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REQUIREMENTS OF THE LHC ON ITS INJECTORS

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The LHC reaches its nominal intensity at the beam–beam limit. This fixes the value of the transverse bunch density that has to be provided by the injectors namely $N/\varepsilon_n = 1.05 \cdot 10^{11}/3.75 \cdot 10^{-6}\,\mathrm{m}$. During the commissioning phase the beam density will be significantly smaller than nominal, but the transverse density should keep its nominal value for maximum performance. The longitudinal bunch emittance at injection must be in the range from 0.5 eV s to 1 eV s.

Keywords: Emittance; Injection; Intensity

1 INTRODUCTION

There are two main challenges involved in the design of the LHC. The first concerns the very high magnetic field which is required to reach collision energies in the TeV range at the constituent level of the protons. The second is the very high luminosity necessary to provide significant event rates at this energy. The luminosity is given by a formula which can be cast into the following form:[1]

$$L = \frac{\gamma}{4\pi e}\frac{1}{\beta^*}\left[\frac{N}{\varepsilon_n}\right][Nkfe]F \tag{1}$$

where γ is the relativistic factor, e the electron charge, f the revolution frequency, N the number of protons in each of the k bunches, ε_n

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the normalized transverse emittance, β^* the value of the betatron function at the collision point, and F the reduction factor caused by the crossing angle, about 0.9 in the LHC.

The first bracket represents the transverse bunch density. It is limited by the space–charge effects in the injectors and, more importantly, by the head-on beam–beam interaction in collision. The second bracket is the total current in one beam. It is limited by the collective instabilities, the cryogenic load arising from synchrotron radiation and induced wall currents, and the ability to handle the large beam stored energy without quenching the magnets.

The nominal parameters of the LHC are shown in Table I. They were found after many iterations involving the variables in equation 1. The required luminosity of $L = 10^{34}\,\mathrm{cm^{-2}s^{-1}}$ is reached in two interaction regions active at the same time with $k = 2835$ bunches of $N = 1.05 \cdot 10^{11}$ protons each, and a transverse emittance $\varepsilon_n = 3.75 \cdot 10^{-6}\,\mathrm{m}$. The value of β^* is 0.5 m, the minimum attainable with present day technology and the LHC interaction region geometry.

The beam current is 0.53 A, and the number of protons per beam $2.98 \cdot 10^{14}$. We will first examine how this large number of particles

TABLE I LHC performance parameters

Energy	E	[TeV]	7.0
Dipole field	B	[T]	8.4
Luminosity	L	$[\mathrm{cm^{-2}s^{-1}}]$	10^{34}
Beam–beam parameter	ξ		0.0034
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]	24.95
Particles per bunch	n_b		$1.05 \cdot 10^{11}$
Stored beam energy	E_s	[MJ]	334
Normalized transverse emittance $(\beta\gamma)\sigma^2/\beta$	ε_n	[μm.rad]	3.75
Collisions			
β-value at I.P.	β^*	[m]	0.5
r.m.s. beam radius at I.P.	σ^*	[μm]	16
r.m.s. divergence at I.P.	σ'^*	[μrad]	32
Luminosity per bunch collision	L_b	$[\mathrm{cm^{-2}}]$	$3.14 \cdot 10^{26}$
Crossing angle	ϕ	[μrad]	200
Number of events per crossing	n_c		19
Beam lifetime	τ_{beam}	[h]	22
Luminosity lifetime	τ_L	[h]	10

can be provided by the existing CERN complex of accelerators. Then we will discuss the importance of the transverse emittance and of the longitudinal bunch parameters.

