16-27 juillet 2012

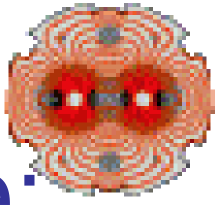
Orsay · Palaiseau · Paris · Saclay

Rencontres DE L'INFINIMENT GRAND à l'infiniment petit

2012 : Promotion Ettore Majorana

Visites de labos, conférences, débats

NIVEAU L3



The CERN LHC machine: a Higgs factory

Massimo Giovannozzi

CERN – Beams Department

- Introduction
- Layout and key parameters
- Beam physics challenges
- Beam commissioning and current status
- Upgrade path(s)
- Outlook

Acknowledgements: G. Arduini, R. Assmann, R. Bailey, O. Brüning, W. Herr, J. Jowett, M. Lamont, E. Métral, L. Rossi, E. Todesco, R. Tomás, F. Zimmermann *et al.*

Introduction

- Large Electron Positron (LEP) collider:
    - It was essentially a Z_0 factory.
    - It allowed accurate measurements of standard model features.

- The characteristics of the next collider (in the same LEP tunnel):
    - Higher energy then LEP.
        - This imposes to switch to hadrons due to synchrotron radiation. ▶
        - This imposes to use superconducting magnets due to the fixed tunnel radius. ▶
    - High luminosity ▶
        - This imposes to have p-p collisions. The generation of p-bar is very inefficient and it is difficult to produce enough intensity.
        - This, in turn, imposes to have two separate rings.
- In summary:

LHC is a two-ring, high-energy, high-luminosity, p-p collider. ▶

Synchrotron radiation - I

- Power radiated by an accelerating particle (in our case on a curved trajectory)

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

- Energy radiated in one turn

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

- Average power radiated over one turn

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

Synchrotron radiation - II

- Comparison between the energy radiated per turn in LEP and LHC.

	LEP	LHC
❒ [m]	**3096.175**	**2803.95**
p_0 [GeV/c]	**104**	**7000**
U_0 [GeV]	**3.3**	**$6.7\ 10^{-6}$**

- In LEP the RF system compensated for an energy loss of ~3% of the total beam energy per turn!
- In LHC the RF should compensate for an energy loss of 10^{-7}% of the total beam energy per turn!
- The total average power radiation (per beam) is 3.9 kW. ◀

Magnetic field

- The magnetic field required to keep a particle of momentum p_0 on a trajectory of radius ρ is given by

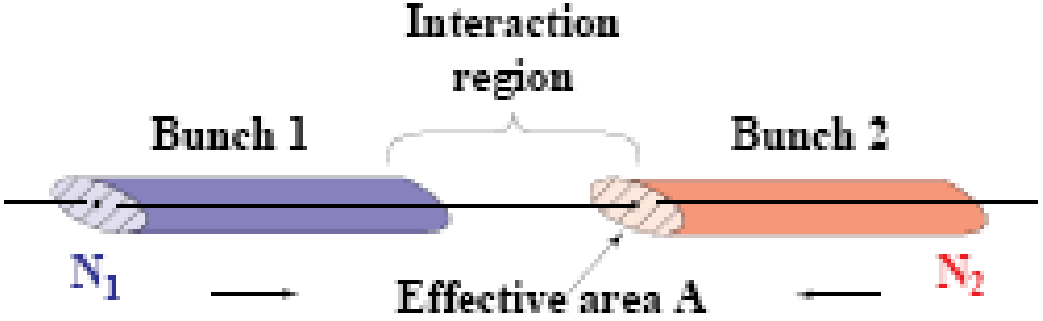
$$B\rho\left[\mathrm{T\,m}\right]=3.3356\; p_0\left[\mathrm{GeV/c}\right]$$

	LEP	LHC
❐ [m]	**3096.175**	**2803.95**
p_0 [GeV/c]	**104**	**7000**
B [T]	**0.11**	**8.33**

- The magnetic field chosen is the current technological limit.
- The slightly different ρ for LEP and LHC is due to some slight changes in the ring geometry. ◀

Luminosity - I

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



- The Luminosity depends only on beam parameters

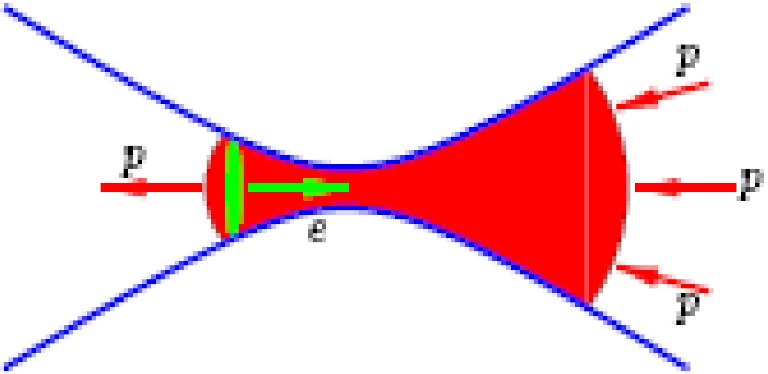
$$L = \frac{N_b^2 \; M \; f_{rev} \, \gamma_r}{4 \, \pi \, \varepsilon_n \, \beta^*} \, F$$

- Unfortunately, head-on collisions are not always possible. In this case a geometrical reduction factor F has to be taken into account

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

Luminosity - II

- Unfortunately, the beam size is changing along the bunch (hourglass effect). This introduces an additional factor of luminosity reduction.



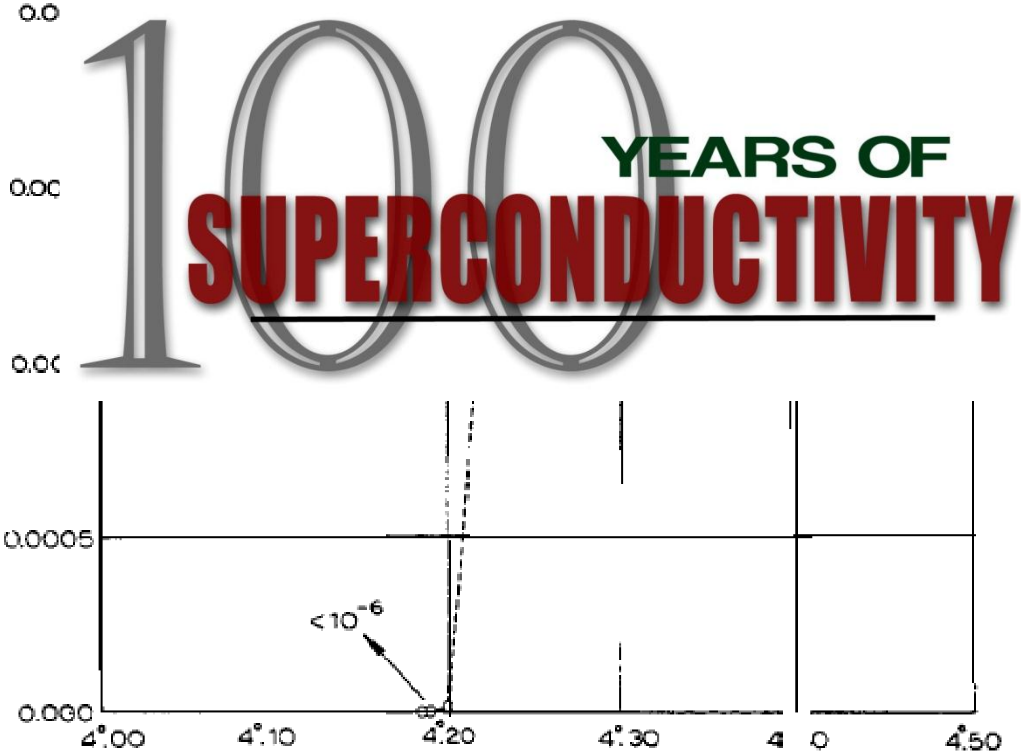
- Peak luminosity for ATLAS and CMS in the LHC is 1×10^{34} cm^{-2} s^{-1}.

- Expected LHC integrated luminosity per year (~10^7 s) is 80-120 fb^{-1}.

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

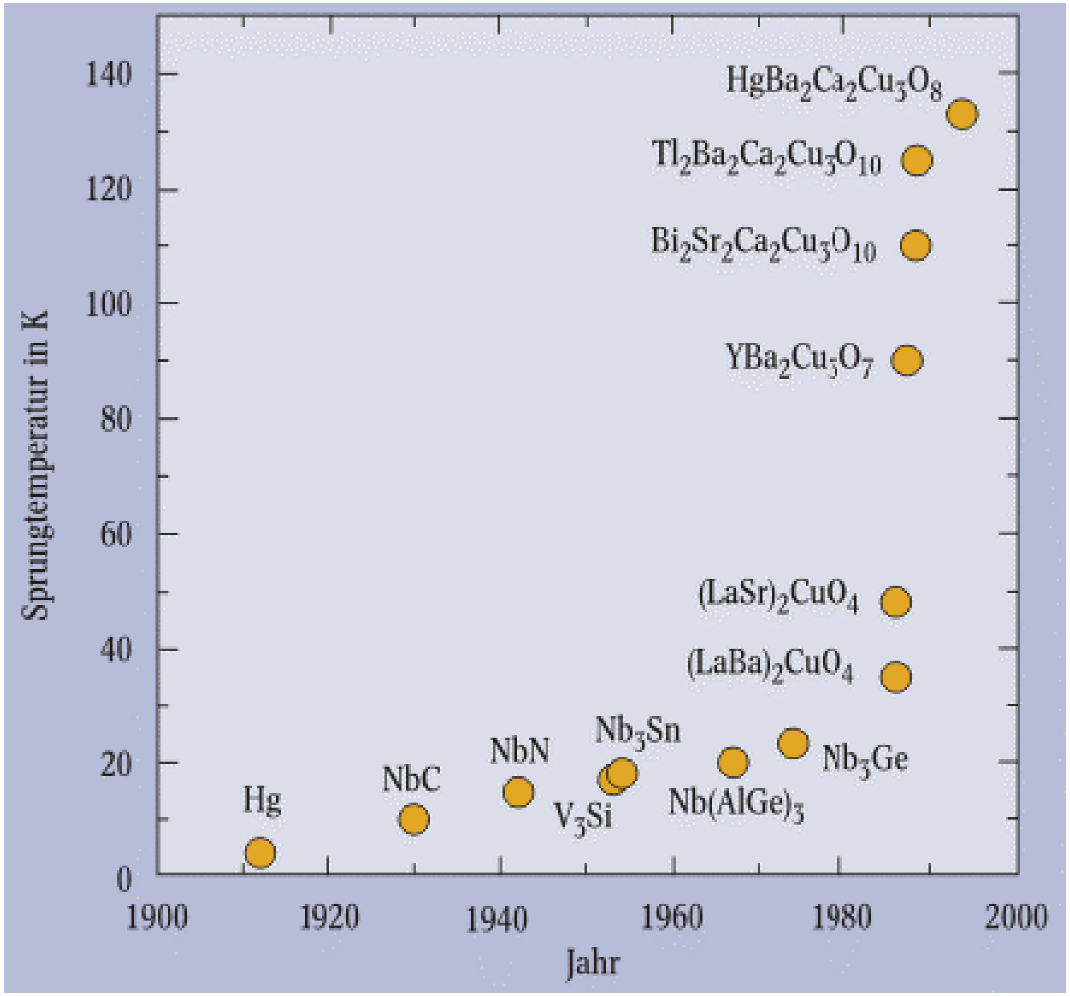
Superconductivity - I

Kamerlingh Onnes liquefies for the first time (1908) Helium and studies the temperature dependence of the electrical resistance of metals. (1911)



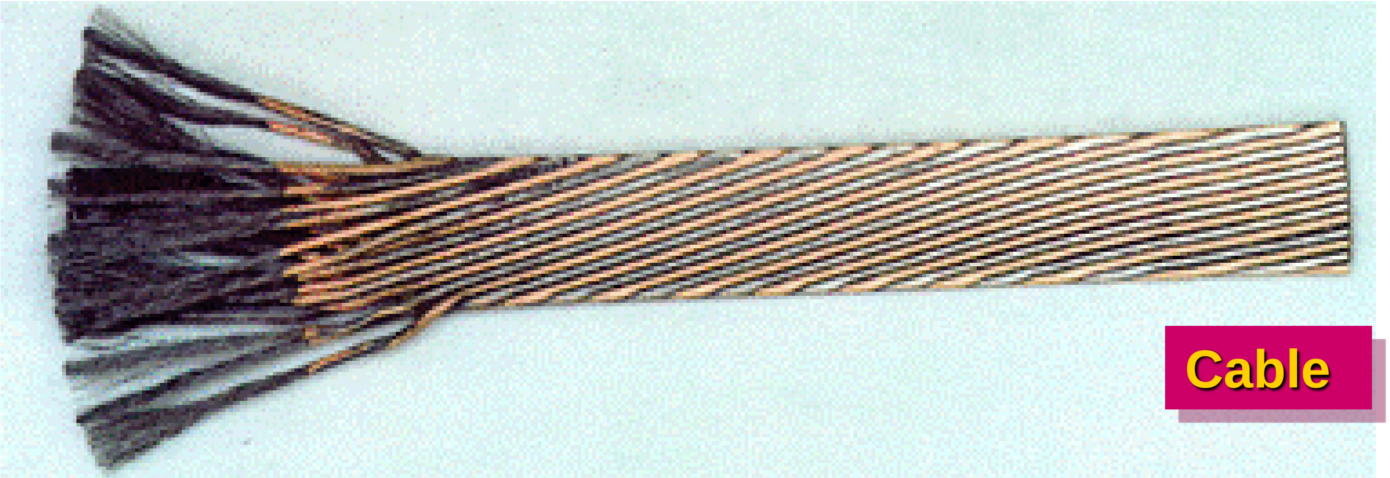
Below a critical temperature the resistance (voltage drop) seems to disappear. He calls the phenomenon “Superconductivity”. He got the Nobel Price in 1913.

Superconductivity - II

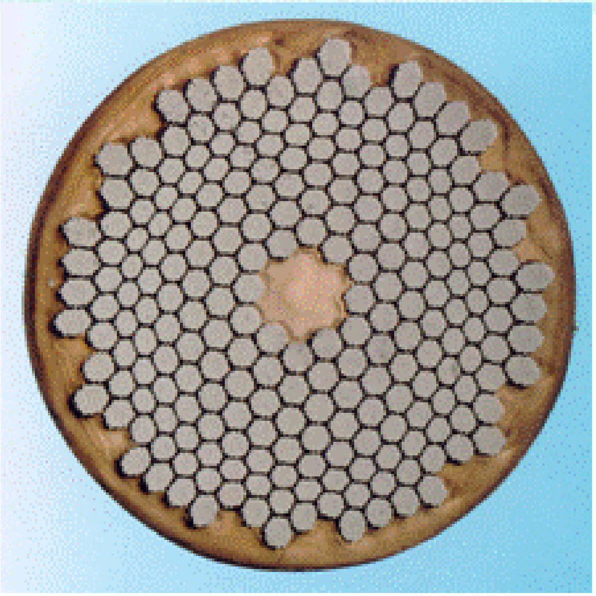


- It took a long time to understand the quantum-mechanical nature of the superconductivity.
- Many metals are superconducting at very low temperature. Also Pb, Nb. Most superconductors in the plot are brittle crystals.
- The ductile Nb-Ti is preferred today.
- Most superconductors are bad normal conductors.

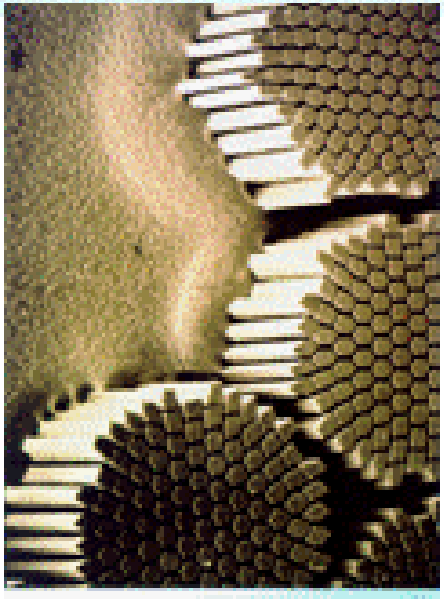
Superconducting cables - I



Cable



Strand



Filaments

Superconducting cables - II

- The cable is made of 36 strands of superconducting wire.
- Each strand is made of 6300 superconducting filaments of NbTi.
- Each filament is about 6 ❍m thick. Around each filament there is a 0.5 ❍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, corresponding to around 7600 km of cable: Total length of filaments is astronomical!

