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RHIC Polarimeter Impedance Analysis with MAFIA

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Abstract

The narrow-band coupling impedance and beam parasitic loss on RHIC polarimeter target box have been analyzed with MAFIA. With an optimized design, the shunt impedances of the target box are under the limits set by beam instability consideration.

1. Introduction

The relatively high intensity and short bunch proton beam in RHIC can generate wake fields inside the beam components. The long-range wake field is more harmful for RHIC longitudinal beam dynamics. In other words, without a low-impedance component design, the proton beam could lose more energy in the component. The long-range wake potential in time domain corresponds to the narrow-band impedance in frequency domain. Those sharply defined frequencies of the impedances relate to the resonance modes in a cavity-like beam component. To minimize the narrow-band impedance of a beam component is just opposite to design a high (shunt) impedance RF cavity. The shunt impedance of RHIC beam components must be kept below certain limits to prevent emittance blowup and possible beam loss due to coupled bunch instabilities. Consequently, the RHIC CNI polarimeter [1] target box requires a careful impedance analysis to fit into RHIC impedance budget.

There have been two independent impedance limit calculations done for RHIC proton beam based on different scenarios. One was done by V. Mane using ZAP program, which analyzed both injection and storage cavities with dipole modes only. The limit was based on bunch area 0.3 eV-sec, the RHIC design value [3]. J. Rose did an analysis for injection cavity but included both dipole and quadrupole modes [2]. The limit was based on the extended bunch area 0.5 eV-sec [4]. We have modified Rose's output to include extra sextupole and octupole modes for a more cautious limit [5]. We used these two limits as our impedance limit guideline.

It is desirable for the polarimeter to measure both horizontal and vertical beam polarization profiles. Six silicon strip detectors(SSD) and two separate targets assemblies(horizontal and vertical) are used. Since the thin carbon target has a relative short life time at the full RHIC beam luminosity, each assembly has four target holders available. The target box radius is determined by the target driving assembly, minimized by the impedance reduction requirement. An analytical calculation has shown the scale of the shunt impedance with radius for the monopole modes of a pillbox cavity [6]. A 10% reduction in the radius of the target box may lead to a 15% shunt impedance reduction. The final radius is 16.03 cm. Since the distance between detector and interaction point should be 15 cm to optimize the measurement performance, the detectors will be in socket shape and sunk into the cylinder box. The minimum target box length is determined by the relative position of target, view port and detector sockets, which is 50.8 cm.

During conceptual design stage, we used a 3-D electromagnetic field codes MAFIA [7] to minimize the shunt impedance of structure. We found a 5:1 conical tapering-down structure is needed on each sides of cylinder box. The tapering ratio is also in consistent with the so-called "five-to-one" rule [8], which is defined as the ratio of the length to the difference of pipe radii and is now applied to all RHIC aperture transitions. The 3-D plots of the inside and outside of the target box are shown in Fig. 1. The detail of the target parts is shown in Fig. 2. A 2-D layout of the polarimeter and the position relative to other ring is shown in Fig. 3. MAFIA can also assess the beam parasitic loss into the box. The calculation from the MAFIA data is also presented in this paper.

2. Impedance analysis

MAFIA has been used as a main impedance analysis tool for many RHIC beam components [9−12] by V. Mane. The similar method was followed, using the eigenmode solver (frequency domain E code) to do the narrow-band analysis. It normally needs 3D simulation and a large number of modes to calculate. Consequently, a large memory and disk space and a long CPU time are needed. In one typical run of whole volume simulation, about average 1 mesh/0.5 cm in X-Y dimensions(cross section) were used. In Z dimension, about 1 mesh/0.5 cm were used in the target box section and 1 mesh/1 cm in the tapering section.*

We took a careful strategy toward our goal in order to convince the impedance police. As the first step, a simple cylindrical pillbox cavity was analyzed with MAFIA, whose impedance can be solved analytically. The separated Mathcad programs for TM and TE modes were used to get the analytical calculations. The numerical integration results for TM monopole modes agree with formulae in ref [6]. MAFIA used the same cylinder radius, length and 3D meshing configuration as the target box without implanting any symmetry plane. Up to 60 modes were calculated and 50 modes solutions were stored. The highest frequency stored is 1.612GHz. The E code can check the field solution after final iteration according to the Maxwell's equations. When the solution accuracy is beyond a defined limit, a warning message of " not a good solution" is given. Four bad solutions have been found in this run. All of them are found being not physical by comparing with analytical results. We

*The total mesh nodes were about 1 million. The total CPU time on SUN2 for a 40-modes calculation was about 17 hours.