2 INJECTING THE REQUIRED BEAM INTENSITY

The ratio of SPS and LHC circumference is 7/27. The record beam charge accelerated up to now in the SPS is $4.6 \cdot 10^{13}$ p, and the machine works reliably at around $4 \cdot 10^{13}$ p/cycle. This is insufficient to fill the LHC with the minimum number of SPS cycles which is 4. Therefore we have based the LHC injection sequence on 12 SPS cycles. In this way the SPS accelerates only $2.55 \cdot 10^{13}$ p/cycle, although with a beam concentrated over about one third of the circumference, that is with a large local density. Moreover this scheme should allow later on to reach the "ultimate" luminosity of $2.5 \cdot 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in the LHC, which requires $1.66 \cdot 10^{11}$ protons per bunch instead of $1.05 \cdot 10^{11}$ for the nominal case, that is $3.83 \cdot 10^{13}$ p/cycle in the SPS instead of $2.55 \cdot 10^{13}$. Using 12 cycles has the additional advantage that one can place the subsequently injected batches in the LHC so as to provide a four-fold symmetry of the bunch sequence around the machine. This ensures that all bunches find a colliding partner in the other beam at each of the 8 possible crossing points.

Concentrating the beam in a small fraction of the SPS circumference poses severe transient beam-loading problems. On the other hand it allows sophisticated RF gymnastics like rephasing the cavities voltage at each turn during the gap. The SPS is loaded by 3 PS cycles, each of them accelerating $8.5 \cdot 10^{12}$ p, a comfortable value for the PS.

Figure 1 shows the bunch disposition in the LHC, SPS and PS. The harmonic number in the LHC with a 400 MHz RF is 35640. The wavelength is 0.75 m or 2.5 ns, and we chose to fill only every tenth RF bucket to obtain bunches separated by 25 ns, a value well suited for the experiments and allowing at the same time a good optimisation of the machine performance. In order to accommodate the risetimes of the different injection kickers and of the dump kicker, a number of gaps have to be provided in the bunch sequence, as seen

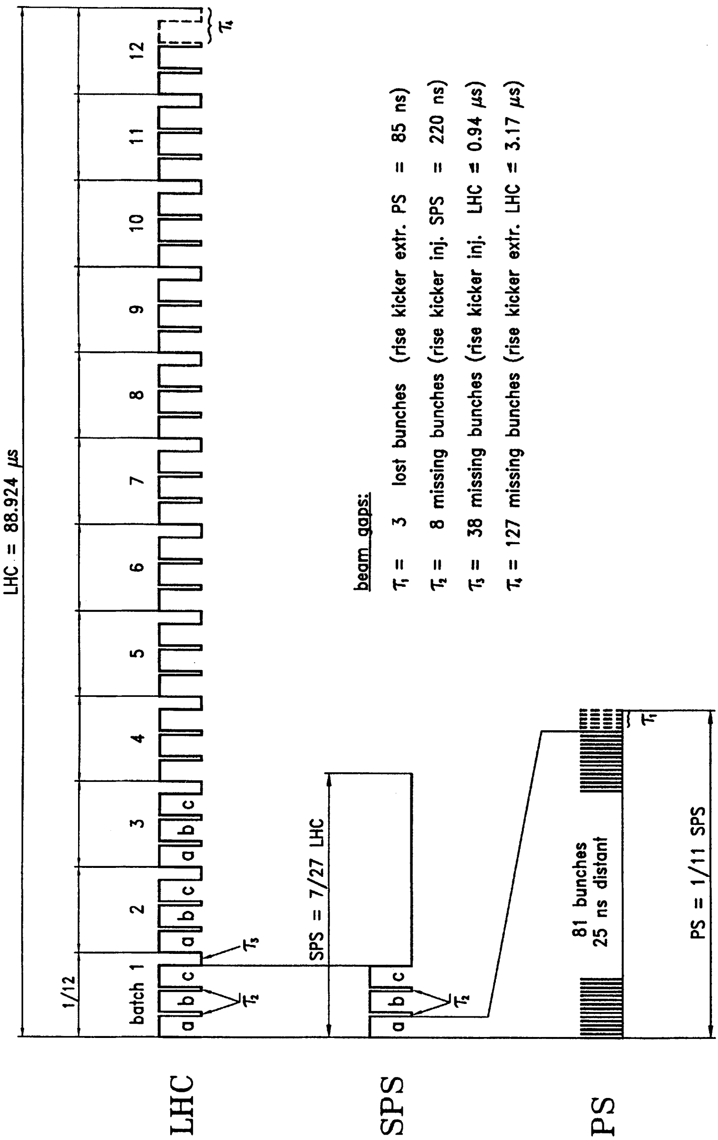

FIGURE 1 Bunch disposition in the LHC, SPS and PS.

on Figure 1. There are in total 729 bunches missing, that is about 20% of the total.

