Introduction to the LHC

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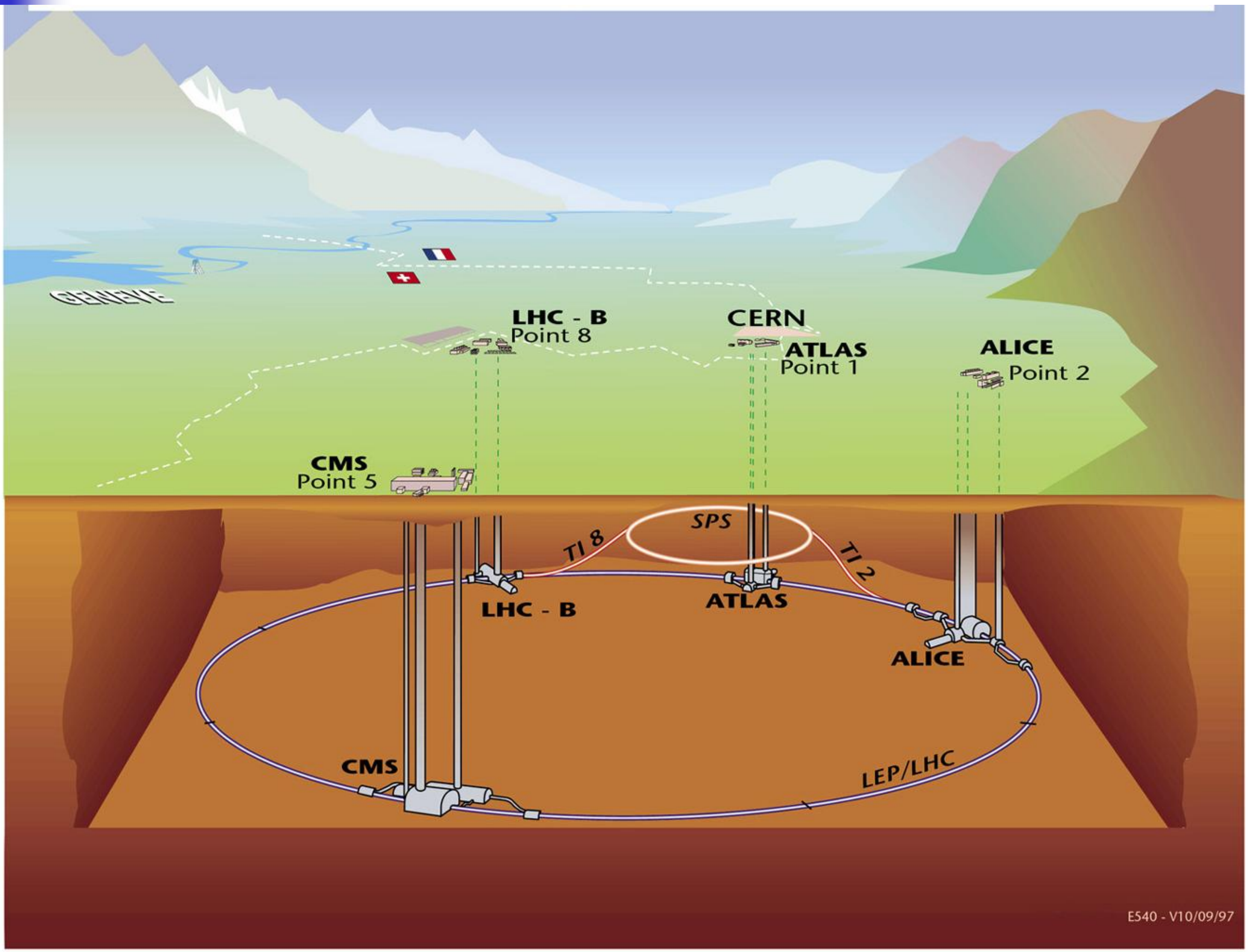
CERN – Beams Department

- General layout
- The cell
- The IRs
- Aperture
- Filling
- Nominal vs. actual beam parameters

LHC layout



IP4
IP3
ALICE

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Experimental magnets - I

- Toroid -> no impact on beams
  - ATLAS
- Solenoid -> linear coupling
  - ATLAS
  - ALICE
  - CMS
- Spectrometer -> orbit bump closed by means of three dipoles (see later).
  - ALICE (vertical bump)
  - LHCb (horizontal bump)

Experimental magnets - II

- Solenoids (ATLAS, Alice, CMS) -> linear coupling

$$c^{\mp} = -\frac{i}{4\pi}\frac{B_s l}{B\rho}\left(\sqrt{\frac{\beta_y^*}{\beta_x^*}} \pm \sqrt{\frac{\beta_x^*}{\beta_y^*}}\right)$$

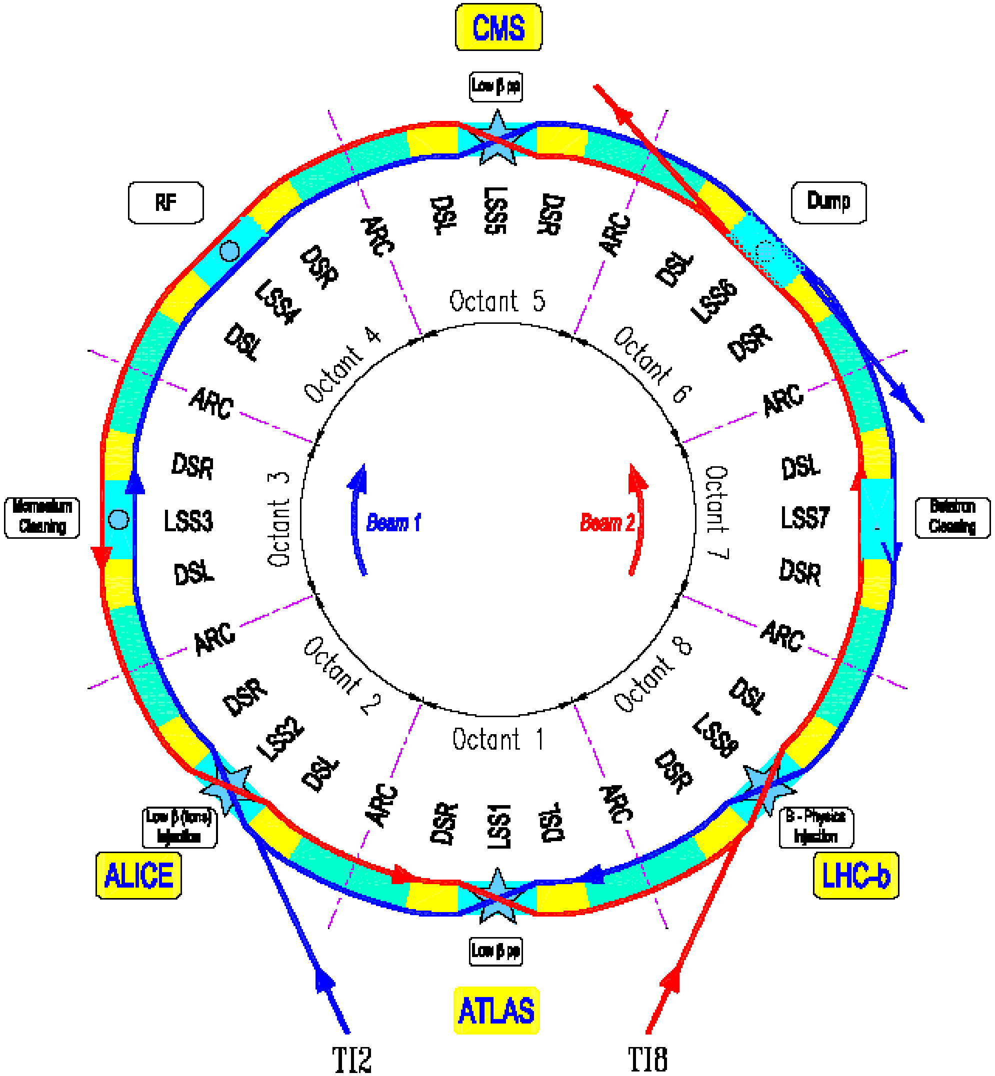
	B_s [T]	B_s L [Tm]	c-, 450 GeV	c-, 7 TeV	θ, mrad
IR1 Atlas	2	12	0.00127	0.00008	4.00
IR2 Alice	0.5	6.05	0.00064	0.00004	2.02
IR5 CMS	4	52	0.00551	0.00035	17.3
			0.00743	0.00048	

Courtesy H. Burkhardt - CERN

Key nominal parameters

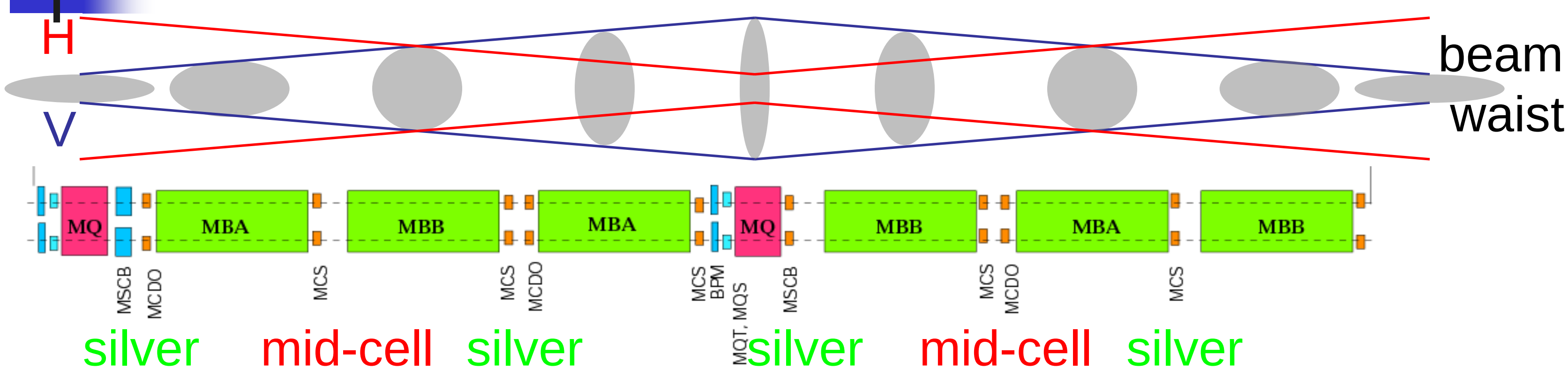
		Injection	Collision
Beam Data			
Proton energy	[GeV]	450	7000
Relativistic gamma		479.6	7461
Number of particles per bunch		1.15×10^{11}	
Number of bunches		2808	
Longitudinal emittance (4σ)	[eVs]	1.0	2.5^a
Transverse normalized emittance	[μm rad]	3.5^b	3.75
Circulating beam current	[A]	0.582	
Stored 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}

