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Functional Specification

BEAM SCREENS FOR THE LHC LONG STRAIGHT SECTIONS

Abstract

This Functional Specification describes the requirements of the beam screens that will be inserted into the LHC Long Straight Sections cold bores.

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	2003-03-17	All	Old reference [31] replaced with new reference [33]. Submission for engineering check, engineering check closed, start approval process (3).
	2003-04-07	6	Section 2.4.1, ... temperature controllable up to about 75 K ... (instead of 100 K).
		11	Update of reference [24].
1.0	2003-04-10	All	Released version
1.1	2004-08-26	4	Table 1: modification of bs orientations for Q7, DFBA and DFBX following ECO LHC-VSS-EC-0008. Replacement of ref [4].
		7	Section 2.4.1 rephrased, addition of ref [24].
		7	Section 2.4.2 addition of paragraph on saw teeth and ref [27].
		8	Section 2.6 replacement of reference [31].
		9	Section 2.7 addition of refs [35] and [36].
	2004-09-28		Table 3: modif. of aperture values following ECO LHC-VSS-EC-0006. Submission for approval.
	2004-10-13	4	Addition:according to Eng. Change Order LHC-VSS-EC-0008.....
		6	Section 2.3.2 addition of last phrase and reference [20].
		6	Section 2.4 1 st paragraph rephrased, 2 nd paragraph added.
1.2	2004-10-15	All	New version released.

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1. INTRODUCTION

The functionality and vacuum requirements of the beam screens in the LHC Long Straight Section (LSS) have been presented previously [1].

Beam screens are actively cooled beam tubes with distributed pumping slots. Beam screens shall be located in all the cold bores of all the cryogenics elements (except the superconducting cavities) *i.e.* in superconducting magnets at 1.9 K or 4.5 K and Distribution Feed Boxes (DFBX) of the LSS. The locations of these cryogenic elements in the LSS are shown in Table 1 (optics V6.4). All cold bores operate at 1.9 K or 4.5 K [2]. All connecting cryostats in the LSS have been eliminated [3] and all DFBA's are assumed to be off the beam axis.

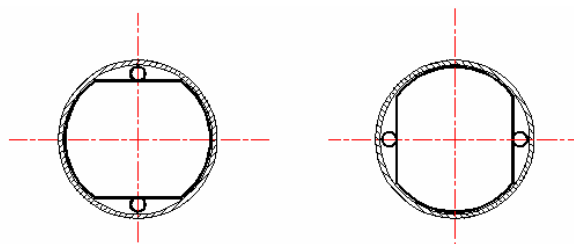
Table 1 also shows the orientation of the beam screens for beams 1 and 2, according to Engineering Change Order LHC-VSS-EC-0008 [4]. For example: **HV** indicates that beam 1 has the smallest aperture in the **H**orizontal direction and beam 2 has the smallest aperture in the **V**ertical direction.

Table 1 : Location of cryogenic elements in the LSS

Cold Bore			Interaction Region							
Operating Temp. (K)	Type	Nominal ID/OD (mm)	1	2	3	4	5	6	7	8
4.5	50	50/53 [#] <i>(replaces 46/49)</i>	Q6L VH Q5L HV Q5R VH Q6R HV	Q6L HV Q5R HV Q6R VH	Q6L VH Q6R HV		Q6L VH Q5L HV Q5R VH Q6R HV		Q6L VH Q6R HV	Q6L HV Q5L VH Q6R VH
1.9	50	50/53	Q7L HV Q7R VH	Q7 VV	Q7 VV	Q7 VV	Q7L HV Q7R VH		Q7 VV	Q7 VV
1.9	53	53/57 [5]	Q1 H	Q1 H			Q1 V			Q1 V
4.5	63	62.98/ 66.5 [#] <i>(replaces 60/64)</i>	Q4 VV	Q5L HH Q4 HH		Q6L HV Q5L VH Q5R HV Q6R VH	Q4 VV	Q5L VH Q4L HV Q4R VH Q5R HV		Q5R HH Q4 HH
1.9	63	62.98%/ 66.5	Q2 H Q3 H DFBA VV	Q2 H Q3 H DFBA VV	DFBA VV	DFBA VV	Q2 V Q3 V DFBA VV	DFBA VV	DFBA VV	Q2 V Q3 V DFBA VV
4.5	69	69.08/73	D2 VV	D2 HH		D4L VH D3L VH D3R VH D4R HV	D2 VV			D2 HH
1.9	74	74/78	DFBX H	D1 V DFBX H			DFBX V			D1 V DFBX V

