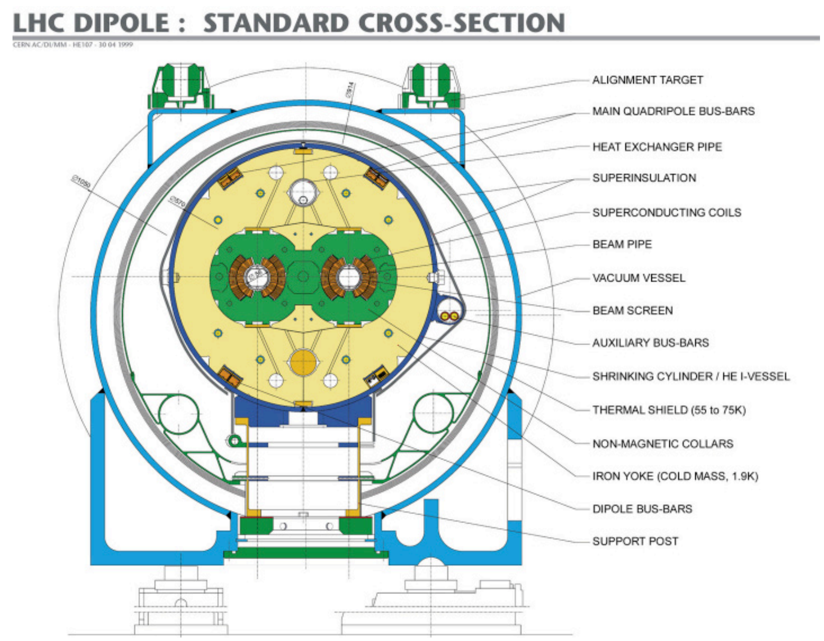
Overview of LHC Accelerator

Mike Syphers
UT-Austin
1/31/2007



Outline of Presentation

- Brief history...
- Luminosity
- Magnets
- Accelerator Layout
- Major Accelerator Issues
- U.S. Participation

A Brief History...

- CERN built LEP Collider (27 km) in 1980's to study Z, etc.; ran very successful program from 1989-2000.
- In 1989 U.S. authorized building of SSC -- 20 TeV x 20 TeV, p-p, 87 km, 6.6 T magnets -- $10^{33}cm^{-2}sec^{-1}$; scheduled completion date of 1997.
- ~1990, CERN specified the Large Hadron Collider (LHC), using LEP tunnel, to compete with SSC -- 8 TeV (lowered to 7 TeV; 8 T), $10^{34}cm^{-2}sec^{-1}$.
- After $2B spent on site in Texas, SSC cancelled by U.S. government in 1993; LHC spec's remained the same, nearing completion now 13 years later...

Luminosity

- Want to achieve $10^{34}\text{cm}^{-2}\text{sec}^{-1}$ luminosity at 7 TeV...
- For counter-rotating bunches of particles:

$$\mathcal{L} = \frac{fN^2}{4\pi\sigma^2} \cdot \mathcal{F}(\theta)$$, where...

$$\begin{aligned} f &= \text{frequency of bunch collisions} \\ N &= \text{number of particles per bunch} \\ \sigma &= \text{rms transverse beam size at interaction point} \\ \mathcal{F} &= \text{luminosity reduction factor due to crossing angle, } \theta \end{aligned}$$

$$f = c \;/\; \text{bunch spacing} = 3 \times 10^8/7.5 = 40\ \text{MHz} = 1/(25\ \text{nsec})$$

$\mathcal{F}(\theta)$ depends on beam crossing angle, but also on beam size, bunch length -- ~85% for LHC

Luminosity (cont'd)

- When adiabatically accelerated, the beam size will vary inversely to square root of momentum

$$\sigma^2 = \beta^* \, \epsilon_N \; / \; \gamma$$

β^*	= optical function of the accelerator
$\pi \cdot \epsilon_N$	= rms phase space area of particle oscillatons

$$\text{Tev: } \sqrt{(0.35 \text{ m})(4 \text{ mm-mr})/1000} = 66 \ \mu\text{m}$$
$$\text{LHC: } \sqrt{(0.55 \text{ m})(4 \text{ mm-mr})/7000} = 17 \ \mu\text{m}$$

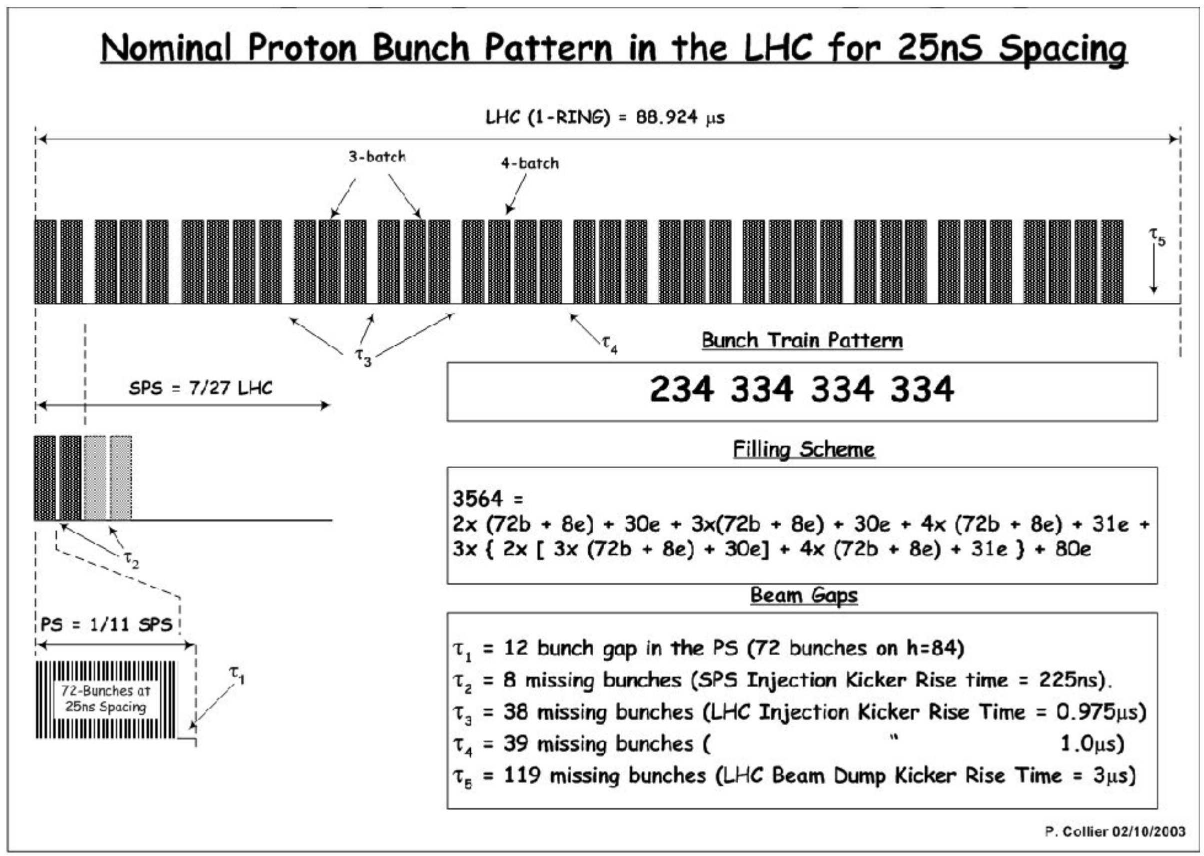
- Put it together, requires 10^{11}/bunch...

for $N \approx 10^{11}$,

$$\mathcal{L} = \frac{(10^9/25)(10^{11})^2}{4\pi(17 \cdot 10^{-4})^2 \text{cm}^2 \text{sec}} \cdot 0.85 \approx 10^{34} \text{ cm}^{-2} \text{sec}^{-1}$$

Bunch Spacing

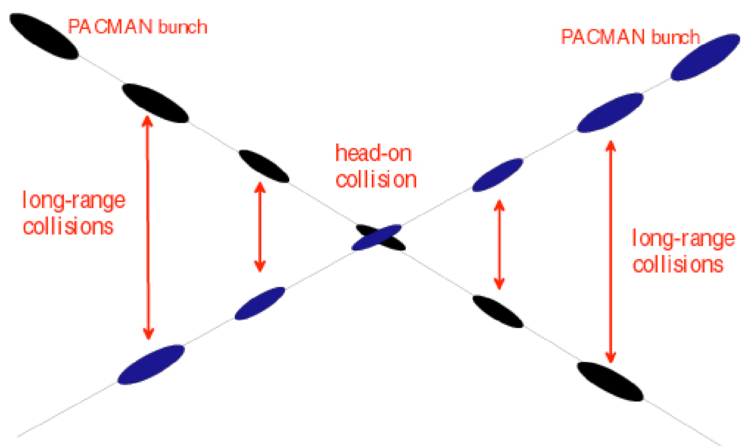
- Quoted as 25 nsec, but structure is more complicated due to filling scheme from the SPS.
- So, there will be various gaps created, with minimum spacing 25 nsec...



Hence, fewer bunches than simply 27km/7.5m ...

Why a Crossing Angle?

