Preliminary beam screen and beam pipe engineering design: Deliverable D4.3

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PRELIMINARY BEAM SCREEN AND BEAM PIPE ENGINEERING DESIGN

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PRELIMINARY BEAM SCREEN AND BEAM PIPE ENGINEERING DESIGN

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Abstract:
Drawings of the beam screen and surrounding beam pipe mechanical design as produced for the measurements at the light source. Description of the materials and manufacturing processes used to produce the test element.
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1. INTRODUCTION

Beam screen dimensions are derived to optimize beam nominal aperture, knowing that the beam screen must be inserted in the 44 mm diameter cold bore, while ensuring vacuum stability, heat transfer to the cryogenic cooling system and good mechanical strength [1-4].

The design of the beam screen results from different iterations in order to obtain the above mentioned optimisation.

It started with the conceptual design shows in Figure 1, is based on a non-symmetrical shape with an antechamber used to channel the photons only in the synchrotron radiation side. A deflector is used to deviate photons toward the antechambers and therefore to avoid large reflection of photons backward the central chamber. The central chamber has a racetrack shape with a slit and internal copper layer is considered on the inner wall for impedance reasons. Sharp edges introduced on the slit to reduce the photon backscattering. External copper coating is also considered for the heat transfer of the synchrotron radiation power to the cooling channels. Heat deposition was mainly expected in the deflector tip area and uniform distribution along the beam screen was assumed. Pumping slots were implemented in the central chamber wall to provide enough transmission probability of gas molecules to the cold bore. Then, a symmetrical design has been proposed for impedance considerations (Figure 2).

Larger pumping slots have been implemented to increase the pumping efficiency [3]. External copper strips were added with a longitudinal discontinuity, which is required to reduce the Lorentz forces induced during a magnet quench. Polygonal shape (half octagon) of the central chamber was introduced to ease the manufacturing (Figure 3 and Figure 4).
This has been even further simplified with a half hexagon shape of the central chamber (Figure 5). The sharp edges have been removed reducing the manufacturing steps as well (and therefore cost). Still for economical and large scale feasibility reasons, the connection between the deflectors and the cooling channels is considered.

Finally, under consideration is the scenario of removing the deflector and adding a sawtooth profile, Figure 6. Under consideration at the moment of writing this report, section 4.
2. BEAM SCREEN AND SURROUNDING BEAM PIPE MECHANICAL DESIGN

Beam screen dimensions are derived to optimize beam nominal aperture, knowing that the beam screen must be inserted in the 44 mm diameter cold bore, while ensuring vacuum stability, heat transfer to the cryogenic cooling system and good mechanical strength [1-4].

2.1. BEAM SCREEN MECHANICAL DESIGN

In the present design, the vertical and horizontal beam screen aperture is 26.4 and 29.58 mm, respectively, with an overall diameter of 41.6 mm (Figure 7).

![Figure 7: Beam screen layout and dimensions](image)

Space for the circulating beam is delimited by a so called central chamber with a 5 mm slit (Figure 1) on both sides to allow the escape of synchrotron radiation coming from the beam and therefore to avoid possible vacuum instabilities. Also, this gap will permit the transmission of the residual gas to the cold bore through the pumping holes. This ensures an acceptable beam lifetime and reduces heat load to cold bore produced by scattered beam particles [5]. The central chamber is made of a dedicated high nitrogen high manganese austenitic stainless steel (P506) ensuring a low magnetic permeability [6]. It has a 1.25 mm thickness and is clad, in the inside, by a 0.3 mm thick copper layer to reduce image currents power losses and to provide low transverse resistive-wall impedance [7] (Figure 8). High electrical conductive OFE copper is used with typical RRR of 100.
The slit in the central chamber is followed by a P506 stainless steel deflector to redirect photons coming from synchrotron radiation to an antechamber where they are absorbed at the different parts of the beam screen (Figure 9). This photon absorption is the main heat source in the beam screen and will be analysed in detail in section 2, thermal mechanical behaviour of beam screen.

Between the central chamber and the deflectors, there is a set of four stainless steel stiffeners (one set each 70 mm in longitudinal direction) whose functions are first to avoid big deformations of the central chamber during a magnet quench and secondly to act as a photon stoppers absorbing synchrotron radiation coming from the deflector. These ribs are, on the deflector side, inserted and welded in the beam screen outer surface and, in the other side, touching outer surface of central chamber (Figure 10).