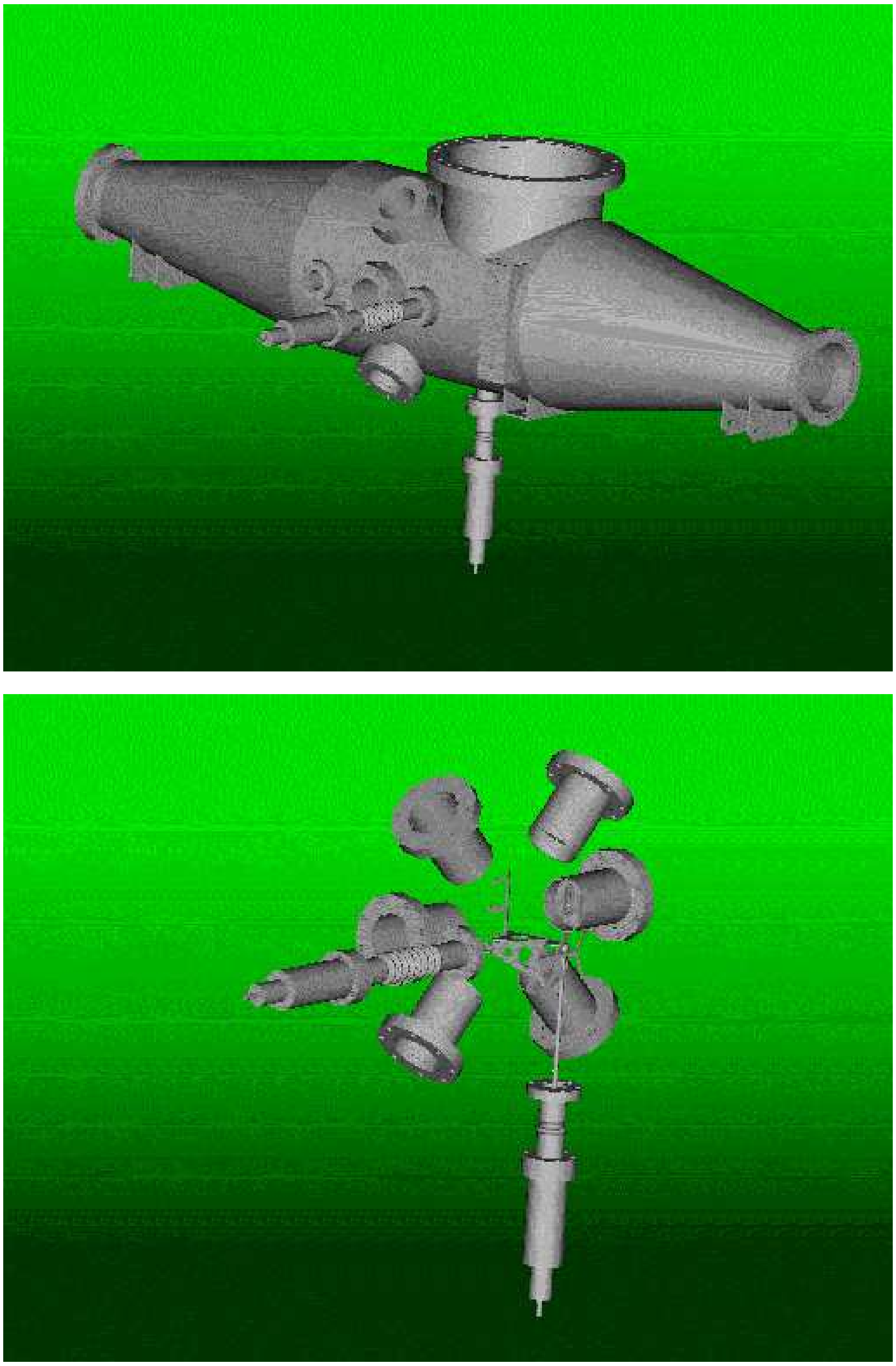

Fig. 1. RHIC CNI polarimeter target box. Top is assembly view and bottom is exploded view. Beam goes from the left to the right.

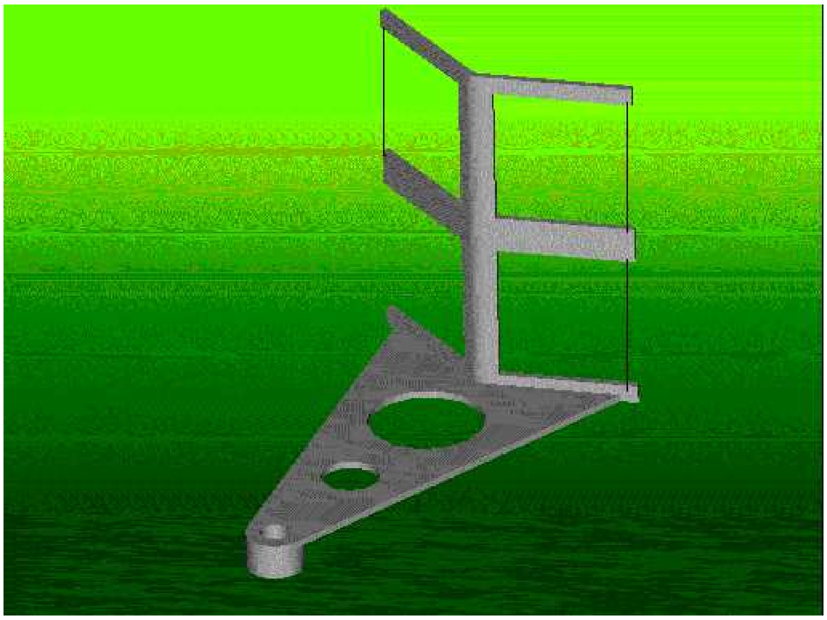

Fig. 2. Metal target frame and the ceramic V Plate. The holes in the V shape reduce the inertia of the target assembly. The target is a $6\mu m$, $4\mu g/cm^2$ ultra-thin carbon ribbon. It is 3cm long.

