ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPR18

THE DESIGN AND ELECTROMAGNETIC ANALYSES OF THE NEW ELEMENTS IN THE FCC-ee IR VACUUM CHAMBER*

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Abstract

High currents of bunched electron and positron beams plan to be used in the proposed FCC-ee collider to achieve a high luminosity. Naturally, the impedance of the interaction region of the FCC must be as small as possible. Previously, a very smooth beam pipe in the interaction region was designed, and now necessary elements are added being important for beam operation, reduced backgrounds, and assembly. Among these elements are BPMs, expansion bellows, extension of the common beam pipe, and an elliptical synchrotron radiation mask. These new elements will be analysed to see if they increase the impedance and then, followed by discussions how to mitigate any issue.

INTRODUCTION

The project of future e+e− circular collider (FCC-ee) will have a very high energy, up to 375 GeV in the center of mass and unprecedented luminosities [1]. To achieve high luminosity, currents of the electron and positron beams must be more than 1.2 A. High current beams will produce large enough heating of the beam pipe in both rings and in the interaction region to be a concern. Additionally, to the wall heating due to resistivity of the metal pipe walls, there is a heating due to the abortion of the wake fields exciting on inhomogeneity of the beam pipe when the electromagnetic field of the beam is diffracted on this inhomogeneity. The FCC Interaction Region (IR) consists of the intersection of four beam pipes and present a very complicated inhomogeneity geometry. Both beams generate electromagnetic fields in IR. Depending upon the bunch spacing frequency, this may lead to a resonant excitation of a trapped mode located in some special places. Naturally, the beam also loses energy as it is decelerated by the longitudinal electric component of the excited fields. Important parameters, which characterize the excited field are the loss factor and impedance. The loss factor tells how much energy a bunch of particle losses passing by some beam pipe element. This is equivalent to the total amount of energy of the excited fields. The loss factor strongly depends upon the bunch length. Shorter bunches lose more energy. The impedance is a Fourier spectrum of a wake potential. The wake potential is an integral of the longitudinal electrical component of the excited fields along the bunch trajectory. The calculated impedance shows possible trapped modes as resonate spikes in the frequency spectrum.

* Work supported partially by US DoE, Contract No. DE-AC02-76SF00515, and by the EC HORIZON 2020 project FCC-IS, grant agreement n.951754.
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The design of the FCC IR beam pipe is based on the optimization study of the wake field losses of the colliding beams. We developed a special geometry of the interaction region (IR) vacuum chamber, which have a very smooth transitions from two pipes into a single collision pipe. In this way we got the minimum possible impedance of interaction of the beam and the IR beam pipes [2-6]. Additionally, this geometry has only one trapped mode, located near the pipe conjunctions, naturally in two places [2]. If the symmetry of the beam pipe breaks, then a single trapped mode split into two trapped modes which can be seen in the wake field spectrum or impedance. The geometry of the optimized IR vacuum chamber is shown in Fig. 1.

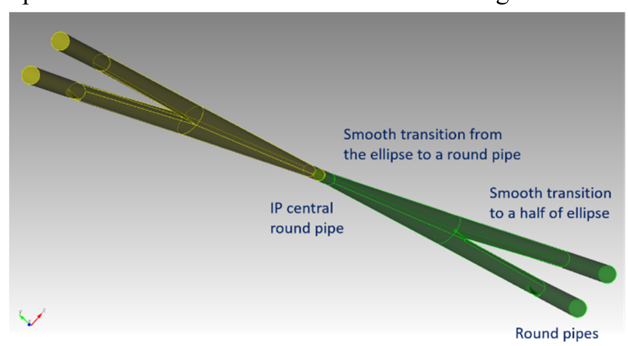

Figure 1: Geometry of the low impedance IR vacuum chamber.

The following step is to include the additional elements, which are important for detector protection, stability, and beam operation in the IR region as a part of the FCC-ee collider. These elements are: IR synchrotron radiation masks, IR bellows and IR beam position monitors (BPMs).

To make an estimate of the additional impedance growth due to the new elements we need the FCC-ee beam parameters. We use the same relevant beam parameters as we use in previous calculations. These parameters were presented at the FCC Week Workshop in Paris in 2022 [7] and are shown in Table 1.