- Across each interaction region, for about 120 m, the two beams are contained in the same beam pipe
- Thus, there would be ~(120/(7.5/2)) ~ 30 bunch interactions through the region
- Want a single Head-on collision ***at*** the IP, but will still have long-range interactions on either side
- Beam size grows away from IP, and so does separation; can tolerate beams separated by ~10 sigma
- $d/\sigma = \theta \cdot (\beta^*/\sigma^*) \approx 10$
  $\longrightarrow \qquad \theta = 10 \cdot (0.017)/(550) \approx 300\ \mu\text{rad}$



Magnets

- Required Bend Radius:
  - circumference ~27 km; ~65% packing fraction
    - pckg. frac. small, due to prior use as e-collider
  - thus, bend radius ~ 2.8 km

$$B = (B\rho)/\rho = (p/e)/\rho = \frac{10}{3} \cdot 7000 \text{ T-m}/2800 \text{ m} = 8.3 \text{ T}$$

- Use superconducting magnets, at superfluid He temperatures (1.8 K) to get maximum field

Magnets (cont'd)

- "Cosine theta" design...
  - Tevatron, for instance:
- LHC -- dual-bore:

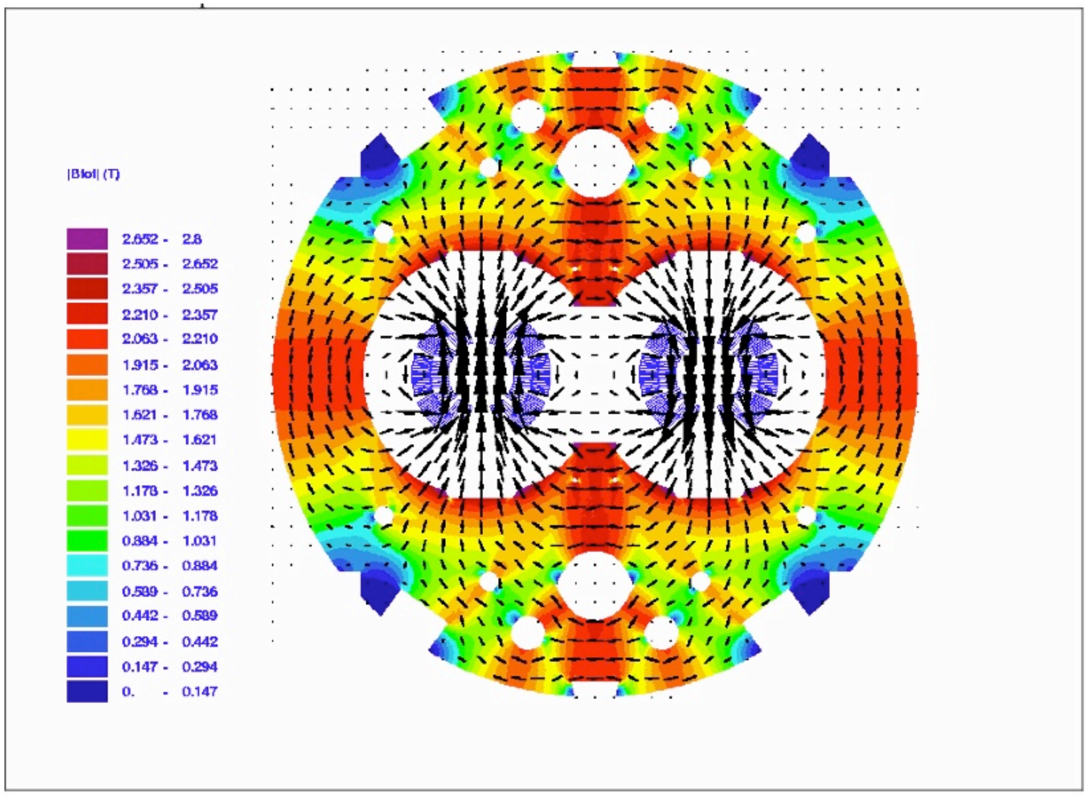
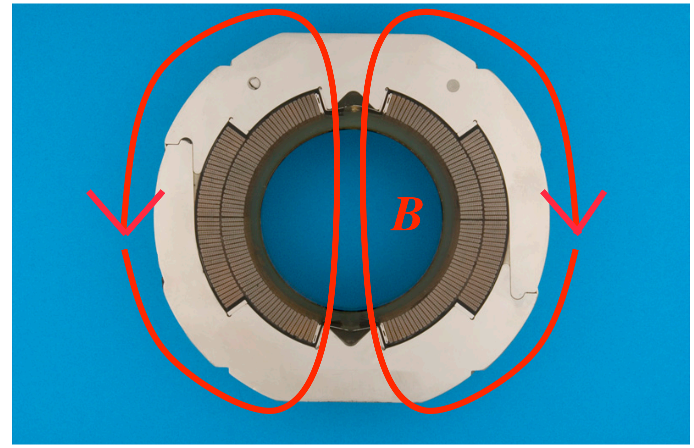


Figure 7.5: Dipole magnetic flux plot



Tevatron Dipole Coil

coil thickness

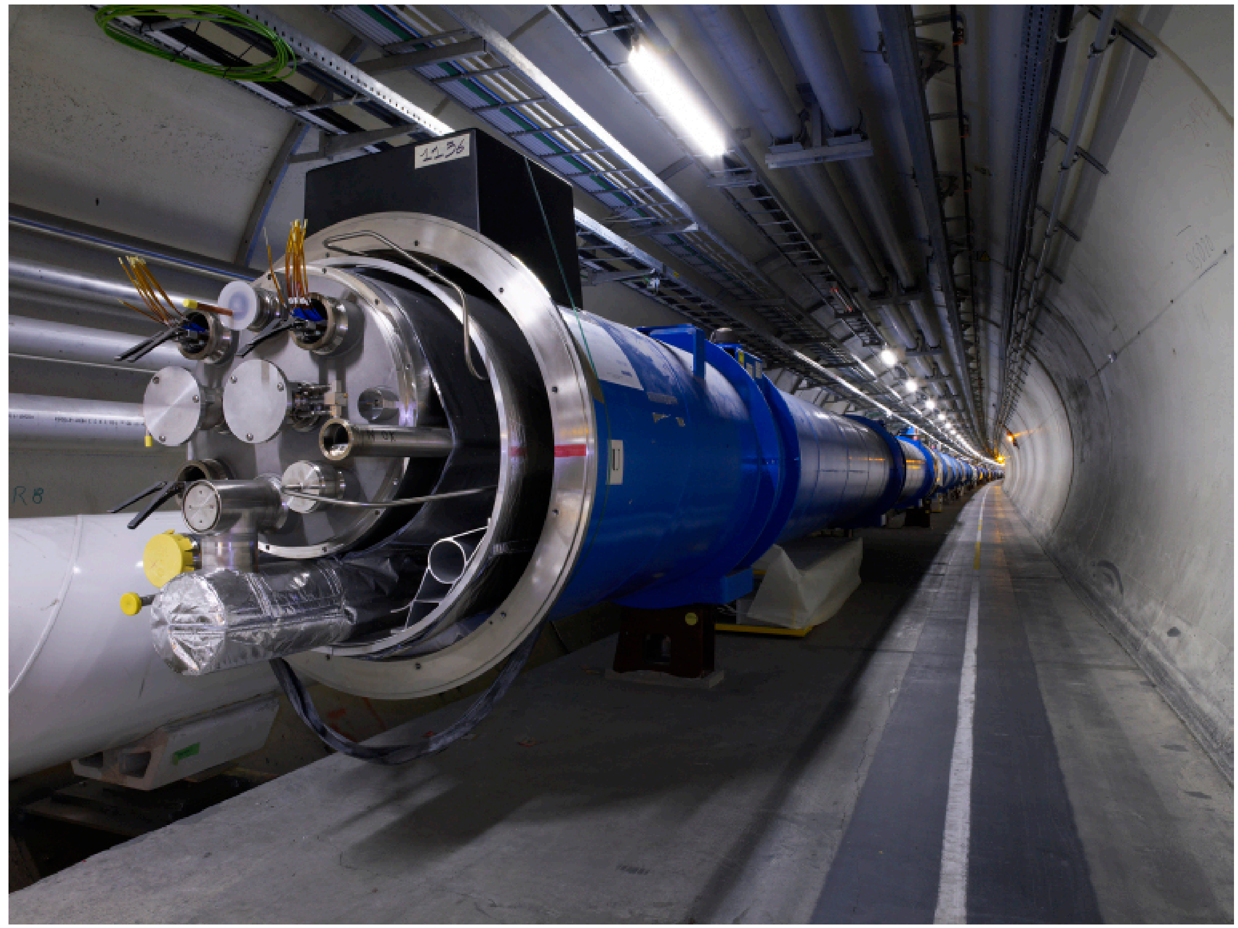
$$\vec{B} = \frac{\mu_0 \, J \, d}{2} \; \hat{j}$$

$$B \approx \left(\frac{4\pi \; T \; m/A}{10^7}\right) \frac{(500 \; A/mm^2)(25 \; mm)}{2}$$
$$\approx \; 8 \; \mathrm{T}$$

(crude approx.)