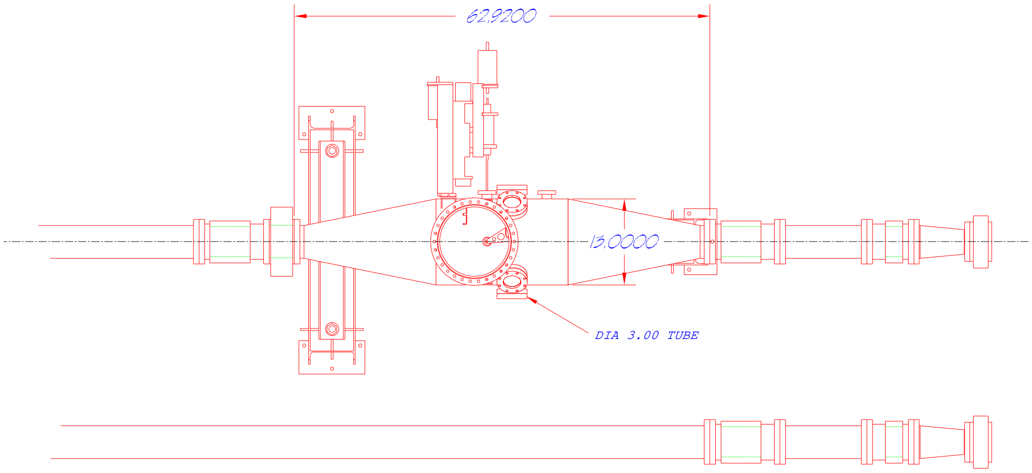

Fig. 3. Polarimeter layout in the RHIC beamlines. The units are in inches.

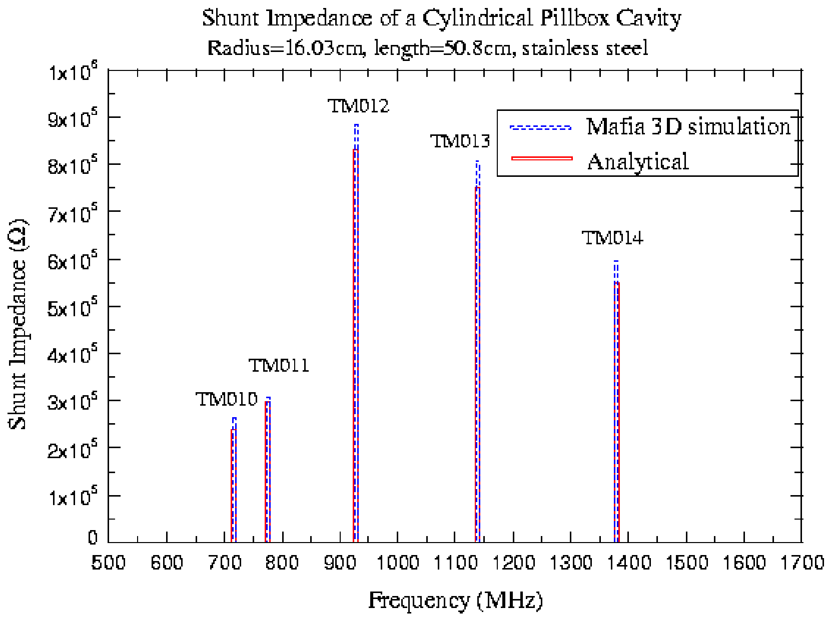

Fig. 4. MAFIA vs analytical impedance calculations for a simple pillbox.

call these bad modes as the "ghost mode". Five non-zero shunt impedance modes are found being monopole modes from TM010 $\sim$ TM014. A comparison with analytical formulae is shown in Fig. 4. It shows good agreement and the overall discrepancy is within 10%. All other 41 modes found by MAFIA are TE modes or degenerated TM modes, with zero on-axis shunt impedances. Among them, three were monopole TE modes, 20 dipole and higher azimuthal TE and TM modes gave redundant solutions except 2 modes near the highest frequency. The redundant solutions have very little difference in parameters. A detail examination shows their field patterns are just about X or Y symmetric. That is reasonable because no symmetry condition was put in the simulation. Fig. 5 gives their comparison with analytical solutions, which shows that the discrepancy is within 7% on the quality factors, and within 1% on the frequencies. In summary, we found that MAFIA 3D simulation gave us reliable results on impedance and quality factor except ghost modes.