Large pumping slots are required to optimize pumping efficiency. They cover about the 20% of the whole exterior beam screen surface. The holes are hidden from the beam by the central chamber wall, optimizing the longitudinal and transverse impedances (Figure 11).
To reduce cryogenic operation cost, the synchrotron radiation power is intercept at a high temperature level. The temperature range, compatible with vacuum stability, is fixed between 40 and 60 K. To ensure the beam screen temperature while being subjected to high heat deposition (around 30W/m), the beam screen is equipped with two cooling channels with as large as possible cross-section (transversal area of around 53 mm$^2$ per tube). They are welded on top and bottom of the central chamber (Figure 12). Local discontinuous welds are foreseen to avoid trapped volume. In these tubes circulates gaseous helium at 50 bars and 40K in the inlet feedthrough. The helium temperature at the circuit outlet is assumed to be 57 K, ensuring a temperature margin of at least 3 K between the helium and coldest part seen by the beam, namely the inner copper layer [8].

The synchrotron radiation power is mainly deposited on the deflector and the stiffeners. They are both made of stainless steel that has a poor thermal conductivity at cryogenic temperature. They are the warmest parts of the beam screen in normal conditions (Section 2, thermal mechanical behaviour of beam screen). To increase the heat transfer to the cooling channel, 0.3 mm thick copper strips are distributed all along the outer surface of the beam screen (Figure 13). The stiffeners absorbing the largest amount of synchrotron radiation power, the distribution of these strips has been done focusing on the ribs surroundings area, thus, a 12.5 mm width strips are situated on ribs area and a 6.25 mm width strip between one rib and another, letting the interspace between strips for the pumping holes (Figure 14).
2.2. THERMAL MECHANICAL BEHAVIOUR

2.2.1. Synchrotron radiation heat transfer and temperature profile

An important task regarding the design of the beam screen is the thermal behaviour in nominal operating conditions. For the FCC-hh energy (50 TeV) synchrotron radiation power per beam is expected to be about 31 W/m. This is the main heat source during stable beam, reason why image currents (3 W/m) [9] and electron cloud (0.1 W/m) [10] thermal effects are neglected in this study. The photon emission is produced in the tangent direction of the trajectory of the particles when passing through a dipole magnet (Figure 15).

![Figure 15: Synchrotron radiation emission](image)

After passing through the central chamber gap, and being reflected by the deflector, most of the photons will be absorbed by the beam screen walls and in particular by the ribs. This synchrotron radiation power has to be efficiently carried to the beam screen cooling channel to avoid large heat load to the cold mass. In order to understand better the beam screen thermal behaviour under these conditions, the beam screen temperature profiles have been studied at the beginning and at the end of the half-cell, where the helium temperature is 40 K and 57 K, respectively [8]. A convection coefficient of 5000 W/K/m² has been assumed between helium and the cooling channel internal surface.

The synchrotron radiation deposition field has been assessed with a Monte Carlo ray tracing code (SynRad). Maximum heating occurs on the ribs and on the deflector. In addition, the synchrotron radiation deposition is not uniform along the beam screen (Figure 16). For this analysis, the heat deposition has been conservatively considered as the maximum radiation density absorbed by the stiffeners along the beam screen, occurring at around 4 m inside the dipole.
All the calculations have been done using a detailed 3D model implemented in COMSOL Multiphysics using the heat transfer module. Temperature dependent thermal conductivity has been considered for copper and stainless steel (Figure 17). The main heat path is governed by the copper thermal conductivity (orders of magnitude higher than stainless steel at cryogenic temperature) which is strongly temperature dependent. Copper with RRR of 100 has been used for the analysis.

2.2.2. Cooling circuit inlet

The temperature profile corresponding to an helium temperature of 40 K (Helium inlet temperature) is shown in Figure 18 and Figure 19.
Analysing two sections indicated in Figure 19, it can be seen how, in section 1, synchrotron radiation coming from the reflector is absorbed by the stiffeners (that act as photon stoppers) heating them up to 80 K. Second important part is the deflector (section 2), where most of the total synchrotron radiation impacts against it all along the dipole. The maximum temperature at this location is 77 K. It is worth to note that the inner chamber copper layer remains at 40.6 K (0.6 K difference with respect to the helium temperature).

Thermal stress and deformation produced by this heat load have been analysed. The maximum thermal stress (130 MPa) remains much below the elastic limit (1350 MPa) at cryogenic conditions. Furthermore, a maximum local displacement of 0.003 mm is observed (Figure 20).
2.2.3. Cooling circuit outlet

The temperature profile corresponding to an helium temperature of 57 K (Helium outlet temperature) is shown in Figure 21 and Figure 22.

*Figure 20: Thermal stress and deformation at 40 K He*

*Figure 21: Beam screen temperature profile with 57 K He*
As the cooling tubes temperature is increased, mean beam screen temperature rises with a maximum temperature of 93 K in the stiffeners. Nevertheless, as shown in Figure 22, inner copper layer still remains within the temperatures limit defined (40-60 K). In this particular case, mean temperature in Cu layer is 57.6 K.

