Some Aspects of 704 MHz Superconducting RF Cavities

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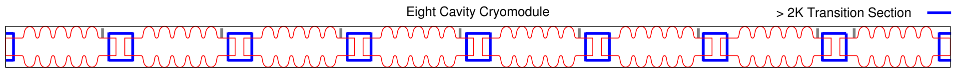
Introduction

Recently superconducting RF (SRF) technology in the 704 MHz frequency range is increasingly popular for high average current and high intensity electron and proton linacs. The need for high duty factor (in some cases CW beams) make it favorable for linac technology with sub-giga Hertz frequencies both for overall accelerating efficiency and handling of higher order modes (HOM). Detailed studies from CW electron linacs and high intensity proton linacs have converged to the specific 700 MHz frequency [1, 2, 3]. Additionally, the number of cells per structure which is a typically a trade off between accelerating gradient and HOM performance has realized into a generic five-cell structure. Three future machines planned to work in the 700 MHz frequency range are listed in Table below.

Parameter	eRHIC	SPL	ESS-S
Inj energy [MeV]	5	180	200
Max energy [MeV]	3-10	4-5	2.5
Beam current [mA]	50	20-40	
Pulse Length [ms]	-	0.4-1.9	1.5-2.0
Repetition rate [Hz]	CW	2-50	20
Peak Power [MW]	0.05	1.0	1.0
Cav/Cryomodule	6	8	8
Duty Factor	CW	4%	4%
Energy recovery eff	> 99.95 %	-	-

Each accelerating structure is expected to comprise of several five-cell SRF cavities (Niobium) in a single cryomodule operating at approximately 1.8 K as shown in figure below. A continuous superconducting channel using super fluid helium is desired to reduce cryogenic complexity and avoid external noise sources onto the accelerating structures. The only existing SRF cavity at this frequency is cavity designed for the electron cooling project at RHIC [1]. The design and development of this SRF module has served as a valuable test bed and a successful demonstration of the technology. The first design although adequate for single high current module, presented a few shortcomings which required modifications for long linacs.



1 Geometrical Design

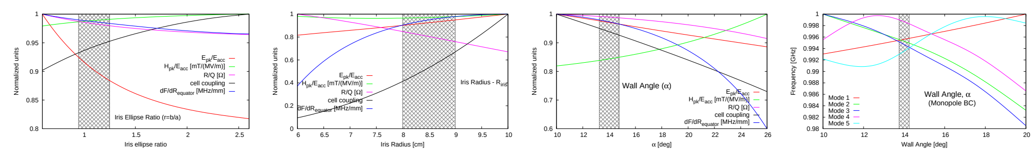
The original design was proposed as a solution to provide a strongly damped multi-cell structure for CW energy recovery in the high current regime [1, 2]. The approach taken to reach the original design involved

- Optimization of fundamental mode RF parameters (see figure below)
- Adopt a large aperture to reduce the overall power lost into the higher order modes (HOMs) and subsequently damp them strongly
- Mechanically stiff to provide a stable design to combat Lorentz forces without cavity stiffeners.

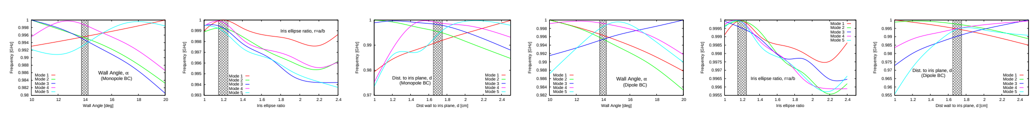
However, further analysis and fabrication of the five-cell cavity, it was found that the cavity stiffness was close to the yield strength of Niobium. Therefore, it was deemed necessary to modify the cavity shape to reduce the stiffness while keeping the HOM characteristics similar.

1.1 Fundamental Mode & HOMs

The cavity peak fields, R/Q and cell-to-cell coupling were optimized for the mid-cell. As a result of the scan, the stiffness was approximately reduced by a factor of 2 and the peak surface magnetic field by 18% or more.



The HOM frequencies and their respective cut-off frequencies were scanned simultaneously as a function of the geometrical parameters. Figure below shows the frequency dependence of various HOMs (both monopole and dipole) as a function of different geometrical parameters. In general, the optimum values for the fundamental mode overlap well with the desired values from the HOM frequency scans.