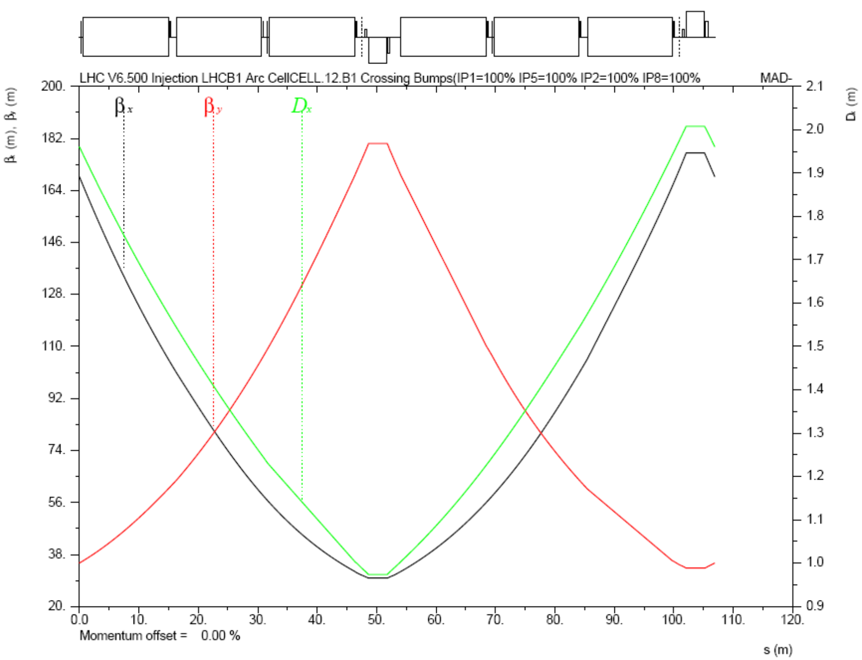
LHC symmetry



- The LHC machine has an height-fold symmetry.
- Eight arcs.
- Sixteen dispersion suppressors to match the arc with the straight sections (geometry and optics).
- Eight long straight sections.
- Tunes:
  - 64.28/59.31 injection
  - 64.31/59.32 collision

The arc cell





Six dipoles are located in each cell. Each dipole comprises spool pieces made of:

- Sextupoles

or

- Sextupoles, octupoles, and decapoles

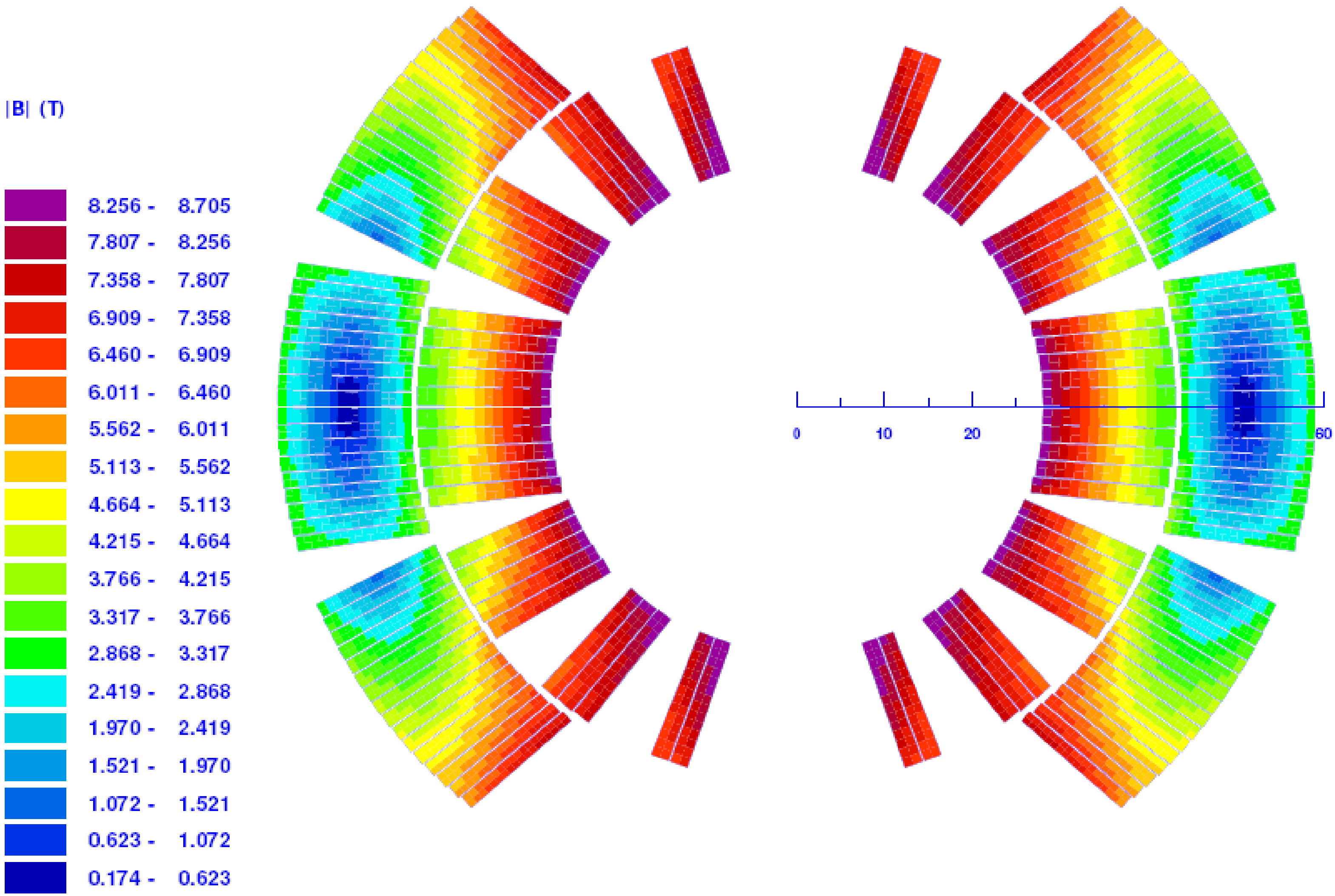
Two quadrupoles are located in each cell. Each quadrupole is equipped with:

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

Main dipoles - I

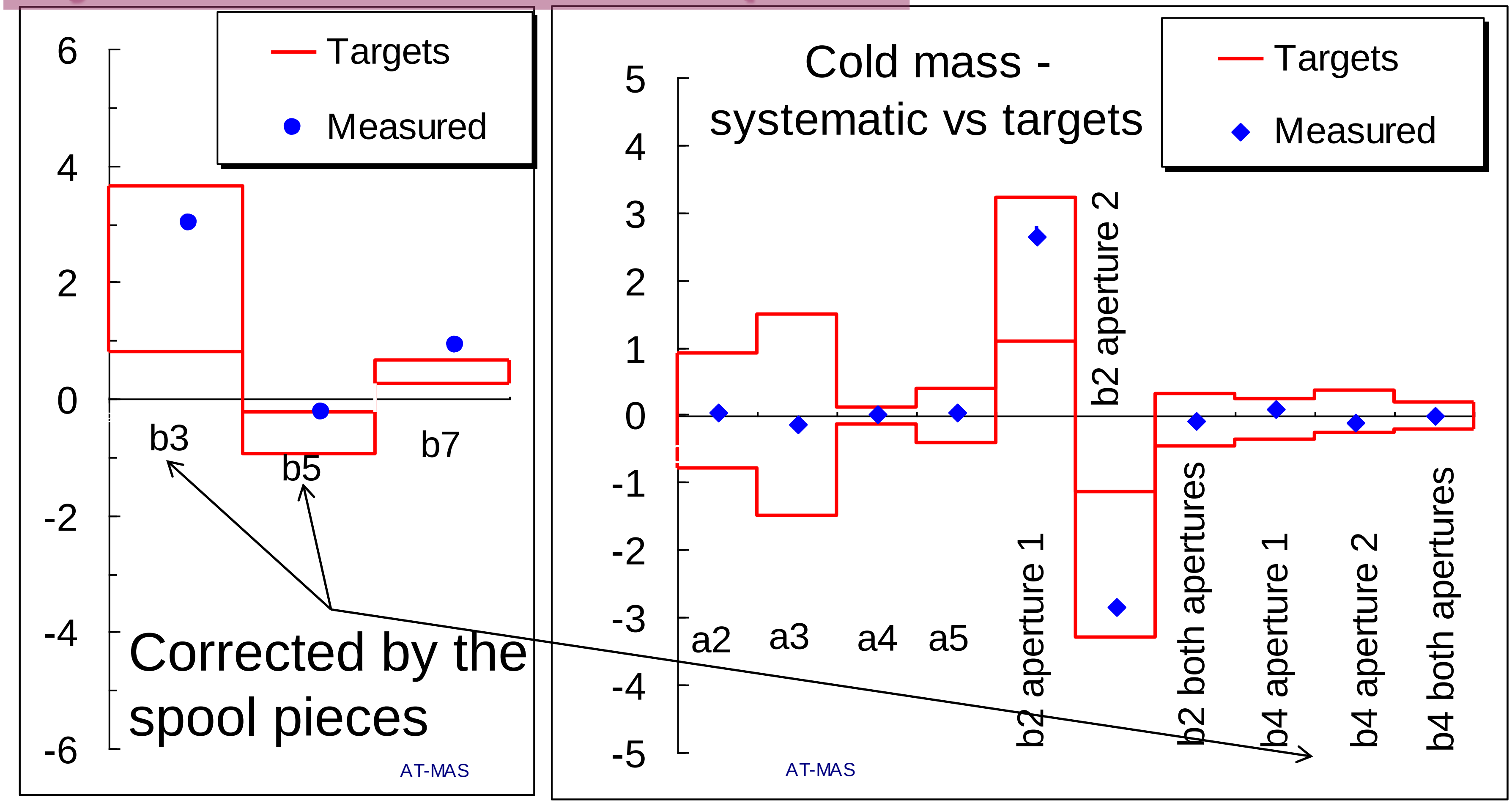
Heat Exchanger Pipe
Beam Pipe

7TeV



Main dipoles - II

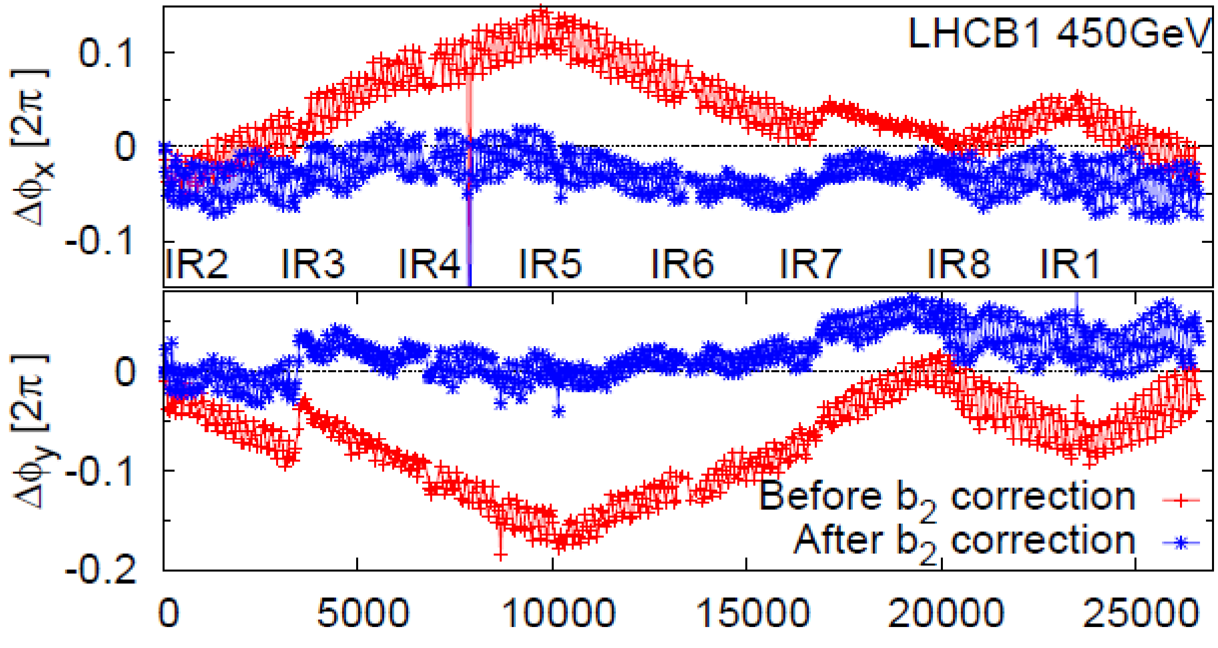
Systematic field errors in dipoles



Other arc correctors - I

- Additional lattice correctors are installed in SSS to correct linear and non-linear effects:
  - Trim quadrupoles: independent tuning of the two rings and compensation of the b2 of main dipoles

