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ESTIMATED HEAT LOAD AND PROPOSED COOLING SYSTEM IN THE FCC-EE INTERACTION REGION BEAM PIPE. *

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Abstract

We discuss the beam power loss related to the heating of the beam pipe walls of the FCC-ee interaction region. We analyze 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 show the distribution of the heat load along the central part of the interaction region. We also present the cooling system design and results for temperature distribution in interaction region in the operational mode.

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 on inhomogeneities of the beam pipe. In a time, the diffracted fields are absorbed in the metal wall. 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.

Another heating effect is an excitation and diffusion of the image currents 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 currents.

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. Using the correspondent conductivity of the materials we calculate the heat load distribution along IR beam pipe.

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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 saw traveling waves propagating for more than 100 m long [6]. The second type is the when fields are excited and absorbed in some trapped locations. Your cannot avoid one mode located near the pipe connection [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 due to heating effects.

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 is strongly depend 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 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.

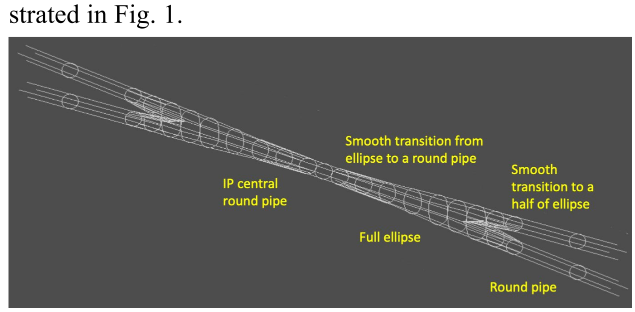

Figure 1: Smooth Transitions in IR

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

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pipe from two pipes. An important point is that the 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, where electron and positron beams collide. 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.

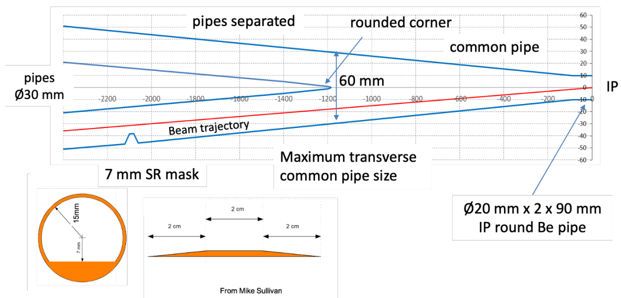

Figure 2: Present FCC IR Geometry and SR Mask Shape

This new geometry differs from the previous geometry described in FCC-ee CDR [1], mainly by the size of the central pipe. In the previous geometry the radius of the central beam pipe was larger, being 15 mm. Decreasing the size of a central part gives a possibility for the FCC detector to make more precise tracking [8].

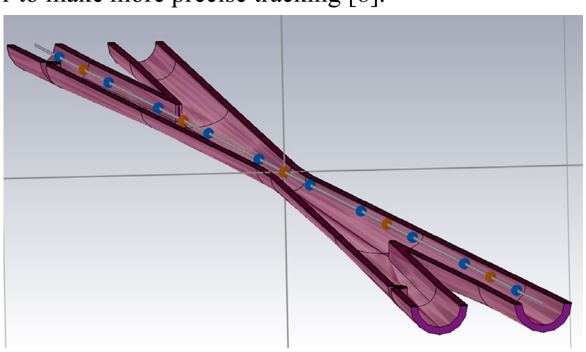

Figure 3: CAD Model for the Wake Field Calculations.

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 is shown in Fig. 3. A line with blue and orange balls shows the beam trajectory.

WAKE POTENTIALS AND TRAPPED MODES

Using this CAD model, we performed wake field calculations giving to 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 is shown in Fig. 4 by a red line. We can see two beating oscillations with a smaller amplitude. The distance between maximums is approximately 48.1 mm that corresponds to the frequency of 6.2 GHz. That means we have two trapped modes with close frequencies. Furrier spectrum (Fig. 4) confirms this statement. Later, we found out that the CAD model was not exactly symmetrical with respect to the IP.

