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# REVIEW OF LOW-BETA SUPERCONDUCTING STRUCTURES

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General principles of low- $\beta$  superconducting-structure design will be outlined, so that the specific solutions or compromises used for various designs can be compared. Recent developments with low- $\beta$  structures will be described in the context of resonators which have been operating in accelerators for some time. The discussion will be limited to designs which are in use or under construction.

KEY WORDS: Superconducting rf, low-beta

## 1 INTRODUCTION

Superconducting Low- $\beta$  structures are used to accelerate a variety of particles. In Fig. 1 the  $\beta_0$  values associated with particles from different injectors are illustrated. It is seen that low- $\beta$  structures can be required for velocities as low as 1% of the speed of light, that values of  $\beta$  of 0.10 can be used with tandem Van de Graaff injectors, and that higher  $\beta_0$  values will be needed for energies of 20 or more MeV/nucleon.

Low- $\beta$  structures have two different natural length scales, the rf wavelength,  $\lambda$ , and the particle wavelength,  $\beta_0\lambda$ . For small  $\beta_0$  these two lengths are quite different. Thus a low beta resonator requires some loading structure(s) so that the frequency can be set by a length about  $\lambda/4$ , while the accelerating length will be  $n\beta_0\lambda/2$ , where  $n$  is the number of gaps. For the case of a two-gap, quarter-wave resonator (QWR), these lengths are illustrated in Fig. 2.

To be useful, the low- $\beta$  resonator must either increase the energy of the entering particle by at least a few % of the final energy, or by a substantial factor in order to increase  $\beta$ . Consequently sufficient accelerating length is required, and thus a relatively low frequency is used. This may require a resonator that is quite large. Also, the operating temperature is 4.3K because the BCS losses at low frequency are not a major consideration. In Fig. 3 the choices of frequency for various  $\beta_0$  values are shown. The general trend toward lowest frequency for lowest  $\beta_0$  is clear. The frequencies of 200 MHz and higher have each been chosen for special reasons which will be explained below.

D. W. STORM

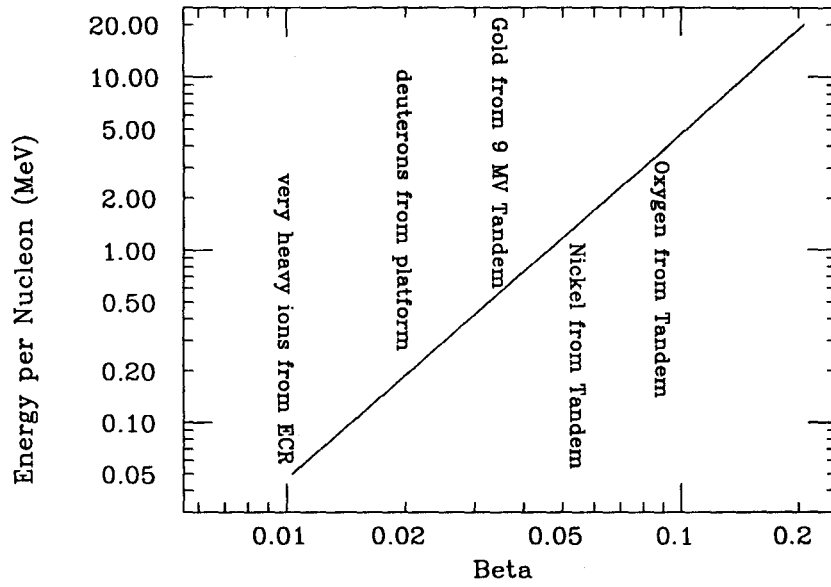


FIGURE 1: The solid line relates the kinetic energy per nucleon of an ion to the quantity  $\beta$ , the particle speed divided by the speed of light.