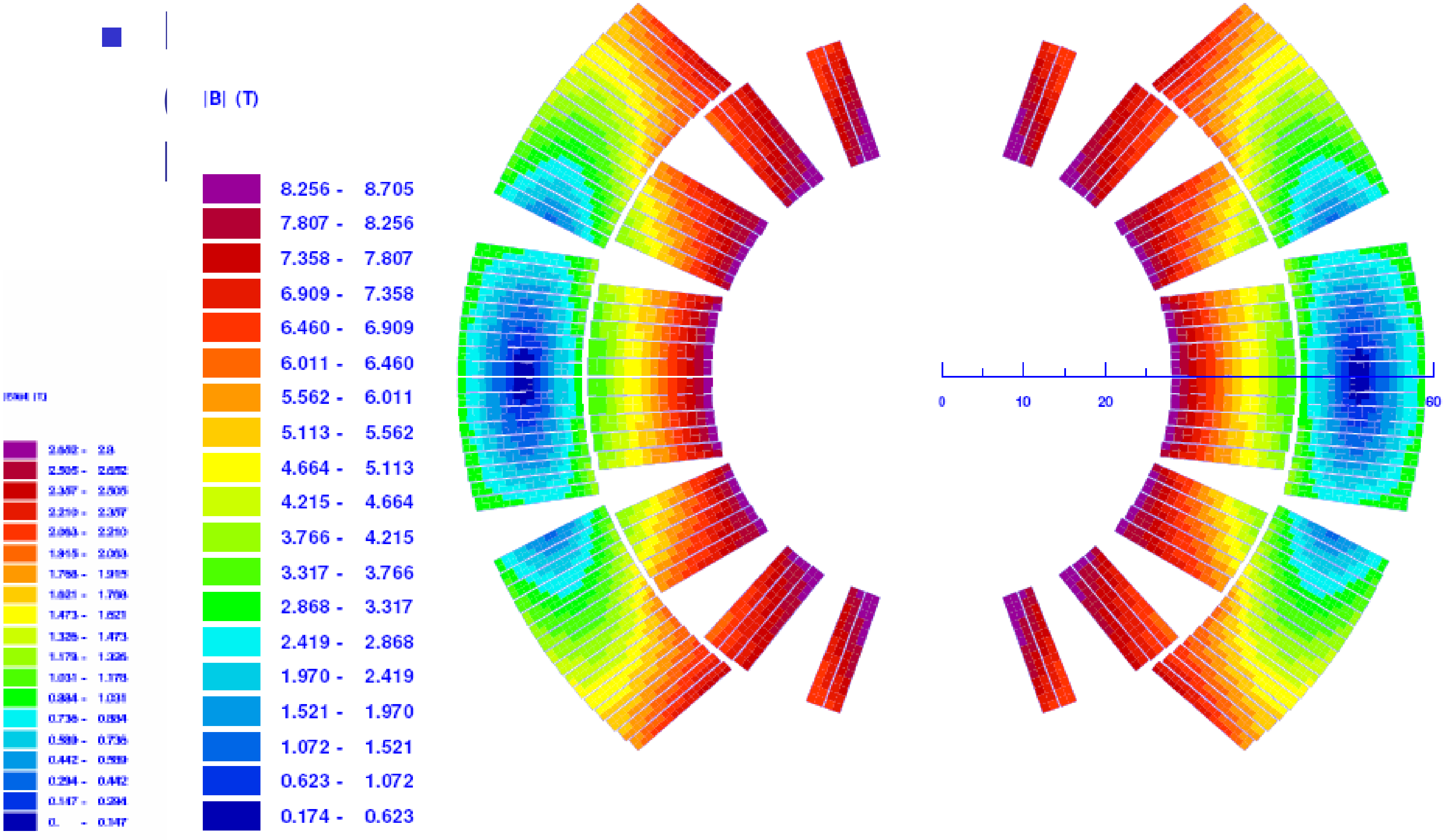
Superconducting cables - III

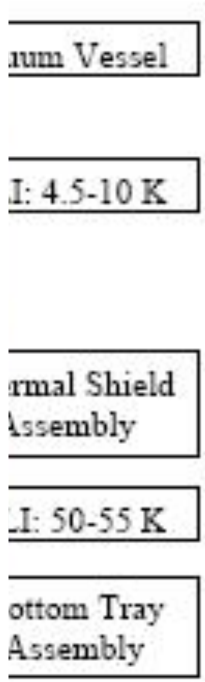
Cable insulation l
double polyimide

Main dipoles - I

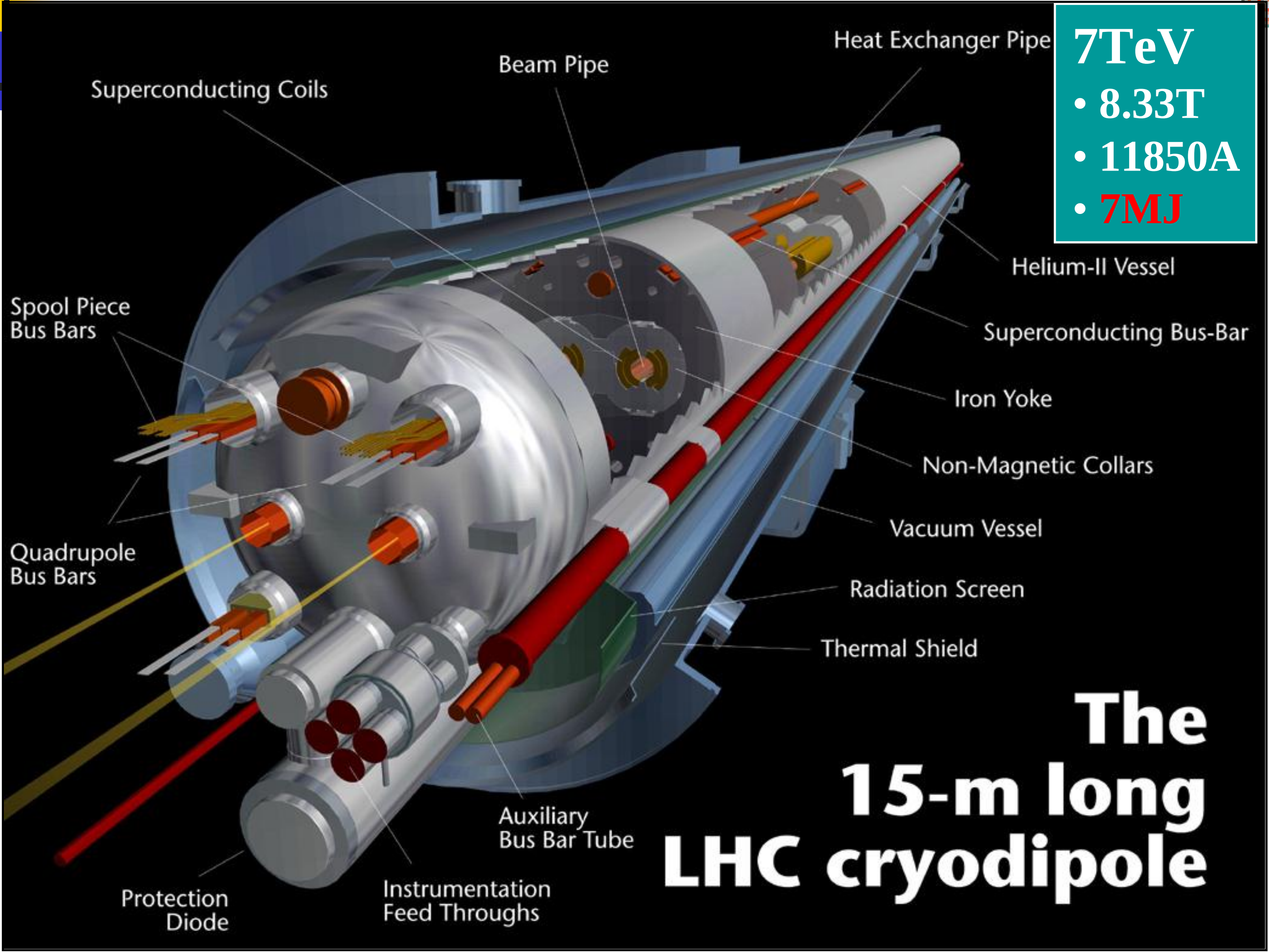
-

les
uid





Main dipoles - II



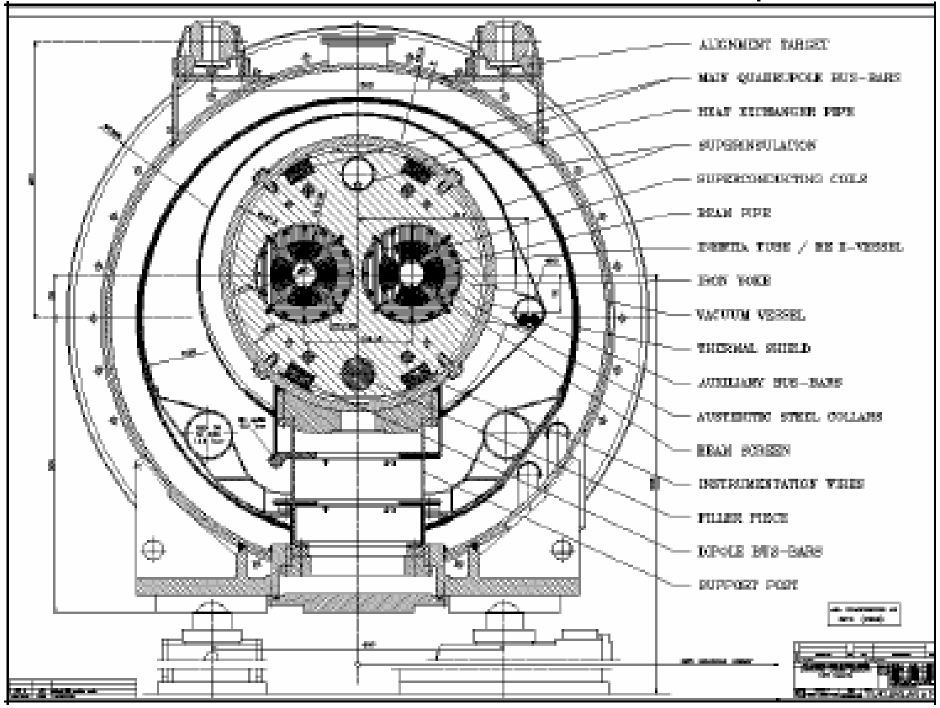
7TeV
- **8.33T**
- **11850A**
- **7MJ**

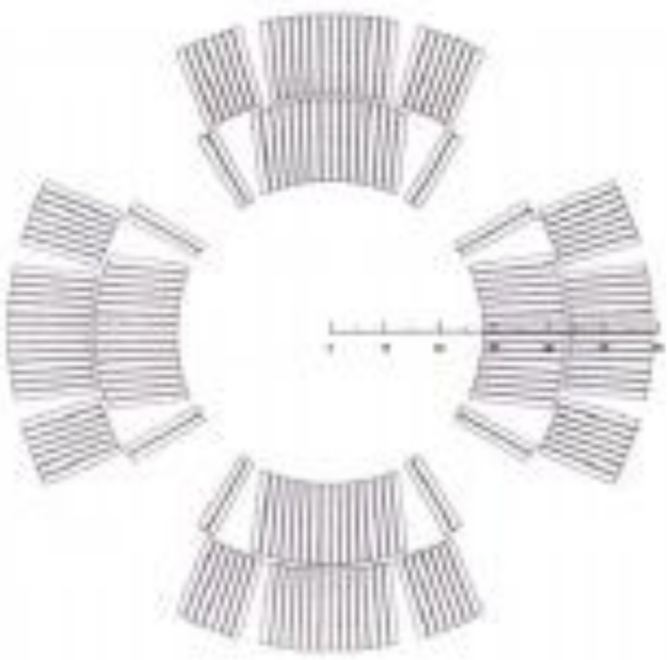
Main dipoles - III

Lowering of a dipole…more than 30 000 km underground at 2 km/h

Main quadrupoles - I

Integrated Gradient	690	T
Nominal Temperature	1.9	K
Nominal Gradient	223	T/m
Peak Field in Conductor	6.85	T
Temperature Margin	2.19	K
Working Point on Load Line	80.3	%
Nominal Current	11870	A
Magnetic Length	3.10	M
Beam Separation distance (cold)	194.0	mm





Main quadrupoles - II

Lowering of a quadrupole

Inner triplet on surface

All superconducting magnets

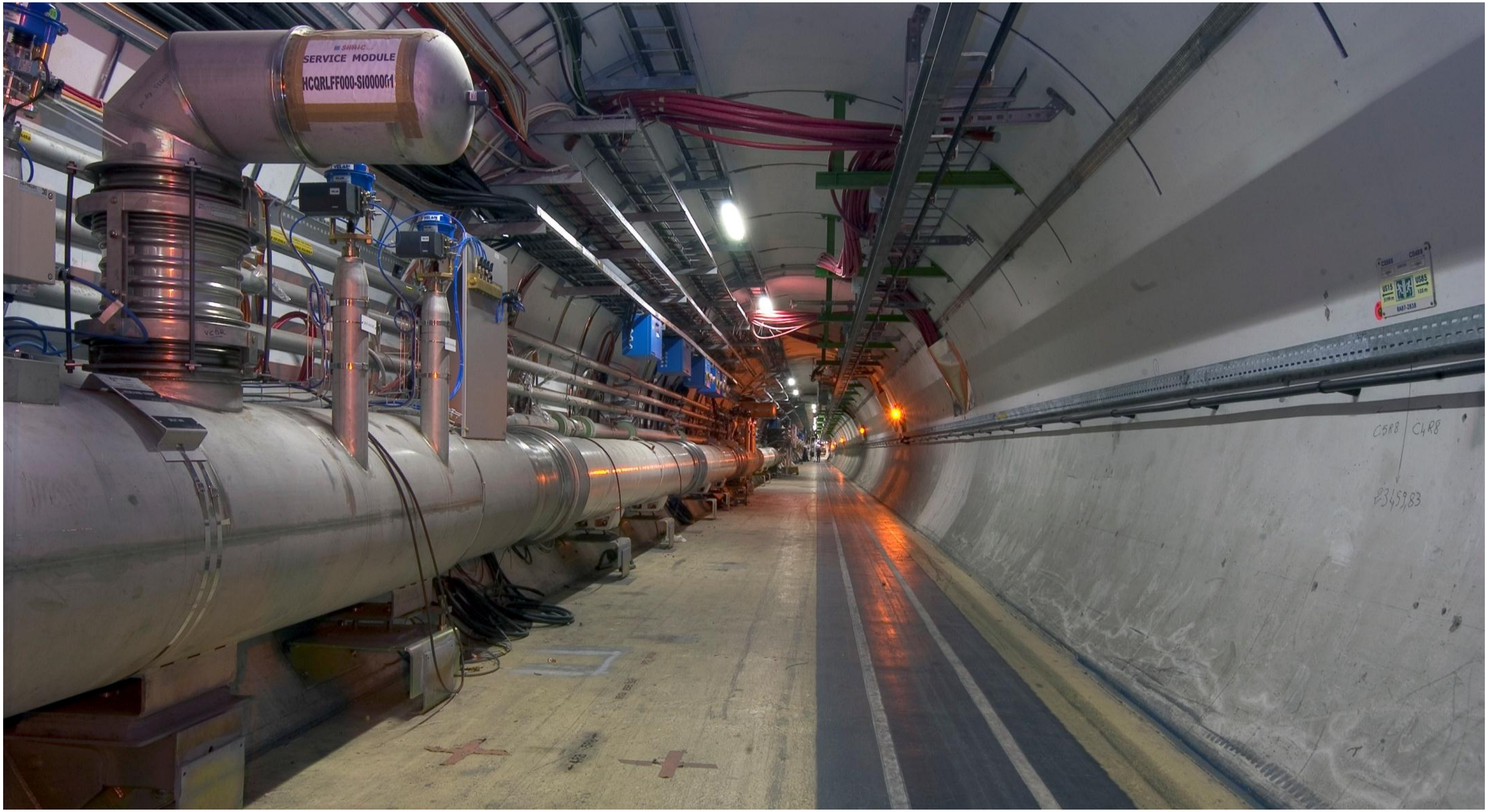
In total there are 6628 superconducting magnets! Not to consider the normal conducting ones…

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

Cryogenics - I

- The cryogenic technology uses superfluid helium, which has unusually efficient heat transfer properties, allowing kilowatts of refrigeration to be transported over more than a km 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 total LHC cryogenics will need 40 000 leak-tight pipe junctions, 12 million liters of liquid nitrogen will be vaporized during the initial cool down of 31 000 tons of material and the total inventory of liquid helium will be 700 000 liters.

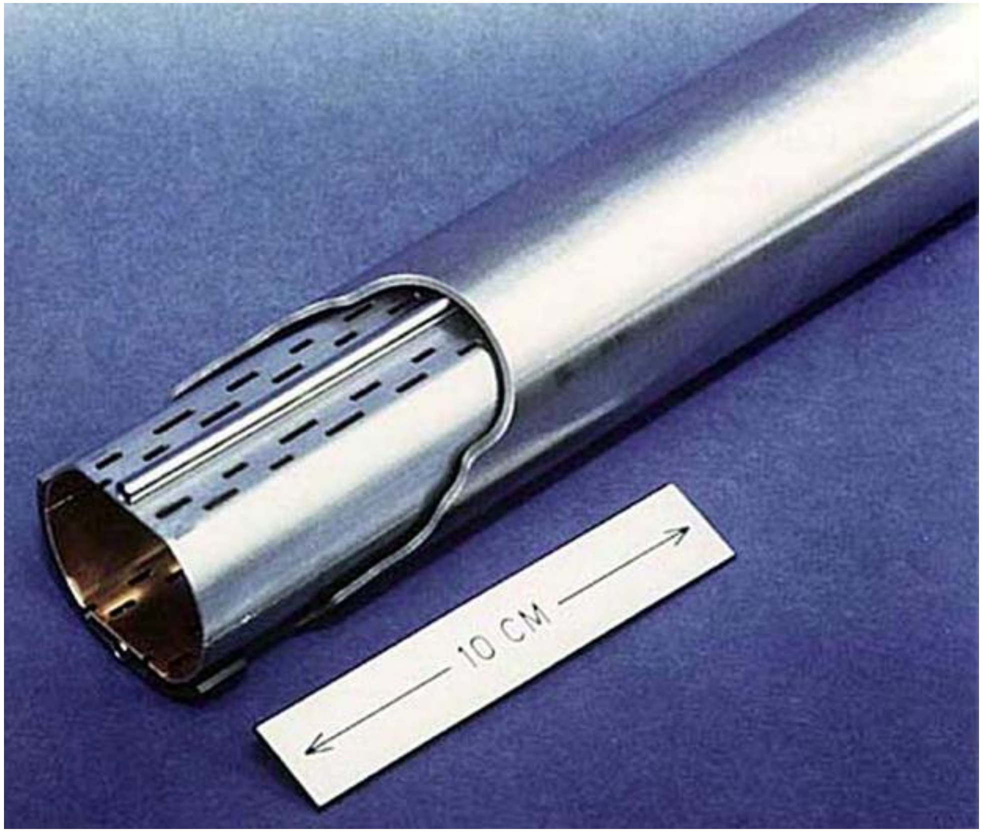
Cryogenics - II



Cryogenics - III

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 needs to be intercepted by a beam screen at an elevated temperature of 5-20 K

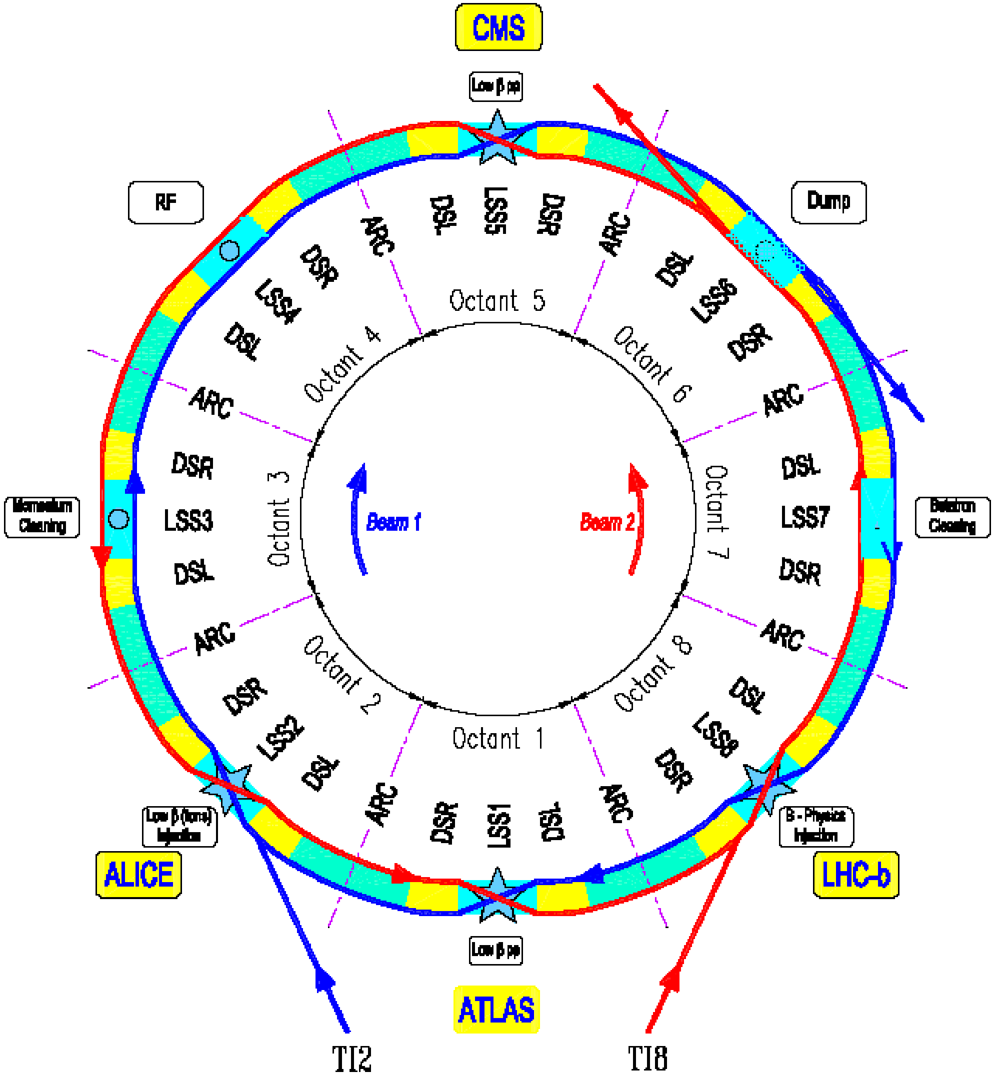


Vacuum

- LHC has 3 vacuum systems:
  - Insulation vacuum for cryomagnets.
  - Insulation vacuum for helium distribution line (QRL).
  - Beam vacuum. 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)

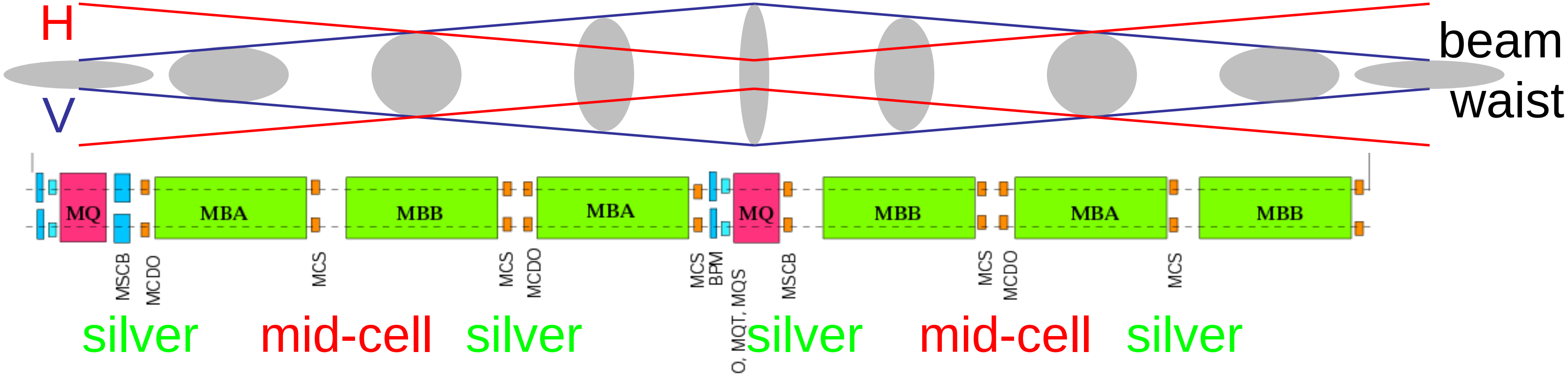
NB: 1 atm = 760 Torr and 1 mbar = 0.75 Torr = 100 Pa.
10^{-10} Torr = ~3 million molecules / cm^3

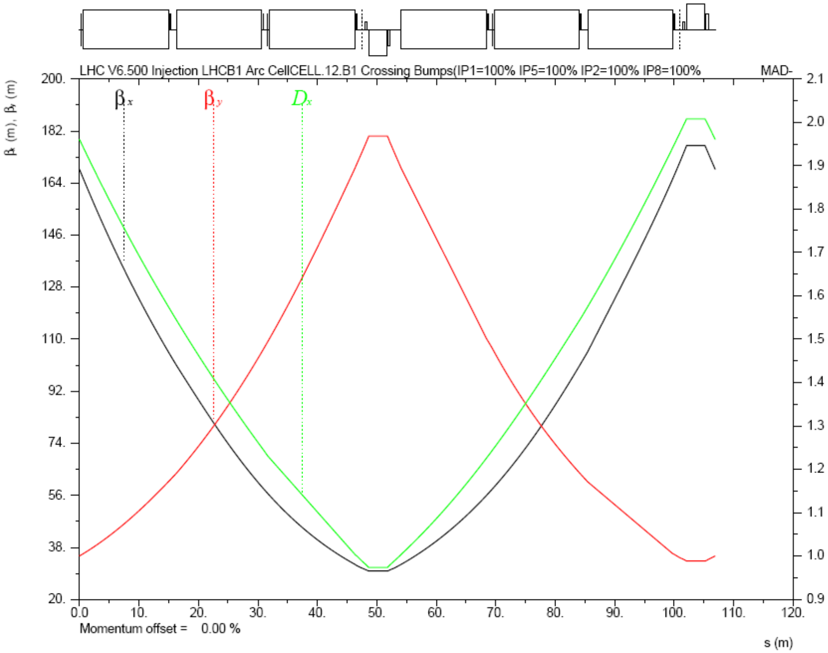
LHC layout - I



- The LHC machine has an height-fold symmetry.
- Eight arcs (arc is the curved periodic part of the machine).
- Sixteen dispersion suppressors to match the arc with the straight sections (geometry and optics).
- Eight long straight sections (also called insertion regions).

