Preliminary cryogenic-beam-vacuum system design: Milestone M4.5

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Abstract:
Integrated report on the cryogenic-beam-vacuum system design, considering all studies and findings so far as input to the preparation of the Conceptual Design Report. Description of the key elements, quantities and data permitting to come to an overall cost estimate of the collider.
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1. OVERVIEW

The FCC-hh is designed to reach 50 TeV of beam energy, surpassing the 7 TeV frontier that the LHC has established. The higher beam energy generates a much higher level of synchrotron radiation (SR), as compared to the present LHC, bringing the FCC-hh at the level of today’s low-energy light sources in terms of SR critical energy, photon flux, and power (see Table 1).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHC</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [TeV]</td>
<td>7</td>
<td>50</td>
</tr>
<tr>
<td>Current [mA]</td>
<td>580</td>
<td>500</td>
</tr>
<tr>
<td>Circumference [km]</td>
<td>26.7</td>
<td>100</td>
</tr>
<tr>
<td>Dipole magnetic field [T]</td>
<td>8.3</td>
<td>15.8</td>
</tr>
<tr>
<td>Photon flux [γ/m/s]</td>
<td>$1 \times 10^{17}$</td>
<td>$1.7 \times 10^{17}$</td>
</tr>
<tr>
<td>SR power [W/m]</td>
<td>0.22</td>
<td>34.6</td>
</tr>
<tr>
<td>SR critical energy [eV]</td>
<td>43.8</td>
<td>4238</td>
</tr>
<tr>
<td>Cold bore aperture [mm]</td>
<td>50</td>
<td>44</td>
</tr>
<tr>
<td>Angle between MB [°]</td>
<td>0.29</td>
<td>0.077</td>
</tr>
<tr>
<td>Beam screen inner T [K]</td>
<td>5-20</td>
<td>40-60</td>
</tr>
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Table 1. Comparison of the LHC’s and FCC-hh’s main parameters concerning the vacuum system.

Vacuum stability at cryogenic temperature is a key element for the design of the hadron collider due to the significant levels of synchrotron radiation that are produced in this machine that result in heat power depositions of the order of 30 W/m.

Early analysis has revealed that it is unlikely to be able to design a beamscreen akin to the one in the LHC that can cope with the operation conditions. A novel design is needed that can effectively shield the cold bore of the superconducting magnets operating at 1.9 K from the heat load.

The concept must also help mitigating electron cloud, resistive and impedance effects from the beginning. The proposed design is currently being experimentally validated. Simulations have shown that it can keep the heat load below 300 mW/m.
1.1. VACUUM REQUIREMENTS IN THE FCC-hh

Ultra High Vacuum (UHV) conditions are normally required in particle colliders to lessen as much as possible the beam distortion by its interaction with the residual gas. The vacuum level is usually expressed in molecular density units, rather than in pressure.

Two main constraints define the molecular density level which the vacuum system of the FCC-hh has to guarantee. From one side, the residual gas beam lifetime should be larger than 100 h, same value as in the LHC. From the other, the maximum cold mass thermal budget allocated for all the sources ending up on the inside of the cold bore shall be maintained below 300 mW/m per beam, as dictated by the cooling capacity specifications [1].

From the above considerations, the required value of the molecular density shall be of the order of $1 \times 10^{15} \text{H}_2 \text{eq}/\text{m}^3$, where $\text{H}_2 \text{eq}$ means the equivalent pure H$_2$ density once the different nuclear scattering cross sections have been taken into account for the other gas species (typically CO, CO$_2$, CH$_4$). This calculated density value is similar to that for the LHC.

1.2. SYNCHROTRON RADIATION IN THE FCC-hh

The SR is expected to be the main source of residual gas in the vacuum chamber, due to the higher SR flux and power as compared to the LHC. Even with a lower baseline beam current, the high beam energy which the FCC-hh is intended to achieve increases dramatically the SR critical energy ($\varepsilon_c$) photon flux ($\Phi$), and power ($P$).

Figure 1 shows a comparison between the LHC, FCC-ee, and FCC-hh flux spectra from 4 eV to 1 MeV. A 4 eV cut-off has been chosen because it is commonly accepted that the generation of photoelectrons starts from a photon energy of ~ 4 eV, corresponding to the typical work-function value of the materials irradiated by the SR photons (copper, stainless steel). Therefore, photons under this energy won’t contribute to the increase of the molecular density inside of the vacuum chamber.

In the LHC, for baseline conditions, the flux is $1 \times 10^{17} \text{ph/s/m}$, and only 52 % of this amount is above 4 eV. In the FCC-hh, on the other hand, the flux is $1.7 \times 10^{17} \text{ph/s/m}$ with 88 % of the flux above 4 eV, meaning in fact more than ~3 times higher effective SR flux.

While the linear photon flux for FCC-hh is only a factor of ~3.5 times higher than that of LHC (Fig.1), the linear SR power density at 50 TeV is almost 200 times higher (due to the dependence on the 4$^{\text{th}}$ power of the beam energy for the SR power), ruling out a scaled version of the LHC beam screen.