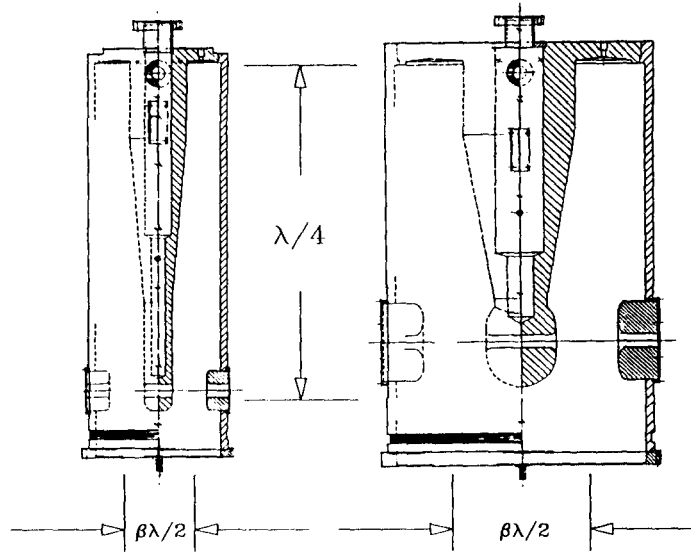


FIGURE 2: Quarter wave resonators of  $\beta_0 = 0.1$  and  $\beta_0 = 0.2$  with the lengths determining the frequency and the  $\beta_0$  values indicated.

## REVIEW OF LOW-BETA SUPERCONDUCTING STRUCTURES

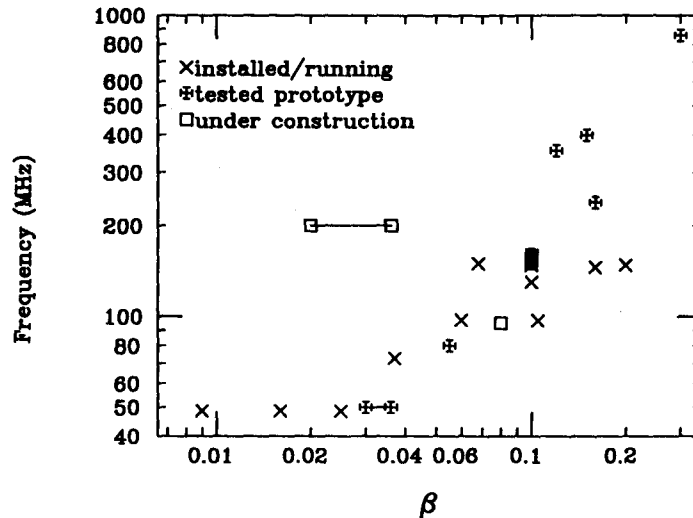


FIGURE 3: The frequency and  $\beta_0$  values several different resonators. Those that are presently being used in accelerators, those that are prototypes, and those presently under construction are distinguished. RFQ's are indicated by two values connected by a line.

## 2 ISSUES AND COMPROMISES

Considerations of peak surface electric field,  $E_s$ , and of phase stability are paramount in low- $\beta$  resonator design. Maximum voltage is usually limited by peak  $E_s$ . In designing the resonator, the peak  $E_s$  is minimized at the expense of the peak magnetic field and at the expense of maximizing the shunt impedance. However, if the peak magnetic field can be reduced without impact on the peak  $E_s$ , this is normally done. In order to phase lock the resonator, the range of the fast tuning scheme must cover the range of the eigen-frequency modulation resulting from mechanical vibrations (microphonics). The large size that is related to a useful acceleration length implies that the stored energy will be relatively large, and sufficient reactive power must be available to phase lock the resonator in the presence of microphonics. This sets a practical lower limit of about 50 MHz on frequency. The mechanical rigidity of the structure determines the range of eigen-frequency modulation. The stiffer the resonator, the less sensitivity to microphonics.

The loading structure has an important impact on the peak  $E_s$ . The peak field will occur somewhere on the drift tube at the end of the loading structure. Ratios of peak  $E_s$  to the average accelerating field,  $\langle E_a \rangle$ , are about 5, although values are as high as 7 in some structures. The loading structure must be mechanically rigid. The loading structure is designed around a number of gaps. Two gaps provide the broadest transit time factor, while more gaps provide a longer acceleration length. A broad transit time factor is desirable when a variety of ions of different charge to mass ratios are to be accelerated.

D. W. STORM

In summary, the designer of a low- $\beta$  resonator will

1. Minimize  $E_s / \langle E_a \rangle$ .
2. Maximize rigidity.
3. Choose frequency to compromise between maximum acceleration length and minimum  $U_{\text{stored}} / \langle E_a \rangle^2$ .
4. Choose a number of gaps to compromise between maximum acceleration length and a wide transit time factor.

