NUMERICAL INVESTIGATION ON THE ELETTRA 500MHZ POWER COUPLER

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Abstract

Due to the high input power required to feed a resonant cavity, the RF input coupler is a critical component for the reliability of an RF system. The 500 MHz RF input coupler for the ELETTRA cavities was specified for 150 kW input power. It is important to investigate the performance limits of the coupler in view of increasing RF power requirements. The coupler's maximum peak field and dissipation versus the input power have been studied by means of the numerical simulator HFSS.

INTRODUCTION

The RF power is fed into the ELETTRA cavities by means of an inductive Input Power Coupler (IPC). The coupling coefficient depends on the orientation of the IPC loop. It is selected during the installation of the IPC on the cavity and it is then fixed.

The maximum RF power delivered through the IPC is 60 kW at ELETTRA, where 6 1/8” coaxial transmission lines are used. A special connection element adapts the IPC to the 6 1/8” line. Similar IPCs with additional forced air-cooling to the connection element have been implemented at the ANKA and SLS storage rings. In these cases waveguides are installed with the proper waveguide to coaxial transition. At SLS the RF power delivered through the IPC is around 100 kW.

An IPC prototype was successfully tested a few years ago at 200 kW at DESY, even though not in final RF layout. Nevertheless two IPCs installed at SLS had some earlier problems during the storage ring commissioning [1].

Considering these experiences and in view of the project to upgrade to 150 kW the ELETTRA RF plants [2], the RF power limits of this IPC as well as improvements to the existing design have then been investigated. The possibility to maintain a coaxial type IPC design is the keystone to keep the actual cavity’s port and consequently the entire cavity project.

The investigation of the maximum sustainable RF power of the IPC benefits from the studies on the transmission lines [3]. The main limiting parameters of these devices are the peak and the average power. The peak power limit depends on the voltage breakdown between inner and outer conductor. In the literature there is a large spread for this value. In the following the 12kV peak value is used as given in [4,5]. The average power is a long-term figure that depends on the maximum operating temperature that the line components, mainly the insulating supports, can safely sustain. In the considered applications, the high RF power at 500 MHz is fed into the IPC in a continuous wave: the lowest value between the average and the peak power limits will be considered.

The transmission line approach is however complicated by the fact that the IPC load, cavity and electron beam, is not a stable one and it is not always predictable (fast beam losses, instabilities). In addition the IPC does not only deliver RF power to the load, but it picks up power lost by the beam in the cavity, at whatever frequency it resonates. This contribution may not be negligible for high current machines.

For these reasons, beside the IPC maximum power evaluated at the fundamental frequency, the peak power limit due to the breakdown voltage at the Higher Order Mode frequencies (HOMs) are also taken into account.

INPUT POWER COUPLER

The ELETTRA IPC is a coaxial line with a non-uniform longitudinal section, having a reduction from the 6 1/8” coaxial line (external conductor diameter Ø = 154 mm) to the CF 100 cavity port (inner diameter $Ø_{port}$ = 84 mm). The IPC is connected to the standard coaxial line by means of a dedicated 80 mm long, 6 1/8” transition element. This element has been simulated together with the IPC. A brazed ceramic window separates the vacuum part from the air part. The vacuum part is water-cooled. IPC inner and outer conductors are in copper, the ceramic window is made of alumina Al203, with ε_r=9.7 and tanδ=1.0e^{-04}. The connection element conductors are in aluminium and in silver plated copper. The ceramic disk support is in steatite C221, ε_r=6.7 and tanδ=3.0e^{-03}. These parameters are valid for temperature of 200 °C [4].

SIMULATIONS

The IPC has been studied with the electromagnetic simulator HFSS v 9.1, from Ansoft.

The IPC and the 6 1/8” connection element have been simulated as a unique device. To simplify the IPC shape the brazing rings of the ceramic window form a unique body with the conductors (see Fig. 1).

The holes inside the insulating support were not simulated, thus overestimating the losses of this dielectric.

The coupling loop is not simulated either. The load due to the cavity and the beam is taken into account during data post processing. Three modes of propagation have been investigated: the TEM, the TE_{11} and TE_{21} from 500 MHz up to 2.3 GHz, which is the highest HOM frequency observed during machine operation. In this frequency range the contribution to the power propagation comes mainly from the TEM-like mode, although the TE_{xx} modes can propagate along the coaxial device as the frequency increases.

The IPC coupling coefficient is chosen in order to cancel the power reflection towards the generator at the maximum beam current. This means zero reflection at the IPC amplifier port ρ_i=0. Maximum beam current means also maximum power delivered by the generator and transmitted to the IPC. As the beam current decreases some power is reflected until the final mismatched condition (no beam). The simulations show that the worst case happens at ρ_i=0 for the voltage breakdown limit.

