2.10 HOM mitigation for FCC-ee

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2.10.1 Introduction

High electron and positron currents (1.5 A) are planned to be used in the Future Circular electron-positron Collider (FCC-ee) with a goal to archive high luminosity of order of 2.3 10^{36} $cm^{-2}s^{-2}$ at the Z-production collision at the beam energy of 45.6 GeV [1, 2]. Coherent effects at the high-current machine impose certain limitations on the magnitude of the impedance of the machine. The potential well distortion due to inductive part of the impedance may give a large bunch lengthening. The microwave longitudinal and transverse instability set the total limit on the effective impedance. The multi bunch longitudinal and transverse mode-coupling can be more dangerous for the beam dynamics, but fortunately the feedback system can be used to damp these instabilities. An additional effect of the resonance part of the impedance is the HOM (Higher Order Modes) heating. It can happen not only in the RF cavities, but anywhere in the machine beam pipe where trapped mode or traveling waves absorb their power. Temperature raise due to HOM heating can be very high in the closed volumes without cooling. Very important the HOM heating is in the Interaction Region (IR), because it brings an additional background. The local heating in the IR can reach tens of kW of power. Some part of the electromagnetic waves, excited by the beam, with a frequency above the cutoff frequency will travel away from the IR and go down the beam pipe. The absorption of these waves can bring heating problems to other parts of the accelerator. A large energy loss of the beams in the interaction region can be a severe problem. The temperature of the IR chamber will go up and the vacuum will be spoiled. If the IR chamber has small gaps or hidden cavities (like in shielded bellows or valves), then electric sparks or arcing may cause additional vacuum spikes. Heating of nonevaporable getters (if they are will be used in the IR) may bring vacuum instability (the temperature can go above the recovery level). All of these things can make the backgrounds much higher. One can find a description of these effects in publications [3, 4]. Impedance study for FCC-ee can be found in reference [5].

2.10.2 HOM excitation.

The dominant contribution to the impedance comes from the resistive-wall wake fields excited in the beam pipe; wake field generated in the very complicated beam pipe geometry like the IR and RF cavities (even HOM damped).There are several other beam pipe elements, which can bring more impedance. They are: beam collimators; feedback cavities and BPMs; injector and abort kickers; bellows and vacuum valves; pumping holes and screens; wall coating. Some of these elements can also adsorb the power of propagating waves, generated in other places and consequently become the HOM heating elements.

2.10.2.1 ***Propagating waves***

In general the reason of excitation of the propagating waves is an obstacle in the beam pipe, like for example a collimator. An energy loss of a point charge due to diffraction of its own field on an obstacle is proportional to the particle energy γmc^2

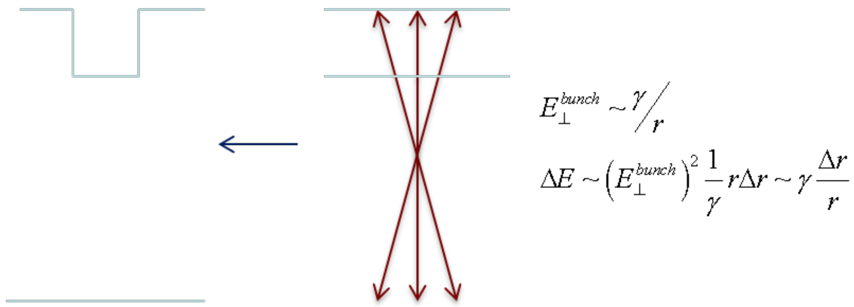

Figure 1: A point charge field energy, diffracted at the obstacle.

We may consider radiation of a point charge as a high frequency part of the radiation of a bunch of particles. However we know that the low frequency part does not depend on the energy in the ultra-relativistic case. That means that radiation of many particles is coherent in the low frequency part and the radiation power will increase in quadrature with a number of particles. To fulfill the coherence condition in this case we need a smaller bunch length in comparison with a wavelength of an excited wave. In the FCC-ee the bunch length will vary in the region of 3-12 mm, which is smaller than the beam pipe transverse dimensions and therefore the radiation will not be shielded by the wall chamber.

A simple estimate of the energy loss factor for an obstacle Δr in a pipe with a radius *r=a*

$$k \sim \frac{Z_0 c}{2\pi^{3/2}\sigma}\frac{\Delta r}{a} \tag{1}$$

For the case when a bunch length σ is 1 mm; pipe radius a is 10 mm; and the size of an obstacle Δr is 1mm the loss factor is 0.1 V/pC.

