SUPERCONDUCTING CAVITIES FOR ION AND PROTON LINACS*

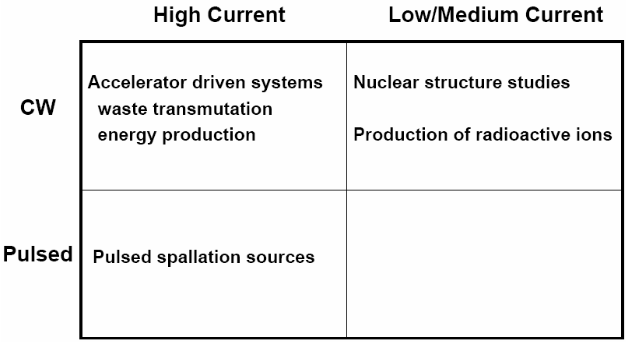
J. R. Delayen[#], Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

Abstract

In the last decade, one of the most active areas in the applications of the superconducting rf (SRF) technology has been for the acceleration of ions to medium energy (~1 GeV/amu) and high power. One such accelerator is under construction in the US while others are being proposed in the US, Japan, and Europe. These new facilities require SRF accelerating structures operating in a velocity region that has until recently been unexplored, and new types of structures optimized for the velocity range from ~0.2 to ~0.8 c have been developed. We will review the requirements imposed by such applications, the properties of the low- and intermediate-velocity structures which have been developed for them and the status of their development.

OVERVIEW OF ION AND PROTON SUPERCONDUCTING LINACS

Superconducting ion and proton linear accelerators can be grouped into three broad categories: high-current cw, high-current pulsed, and low-to medium current cw.



	High Current	Low/Medium Current
CW	Accelerator driven systems waste transmutation energy production	Nuclear structure studies Production of radioactive ions
Pulsed	Pulsed spallation sources	

High-current cw accelerators

The main application of cw high-current ion accelerators is for accelerator driven systems, either for energy production, waste transmutation or (some time ago) tritium production [1-3]. Superconducting structures have also been under consideration for a 40 MeV, 125 mA deuterium accelerator for production of very high neutron fluxes for the International Fusion Material Irradiation Facility [4,5].

The main technical issues and challenges for high-current cw srf linacs are:

- Beam losses (< 1 W/m in order to allow hands-on maintenance)
- Activation
- High cw rf power
- Higher order modes
- Cryogenics losses

The implications for SRF technology are:

- Cavities with high acceptance
- Development of high cw power couplers
- Extraction of HOM power
- Cavities with high shunt impedance

High-current pulsed accelerators

Accelerators in this category are mostly H$^-$ or proton accelerators for neutron production; the best example of these machines is the Spallation Neutron Source (SNS) under construction at ORNL as a collaboration between several laboratories [6], or the proposed European Spallation Source. A different application, although with similar beam parameters, is the proposed 8 GeV injector linac at Fermilab [7].

The main technical issues and challenges for high-current pulsed srf linacs are:

- Beam losses (< 1 W/m)
- Activation
- Higher order modes
- High peak rf power
- Dynamic Lorentz detuning

The implications for SRF technology are:

- Cavities with high acceptance
- Development of high peak power couplers
- Extraction of HOM power
- Development of active compensation of dynamic Lorentz detuning

Low-to-medium-current cw accelerators

The best example of low-to-medium current cw accelerator is the Rare Isotope Accelerator (RIA) under consideration in the US [8]. The RIA driver would be capable of initially producing a 100 kW, 400 MeV/u uranium beam and also a ~ 1 GeV proton beam.

The main technical issues and challenges for low-to-medium-current srf linacs are:

- Microphonics, frequency control
- Cryogenic losses
- Wide charge to mass ratio
- Multicharged-state acceleration
- Activation

The implications for SRF technology are:

- Cavities with low sensitivity to vibration
- Development of microphonics compensation
- Cavities with high shunt impedance

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[#] delayen@jlab.org

- Cavities with large velocity acceptance (few cells)
- Cavities with large beam acceptance (low frequency, small frequency transitions)

All these applications have some common features that differentiate them from the high-energy electron accelerators. Proton and ion srf accelerators are not usually at the high-gradient frontier. Operational and practical gradients are rarely limited by the fundamental properties of the superconducting material but are often limited by: acceptable cryogenics losses in cw applications, rf power to control microphonics in low-current applications, or rf power couplers in high-current applications. In many cases (especially for cw applications), a high shunt impedance is a more important design consideration than maximizing the accelerating gradient. For all high-current applications, minimization of beam losses and activation in order to allow hands-on maintenance after a short cool-down period is obviously an important consideration in the design of the accelerating cavities and the accelerator.

