BEAM SCREEN - COLD BORE CONCENTRICITY

N. Kos, L. Nikitina, G. Schneider and R. Veness
1 Introduction

The LHC beam screen is positioned in the cold bore by means of four flexible metallic supports every 1.7 metres longitudinal distance, see attachment 1.

A maximum concentricity error of ±0.4 mm between the cold bore and the beam screen has been proposed. This means that the centreline axis of the beam screen must be within 0.4 mm of the centreline axis of the cold bore.

The centreline axis of the cold bore is defined as the series of straight lines that connect the geometrical centres of the outer diameter of the cold bore at the positions of the supports.

The centreline axis of the beam screen is defined as the line that is formed by the geometrical centres of the inner diameter of the beam screen along its length.

The current situation is investigated and some possibilities for improvement are discussed.

2 Beam screen - cold bore concentricity

The beam screen - cold bore concentricity is determined by three independent contributions; the beam screen supports, the beam screen and the cold bore.

2.1 Beam screen support effects

The beam screen supports contribute to beam screen - cold bore eccentricity by means of the manufacturing tolerance on the free height (arbitrarily set at ±0.1 mm) and vertical sag under gravity at the supports.

According to attachment 2, the sag under gravity at the supports equals:

\[ dx = \frac{G}{(c_1+c_2)} \]  

with: \( dx = \) gravitational sag at the supports [mm]  
\( G = \) beam screen weight per set of supports [N]  
\( c_1, c_2 = \) upper, lower support spring constants [N/mm]

The beam screen weight is 10.6 N/m (for a wall thickness of 1 mm), the weight carried per set of supports is therefore \( G = 10.6 \cdot 1.7 = 18\text{N} \). The spring constants for both upper and lower supports are \( c_1, c_2 = 37.8 \text{ N/mm} \) (see attachment 3).

\[ dx = \frac{18.0}{(37.8+37.8)} = 0.24 \text{ mm}. \]
\[
\varepsilon = 0.5 \text{mm}, F_z = 3.85 \text{kg}, f_z = 1 \text{mm}
\]

\[C = \frac{F_z}{f_z} = 3.85 \text{ kgf/mm} \]
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\[ dx = \frac{18.0}{(37.8+37.8)} = 0.24 \text{ mm}. \]
The exact distance between the supports will depend on the exact length of the beam screen and may even not be constant along its length. The above figure of 1.7 metres is used as a first approximation.

2.2 Beam screen effects

2.2.1 Straightness

The most important beam screen effect is the straightness between supports. On the basis of discussions with potential manufacturers and measurements on preliminary prototypes, this value is provisionally estimated at 0.50 mm. This means that if the beam screen is positioned in a series of V-blocks at distances of 1.7 metres, its centreline axis will always be within a circle with a radius of 0.5 mm from the theoretical (perfectly straight) centreline axis (gravitational sag between supports is only 0.03 mm and therefore negligible).

Beam screen straightness at the supports can be neglected since the flexibility of the beam screen is such that the supports will re-align it. This can be shown as follows (we consider a straightness error (free offset) in the horizontal plane, where the beam screen has the highest rigidity):

Imagine a beam screen with a free offset $f_0$ over a length of 3.4 metres. After insertion, the free offset $f_0$ is reduced to $dx$ by the supports positioned in the middle, see figure 1.

![Figure 1](image)

Figure 1: The flexibility of the beam screen over 3.4 metres is such that the set of supports in the centre will significantly reduce a possible straightness error.

The required force $F$ exerted on the beam screen is given by the following basic formula (see any mechanical engineering handbook):
\[ F = (f_0 - dx) \cdot 48 \cdot E \cdot I / l^3 \]

with:
- \( F \) = force exerted on the beam screen [N]
- \( f_0 \) = free offset of the beam screen [mm]
- \( dx \) = support deflection after insertion [mm]
- \( E \) = Young’s modulus \( 2 \cdot 10^5 \) N/mm²
- \( I \) = hor. moment of inertia \( 3.54 \cdot 10^4 \) mm⁴
- \( l \) = 2 x distance between supports [3400 mm]

While exerting this force on the beam screen, the supports themselves deflect, see attachment 2:

\[ dx = F / (c_1 + c_2) \]

with:
- \( c_1, c_2 \) = support spring constants \( 37.8 \) N/mm

\( F \) is the same in both equations, allowing to relate \((f_0 - dx)\) (straightening of the beam screen at the supports) to \( dx \) (deflection of the supports):

\[ dx = (f_0 - dx) \cdot 48 \cdot E \cdot I / (l^3 \cdot (c_1 + c_2)) \quad (2) \]

\[ dx = 0.11 \cdot (f_0 - dx) = 0.10 \cdot f_0 \]

This means that even with the maximum specified straightness error of 0.5 mm at a set of supports, the free offset is reduced to 0.05 mm.