Usually these waves propagate away before the next bunch comes to this place. However these waves can be dangerous too as they can propagate long distances and be absorbed in low resistance elements like NEGs or vacuum pumps. Wake fields due to roughness surface or dielectric layer can be also include in this category, as a representative of the Cherenkov radiation.

2.10.2.2 ***Trapped modes***

Trapped modes could exist in a cavity-like element in the beam pipe. A trapped mode has a smaller frequency than a cut-off frequency of the beam pipe for a corresponding electromagnetic field distribution (monopole, dipole, etc.). Sometimes a frequency of a trapped mode is exactly equal to some of the beam spectrum line or a rotation frequency harmonic. The amplitude of the field in this cavity increases linear with a number of bunches passing nearby until the self-saturation due to resistivity of the metal walls. The power of radiation in the resonance case is determined by the beam current squared I^2 , a trapped mode loss factor k and a damping time τ_n of this mode. If a bunch spacing τ_b is much shorter than the damping time then

$$\tau_n >> \tau_b \quad P_{coh} = 2I^2 \sum_n k_n \tau_n \tag{2}$$

In other case when the damping is smaller than a bunch spacing the power will be determined by a bunch spacing

$$\tau_n << \tau_b \quad P_{in} = I^2 \sum k_n \tau_b \tag{3}$$

If a bunch spacing is equal to a damping time than the resonance power is only two time larger than in the case when a trapped mode frequency is not coincident with a bunch spacing harmonics.

To make an estimate of the radiation power (which will be somewhere be absorbed) we may assume relative to the FCC-ee parameter that the bunch spacing is 2.5 nsec, loss factor as in the previous example is 01. V/pC and the beam current is 2 A (this number correspond to the case when only three quarter of a ring is filled with a beam, then effective current becomes larger than the nominal). If we use the last formula for the power will found that the power is 1 kW. This means that loss factor of order of 0.1 V/pC will be responsible for a power of a microwave store. Every small irregularity in the beam pipe becomes very important.

2.10.2.3 ***HOM heating***

If electromagnetic power dissipates in the place without any outside cooling (water or air), the temperature can rise to very high level up to the melting point. Some "cavities" can be hidden outside the beam pipe but have a coupling to the beam through small holes in the metal wall or ceramic windows. Usually they are shielded bellows; shielded vacuum valves and BPM or vacuum pumps feed-through.

I will argue with some "researchers", who allow small gaps in the beam pipe. A small gap in a vacuum chamber can be a source of high intensity wake fields, which may cause electric breakdowns. And usually a small gap in a beam pipe couples the bunch field with an outside "cavity".

HOM absorbers can be used to take away the generated from some unavoidable places like IR and collimator. Longitude wake field can be suppressed by longitudinal shielded metal fingers; however transverse wake fields may escape through the slots between the fingers. They must be absorbed by the HOM absorber. It is planned to use HOM absorbers in the FCC-ee interaction region [6]. The plot of IR with HOM absorbers is shown in Fig. 2.

Due to a smooth geometry of the vacuum chamber IR has a relatively small impedance and only one trapped mode. In the case of the bunch length of 2.5 mm and the beam current of 1.45 A the electromagnetic power is approximately 5 KW in each set of pipe connection, which includes power of the trapped mode and the power of all propagating modes. This power will be mainly absorbed in the HOM absorbers.

