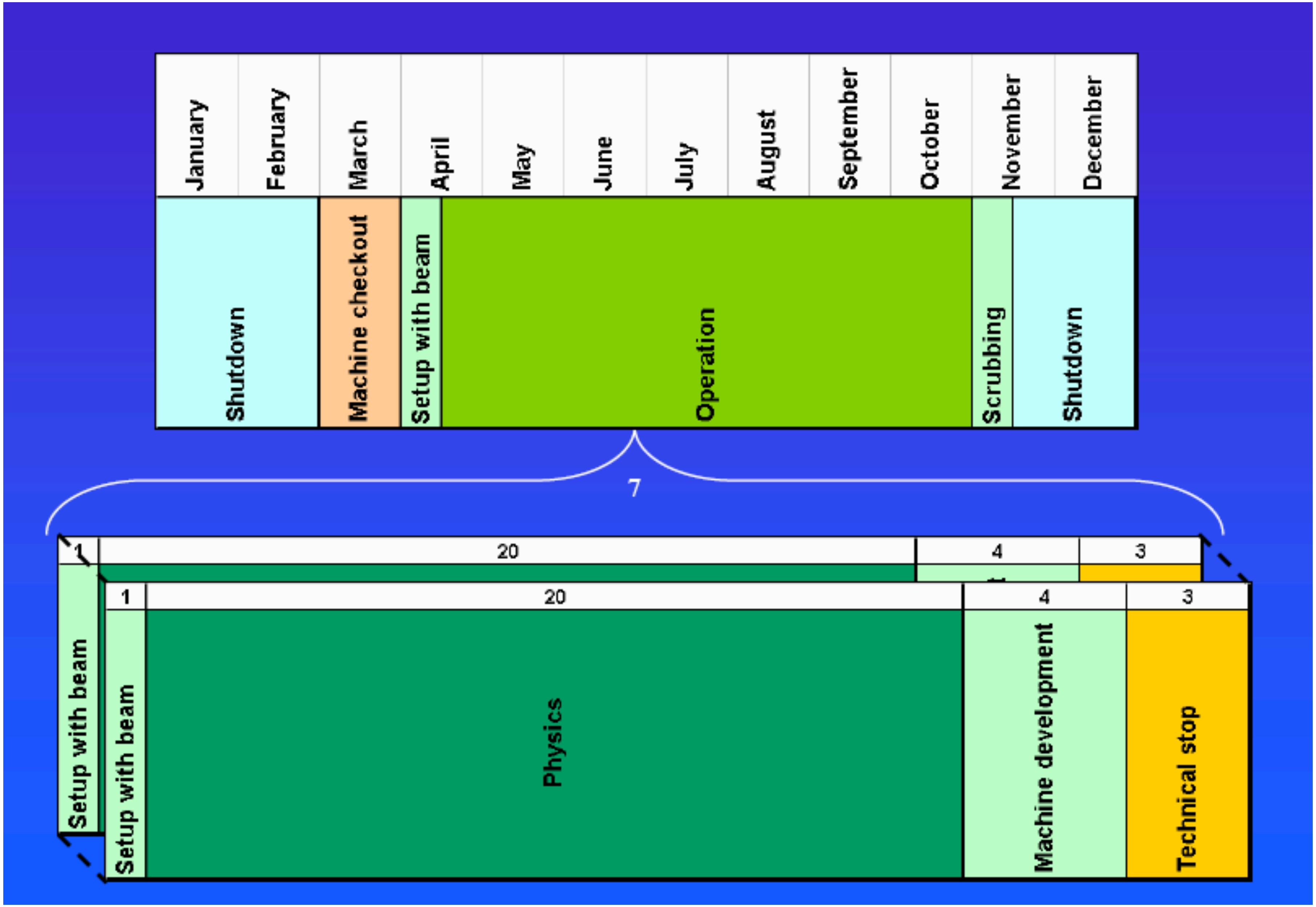
Commissioning with beams

		Total [days]
1	Injection and first turn	6
2	Circulating beam	3
3	450 GeV - initial	5
4	450 GeV - detailed	12
5	450 GeV - two beams	2
6	Snapback - single beam	4
7	Ramp - single beam	8
8	Ramp - both beams	3
9	7 TeV - setup for physics	2
10	Physics un-squeezed	-
	TOTAL to first collisions	**45**
11	Commission squeeze	6
12	Increase Intensity	6
13	Set-up physics - partially squeezed.	2
14	Pilot physics run	30

