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LHC BEAM SCREEN DESIGN ANALYSIS

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We consider the problems connected with the design of a beam screen for dipole magnets of the LHC proton collider — restrictions connected with possible beam screen deformations and heating at quench, on the one hand, and beam dynamics and energy losses on the other. The beam screen design variants of coating with copper strips, and all-over copper coating, were considered. A compromise variant is presented for choice of operating temperature and copper coating thickness.

KEY WORDS: LHC, beam screen, transverse impedance

1 INTRODUCTION

One of principal functions of the beam screen (Figure 1) is the interception of synchrotron radiation (0.4 W/m) and image current ohmic losses (0.35 W/m), so that this power is not dissipated in cold bore walls at the level of 1.8 K.

Owing to its location in a strong magnetic field, the beam screen is subjected to the action of ponderomotive forces due to eddy currents flowing at magnetic field switching-off. The beam screen must be designed to bear multiple magnetic field switchings-off without damages and residual deformations.

For retaining the mentioned low level of image current losses, the beam screen must have small surface impedance with the account of skin effect. For this purpose, it must be coated with a layer of copper. The ponderomotive forces at quench depend on the thickness of this layer, because eddy currents are determined by small copper resistance. Stainless steel at low temperatures in a strong magnetic field has a specific resistance of about 1000 (at maximal energy) — at injection energy 2500 times greater than copper.

An additional condition imposed on the beam screen is connected with ensuring collective stability of symmetrical multibunch transverse oscillation modes. For this, so-called transverse impedance must not exceed given values.[1] This condition is ensured by copper coating. In our opinion, the admittable value of transverse impedance should be chosen by comparing growth rate caused by it with the supposed decrement of a special feedback, which ought to be present proceeding from other requirements:[1] injection mistakes damping, and emittance growth (because of vibrations and other factors) damping.

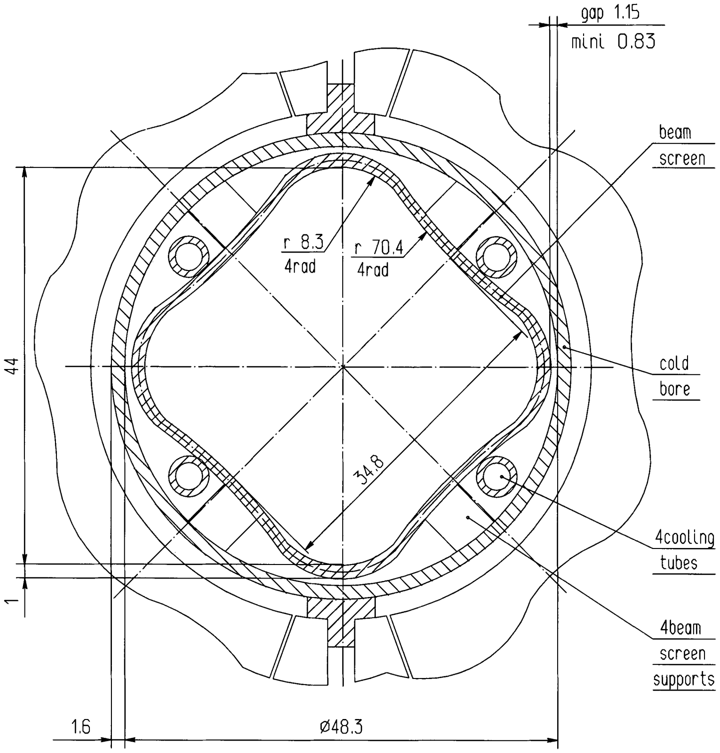

FIGURE 1: The cold bore and beam screen cross-section.