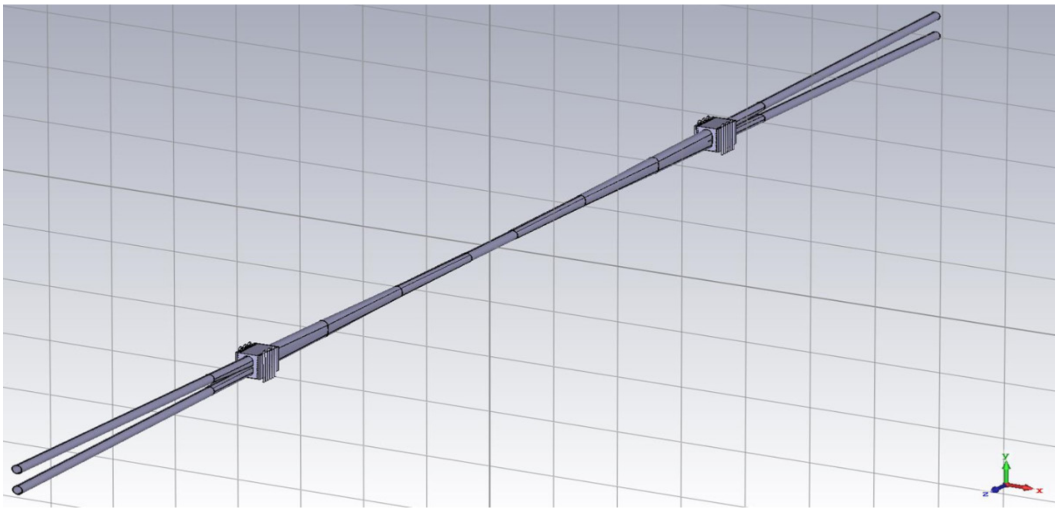

Figure 2: FCC-ee IR beam pipe with HOM absorbers.

2.10.2.4 ***Concept of HOM absorber in IR***

A sketch of the HOM absorber in IR is shown in Fig. 3. The absorber vacuum box is situated near (around) beam pipe connection. Inside the box we have ceramic absorbing tiles and copper plates (walls). The beam pipe has longitudinal slots in this place. These slots connect the beam pipe and the absorber box. Outside the box we have stainless steel water-cooling tubes, braised to the copper plates. HOM fields, which are generating by the beam in the IR have a transverse electrical component and can pass through the longitudinal slots in the beam pipe. Inside the absorber box these fields are absorbed by ceramic tiles, which have high value of the loss tangent. Ceramic tiles are braised to copper plates with columns. The heat from ceramic tiles is transported through the copper plates to water cooling tubes.

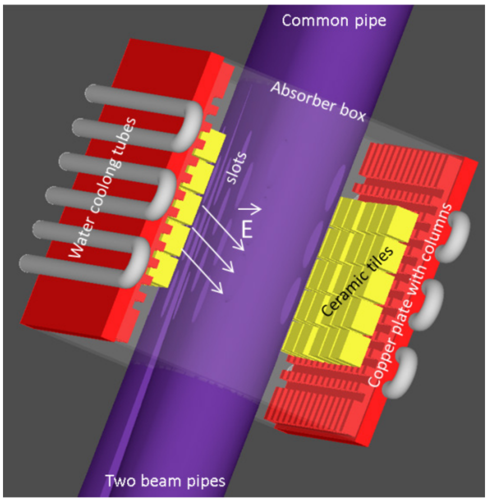

Figure 3: A HOM absorber for FCC-ee IR.

2.10.3 **Summary with recommendations on the beam pipe geometry.**

Electron and positron bunches generate electromagnetic fields at any discontinuity of the vacuum chamber. These fields can travel long distance and penetrate inside bellows, pumps and vacuum valves. Vacuum chamber must be very smooth. HOM absorbers must be installed in every region that has unavoidable discontinuity of the vacuum chamber. Maximum attention to the RF seals designs. Design of a BPM button would contain a cooling possibility. No open (to the beam) ceramic or ferrite tiles. Increase the bunch length as possible. We don't have to forget that beam pipe heating due to resistive-wall wake fields make the beam pipe to be water cooled.

2.10.4 References

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2.11 Final twin quadrupole design for the FCC-ee based on the canted cosine theta concept

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2.11.1 Introduction

The FCC-ee is part of the FCC study [1], an ambitious post-LHC accelerator complex study in the Geneva area. FCC-ee is a powerful e^+e^- circular collider with ultimate luminosity performance. This is achieved partly through extremely small vertical emittances of around 1pm. The FCC-ee interaction region [2] is very challenging, in part because the final focus quadrupoles, 2.2 m from the interaction point (IP) sit very close to each other. The field quality of these magnets needs to be excellent and in any case better than one unit of 10^{-4}. The angle between the 30 mm diameter beam pipes of the electrons and positrons is 30 mrad in the horizontal plane, translating to a distance between the centres of the two quadrupoles at the tip of 6.6 cm. This calls for a very compact design, which also needs to have very high field quality. The use of iron to shield the magnetic field of the neighbouring quadrupole can only work at low fields. For the fields needed here (100 T/m field gradient) the iron will saturate and important cross talk