GRADIENT OPTIMIZATION FOR SC CW ACCELERATORS*

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Abstract

The proposed rare isotope accelerator (RIA) design consists of a normally conducting radio frequency quadruple (RFQ) section, a superconducting (SC) drift tube cavity section, a SC elliptical multi-cell cavity section and two charge strippers with associated charge state selection and beam matching optics. The SC elliptical section uses two or three multi-cell beta cavity types installed into cryomodules to span the energy region of about 84.5 MeV/nucleon up to 400 MeV/nucleon. This paper focuses on the gradient optimization of these SC elliptical cavities that provide a significant portion of the total acceleration to the beam. The choice of gradient coupled with the cavity quality factor has a strong affect on the overall cost of the accelerator. The paper describes the optimization of the capital and operating cost associated with the RIA elliptical cavity cryomodules.

1. INTRODUCTION

Last May [1] a workshop at Argonne National Laboratory (ANL) reviewed the design of a superconducting (SC) ion linac driver for a proposed rare isotope accelerator (RIA). The driver for RIA was originally outlined in 1999, updated at an earlier workshop in 2000 and formally costed for the Harrison Review on behalf of National Science Foundation (NSF) in 2001 [2,3]. Requirements for RIA are to produce and accelerate ions over the full mass range from protons to uranium up to 400 MeV/u. The continuous wave (CW) beams produced are to have at least 100 kW up to a maximum of 400 kW of beam power. The machine is to be able to irradiate two targets simultaneously and produce a beam spot size of less than 1 mm wide on fragmentation targets. The elliptical portion of the super-conducting linac (SCL), discussed here, contains eighteen (18) beta (β) 0.47 cryomodules, twenty-three (23) β 0.61 cryomodules and seven (7) β 0.81 cryomodules for the Michigan State University (MSU) design and fifteen (15) β 0.47 cryomodules, twenty (20) β 0.61 cryomodules and seven (7) β 0.81 cryomodules for the Argonne National Laboratory (ANL) design [4, 5]. ANL is also investigating another low frequency option. The cavities are currently designed for a peak gradient of 27.5 MV/m with a cavity quality factor (Q_0) of 5.0 10^9 at 2.1 K. Raising the peak gradient while maintaining the cavity quality factor, Q_0 allows one to reach the desired machine energy with fewer modules and a concomitant reduction in overall length, but requires additional RF power and refrigeration capacity to counter the increased cavity power dissipation. For pulsed accelerator like SNS and TESLA with low duty factors, one can afford to push the peak gradient (E_{peak}) much higher. The SNS β 0.81 cavities are being pushed to 35 MV/m while TESLA is working at 45 MV/m. The cryomodule (CM) is based on the CEBAF CM with improvements borrowed from LHC, TESLA, SNS and the JLab 12 GeV upgrade and uses the frequency scaled KEK fundamental power coupler (FPC). Figure 1 is the elevation view of the β 0.81 CM, while Figure 2 is the flow schematic.

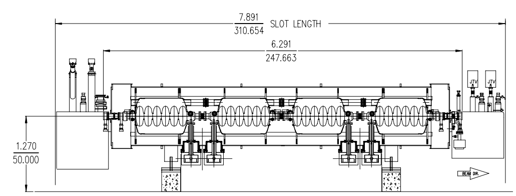

Figure 1. High Beta Cryomodule

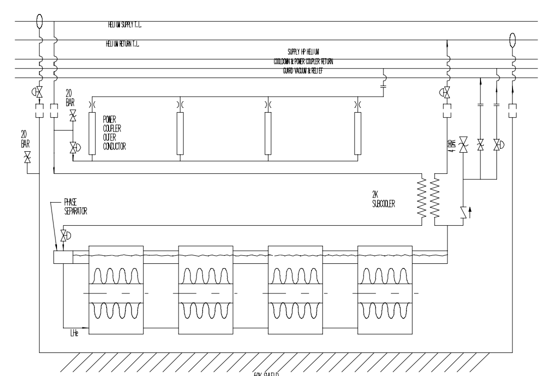

Figure 2. Flow Schematic

The refrigerator produces a 3 bar, 4.5 K stream, which feeds two Joule-Thompson (JT) valves in parallel. The first supplies a small sub-cooler in the CM and then cools the cavity. The second feeds the power coupler outer conductor. The CM shield is cooled by a 4 bar, 35 K stream, which first cools the supply transfer line (TL) shield, then the CM shield, and finally the return TL shield before returning to the refrigerator at 52 K. The bayonet design permits replacement of a CM in less than a day if needed without warming up the entire linac. In the ten years since the initial CEBAF cooldown, the linacs have never been warmed and only four CM have been replaced during scheduled accelerator shutdowns.

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The relevant parameters for low, medium and high beta cavity cryomodules are given in Table 1.

