HIGH CURRENT, LARGE APERTURE, LOW HOM, SINGLE CRYSTAL Nb 2.85GHz SUPERCONDUCTING CAVITY

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Abstract

There is an increasing demand for High beam Current, high Radio-Frequency (RF) power S-band cavities in existing and new accelerator projects, such as for a study of future electron-ion collider (eRHIC) and a very brilliant, broadband, teraherz coherent synchrotron radiation source (CRS). To achieve this goal, the RF cavities must be upgraded to a gap voltage of 1.5 MV in a limited space available in the machine with a high gradient superconducting cavity. At the present time there are no cavities and accessories designed to support the high beam currents of up to 10-100 mA and at the same time provide a high gap voltage at such a high S-band frequency. AMAC proposed a High Current, Large Aperture, Low HOM, Single Crystal Nb 2.85GHz Superconducting Cavity with high RF Power Coupler and HOM absorber device.

INTRODUCTION

In several upcoming projects, high beam current, high accelerating gradient, high voltage gap, and large beam apertures are required with S-band, but with serious concerns on limited space and cost.

For instance, MIT-Bates in collaboration with Brookhaven National Laboratory is working on the design of a future electron-ion collider at BNL, so-called eRHIC [1]. A number of important experiments relevant to the electron beam self-polarization, particularly the kinetic polarization mechanism, could be performed using the MIT-Bates South Hall Ring in the electron beam energy range of 0.5-1.5 GeV. The existing S-band copper RF cavity can only provide 140 kV gap voltage. A clear technical solution to this problem is to replace the present copper cavity with a superconducting cavity with gap voltage up to 1.5 MV, so that the relevant experiments for eRHIC can be carried out. MIT is also proposing to develop an electron storage ring based, very brilliant (up to kWatts/cm^{-1}, broadband (0.03-10 THz), coherent terahertz synchrotron radiation source, at its Bates Linear Accelerator Center in collaboration with BNL/NSLS and LBNL/ALS [2]. A critical technical requirement for optimal performance is again to replace the present single RF cavity with a superconducting single cavity.

In order to meet these challenges, AMAC and MIT-Bates Lab collaborated in the Phase-I project to develop the high Eacc superconducting cavity and the RF couplers for operation with 10-100 mA stored beam at 2.856 GHz, and cooled by superfluid He at 2K. The SC cavity will provide 1.5 MV gap voltages in an existing 1.2m space, has a larger aperture, and is designed to extract and dampen all higher order modes.

In order to reduce the number of superconducting cavities, it is needed to use the highest possible E_{acc}. The Field Emission (FE) and Thermal Breakdown (TB) are two main obstacles, which prevent cavities from reaching the highest E_{acc}. With high current cavities, the power to be coupled to the beam is quite high, which must be handled by the input coupler. With high beam current, removing HOM power and damping HOMs are other significant challenges that arise from the high current and tight bunch spacing.

CAVITY DESIGN

A schematic of the cavity with input coupler, and HOM absorber is shown as Fig. 1.

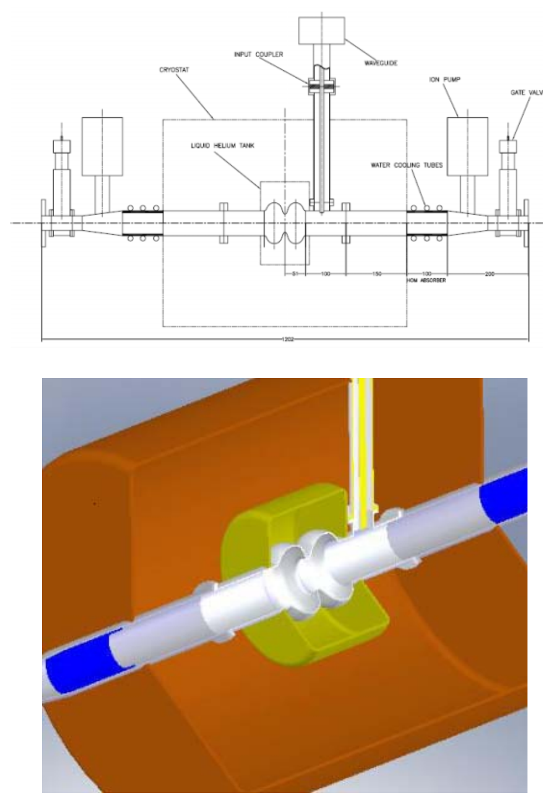

Fig.1. A schematic of the 2.85 GHz SRF cavity with a high RF power input coupler and HOM absorber

The cavity will consist of two elliptical contour cells to provide the required 15 MV/m accelerating electric field gradient and must take into account the high beam current of 100 mA circulating in the cavity during machine operation [3]. The design will be finally optimized to reduce the E_{peak}/E_{acc} and H_{peak}/E_{acc} ratio, reduce the bunch-bunch coupling instabilities, suppress the HOMs, and it will feature large aperture cell(s) and end tubes, to avoid trapping of HOM's, allow the HOM's to be readily removed, and have a good Quality Factor. MAFIA, CST Microsoft Studio, and HFSS have been used to calculate characteristics to have a best compromised cavity.