Measured phase shift with respect to nominal optics without (red) and with (blue) correction with MQTs



Courtesy R. Tomás - CERN

Other arc correctors - II

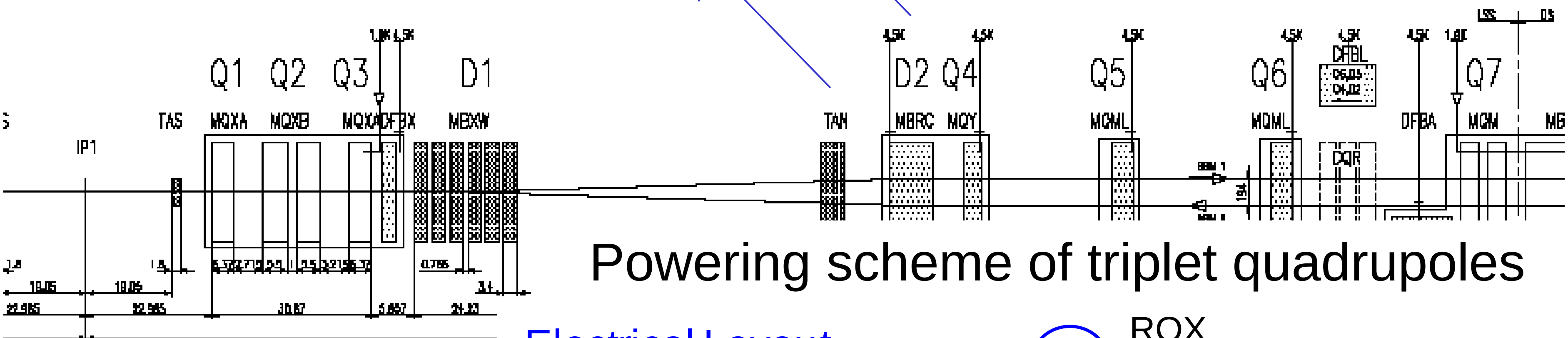
- Skew quadrupoles (some correctors missing in sector 3-4): compensation of linear coupling
- Skew sextupoles (central part of each sector): compensation of a3 effects
- Octupoles: instabilities

LHC layout: IR1/5 - I

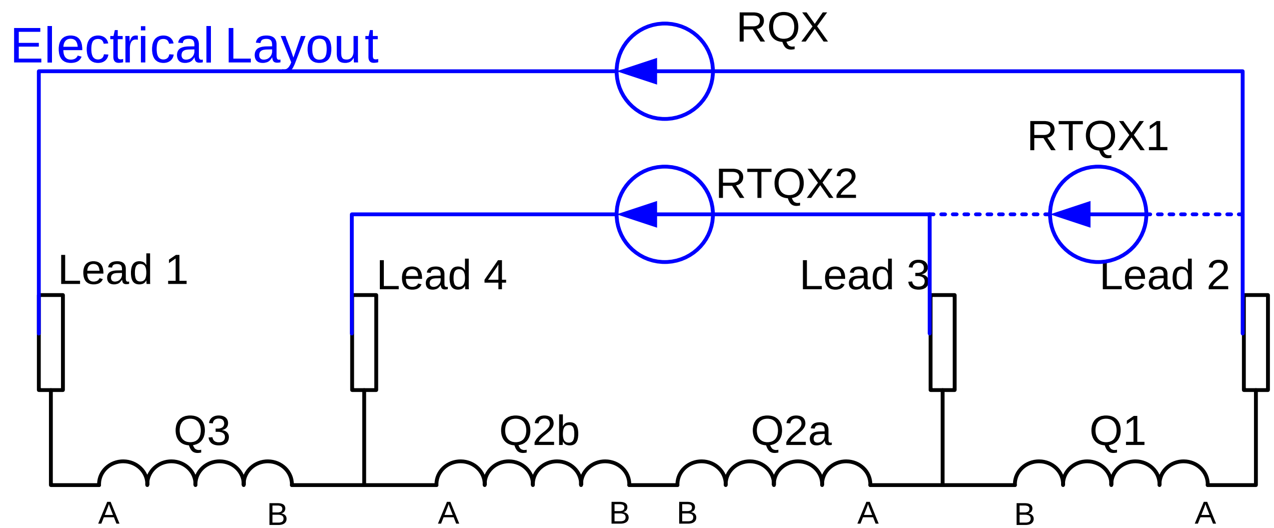
Towards dispersion suppressor and arc

Separation/ricombination dipole

Absorber (neutral particles)