[#]) Increased cold bore diameter as recommended by LCC [6].

[%]) See footnote table 3.



V orientation

H orientation

The beam screen for the undulator in front of D3 in IR4 is under discussion [7].

The beam screens shall maintain the vacuum stability, provide distributed pumping to minimise the background in the experiments of the Interaction Regions (IR) 1, 2, 5 and 8, carry the image currents, minimise the beam induced heat load to the 1.9 K and 4.5 K cryogenic system and provide the largest possible aperture.

Two types of beam screens shall be considered:

1. Beam screens inserted into superconducting magnets with a cold bore temperature of 1.9 K.
2. Beam screens equipped with cryosorber, inserted into superconducting magnets with a cold bore temperature of 4.5 K.

This specification describes the requirements for the LSS beam screens. The requirements of the LHC dispersion suppressor beam screens will be described in a separate document.

2. REQUIREMENTS

All beam screens must be designed for ultimate LHC conditions [8], except those in the inner triplet (IT) where the quadrupole magnets are designed for an integral of 7 years on the basis of 200 days per year operation at 50% of nominal luminosity. Afterwards these magnets, including beam screens, will be replaced [9].

2.1 RADIATION RESISTANCE

The beam screens must be able to withstand a radiation dose of 10^7 Gy [10].

2.2 MAGNETIC

The magnetic permeability of the beam screen at the operating temperature should be kept low to avoid perturbations to the field quality. The maximum acceptable value depends on the beam screen geometry. A simple cylindrically shaped tube (e.g. cold bore) can have any permeability as long as it is constant [11]. A non-cylindrical beam screen with attached cooling tubes should not exceed 1.005 (including welds) [12].

2.3 ELECTRICAL

2.3.1 SURFACE RESISTANCE

The inner surface layer must have a low electrical resistivity at the beam screen operating temperature. In the case of a copper layer at an operating temperature < 30 K, the required thickness is $50 \mu\text{m}$ with a RRR value of at least 50. This corresponds to a maximum allowed surface resistance of $7 \mu\Omega$ [13].

Any structure on the inner surface of the beam screen, such as a saw tooth pattern to lower the forward-scattered reflectivity and photoelectron yield from the direct synchrotron radiation, must exhibit surface topology $\leq 40 \mu\text{m}$ [14].

Longitudinal interruptions in the inner surface layer along the length (e.g. longitudinal weld) shall be limited in width to 2 mm to limit resistive wall losses. Transverse interruptions in the inner surface layer along the circumference (e.g. weld) shall be limited in width to 0.2 mm to limit resistive wall losses [15].

2.3.2 PUMPING SLOTS

Pumping slots with a surface area of up to 4.4% are acceptable in terms of longitudinal and transverse impedance. The length of the pumping slots should have a random variation of $\geq 10\%$ [16].

The length of randomization of the pumping slots should be at least 500 mm longitudinally [17].

The pumping slots should have rounded corners [18].

In order to limit the RF power transmitted through the pumping slots to ≤ 1 mW/m, the maximum slot width is 1.5 mm for 1 mm wall thickness or 1 mm for 0.5 mm wall thickness [19].

Pumping slot shields, as mounted on the arc dipole beam screens [20], will only be necessary on dipole beam screens in V-orientation. In addition they will be mounted on all beam screens of 4.5K magnets to act as cryosorber supports.