Magnets (cont'd)'

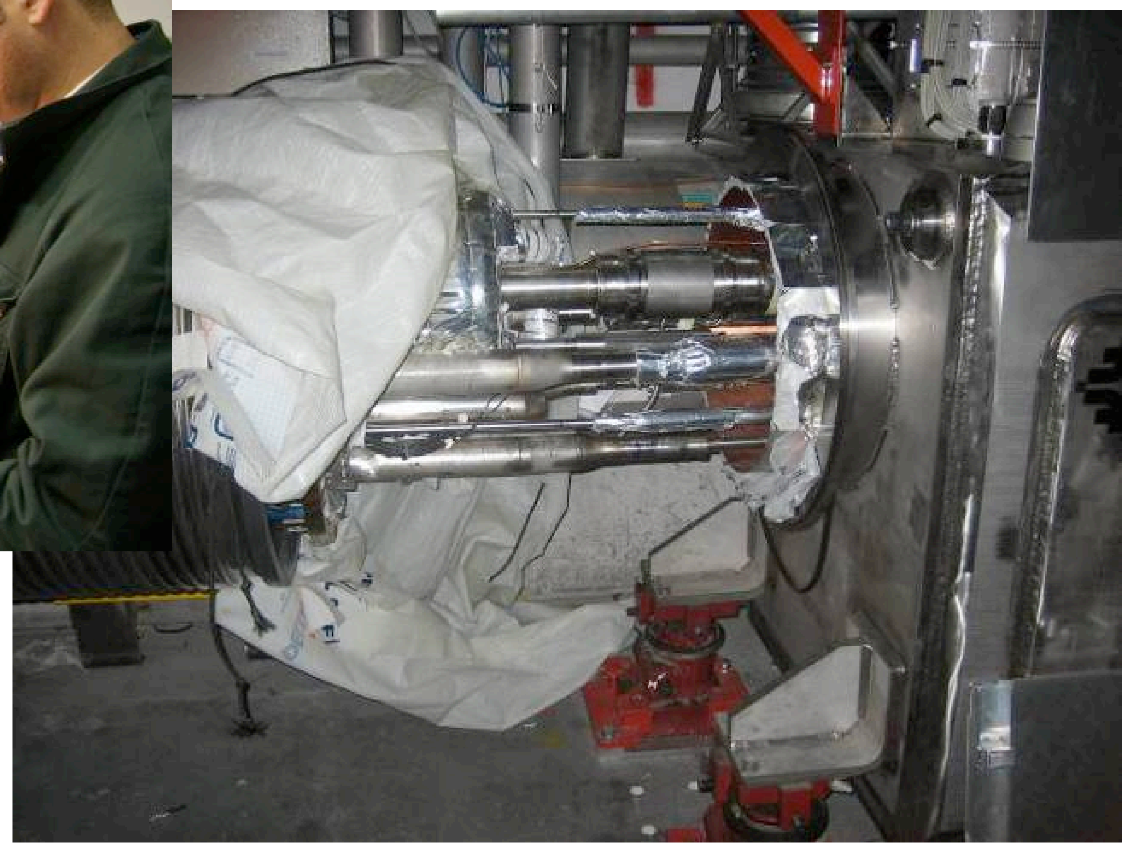
- Very complicated objects!
  - Two magnet systems in one
  - All power cables run through at 1.8K



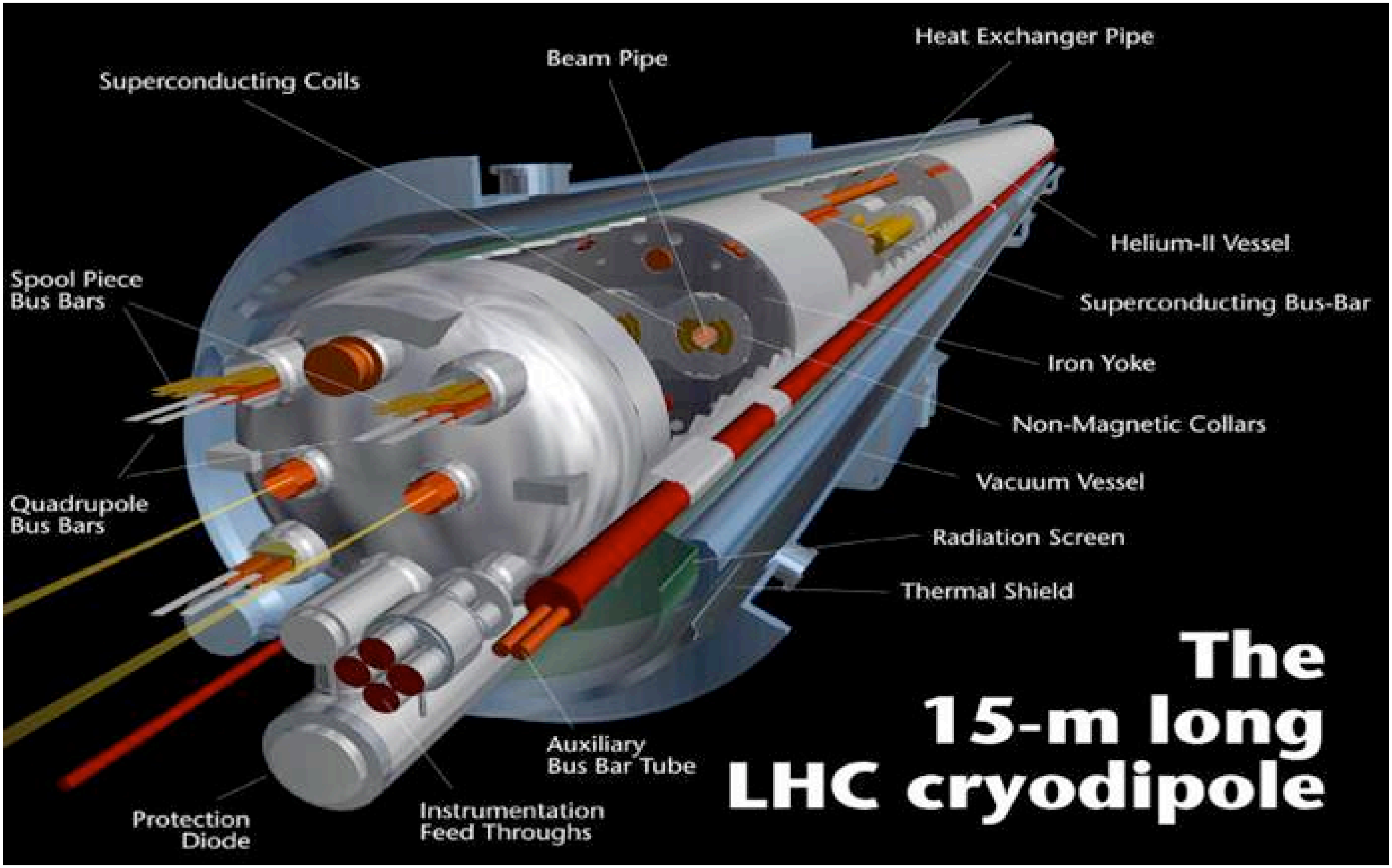
- Final magnet current at 8.3 T -- 11,850 A

Magnet Interconnects

- Not a simple operation ...