Thermal stress has been estimated to 120 MPa and maximum local displacement to 4 µm (Figure 23).
2.2.4. Influence of beam offset

The case of a beam screen not in the beam plane has been considered. In such configuration, part of the synchrotron radiation impacts directly the central chamber (Figure 24) and the heat deposition distribution has to be redefined.

![Figure 24: Synchrotron radiation impact from misaligned beam](image)

The temperature profiles at the inlet and outlet of the cooling circuit are presented in Figure 25 for a beam offset of 2mm. The maximum temperature on the copper layer is 41 K and 61 K, respectively.

![Figure 25: Temperature fields for 40 K and 57 K Helium with a 2 mm beam offset](image)

For a 4 mm vertical beam offset, a significant part of the synchrotron radiation hits directly the internal copper layer. This material has a very good thermal conductivity at cryogenic temperature and no hot spot is observed here. The maximum temperature of the central chamber is 45.7 K and 62.8 K for an helium temperature of 40 K and 57 K, respectively (Figure 26). It is worth to note that the second half of the central screen (not directly impinged by photons) remains at a low temperature (helium temperature) which governs the vacuum behaviour.
2.2.5. Summary
Data for the different maximum temperature, stress and local displacement are summarized in Table 1.

Table 1: Beam screen thermal behaviour for different helium temperature and beam offset

<table>
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</thead>
<tbody>
<tr>
<td>40</td>
<td>0</td>
<td>40.3/40.6</td>
<td>130</td>
<td>0.0048</td>
</tr>
<tr>
<td>57</td>
<td>0</td>
<td>57.2/57.4</td>
<td>120</td>
<td>0.004</td>
</tr>
<tr>
<td>40</td>
<td>2</td>
<td>40.1/43.6</td>
<td>129</td>
<td>0.0047</td>
</tr>
<tr>
<td>57</td>
<td>2</td>
<td>57/60</td>
<td>119</td>
<td>0.004</td>
</tr>
<tr>
<td>40</td>
<td>4</td>
<td>40/45.7</td>
<td>127</td>
<td>0.0043</td>
</tr>
<tr>
<td>57</td>
<td>4</td>
<td>57/62.8</td>
<td>116</td>
<td>0.0038</td>
</tr>
</tbody>
</table>
2.3. HEAT LOAD FROM THE BEAM SCREEN TO THE COLD BORE

The heat transfer from the beam screen to the cold bore has been assessed considering the radiation and the conduction through the supporting system. The study has been carried out for both cooling temperatures.

2.3.1. Radiation

First estimations of the heat radiated from the beam screen to the cold bore have been done with analytical formula [8]:

\[ Q_{rcb} = \frac{\varepsilon_{cb} \cdot \varepsilon_{bs}}{\varepsilon_{bs} + (1 - \varepsilon_{bs})\varepsilon_{cb}} \cdot A \cdot \sigma \cdot (T_{bs}^4 - T_{cb}^4) \]

where:

- \( Q_{rcb} \): radiative heat load to the cold bore (W)
- \( \varepsilon_{cb} \): emissivity of the cold bore tube (0.1)
- \( \varepsilon_{bs} \): emissivity of the LHC beam screen (0.15)
- \( A \): cold bore area (0.138 m² per aperture and per meter)
- \( \sigma \): Stephan-Boltzman constant (5.67e-8 W/m²K⁴)
- \( T_{bs} \): beam screen temperature (40/57 K)
- \( T_{cb} \): cold bore temperature (1.9 K)

The radiated heat has been estimated to 2.15 mW/m and 5.28 mW/m for a beam screen at 40 K and 57K, respectively.

Simulations of radiation have been carried out considering all surfaces as grey surfaces. The temperature profiles (Figure 27 and Figure 28) of the beam screen for the two different helium temperatures have been considered as an input of the simulations.

Figure 10 presents the heat flux to the cold bore for helium at 40 K. Highest heat transfer occurs obviously at locations facing highest temperature. Inward heat flux received by cold bore from beam screen by radiation is: 0.81 mW/m. Similar results are obtained for helium at 57 K. Heat flux from the beam screen to the cold bore is estimated to 2.9 mW/m. The results are in a rather good agreement with the simplified analytical approach.

![Figure 27: Inward radiative heat flux profile with 40 K He](image1)

![Figure 28: Inward radiative heat flux with 57 K He](image2)
2.3.2. Supporting system of the beam screen in the cold bore

2.3.2.1. Mechanical design

The beam screen is supported inside the cold bore by flexible elements which have to ensure its good alignment while minimizing the thermal heat load to the cold mass. These supports, made of stainless steel, are welded locally to the beam screen and have five contact points with the cold bore (Figure 29). The initial height of the support is 1.7 mm inducing a nominal pre-stress of 0.2 mm. Check for 0.1 mm

![Beam screen supports layout](image)

Figure 29: Beam screen supports layout

The Von Mises stress field due to the pre-stress condition of 0.2 mm displacement is shown in Figure 30. High bending stresses occur in the bending radius. To ensure their mechanical strength, the supports have been designed in order to avoid plasticity across their thickness. The stiffness of a single strip is around 25 N/mm.