LHC layout - II





Six dipoles are located in each cell. Each dipole comprises correctors:

- Sextupoles
- Octupoles and decapoles

Two quadrupoles are located in each cell. Each quadrupole is equipped with:

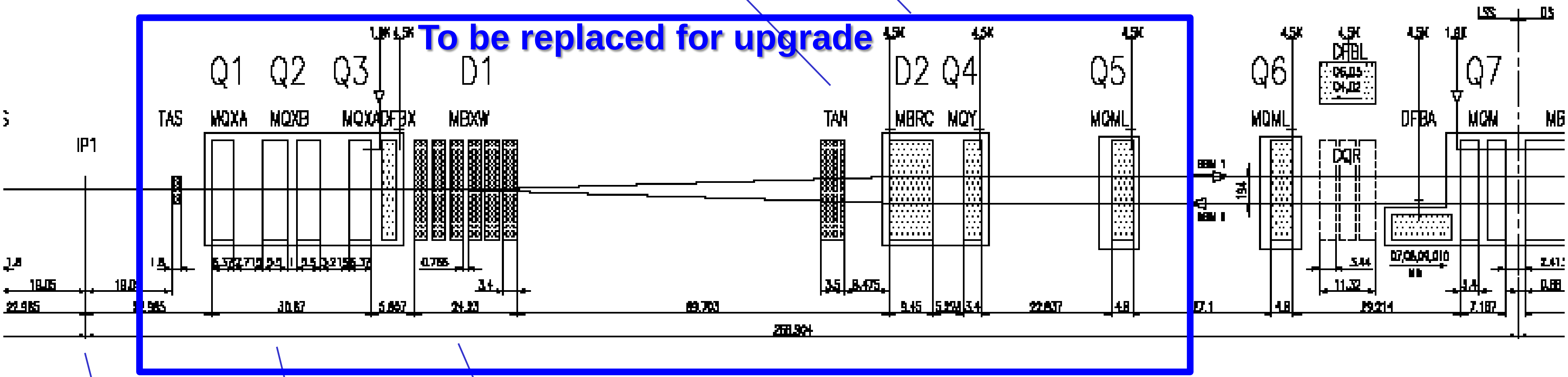
- Beam Position Monitor
- Dipole corrector (for closed orbit)
- Sextupoles (for chromaticity)

LHC layout - III

Separation/ricombination dipole

Towards dispersion suppressor and arc

Absorber (neutral particles)



To be replaced for upgrade

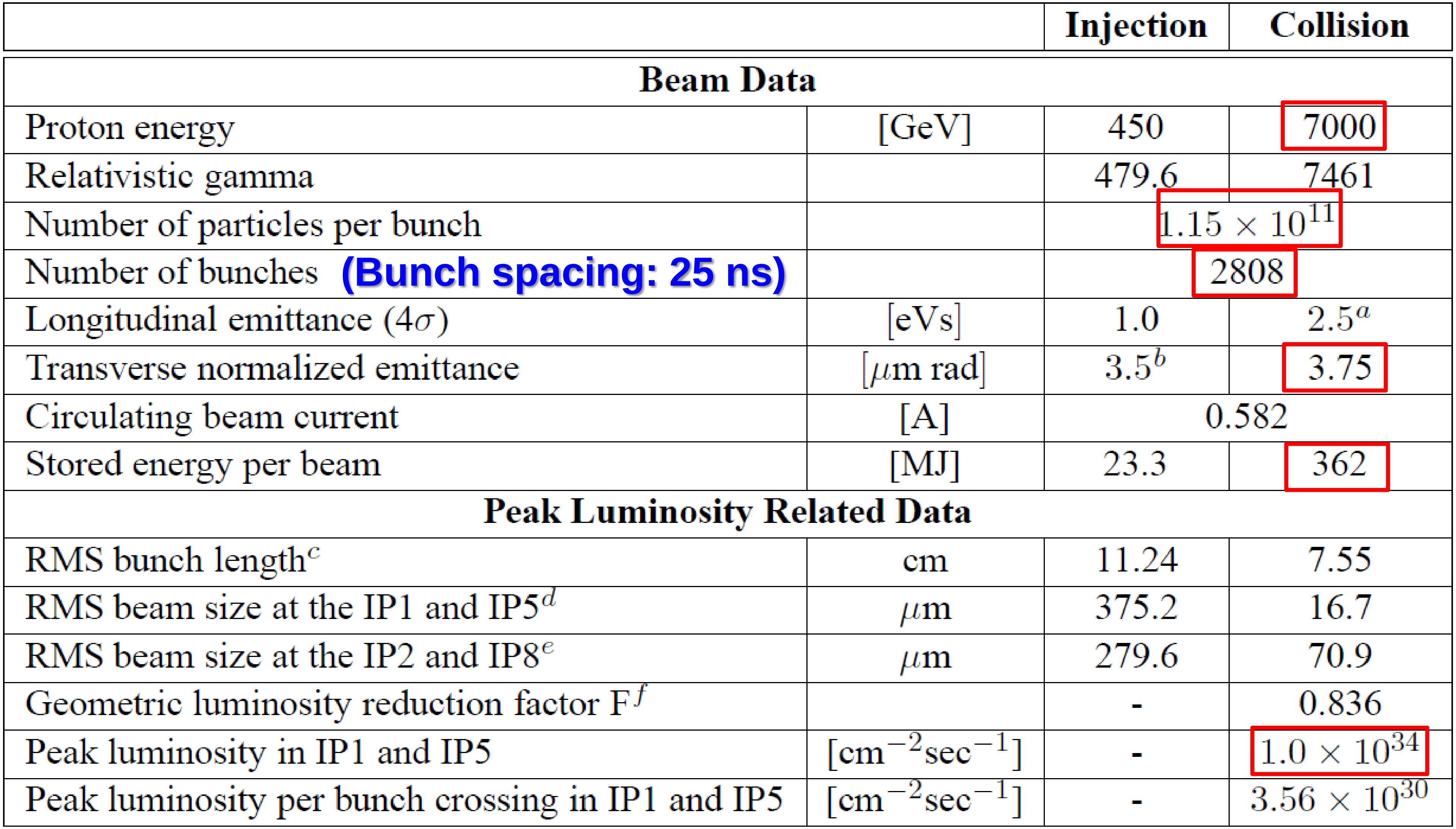
Separation/ricombination dipole

Low-beta quadrupoles

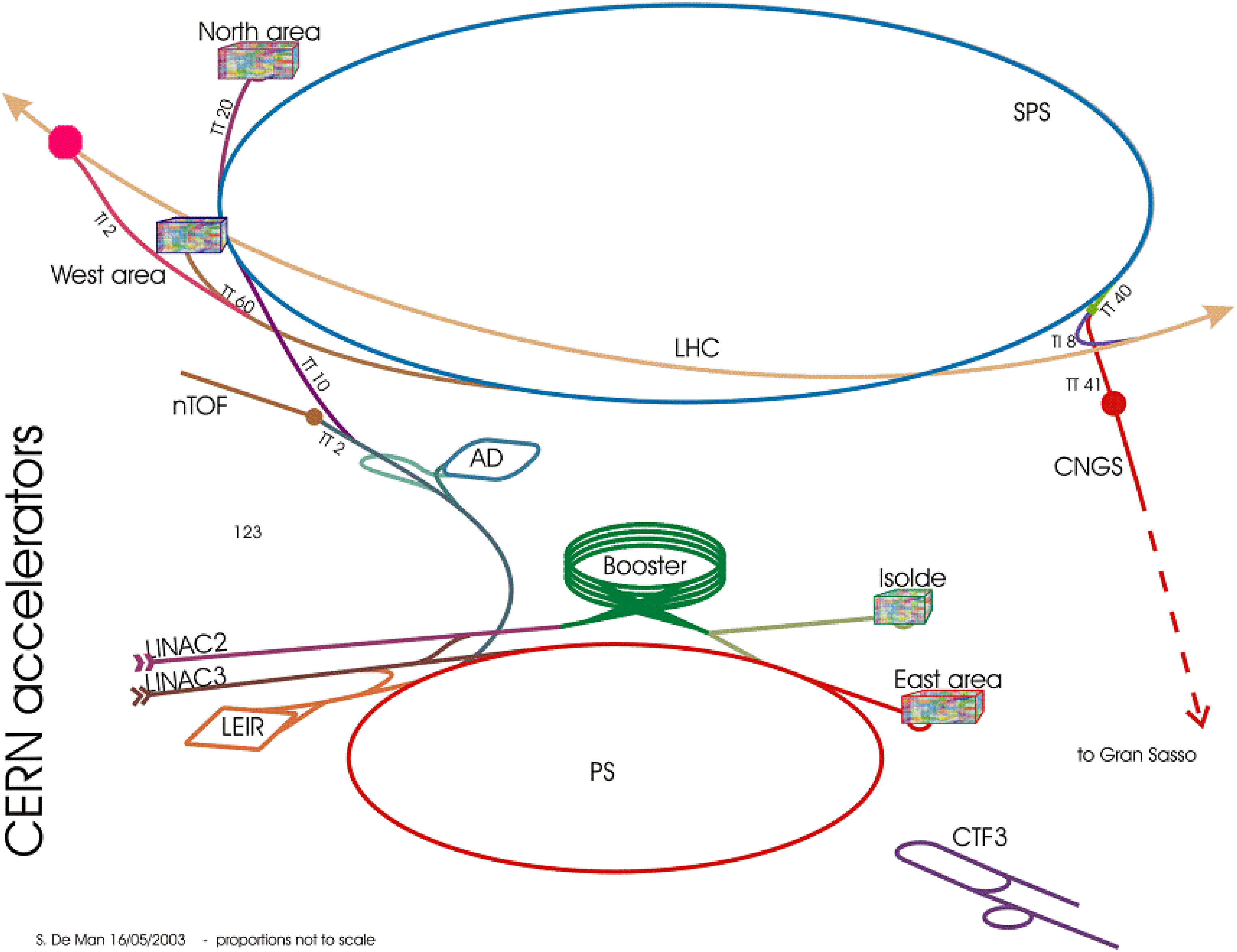
Interaction point

High luminosity insertions

Key parameters



		Injection	Collision
Beam Data			
Proton energy	[GeV]	450	7000
Relativistic gamma		479.6	7461
Number of particles per bunch		1.15×10^{11}	
Number of bunches **(Bunch spacing: 25 ns)**		2808	
Longitudinal emittance (4σ)	[eVs]	1.0	2.5^a
Transverse normalized emittance	[μm rad]	3.5^b	3.75
Circulating beam current	[A]	0.582	
Stored energy per beam	[MJ]	23.3	362
Peak Luminosity Related Data			
RMS bunch length[c]	cm	11.24	7.55
RMS beam size at the IP1 and IP5[d]	μm	375.2	16.7
RMS beam size at the IP2 and IP8[e]	μm	279.6	70.9
Geometric luminosity reduction factor F[f]		-	0.836
Peak luminosity in IP1 and IP5	[$\mathrm{cm}^{-2}\mathrm{sec}^{-1}$]	-	1.0×10^{34}
Peak luminosity per bunch crossing in IP1 and IP5	[$\mathrm{cm}^{-2}\mathrm{sec}^{-1}$]	-	3.56×10^{30}



S. De Man 16/05/2003 - proportions not to scale

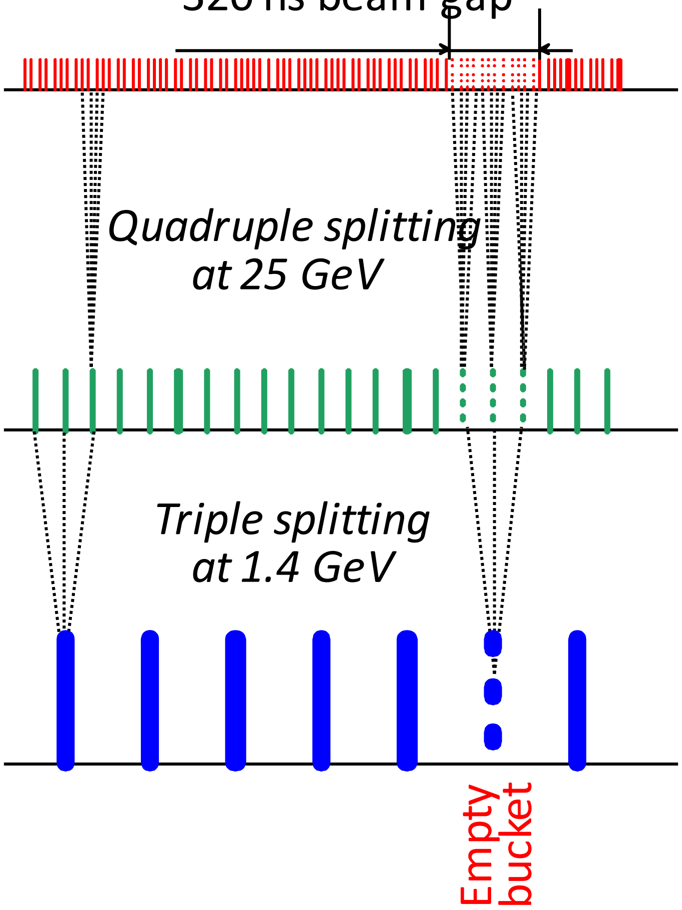
Courtesy E. Métral

Trip of the LHC proton beam along the CERN injectors’ chain

Space charge

- Space charge introduces:
    - Tune shift
    - tune spread
- Interaction with resonances might induce:
    - Emittance growth -> loss of brightness
    - Losses
- LHC beam exceeds brightness limits in injectors. A number of improvements/beam manipulations are needed:
    - Double-batch injection in PS -> alleviates PSB space charge
    - Increase of PSB extraction energy -> alleviates PS space charge
    - Longitudinal bunch splitting in PS-> reduces longitudinal emittance

Nominal LHC beam in PS



320 ns beam gap

PS ejection:
72 bunches
in1 turn

72 bunches
on h=84

Quadruple splitting
at 25 GeV

Acceleration
to 25 GeV

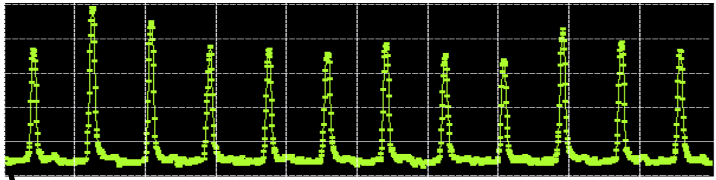
18 bunches
on h=21

Triple splitting
at 1.4 GeV

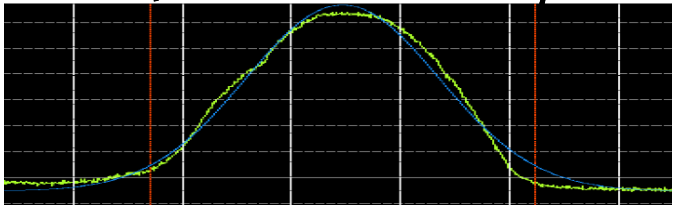
PS injection:
3+3 bunches
in 2 batches

Empty
bucket

6 bunches
on h=7

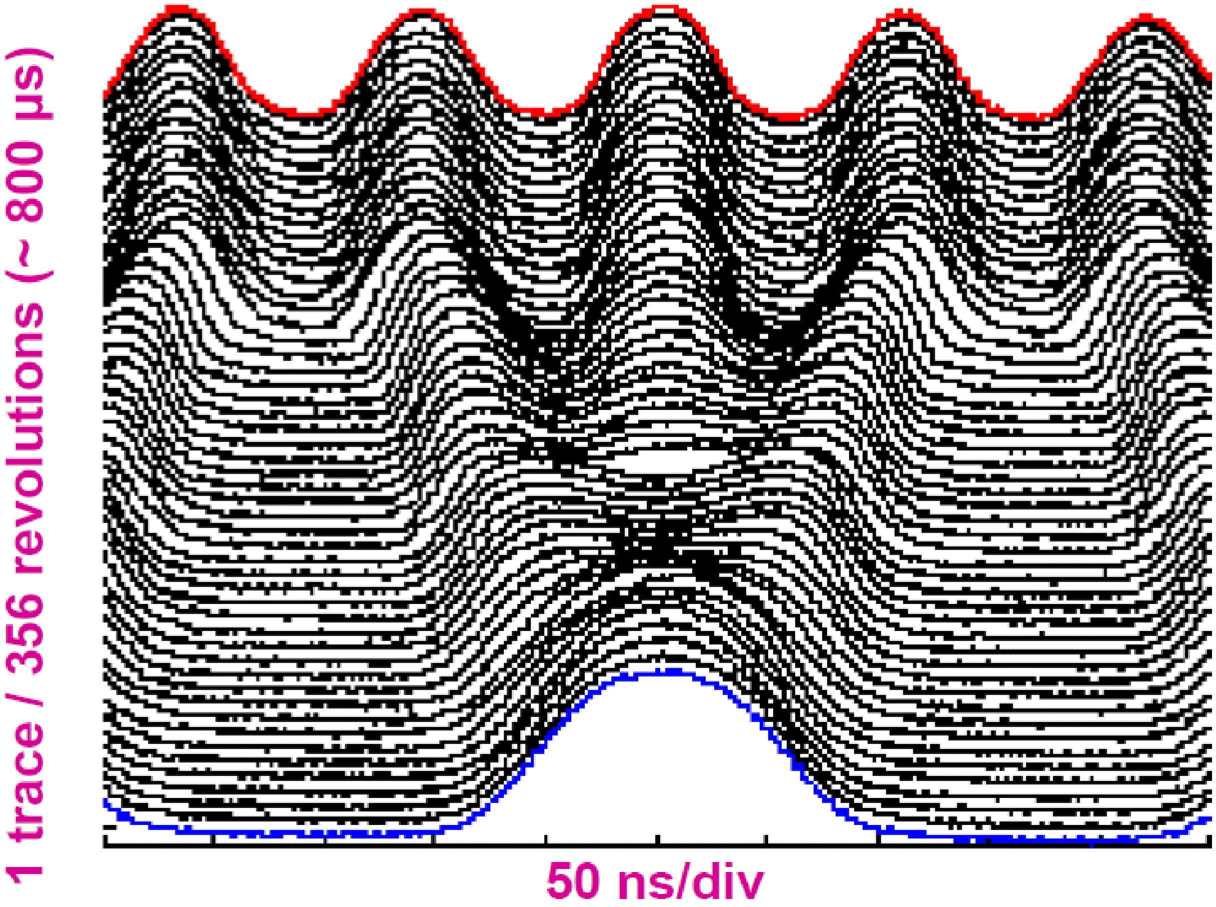


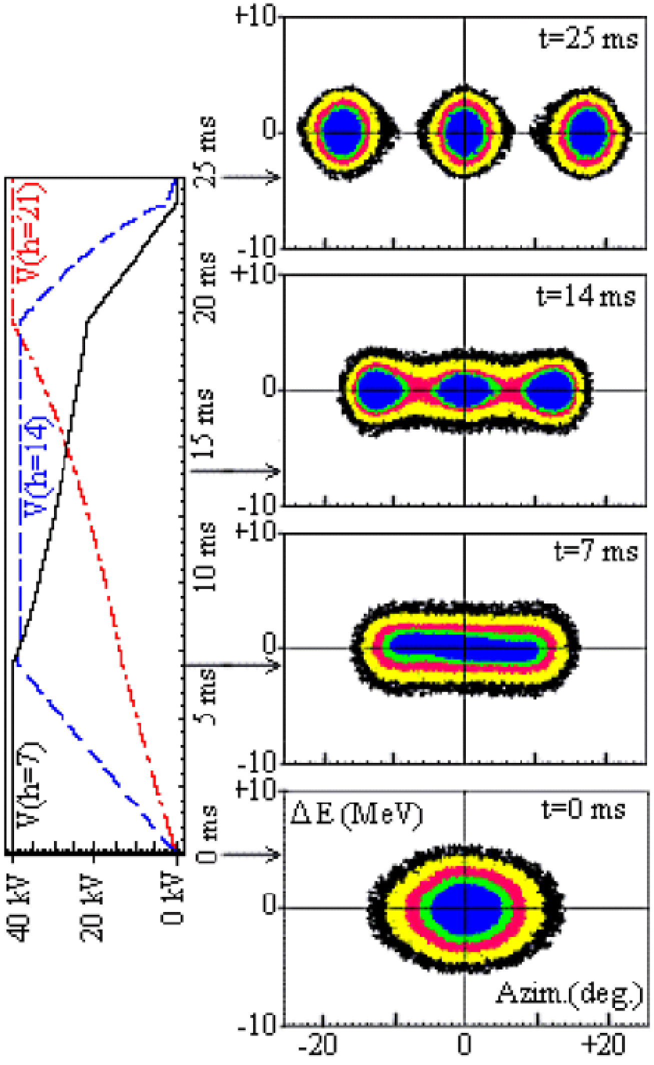
At PS extraction the bunches have the nominal 25 ns spacing



Triple bunch splitting

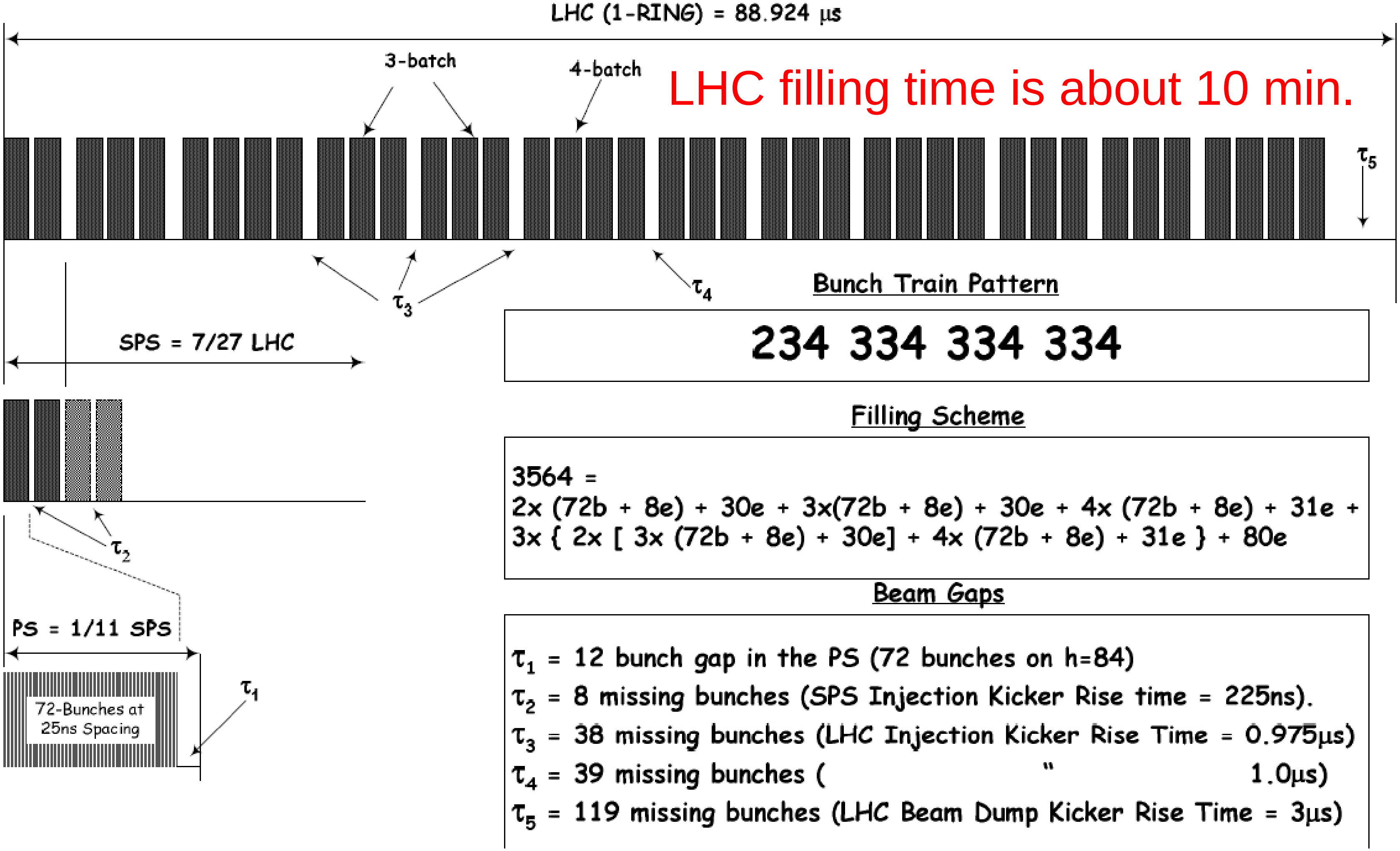
The stable fixed point bifurcates and three stable ones are generated.