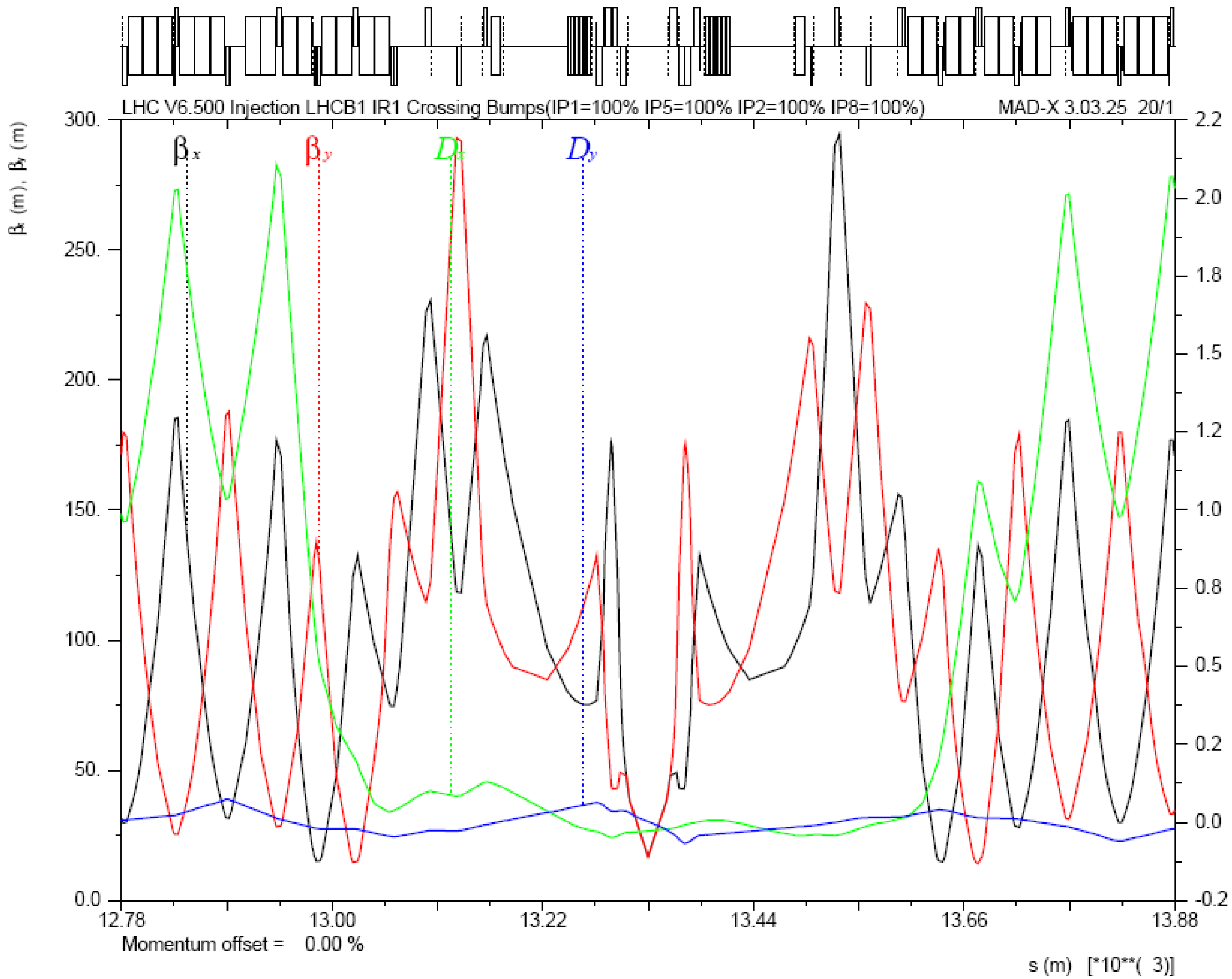
Powering scheme of triplet quadrupoles



Low-b

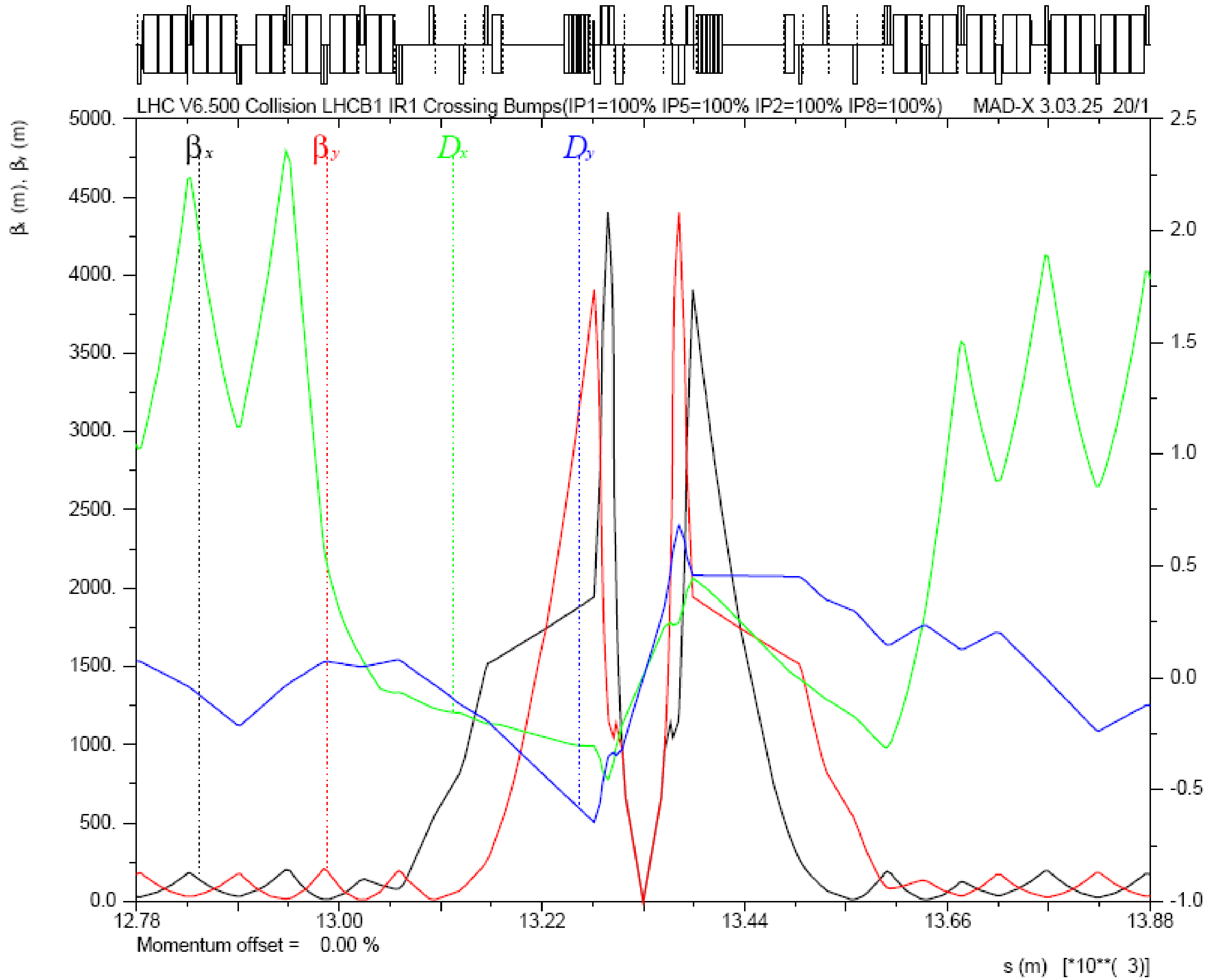
Interaction poi

LHC layout: IR1/5 - II



High luminosity insertions: injection optics. Beta at interaction point equals 11 m.

LHC layout: IR1/5 - III



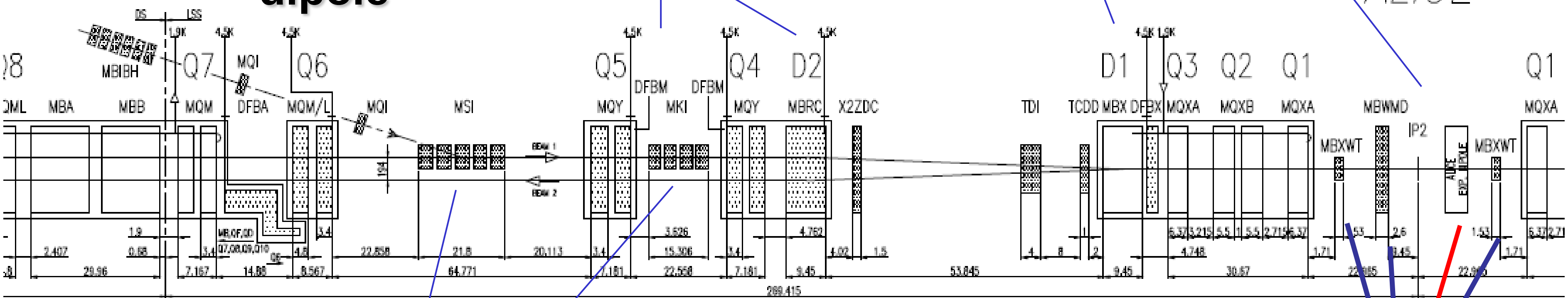
High luminosity insertions: collision optics. Beta at interaction point equals 0.55 m.

LHC layout: IR2/8 - I

Separation/ricombination dipole (SUPERCONDUCTING)

Separation/ricombination dipole

IP ALICE



Injection septum

Injection kicker

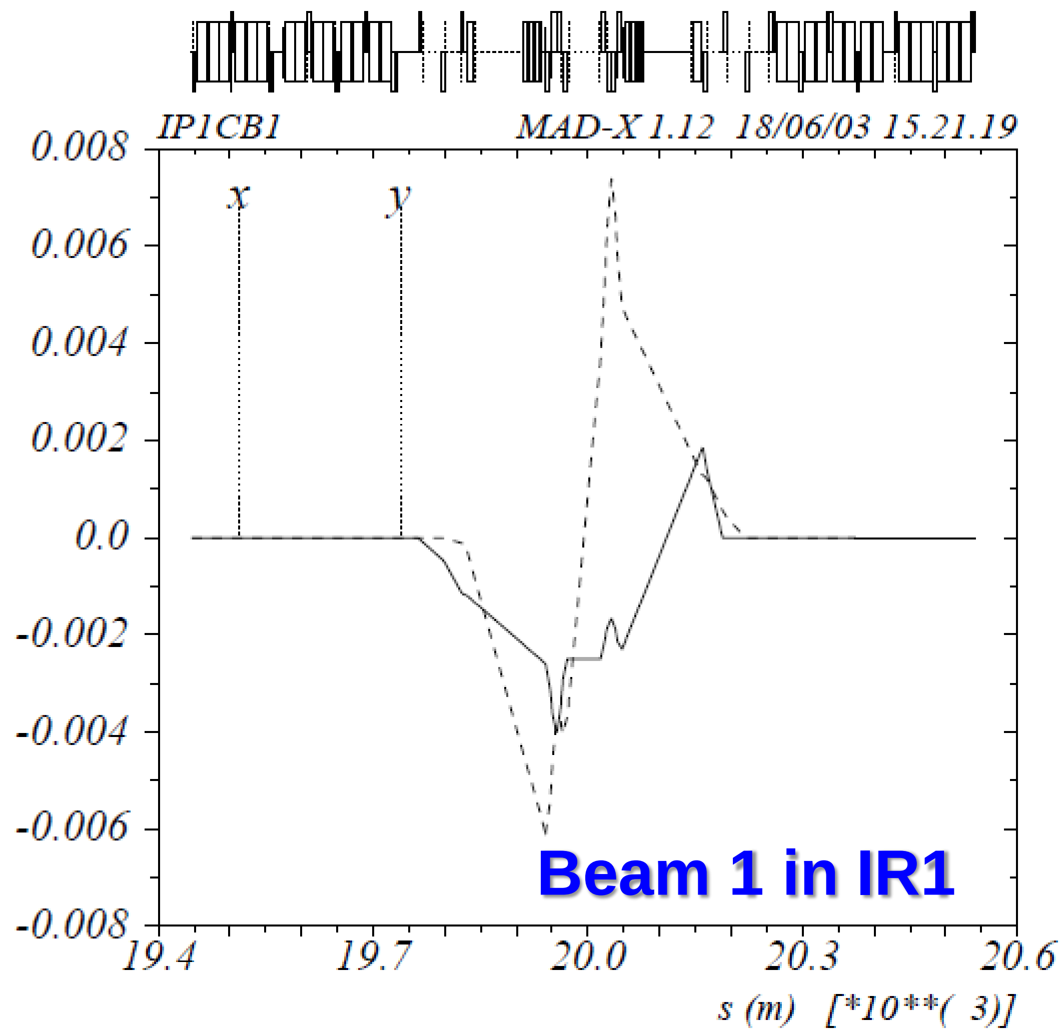
Spectrometer and compensators

LHC layout: IR2/8 - II

- Layout of IR8 is similar apart from a displacement of the IP8 towards IP7 by about 11.25 m
- Injection system and protection devices impose tight constrain on optics (phase advance between key elements)
- Triplets needs to work at higher-than-nominal gradient (220 T/m instead of 205 T/m).
- A stage of strength-reduction at constant beta* is needed before squeeze.

Crossing scheme - I

- To avoid parasi
  in implemented
  - IR1/5: the bum
  - IR2/8: the bum
- Crossing plane
  - IR1/2: V-plane
  - IR5/8: H-plane
- Spectrometers
  - IR2: V-plane, p
  - IR8: H-plane, p



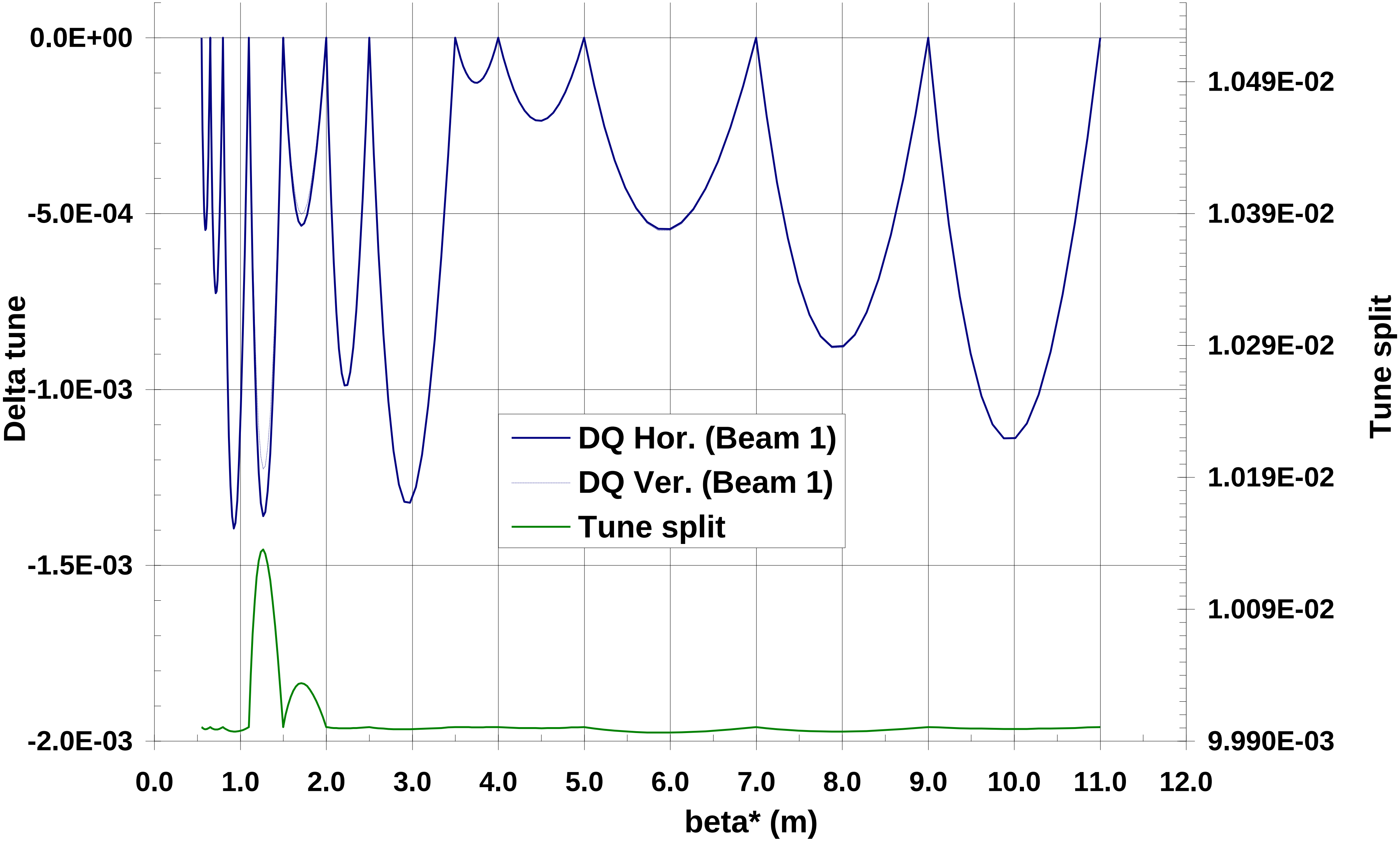
Crossing scheme - II

- Spectrometers and crossing scheme:
  - The real crossing angle is the superposition of:
    - Spectrometer crossing angle (so-called internal angle)
    - External crossing angle (generated by the magnets in the separated region))
- Nominal parameters (IR1/5 for simplicity)
  - Half separation: 2 mm (injection); 0.5 mm (7 TeV)
  - Half crossing angle: 170 μrad (injection); 142.5 μrad (7 TeV).