ACCELERATING STRUCTURES

The majority of the superconducting structures that are being developed for ion and proton accelerators fall into two categories. In the first category they are based on resonant transmission line modes (TEM-like); they can be either λ/4 (quarter-wave resonators) or λ/2 (coaxial half-wave and spoke geometry). In the second category they are based on a transverse magnetic (TM) mode producing cavities that are compressed versions of the familiar "elliptical" geometry used in high-energy accelerators [9-12].

TEM-class cavities

In the lowest velocity range the most common resonator geometry for resonator under development is based on λ/4 resonant lines, the quarter-wave resonator (QWR) and its variants. The split-ring geometry has been used extensively in the past but is not proposed any more for future applications.

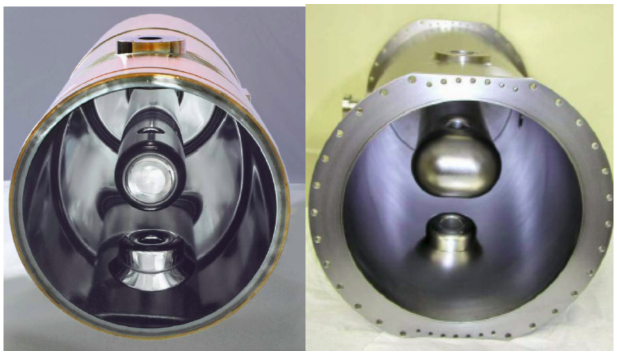

Fig 1: Examples of quarter-wave cavities; LNL and MSU-LNL.

Because of the lack of symmetry around the beam line in QWRs, the electric and magnetic fields induce a vertical steering on the beam which increases with frequency. This effect can be reduced by shaping or intentional misalignment of the center conductor.

The λ/2 structures that have been developed and are under consideration for proposed applications are of two types: the coaxial half-wave (mostly in the low-velocity region) [13-15], and the spoke geometry (mostly in the medium-velocity region) [13, 16]; the latter having the advantage of being able to be used as a building block for longer multi-gap structures [17-20]. Structures based on λ/2 resonant lines have a higher degree of symmetry than those based on λ/4 and thus do not have a dipole component, although they still have a quadrupole component.

Fig 2: Examples of coaxial half-wave cavities; ANL, MSU and ACCEL/SARAF.

Fig 3: Examples of single-, double-, and triple-spoke cavities developed at ANL [16, 31,32].

Structures with a large number of loading elements are also possible and are under development. They could, in principle, offer a higher real estate gradient, but at the expense of being fixed-velocity profile structures sensitive to manufacturing imperfections requiring tight alignment and tuning requirements. When the number of loading elements is large and they are rotated by 90° from one to the next, these cavities are sometime referred to as H-type cavities [19].

A number of laboratories worldwide are now involved in the development of spoke cavities [18-32].

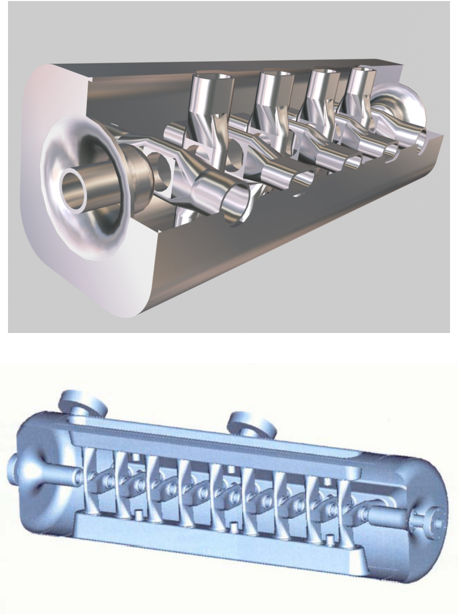

Fig 4: Examples of multi-spoke or CH cavities; Juelich and IAP-Frankfurt.

For lower velocities a "ladder"-type cavity where the four loading elements are parallel is being developed at LNL [34].

Fig 5: Ladder cavity under construction at LNL [34].

