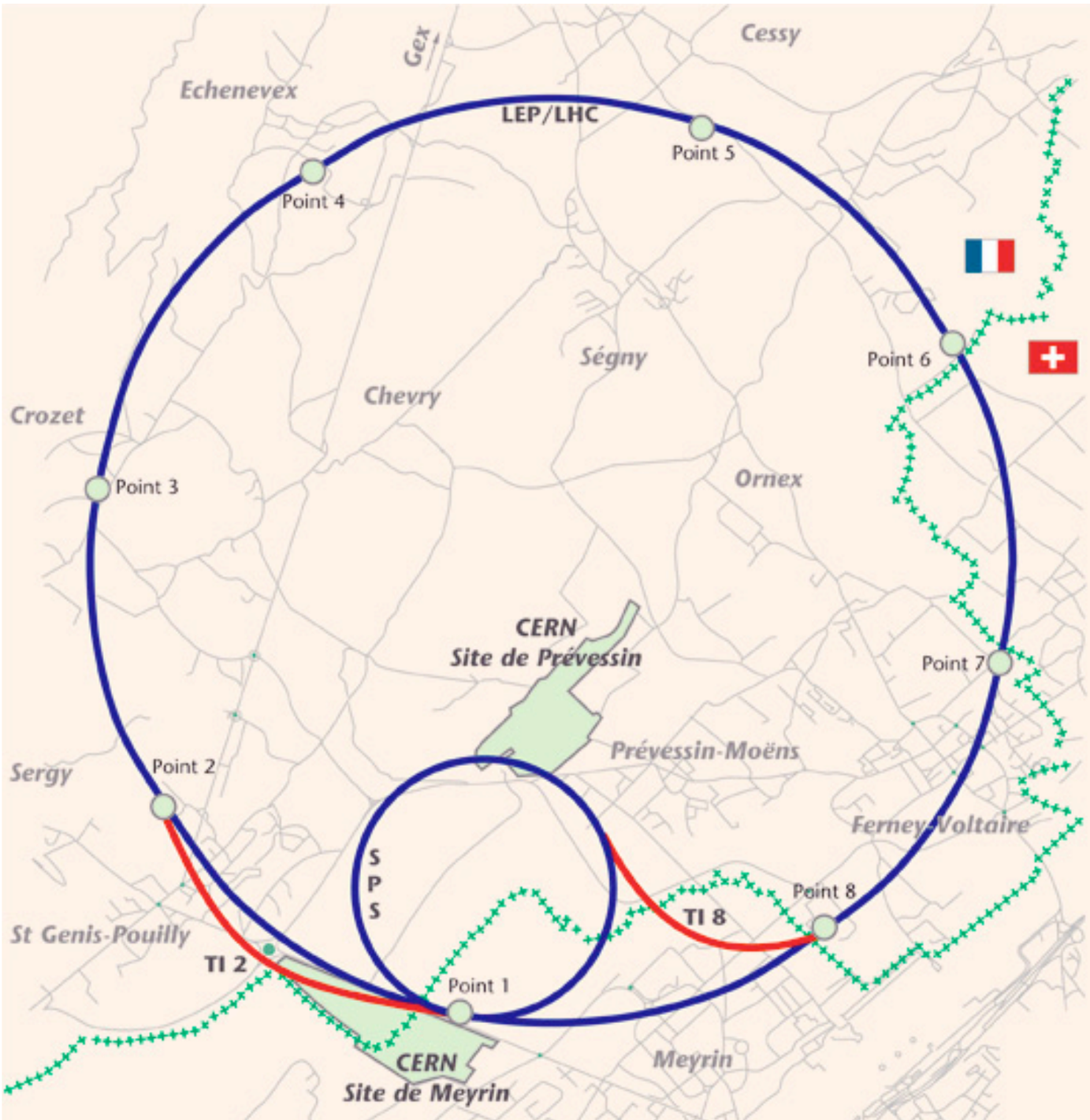
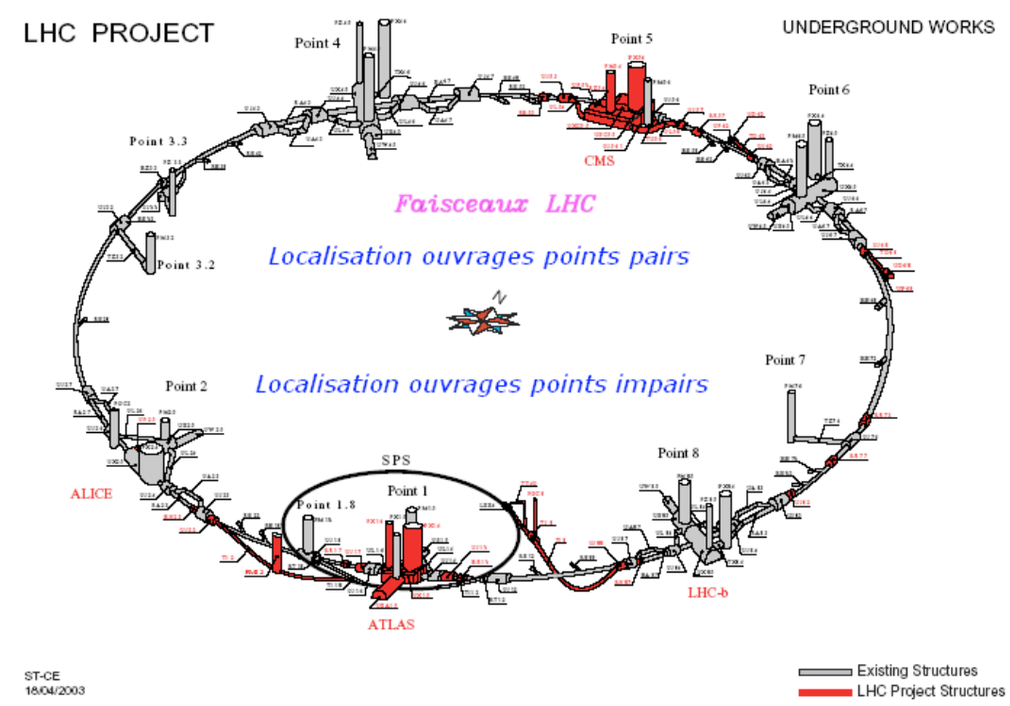
LHC Overview

Design Optics and General Features



Mike Syphers
LARP Mtg, 7/19/05



From LHC Design Report, Vol. I

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	[cm^{-2}sec^{-1}]	-	1.0×10^{34}
Peak luminosity per bunch crossing in IP1 and IP5	[cm^{-2}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	[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]	±160	±142.5
Half parallel separation at IP for ATLAS and CMS (IP1/IP5)	[mm]	±2.5	0.0
Half crossing angle at IP [a] for ALICE (IP2)	[μrad]	±240	±150
Half parallel separation at IP for ALICE	[mm]	±2.0	±0.178 (5 σ total separation)
Half crossing angle at IP [a] for LHCb (IP8)	[μrad]	±300	±200
Half parallel separation at IP for LHCb (IP8)	[mm]	±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

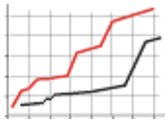
[a] A second optional low harmonic 200 MHz RF system can be installed after the initial running period.

http://lhc-new-homepage.web.cern.ch/lhc-new-homepage/

General Information | Organization | Publications | Seminars | Illustrations | CERN