2.4 VACUUM

The dynamic beam vacuum gas density is determined by the balance of the quantity of gas desorbed from the beam screen by photon, ion and electron stimulated desorption and the quantity of gas removed. The pumping slots, providing vacuum stability by means of distributed pumping along the beam screen, must not be located where they permit direct electron and ion bombardment of the cold bore [21]. If such locations can not be avoided, the slots must be shielded as for the arc dipole beam screens.

On beam screens in H-orientation, part of the synchrotron radiation will irradiate the pumping slots. Assuming a maximum slot length of 10 mm and a total beam screen wall thickness of 0.675 mm, all synchrotron radiation up to an angle of $\arctan(0.675/10) = 67$ mrad will be intercepted on the beam screen wall. Since the synchrotron radiation angle with the beam screen is < 4 mrad, no synchrotron radiation will directly irradiate the cold bore. No shielding of the slots is therefore necessary.

The dynamic gas density must be compatible with operation of the experiments and a hydrogen equivalent dynamic gas density must be less than $1 \cdot 10^{15}$ molecules m^{-3} [22].

The impact of the dynamic gas density on the radiation dose and contact dose onto the elements is currently under evaluation.

The vapour pressure of all gases, other than hydrogen and helium, remains insignificant to the gas density, if the temperature of the inner beam screen surface is maintained below 20 K. In order to desorb physisorbed gas layers accumulated on the beam screen, desorbed from the cold bore during a magnet quench, it must be possible to heat the beam screen. The temperature of the beam screen during this operation must be at least that reached by the maximum cold bore temperature after a quench at ultimate conditions. A temperature > 80 K will ensure the thermal desorption of H_2 , CH_4 , CO and CO_2 .

If a beam screen temperature of 20 K can not be guaranteed, it must be possible to heat the beam screen after a magnet quench and occasionally between fills. A beam screen temperature of up to about 24 K will require warming up at least on the monthly time scale for a fully conditioned beam screen. A beam screen temperature above 24 K will require warming up on the weekly time scale for a fully conditioned beam screen.

For a beam screen operating temperature > 20 K, the heat load to the 1.9 K or 4.5 K circuit may increase and the beam lifetime may decrease [23, 24].

A commissioning of the vacuum system will be mandatory to reduce the desorption yields, photoelectron yields and secondary electron yields, such that the required densities at nominal and ultimate machine conditions may be met.

2.4.1 BEAM SCREEN WITH CRYOSORBING MATERIALS

It is expected that ~ 150 monolayers of hydrogen will be desorbed per year [24]. Cryosorber is therefore required in cryoelements with a vacuum cold bore of temperature higher than 3 K and shall act as a sink of gas in a similar manner to the 1.9 K cold bore. It will be located on the outer surface of the beam screen. The cryosorber shall be thermally anchored to the beam screen. It shall be thermally isolated from the cold bore to allow regeneration and gas transfer in case of plugging of its pores *i.e.* when the bulk of the cryosorber is no longer accessible to the gas.

The beam screen cross-sections are optimised for aperture. As a consequence, the available space for cryosorbing materials is very limited. The aim will be to have an amount of cryosorbing material providing a pumping speed which is at least equal to the slot's pumping speed. An analysis of the required performances of the cryosorbers is given in [25]. Experimental data have shown that the beam screen must be temperature controllable up to about 75 K to allow regeneration of the cryosorber [26].

The cryosorbing materials shall not be damaged or detached during a quench.

2.4.2 PHOTON, ELECTRON AND ION INDUCED DESORPTION

To meet the 100 hour machine lifetime, a hydrogen equivalent dynamic gas density due to photon, electron and ion stimulated desorption must be less than $1 \cdot 10^{15}$ molecules m^{-3} . Table 2 shows the relative proton-nuclear scattering cross section, σ/σ_{H_2} of various gas species used to compute the beam life time for given gas densities [27].

