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FCC-ee MDI: TRAPPED MODES AND OTHER POWER LOSSES*

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Abstract

We discuss the beam power loss related to the heating of the vacuum beam pipe walls of the FCC-ee interaction region (IR). We analyse the excitation of trapped modes, which can accumulate electromagnetic energy and determine the locations of these modes. We study the unavoidable resistive-wall wake field, which is responsible for the direct beam pipe walls heating. We present the distribution of the heat load along the central part of IR. The results are very important for knowledge of the temperature distribution and the following cooling system design.

INTRODUCTION

It is planned that a future e+e– collider (FCC-ee) will have a very high energy, up to 375 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 an additional heating of the beam pipe in both rings and in the interaction region. The heating of the beam pipe happens when a beam excites electromagnetic fields due to diffraction of the beam self-field from the inhomogeneous beam pipe. In a time, the diffracted fields are absorbed in the metal walls somewhere in the beam pipe. The beam loses its kinetic energy to restore its self-field when it is deaccelerated by the diffracted fields. The diffracted fields are usually called as wake fields. The FCC IR consists of an intersection of four beam pipes and present a very complicated inhomogeneity geometry. Both beams generate electromagnetic fields in IR. Depends upon the bunch spacing frequency, this may lead to a resonant excitation of a trapped mode located in some special places. There can be several trapped higher order modes (HOMs).

Another heating effect is an excitation and diffusion of the image current inside the metal beam pipe walls. This leads to a direct heating of the beam pipe. Naturally, the beam also loses energy as it is decelerated by the longitudinal electric component of the field generated by the image current. These fields are usually called as resistive-wall wake fields.

Previously, we optimized the geometry of the FCC IR beam pipe for a minimum geometrical impedance [2-4]. We use a numerical code CST [5] for 3D electromagnetic calculations. In these calculations we assume that the beam pipe materials have infinite electrical conductivity. Now the engineering design of the IR suggests what kind of materials will be used. So now, we include the additional beam losses due to interaction of the beam electromagnetic field with conductive materials of the beam pipe. Using the correspondent conductivity of the materials we calculate the heat load distribution along IR beam pipe.

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In the first section of this paper, we discuss what kind of electromagnetic fields are excited in IR. Then we present our concept of a low impedance IR beam pipe and show the last CAD model. Next we present results for geometrical wake potentials and an estimate beam energy loss. Then we discuss how we calculate the heat load distribution from the circulating beams and present results for wake potentials and trapped modes. Finally, we present the heat load distribution in IR. In the conclusion section we discuss the importance of the results for a colling system and future steps.

ELECTROMAGNETIC FIELDS IN IR

We can distinguish three types of the fields excited in the FCC IR by circulating beams. The first type is the electromagnetic field, which is exciting in IR in the form of propagating waves that can leave IR and then be absorbed somewhere in the rings. During the PEP-II SLAC B-Factory operation we watch these traveling waves propagating the distance more than 100 m long [6]. The second type is the field that is excited in some trapped locations of IR and be absorbed there. These fields are usually called higher order modes HOMs. There is one mode located near the pipe connection is an unavoidable mode [2]. Under resonant conditions the amplitude of the trapped mode field can be strongly magnified. The third type is an unavoidable resistive-wall wake field, which is responsible for directly heating of the metal walls. Excitation and absorption of these fields in IR may lead to additional detector background because heating effects and high frequency waves interference.

Important parameters, which characterize the excited field are a loss factor and an 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 is strongly depending upon the bunch length. Smaller 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 impedance shows possible trapped modes as resonate spikes in the frequency spectrum.

CONCEPT OF A LOW IMPEDANCE IR BEAM PIPE AND CAD MODEL

The main idea to decrease the wake field radiation or minimize the impedance of the chamber is naturally to use a very smooth transition from one pipe to a conjunction of two pipes. One of possibilities how to make it, is demonstrated in Fig. 1. Starting with a round pipe we make a smooth transition to a pipe with a cross section of a half of ellipse. Then we combine two half-ellipses in one full ellipse making one pipe from two pipes. It is important the

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inner part at the conjunction location must be rounded. Finally, we make a smooth transition from a pipe with an elliptical cross section to a round pipe, which is the main central part of the interaction region. In the center of this pipe is the interaction point (IP), where electron and positron beams collide.