The value of 0.05 mm can not contribute to the worst case situation since a maximum straightness error between the supports can not co-exist with a maximum straightness error in the same direction at the adjacent supports.

The above calculation is a simplified worst case situation since it considers both extremities of the 3.4 metres of beam screen laterally fixed, whereas in reality these are also positioned on springy supports, making the screen even more flexible.

### 2.2.2 Twist

Beam screen twist does not influence the concentricity and is therefore not included.

### 2.2.3 Gravitational sag

Gravitational sag \( f \) between the supports (see figure 2) can be calculated with the following basic formula (see any mechanical engineering handbook):
\[ f = q \cdot l^4 / (384. E. I) \]  

with:  
\( f \) = gravitational sag between supports [mm]  
\( q \) = beam screen weight [0.0106 N/mm]  
\( l \) = distance between supports [mm]  
\( E \) = Young's modulus [2 \cdot 10^5 N/mm²]  
\( I \) = vert. mom. of inertia [3.34 \cdot 10^4 mm⁴]

\[ f = 4.1 \cdot 10^{-15} \cdot l^4 \]

Figure 2: Gravitational sag between supports.

The cooling tubes on top and bottom of the beam screen have been taken into account since they contribute significantly to the rigidity (the vertical moment of inertia increases by 16%).

For \( l = 1700 \) mm, the sag is only 0.03 mm. It increases very strongly with increasing distance between the supports (for \( l = 2500 \) mm, \( f = 0.16 \) mm).

The sag between supports is independent of the beam screen wall thickness since both the weight and the moment of inertia scale linearly with the wall thickness.

### 2.2.4 Tolerance on the section

The tolerance of the beam screen section, in terms of absolute size, does not have an influence on the concentricity. Irregularities in the shape, however, could have an effect, which is arbitrarily estimated at \( \pm 0.10 \) mm.

### 2.2.5 Tolerance on the wall thickness

The tolerance on the beam screen wall thickness is \( \pm 0.03 \) mm for formed and welded co-laminated material (as specified by Heraeus) or \( \pm 0.10 \) mm for a seamless screen (ISO1127-T5).
2.3 Cold bore effects

The third contribution to the eccentricity comes from the cold bore wall thickness tolerance, see figure 3. Straightness of the cold bore between the supports does not influence the aperture and is therefore not taken into account. The straightness of the external diameter of the cold bore at the supports is our reference.

![Diagram of cold bore wall thickness tolerance](image)

Figure 3: The tolerance t on the cold bore wall thickness d contributes to cold bore - beam screen eccentricity.

2.4 Summary

The worst case in the current situation is summarised in table 1.

<table>
<thead>
<tr>
<th>Support effects:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Support height (manuf. tolerance, free height ± 0.10 mm)</td>
<td>-0.10 mm</td>
</tr>
<tr>
<td>- Gravitational sag at supports (37.8 N/mm per support)</td>
<td>-0.24 mm</td>
</tr>
<tr>
<td></td>
<td>-0.34 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beam screen effects:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Straightness of beam screen (between supports)</td>
<td>-0.50 mm</td>
</tr>
<tr>
<td>- Gravitational sag between supports (support distance 1.7 m.)</td>
<td>-0.03 mm</td>
</tr>
<tr>
<td>- Tolerance on beam screen section</td>
<td>-0.10 mm</td>
</tr>
<tr>
<td>- Tolerance on beam screen wall thickness (formed/welded)</td>
<td>-0.03 mm</td>
</tr>
<tr>
<td></td>
<td>-0.66 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cold bore effects:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Tolerance on cold bore wall thickness (eccentricity of ID)</td>
<td>-0.10 mm</td>
</tr>
<tr>
<td>Maximum total concentricity error</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>-1.10 mm</td>
</tr>
</tbody>
</table>

Table 1:  Worst case eccentricity with the centreline axis of the beam screen below the centreline axis of the cold bore.
Summation of all the tolerances moves the beam screen centreline axis down by as much as 1.10 mm with respect to the cold bore centreline axis. This will reduce the aperture and may, in the case of a beam screen diameter with a positive tolerance and a cold bore diameter with a negative tolerance, result in a thermal short between the cold bore and the cooling tubes attached to the beam screen.

