# STRUCTURES FOR RIA AND FNAL PROTON DRIVER

Michael Kelly, Argonne National Laboratory, Argonne, IL 60439, U.S.A*

## *Abstract*

Superconducting (SC) cavities for two new large ion linacs, the Rare Isotope Accelerator driver and a proposed 8-GeV proton driver at Fermilab, are being developed at several institutions. Cavity structures range from co-axial quarter- and half-waves to elliptical-cell geometries and multiple-spoke loaded cavities in the mid- and high-beta velocity range. Both novel designs and also designs adapted from existing structures are being developed to fulfill diverse requirements. The CW RIA linac requires 400 SC cavities for accelerating ions over the full mass range with beta up to ~0.8, and the pulsed proton driver linac requires 500 cavities spanning the full range of velocities. Gradients required for RIA and the proton driver ($E_{peak}$ ~ 30 MV/m) have already been demonstrated in prototype cavities in large part through the incorporation of modern clean handling and processing techniques. Critical issues in the final choice of RIA cavities will be beam dynamics, microphonics and RF phase control. Proton driver cavity design will be driven largely by the requirements for high-power pulsed operation. The present status of various structures developed for RIA and the FNAL Booster is presented here.

## INTRODUCTION

The U.S. Rare Isotope Accelerator [1] (RIA) is the proposed next generation radioactive beams facility in the U.S. while the proposed 8-GeV Proton Driver [2] at Fermilab would deliver intense proton beams to the main injector for use in the FNAL neutrino science program.

Though both machines are based on large superconducting ion linacs several hundred meters in length and contain 400-500 superconducting cavities spanning most or all of the full range of particle velocities (see Figures 1-3), there are essential differences. A full three-quarters of the proton driver linac is comprised of 1.3 GHz elliptical cavities requiring little modification from the existing TESLA design. Pulsed operation for these cavities has also been carefully studied [4].

R&D on TEM cavities for the mid-beta proton driver linac, particularly in the area of pulsed operation, is underway (see *e.g.* Ref. [5]) but still requires substantial effort. For the CW RIA linac, microphonics has been a major driver of cavity design for both elliptical and TEM cavities. The accelerating gradients required for RIA and for the proton driver has been largely achieved, as will be discussed in this paper, using clean techniques introduced initially through ongoing R&D for the International Linear Collider (ILC) and adapted for TEM-cavities during RIA development. The proton driver proposes to use directly the 1.3 GHz structures and clean technology developed for the ILC.

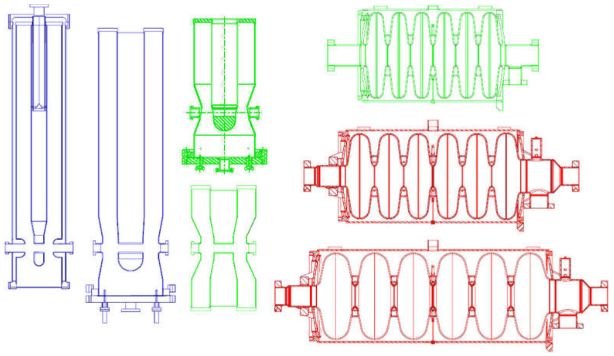

Figure 1: A cavity array for RIA proposed by Michigan State University. Shown are a pair of quarter-waves at 80.5 MHz (left), mid-beta quarter- and half-waves at 161 MHz and 322 MHz (center), and three elliptical-cell cavities at 805 MHz (right).

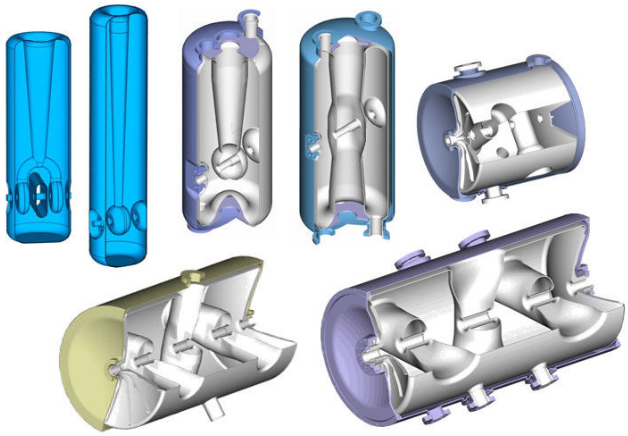

Figure 2: Cavities developed for RIA at Argonne National Laboratory. Shown are a pair of quarter-waves at 57.5 MHz (top left), mid-beta quarter and half-waves at 115 MHz and 172 MHz (top center) and three multi-spoke cavities at 345 MHz (see Ref. 3).