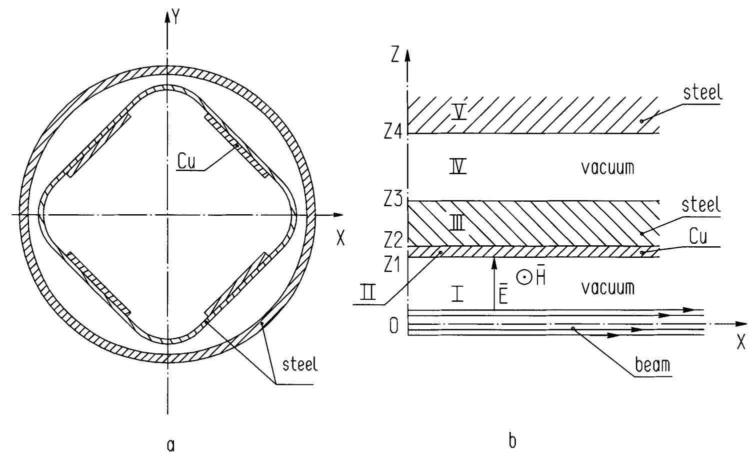

FIGURE 2: The model of the multilayer chamber wall.

The following values are pointed out: 1000 s^{-1} at injection energy and 500 s^{-1} at maximal energy. Caused growth rates should have a reserve less than these values.

And finally, the operating temperature of the beam screen must be chosen in an optimal way. With respect to thermodynamics, it is preferable to take this temperature sufficiently high. In this case, copper resistance will increase, bringing about a decrease in mechanical stresses and beam screen deformations at quench. But this can also result in a prohibitive increase in image current ohmic losses and transverse impedance going over a given limit.

In order to have the possibility of optimal variant choice, we have calculated beam screen electrodynamic parameters (growth rates of transverse multibunch instabilities, transverse impedances and ohmic losses due to image currents) and mechanical parameters (stresses, deformations and heating of the beam screen during quench) in various conditions. All-over copper coating and copper strips coating half a beam screen[2] were considered, for copper thickness 10–1000 μm, and at operating temperatures of 20, 50 and 70 K, at both the injection and maximal energies.

2 ELECTRODYNAMIC PARAMETERS CALCULATION

In this chapter we discuss the limitations on the thickness of the copper coating of the beam screen caused by the multibunch transverse resistive instability.

2.1 Storage ring parameters

The storage ring parameters[1,3] used for calculations are the following:

$I_0 = 0.53$ A — average beam current;

$n_{b0} = 2835$ — number of bunches in the beam;

$\tau_b = 25$ ns — bunch spacing;

$T_{rev} = 88.924\ \mu s$ — revolution period;

$h_{rf} = 35640$ — harmonic number;

$\sigma_b = 0.075$ m — r.m.s. bunch length;

$E_i = 0.45$ TeV — injection energy;

$E = 7.0$ TeV — maximal energy;

$R = 4242.89$ m — storage ring average radius;

$\nu_y = 68.3$ — betatron frequency;

$\beta_{av} = 82.5$ m.

The beam with the above given values of bunch spacing and bunch numbers should have gaps (about 1/5 from the whole beam length). Further growth rate estimations are for

TABLE 1: Copper resistance values.

T, K	ρ_c (Ohm·m·10^{10})	
	B=0.0 T	B=10.0 T
20	1.55	6.16
50	6.20	10.5
70	15.0	19.1

a symmetrical beam. We deal with a symmetrical beam having the same values of bunch spacing and bunch charge — i.e., the beam with the number of bunches

$$n_b = 3564\ ,$$

and the beam current

$$I = I_0 \cdot (n_b/n_{b0}) = 0.666\ \mathrm{A}\ .$$

The stainless steel resistance is 5×10^{-7} Ohm·m. The following values of copper resistance ρ_c (Ohm·m·10^{10}) for the different beam screen wall temperatures T and the magnetic field B were used:[2] see Table 1.

2.2 *Surface impedance and boundary conditions for a multi-layered wall*

When calculating the electromagnetic field in a chamber that does not have ideal walls, the finite resistivity is usually taken into account in the form of Leontovich boundary conditions. For normal wave incidence on a wall of infinite thickness the Leontovich boundary conditions are expressed in terms of the usual surface impedance,

$$\xi(s) = Z_0\sqrt{\mu/\epsilon(s)} = \sqrt{s\mu/\sigma}\ ,$$

where Z_0 is the free space impedance, σ is the metal conductivity, ϵ and μ are relative electric (complex, depending on metal frequency) and magnetic permeabilities, respectively, and s is a Laplace variable.

