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LHC MAIN PARAMETERS

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The overall structure of the LHC is briefly described, and a list of parameters is presented. The reasons behind the choice of the most important parameters are outlined.

KEY WORDS: Synchrotrons, superconducting

1 INTRODUCTION

The LHC is a high field, high luminosity collider which will be installed in the 27 km long tunnel of LEP. Its main purpose is to provide proton-proton collisions at a center of mass energy of 14 TeV with a luminosity of up to $10^{34}\text{cm}^{-2}\text{s}^{-1}$. But the LHC can add other strings to its bow since it is foreseen to collide heavy nuclei like lead, and in a later stage to arrange collisions between hadrons in LHC and leptons in LEP. However, for the purpose of this workshop, we will only consider the operation of the LHC with intense proton beams, which is by far the more challenging one as far as collective effects are concerned. The parameters of the LHC have been optimized so as to reach at the same time limits on the beam-beam effects and single bunch current imposed by beam physics, and limits on total beam current imposed by reasonable choices governed by technological and financial considerations. We will give a brief description of the machine structure, before justifying some of the most important choices which lead finally to the parameter tables presented. The operational magnetic field corresponding to a center of mass energy of 14 TeV is 8.65 T in the version presented here, which is called Version 2 and has been well documented in the "White Book".[1] The current working version (at the end of 1994) is Version 4 which has 23 cells per arc compared to 24 for Version 2, and a few other differences. These differences have an insignificant impact on collective effects. As a matter of fact, most of the early evaluations of collective effects in the LHC were done on Version 1, and can be found in the "Pink Book".[2]

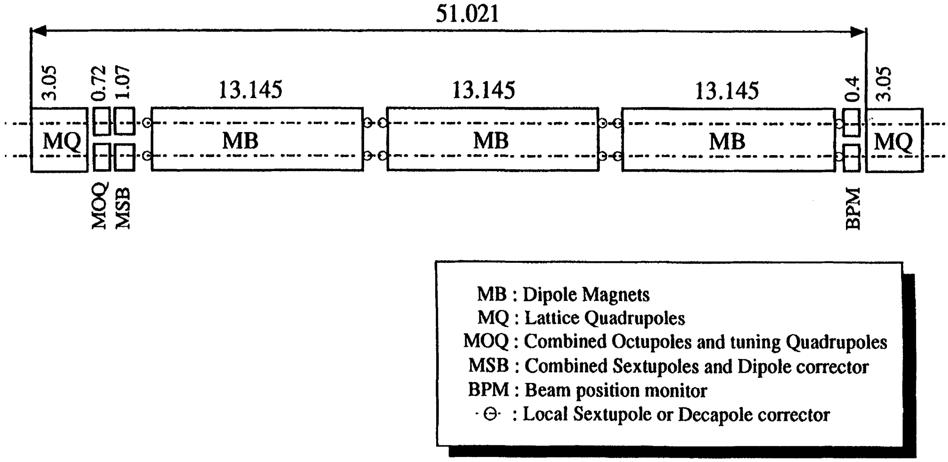

FIGURE 1: Schematic representation of a half-cell (even sector).

2 THE MACHINE STRUCTURE

The LHC has the same overall structure as LEP, with 8 arcs separated by 8 straight sections. Each arc is made up of 24 cells with 90° phase advance (in Version 2), each 50 m long half cell comprising 3 bending magnets, an octupole corrector and a combined dipole and chromaticity sextupole corrector (Figure 1).

Each bending magnet is fitted with two small correcting coils in its ends, to compensate for the systematic part of its sextupole and decapole errors.

The straight sections contain identical dispersion suppressors and different insertions depending on their location around the machine. At present it is foreseen to have the two large pp experiments Atlas and CMS respectively in section 1 and 5, an ion experiment in 2 and a B physics experiment in 8. The two beams cross from the inner to the outer arc or vice versa in the center of these 4 straight sections, whereas they stay parallel and separated horizontally by 18 cm in the other straight sections as they do in the arcs. This gives the machine a twofold symmetry (Figure 2).

The four straight sections which house an experiment are equipped with low beta insertions. Section 3 under the Jura houses the beam halo cleaning insertion using FODO cells made up of classical, room temperature quadrupoles. A similar insertion could be used in section 7 diametrically opposite. Section 6 houses the dump insertion, and section 4 is not used for the time being and could be fitted with a cheap insertion resembling the dump insertion.

The two beams are injected in sections 2 and 8.

