INPUT COUPLING AND HIGHER-ORDER MODE ANALYSIS OF SUPERCONDUCTING AXISYMMETRIC CAVITIES FOR THE RARE ISOTOPE ACCELERATOR*

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Abstract

The driver linac of the Rare Isotope Accelerator (RIA) project plans to use 6-cell, axisymmetric cavities with geometric β (=v/c) values of 0.47, 0.61 and 0.81. Since RIA is a relatively low current continuous wave (cw) linac, several simplifications are possible compared to the Spallation Neutron Source (SNS) linac. Detailed analysis of the β=0.47 cavity is presented here. The design input coupling of $2x10^7$ is accomplished with the smaller beam pipe used for the cavity flanges. The input power coupler and pick-up probe adequately damp longitudinal and transverse higher-order modes (HOMs). Therefore, additional HOM couplers and associated loads are not required. Also, the cavity end sections are greatly simplified, and the number of half-cell dies is reduced. Similar analysis is required for the other superconducting cavities planned for RIA.

1 INTRODUCTION

The Rare Isotope Accelerator (RIA) project proposes to use a superconducting linac for heavy-ion acceleration to ≥400 MeV/nucleon. The last segment of this linac will use 805 MHz, axisymmetric, 6-cell cavities with geometric β (=v/c) values of 0.47, 0.61 and 0.81 to accelerate the beam from ~85 MeV/nucleon to ≥400 MeV/nucleon. The β=0.47 cavity is being developed specifically for RIA [1, 2]. The higher β cavities are being developed for the Spallation Neutron Source (SNS) project [3], but will also be used in the RIA linac. The coupling will be different for the SNS linac operating at a lower duty factor (~6%) and higher current (52 mA) than the RIA linac with a cw beam of lower current (0.38 mA).

The bunch spacing for RIA is determined by the RFQ frequency, and two alternative frequencies of 57.5 and 80.5 MHz are proposed. The accelerating mode's external Q required for efficiently coupling power to the RIA beam is determined, taking into account microphonics and beam loading. In addition, the external Q of pass-band and higher order modes (HOMs) required for longitudinal and transverse stability are determined. Finally, damping of the HOMs with the fundamental power coupler and pickup coupler instead of separate HOM couplers is explored.

Detailed input coupling and HOM analysis of the β=0.47 cavity is presented. Similar results and conclusions apply for the other axisymmetric cavities.

2 INPUT COUPLING (Q_{EXT})

The following analysis is for the axisymmetric 6-cell cavity with a geometric β=0.47 using the TM010,π mode at 805 MHz for acceleration. The input coupling, Qext, is determined primarily by three factors; beam loading, microphonics and HOM stability. Beam loading in RIA would require a Qext~$7x10^7$ for optimum coupling, and corresponds to an rf power requirement of ~1.6 kW for beam on crest. This Qext requires microphonics or vibration levels that are lower than has been demonstrated in existing superconducting linacs. Assuming a microphonics budget of ±20 Hz, which is comparable to the CEBAF upgrade specifications, gives a Qext ~$2x10^7$ and 5 kW of rf power. This higher Qext allows a smaller diameter beam pipe and coupling port such that both ends of the cavity can be symmetric and

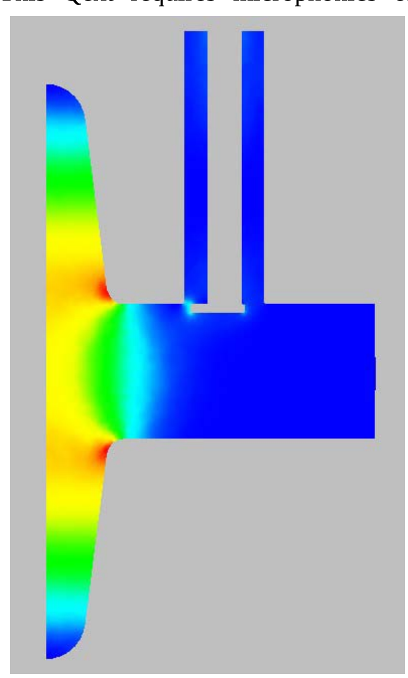

Fig. 1 Cross section of end cell and input power coupler.

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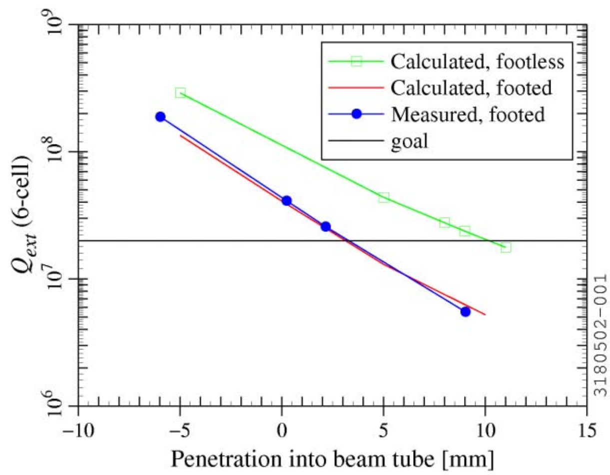

Fig. 2 Qext versus antenna penetration (calculated [5] and measured) for 6-cell TM010,π.

only require two types of half-cells.