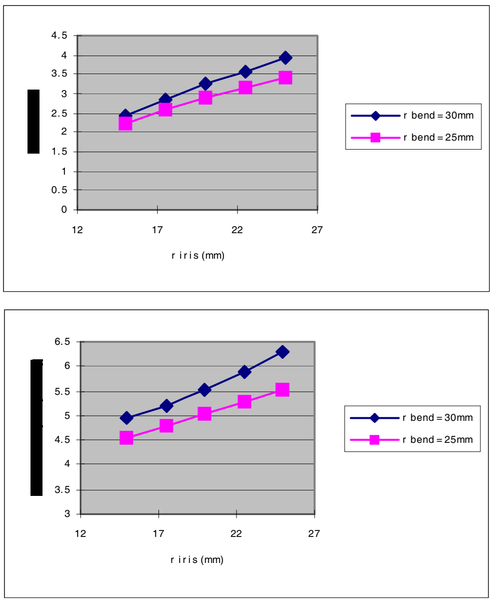

Fig 2: First Simulation Results of E and H fields

To reduce the surface field in the cavity, the iris and beam-pipe radii were changed and simulated by the "parameter sweep" function in Microwave Studio. It can be seen that B_{max}/E_{acc} and E_{max}/E_{acc} can be reduced if we use a smaller iris and beam-pipe diameter. However, the smaller iris and bean pipe are not in favor of HOM extraction and input coupler design. Fig. 2 shows part of the simulation results. Further calculations and optimizations, and the adaptation of the enlarged cut-off tube concept produced good compromised results, and the parameters were fixed. Fig. 3 shows the improved geometry, and Table 1 summarizes the calculation results. This cavity design was then analyzed for its HOM and wakefield properties. The use of single crystal Niobium, with predictable good material properties and high purity will be the preferred fabrication procedure to operate the cavity with a 15 MV/m operating gradient at 2.85 GHz [4].

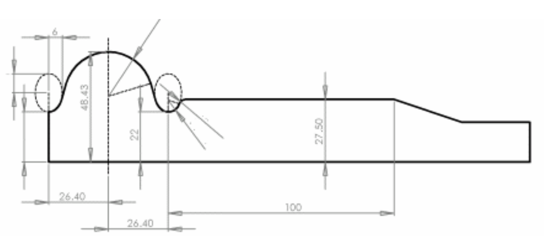

Fig 3: Cavity configuration after several series of optimization

Table 1: Calculation Results for the Final Cavity Configuration

Stored Energy (J)	0.0096644
V_acc (V)	115091.916
R/Q (Ohm)	76.433
Emax (MV/m)	5.526
Hmax (A/m)	8676.82
Bmax (mT)	10.90
Bmax / V_acc (mT/MV)	47.37
Bmax / (V_acc/lambda) (mT/(MV/m))	4.97
Emax / (V_acc/lambda)	2.52

HOM SIMULATION

The challenge in the HOM coupler design is extracting and removing the high power dissipated of the HOM due to the high beam current. This removal is critical to avoid beam breakup. The boundary conditions must also be analyzed in order to determine the HOM propagation into the cut off tubes, and to determine the optimum position of the ferrite absorbers. The goal is to extract the HOM power from the cavity and absorb in water cooled Ferrite-50 segments built into the end tube(s) of the cavity.

The Higher Order Modes (HOM) analysis was done in three steps. The MAFIA E-Module was used to determine the electric and magnetic fields characteristics of the HOMs. First, the natural HOM frequencies without electron beam and without any damping were studied. In the second step, the calculations were done for the case of multi-bunch beam operation with varying bunch lengths, bunch numbers and in and off axis beam position. In the third step the HOM absorbers were studied using the MAFIA code to inspect the dumping of the higher order modes induced by the beam.

Eight representative points were chosen for the analysis (coordinates z/x in mm, where z is measured from the center of the cavity, and x is measured from the center of the beam).