The maximum offset between the centreline axes in the horizontal plane can be found by ignoring the gravity components and equals $\pm 0.10 + \pm 0.50 + \pm 0.10 + \pm 0.03 + \pm 0.10 = \pm 0.83$ mm.

The maximum offset with the beam screen centreline axis above the cold bore centreline axis can be found by giving a negative sign to the gravity components and a positive sign to the other components. It equals $0.10 - 0.24 + 0.50 - 0.03 + 0.10 + 0.03 + 0.10 = 0.56$ mm.

Figure 4 shows the maximum offsets in all directions.

Figure 4: The centreline axis of the cold bore is represented by the intersection of the two dash-dotted lines. The beam screen centreline axis is proposed to be within the circle.
3 Possible improvements

3.1 Reduced beam screen wall thickness

A reduced beam screen wall thickness will decrease the gravitational sag at the supports and therefore also the concentricity error. For example, taking a stainless steel wall thickness of 0.70 instead of 1.00 decreases the gravitational sag at the supports by 30% to 0.17 mm, resulting in maximum vertical offsets of +0.63 and -1.03 instead of +0.56 and -1.10 mm (see table 1).

The possibility to reduce the beam screen wall thickness will depend on the results of strength calculations (beam screen deformation, stresses under quench) and power transmitted through the slots.

3.2 Shorter distances between supports (using more supports)

An obvious solution to improve the position accuracy of the beam screen in the cold bore would be to have shorter longitudinal distances between the supports. Let's assume this distance was halved from 1.7 to 0.85 metres.

Several effects from table 1 would not be influenced, namely the support height tolerance, the tolerances on the beam screen section and wall thickness and the tolerance on the cold bore wall thickness.

The gravitational sag at the supports, given by (1) would halve from 0.24 to 0.12 mm since G would halve.

The gravitational sag between supports can be calculated with (3) and equals

\[ f = 4.1 \times 10^{-15} \cdot 850^4 = 2.1 \times 10^{-3} \ mm \]

The straightness between supports would improve. In paragraph 2.2 we considered 0.5 mm to be the maximum straightness error between supports. In the new situation with half the distance between the supports, this straightness error would be reduced, but it would probably not be halved. Let's assume it would be \( 2/3 \cdot 0.50 = 0.33 \) mm.

Beam screen straightness at the supports would improve because of the larger amount of aligning elements (supports). It will not contribute to the worst case situation of eccentricity, as is already explained in paragraph 2.2.

The worst case situation of table 1 would become 

\[-0.10 + -0.12 + -0.33 + -0.00 + -0.10 + -0.03 + -0.10 = -0.78 \ mm \]

instead of -1.10 mm. The maximum offset in the upwards direction would equal 

\[ 0.10 + -0.12 + 0.33 + -0.00 + 0.10 + 0.03 \]
+ 0.10 = 0.54 mm instead of 0.56 mm. The maximum offset in the horizontal direction would equal 0.10 + 0.33 + 0.10 + 0.03 + 0.10 = 0.66 mm instead of 0.83 mm.

A larger amount of supports would of course have an effect on the thermal conduction losses to the cold bore and on the required insertion force for the beam screen. These effects should be carefully analysed.

It should also be remembered that the above solution only helps for a perfectly straight cold bore. If the cold bore has a straightness error, the additional supports will force the beam screen to follow this error.

3.3 Compensating beam screen supports

It may be possible to design upper and lower supports with different properties to compensate for gravitational sag at the supports. Three options have been studied and are described below.

3.3.1 Rigid lower supports

Gravitational sag at the supports could be avoided by using rigid lower supports, acting as spacers, and spring loaded upper supports.

The required height for the rigid lower supports would equal the nominal gap between the beam screen and the cold bore, i.e. 1.5 mm.