LHC - THE LARGE HADRON COLLIDER

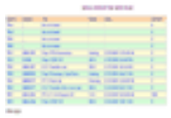
LHC Design Report



Click here to go to the LHC Progress Dashboard

Click here to go to the LHC General Co-ordination Schedule

NEWS! Click here to go to the LHC News



Click here to go to the Status of the LHC Magnet Test Facility

Beam Parameters

- Design Performance
- Configurations
- Beam Dynamics
- Lattice & Optics (under approval)
- Beam Cleaning
- Ejection & Dump
- Injection/Filling Schemes

Hardware Parameters

- Cryogenics
- Injectors & Transfer Lines
- Beam Instrumentation
- Magnets for the Ring(new, under approval)
- Magnets for the Ring(old version)
- Powering & Quench Protection
- RF & Feedback
- Vacuum

Layout

- General
- Mechanical
- List of Assemblies
- Database Navigator
- Search / Utilities
- Equipment Catalog
- EDMS Doc. Version Management

Integration

- Tunnel
- Pits and Surface Buildings
- Installation Drawings

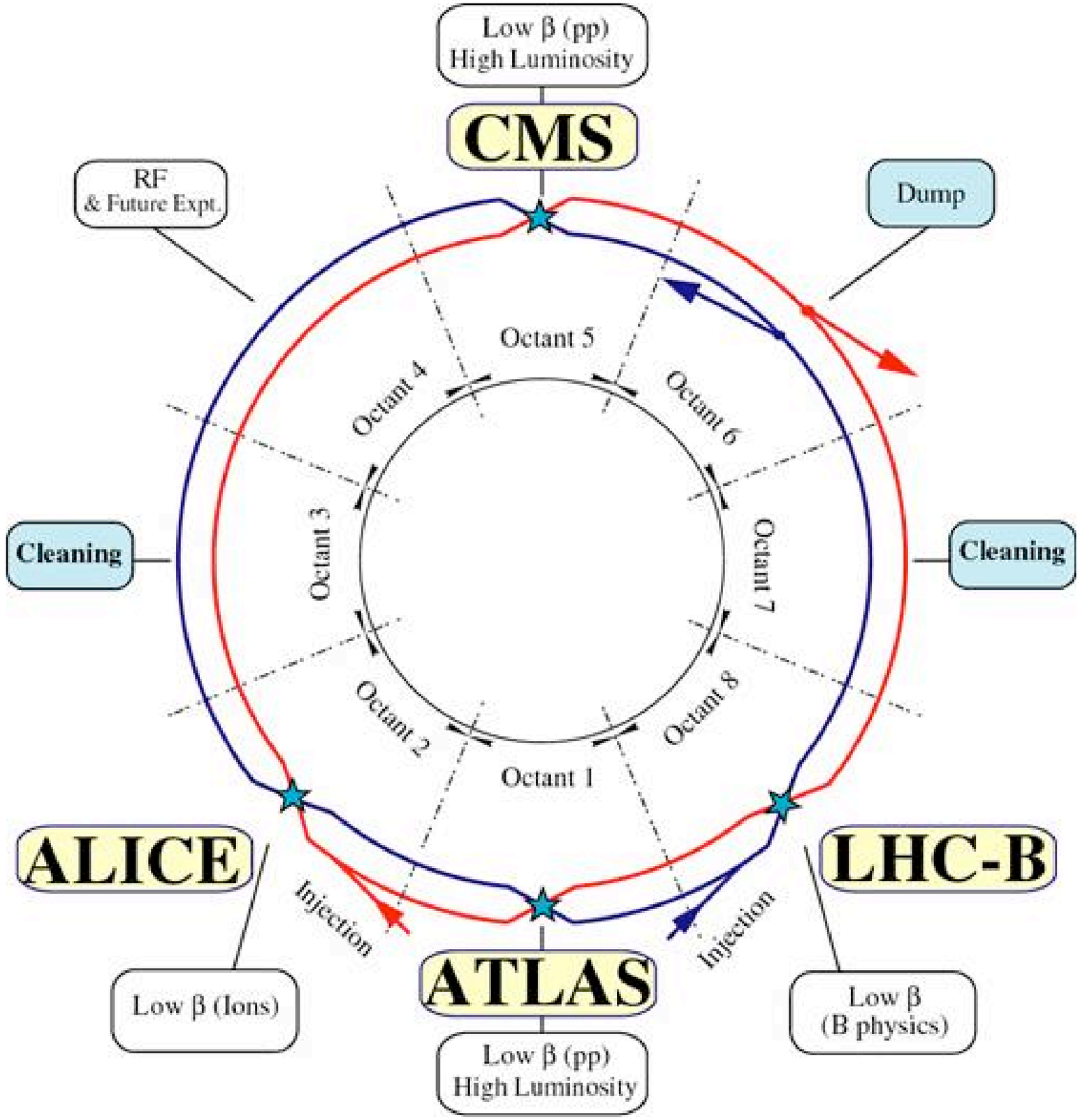
Installation Coordination

- Who's Who
- Access Permits
- General Documentation

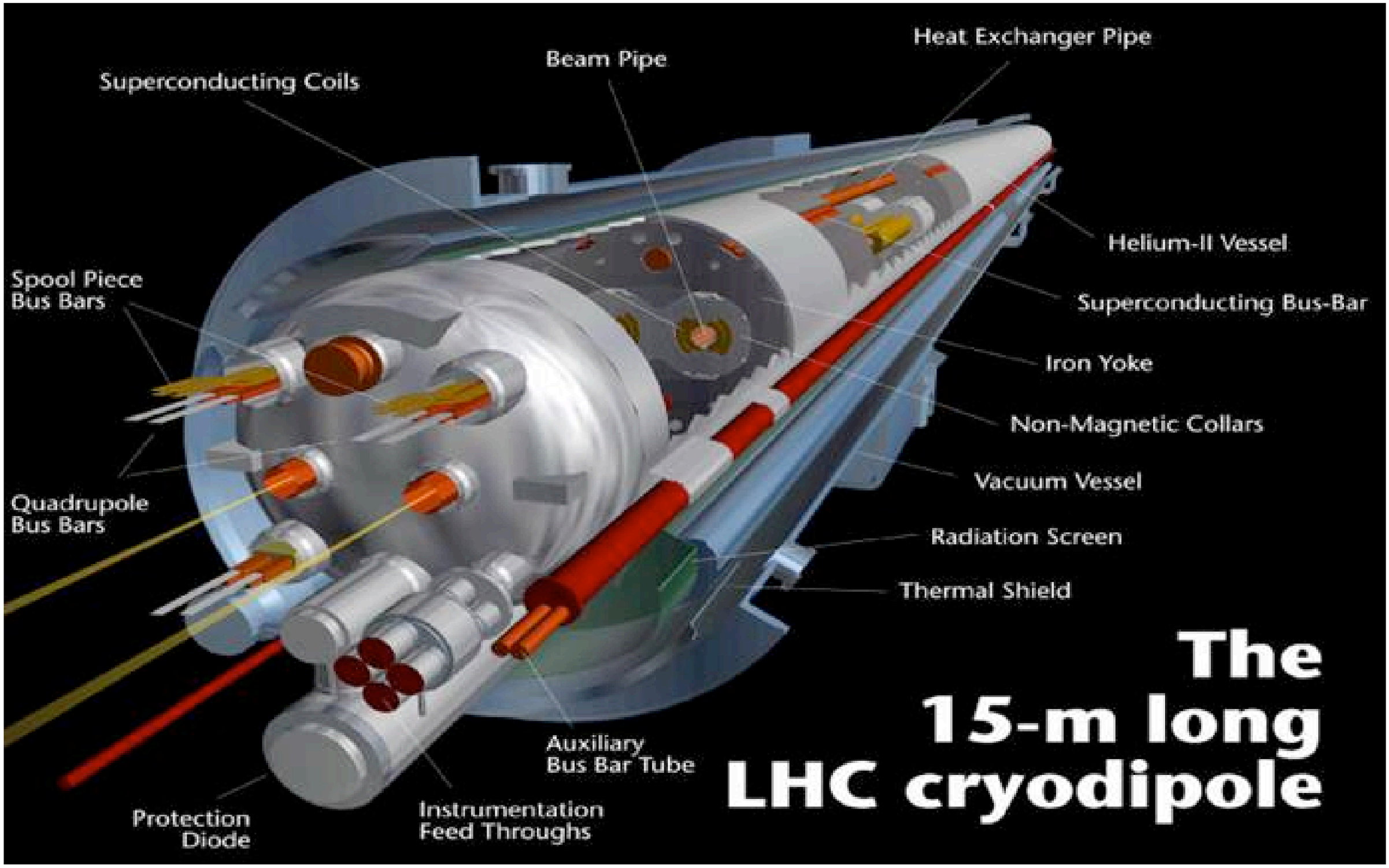
Baseline Documentation | Quality Assurance | Naming & Conventions | Useful Links | LHC Sites | LHC Experiments