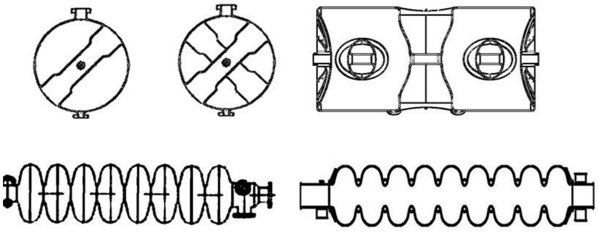

Figure 3: A (schematic) cavity array for the FNAL proton driver using spoke cavities at 325 MHz (top) for $0.2<\beta<0.8$ and 1.3 GHz elliptical cavities for $0.8<\beta<1.0$ (bottom).

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## CAVITIES

In the mid-1990's it was recognized that a high-power multi-ion driver linac for RIA required development of new cavities in the intermediate velocity region. Drift-tube cavities at low-beta and elliptical cell structures for beta near 1 have been in operation for years so that the most cavity development for RIA has been focused on the intermediate velocity region.

A set of seven superconducting cavities for RIA based on the 10th subharmonic of 805 MHz (80.5 MHz) has been proposed at Michigan State University. Cavity types are shown in Figure 1. Low-beta TEM structures were developed in collaboration with INFN-Legnaro [6]. These structures are bulk niobium double-wall quarter-wave cavities similar to those developed previously at Legnaro. In addition, a 322 MHz co-axial half-wave and has been prototyped for RIA [7]. New medium beta elliptical-cell cavities have been built jointly with Thomas Jefferson National Accelerator Facility (JLab) [8] and are an adaptation for lower velocities of the design developed for the Spallation Neutron Source (SNS). Roughly 500 SC cavities of seven different geometries would be required in this proposal.

A cavity array for RIA proposed at Argonne National Laboratory, shown in Figure 2, uses structures running at the 14th subharmonic of 805 MHz (57.5 MHz) and includes a fork-type quarter-wave resonator, a pair of 2-gap quarter-waves [9], a co-axial half-wave cavity [10] and two different three-spoke resonators [3]. The total cavity count in this case is close to 300 using six different geometries.

The proton driver linac and cavities leverage existing designs taken from development for the ILC and RIA. The high-energy section of the linac takes cavities; cryomodules and RF subsystems developed by the TESLA collaboration and would represent a 1½% demonstration of the ILC linac. For beta $0.8<\beta<1.0$ a 'scaled' 8-cell elliptical cavity at 1300 MHz has been designed. The baseline design for the low- and mid-beta linac sections use single-, double- and triple-spoke resonators operating at 325 MHz, the fourth subharmonic of 1300 MHz and also the frequency of existing klystrons developed for JPARC.

## FABRICATION & PROCESSING

### Fabrication

TEM-class drift-tube loaded cavities for RIA and the proton-driver have been designed using modern 3D simulation codes such as MAFIA, Microwave Studio, and ProEngineer/ANSYS. Niobium cavity subassemblies are formed from high RRR (~250) 3 mm niobium sheet using hydroforming or deep-drawing techniques and joined by electron beam welding. All niobium cavities are housed in an integral helium jacket constructed from either stainless steel or titanium.