![Pre stressed beam screen supports stress](image)

Figure 30: Pre stressed beam screen supports stress
The number of supports along the beam screen is a trade-off between the mechanical deformations, in particular under the gravity, and the thermal performance. A configuration of two sets of supports per beam screen meter has been defined. The corresponding deflection can is shown in Figure 31.

![Figure 31: Beam screen deflection with 2 supports set per meter](image1)

It turns out that, for this configuration and nominal perfect geometry, the beam screen is almost centred with respect to the cold bore: an offset of 0.015 mm (Since there are two supports in the bottom, final displacement ends to be positive) and a theoretical sag of 2 µm have been estimated.

### 2.3.2.2. Heat transfer by conduction through the supports

The temperature profile in the supports and beam screen, obtained for helium at 40 K, is shown in Fig. 32. The heat flux depends strongly on the contact between the supports and the cold bore. Based on the mechanical analysis and the contact force of around 10 N, first estimations of the heat transferred by conduction to cold bore has been carried out. They turn out to be 0.05 W/m and 0.1 W/m for helium at 40 K and 57 K, respectively.

![Figure 32: Beam screen and supports temperature profile](image2)
2.3.2.3. Overall beam screen deformation under nominal thermal loads

Local effect of thermal stresses on the beam screen has been shown in section 2.1. Nevertheless, overall column deformation, with a “banana shape”, may occur because of the temperature gradient across the beam screen section (Chapter 2.1). The temperature heterogeneity induces local bending moments leading to a deformation that depends strongly on the stiffness of the supporting system of the beam screen in the cold bore. For a beam screen, 15 m long, clamped on one side and subjected to this temperature distribution, a transversal displacement of 18 mm is expected at the second extremity. A model of the beam screen supported by springs, 50 N/mm equivalent stiffness, pre-stressed by 0.2 mm and distanced by 50 cm has been done. The beam screen is assumed clamped on one side. On the other side, two extreme boundary conditions have been considered to model the beam screen bellows that has to compensate for the differential thermal expansion/contraction of the beam screen with respect to the cold bore: beam screen extremity free or simply supported. The corresponding deformation are reported in Figure 33 and Figure 34.

![Figure 33: Overall thermal deformation of the beam screen with free extremity](image1)

![Figure 34: Overall thermal deformation of the beam screen with simply supported extremity](image2)

The deformation of the beam screen is localized in the last third of the length. For the beam screen with a free extremity, the maximum deformation is around 0.025 mm. The addition of a support at his extremity reduces the maximum deformation of the beam screen to around 0.014 mm.
2.4. MECHANICAL BEHAVIOUR OF THE COOLING CHANNEL UNDER INTERNAL PRESSURE

To increase the cryogenic system efficiency, the beam screen cooling is operated at 50 bars, nominal absolute pressure. The cross section of the channel has to be reduced to allow a large helium mass flow. Thus, the cooling channel thickness has been optimized and is 1 mm. The Von Mises stress field in the beam screen under this pressure is shown in Figure 35. The maximum stress in the cooling channel is around 400 MPa, singularities in the welds excluded.

The safety valve setting is fixed at 55 bars, defining the maximum allowable and design pressure. The beam screen has to fulfill safety requirements, namely the standard EN 13445-3 dedicated to the design of unfired pressure vessels. The most critical loading case, corresponds to the pressure test done at room temperature and with a pressure of 80 bars, according to the EN 13445-5 (safety coefficient of 1.43 with respect to the maximum allowable pressure).

The study of the cooling channel has been carried out according to the Annex B of the standard EN 13445-3 (Design by analysis - direct route).

The strength of the pressure vessel is driven by the thickness of the vessel, i.e. 1 mm for the cooling channel and the mechanical properties of the material. Typical tensile curve of the high-manganese high-nitrogen austenitic stainless steel (called P506) is shown in Figure 36.
The tensile strength properties of this material at room temperature are summarized in Table 2.

<table>
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<th>Property</th>
<th>Strength [MPa]</th>
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<tr>
<td>Tensile strength</td>
<td>825</td>
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<tr>
<td>0.2 % proof strength</td>
<td>440</td>
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<tr>
<td>1 % proof strength</td>
<td>494</td>
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For austenitic stainless steel with large deformation to rupture, the material strength parameter is defined by the 1 % proof strength and a partial safety factor. A linear-elastic ideal-plastic constitutive law has been used to model the material. A Von Mises's yield condition has been applied with the yield stress defined by the material strength parameter multiplied by $\sqrt{3}/2$.