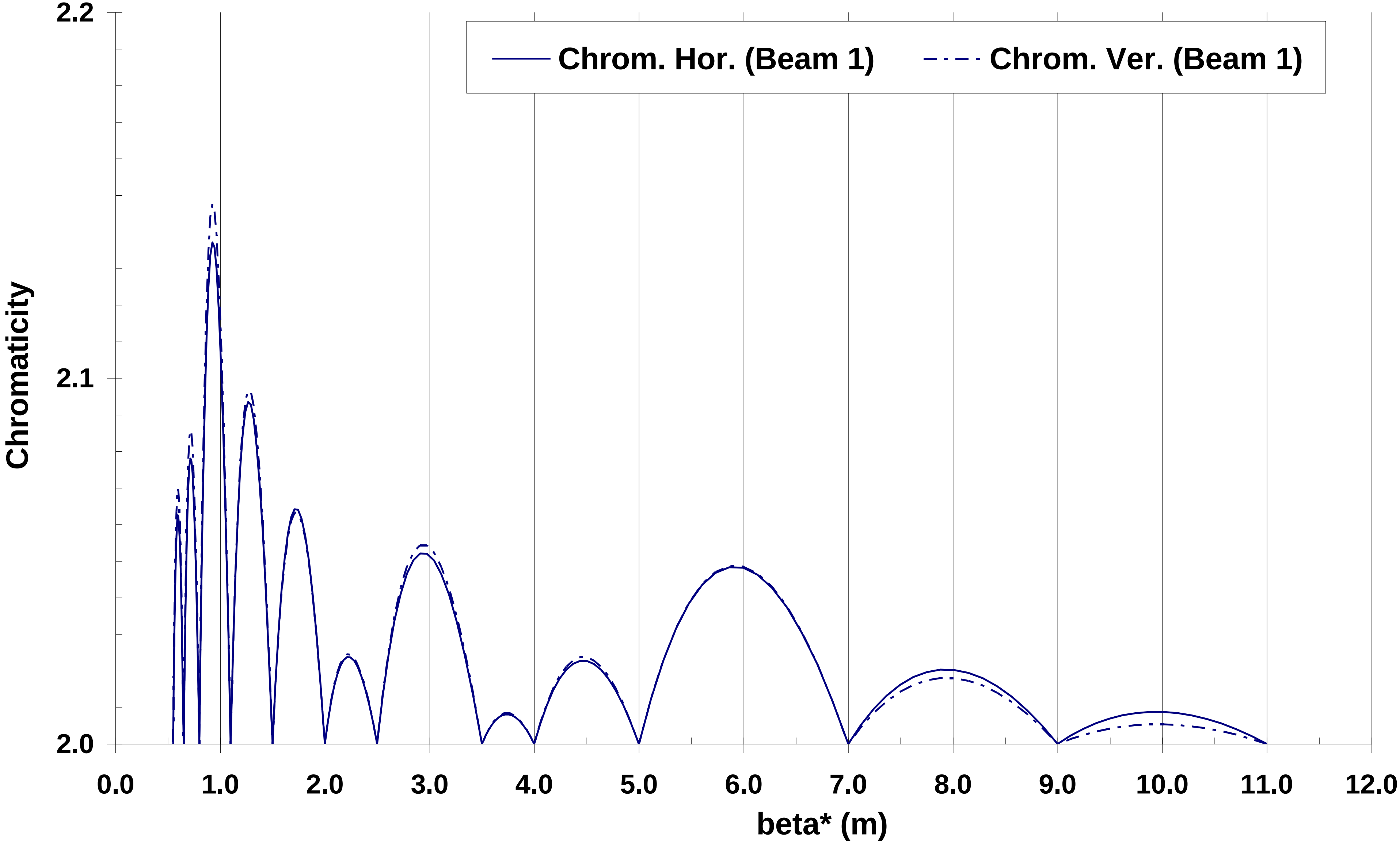
Nominal beta* and squeeze

- Nominal beta*:
  - IR2: 10 m (injection); 10 m (p collision, smaller value during initial commissioning – 0.5 m for Pb collisions)
  - IR8: 10 m (injection): 10 m (collision, smaller value during initial commissioning phases)
  - IR1/5: 11 m (injection); 0.55 m (collision)
- Squeeze challenges (only few listed):
  - Orbit control
  - Optics control (e.g., quadrupoles hysteresis)
  - Aperture
  - Non-linear aberrations below 1 m beta*

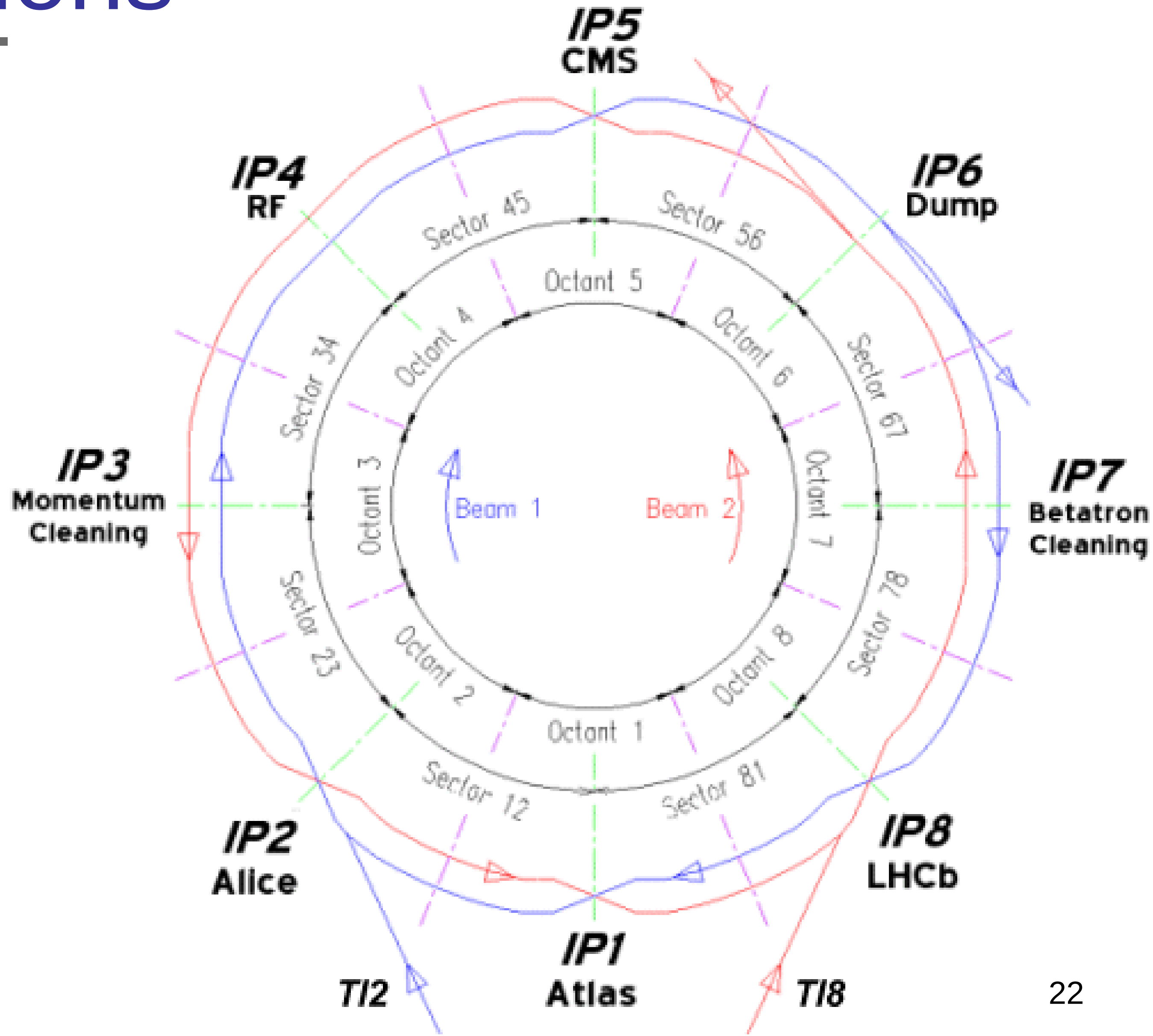
Behaviour of optical parameters during squeeze of IR1 - I