### 3 MATERIALS AND CONSTRUCTION STYLES

Materials available for construction include niobium sheet, niobium bonded to copper, niobium sputter coated on copper, and lead electroplated on copper. The excellent heat conductivity of copper at liquid helium temperature permits cooling most of the resonator by conduction when a copper substrate is used. Niobium sheet must be cooled by contact with liquid helium. Even then, quenching may occur at high power, while resonators made of copper coated with a film of lead or niobium do not quench. The superior superconducting properties of niobium must be balanced against the higher cost of construction. Progress is still being made with lead electroplating, and some recent excellent results will be presented below.

Most resonators that have been produced for accelerators recently are QWR's. Previously several split-loop (SL) designs have been installed, and these are still performing well. The QWR's have two gaps, so more resonators are required for a given accelerator, while the three-gap SL units provide more acceleration each. The construction of a QWR seems substantially easier than a SL, however, and the lower stored energy and higher stiffness makes rf control more straightforward. Thus the relative cost of equivalent accelerators based on QWR or SL designs is by no means determined by the relative number of units.

### 4 EXAMPLES

In this section we will describe several different low- $\beta$  resonators that are either in use or under development. It has been conventional to state the average accelerating field,  $\langle E_a \rangle$ , as a quantity for evaluating resonators. However, this quantity, which is defined as the energy gain per unit charge of a particle of optimum velocity, divided by some nominal acceleration length, is misleading because it rewards short acceleration lengths. A much more useful quantity is the actual energy gain per unit charge (at  $\beta_0$ ). This should be compared to the rf power consumed at helium temperature, to determine cooling costs. However the energy gain per resonator is itself important. Thus both energy gain (either as used or as proposed in the accelerator) and the power corresponding to this value will be presented with the examples.

REVIEW OF LOW-BETA SUPERCONDUCTING STRUCTURES

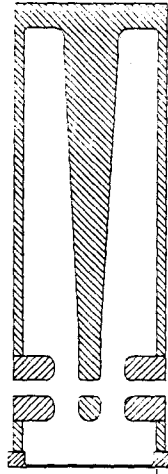


FIGURE 4: The  $\beta_0 = 0.068$  QWR installed in the Stony Brook superconducting linac.

*4.1 New Developments*

Recent work in QWR's has been done at Stony Brook<sup>1</sup>, where  $\beta_0 = 0.05$  SL resonators have been replaced by  $\beta_0 = 0.068$  QWR's. These 150 MHz resonators have a inside diameter of 17 cm, which is typical for QWR's of  $\beta_0$  around 0.1. The lower  $\beta_0$  value is obtained by making the ground drift tubes fairly long, pushing the gaps toward the center of the resonator. The Stony Brook QWR's are lead-plated copper resonators, and are illustrated in Fig. 4.

QWR's made of bulk niobium<sup>2</sup> are being developed at the Laboratori Nazionali di Legnaro (LNL). Three models, with inside diameters of 18 cm have been prototyped and tested. They have  $\beta_0$  values of 0.055, 0.11, and 0.17, and operate at 80, 160, and 240 MHz, respectively. They are illustrated in Fig. 5. The group at LNL had trouble with multipacting with lead-plated QWR's when the center conductor was tapered as are those of Figs. 2 or 4. Consequently they adopted a straight center conductor. The peak magnetic field is higher than with the taper, but the multipacting was less severe. The LNL niobium QWR's also have the straight center conductor.

Others at LNL have been developing sputter coating techniques for applying niobium to resonators constructed of copper<sup>3</sup>. Working with a simplified developmental geometry in which there are no beam holes, 1.2 MV is obtained at 7 W<sup>4</sup>. Using the resonator with ground drift tubes, 0.7 MV is obtained, also at 7 W. This is a considerable achievement, considering the relatively complicated geometry of the QWR compared to the LEP cavities which have been successfully sputter coated for some time now<sup>5</sup>. The group at LNL uses biased diode sputtering, which enables them to coat the entire surface at once.