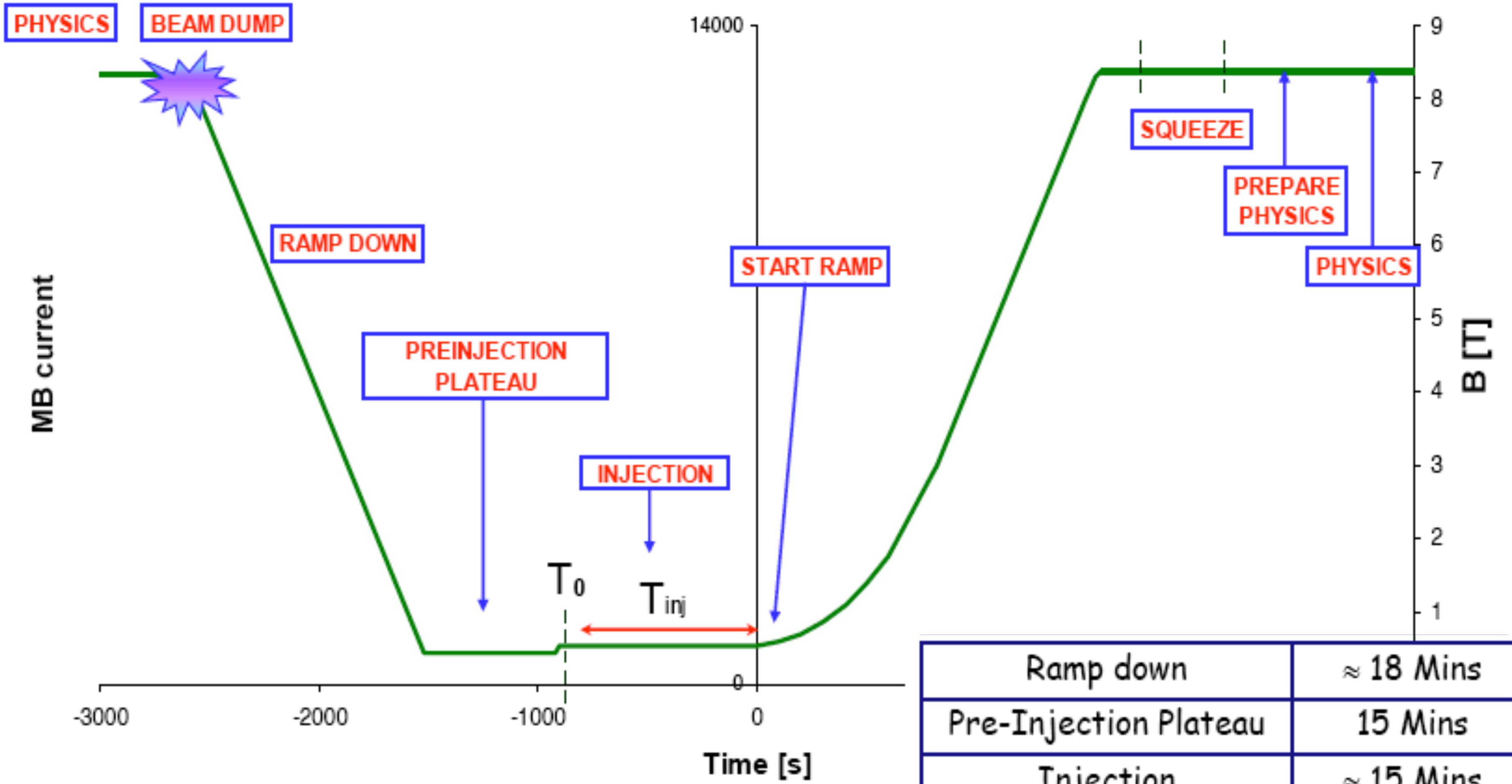
Given reasonable machine availability might expect first 7 TeV collisions in around 2 months

RHIC 2000:
- **First beam April 3rd**
- **First successful ramp: June 1st**
- **First collisions June 12th**

A typical LHC year



Daily 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

Heavy Ions beams

✓ energy:

- E_{beam} = 7 x Z/A [TeV] => √s = 5.5 TeV/A
  or 1.14 PeV (Pb-Pb)

✓ beams:

- possible combinations: pp, pA, AA
- ~ 4 weeks/year(10^6 s effective); typically after pp running (like at SPS)
- 1 dedicate detector
  ALICE
  + ATLAS and CMS

✓ luminosity:

- integrated luminosity
  0.5 nb^{-1}/year (Pb-Pb)

	p-p	Pb-Pb
Luminosity	10^{34} $cm^{-2}s^{-2}$	10^{27} $cm^{-2}s^{-2}$
Annual integrated L	5×10^{40} cm^{-2}	
CM Energy	14 TeV	5.5 TeV/N
$\sigma_{inelastic}$	~70mb	~6.5b
Interactions/bunch	~20	0.001
Tracks/unit rapidity	~140	3000-8000
Beam diameter	20μm	20μm
Bunch length	75mm	75mm

Parameter	unit	nominal operation	early operation
Initial Luminosity	$cm^{-2}s^{-1}$	10^{27}	5×10^{25}
Energy/nucleon	TeV/u	2.76	2.76
Number of bunches		592	60
Bunch spacing	ns	100	
b^*	m	0.5	1.0
Transverse normalized rms emittances	μm	1.5	1.5
Transverse rms beam size	μm	16	16
Luminosity half-life with 2/3 experiments	hrs	4.7/3.1	9.4/6.2