HIGH CURRENT SUPERCONDUCTING CAVITIES AT RHIC*

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Abstract

A five-cell high current superconducting cavity for the electron cooling project at RHIC is under fabrication. Higher order modes (HOMs), one of main limiting factors for high current energy-recovery operation, are under investigation. Calculations of HOMs using time-domain methods in Mafia will be discussed and compared to calculations in the frequency domain. Beam breakup thresholds determined from numerical codes for the five-cell cavity will be presented. A possible motivation towards a 2x2 superstructure using the current five-cell design will also be discussed.

INTRODUCTION

Electron cooling is a key component in RHIC II, the next luminosity upgrade. Cooling gold beams at 100 GeV/nucleon require an electron beam energy of 54 MeV and a high average current of about 200 mA. Future projects such as eRHIC (electron-ion collider) push the operational current to 300 mA-600 mA at 20 nC bunch charge or higher. Such high current electron beams call for energy recovery superconducting linacs to accelerate the beam while minimizing RF power losses. A five cell superconducting cavity is under fabrication as a fundamental unit for the linac structure to accelerate the electron beam from 2.5 MeV to 54 MeV [1].

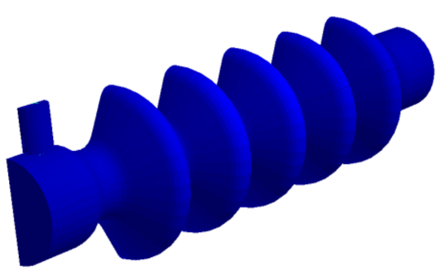

Figure 1: Graphic of five-cell SRF cavity.

Higher Order Modes

The complex structure of multi-cell cavities often cause modes to be trapped inside the cavity. HOMs to be trapped inside the cavity mainly due to three reasons:

1. The end cell geometry is different from the middle cells and may reflect HOMs back into the cavity.
2. Also small irises may result poor cell to cell coupling and cause HOMs to get trapped inside the structure.
3. It is also possible to find HOMs below the cutoff frequency of the beam pipe, preventing the mode from propagating out of the structure. These modes exponentially decay in the beam pipe before they reach the HOM absorbers.

Trapped HOMs pose two main problems for high current operation:

1. Multi-pass, multibunch instabilities driven by high Q dipole modes.
2. Large loss factor which is power lost into HOMs. This power has to be carefully extracted to reduce cryogenic losses.

It is very important to carefully analyze such trapped modes and design the cavity structure to propagate them. It is common practice to use HOM couplers to couple out harmful modes. However, we proposed an optimized cavity design using ferrite absorbers demonstrating the possibility to operating at currents $>$ 1 Amp in numerical simulations [1]. This paper describes an ongoing study of HOMs and will focus on time-domain simulations to calculate beam impedances.

TIME DOMAIN METHOD

Boundary conditions play an important role in accurately simulating propagation of HOMs in a cavity. In frequency domain, one is limited to closed boundary conditions to solve for the modes in a resonator. However, Mafia's time domain module allows one to specify an infinitely long waveguide. The calculations are performed using only the half structure by taking advantage of the symmetry of the cavity, the fundamental coupler and the ferrite as shown in Fig. 1. Addition of HOM couplers with entail the use of full 3D structure increasing the computation time which will not be discussed in this paper.

Two ports at either end of the cavity are defined such that all waves above the cut-off frequency of the waveguide propagate without any reflection. To accomplish such boundaries, a 2D cross section of the ports in interest are considered for which eigenmodes are computed upto a desired frequency which in our case is 2 GHz. These waveguide modes are loaded into the 3D computation domain which then allows one to define the boundaries as perfectly transmitting (waveguide) ports [2].