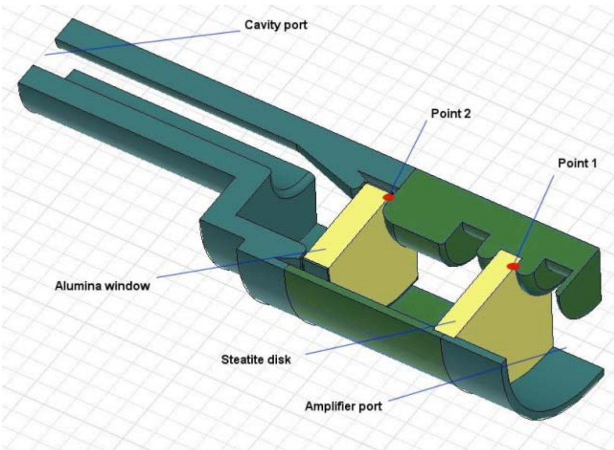

Figure 1: IPC simulated shape. Inner and outer conductors are in green, in yellow the insulator disks. Red dots show the “hot points” of the structure located on the air-side.

Average Power

The largest contribution to the power dissipation comes from the dielectric supports. At 500 MHz, the maximum power that could be dissipated on the alumina window is 15 Watts corresponding to an input power of 220 kW when ρ_i is zero. This power decreases up to 180 kW in case of maximum reflection, no beam. The maximum dissipation, without cooling, on the steatite disk limits the input power to 95 kW when ρ_i is zero. As ρ_i increases, the input power limit decreases. To overcome this limit the connection element has to be cooled. Thermal analysis will be performed to verify the new input power limit. An adopted forced air solution routinely runs with an input power of about 100 kW.

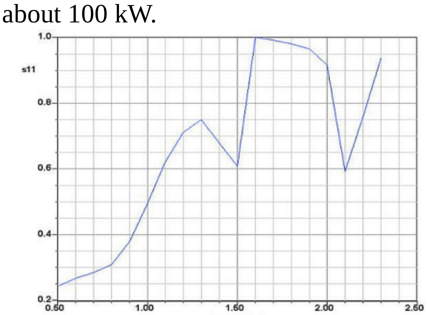

Figure 2: IPC reflection coefficient: a significant e- field increment exists in correlation with the two minima.

Peak Power

Two IPC points exhibit the largest electric field at any frequency. These points are shown with red dots in figure 1. Point 1 is located on the connection element near the steatite disk and point 2 is close to the ceramic window.

According to the voltage breakdown limit, at 500 MHz the maximum power sustainable at point 2 is 190 KW coming from the main amplifier. This value decreases to 108 kW at point 1, when the ρ_i=0 condition is imposed. This can be explained by the standing waves generated downstream of this connection element due to the sharp diameter change of the external conductor.

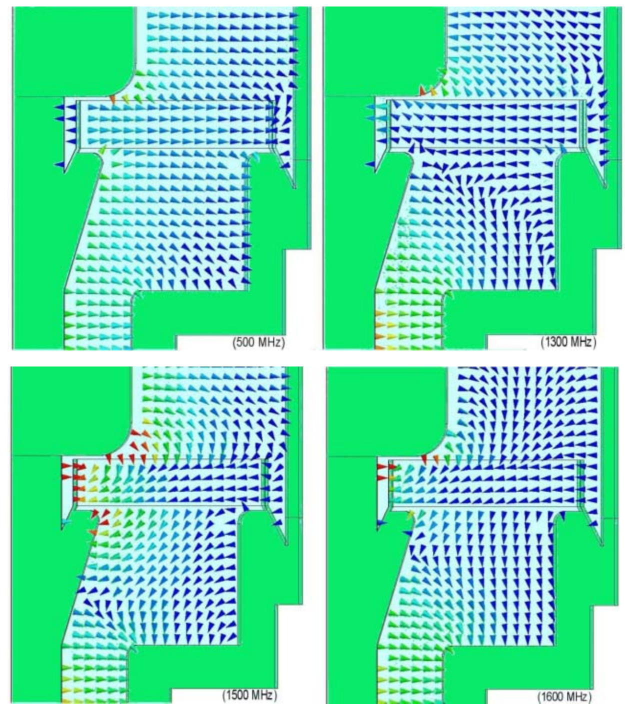

Figure 3: Arrow plots of the E-field at the frequencies indicated. At 1.5GHz there is a huge increment. The colour scale is the same for all four plots.

In the HOMs frequency interval, the IPC shows another unwanted effect due to this change (see Fig. 2). This discontinuity generates evanescent TM_{xx}-like modes. While at 500 MHz the TEM mode is dominant over these modes, at higher frequencies the longitudinal field becomes more enhanced and finally it does not transform back into a purely transverse one (see Fig. 3). In particular at 1.5 GHz a huge stationary phenomena exists: the electric field near the alumina window, point 2, is 20 times greater in comparison to the field at 500 MHz generated by the same input power. This means that a relatively low power delivered by the beam at this frequency, for example in the longitudinal HOM L4=1510MHz, could add to the RF power coming from the power amplifier leading to a huge increase of the local electric field.