Table 1: Relevant Beam Parameters

parameter	value
beam energy [GeV]	45
beam current [mA]	1280
number bunches/beam	1000
rms bunch length with SR / BS [mm]	4.38 / 14.5
bunch spacing [ns]	32

SYNCHROTRON RADIATION MASKS

To protect the IR detector from the synchrotron radiation generating from the last bend a quadrupole magnet we use small bumps located at the 2.2 meters from the interaction

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point (IP) in both directions. This type of masks was suggested by Mike Sullivan [8] and is shown in Fig. 2.

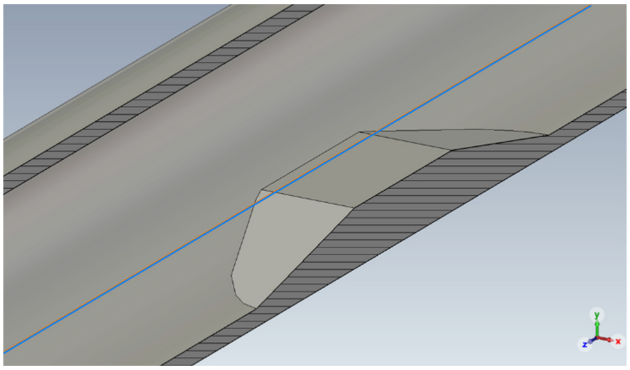

Figure 2: Synchrotron radiation mask in a shape of a bump (M. Sullivan).

Anther mask was suggested by Kévin André as a possible FCC–ee beam structure [9]. The shape of this mask is elliptical and in this way the mask shadows more possible resources of the synchrotron radiation. This mask is shown in Fig. 3.

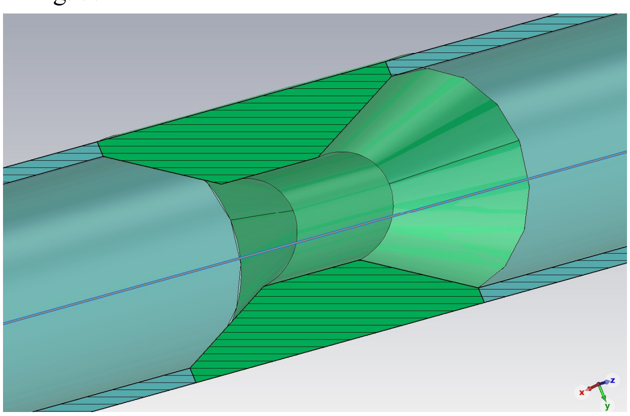

Figure 3: Elliptical synchrotron radiation mask (K. André).

We have analyzed both masks [10]. The comparison of the wake field potentials is shown in Fig. 4. Wake potentials for both masks are very close and have the inductive character. However, the elliptical mask has more inductive character. The beam interacts with more trapped modes located between an elliptical mask and IP. One of the trapped mode field distributions is shown in Fig. 5. The "head" of the beam excites these modes and losses energy. The "tail" of the beam is accelerated by the fields of these modes and then, these modes almost disappear from the beam pipe.

Do we need really an elliptical mask? The elliptical mask produces more trapped modes. Even the interaction with a beam has an inductive character, these modes will interact more when adding other beam pipe elements like bellows and BPMs. We believe that upper half of the elliptical mask does not catch SR but may catch errant beam particles. If we need an elliptical mask only for time of beam injection, then can we can briefly switch off the detector during beam injection, as we did at PEP-II. And finally, the mask is situated inside the superconducting cryomodule. The cryomodule can take a limited amount of dipositive power.

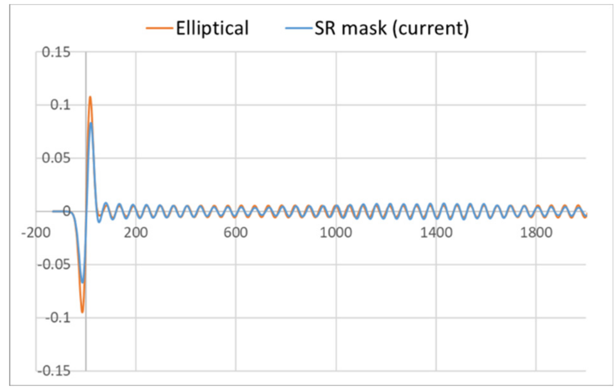

Figure 4: Comparison of the wake potentials for different masks.

We can see two modes beating in Fig. 4. This is because the IR geometry was a little bit changed in comparison with geometry presented in Fig. 1 with the purpose to give more space for BPMs. We will discuss this in the next chapter.