In addition, the high amount of SR linear power density, 35.4 W/m, rules out the possibility of operating the machine at the LHC’s range of temperatures and cooling capacity, making necessary to raise them to improve the cooling efficiency [2].
Figure 1: Comparison of the SR flux spectra for LHC, FCC-ee (Z-pole) and FCC-hh. The critical energy, flux and power values are indicated.
2. BEAM VACUUM CHAMBER DESIGN

The design of the vacuum chamber has required several iterations in order to cope with all the different aspects which the chamber has to deal with:

- Enough pumping speed to achieve the required molecular density
- Absorb the synchrotron radiation heat load
- Vacuum stability at the working cryogenic temperature
- Mechanical stability, mainly to absorb the quenches forces
- Low secondary electron yield to minimize the electron cloud effects
- Beam current image continuity and low impedance
- Easy manufacturing in order to maintain a moderate construction cost

In this section we present the latest design and in the following sections a summary of the performed studies to reach this last design.

2.1. CROSS SECTION

The latest beam screen (BS) cross section design can be seen in Figure 2, where the chamber layout and surface treatments have been highlighted.

![Figure 2: FCC-hh beam screen aimed for bending magnets, showing the LASE treatment of the upper and lower flat areas of the inner chamber](image)

The main functions and parts of the BS are indicated in figure 2, with details of the temperature distribution. The internal part has a height of 26.9 mm and a width “B” of 27.55 mm. The large pumping slots provide an effective pumping speed for H2 inside the beamscreen of 860 l/m/s at 50K (LHC: _480 l/s/m at 15 K, as derived from [3]). The thickness of the copper layer on the inside of the ante-chamber areas, including the sawtooth, has been reduced to 80 μm.
2.2. DESIGN CONSIDERATIONS

This design is substantially more complex than the LHC’s beam screen. New features have been implemented in order to cope with all the drawbacks derived from the higher beam energy as compared to the LHC.

A summary of the main design considerations are:

- Calculations [4] have ruled out the possibility of using LHC-sized capillaries (<4 mm) because the supercritical helium flow rate would not be sufficient. The required number of pumping slots would also affect the impedance budget too much [5]. For these reasons the design concept has longitudinal slots along the external part of the beamscreen in the plane of the orbit, to where the highly collimated SR photon fan is directed.

- The beam screen has been divided in two chambers, being the most characteristic feature of this new design (see Figure 2). The inner chamber, where the proton beam circulates, has a 0.3 mm thick Cu co-lamination, four times thicker than in the LHC, 75 µm. It is kept cold by being in direct contact with the cooling channel and without receiving direct heat load from the SR, keeping the surface properties within an acceptable window for impedance reasons, a parameter of higher importance in this collider as compared to the LHC.

- At the same time, the inner chamber acts as a double-sided shield: on one hand it prevents the larger vertical angle of SR radiation tails to reach the cold bore through the holes, which could rise the heat load on the cold bore and trigger the recycling of the condensed gas species. Screening the holes also keeps the impedance within acceptable levels. Were the inner chamber not present, the Transverse-Mode Coupled Instability (TMCI) budget at injection would be exceeded [6]. On the other hand, it lowers the amount of scattered radiation which is reflected back to the main chamber after hitting the inner area of the secondary one, owing to the narrow aperture. Lowering the amount of radiation reaching the inner chamber area is of the utmost importance, since the electron cloud density is directly proportional to the amount of photoelectrons generated on the surfaces within which the build-up happens.

- Following the LHC example, to minimize the amount of scattered radiation a sawtooth copper surface has been chosen as the element to directly receive and absorb most part of the SR on the BS (see Figure 3).
• In order to mitigate SEY and then the e-cloud build-up, it is LASE which has been at the moment chosen from the two initially proposed alternatives [7], because of the possibility of applying it directly in the series manufacturing under atmospheric pressure, lowering then the manufacturing costs, and for its very low SEY values (see Figure 4) which can easily achieve the SEY specifications necessary to avoid critical densities. For this, the critical build-up areas in the inner chamber of the BS are proposed to be treated. This would allow to reduce the electron density by orders of magnitude under the established instability threshold. Lowering the electron density would also decrease the pressure contribution coming from ESD, placing this effect in a second place, behind the PSD. As a comparison, in the LHC, ESD is contributing to the total pressure for around 90 %, due to the not so low SEY of pure Cu and the low SR critical energy. As an alternative to LASE, amorphous carbon (a-C) has been considered. The disadvantage of a-C is that it cannot be deposited on the separate parts of the BS prior to assembling/welding them together, and ways to sputter it inside a dipole’s length BS has not been studied yet. Amorphous carbon is anyway considered as a possible EC mitigation measure.

Figure 3: Detail of the sawtooth treatment on the BS’s secondary chamber area

Figure 4: 1.00 K and 5.00 K SEM augmentations of a Cu baseline LASE sample, showing the high roughness and aspect ratio the surface presents, measured at CERN
Finally, the design has been optimized to maximize the overall pumping speed, thus lowering the MD contribution coming from all the beam induced effects at the same time. Not being the holes’ size an issue for the impedance anymore (as they are geometrically screened), they have been enlarged trying to limit as much as possible the SR leakage to the cold mass. Even if the SR power leakage is negligible, a high amount of flux could lead to the desorption of the condensed gas increasing the pressure over time. Besides, the higher BS temperature (especially in the outgassing areas) further favours the conductance and pumping speed directly, via a dependence with the square root of the absolute temperature. The resulting pumping speed can be read in Table 2. Comparison of the LHC’s and the FCC-hh’s relevant pumping speeds, going for H$_2$ from 240 l/s/m at 15 K to 844 l/s/m at 50 K, resulting in an increment of 3.5 times compared to the LHC.