Courtesy R. Garoby

Nominal LHC filling scheme



LHC filling time is about 10 min.

Bunch Train Pattern

234 334 334 334

Filling Scheme

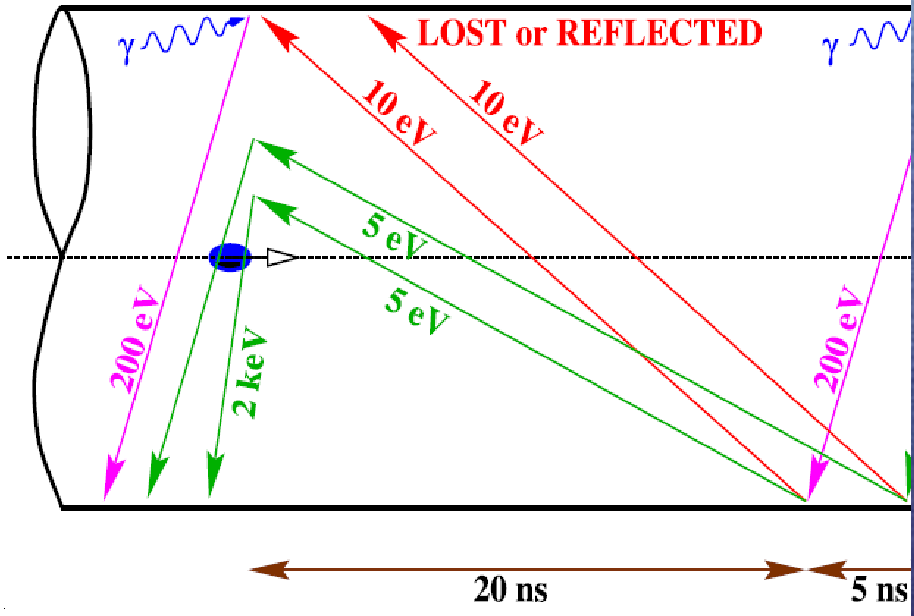
3564 =
2x (72b + 8e) + 30e + 3x(72b + 8e) + 30e + 4x (72b + 8e) + 31e +
3x { 2x [3x (72b + 8e) + 30e] + 4x (72b + 8e) + 31e } + 80e

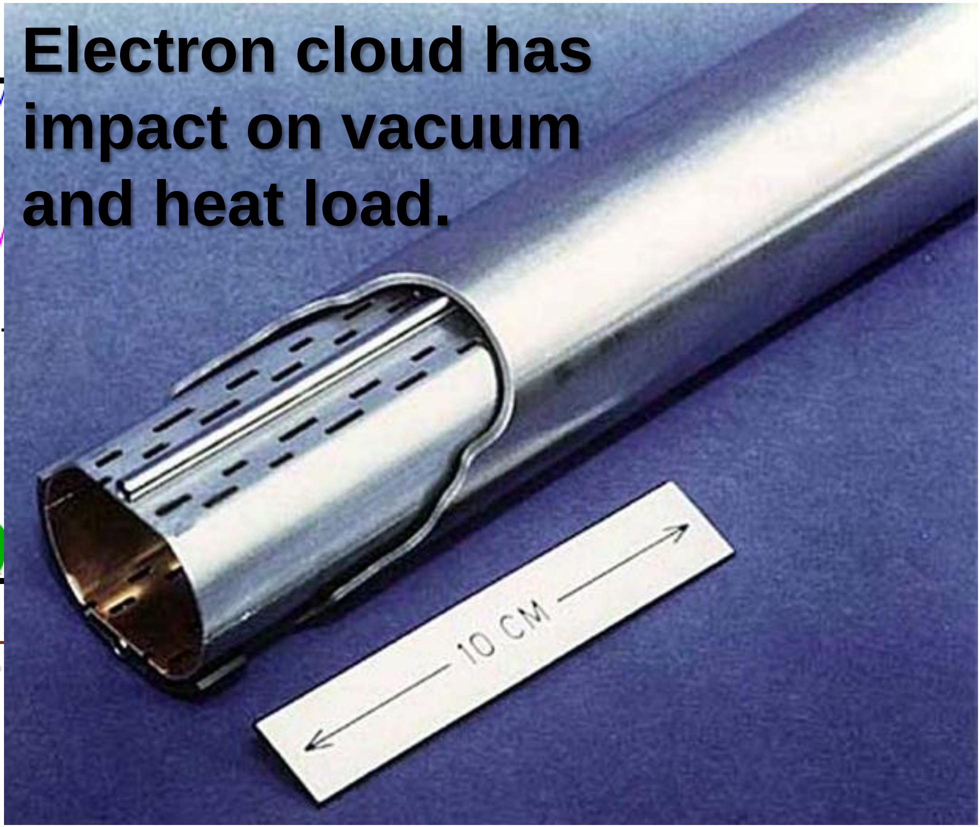
Beam Gaps

τ_1 = 12 bunch gap in the PS (72 bunches on h=84)
τ_2 = 8 missing bunches (SPS Injection Kicker Rise time = 225ns).
τ_3 = 38 missing bunches (LHC Injection Kicker Rise Time = 0.975μs)
τ_4 = 39 missing bunches (" 1.0μs)
τ_5 = 119 missing bunches (LHC Beam Dump Kicker Rise Time = 3μs)

Electron-cloud - I

- 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.





Electron cloud has impact on vacuum and heat load.

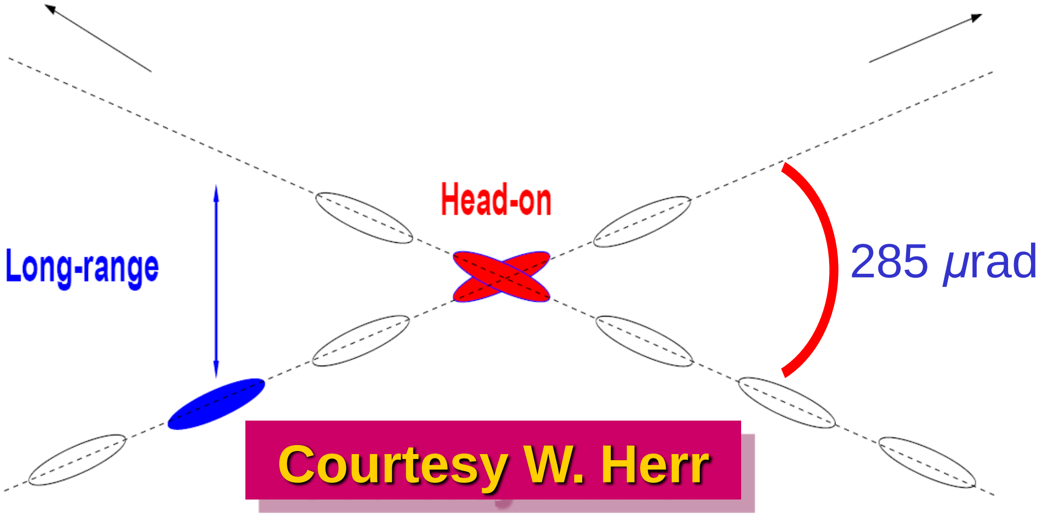
Courtesy F. Ruggiero

Electron-cloud - II

- Four approaches used to suppress/mitigate electron-cloud build-up:
  - A saw tooth chamber in the arcs (a series of 30-❍m high steps spaced at a distance of 500 ❍m in the longitudinal direction) to reduce the photon reflectivity.
  - Shielding the pumping holes inside the arc beam screen so as to prevent multipacting electrons from reaching the cold bore of the dipole magnet.
  - Coating the warm regions by a special Non Evaporable Getter (NEG) material, TiZrV, with low secondary emission yield.
  - Conditioning of the arc chamber surface by the cloud itself (beam scrubbing), which will ultimately provide a low secondary emission yield.

A fifth method to alleviate electron-cloud: install solenoids in the transition regions.

Beam-beam - I



Courtesy W. Herr

In case the collisions would occur head-on, plenty of parasitic collisions would take place in the common vacuum pipe.

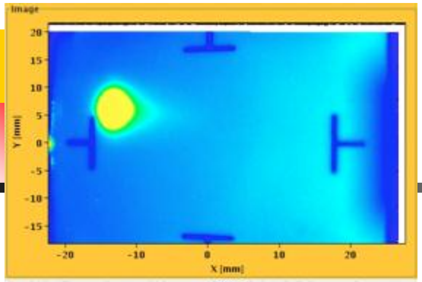
A crossing angle is used to separate bunches after the first wanted collision.

- The crossing angle cannot cope with additional effects, the so-called PACMAN bunches.
- The LHC filling pattern is not continuous, but gaps have to be included.
- Hence three types of collisions can occur:
  - Bunch-bunch
  - Bunch-hole
  - Hole-hole

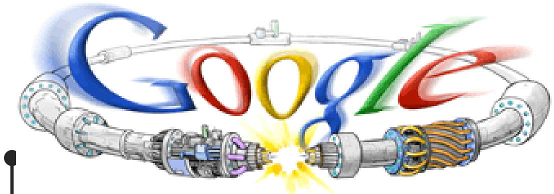
Alternating the crossing plane mitigates the PACMAN effect!

Courtesy M. Lamont

August 2008
First injection test



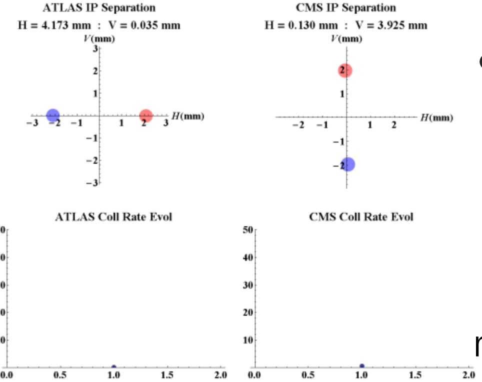
September 10, 2008
First beams around



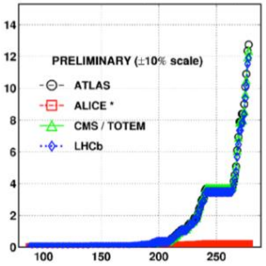
September 19, 2008
Disaster
Accidental release of 600 MJ stored in one sector of LHC dipole magnets

November 29, 2009
Beam back

March 30, 2010
First collisions at 3.5 TeV

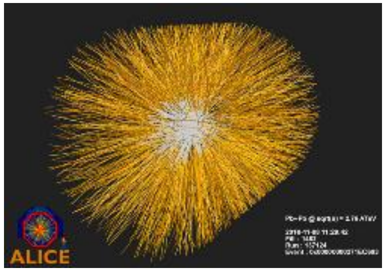


April 2010
Squeeze to 3.5 m



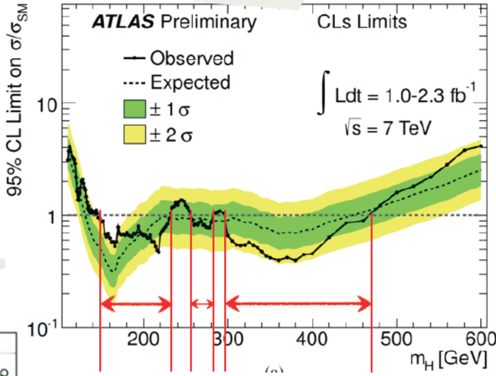
October 14 2010
1×10^{32}, 248 bunches

November 2010
Ions



June 28 2011
1380 bunches

1380

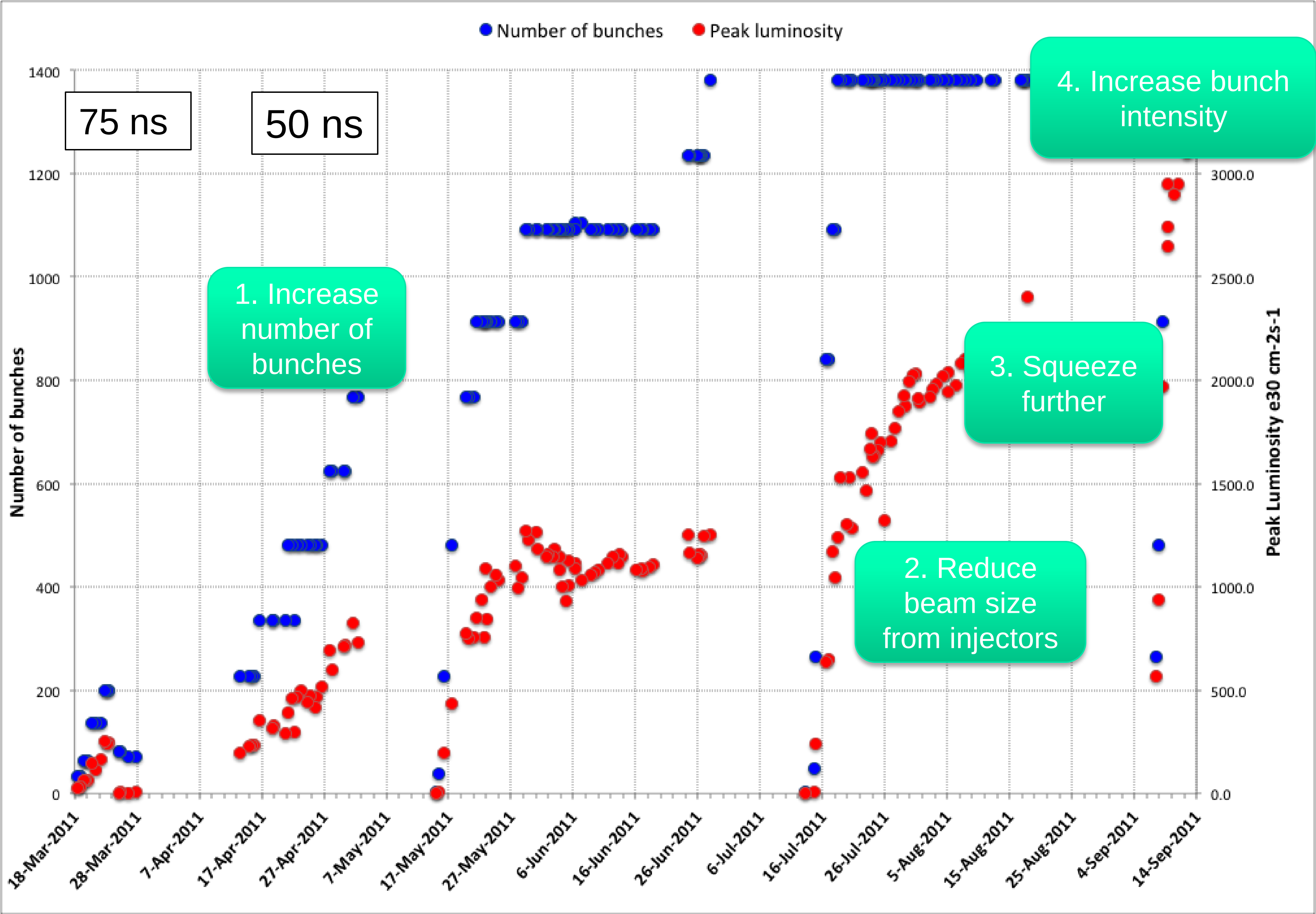


August, 2011
2.3×10^{33}, 2.6 fb^{-1}
1380 bunches

2008 2009 2010 2011

2011

Courtesy M. Lamont



1. Increase number of bunches

2. Reduce beam size from injectors

3. Squeeze further

4. Increase bunch intensity

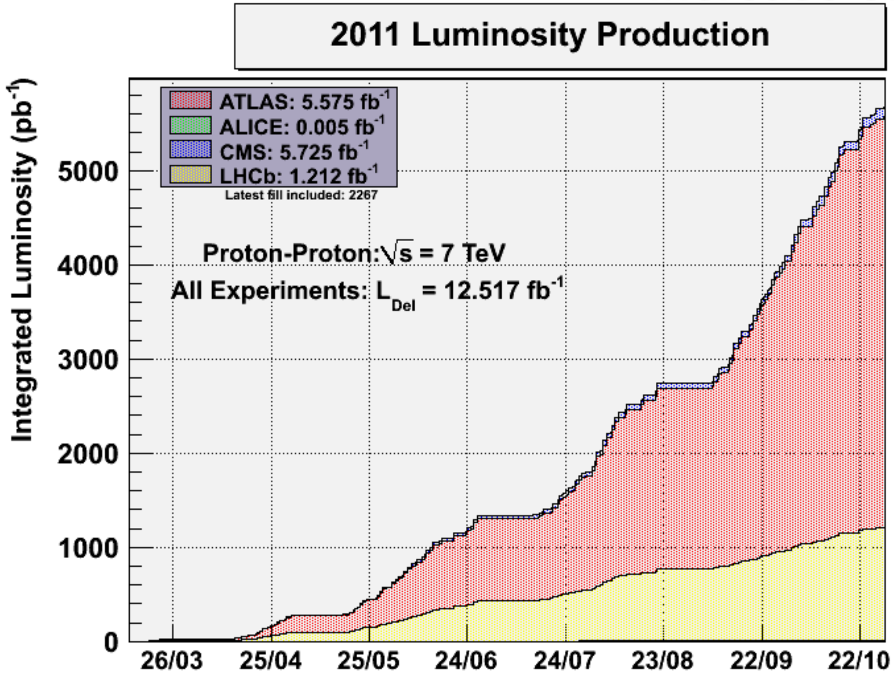
Goals for 2010-2012

- 2010: commissioning of peak luminosity of 10^{32} cm^{-2} s^{-1} (achieved in October)
- 2011: ≈1fb^{-1} delivered to ATLAS and CMS (achieved in June)
- 2012: ≈15 fb^{-1} delivered to ATLAS and CMS before LS1.

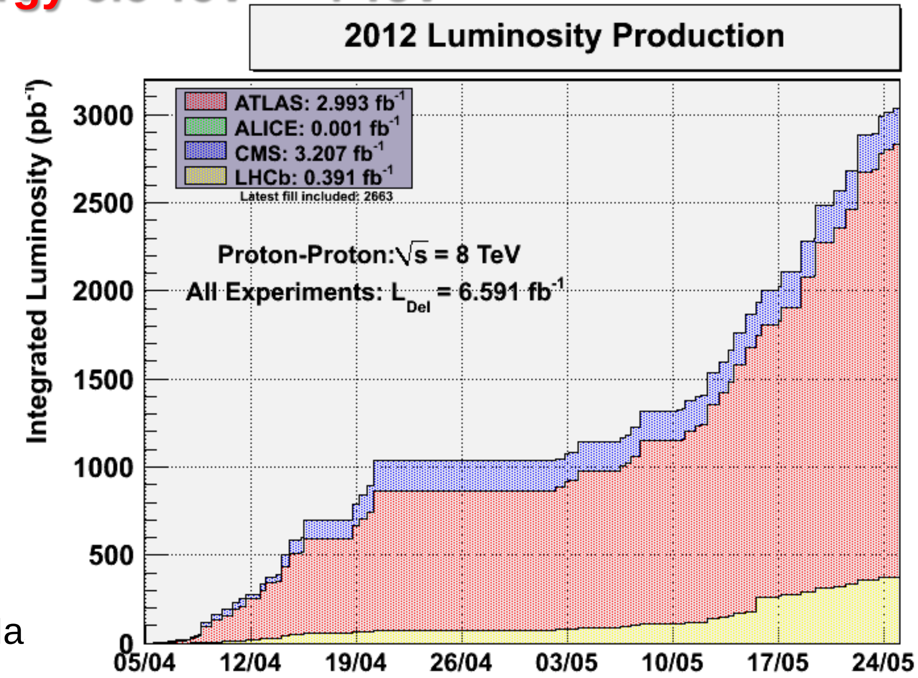
2011-> 2012:

reduction of β^* 1 m -> 0.6 m

Increase of energy 3.5 TeV -> 4 TeV

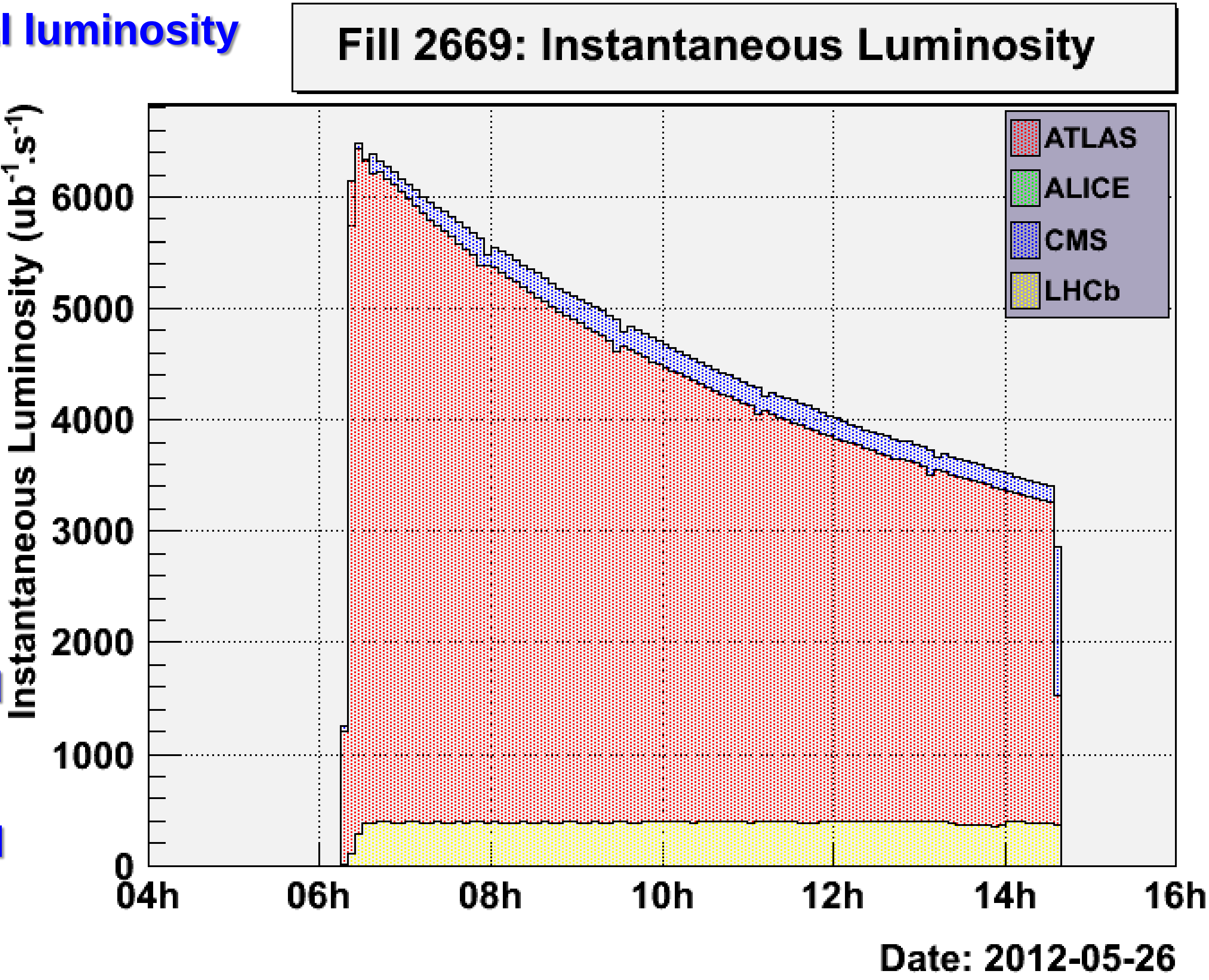


Ma



Current situation

2/3 of the peak nominal luminosity achieved!!!
Still some margin of increase (bunch intensity).