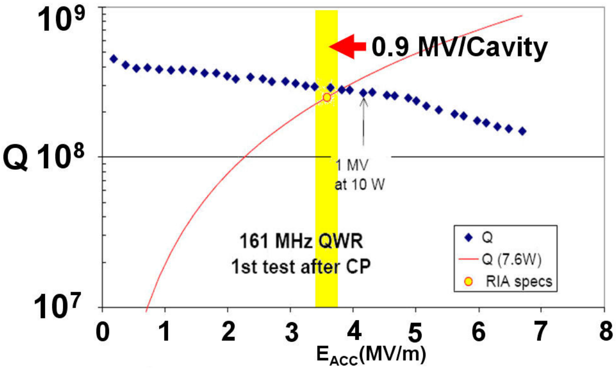

Figure 4: First Q-curve results at T=4 K for a beta=0.16 QWR developed jointly by INFN-LNL and MSU. The vertical band indicates the RIA performance goal.

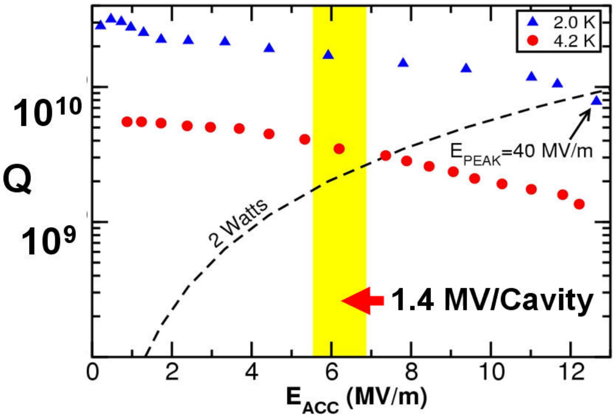

Figure 5: Q-curve test results for a beta=0.15 QWR developed at ANL. The vertical band indicates the RIA performance goal.

### Processing

All cavity prototyping for RIA has all included some form of clean processing and handling techniques developed initially at places like KEK, DESY and JLab. Cavity processing facilities at Michigan State University and JLab have generally used buffered chemical polishing (BCP) to remove ~150 microns of niobium from the RF surface after fabrication. Alternatively, electropolishing, used at Argonne for decades, was used to do the major removal from the RF surface on all of the ANL prototype cavities. All cavities were high-pressure rinsed using filtered deionized water in a (class 100) clean area for at least one hour. Final assembly of the cavity together with the coupler and the vacuum hardware has, likewise, been performed in a (class10-100) clean area.

## CAVITY PERFORMANCE

### Quarter-wave resonators

Quarter-wave resonators for RIA at somewhat higher beta than has been used elsewhere have been developed both at Argonne and MSU. Both cavities have tilted drift-tube faces [11] to reduce the beam steering effect inherent in the quarter-wave structure and which would otherwise lead to beam emittance growth. Both cavities are intended

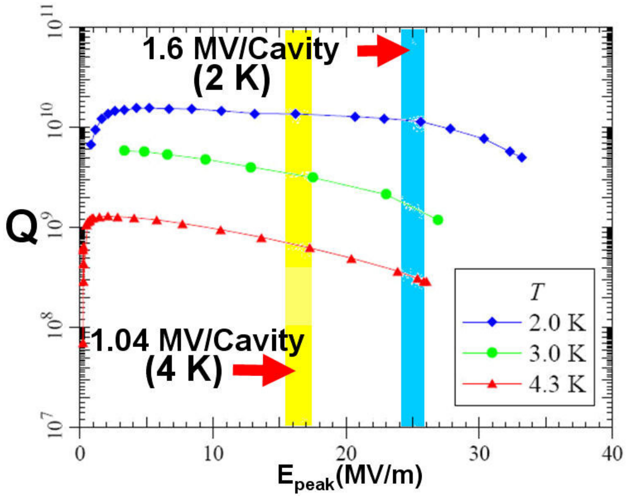

Figure 6: Q-curve test results for a beta=0.28 HWR developed at MSU. The vertical bands indicate the RIA performance goals. Note $E_{peak}$=3x$E_{ACC}$.