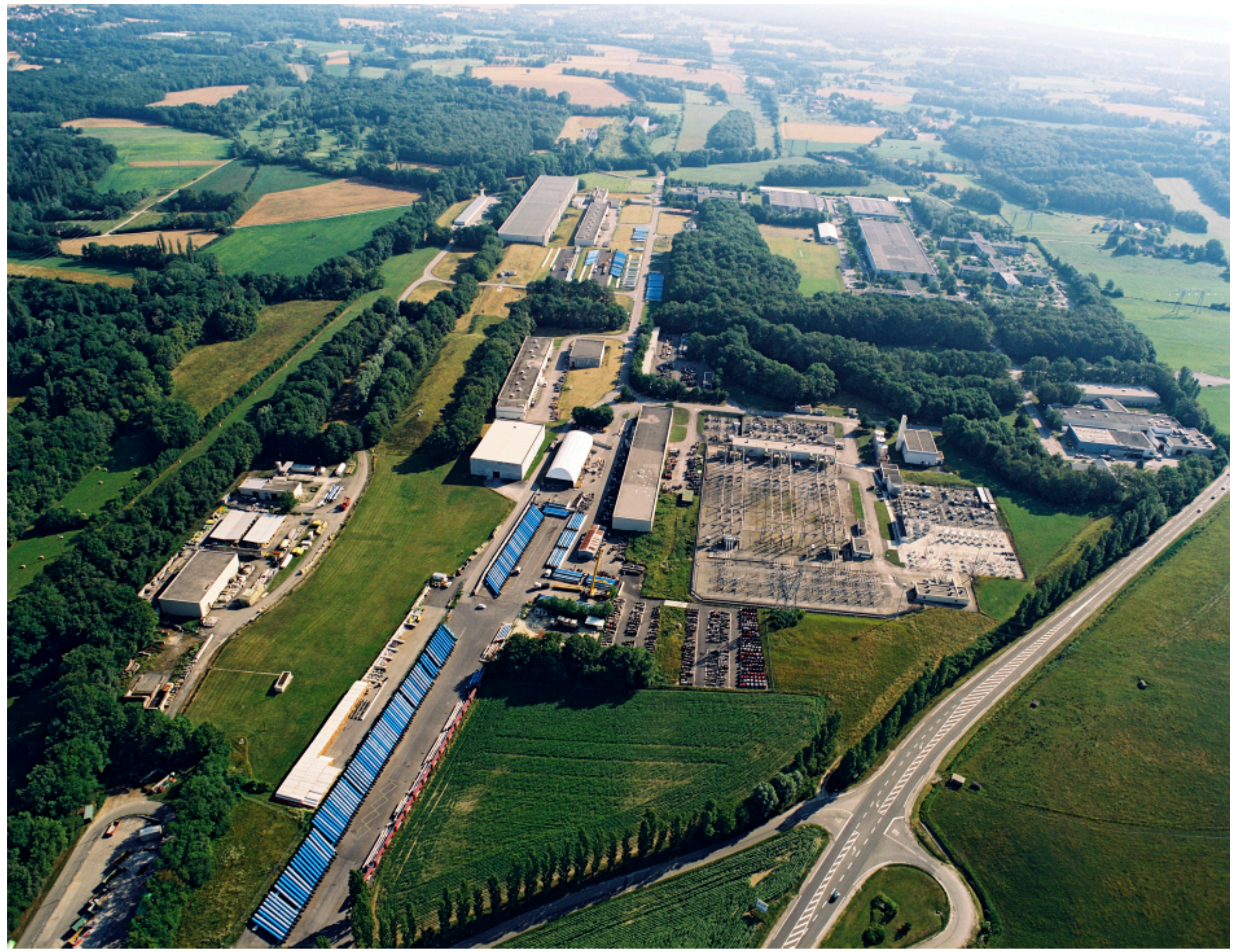


Magnets (cont'd)"



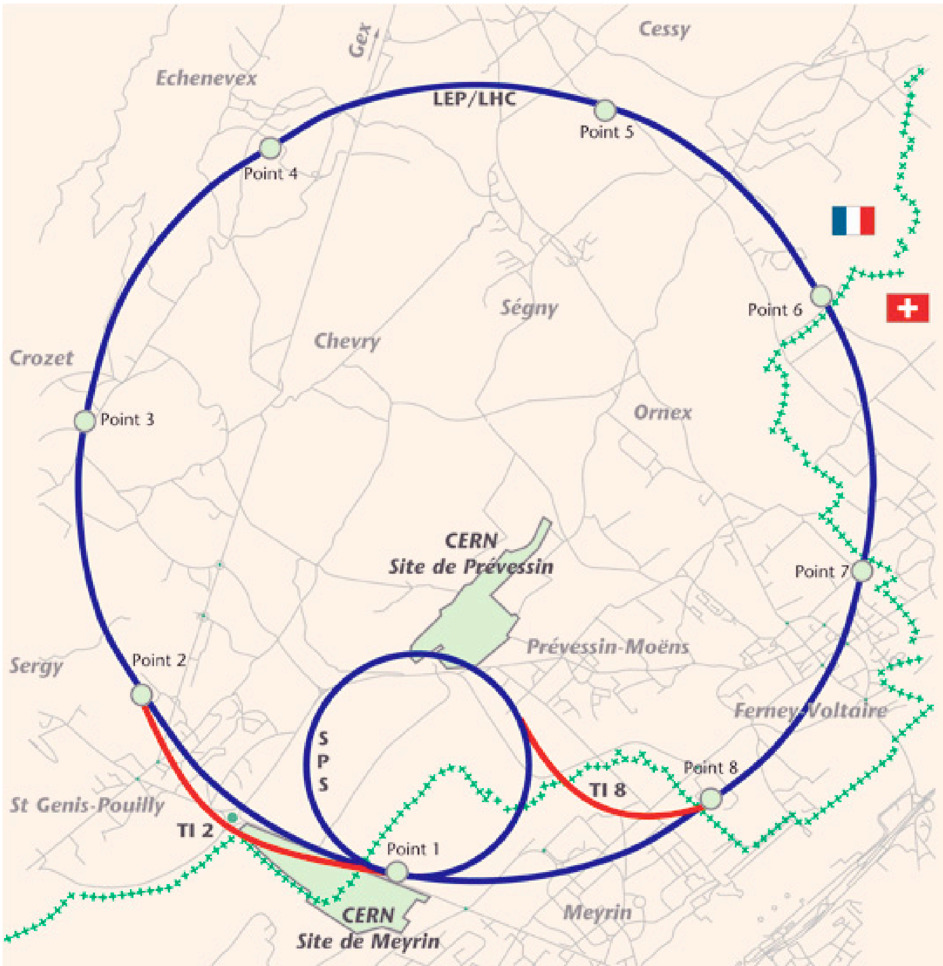
Magnets (cont'd)'''

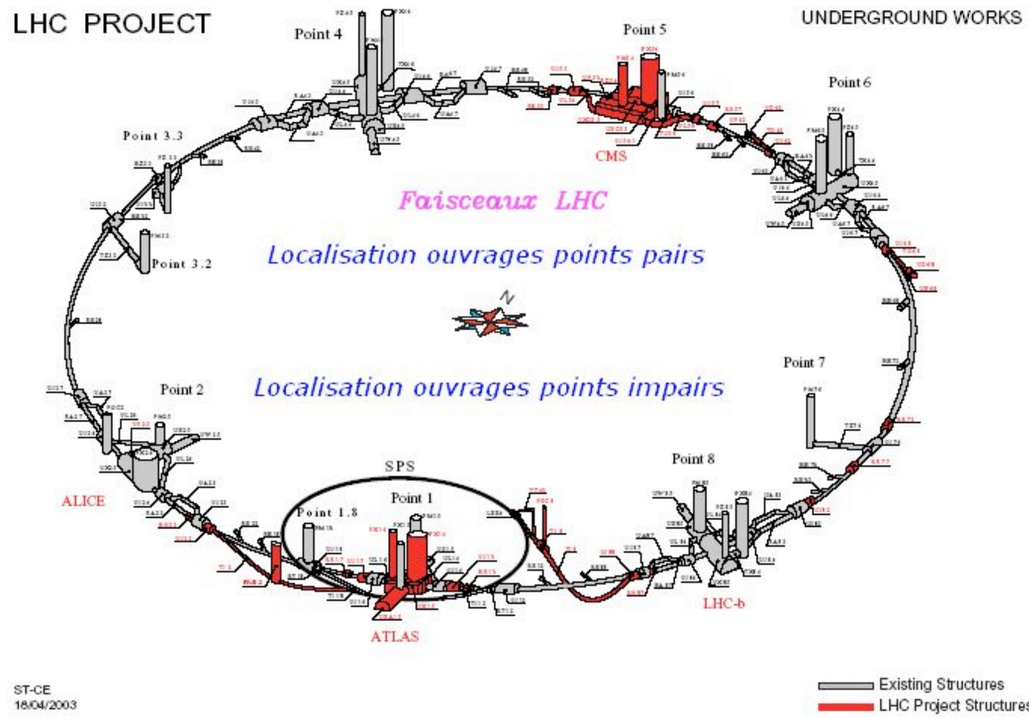
- Parts produced by outside vendors, final assembly at CERN (Prevessin)



- 1232, 15 m-long dipole magnets + quadrupoles!