About 130 pb^{-1} collected during this fill.
Maximum (to date) integrated luminosity/fill is over 200 pb^{-1}.

Overview of beam parameters

	LHC nominal	2011 50 ns	2012 50 ns
Energy [TeV]	7.0	**3.5**	**4.0**
# Bunches	2808	**1380**	**1380**
p/bunch [10^{11}]	1.15	**1.4**	**1.5-1.6**
$\gamma\varepsilon_{x,y}$ [μm]	3.75	**2.5**	**2.5**
β^* [cm] (baseline)	55	**100**	**60**
Lumi loss factor (F)	0.84	**0.91**	**0.81**
Peak lumi [10^{34}]	1.0	**0.32**	**0.6-0.7**
# of events per crossing	25	**16**	**32**

Upgrade ideas (until 2010)

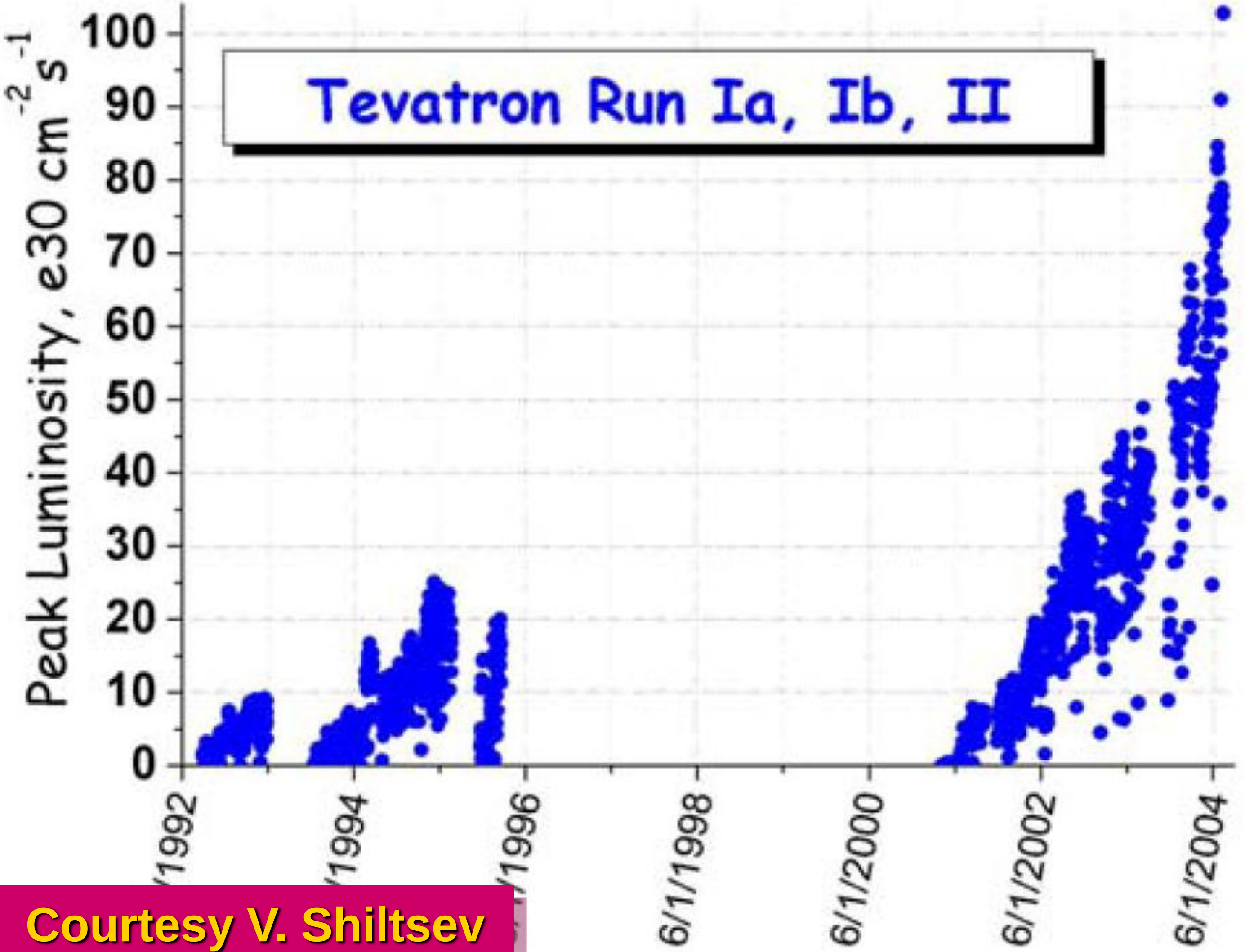
- Assumptions (or common belief)
  - Lifetime of triplets under nominal conditions is few years (radiation due to debris) -> they should be replaced
  - Nominal parameters are probably tight and nominal luminosity might be difficult to achieve (triplets' aperture)
- Hence, two-stage approach:
  - Phase 1: "Consolidate" the machine with new triplets aiming at reaching ~ $2\text{-}3\times10^{34}$ cm^{-2} s^{-1}.
  - Phase 2: "Real" luminosity upgrade aiming at 10^{35} cm^{-2} s^{-1}. This includes a major upgrade of the detectors.

Phase 1 in short

- Rough summary of Phase 1 approach
  - Replace “only” triplets with larger aperture magnets to enable reaching smaller β*.
- Intense studies performed:
  - Minimum β* achievable: ~ 30 cm
  - Limits have been found in other parts of the machine -> much more elements than the triplets should be changed!
  - Very complex optical gymnastics in order to fulfill the correction of chromatic aberrations -> not much operational flexibility left.

S. Fartoukh at Chamonix 2010 Workshop

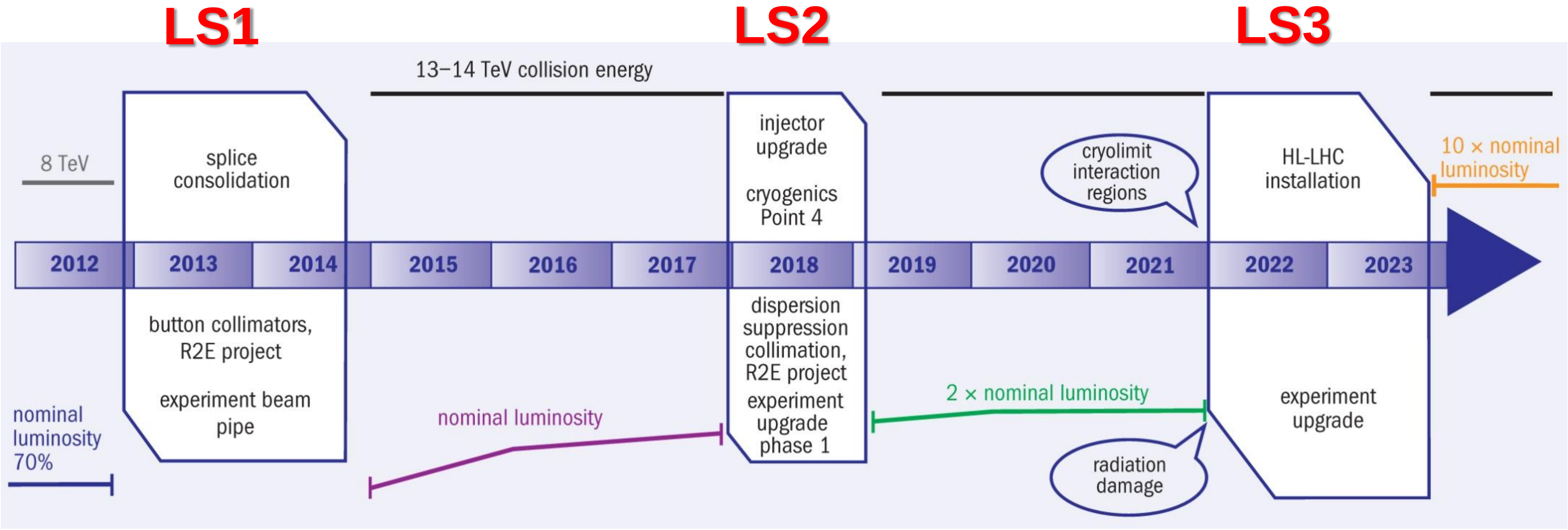
How many upgrades?



Courtesy V. Shiltsev

Each upgrade will require a non-negligible time to recover from the stop and gain in INTEGRATED luminosity.

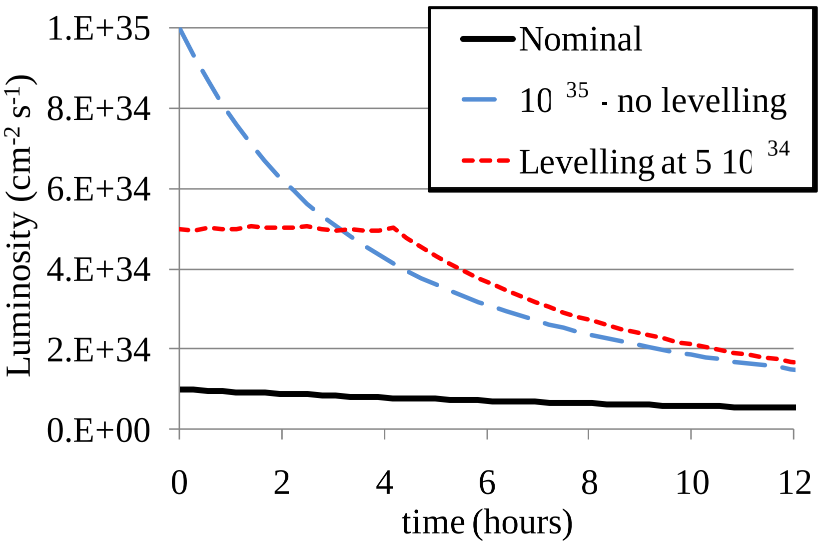
LHC programme for the next 10 years

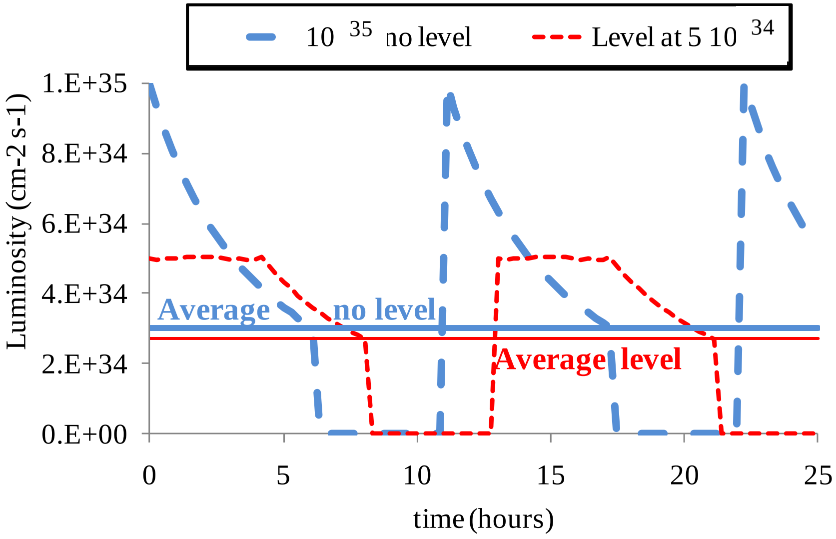


Courtesy L. Rossi

Scope of High-Luminosity upgrade of LHC

- Targets:
  - A peak luminosity of 5×10^{34} $cm^{-2}s^{-1}$ **with leveling**
  - An integrated luminosity of 250 fb^{-1} per year, enabling the goal of 3000 fb^{-1} in twelve years.





Courtesy E. Todesco

Performance - I

- The peak luminosity depends on

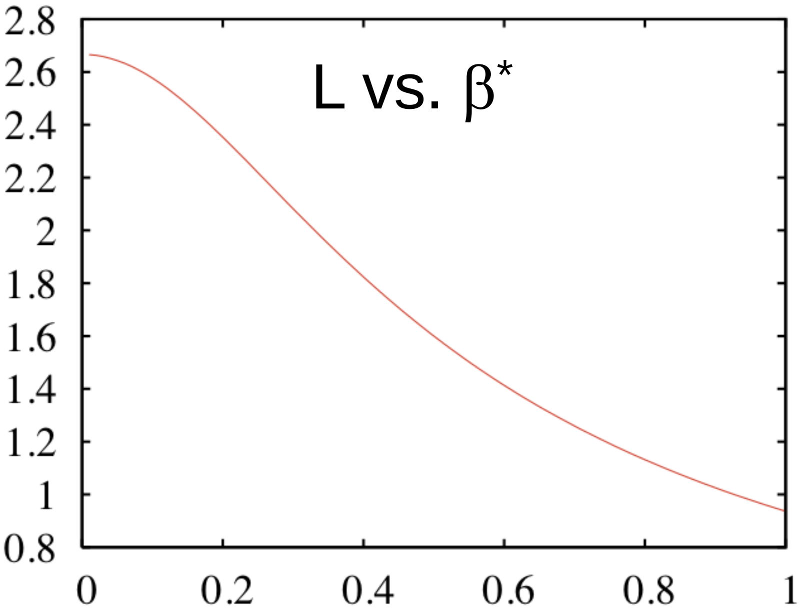
$$L = \boxed{\frac{M\ f_{rev}\ \gamma_r}{4\pi\ \beta^*}F}\boxed{\frac{N_b^2}{\varepsilon_n}}$$

LHC-specific **Injectors-specific**

- Due to the crossing angle, the geometrical reduction factor F is different from unity and reads

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

- NB: β^* enters in the factor F via θ_c and σ^*: no gain in reducing β^* below a certain value.
  Flat beams represent a mitigation of this effect.



Performance - II

- Possible strategies for upgrading performance:
  - Maximize bunch brightness (beam-beam limit)
  - Minimize beam size (aperture in triplets)
  - Maximize number of bunches (beam power, e-cloud)
  - Compensate for F
- LHC Upgrade (HL-LHC):
  - Smaller β^*; new triplets quadrupoles; possibly new technology (Nb_3Sn instead of Ni-Ti).
  - Mitigation measures for higher currents (e.g., collimator system upgrade, cooling, beam-beam compensation wires)
  - Flat beams or crab cavities
- Injectors' Upgrade (LIU):
  - Increase beam brightness
  - Mitigation measures for higher currents (e.g., coating SPS vacuum chambers).

LHC upgrade: parameter space

- 25 ns is the baseline,

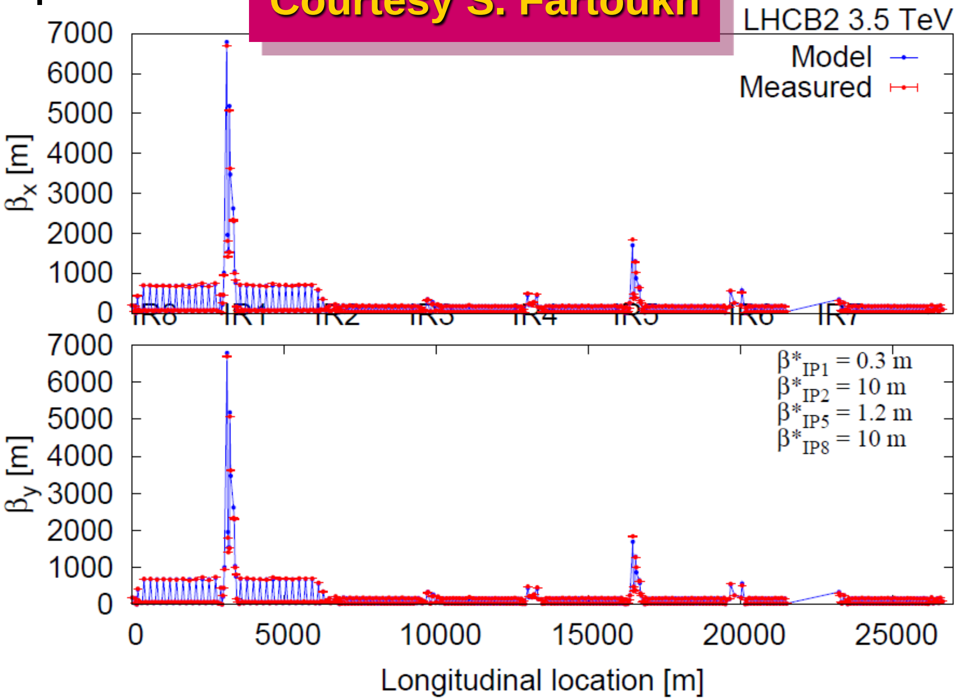
  50 ns is a back-up (e.g. for e-cloud).
- Parameters still under discussion with the LHC Injector Upgrade project.
- Relies on crab-cavity

	LHC nominal	HL-LHC 25 ns	HL-LHC 50 ns
# Bunches	2808	2808	1404
p/bunch [10^{11}]	1.15 (0.58A)	**2.0 (1.01 A)**	**3.3 (0.83 A)**
ε_L [eV.s]	2.5	2.5	2.5
σ_z [cm]	7.5	7.5	7.5
$\sigma_{\delta p/p}$ [10^{-3}]	0.1	0.1	0.1
$\gamma\varepsilon_{x,y}$ [μm]	3.75	**2.5**	**3.0**
β^* [cm] (baseline)	55	**15**	**15**
X-angle [μrad]	285	**590 (12.5 σ)**	**590 (11.4 σ)**
Lumi loss factor (F)	0.84	**0.30**	**0.33**
Peak lumi [10^{34}]	1.0	6.0	7.4
Virtual lumi [10^{34}]	1.2	20.0	22.7
$T_{leveling}$ [h] @ 5E34	n/a	**7.8**	**6.8**
#Pile up @5E34	25	**123**	**247**

Courtesy S. Fartoukh

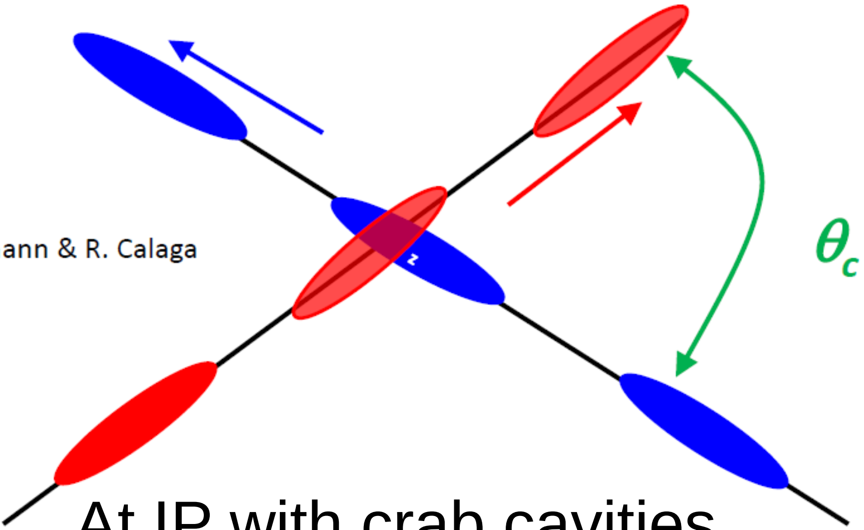
The proposed optics

- The Achromatic Telescopic Squeeze optics (invented by S. Fartoukh) enables:
  - Reaching very small b* values
  - At the same time, it enhance the strength of the chromatic sextupoles thus enabling the compensation of the chromatic aberrations that stem from the new triplet quadrupoles.
- A vigorous experimental programme in the LHC successfully showed the feasibility of the scheme