In the second step, the target box with all interior components was simulated. Fig. 6 shows the comparison with same size pillbox. For all monopole TM modes, impedances have been reduced but are higher than other modes. From TM011 mode and up, impedance splits into two peaks. All TM mode frequencies shift higher except the TM011 mode. Other new lower peaks are TE like modes. All of these changes can be explained by the perturbation of interior components to the pillbox.

In the next step, the 5:1 tapers were added to the target box. Fig. 7 shows MAFIA mesh geometry(target in position) and the electric field arrows of TM010

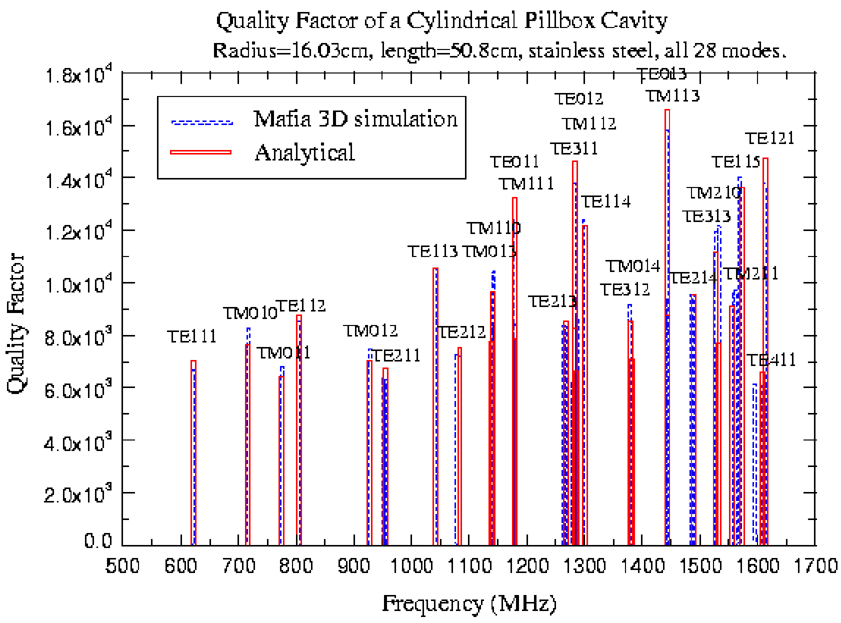

Fig. 5. MAFIA vs analytical Q calculations for a simple pillbox.

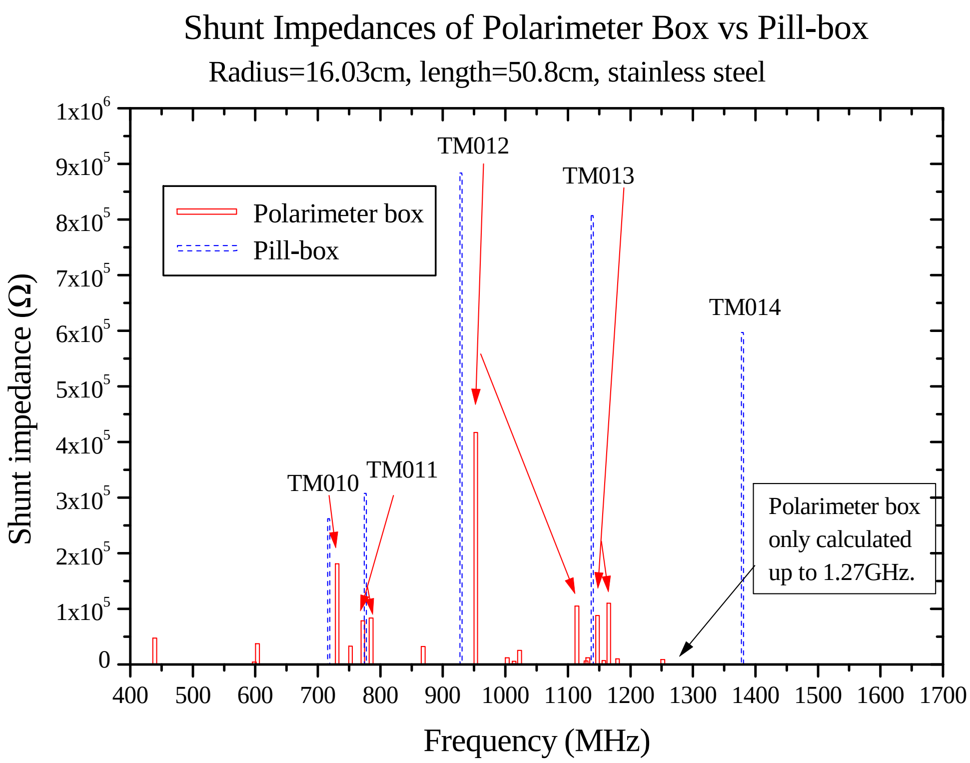

Fig. 6. Polarimeter box vs pillbox impedance calculations by MAFIA.