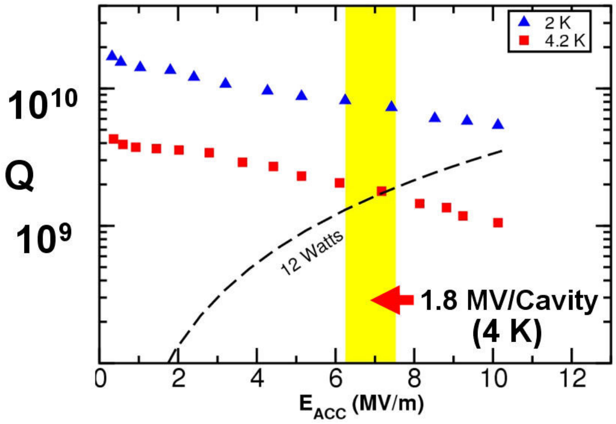

Figure 7: Q-curve test results for a beta=0.25 HWR developed at ANL. The vertical band indicates the RIA performance goal.

for 4 Kelvin operation and easily meet the RIA design field gradients of 18 (see Figure 4) and 23 MV/m (see Figure 5) peak surface electric field.

## *Half-wave resonators*

Co-axial half-wave resonators (HWR) for particles moving with roughly one quarter the speed of light have been developed each at both MSU and Argonne for the RIA driver. The MSU HWR at 322 MHz was originally tested at 4 K and achieved RIA design goal, however, the proposed operating temperature has been changed to 2 K to take advantage of the good performance at that temperature. Results at both temperatures, showing $E_{peak}$ rather than $E_{ACC}$, are shown in Figure 6. The ANL half-wave at 161 MHz is intended for 4 K operation and exceeds the RIA design goal at that temperature as shown in Figure 7.

## *Elliptical-cell cavities*

A pair of 805 MHz elliptical-cavities for RIA with beta=0.47 has been tested at MSU in order to span the velocity region between the low-beta TEM cavities and the beta=0.61 SNS elliptical-cell cavity. Cavity preparation, including buffered chemical polishing and high-pressure rinsing was performed using the same facilities as for the SNS production cavities. Cold test results for these cavities at T=2 K and after high power pulsed conditioning are shown in Figure 8. Both cavities meet the design goal of $E_{ACC}$ just over 10 MV/m. Some field emission and drop in cavity Q were observed at these fields similar to that seen in the SNS production cavities. A demonstration of amplitude and phase control in the presence of microphonics, likely be the key technical issue for the RIA mid-beta cavities, is planned.

## *Triple-spoke resonators*

Spoke loaded cavities at 345 MHz offer an alternative to the 805 MHz beta<1 cavities in the RIA driver linac and, with a slightly reduced frequency of 325 MHz, are part of the baseline design for the proton driver. Test results for the three multi-spoke cavities developed for RIA are shown in Figures 9, 10 and 11.

Two-spoke cavity results easily exceed the initial RIA design goal and show no substantial field emission out to the highest obtainable fields. More recent tests of the beta=0.5 and beta=0.63 triple spoke resonators at T=4.2 K show performance that meets the RIA design goal even though the development is not yet complete. In particular, tests performed to look for hydrogen Q-disease in the beta=0.63 triple spoke cavity by holding the temperature in the hydride formation region showed a strong Q drop indicating the presence of hydrogen. Hydrogen degassing in a vacuum furnace at 600°C has been performed and additional cold tests will be performed.

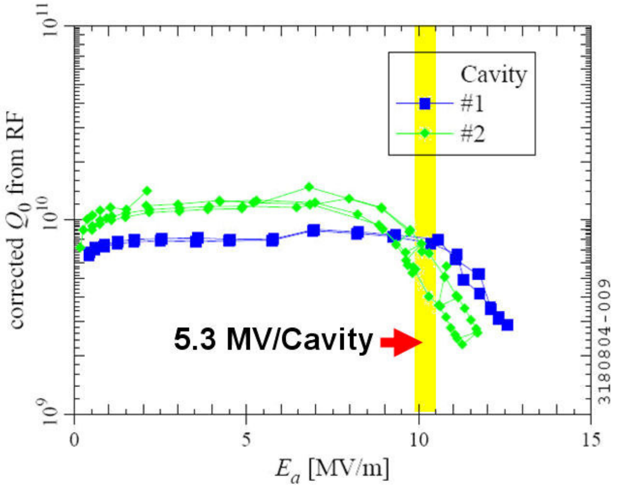

Figure 8: Q-curve test results for two beta=0.47 elliptical cell cavities developed jointly at JLab/MSU. The vertical band indicates the RIA performance goal.