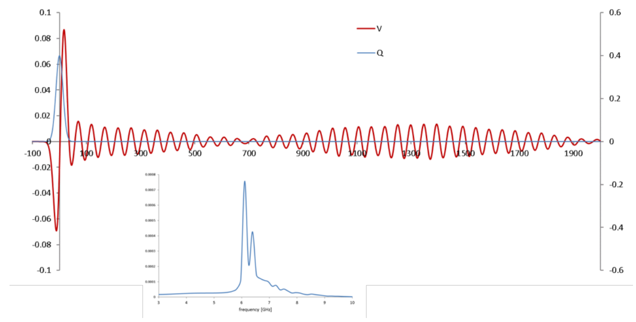

Figure 4: Wake Potential and Frequency Spectrum

We also did a special eigen mode calculation for this geometry The electric force line distribution of the mode is shown in Fig. 5.

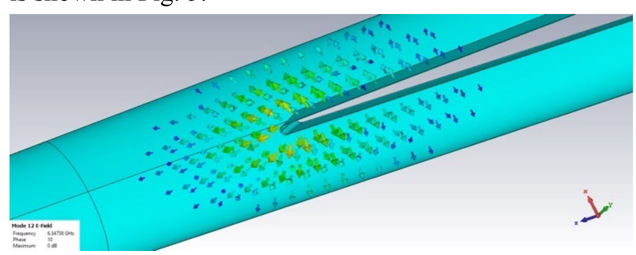

Figure 5: An Unavoidable Trapped Mode. Electric Force Lines Distribution.

The trapped mode is concentrated near the conjunction of two pipes, in a region with a maximum transvers size. This mode has a longitudinal electric component in the common pipe that interacts with the beam. We call this mode as an unavoidable trapped mode in the IR [2]. The smaller size of the central pipe decreases the geometrical impedance and moves the unavoidable trapped mode to higher frequency, in this way decreasing the interaction with the beam. There are several other trapped modes due to SR masks but they do not interact much with the beam.

However, the decrease of the central beam pipe leads to more image current losses due to the conductivity of the metal pipe walls. The first estimate of heat load in the central gives approximately 150 W/m.

HEAT LOAD DISTRIBUTION IN IR

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. It contains five parts. The central part is made from AlBeMet162 but coated with gold. This material has a conductivity of $2.842*10^{-7}$ S/m, a little bit higher than the conductivity of a pure beryllium. Gold has

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conductivity of 4.561*10^{-7} S/m. Two transition parts are also made from AlBeMet162. The other two parts are made from copper, which conductivity is 5.8*10^{-7} S/m. At first, perform wake field calculations, assuming that all materials have an infinite conductivity. Then perform 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. Table 1 shows relevant beam parameters, for this study presented at the FCC Week in Paris in 2022 [8]. In Fig. 6 we present the distribution of the heat load along the central part of IR (+- 4.5 m).

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

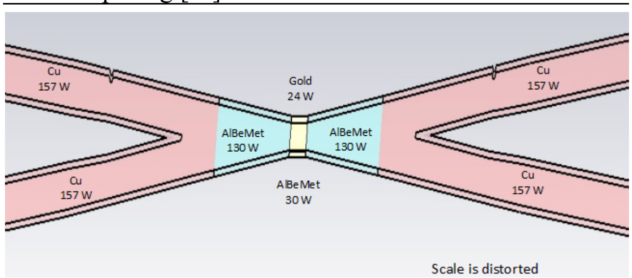

Figure 6: Heat Load Distribution in the FCC IR

THE COOLING SYSTEM

In order to remove the heat produced, we will use a liquid coolant that will flow within the cooling channel [9]. We intend to use an alloy named AlBeMet162, a light material as beryllium, for the central part and in the transition up to Luminosity Monitor. Additionally, a few microns of gold coating will reduce heat load and help to protect the detector from SR photons.

