The LHC beam screen - specification and design

B. Angerth, F. Bertinelli, J.-C. Brunet, R. Calder, F. Caspers, O. Gröbner,
A.-G. Mathewson, A. Poncet, C. Reymermier, F. Ruggiero, R. Valbuena
CERN
CH - 1211 Geneva 23

Abstract

The Large Hadron Collider (LHC) being designed at CERN will be the first hadron machine operating at cryogenic temperature (1.9 K) with a significant synchrotron radiation power emitted by the 7 TeV protons (up to 0.2 W/m from each of the two 530 mA beams).

The superconducting magnet cold bores will be shielded by a so-called beam screen, having as primary function to intercept the synchrotron radiation and image current power at an intermediate temperature (5-20 K or, possibly higher), and to protect the cold 1.9 K cryo-pumping surfaces from the associated photon flux. The screen will be perforated to permit cryo-pumping at 1.9 K and thus limit the dynamic pressure rise. The inner surface will be coated with a high electrical conductivity copper layer to minimise both the power dissipated by the beam image currents and the impedance seen by the beam. The screen will be subjected to large eddy current forces in the case of a magnet quench. Finally, the screen geometry should provide a maximum aperture for the beam.

A functional description of the LHC beam screen is presented together with a preliminary design fulfilling its specification.

1. INTRODUCTION

The LHC will operate with two counter rotating high intensity proton beams, to provide high luminosity collisions at 3 crossing points disposed around its 27 km circumference. The beams will be guided around their trajectory by 8.7 Tesla twin aperture superconducting dipole magnets operating in super fluid helium at 1.9 K.

At this level of magnetic field and beam energy, a beam screen will be required to shield the 1.9 K cold bore from the synchrotron radiation power emitted by the beam (0.22 W/m per beam) and the power dissipation (0.10 W/m per beam) by the beam image currents due to the finite resistivity of the walls [1]. Without such a shield the refrigeration requirements at the 1.9 K level would be prohibitively expensive. The screen must there-fore be cooled at some intermediate temperature (5-20 K) and plated on the inside with a rather thin but high conductivity Cu larger. Further essential functions of the beam screen will be to shield the pumping surface of the cold bore from the large flux of photons emitted by the beam, which would otherwise photo-desorb gas, and to limit the gas density rise due to photo-desorption inside the screen by providing pumping through holes perforated on its surface.

Owing to its basic functions, its proximity to the beam and its situation in a strong magnetic field, the beam screen design is subject to a number of constraints.

Table 1 summarises the requirements.

Table 1
LHC Beam Screen Requirements (nominal)

Minimum aperture including orbit and alignment errors :	12 rms beam sizes
Length :	up to 15 m
Max. outer diameter :	46 mm
Temperature :	< 70 K
Heat transport :	< 1 W/m
Heat leak to 1.9 K :	< .05 W/m
Photodesorption yield :	< 10^{-3} (mol. / photon)
Hole pumping speed (H2) :	> 100 l/sec/m (5 K)
Magnetic permeability :	< 1.005
Image current losses :	< 0.2 W/m (530 mA)
Transverse resistive impedance (β_{av} R_e [Z_t]) :	< 10 GOhm (3.3 kHz)
Longitudinal impedance (Z_L/n) :	< 0.5 Ohm
Quench resistance :	> 50 quenches with $B\dot{B}$ = 300 T^2/sec
Screen radiation resistance :	10^9 rad

2. OVERVIEW OF REQUIREMENTS AND DESIGN

2.1 Aperture and geometrical tolerances

The beam screen, inserted in the cold bore of the superconducting magnets, has to provide maximum clearance for the beam while leaving enough space to accommodate cooling tubes, mechanical supports, and a sufficient wall thickness to withstand the quench forces. An optimised geometrical shape giving maximum aperture is shown schematically in figure 1.

Sufficient clearance between screen and cold bore has to be provided for ease of mounting and to avoid thermal shorts susceptible to increase the thermal load to 1.9 K. With manufacturing tolerances of a few tenths of mm it will be possible to provide a minimum of 12 rms beam sizes at injection and locations of average and maximum beta functions, taking into account alignment errors and orbit distortions.