Table 1. CM Baseline Parameters/ 4 cavities per CM

Beta	0.47	0.61	0.81
Slot length	6.34 m	7.00 m	7.891 m
CM length	4.74 m	5.4 m	6.291 m
Ea Gradient	8 MV/m	10.1 MV/m	12.3 MV/m
Q_0	5.0 10^9	5.0 10^9	5.0 10^9
CM cost	\$1300 k	\$1350 k	\$1400 k

The costs indicated are in 2003 dollars and assume scaling from SNS experience. Note that for the 27.5 MV/m peak gradient, the current design for β 0.47, 0.61 and 0.81 is respectively Eacc 8, 10.1 and 12.3 MV/m. As E peak increases, Eacc scales. For example, at an E peak of 32.5 MV/m Eacc is respectively 9.5, 12 and 14 MV/m. For purposes of this optimization, the average gradient of 10.1 MV/m is equivalent to an E_{peak} of 27.5 MV/m i.e we will use the β 0.61 cavity, the most common cavity as a baseline.

2. HEAT LOADS

There are three sources of heat that govern the cryomodule primary circuit power dissipation. The first is the static heat load, associated with the bore tube, power couplers, tuners, bayonets, etc. The cavity dynamic heat load is made up of two components – the temperature independent resistance caused by localized resistive areas where defects, impurities or surface dirt affect the SC properties; and the temperature dependent surface resistance or the Bardeen, Cooper, and Schrieffer (BCS) theory, which is due to unbound Cooper Pairs of electrons. In the earlier work [6] discussing cavity optimization, the following approximations were used for total power in W/m:

P total = P static + P res + P bcs (W/m)

$$P_{total} = 8 / (f/500)^{0.5} + E^2 / 380\,(f/500)^{0.9}\ Q_{res} + E^2\,(f/500)^{1.1}\ 0.0000223\ Exp^{-17.67/T} / 380\ 280\ T \ (W/m)$$

Where f is frequency in MHz, E is accelerating gradient in V/m, T is absolute temperature in Kelvin and Qres is the temperature independent resistive component of cavity losses. [Q=g/R, g = geometry factor ~ 200 Ohm]

The change in refrigerator efficiency as a function of temperature is factored into the overall heat load, as shown on figure 3. At 4.4 K one can achieve 30 % of Carnot while below 1.8 K the efficiency is less than half of this value. As reported previously [7], there is a significant shift in Q_0 the quality factor across the Lambda line at higher gradients as a result of the slope in Q_0 vs. Eacc above Lambda. This change is attributable to the heat transfer associated with the superfluid. To account for this shift Q_0 in the optimization, the Qres is reduced by a factor of three once the temperature exceeds Lambda to match experimental results shown in figure 4.

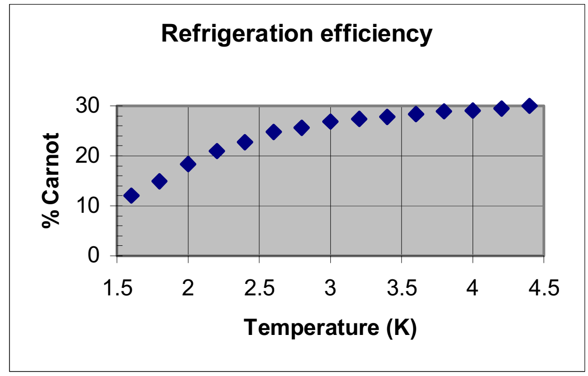

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Figure 3 Refrigerator Efficiency

Linac capital cost consists primarily of the tunnel, cryomodules, RF, and cryogenics, while the operating cost consists primarily of the RF and cryogenics. The tunnel and cryomodule cost vary as 1/G (Gradient). The total RF power increases proportional to G and therefore its operating cost since this is a low current accelerator, but the number of RF systems decreases as 1/G. Therefore we will model the RF capital cost as a constant. The dynamic refrigeration wattage varies proportional to G; for CW machine above a gradient of 5 MV/m this is the predominant load. The capital and operating cost for the refrigerator vary to the 0.7 and 0.85 power of total wattage respectively.

3. DISCUSSION

A typical Q_0 versus accelerating gradient for a β 0.47 RIA cavity recently measured at JLab is shown in figure 4. At 2.1 K this curve drops from 15 to about 4 E 09. As the temperature increases over lambda the Q_0 drops by a factor of two to three. We know the optimal temperature for cavities operating at 805 MHz is 2.1 K. Figure 5 shows this temperature optimization for a cavity with a Q_0 5.0 10^9 at 2.1 K, the base line design.