A Gaussian bunch of the desired length is launched into the cavity structure with monitors to record the wakefields generated in the structure. The bunch can be launched in the center of the beam tube to excite azimuthally symmetric modes (monopole), or launched off-center with appropriate

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boundary conditions to excite transverse modes (dipole). Mafia computes the longitudinal wake $W_{||}(x,y,s)$ as a function of bunch coordinate (s = ct) which is given by

$$W_{||}(x,y,s) = \frac{1}{q}\int_{-\infty}^{\infty} E_z(x,y,(s+z)/c)\,dz \qquad (1)$$

A Fourier transform of the longitudinal wake normalized by the bunch spectrum yields the broadband impedance given by

$$Z_{||} = \frac{1}{cI(\omega)}\int_{-\infty}^{\infty} W_{||}(x,y,s)e^{-i\frac{\omega}{c}s}ds \qquad (2)$$

where

$$I(\omega) = qe^{-\frac{1}{2}\frac{(\sigma_s\omega)^2}{c^2}} \qquad (3)$$

In the case where the bunch is launched off-center, the transverse wake is related to the longitudinal wake given by Panofsky-Wenzel theorem. Therefore the impedance for transverse modes can be derived which is given by [3]

$$Z_{\perp} = \frac{Z_{||}(x,y,s)}{kr^2} \qquad (4)$$

where $k = \frac{w}{c}$ and r is the bunch offset from the center of the beam tube.

SIMULATIONS

The broadband impedance spectrum of the both short-range and lone-range wakefield is quite useful in understanding the behavior of HOMs.

Broadband Impedance

Since the goal of this simulation is to investigate high Q dipole like modes, long-range wake computations upto to 300m is computed to observe any high Q modes slowly decaying long after the passage of the bunch. Sometimes, longer computation is required if the finer frequency resolution is required. If a mode is still ringing, the spectrum of that mode is broadened and true impedance of this mode can be determined with the aid of two different time domain runs [4]. Fig. 2 shows longitudinal wake for the bunch traveling on-axis. The impedance spectrum is dominated by the fundamental mode and rest of the spectrum contains modes with significantly smaller impedance.

A similar calculation for transverse deflecting modes can be performed by displacing the bunch by an offset (3 cm). From Fig. 3 we can see that wake function is exponentially decaying except for a few modes that show beating effect. This can be clearly seen in the impedance spectrum as two bands near 0.9 GHz and 1.8 GHz. The Q factors of these modes are estimated in Table 1 and compared to that of frequency domain simulations. The Q factors estimated in time domain in the region between 0.8-1.0 GHz are smaller due to truncation of wake computation before all the stored energy in the cavity has decayed. This causes artificial broadening of the peaks and hence the lower Q

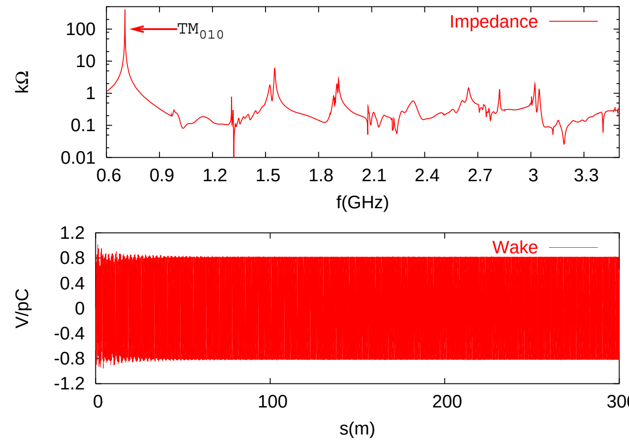

Figure 2: Impedance spectrum and wake function for azimuthally symmetric modes

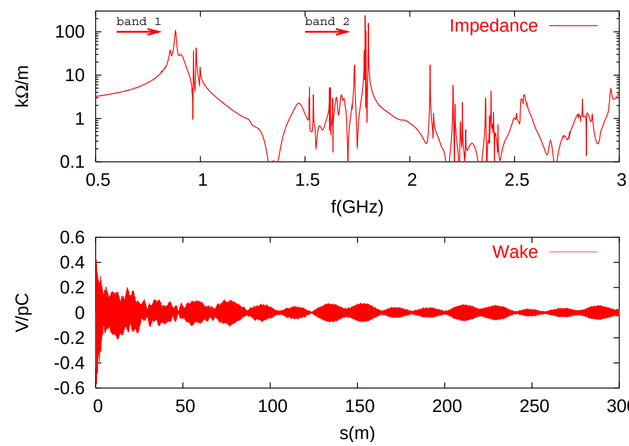

Figure 3: Impedance spectrum and wake function for transverse modes

values. However, the complex frequency domain is known to yield Q factors which are higher than in real conditions due to closed boundary conditions [5]. Also, ferrites can only be simulated as low loss materials and we expect much better damping which will be tested in a copper prototype of the niobium cavity in the near future. The band of modes between 1.7-1.8 GHz shows impedances much

Table 1: Q comparison between time-domain and freq-domain for dipole modes. NC - Not Estimated

Freq(GHz)	$Q_{freq-domain}$	$Q_{time-domain}$
0.862	311	244
0.882	1250	< 110
0.968	1606	< 483
0.979	2304	< 244
1.787	NE	1276
1.791	NE	1790
1.802	NE	1287

larger than what we estimate from a similar ABCI calculationin 2D [6]. The field profiles of these modes are being analyzed carefully to resolve any discrepancies.