TM-class cavities

All the superconducting cavities in operation today for velocity-of-light particles are of the same design with only subtle differences. They are of the so-called elliptical geometry, *i.e.* rounded pill-box cavities operating in the TM_{010} mode with transverse dimension close to λ. This geometry can straightforwardly be extended to lower β by reducing the length of the cells while maintaining a constant frequency.

A number of TM mode multi-cell cavities have been designed and tested for βs as low as 0.47 [35-43].

Figure 6: Examples of β=0.81, 0.61, and 0.47 elliptical cavities [35, 43].

For much lower velocities, single-cell TM-type reentrant cavities can be designed. They would be usable over a very wide range of velocities but are sensitive to Lorentz detuning [44].

Fig 6: Reentrant cavity developed at LNL [44].

DESIGN CONSIDERATIONS

General considerations

Low and intermediate-velocity accelerators for protons and ions usually are not designed to operate at very high gradients and, unlike high-energy electron accelerators, will not push the SRF technology in that direction. Operational gradients are in the 8-15 MV/m region and are limited by practical considerations. In cw applications, operating fields are limited by the load to the cryogenic system. In high current applications, the fields are limited by the capability of the fundamental power couplers. In the low-current applications, the fields are limited by the rf power required for field control. For cw applications, a high shunt impedance is often a more important objective than high gradient.

To various degrees, beam losses and activation are fundamental issues for medium-energy accelerators and important considerations in the design of the accelerating structures and the accelerators.

Superconducting ion accelerators in the medium-energy range are mostly used for the productions of secondary species: either neutrons in spallation sources, or exotic ions in the radioactive beam facilities. This is accomplish by having a medium-power (~ 100s kW) or high-power (~MWs) primary beam impinging and depositing its energy on a target. Thermal properties and the thermal dynamics of the target are important considerations in the design of the facility and the operation of the accelerator, and put strict constraints on the rate, duration, and recovery from beam interruption. Beam interruptions of a few ms may be without consequences, but could affect the lifetime of a target when they last several seconds. The implications on the cavity and accelerator designs are that the cavities should not be operated “close to the edge” and be provided with an ample frequency control window.

The main considerations that enter in the design of superconducting structures are:

- Low cryogenics losses
    - High $QR_S * R_{sh}/Q$
    - Low frequency
- High gradient
    - Low E_p/E_{acc}
    - Low B_p/E_{acc}
- Large velocity acceptance
    - Small number of cells
    - Low frequency
- Frequency control
    - Low sensitivity to microphonics
    - Low energy content
- Large beam acceptance
    - Large aperture (transverse acceptance)
    - Low frequency (longitudinal acceptance)

Peak surface fields

As mentioned earlier, medium-energy accelerators usually do not require, or cannot afford, operation of the cavities at very high gradients. Nevertheless, it is always good practice to limit the peak surface fields both electric and magnetic. We do not have, at present, extensive experience in this velocity and frequency range, especially in continuous operation, however peak surface fields around 27.5 MV/m and peak surface magnetic fields around 80 mT seem reasonable. It may turn out that these values are conservative but they still need to be demonstrated in large scale, routine operation.

Figure 8 shows the peak surface to accelerating fields that have been achieved in intermediate-velocity cavities. In the intermediate velocity region TEM- and TM-class cavities show similar peak surface to accelerating field values.

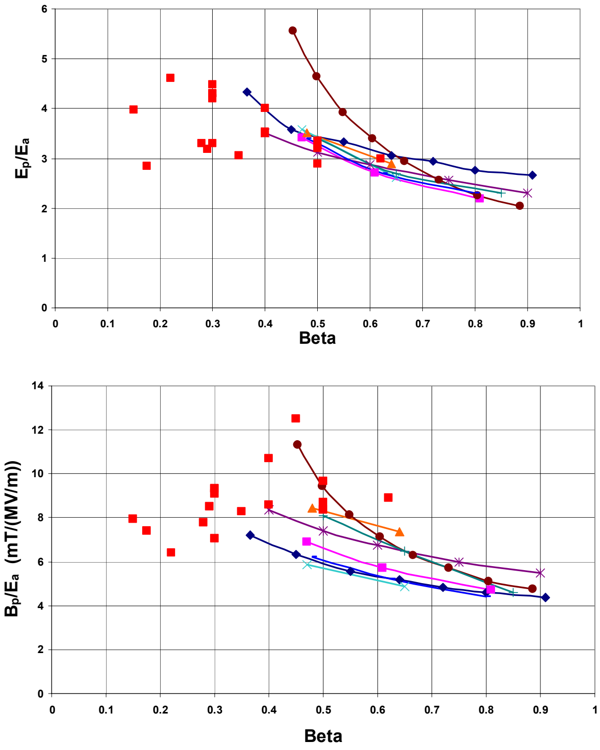

Figure 8: Peak surface electric field (upper) and magnetic field (lower) normalized to accelerating field. Data points joined by lines are for TM-class structures, isolated points (red squares) are for TEM-class structures.