The parameters of the beam bunches are: Bunch energy 0.85 GeV, bunch charge 0.06nc, bunch length 1mm (3.3ps), bunch spacing 105 mm (350 ps), bunch size: 0.1mm (in beam axis direction) and 1mm (radial dimension). The simulation was performed for 1, 6, 30, 40, and 60 bunches. Figure 4 and 5 show an example of the calculation results with 6 bunches passing the cavity and the induced RF electric field (wake field) by them. Arrows show the induced RF electric field

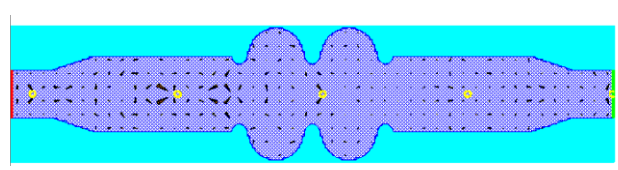

Fig 4. 6 Bunches are passing the cavity (the 1st one has passed through).

The results of the complete calculations performed in Phase-I show that the strong higher order modes are located in the high frequency range, and that the strongest

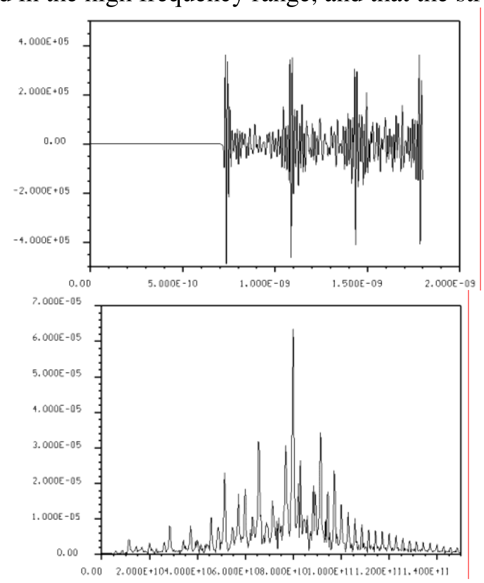

Fig 5. Examples: RF electric field at point 1 & frequency spectrum induced by 6 bunches

mode is near 76 GHz. This will allow the HOM to propagate into the beam pipe to the ends where the absorbers will be located. Calculations were done with RF damping elements (lossy ceramic and ferrite absorber material) to determine the reduction in the longitudinal and transverse HOMs for different frequencies. The calculation results show that good damping of the HOMs is achieved with the use of the room temperature beam absorbers at the ends of the cavity.

ABSORBERS DESIGN

The HOM damp is very efficient that HOM Q has been reduced by an order of about 4-5. The damper has no effect on the fundamental mode. The frequency and Q of fundamental mode is kept constant. The properties of a lossy ceramic material (TiO_2) was used to calculate the damping for the traverse modes. The results are shown in the HOM analysis consisted in the calculation of the damping effect obtained by adding ferrite and lossy ceramic absorber sections at the ends of the cavity. Ferrite absorbers best damp the longitudinal modes.

HOM Absorber Design Concept

The preliminary estimates for the MIT/Bates cavity HOM dissipated power is 50 Watts, or 25 Watts on each side of the cavity [ ]. The basic concept for the absorber design is as following: two ferrite/lossy ceramic absorbers assemblies are placed on each side of the beam pipe (see Fig.1) in the room temperature sections adjacent to the cavity. Each ferrite and ceramic absorber will consist of 5mm thick, 50mm long elements with tapered ends, and arranged on the inside circumference of the beam pipe. Figure 10 shows an absorber assembly fabricated for MIT/Bates with similar ferrite blocks.

Fig 6. Ferrite HOM absorber at MIT-Bates

The new absorber will be fabricated using similar proven materials and brazing techniques. The width of each element will be approximately 10mm, and will be optimized for manufacturability to facilitate the brazing procedure inside the beam tube section.

Material Characteristics

A number of important requirements must be considered in selecting any material used as a HOM absorber. These include:

1) High electric or magnetic loss factors are needed at the HOM RF frequencies.

2) Relatively low dielectric constant and permeability at HOM RF frequencies are useful properties to allow adequate penetration of the RF fields into the absorbing material. Many materials that rely upon an electrical conductivity for RF absorption also have high dielectric constants that reduce the RF fields within the material, reducing the efficacy of the RF absorption.

3) The dissipated RF power in the damper must be removed to prevent excessive heating of the material. Consequently, materials with good thermal conductivity are preferred.

4) Any significant heating of the absorbing material, or its substrate during fabrication or operation, can result in substantial mechanical stress from thermal gradients. The material must tolerate these stresses without cracking or fracturing.