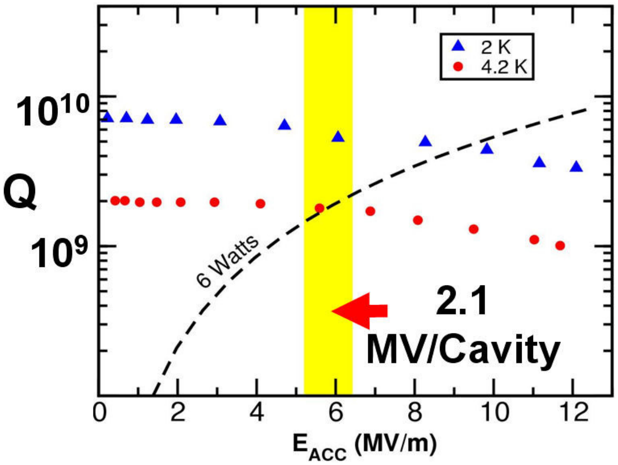

Figure 9: Q-curve test results for a beta=0.40 double-spoke cavity developed at Argonne. The vertical band indicates the RIA performance goal.

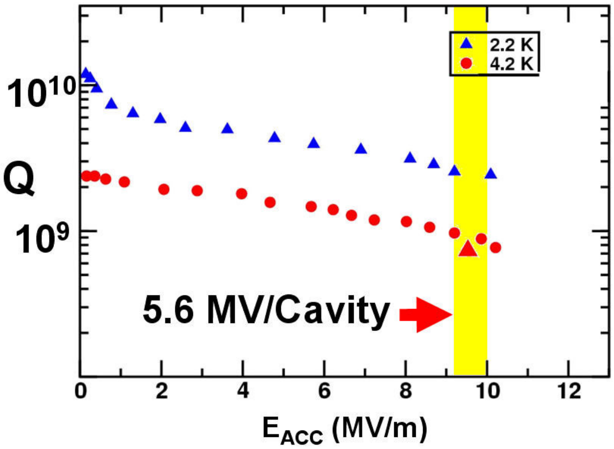

Figure 10: Q-curve test results for a beta=0.50 triple-spoke cavity developed at Argonne. The vertical band indicates the RIA performance goal.

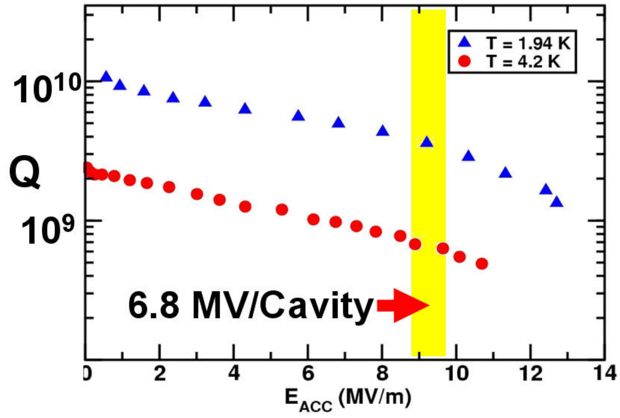

Figure 9: Q-curve test results for a beta=0.63 triple-spoke cavity developed at Argonne. The vertical band indicates the RIA performance goal.

## FAST TUNING

An outstanding issue for all RIA and proton driver cavities is method of fast tuning. A VCX tuner is available for the low frequency beta~0.1 RIA cavities, however, substantial further development for cavities with higher frequencies and stored energies is not planned. Overcoupling may be used to compensate for microphonics in RIA at the expense of a substantial additional RF power requirement. Another technique uses a small mechanical transducer such as a piezoelectric or magnetostrictive device and may offer substantial cost savings compared to the overcoupling. The use of these devices for microphonic damping has been demonstrated and is the subject on ongoing studies, however, the technique is not in common use.

## CONCLUSION

Overall, cavity development for RIA and the proton driver is well advanced. Cavity gradients required for RIA of 16 MV/m<$E_{peak}$<32.5 MV/m have largely been demonstrated in two sets of prototype cavities at Argonne National Laboratory and Michigan State University. Proposed cavity gradients for the proton driver of ~$E_{peak}$=30 MV/m appear to be achievable.

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