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SUMMARY OF MODELLING STUDIES ON THE BEAM INDUCED VACUUM EFFECTS IN THE FCC-hh

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Abstract

EuroCirCol is a conceptual design study of a Future Circular Collider (FCC-hh) which aims to expand the current energy and luminosity frontiers that the LHC has established. The vacuum chamber of this 50 TeV, 100 km collider, will have to cope with unprecedented levels of synchrotron radiation power for proton colliders, dealing simultaneously with a tighter magnet aperture. Since the high radiation power and photon flux will release large amounts of gas into the system, the difficulty to keep a low level of residual gas density increases considerably compared with the LHC. This article presents a study of the beam induced vacuum effects for the FCC-hh novel conditions, the different phenomena which, owing to the presence of the beam, have an impact on the vacuum level of the accelerator. To achieve this, a novel beam screen has been proposed, featuring specific mitigating measures aimed at dealing with the beam induced effects. It is concluded that thanks to the new beam screen design, the vacuum level in the FCC-hh shall be adequate, allowing to reach the molecular density requirement of better than 1×10^{15} H_2/m^3 with baseline beam parameters within the first months of conditioning.

INTRODUCTION

The FCC-hh is a superconducting proton collider designed to reach 50 TeV per beam [1, 2], around 7 times higher than the LHC, which was designed to reach 7 TeV. This increase in particle energy has dramatic consequences in the vacuum system design. It implies an increment in the emitted synchrotron radiation (SR) power (P) by a factor of 160, going from 0.22 W/m in the LHC up to 35.4 W/m in the FCC-hh (see Table 1), with critical energies (ε_c) of 43.8 eV and 4286 eV, respectively.

Larger amounts of gas are then expected to be desorbed from the vacuum chamber walls in dynamic mode, since both the photon stimulated desorption (PSD) and the electron stimulated desorption (ESD), the effects with the largest outgassing rate contribution, depend on the ε_c.

In order to enhance the system's pumping speed and to mitigate the beam induced vacuum effects, a new beam screen (BS) has been designed [3]. At the cost of a higher complexity and manufacturing costs, it intends to guarantee a good vacuum level within affordable conditioning times for the much demanding conditions of the FCC-hh.

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Table 1: Comparison of the LHC's and the FCC-hh's Relevant Baseline Parameters [2, 4]

Parameter	**LHC**	**FCC-hh**
Energy [TeV]	7	50
Current [mA]	580	500
Circumference [km]	26.7	100
Beam screen temperature [K]	5-20	40-60
Dipole magnetic field [T]	8.3	15.96
Photon flux [ph m^{-1} s^{-1}]	1×10^{17}	1.7×10^{17}
SR critical energy [eV]	43.8	4286
SR power [W/m MB arc]	0.22	35.4

THE FCC-hh NEW BEAM SCREEN

Figure 1 shows a view of the FCC-hh BS. As in the LHC, its main purpose is to absorb the power generated by SR, e-cloud, beam induced currents and wake losses at higher temperatures (40-60 K) than the cold mass (1.9 K) decreasing in this manner the cooling power. In addition, it prevents the emitted SR fan to directly hit the cold bore, an event which would lead to a re-desorption of the gas condensed on the coldest surface and thus to a pressure increase inside the vacuum chamber.

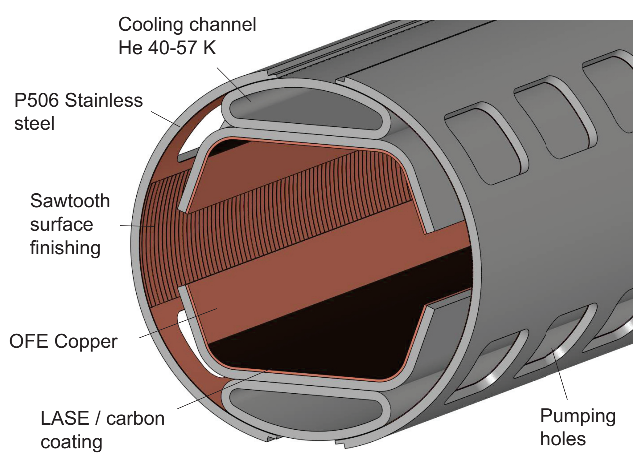

Figure 1: FCC-hh beam screen for dipoles.

As a principal novelty, the BS features a double chamber layout, hiding the pumping holes from the beam's sight and allowing them to be much larger, yielding a pumping speed of 898 l $s^{-1}m^{-1}$ (for H_2 at 40 K, calculated from the inner chamber). Being placed in the secondary chamber, the pumping holes don't contribute to the total impedance budget and the e-cloud cannot be leaked through them. The

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cooling channel has also been enlarged to increase the cooling capacity. On the inner chamber an SEY (Secondary Electron Yield) mitigation surface treatment is proposed to be applied, either carbon coating [5, 6] or LASE (Laser Ablation Surface Engineering) [7, 8]. These treatments can lower the SEY to values even below the unity for 0-1000 eV of primary electron energy, completely suppressing the e-cloud and lowering the ESD contribution to the total gas load. The surface receiving the SR has a sawtooth finishing, as in the LHC, aimed to maximize the photon absorption, which lowers the outgassing due to PSD and the electron cloud. The inner chamber is coated with a 0.3 mm OFE Cu layer, required to limit the resistive wall impedance. The BS is inserted inside the cold bore of each cryostat, with 44 mm of ID. This 1.9 K surface provides the only means of pumping in the arcs during operation, by cryocondensation.