Loading conditions, safety coefficient and material yield stress used for the numerical simulations are presented in Table 3.

<table>
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<th>Nominal Test pressure</th>
<th>Safety coefficient for loads</th>
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<td>Applied pressure for simulations</td>
<td>67.2 bars</td>
<td>80 bars</td>
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<tr>
<td>Safety factor for the material strength</td>
<td>1.25</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Yield stress</td>
<td>342 MPa</td>
<td>356 MPa</td>
<td></td>
</tr>
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</table>

The maximum principal strain fields are shown in Figure 37 and Figure 38, for the nominal and test pressure loading cases, respectively. The maximum principal strain values are 1.43 % for the nominal...
case and around 3.1 % for the pressure test. This is below the maximum allowable principal strains of 5 % and 7 %, respectively. The gross plastic deformation criterion is therefore fulfilled.

In a similar way, progressive plastic deformation criterion has been checked. No evolution of the accumulated plastic strain is observed in the cooling channel after the first pressure cycle. Therefore, an elastic shakedown is reached.

An analysis based on stress category method (standard EN-13445-3, annex C) has been carried out as well. It leads to the same validation of the proposed design of the beam screen cooling channel under internal pressure.

### 2.5. MECHANICAL BEHAVIOUR OF THE BEAM SCREEN DURING A MAGNET QUENCH

The beam screen is designed to ensure its mechanical integrity after magnet quenches. Plastic deformations in the beam screen has to be avoided.

![Figure 37: Principal strains under nominal pressure](image)

![Figure 38: Principal strains during pressure test](image)

![Figure 39: Magnetic field decay during a magnet quench](image)
Following Maxwell equations, a fast magnetic field decay, as the one in the FCC-hh magnets (Figure 39), produces large induced currents and furthermore big transversal forces during a short period of time (Figure 40). These forces, called Lorentz forces and noted \( F_L \), depend not only on the magnetic field \( B \) and its decay rate, but also on geometrical factors like the horizontal distance to the centre of the beam screen, \( x \) or, more important, on the conductivity, \( \sigma \), of the materials surrounded by the magnetic field (Eq. 1).

\[
F_L = B(t) \cdot B'(t) \cdot x \cdot \sigma(T)
\]  

(1)

Figure 40: Horizontal forces produced during quench

Mechanical simulations during magnet quench have been done using 3D massive finite element model with the simulation software COMSOL Multiphysics. The strong dependence of the material properties, namely the electrical conductivity, with temperature has a great influence on the evolution of electrical currents, therefore on the Joule heating and finally on the temperature evolution during a quench. This effect is taken into account by setting a two-way coupling calculation between electromagnetic and thermal physics in the simulation. Self-inductance is accounted as well. Given the geometrical and loading symmetries, only one quarter of the beam screen has been considered in the simulation, reducing significantly the computational cost.

2.5.1. Current and temperature evolution during a quench

Electromagnetic and thermal behaviours are governed by the two following equations (Faraday’s law and heat equation):

\[
\bar{\rho} \bar{\sigma} \bar{t}(\rho_e(T) \cdot \bar{j_e}) = \frac{\partial \bar{B}}{\partial t}
\]

\[
\rho C_p \frac{\partial T}{\partial t} - \nabla(k \bar{v} T) = \rho_e(T) \cdot \bar{j_e} \cdot \bar{j_e}
\]

Where \( \rho_e \) and \( j_e \) stand for the electrical resistivity and the electrical current density, respectively. The magnetic field decay is fast, therefore heating is almost adiabatic. Current density and temperature profiles are presented in Figure 41.
Current peak (1.2E9 A/m²) occurs at 0.055 seconds after quench is initiated. Maximum temperature reached at this moment is 58.2 K, that is the temperature obtained after the quench (0.55s). As expected due to the low electrical resistivity, both maximum current and temperature are obtained in the inner copper layer (Figure 41). It is worth to note that the contribution of the external copper strips, which are discontinuous in the longitudinal direction, is marginal.

### 2.5.2. Lorentz forces and stress analysis

Specific Lorentz forces are represented in Figure 42 and Figure 43.

As expected the Lorentz forces point outwards the beam screen with intensity increasing with the horizontal distance from the beam screen mid plane. The maximum force is obtained in the inner copper layer. The integrated force over half a beam screen is 166 N/mm.
The Von Mises stress field obtained for the maximum forces is shown in Figure 44.

