# OVERVIEW OF THE LHC AND ITS INJECTOR CHAIN

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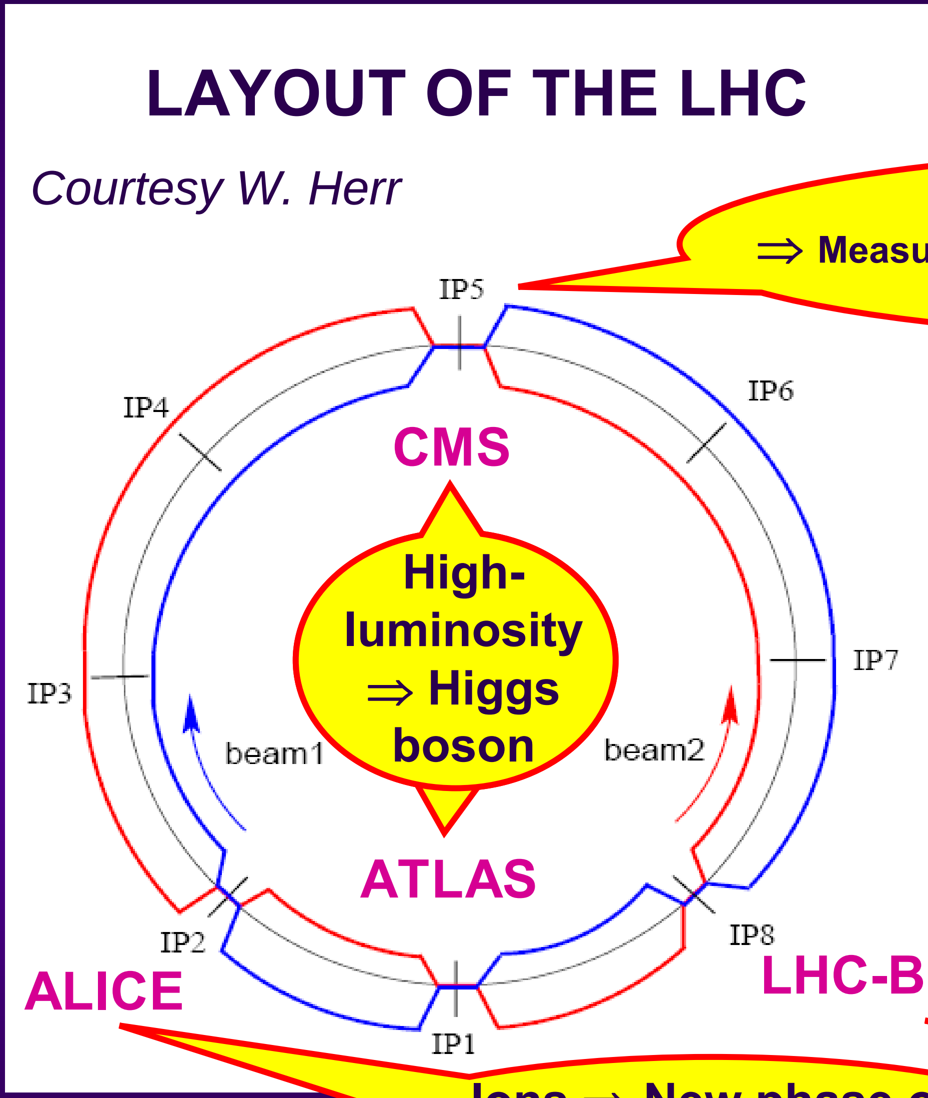
- Introduction: High-luminosity for ATLAS and CMS ⟹ Higgs boson
- LEP vs. LHC magnets: Change of Technology
  ⟹ Superconductivity and cryogenics
- LHC's challenges in accelerator physics
  - Beam optics
  - Synchrotron radiation
  - $e^-$ cloud effects (seen also in the PS & SPS and transfer line in between)
  - Beam-beam
  - Collimation
- LHC injectors' challenges ⟹ "Preservation" of the transverse emittance + generation of the longitudinal structure (25 ns bunch spacing)
- LHC filling scheme and operational cycle
- Future work in 2007 & 08: Move from installation to commissioning

# Introduction (1/11)




**+ TOTEM**

⇒ Measure the total proton-proton cross-section and study elastic scattering and diffractive physics

**High-luminosity ⇒ Higgs boson**

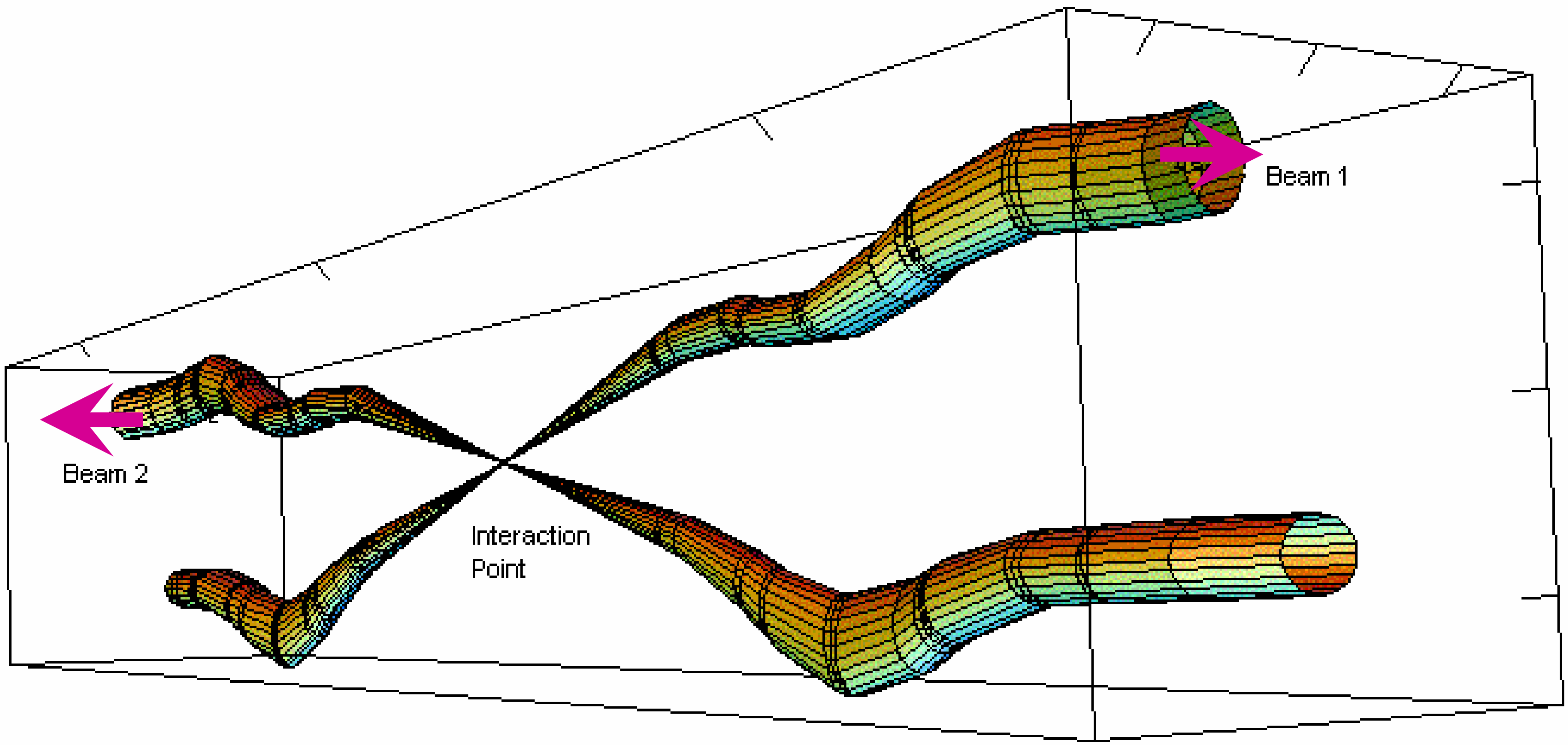
**IP = Interaction Point**

**Ions ⇒ New phase of matter expected: Quark-Gluon Plasma (QGP)**

**Beauty quark physics ⇒ CP violation in B decays**

# Introduction (2/11)

- COLLISION in IP1 (ATLAS)




Relative beam sizes around IP1 (Atlas) in collision

⇒ **Vertical crossing angle in IP1 (ATLAS) and horizontal one in IP5 (CMS)**

# Introduction (3/11)

◆ **Machine LUMINOSITY**

$$L = \frac{N_{events/second}}{\sigma_{event}}$$

Number of events per second generated in the collisions

Cross-section for the event under study

[cm$^{-2}$ s$^{-1}$]

- **The Luminosity depends only on the beam parameters $\Rightarrow$ It is independent of the physical reaction**
- **Reliable procedures to compute and measure**

# Introduction (4/11)

⇒ **For a Gaussian (round) beam distribution**

$$L = \frac{N_b^2 \; M \; f_{rev} \; \gamma_r}{4 \, \pi \, \varepsilon_n \; \beta^*} \; F$$

- Number of particles per bunch
- Number of bunches per beam
- Revolution frequency
- Relativistic velocity factor
- Normalized transverse beam emittance
- β-function at the collision point
- Geometric reduction factor due to the crossing angle at the IP

◆ **PEAK LUMINOSITY for ATLAS&CMS in the LHC =** $L_{peak} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

# Introduction (5/11)

| | | |
|---|---|---|
| Number of particles per bunch | $N_b$ | $1.15 \times 10^{11}$ |
| Number of bunches per beam | $M$ | 2808 |
| Revolution frequency | $f_{rev}$ | 11245 Hz |
| Relativistic velocity factor | $\gamma_r$ | 7461 ($\Longrightarrow E$ = 7 TeV) |
| $\beta$-function at the collision point | $\beta^*$ | 55 cm |
| Normalised rms transverse beam emittance | $\epsilon_n$ | $3.75 \times 10^{-4}$ cm |
| Geometric reduction factor | $F$ | 0.84 |

$$F = 1/\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$$

| | | |
|---|---|---|
| Full crossing angle at the IP | $\theta_c$ | 285 $\mu$rad |
| Rms bunch length | $\sigma_z$ | 7.55 cm |
| Transverse rms beam size at the IP | $\sigma^*$ | 16.7 $\mu$m |

# Introduction (6/11)

- **INTEGRATED LUMINOSITY** $$L_{\text{int}} = \int_0^T L(t)\, dt$$

$\Rightarrow$ **The real figure of merit =** $$L_{\text{int}}\ \sigma_{event} = \text{number of events}$$

- **LHC integrated Luminosity expected per year (~$10^7$ s): [80-120] $fb^{-1}$**

**Reminder: 1 barn = $10^{-24}$ cm$^2$
and femto = $10^{-15}$**

# Introduction (7/11)

- The total proton-proton cross section at 7 TeV is ~ 110 mbarns:
  - Inelastic $\Longrightarrow \sigma_{in}$ = 60 mbarns
  - Single diffractive $\Longrightarrow \sigma_{sd}$ = 12 mbarns
  - Elastic $\Longrightarrow \sigma_{el}$ = 40 mbarns

- The cross section from elastic scattering of the protons and diffractive events will not be seen by the detectors as it is only the inelastic scatterings that give rise to particles at sufficient high angles with respect to the beam axis

- Inelastic event rate at nominal luminosity = $10^{34} \times 60 \times 10^{-3} \times 10^{-24}$ = 600 millions / second per high-luminosity experiment

# Introduction (8/11)

- The bunch spacing in the LHC is 25 ns $\Longrightarrow$ Crossing rate of 40 MHz

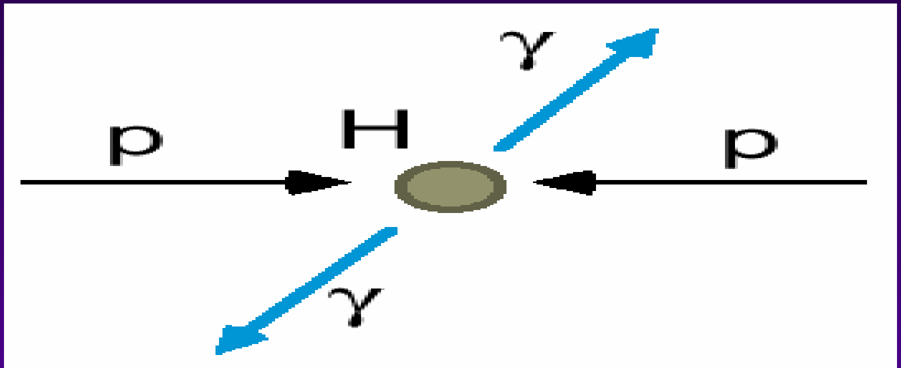
- However, there are bigger gaps (for the kickers) $\Longrightarrow$ Average crossing rate = number of bunches × revolution frequency = 2808 × 11245 = 31.6 MHz

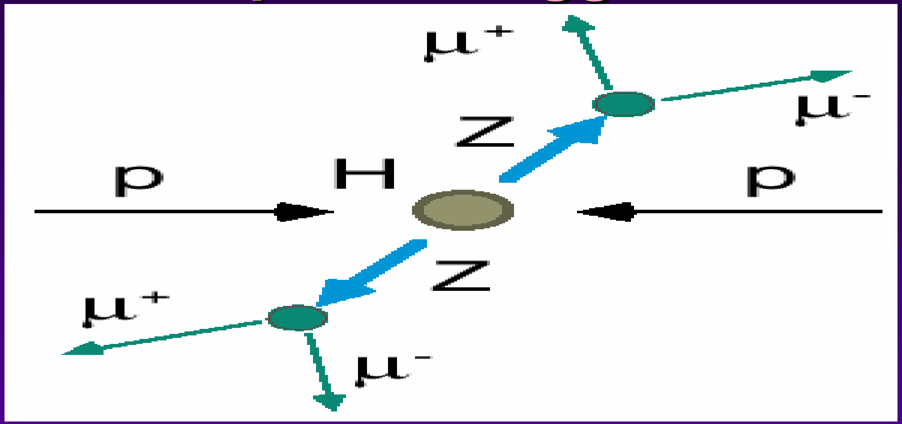
- (600 millions inelastic events / second) / ($31.6 \times 10^6$) = 19 inelastic events per crossing

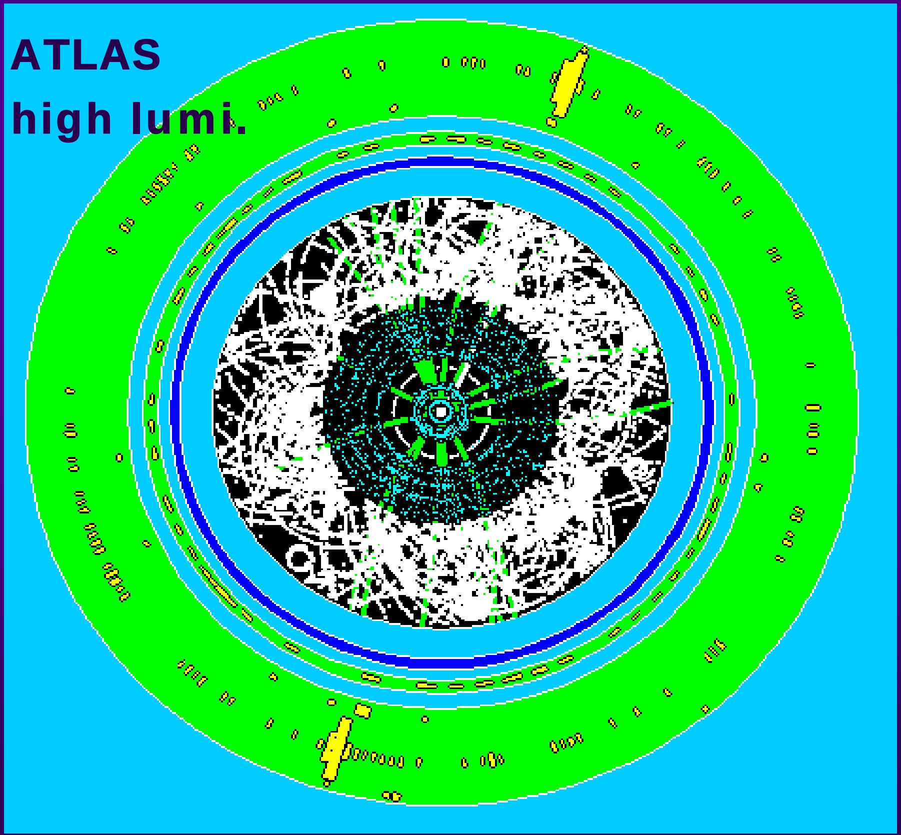
- Total inelastic events per year ($\sim 10^7$ s) = 600 millions × $10^7$ = $6 \times 10^{15}$ $\sim 10^{16}$

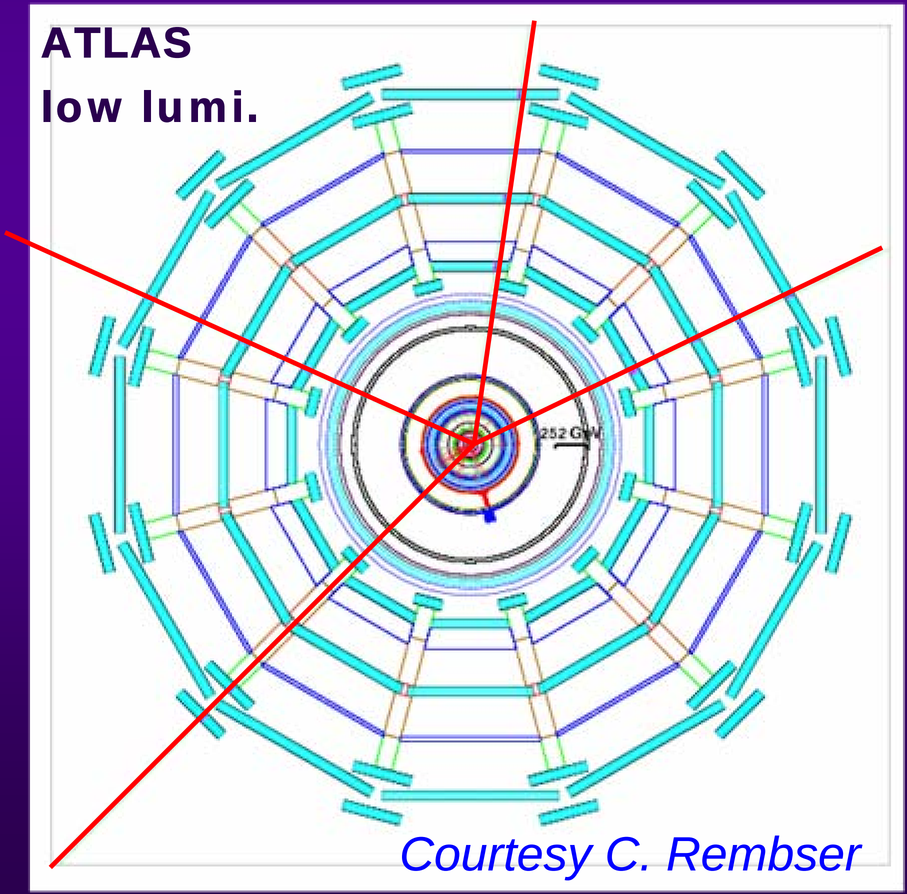
- The LHC experimental challenge is to find rare events at levels of 1 in $10^{13}$ or more $\Longrightarrow$ ~ 1000 Higgs events in each of the ATLAS and CMS experiments expected per year

# Introduction (9/11) Examples of expected Higgs events

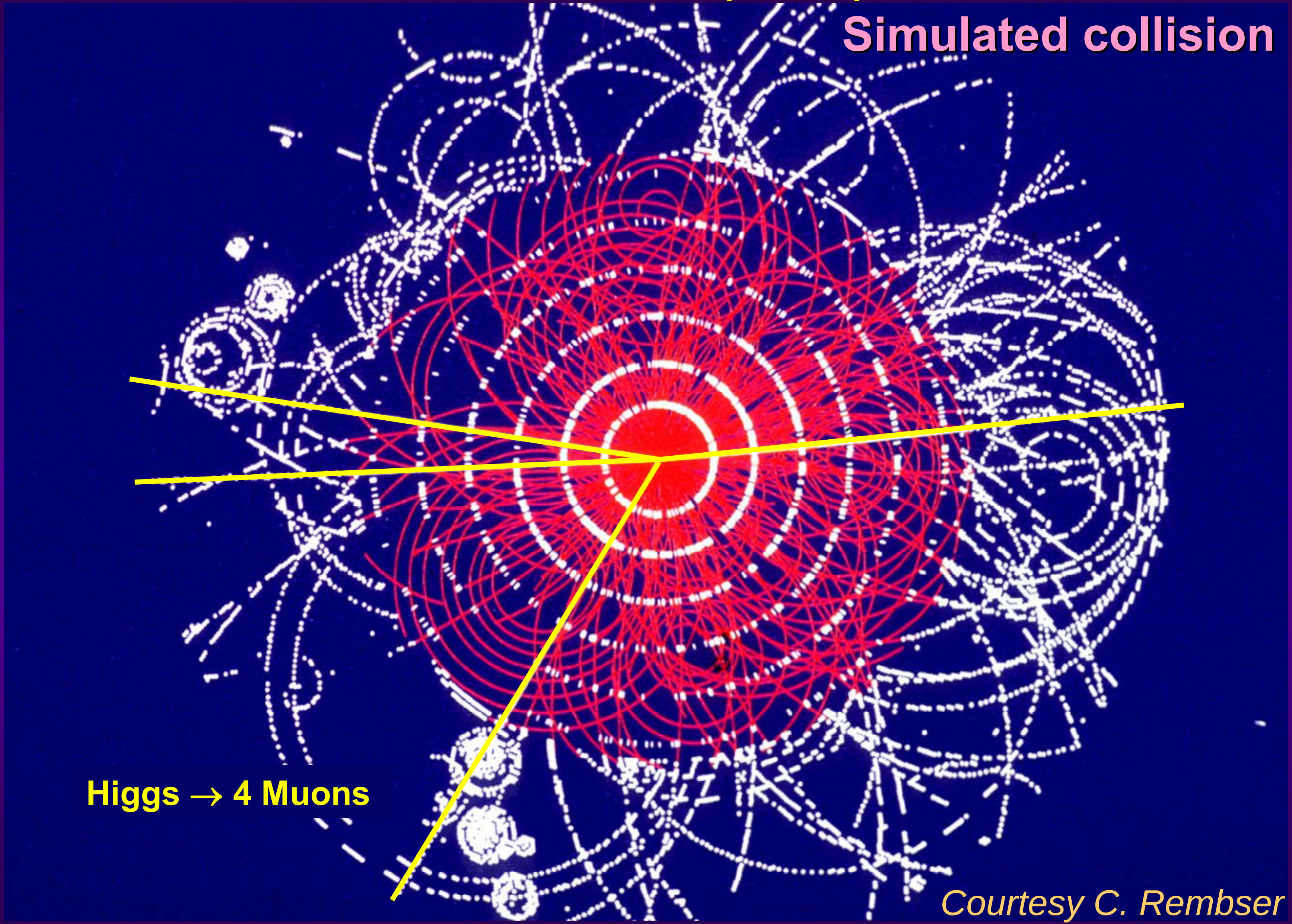


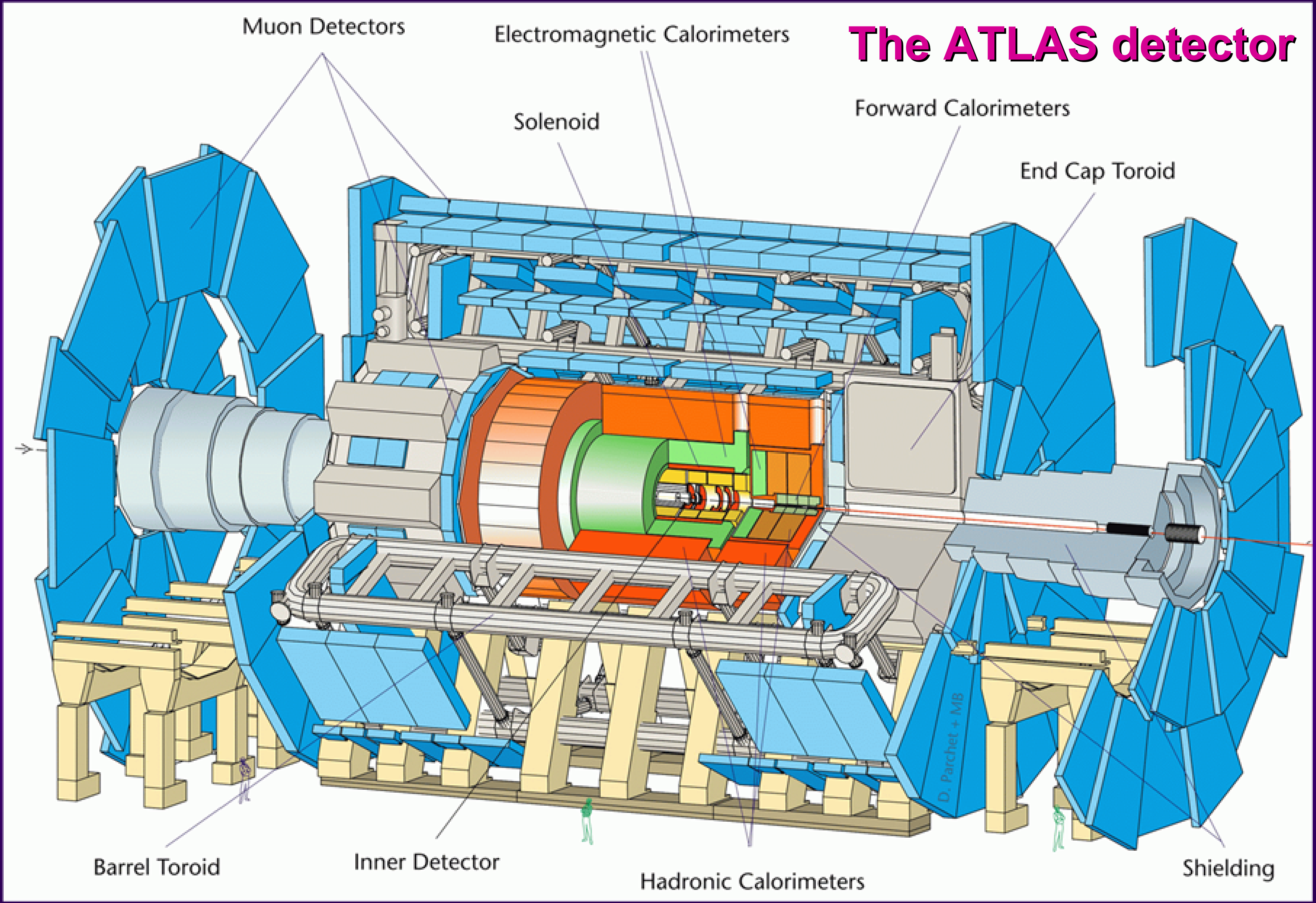



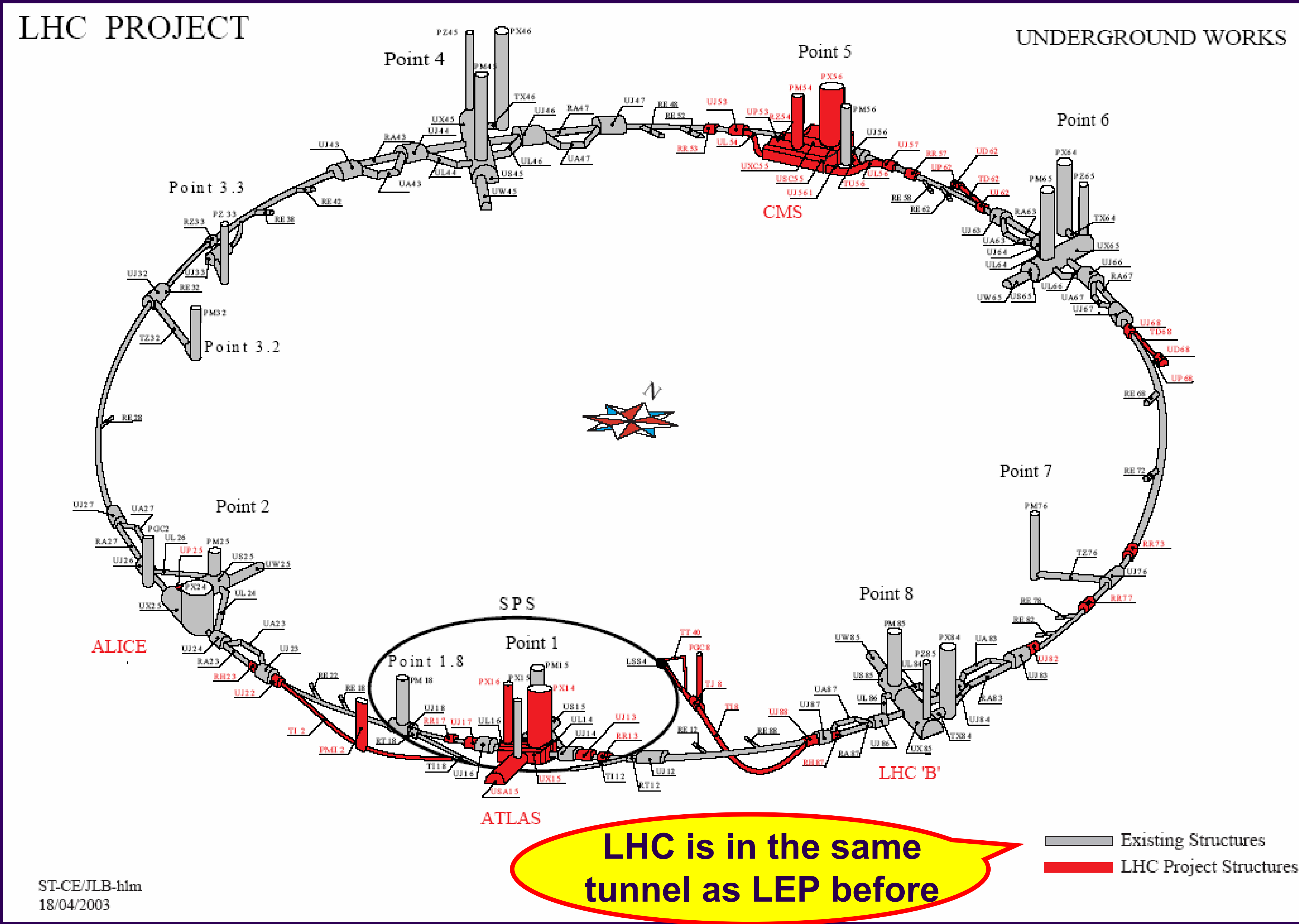
# Introduction (10/11)