Now assume the cold bore at maximum internal diameter and the beam screen at minimum external diameter, see figure 5. The average gap now becomes \[ \left[ (49+0.46) - (46-0.2) \right] / 2 = 1.83 \text{ mm}. \]

![Figure 5](image-url): Centreline axes of beam screen and cold bore with rigid lower supports. On the left, cold bore and beam screen at nominal diameter, on the right the cold bore at max. and the beam screen at min. diameter, resulting in a vertical offset \( f \).
The resulting vertical offset at the supports is approximately \( f = (1.83-1.50)\sqrt{2} = 0.47 \text{ mm} \) with the beam screen centreline axis below the cold bore centreline axis.

The offset is equal, but in the opposite direction when the beam screen external diameter is maximum and the cold bore internal diameter is minimum.

A possible offset of \( \pm 0.47 \text{ mm} \) is certainly not an improvement compared with the value of 0.24 mm in table 1. Rigid lower supports are clearly not a good solution to improve the concentricity error.

### 3.3.2 Upper and lower supports with different spring constants

Gravitational sag at the supports could be compensated for by using lower beam screen supports with a higher spring constant. This option will be analysed using the model of figure 6. This model is the equivalent in the vertical direction of the real situation with four supports under 45° angles, as is explained in attachment 2.

![Figure 6](image)

**Figure 6**: Simplified model of the beam screen supported in the cold bore. The upper and lower supports have different spring constants (\(c_1\) and \(c_2\)). The three arrows on the right indicate the forces acting on the beam screen.

The vertical forces are in equilibrium for static conditions:
\[ c_1 \cdot (f_0 - f_1) + G = c_2 \cdot (f_0 - f_2) \]

with:

- \( c_1 \) = upper support spring constant [N/mm]
- \( f_0 \) = free support height [mm]
- \( f_1 \) = upper gap [mm]
- \( G \) = gravity per 1.7 m beam screen [N]
- \( c_2 \) = lower support spring constant [N/mm]
- \( f_2 \) = lower gap [mm]

In the case of compensated gravitational sag at the supports \( f_1 = f_2 = f \):

\[ c_2 = c_1 + G / (f_0 - f) \]  \( (4) \)

The required additional value for the spring constant of the lower supports is \( G / (f_0 - f) \). In this formula, \( G \) and \( f_0 \) are constants but the average gap size \( f \) will be different at every single support position due to the manufacturing tolerances. This means that all the lower supports will need to have different spring constants, which is not realistic.

Compensation of gravitational sag at the supports by means of using different spring constants for the upper and the lower supports is therefore also not a good solution.

### 3.3.3 Upper and lower supports with different free heights

Gravitational sag could be compensated for by using lower beam screen supports with a bigger free height than the upper supports. This option will be analysed using the model of figure 7.

The vertical forces are in equilibrium for static conditions:

\[ c \cdot (f_{01} - f_1) + G = c \cdot (f_{02} - f_2) \]

with:

- \( c \) = spring constant [N/mm]
- \( f_{01} \) = free height upper support [mm]
- \( f_1 \) = upper gap [mm]
- \( G \) = gravity per 1.7 m beam screen [N]
- \( f_{02} \) = free height lower support [mm]
- \( f_2 \) = lower gap [mm]
Figure 7: Simplified model of the beam screen supported in the cold bore. The upper and lower supports have different free heights \((f_{01} \text{ and } f_{02})\). The three arrows on the right indicate the forces acting on the beam screen.

In the case of compensated gravitational sag at the supports \(f_1 = f_2 = f\):

\[ c \cdot (f_{02} - f_{01}) = G \]  

\[ \text{or} \quad (f_{02} - f_{01}) = \frac{G}{c} \quad (5) \]

The required additional free height for the lower supports \((f_{02} - f_{01})\) is a constant and therefore independent of the actual size of the gap between the beam screen and cold bore. This means that full compensation of the gravitational sag at the supports is possible (within the limits of manufacturing accuracy).

The maximum (vertical) offset could thus be reduced by 0.24 mm and would become -0.86 mm (see paragraph 2.4). The maximum offset in the horizontal direction would be unaffected at 0.83 mm.

In combination with doubling the amount of supports (see paragraph 3.2), we could eliminate the gravitational sag between the supports (0.03 mm) and reduce the beam screen straightness error between supports by 0.50-0.33 = 0.17 mm. This would result in an additional improvement of 0.03 + 0.17 = 0.20 mm in the vertical direction and 0.17 mm in the horizontal direction. The maximum offset would be reduced to ±0.66 mm in both directions.