General Map



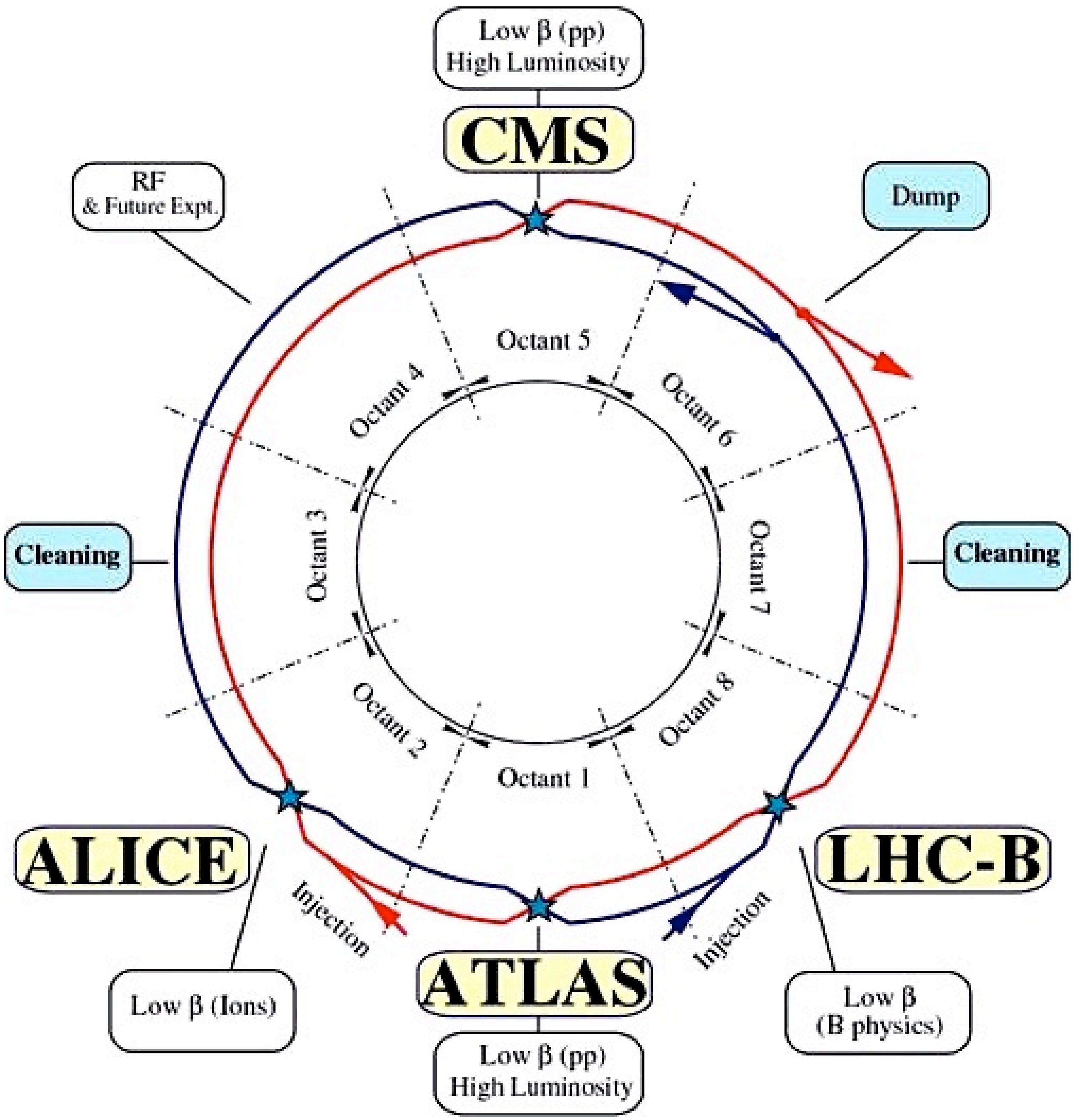


Underground Facilities

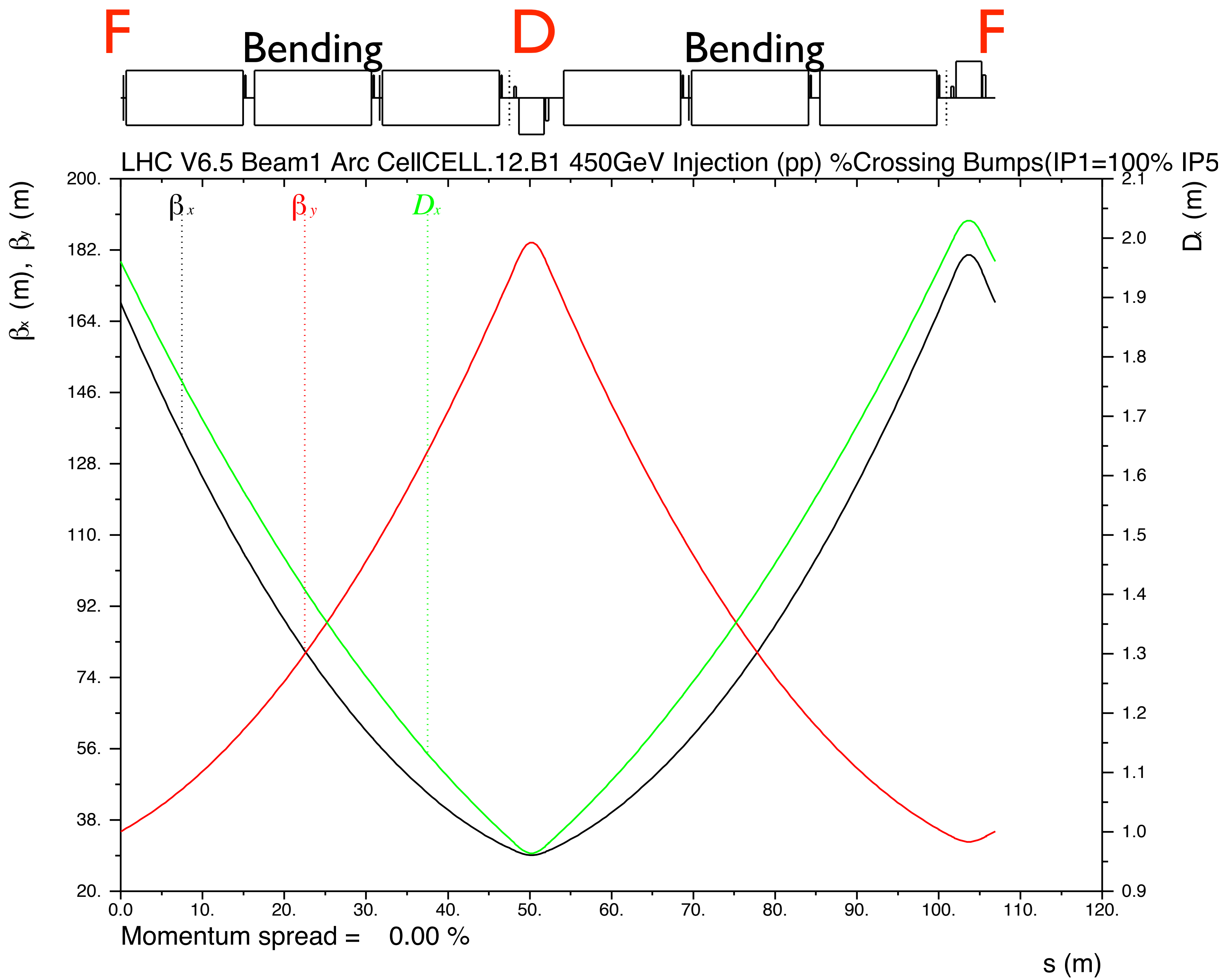
red = LHC project

rest = from LEP

General Layout

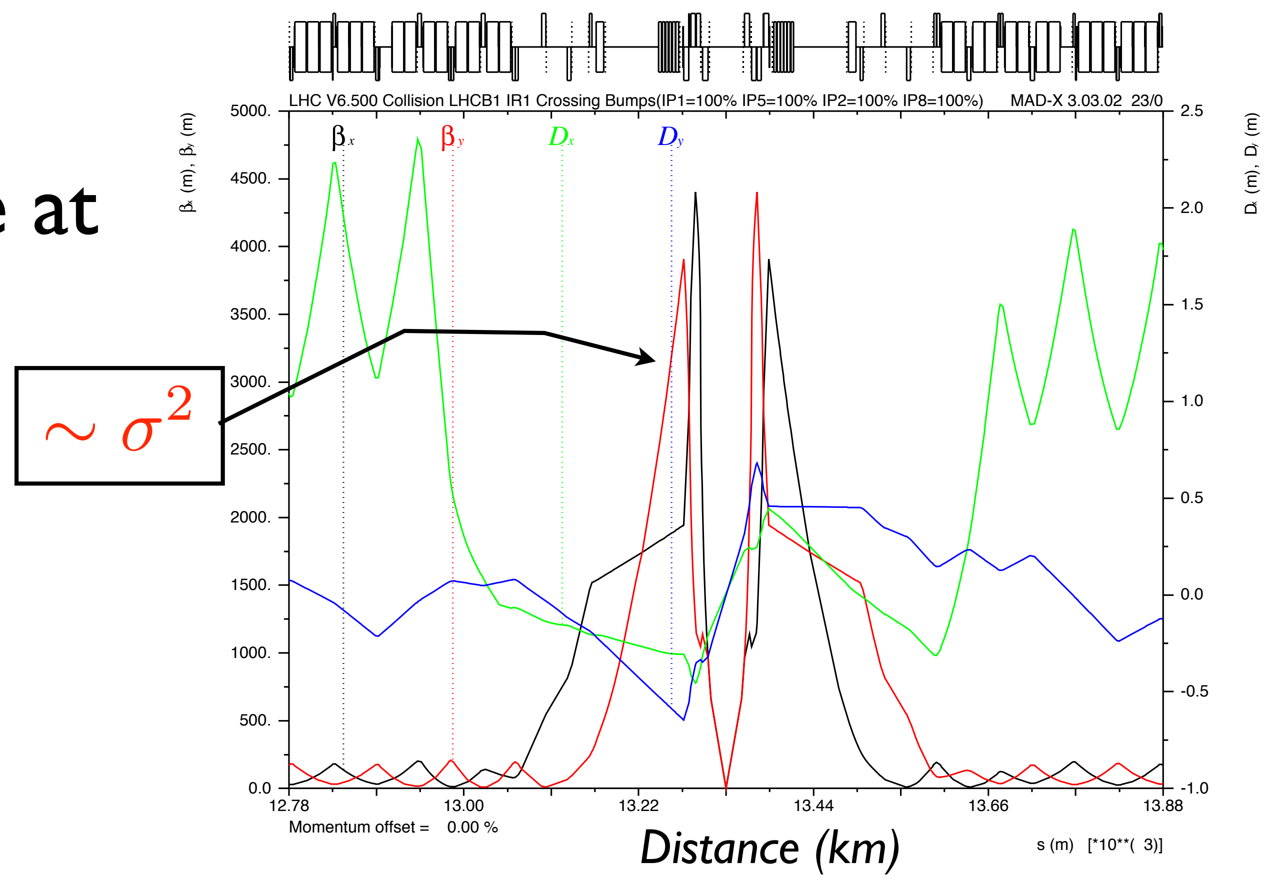


Standard Cell



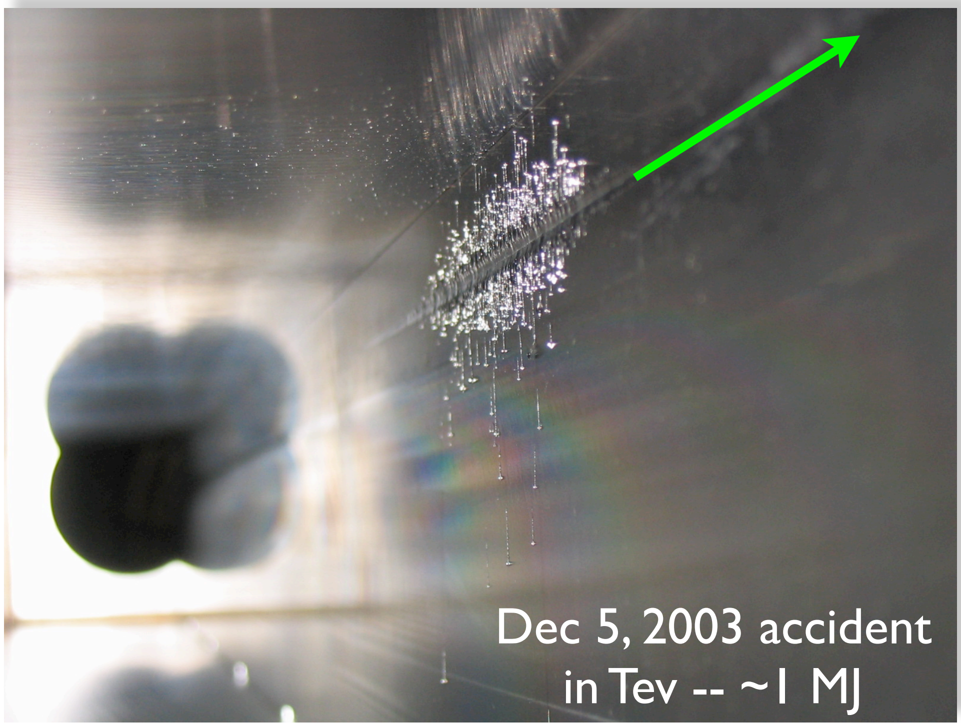
Interaction Regions

- Beams collide in region much like at Tevatron, RHIC...
  - asymmetric triplet magnets focus to small spot
  - zero momentum dispersion
  - optics adjusted ("squeeze") once at final energy

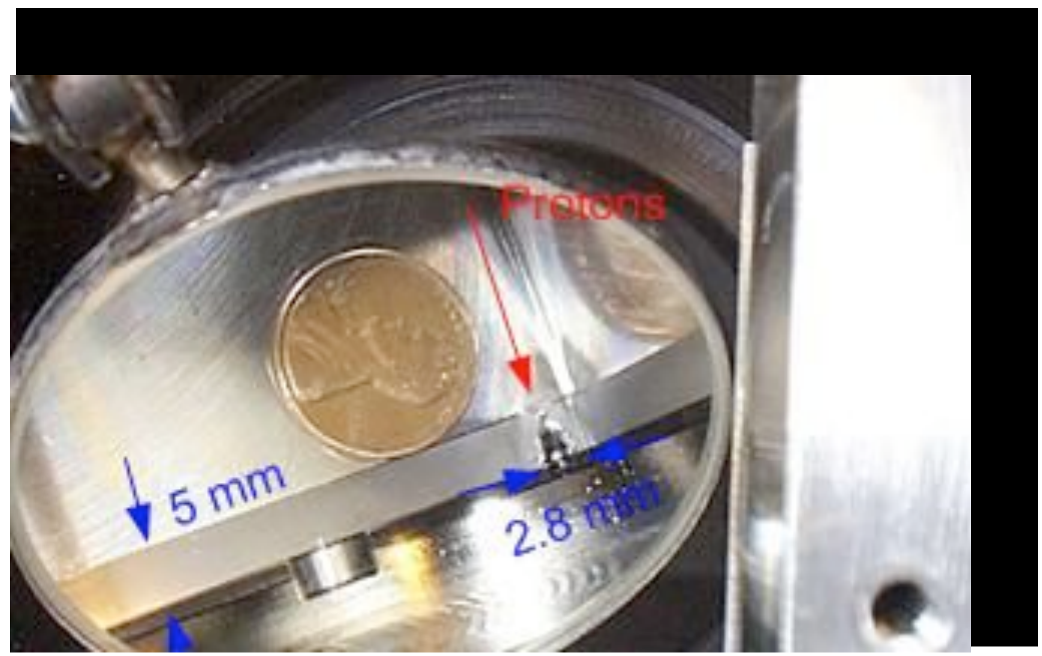


Major Accelerator Issues

- Stored Energy
  - Tevatron = 1-2 MJ per beam;   LHC = **360** MJ !
  - extensive collimation and protection system



E03 1.5m collimator



D49 target

Major Accelerator Issues

- IR Protection
  - not only stored energy of beam, but also the product power at the IP:

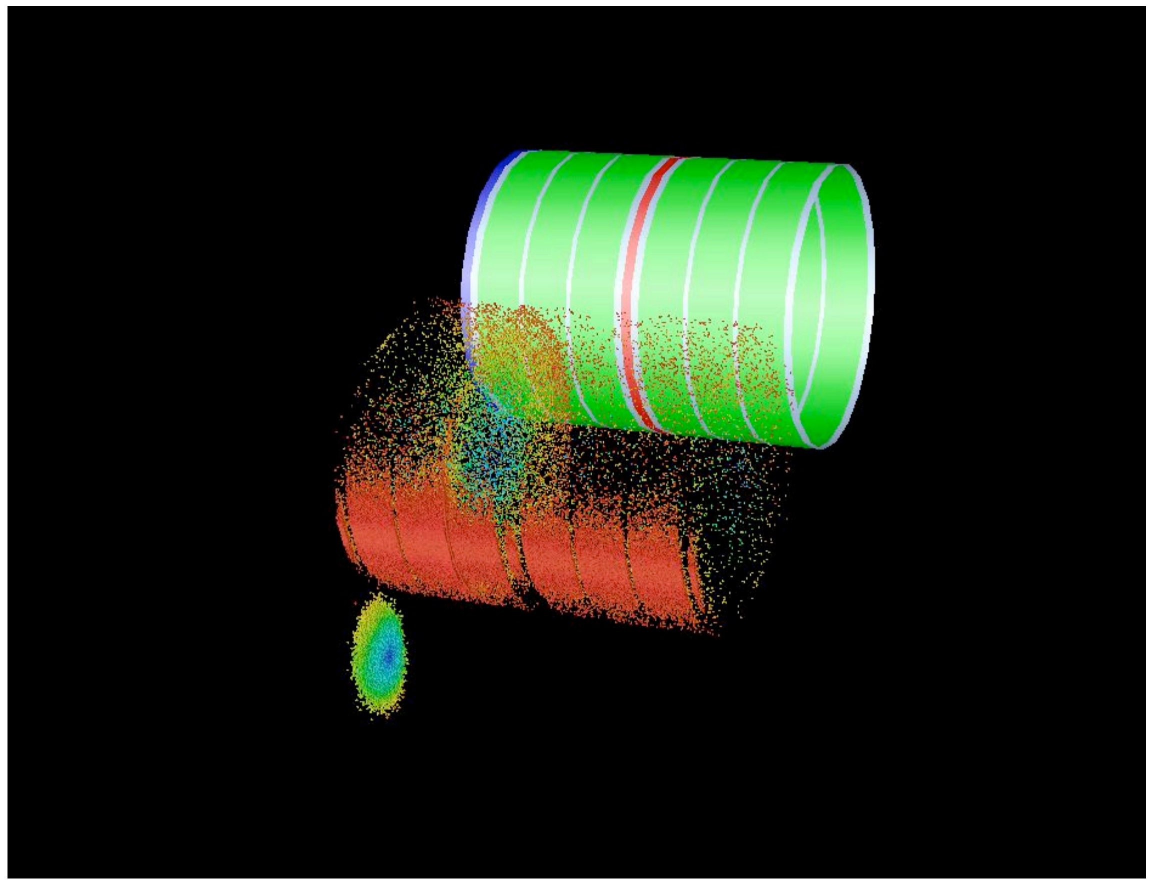
$$(60\ \mathrm{mb})(10^{34}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1})(2\times 7\cdot 10^{12}\ \mathrm{eV}) = 1.3\ \mathrm{kW}$$

significant fraction of this power will be deposited into SC magnets at each IR!

Certainly an issue for future increases in luminosity

Accel. Issues (cont'd)

- Electron Cloud
  - Protons in the LHC will emit synchrotron radiation -- 6.7 keV/turn -- 3.6 kW/ring!
  - photo-electrons emitted from beam pipe wall, can further interact with wall molecules and cause a build-up of vacuum pressure -- beam screen required
  - photo-electrons can also interact with beam, causing beam instabilities



Accel. Issues (cont'd)

- ... and many others...
  - Persistent Currents and Field Control of magnets
  - Beam-beam interactions -- head-on and long-range
  - Impedance effects and beam instabilities
  - Future luminosity upgrade path....
- Exciting accelerator project!!