28-Jun-2005 LHC Webmaster

General Layout



The Magnet


Heat Exchanger Pipe
Beam Pipe
Superconducting Coils
Helium-II Vessel
Spool Piece
Bus Bars
Superconducting Bus-Bar
Iron Yoke
Non-Magnetic Collars
Vacuum Vessel
Quadrupole
Bus Bars
Radiation Screen
Thermal Shield
The
15-m long
LHC cryodipole
Auxiliary
Bus Bar Tube
Protection
Diode
Instrumentation
Feed Throughs

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} cm^2s^1
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

Luminosity

- Goal: compete with SSC (20 TeV, 10^{33}), but with 7 TeV ===> 10^{34}

$$\mathcal{L} = \frac{f_0 B N^2 \gamma}{4\pi\beta^* \epsilon_N} \cdot \frac{1}{\sqrt{1 + \left(\frac{\alpha\sigma_z}{2\sigma_0}\right)^2}} \qquad \textbf{if}\, \sigma_z \ll \beta^*$$

Some Givens:

$$f_0 = \frac{c}{C} = \frac{3 \times 10^8}{2.67 \times 10^4}\ \mathrm{Hz} = 11.2\ \mathrm{kHz}$$

$$\gamma = 7000/0.938 = 7500$$

$$\epsilon_N = 3.75\ \mu\mathrm{m} \quad (= 22.5\pi\ \mathrm{mm} \cdot \mathrm{mrad}, \mathrm{FNAL})$$

(from SPS)

Lumi (cont'd)

Take $\beta^* \approx \frac{1}{2}$ m; choose $\sigma_z = 7$ cm $\ll \beta^*$ (*see next slide*)

Choose $f_{rf} = 400$ MHz (200 MHz at injection)...
$h = 35640$; then, fill every 10 buckets $\longrightarrow B = 3564$ (25 nsec)
gaps, for abort, filling scenarios, etc. $\longrightarrow B = 2808$

α: use 285 μrad (gives $\hat{x} = 6$ mm in triplet quads)

$$\frac{d}{\sigma} \approx \alpha\sqrt{\frac{\beta^*}{\epsilon_N}\gamma} = 285 \cdot 10^{-6}\sqrt{\frac{1/2}{3.75 \cdot 10^{-6}}(7.5 \cdot 10^3)} = 9$$

note: $\sigma_0^* = \sqrt{\epsilon_N \beta^*/\gamma} = \sqrt{(3.75)(0.5)/7500} = 16\ \mu\text{m}$

then,

$$\frac{\alpha\sigma_z}{2\sigma_0} = \frac{(285)(0.07)}{2(16)} = 0.623$$

and

$$\frac{1}{\sqrt{1+(0.623)^2}} = 0.85$$

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

$$\mathcal{L} = \frac{(11.2 \times 10^3)(2808)(10^{11})^2(7500)}{4\pi(50)(3.75 \cdot 10^{-4})\text{cm}^2\text{sec}} \cdot 0.85 = 8 \times 10^{33}\ \text{cm}^{-2}\text{sec}^{-1}$$

So, tweak... $N = 1.15 \times 10^{11} \longrightarrow \mathbf{1 \times 10^{34}}\ \text{cm}^{-2}\text{sec}^{-1}$

Note: $$\langle n \rangle = \frac{\mathcal{L}\Sigma_{int}}{B f_0} = \frac{10^{34} \cdot (0.060 \cdot 10^{-24})}{2808 \cdot 11,200} = 19 \;\; !!$$

(Interactions per bunch crossing)

To get $\sigma_z \approx 7$ cm ...

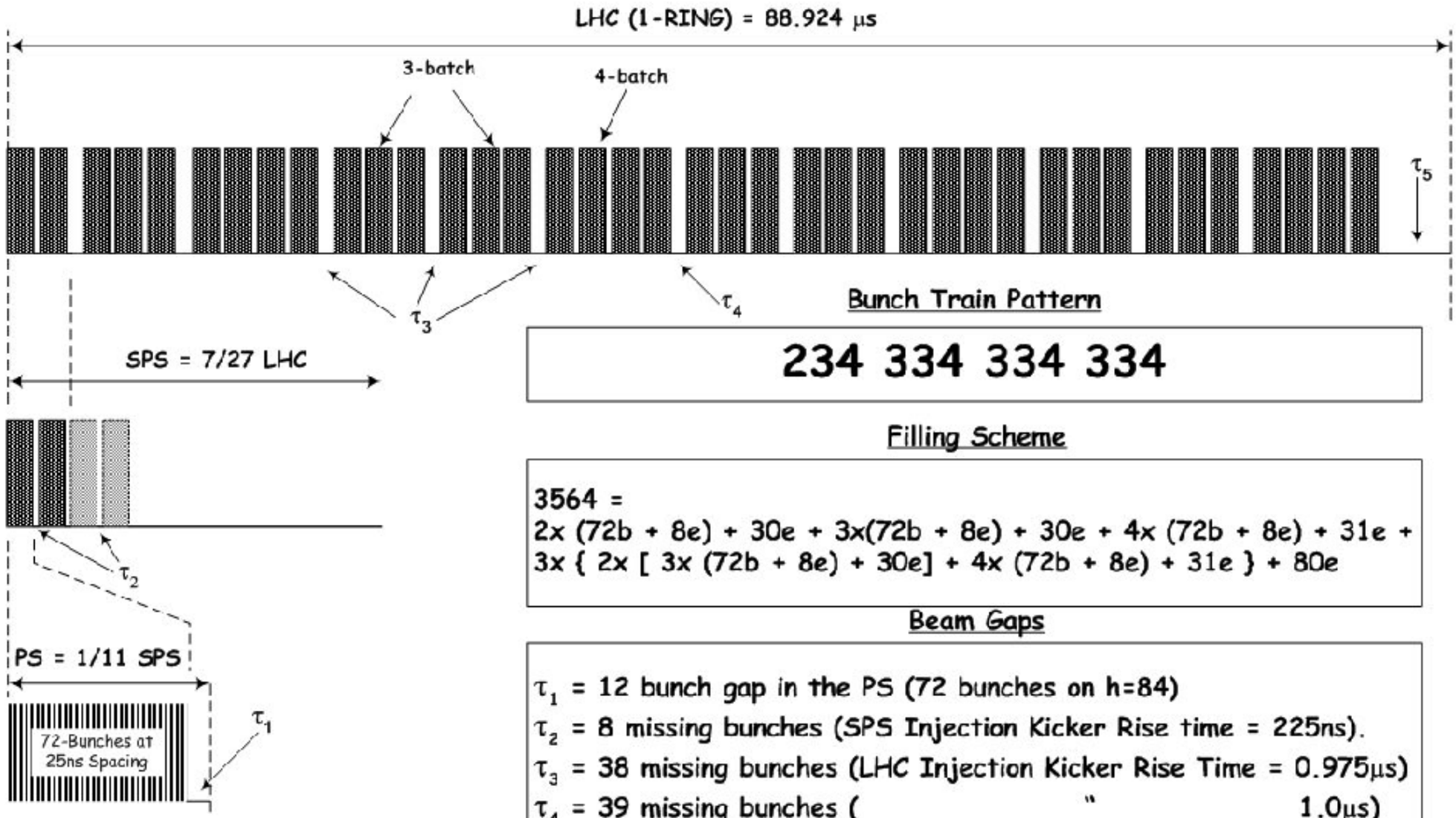
$$\frac{S}{\mathcal{A}} = \frac{3\pi}{8}\sigma_\phi^2 = \frac{3\pi}{8}\left(\frac{2\pi f_{rf}\sigma_z}{c}\right)^2 = 0.4$$