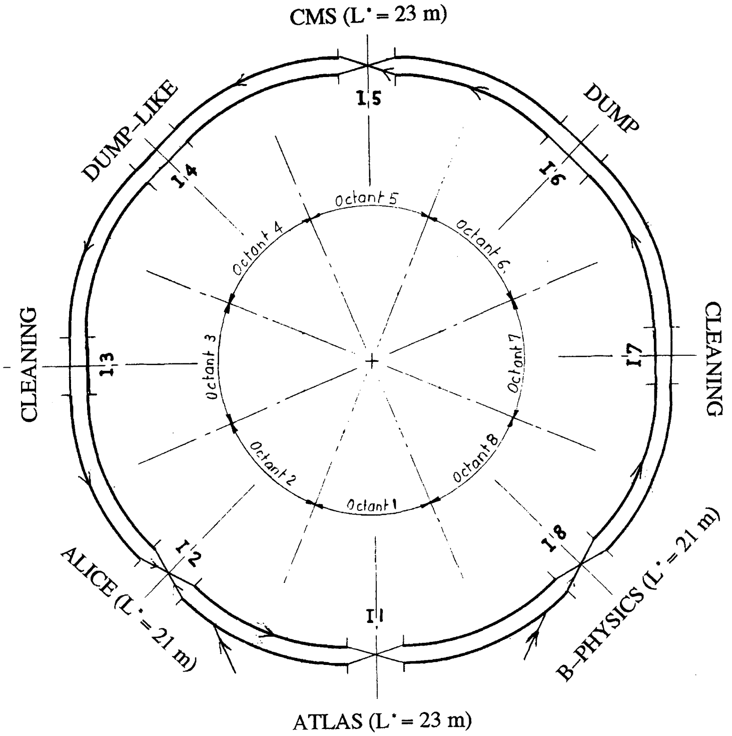

FIGURE 2: LHC Schematic Layout

3 THE BEAM STRUCTURE

Each beam is made up of 2835 bunches of 10^{11} protons each, separated in time by 25 ns. Its detailed structure is governed by the injection scheme and the properties of the dump system. The bunches are formed in the 26 GeV CERN PS with the right 25 ns spacing by adiabatic capture of a previously debunched beam with a 40 MHz RF system. Three trains of 81 bunches each are transferred to the SPS on three consecutive PS cycles and stacked in the SPS one after the other to fill approximately 1/3 of the machine circumference with a total charge of 2.43 10^{13} protons. This is not far from the maximum beam handling capabilities of the SPS.

This beam is thereafter accelerated to 450 GeV and transferred to the LHC. This operation is repeated 12 times for each of the counterrotating beams of the LHC.

At each transfer enough space has to be reserved in between bunch trains to accomodate the risetime of the injection kickers. These holes have a length of 220 ns between each PS batch of 81 bunches (SPS injection kicker risetime) and 0.94 μs between the groups of 3 PS batches (LHC injection kicker risetime).

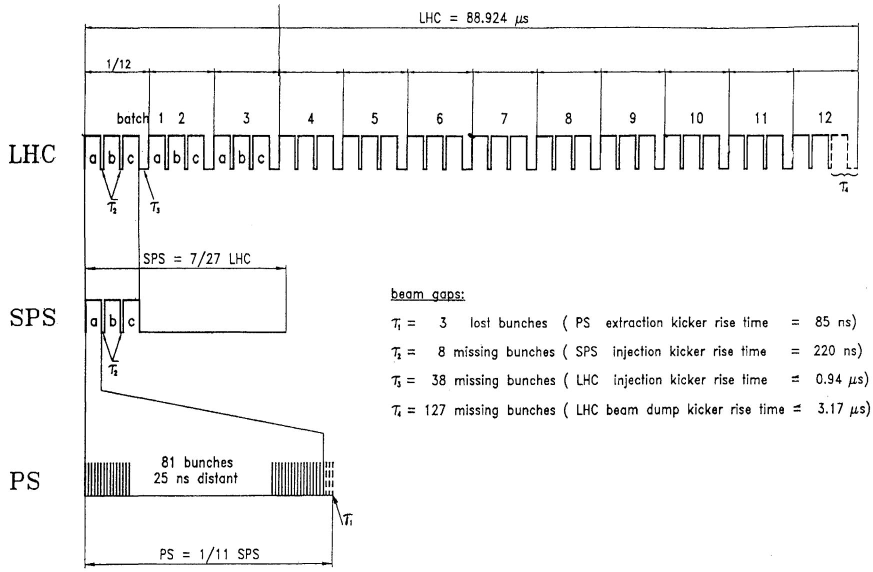

FIGURE 3: Bunch disposition in LHC, SPS and PS.

Finally a longer gap of 3.17 μs has to be reserved to accomodate the risetime of the dump kicker, by eliminating one PS batch in the last transfer. The bunch structure obtained is shown in Figure 3.

It has implications in certain aspects of beam physics, in particular for the long range beam-beam effect.