Saw teeth, to intercept synchrotron radiation, are not necessary on the LSS beam screen inner surface [28]. Only the Q7 beam screens will have saw teeth since they will be produced from arc-type beam screen tube.

Table 2 : Relative proton-nuclear scattering cross section at 7 TeV.

	σ/σ_{H_2}
H ₂	1
He	1.26
CH ₄	5.4
H ₂ O	5.4
CO	7.8
CO ₂	12.2

2.4.3 ION INDUCED BEAM INSTABILITY

The beam vacuum must remain stable and not exhibit run-away pressure rises due to ion induced desorption up to the ultimate machine current [8]. The ion-induced pressure instability can be avoided by ensuring that the molecules are cryosorbed on surfaces, which are in the shadow of the beam [27]. The beam screen provides the shadow.

2.4.4 LEAK TIGHTNESS

As a design principle, helium to beam vacuum welds shall be avoided.

As a design principle, the installation of helium carrying components with a measurable leak to the beam vacuum shall not be permitted.

The maximum allowed leak rate under operating conditions from helium to beam vacuum shall be calculated to verify that the sensitivity of the applied leak testing procedures will be sufficient.

2.5 CRYOGENIC

2.5.1 BEAM SCREEN COOLING

The cryogenic elements in the LSS have been designed to accept both the static and dynamic heat loads into the cryogenic circuit of the cold bore. Therefore a beam screen is not required to intercept the dynamic heat loads [29].

However for vacuum requirements beam screens are mandatory (section 2.4).

In order to maintain their required operating temperature, the dynamic heat load must therefore be extracted (in the arcs, the expected distributed ultimate heat load into the beam screen is 1.13 W m^{-1} from resistive heating, synchrotron radiation and photoelectrons). The hydraulic resistance of the beam screen cooling tubes and the thermal resistance of the cooling tube attachment to the beam screen shall allow to evacuate the dynamic heat load [30].

Depending on the thermal resistance between the helium and the beam screen inner surface, the maximum helium temperature shall be slightly lower than the maximum allowed beam screen temperature.

The heater on the inlet of the beam screen cooling circuit should be rated to permit the beam screen temperature to be raised to $\geq 80 \text{ K}$ occasionally between fills in order to limit the coverage of physisorbed gases (see section 2.4).

2.6 MECHANICAL

The beam screen must remain mechanically stable during all aspects of manufacture, installation and operation. The beam screen is subjected to large forces due the magnetic field decay following a magnet quench, and may have $B \cdot dB/dt_{\max}$ as large as $275 \text{ T}^2/\text{s}$ (value for arc dipole magnet, assumed here to be the worst case [31]). Calculations have been performed to verify the mechanical stability during a quench [32]. Further calculations will be performed for rotated beam screens, in particular with respect to the stress concentration factor between cooling tube and sliding rings.

If the beam screen deformation during quench exceeds the width of the annular gap between the beam screen and cold bore, forces will be transferred to the latter.

In the arc dipole magnets, a lateral horizontal displacement of the beam screen has been observed during quench, due to the asymmetry of the magnetic field [33]. The implications of this effect for the LSS magnets should be investigated.

The beam screen must remain undamaged and without residual deformation after 100 magnet quenches [8].

2.7 APERTURE AND LENGTH

The beam screens shall be designed to maximise the beam aperture.

The beam screens shall be inserted in the given cold bores of nominal ID of 50, 53, 62.98, 69.08 and 74 mm. Extrapolated from the existing technology developed for the arc beam screen [34], the LSS beam screens nominal dimensions and provided apertures at their operating temperature are shown in Table 3. The apertures are calculated with cumulative error propagation [35] and based on a longitudinal distance between sliding rings of 757 mm (50A type beam screens) [36] and 383 mm (all other beam screen types) [37].

The tolerance on the diameter of the arc beam screens is ± 0.2 mm. For the LSS beam screens, the tolerance is assumed to scale linearly with the diameter.