Choose bucket area $\mathcal{A} = 8$ eV-sec,
and longitudinal emittance $S = 2.8$ eV-sec: $eV = 2\pi h\eta E_s \left(\frac{\pi \mathcal{A} f_{rf}}{8E_s}\right)^2 \rightarrow V = 16$ MV

bucket height, $k = \frac{\pi f_{rf}\mathcal{A}}{4E_s} = 3.6 \times 10^{-4}$

$\nu_s = h\eta \cdot k/2 = 1/472$ synchrotron frequency: $f_s = f_0\nu_s = 23$ Hz

Nominal Proton Bunch Pattern in the LHC for 25nS Spacing



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)

P. Collier 02/10/2003

Optics

- Use of LEP tunnel ... $\longrightarrow \rho \sim 2.8 \text{ km}$

$$\frac{B\rho}{\rho} = \frac{7000 \cdot 10/3 \ \ \text{T m}}{2.8 \times 10^3 \text{m}} = 8.33 \text{ T}$$

$$N_{cells} \sim \sqrt{2C_{feet}} \approx \sqrt{87464} \approx 300$$

each IR $\approx$ 9 cells + 4 DS $\approx$ 13 cells

thus, $300 - 8{\times}13 = 196$

$\frac{196}{8} = 24.5$ cells/arc

(optimization $\longrightarrow$ 23 cells/arc)

$$L \approx \frac{30 \text{ km}}{300} \cdot \frac{1}{2} \approx 50 \text{ m}$$

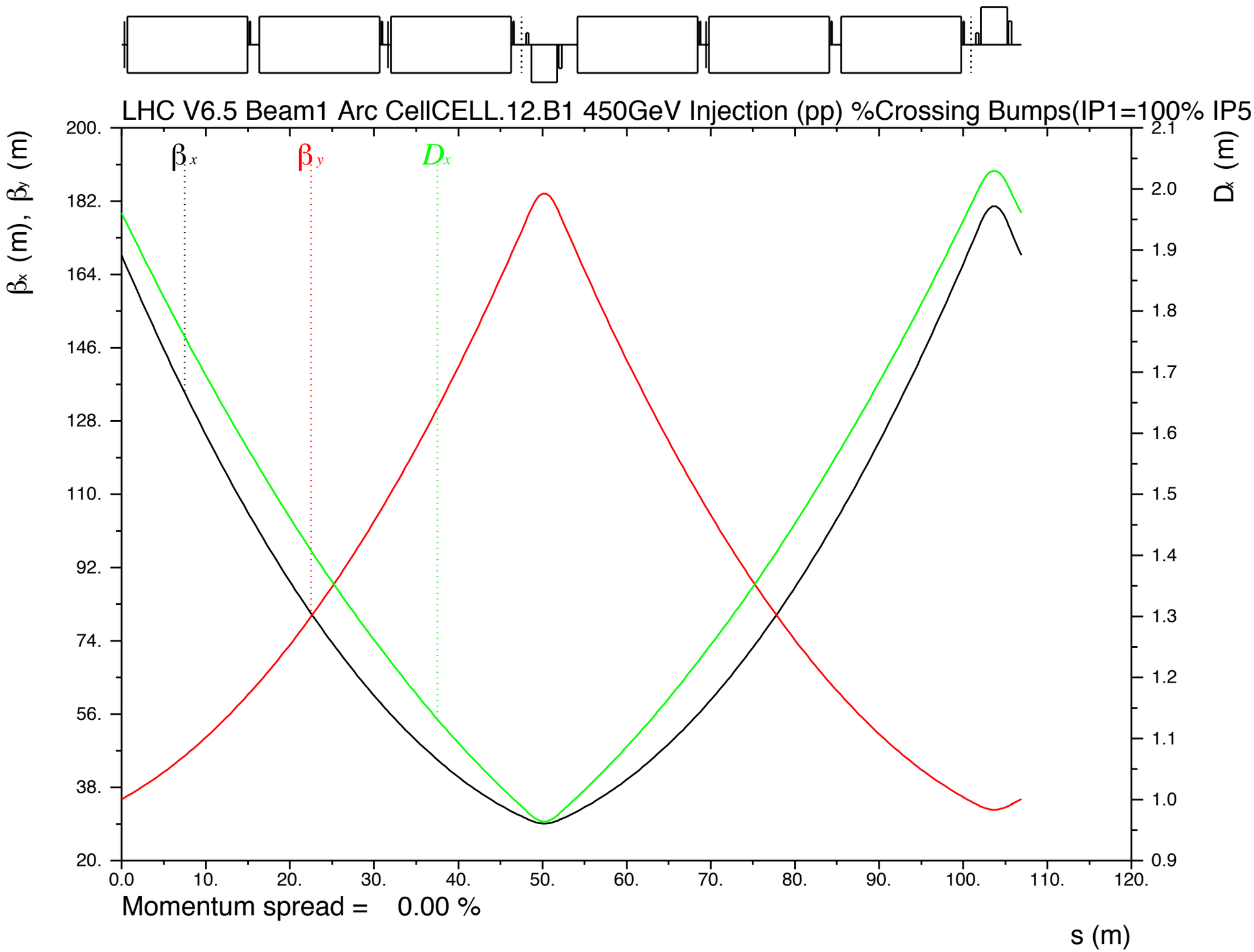
Chosen value : $L = 53.45$ m

Also chose: $\mu = 90°/\text{cell}$

$$\hat{\beta} = \frac{53.45}{\sqrt{2}/2}\sqrt{\frac{1+\sqrt{2}/2}{1-\sqrt{2}/2}} = 182 \text{ m}$$

$$\check{\beta} = \frac{53.45}{\sqrt{2}/2}\sqrt{\frac{1-\sqrt{2}/2}{1+\sqrt{2}/2}} = 30 \text{ m}$$