4 THE BEAM-BEAM EFFECT

The most important limitation to luminosity comes from the beam-beam interaction. This effect has two components in the case of the LHC. There is the unavoidable head-on interaction of the colliding beams at the wanted interaction points and there is also the long-range interaction which occurs on either side of the interaction regions in the common stretch of the beam pipe in which both beams run side by side. The importance of the head-on interaction is determined by the beam-beam tune shift parameter ξ

$$\xi = N r_{\rm p}/4\pi\varepsilon_n,$$

where N is the number of protons per bunch, ε_n the normalized emittance and r_p the classical proton radius. The long-range interaction depends on the total beam current and the crossing geometry. The head-on interaction excites high-order betatron resonances and creates a tune spread across the beam distribution, while the long-range interaction essentially adds

TABLE 1: The LHC list of parameters.

Ring Parameters			
Circumference	$2\pi R$	m	26658.87
Revolution frequency (β=1)	f_{rev}	kHz	11.24551
Revolution period	T_{rev}	μs	88.924
Dipole bending radius	ρ	m	2700.27
Orbit separation		mm	180
Free space for detectors		m	32
Cell length		m	102.042
Number of cells per arc			24
Horizontal tune	Q_{h}		68.28
Vertical tune	Q_{v}		68.31
Phase advance per cell	ϕ_{β}		90
Max. beta value	β_{max}	m	172.8
Min. beta value	β_{min}	m	30.3
Max. dipersion	D_{max}	m	2.02
Min Dispersion	D_{min}	m	0.98
Ramping time		s	1200
RF frequency	f_{rf}	MHz	400.8
Harmonic number	h_{rf}		35640
Number of single-cell cavities			8
Number of klystrons			8
Cavity R/Q		Ω	44
External Q	Q_{ext}		6.6×10^{4}
Momentum compaction factor	α_p		2.94×10^{-4}

a contribution to the tune spread. Experience at the SPS proton-antiproton collider has shown that both the beam-beam parameter ξ and the total tune spread have to stay below certain limits. The total tolerable tune spread is limited by the maximum area of the tune diagram free of resonances of order less than 12. Such areas exist close to the diagonal in the vicinity of low order resonances. In the case of the SPS the best working point was close to the 1/3 resonance where a tune spread up to 0.02 could be accomodated. In a superconducting machine like the LHC, the strong excitation of the 1/3 resonance due to magnet errors is likely to further reduce this value. Therefore we have based the LHC nominal performance on a total tune spread of 0.015, of which 0.01 comes from the beam-beam effect and the remaining 0.005 from the machine non linearities. This is evaluated for particles with an amplitude of 4σ. With two experiments operating simultaneously, the corresponding luminosity is $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. In case a beam-beam tune spread of 0.015

TABLE 2: The LHC list of parameters: proton–proton collider design parameters.

Proton collider (Design parameters)			
Energy	E	TeV	7.0
Dipole field	B	T	8.65
Luminosity	$\mathcal{L}$	$cm^{-2}s^{-1}$	10^{34}
Beam–beam parameter	ξ		0.0032
Total beam–beam tune spread*			0.01
Injection energy	E_i	GeV	450
Circulating current/beam	I_{beam}	A	0.53
Number of bunches	k_b		2835
Harmonic number	h_{rf}		35640
Bunch spacing	τ_b	ns	25
Particles per bunch	n_b		1×10^{11}
Stored beam energy	E_s	MJ	332
Normalized transverse emittance: $(\beta\gamma)\sigma^2/\beta$	ϵ^*	mrad	3.75×10^{-6}
R.m.s bunch length	σ_s	m	0.075
Collisions			
Beta-value at I.P.	β^*	m	0.5
R.m.s. beam radius at I.P.	σ^*	μ m	16
R.m.s. divergence at I.P.	σ'^*	μ rad	32
Luminosity per bunch collision	$\mathcal{L}_b$	cm^{-2}	3.2×10^{26}
Crossing angle	ϕ	μ rad	200
Number of events per crossing	n_e		19
Beam lifetime	τ_b	h	22
Luminosity lifetime	τ_l	h	10
Nuclear events per IP per s	n_{nucl}	s^{-1}	1.0×10^9
Inelastic events per IP per s	n_{inel}	s^{-1}	6.0×10^8
Elastic events per IP per s	n_{elst}	s^{-1}	4.0×10^8
Synchrotron radiation (top energy)			
Energy loss per turn	U_0	keV	6.9
Critical photon energy	u_c	eV	45.6
Total radiated power per beam	P_s	kW	3.7
Power per unit length for two beams	P_m	$W\ m^{-1}$	0.44
Transverse damping time	τ_x	h	24.9
Longitudinal damping time	τ_s	h	12.5

*With two high-luminosity IP + distant crossings.