# Introduction (11/11)



# Superconductivity and cryogenics (1/11)



# Superconductivity and cryogenics (2/11)

- **LEP vs LHC: Magnets ⟹ A change in technology**

**BEAM RIGIDITY** $B\,\rho\,[\mathrm{T\,m}] = 3.3356\; p_0\,[\mathrm{GeV/c}]$

Magnetic field

Curvature radius of the dipoles

Beam momentum

| | LEP | LHC |
|---|---|---|
| $\rho$ [m] | 3096.175 | 2803.95 |
| $p_0$ [GeV/c] | 104 | 7000 |
| $B$ [T] | 0.11 | 8.33 |

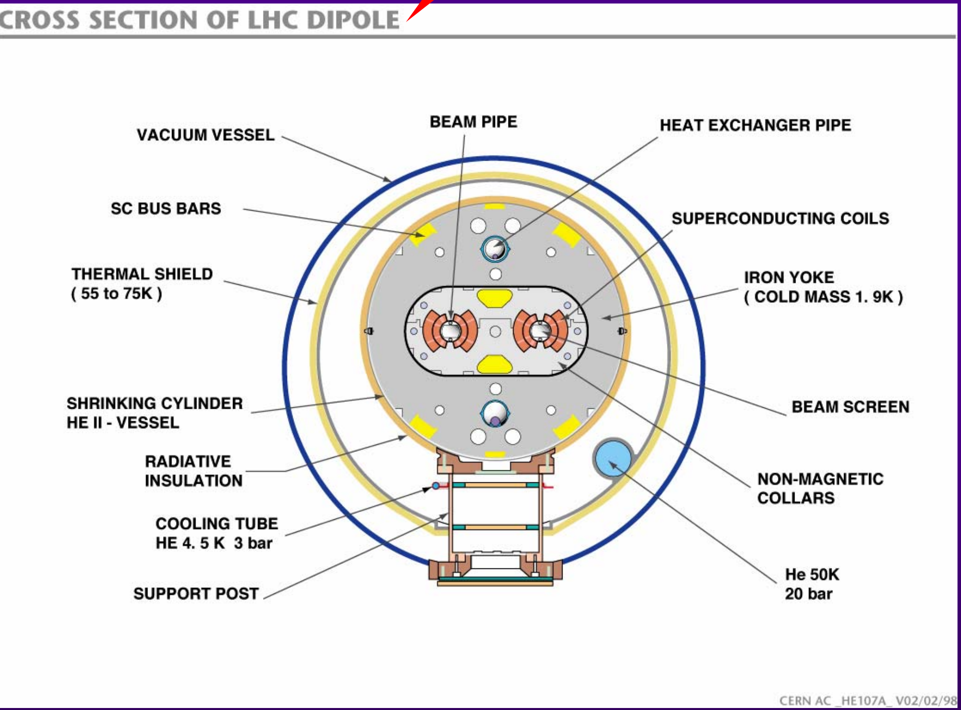
Room-temperature coils

Superconducting coils

# Superconductivity and cryogenics (3/11)

- Main elements are the 2-in-1 superconducting dipoles and quadrupoles operating in superfluid helium at a temperature of 1.9 K

1232

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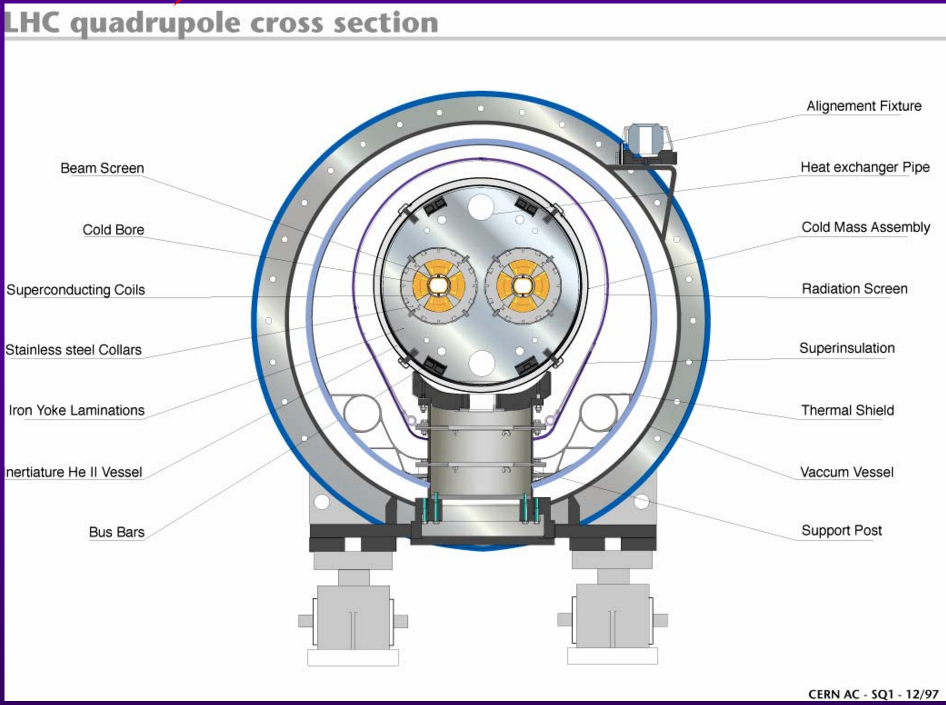
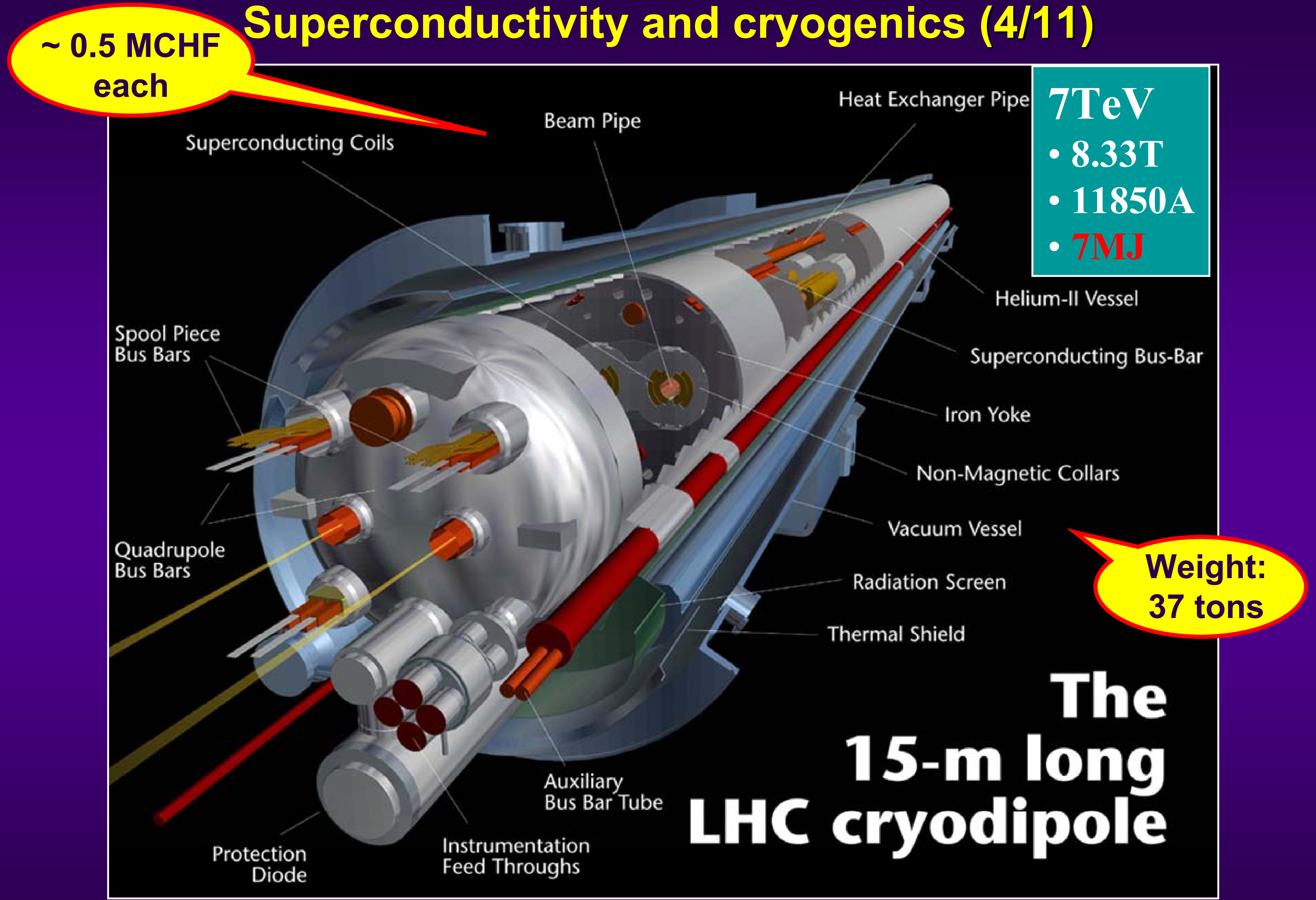
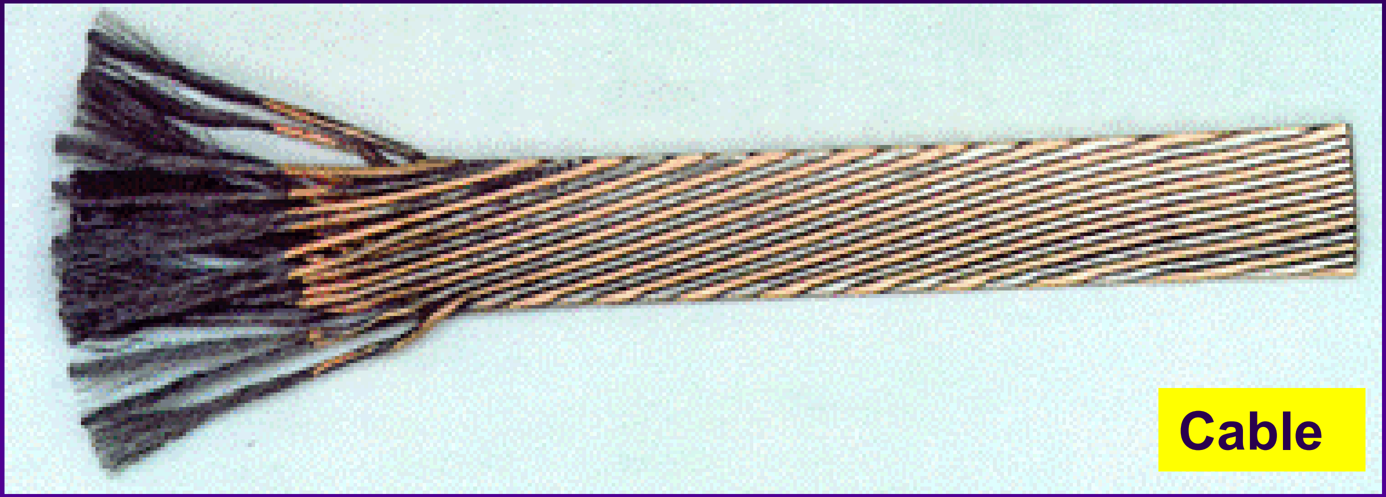


# Superconductivity and cryogenics (4/11)

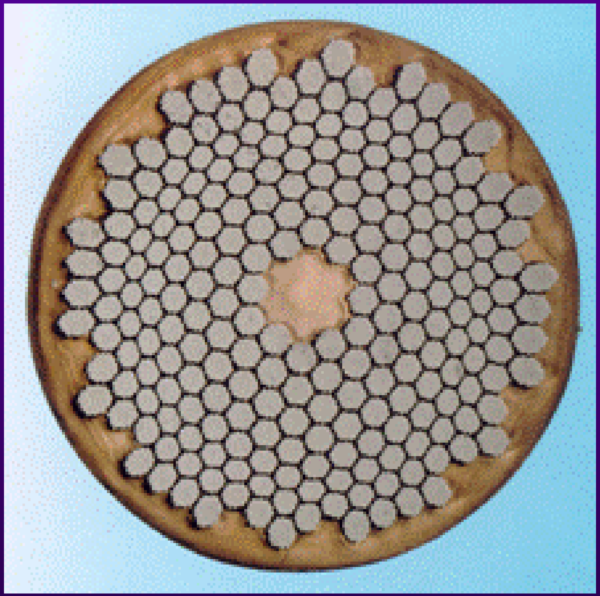


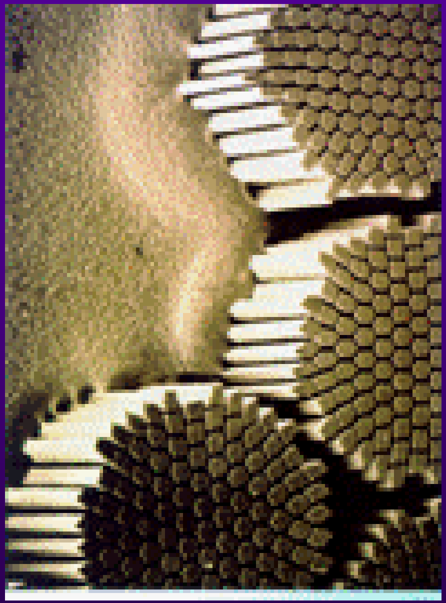
# Superconductivity and cryogenics (5/11)

- LHC superconducting cables




Strand





Filaments

# Superconductivity and cryogenics (6/11)

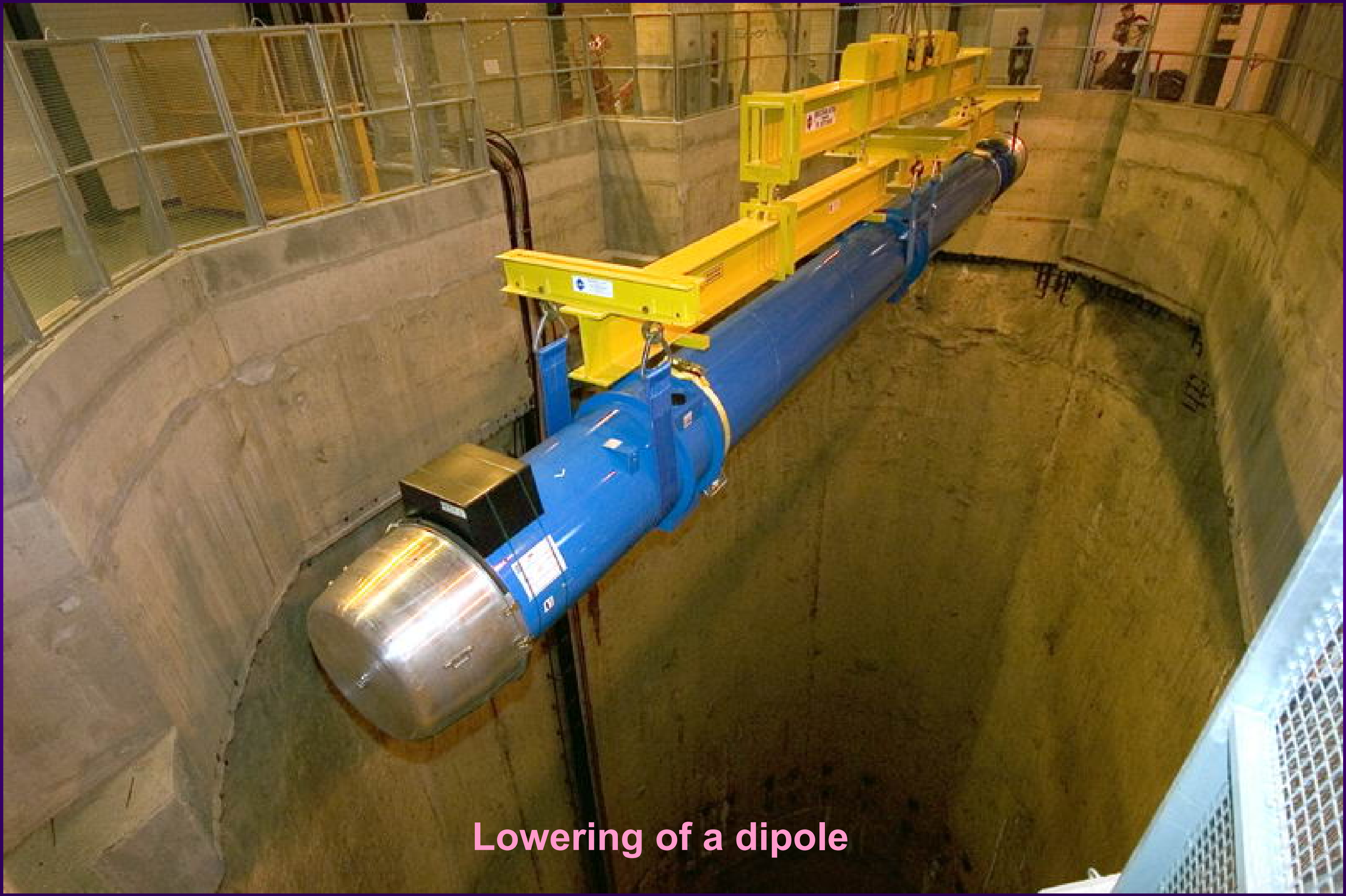
- The cables house 36 strands of superconducting wire
- Each strand being exactly 825 $\mu$m in diameter. Each strand houses 6300 superconducting filaments of Niobium-titanium (NbTi)
- Each filament is about 6 $\mu$m thick, i.e. 10 times thinner than a normal human hair
- Around each filament there is a 0.5 $\mu$m layer of high-purity copper
- Copper is an insulation material between the filaments in the superconductive state, when the temperature is below -263C. When leaving the superconductive state, copper acts as a conductor transferring the electric current and the heat
- Total superconducting cable required 1200 tons which translates to around 7600 km of cable $\Longrightarrow$ Total length of filaments is astronomical: 5 times to the sun and back with enough left over for a few trips to the moon!

# Superconductivity and cryogenics (7/11)

- **Full list of superconducting magnets and their function**

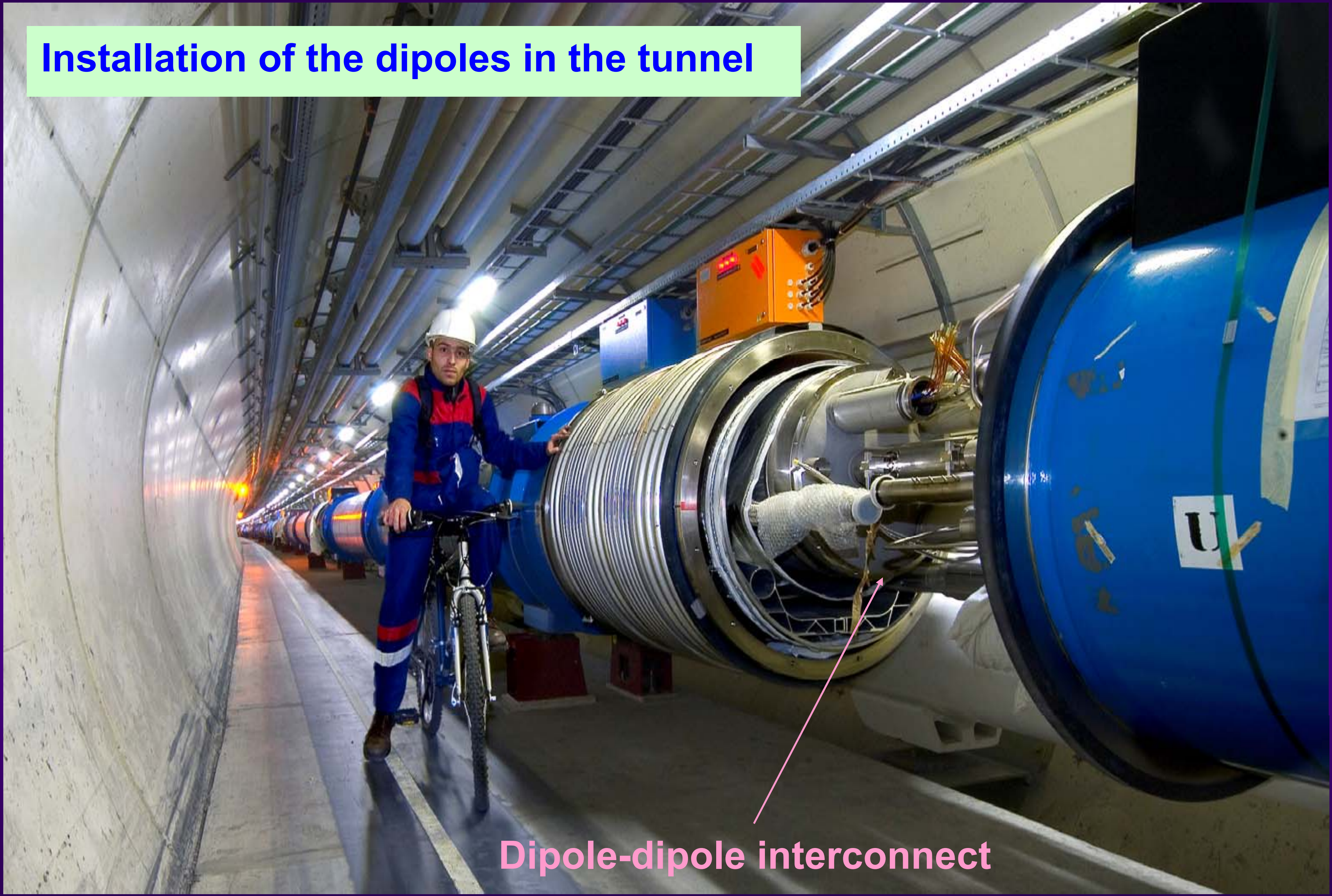
| Type | Number | Function |
|---|---|---|
| MB | 1232 | Main dipoles |
| MQ | 392 | Arc quadrupoles |
| MBX/MBR | 16 | Separation and recombination dipoles |
| MSCB | 376 | Combined chromaticity and closed orbit correctors |
| MCS | 2464 | Sextupole correctors for persistent currents at injection |
| MCDO | 1232 | Octupole/decapole correctors for persistent currents at injection |
| MO | 336 | Landau damping octupoles |
| MQT/MQTL | 248 | Tuning quadrupoles |
| MCB | 190 | Orbit correction dipoles |
| MQM | 86 | Dispersion suppressor and matching section quadrupoles |
| MQY | 24 | Enlarged-aperture quadrupoles in insertions |
| MQX | 32 | Low-beta insertion quadrupoles |

# Superconductivity and cryogenics (8/11)



Lowering of a dipole

# Superconductivity and cryogenics (9/11)



# Superconductivity and cryogenics (10/11)

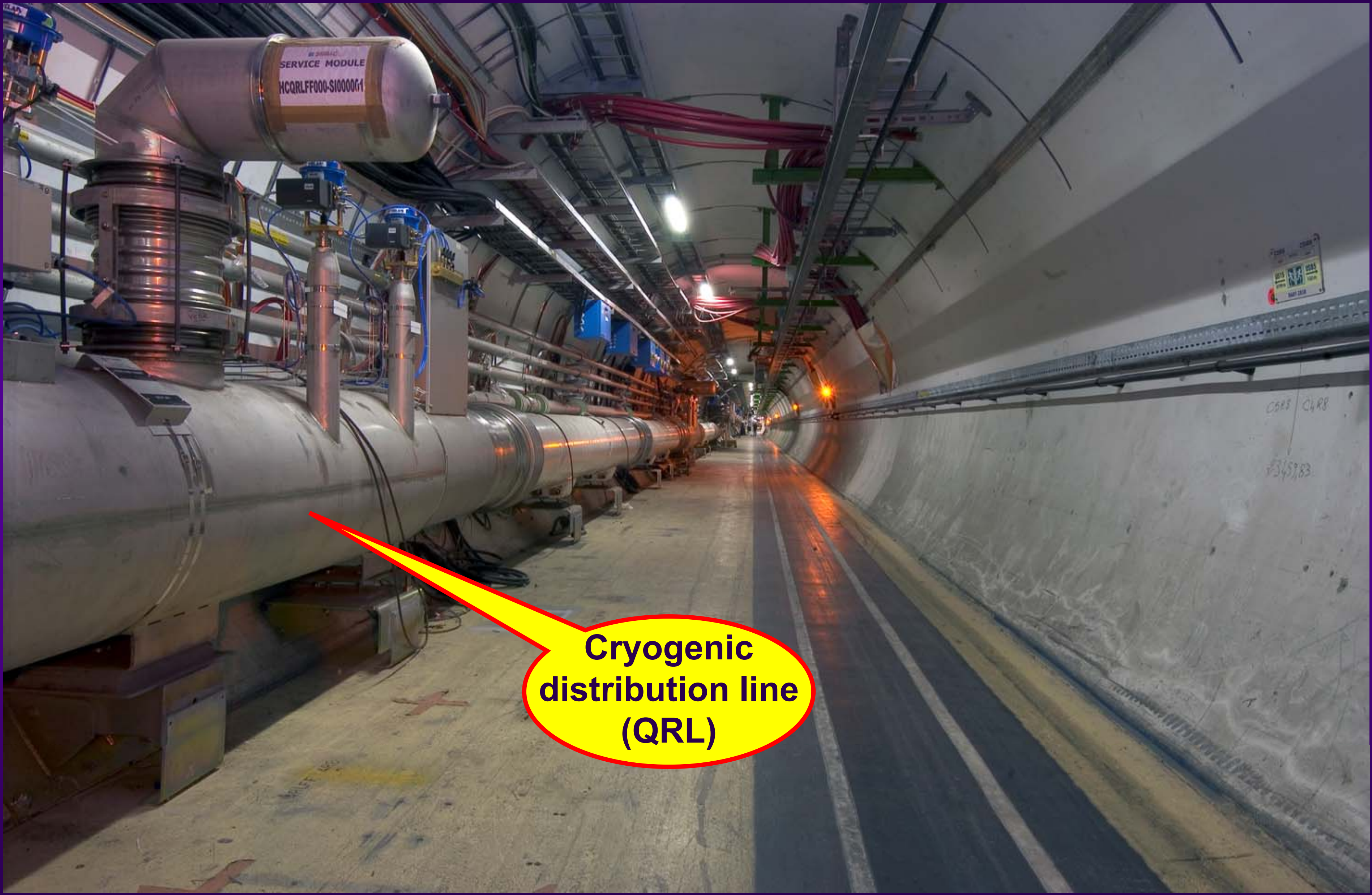
## CRYOGENICS

- The cryogenic technology uses superfluid helium, which has unusually efficient heat transfer properties, allowing kilowatts of refrigeration to be transported over more than a kilometre with a temperature drop of less than 0.1 K

- LHC superconducting magnets will sit in a 1.9 K bath of superfluid helium at atmospheric pressure. This bath will be cooled by low pressure liquid helium flowing in heat exchanger tubes threaded along the string of magnets