Standard Cell



Other parameters...

$$\begin{aligned}\#\text{ standard bends} &= N_b \\ &= 8\cdot[3\cdot 2\cdot N_{cells/arc} + 2\cdot 2\cdot 2\cdot 2] \\ &= 8\cdot(6\cdot 23 + 16) \\ &= 1232\end{aligned}$$

(#dip, 1/2 cells, cells, sides)

so, $\theta_0 = 3\cdot\frac{2\pi}{1232} = 15.3\ \text{mrad}$ (per half cell)

$$\hat{D} = \frac{L\theta_0}{(\sqrt{2}/2)^2}\left(1+\frac{1}{2}\frac{\sqrt{2}}{2}\right) = 2.2\ \text{m}$$

$$\nu \approx 8\cdot(23+4+4)\cdot\frac{1}{4} + 4\cdot\frac{1}{2} \approx 60$$

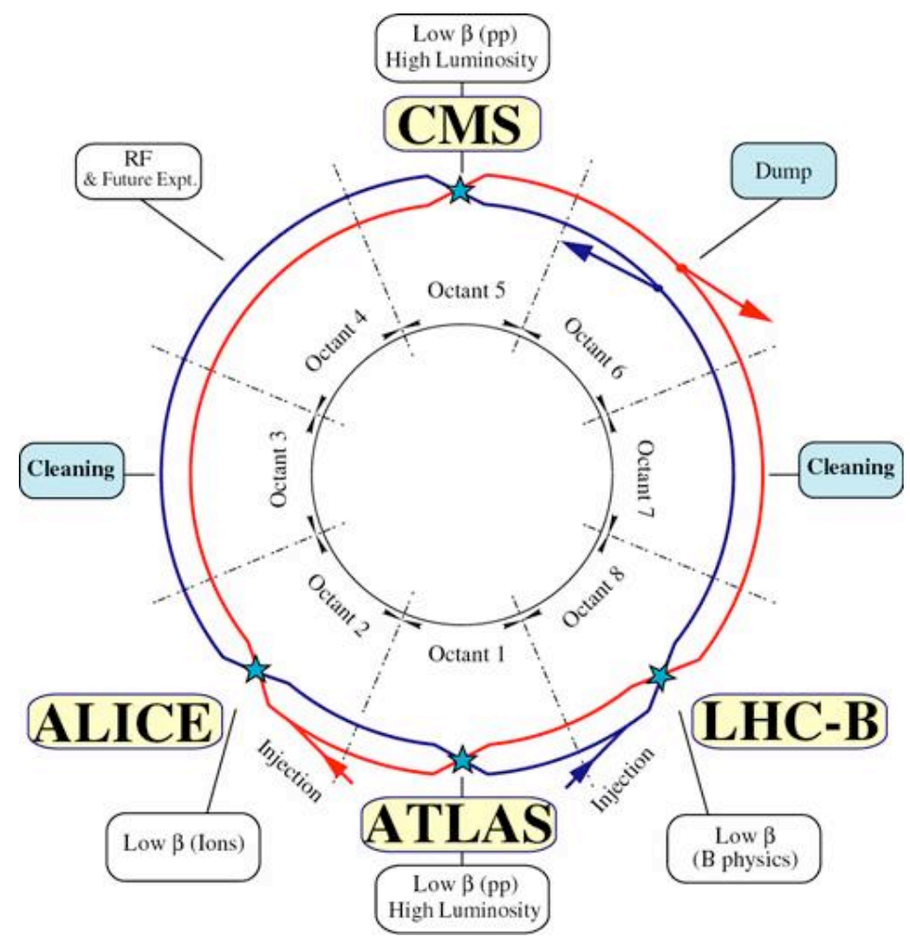
$$\gamma_t \approx \nu_x^{bends} \approx (23+4)\cdot\frac{1}{4}\cdot 8 = 54 \qquad (55.7)$$

To deal with coupling, split tunes: $\nu_x - \nu_y = 5$

$$\mu_x - \mu_y \approx 5/(8\cdot 23) = 0.027 = 1.5^\circ$$

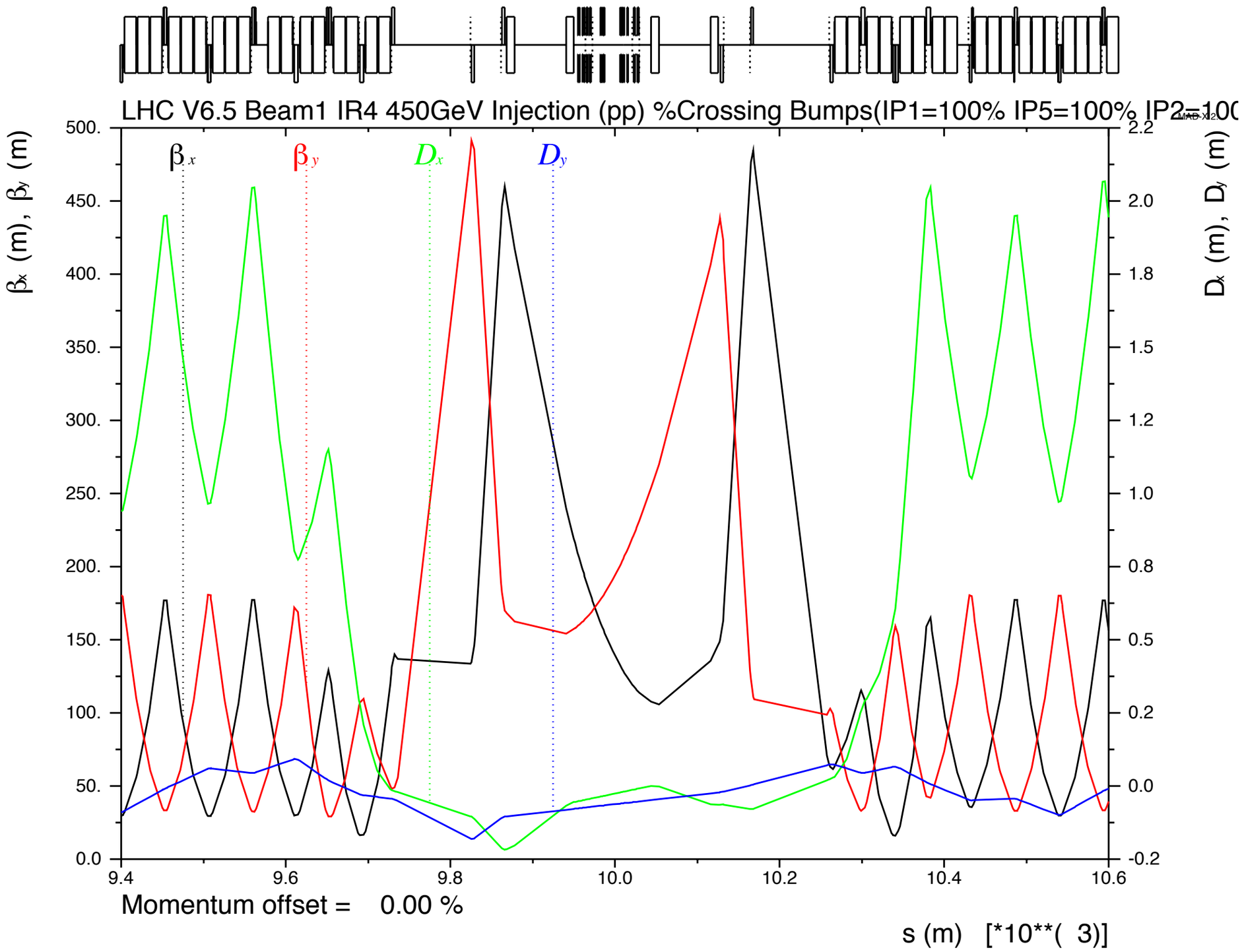
Straight Sections

- 1,5: Low-beta (JJ, next)
- 2,8: not-so-low beta (JJ?)
- 3,7: cleaning
  - 3: momentum; 7: x-verse
- 4: RF
- 6: abort/dump