Power dissipation

In cw operation the load imposed on the cryogenic system is a major consideration and is often the main limitation on the operating gradient. The power dissipation in an accelerating cavity at a given field is obtained from two parameters, one that his purely geometrical, and one that depends on the material properties of the cavity (the effective surface resistance R_s).

$$P = \frac{E^2 l^2}{R_s \; R_{sh}} R_s \qquad (1)$$

The geometrical parameter [denominator in Eq. (1)], is the product (in Ω^2) of the shunt impedance R_{sh} of the structure and the surface resistance R_s and depends only of the shape of the structure. Since it is proportional to the number of cells, it is shown per cell in Fig. 9 for the structures for which that data is available. Everything else being constant, TEM structures require less power dissipation than TM structures to provide energy gain.

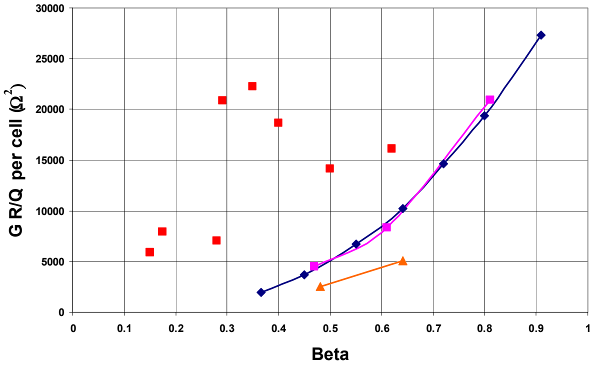

Figure 9: Product of shunt impedance and surface resistance (R_{sh} R_s) per cell or loading element.

Energy Content

The effect of the energy content is already included in the above parameters but is important in itself for the low current applications (such as RIA). When the beam loading is negligible, the amount of rf power involved in phase stabilizing a structure at a given gradient with a given amount of detuning (microphonics) is given by the product of the energy content and the detuning. When stabilization is obtained by negative phase feedback the rf power that needs to be available from the rf source is $P = U \Delta\omega$. When stabilization is obtained *via* an externally controlled reactance the amount of reactive rf power that must be switched or controlled is given by $P = 4 U \Delta\omega$.

Not only is the energy content proportional to the number of cells or loading elements but it also depends on the gradient and frequency as $U \propto E^2 \omega^{-3}$. The numbers quoted will be per cell or loading element, at 1 MV/m, and for a geometry scaled to 500 MHz. At the same gradient and frequency TEM-class cavities have much lower energy content than TM-class cavities.

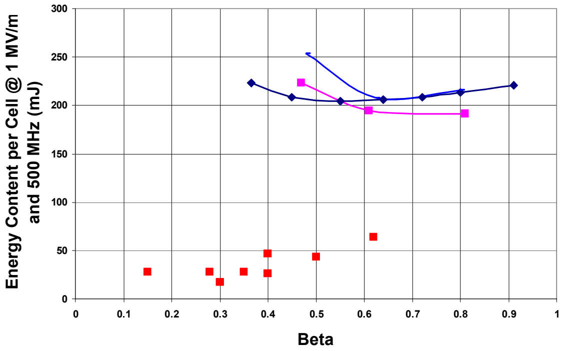

Figure 10: Energy content per cell or loading element at 1 MV/m for 500 MHz structures.

Lorentz Detuning and Microphonics

The Lorentz detuning coefficient (both static and dynamic) and the sensitivity to microphonics depend on the geometry of the cavity but are also strongly dependent on the details of the mechanical design (material thickness, stiffening, boundary conditions, *etc,*) and the environment. This is particularly true of the dynamic Lorentz coefficient where a small shift in the frequency of a mechanical mode can make it to correspond to a harmonic of the rf repetition rate and drastically increase the frequency excursion in pulsed mode. Measurement of the dynamic Lorentz coefficient on the SNS cryomodules showed large differences between supposedly identical cavities. However, use of piezo tuners has been very effective in reducing the frequency excursions during pulsed operation to acceptable levels [45].