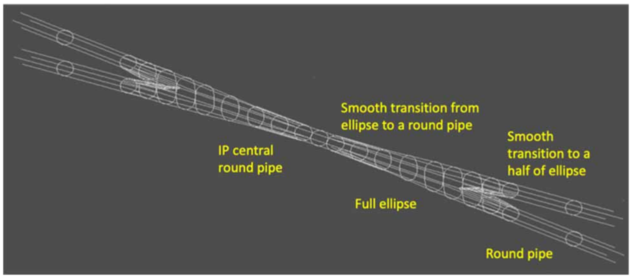

Figure 1: Smooth transitions in IR.

We use this approach to design the FCC IR beam pipe. The last geometry of the FCC IR beam pipe [3, 7] is shown in Fig. 2. Two symmetric beam pipes with radius of 15 mm are merged at 1.2 m from the IP. The central part has a 10 mm radius for ± 9 cm from the IP. There are two synchrotron radiation (SR) 7 mm masks [7] in incoming beam pipes at the distance of ±2.1 m from IP. The shape of the mask and dimensions are also shown in Fig. 2.

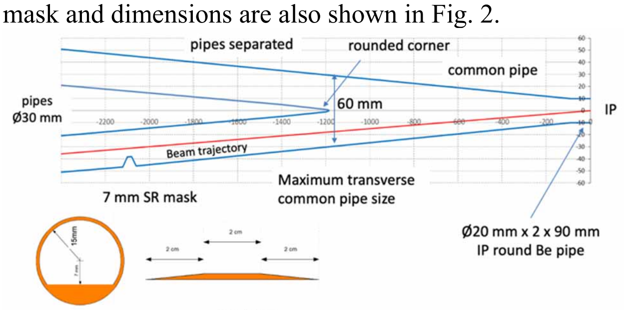

Figure 2: Last FCC IR geometry and SR mask shape.

This new geometry differs from the previous geometry described in FCC-ee CDR [1], mainly by the size of the central pipe. In previous geometry the radius of the central beam pipe was larger -15 mm. Decreasing the size of a central part gives a possibility for the FCC detector to make more precise tracking [8]. On the other as it will be shown later smaller size of a central pipe decreases the geometrical impedance and moves the unavoidable trapped mode to higher frequency, in this way making less the interaction of trapped mode with the beam.

Based on this geometry a special CAD model was developed for the wake field calculations. The difference with a real engineering CAD model is that the CAD model for the calculation does not contains small elements with dimensions less than 1 mm. The reason for this is a long length of the model: 8-10 m and a correspondent number of mesh points during calculations will reach several hundred million. The IR beam pipe CAD model designed by Luigi Pellegrino (INFN) is shown in Fig. 3. We can see smooth transitions, rounded corners where pipes merge into a single pipe and SR masks. A line with blue and orange balls shows a single beam trajectory. Presented in Fig. 3 a special view of the beam pipe does not show real dimensions. A more realistic view of the shape of a SR mask is shown on Fig. 4.

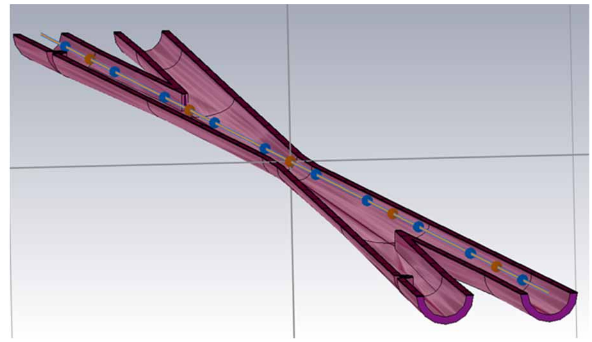

Figure 3: CAD model for the wake field calculations.

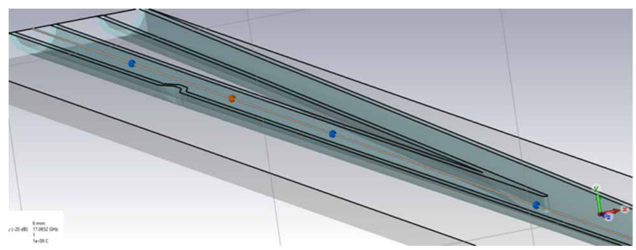

Figure 4: A more realistic view of the shape of the SR mask.

WAKE POTENTIALS AND TRAPPED MODES

Using this CAD model, we did wake field calculations giving all wall materials an infinite conductivity. This approach is usually used for calculation of the so called "geometrical" wake potentials. The result for the wake potential of a 12-mm bunch is shown in Fig. 5 by a red line. The shape of a bunch charge distribution is also shown there by a blue line.