Table 2. Comparison of the LHC’s and the FCC-hh’s relevant pumping speeds

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHC</th>
<th>FCC-hh</th>
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<tbody>
<tr>
<td>Inner BS temperature range [K]</td>
<td>5-20</td>
<td>40-60</td>
</tr>
<tr>
<td>Nominal minimum H$_2$ pumping speed [l/s/m]</td>
<td>240</td>
<td>800</td>
</tr>
<tr>
<td>Normalized H$_2$ pumping speed at 50 K [l/s/m]</td>
<td>765</td>
<td>844</td>
</tr>
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The central slot height has been adapted to allow a beam vertical misalignment of 2 mm at 50 TeV beam energy. A too small slot would make the SR beam hit directly the inner chamber, rising its temperature and scattering an excessive amount of radiation which could also induce electron multipacting in the beam region. A too big slot, on the other hand, would mean smaller pumping holes (they should always be placed behind the inner shields, out of the beam sight, as previously mentioned) more radiation leaked to the inner chamber and less pumping speed. As a conservative solution, it has been chosen to fix the central slot height at 7.5 mm, letting pass more than 99% of the total power and more than 90% of the flux, as it can be seen in Figure 5.
2.3. **ARCS REGION**

The vacuum chamber at the arc regions is a continuous chamber with the previous described cross section which shall allocate the emitted synchrotron radiation (see Figure 6).

![Ray tracing results of the SR power generated by a 50 TeV, 500 mA beam, 15.78 T in a standard arc dipole chamber, as obtained with Synrad+ [8]. The beam sagitta and photon trajectories can be clearly appreciated.](image)

Ray tracing simulations indicate that the SR emitted at the end of one dipole reaches two dipoles downstream, with an average photon path of 21 m.

Regarding the SSS, the radiation produced by the quadrupoles (MQ) and other magnets has been found to be negligible compared to the one emitted by the MB, both in flux and in critical energy, so they have been discarded from the analysis.

Summary of the power deposition on different parts of the vacuum chamber is given in Table 3.

<table>
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<th>Area</th>
<th>Power</th>
<th>Fraction of MB</th>
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<tr>
<td>Irradiated baffle</td>
<td>449.8 W</td>
<td>91.3 %</td>
</tr>
<tr>
<td>End absorber</td>
<td>42.4 W</td>
<td>8.6 %</td>
</tr>
<tr>
<td>Inner copper primary chamber</td>
<td>0.09 W</td>
<td>0.02 %</td>
</tr>
<tr>
<td>Interconnect</td>
<td>0.07 W</td>
<td>0.01 %</td>
</tr>
<tr>
<td>Non-irradiated baffle</td>
<td>0.04 W</td>
<td>0.01 %</td>
</tr>
<tr>
<td>Other BS areas</td>
<td>0.01 W</td>
<td>&lt; 0.001 %</td>
</tr>
<tr>
<td>Cold bore</td>
<td>0.001 W</td>
<td>&lt; 0.001 %</td>
</tr>
<tr>
<td><strong>Total per arc dipole</strong></td>
<td><strong>492.4 W</strong></td>
<td><strong>100 %</strong></td>
</tr>
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In addition, a differential LASE treatment depending on the magnets (i.e. magnetic field) where it is located is proposed in order to minimise the electron cloud generation depending on the magnetic field map geometry that the electrons experience. As can be seen in Figure 7: Electron density graphs for an LHC-type BS and SEY curves Cu-like, with the FCC-hh parameters, and associated areas in a previous FCC-hh BS geometry. Courtesy of L. Mether, EuroCirCol WP2 [9, 10].

![Dipole 25ns LASE regions, Quadrupole 25ns LASE regions, BS drift space 12.5ns LASE regions](image)

Figure 7: Electron density graphs for an LHC-type BS and SEY curves Cu-like, with the FCC-hh parameters, and associated areas in a previous FCC-hh BS geometry. Courtesy of L. Mether, EuroCirCol WP2 [9, 10]

### 2.4. INTERCONNECTION REGION

The interconnections between magnets (see Figure 8 and Figure 9) are the most critical regions in the arcs. All the components have to be assembled with tight tolerances, ensuring good electrical contact between them and minimizing the irradiation of these areas. There is no active cooling because of the He bypass, only conduction cooling leading to a somewhat higher temperature gradient in the area. The absence of distributed pumping, added to the small conductance due to the small dimensions, creates a high pressure peak in this region, which increase considerably the average pressure in the CELL.

The proposed conservative solution to avoid the direct irradiation in this area, is to place one photon absorber at the end of each dipole and short straight section (SSS). This gently tapering geometry (for minimizing the effect on the geometric impedance) absorbs 42 W of SR in the most irradiated magnet, creating a shadow of around 1 m downstream of it, effectively protecting all the elements, and distributing uniformly the radiation on its surface as found in the simulations. To avoid further SR scattering and excessive photoelectron generation in the area without pumping, the surface which receives directly the radiation (the parts depicted with a thick black line in Figure 7) is recommended to be treated with LASE. In the beginning of the collaboration it was contemplated the possibility of cooling the absorbers with a separate circuit at a higher temperature to improve the cooling efficiency, but the idea was finally discarded owing to the cost increase of the additional circuit. From the vacuum...
point of view, another solution could be chosen, avoiding the use of the absorber if the second taper (after the RF fingers) had a diameter larger than the outer chamber and the impact area had a photoelectron mitigation treatment (as LASE) to avoid electron multipacting in the irradiated area. This would also require tighter assembling tolerances and could slightly rise the average pressure in the area.