Maintaining the level of vibration-induced frequency excursions (microphonics) to a low level is an important consideration in low-current applications since they determine the amount of rf power that will be needed to power the cavity and stabilize the fields. In most cases microphonics can be modeled by a number of parallel harmonic oscillators (the mechanical modes of the cavity) excited by white noise and the probability density of the microphonics would be gaussian (Fig. 11, upper). In some cases there is a dominant single-frequency driving term and the probability density would have the characteristic double maximum (Fig. 11, center). If the probability density is measured over a long time it sometimes can be represented by the sum of 2 gaussians (Fig.11, lower); this is indicative of an enhanced driving term of short duration. It is important to remember that, for large facilities comprised of a large number of cavities where the probability of any cavity being out-of-lock must be small, it is those rare occurrences of large levels of microphonics that must be accommodated by the rf control window. If the probability density is assumed to be gaussian then the probability of any cavity being out-of-lock of $<10^{-5}$ requires the control window to be at least 12 times the rms value of the microphonics [46].

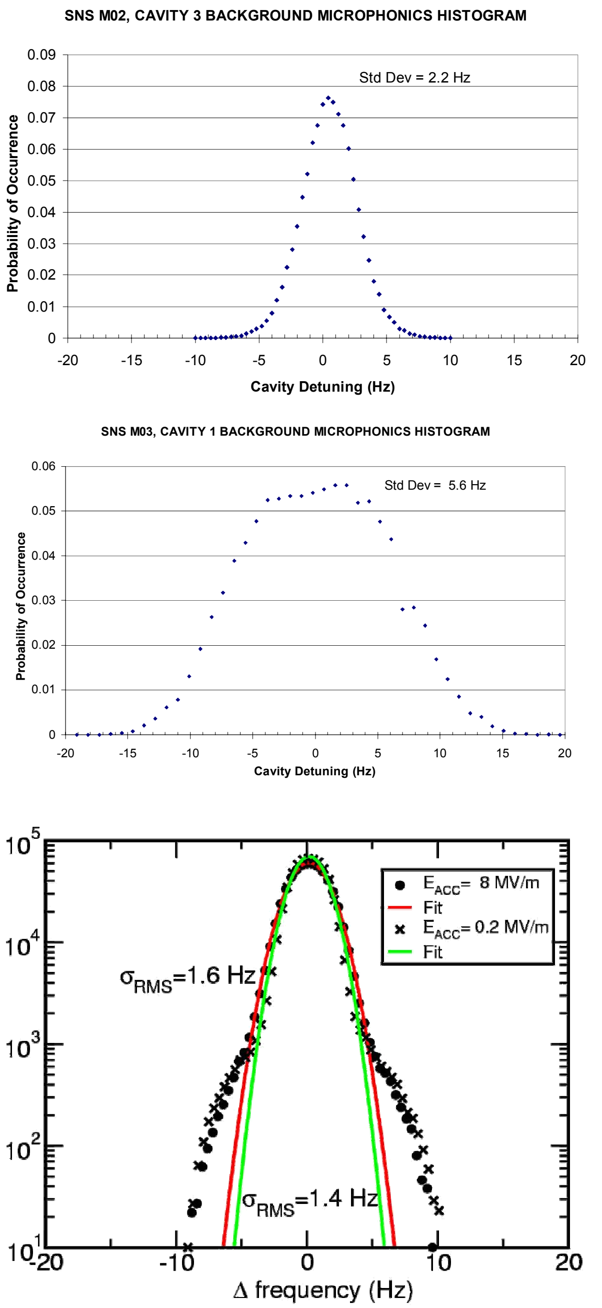

Figure 11: Probability density of microphonics. Upper: Gaussian; modes driven by noise [45]. Center: bimodal; modes driven by single-frequency term [45]. Lower: dual Gaussian; non-stationary driving term [47].

In the intermediate-velocity region, both TEM-class and TM-class cavities that have been developed so far have demonstrated levels of microphonics that are similar in magnitude although it is difficult to generalize since they are dependent on the environment and the cryostat design and, in the case of TM-class cavities at least, have shown large variations between supposedly similar cavities [48].