![Figure 44: Von Mises stress field at maximum Lorentz force](image)

Two critical zones have been identified. The first one is the edge of the central wall where maximum Lorentz force occurs. The second one corresponds to the weld with the cooling channel. The weld acts as an embedment/fixed constrain, absorbing the forces and moments produced onto the central chamber. In addition, geometrical singularities in the welded zone induces stress concentration. The stresses are lower at the reinforcement location. The maximum Von Mises stress reaches during a magnet quench is 700 MPa and remains under the elastic limit at cryogenic temperature (1150 MPa at 77 K). Even if local plastic deformation is not excluded in the vicinity of the welds, no significant plasticity is expected. Therefore the mechanical integrity is ensured. The maximum horizontal displacement is 0.35 mm.
3. BEAM SCREEN PROTOTYPE MANUFACTURING

The cross section retained for the first beam screen prototype is presented in Figure 45. It is based on a symmetrical geometry with an octagonal shape for the internal wall.

For the beam screen prototype, some specific features have been added (Figure 46):

- A chimney has been implemented in the middle of the beam screen. It allows direct connection to the central part of the component to measure the gas density during the experiment carried out in the synchrotron light source ANKA. A short tube is welded on the internal screen. It requires also a modification of the cooling circuit whose flow is split in two at this location. The geometry of the cooling channel is done in such a way to keep a constant cross section area along the circuit.

- End plates have been welded at the beam screen extremities to close the antechamber and therefore avoid the scattering of reflected photons in the measurement chambers.

- Pieces have been integrated at the extremities of the cooling circuit. They ensure the transition to the U shape return part on one side and metal hoses on the other side. Metal hoses are used to decouple the beam screen from the vacuum chamber.
Specific materials should be used for the FCC beam screen in particular a high manganese austenitic stainless steel (P506) with a low magnetic permeability. Due to availability reason and the non-necessity for this prototype purpose, standard austenitic stainless steels have been used (Table 4). The internal wall has been produced from a 1.5 mm thick stainless steel sheet with a 50 µm layer of copper instead of a colamination copper-stainless steel.

Table 4: Material used for the first beam screen prototype

<table>
<thead>
<tr>
<th>Beam screen part</th>
<th>Material for the prototype</th>
<th>Material for the series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling channel</td>
<td>3D printed AISI 316L</td>
<td>P506</td>
</tr>
<tr>
<td>Internal wall</td>
<td>1.5 mm AISI 304L + 50 µm electroplated copper</td>
<td>1.25 mm P506 + 300 µm colaminated copper</td>
</tr>
<tr>
<td>Deflector</td>
<td>AISI 304L</td>
<td>P506</td>
</tr>
<tr>
<td>Ribs</td>
<td>AISI 304L</td>
<td>P506</td>
</tr>
<tr>
<td>External rings</td>
<td>Cu 99.95%</td>
<td>OF copper</td>
</tr>
</tbody>
</table>

3.1. MANUFACTURING PROCESS

The method of construction must consider the technical constraints as well as the difficulty to economically produce a few beam screen prototypes in lengths of 2 metres. For each step in the manufacturing process, many different techniques are possible. Figure 47 shows the methods of construction that have been retained. Intermediate cleaning and controls such as leak tests or geometrical measurements have been implemented in the procedure.
Figure 47: Manufacturing procedure of the beam screen prototype
3.2. KEY TECHNOLOGY VALIDATION

Prior to the manufacturing of the 2m long prototype, all key technologies have been qualified on a 30 cm long prototype (Figure 48).

3.2.1. Copper electroplating

The first step of surface treatment to prepare the beam-screen is a standard degreasing as for regular UHV components and is performed in a detergent bath with ultrasonic agitation. After the degreasing, part of the piece is masked with an appropriate removable tape in order to protect the surface, which should not be further processed. A sulphuric inversion enables to dissolve locally the passive oxide layer on the stainless steel surface before the electroplating step, consisting of a copper layer with a gold under-layer. Gold was preferred to nickel for its non-magnetic properties. About 2 µm of gold (bath of KAu(CN)₄⁻) are deposited, followed by 25 µm of copper (bath of [CuSO₄(H₂O)₅] + H₂SO₄). The tape used to protect the surface can be removed. After plating any copper oxide traces are removed by hydrochloric acid etching followed by a passivation in a solution of chromic-sulphuric acid. The part is finally rinsed in demineralised water.

3.2.2. 3D printing

The possibility to manufacture quickly complex geometrical shape makes the 3D printing technology very attractive. This is definitively interesting for the cooling channel and in particular for the central element that has a very special geometry to integrate the chimney for the gas density measurement. This process being relatively new, it requires a full validation for this application. Tightness of 3D printed 316L material has been checked on specific disc with a thin membrane (down to 0.25 mm thick membrane that seems for the time being a technological limit) (Figure 49). No leak higher than the leak detector sensitivity (10⁻¹⁰ mbar.L.s⁻¹) has been measured.