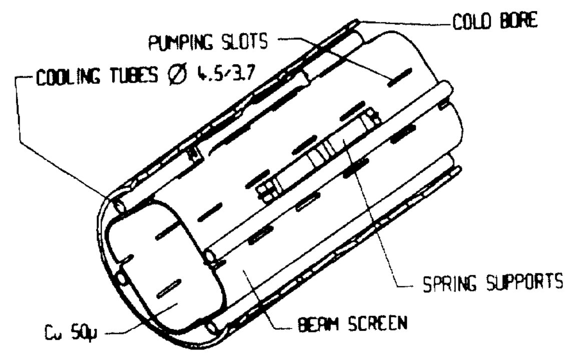

Figure 1. LHC dipole beam screen

In order to keep the screen precisely centred inside the cold bore, 4 spring supports of the beam type will be located every 1.7 m along its length. These supports must have low thermal conductivity, be electrically insulating to avoid eddy current loops, and be radiation resistant. A glass fibber reinforced polyetherimide material ULTEM (TM by General Electric C.) is being considered.

2.2 Magnetic properties

The magnetic permeability of the constituent materials must be kept low. A simple cylindrical tube such as the magnet cold bore may have a permeability of 1.01, achievable at 2 K with classical stainless steels, without introducing harmful field harmonics [2]. A square beam screen with cooling tubes does not respect the same axial symmetry and introduces multipoles, depending on the number of cooling tubes (quadrupole and sextupole with 2 cooling tubes, sextupole only with 4 symmetrically arranged tubes). The specification for the LHC screen is for a magnetic permeability not exceeding 1.005.

2.3 Operating temperature and Cooling Scheme

The choice of the screen temperature depends on a number of conflicting requirements. The need to keep the real part of the screen impedance low, which depends on the copper surface resistivity, pleads in favour of a low operating temperature (5-20 K). Further, with a copper thickness larger than the skin depth, given by the spectrum of beam current frequencies, the image current ohmic losses will be reduced. The transverse instabilities growth rates at low frequencies would also be reduced, thus making feed-back stabilisation easier.

A low temperature would also limit the thermal losses to the 1.9 K cold bore but, of course, a higher operating temperature (50-75 K) would be thermodynamically more efficient, and provide a higher gas pumping speed through the screen pumping slots.

There are, however, other technical considerations of the project which also need to be taken into account. The currently preferred scheme assumes a screen temperature of 5-20 K using a cooling circuit with the four beam screens of a half cell (50 m) connected in series with the heat intercepts of the magnets supports. Supercritical Helium (3 bar) flowing through one of the (4 mm I.D.) cooling tubes will maintain the screen at the chosen temperature.

2.4 Slots and pumping speed

To limit the gas density rise due to photodesorption to acceptable values, the screen must be perforated to let the gas escape and be cryo-pumped at 1.9 K on the cold bore surface. With the present photodesorption data at least 2% of the screen surface should be transparent to gas [3]. A 4% perforation of the screen surface is specified, taking into account clausing reduction factor due to the thickness of the wall. A large surface fraction with holes would ease the vacuum problems, but the screen impedance and RF power leaking into the cold bore - screen gap would be enhanced. SSC and LHC studies [4] have confirmed the advantage of narrow longitudinal slots (1.5 x 6 mm for LHC), as compared to round holes, for a given surface coverage, to minimise the contribution to the screen impedance budget. Due to the low width to depth ratio, this contribution is small and the RF power leaking into the screen cold bore gap is negligible [5]. To limit resonances above the screen cut-off frequency, it is foreseen to provide some randomness in the slot locations.

2.5 Beam screen copper coating

The inner surface of the screen must be coated with a high conductivity copper layer to contain the real part of the impedance, to limit the rate of rise of transverse instabilities and the power dissipated by image currents [1]. Conflicting requirements exist : the copper layer has to be sufficiently thick to achieve an acceptable transverse resistive wall instability rise time. However a thicker copper layer will mean larger eddy currents during magnet quenches, and an increased risk of damage to the screen.

A compromise for LHC is found with a 50 to 100 μ thick copper layer of purity corresponding to a RRR = 100, valid for a screen temperature anywhere between 5-70 K, in a magnetic field of 8.7 T [6].

With a square beam screen, the surface image current density is lowest in the corners, where the beam induced magnetic field is lowest. Slots are therefore most conveniently located near to these corners. Additionally, two 2 mm wide strips could be left free of copper at the top and bottom corners without entailing too much power losses, should the screen construction impose longitudinal welds in these places.