Behaviour of optical parameters during squeeze of IR1 - II

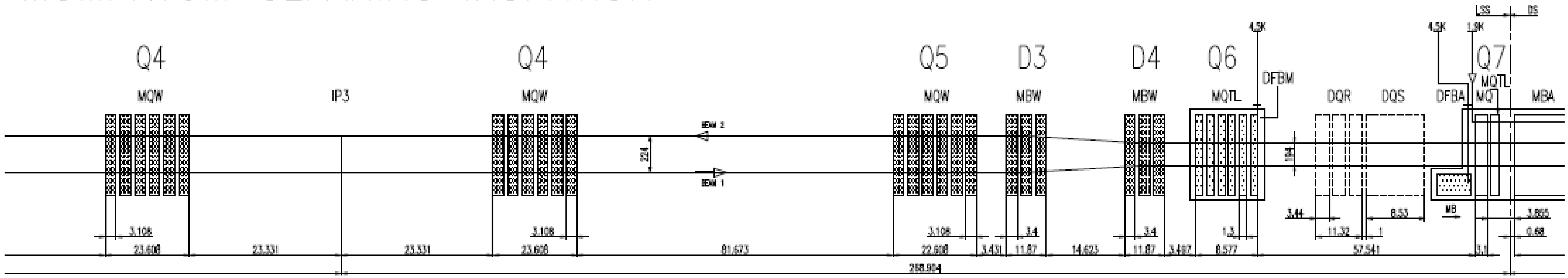


LHC layout: the other insertions



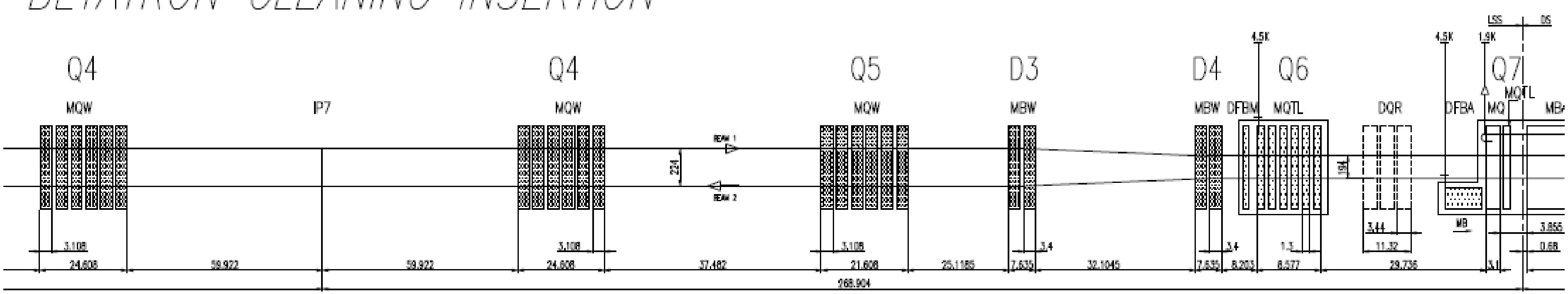
IR3/7: Collimation system - I

MOMENTUM CLEANING INSERTION



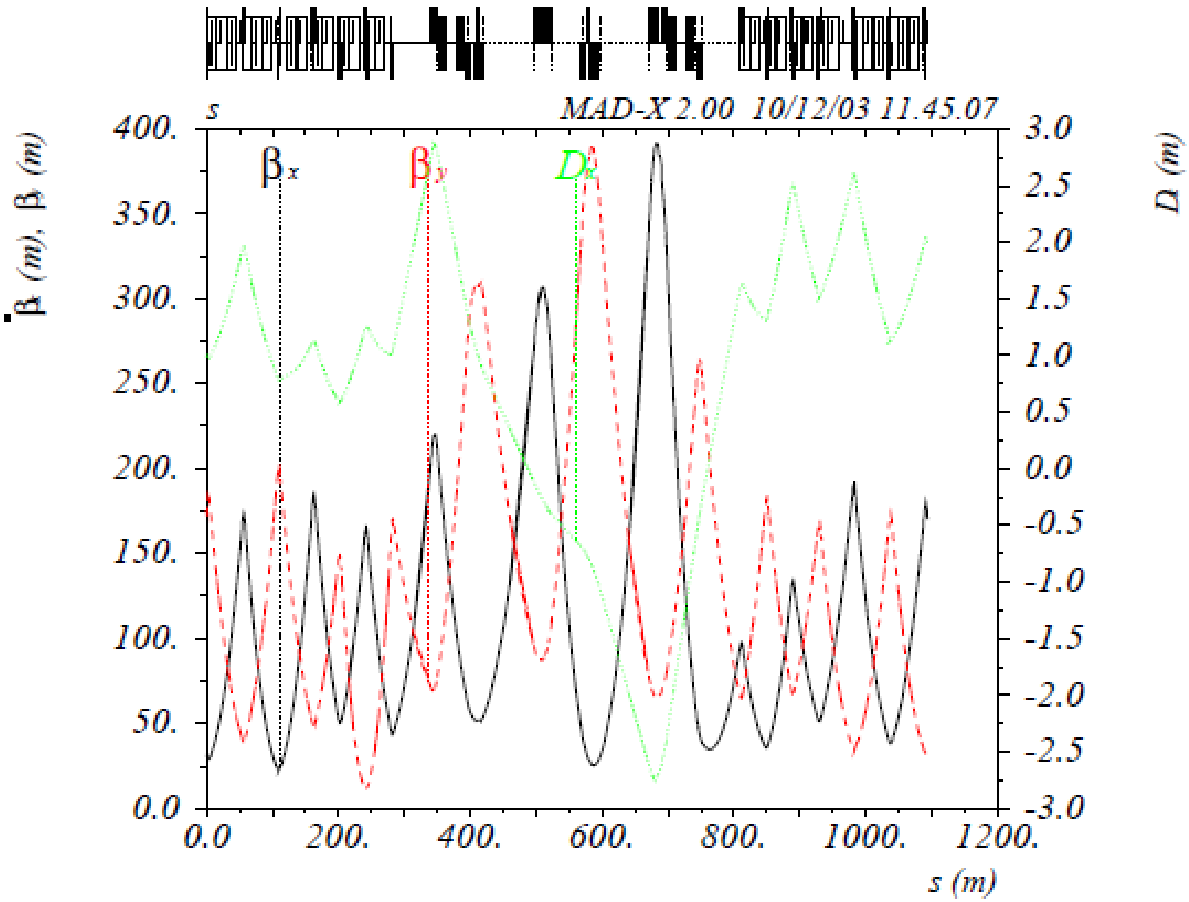
- The magnets in between Q6 (left and right) are normal conducting.
- Difference in dogleg magnets.

BETATRON CLEANING INSERTION



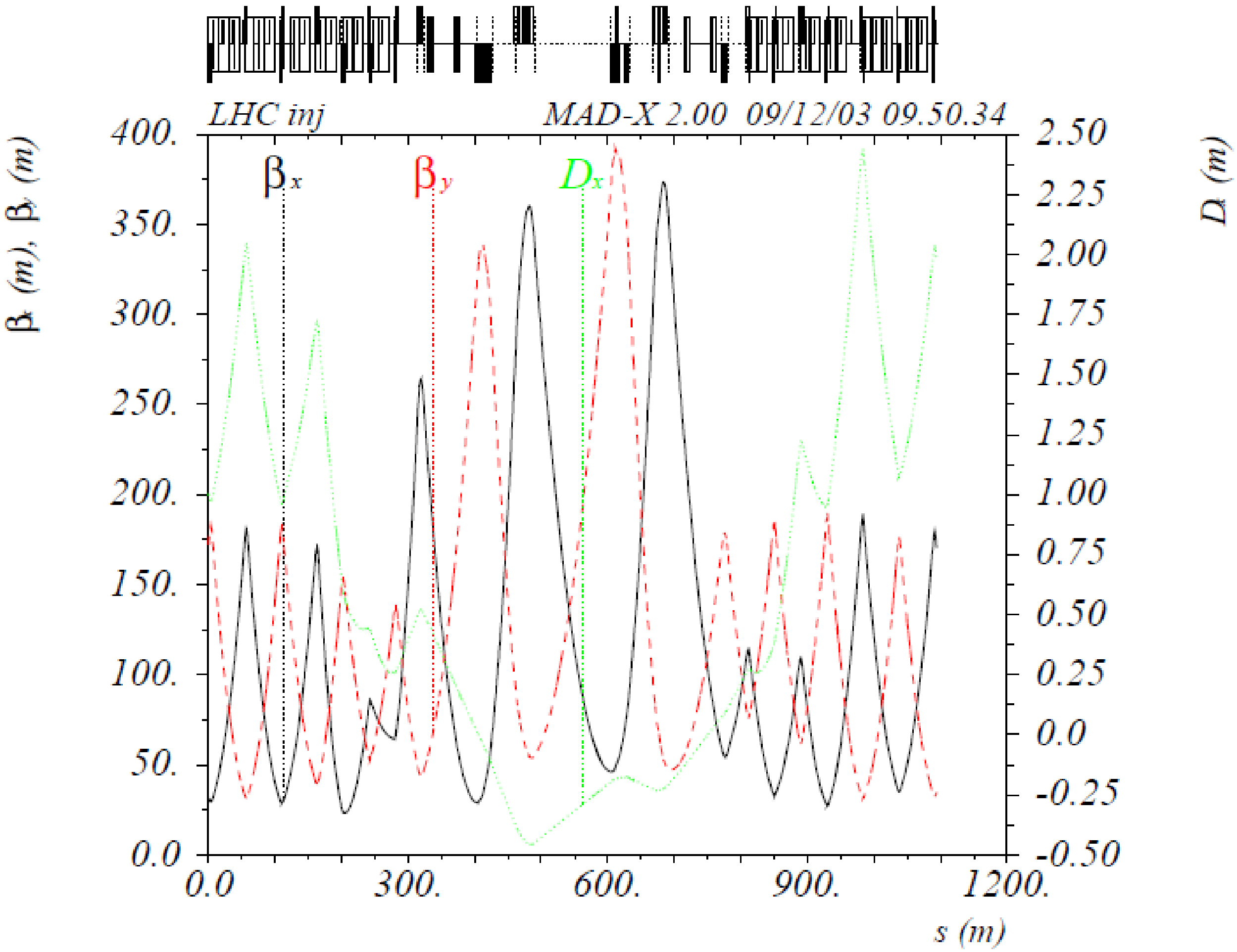
IR3/7: Collimation system - II

- IR3 features a large normalised dispersion to improve momentum collimation.
- A so-called detuned optics (with nominal dispersion exists).