D. W. STORM

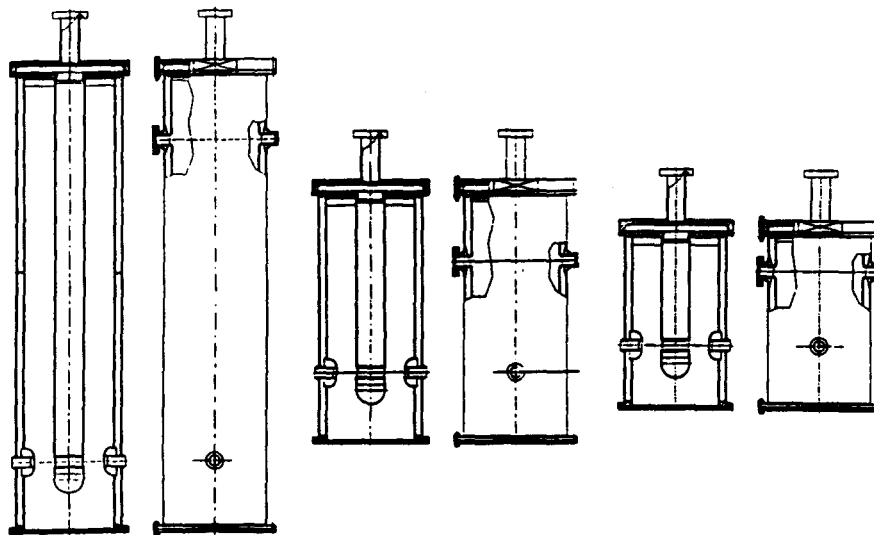


FIGURE 5: The three QWR's which have been prototyped and tested at LNL.

Sputter coating of a QWR using magnetron sputtering has been under development at the Australian National University (ANU). The magnetron discharge is more stable than the diode discharge, but, because of the confined geometry of the QWR, the magnets must be moved during the sputtering process in order to cover the entire surface. Presently it appears that oxygen contamination is limiting the performance of the ANU sputter coated resonator<sup>6</sup>.

At Argonne National Laboratory (ANL), work is being done in collaboration with the Nuclear Science Centre at New Delhi, developing bulk niobium QWR's<sup>7</sup>. These will operate at 95 MHz with  $\beta_0 = 0.08$ . The unusual shape of the center conductor was chosen to increase capacitive loading of the resonant line, so it is shorter than a quarter wavelength. See Fig. 6. This loading increases the relative peak magnetic field and lowers the shunt impedance, but the shortening reduces the stored energy and the amount of niobium material required. To reduce costs, the outer jacket of the resonator is stainless steel, which is connected to the niobium with explosively bonded tubes. This resonator has undergone multipacting tests but has not yet been tested at high fields.

For the traditional heavy ion applications of superconducting low- $\beta$  resonators, beam currents are low enough that neither beam-loading nor space-charge considerations are important. However, for very high beam currents, operation at high frequencies is an advantage<sup>8</sup>. Three different<sup>9,10,11</sup> high frequency resonators have been prototyped at ANL for  $\beta_0$  values of 0.12, 0.15, and 0.30. The corresponding frequencies are 355, 400, and 855 MHz. The 400 MHz unit is a QWR, but for high frequencies the length of the loading arm becomes comparable to the space

