

# BROADBAND IMPEDANCE OF PUMPING HOLES AND INTERCONNECTS IN THE FCC-HH BEAMSCREEN\*

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## Abstract

In the proposed Future Circular Collider (FCC-hh) pumping holes and interconnects between sections of the beam-screen can be sources of unwanted broadband impedance, potentially leading to the transverse mode coupling instability (TMCI). The pumping holes pose a greater challenge to the impedance calculation due to their small contribution per hole. Unlike for the Large Hadron Collider (LHC), analytical methods cannot be applied due to the complex beam-screen geometry and the greater size of the holes. Instead, two computational methods are used and compared to each other. For the interconnects, the impedance due to a sophisticated system of tapers is also estimated using computational methods.

## INTRODUCTION

In the FCC-hh the beam-screen separates the particle beam from the magnet cold bore to avoid having the synchrotron radiation heat load on the cold mass [1]. Extending throughout the long and the short bending arcs, the beam-screen occupies 85% of the collider circumference. Coupling impedance of the beam-screen comes from two sources: resistivity and the geometric shape of the walls facing the beam. Here we only discuss the geometric part, responsible for the high frequency “broadband” impedance contribution. The imaginary part of the dipolar broadband impedance determines the TMCI threshold, which poses a potentially critical limitation to the bunch intensity. At injection energy of 3.3 TeV, the broadband impedance of the beam-screen is among the most important contributors to the TMCI, and needs to be within an allowed impedance budget.

The geometric contribution to the coupling impedance is caused by irregularities in the beam-screen shape that break the translational symmetry in the direction of the beam travel. One kind of irregularity occurs due to the pumping holes that link the inner beam-screen region to the outer region connected to the system of vacuum pumps (Fig. 1, a). Another kind of irregularity occurs due to the tapers in the interconnects between the magnets (Fig. 1, b). Apart from the interconnects, the tapers in the FCC-hh beam-screen are also present at the location of the beam position monitors (BPM) that are not considered in this paper.

The pumping holes present a novel and challenging case for impedance calculation in comparison to the LHC. On one hand, the pumping holes occupy about 5 times larger relative surface area than in the LHC beam-screen. On the other hand, the holes are positioned behind the shield and are only

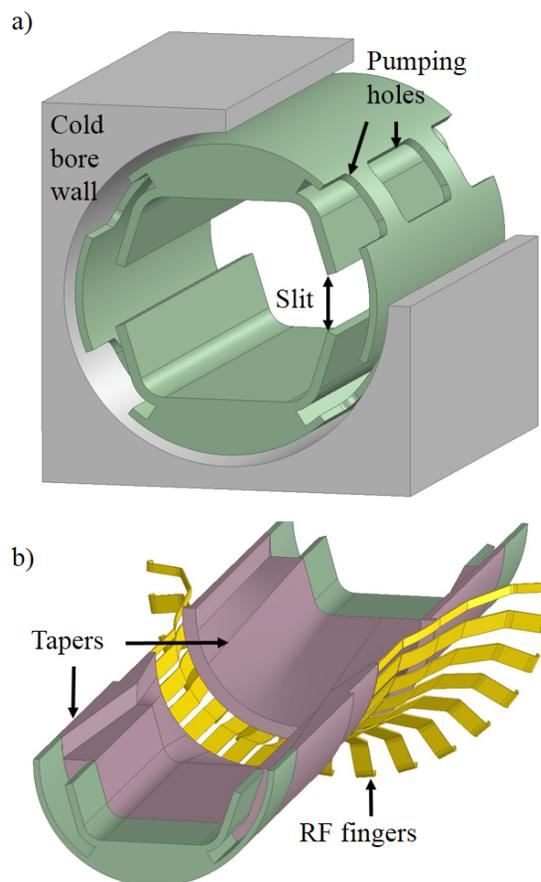


Figure 1: Pumping holes (a) and interconnects (b) in the FCC-hh beam-screen. The tapered sections of the interconnect are shown in purple and the beam-screen is shown in green (cooling channels are not shown as these do not impact the impedance).

connected to the central region through a narrow opening (the slit). The main purpose of this shielding is to decrease the otherwise unacceptable impedance of the enlarged holes. However, these complications in the geometry do not allow us to use the analytical methods for impedance calculation developed earlier for the LHC beam-screen [2–6]. Instead, we rely on two independent simulations techniques described in the next Section.

The tapers at the interconnects transform the complex beam-screen shape to a circle on both sides such that the two sides can be connected with RF fingers. Unlike in the LHC, such transformation involves an abrupt change in the cross section, although only behind the shielding. Another complication arises from the necessity to block the intense synchrotron radiation from hitting the RF fingers. To block

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the radiation, the upstream taper is made of the taper-down and the taper-up parts to form a barrier (the radiation absorber).