Courtesy S. Fartoukh

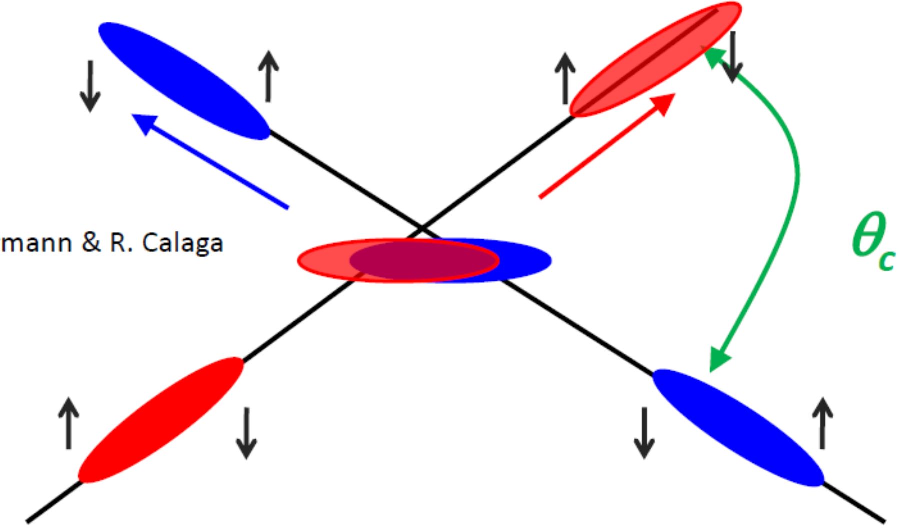
Crab cavities

At IP without crab cavities

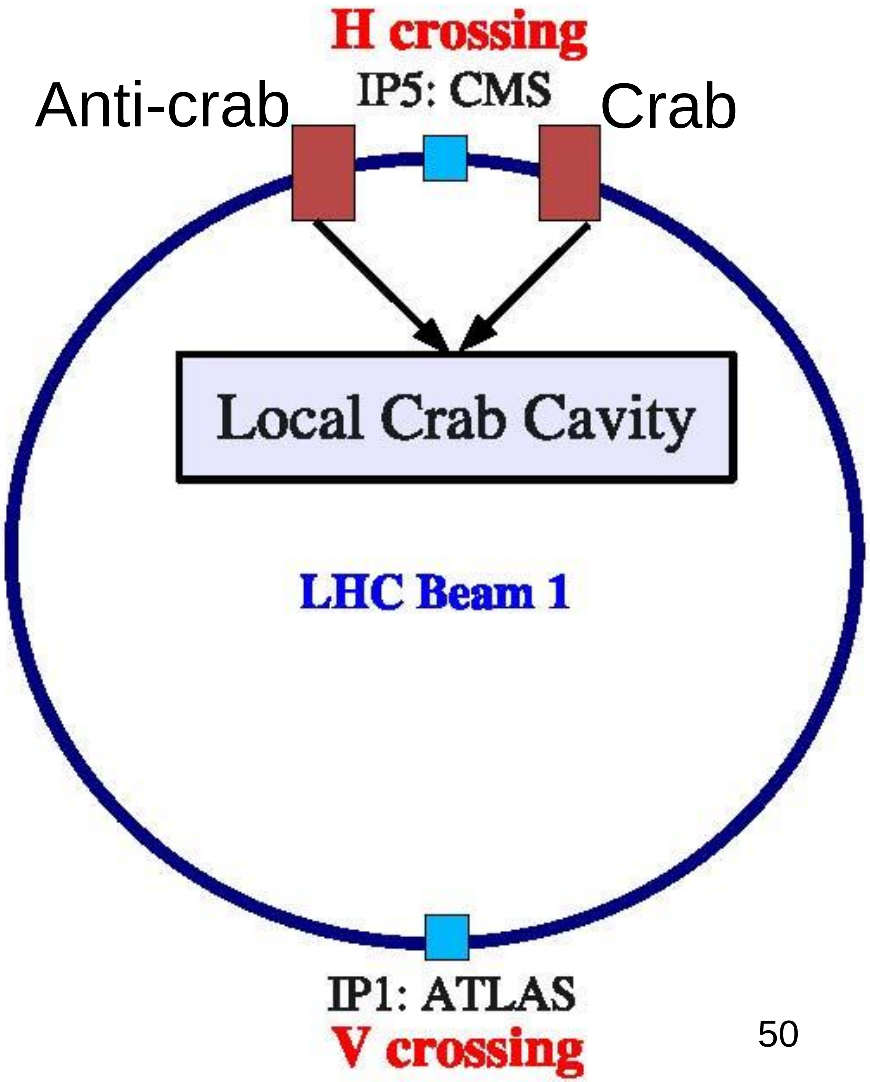


F. Zimmermann & R. Calaga

At IP with crab cavities

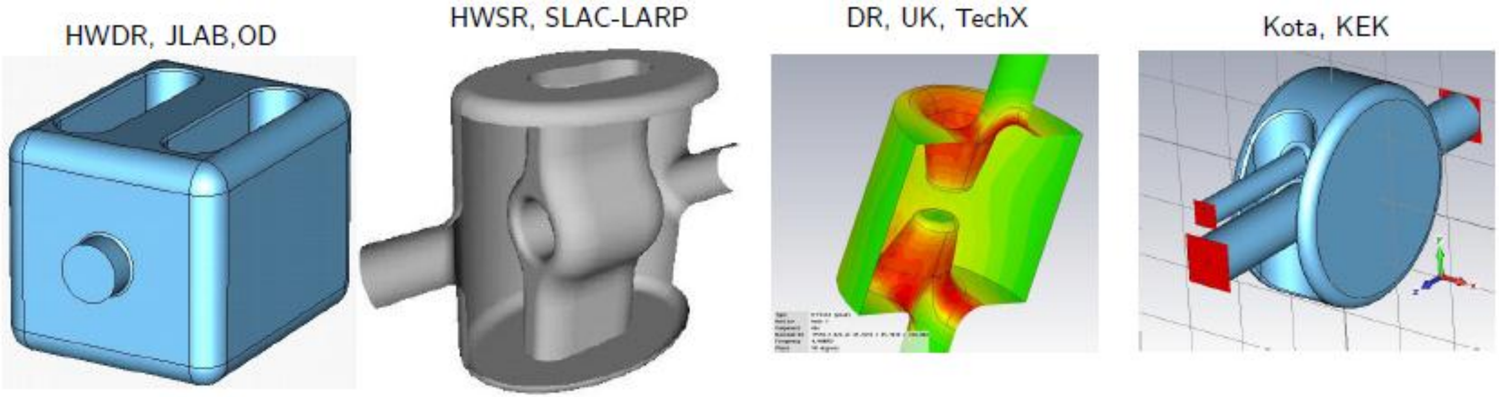


F. Zimmermann & R. Calaga



Potential issues of crab cavities

- RF Noise
  - It could induce emittance growth. So far never used in any proton machine!
- Design
  - Very limited transverse space in the LHC
  - Imposes creative designs
  - Two types are needed: H and V crossing
- Machine protection!



HWDR, JLAB,OD

HWSR, SLAC-LARP

DR, UK, TechX

Kota, KEK

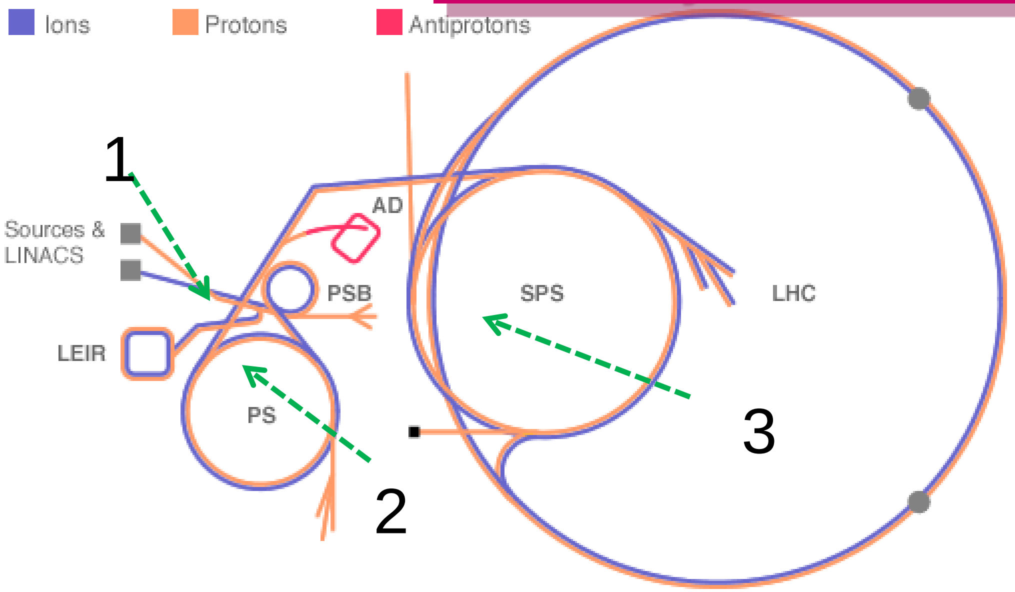
Compact cavities aiming at small footprint & 400 MHz, ~5 MV/cavity

Luminosity levelling

- Three options at hand:
  - Vary crossing angle (crab cavities help here!)
    - It can be performed with dipoles
    - Easy, but requires aperture in triplets
  - Vary separation
    - It can be performed with dipoles
    - Easy (already tried with LHCb), but requires aperture
  - Vary β^*
    - Never tried in existing machines
    - Requires an excellent control of optics and crossing scheme

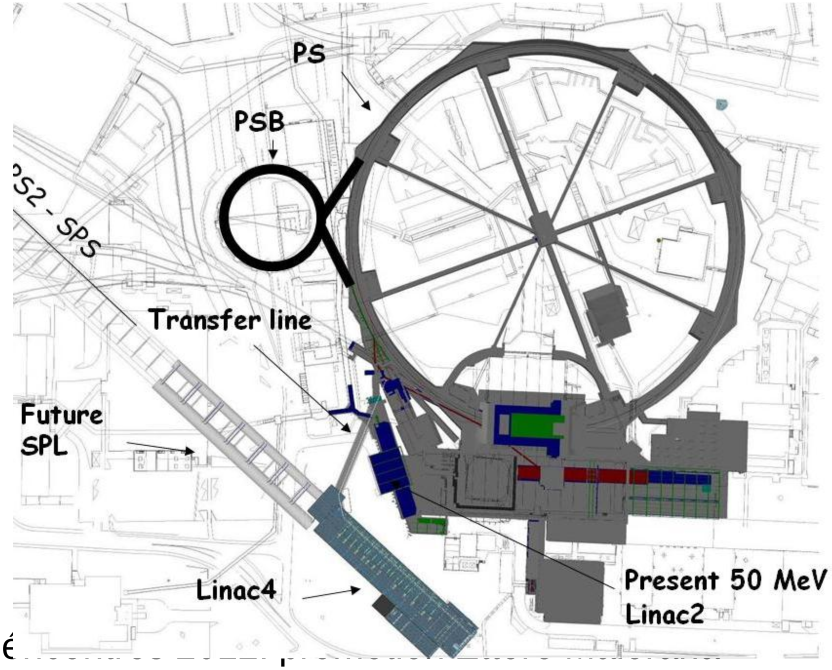
Upgrade of the injectors

Courtesy M. Vretenar



Three bottlenecks identified for higher intensity and/or brightness from the LHC injectors:

1. Space charge tune shift at PSB injection (50 MeV).
2. Space charge tune shift at PS injection (1.4 GeV).
3. Electron cloud and other



Low injection energy into the PSB is the first and most important bottleneck →
Decision (2007) to build a new linac (Linac4) to increase from 50 to 160 MeV.

After Linac4, new program (2010):

- Upgrade of PSB final energy to 2 GeV.
- Upgrade (coating, new RF) of SPS. Instabilities control.

High Energy-LHC

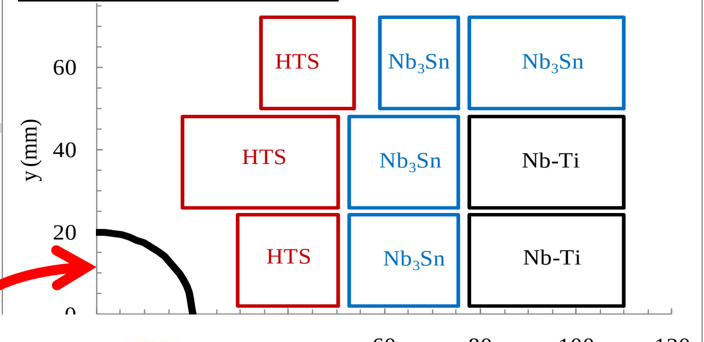
BE-EN-TE working group since April 2010

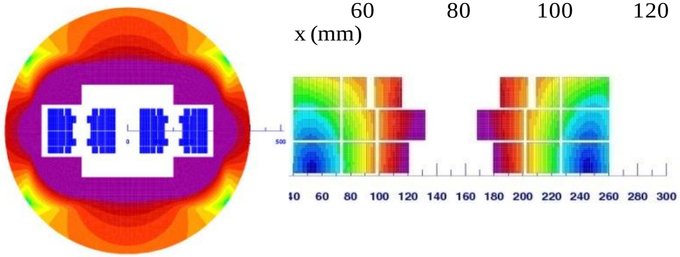
EuCARD AccNet workshop HE-LHC'10 ,

14-16 October 2010

	Turns	%
Nb-Ti	40	28%
Nb_3Sn	58	41%
HTS	45	31%

E. Todesco





O. Dominguez, F. Zimmermann

key topics

beam energy 16.5 TeV; 20-T magnets

cryogenics: **synchrotron-radiation heat load**

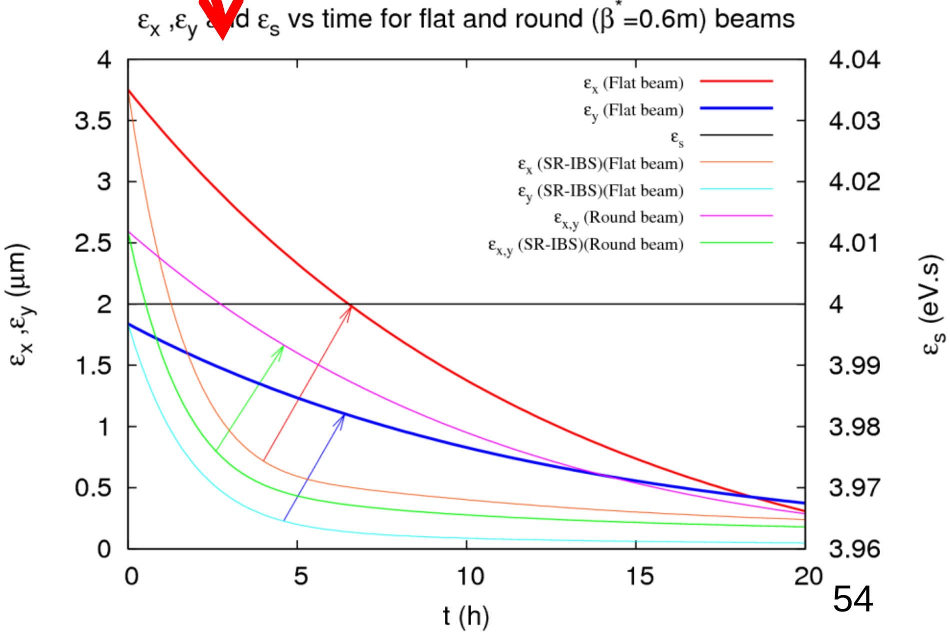
radiation damping & emittance control

vacuum system: synchrotron radiation

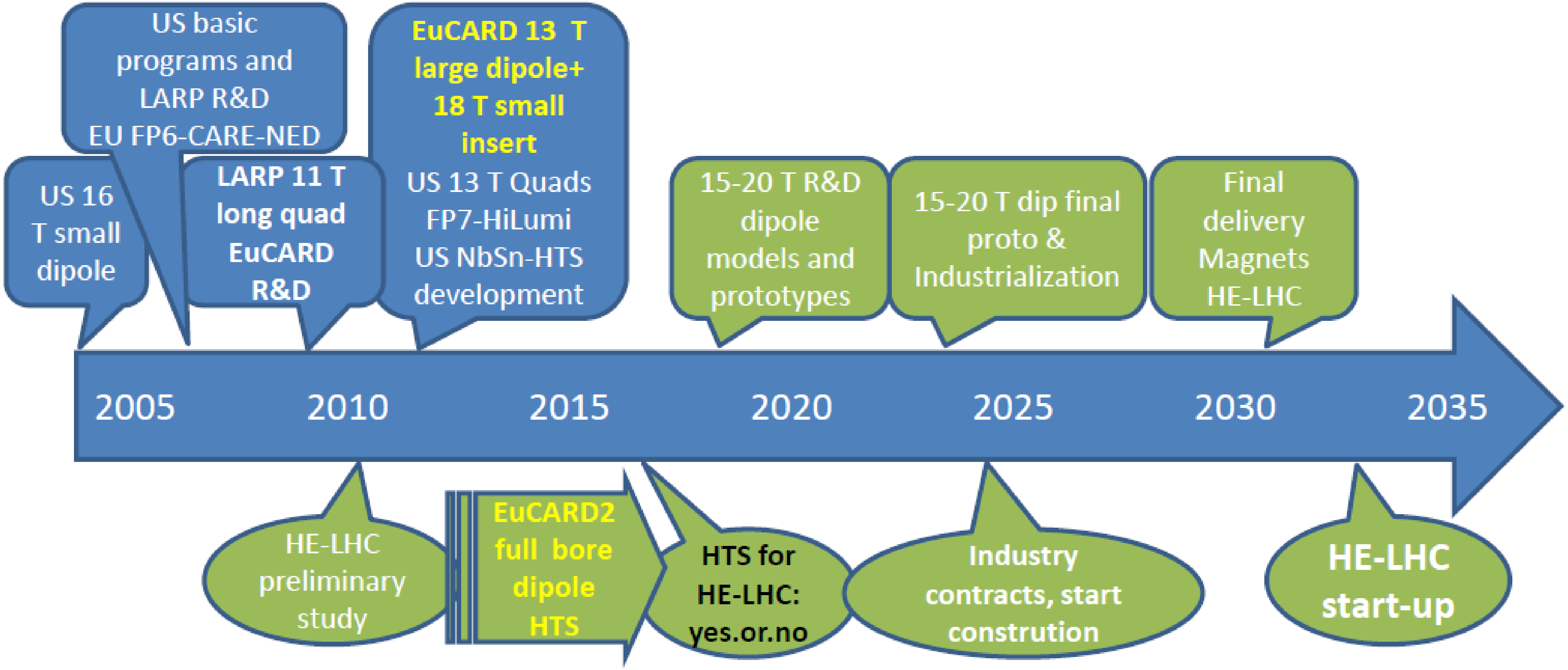
new injector: energy > 1 TeV

parameters

	LHC	**HE-LHC**
beam energy [TeV]	7	16.5
dipole field [T]	8.33	20
dipole coil aperture [mm]	56	40
#bunches	2808	1404
IP beta function [m]	0.55	1 (x), 0.43 (y)
number of IPs	3	2
beam current [A]	0.584	0.328
SR power per ring [kW]	3.6	65.7
arc SR heat load dW/ds [W/m/ap]	0.21	2.8
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	1.0	2.0
events per crossing	19	76


ε_x ,ε_y and ε_s vs time for flat and round (β^*=0.6m) beams

A tentative schedule for HE-LHC



US 16 T small dipole

US basic programs and LARP R&D
EU FP6-CARE-NED

LARP 11 T long quad EuCARD R&D

EuCARD 13 T large dipole+ 18 T small insert
US 13 T Quads
FP7-HiLumi
US NbSn-HTS development