3 REQUIREMENTS ON TRANSVERSE EMITTANCE

3.1 Nominal Performance

The main limitation of the LHC performance comes from the effect of the beam–beam interaction. This has two components in the LHC: the head-on interaction at the crossing point and the long range interactions on either side of the crossing point in that part of the trajectory where the two beams run side by side in the same pipe. In order to reduce the effect of the long range interactions the beams cross at the angle of 200 μrad.

Both the head-on and the long range interactions produce a total tune spread over the particles in the beam distribution. The resulting total tune spread ΔQ_t is limited by the maximum area available in the tune diagram in-between betatron resonances of order less than 12. Experience at the *S$\bar{p}$pS* and at Fermilab has shown that resonances of order less than 12 can extract particles from the far tails of the distribution of transverse amplitudes, leading to poor beam lifetime and increased background in the experiments. The LHC has been optimized so that the total beam–beam tune spread ΔQ_t reaches 0.01 for the nominal luminosity of 10^{34} and 0.015 for the "ultimate" luminosity of $2.5 \cdot 10^{34}$. The "ultimate" case corresponds to the maximum tune spread reached in the *S$\bar{p}$pS*. The head-on interaction accounts for about 70% of the total tune spread, while the long range interactions are responsible for the remaining 30%.

The head-on tune spread is proportional to the ratio N/ε_n of the bunch population to the transverse emittance. The long range tune spread is proportional to the beam current (that is $k * N$) and becomes more harmful if the transverse emittance ε_n is increased, because particles in the tail of the distribution pass closer to the opposing beam.

Therefore the maximum luminosity can be reached only if the transverse emittance stays close to the nominal value $\varepsilon_n = 3.75 \cdot 10^{-6}$ m. A larger emittance implies obviously a lower luminosity (see formula 1), and anyway there is no safety margin in both the geometric and the dynamic aperture of the LHC to accommodate a much larger emittance. A smaller emittance implies a proportional reduction of the bunch intensity N to keep the head-on tune shift below the limit, and hence again a reduced luminosity because L is proportional to N^2/ε.

4 STRATEGY FOR STARTUP

The LHC is the first superconducting collider foreseen to operate with a large value of the beam current. Superconducting magnets tolerate only extremely small beam losses. In order to prevent excessive quenching of the magnets the particles in the beam halo which slowly diffuse out towards the beam-pipe walls have to be intercepted very efficiently by collimators in a warm section of the machine. Although we do not yet know with precision the tolerance level of the LHC magnets to beam losses, after careful studies we are confident that a collimation system can be built to give adequate performance, and two straight sections have been reserved for this purpose.

However, learning how to operate the LHC in such conditions will take some time, and the initial commissioning of the machine will be done with beams of much smaller intensity than the nominal one. We can avoid a dramatic reduction of luminosity, proportional to the square of the beam current by operating with a reduced transverse emittance ε_n. This is possible as long as the transverse beam density N/ε_n stays below its nominal value, which is limited by beam–beam effects in the LHC and the space–charge problems in the injectors.

One should therefore aim at providing the LHC with a constant value of N/ε_n for $N < N_{\mathrm{nominal}}$. In this case the luminosity is porportional to the achievable beam current.

Preserving small emittances in a long chain of injectors is difficult because at each transfer the unavoidable injection errors and mismatch produce relatively larger dilutions. In the LHC design report[1] we assume that after one year of commissioning the LHC can be operated with a beam current and a transverse emittance respectively equal to 16% and 26% of their nominal values, providing a luminosity of $10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The corresponding parameters are shown in Table II.