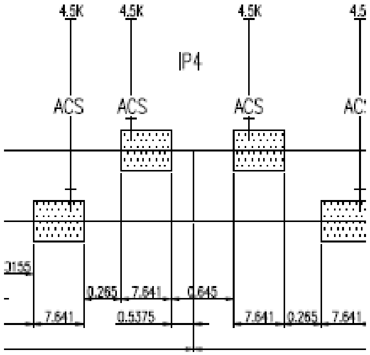


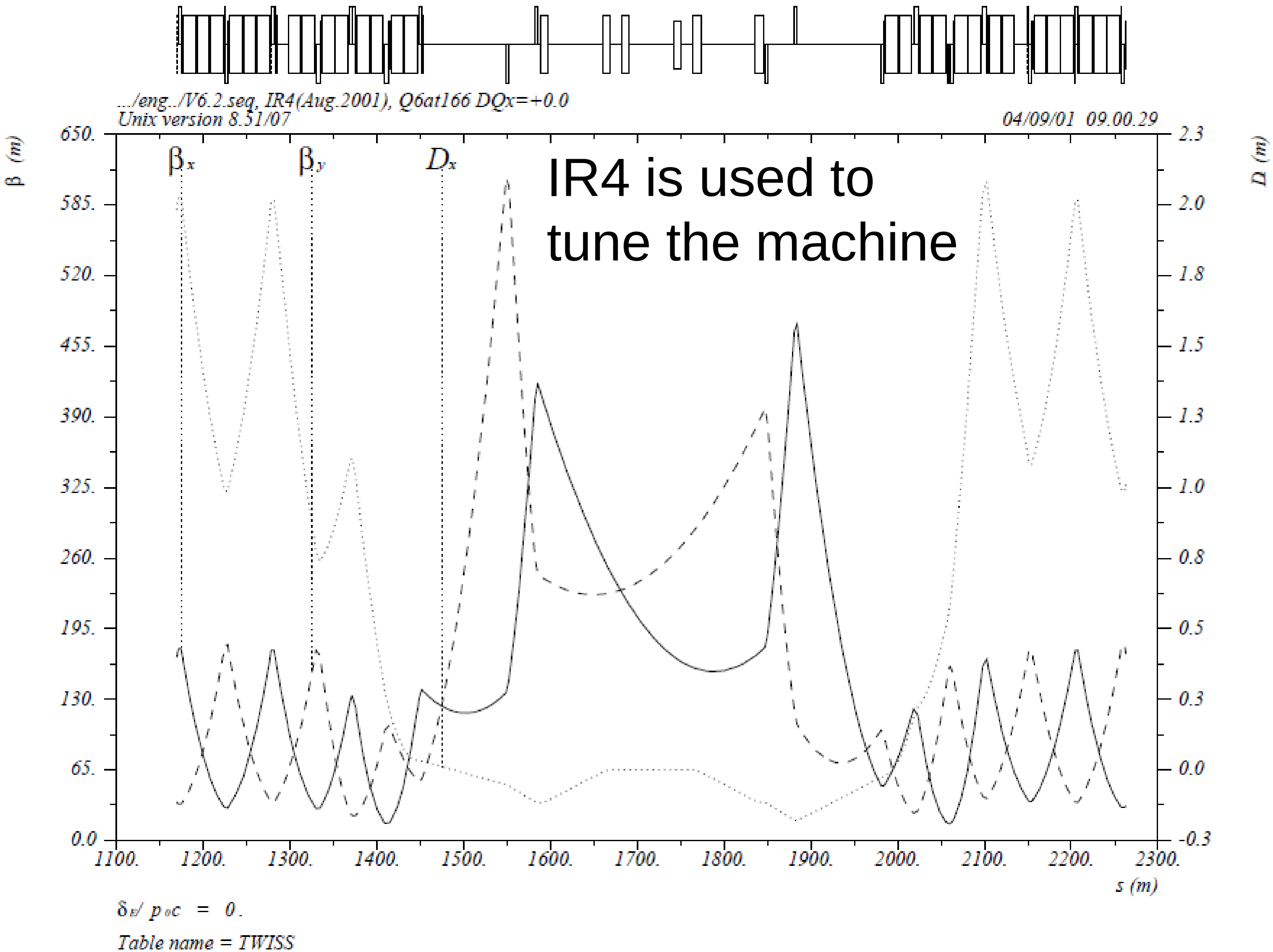
IR3/7: Collimation system - III

- IR7 features a small dispersion to improve betatron collimation.
- For the details of the collimation system see later talks



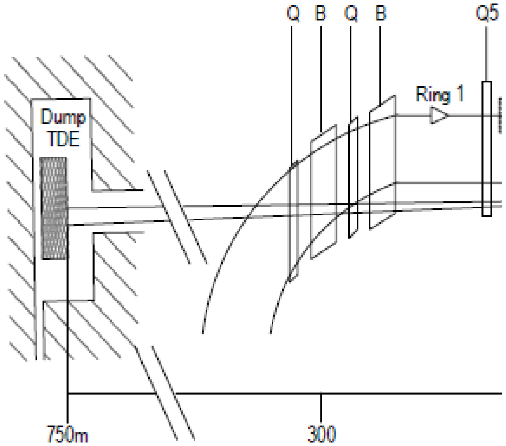
IR4: RF and instrumentation



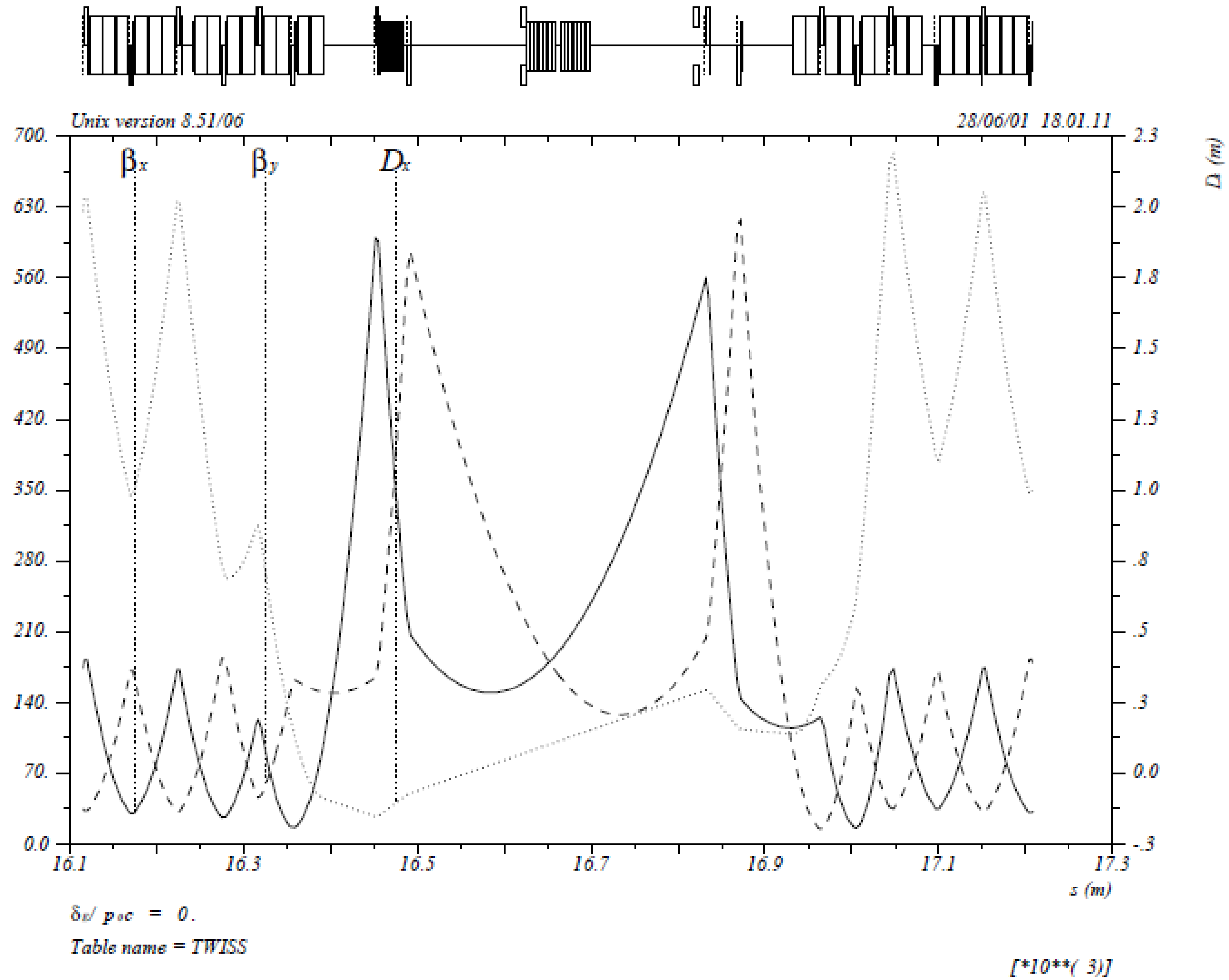


- RF equip
- Instrume transform
- Some fea
  - Larger-
  - Superc
  - Missing

IR6: Beam dumping system



- From the optic
  quadrupoles
  tight aperture
  more details).



Aperture - I

- Key quantity used to measure the available beam aperture in the design phase is “n1”.
- It is not a simple conversion of the mechanical aperture in beam sigmas!
- It is clearly LHC-oriented.
- The computation is implemented in MAD-X
- Its computation is based on
  - Knowledge of mechanical aperture
  - tolerances on key parameters (alignment, orbit, optics)
  - shape of the beam halo generated by interaction with a primary collimator.

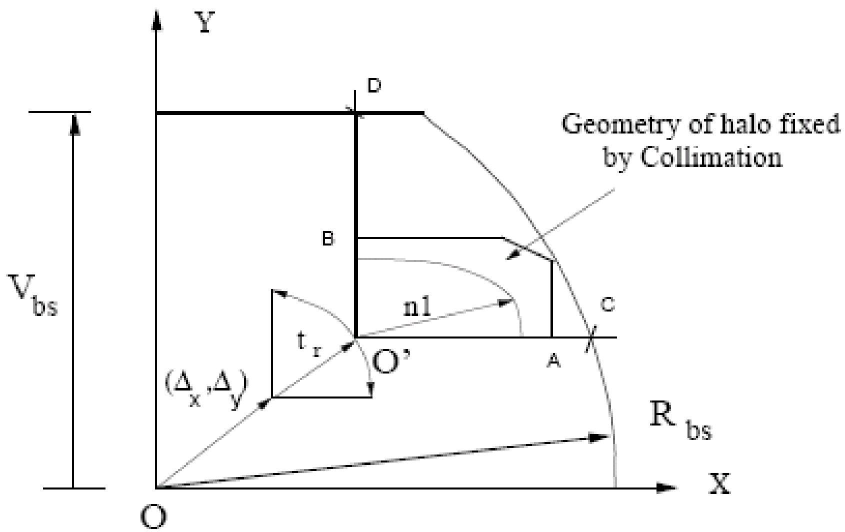
Aperture - II

$$\vec{\Delta}(s) = \vec{d}_{\text{sep}}(s) + \vec{d}_{\text{axis}}(s) + \vec{d}_{\text{inj}}(s)$$

$$\vec{u} = (t_r + CO)(\cos\alpha, \sin\alpha) \quad \text{with} \quad \alpha \,\epsilon\, [0\,,\, \pi/2]$$

$$\vec{d}_{\text{disp}}(s) = (1 + k_\beta)\left[\vec{D} + k_D \frac{D_{\text{x,QF}}}{\sqrt{\beta_{\text{x,QF}}}}\sqrt{\vec{\beta}}\right]\delta_p$$

$$\overrightarrow{OO'}\,(s) = \vec{\Delta}(s) + \vec{u} + \vec{d}_{\text{disp}}(s)$$

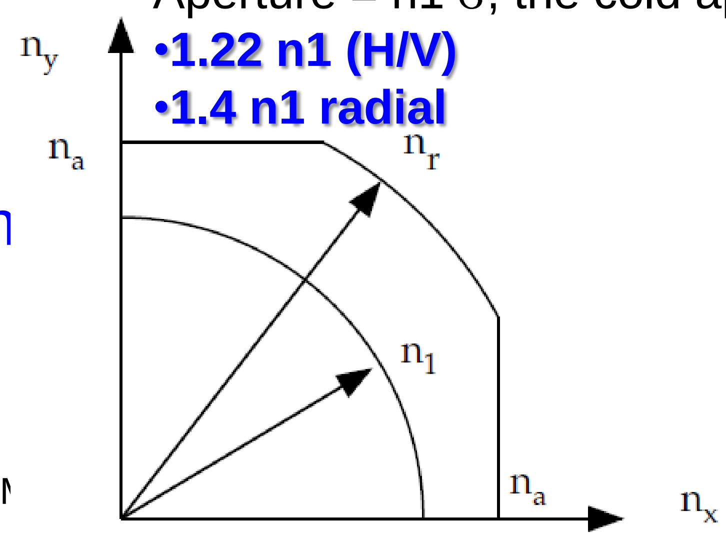


- Nominal parameters:
  - Beta-beating: 20%
  - Closed orbit tolerance: 4 mm (injection); 3 mm (collision)