The required value for the additional free height of the lower supports can be calculated with (5). \(G\) is the beam screen weight per 1.7 metres (= 18 N) and \(c\) the spring constant per support (= 37.8 N/mm):

\[ (f_{02} - f_{01}) = \frac{G}{c} = \frac{18.0}{37.8} = 0.48 \text{ mm}. \]
The increase in free height of the lower supports will generate higher stresses in the supports themselves. Drawing 06LHCVHNSA01763 proposes a free height of 1.83 mm. After adding the additional free height, the free height of the lower support would become 1.83 + 0.48 = 2.31 mm. The minimum gap between the beam screen and the cold bore is \((49-0.46)-(46+0.2))/2 = 1.17 \text{ mm.}\) The maximum deflection of the lower support is therefore 2.31-1.17 = 1.14 \text{ mm.}\)

The stress in the supports when deflected over 1.0 \text{ mm} are 37.307 \text{ kgf/mm}^2 (see attachment 3, calculated by L. Nikitina, 03-10-96). A deflection of 1.14 \text{ mm} will approximately give a maximum stress of 1.14\cdot37.307 = 42.5 \text{ kgf/mm}^2 (417 \text{ MPa}). This would imply the use of high manganese stainless steel with a yield strength of 550-650 \text{ MPa} (at room temperature) for the manufacturing of the supports.
4 Conclusion

In the current situation, the maximum (vertical) offset between the centreline axes of the beam screen and the cold bore is 1.10 mm (worst case situation). This is not in conformity with the proposed value of 0.4 mm.

Such an offset will reduce the aperture and may, in the case of a beam screen diameter with a positive tolerance and a cold bore diameter with a negative tolerance, result in a thermal short between the cold bore and the cooling tubes attached to the beam screen.

The most important offset contribution is the tolerance on the beam screen straightness. The value of 0.5 mm/m is an arbitrary estimate based on a few measured tubes and needs to be verified with representative prototypes.

Halving the longitudinal distance between the supports would better align the beam screen with respect to the cold bore. In the case of a perfectly straight cold bore this would reduce the maximum (vertical) offset from 1.10 to about 0.78 mm. The maximum offset in the horizontal direction would go down from 0.83 to 0.66 mm. However, the double amount of supports would double the insertion force and the thermal conduction losses to the cold bore.

The second most important contributor is a systematic vertical offset due to gravitational sag at the supports. This effect can possibly be compensated for by using upper and lower beam screen supports with different free heights. This would reduce the maximum vertical offset from 1.10 to 0.86 mm. The maximum offset in the horizontal direction would be unaffected at 0.83 mm.

Using different upper and lower supports has the potential danger of interchanging them. They should therefore be visibly different.

If the two measures are combined (double amount of supports, compensated for gravitational sag) the maximum offset will be reduced to 0.66 mm in all directions.

When considering the consequences of the worst case offset, one should keep in mind that this situation will, if ever, only rarely occur along the perimeter of the machine.

Prototypes of supports, beam screens and cold bores will be necessary to validate the estimated and/or calculated results.
\[\begin{align*}
F &= F_0 - c_1 \, dl \\
F_v &= F \cdot \sin 45° \\
&= \frac{1}{2} V_l^2 (F_0 - \frac{1}{2} V_l^2 \cdot c_1 \, dx) \\
F &= F_0 + c_2 \, dl \\
F_v &= F \cdot \sin 45° \\
&= \frac{1}{2} V_l^2 (F_0 + \frac{1}{2} V_l^2 \cdot c_2 \, dx) \\
F_v &= F_0 - c_1 \, dl \\
F_v &= F_0 - c_1 \, dl \\
&= \frac{1}{2} V_l^2 (F_0 - \frac{1}{2} V_l^2 \cdot c_1 \, dx) \\
F &= F_0 + c_2 \, dl \\
G &= \sqrt{V_l^2 - F_0 - c_1 \, dx} \\
&= \sqrt{V_l^2 \cdot F_0 + c_2 \, dx} \\
&= (c_1 + c_2) \, dx \\
dx &= \frac{G}{(c_1 + c_2)}
\end{align*}\]