The Qext was calculated using 3D electromagnetic simulations [4, 5, 6]. A 50 Ω coaxial transmission line was capacitively coupled to the cavity with an offset disc as shown in Figure 1. Figure 2 shows the calculated values of the accelerating modes' Qext versus antenna penetration past the beam pipe diameter for the offset disc and rounded center conductor.

Measured values on a room temperature copper model are also shown and give good agreement. The design value of $2\text{x}10^7$ occurs with the disc penetrating 3.0 mm or the round stub penetrating 10.1 mm into the beam pipe. Although both antenna remain outside any possible beam halo, the disc is conservatively chosen. The accelerating gradient of 8 MV/m has peak surface fields in the cavity of 27.5 MV/m and much lower peak fields in the coupler of 1.0 MV/m.

3 HOM ANALYSIS

Higher order mode analysis of the 6-cell cavity requires calculation of the HOMs resonant frequency, effective shunt impedance, R/Q, and loaded Q, QL [7, 8, 9]. The effective shunt impedance is defined as:

$$\frac{R}{Q} = \frac{\left| \int E_z(r,z)\exp(i\omega z/v)dz \right|^2}{\omega U}$$

where the monopole, m=0, modes are calculated on axis and the m>0 (dipole, quadrupole, etc.) modes at r=5 mm and a constant angle ϕ such that E_z is maximum. Simulations of transverse beam dynamics show <5 mm maximum and 1 mm rms displacement off-axis of the beam centroid through the axisymmetric cavities [10]. Figure 3 shows the maximum R/Q of each higher order mode over the relevant range of velocities for RIA. The highest R/Q is the TM010,π accelerating mode at 805 MHz. The Fourier beam components for 80.5 MHz bunch spacing are shown in Figure 3 as dotted lines.

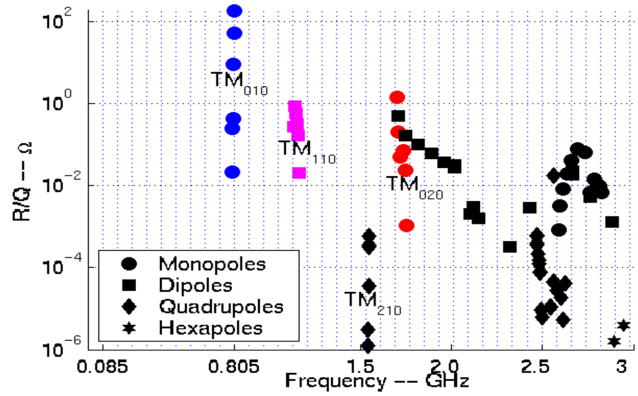

Fig. 3 Maximum R/Q of HOMs (β=0.40-0.52, m=0 monopoles on axis, m>0 at r=5 mm).

Since RIA is a cw linac there is no macrobunch structure or corresponding Fourier beam components to interact with the TM010 passband modes. No modes above 3 GHz are considered since this is above the beam pipe cutoff frequencies of 2.28 GHz for TE11 and 2.97 GHz for the TM01 waveguide modes. No trapped modes were observed as was true for SNS and APT [7, 11].

The HOMs can be damped with the input power coupler, the pickup coupler and if necessary additional HOM couplers. In addition, the cavity could be polarized so the input power coupler damps all modes, including the orthogonal/degenerate transverse modes [12]. The input coupler is rotated 115 degrees relative to the input coupler. Table 1 shows the calculated single-cell Qext values for the input coupler. The pickup coupler will have a Qext of $5\text{x}10^9$ for the accelerating mode, and its coupling to HOMs is assumed to scale the same as the input coupler. The multi-cell Qext values are calculated from the single cell value and the ratio of stored energy in the individual cells.