But our problem differs essentially from this model:

(1) the wave in the chamber is propagating together with the beam, not normally, but along the wall, with the beam's phase velocity;

(2) the wall consists of several layers of different conductivities and thicknesses comparable or even less then the skin depth.

Thus, the surface impedance needs to be modified to correctly describe our problem.

The most common case considered is shown in Figure 4b. The chamber wall consists of two layers (copper and steel), a vacuum gap separates the outer side of the wall from the surrounding screen of infinite thickness (which can have $\epsilon(s) = 1$, where this screen is absent).

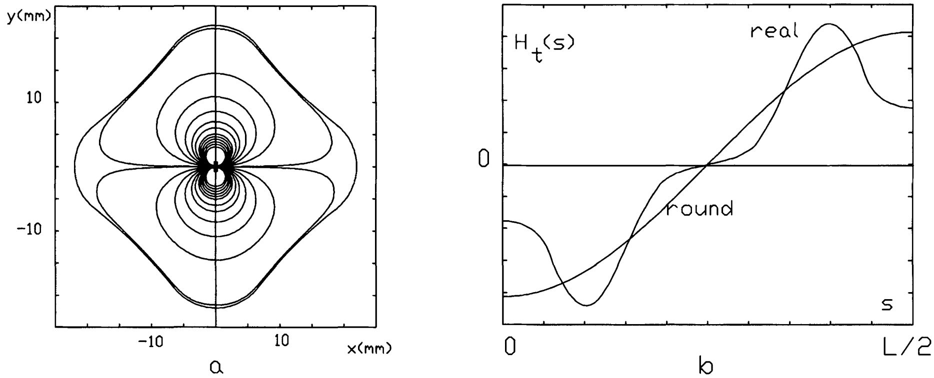

FIGURE 3: The magnetic field of a dipole current.

It can be shown[4] that taking into account the outer steel surrounding is equivalent to the case of a continuous steel wall of infinite thickness. It means that the gap between the wall and outer surrounding 'is not seen' by the wave propagating along the wall.

It is worth noting that for the thin steel wall without surrounding, and with a thickness greatly inferior to the skin depth, the ohmic losses are much less than if we take a surrounding into account. This can be seen if we compare image currents for these two cases.

Due to the boundary conditions on the outer surface of the wall, the magnetic field inside the steel wall without a steel surrounding is

$$H_1 = H_0 \cosh\,[ik_z(z - z_3)]/\cosh\,[ik_z(z_2 - z_3)]\,,$$

and in the case of an infinite steel wall (equivalent to the case of steel surrounding),

$$H_2 = H_0 \exp\,[ik_z(z - z_2)]\,,$$

where H_0 is the magnetic field on the inner steel surface, k_z is the wave number in the steel wall, and z_2 and z_3 are the z-coordinates of the inner and outer surfaces of the steel wall.

Within our parameters (steel wall thickness $d_{st} \sim 1$ mm, skin depth in steel ~ 4 mm for the frequency 7.87 kHz), the full current flowing in steel in the first case makes up only about 0.03 of that for the second case, when the surrounding is taken into account:

$$I_2 \sim H_0; \quad I_1 \sim H_0|k_z d_{st}|^2/2 \approx 0.03\, I_2\,.$$

The difference in the currents results in an analogous difference in the losses.

For numerical calculations we have choosen the two-layer wall model with an outer screen of infinite thickness.