Figure 49: 3D printed specimen for vacuum performance measurement
The cooling channel has been manufactured from 30 cm long pieces. Each piece has been individually leak tested at reception.

The geometrical tolerance reached for these parts is not sufficient for welding process or to ensure high assembly precision. Therefore, machining of the functional surfaces is required. Internal stress release leading to deformation of the piece has been observed. Special tooling and procedure has been developed to mitigate this effect.

### 3.2.3. Deflector forming

The limited length and quantity of beam screen prototypes to produce reduces the manufacturing processes suitable for such product. Whereas extrusion process could be considered for large series production, a manufacturing process based on machining and roll forming has been used for the deflector. The roll forming set-up is presented in Figure 50. It consists in several sets of rollers, either in steel or polyamide. The rollers are brought closer progressively, deforming smoothly the deflector at each passage in the forming set-up.

![Roll forming tooling for the deflector manufacturing](image)

### 3.2.4. Cold spray

The gas dynamic cold spray coating has been used to produce the copper external rings. It is based on the projection of solid powder at high velocity. A compressed gas is heated before entering in a DeLaval Nozzle where it is accelerated. The powder is injected in the gas stream and accelerated as well, reaching high velocity (in the order of 1000 m.s$^{-1}$). The powder is plastically deformed and the coating is building up. This process allows coatings rather thick (in 0.1 mm to cm range).

To enhance the adhesion of the copper coating to the stainless steel substrate, a surface preparation is required to increase the roughness (ideally around 8 um). Different methods have been evaluated (chemical etching, mechanical actions). Finally, grit blasting has been chosen. Specific tooling has to be used to mask the pumping holes and therefore avoid any contamination of the beam screen during
this operation. The copper coating can be used as is or be machined (Figure 51, Figure 52, Figure 53, Figure 54).

Figure 51: Test of copper cold sprayed on a stainless steel tube

Figure 52: Surface preparation by blasting (Al2O3)

Figure 53: Copper surface

Figure 54: Cross section of copper sprayed on stainless steel substrate
3.3. BEAM SCREEN ASSEMBLY

3.3.1. Cooling channel and internal screen sub-assembly

The cooling channels have been made from 3D printed pieces whose length can’t exceed around 30 cm (Figure 55). Interfaces have been integrated in the design and machining is carried out to get a good surface before butt welding. A 2m long specific tooling has been developed to position the different parts of the cooling channel during the laser welding (Figure 56).

The internal screen is produced by sheet metal working. It is then electroplated with copper before machining of the sharp edges. The cooling channel and internal screen sub-assemblies are carefully positioned one with respect to the other and then welded together by laser (Figure 57). Discontinuous welds are done to avoid trap volumes. Finally, the cooling channels are slightly machined on the side in the longitudinal direction to ensure a good positioning of the deflectors (Figure 58).

3.3.2. Assembly

The two internal screens with the cooling channel are positioned precisely with a specific tooling that ensures the distance between the two screens. Its design allows an easy removal without damaging the internal copper surface that could occur due to slight shrinkage expected due to the welds. The reflectors are installed on each side and the whole assembly is kept in position with external adjustable tooling. Specific machining has to be done on the deflectors to have a tight fitting close the central cooling channel element (with the chimney). Continuous laser welds are done between the cooling channels and the deflectors (Fig. 59).
In a second step the ribs and the end plates are installed in the corresponding slots and laser welded from the external side (Figure 60).

Copper external annular strips are added by cold spray process. The locations of the beam screen with some singularities (central part or connections between the cooling channel elements) have not been treated. Then, the cooling circuit is completed by the TIG welding the U shaped return tube as well as the metal hoses and transitions pieces. For the first prototype, the instrumentation has been mechanically connected to the beam screen thanks to studs, welded onto the external side of the deflectors by capacitive electrical discharge (Figure 61).
Vacuum acceptance tests based on thermal outgassing and residual gas analysis have been carried out before installation of the beam screen in the ANKA facility.

*Figure 61: Instrumentation supports*
4. OUTLOOK

Additional requirements for the beam screen design have been quantitatively specified based on studies of work package 2. In particular, horizontal aperture have to be enlarged for injection purpose and the amount of backscattered photons to the central chamber has to be minimized. An evolution of the design is therefore studied and proposed. The beam screen is still based on the concept of an antechamber with an internal wall cooled with large cooling channel and shielding big pumping holes of the external wall. The photons, entering in the antechamber, instead of being reflected and deviated to the ribs, are absorbed directly on the external wall thanks to a saw tooth profile (Figure 62). The proposed design is shown in Figure 63.