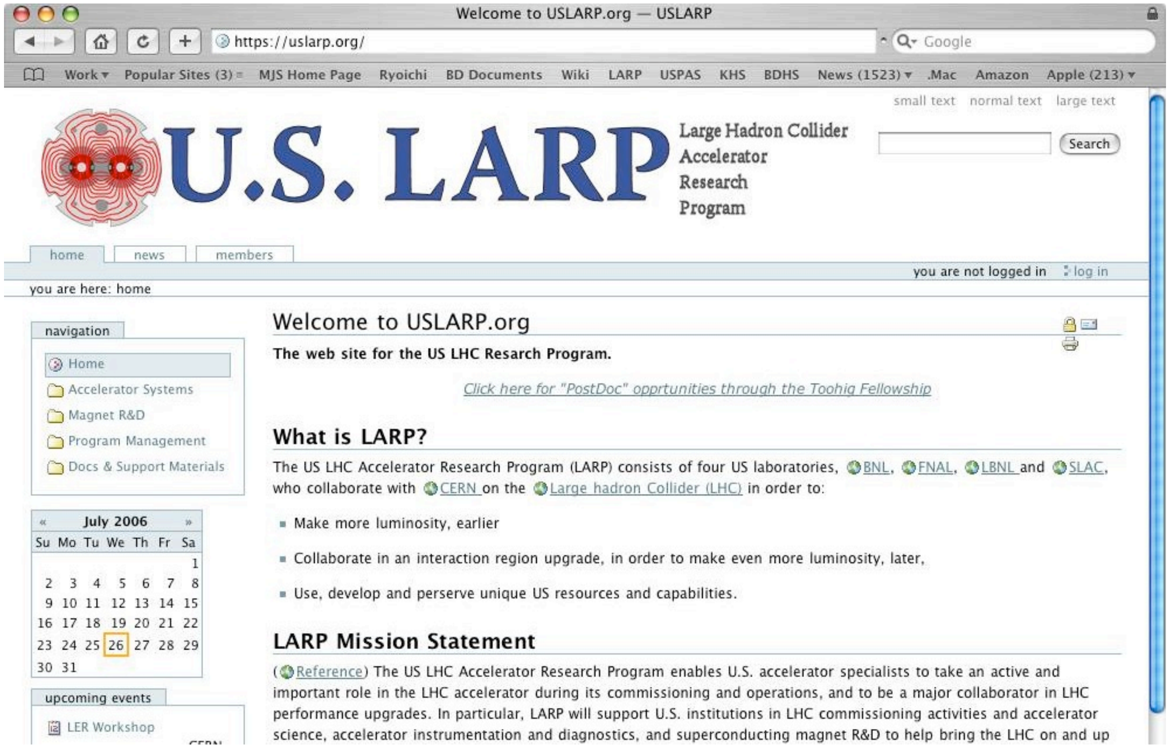
Schedule (as I know it...)

- Nov 2007 (for ~16 days)
  - 450 GeV (per beam) calibration run
- beginning in 2008 -- 7 TeV commissioning, in stages:
  - 43 x 43 (moving to 156 x 156) with moderate intensities. First collisions "un-squeezed"; followed by partial squeeze
  - Move to 75 ns, and to 3-4e10 per bunch
  - Move to 25 ns, and 3-4e10 per bunch
  - ... shutdown for installation of Phase II collimation and additional beam dump dilutors
  - Move to Stage 4, final configuration, to final design params

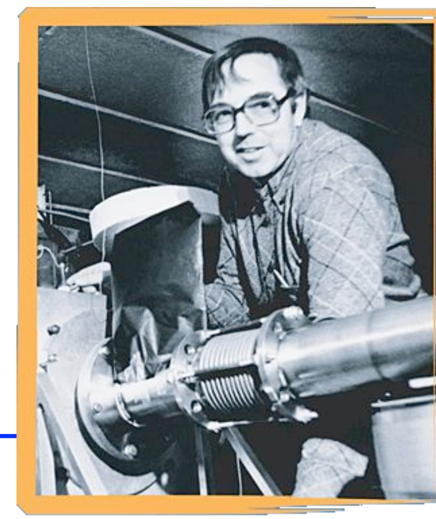
U.S. LHC Accelerator Research Program (LARP)

- DoE-funded program (~$11M/year) which provides...
  - help with commissioning of hardware and beam
  - accelerator physics calculations
  - instrumentation development
    - luminosity monitors, beam diagnostics, *etc.*
  - studies of collimator improvements for future luminosity upgrades
  - help for development of future IR and IR magnet upgrades

Visit our web site at ...



http://uslarp.org



- Toohig Fellowships
  - LARP is pleased to announce the Toohig Fellowships for recent PhDs in science, technology and engineering interested in pursuing studies in accelerator science.
  - Dr. Timothy Toohig, SJ, was a physicist and Jesuit priest who devoted his life to promoting accelerator science and increasing understanding among scientists of all nations and religions.
  - Fellowship recipients will participate with U.S. scientists in the commissioning, operation and other activities designed to understand the LHC.

LHC@FNAL

- Opportunity for accelerator and HEP experimentalists to work side-by-side

References

http://lhc.web.cern.ch/lhc/

LHC - THE LARGE HADRON COLLIDER

EDMS
CDD
MTF
SEARCH

LHC dashboard

Magnet test facility

LHC NEWS

Design report

LHC Co-ordination schedule and status

Golden Hadron Awards

General Information and Outreach

LHC@ interactions.org

Organization and Committees

Quality Assurance

Publications

Seminars and Workshops

Presentations

Images

Surface Sites

Underground Sites

LHC Experiments

Beam Parameters

Lattice and Optics

Baseline Documentation

Equipment Catalogues

Naming and Conventions

Layouts

Integration

Installation

Hardware Commissioning

Sector Test

Beam Commissioning

Power tests in one of the tunnel enlargements

Revised: 2006-06-15 LHC Webmaster

Parameters

General LHC Parameters Version 4.0 (These parameters correspond to optics version 6.4 and the RF parameter update from the 14. LTC meeting (15. October 2003)) (the Version 3 parameters can be found here)		
Momentum at collision	7	TeV / c
Momentum at injection	450	GeV / c
Machine Circumference	26658.883	m
Revolution frequency	11.2455 (*)	kHz
Super-periodicity	1	
Lattice Type	FODO, 2-in-1	
Number of lattice cells per arc	23	
Number of insertions	8	
Number of experimental insertions	4	
Utility insertions	2 collimation 1 RF and 1 extraction	
Dipole field at 450 GeV	0.535	T
Dipole field at 7 TeV	8.33	T
Bending radius	2803.95	m
Main dipole coil inner diameter	56	mm
Distance between aperture axes (1.9 K)	194	mm
Main Dipole Length	14.3	m
Main Dipole Ends	236.5	mm
Half Cell Length	53.45	m
Phase advance per cell	90	degree
Horizontal tune at injection	64.28	
Vertical tune at injection	59.31	
Horizontal tune at collision	64.31	
Vertical tune at collision	59.32	
Maximum beta-function (cell)	177 / 180 (**)	m
Minimum beta-function (cell)	30 / 30 (**)	m
Maximum dispersion (cell)	2.018 / 0.0 (**)	m
Maximum beta-function (service insertions)	594.5 / 609.3 (**)	m
Free space for detectors	+/-23	m
Gamma Transition	55.678	
Momentum Compaction	0.0003225 (**)	
Main RF System	400.8	MHz
Harmonic number	35640	
Voltage of 400 MHz RF system at 7 TeV	16	MV
Synchrotron frequency at 7 TeV	23.0	Hz
Bucket area at 7 TeV	7.91	eV.s
Bucket half-height at 7 TeV	3.56	10^{-4}
Voltage of 400 MHz RF system at 450 GeV	8	MV
Synchrotron frequency at 450 GeV (without 200 MHz RF)	63.7	Hz
Bucket area at 450 GeV	1.43	eV.s
Bucket half-height at 450 GeV	10	10^{-4}
Capture RF system	200.4	MHz