## PUMPING HOLES

The beamscreen section in each cryo-dipole consists of about 450 repeating periods, each period containing four holes (Fig. 1a shows two periods). Unlike in the LHC beamscreen, longitudinal positions of the holes are not randomized in order to simplify the manufacturing process. The problem is equivalent to computing the impedance per one period of an infinitely repeating periodic structure.

Numerical impedance estimates were performed based on two different methods. The first method is the Wakefield solver of CST [7] - a well-established tool for wake and impedance calculation. To simulate the infinitely repeating pattern of the holes, a 10 period long structure was terminated with open boundary conditions at the ends. Since the open boundary does not represent an infinitely repeating structure, reflected waves from the ends produce an unwanted contribution to the impedance. To cancel out this contribution, a 20 period long structure was simulated and the difference between 10 and 20 periods was considered for impedance calculation. Care was taken to make sure that this difference is reproduced when 30 periods are compared to 20 periods.

As an alternative to the wakefield method, an independent impedance estimate was performed by summation of impedances of synchronous traveling waves. For this, the Eigenmode solver of ANSYS Electronics Desktop [8] was employed, taking use of the tetrahedral mesh that better approximates the curved beamscreen geometry. The phase advance over 1 period of the structure was scanned to obtain dispersion curves as depicted in Fig. 2. The synchronous waves were given by the intersections of the dispersion curves with the synchronous line  $\omega = kc$ , where  $k$  is the wave number and  $c$  is the speed of light. For each synchronous wave  $n$  the shunt impedance  $(R/Q)_{\perp n}^s$  was calculated. At frequencies much lower than the frequencies of the synchronous waves, the imaginary part of the broadband impedance can be found and is given as

$$\frac{\text{Im}(Z_{\perp})}{N} = \sum_n \alpha_n \left( \frac{R}{Q} \right)_{\perp n}^s, \quad (1)$$

provided that the “wakefield definition” of shunt impedance is used, as in [9]. Here  $N$  is the number of periods and  $\alpha_n = 1/(1 - v_g/c)$  are the corrections due to non-zero group velocities  $v_g$  of the waves, mentioned for example in [10]. Most of the impedance contribution tends to come from the first 10 synchronous modes, nevertheless the summation was performed up to the frequency of 20 GHz, covering 34 modes.

It is important to note that the simplified relation given in equation (1) is only valid because the frequencies of all synchronous waves are higher than the frequency range of interest, which is determined by the bunch length ( $\sim 1$  GHz

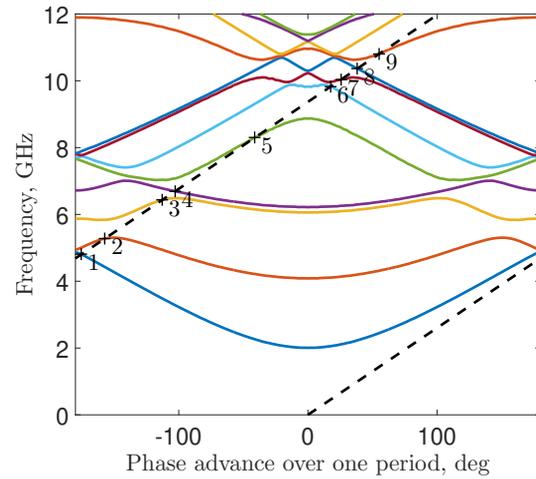


Figure 2: Dispersion curves calculating the dipolar impedance in the horizontal plane with a slit width of 7.5mm. Only modes possessing magnetic and electric symmetry in the  $x$  and  $y$  plane respectively are shown.

for the FCC-hh). Otherwise, the shunt impedances would have to be included in the form of resonator impedances together with the quality factors of the modes  $Q_n$ . This would be the case if the low-frequency TEM-like mode was taken into account, necessary for a calculation of the longitudinal impedance.

The horizontal broadband impedance given by the two methods is shown in Fig. 3. Because the impedance per one period of the actual geometry is very low, the slit size was varied to artificially make the impedance higher. The wakefield method allows the impedance to be measured for geometries with larger slit, but for the actual geometry the measured value becomes lower than numerical noise. In contrast, the traveling wave method only requires simulations of one period of the structure, which significantly increases sensitivity to small impedances. The estimate for the traveling wave method can therefore be extended all the way to the actual slit size of 7.5 mm.