BEAM INDUCED VACUUM EFFECTS

The total dynamic molecular density n_d of the residual gas in the vacuum chamber can be expressed with the following simplified equation, representing each addend a unique outgassing effect caused by the beam's presence:

$$n_d = \frac{(\eta_{ph} + \eta'_{ph})\,\dot{\Gamma}_{ph} + \eta_e \dot{\Gamma}_e + \eta_{i+}\dot{\Gamma}_{i+}}{S} \tag{1}$$

where η_{ph} and η'_{ph} are the primary and secondary photon molecular desorption yield, $\dot{\Gamma}_{ph}$ is the photon flux, η_e the electron molecular desorption yield, $\dot{\Gamma}_e$ the electron impingement rate, $\eta_{i+}\dot{\Gamma}_{i+}$ are the analogue terms which express the ion stimulated desorption (ISD) contribution and S is the pumping speed. The n_d requirement is established in order to provide a minimum of 100 h of nuclear scattering beam lifetime (τ_{bg}), as in the LHC. To determine this required maximum n_d, the following expression has been used:

$$n_d = \frac{1}{\sigma_g\, c\, \tau_{bg}} < 1 \times 10^{15}\ H_2/m^3 \tag{2}$$

which results in a maximum of around $1{\times}10^{15}$ H_2/m^3, for a beam-gas cross section (σ_g) of 90 mbarn [9].

Photon Stimulated Desorption (PSD)

Thanks to the SEY mitigation and the high ε_c the PSD is expected to be the main contributor to the total gas density, as in common synchrotron light sources. In a worst case scenario, it would have a contribution of around 90% of the total gas load, contrary to the LHC's case, where the highest gas load is attributed to ESD. $\dot{\Gamma}_{ph}$ has been first of all calculated with Synrad+ [10], a photon ray tracing software, obtaining a detailed map of the flux density on the latest vacuum chamber geometry. The calculation has considered the reflectivity of the used materials and the angular offset between the cell components. Baseline parameters have been used (see Table 1). Using the primary and secondary η_{ph} values, the total outgassing was then calculated with Molflow+ [10]. Since η_{ph} for the FCC-hh conditions has never been measured, it has been estimated. The estimated

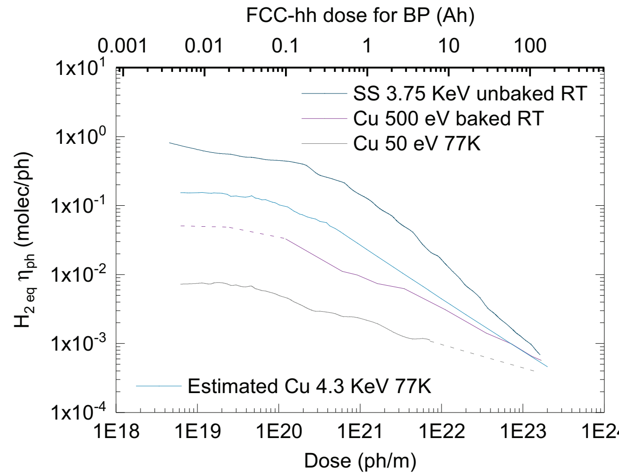

Figure 2: H_2 equivalent molecular yields from the literature [11–13] compared with the FCC-hh's estimation [14].

values are plotted in Fig. 2 and compared with data for different conditions, including the LHC's ones [11] (represented in grey).

η'_{ph} has only been considered for the cold bore. The gas coverage on the irradiated BS surfaces are considered to be equilibrium, well under the monolayer, so no secondary desorption is considered there. Values from [15] have been taken as a pessimistic scenario even if measured for a higher ε_c than the equivalent one arriving to the cold bore.

Electron Stimulated Desorption (ESD)

The ESD depends directly on the electron impingement rate on the BS ($\dot{\Gamma}_e$), which in turn depends on the electron generation rate (N_e) at the BS surfaces where the electron build-up happens and on the SEY, which multiplies the N_e. The N_e is calculated with the following expression, using as an input the photon ray tracing results:

$$N_e = \int_{E_{min}}^{E_{max}} \dot{\Gamma}_{ph}(E)\, Y_{ph}(E) \tag{3}$$

where $Y_{ph}(E)$ is the photoelectron yield, depending on the material, photon energy and angle of incidence. For LASE's case, it is considerably low [16]. Thanks to the low reflectivity of the sawtooth treatment, the SR flux reaching the BS inner chamber generates a reasonably low amount of photoelectrons. Provided that the SEY is under the multipacting threshold, the ESD outgassing inside the magnets is one order of magnitude lower than the outgassing of PSD. Nevertheless, in the magnets interconnect, for a pessimistic case of total absence of magnetic field and without SEY mitigation, N_e and the resulting $\dot{\Gamma}_e$ are considerably high (see Fig. 3) and can result in ESD outgassing values even higher than PSD in that region. Figure 3 shows a comparison of the projected $\dot{\Gamma}_e$ for dipoles, quadrupoles and drifts, where the high inpingement on this latter region can be appreciated.