LHC Parameters for Nominal Proton Performance Version 4.0 (7. LTC) (the Version 3 parameters can be found here)		
Number of experiments	2 high and 2 low luminosity	
Number of particles per bunch	1.15	10^{11}
Number of bunches	2808	
Bunch harmonic number	3564	
Filling time per ring	4.3	min
Bunch spacing	25	ns
Number of long range interactions per experimental insertion	30	
Total number of particles	3.23	10^{14}
DC beam current	0.582	A
Stored energy per beam	362	MJ
Longitudinal emittance at 450 GeV	1.0	eVs
Longitudinal emittance at 7 TeV GeV (****)	2.5	eVs
Normalized transverse emittance (r.m.s.)	3.75	μm
Maximum transverse beam size in the arc at injection (r.m.s.)	1.19	mm
Maximum transverse beam size in the arc at 7 TeV	0.3	mm
Transverse beam size at IP (r.m.s.) at 7 TeV	16.63 (**)	μm
Transv. beam divergence at IP (r.m.s.)	30.23 (**)	μrad
Average beam beam parameter without crossing	3.733	10^{-3}
Total head on beam beam tune spread	0.011	
Total tune spread (beam-beam + lattice)	0.015	
Beta-function at IP (high luminosity experiments)	0.55	m
Maximum beta-function in triplet	4705	m
Luminosity (high luminosity experiments)	1.0	10^{34} cm²s¹
Events per crossing	19	
Total crossing angle	285	μrad
Minimum beam separation at parasitic crossings	7	sigma
Total inelastic cross section	60	mbarn
Luminosity lifetime due to 2 high luminosity insertions (head-on beam-beam interaction only; decay to 1/e of initial value)	28.1 (*)	h
Vacuum beam lifetime	84	h
Horizontal IBS growth time at injection (with 200MHz RF)	48	h
Longitudinal IBS growth time at injection (with 200MHz RF)	20	h
Horizontal IBS growth time at injection (without 200MHz RF)	38	h
Longitudinal IBS growth time at injection (without 200MHz RF)	30	h
Horizontal IBS growth time at 7 TeV (without 200MHz RF)	80	h
Longitudinal IBS growth time at 7 TeV (without 200MHz RF)	61	h
Total luminosity lifetime due to IBS, beam-beam, restgas [radiation damping neglected]	13.9 (*)	h
Energy loss per turn	7	keV
Total radiated power per beam	3.8	kW
Critical photon energy	44.1	eV
Longitudinal emittance damping time (at 7TeV)	13	hours
Transverse emittance damping time (at 7TeV)	26	hours
Voltage of 200 MHz RF system at 450 GeV	3(***)	MV
RMS bunch length at injection	11.24 (**)	cm
Relative rms energy spread at injection	4.716 (**)	10^{-4}
RMS bunch length at 7 TeV	7.55 (**)	cm
Relative rms energy spread at 7 TeV	1.129 (**)	10^{-4}

as found on-line 7/15/05

From LHC Design Report, Vol. 1

CHAPTER 2

BEAM PARAMETERS AND DEFINITIONS

2.1 LHC BEAM PARAMETERS RELEVANT FOR THE PEAK LUMINOSITY

This Chapter provides a summary of the main parameters for the nominal proton beam operation, a glossary and a list of definitions that are used throughout the chapters of the LHC design report. The equipment names and the circuit counts are summarized in dedicated tables at the end of this Chapter. A derivation and detailed explanation of the parameters can be found in Chapters 3 to 6 of Volume I of the design report. A discussion of the variation of the beam parameters from these nominal values in different operation scenarios is given in Chapter 20.

Table 2.1: LHC beam parameters relevant for the peak luminosity

		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		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	[$\text{cm}^{-2}\text{sec}^{-1}$]	-	1.0×10^{34}
Peak luminosity per bunch crossing in IP1 and IP5	[$\text{cm}^{-2}\text{sec}^{-1}$]	-	3.56×10^{30}

[a] The base line machine operation assumes that the longitudinal emittance is deliberately blown up at the middle of the ramp in order to reduce the intra beam scattering growth rates.

[b] The emittance at injection energy refers to the emittance delivered to the LHC by the SPS without any increase due to injection errors and optics mis-match. The RMS beam sizes at injection assume the nominal emittance value quoted for top energy (including emittance blowup due to injection oscillations and mismatch).

[c] Dimensions are given for Gaussian distributions. The real beam will not follow a Gaussian distribution but more realistic distributions do not allow analytic estimates for the IBS growth rates.

[d] The RMS beam sizes in IP1 and IP5 assume a β-function of 0.55 m.

[e] The RMS beam sizes in IP2 and IP8 assume a β-function of 10 m.

[f] The geometric luminosity reduction factor depends on the total crossing angle at the IP (see Sec. 3.1.1). The quoted number in Table 2.1 assumes a total crossing angle of 285 μrad as it is used in IR1 and IR5.

2.2 LHC BEAM PARAMETERS RELEVANT FOR THE LUMINOSITY LIFETIME

Table 2.2: LHC beam parameters relevant for the luminosity lifetime

		Injection	Collision
Interaction data			
Inelastic cross section	[mb]	60.0	
Total cross section	[mb]	100.0	
Events per bunch crossing		-	19.02
Beam current lifetime (due to beam-beam)	[h]	-	44.86
Intra Beam Scattering			
RMS beam size in arc	[mm]	1.19	0.3
RMS energy spread $\delta E/E_0$	$[10^{-4}]$	3.06	1.129
RMS bunch length	[cm]	11.24	7.55
Longitudinal emittance growth time	[hours]	30^a	61
Horizontal emittance growth time	[hours]	38^a	80
Total beam and luminosity lifetimes^b			
Luminosity lifetime (due to beam-beam)	[hours]	-	29.1
Beam lifetime (due to rest-gas scattering)^c	[hours]	100	100
Beam current lifetime (beam-beam, rest-gas)	[hours]	-	18.4
Luminosity lifetime (beam-beam, rest-gas, IBS)	[hours]	-	14.9
Synchrotron Radiation			
Instantaneous power loss per proton	[W]	3.15×10^{-16}	1.84×10^{-11}
Power loss per m in main bends	$[\mathrm{Wm}^{-1}]$	0.0	0.206
Synchrotron radiation power per ring	[W]	6.15×10^{-2}	3.6×10^{3}
Energy loss per turn	[eV]	1.15×10^{-1}	6.71×10^{3}
Critical photon energy	[eV]	0.01	44.14
Longitudinal emittance damping time	[hours]	48489.1	13
Transverse emittance damping time	[hours]	48489.1	26

^{a} IBS growth times are given without the 200 MHz RF system.

^{b} lifetime estimates including the effect of proton losses due to luminosity production, IBS and vacuum rest gas scattering. It is assumed that the effect of the non-linear beam-beam interaction and RF noise are compensated by the synchrotron radiation damping.

^{c} The desorption lifetime should be slightly better at injection energy because the cross sections for rest gas scattering decrease with energy. For more information see Vol II, Chap. 28 and [1].

2.3 LHC MACHINE PARAMETERS RELEVANT FOR THE PEAK LUMINOSITY

Table 2.3: LHC machine parameter relevant for the peak luminosity

		Injection	Collision
Interaction Data			
Number of collision points		4	
Half crossing angle for ATLAS and CMS (IP1/IP5)	[μrad]	$\pm$160	$\pm$142.5
Half parallel separation at IP for ATLAS and CMS (IP1/IP5)	[mm]	$\pm$2.5	0.0
Half crossing angle at IP [a] for ALICE (IP2)	[μrad]	$\pm$240	$\pm$150
Half parallel separation at IP for ALICE	[mm]	$\pm$2.0	$\pm$0.178 (5 σ total separation)
Half crossing angle at IP [a] for LHCb (IP8)	[μrad]	$\pm$300	$\pm$200
Half parallel separation at IP for LHCb (IP8)	[mm]	$\pm$2.0	0.0
Plane of crossing in IP1		vertical	
Plane of crossing in IP2		vertical	
Plane of crossing in IP5		horizontal	
Plane of crossing in IP8		horizontal	
β at IP1 and IP5	[m]	18	0.55
β at IP2	[m]	10	0.5 for Pb / 10 for p
β at IP8	[m]	10	1.0 $\leftrightarrow$ 50

[a] The crossing angle in IP2 and IP8 is the sum of an external crossing angle bump and an 'internal' spectrometer compensation bump and depend on the spectrometer polarity. The values quoted above represent the maximum values from the different possible configurations. The external bump extends over the triplet and D1 and D2 magnets. The internal spectrometer compensation bump extends only over the long drift space between the two triplet assemblies left and right from the IP.

2.4 LHC STORAGE RING PARAMETERS

Table 2.4: LHC storage ring parameters

		Injection	Collision
Geometry			
Ring circumference	[m]	26658.883	
Ring separation in arcs	[mm]	194	
Bare inner vacuum screen height in arcs	[mm]	46.5	
Effective vacuum screen height (incl. tol.)	[mm]	44.04	
Bare inner vacuum screen width in arcs	[mm]	36.9	
Effective vacuum screen width (incl. tol.)	[mm]	34.28	
Main Magnet			
Number of main bends		1232	
Length of main bends	[m]	14.3	
Field of main bends	[T]	0.535	8.33
Bending radius	[m]	2803.95	
Lattice			
Maximum dispersion in arc	[m]	2.018 (h) / 0.0 (v)	
Minimum horizontal dispersion in arc	[m]	0.951	
Maximum β in arc	[m]	177 (h)/ 180 (v)	
Minimum β in arc	[m]	30 (h) / 30 (v)	
Horizontal tune		64.28	64.31
Vertical tune		59.31	59.32
Momentum compaction	10^{-4}	3.225	
Slip factor η	10^{-4}	3.182	3.225
Gamma transition γ_{tr}		55.68	
RF System			
Revolution frequency	[kHz]	11.245	
RF frequency [a]	[MHz]	400.8	
Harmonic number		35640	
Total RF voltage	[MV]	8	16
Synchrotron frequency	[Hz]	61.8	21.4
Bucket area	[eVs]	1.46	8.7
Bucket half height ($\Delta E/E$)	[10^{-3}]	1	0.36

[a] A second optional low harmonic 200 MHz RF system can be installed after the initial running period.