- In all, LHC cryogenics will need 40 000 leak-tight pipe junctions, 12 million litres of liquid nitrogen will be vaporised during the initial cooldown of 31 000 tons of material and the total inventory of liquid helium will be 700 000 litres

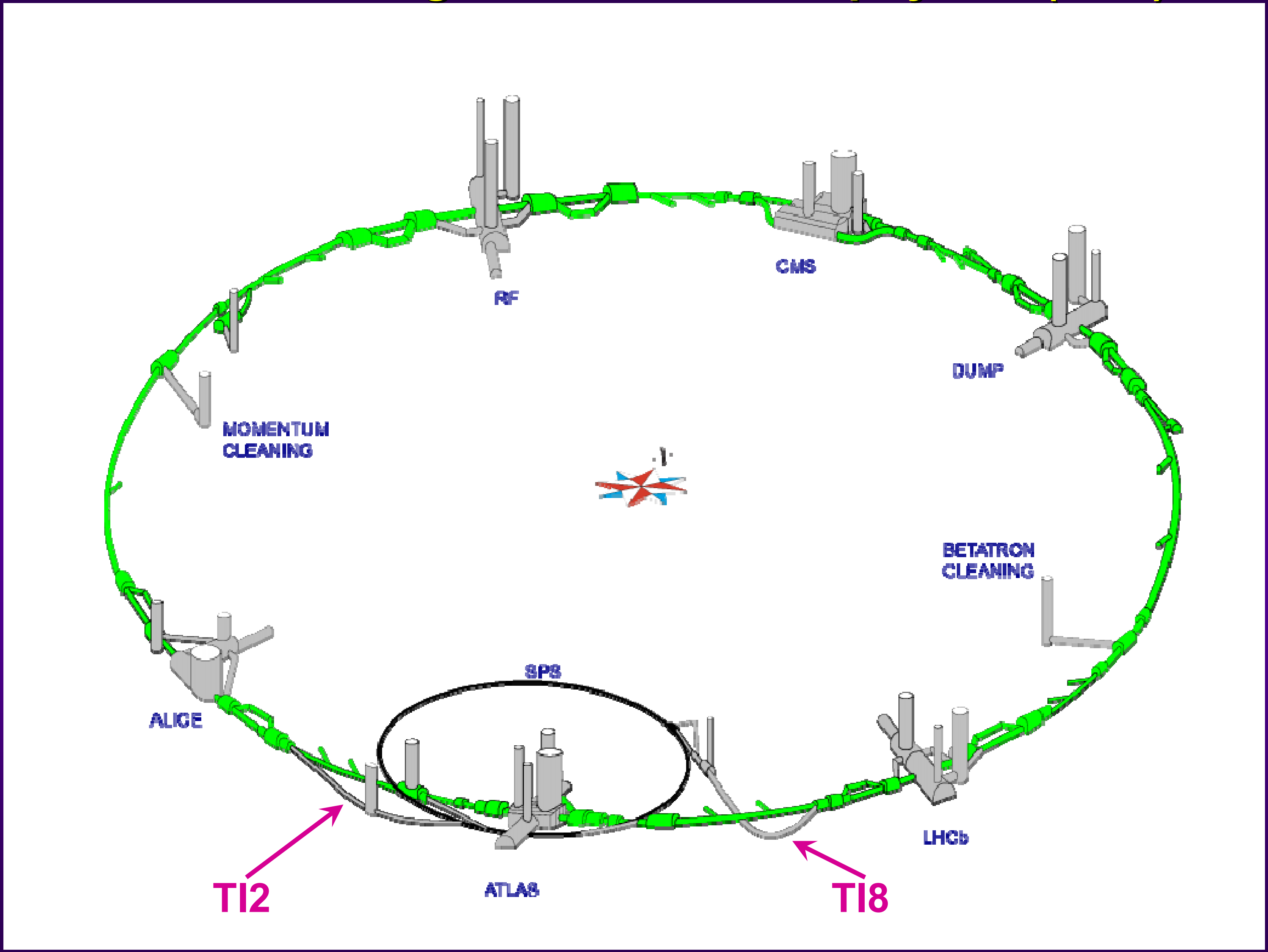
# Superconductivity and cryogenics (11/11)



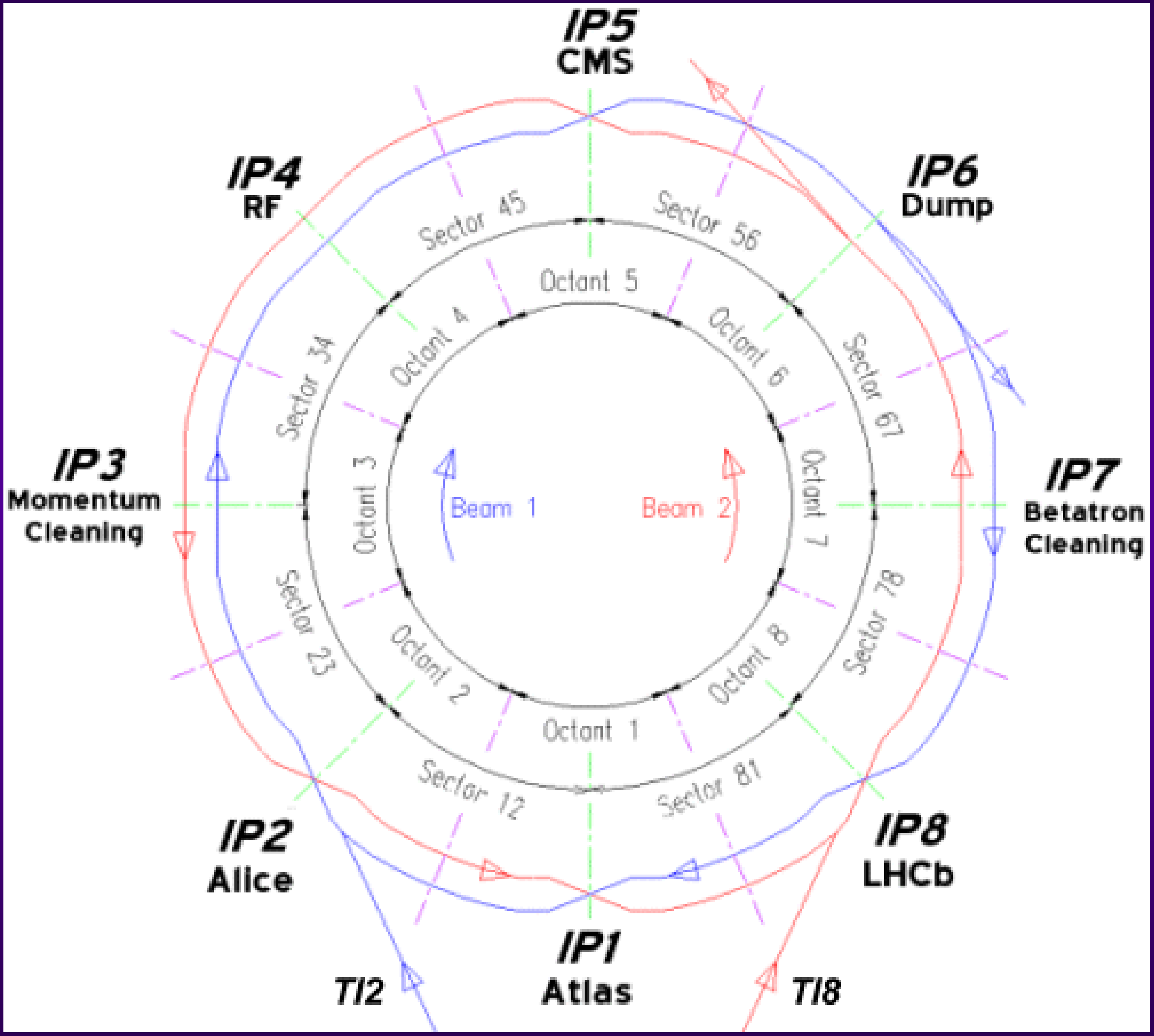
# LHC's challenges in accelerator physics (1/35)

- The LHC lattice should be flexible ⟹ Allow further upgrades…
- Particles have to remain stable for long times ⟹ Persistent current effects in the superconducting cables (decay and snap back)
- Synchrotron radiation is significant in the LHC ⟹ Power emitted cannot be neglected as it has to be absorbed by the beam pipe at cryogenic temperature + it creates photo-electrons which add to the cryogenic load and may induce emittance growth and instabilities ($e^-$ cloud)
- Collective effects must be controlled ⟹ $e^-$ cloud!
- The beam-beam effect limits the bunch density
- Beam losses should not quench the magnets ⟹ Efficient collimation system with collimators very close to the beam (few mm) leading to high transverse resistive-wall impedance

# LHC's challenges in accelerator physics (2/35)

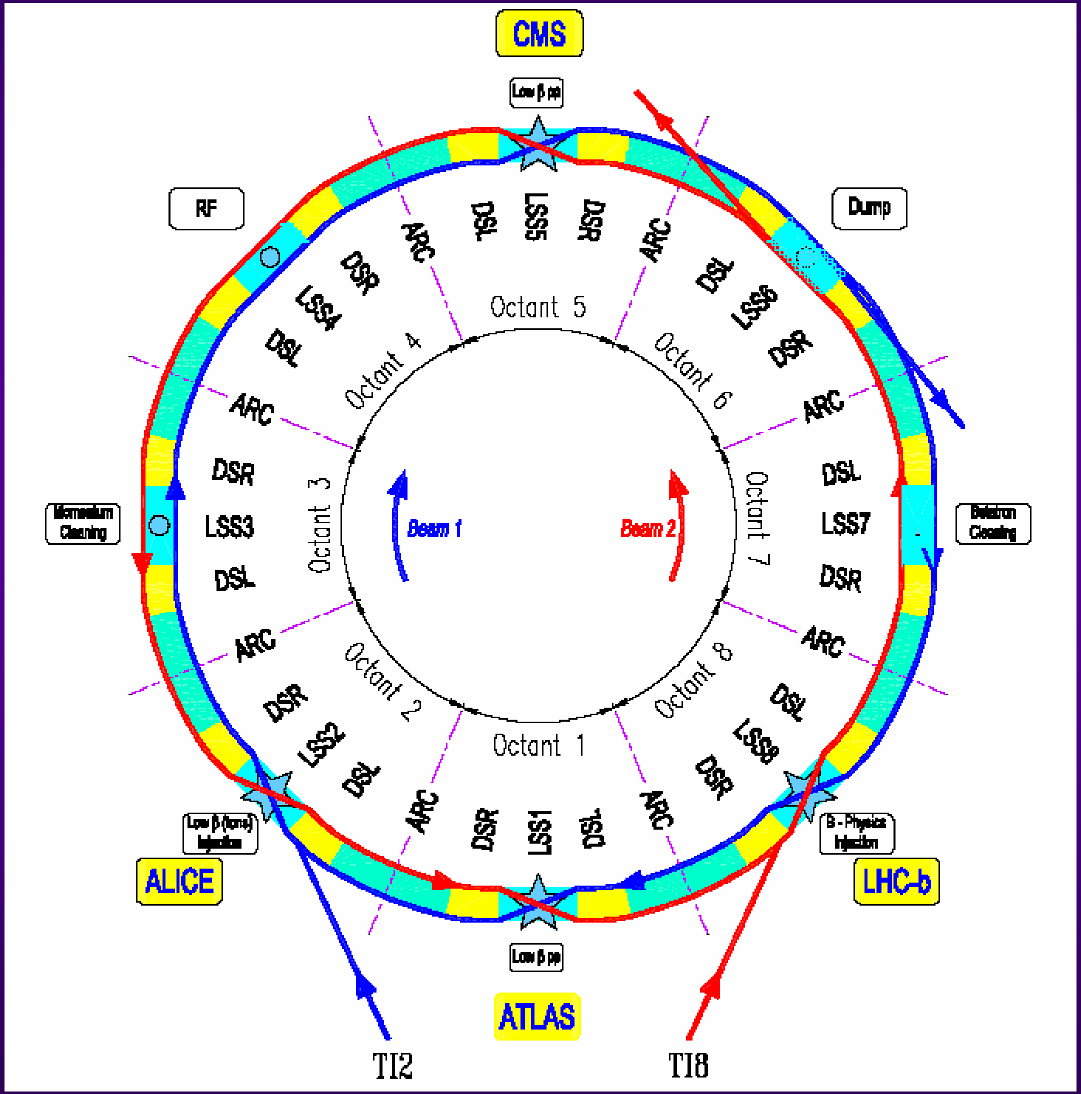


# LHC's challenges in accelerator physics (3/35)



# LHC's challenges in accelerator physics (4/35)

## Beam optics

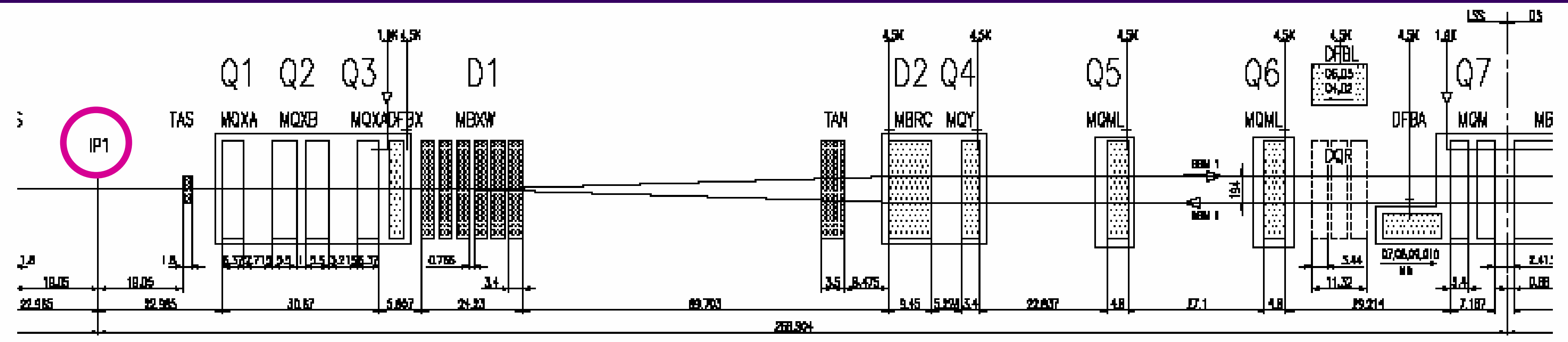



Long Straight Section

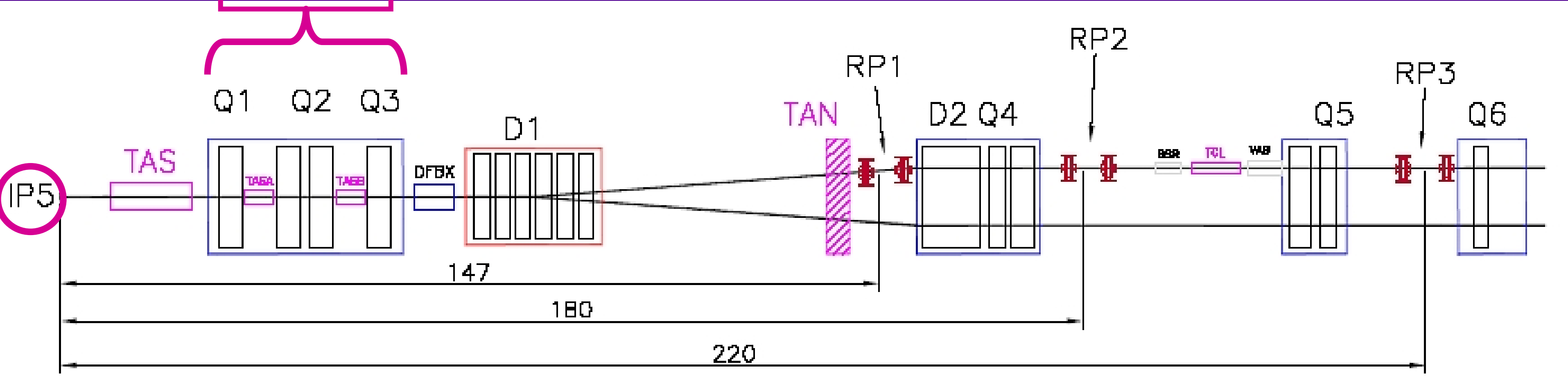
- 8 arcs
- 8 LSS (~ 528 m long)
- 16 dispersion suppressors
- 4 main experiments

# LHC's challenges in accelerator physics (5/35)

## ◆ IR1* (ATLAS)

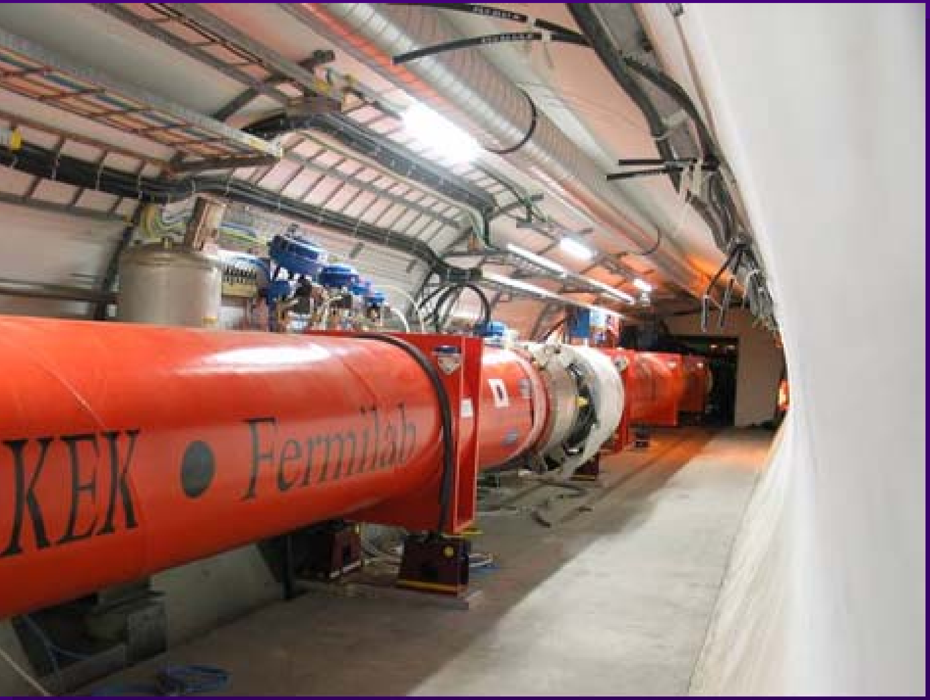



## ◆ IR5 (CMS + TOTEM)




**IR* = Insertion region (between the 2 dispersion suppressors)**

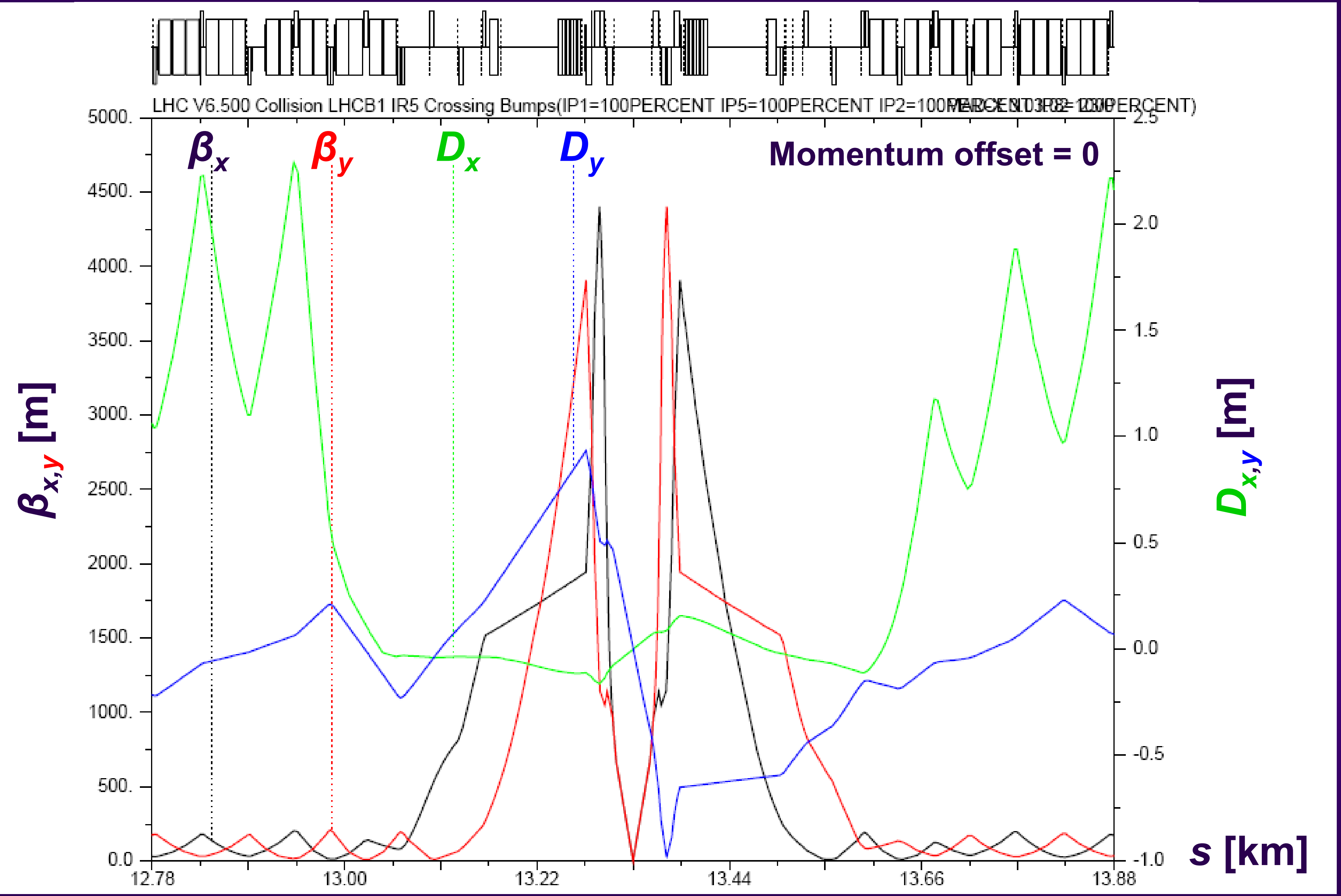
## One of the triplet at IP5




Experimental hall of CMS

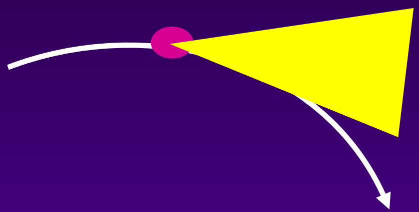
# LHC's challenges in accelerator physics (7/35)

- LHC optics for the Interaction Point (IP) 5 (CMS) in collision



# LHC's challenges in accelerator physics (8/35)

## Synchrotron radiation



- **Power radiated by a particle (due to bending)**

$$P_{\perp} = \frac{q^2 \, c \, \beta^4 \, E^4}{6 \, \pi \, \varepsilon_0 \, \rho^2 \, E_0^4}$$

Particle total energy

Curvature radius of the dipoles

Particle rest energy

- **Energy radiated in one ring revolution**

$$U_0 = \frac{q^2 \, \beta^3 \, E^4}{3 \, \varepsilon_0 \, E_0^4 \, \rho}$$

- **Average (over the ring circumference) power radiation**

$$P_{av} = \frac{U_0}{T_0}$$

Revolution period

# LHC's challenges in accelerator physics (9/35)

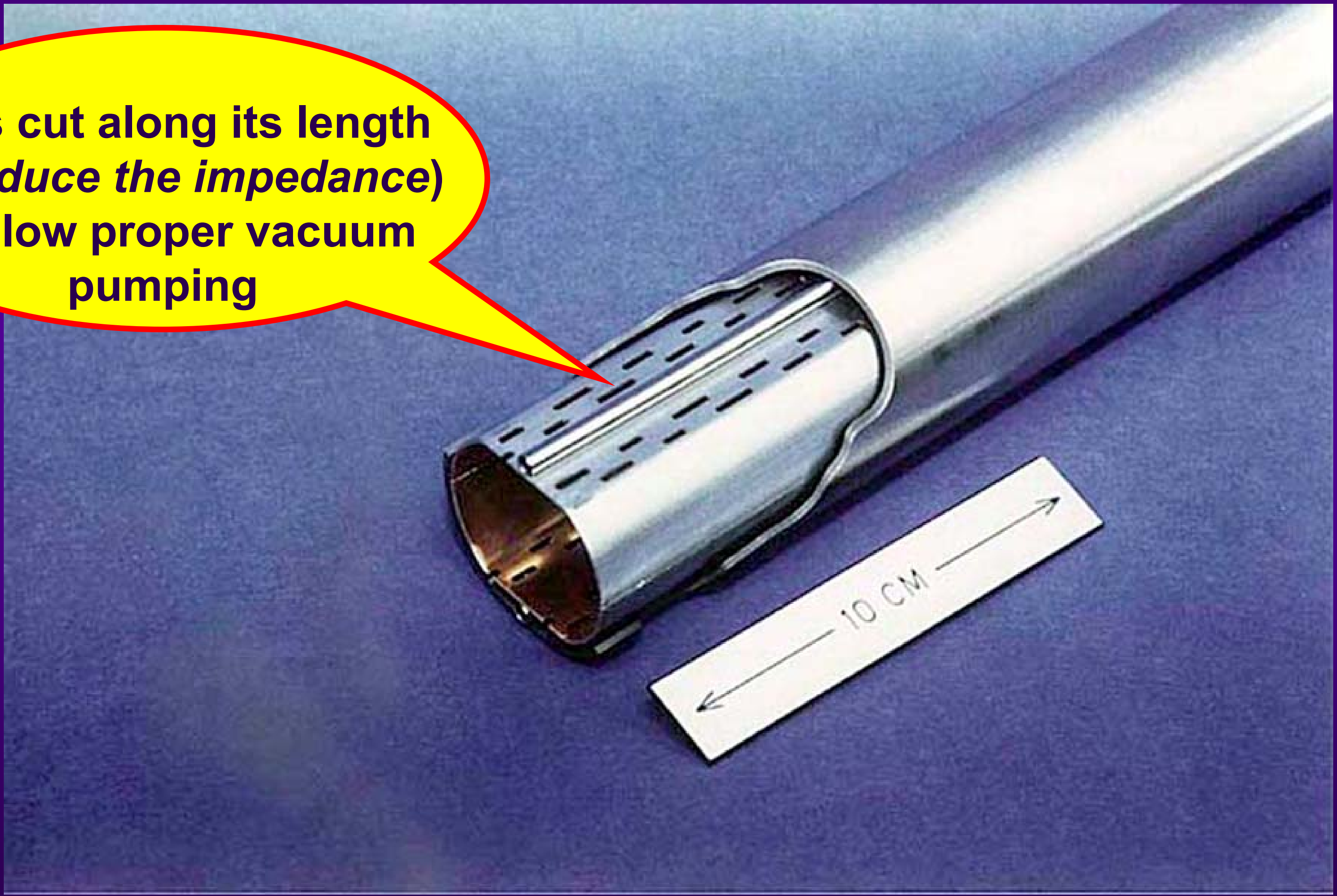
| | LEP | LHC |
|---|---|---|
| $\rho$ [m] | 3096.175 | 2803.95 |
| $p_0$ [GeV/c] | 104 | 7000 |
| $U_0$ | 3.3 GeV | 6.7 keV |

The RF system had therefore to compensate for an energy lost of ~3% of the total beam energy per turn!