Figure 8: MB interconnect conceptual simplified representation, using LHC's bellows and RF fingers geometry

Figure 9: LHC’s bending magnet interconnect, from CERN’s CAD database
3. CRYOGENIC BEAM VACUUM SYSTEM STUDIES

In this section a summary of the different studies performed by the Work Package 4 team of the EuroCirCol project is presented. It includes:

- the study of the beam induced vacuum effects, mainly the photon desorption but also the electron and ions contribution,
- the investigations done in surface treatment in order to mitigate the secondary electron yield and so the electron cloud effect,
- the study of the vacuum stability as a function of the temperature in the cryogenic range of interest
- mechanical studies, with thermal and quenches stress, including construction considerations
- and finally, the production of different chambers prototypes, tested under synchrotron radiation irradiation at the KARA facility, as a bench mark of the design.

3.1. STUDY OF BEAM INDUCED VACUUM EFFECTS

We are presenting here the summary of the studies done on Task 4.2 of the Work Package 4, which have been detailed in a previous Deliverable Report: D.4.4, Title: Analysis of beam-induced vacuum effects.[11]

The analysis of the vacuum effects means checking the different desorption mechanisms which occur inside the vacuum chamber, which are:

- Photon induced desorption,
- Electron induced desorption,
- Ion induced desorption,
- Thermal outgasing.

Each of these effects contribute to the molecular density of the residual gas in the FCC-hh vacuum chamber can be expressed with the following formula:

\[
    n_g = \frac{P}{kT} = \frac{Q}{S \cdot kT} = \left( \eta_{ph} + \eta'_{ph} \right) \cdot I_{ph} + \left( \eta_e + \eta'_e \right) \cdot \varphi_e + \Sigma(\eta_f + \eta'_f) \cdot \sigma_g \cdot \frac{I}{e} n_g + A \cdot q_g
\]

Where \( n_g \) is the molecular gas density, which as defined in Section 1 has to be < 1 \cdot 10^{15} \text{ H}_2 \text{ eq/m}^3,

\( P \) is the pressure,
\( k \) the Boltzmann constant,
\( T \) is the temperature,
\( Q \) is outgassing,
\( S \) is the pumping speed, expressed in the same range as the outgassing,
\( \eta_{ph} \) and \( \eta'_{ph} \) are the primary and secondary photon MDY, respectively,
\( \eta_e \) and \( \eta'_e \) are the primary and secondary electron MDY,
\( \dot{I}_{ph} \) is the photon flux on the chamber’s wall,

\( \varphi_e \) is the electron impingement rate hitting the chamber’s wall,

\( \sigma_g \) is the gas ionization cross section,

\( \eta_j \) and \( \eta_j' \) are the primary and secondary ion MDY,

\( A \) is the area, in the same range as \( Q \) and \( S \), and \( q_g \) the thermal outgassing per area unit.

In all cases, all four main species (H\(_2\), CO, CO\(_2\), CH\(_4\)) have been contemplated for all the outgassing sources.

We have considered that the thermal outgassing and vapor pressures are the only sources of outgassing during static mode, without beam, and they are negligible during dynamic mode, when the main beam induced effects surpass its contribution by many orders of magnitude.

Also, we have considered that the interior of the beam screen to be at equilibrium during dynamic mode: the increase of desorption derived from the coverage growth is balanced by the effective pumping of the surfaces at 40-60 K.

It is also important to highlight that most of the inputs necessary to perform the corresponding calculations are missing in the literature, so conservative estimations have been used in most cases.

The resulting global gas composition estimation in the arcs is found adding the contributions of all these effects for the four most common gas species (H\(_2\), CO, CO\(_2\), CH\(_4\)), as shown in Figure 10. However, the real composition is expected to give H\(_2\) a smaller percentage, since the recycling effect, which is mostly H\(_2\), has been calculated in a conservative way due to the lack of experimental data.

\[\text{Figure 10: Expected gas composition in the MB, expressed in absolute values and in } H_2^\text{eq} \text{ multiplying each gas by its relative cross section.}\]
The H₂ primary molecular density (MD) profile for a representative arc cell length is shown in Figure 11. The lengths of the MB and SSS are also shown. The pressure bumps in the interconnects can be clearly seen.

Figure 12 shows the MD profile with all the calculated beam induced effects for the MB with highest pressure, for the current geometry, with a smaller bump in the interconnect.

For an integrated beam dose of 36 A·h, these preliminary estimations show that the total MD would be below the specifications with enough safety margin. This dose is equivalent to less than 9 days of baseline conditions and a few months of beam current ramping conditioning, limiting the beam energy and current.

Figure 11: H₂ (non-equivalent) primary PSD MD profile along a representative arc cell length for 50 TeV, 500 mA, 36 A·h.

Figure 12: Molecular density profile in the most irradiated FCC-hh MB, for 50 TeV, 500 mA, 36 A·h ideal sawtooth geometry and preliminary ESD data showing the estimated contribution of each beam induced effect.
3.2. MITIGATION OF BEAM INDUCED VACUUM EFFECTS

We are presenting here the summary of the studies done on Task 4.3 of the Work Package 4, which have been detailed in a previous Milestone Report: M.4.4, Title: Proposal of coatings to mitigate electron-cloud effect. [12]

One of the most critical problems for the beam stability connected to the vacuum system for a positively charged beam accelerator are related with electron desorption due to the effects reported in the previous section.