Wake potential plot shows that addionally to the bunch looses (the region in the bunch region) we have two beating oscilations with a smaller amplidude. The distance between maximums is aproximatelly 48.1 mm that corresponds to the the frequency of 6.2 GHz. We may conclude that there are two trapped modes with close frequencies. Furier spectrum (Fig. 6) of the wake potential confirms this statement. Later, we found out that the CAD model was not exacly symmetrical relative to IP. That was the reason why the trapped modes at different sides of IP have different frequencies.

We did a special eigen mode calculation (that is also possible to do using the CST code) for this geometry to find a trapped mode field distribution and its frequency. One of the results, the electric force line distribution is shown in Fig. 7. The trapped mode is concentrated near the

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conjunction of two pipes, in a region with maximum transverse size. This mode has a longitudinal electric component in the common pipe. Due to this component the beam with a longitudinal velocity can easily excite this mode. We call this mode by an unavoidable trapped mode in IR [2].

There are several other trapped modes due to SR masks. These modes are distributed alone large distance (Fig. 8) and ,in average, do not interact with a beam

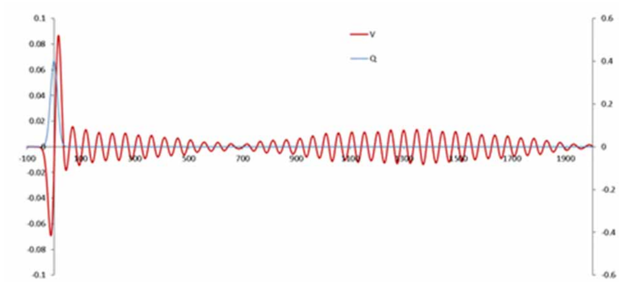

Figure 5: Wake potential of a 12-mm bunch passing the 10-m long beam pipe of the FCC IR.

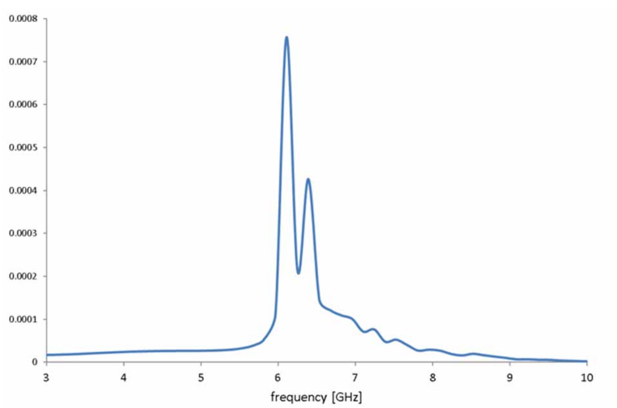

Figure 6: Spectrum of the wake potential

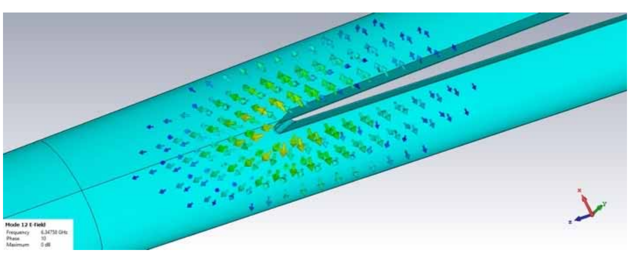

Figure 7: Unavoidable trapped mode. Electric force lines.

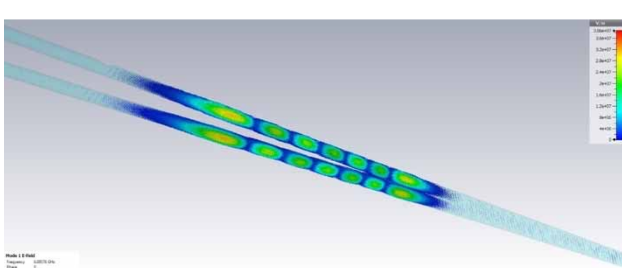

Figure 8: Another trapped mode.

The double effect of smoothing the geometry and a smaller central pipe reduces the local heating power by a factor ten with respect to the CDR design. Due to a smaller central part the unavoidable trapped mode was shifted to a higher frequency, that considerably decrease the interaction with a beam. For a bunch length of 12 mm, the nominal value with beams in collision at the Z-pole energy, the loss factor is 0.0035 V/pC per beam and the most part of the radiated power will travel out away from the IP.