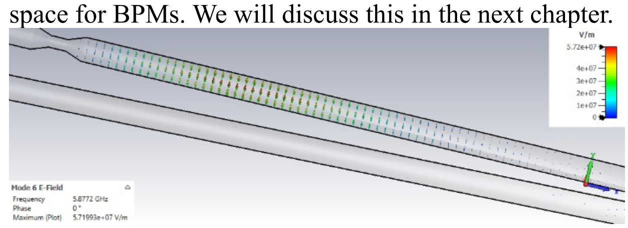

Figure 5: Trapped mode, excited due to an elliptical mask.

BPMS OPTIMIZATION

At first, we had to find a place for BPMs. The proposal was to cut the mutual inner part of the pipes (crotch) as it shown in Fig. 6.

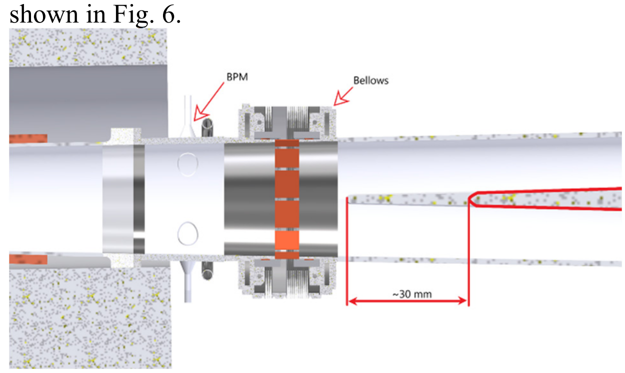

Figure 6: BPMs, bellows and the crotch cut.

Based on the Pantaleo Raimondi suggestion [11], we did study how the BPM button shape may change the wake field losses. We study the circular and elliptical shape of the button [12]. The FCC IR beam pipe, where we plan to install BPMs has an elliptical shape. There is a symmetry in both directions. To get a better accuracy of wake field calculation, we use only a quarter of the beam pipe. While using planes of symmetry we need to move the beam trajectory away from the BPM center. We shift the trajectory by 5 mm in X and Y direction. To avoid to be lost in the complicated transitions of the BMP wire and ceramic we choose a simple geometry, just using the shape of a button. Additionally, we made an "antenna" at the end of the BPM wire to decrease the reflected power from the end. We choose 1mm gap between a button and the beam pipe body.

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To make a comparison of the different button shape we assume that the area of a button must be the same, intuitively thinking that in this case the signal from a button will be the same. We choose the area of a button to be 24 mm^2, that means for a circular button the radius will be around 4.9 mm. For elliptical shape with a and b axes we choose a/b=0.67 (4x6 mm), 0.338 (3x8 mm), 0.17 (2x12mm) and 0.04 (1x24 mm). The shape of a circular button is shown in Fig. 7.

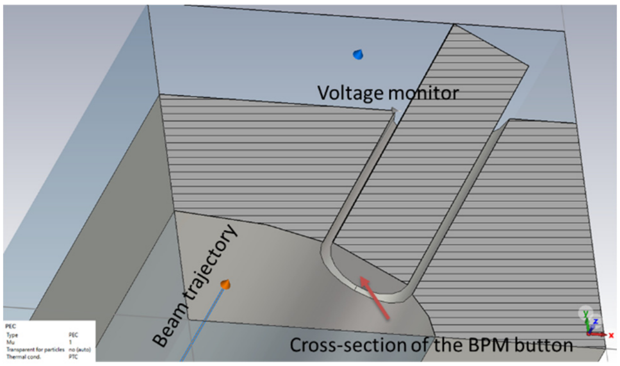

Figure 7: A circular button.

The shape of an elliptical button with ratio a/b=0.17 (2x12mm) is shown in Fig. 8.

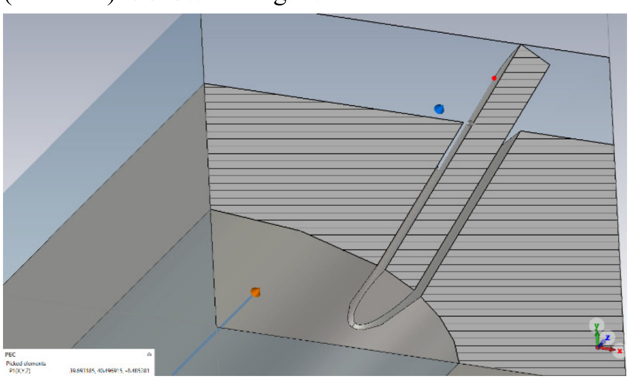

Figure 8: An elliptical BPM button.