The electron desorption can cause Beam Induced Electron Multipacting (BIEM) and electron cloud (e-cloud), both could dramatically limit the beam emittance and increase the power load on cryogenic systems on a positively charged beam ring, moreover the BIEM will cause electron stimulated gas desorption (ESD).

Thus the main challenge for the beam vacuum is a combined solution that allows not only meeting vacuum specification but also a mitigation or complete eradication the BIEM and e-cloud. The two technologies that have been studied are:

- Low SEY laser treated surface. A recent invention that allows obtaining surfaces with SEY < 0.6 for complete eradication of the BIEM and e-cloud.
- NEG coated surface. NEG film can be deposited to provide SEY < 1. After activation this film also provides a reduced PSD and ESD and distributed pumping speed. It works at cryogenic temperatures and may allow use of a beam screen without pumping slots, separating beam vacuum

3.2.1. LASE: Low SEY surfaces obtained after laser treatment

The technique of Laser Ablation Surface Engineering (LASE) has shown the possibility of creating low SEY< 0.9 surfaces by modifying metal surfaces by nanosecond pulsed laser [Valizadeh et.al. [13, 14, 15].

The underlying reason of the reduction of the SEY is the fabrication of hierarchical structures containing both micro- and nanostructures (see Figure 13). Further reduction in SEY is happening due to the scrubbing (or conditioning) effect, known on flat copper, aluminium and stainless steel surfaces.

The work was focused on studying the influence of micro- and nano-structures induced by laser surface treatment in air of copper samples as a function of various laser irradiation parameters such as peak power, wavelength, number of pulses per point (scan speed and repetition rate) and fluence, on the SEY [16]. It was demonstrated that for each type of laser (which were tested) one can find a set of laser parameters that allows to create a desired surface. Thus, the samples were produced with a Coherent Aviva NX laser operating at \( \lambda = 355 \text{ nm} \), \( f = 40 \text{ kHz} \), pulse duration of 75 ns and 3W average power. The laser scanning speed was varied between 30 and 180 mm/s resulting in grooves with depths varying between 5 to 60 \( \mu \text{m} \) superimposed with submicron and nanometre sized structures shown in Figure 13.
Figure 13: Low (on the left), high (in the middle) resolution planar and cross sectional (on the right) SEM micrographs of 1 mm thick Cu samples.

In Figure 14 it can be seen the effectiveness of the LASE treatment by comparing the baseline LASE’s SEY [15] and raw Cu [13] SEY, conditioned and unconditioned. The range of most common electron energies is also shown for SEY curves Cu-like.
In addition, in comparison with other technologies for currently used surface engineering the laser treatment has a few advantages:

– The equipment is simpler;

– The treatment can be done in air or selected gas at atmospheric pressure, so there is no need for vacuum;

– Hierarchical structures containing both micro- and nanostructures can be created in a single laser treatment process; thus, the process is efficient;

– Surface modification is contactless.

### 3.2.1. **NEG coated surface**

A getter is a material that is able to chemisorb gas molecules on its surface. The advantage of nonevaporable getter (NEG) to evaporable getters is that a new surface is not needed each time to be deposited. The surface is activated simply by heating the layer to particular temperature (activation temperature) which depends on the exact composition of the NEG layer. NEG coating was invented in 1990s at CERN by C. Benvenuti [18].

Over the following years the NEG coatings have become an important vacuum technology used in many particle accelerators [19,20,21,22]. The main advantages of a NEG coated vacuum chamber compared to that of bare stainless steel, aluminium or copper are that NEG coating has much lower thermal outgassing rates [23], lower photon and electron stimulated desorption (PSD and ESD) yields [23] as well as provides evenly distributed pumping [24]. These properties allow the system to reach the required UHV conditions with fewer pumps with lower overall pumping speed.

For particle accelerators the NEG coating provides another advantage; the beam losses due to collisions with residual gas molecules increase with interaction cross section which in turn increases with molecular mass, i.e. the lighter the gas molecules the less harm to the beam from the residual gas at the same gas density. The residual gas spectrum in a conventional vacuum chamber mainly consists...
of H2, CO and CO2 while in the NEG coated vacuum chamber mainly consists of H2 and CH4, the latter is much lighter and therefore less harmful to the beam than CO and CO2.

The most important characteristics of a good NEG composition is that the NEG material should have high chemical affinity for the gas species to be pumped, a high diffusivity of the surface chemisorbed species into the bulk and a high oxygen solubility. Among the known elements Ti, Zr and Hf have the highest oxygen solubility where V has a high oxygen diffusivity. Therefore a thin film composed of either single element or multiple elements (binary, ternary or quaternary) alloy will be a very good candidates for NEG.

Different studies have been carried out in order to optimise the structure of the NEG material deposited on copper, as can be seen in figure 15, where high resolution X-sectional scanning electron microscopy (SEM) images allows to examine the growth structure and distinguish between dense and columnar NEG grow.

![Cross-sectional SEM micrographs of NEG coating on copper substrate deposited using (a) HIPIMS and (b) DC sputtering.](image)

**Figure 15**: The cross-sectional SEM micrographs of NEG coating on copper substrate deposited using (a) HIPIMS and (b) DC sputtering.