The total average (over the ring circumference) power radiation (per beam) is 3.9 kW (2808 bunches of 1.15 $10^{11}$ protons)

# LHC's challenges in accelerator physics (10/35)

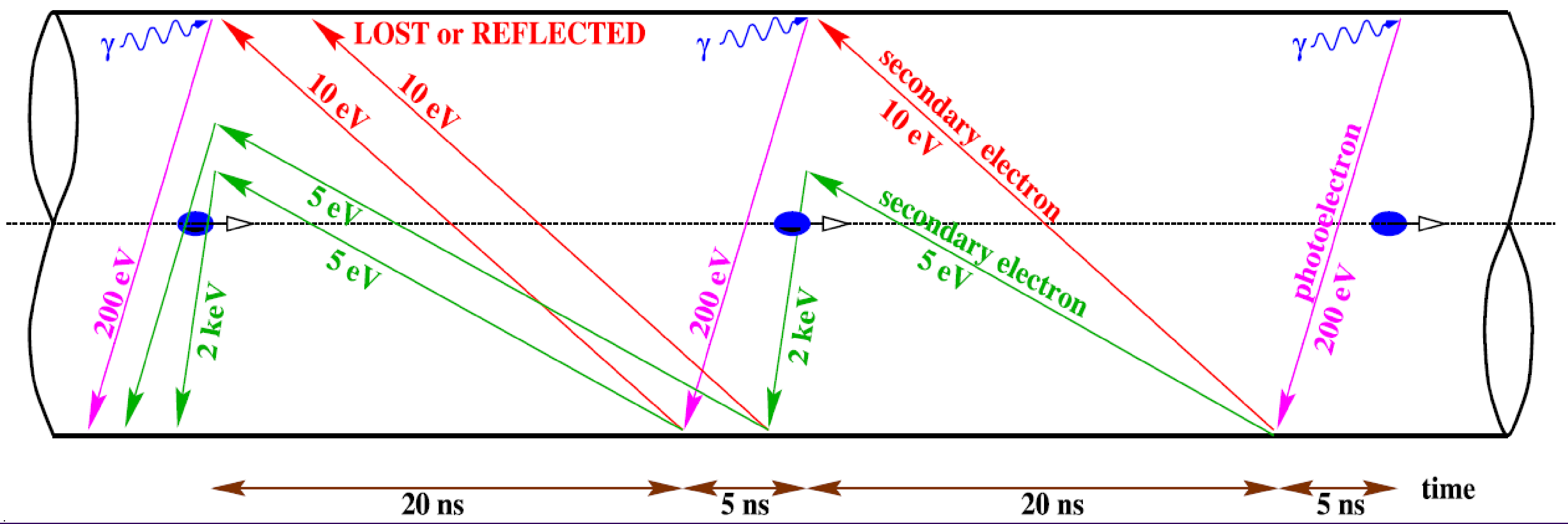
- LHC is the 1st proton storage ring for which synchrotron radiation becomes a noticeable effect ⟹ It gives rise to a significant heat load at top energy, which is intercepted by a beam screen at an elevated temperature of 5-20 K




Slots cut along its length (*to reduce the impedance*) to allow proper vacuum pumping

## Electron cloud

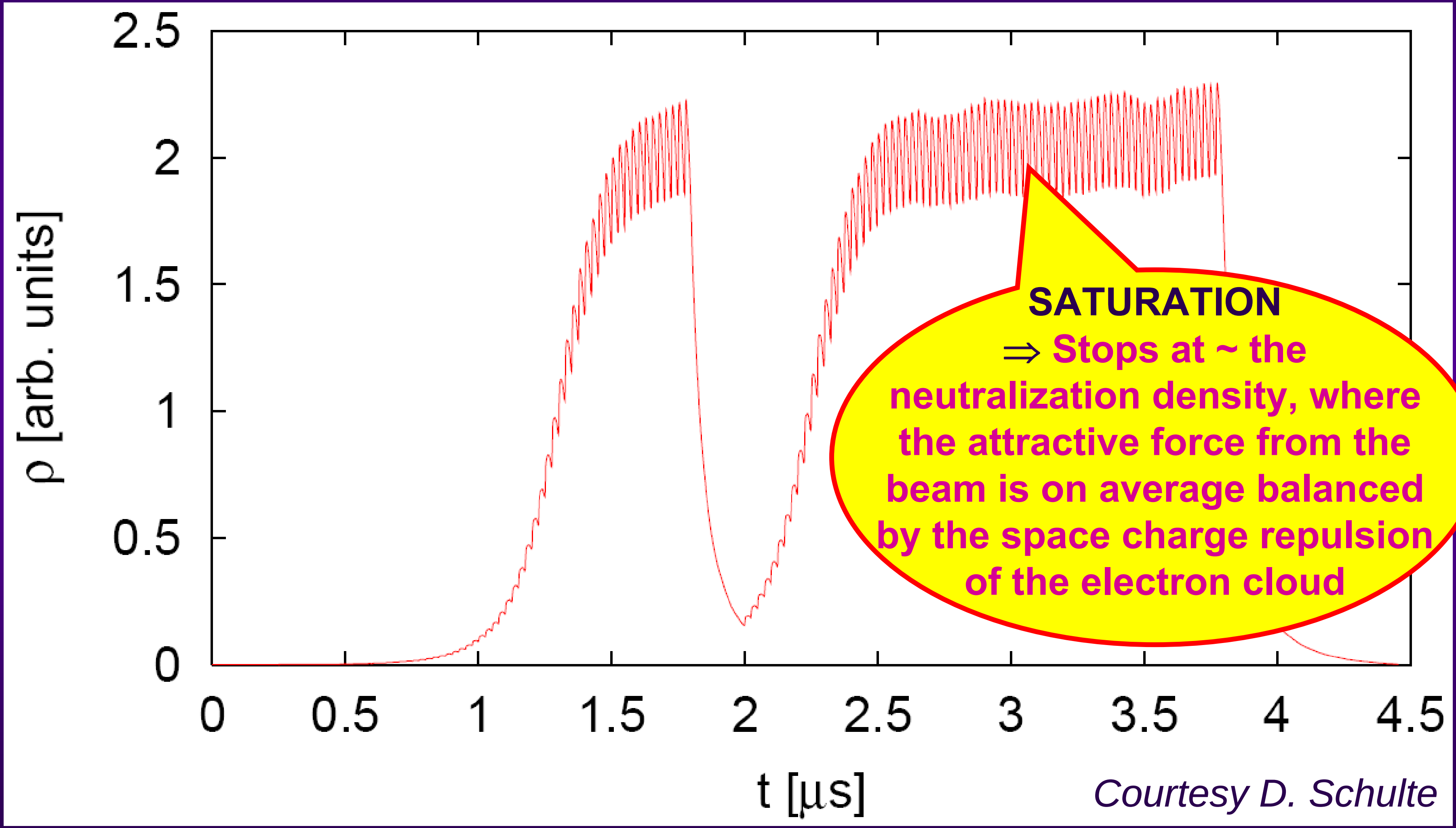
- Schematic of electron-cloud build up in the LHC beam pipe during multiple bunch passages, via photo-emission (due to synchrotron radiation) and secondary emission




*Courtesy F. Ruggiero*

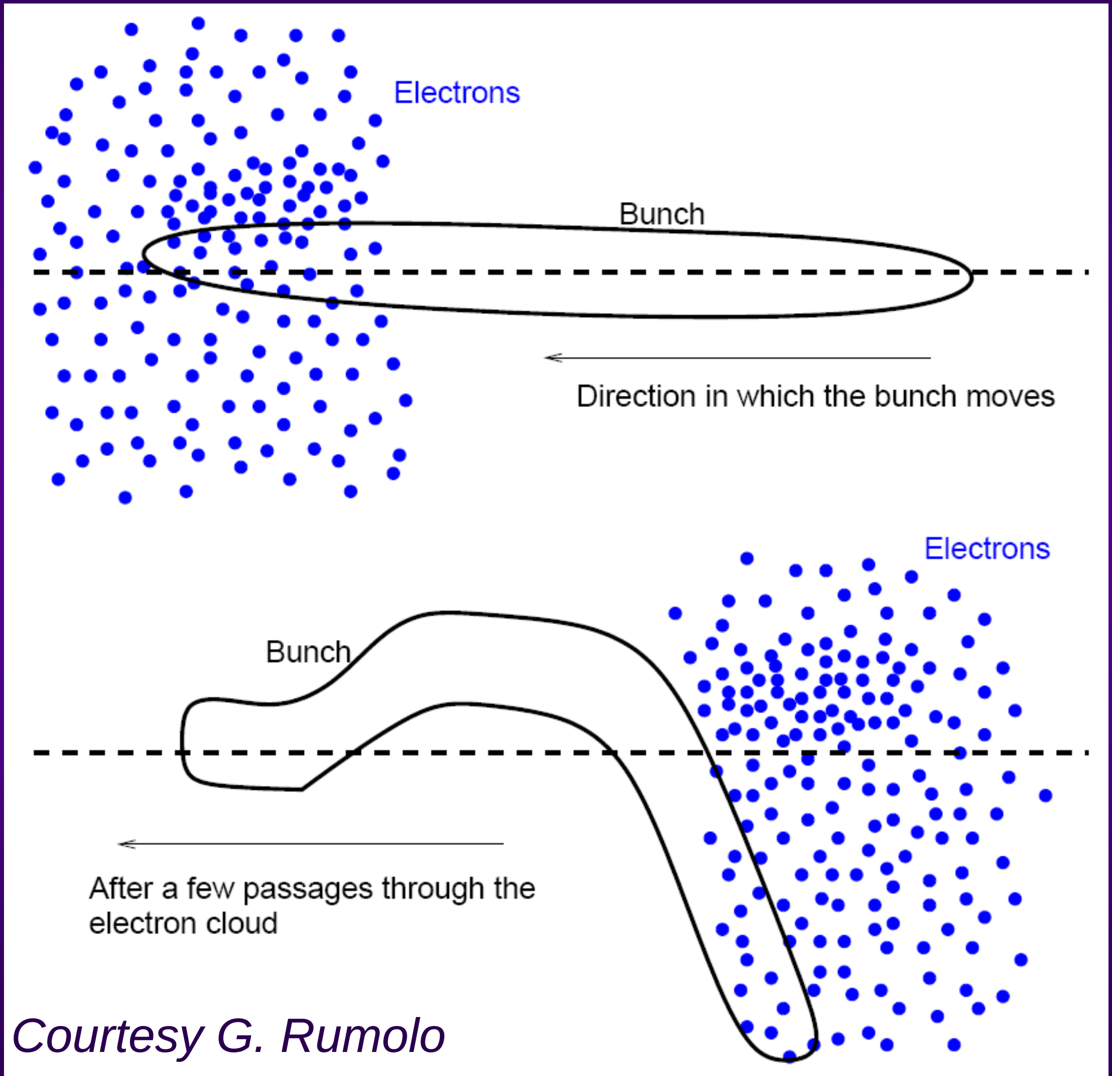
# LHC's challenges in accelerator physics (12/35)

- Simulations of electron-cloud build-up along 2 bunch trains (= 2 batches of 72 bunches) of LHC beam in SPS dipole regions



# LHC's challenges in accelerator physics (13/35)

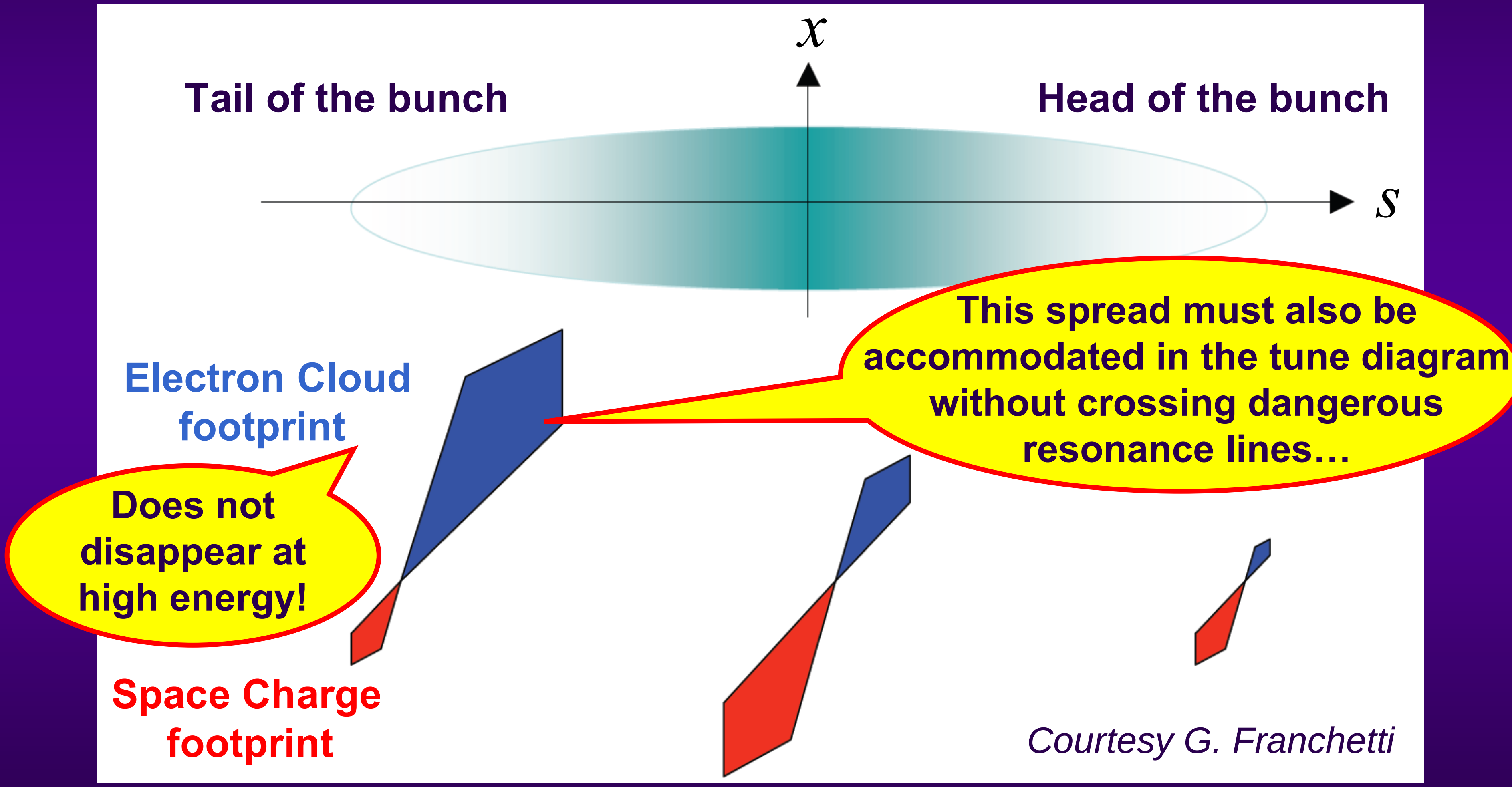
- **Schematic of the single-bunch (coherent) instability induced by an electron cloud**




**MOVIE**
Single-Bunch Instability From ECloud.mpeg

*Courtesy G. Rumolo and F. Zimmermann*

- Incoherent effects induced by an electron cloud



# LHC's challenges in accelerator physics (15/35)

- **The LHC design has adopted a fourfold strategy which aims either at suppressing an electron-cloud build-up or at alleviating its effect:**
  - **(1) A sawtooth chamber in the arcs (a series of 30-$\mu$m high steps spaced at a distance of 500 $\mu$m in the longitudinal direction), which reduces the photon reflectivity**
  - **(2) Shielding the pumping holes inside the arc beam screen so as to prevent multipacting electrons from reaching the cold bore of the dipole magnets**
  - **(3) Coating the warm regions by a special Non Evaporable Getter (NEG) material, TiZrV, with low secondary emission yield**
  - **(4) Conditioning of the arc chamber surface by the cloud itself (*beam scrubbing*), which will ultimately provide a low secondary emission yield. During commissioning the bunch spacing can be increased and/or the beam energy be reduced to process the chamber while staying within the available cooling capacity**

# LHC's challenges in accelerator physics (16/35)

**Beam-beam interaction**

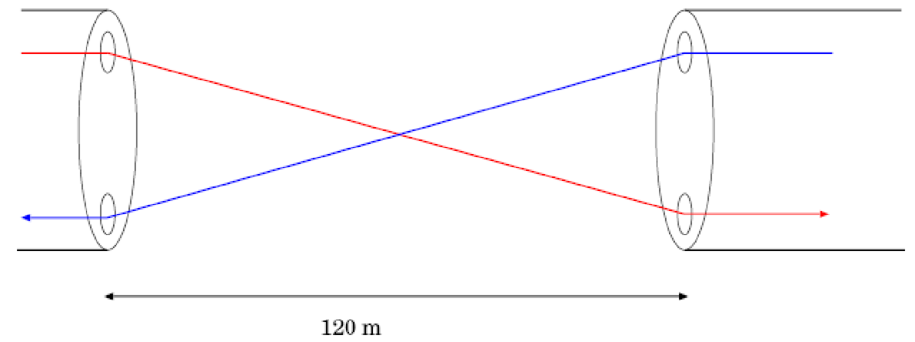
- **Incoherent beam-beam effects ⇒ Lifetime + dynamic aperture**

- **PACMAN effects ⇒ Bunch to bunch variation**

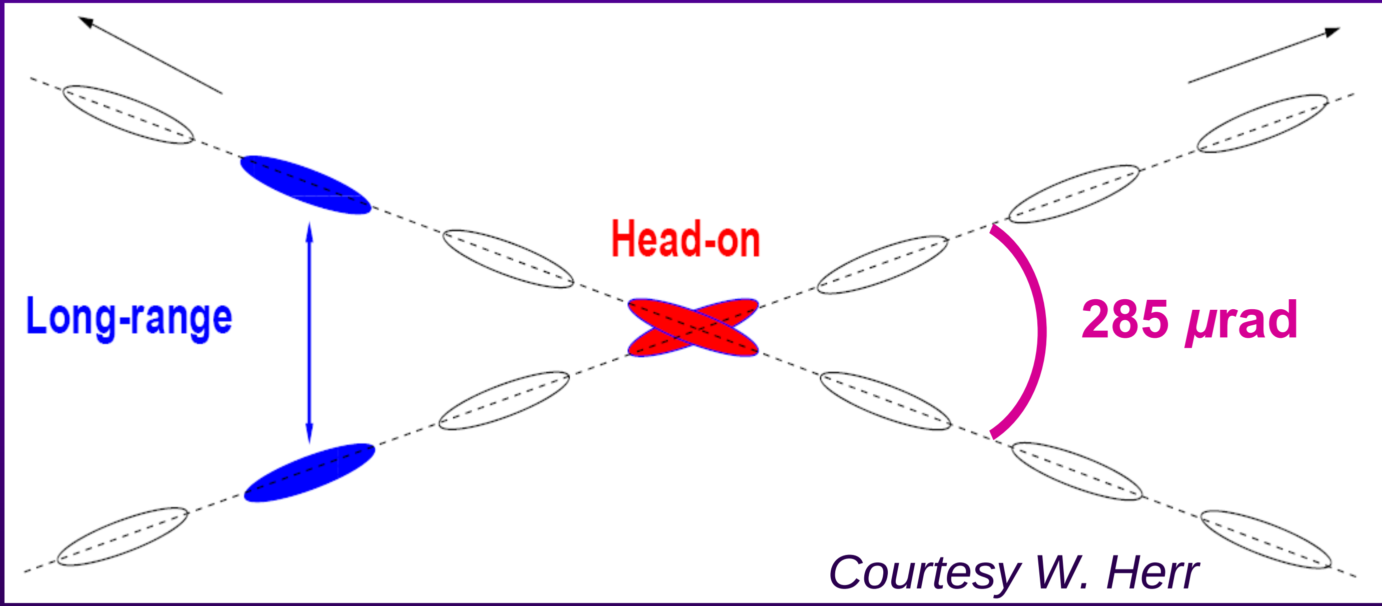
- **Coherent beam-beam effects ⇒ Beam oscillations and instabilities**

# LHC's challenges in accelerator physics (17/35)

**CROSSING ANGLE ⇒ To avoid unwanted collisions, a crossing angle is needed to separate the 2 beams in the part of the machine where they share a vacuum chamber**



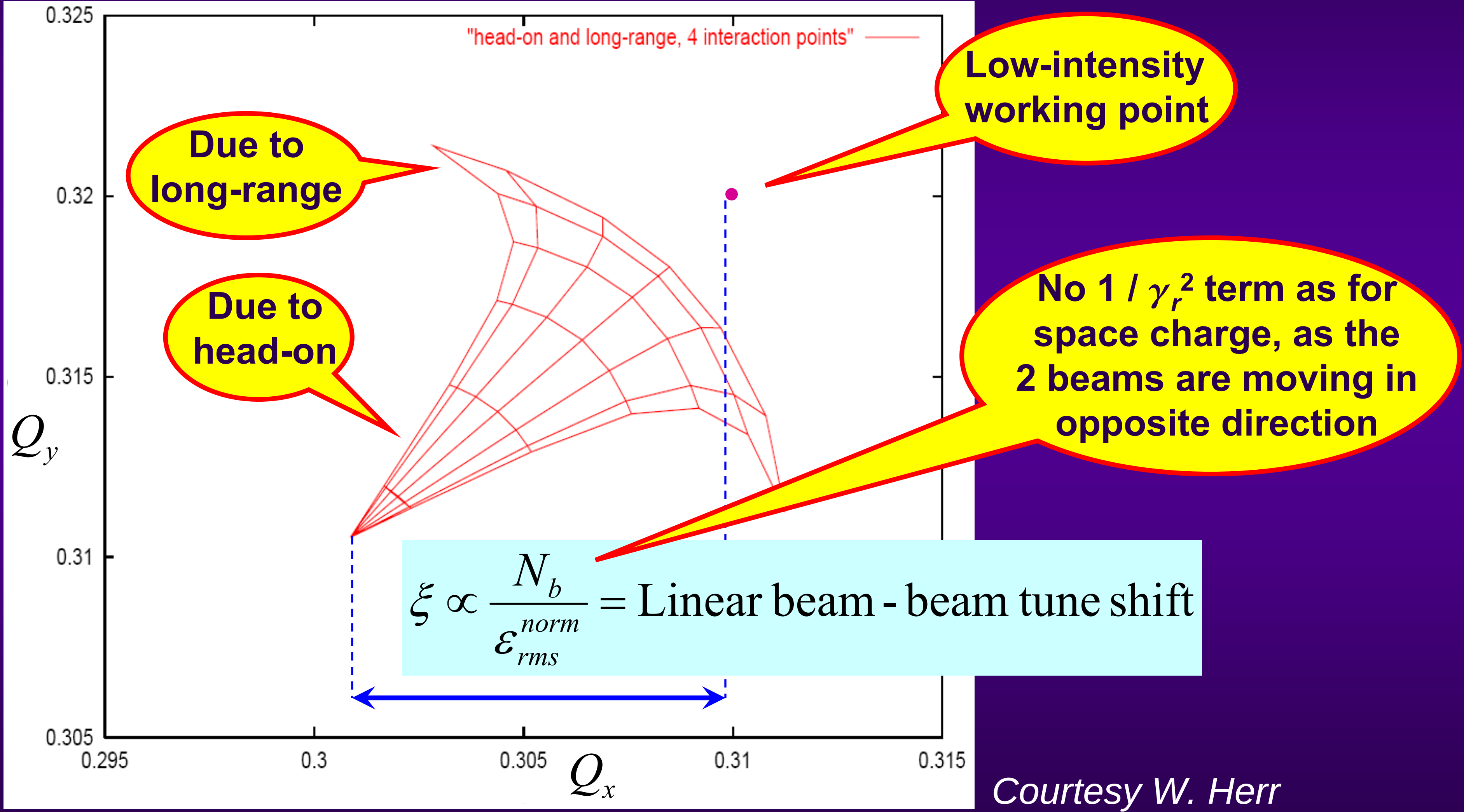

*Courtesy W. Herr*




- **30 long-range interactions around each IP ⇒ 120 in total**
- **Separation: 9 σ**

# LHC's challenges in accelerator physics (18/35)

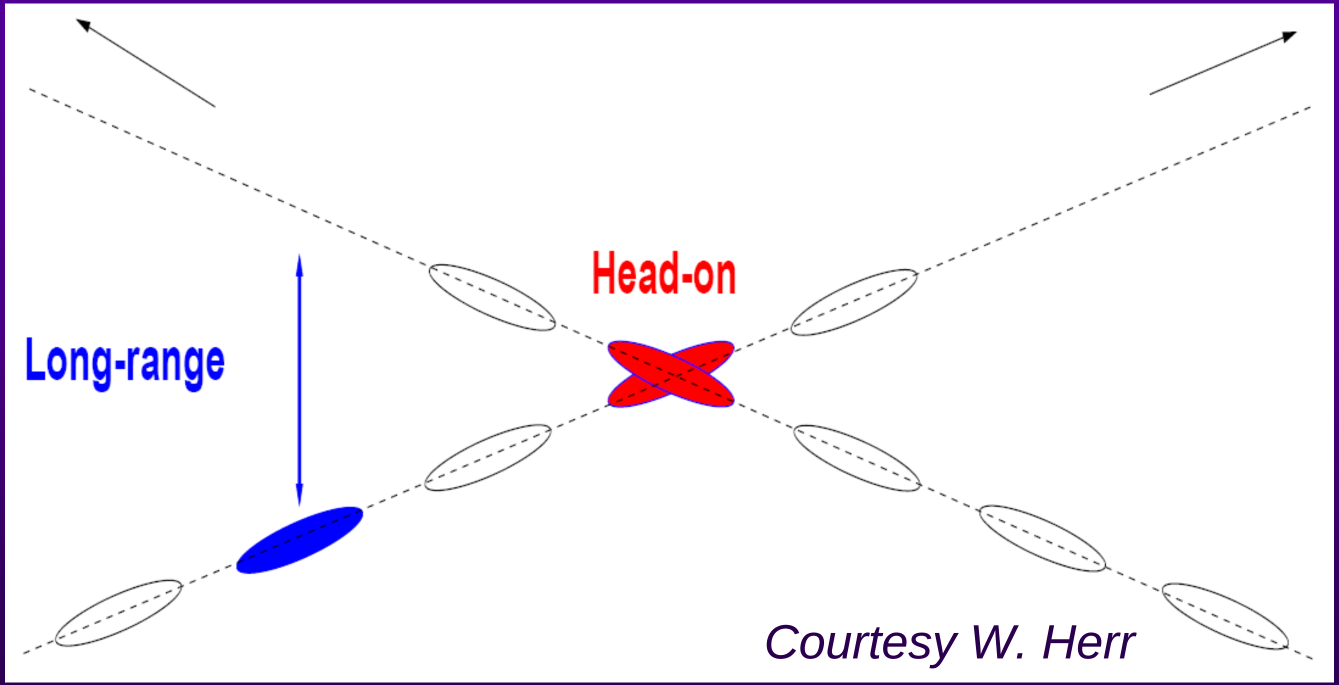
- 2D tune footprint for nominal LHC parameters in collision. Particles up to amplitudes of 6 $\sigma$ are included




*Courtesy W. Herr*

# LHC's challenges in accelerator physics (19/35)

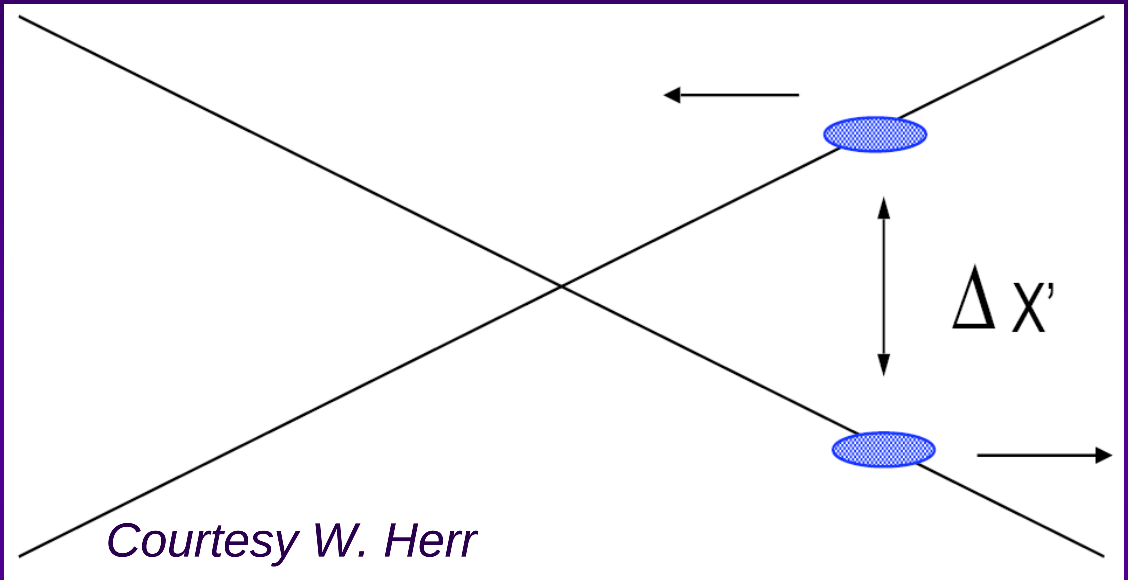
- **PACMAN BUNCHES**
  - **LHC bunch filling not continuous: Holes for injection, extraction, dump…**
  - **2808 bunches out of 3564 possible bunches $\Rightarrow$ 1756 holes**
  - **Holes will meet holes at the IPs**
  - **But not always… a bunch can meet a hole at the beginning and end of a bunch train**



# LHC's challenges in accelerator physics (20/35)

- Bunches which do not have the regular collision pattern have been named PACMAN bunches ⇒ ≠ integrated beam-beam effect
- Only 1443 bunches are regular bunches with 4 head-on and 120 long range interactions, i.e. about half of the bunches are not regular
- The identification of regular bunches is important since measurements such as tune, orbit or chromaticity should be selectively performed on them
- SUPERPACMAN bunches are those who will miss head-on interactions
  - 252 bunches will miss 1 head-on interaction
  - 3 will miss 2 head-on interactions
- ALTERNATE CROSSING SCHEME: Crossing angle in the vertical plane for IP1 and in the horizontal plane for IP5 ⇒ The purpose is to compensate the tune shift for the Pacman bunches

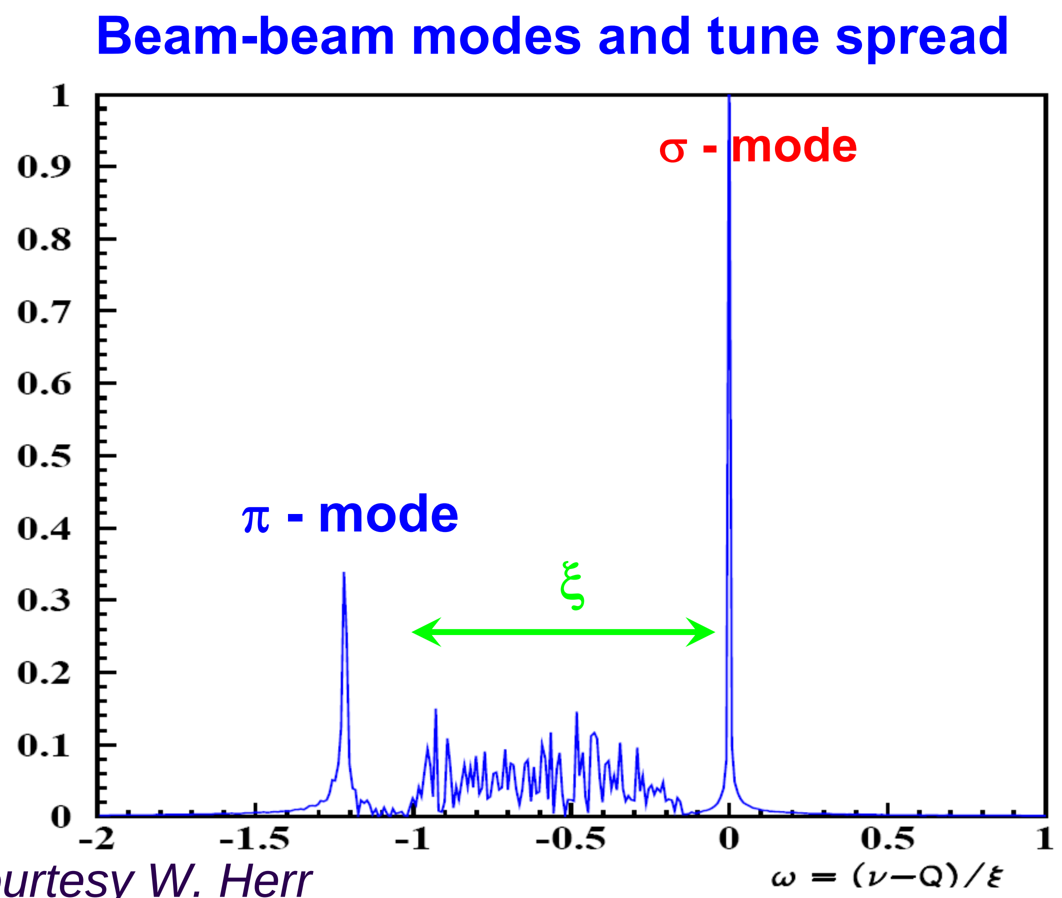
- COHERENT BEAM-BEAM EFFECT




- A whole bunch sees a (coherent) kick from the other (separated) beam ⇒ Can excite coherent oscillations

- All bunches couple together because each bunch "sees" many opposing bunches ⇒ Many coherent modes possible!