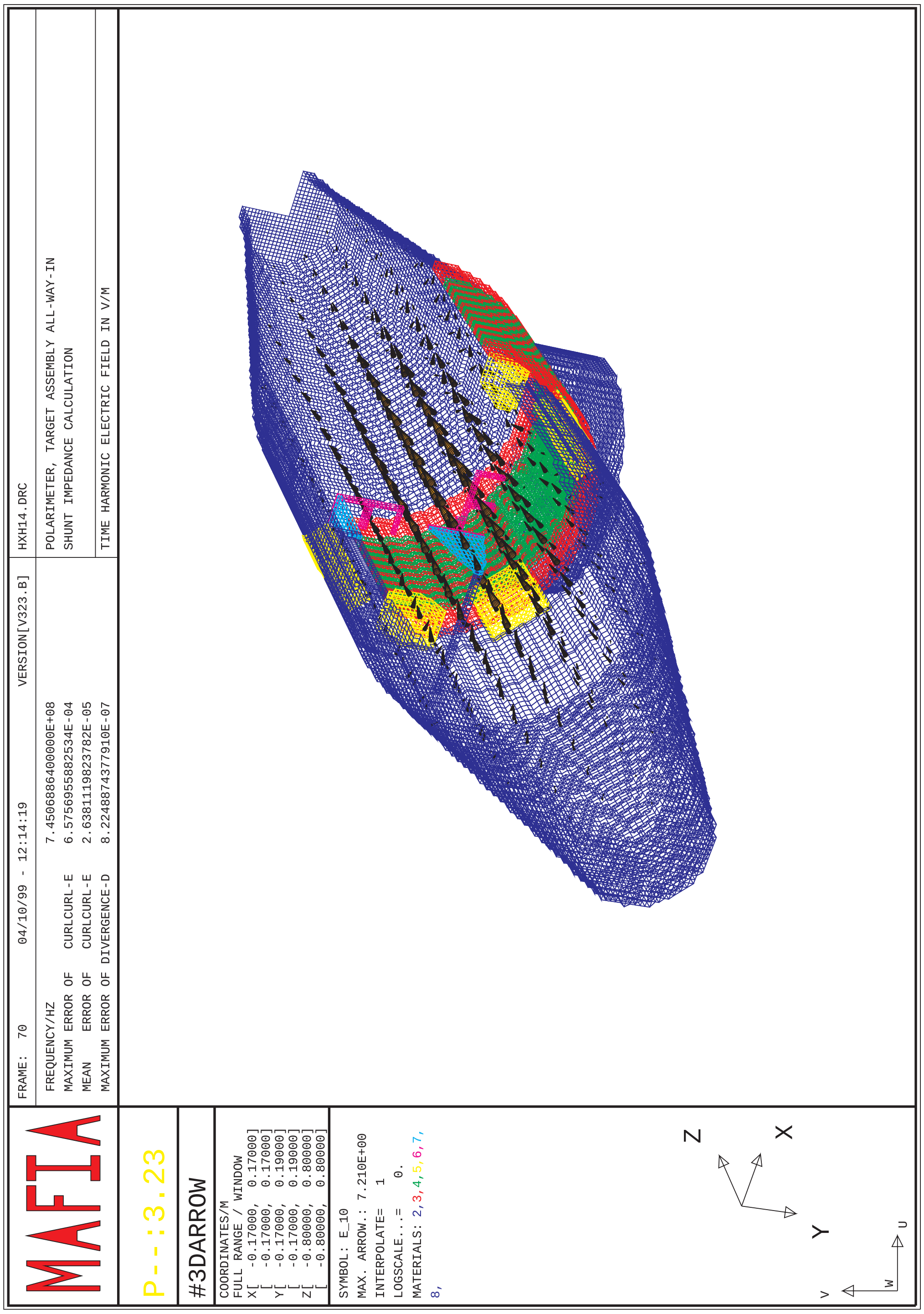

Fig. 7. MAFIA 3D simulation shown with a 1/4 body cut-away and the electric field arrows of TM010 mode.