### 3.2.2. Proposed surface engineering solution

Two possible solutions have been studied for the FCC beam chamber. These solutions should meet the specification to a maximum gas density, ion induced instability suppression and e-cloud and BIEM mitigation.

The two technologies described in this report are:

- A beam screen with pumping holes and low SEY laser treated surface (LASE).
- A beam screen without pumping holes with NEG coated surface.

Both technologies are potentially feasible but it has been considered that the LASE solution is the most adequate and we have demonstrate its feasibility, so it is the solution proposed in this study.
3.3. STUDY OF VACUUM STABILITY AT CRYOGENIC TEMPERATURES

We are presenting here the summary of the studies done on Task 4.4 of the Work Package 4, which have been detailed in a previous Delivery Report: D.4.1, Title: Analysis of vacuum stability at cryogenic temperature [25].

Vacuum stability at cryogenic temperature is a key element for the design of the proton-proton future circular collider FCC-hh. To thermally screen the cold bore of all superconducting magnets a beam screen is a mandatory solution. Its design, operating temperature and structure must fulfil a number of different technical requirements.

The objective of this study was to validate on small test samples, the proposed temperature and the various material surfaces produced by the collaboration.

This task has been performed by using two dedicated UHV systems to study gas adsorption/desorption on small test samples. Secondary Electron Yield (SEY) has been individuated as a novel technique to be associated to Temperature Programmed Desorption (TPD) and mass spectrometry to qualify beam screen materials and their adsorption/desorption properties.

To decide the best temperature window at which one should design and operate the beam screen for FCC-hh, one must find the required BS vacuum stability. In simple terms, given the notion that the beam screen temperature may vary, during operation, by few degrees, the chosen temperature has to be such that either a gas is always cryosorbed in a stable manner onto it or always not, in the entire temperature range foreseen.

If the temperature chosen is such that a small unavoidable temperature fluctuation induces complete gas desorption of an otherwise cryosorbed layer, this may cause pressure burst and a severe malfunction of the machine. This issue is better understood by looking at Error! Reference source not found., were saturated vapour pressures are shown for different gas species. Each line, following the Clausius-Clapeyron equation, shows the pressure and temperature at which a thick layer of adsorbed gas can coexist with its vapour.

For LHC the beam screen temperature window was chosen to be between 5 K and 20 K. In this region, as from Error! Reference source not found., different gas species figure are either stably adsorbed on the BS surface or free to diffuse to the cold bore surface, which is acting as a very efficient gas sink in the LHC.

![Figure 16: Saturated vapour pressure from Honig and Hook (1960) (C2H6 Thilbault et al.)](image-url)
From Figure 16, a temperature between 40 K and 60 K and one between 90 and 110 K have been individuated to allow vacuum stability of thick ices. The 90–110 K region should be excluded for impedance reason while the 40 -60 K is the chosen temperature and have been studied in detail [references].

3.4. MECHANICAL DESIGN FOR THE CRYOGENIC BEAM VACUUM SYSTEM

We are presenting here the summary of the studies done on Task 4.5 of the Work Package 4, which have been detailed in a previous Delivery Report: D.4.3, Title: Preliminary beam screen and beam pipe engineering design.[26]

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 [27, 28, 29, 30].

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 17, 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 18).
Larger pumping slots have been implemented to increase the pumping efficiency [29]. 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 19 and Figure 20).

![Figure 19: Beam screen with outer copper strips](image1.png)

![Figure 20: Polygonal central chamber](image2.png)

This has been even further simplified with a half hexagon shape of the central chamber (Figure 21). 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.

![Figure 21: Present beam screen design](image3.png)

![Figure 22: Possible evolution with sawtooth profile](image4.png)

Finally, several iterations it was decided to remove the deflector and add a sawtooth profile, Figure 22.

Additional requirements for the beam screen design have been quantitatively specified based on studies of work package 2.

In particular, horizontal aperture has 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 23). The proposed design is shown in Figure 24.

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 Figure 25 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 Figure 26. 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.

Also, and in conjunction with the results of task 4.3 on mitigation of the beam-induced vacuum effects, the optimum surface treatment of the flat top of the inner vacuum chamber is still under study with the purpose of minimizing the electron cloud secondary emission yield, ideally below 1.

Two options are promising at the moment, either laser surface treatment which reduces the yield but with a bigger impact on surface resistance; or carbon coating, convenient for both, yield reduction and low impact on the surface resistance, but more expensive for a mass production.

### 3.5. HEAT LOAD ON THE COLD MASS

The magnets' cold mass is cooled down up to 1.9 K to achieve superconducting properties, with a current density high enough to obtain the required 16 T magnetic field. To keep this temperature constant, the liquid He cryoplants deliver the necessary cooling power to counter the different heat loads to which it is subject. 0.3 W/m/aperture [1] are allocated in the heat load budget to the heat coming from inside the cold bore, which in total is 40% of the total thermal budget per magnet.
Heat load from inside the 1.9 K cold bore

![Heat load chart]

<table>
<thead>
<tr>
<th>Heat source</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear scattering</td>
<td>191 mW/m</td>
</tr>
<tr>
<td>Conduction through supports</td>
<td>83.2 mW/m</td>
</tr>
<tr>
<td>Thermal radiation</td>
<td>3 mW/m</td>
</tr>
<tr>
<td>Leaked SR power</td>
<td>0.5 mW/m</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>277.7 mW/m</strong></td>
</tr>
</tbody>
</table>

**Figure 27: Distribution of the heat loads to the cold mass coming from the beam screen**

With the present design, and for the maximum molecular density and baseline parameters, the maximum leaked power emitted from the beam screen towards the inner area of the cold bore is kept below the budget, although with little margin (see Figure 27 for details). More information can be found in [31].