# LHC's challenges in accelerator physics (22/35)




Courtesy W. Herr

For 2 colliding bunches

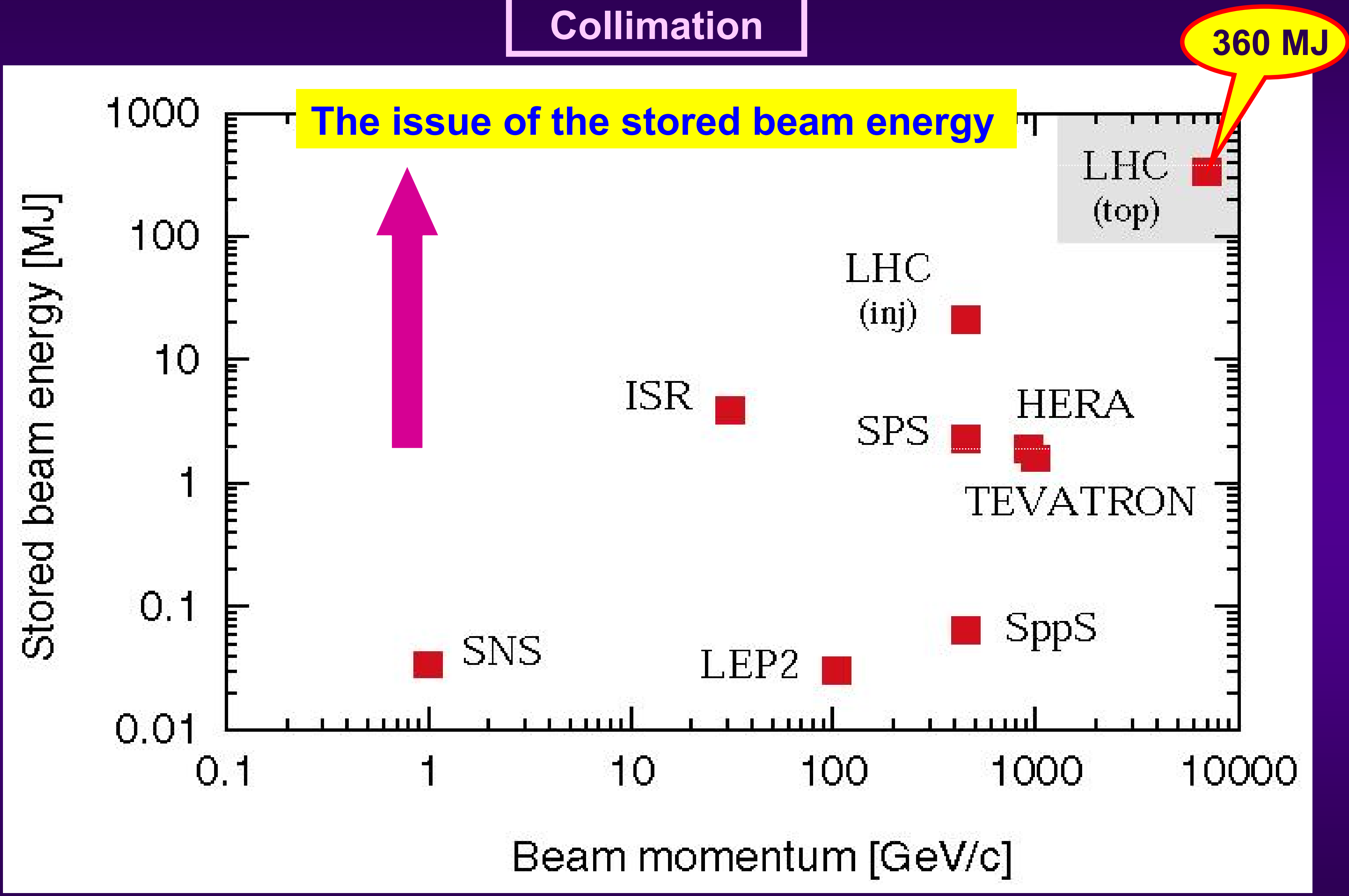
- σ-mode (in phase) is at unperturbed tune
- π-mode (out of phase) is shifted by 1.1 – 1.3 ξ
- Incoherent spread between [0.0,1.0] ξ

It can be restored when the symmetry between the 2 beams is broken

⇒ Landau damping is lost
(coherent tune of the π-mode not inside the incoherent tune spread)

# LHC's challenges in accelerator physics (23/35)

**Collimation**



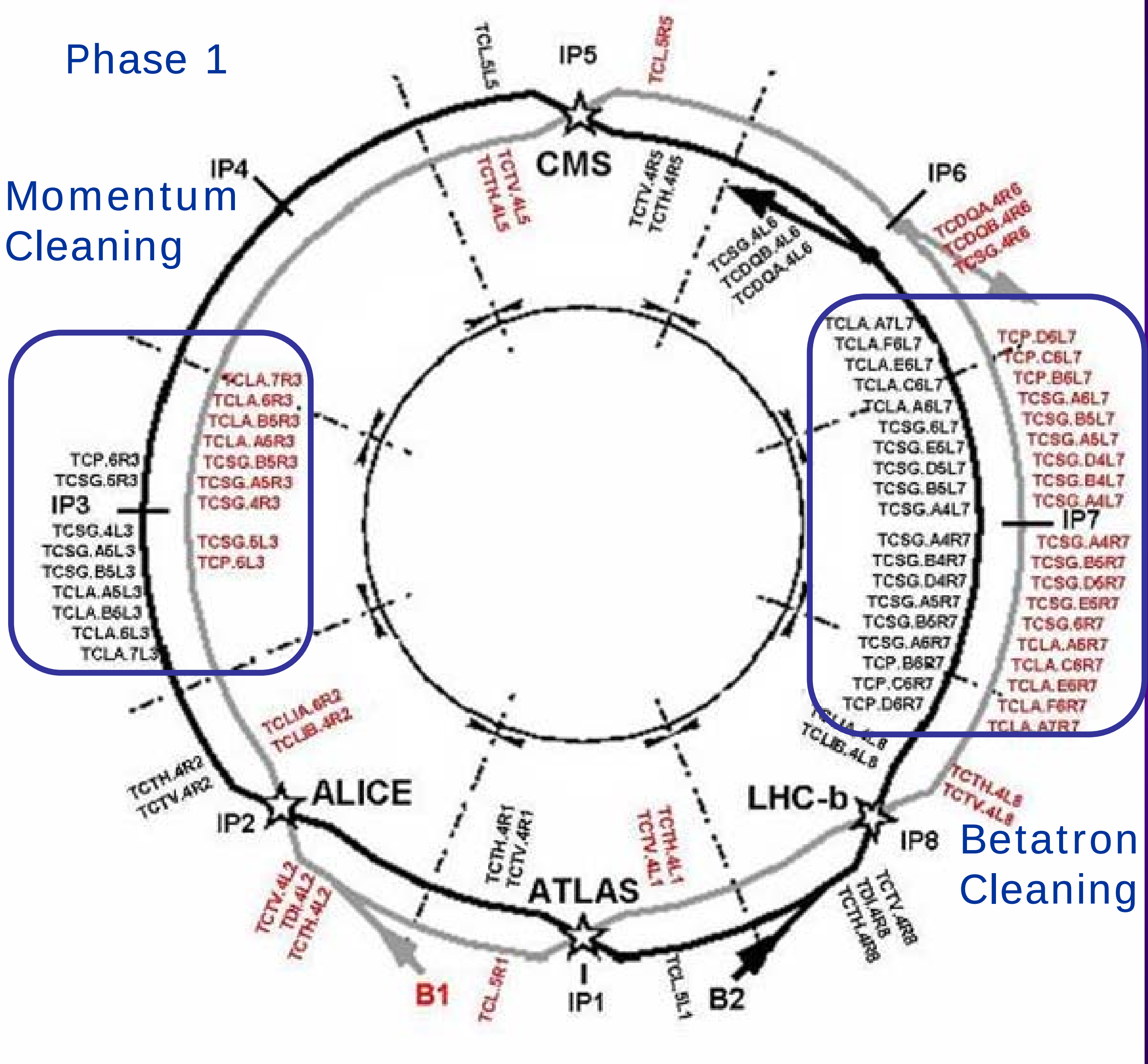
# LHC's challenges in accelerator physics (24/35)

- The transverse energy density of the nominal beam is 1000 times higher than previously achieved in proton storage rings (1 GJ/mm$^2$)

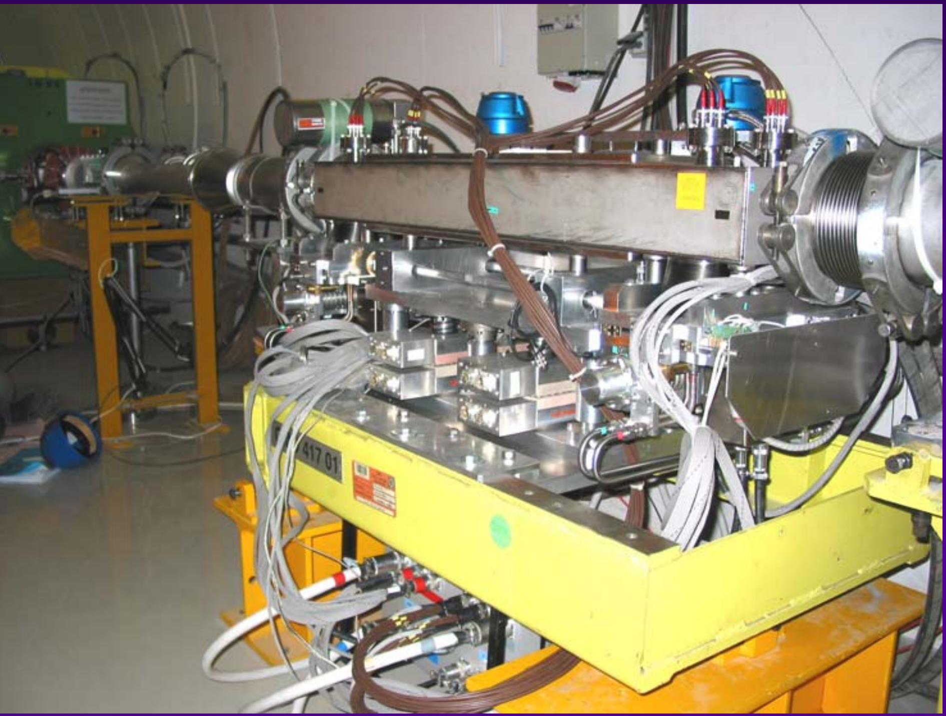
- Tiny fractions of the stored beam suffice to quench a super-conducting LHC magnet or even to destroy parts of the accelerators

- Note that a $10^{-5}$ fraction of the nominal LHC beam will damage Copper. The energy in the two LHC beams is sufficient to melt almost 1 ton of copper!

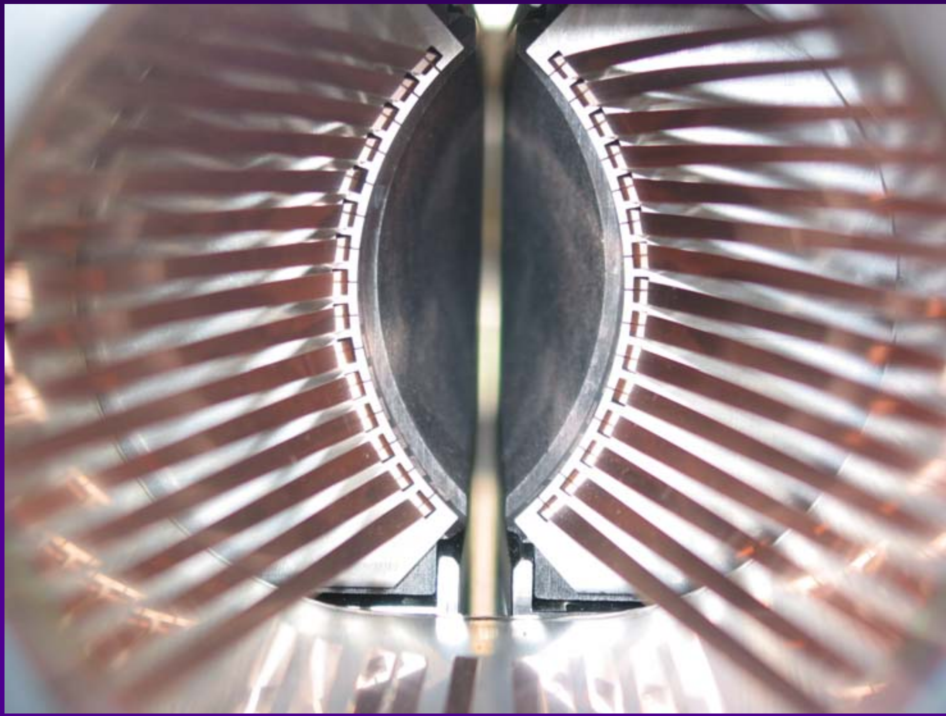
# LHC's challenges in accelerator physics (25/35)



# LHC's challenges in accelerator physics (26/35)



Collimator prototype in the SPS

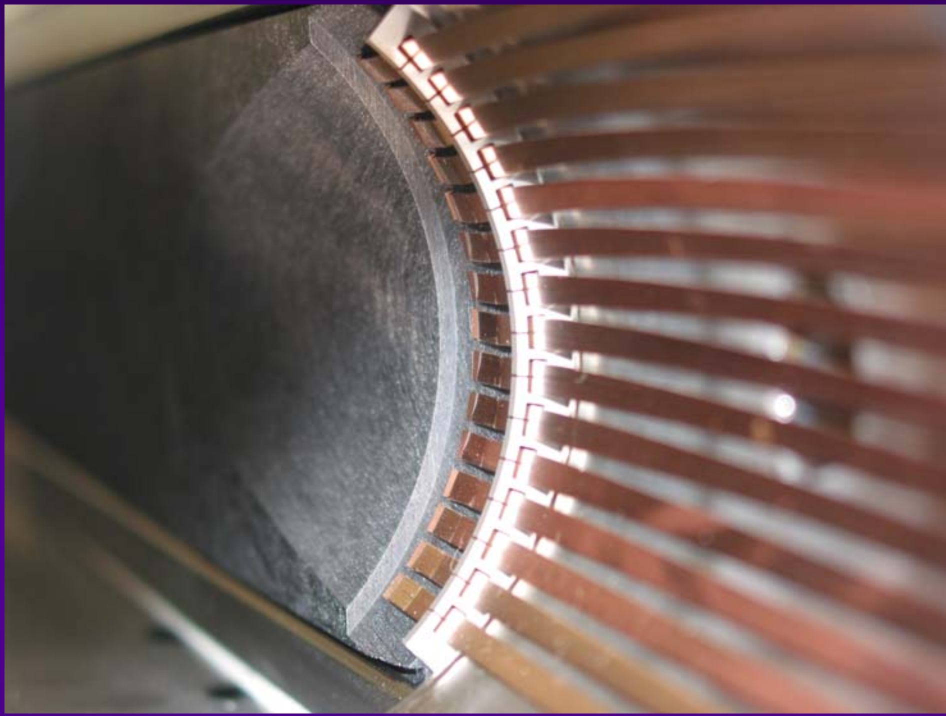


View along beam path

**Beam-based studies performed in 2004 and 2006**

# LHC's challenges in accelerator physics (27/35)

Carbon carbon jaw



RF contacts for a single jaw

# LHC's challenges in accelerator physics (28/35)

- RF contacts connect the moving carbon-fibre-reinforced carbon composite (CFC) jaws with the vacuum flanges

  - Allow for a smooth geometrical transition from the flat jaws to the round flanges and beam pipe

  - Guarantee electrical continuity for the beam induced currents

$\Longrightarrow$ CuBe alloy of the C17410 type plated with Ag, acting over stainless steel plated with Rh (to avoid cold welding, etc.)

# LHC's challenges in accelerator physics (29/35)

- **Transverse resistive-wall impedance induced by the collimators**

  - **First unstable betatron line** $f_\beta^1 \approx 8 \text{ kHz}$

  - **Skin depth for graphite ($\rho$ = 10 μΩm)** $\delta\left(8 \text{ kHz}\right) = 1.8 \text{ cm}$

  - **Collimator thickness** $d_{th} = 2.5 \text{ cm}$

$$\Rightarrow \quad \delta\left(f_\beta\right) = \sqrt{\frac{\rho}{\pi \mu f_\beta}} < d_{th}$$

$\Rightarrow$ **One could think that the classical "thick-wall" formula would be about right**

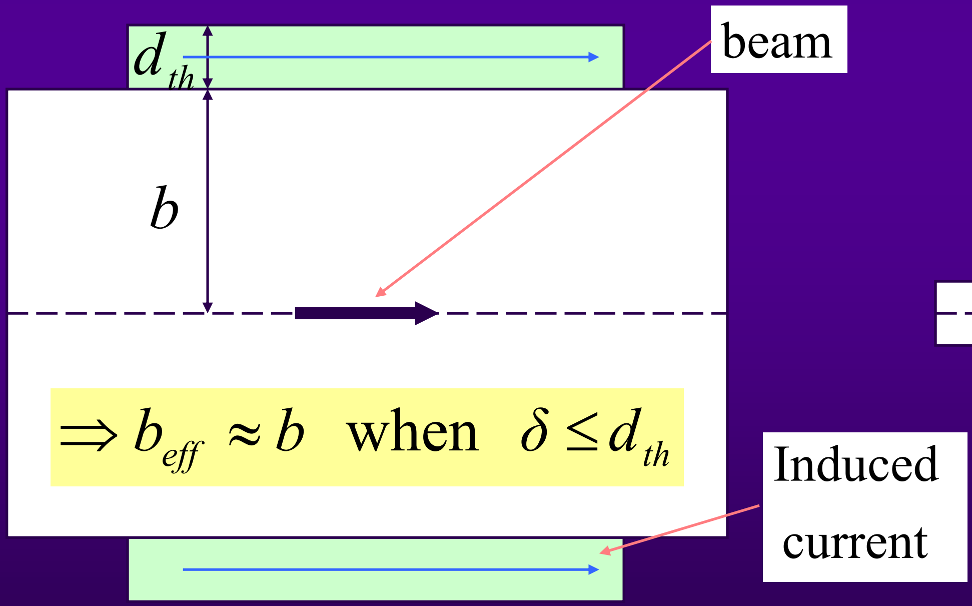
$$Z_\perp^{\text{thick-wall}}\left(f\right) \propto \frac{1}{b^3 \sqrt{f}}$$

# LHC's challenges in accelerator physics (30/35)

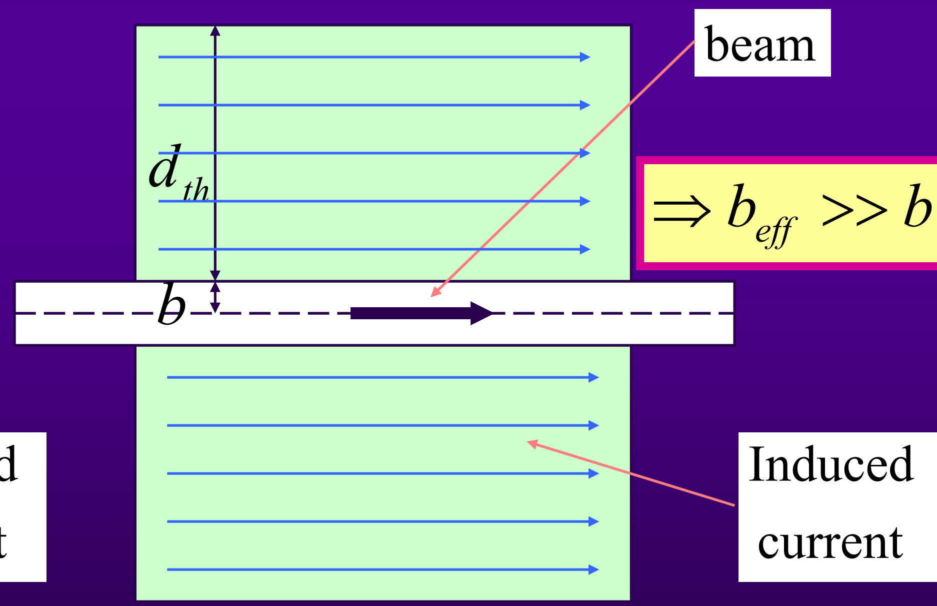
- In fact it is not $\Rightarrow$ The resistive impedance is ~ 2 orders of magnitude lower at ~ 8 kHz !

**$\Rightarrow$ A new physical regime was revealed by the LHC collimators**

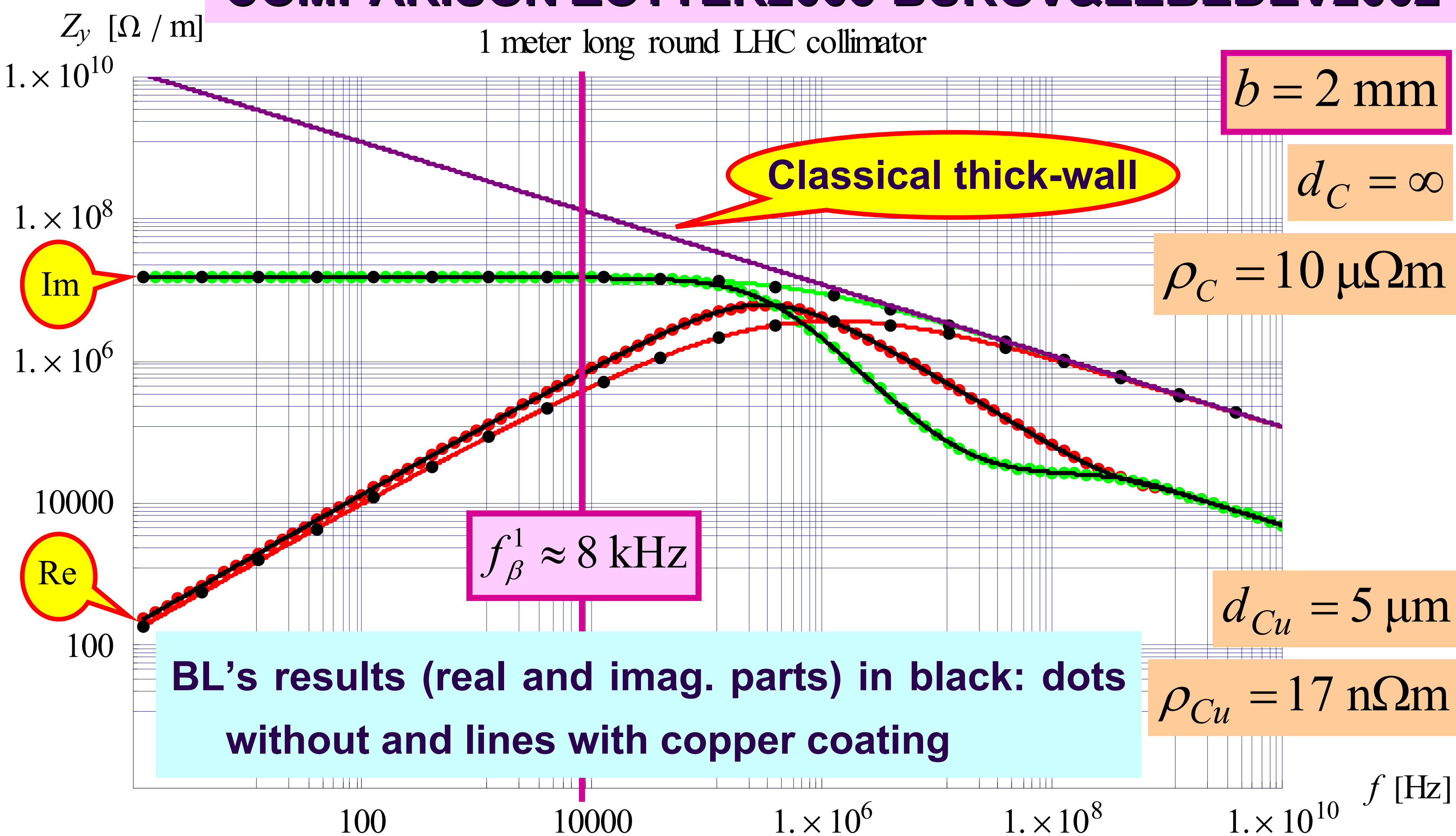
**Usual regime :** $d_{th}\,, \delta < b$