REVIEW OF LOW-BETA SUPERCONDUCTING STRUCTURES

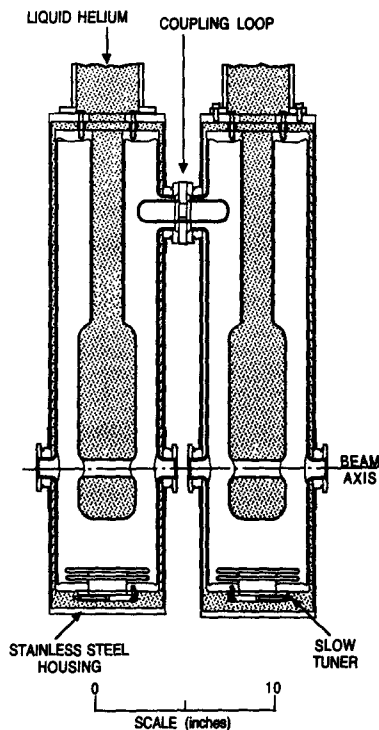
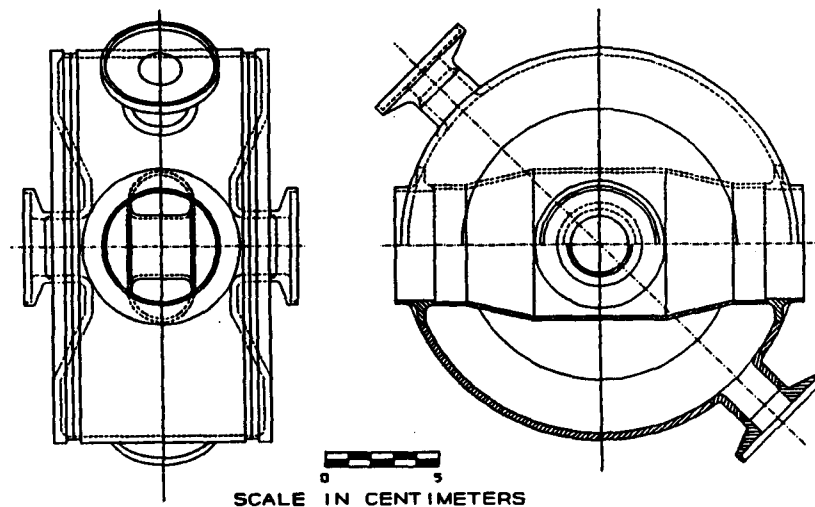


FIGURE 6: The  $\beta_0 = 0.08$  QWR being prototyped at ANL. A pair of resonators are shown driven by a common coupler. This scheme requires half as many control units as would be needed for single resonators. By selecting the normal modes where the two resonators are either in or 180 degrees out of phase, different velocity particles are favored. However, the transit time factor curve of a single QWR is not achieved.

between the end of the loading arm and the bottom of the resonator. Furthermore the beam hole is relatively big. Consequently half wave (HW) structures have been developed<sup>9,11</sup> in which the loading arm passes from one side to the other of the outer conductor. The 355-MHz HW unit is cylindrical, with the beam passing on a radius, like the usual QWR's. The 855-MHz device has the beam passing on the cylinder axis, while the loading arm connects the cylinder walls. The designers call this a "spoke" resonator. See Fig. 7. It provides good field symmetry, high rigidity, and several can be stacked to produce a multi-gap structure.

Development of superconducting radio frequency quadrupoles (RFQ's) is taking place at Stony Brook<sup>12</sup>, ANL<sup>13,14</sup>, and Los Alamos National Laboratory<sup>15</sup> (LANL). The units are one third to one half meter long. The Stony Brook work, in collaboration with LNL, is directed toward a specific accelerator, while the other work is more experimental and is aimed at studying the limits and limitations of superconducting RFQ's. One natural application for RFQ's is for high currents, where it is advantageous to apply acceleration in as short a space as possible to avoid space-

D. W. STORM


 FIGURE 7: The 855 MHz "Spoke" resonator with  $\beta_0 = 0.30$ .

charge blow up. The possibility of using an RFQ for a radioactive-beam accelerator is also interesting. Normal conducting RFQ's can not achieve the high fields in cw operation that superconducting units may reach. On the other hand, issues of beam impingement and stabilization are more significant for superconducting units.

The Stony Brook work<sup>12</sup> involves a scheme where six "RFQ-lets" will be used together. Bunching will be done before this system, which is optimized for acceleration with an assumed peak  $E_s$  of 15 MV/m. The third of the six units has been prototyped and operated at about 10 MV/m  $E_s$ , which provides 0.70 MV accelerating voltage. It is 55-cm long, with an aperture radius of 1.57 cm, and operates at 57 MHz. It accelerates particles from  $\beta = 0.030$  to 0.036. This is a lead-plated copper device, illustrated in Fig. 8.

The group at ANL found very high  $E_s$  could be achieved with small unmodulated rods attached to a split-loop resonator in a quadrupole geometry<sup>13</sup>. Consequently an RFQ which, with  $E_s = 120$  MV/m, will accelerate particles with charge to mass ratio of 1/10 from  $\beta = 0.020$  to 0.036 is being prototyped<sup>14</sup>. If such high fields are not possible, the same  $\beta$  values can be obtained for a higher charge to mass ratio. High frequency (200 MHz) has been chosen in spite of the fact that with high frequency the aperture must be small (2.9 mm radius). The length is 47 cm. At this high frequency the device is small and stored energy is manageable, even with the high fields. Warm model tests have been performed.