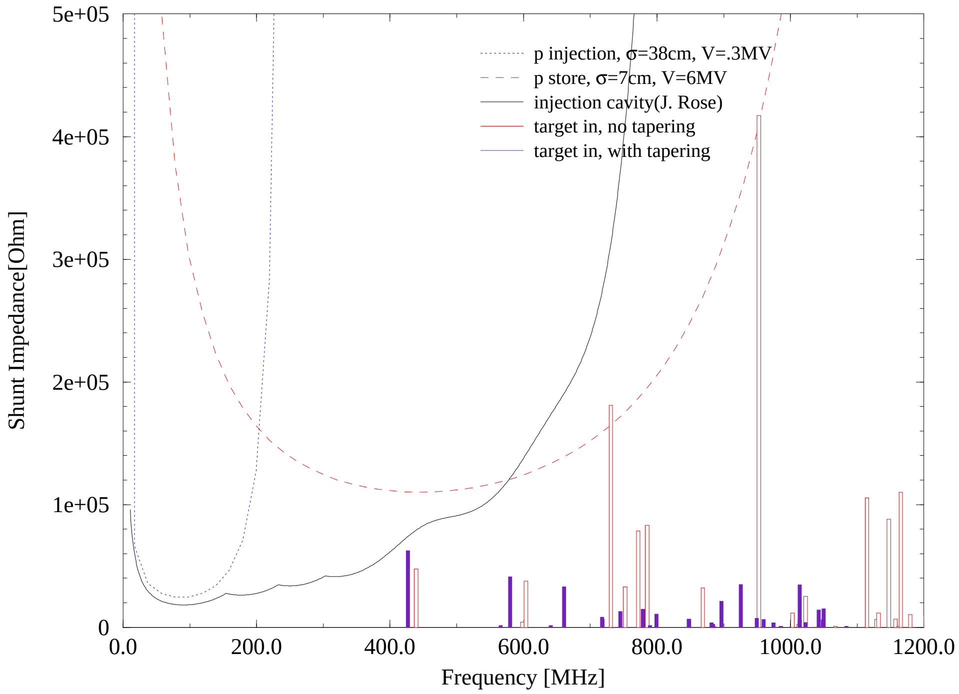

Fig. 8. Comparison of simulations with and without tapers. 5:1 taper structure selectively reduces shunt impedances. Opaque bars are impedances without tapering, filled bars are impedances with tapering.

mode. Fig. 8 shows that the tapers reduce the background(broad-band) impedance and bring down the narrow-band peaks but mainly at high frequency band. The lines are impedance limits. The dotted line and dash-line are Mane's results. the solid line is the modified Rose's results. The simulation results from MAFIA are plotted as bars. During this step, we found that the target frames have to be insulated from the cavity wall. Otherwise, even with the tapering structure, the impedance at low frequency could not be suppressed due to the selective damping of the tapers. Fig. 9 compares the impedances with ceramic V plates and with metal V plates. With metal V plates, the target assemblies act like conducting membrane planes, which enhance the monopole electric fields. From the beam loss analysis in next section, we can see the average power loss in the case of metal V plates is not tolerable for storage beam. Simulations for target in (deepest), out (standby) and in-between positions were carried out. Fig. 10 shows these variations and comparison with the impedance limits. It shows that shunt impedances of the target box for all target positions are below the impedance limits. All three cases are for ceramic V shape.

In the final step, we put the viewport and screen in the MAFIA simulation. The screen only has a 6-inch hole of mesh area. The mesh hole size in the simulation is about 0.5 cm$\times$ 0.5 cm. The purpose of the screen shielding is to reduce the broadband impedance induced by the viewport [9]. This MAFIA simulation is mainly for narrow-band. So the impedance should have no visible difference from the closed cylinder cavity. We have confirmed that with a solid screen the solution is exactly the same

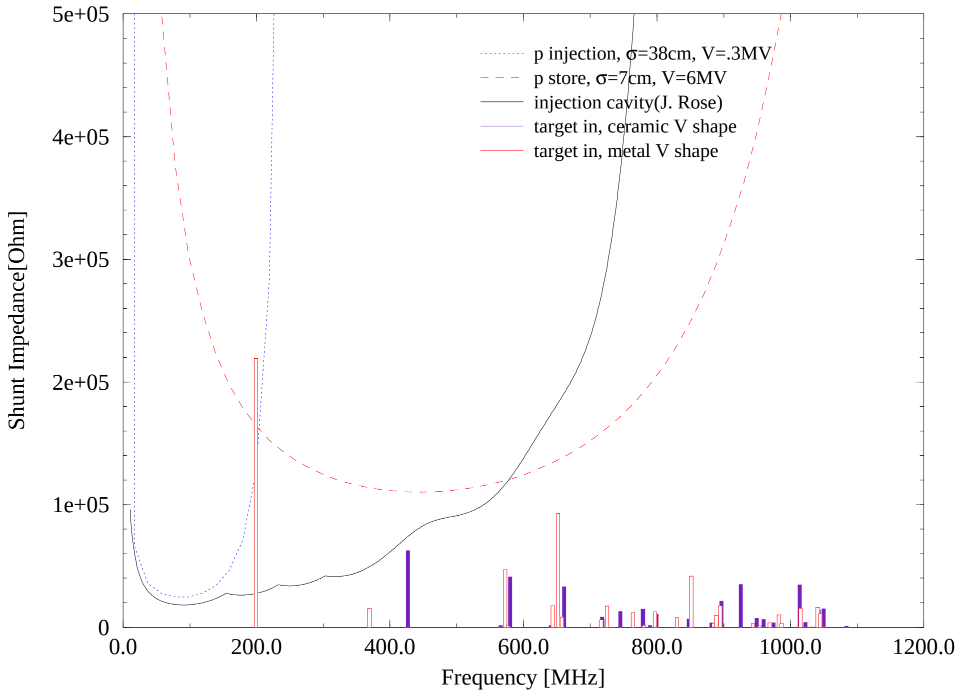

Fig. 9. Comparison of simulations with different material for the V shape. Opaque bars are impedances with metal V shape, filled bars are impedances with ceramic V shape.