Table 1: Input power coupler Qext for single cell HOMs with penetration into beam tube of 5mm.

f	Qext	Type	*f*	Qext	Type
0.805[a]	$2.17\text{x}10^6$	TM010	**2.041**	$1.11\text{x}10^4$	TM120
1.154[b]	$9.58\text{x}10^5$	TM110	**2.270**	$6.40\text{x}10^{11}$	TM410
1.547	$1.58\text{x}10^8$	TM210	**2.476**	$3.10\text{x}10^5$	TM220
1.725[c]	$3.41\text{x}10^5$	TM020	**2.591**	$2.43\text{x}10^4$	TE211
1.897	$6.30\text{x}10^3$	TE111	**2.627**	$5.61\text{x}10^3$	TM030
1.939	$1.93\text{x}10^4$	TM310	**2.720**	$3.90\text{x}10^2$	TM121

Qext results confirmed experimentally:
(a) $2.82\text{x}10^6$ *(b)* $1.53\text{x}10^6$ *(c)* $4.42\text{x}10^5$

For a beam on-axis, only the TM monopoles (m=0) can couple to the beam and drive longitudinal instabilities. If the beam is off axis, then m>0 modes (dipoles, quadrupoles, etc.) can couple power to the modes and drive longitudinal or transverse instabilities. During start-up consecutive beam bunches induce a voltage in the cavity that adds to the existing field. While the fields are growing individual beam bunches see different kicks, but once equilibrium is reached all of the bunches receive the same longitudinal or transverse kick.

The steady state voltages are calculated here to determine an upper limit on voltages and acceptable damping [13]. For RIA, significant voltages are generated only if a Fourier beam component is within a bandwidth of an HOM.

Beam dynamics simulations show that an HOM induced energy spread or transverse momentum kick of $\pm 10^{-4}$ per cavity is acceptable [10]. These values correspond to a longitudinal kick of ~25 kV and transverse kick of ~50 kV per cavity. For a single cavity, significantly higher values are acceptable. In addition, HOM power dissipated in the cavity cryogenics should be limited to about 1 W per cavity.

Due to fabrication techniques the HOM frequencies will differ from the calculated values. Using the same uncertainty as SNS of ±0.8% of the calculated value, the cavity frequency is shifted toward the closest Fourier component and assumed to be on resonance if the Fourier component is within the uncertainty range. Table 2 shows the most problematic modes. All modes that couple to the input power coupler are adequately damped. This includes all monopole modes, and one component of the transverse modes. The orthogonal/degenerate component of the transverse modes that couple to the pickup are the only potential problems for either 57.5 or 80.5 MHz bunch spacing. As shown in Table 2, only a few modes have the potential to generate instabilities, and these require the beam to be off axis (at an azimuthal position that couples only to the pickup), and the mode on resonance. Due to fabrication tolerances the frequency spread used by SNS is 0.02% (standard deviation). In this case the probability that one of the roughly 60 cavities hits resonance is less than 10^{-3}. In the unlikely case that all three criteria are met, monitoring the pickup probe will show the problem cavity and it can be retuned to take the mode off resonance, or the beam can be steered on axis. Thus the RIA β=0.47 6-cell cavities will not require additional HOM dampers.

Table 2: Steady state HOM longitudinal and transverse voltages (a) 57.5 MHz bunching (b) 80.5 MHz bunching.

(a) *f* (GHz)	**Qext**	**Vb (Volts)**	**Pc (Watts)**	**Vt (Volts)**
1.143$^{\perp}$	1.52×10^{9}	3.34×10^{5}	1.94×10^{1}	2.78×10^{6}
1.143	4.32×10^{6}	9.50×10^{2}	1.56×10^{-4}	7.89×10^{3}
1.151$^{\perp}$	1.16×10^{9}	1.44×10^{5}	6.35×10^{0}	1.19×10^{6}
1.158$^{\perp}$	1.37×10^{9}	8.62×10^{4}	4.49×10^{0}	7.15×10^{5}
1.888$^{\perp}$	3.91×10^{6}	5.24×10^{2}	4.33×10^{-4}	2.64×10^{3}
(b) *f* (GHz)	**Qext**	**Vb (Volts)**	**Pc (Watts)**	**Vt (Volts)**
1.132$^{\perp}$	1.00×10^{10}	1.06×10^{6}	4.02×10^{2}	8.96×10^{6}
1.132	3.07×10^{7}	3.25×10^{3}	5.30×10^{-3}	2.75×10^{4}
1.701^{M}	3.41×10^{5}	3.18×10^{3}	6.82×10^{-4}	N/A
2.014$^{\perp}$	2.05×10^{7}	2.14×10^{2}	1.66×10^{-4}	1.02×10^{3}

Vb = Magnitude of beam-induced longitudinal voltage,
Pc = Cryogenic power loss, Vt = Transverse voltage,
⊥ = Orthogonal component, M = Monopole

4 CONCLUSIONS

The input coupler for the 6-cell, β=0.47 RIA cavity has been designed with a Qext~2×10^{7} using a smaller beam pipe and coupling port than SNS which allows equal end cell and beam pipe diameters on both ends of the cavity. HOM analysis shows the required damping is met using the input power coupler and the pickup coupler. Only two modes have a small possibility to degrade the beam, but these can be diagnosed and the linac retuned. Therefore, this RIA cavity will not require HOM dampers. Similar analyses for SNS cavities that will be used for RIA are underway. Since the beam is more rigid at higher energy it is anticipated that their HOM dampers will not be needed for RIA.

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