For the slit sizes that permit the impedance estimation with the wakefield method, the two methods agree. The methods also show a similar exponential decrease in the impedance with the slit size. An order-of-magnitude estimate for the impedance of the holes is

$$\text{Im}(Z_x)_{\text{total}}^{\text{holes}} \sim 4 \times 10^4 \Omega/m. \quad (2)$$

The red line in Fig. 3 indicates the maximum allowed broadband impedance at injection for the entire accelerator ring. The presented impedance of the holes is not weighted by the local betatron function  $\beta_x$ , hence the somewhat higher  $\beta_x$  in the arcs is accounted for by proportionally scaling the TMCI limit [11] down in Fig. 3. The contribution of the pumping holes is required to be much lower than the total budget, and the current estimate satisfies this criterion with a comfortable margin.

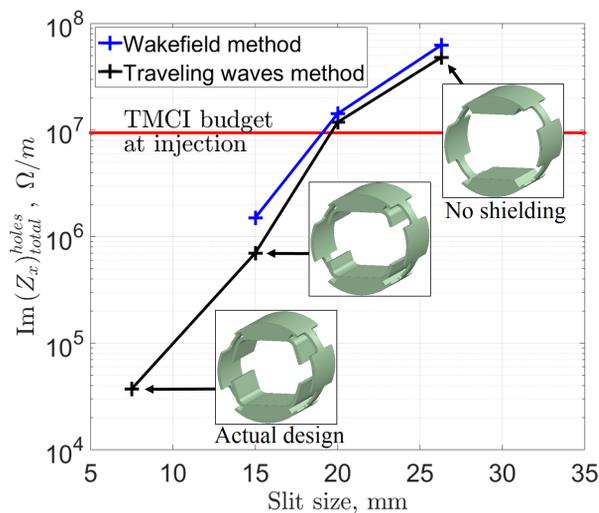


Figure 3: Broadband dipolar impedance of the pumping holes (not weighted by  $\beta$  function) as a function of the slit size. Only the horizontal impedance  $Z_x$  is shown as the most critical. All 10.5 million holes in the ring are taken into account.

## INTERCONNECTS

The current FCC-hh FODO cell design consists of 12 cryodipoles and 2 short straight sections containing quadrupoles and other magnets. This implies 14 interconnects per FODO cell with the total number of 5516 interconnects in the ring. The average betatron function at the location of the interconnects is similar to the average betatron function in the arcs.

Impedance for an earlier version of FCC-hh interconnects was calculated before [12]. However, here we only present the latest results as the geometry has changed considerably. Horizontal and vertical dipolar impedances of the interconnects were simulated with the CST Wakefield solver [7] and are shown in Fig. 4. In these simulations, the RF fingers were replaced with a solid wall, hence their impedance is not included and only the taper contribution is considered. The resulting total broadband imaginary impedances are

$$\text{Im}(Z_x)_{\text{total}}^{\text{inter}} = 1.5 \times 10^6 \Omega/m, \quad (3)$$

$$\text{Im}(Z_y)_{\text{total}}^{\text{inter}} = 1.9 \times 10^6 \Omega/m, \quad (4)$$

which constitutes a significant part of the allowed broadband impedance at injection (the red line as in Fig. 3). If necessary, this number can be reduced by minimizing the “steps” where the RF fingers connect to the wall.

## CONCLUSIONS

The dipolar broadband impedance of the FCC-hh beam-screen was calculated. The contribution of the pumping holes was estimated with two independent methods in a range of different slit sizes. For the present design with a

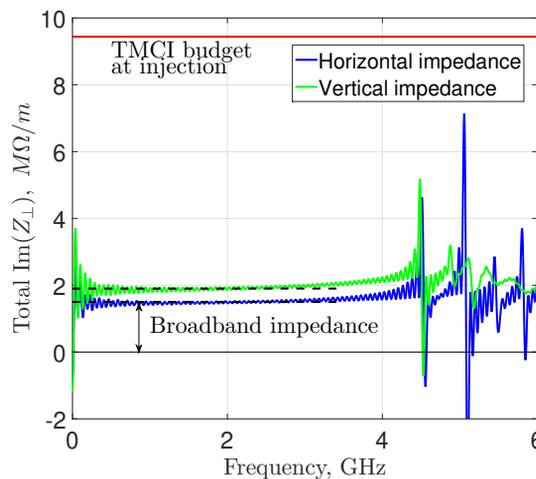


Figure 4: Horizontal and vertical dipolar impedances of the interconnects (not weighted by  $\beta$  function). All 5516 interconnects are taken into account. The TMCI limit is defined as in Fig. 3.

slit size of 7.5 mm, the contribution from the holes to the impedance was found to be negligible thanks to the novel concept of shielding the holes from the beam. The contribution of the interconnects is not negligible but is within the acceptable limits [11].

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