5) The material must have a low out-gassing rate, so that the material may be used inside the high-vacuum systems. No material meets all these requirements perfectly, and engineering compromises are necessary for any particular application. Ferrite ceramics can be very good RF absorbers, with high magnetic loss factors, while the magnitudes of the dielectric constant and permeability remain sufficiently low to permit good penetration of the RF fields into the material. However, most ferrites have low tensile strength and poor thermal conductivity, posing significant engineering problems for manufacture and operation. High-density ferrites are usually suitable high-vacuum materials with low out-gassing rates at typical operating temperatures (below 200°C). Lossy ceramics

used as RF absorbers in the vacuum space have similar requirements.

HIGH POWER INPUT COUPLER

Major Objectives: Design and propose a 10 kW CW at 2.85GHz RF Power Input Coupler. Optimize the Q-ext of coupler to the beam. The RF properties, such as the electric and magnetic fields, and the design geometry were determined in the Phase-I by calculations using HFSS. These results were used to optimize the VSWR characteristics and the S-parameters to minimize the insertion losses. The main results of the HFSS simulations with the plots of the electrical and magnetic fields are shown for the two investigated options are shown in Figs 6a & 6b. Both options meet the design specifications stated in the Technical Objectives, and use the window/coax impedance matching geometry developed by AMAC for SNS and TESLA couplers [5,6]. This geometry presents a smaller surface area exposed to the vacuum compared with the choke geometry and facilitates the processing of the components to obtain a good vacuum. The secondary electron multipacting is the most serious limit to very high RF power couplers as the E fields become higher with the increasing RF power. In Phase-I, AMAC has also investigated a simplified straight coaxial coupler alternative (without chokes), and the results of the planned multipacting calculations will determine the selected choice for fabrication. Titanium-nitride thin film coatings will be applied to vacuum-side of the window. Fig.8. show the thermal model for tapered coax coupler.

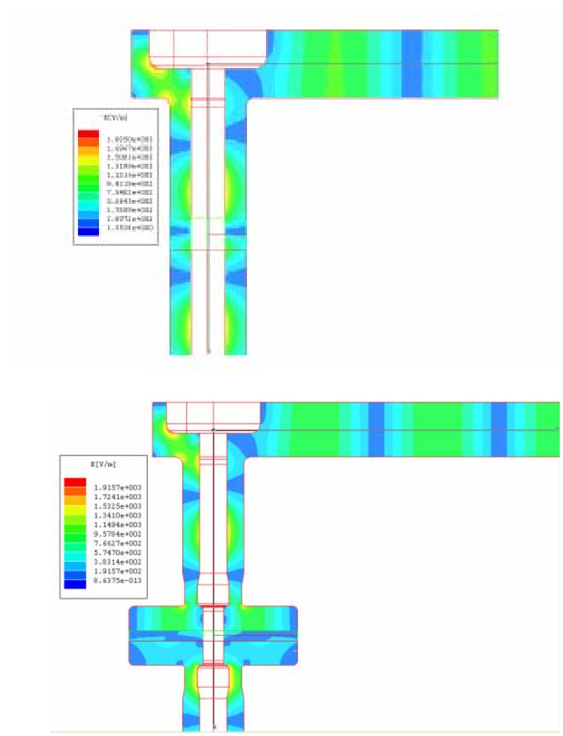

Fig 7. Straight Coaxial RF Coupler Section and Tapered Coaxial Coupler Section.

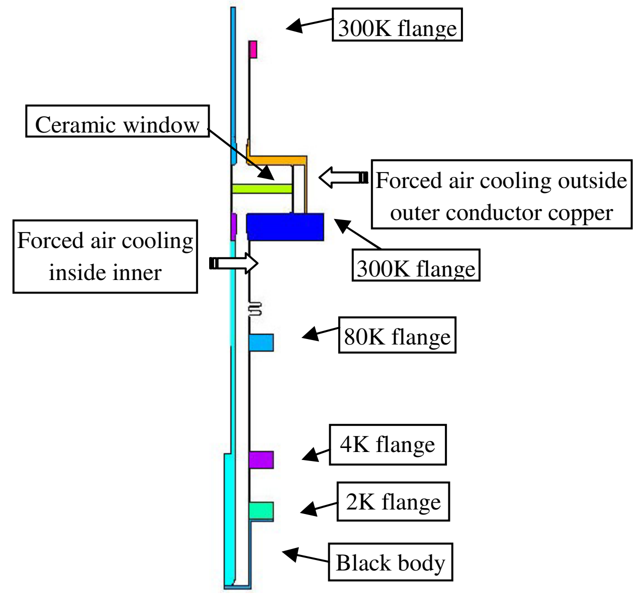

Fig 8. Thermal model for tapered coax coupler

CONCLUSION

The comprehensive study has demonstrated the feasibility of the technical approaches of the proposed project. The innovative SRF cavity design and High RF power coupler will meet all aspects of the project technical requirements. The technology developed in the project will be widely used in many applications for DOE, NASA and NAVY.

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