TABLE II LHC parameters: commissioning and nominal

Parameter	*Symbol*	*Unit*	*Commissioning*	*Nominal*
Luminosity	L	[$cm^{-2}s^{-1}$]	10^{33}	10^{34}
Circulating current/beam	I_{beam}	[A]	0.087	0.53
Particles per bunch	n_b		$0.17 \cdot 10^{11}$	$1.05 \cdot 10^{11}$
Number of bunches	k_b		2835	2835
Normalized transverse emittance	ε_n	[μm.rad]	1	3.75
Beam–beam parameter	ξ		0.0021	0.0034

5 LONGITUDINAL BUNCH PARAMETERS

At collision energy the bunches must be short enough to keep the reduction of luminosity due to the crossing angle below, say, 10%. Apart from that the longitudinal emittance has no influence on the luminosity.

However, both at injection and in collision the longitudinal emittance must be carefully adjusted to combat Intra Beam Scattering and instabilities, while maximizing the transverse dynamic aperture.

Intra Beam Scattering (I.B.S.) produces a growth of longitudinal and horizontal emittances at a rate proportional to $NF'/\varepsilon_n^2 A$ where A is the longitudinal bunch emittance in eV s and F' a complicated form factor depending on machine parameters. Since both N and ε_n are fixed by the requirements of maximum luminosity, we must control the I.B.S. through A. Table III shows that for the nominal beam intensity and a bunch emittance at injection of 1 eV s the I.B.S. growth times are comfortably large. In fact we have taken a safety margin here to be able to accelerate in the future the much larger bunch currents needed in the *e–p* option of the LHC. At high energy, however, the bunch emittance has to be increased up to 2.5 eV s in order to provide sufficiently long growth times. It is foreseen to progressively dilute the bunches by gentle shaking during the 20 min long ramp.

TABLE III LHC parameters: related to RF

			Injection	*Collision*
Intrabeam scattering growth time				
Horizontal	τ_h	[h]	45	100
Longitudinal	τ_p	[h]	33	60
Radio frequency				
RF voltage	V_{RF}	[MV]	8	16
Synchrotron tune	Q_s		$5.5 \cdot 10^{-3}$	$1.9 \cdot 10^{-3}$
Bunch area (2σ)	A_b	[eV s]	1	2.5
Bucket area	A_{rf}	[eV s]	1.46	8.7
Bucket half-height	$\Delta p/p$		$1 \cdot 10^{-3}$	$3.6 \cdot 10^{-4}$
r.m.s. bunch length	σ_s	[m]	0.13	0.075
r.m.s. energy spread	σ_e		$4.5 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$

Collective instabilities, both transverse and longitudinal, are easier to control for large longitudinal bunch emittances. For instance the threshold for Transverse Mode Coupling Instability (T.M.C.I.) N_{th} is proportional to the product $Q_s\sigma_s$ where Q_s is the synchrotron tune and σ_s the bunch length. Therefore at constant RF voltage N_{th} is proportional to $\sqrt{A}$. However one cannot increase A too much because one needs to inject in the LHC with a very good efficiency (small losses) and this is easier if the ratio of the bunch area to bucket area stays below a reasonable limit. In addition, the transverse dynamic aperture which is limited by unavoidable multipole errors in the superconducting magnets tends to decrease for large momentum deviations.

Considering all these effects, we conclude that the LHC can accept a longitudinal emittance at injection ranging from 0.5 eV s to 1 eV s. For instance at $A = 0.5$ eV s the IBS growth time is still 7 h and the threshold of TMCI is $N_{th} = 3.5 \cdot 10^{11}$, providing a sufficient safety margin.

6 CONCLUSIONS

The LHC requires 2835 bunches per beam, with $N = 10^{11}$ p per bunch (nominal case) and $1.66 \cdot 10^{11}$ p per bunch ("ultimate" case). The transverse normalised emittance in both planes must be close to $3.75 \cdot 10^{-6}$ m for the nominal beam intensity and above.

During commissioning at intensities smaller than nominal, the transverse density has to kept equal to the nominal one. The LHC can accept bunches with longitudinal emittances ranging from 0.5 to 1 eV s (or proportionally smaller at intensities smaller than nominal).

References

[1] The Large Hadron Collider, CERN/AC/95-05 (LHC).