2.6 Resistance to quench

During a superconducting magnet quench, large eddy currents will be induced in the low resistance copper layer, which, combined with the decaying magnetic field will give rise to strong horizontal outward forces.

The LHC dipole magnet has an ultimate field of 9 T decaying in 0.2 s, giving a maximum $B\dot{B} = 300\ T^2/s$ at quench.

The maximum eddy current in a 100 μ (RRR = 100) copper layer would be 6 kA, giving rise to 690 MPa stresses in the 1 mm thick stainless steel wall, and a horizontal deflection of 1 mm. Stresses in the copper would be above the elastic limit [7]. Although initial tests of a screen in a model LHC magnet at CERN have confirmed these values, they have also shown no damage to the copper layer after repeated quenches.

3. CONSTRUCTION

The choice of the screen material is governed by the requirements of low magnetic permeability and strength. Highly stable austenitic stainless steels alloyed with Mn and N, such as ARMCO Nitronic 40, UGINE UNS 21904, SANDVIK 13RM19 or AUBERT & DUVAL X20MD have the required properties at low temperature. The steel could be electroplated or co-laminated with copper, mechanically perforated, rolled to shape, welded and finally calibrated to precise shape.

In this manufacturing method the welding might imply 2 longitudinal strips (e.g. 2 mm) left free of copper at the location of the weld(s) (see sect. 2.5).

Another alternative would be to start from a square section seamless tube, drill the slots by laser or electro-erosion, braze the cooling tube(s) and electro-deposit the copper.

Promising preliminary tests of co-laminated copper on stainless steel using a so-called "Skive-Inlay" technique (TMI corporation - USA) have been performed, showing a very strong copper to stainless steel bond.

4. INTERCONNECTIONS AND ASSEMBLY

Figure 2 shows the interconnections of the screen between two magnets for one beam channel. The screen cooling tubes are specified to be without welds in the beam vacuum. A sealing weld where the tube passes out through the wall of the cold bore will separate the beam channel vacuum from the insulation vacuum. The low weld area, long thermal path and low stainless steel thermal conductivity will limit the thermal leak to the 1.9 K magnet cold mass. RF sliding contacts will ensure electrical continuity of the screen between magnets and shield the interconnecting beam vacuum bellows. After installing the screen connection, these bellows will be slid into place and welded, finally separating the beam vacuum from the insulating vacuum.

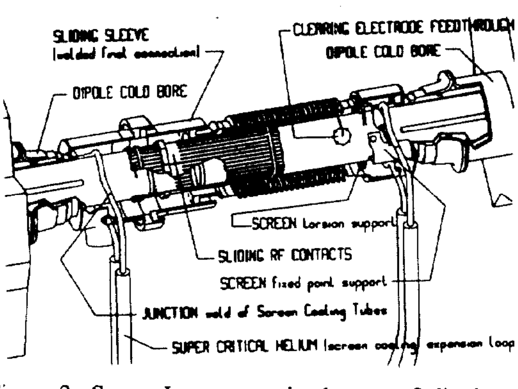

Figure 2. Screen Interconnection between 2 dipoles

Table 2
LHC Beam Screen main parameters

Square Shape I.D.	36 x 36 mm (↔ 50.9)
Stainless steel thickness	1 mm
Inner copper layer thickness	50 μ (RRR = 100)
Cooling tube (s)	1 (4) 3.9 / 4.4 mm
Pumping slots per m	666 x (1.5 x 6 mm)
Operating temperature	5 - 20 K
Image current Power losses	0.10 W/m per beam
Synchrotron radiation Power	0.22 W/m per beam
Re (Z_t) β_{av}	7 G Ω
Im (Z_t) β_{av}	30 M Ω/m
Z_l/n	0.33 Ω
Max stress during quench	340 MPa
Max screen deflection	0.5 mm

5. CONCLUSIONS

The mechanical, thermal and electrical requirements of the LHC beam screen have been reviewed together with a preliminary design fulfilling its basic functions of vacuum pump and thermal shield. Sufficient confidence in the design has led to the start up of the prototype phase, aimed at validating the various technical choices (thermal, mechanical and quench tests, measurements of the vacuum behaviour, impedance and power losses, etc...). Table 2 gives a summary of the main parameters of a screen in a LHC dipole.

6. REFERENCES

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