15-20 T R&D dipole models and prototypes

15-20 T dip final proto & Industrialization

Final delivery Magnets HE-LHC

HE-LHC preliminary study

EuCARD2 full bore dipole HTS

HTS for HE-LHC: yes.or.no

Industry contracts, start constrution

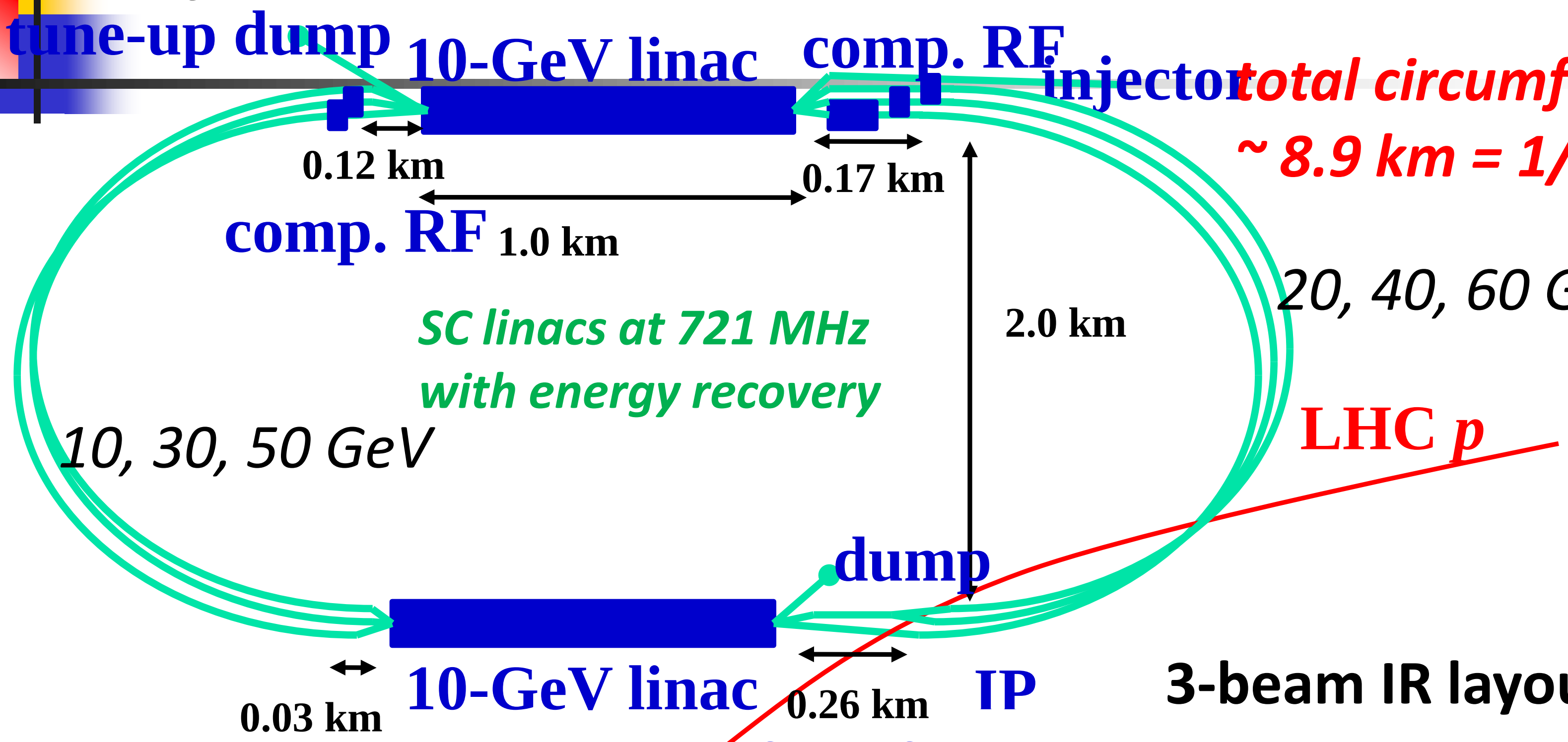
HE-LHC start-up

Courtesy L. Rossi

Linac-Ring LHeC

overall layout

O. Brüning, M. Klein, D. Schulte, R. Tomas, F. Zimmermann, et al



tune-up dump

10-GeV linac

comp. RF

injector

total circumference ~ 8.9 km = 1/3 LHC

0.12 km

0.17 km

comp. RF

1.0 km

20, 40, 60 GeV

2.0 km

SC linacs at 721 MHz with energy recovery

10, 30, 50 GeV

LHC *p*

dump

10-GeV linac

0.03 km

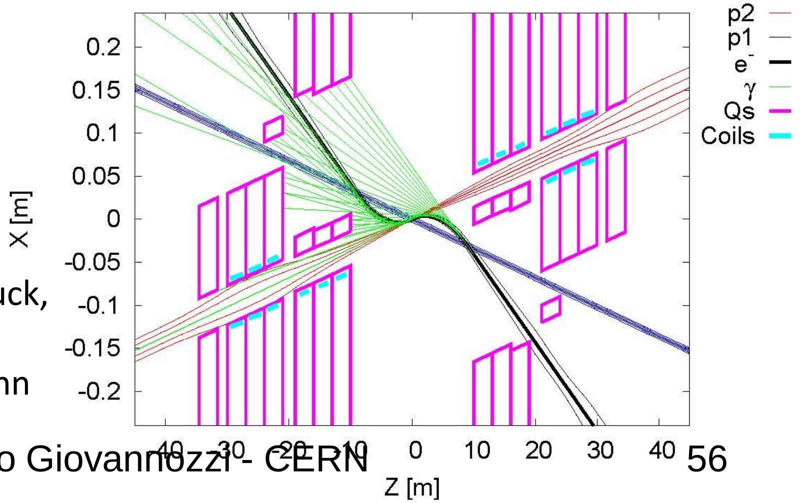
0.26 km

IP

e- final foc

- e- energy ≥60 GeV
- luminosity ~10^{33} cm^{-2}s^{-1}
- total electrical power for e-: ≤100 MW
- e^+p collisions with similar luminosity?
- simultaneous with LHC *pp* physics
- e^-/e^+ polarization
- detector acceptance down to 1°

3-beam IR layout



S. Russenschuck,
R. Tomas,
F. Zimmermann

Conclusions and outlook

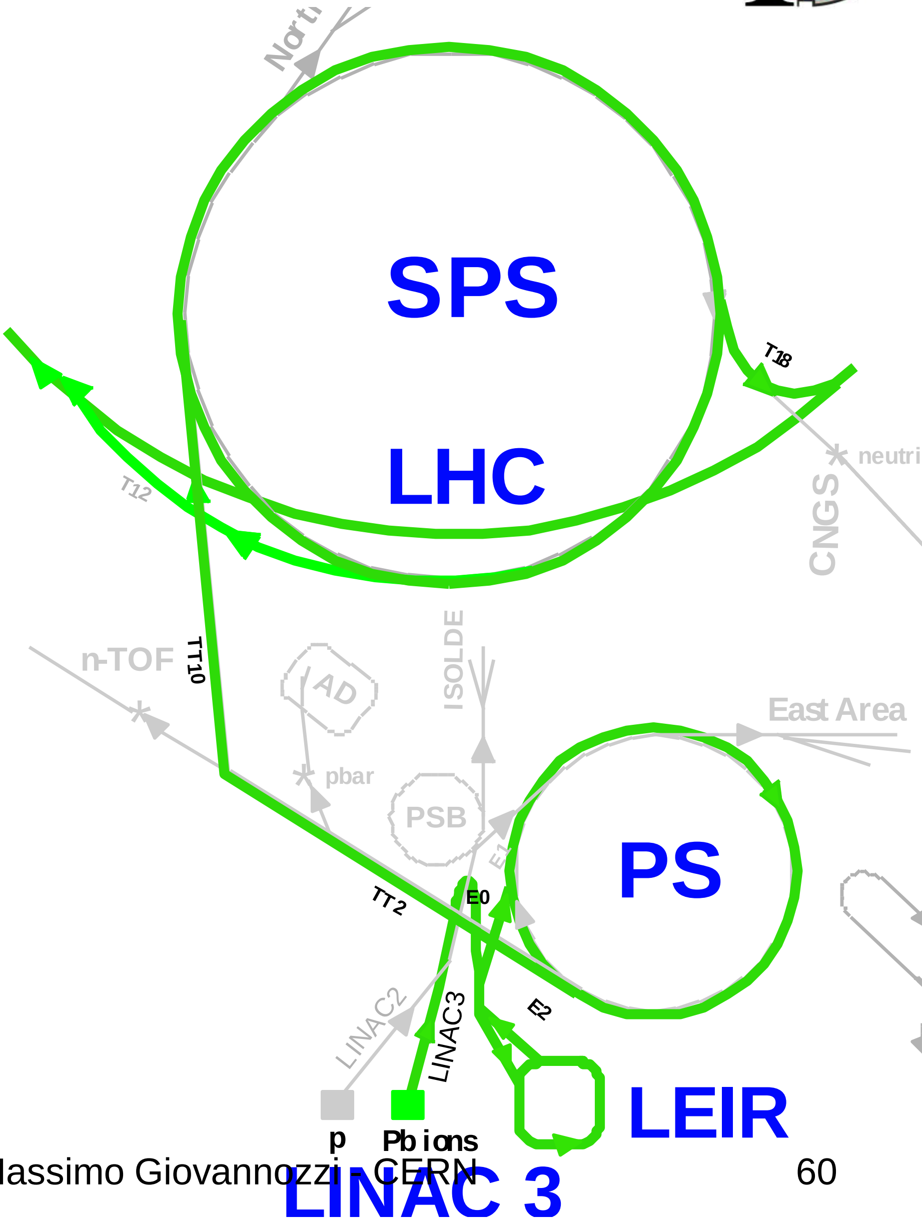
- Remarkable performance of the LHC and of its injectors!
- 2012 has been already a discovery year!
- Very rich upgrade programme:
  - HL-LHC:
    - studies and R&D on beam dynamics and hardware (the nominal machine can be used to perform beam dynamics experiments).
    - Contributions from US-LARP and HiLumi partners (FP7 European Project).
  - LIU:
    - Vigorous programme of consolidation and upgrade of the injectors.
- Future options: High-Energy LHC and LHeC.

Thank you for your attention

Spare slides

LHC Ion Injector Chain

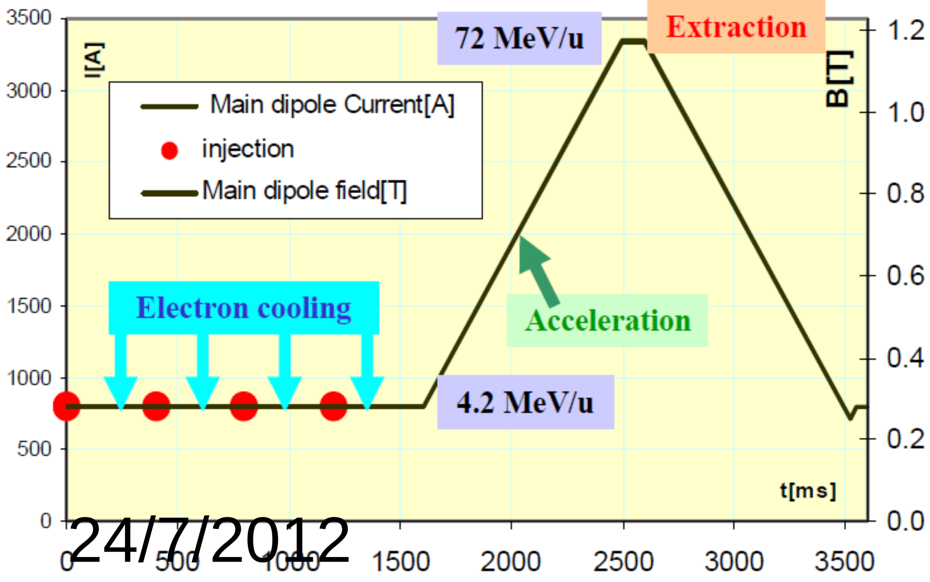
- ECR ion source (2005)
  - Provide highest intensity of Pb^{29+}
- RFQ + Linac 3
  - Adapt to LEIR injection energy
  - strip to Pb^{54+}
- LEIR (2005)
  - Accumulate and cool Linac3 beam
  - Prepare bunch structure for PS
- PS (2006)
  - Define LHC bunch structure
  - Strip to Pb^{82+}
- SPS (2007)
  - Define filling scheme of LHC

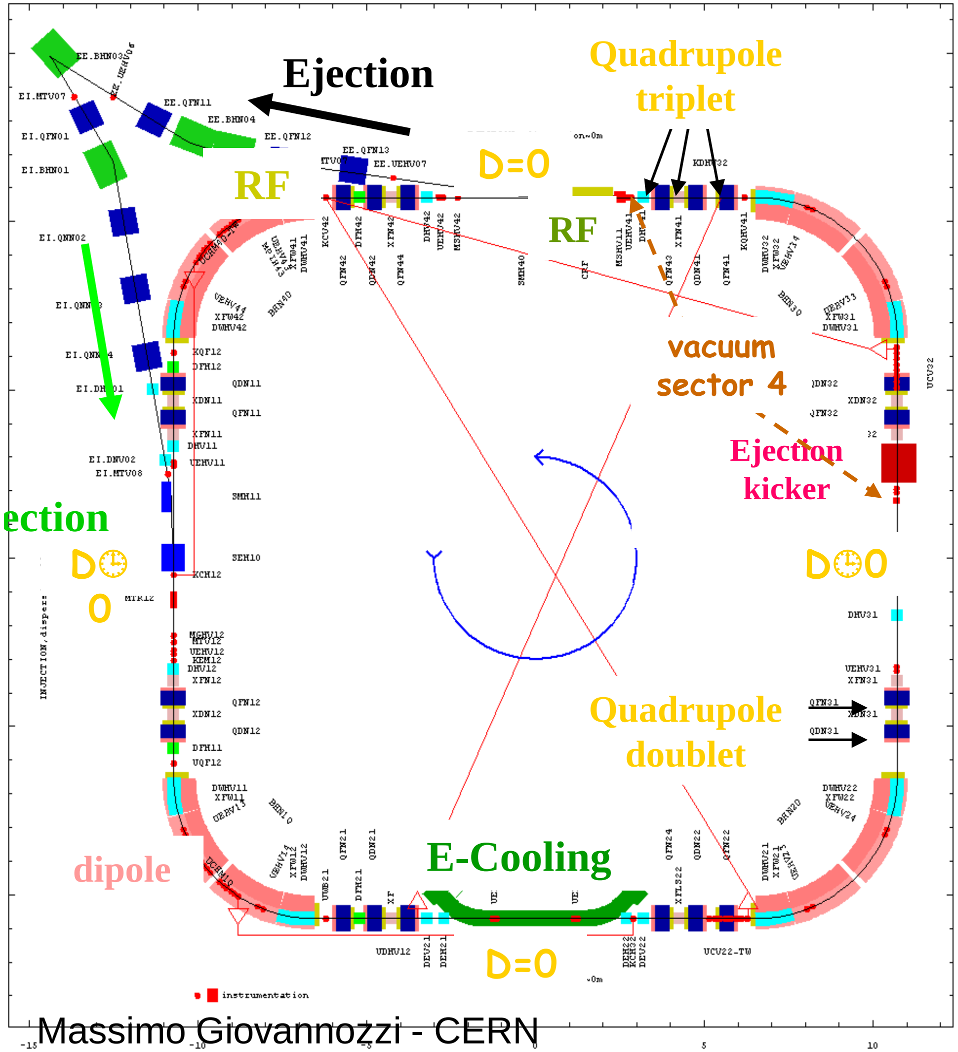


LEIR (Low-Energy Ion Ring)

- Prepares beams for LHC using electron cooling
- circumference 25 π m (1/8 PS)
- Multiturn injection into horizontal+vertical+longitudinal phase planes

Expected Cycle for Lead Ions





LHC Pb Injector Chain

Design Parameters for luminosity 10^{27} cm^{-2} s^{-1}

	ECR Source →	**Linac 3** → 4 →	**LEIR** →	**PS** → 13,12,8 →	**SPS** → 12 →	**LHC**
Output energy	**2.5 KeV/n**	**4.2 MeV/n**	**72.2 MeV/n**	**5.9 GeV/n**	**177 GeV/n**	**2.76 TeV/n**
^{208}Pb charge state	**27+**	**27+ ⋮→ 54+**	**54+**	**54+ ⋮→ 82+**	**82+**	**82+**
Output Bρ [Tm]		2.28⋮→ 1.14	4.80	86.7 ⋮→57.1	1500	23350
bunches/ring			2 (1/8 of PS)	4 (or 4x2)[4]	52,48,32	592
ions/pulse	9 10^9	1.15 10^9 1)	9 10^8	4.8 10^8	≤ 4.7 10^9	4.1 10^{10}
ions/LHC bunch	**9 10^9**	**1.15 10^9**	**2.25 10^8**	**1.2 10^8**	**9 10^7**	**7 10^7**
bunch spacing [ns]				100 (or 95/5)[4]	100	100
ε*(nor. rms) [μm][2]	**~0.10**	**0.25**	**0.7**	**1.0**	**1.2**	**1.5**
Repetition time [s]	0.2-0.4	0.2-0.4	3.6	3.6	~50	**~10'fill/ring**
ε_{long} per LHC bunch[3]			0.025 eVs/n	0.05	0.4	1 eVs/n
total bunch length [ns]			200	3.9	1.65	1

⋮ Stripping foil

[1] 50 eμA$_e$ x 200 μs Linac3 output after stripping

[2] Same physical emittance as protons. The normalised emittance is a relativistic invariant

Pair Production in Heavy Ion Collisions

Racah formula (1937) for free pair production in heavy-ion collisions

$$Z_1 + Z_2 \to Z_1 + e^- + e^+ + Z_2$$

$$\sigma_{PP} = \frac{Z_1^2 Z_2^2 \alpha^2 r_e^2}{\pi}\left[\frac{224}{27}\log\left(2\gamma_{CM}\right)^3 + \cdots\right] \approx \begin{cases} 1.7\times 10^4\,\text{b for Au-Au RHIC} \\ 2.\times 10^4\,\text{b for Pb-Pb LHC} \end{cases}$$

Cross section for Bound-Free Pair Production (BFPP) (several authors)

$$Z_1 + Z_2 \to \left(Z_1 + e^-\right)_{1s_{1/2},\ldots} + e^+ + Z_2$$

has very different dependence on ion charges (and energy)

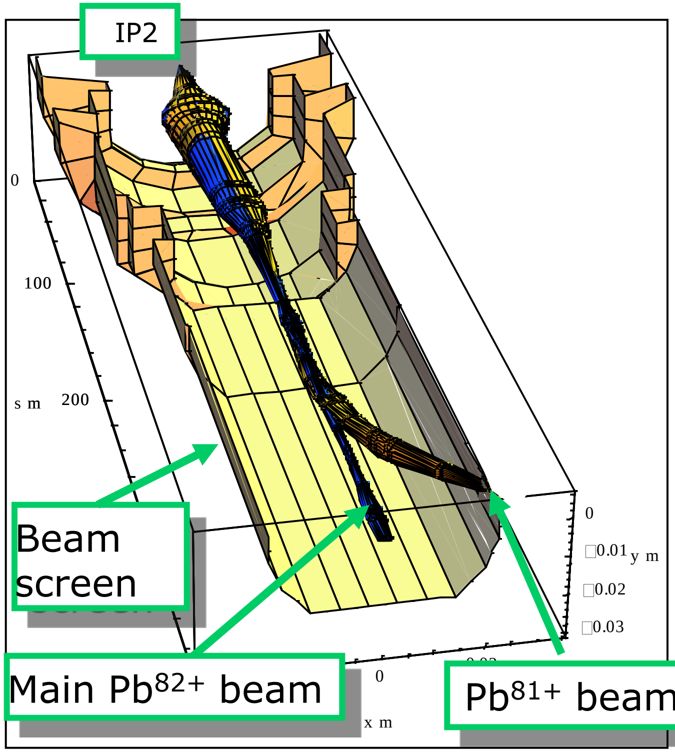
$$\sigma_{PP} \propto Z_1^5 Z_2^2\left[A\log\gamma_{CM} + B\right]$$

$$\propto Z^7\left[A\log\gamma_{CM} + B\right] \text{ for } Z_1 = Z_2$$

$$\approx \begin{cases} 0.2\text{ b for Cu-Cu RHIC} \\ 114\text{ b for Au-Au RHIC} \\ 281\text{ b for Pb-Pb LHC} \end{cases}$$

Luminosity Limit from bound-free pair production

$$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{81+} + e^{+}$$



IP2

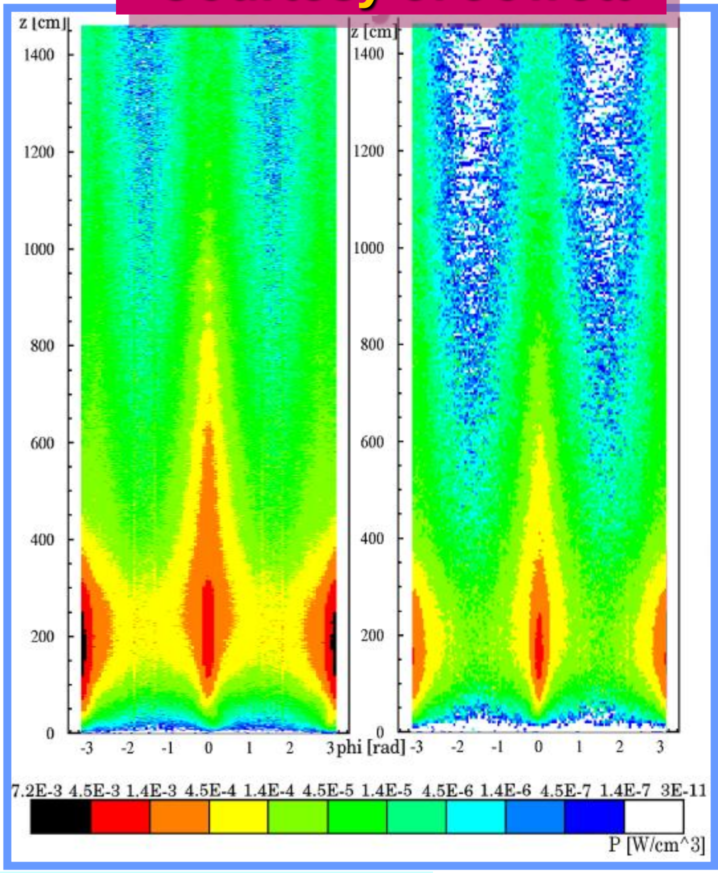
Beam screen

Main Pb^{82+} beam

Pb^{81+} beam

Secondary Pb^{81+} beam (25 W at design luminosity) emerging from IP and impinging on beam screen. Hadronic shower into superconducting coils can quench magnet.