2.3 *Transverse resistive impedance of the vacuum chamber*

The transverse resistive impedance Z_t can be calculated from the dipole longitudinal impedance Z_l, via the Panofsky–Wenzel theorem. Considering[5] a beam of a current I, shifted on a distance x off the axis of a chamber with walls of surface impedance $\xi(s)$, we can write the losses in the chamber walls P as the integral over the chamber surface:

$$P = Z_l I^2/2 = 2\pi R \int \xi(s) \frac{H_t^2(s)}{2} ds \,.$$

From the Panofsky–Wenzel theorem the transverse resistive impedance is

$$Z_t = Z_l/(x^2\omega/c) \,.$$

We calculate the tangential magnetic field on the chamber surface for a dipole current via the code SAM.[6] The magnetic field map and the field along the surface (together with that for a modelled chamber with a round cross-section) are shown in Figure 3.

2.4 *Growth rate calculations for multibunch transverse instability*

We consider transverse oscillation growth rates for resistive instability in a storage ring chamber with a multi-layered wall with surface impedance, which is not now uniform over a cross-section circumference.

The method applied here is analogous to the previous paper,[7] the non-uniform boundary conditions being the main difference.

The round cross-section model of the same diameter was used, and in addition the geometry factor describing the actual geometry (Figure 4a) was taken into account.

The growth rates of multibunch beam oscillation modes are defined from the system of bunch motion in variable action (J_y), phase (ψ_y):

$$\begin{aligned} \dot{J}_y &= 2\sigma_y J_y = \overline{F_y(\partial y/\partial \psi_y)} \,; \quad \dot{\psi}_y = \Omega + \overline{F_y(\partial y/\partial J_y)} \,; \\ y &= \sqrt{2J_y/(m_s\Omega)} \sin(\psi_y) \,; \quad \dot{y} = \Omega\sqrt{2J_y/(m_s\Omega)} \cos(\psi_y) \,. \end{aligned}$$

In these equations, written in the reference system of the equilibrium particle, y is the transverse deflection of the bunch from the equilibrium orbit, F_y is the transverse force, which sums up the action of fields, induced by all bunches, and on this bunch, Ω is the frequency of betatron oscillations and m_s is the mass of the equilibrium particle. The line over the right hand sides denotes averaging over the time.

For a symmetrical beam the growth rates of oscillation eigen modes can be found directly from motion equations. Thus, for a mode with a phase shift between neighbour bunches of $2\pi l/n_b$ $(l = 0, \ldots, n_b)$ the growth rate is

$$\begin{aligned} \sigma_y^l &= -\frac{1}{4\pi}\,\omega_0\,\frac{I}{V_s} Re\,\{\langle Z_{t\beta}\,[i\omega_0(l+\nu_y')]\rangle \\ &\quad + \sum_{p>0} \langle Z_{t\beta}\left[i\omega_0(pn_b + l + \nu_y')\right]\rangle - \langle Z_{t\beta}\left[i\omega_0(pn_b - l - \nu_y')\right]\rangle\} \,. \end{aligned}$$

Here $Z_{t\beta}\,(i\omega)$ is the transverse resistive impedance (see subsection 2.3) multiplied by the machine average beta function β_{av}; ω_0 is the revolution frequency; ν_y' is the fractional part of ν_y.

TABLE 2: Growth rates and transverse impedance.

E [TeV]	T [K]	Δ [μm]	all over Cu coating		0.5 Cu strips coating	
			$\sigma_{\max}, 1/s$	$R_{t\beta}$,GΩ	$\sigma_{\max}, s^{-1}$	$R_{t\beta}$, GΩ
0.45	20	10	94.38	11.35	195.8	23.69
		20	49.02	5.898	160.4	19.42
		50	20.37	2.464	134.9	16.35
		100	12.47	1.514	125.8	15.24
		200	13.13	1.588	129.7	15.72
		500	13.19	1.597	129.8	15.72
	50	10	275	33.05	345.5	41.76
		20	157.7	18.97	248.4	30.05
		50	68.62	8.27	172.9	20.93
		100	36.01	4.347	145.8	17.66
		200	23.17	2.806	135.5	16.41
		500	24.89	3.018	135.8	16.45
	70	10	462.3	55.56	499.9	60.38
		20	309.5	37.21	374.1	45.21
		50	150.4	18.1	241.6	29.24
		100	80.71	9.738	184	22.28
		200	44.27	5.353	155.4	18.83
		500	37.26	4.513	150	18.17
7.0	20	10	17.08	31.95	21.66	40.74
		20	9.738	18.23	15.56	29.28
		50	4.218	7.91	11.07	20.85
		100	2.215	4.172	9.354	17.62
		200	1.449	2.732	8.701	16.39
		500	1.56	2.944	8.722	16.44
	50	10	24.42	45.66	27.98	52.58
		20	15.15	28.33	20.01	37.64
		50	6.941	13	13.36	25.15
		100	3.664	6.876	10.68	20.13
		200	2.095	3.941	9.328	17.58
		500	2.031	3.83	9.317	17.55
	70	10	32.73	61.19	34.69	65.17
		20	23.08	43.16	26.7	50.18
		50	11.73	21.97	17.35	32.64
		100	6.396	12	12.94	24.37
		200	3.47	6.535	10.38	19.56
		500	2.631	4.947	9.69	18.26

