DEVELOPMENT OF NIOBIUM SPOKE CAVITIES FOR A SUPERCONDUCTING LIGHT-ION LINAC

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Abstract

This paper reports the development of 350 MHz niobium superconducting cavities for the velocity range 0.2 < v/c < 0.6. Such cavities could be used to form a linac of exceptional flexibility, capable of efficiently accelerating beams of either protons, deuterons, or any of a wide range of light ions, at intensities sufficient for a production beam for a radioactive beam facility. Results of numerical modeling for several resonator geometries are presented. The design and construction status of prototype niobium cavities is discussed.

1 INTRODUCTION

For more than a decade, various concepts for an ISOL-type (isotope separator on-line) radioactive ion beam facility have been developed and discussed within the nuclear physics community [1,2]. The Argonne Physics Division several years ago put forward a concept requiring a linac for protons and light ions as a driver for spallation sources [3]. As initially proposed, the driver linac would be a fixed velocity profile, 220 MV, normally-conducting linac which could provide various beams of protons or light ions at a output energy of 100 MeV per nucleon with a total beam power of 100 kW. The different beams would be used in a variety of different production mechanisms.

To be cost-effective, however, a normal-conducting linac would have several limitations. To maximize shunt impedance, the velocity profile would need to be fixed. Consequently, for the lighter ions, particularly protons, the linac would have to be operated at substantially less than its maximum gradient. Also, operation would be pulsed, at 120 Hz, with a duty factor of at most a few percent. This mode of operation would aggravate heating problems in the spallation source and might also make voltage stability of the radioactive ion source problematic.

These limitations could be overcome by making the driver linac superconducting [4]. In this case, shunt impedance would not be a strong consideration, and the linac could be formed of short independently-phased cavities. The resulting broadly variable velocity profile would enhance performance, for example roughly doubling the maximum proton energy.

A superconducting linac would provide for cw operation, which would be advantageous in several respects beyond that of reducing target heating transients. Requirements for the injecting ion sources would be simplified. The reduction of space charge effects could provide for increased beam currents, opening, for example, the possibility of driving several targets simultaneously.

However, to date little development work has been done on superconducting cavities with the characteristics required for such a machine, most particularly in the upper part of the required velocity range . Before such a machine can be designed in detail, suitable cavities need to be fully developed and characterized.

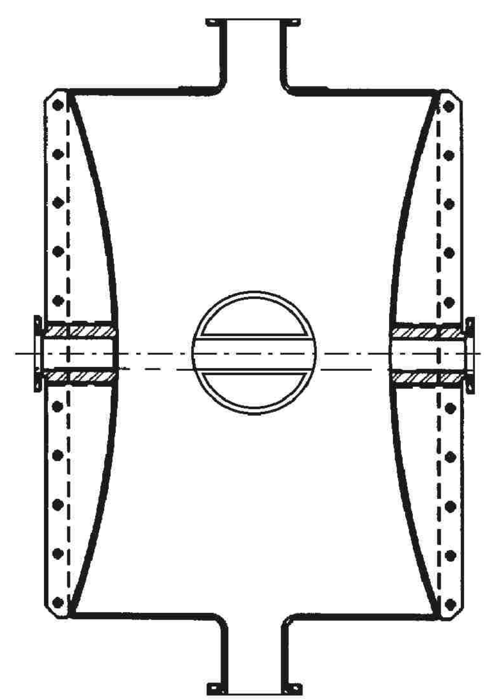

Figure 1: Section for a 44 cm diameter, 350 MHz spoke cavity

Medium-beta cavities are currently being developed for protons of 200 MeV and higher energies, in the form of foreshortened versions of the multi-cell elliptical cavities long used for electron acceleration [5]. The present application, however, is aimed at energies below 200 MeV, and the cavities required would be excessively foreshortened, with several adverse consequences. To obtain a reasonable accelerating voltage, particularly in single or double cell structures, cavities of adequate length would require large diameters, approaching a meter. Construction, handling, and cryostat design would all be rendered more difficult. Also, the mechanical stability of such large, highly foreshortened cavities would be marginal.

For the present application, a more promising geometry is the spoke resonator, which has been successfully prototyped in the form of an 855 MHz, single-cell superconducting niobium cavity [6, 7]. For the linac contemplated here, a substantially lower frequency is desirable. As will be shown below, a frequency choice in the range 300-400 MHz can provide for increased voltage, larger beam aperture, and enable higher operating temperatures. This frequency range differs nearly a factor of three from the single spoke cavity tested to date. Further prototyping is required to establish reliable estimates of the performance of the needed structures.

We have evaluated several possible configurations. In what follows, we discuss parameter choices for several prototype cavities, describe the resulting designs, and report the status of construction and tests.

2 PROTOTYPE CAVITY DESIGN AND CONSTRUCTION

The spoke resonator, in either single or double cell configuration, has a broad enough velocity acceptance that for the linac contemplated here only two different types of structure are required to cover efficiently the velocity range $0.2 < \beta = v/c < 0.7$ [4]. We need consider only the velocity range above 0.2c, since many resonator types have been successfully developed for the velocity range below 0.2c [8].