![Figure 62: Saw tooth profile of LHC beam screen](image1)

![Figure 63: FCC beam screen with saw tooth absorber](image2)

Based on the LHC design, it includes a soft layer made of material with a good thermal conductivity, i.e. copper in our case. Larger slit opening, namely 7.5 mm, has been integrated to increase the horizontal aperture. Consequently, it improves also the pumping efficiency in the central chamber. In addition, it reduces significantly the Lorentz forces on the internal wall. Ribs would not be required anymore neither from a photon absorption point of view nor for mechanical aspects. The synchrotron radiation heat is distributed on the copper layer on the external wall. No additional, external copper rings would be required. Preliminary thermal mechanical behaviour has been studied. Temperature profile under synchrotron radiation heat deposition determined with SynRad software is shown in Fig. 64 for an helium temperature of 40 K. A maximum temperature gradient between helium and the beam screen of 23.8 and 24.9 K is estimated for helium temperature of 40 and 57 K, respectively. Von Mises stress field during a magnet quench is presented in Fig. 65. A maximum stress in the range of 850 MPa is reached locally. No generalized plastic deformation is expected.
The design does not yet take into account industrialisation constraints. Actually, even if the saw tooth profile can be easily produced at reasonable cost onto a copper stainless steel colamination, the integration of the lateral parts with the cooling channel requires further studies and design optimisation. In addition, the parameters of the sawtooth profile or in a more general view the technologies for the photon absorbers at grazing angle have to be assessed.
5. CONCLUSIONS

The beam screen design results from the optimisation of the beam aperture while ensuring the vacuum stability, a low impedance, a good heat transfer of the synchrotron radiation power to the cryogenic cooling circuit as well as the mechanical integrity after a magnet quench. Several iterations have led to a design based on the concept of deflector to deviate and channel the photons in an antechamber. This avoid large stimulated desorption inside the central chamber. Thermal mechanical simulations have been carried out and show the adequacy of the design and the requirements. Further analysis of the supporting system is required to confirm the thermal performance and also to assess the overall deformation of the beam screen in the cold bore at nominal operating temperature. An optimisation of the pre-stress has to be carried out to minimize the plastic deformation in the supports while ensuring a good positioning of the beam screen. The behaviour during a magnet quench has been studied with a magnetic thermal mechanical coupled model. The beam screen robustness has been demonstrated. All simulation tooling have been developed and are available for further iterations of the design.

A first 2 m long beam screen prototype has been manufactured. Different technologies have been used and qualified for this purpose. In particular, two new technologies have been introduced for UHV applications: 3D printing and gas dynamic cold spray. Both represent a step forward for the manufacturing of vacuum components and in particular for prototyping. The manufacturing processes employed here are suitable for prototypes. For series production, the method of construction as well as the mechanical design must consider the technical constraints and the necessity to economically produce hundreds of kilometres of beam screen in lengths of 16 metres. This will be the subject of a trade-off between performance and cost and to further investigations.

An evolution of the beam screen design, based on sawtooth absorber, is being considered and analysed. First results in term of thermal and mechanical behaviour are promising.
6. REFERENCES


7. ANNEX GLOSSARY

SI units and formatting according to standard ISO 80000-1 on quantities and units are used throughout this document where applicable.

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAG</td>
<td>Bayard Alpert Gauge</td>
</tr>
<tr>
<td>BS</td>
<td>Beam Screen</td>
</tr>
<tr>
<td>c.m.</td>
<td>Centre of Mass</td>
</tr>
<tr>
<td>FCC</td>
<td>Future Circular Collider</td>
</tr>
<tr>
<td>FCC-hh</td>
<td>Hadron Collider within the Future Circular Collider study</td>
</tr>
<tr>
<td>FODO</td>
<td>Focusing and defocusing quadrupole lenses in alternating order</td>
</tr>
<tr>
<td>HE-LHC</td>
<td>High Energy - Large Hadron Collider</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>High Luminosity – Large Hadron Collider</td>
</tr>
<tr>
<td>IBS</td>
<td>Intra Beam Scattering</td>
</tr>
<tr>
<td>IP</td>
<td>Interaction Point</td>
</tr>
<tr>
<td>KIT</td>
<td>Karlsruher Institut für technologie</td>
</tr>
<tr>
<td>LHC</td>
<td>Large Hadron Collider</td>
</tr>
<tr>
<td>Nb3Sn</td>
<td>Niobium-tin, a metallic chemical</td>
</tr>
<tr>
<td>Nb-Ti</td>
<td>Niobium-titanium, a superconducting alloy</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RGA</td>
<td>Residual Gas Analizer</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
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<tr>
<td>SR</td>
<td>Synchrotron Radiation</td>
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<tr>
<td>SSC</td>
<td>Superconducting Super Collider</td>
</tr>
<tr>
<td>UHV</td>
<td>Ultra High Vacuum</td>
</tr>
<tr>
<td>VI</td>
<td>Virtual instrument</td>
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