The frequency spectra of the microphonics are, however, very different between the two types of cavities. TM-class cavities show a rich spectrum where many mechanical modes are excited from a few 10s to several 100s Hz [48]. For the TEM-class cavities, the microphonics are dominated by low-frequency modulations caused by fluctuations in the cryogenics system with a few high-frequency mechanical modes being excited and contributing little to the microphonics [49]. The low-frequency excursion ought to be easily removed with a piezo-tuner-based feedback system. A piezo-based feedforward system has also been demonstrated to reduce single-frequency-driven microphonics in elliptical cavities [50].

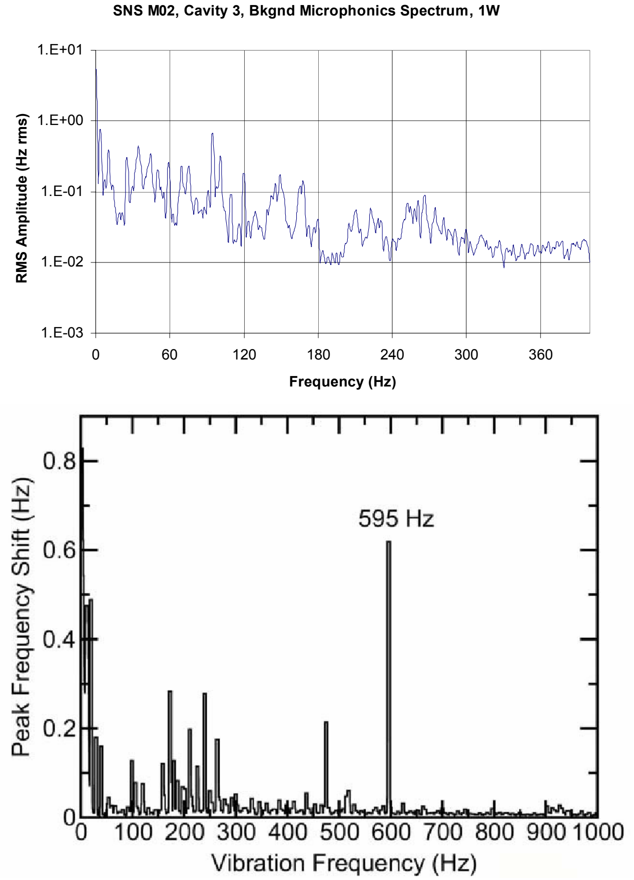

Figure 12: Spectrum of microphonics for a TM-class cavity (upper) [48] and a spoke cavity (lower) [49].

The same can be said of the Lorentz transfer functions (response of the cavity frequency to a sinusoidal modulation of the field). TM-class cavities show a very rich spectrum [48], while TEM-class cavities show a response at only a few high-frequency modes [51].

As shown in Fig. 14 very low levels of microphonics (~1 Hz rms) have been achieved in spoke-cavities [31]. It can be noted that the probability density of the microphonics is gaussian over 5 orders of magnitude. Fig. 15 shows that only the low-frequency components of microphonics contribute significantly to the phase error so that a fast mechanical tuner (piezoelectric or magnetostrictive) could substantially reduce the amount of microphonics and the requirements on the rf control system.

In pulsed applications, piezo electric tuners have been successfully used in reducing the amount of dynamic Lorentz detuning [45].