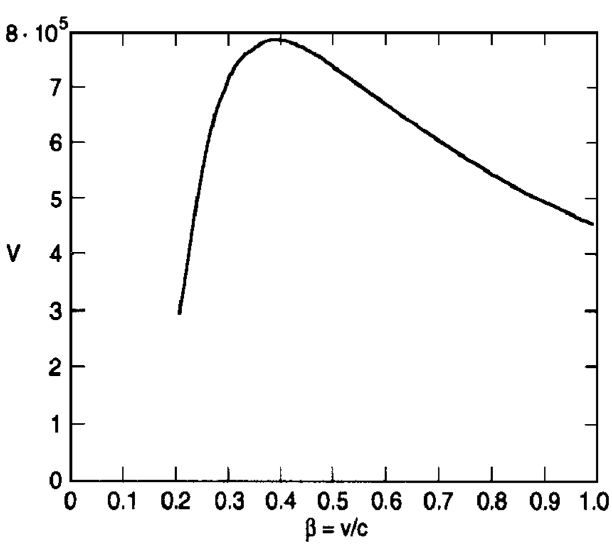

Figure 2: Velocity acceptance characteristic for the two-gap, $\beta = 0.4$ spoke cavity. The voltage gain is given in volts for an rf energy content of 1 joule, corresponding to an accelerating field of 3.4 MV/m in the 22.9 cm long structure.

Table I: Calculated and measured parameters for the $\beta = 0.4$ prototype niobium spoke cavity

Parameter	Calculated	Measured
Frequency	351.89 MHz	348.56 MHz
Active Length	-	22.9 cm
Q (niobium)	5491	5223
U_0*	80.4 mJ	85.3
Peak Electric Field*	4.0 MV/m	-
Peak Magnetic field*	107 Gauss	-
Optimum β (v/c)	0.40	0.39

* At an accelerating field of 1 MV/m

The prototype design, shown in Figure 1, was chosen to minimize the number of sheet-metal forming dies required. To further minimize time and cost, we form spoke cavities for two different velocities by changing only the cavity length and spoke diameter.

The cavity housing is formed from 1/8 inch sheet, and the central spoke of 1/16 inch sheet niobium. The 17 inch diameter bulkheads at either end are dished inwards by 1.2 inches to reduce cavity deformation under external pressure. However, numerical finite element analysis indicated that to obtain adequate mechanical stability, a series of support ribs should be welded to the bulkhead exterior, as shown in Fig. 1.

The 2.5 cm diameter beam aperture could be increased with little effect on either energy gain or peak surface electric field. The two coupling ports provide access for vacuum and rf coupling, and also for chemical processing.

2.1 Prototype Cavity for $\beta \geq 0.4$

The first of the two prototype cavities is sized for an optimum particle velocity $\beta = 0.4$ and is shown in Figure 1. The active length of the structure, *i.e.* the interior distance between beam ports, is 22.9 cm. The diameter of the central spoke is 10 cm.

The electromagnetic properties of the prototype cavities have been calculated by numerical modeling using MAFIA. In Table 1 the calculated values are compared with values measured for the recently completed prototype $\beta = 0.4$ niobium cavity.

Figure 2 shows the voltage gain as a function of particle velocity through the two-gap cavity, for an rf field level corresponding to an energy content of one joule. The broad velocity acceptance of the structure makes it particularly suitable for the present application.

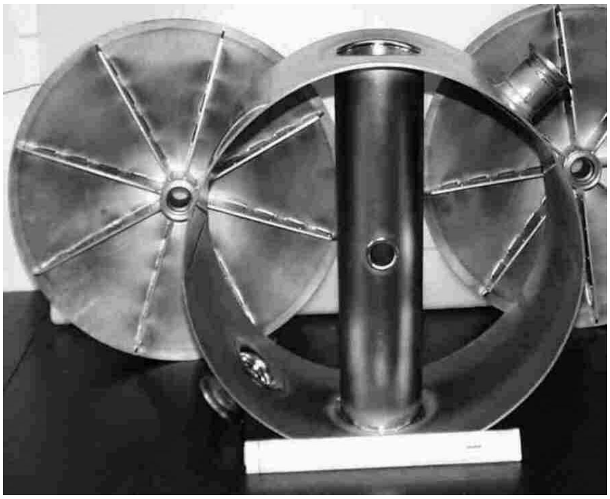

Figure 3: Elements of the prototype niobium cavity just before closure welds attached end sections to the spoke mid-section. A twelve-inch scale is shown.

2.2 Prototype Cavity for $\beta \geq 0.29$

Also under construction is a prototype cavity sized for an optimum particle velocity β = .29. The cavity differs from that shown in Fig. 1 in that the active length is shortened to 18 cm, and the diameter of the central spoke is reduced to 6.25 cm. For use in a linac, the cavity diameter would need to be reduced slightly to bring the frequency to 350 MHz to match the β = .4 cavity. But for purposes of evaluating resonator performance, the slightly lower frequency that results from using the same tooling as for the higher velocity cavity is of no consequence. Table II details the main parameters of the cavity. As in the section above, the electromagnetic properties shown are the results of numerical modeling (MAFIA).

3 RESULTS AND CONCLUSIONS

Designs for spoke cavities operating at 350 MHz have been developed which have low rf losses and low peak surface fields. Room temperature measurements have been made on the recently completed β = .4 cavity, and are compared in Table I with the design values. The measured Q agrees well with the calculated value, confirming that the rf losses for these structures are quite low. With niobium surfaces of good, currently attainable quality, i.e. residual resistivity of 10 nΩ or less, economic operation of the 350 MHz structures at 4.2 K should be feasible. Also, preliminary indication that the mechanical stability of the β = .4 structure is very good.

Plans for further work include finishing the β = .29 prototype, which is nearly complete, and performing low temperature tests of both prototypes. The major remaining question for these cavity designs is the nature of multipacting and other electron loading properties, which can be resolved only by cold tests.

Table II: Parameters for the β = 0.29 Prototype Niobium Spoke Cavity

Parameter	Design Value
Frequency	338.05 MHz
Active Length	18.0 cm
Q (niobium)	5384
U_0*	51.4 mJ
Peak Electric Field*	4.24 MV/m
Peak Magnetic field*	90.4 Gauss
Optimum β (v/c)	0.29

* At an accelerating field of 1 MV/m

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