Aperture = n1 σ, the cold aperture is

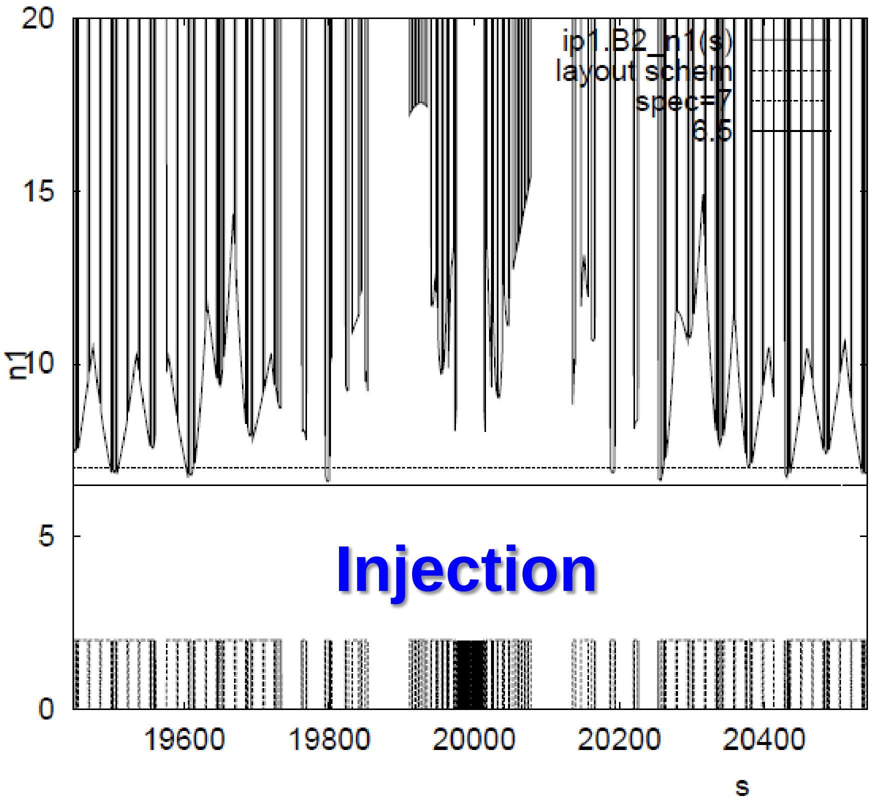
•1.22 n1 (H/V)

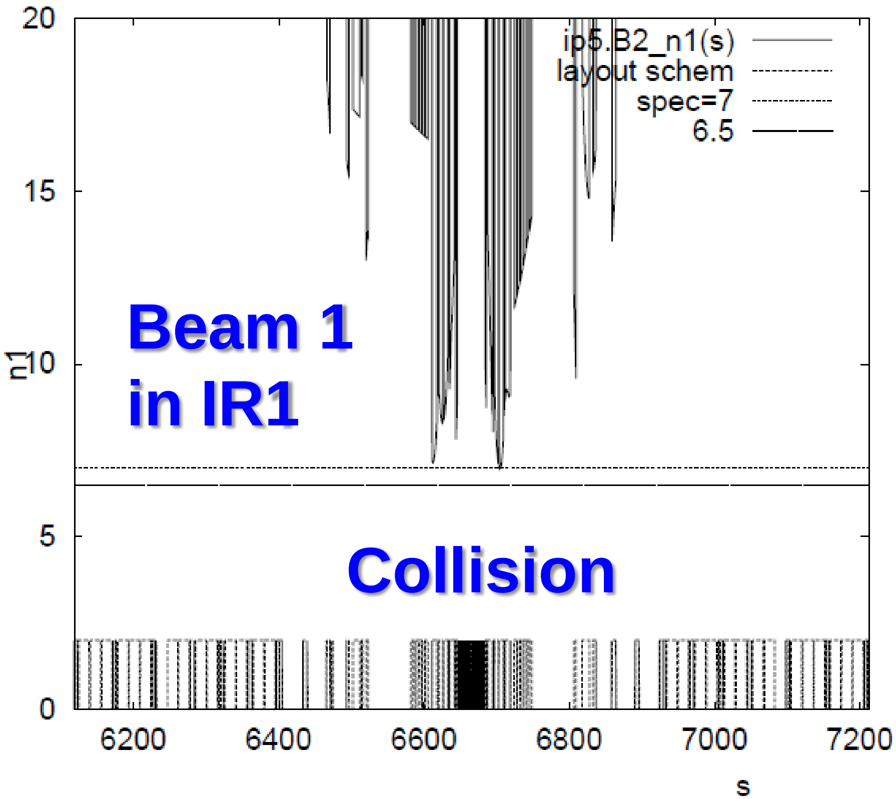
•1.4 n1 radial



Aperture - III

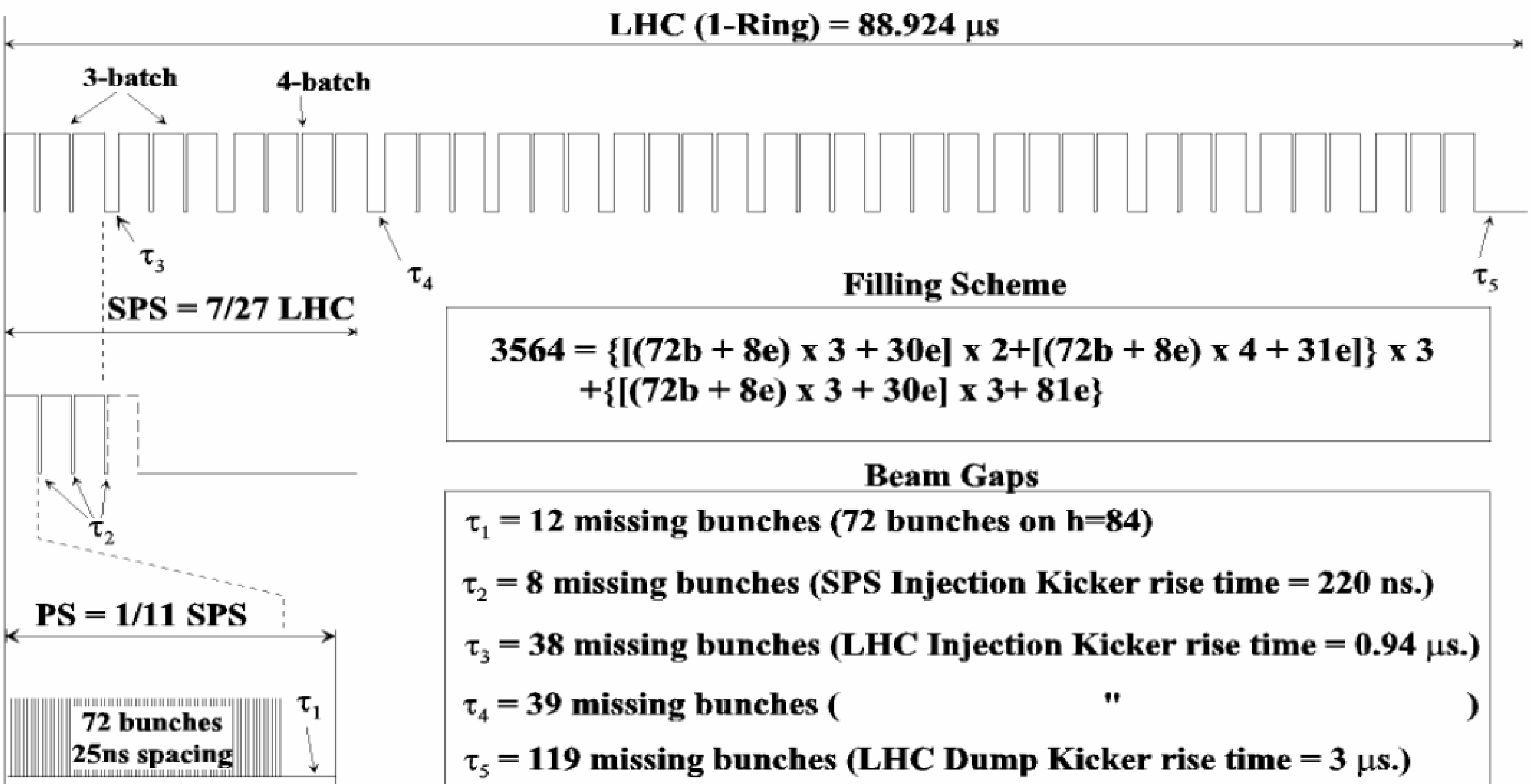
- Design criterion: n1 ≥ 7 σ in superconducting magnets.
- Injection: arcs and dispersion suppressors are the aperture limits
- Collision: triplets are the aperture limits





LHC filling

Bunch Disposition in the LHC, SPS and PS



Filling Scheme

$$3564 = \{[(72b + 8e) \times 3 + 30e] \times 2 + [(72b + 8e) \times 4 + 31e]\} \times 3 + \{[(72b + 8e) \times 3 + 30e] \times 3 + 81e\}$$

Beam Gaps

τ_1 = 12 missing bunches (72 bunches on h=84)

τ_2 = 8 missing bunches (SPS Injection Kicker rise time = 220 ns.)

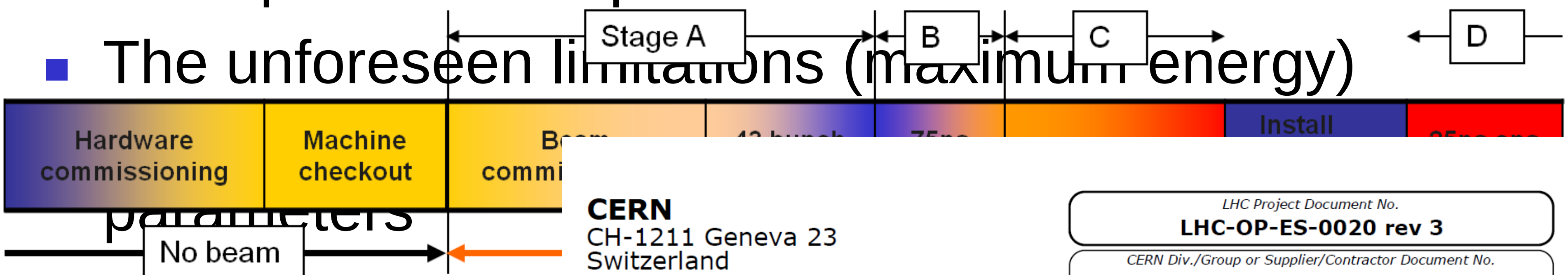
τ_3 = 38 missing bunches (LHC Injection Kicker rise time = 0.94 μs.)

τ_4 = 39 missing bunches (")

τ_5 = 119 missing bunches (LHC Dump Kicker rise time = 3 μs.)

Nominal vs. actual beam parameters

- Beam commissioning needs to be split in stages (which were already outlined in the Design Report) with special beam parameters.
- The unforeseen limitations (maximum energy) … parameters



A complete discussion of the beam parameters for 2010/11 in the next talk…

CERN
CH-1211 Geneva 23
Switzerland

the **Large Hadron Collider** project

LHC Project Document No.
LHC-OP-ES-0020 rev 3

CERN Div./Group or Supplier/Contractor Document No.
LHCCWG

EDMS Document No.
1059898

Date: 2010-03-08

Engineering Specification

LHC BEAM PARAMETERS FOR THE PHYSICS RUN AT 3.5 TEV

Backup material

Other nominal parameters - I

		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

Other nominal parameters - II

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