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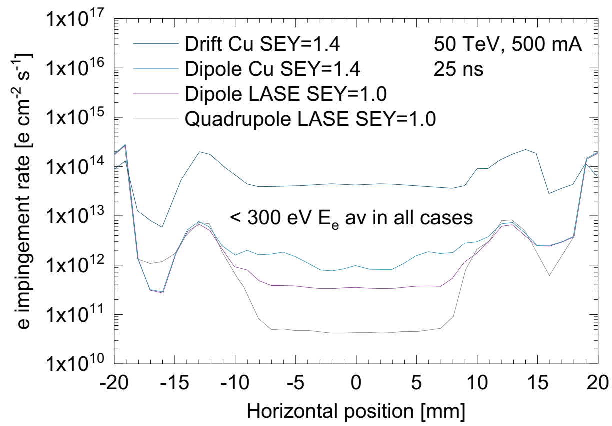

Figure 3: Comparison of the horizontal projection of the electron impingement rate inside the FCC-hh BS for dipoles, drifts and quadrupoles. Baseline conditions. Calculations performed with the PyECLOUD code [17, 18].

The average electron energy is in all cases kept under 300 eV. To calculate the ESD pressure contribution, η_e values have been taken from [19], estimated for Cu at 77 K and 300 eV of electron energy.

Ion Stimulated Desorption (ISD)

Thanks to the high pumping speed of the BS, ISD plays a minor role in terms of pressure contribution. To calculate the critical current (I_c) and the pressure increase for the baseline one, a two gases system approach has been followed [20]. The basic expression defining the maximum current I_c the collider can store before triggering a pressure overrun can be summarized in the following way:

$$I_c(A, B^+) = \frac{C_A\, e}{\eta_{A,B^+}\, \sigma_B} \quad (4)$$

where the η_{A,B^+} values have been taken from [20], and σ_B, different for each gas species, from [21]. The resulting I_c values in the arcs bending magnets (MB) and its related n_d increase are displayed in Table 2, for a worst case of a residual gas mixture composed entirely of CO and CO_2. In this case, the ISD would increase only by around 3% the n_d produced by the other effects.

Table 2: I_c and related pressure increment, for the nominal current, in the BS of the arc magnets for a pure CO and CO_2 gas mixture, at 40 K.

	BS inside MB	**MB-MB interconnect**
I_c	19 A	6.8 A
Related Δn_d	2.7 %	7.9 %

MOLECULAR DENSITY EVOLUTION

Using Eq. 1 for different time steps the molecular density (MD) evolution in the arcs has been calculated, estimated as the MD in the most irradiated MB, the MBs are more than the 85% of the total cell length. It is displayed in Fig. 4.

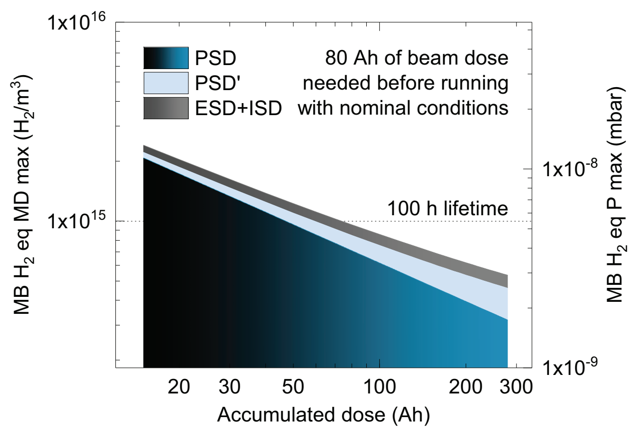

Figure 4: Molecular density evolution over dose in an FCC-hh bending magnet (MB).

The performed estimations show a necessary machine conditioning of about 80 Ah before being able to run at baseline parameters without going under the 100 h nuclear scattering beam lifetime requirement. It is equivalent to around 4 months with an average current of 30 mA, a value corresponding to the first years of the LHC commissioning.

CONCLUSIONS

According to the performed calculations, it is concluded that despite the much higher synchrotron radiation power, the cryogenic vacuum system of the FCC-hh should be feasible, reaching the baseline beam parameters (energy and current) and staying within the nuclear scattering limits with a reasonable conditioning time, equivalent to a few months of commissioning using low currents. This is expected to be possible thanks to the new BS features, which allow a large pumping speed and relegate ESD to a minor role.

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