End-cell tuning can result in field enhancement in the end cell which may ultimately prove to be the limiting factor the maximum cavity gradient. Only the cavity wall angle and iris region were optimized for minimum field enhancement for the end cell.

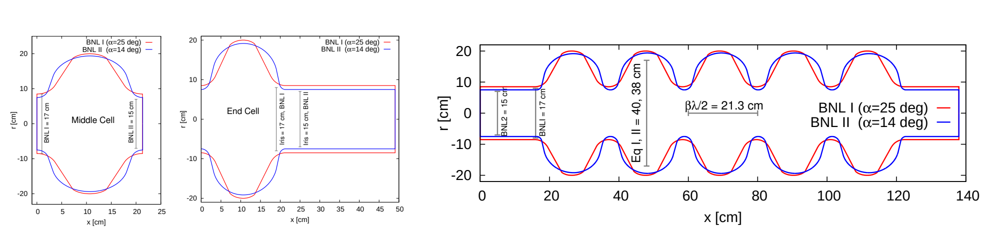
2 Final Design

Based on these scans, a set of parameters are proposed for a ”semi-optimum” design for the improved BNL II design listed in table below.

Parameter	BNL I {Mid, End}	BNL II {Mid, End}
Frequency [MHz]	703.75	703.75
Iris Radius, R_{iris} [cm]	8.5	8.5
Wall Angle, α [deg]	25	{14,12}
Equatorial Ellipse, $R = \frac{B}{A}$	1.0	1.0
Iris Ellipse, $r = \frac{b}{a}$	1.1	1.2
Cav wall-iris plane, d [cm]	2.5	{1.7,1.2}
$\frac{1}{2}$ Length, $L = \frac{\lambda\beta}{4} [cm]$	10.65	10.65
Eq. Radius [cm]	20.9	{19.7,19.4}
Cavity Beta, $\beta = \frac{v}{c}$	1.0	1.0

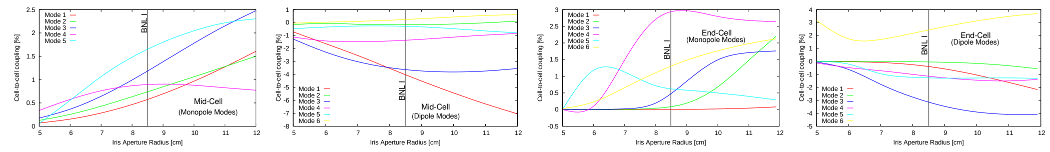
Parameter	BNL I	BNL II
Frequency [MHz]	703.75	704
Number of cells	5	5
E_p/E_a	1.97	2.16
H_p/E_a [mT/MV/m]	5.78	4.45
R/Q [Ω]	404	497
dF/dR [MHz/mm]	4.18	3.83
Cell-cell coupling	3%	2.99%

The corresponding middle and end cells and the five-cell cavity are shown in figure below for the two designs.