Note that this expression has a general form, not depending on the chamber cross-section geometry, which determines only the transverse impedance.

The maximal value of the growth rate over all symmetrical modes is for the mode number $l = n_b - 1$, and this maximal growth rate can be estimated by its main term: at the frequency $\omega_0 \cdot (1 - \nu'_y) = 7.87$ kHz :

$$\sigma_y = \frac{1}{4\pi}\,\omega_0\,\frac{I}{V_s} Re\left\{\langle Z_{t\beta}\left[i\omega_0(1-\nu'_y)\right]\rangle\right\}.$$

This growth rate is determined by the impedance at the frequency $\omega_0(1 - \nu'_y) = 7.87$ kHz, rather than that at the minimal spectrum frequency $\omega_0\dot{\nu}'_y = 3.38$ kHz, because the first gives a positive addition to the growth rate, and the second introduces the decrement.

Note that for a beam with arbitrary charges of bunches an eigenvalue problem arising from motion equations can be solved for determining eigen oscillation mode growth rates. The numerical calculations[7] show that the maximal growth rate for a multibunch beam with a small gap does not exceed that for a symmetrical beam with the same average current and distance between bunches. Table 2 gives the results of calculations of the maximal growth rate $\sigma_{\max}$ of multibunch transverse instability, and of the beam screen wall transverse impedance $R_{t\beta} = R_t\,\beta_{\text{av}}$ for the frequency of 7.87 kHz, for different values of copper coating thickness Δ. Calculations have been done both for beam injection energy and operating energy for all-over and for 0.5 partial copper coating.

2.5 *Ohmic losses caused by image currents*

The power losses due to the wall resistivity can be calculated as the integral over the surface:

$$P = \frac{1}{2} Re \int (E \times H_0^*)_n ds .$$

Calculating the power losses at low temperatures (when the skin depth at high frequencies becomes comparable to or even less than the electron free length) we have taken into account[8] the anomalous skin-effect following the model and interpolation formulas of Pippard and Chambers[9,10] for copper surface impedance.

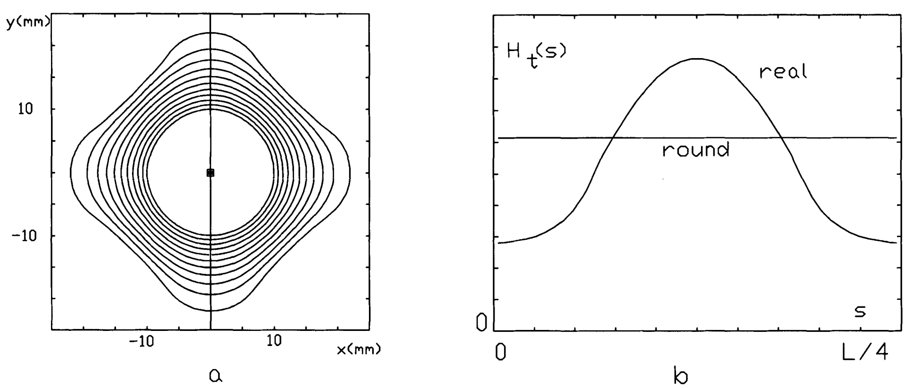

FIGURE 4: The magnetic field of a monopole current.