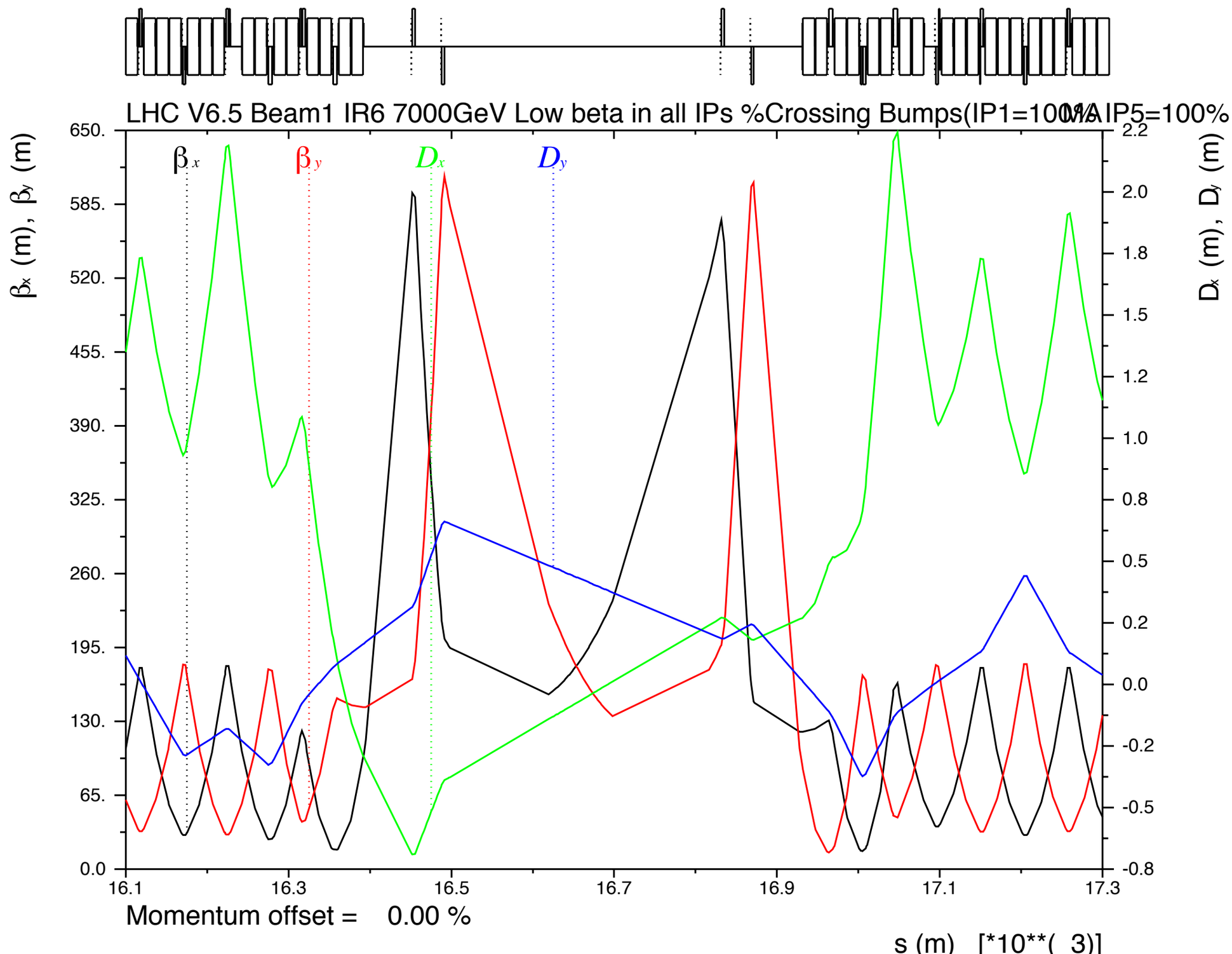


All different designs, with different requirements

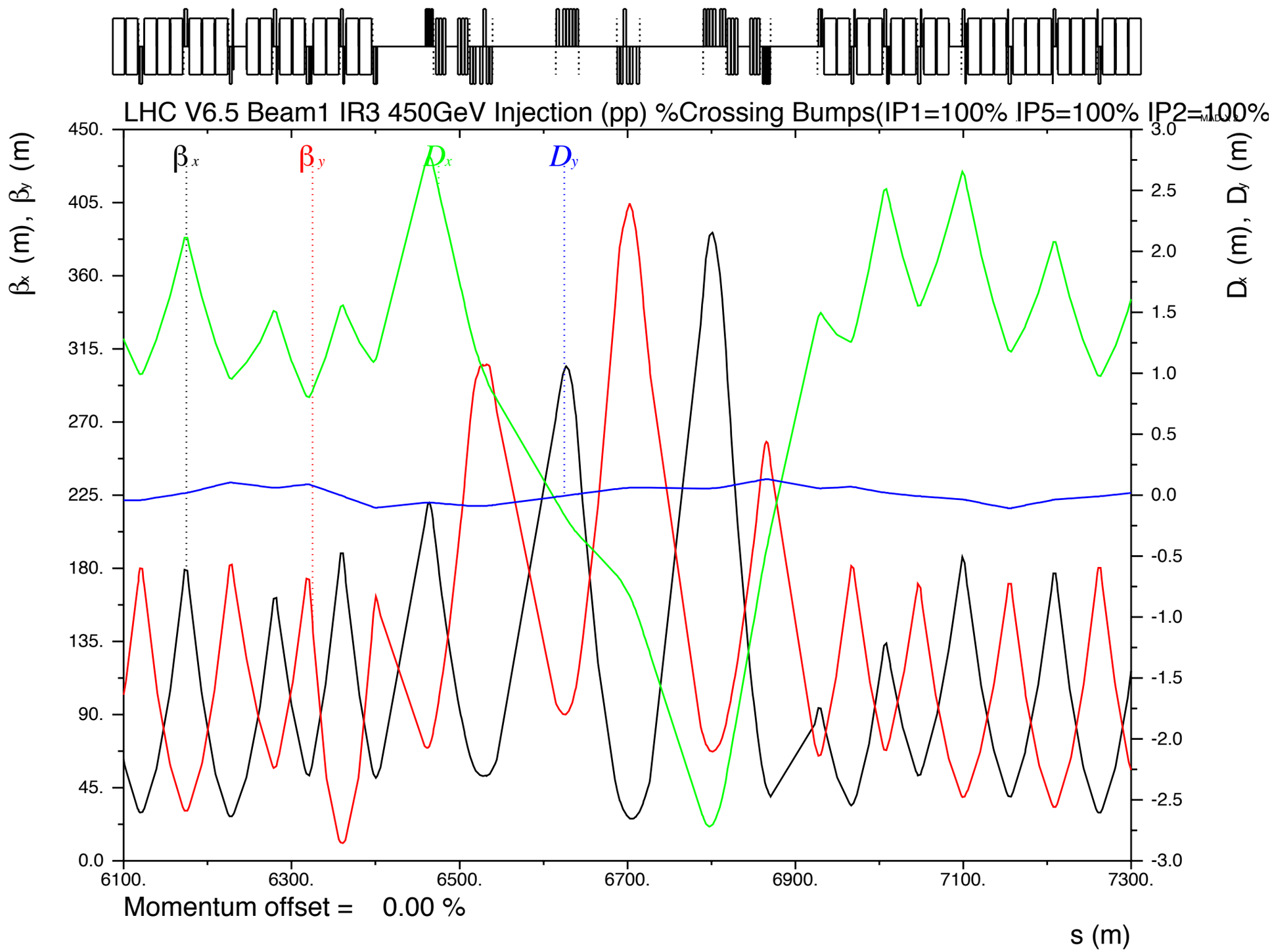
RF straight section



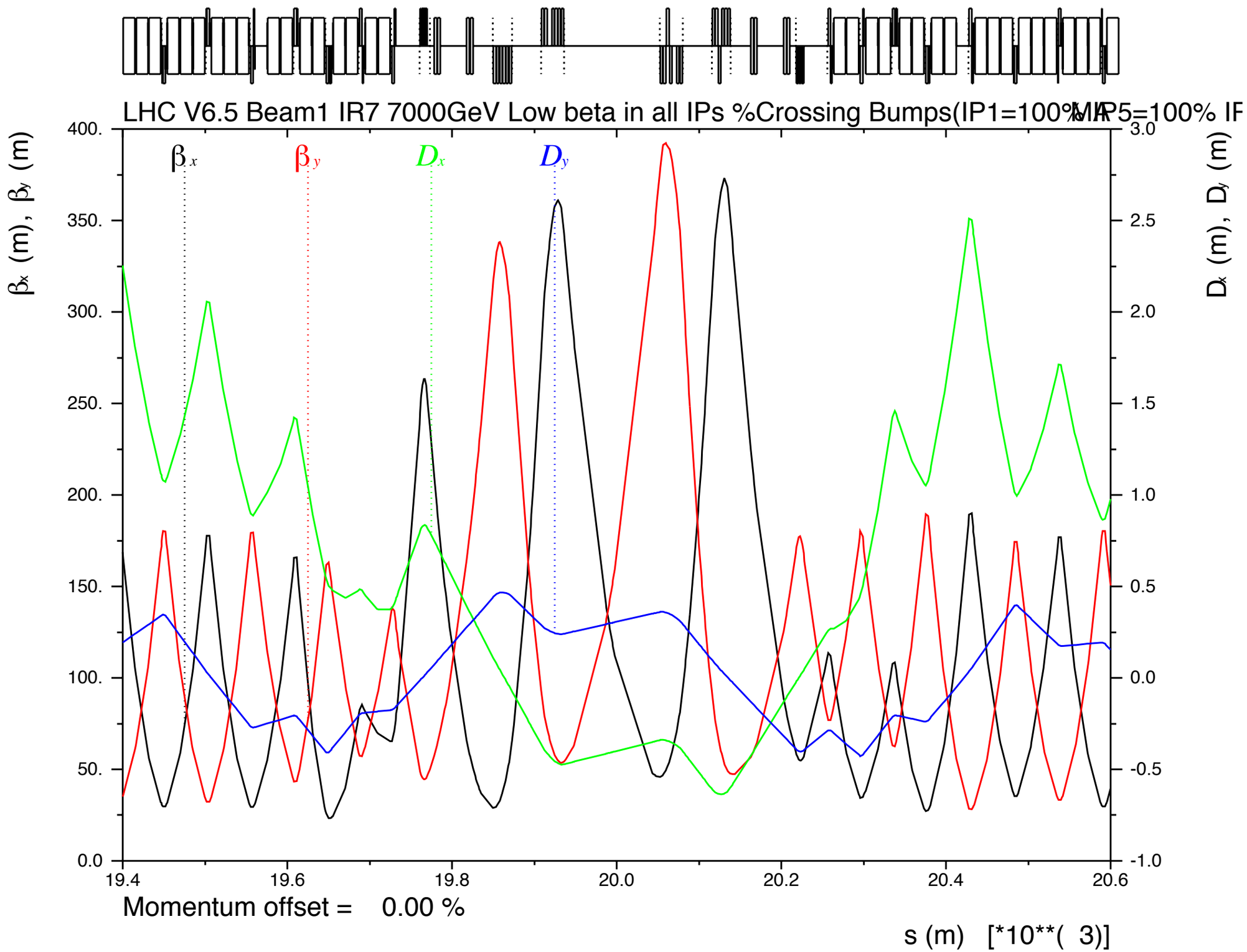
Beam Dump SS


LHC V6.5 Beam1 IR6 7000GeV Low beta in all IPs %Crossing Bumps(IP1=100% IP5=100%
βx
βy
Dx
Dy
βx (m), βy (m)
Dx (m), Dy (m)
650.
585.
520.
455.
390.
325.
260.
195.
130.
65.
0.0
2.2
2.0
1.8
1.5
1.2
1.0
0.8
0.5
0.2
0.0
-0.2
-0.5
-0.8
16.1
16.3
16.5
16.7
16.9
17.1
17.3
Momentum offset = 0.00 %
s (m) [*10**(3)]