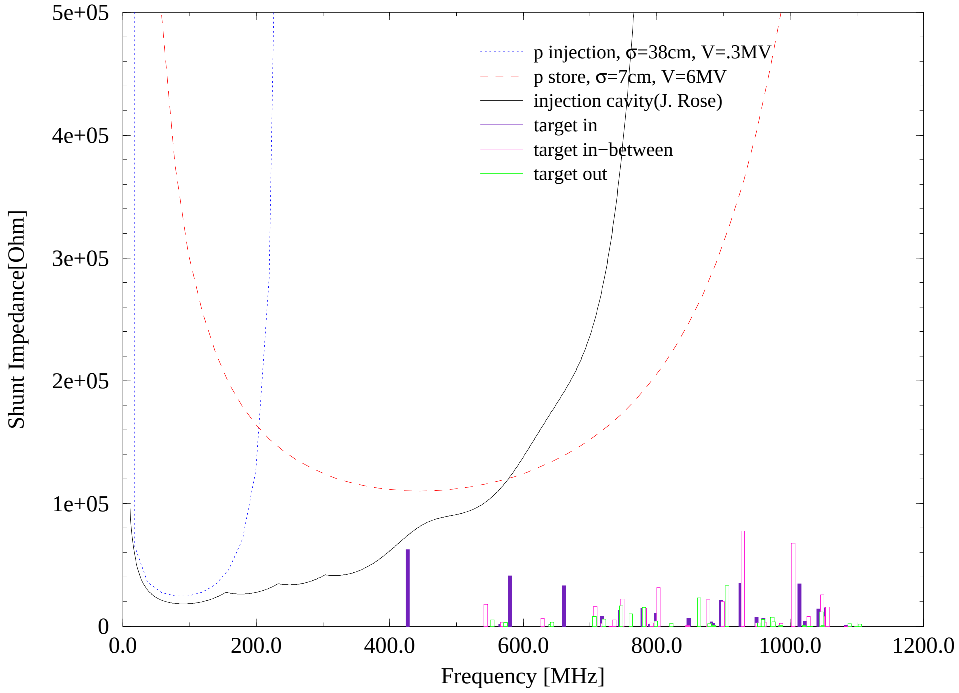

Fig. 10. Comparison of simulations with different target positions. Filled bars are impedances with target in.

as the mesh screen except a ghost mode, which shows a field leaking out of the mesh screen. An analytical calculation for a small hole radiation [13] shows that for a 0.5 cm diameter hole, a 2 GHz planar wave RF can only transmit 0.4% power and should not be visible from the simulation. So this mode is not physical.

3. Beam parasitic loss

As a bunch beam traverses a component, it loses a certain amount of energy due to the shunt impedance. The energy loss for a Gaussian bunch with rms length σ_z is [14]

$$\Delta\epsilon = q^2 \sum_i k_i \exp[-(\frac{\omega_i \sigma_z}{c})^2], \tag{1}$$

where q is total charge in the bunch (for full luminosity of polarized proton in RHIC, $q = 2 \times 10^{11} \times 1.602 \times 10^{-19} C$), c is the speed of light, k_i is called K loss factor for a point charge,

$$k_i = \frac{\omega_i R_{si}}{4 Q_i}, \tag{2}$$

where R_{si} is the shunt impedance, Q_i is the quality factor, $\omega_i = 2\pi f_i$ is the resonance frequency. Note i is for ith mode. All these parameters can be obtained from MAFIA.

We need convert this energy loss per bunch to average power loss. Ignoring the wake fields between bunches, total average beam power loss is

$$P_{ave}(\sigma_z) = \frac{N_b c q^2}{4 R_0} \sum_{i=0}^{28} f_i \frac{R_{si}}{Q_i} \exp[-(\frac{2\pi f_i \sigma_z}{c})^2], \tag{3}$$

where R_0 is the average radius of collider ring. N_b is the beam bunch number in the ring. The sum covers the 29 modes calculated by MAFIA. The metal material is stainless steel with a conductivity of $\sigma_c = 1.39 \times 10^6$ $(\Omega m)^{-1}$. Fig. 11 gives this loss as function of rms bunch length. It was suggested that the ceramic V plate uses MACOR^{TM} material, which has a dielectric loss property of $\tan\delta < 7.1 \times 10^{-3}$ at $f < 8.5$ GHz. We used $\tan\delta = 0.01$ in the simulation. From Fig. 11, we can conclude that our insulated target design significantly reduce beam power loss. The 5:1 tapering only relax beam power loss when $\sigma_z < 0.12$ m. In our optimum design, two extreme losses $P_{ave}(\sigma_z = 0.091m) = 243$ W and $P_{ave}(\sigma_z = 0.5m) = 0.31$ μW represent cases at RHIC storage and injection rms bunch lengths. The dielectric loss on the insulator is a major part of the parasitic loss. In our optimum design, the loss in the ceramic V plates found by MAFIA, is 62.4% of total loss for TE111 like mode, and 34.6% for TM010 like mode. That means each target assembly has to handle $\sim$ 70 W heat. A special cooling may be needed. Otherwise, a material with smaller dielectric loss has to be used, such as Al_2O_3. The dissipation factor is only $\tan\delta = 0.0001 \sim 0.0003$. Then the dielectric loss can be reduced to $\sim$ 2 W. No