Loss Factor

Another major concern in cavity design is power dissipated in the HOMs which is given by

$$P_{HOM} = f_{beam} k_{loss} q^2 \qquad (5)$$

where f_{beam} is the revolution frequency, q the bunch charge, and k_{loss} is the loss factor which is given by

$$k_{loss} = \frac{1}{2\pi} \int_0^\infty Z_r(\omega) d\omega \qquad (6)$$

The loss factor was calculated using ABCI [6], using a single bunch with a rms length of 1 cm and was found to 1.2 V/pC [1] which is about six times smaller than the TESLA cavity.

Multibunch Instabilities

Multibunch instabilities due to poor damping of transverse HOMs are a major limiting factor for superconducting cavities. Some of the key factors contributing strongly to these instabilities are

- High Q dipole modes.
- Feedback loop between the beam and the cavity.
- Combination of high current and high bunch charge.

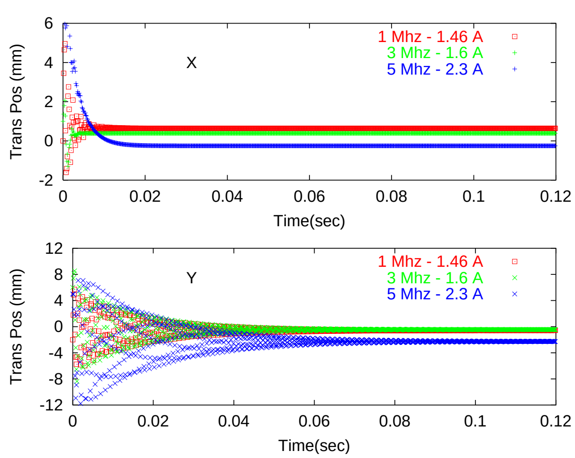

Figure 4: Beam breakup simulation using TDBBU.

Design modifications to adequately damp dipole like modes are discussed elsewhere [1]. Numerical simulations using TDBBU [7] are shown in Fig. 4 for a four-cavity 54 MeV electron cooler configuration with unit transport matrix. HOM parameters from frequency domain calculations are used for this calculation. The frequencies of the HOMs for each cavity were given a Gaussian distribution to account for manufacturing errors. Three different distributions yields similar results with very high currents between 1.4-2.4 Amps which is comfortably higher than the requirement for electron cooling.

SUPERSTRUCTURE

A possible 2x2 superstructure using the current five-cell design as shown in Fig. 5 is being investigated. Superstructure may not be required for electron cooling, but future projects such as eRHIC (10 GeV linac) will benefit greatly with its numerous attractive features [8]. Copper model testing will be conducted for the five-cell as well as a superstructure to investigate the advantages and limitations.

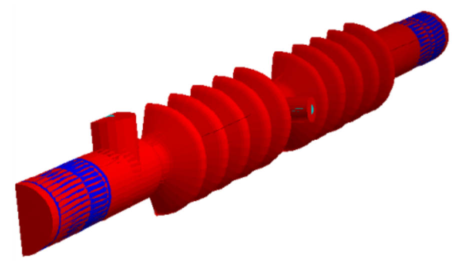

Figure 5: 2x2 superstructure graphic using five-cell design.

SUMMARY

A superconducting linac consisting of four five-cell cavities is under development for very-high current energy-recovery operation at 703.75 MHz. Time domain simulations were performed to calculate impedances and were compared to frequency domain calculations and discrepancies are being investigated. Particular HOMs of interest were used in TDBBU in a small 54 MeV energy recovery linac to simulate multibunch instability thresholds. The ERL threshold current for beam breakup was calculated to be between 1.4-2.4 Amps.

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