TABLE 3: Power losses per unit length P_1.

		Power losses, [W/m]			
E	T	Class	Anom.	Anom.	0.5 Copper
TeV	K	skin	diff.	refl.	strips
0.45	20	0.042	0.061	0.051	0.42
	50	0.079	0.085	0.079	0.44
	70	0.121	0.125	0.135	0.48
7.0	20	0.077	0.084	0.077	0.436
	50	0.100	0.105	0.104	0.45
	70	0.135	0.142	0.161	0.50

We calculate the tangential magnetic field on the chamber surface for a current flowing along the chamber axis via the code SAM.[6] The magnetic field map and the field along the surface for this current (together with that for a modelled chamber with round cross-section) are shown in Figure 4.

Table 3 shows the losses per unit length, calculated taking into account surface impedance dependent on beam energy and temperature, for all-over and 0.5 copper coating. The losses have been calculated both for the classical skin-effect model, and for anomalous skin effect (Chambers formulae, diffusion and full reflection models) — the results for all three models are close. Wall losses for partial coating are much greater than for all-over copper coating. Thus, copper strips look to be unacceptable.

3 MECHANICAL CONSIDERATIONS

In this section, we give the results of our analysis[4] of mechanical stresses and deformations of a beam screen and its heating by the quench currents, on the basis[11] of the beam screen construction (Figure 1).

At a superconductivity break-down ('quench') the magnetic field decreases rather quickly (within $\sim$0.3 s[5]) from B = 10 T to zero. The eddy currents induced at this time in the beam screen produce the ponderomotive forces, which deform the screen, tensing it in the horizontal direction and contracting it in the vertical one. The screen must bear[11] not less than 20 such cycles without mechanical damages and residual deformations.

We consider here only all-over copper coating, because of its essential advantages, shown above, particularly with respect to the beam image current power losses.

In order to decrease ohmic losses, it is natural to decrease the electric resistance of the screen inner coating. It can be achieved through lowering the screen operating temperature, which decreases the copper's specific resistance. But it increases eddy currents and, therefore, mechanical stresses and screen deformations. For the best solution choice, coatings of three thicknesses were analyzed (20, 50 and 100 μm), made from copper of purity RRR100. The screen operation at quench was studied at three temperatures, 20, 50 and 70 K.

The inner copper coating presence gives rise to one more mechanical problem at quench — a problem of the joint operation of the steel screen shell and thin copper coating. The analysis shows that practically at any possible constructive and operating screen parameter mechanical stresses in the copper coating cannot be less than the elastic limit. Nevertheless, the screen must fulfill a necessary number of quench cycles without mechanical damage. An adequate solution to this problem seems to us to be the following. The copper layer shake-down, when working in the elastic–plastic region (i.e., at the stresses about the copper elastic limit or higher) is determined by the actual values of relative deformations of this layer. And this deformation of the copper layer is established by the steel shell. Therefore this shell must work in the elastic region and at the stresses, when the relative deformation at the 'steel–copper' boundary are possibly less.

Finally, it is necessary to estimate the influence on the screen operation at quench of the dynamic nature of the quench forces. A precise calculation of the corresponding plane-bending oscillation mode eigen frequency, mounted on a support screen with a rather complicated cross-section (Figure 1) was not made. However, this frequency must, in any case, be higher than one for a free steel round ring with an average radius of 22.5 mm and a wall thickness of 1 mm. And the estimation of the latter frequency[8] gives 1200–1300 Hz, when the characteristic frequencies of quench force action lie within 1.5–3 Hz (at the quench time 0.3 s). On this basis, the forces acting on the screen during quench were treated by us as static ones.

The processes of screen heating by the currents induced at quench are also considered.