A comparison of the wake potentials is shown in Fig. 9.

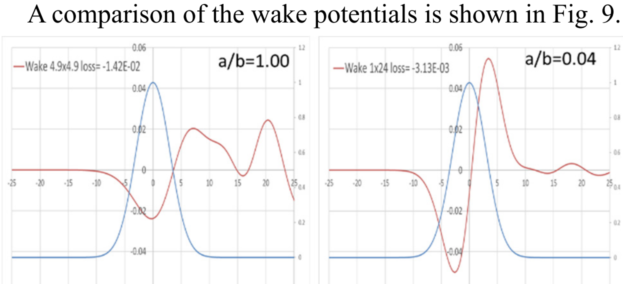

Figure 9: Wake potentials for a 3mm bunch.

It is clearly seen that with a smaller ration a/b the wake potential becomes more inductive, and the total loss comes smaller. The spectrum comparison is shown in Fig. 10. Wake field spectrum confirmed the previous statement: a red line for a round button, a blue line for a longer elliptical button. There are a lot of resonances for a round button, which are responsible for the wake field losses.

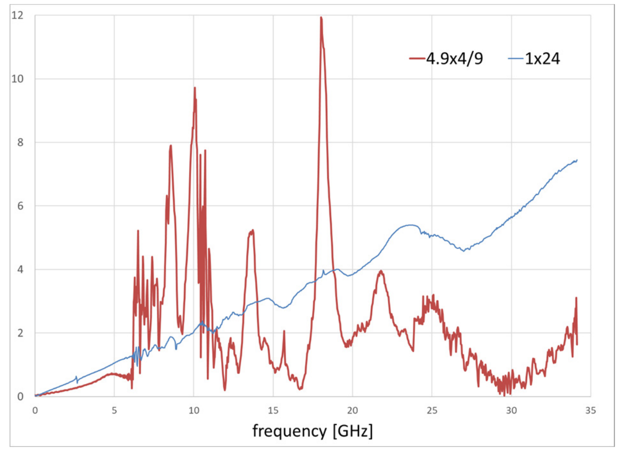

Figure 10: Mode spectrum.

The loss factor versus ellipse ratio is shown in Fig. 11. The loss factor goes down with a longer ellipse. It does not go to zero as the beam trajectory is shifted from the beam pipe center. A beam passing the elliptical button with a ratio a/b=0.04, loses more than 4 times less energy in comparison with a round button.

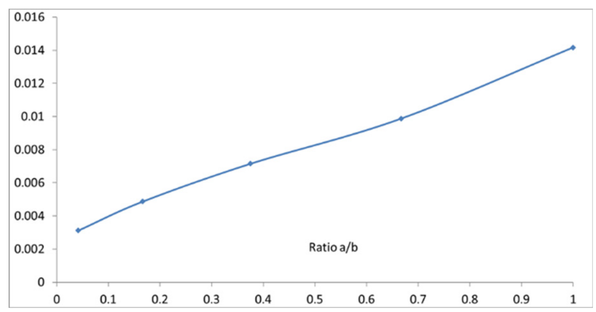

Figure 11: Loss factor.

BELLOWS

And finally study the bellows, which are needed for the design support and can be used as HOM absorber. We did the first step, calculating the spectrum of inner bellows cavity (Fig. 12).

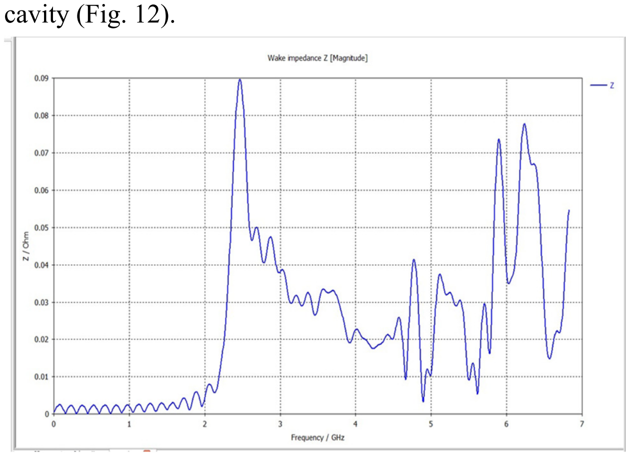

Figure 12: A bellows trapped mode spectrum.

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