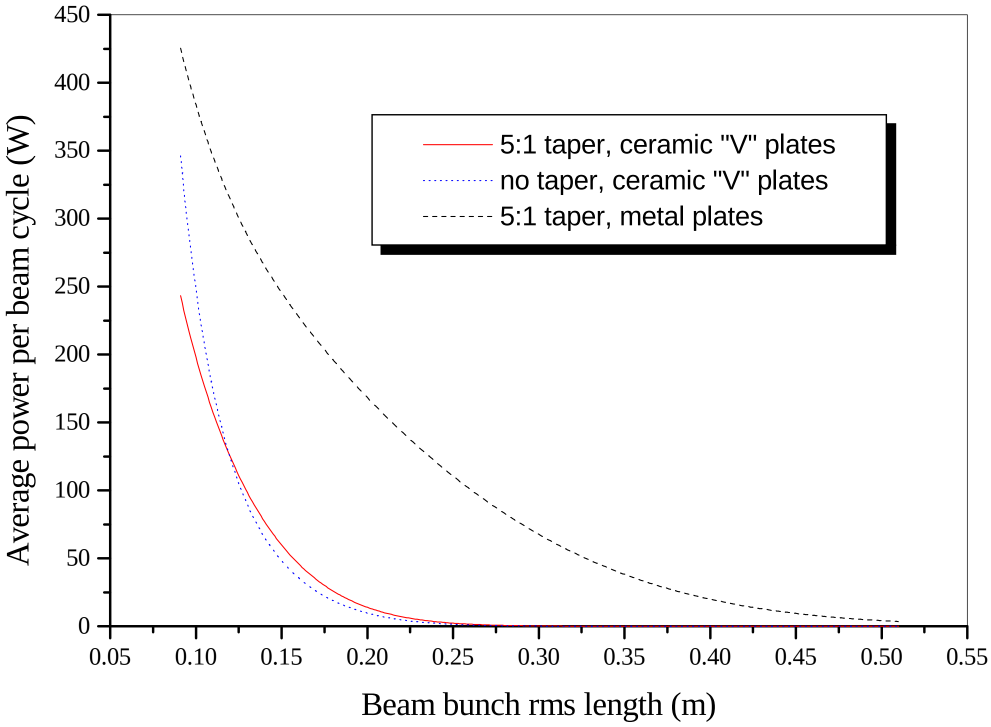

Fig. 11. Average beam power loss to polarimeter.

special cooling is needed. The thermal and vacuum properties of Al_2O_3 are excellent but harder to machine. Total metal loss power ~ 240 W could be dissipated over the large surface area. The deposit density is only 20 mW/cm^2. No cooling is needed.

4. Charge release

When the proton beam hits the carbon target, electrons scattered from the target could lead to a charge buildup on the insulated target. A resistive coating on the ceramic is a normal solution for this kind of problem. A high resistance coating may have a too low leaking rate for a 9.4 MHz(120 bunches, 78 kHz revolution frequency) charging rate. An alternative choice is to connect an inductive wire to the target frames. Through a vacuum feedthrough, the wire leads to a dumping resistor R_d for the accumulated charge to flow away. The voltage cross the resistor R_d can be used to monitor the discharge current. This dumping loop can be described as a series LRC resonance circuit. The shunt impedance analysis by MAFIA is equivalent to a parallel LRC resonance circuit calculation. The capacitances in two circuits represent same resonator capacitor. The series LRC circuit resonates in low frequency band (less than 10 MHz). The parallel LRC circuit resonates in high frequency band (more than 100 MHz). Two circuits can be considered separately without cross-talk due to their different frequency bands. In the low frequency dumping circuit, the inductance on the conducting wire L_d could not be too small. Otherwise, the resonate frequency

ω_d could be close to the high frequency band, and the impedance to the beam could be high enough like the metal V plate case in the MAFIA simulation. The resonator capacitance C_d can be obtained from MAFIA $C_i = 1/(2k_i)$, the smallest capacitance in a mode will be from the highest K loss factor. If we want the resonating frequency $f_d = \frac{1}{2\pi\sqrt{L_d C}} \ll 10$ MHz, the L_d has to be $\gg 17.5$ μH. The R_d could not be small either, in order to let discharge time shorter than the bunch interval $T = 106$ ns, that is $t_d \sim Q_d/\omega_d = L_d/R_d \ll T$. So a resistor of $R_d = 200\ \Omega$ will probably be required.

5. Conclusion

As shown in the simulations, with 5:1 tapers and insulated target design, the shunt impedance of RHIC polarimeter is under impedance limits of both injection and storage cavities. For the short storage beam bunches, only ~ 2 W power dissipated on target insulator. A 20 mW/cm^2 power loss density on the metal surface is acceptable. The accumulated charge on the polarimeter target could be discharged by a conducting wire design without inducing a high impedance to the beam.

6. Acknowledgment

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