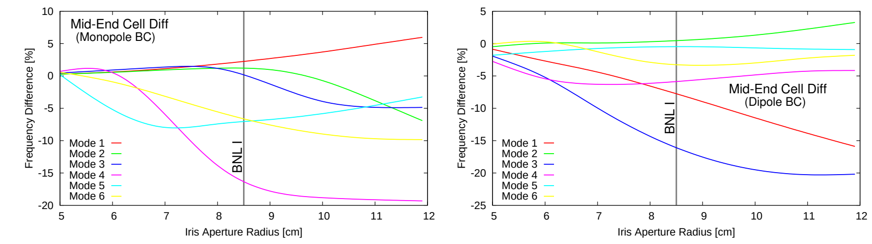


3 HOM Considerations

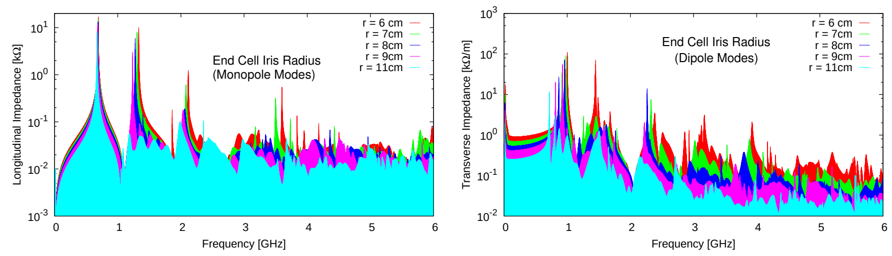
There are also important criteria for HOM damping in SRF structures which will confine the aperture to an optimum values. Cell-to-cell coupling and difference in the mid-cell and the end-cell as suggested in Ref. [1, 2, 5] are evaluated. The iris aperture of the mid and the end-cells are varied with the cavity parameters fixed to previous optimized values. Figure below shows the cell-to-cell coupling for first five monopole and dipole modes of the cavity mid-cell and end-cell as a function of aperture. The aperture radius of 8.5 cm is reasonably suited for both monopole and dipole modes to have sufficient cell-to-cell coupling without compromising the fundamental performance. It is also evident from this scan that a decrease of the aperture to 7.5 cm has relatively small effect on the HOMs while minimizing the relative frequency shift of fundamental mode to mechanical imperfections.



The addition of the end group with beam pipes require the tuning of the mainly by the end-cell to rematch to the resonant frequency. Due to the retuning of the fundamental mode, it is possible that the mid-cell and end-cell resonate differently for different HOM pass-bands [1, 2]. If the frequency difference becomes vastly different, it becomes difficult to avoid trapped modes in the center of the cavity without easy means to damp them. The reduction of the frequency difference in the BNL II design is studied only as a function of the iris aperture as the other parameters are already fixed from previous scans. From figure below, the reduction of the frequency difference between mid-cell and end-cell calls for a reduction in the aperture. An aperture radius of approximately 7.5 cm can reduce the frequency difference for most modes with some marginal compromise on the cell-to-cell coupling.



Time domain simulations were also carried to estimate the longitudinal and transverse impedances as a function of aperture to understand the coupling impedance characteristics. Figure below shows impedance spectrum of both monopole and dipole modes as a function of iris aperture. The impedance is calculated from a wake of 100 m corresponding to a medium range wake. It should be noted that the exact impedance for modes below the cut-off of the beam pipe may not be accurate due to artificial wake truncation. However, the trend of the impedance spectra is clearly visible.



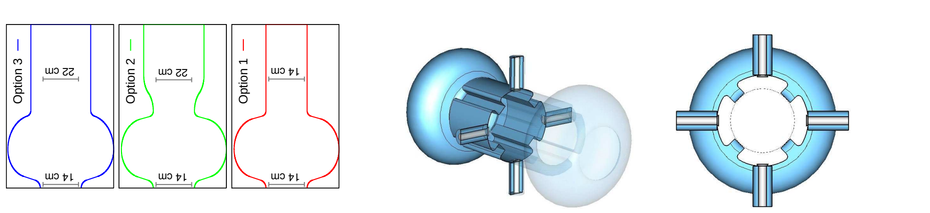
Although there is no single optimum aperture, a minimum aperture suited for HOM damping is preferred to maintain the best acceleration efficiency. Based on the frequency and time domain results, the minimum aperture can be confined to 7.5cm which is used as a baseline for further calculation in the multi-cell models. An alternative 8.5 cm iris is also used for comparison when required.

4 Transition Section

It is desirable to minimize the length of the transition section between subsequent cavities. It is envisioned that the typical 704 MHz cryomodule will consist of 6-8 cavities and the cyomodules will stacked in a long linac configuration at 2K with minimal thermal transitions. Therefore, solutions are considered to design a short transition section ($\leq$0.5-0.6 m) while maintaining two important criteria

- Maintain strong damping as in BNL I and use the beam pipe to propagate the HOMs to the dedicated couplers located within the transition section.
- Minimize cross talk for the operating mode between the cavities.

Therefore, three different options are being considered for the most effective interconnection as shown as in figure below. The exact diameter of the transition from end-cell to the beam pipe will be the outcome of future studies to improve the propagation of HOMs into the transition section. Based on the final aperture of the beam pipe, the transition step will be optimized to minimize cross talk. The step will additionally provide an enhancement of the HOM fields so increase the coupling to the HOM probes located across the step.



References

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