Courtesy J. Jowett



Distinct EMD process (similar rates) does not form spot on beam pipe

$$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\mathrm{GDR}} {}^{208}\mathrm{Pb}^{82+} + {}^{207}\mathrm{Pb}^{82+} + n$$

Bound-free pair production

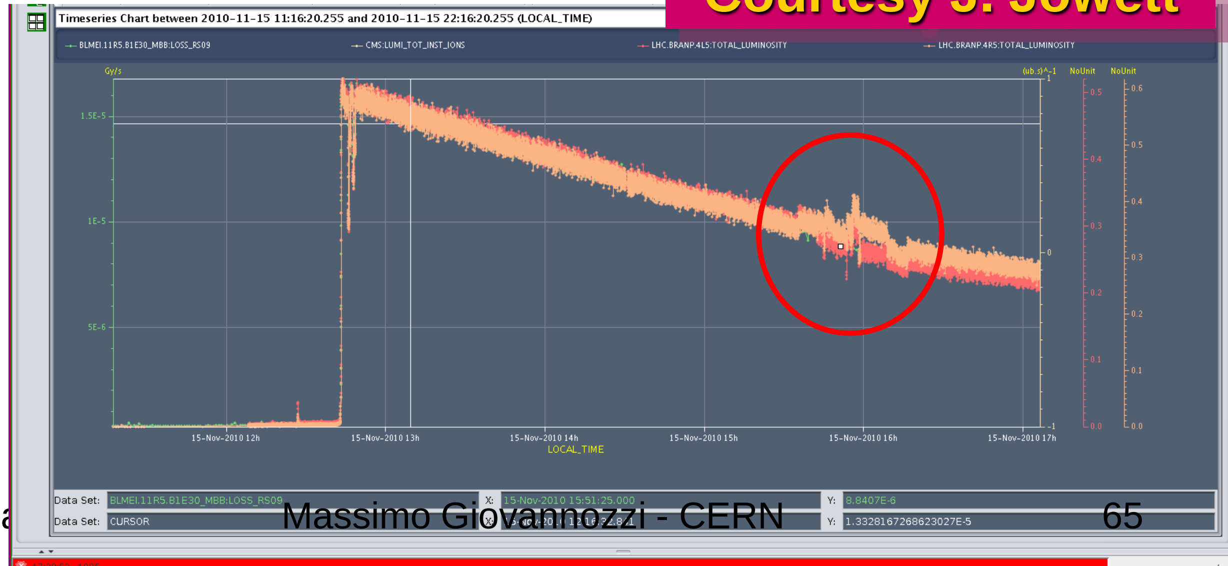

Total Losses: 1.676E-03 [Gray / s]

15.11.2010 17:19:45

17:19:45 - Data received: 15.11.2010 17:19:45

Perfect correlation of Beam Loss Monitor at Q11 with luminosity

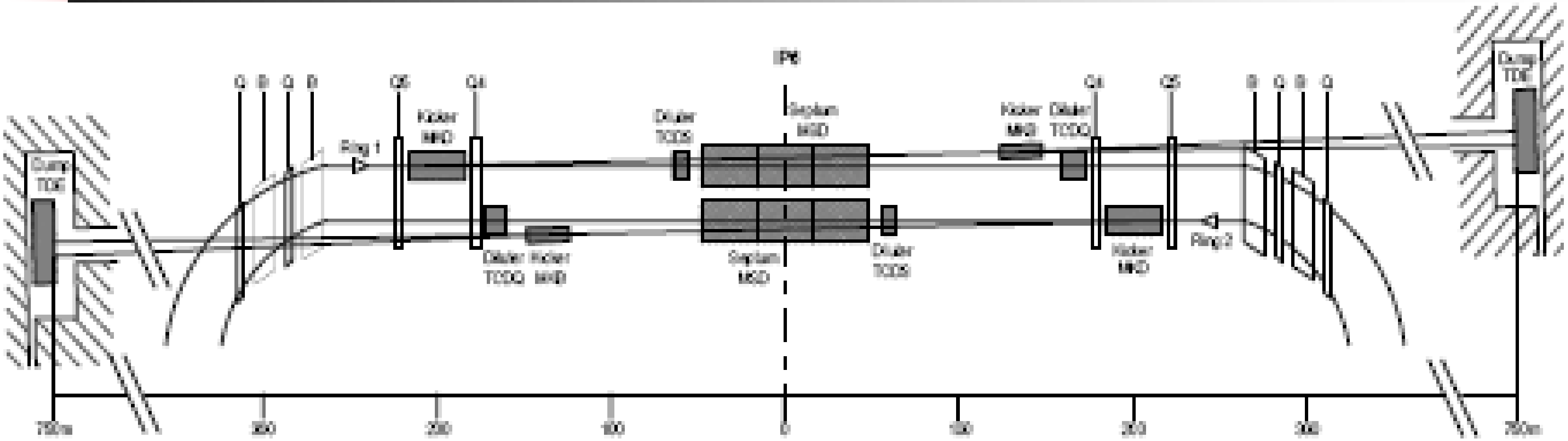
Courtesy J. Jowett

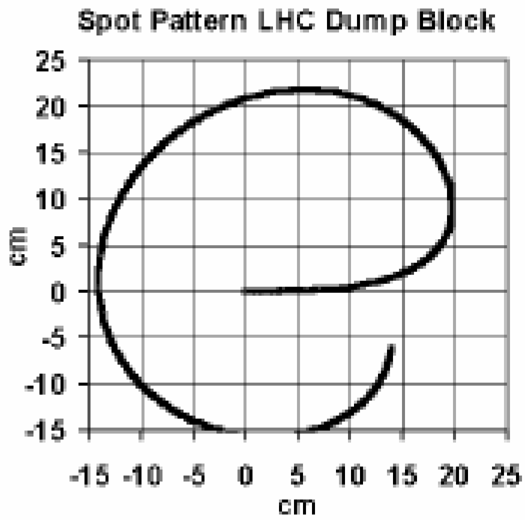

Timeseries Chart between 2010-11-15 11:16:20.255 and 2010-11-15 22:16:20.255 (LOCAL_TIME)

Data Set: BLMEI.11R5.B1E30_MBB:LOSS_RS09 X: 15-Nov-2010 15:51:25.000 Y: 8.8407E-6

Data Set: CURSOR X: 15-Nov-2010 12:16:32.821 Y: 1.3328167268623027E-5

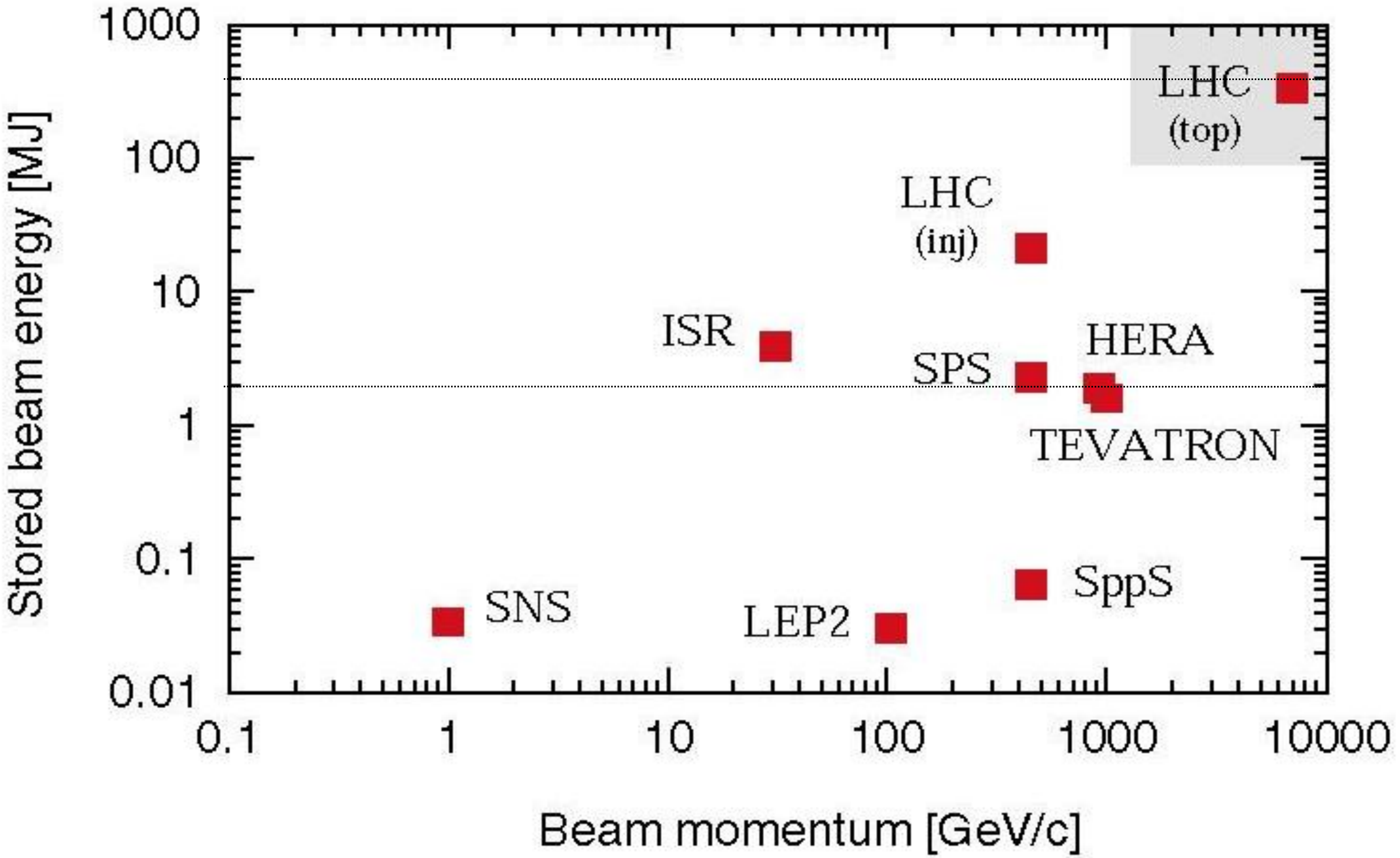
IR6: Beam dumping system



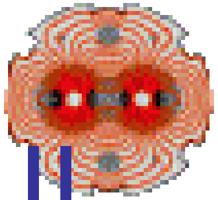


- The beam dumping system will fast-extract the beam in a loss-free way from each ring of the collider and transport it to an external absorber.
- Given the destructive power of the LHC beam, the dumping system must meet extremely high reliability criteria, which condition the overall and detailed design.

IR3/7: Collimation system - I



IR3/7: Collimation system - II



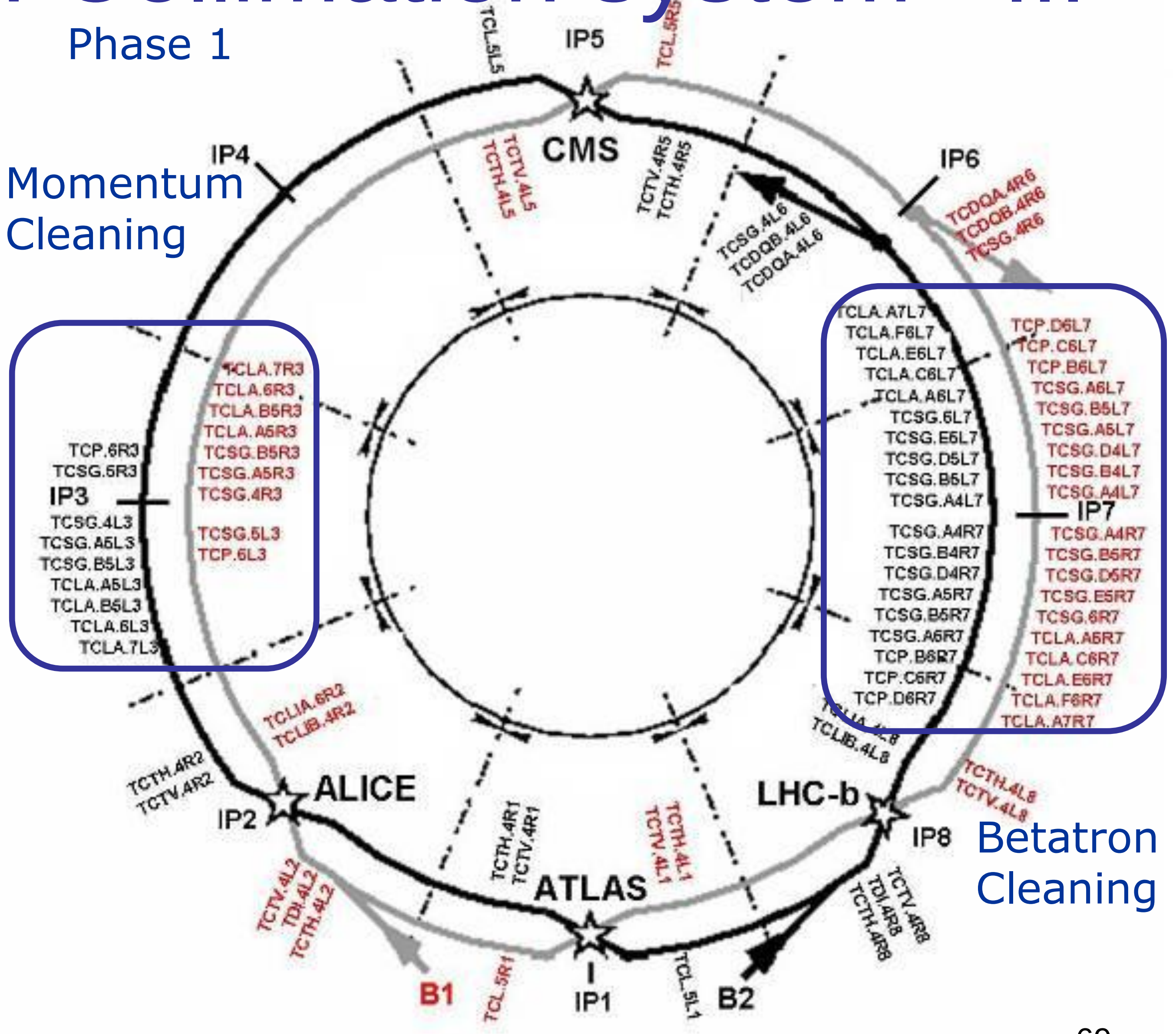
- The transverse energy density of the nominal beam is 1000 times higher than previously achieved in proton storage rings (1 GJ/mm^2).
- Tiny fractions of the stored beam suffice to quench a super-conducting LHC magnet or even to destroy parts of the accelerator.
- Note that a 10^{-5} fraction of the nominal LHC beam will damage copper.
- The energy in the two LHC beams is sufficient to melt almost 1 ton of copper!
- The tolerable inefficiencies of the collimation system are about 10^{-3} at collision.

IR3/7: Collimation system - III

Phase 1

In the insertion regions IR3/7 the magnets are normal conducting!

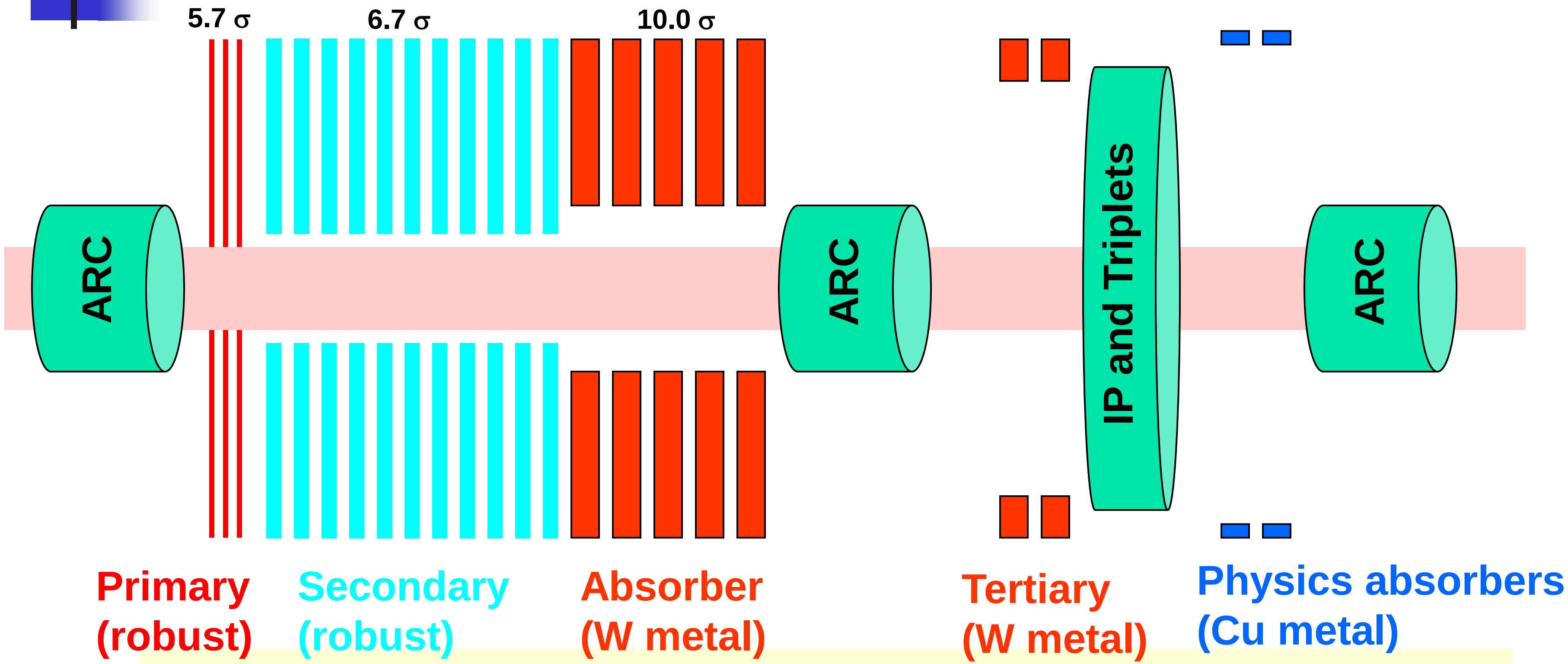
This is imposed by the high beam losses due to the collimation system.



Momentum Cleaning

Betatron Cleaning

IR3/7: Collimation system - IV



Primary (robust)

Secondary (robust)

Absorber (W metal)

Tertiary (W metal)

Physics absorbers (Cu metal)

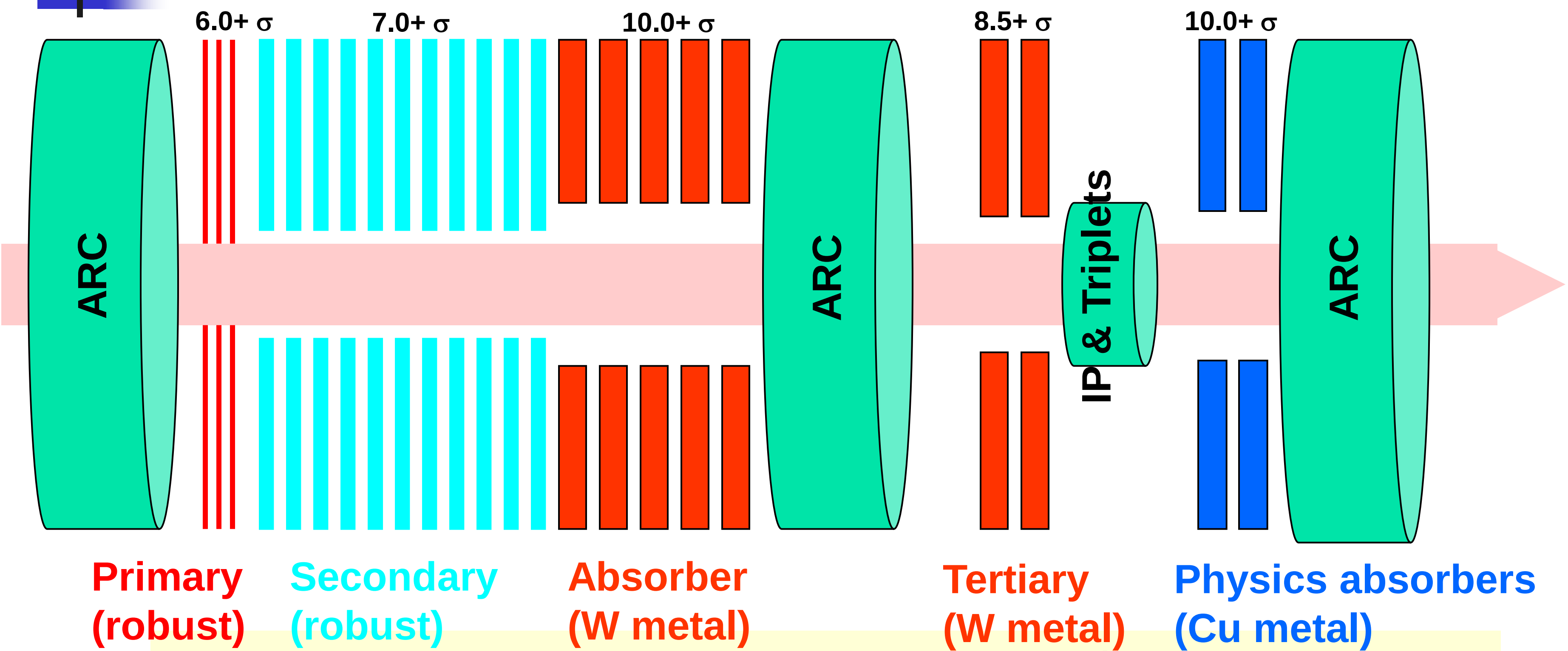
Relevant aperture limit is the arc!

Protected by 3 stages of cleaning and absorption!

First and second aperture limits by robust collimators!

Then metallic collimators with good absorption but very sensitive!

IR3/7: Collimation system - V



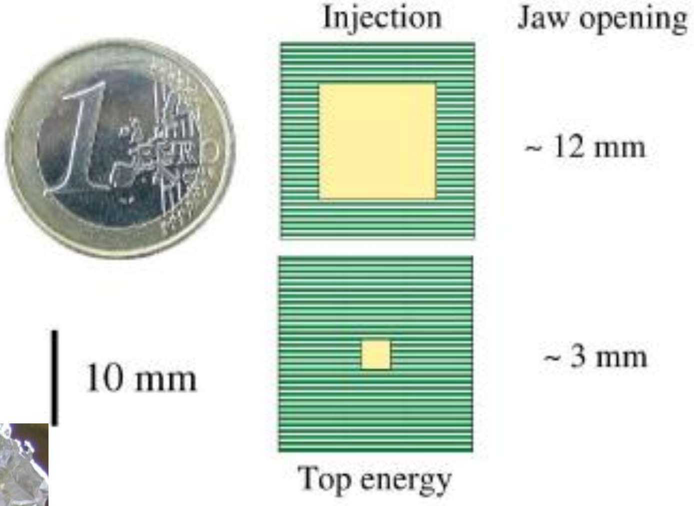
Relevant aperture limit are the triplets at the IP's!

Protected by 4 stages of cleaning and absorption!

First and second aperture limits by robust collimators!

Then metallic collimators with good absorption but very sensitive!

IR3/7: Collimation system - VI



IR3/7: Collimation system - VII

- There is tradeoff between robustness and impedance (interaction with the electromagnetic fields generated by the bunches) of the collimators, namely:
  - Low Z materials: high robustness, but low conductivity. Hence they feature high impedance. They will limit the value of the beam size at the interaction region.
  - High Z materials: low impedance, but low robustness. They will limit the total current in the ring.
- In both cases the luminosity will be limited to a smaller value than nominal.
- Staged approach is applied.
  - Stage 1 collimation system will be implemented with low Z materials.
  - Stage 2 aim at removing the limitations. It requires heavy R&D programme.