The nuclear scattering has been calculated for a 100 h lifetime. The beam conditioning is thus expected to decrease this heat source over time as the pressure drops. Besides, the average heat load over time will be somewhat lower than the maximum values shown above due to the current and beam screen temperature decay during runs.
3.6. BEAM SCREEN PROTOTYPE MANUFACTURING

The cross section, as shown previously, 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 28):

- A chimney has been implemented in the middle of the beam screen. It allows a direct connection to the central part of the component to measure the gas density during the experiment carried out in the synchrotron light source KARA. 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.

![Figure 28: a) Chimney and central cooling channel, b & c) End plates and cooling circuit extremities](image)

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 reasons 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 co-lamination copper-stainless steel.
### Table 4: Material used for the beam screen prototypes

<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 um electroplated copper</td>
<td>1.25 mm P506 + 300 um 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>

### 3.7. MEASUREMENTS OF VACUUM CHAMBER AT KARA LIGHT SOURCE

We are presenting here the summary of the studies done on Task 4.6 of the Work Package 4, which have been detailed in a previous Delivery Report: *D.4.2, Title: Measurements of vacuum chamber at light source* [32], and the measurements taken in the facility for the three prototypes that have been fabricated [33, 34].

#### 3.7.1. BESTEX Setup

In order to be able to irradiate the beam screen prototype with appropriate synchrotron light at the KARA facility, KIT, Karlsruhe, a port with bending magnets was chosen. The port have enough beam aperture for a wide radiation fan to reach the prototype with enough space for the installation of the foreseen two meter long screen prototype.

Photons with similar energy spectrum and power as expected to impinge on the FCC-hh arc vacuum chamber are extracted from one of the ANKA bending magnets using a fixed aperture crotch absorber.

The measurement setup, named by the team BESTEX (BEam Screen TEstbench EXperiment) is shown in Figure 29, Figure 30, Figure 31 and Figure 32. It is composed of two main parts, the front end and the test bench, linked by a bellow. Figure 29 shows the 3D model of the installed test bench.

The setup is equipped with a residual gas analyser (RGA) and a series of Bayard Alpert pressure gauges (BAGs) strategically placed along the test bench, see orange highlighted parts in Figure 29b. Two BAGs are placed symmetrically at each extremity of the bench, named front and back BAG, respectively.

A third BAG (middle BAG) and an RGA are installed together in the middle instrumentation assembly, at the middle point of the setup. As shown in Figure 29b, the middle instrumentation assembly is connected to the interior part of the beam screen prototype through a chimney connection which allows direct pressure and gas analysis inside the test BS.
Figure 29: Drawing with the different component of the test setup

Figure 30: Implementation of the test setup in the KARA facility
3.7.2. Measurement results

Three different prototypes (see Figure 33) have been measured in the Bestex setup:

- 1st prototype: Has been used to validate the temperature profile and the vacuum performance of the screen design
- 2nd prototype: With isolated electrodes, have been used for measuring the photoelectron production due to synchrotron radiation
- 3rd prototype: With all the lessons learned in the different work packages has incorporated bigger pumping slots, sawtooth profile for photon absorption and LASE treated surface for low SEY.
Figure 33: Schematic drawings of the three prototypes measured at KARA.

Figure 34 shows the summary of the three different measurement campaigns.

\[ P = P_0 \cdot D^{-\alpha} \]

Figure 34: Summary of the results of the measurements of the prototypes at KARA.
3.7.3. Analysis of the measurements

The conclusion obtained which have been used for the design of the FCC-hh cryogenic vacuum system can be summarized as follows:

- The theoretical SR scattering caused by a rounded reflector has been experimentally detected, reinforcing the viability of the latest beam screen geometry.

- The experimental results are in good agreement with the calculated pressures and photon scattering. In Table 5, a comparison of the experimental pressures and the calculated ones is shown, with discrepancies always under 30%. These results contribute to the validation of the theoretical model.

Table 5: Comparison of the experimental pressure readings and the calculations at BESTEX experiment.

<table>
<thead>
<tr>
<th>Dose</th>
<th>3.12Ah</th>
<th>9.36 Ah</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experiment</td>
<td>Calculations</td>
</tr>
<tr>
<td>Middle (mbar)</td>
<td>5.8E-9</td>
<td>6.3E-9</td>
</tr>
<tr>
<td>Front (mbar)</td>
<td>3.0E-9</td>
<td>3.0E-9</td>
</tr>
<tr>
<td>Back (mbar)</td>
<td>2.0E-9</td>
<td>2.8E-9</td>
</tr>
</tbody>
</table>

- Power deposition calculations, and their related temperature estimations have been experimentally checked in the experiment by the use of PT-100 temperature sensors. Their good match gives good confidence in the photon ray tracing simulations.

- In a vacuum system, the influence of photon scattering increases the theoretical outgassing according to the total received dose. Thus, the sawtooth surface finishing as a scattering mitigation solution has been validated.