TABLE 3: LHC list of parameters: proton–proton collider design parameters (cont.)

Proton collider (Design parameters cont.)			Injection	Collision
Intrabeam scattering				
Horizontal growth time	τ_h	h	45	100
Longitudinal growth time	τ_p	h	33	60
Radiofrequency				
RF voltage	V_{rf}	MV	8	16
RF power (peak)	P_{rf}	MW	1.65	1
Beam-loading-induced detuning		kHz	13.7	8.6
Synchrotron tune	Q_s		5.5×10^{-3}	1.9×10^{-3}
Bunch area (2σ)	A_b	eV/s	1	2.5
Bucket area	A_{rf}	eV/s	1.46	8.7
Bucket half-height	$\Delta p/p$		1×10^{-3}	3.6×10^{-4}
R.m.s bunch length	σ_s	m	0.13	7.5×10^{-2}
R.m.s energy spread	σ_e		4.5×10^{-4}	1.0×10^{-4}

could be eventually accomodated after fine tuning of the machine, the beam-beam limited luminosity could reach $2.5\ 10^{34}\text{cm}^{-2}\text{s}^{-1}$. The machine hardware is designed to allow this possibility, in which the bunch population increases from 10^{11} to $1.7\ 10^{11}$ protons.

5 RF AND BUNCH PARAMETERS

The bunch length must be small enough to keep the unavoidable degradation of luminosity due to the beam crossing angle tolerable. The longitudinal emittance on the other hand must be sufficiently large to reduce the Intra Beam Scattering induced growth rate of the transverse emittances, both at injection and in collision. Both conflicting requirements are satisfied with an RF operating at 400 MHz and a bunch longitudinal emittance of 1 eVs at injection and 2.5 eVs at 7 TeV. The RF voltage needed to achieve that is modest (8 MV at injection and 16 MV in collision) and is provided by 8 superconducting cavities. These have the advantage of a very low coupling impedance (very large beam pipe diameter) and allow to control the very severe beam loading conditions. The R.M.S. bunch length is 13 cm at injection and 7.5 cm in collision.

6 VACUUM CHAMBER AND BEAM SCREEN

Each beam emits in the nominal conditions 3.7 kW of synchrotron radiation, which has to be absorbed in the surrounding pipe. In addition, a comparable amount of power is dissipated in the walls by the beam induced image currents. It would be excessively expensive to absorb

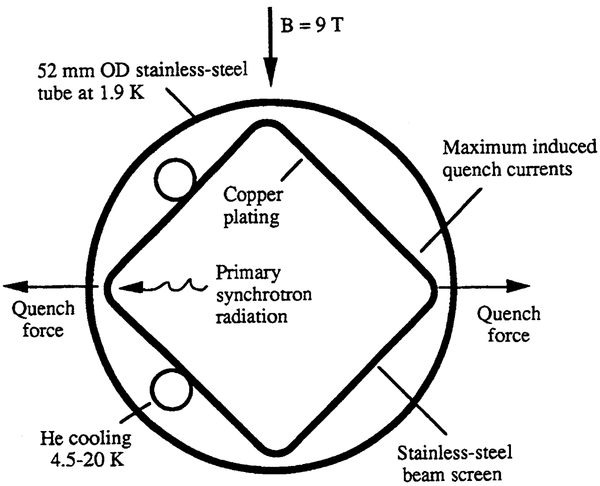

FIGURE 4: A schematic diagram of the square-section beam screen.

all this power in the vacuum chamber which is cooled, as the entire magnetic cold mass, to 1.9 K. Therefore it is foreseen to place an additional pipe, the "beam screen" inside the vacuum chamber. The beam screen will be separately cooled by helium gas at a temperature much higher than 1.9 K, say 20 K.

However, the molecules which are desorbed from the walls of the beam screen by impinging synchrotron radiation photons cannot be cryopumped with the required efficiency at temperatures higher than a few K. Therefore holes have to be drilled in the walls of the beam screen to allow these molecules to escape from the beam enclosure and be absorbed safely on the walls of the vacuum chamber at 1.9 K, which are not exposed to synchrotron radiation. These holes, which must cover about 5% of the beam screen surface, present an interesting problem as far as the electromagnetic interaction of the beam with its surroundings is concerned. A large amount of work has already been devoted to the understanding of their properties in terms of coupling impedance and beam power leakage into the coaxial structure between beam screen and outside vacuum chamber.

The dimensions and shapes of the holes have been chosen to minimize the detrimental electromagnetic effects while providing the necessary pumping speed. A cross section of the proposed beam screen is shown in Figure 4.

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2. Design study of the LHC CERN 91–03 (1991).