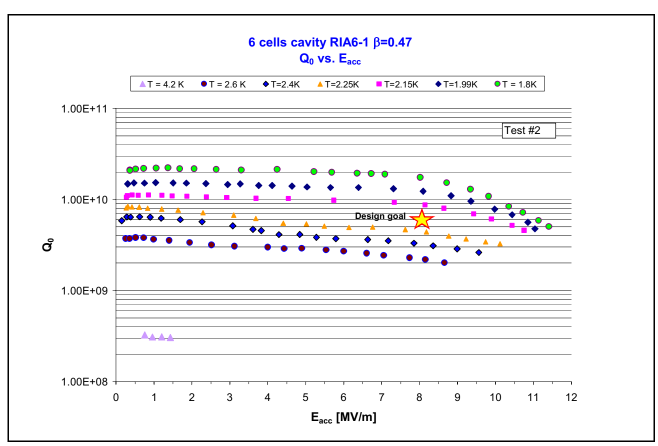

Figure 4. β 0.47 Gradients vs. Q_0 Performance

The assumed baseline costs, scaled from CEBAF to the RIA accelerator [8] for the refrigerator is $40 million, RF is $21.1 million , cryomodule is $ 70.9 M and tunnel is $ 15 M. Operating costs for the refrigerator over a ten year period are 49 million and RF is 8.4 million. As the temperature increases the refrigerator efficiency increases from 12 to 30 %; this together with the 1/T effect generates another minimum above Lambda. It is believed that above Lambda and above 15 MV/m peak there is severe turbulence and therefore the RF system will require large amounts of power to compensate for microphonics. Suffice to say that cavities at higher frequencies, greater than 800 MHz, the optimum is below lambda.

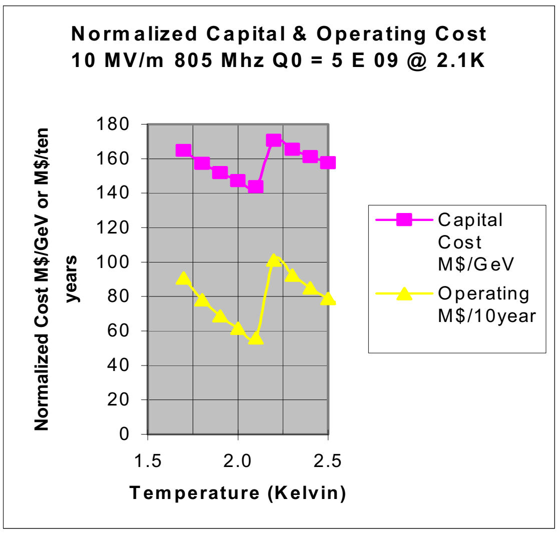

Figure 5. Temperature optimization at baseline

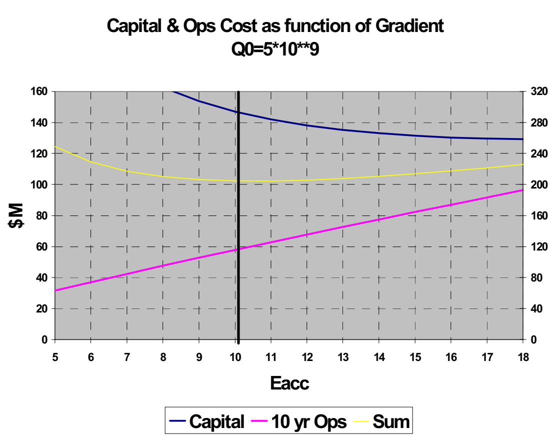

Figure 6 Optimization for Q_0 5 E 09 @ 2.1K

The optimizations show a minimum in capital cost for a given gradient at a particular Q_0. This minimum shifts to a higher gradient as the Q_0 improves. With a Q_0 of 5 E 09 the optimum is 10 MV/m, the design for the RIA project. As Q_0 increases to 10 E 09, the optimum shifts to a gradient of 14 MV/m. The higher value would represent an E peak of 37.5 MV/m, a major challenge. The overall cost of the project, for both capital and operating, decreases as the Q_0 is improved. Referring to figures 6 and 7, as the Q_0 increases from 5 to 10 E 09 at 10 MV/m, equivalent to the 27.5 MV/m peak, the capital costs decreases from 147 M$ to 132 M$ and the operating cost decreases from 58 to 36 M$ during the 10 year operating period. This is a net saving of 37 M$.

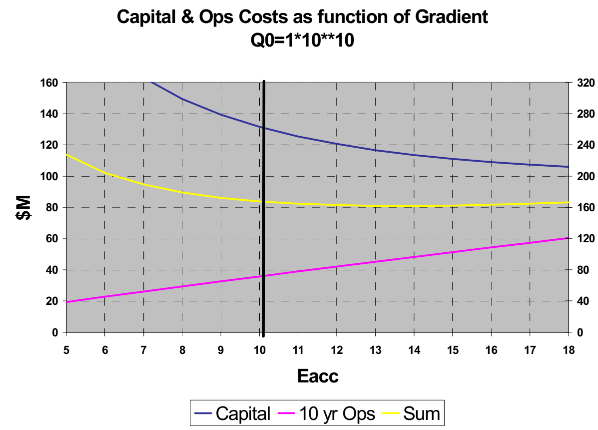

Figure 7.Optimazation for Q_0 10 E 09

4. CONCLUSION

As shown above, the cost optimised gradient for an accelerator like RIA is determined by the achievable Q-value at the design gradient. Improving the Q-value from the present design value of 5 E 09 at a peak surface field of E peak = 27.5 MV/m to a value beyond 1 E 10 will significantly reduce the construction and operating costs. Therefore improvement of the Q-value at high gradients through proven techniques must become the primary focus of the cavity R&D program.

5. ACKNOWLEDGEMENTS

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