The electric field sums up if the phase of the signal picked up from the beam and that coming from the main amplifier are the correct ones in that point. When the IPC is fed at 60kW in CW regime and 300 mA are stored in ELETTRA, a simultaneous beam power picked up by the IPC of about one hundred Watt at 1.5GHz could build up a voltage in point 2 that exceeds the breakdown limit. The same phenomena exists at 2.1GHz, frequency that corresponds to the longitudinal HOM L9=2125MHz, but the field increment is less impressive: only 4 times greater than the field level at 500 MHz, that means some hundreds of Watts for an electron beam of 300 mA.

The connection element is very critical since it experiences the IPC's mismatching due to the external diameter step. The most critical part is not the "under vacuum" side of the IPC, but the air part required to connect it to the power transmission line. According to these results, the IPC could not tolerate any power coming from a beam current of 300 mA when it is powered more than 110 kW by the amplifier.

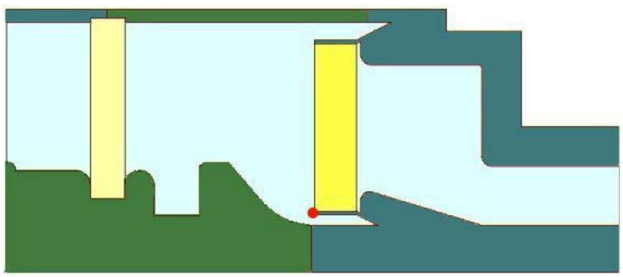

Figure 4: Profile of the IPC connection element optimised for the HOMs power. Red dot shows point 2.

NEW DESIGN

A modified shape of the connection element has consequently been investigated to reduce the HOM effects while keeping constant the performances at 500MHz (see Fig. 4). In fact although a proper cooling of the inner part of the connection element can increase the average power limit, a voltage breakdown risk exists due to the huge resonance at 1.5GHz.

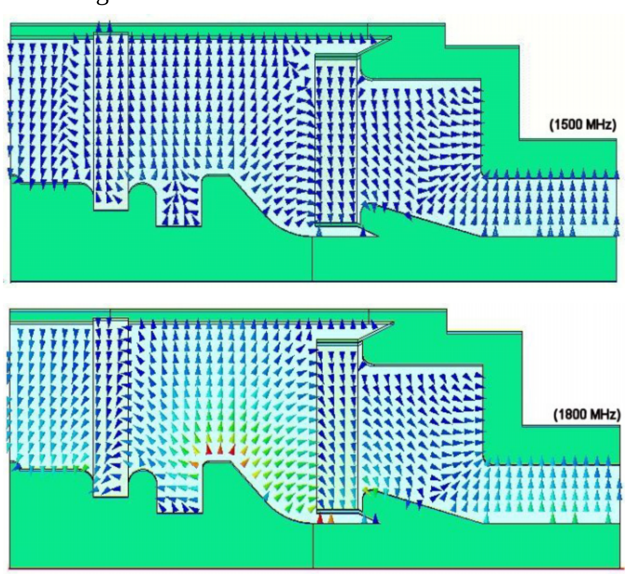

Figure 5: Arrow plot of the E-field at 1.5GHz and 1.8GHz.The colour scale is the same as fig. 3.

The inner conductor profile has been shaped to enlarge the small volume between it and the brazing ring. The peak electric values in point 2 have been lowered at all frequencies (see table 1). But the brazing ring of this profile remains unshielded: tests are required to check the validity of this solution, even if the maximum E-field on point 2 is 3 times less than the original shape.

This structure can work with an input power of 195 kW before the power coming from the beam at 2.1GHz can cause any breakdown. The reflection coefficient of this element at 500 MHz is s_{11}=0.029.

Table 1: Maximum E- field in point 2 normalized to the peak value at 500MHz for the same input power and ρ_i=0.

Frequency	Original Shape	New Profile
500 MHz	1.00	0.33
1.5 GHz	20.65	0.24
1.8 GHz	5.24	0.95
2.1 GHz	3.79	1.05

CONCLUSION

The results presented here are conservative: they have been evaluated with a margin on the breakdown and using the electric properties of material valid for 200 °C. On the other hand, average and peak power limits are not uncorrelated quantities: increasing the temperature the voltage breakdown risk increases too. In addition the manufacturing of these devices, roughness and surface treatment strongly influence the actual RF high power behaviour. The ELETTRA IPC can safely sustain up to 190 kW when perfectly matched and without power coming from the beam. This result confirms the high power tests executed at DESY. The connection element must be cooled in order to sustain this power. Thermal analysis will be performed to check the average power limit on this element.

The ELETTRA IPC is very sensitive to HOM power. The input power limit is strongly decreased if there exists the possibility to interact with HOMs. This result can explain the IPC problems that have been experienced at the SLS.

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