**New regime :** $d_{th} >> b\,,\ \delta \le d_{th}$



## COMPARISON ZOTTER2005-BUROV&LEBEDEV2002

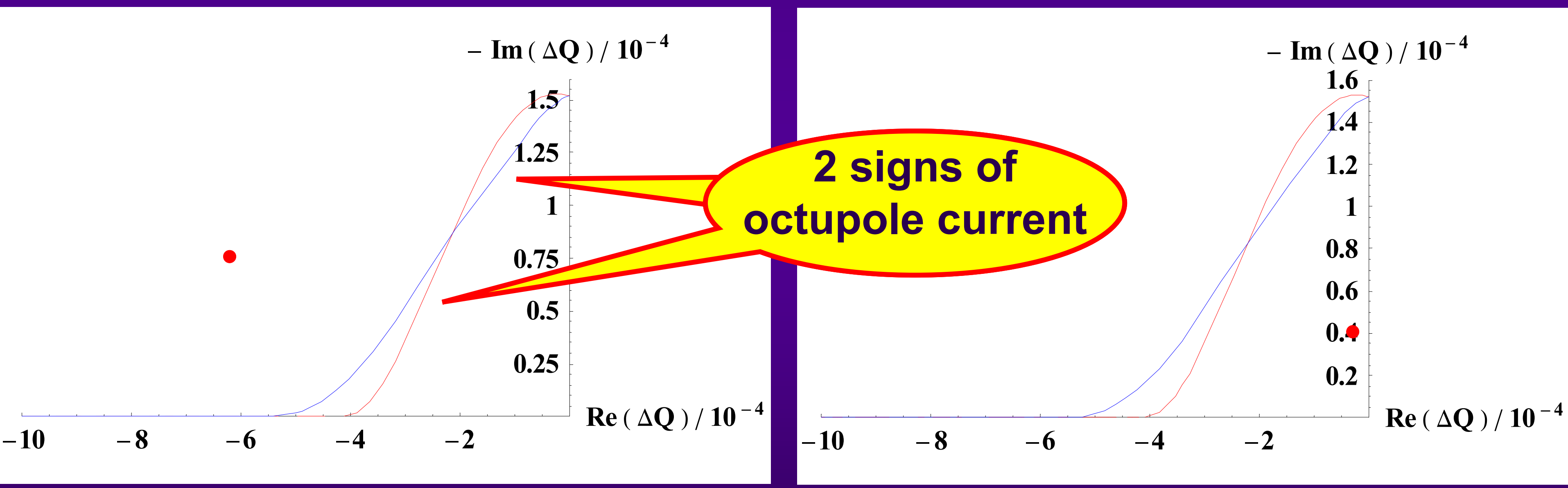



**BL's results (real and imag. parts) in black: dots without and lines with copper coating**

# LHC's challenges in accelerator physics (32/35)

**Stability diagram (maximum octupoles) and collective tune shift for the most unstable coupled-bunch mode and head-tail mode 0 (1.15e11 p/b at 7 TeV)**

With collimators | **Y-plane** | Without collimators




⇒ **The intensity in the LHC is limited to ~50 % of the nominal one**

# LHC's challenges in accelerator physics (33/35)

## VACUUM

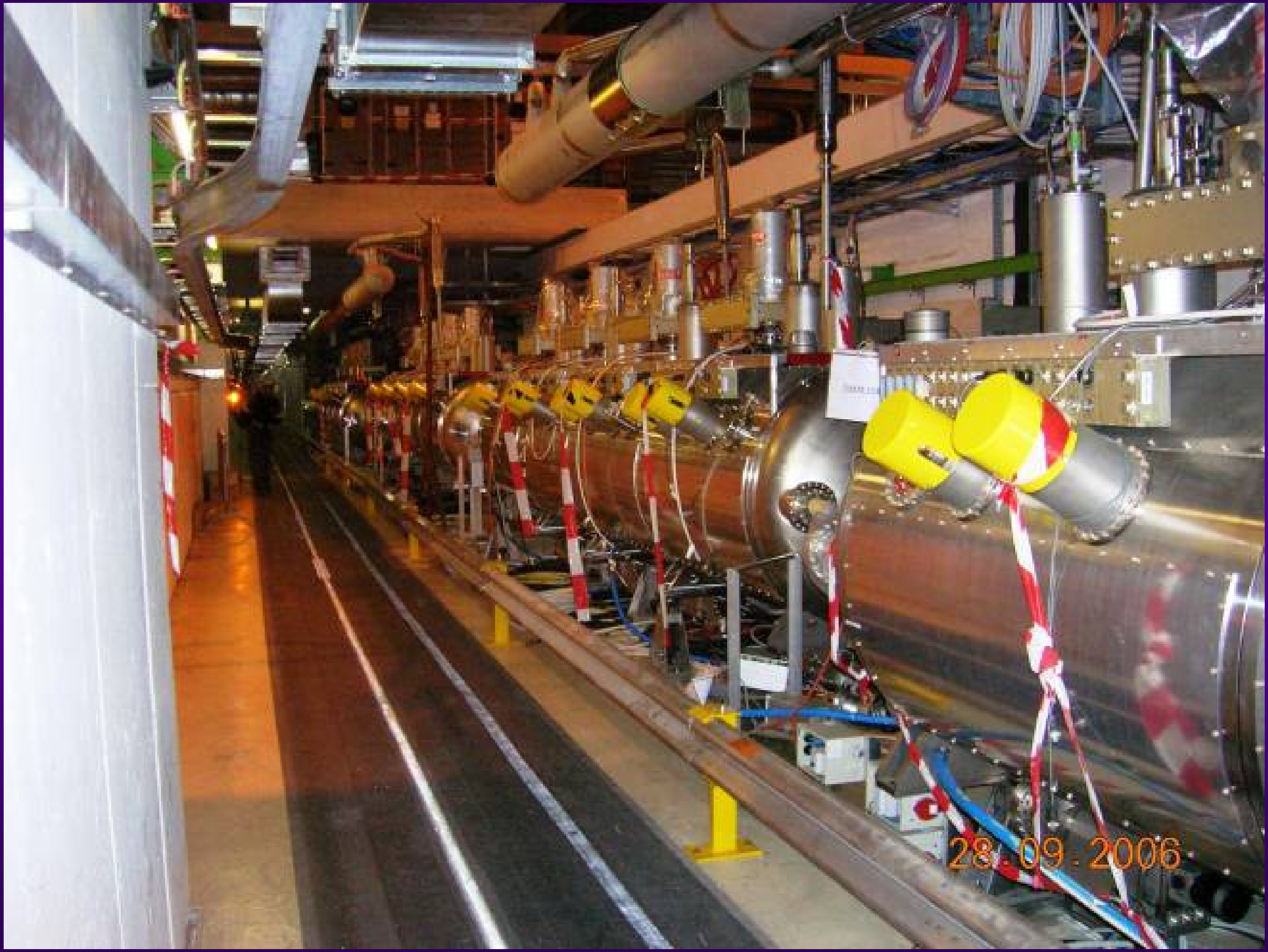
- **LHC has the particularity of having not one, but 3 vacuum systems:**
  - **Insulation vacuum for cryomagnets**
  - **Insulation vacuum for helium distribution line (QRL)**
  - **Beam vacuum $\Longrightarrow$ The requirements for the room temperature part are driven by the background to the experiments as well as by the beam lifetime and call for a value in the range from $10^{-8}$ to $10^{-9}$ Pa (i.e. from $10^{-10}$ to $10^{-11}$ mbar)**

**Reminder 1:** 1 atm = 760 Torr and 1 mbar = 0.75 Torr = 100 Pa

**Reminder 2:** $10^{-10}$ Torr = ~3 million molecules / $cm^3$

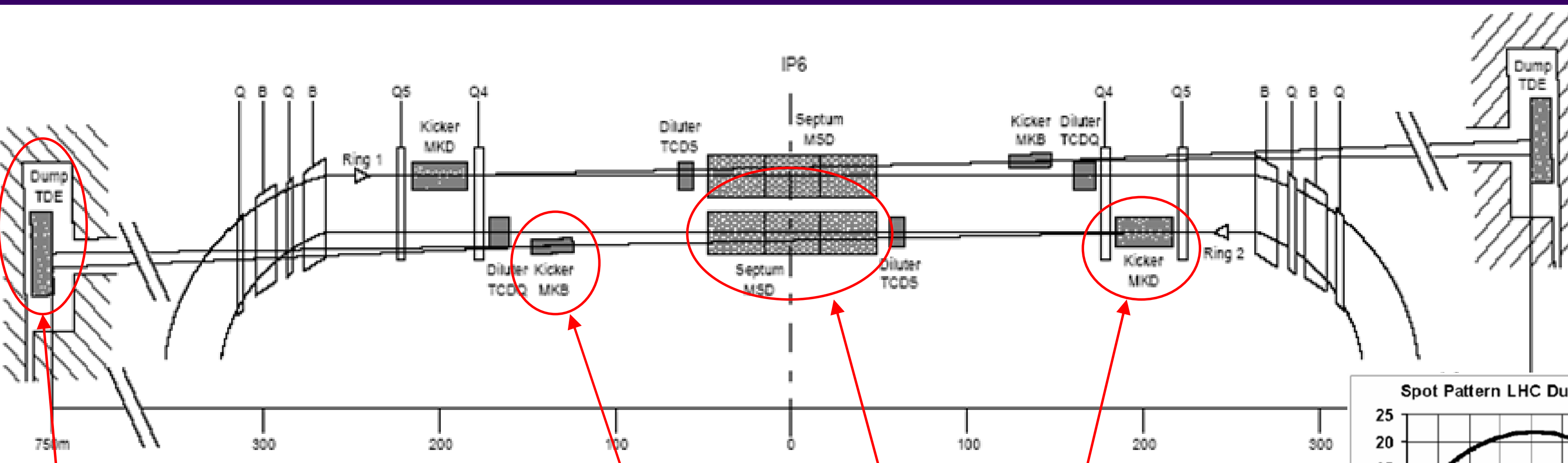
# LHC's challenges in accelerator physics (34/35)

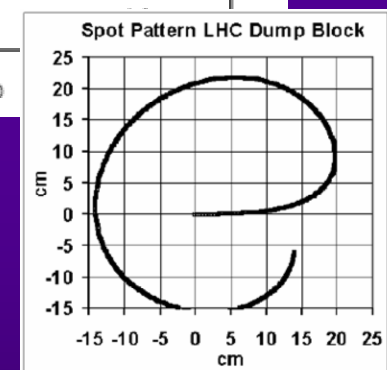
## RF CAVITIES IN IR4



# LHC's challenges in accelerator physics (35/35)

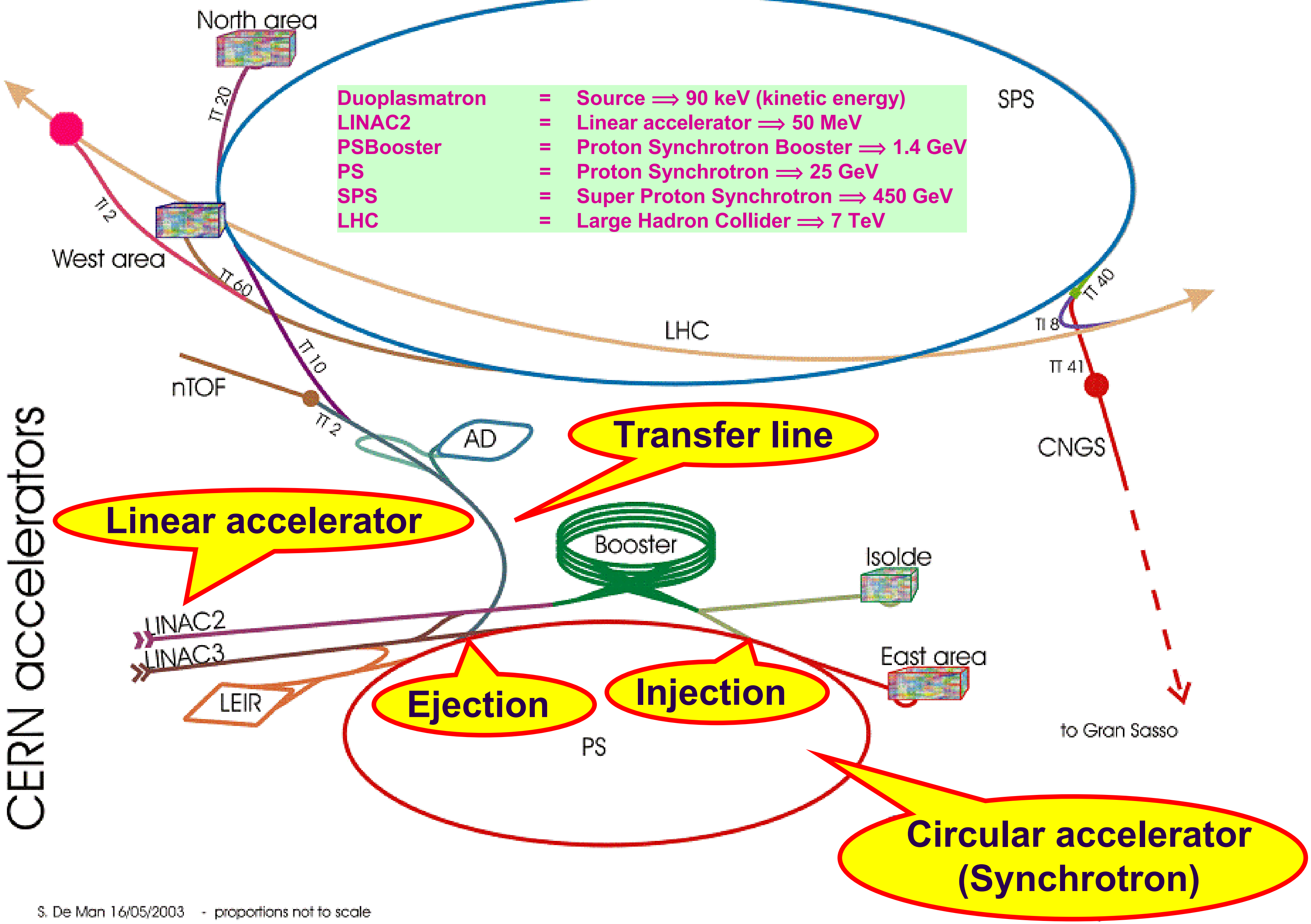
## BEAM DUMPS IN IR6



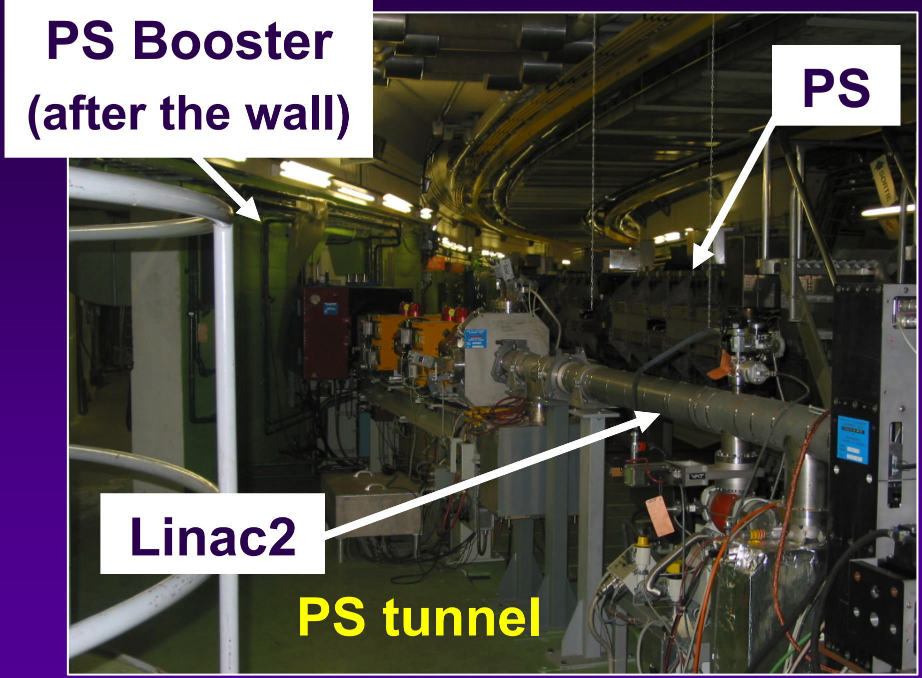




- Symmetrical around IP
- Horizontal kick by MKD into septum magnet
- Vertical deflection by MSD into transfer tunnel
- Beam dilution kicker magnets MKB to spread beam on dump
- Beam dumps TDE located 750m from the septum

*Courtesy R. Bailey*

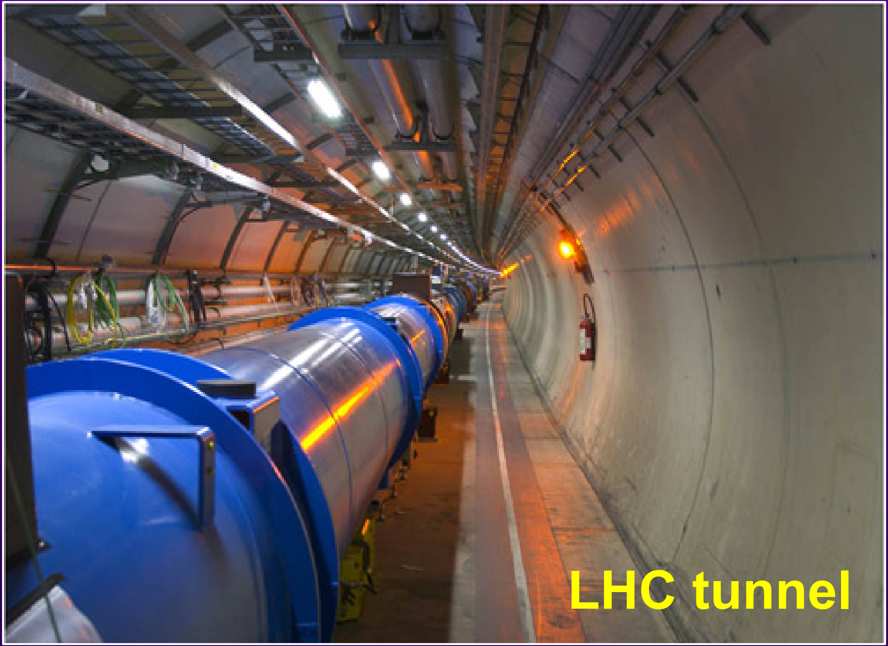



# LHC beam in the injector chain

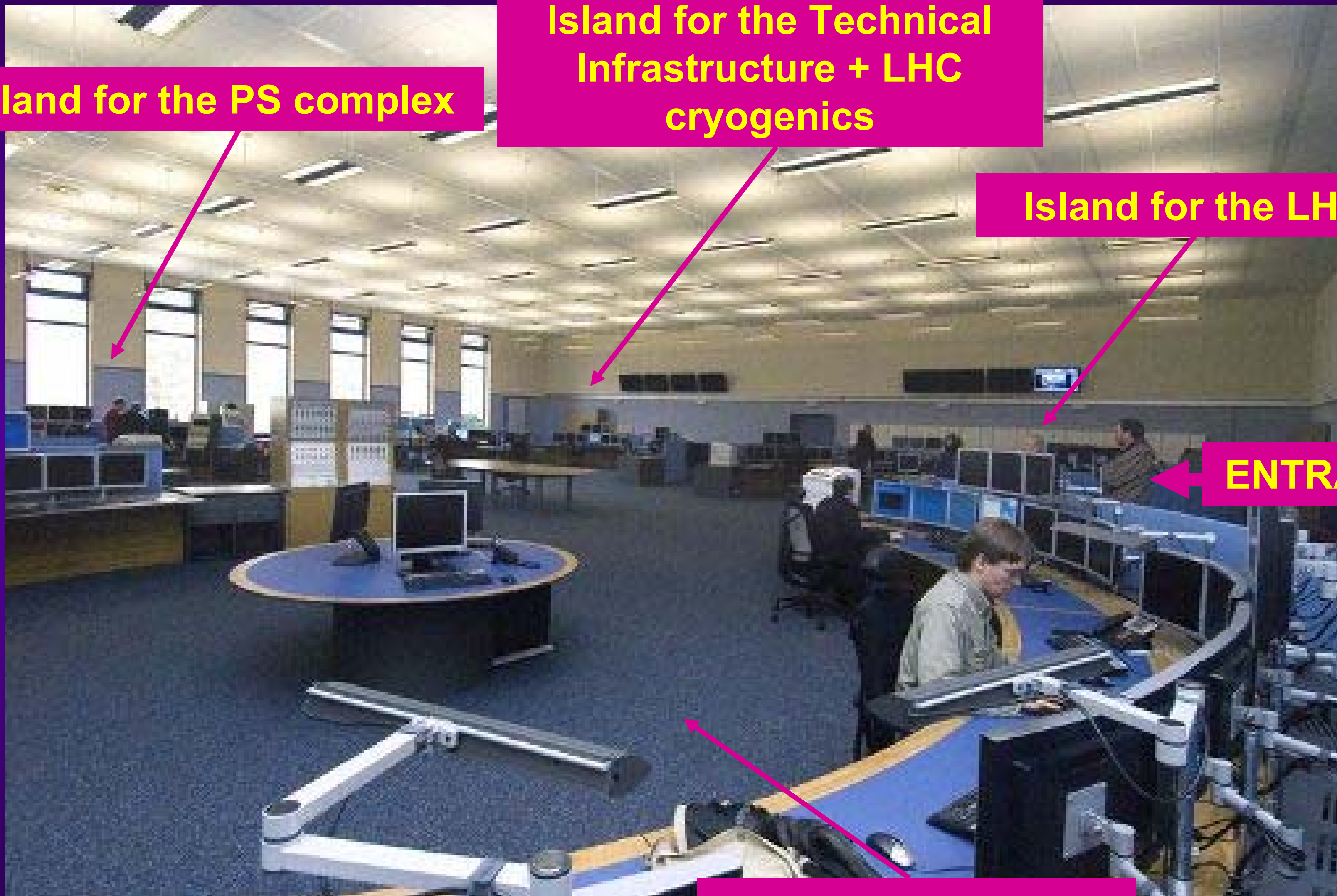

PS Booster
(after the wall)
PS
Linac2
PS tunnel


SPS tunnel


Vacuum chamber
($\phi$ = 13 cm here)
TT2 transfer line tunnel

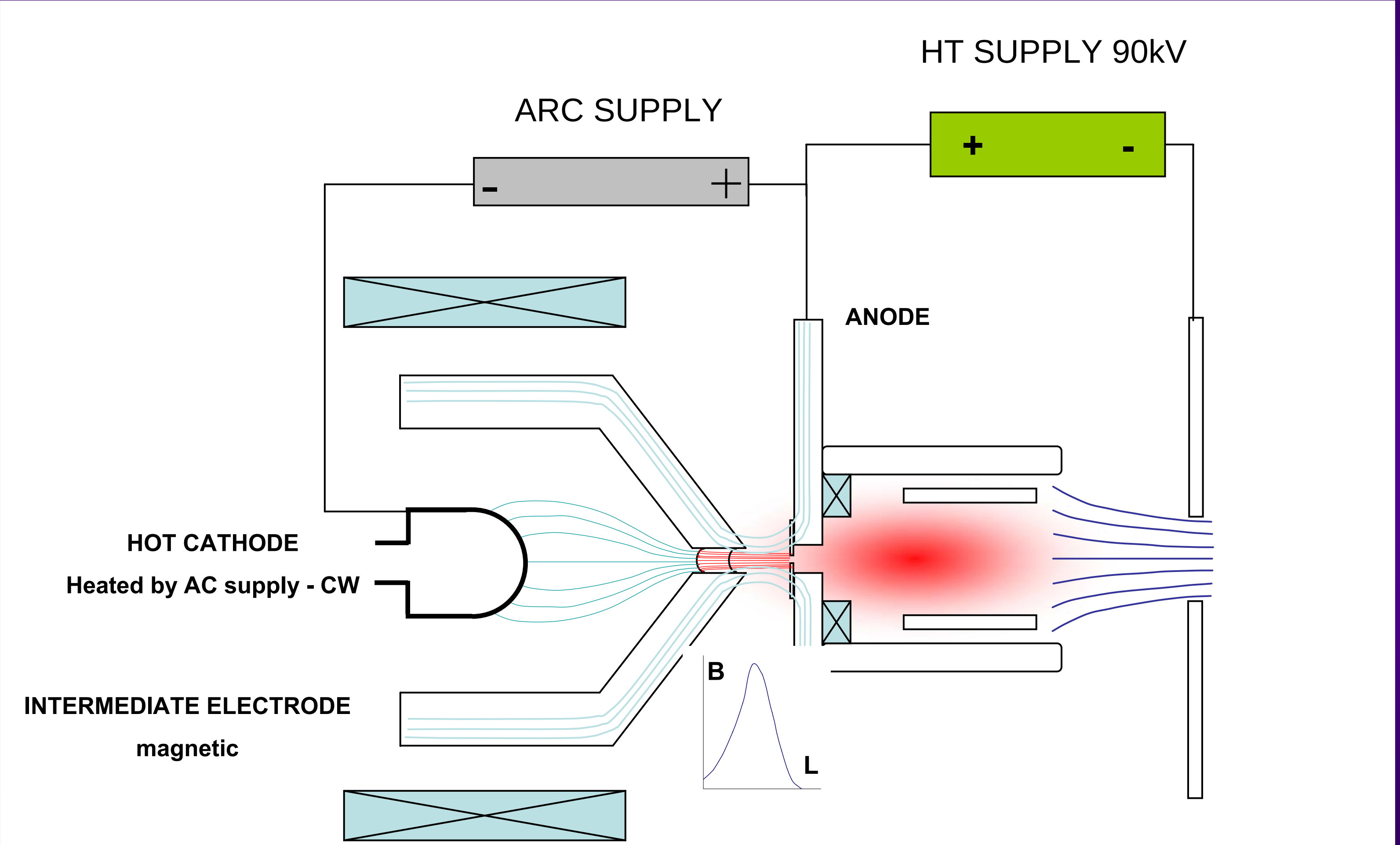

LHC tunnel

# New CERN Control Centre (CCC) at Prevessin since March 2006



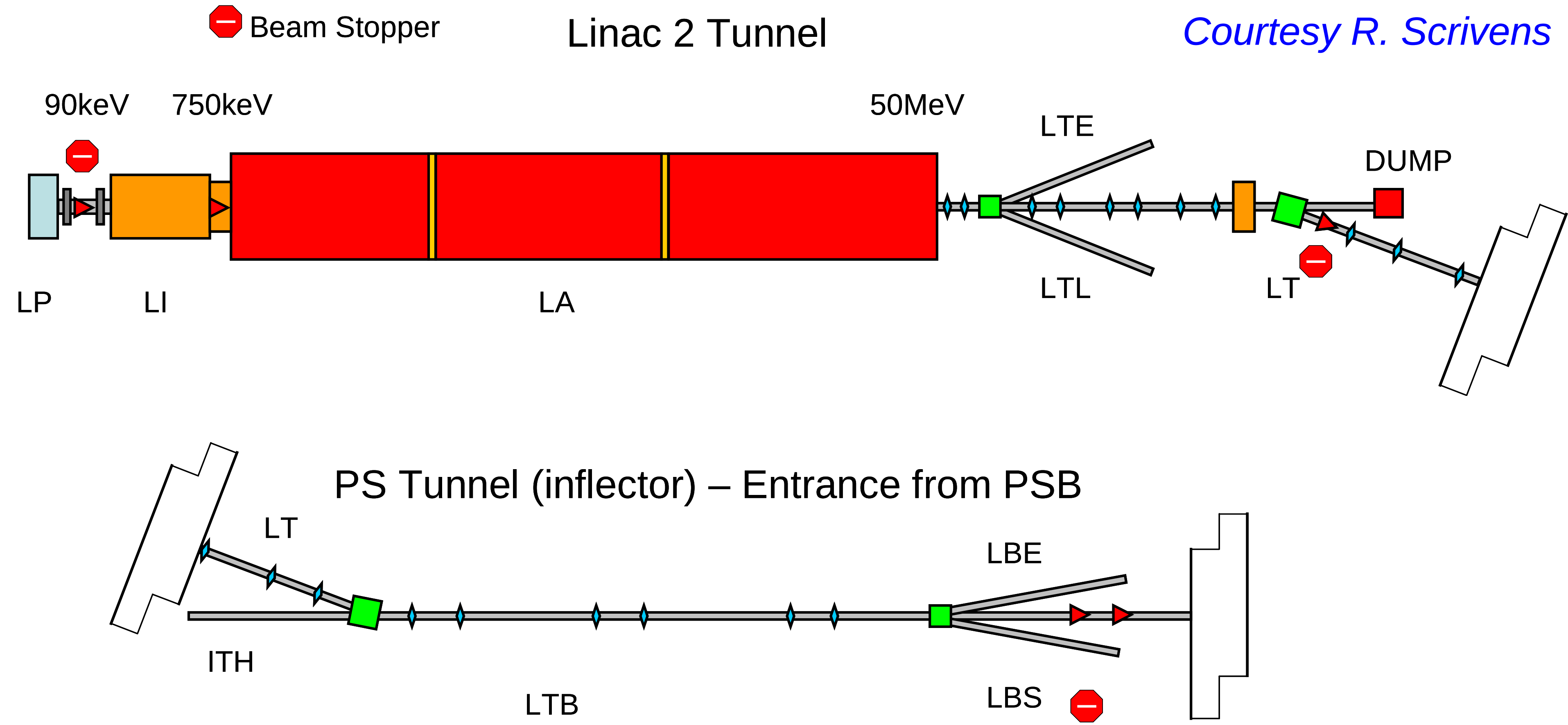
# SOURCE: duoplasmatron

⟹ Protons (at 90 keV) are produced by the ionization of a $H_2$ plasma enhanced by an electron beam