The group at LANL<sup>15</sup> is building an RFQ with light ions in mind. It will operate at 425 MHz. Parts have been made but not welded yet. The device is 32.5 cm long with an aperture radius of 4.3 mm.



REVIEW OF LOW-BETA SUPERCONDUCTING STRUCTURES

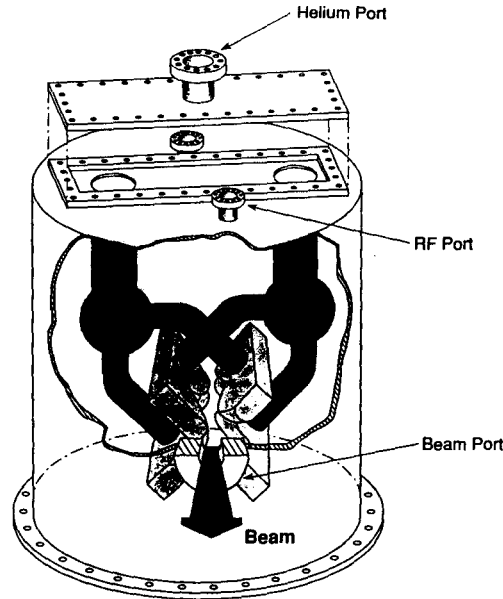


FIGURE 8: The "RFQ-let" prototyped at Stony brook. The copper structure is plated with 98%Pb - 2%Sn alloy.

#### 4.2 Performance

**4.2.1 Production Resonators** The performance of several resonators currently in use is summarized in Tab. 1. Among resonators in production, the niobium QWR's being installed at JAERI<sup>16</sup> are the state of the art in terms of high energy gain and low power consumption. These resonators have only a 15 cm acceleration length, and the particle energy gain is stated for 4.0 Watt rf power consumption. Recently installed units test at  $\Delta E/q$  of 1.0 MV, while earlier units produce 0.7 MV. The difference is attributed to hydride precipitation. The Stony Brook QWR's<sup>1</sup> exceed  $\Delta E/q$  of 0.51 MV at 6 Watts, in spite of the relatively high ratio  $E_s / \langle E_a \rangle$  of 7. The group at Stony Brook has been plating lead with 2% (atomic) tin. A thin (approx 1  $\mu$ meter) layer is plated, the resonator is rinsed with deionized water under a nitrogen atmosphere, and then it is dried with nitrogen.

For reference, the lead-plated,  $\beta_0 = 0.1$  resonators at the University of Washington provide 0.54 MV at about 8 watts, while the  $\beta_0 = 0.2$  units provide 0.86 MV at about 16 watts. These are average values including all resonators in the linac during operation. The  $\beta_0 = 0.1$  SL resonators at Stony Brook which have been re-plated with the lead-tin alloy provide 0.67 MV at about 6 Watts<sup>17</sup>, while the niobium  $\beta_0 = 0.11$  SL resonators at ANL provide 1.08 MV with about 4 Watts of rf dissipated in the superconductor<sup>18</sup>. Some additional heat load comes from the fast tuners, which are voltage controlled reactances closely coupled to the resonators. These are used in the ANL SL resonators, because of the high stored energy and

D. W. STORM

TABLE 1: Comparison of resonators operating or in production

| Laboratory  | type      | $\beta_0$ | freq<br>(MHz) | $\Delta E/q$<br>(MV) | Power<br>(W) |
|-------------|-----------|-----------|---------------|----------------------|--------------|
| Stony Brook | Pb/Sn QWR | 0.068     | 150           | 0.51                 | 6            |
| Stony Brook | Pb/Sn SL  | 0.10      | 150           | 0.67                 | 6            |
| JAERI       | Nb QWR    | 0.08      | 129           | 0.51                 | 4            |
| U.Wash      | Pb QWR    | 0.10      | 149           | 0.54                 | 8            |
| U.Wash      | Pb QWR    | 0.20      | 149           | 0.86                 | 16           |
| ANL         | Nb ID     | 0.009     | 49            | 0.45                 | 6            |
| ANL         | Nb ID     | 0.016     | 49            | 0.48                 | 6            |
| ANL         | Nb ID     | 0.025     | 49            | 0.76                 | 6            |
| ANL         | Nb ID     | 0.037     | 73            | 0.76                 | 6            |
| ANL         | Nb SL     | 0.1       | 145           | 1.08                 | 4            |

ID: interdigital geometry

significant microphonics.