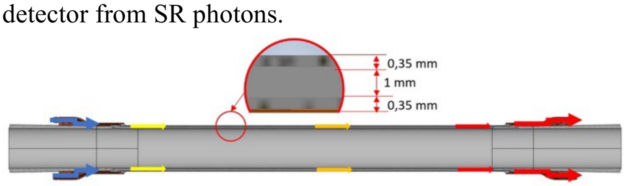

Figure 7: Paraffin Cooling System

The cooling system consists of paraffin cooling of the central chamber (Fig.7) and of asymmetric water cooling channels in the trapezoidal chamber , just before the luminosity monitor (Fig. 9). The trapezoidal chamber is created using the 50 mrad cone as the cutting profile, to assure the respect of the spatial constraint. To reduce the cooling material, the design provides five couples of channels for each side; in this way it is possible to use the required quantity of coolant and reduce the material, creating a lightweight structure. To create the embedded channel it is necessary an additive manufacturing technique, like the "thick copper deposition". We performed a thermo-structural analyses using a detailed model for FEA (Ansys) to calculate temperature distribution along the pipe. Paraffin flow rate: 0,015 kg/s, cross-section:68,17 mm2, velocity: 0.3 m/s. Inlet temperature: 18°C. Convective coefficient: 900 W/m2K.Water flow (20 different channel) rate: 0.0019 kg/s, cross-section: 9.62 mm2, velocity: 0,2 m/s. Inlet temperature: 18°C. Convective coefficient: 1200 W/m2K.

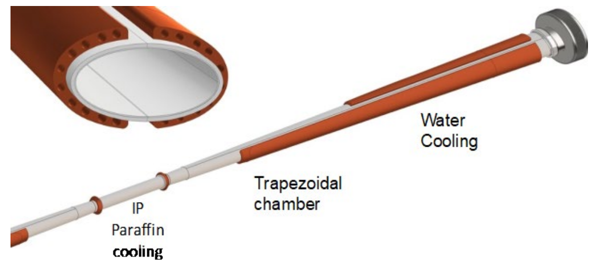

Figure 8: Water Cooling System

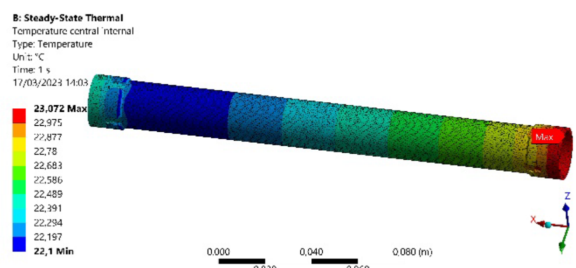

Figure 9: Ansys Simulation of The Temperature in The Central Chamber.

The temperature distribution in the central chamber. is shown in Fig. 9 and the correspondent temperature in other IR parts of the chamber is shown in Fig.10. In the central part we can notice a linear increase of the temperature without any asymmetry, instead along the trapezoidal chamber there is an asymmetric temperature distribution due to the configuration of the cooling channels.

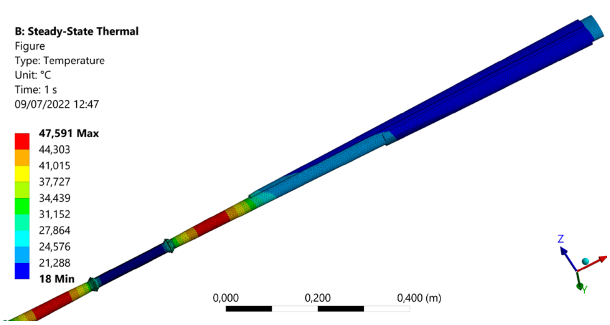

Figure 10: Temperature Distribution in Other Parts.

In both parts of the chamber the cooling is efficient and keeps the temperature low as wanted.

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