Momentum Cleaning SS

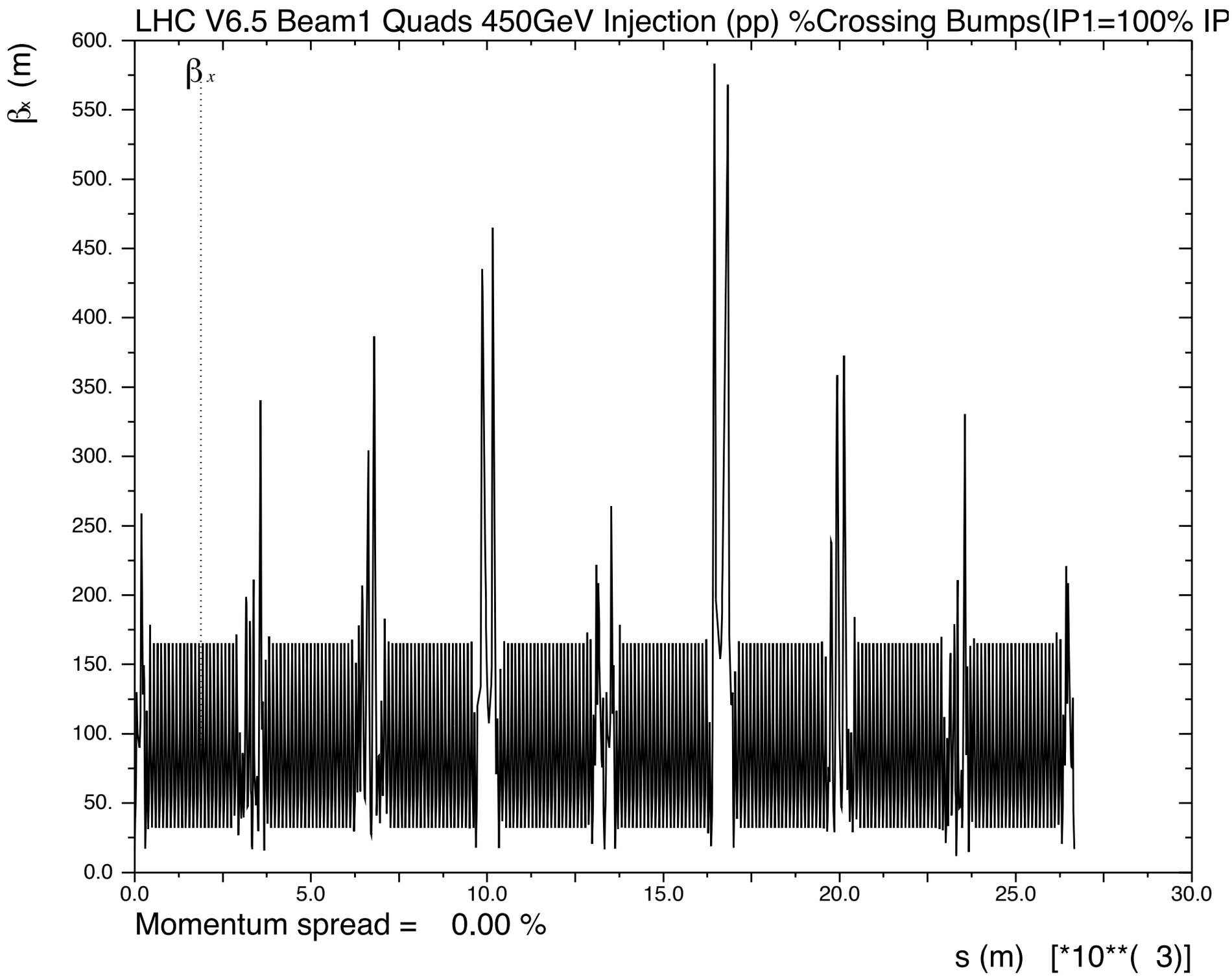


X-verse Cleaning SS

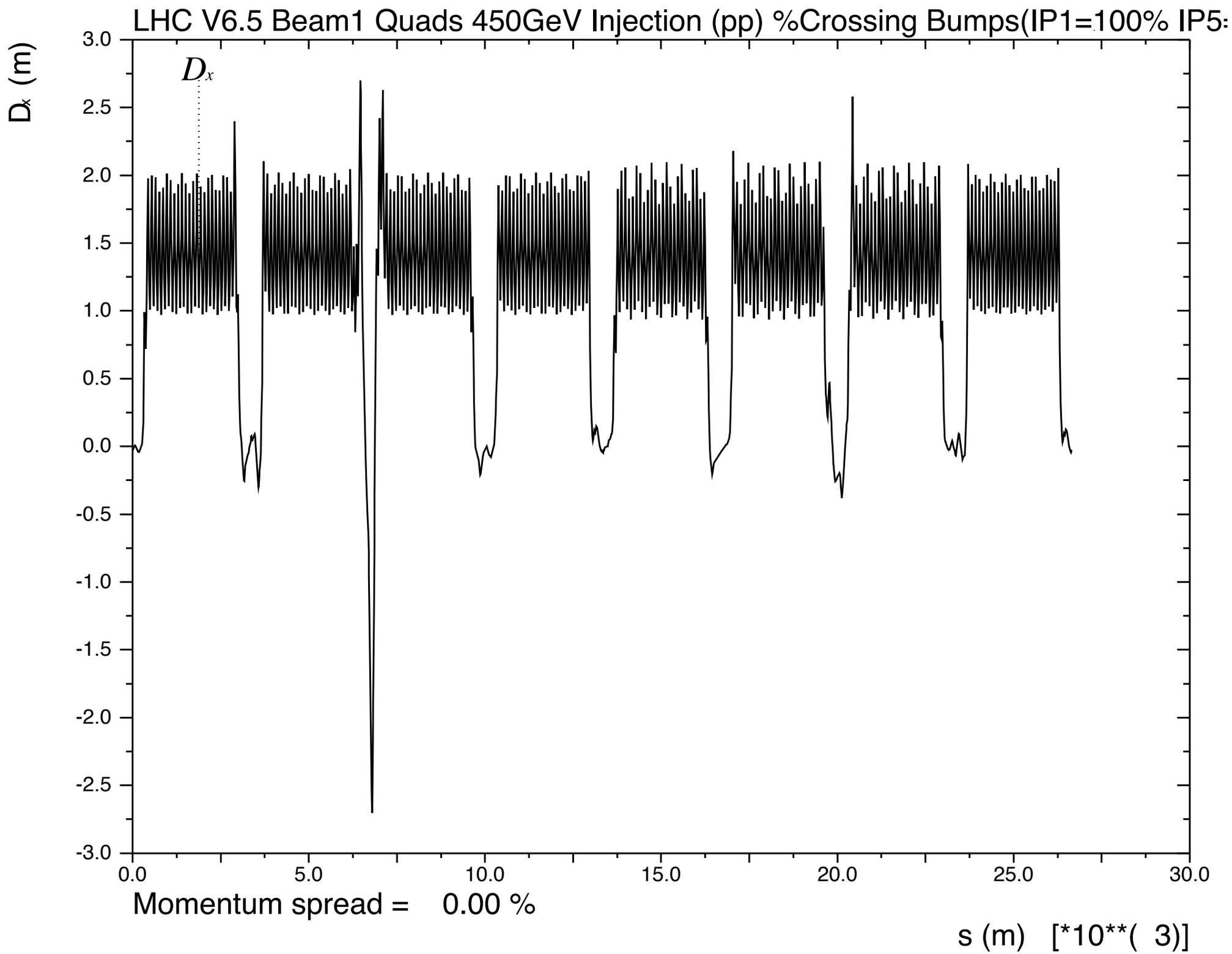


All Together (inj optics)...

Horiz only



Dispersion


LHC V6.5 Beam1 Quads 450GeV Injection (pp) %Crossing Bumps(IP1=100% IP5=
D_x (m)
D_x
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
Momentum spread = 0.00 %
s (m) [*10**(3)]

Chromaticity

- au Naturale ...

$$
\begin{aligned}
\xi_{nat} &= -8(N_c+4)\frac{\mu}{2\pi} - 8(4\cdot\frac{\mu}{2\pi}) - 4\left(\frac{1}{4\pi}\frac{2L^*}{\beta^*}\right) \\
&= -8(23+4)\cdot\frac{1}{4} - 8(4\cdot\frac{1}{4}) - 4\left(\frac{1}{4\pi}\frac{50}{1/2}\right) \\
&= -54 - 8 - 4(8) \\
&= -94
\end{aligned}
$$

- Systematic b_3 (b_2 *a' la* FNAL -- sextupole)

$$b_3 = 10\ units = 10\times 10^{-4}/(17\ \mathrm{mm})^2$$

$$\xi_{b3} = \langle b_3 D\beta\rangle \approx \frac{10}{(1.7)^2}\cdot(1.5)\cdot(100) \approx 519 \qquad \text{if } b_3 = 3 \longrightarrow 160$$

- drift, snapback, ... real concerns