*Courtesy R. Scrivens*

# LINAC2 (1/2)




**LA** = **Linac 2 - Accelerator**

**LBE** = **Linacs (2,3) - Booster Emittance line**

**LBS** = **Linacs (2,3) - Booster Spectrometer line**

**LI** = **Linac 2 - Injection**

**LP** = **Linac 2 - Source**

**LT** = **Linac 2 Transfer line**

**LTB** = **Linacs (2,3) Transfer to Booster**

**LTE** = **Linac 2 - Emittance line**

**LTL** = **Linac 2 - Longitudinal measurement line**

# LINAC2 (2/2)

- The beams in the Linac2 are quasi square pulses with a length which varies depending on the user (the beam length varies between 25 μs and 120 μs and it is limited at the source)

- The nominal LHC requirement is a beam of 180 mA in 30 $\mu$s at the entrance of the PSBooster

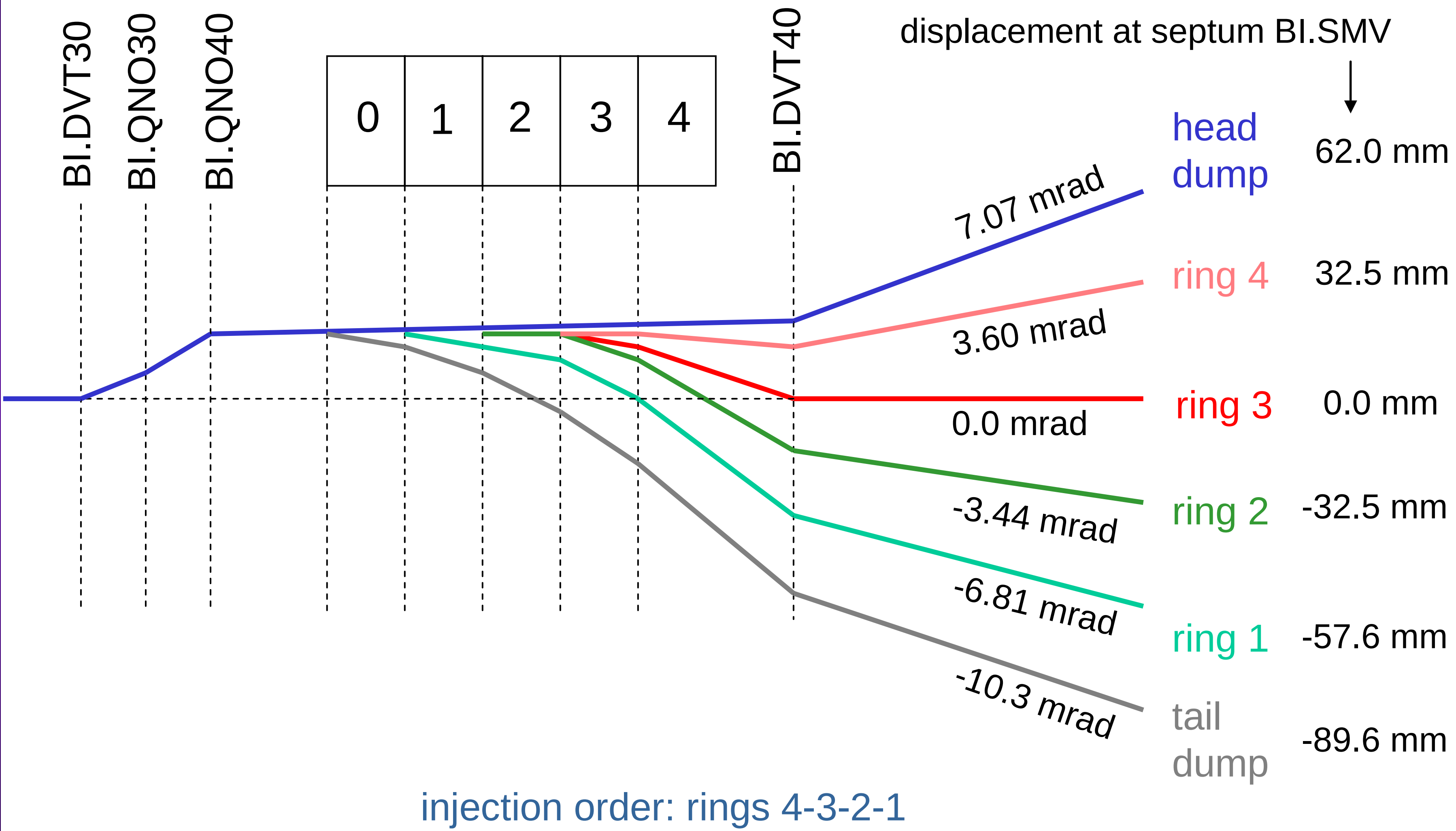
- The transverse normalised rms beam emittance is 1.2 $\mu$m

$\Longrightarrow$ Challenge of transverse emittance preservation in the injectors

| | | |
|---|---|---|
| - PSBooster ejection | $\Longrightarrow$ | 2.5 $\mu$m |
| - PS ejection | $\Longrightarrow$ | 3 $\mu$m |
| - SPS ejection | $\Longrightarrow$ | 3.5 $\mu$m |
| - LHC top energy | $\Longrightarrow$ | 3.75 $\mu$m |

# PSBOOSTER (1/3)

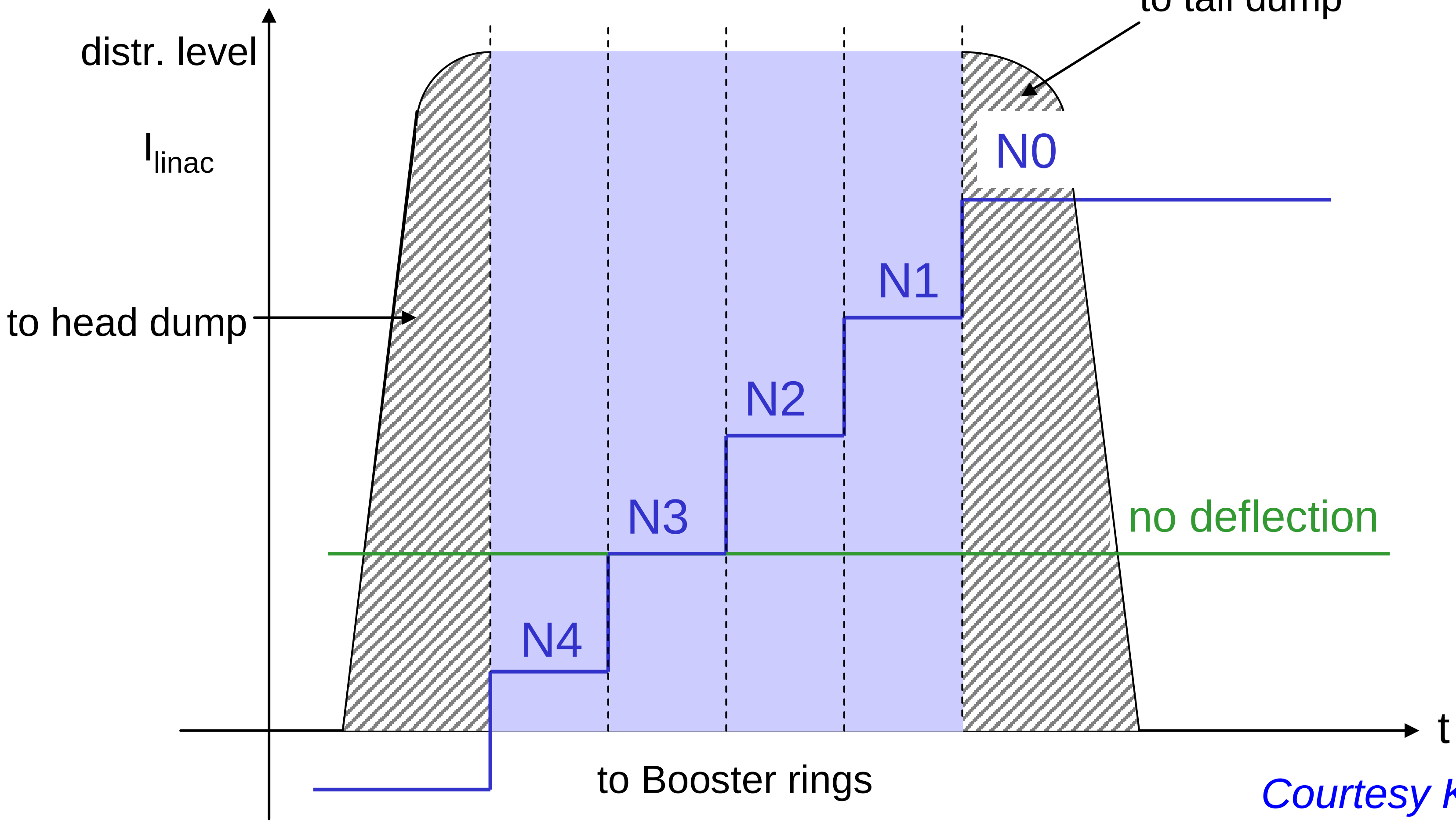
⇒ **Proton distributor: System of pulsed magnets, which kick slices of the beam to different vertical positions at the vertical septum**




*Courtesy K. Hanke*

# PSBOOSTER (2/3)

separation of linac beam slices done by 5 modules (levels 0,1,…4)
the length of the linac pulse and of the distributor levels is determined by the number of turns to be injected (operator's choice!) ⇒ **"Horizontal stacking"**
head and tail of linac pulse are cut off



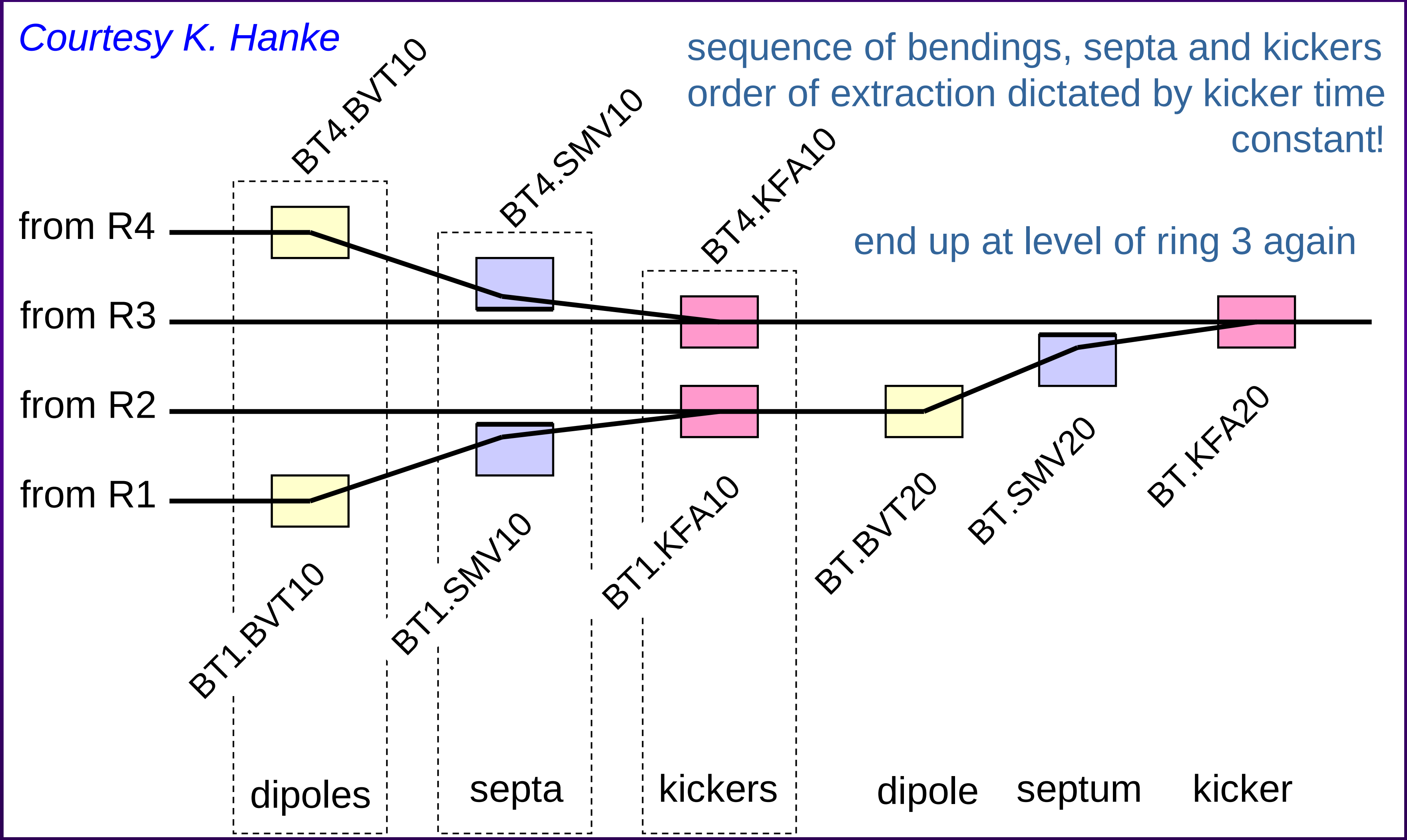

*Courtesy K. Hanke*

# PSBOOSTER (3/3)

Due to space charge in the PS

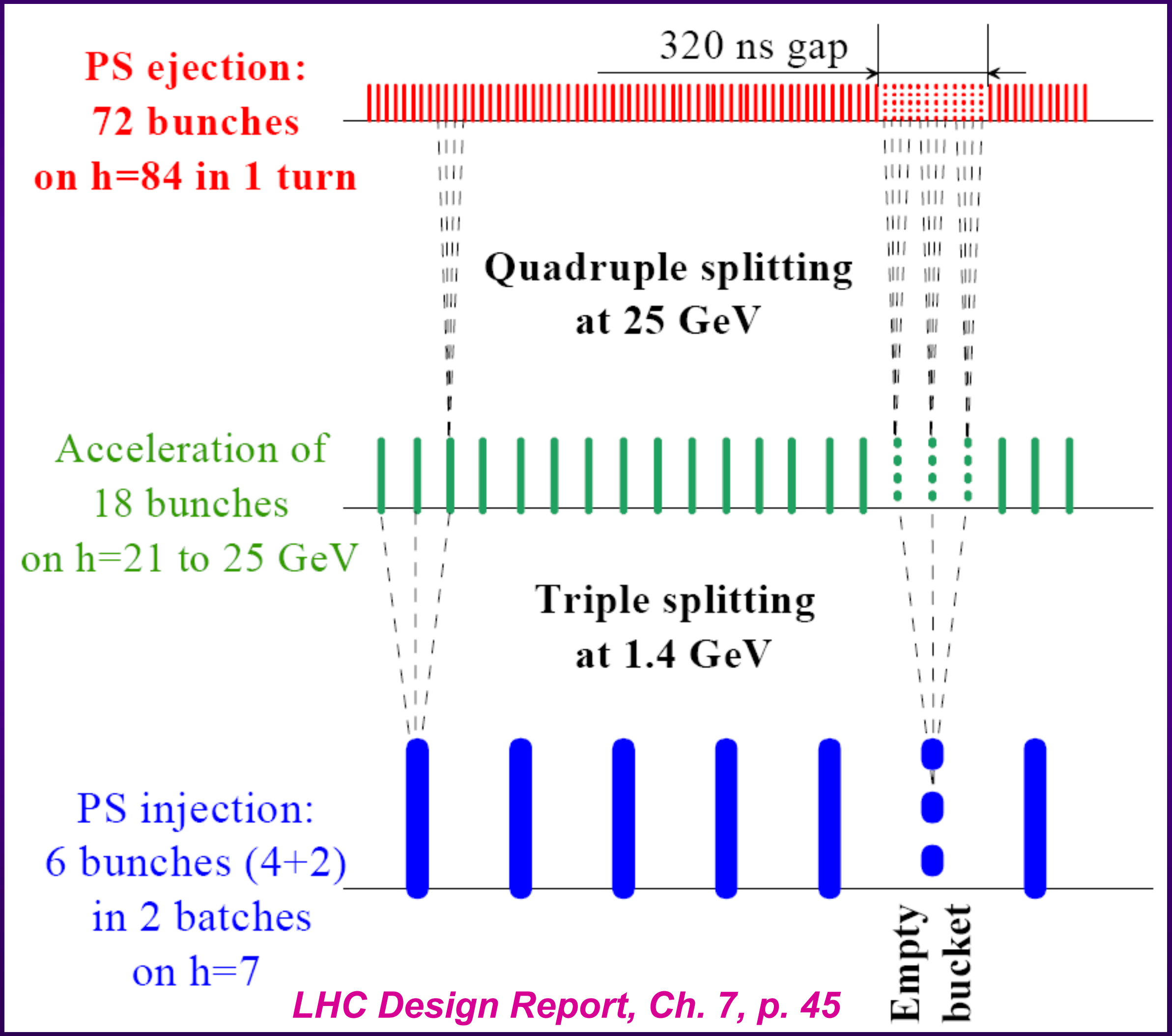
⇒ **Acceleration in the PSBooster, extraction (at 1.4 GeV instead of 1 GeV before) and then recombination process**

*Courtesy K. Hanke*



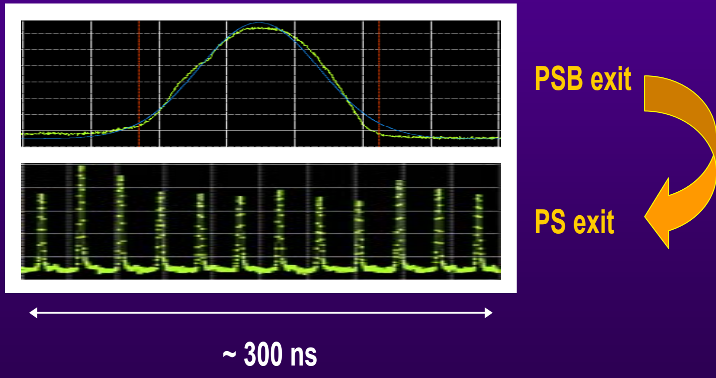
# PS (1/4)

- **The generation of the nominal bunch train for LHC (25 ns bunch spacing) is done in the PS**




*LHC Design Report, Ch. 7, p. 45*

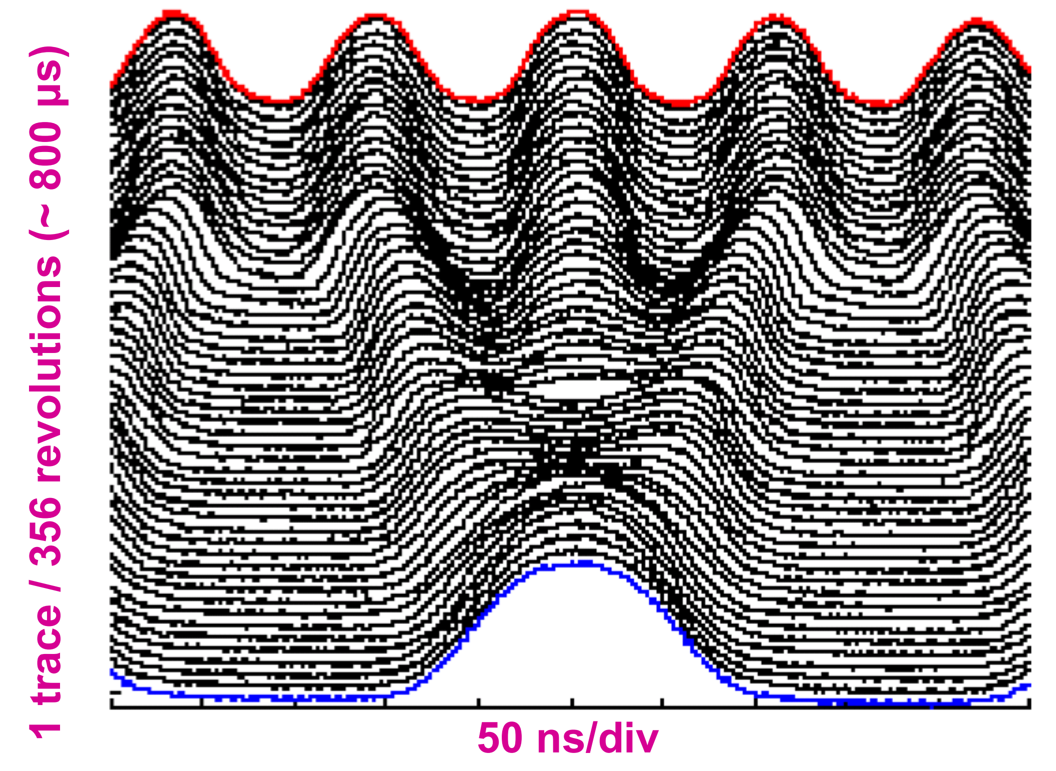
- **Double-batch injection from PSBooster due to space charge in the PSBooster**
- **Bunch splittings used instead of debunching / rebunching due to longitudinal microwave instability**