3.1 Mechanical stresses at quench

The mechanical stresses on the inner surface of the beam screen steel shell are of most interest. Maximal tension stresses σ_t and maximal contraction stresses σ_c are given in Table 4.[4] Thus, for the copper coating thickness $\Delta = 100\ \mu$m at all considered temperatures, and for $\Delta = 50\ \mu$m at the temperature 20 K, the stresses in the steel shell on the 'steel-copper' boundary either exceed or are dangerously close to the elastic limits of the possible steel variants for the beam screen material (316LN, X20MD, 13RM19, a Russian specification 12h18n10t and others). As acceptable variants, we can consider here the copper coating thickness 20 μm at all (20–70 K) operating temperatures, or the thickness 50 μm at the temperatures 50–70 K.

TABLE 4: Stresses, daN/mm^2.

Δ, μm	Operating temperature, K					
	20		50		70	
	σ_t	σ_c	σ_t	σ_c	σ_t	σ_c
20	31.7	–21.7	16.7	–11.4	9.2	–6.3
50	77.5	–52.9	39.6	–27.1	21.1	–14.4
100	153.6	–105.0	78.0	–53.2	40.8	–27.8

The analysis of a copper coating state on the basis of a linearized joint steel and copper test diagram[4] allows us to hope that copper coating thickness of 20–50 μm at the operating temperature 50–70 K will work reliably during the required 20 quench cycles.

3.2 *Beam screen deformations at quench*

Maximal beam screen deformations by the quench force action are changes in its horizontal and vertical transverse dimensions. These values, depending on the operating temperature and copper coating thickness, are given in Table 5, allowing the following important conclusions:[4]

- at the nominal gap value between the beam screen and the cold bore 1.15 mm (Figure 1) obtained deformation values at Δ = 100 μm for temperatures 20–50 K and at Δ = 50 μm for a temperature of 20 K are unacceptable;
- actual screen deformations can be somewhat (but not essentially, in our opinion) different from those given in Table 5, because of screen supports, which were not taken into account in the calculations;
- at the stresses corresponding to Δ = 100 μm at all temperatures and to Δ = 50 μm at T = 20 K (Table 4), a dependence between deformation and stress becomes nonlinear, and as a result, actual values of deformations can far exceed (10 times and more[12]) those given in Table 5 based on the linear dependence.

Therefore, in this case also, the only possible combinations are Δ = 20 μm at T = 20–70 K and Δ = 50 μm at T = 50–70 K.

Note that below 20 K the copper resistance practically does not change with the temperature,[13] therefore, the working temperature can be decreased for smaller copper thicknesses, for example, for Δ = 10 μm.

3.3 *Beam screen heating at quench*

Currents, induced in the beam screen at quench, except dangerous stresses and deformations, produce its essential heating. Different screen sections are heated in the process differently,

TABLE 5: Screen deformations, mm.

Δ, μm	Operating temperature, K					
	20		50		70	
	δ_x	δ_y	δ_x	δ_y	δ_x	δ_y
20	31.7	–21.7	16.7	–11.4	9.2	–6.3
50	77.5	–52.9	39.6	–27.1	21.1	–14.4
100	153.6	–105.0	78.0	–53.2	40.8	–27.8

TABLE 6: Temperature after quench, K.

Δ, μm	Operating temperature, K		
	20	50	70
20	44.8	56.2	72.1
50	55.0	62.0	74.5
100	64.1	68.5	77.7

and one can show that no essential heat redistribution over a screen contour takes place during quench.[2] The maximal temperatures over the beam screen contour, for different thicknesses of copper coating and operating temperatures,[4] are given in Table 6.

As seen from Table 6, an essential screen overheat during quench relative to the operating temperature takes place for all coating thicknesses at an operating temperature of 20 K and at all operating temperatures for a coating thickness of 100 μm. Therefore, preferable parameters in this case are a copper coating thickness 20–50 μm at operating temperatures of 50–70 K.

4 CONCLUSION

To summarize our conclusions, it seems to be advantageous for an LHC beam screen at the offered cross-section[5] to adopt the following main parameters:

- everywhere inner copper coating thickness 20–50 μm;
- operating temperature 40–50 K.

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