However, the decrease of the the central beam pipe leads to more image current losses due to the conductivity of the metal pipe walls. To remove this heat, we will use a liquid coolant that will flow within the room temperature solutions. We plan to use paraffin in the central chamber and water outside. We plan to use an allow AlBeMet, like a beryllium as a light material for the central part and in the transition up to Lumi Monitor. Additionally, a few microns of gold coating will reduce heat load and help to protect the detector from SR photons.

The first estimate of heat load in the central gives approximately 150 W/m for a 12 mm bunch. However, to calculate more realistic number we developed a new CAD mode.

THE METHOD OF CALCULATIONS OF HEAT LOAD DISTRIBUTION

We use specially designed CAD model as an input for the wake filed calculations using the CST code. This CAD model consists of different elements, which have different materials. The CAD model, which was developed by Francesco Fransesi (INFN) is shown in Fig. 9. The model contains five parts. The central part is made from AlBeMet but coated with a gold. The allow AlBeMet has a conductivity of $2.842*10^{-7}$ S/m, a little bit higher than conductivity of a pure beryllium. The gold has conductivity of $4.561*10^{-7}$ S/m. Two transition parts are also made from AlBeMet. And other two parts are made from copper, which conductivity is $5.8*10^{-7}$ S/m

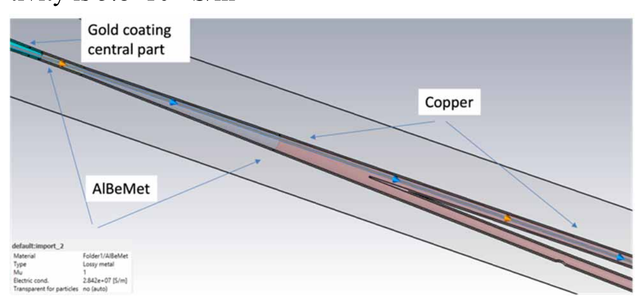

Figure 9: CAD model with different materials.

Using this model, we calculate the local heat load in following way. At first, we do wake field calculations, assuming that all materials have infinite conductivity. Then we do wake filed calculations, still assuming that all materials have infinite conductivity, except the interested part, which is given the correspondent material. And finally, we take the difference, which shows how much power is lost in this part. Naturally, it needs a lot of calculations, but the result

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is important for the cooling system design. After calculating the wake potentials, we calculate the loss factor and the heat load power using the following formula:

$$P = k\tau I^2$$

Power = Loss factor * bunch spacing * Current**2.

The required parameters are determined by the FCC-ee beam parameters, which are presented in Table 1. This table is based on the beam optics parameters, presented at the FCC Week in Paris in 2022 [8].

Table 1: Important Beam Parameters

Parameter	Value
beam energy [GeV]	45
circumfarences [km]	91.2
beam current [mA]	1280
bunch intensity $[10^{11}]$	2.43
number bunches/beam	1000
rms bunch length with SR / BS [mm]	4.38 / 14.5
bunch spacing [ns]	32

HEAT LOAD DISTRIBUTION IN IR

In Fig. 10 we present the distribution of the heat load along the central part of IR (+- 4.5 m). These results are very important for the temperature distribution and correspondent cooling system design.

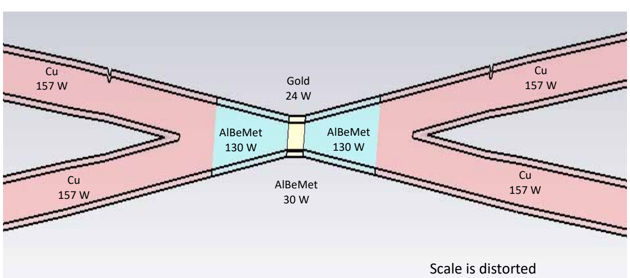

Figure 10: Heat load distribution in the FCC IR.

CONCLUSION

Calculations showed that in the IR region (±4 m) approximately 1 kW power is dissipated in the pipe wall. Necessary cooling is needed. No sing of the strong trapped modes because of the special shape of the IR chamber. However almost 3 kW power, which is generated in IR will go out in 4 pipes and will be dissipated somewhere in the rings. For the next steps it is very important to include all necessary details of the real IR chamber design in the CAD model.

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