Finally, the positive ion injector (PII) built at ANL uses four different resonator designs<sup>19</sup>. These are basically QWR's which are built with four acceleration gaps by using a ground section attached to the bottom of the outer conductor. These are called interdigital resonators. The  $\beta_0$  values of 0.009, 0.016, 0.025 and 0.037 are achieved with 48.5 MHz for the first three models and 72.8 MHz for the fourth. In order to accelerate ions with a charge to mass ratio of 1/10, they must provide 0.45, 0.48, 0.76, and 0.76 MV. They exceed these requirements while consuming approximately 6 Watts<sup>20</sup>. It is seen that the reasonable voltage gains require very low frequency in addition to the use of four gaps, when  $\beta_0$  is very low.

*4.2.2 Developmental Resonators* The three different models of bulk niobium resonators built and under test at Legnaro have performed well, providing 0.76, 0.90, and 0.85 MV with 5, 10, and 6 watts, for the 80-, 160-, and 240-MHz resonators described above. After pressure washing the 80-MHz unit, 0.72 MV was obtained with 1 W (quench limited). It will be interesting to see whether the pressure washing technique will produce similar and repeatable results for all the units.

The 855-MHz spoke resonator is intended for 2K operation, but has been tested at 4.3K, where it provides 0.43 MV with 24 W. The 355 MHz unit operates at relatively high power as well, and provides up to 1.26 MV. See Tab. 2 for performance figures for these resonators.

## 5 Summary

The designs which have been described cover a broad range in parameters depending on the specific applications and the economics involved. Several variations of

## REVIEW OF LOW-BETA SUPERCONDUCTING STRUCTURES

TABLE 2: Comparison of prototype resonators

| Laboratory           | type     | $\beta_0$ | freq<br>(MHz) | $\Delta E/q$<br>(MV) | Power<br>(W) |
|----------------------|----------|-----------|---------------|----------------------|--------------|
| Legnaro              | Nb QWR   | 0.056     | 80            | 0.76                 | 5            |
| Legnaro <sup>a</sup> | Nb QWR   | 0.056     | 80            | 0.72                 | 1            |
| Legnaro              | Nb QWR   | 0.11      | 160           | 0.90                 | 10           |
| Legnaro              | Nb QWR   | 0.17      | 240           | 0.85                 | 6            |
| ANL                  | Nb HWR   | 0.12      | 355           | 1.26                 | 40           |
| ANL                  | Nb HWR   | 0.12      | 355           | 1.05                 | 10           |
| ANL                  | Nb QWR   | 0.15      | 400           | 0.82                 | 21           |
| ANL                  | Nb Spoke | 0.30      | 855           | 0.43                 | 24           |

<sup>a</sup> pressure washed

the basic QWR are being built or prototyped for accelerators presently under construction. At Stony Brook, the lead-plated copper SL resonators of the earliest design are being replaced with QWR's. The higher  $\beta$  SL's at Stony Brook are being replated using a simpler technique which promises a substantial improvement in performance. The SL's that have been running well for some time at ANL are performing competitively compared to newer resonators.

The niobium sputter coating development programs at Legnaro and ANU are showing significant promising results. Success with this process is by no means trivial, as can be measured by the number of years of development effort at each of those laboratories. It appears that the expectation that niobium sputtered resonators will provide the performance of bulk niobium can be realized, but the idea that the cost will rival the cost of lead-plated resonators is overly optimistic.

The region of very low  $\beta$  is being pushed with RFQ's, which so far have been short sections, either to be used for experimental studies or in conjunction with several other "RFQ-lets" to accelerate ions from  $\beta$  of 0.01 up to about 0.05. The PII works very well for heavy ions in this range, but RFQ's may be necessary for beams where space-charge limitations are significant.

The highest  $\beta$  region is being explored with high current beams in mind, where high frequency is required, and consequently even with high  $E_s$  the energy gain per resonator must be relatively low.

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D. W. STORM

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