- PSD of LASE is considerably lower than for sawtooth, as expected due to the photoelectron yield of LASE being considerably lower than for sawtooth.

- Plateau at very low doses indicates that LASE surface was not preconditioned during previous sawtooth irradiation. Such observation satisfactorily confirms the very low reflectivity of sawtooth profile.

- Cleaning procedures, manufacturing procedures, bake out efficiency are critical parameters for a fast conditioning of the vacuum chamber.
4. KEY ELEMENTS AND QUANTITIES

Table 6 summarises the key elements of the vacuum system and the estimated quantities for the assembly of one arc cell of the FCC-hh collider.

Table 6: Elements in an arc cell of FCC-hh (see Figure 11)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Quantities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cells Dipoles</td>
<td>14.3 m long chamber at the dipole area with beam screen and specific LASE treatment</td>
<td>3</td>
</tr>
<tr>
<td>Cells Quadrupoles</td>
<td>4.2 m long chamber at the quadrupole area with beam screen and specific LASE treatment</td>
<td>1</td>
</tr>
<tr>
<td>Interconnections</td>
<td>Interconnection chamber between modules, with integrated absorber</td>
<td>4</td>
</tr>
</tbody>
</table>
5. CONCLUSIONS AND FUTURE WORK

- The conclusion of the study is that the concept of the vacuum system of the FCC-hh based on a novel Beam Screen design looks adequate. A more refined mechanical design of the BS components has been made, in order to assure a cost-effective fabrication for large-scale industrial production [35].

- In particular, the molecular density in the arcs of the FCC-hh shall be sufficiently low, with a reasonably short conditioning time corresponding to running the machine for a few months at nominal current, similar to that of the LHC. No critical showstoppers has been identified up to now.

- CO seems to be the most impacting gas species on the beam lifetime, while H₂ is the most common, as expected.

- The proposed SEY mitigation solution, LASE, would reduce considerably the ESD pressure contribution, for an ideal sawtooth geometry. LASE parameters could be adjusted to meet the specifications with a narrower margin and thus improve its impedance properties.

- The BESTEX experiment has demonstrated to be very useful by providing confirmation of small samples data and for validating the computer tools used to carry out the vacuum simulations for the FCC-hh.

- The manufacturing of the prototypes has provided useful inputs for the beam screen design for the two 100 km rings.

- Due to the high uncertainty of the performed estimations, an extensive experimental plan is required to completely validate the analysis of the beam induced vacuum effects and the efficacy of the proposed mitigation measures. Tests of the prototype at cryogenic temperature and with the FCC-hh SR features shall be performed to measure the photon MDY and the recycling contribution to the total MD in the vacuum chamber. It is also mandatory to measure the ESD for the latest SEY mitigation feature chosen and under cryogenic conditions. We plan to test some of the already tested BSs at liquid nitrogen temperatures. To this aim, modifications of BESTEX and purchasing of necessary hardware are under way. The first results are expected to be obtained by mid-2019.

- Further simulations with a more realistic sawtooth surface geometry are on-going. The deviations of the real manufactured product from the ideal geometry are expected to increase the outgassing due to PSD and the amount of generated photoelectrons in the vacuum chamber, increasing consequently the ESD outgassing and total pressure. Deviations of the real reflectivity from the theoretical one have been already observed experimentally at dedicated measurements at the light source BESSY II. Therefore, additional studies to adapt the LHC sawtooth geometry to cope with the FCC-hh conditions will also have to be carried out in the future.
6. REFERENCES


### 7. ANNEX GLOSSARY

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAG</td>
<td>Bayard Alpert Gauge</td>
</tr>
<tr>
<td>BESTEX</td>
<td>BEam Screen Testbench EXperiment</td>
</tr>
<tr>
<td>BS</td>
<td>Beam Screen</td>
</tr>
<tr>
<td>ESD</td>
<td>Electron stimulated desorption</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>ISD</td>
<td>Ion stimulated desorption</td>
</tr>
<tr>
<td>KIT</td>
<td>Karlsruhe Institute of Technology</td>
</tr>
<tr>
<td>LASE</td>
<td>Laser ablation surface engineering</td>
</tr>
<tr>
<td>LHC</td>
<td>Large Hadron Collider</td>
</tr>
<tr>
<td>MB</td>
<td>Dipole, bending magnet</td>
</tr>
<tr>
<td>MDY</td>
<td>Molecular desorption yield</td>
</tr>
<tr>
<td>MM</td>
<td>Molecular mass</td>
</tr>
<tr>
<td>MQ</td>
<td>Quadrupole, focusing magnet</td>
</tr>
<tr>
<td>PSD</td>
<td>Photon stimulated desorption</td>
</tr>
<tr>
<td>PY</td>
<td>Photoelectron yield</td>
</tr>
<tr>
<td>RGA</td>
<td>Residual Gas Analizer</td>
</tr>
<tr>
<td>RT</td>
<td>Room temperature</td>
</tr>
<tr>
<td>SEY</td>
<td>Secondary Electron Yield</td>
</tr>
<tr>
<td>SR</td>
<td>Synchrotron Radiation</td>
</tr>
<tr>
<td>SS</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>SSS</td>
<td>Short straight section</td>
</tr>
<tr>
<td>UHV</td>
<td>Ultra High Vacuum</td>
</tr>
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</table>