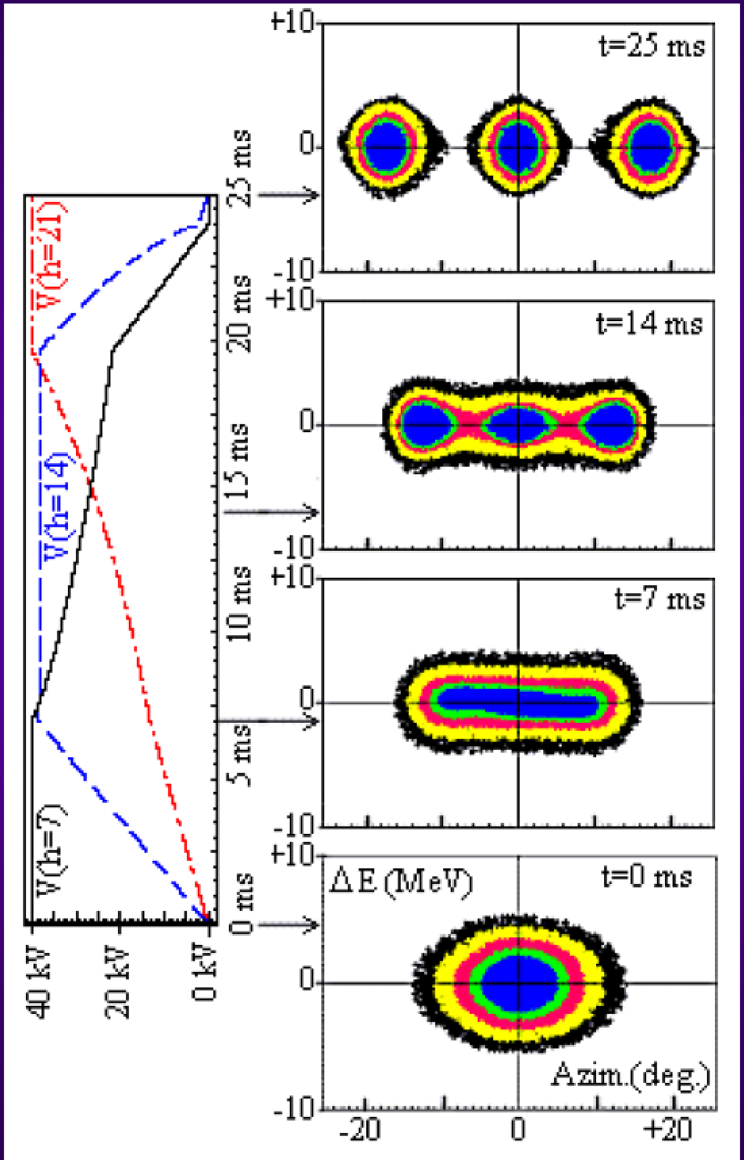


# PS (2/4)

**Triple bunch splitting**

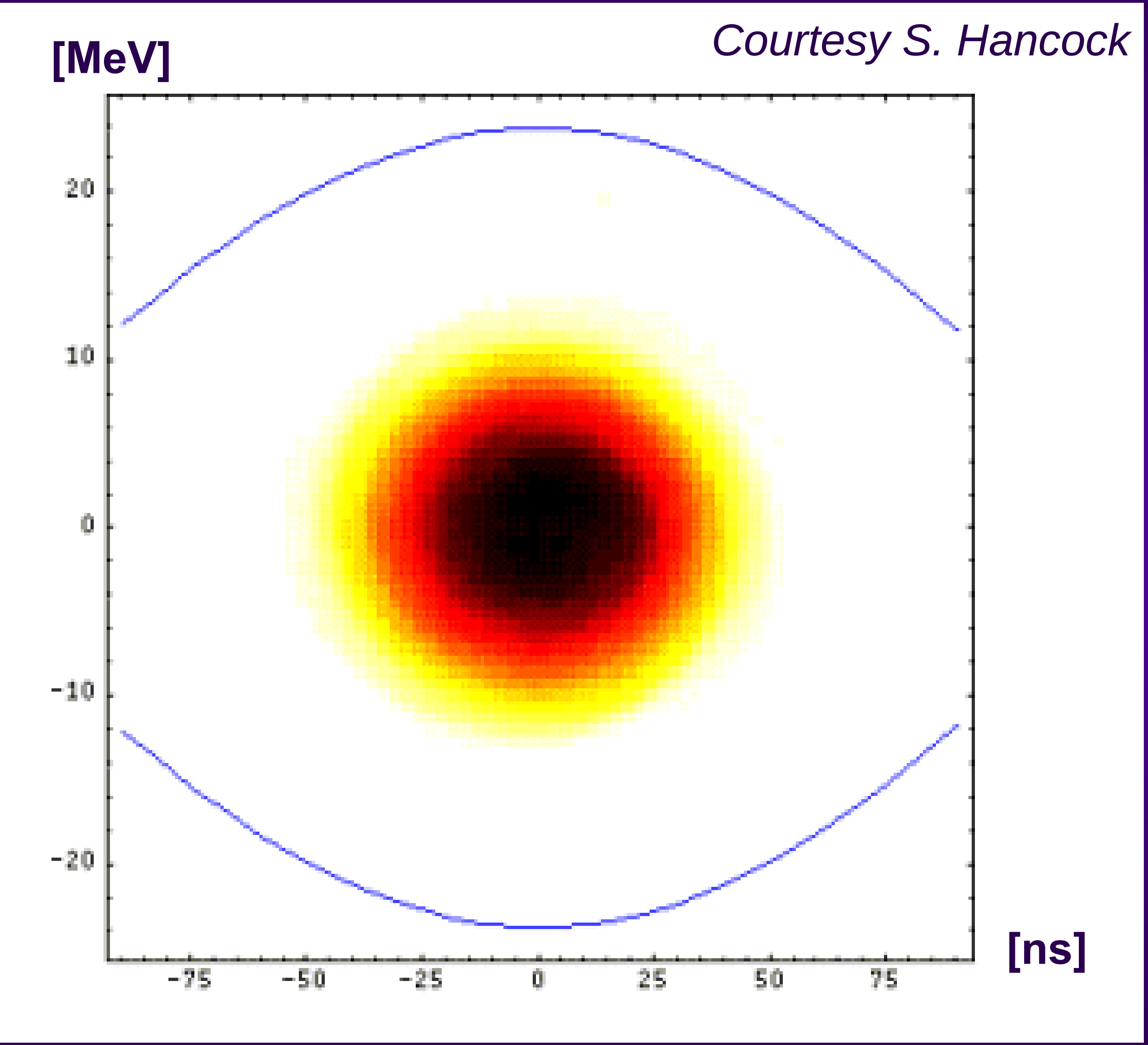
*Courtesy R. Garoby*



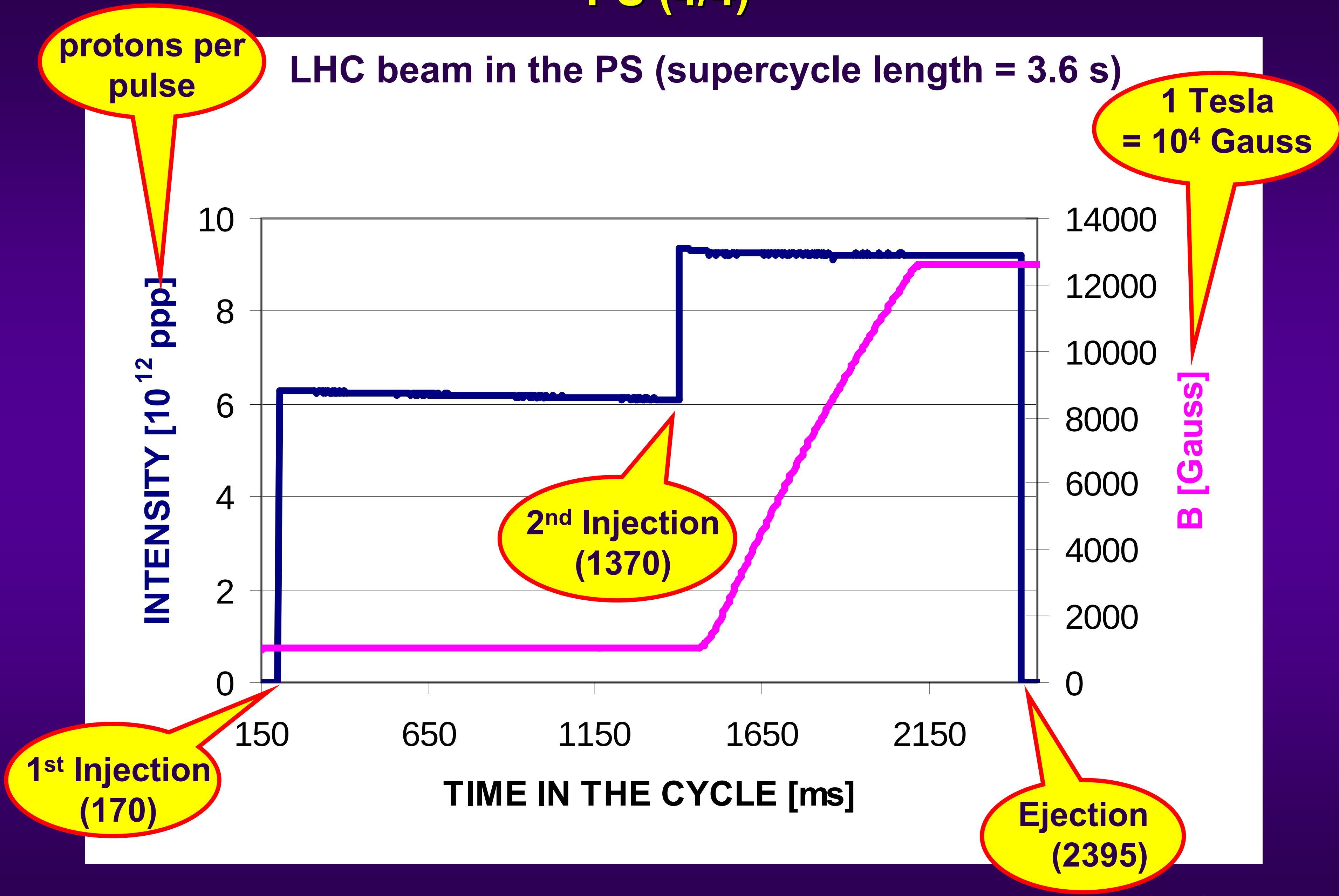



# PS (3/4)

**Longitudinal BUNCH SPLITTING**



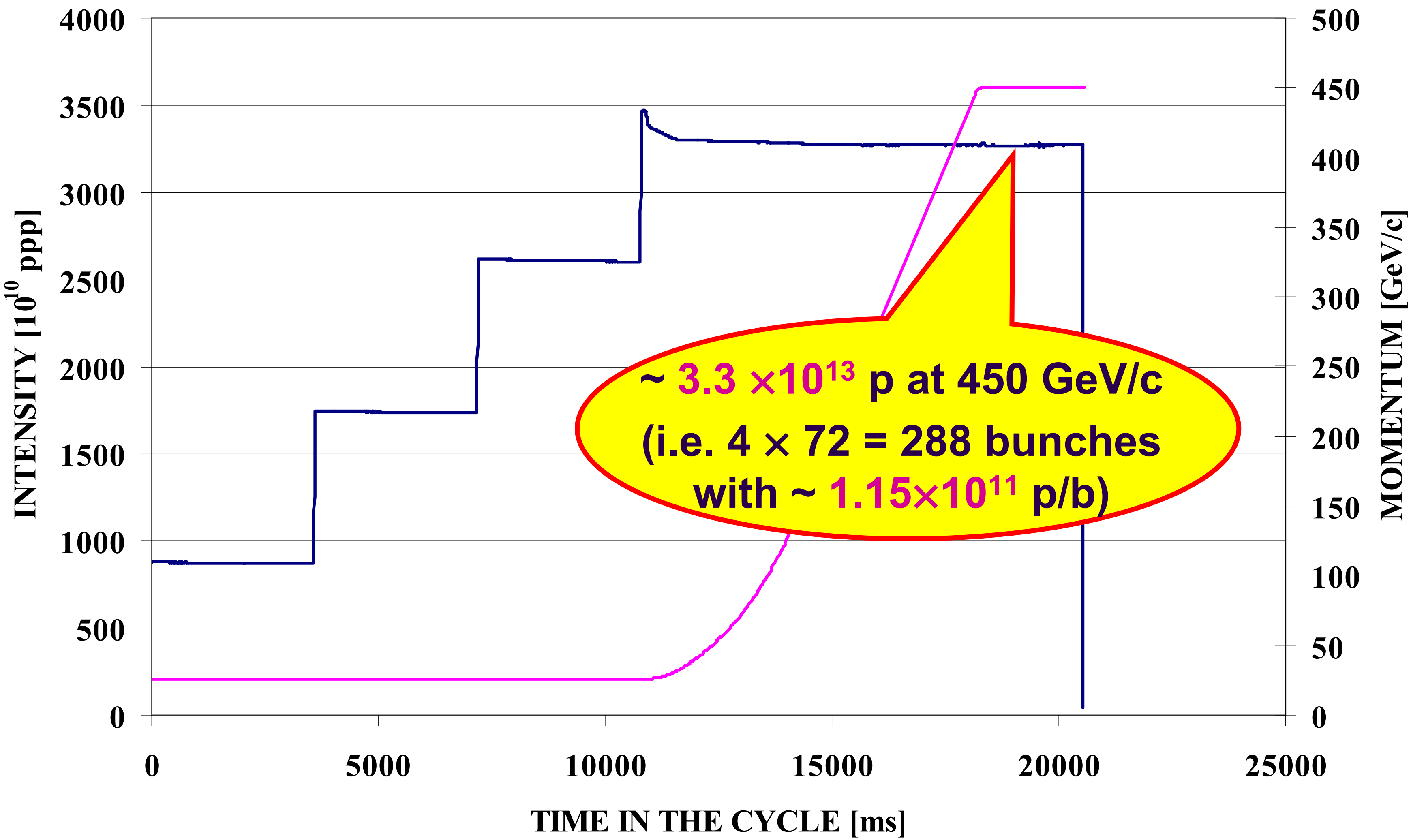
# PS (4/4)



LHC beam in the PS (supercycle length = 3.6 s)
protons per pulse
1 Tesla = $10^4$ Gauss
INTENSITY [$10^{12}$ ppp]
B [Gauss]
10
8
6
4
2
0
14000
12000
10000
8000
6000
4000
2000
0
150
650
1150
1650
2150
TIME IN THE CYCLE [ms]
2nd Injection (1370)
1st Injection (170)
Ejection (2395)

# SPS (1/2)

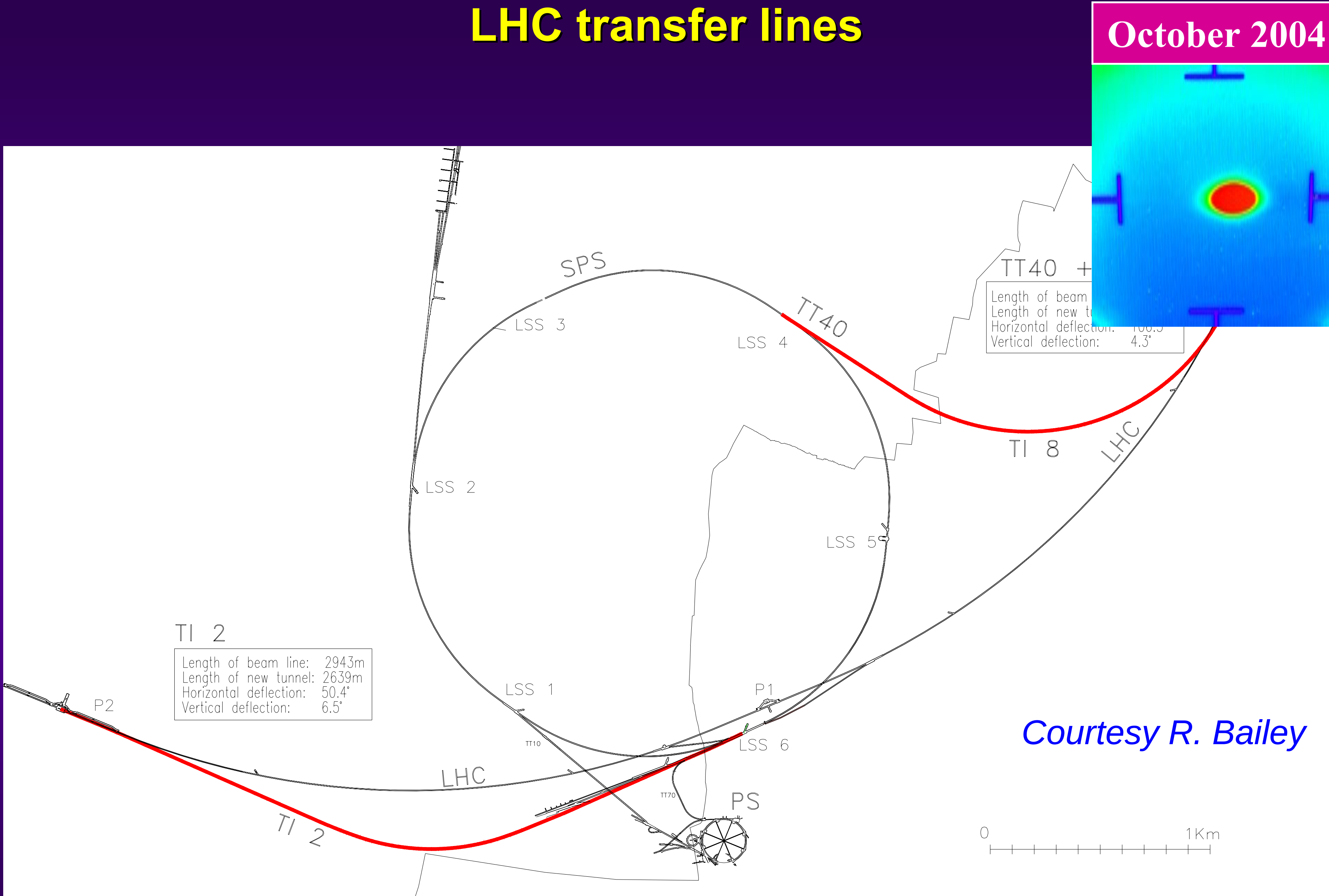
## LHC beam in the SPS (supercycle length = 21.6 s)



# SPS (2/2)

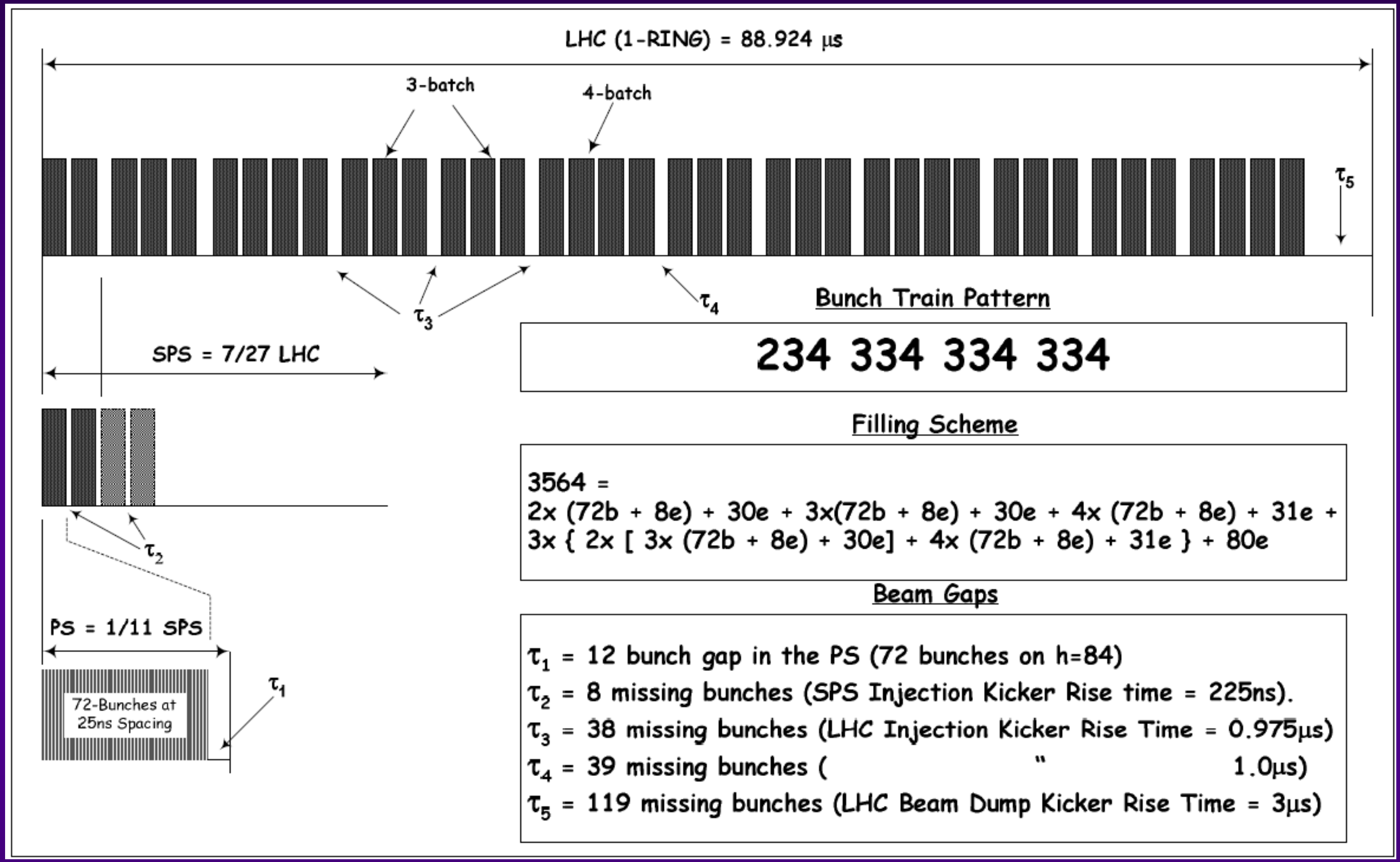
- Impedance reduction programme in the SPS has made a major contribution to the ability of the SPS to produce the LHC beam
  - Shielding of specific equipment, such as the magnetic septa, identified as an impedance source
  - Shielding of some 900 intermagnet pumping ports has reduced significantly the resonant impedance in the machine and increased the stability of the LHC beam
- The nominal beam has successfully been accelerated to 450 GeV/c, despite the discovery that the electron cloud effect is a major issue for the SPS $\Longrightarrow$ Continued machine development to understand and cure the phenomena in the SPS has been accompanied by additional studies using the SPS as a test-bed for the LHC. Periods of beam conditioning are now routinely used to "scrub" the surface of the vacuum chambers, reduce the secondary electron yield and minimise the vacuum pressure rise

# LHC transfer lines



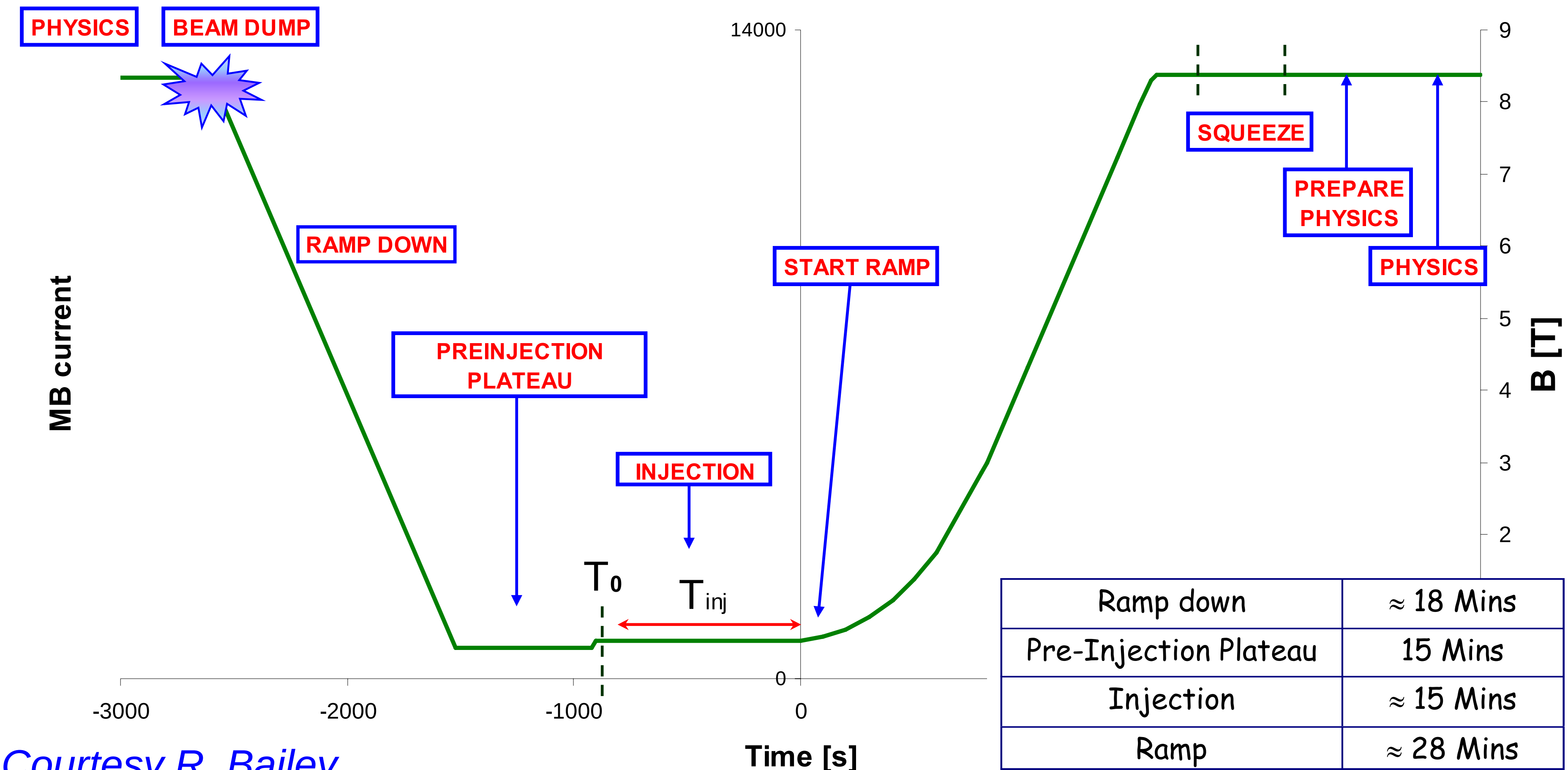

*Courtesy R. Bailey*

# Filling scheme for the nominal LHC beam




- **PS cycle length = 3.6 s**
- **SPS cycle length = 21.6 s**
- **LHC filling time (for the 2 rings) = 8 min 38 s (= 12 SPS cycles of 21.6 s per beam ⟹ 24 in total, i.e. a filling time of 24 × 21.6 s = 518.4 s)**

# LHC operational cycle




*Courtesy R. Bailey*

| | |
|---|---|
| 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 |

# Future work (1/4)

**From L. Evans (LHC Project Report 983, presented at APAC07, 29/01/07-02/02/07)**

- **The installation of the Large Hadron Collider at CERN is now approaching completion. Almost 1100 of the 1232 main bending magnets are installed and the whole ring will be installed by the end of March 2007**

- **Emphasis is now moving from installation to commissioning, with the cool down of the first of the 8 sectors to liquid helium temperature well underway**

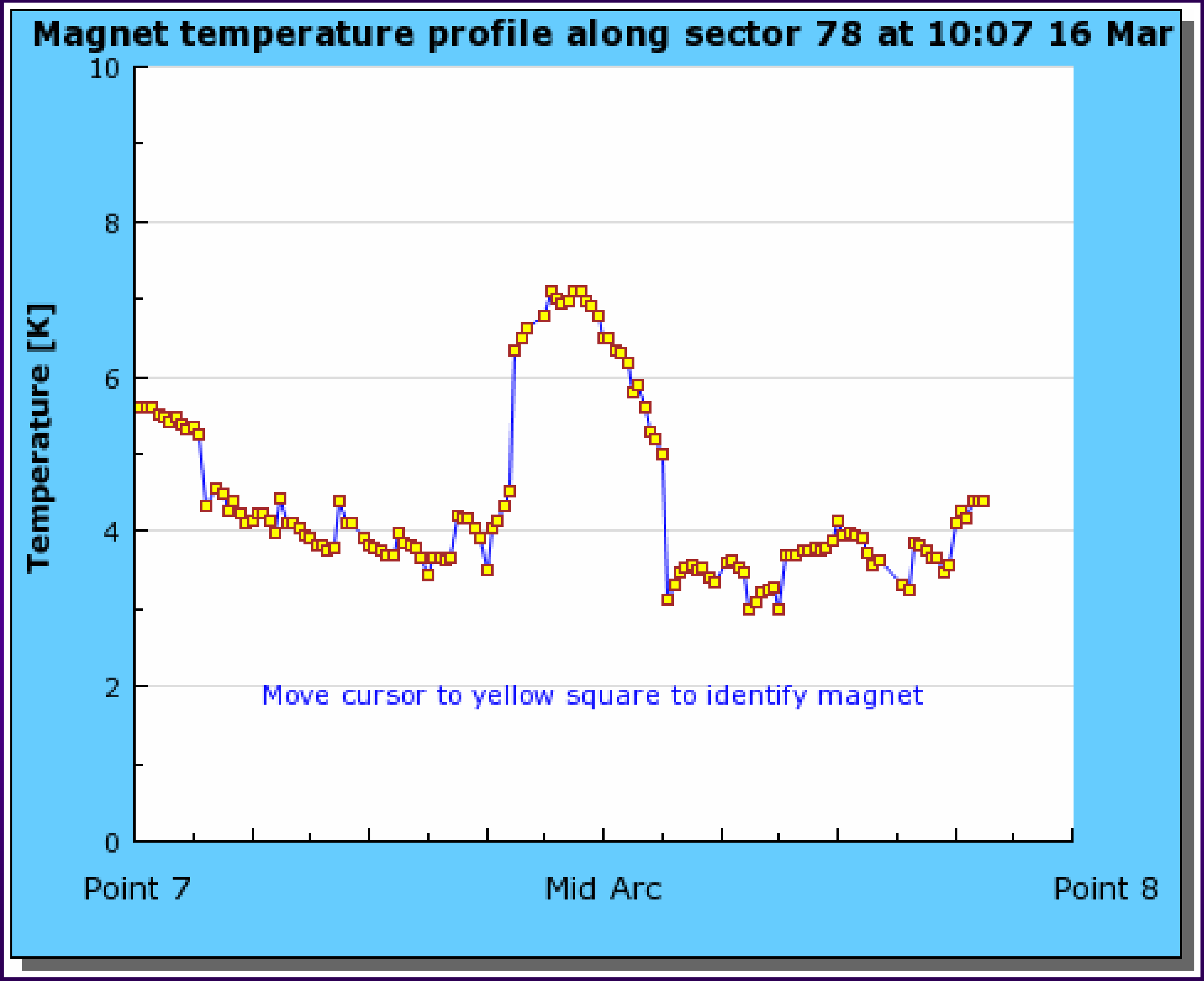
- **In the other sectors, interconnect work is proceeding at a satisfactory pace and will be finished by the end of August**

# Future work (2/4)

- It is foreseen to inject the first beam into the LHC in November with the objective of having first collisions at the injection energy (450 GeV/c) in order to debug the machine and detectors before stopping for the annual winter shutdown

- During this time, the detector installation will be finished and the machine will be pushed to full current ready for the first physics run at 7 TeV per beam in 2008

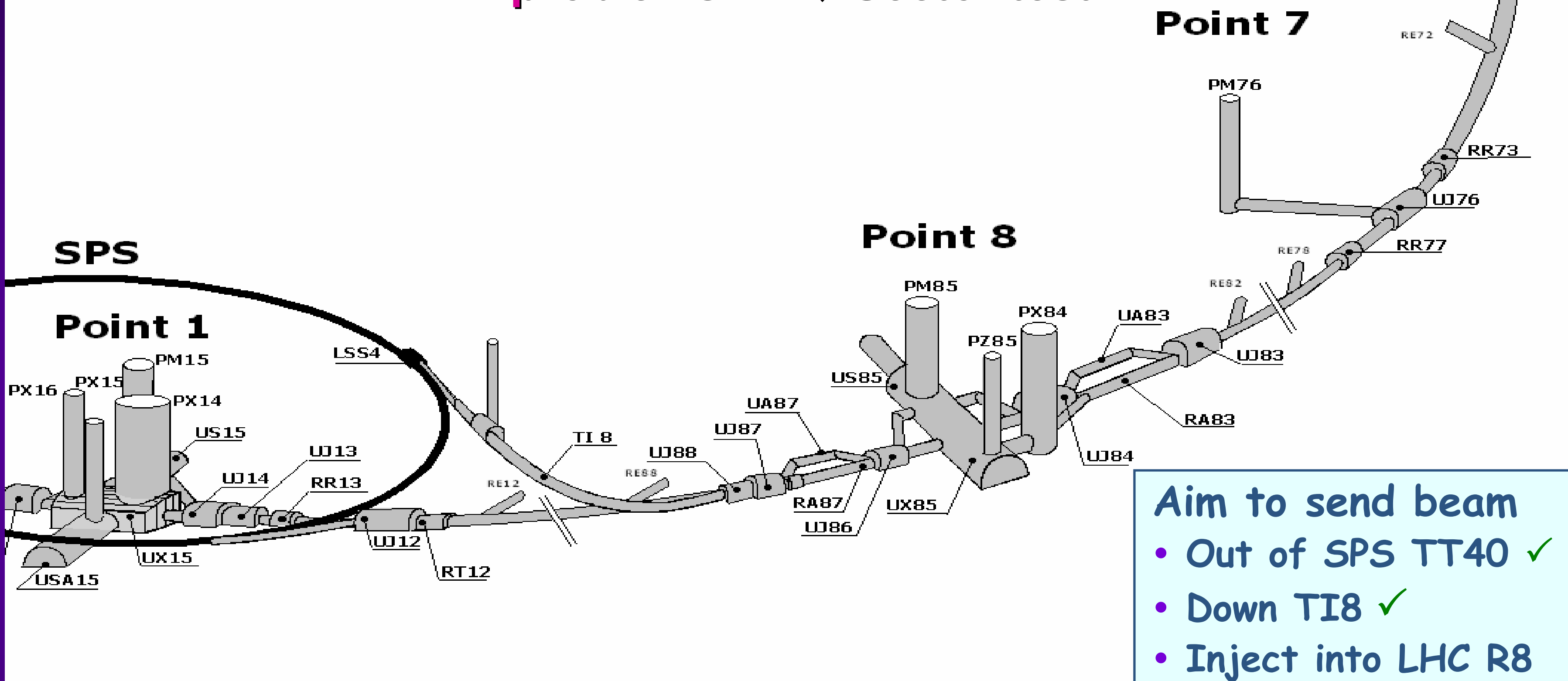
# Future work (3/4)

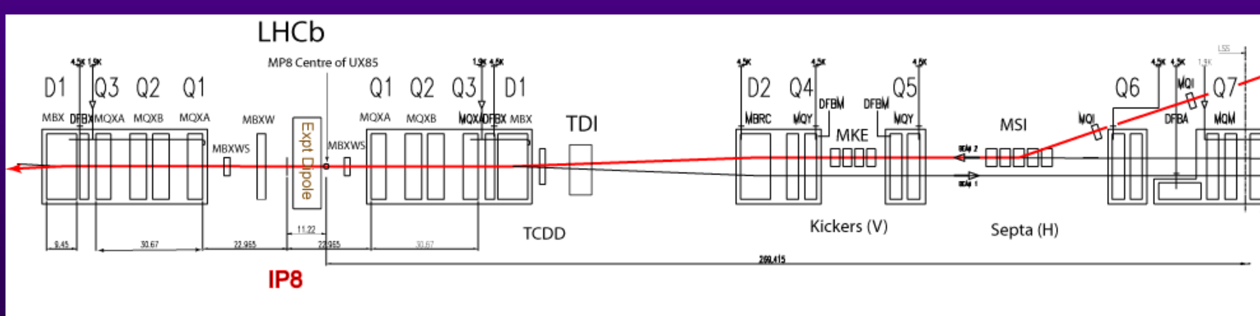


# Future work (4/4)

*Courtesy R. Bailey*

**If problems... ⟹ Sector test**




**Aim to send beam**

- Out of SPS TT40 ✓
- Down TI8 ✓
- Inject into LHC R8
- Through insertion R8
- Through LHCb
- Through IP8
- Through insertion L8
- Through arc 8-7
- To dump at Q6 R7