The assumed copper thickness of 75 μm in table 3 is the maximum foreseen thickness and therefore represents the worst case in terms of aperture. The beam screen apertures between flats are based on a nominal cooling tube outer diameter of 4.76 mm. The calculated aperture takes into account the cold bore inner diameter tolerance. This tolerance should therefore not be included in the global alignment and mechanical tolerances. Beam screen materials consist of P506 grade stainless steel co-laminated with OFE copper.

Where possible, the inner cold bore diameters of the finished magnets will be measured with go/no go gauges before beam screen manufacture, to ensure that the proposed beam screen diameter is appropriate.

The Q1 beam screens will be built with a diameter transition to increase the aperture in the Q1-Q2 interconnect.

Table 3 : Nominal LSS beam screens dimensions, apertures at their operating temperature and approximate cumulative lengths.

B. screen type	Cold Bore		Nominal Beam Screen Dimension			Beam screen aperture		Length (m)
	ID/OD (mm)	ID Tolerance (mm)	Steel + Cu thickness (mm)	Radial OD (mm)	Between flats OD (mm)	Radial ID (mm)	Between flats ID (mm)	
50A *	50/53	0.35 [40]	1.0+0.075	48.5	38.9	44.0	34.3	314
50L ⁺	50/53	0.35 [40]	0.6+0.075	48.5	38.9	45.1	35.3	365
53	53/57	0.50 [38]	0.6+0.075	51.3	41.7	47.7	37.9	71
63	62.98%/66.5	0.38	0.6+0.075	61.4	51.8	57.8	48.0	513
69	69.08/73	0.74 [39]	0.6+0.075	67.1	57.5	62.6	52.8	273
74	74/78	0.78 [39]	0.6+0.075	72.0	62.3	67.4	57.6	68
Provisionally obsolete beam screen types that have been replaced by larger diameter beam screens:								
46	46/49	0.35 [40]	0.6+0.075	44.5	34.9	41.2	31.5	
60	60/64	0.55 [40]	0.6+0.075	58.2	48.6	54.4	44.6	

*) Arc type beam screens for 1.9 K elements.

+) LSS type beam screens for 4.5 K elements.

%) The cold bore diameter has changed with respect to the previous version of this document. The specified OD is 66.5 ± 0.25 , the specified wall thickness is 1.85 ± 0.15 [41]. Specified ID is therefore 62.8 ± 0.55 . ID measurements at CERN with go/no go gauges showed a minimum ID of 62.6 mm [42]. The maximum ID, calculated from the tolerances is 62.8+0.55=63.35. Nominal ID, calculated as the average of measured minimum and the specified maximum, then becomes (62.6+63.35)/2 = 62.98. ID tolerance becomes ± 0.38 mm. It is imperative that the cold bore diameter does not change during cold mass assembly.

2.8 ASSEMBLY

2.8.1 INSERTION

The beam screens shall be inserted in the cold bore apertures before magnet installation in the tunnel. Straightness, twist and dimensional tolerances of the beam screens shall allow for insertion without damaging the beam screen or the magnet.

Insertion shall be a clean process since no further cleaning will take place after insertion.

Repair or replacement of a beam screen will require displacement of the magnet. The radiation contact dose rate may complicate the work.

2.8.2 INTERCONNECTION

The continuity of the electrical conductivity of the inner beam screen surface shall be assured by interconnections [43].

The beam screen thermal expansion and contraction shall be allowed for by the support system and the interconnections.

2.9 RELIABILITY

The beam screens will be inside the apertures of the cryo-elements. Any repair or replacement will require replacement of the cryo-element and possibly up to 2 interconnects.

The beam screen design and manufacture shall therefore be based on well understood techniques and materials. They shall allow for testing under representative conditions before installation.

Manufacturing shall be according to a recognised quality assurance system.

2.10 SAFETY

The beam screen design shall allow manufacturing, testing and operation in accordance with applicable CERN safety regulations.

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