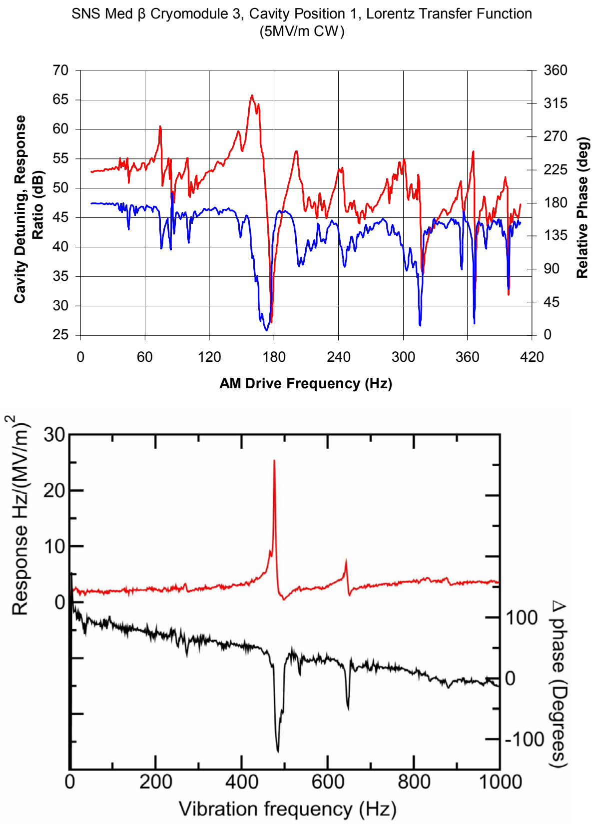

Figure 13: Lorentz transfer function of a β=0.61, 805 MHz 6-cell elliptical cavity (upper) [48] and of a double-spoke 352 MHz, β=0.4 cavity (lower) [51].

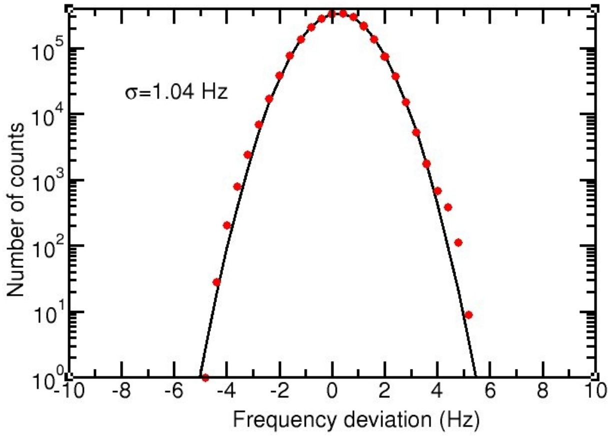

Figure 14: Probability density of microphonics in a triple-spoke, 345 MHz, β=0.50 cavity [31].

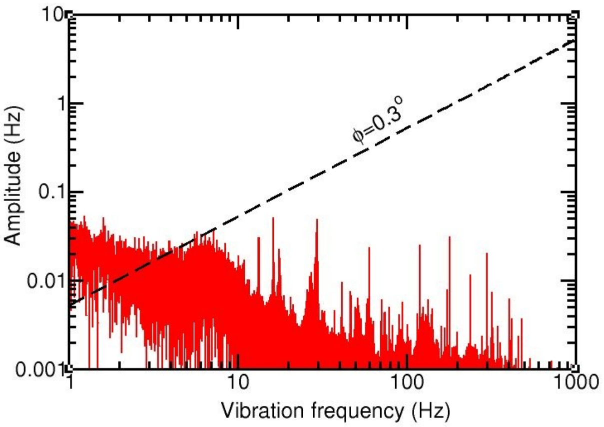

Figure 15: Frequency spectrum of the microphonics of Fig. 13 [31].

EXPERIMENTAL RESULTS

It would be impossible to present all the experimental results obtained to date. The best representative sample for the TM-class cavities is that of the 805 MHz cavities for SNS and RIA shown in Fig. 16. For the TEM-class cavities Fig. 17 shows results for a 352 MHz, β=0.35 single-spoke from Orsay [29] and Fig. 18 shows Q-curves for a 345 MHz, β=0.5, triple-spoke (upper) [31]; and 345 MHz, β=0.63, triple-spoke (lower) [32] from ANL.

A large ensemble of cavities, such as those tested for the SNS, have provided an opportunity to perform a statistical analysis on a non-negligible population size. As there is interest in utilizing similar cavity structures for other SRF accelerator projects, such as the Proton Driver, and Rare Isotope Accelerator, an analysis of the cavity qualification rate as a function of achieved gradient and Q_0 specifications was performed [52]. In this manner, one might be able to predict the cavity yield for similar cavities, processed in an identical fashion, but for a range of desired gradient and Q_0 performance.

In Figures 19 and 20, the normalized production yield for the SNS medium-β cavities is shown. Similarly, in Figures 21 and 22, the high-β yield is plotted. From inspection of these curves, it is clear that cavity qualification yield declines sharply as the cavity performance parameters are made increasingly more stringent. To achieve a reasonable cavity qualification yield for performance specifications significantly more demanding than those of the SNS will require an improved level of contamination control and more robust processing methodologies and infrastructure.

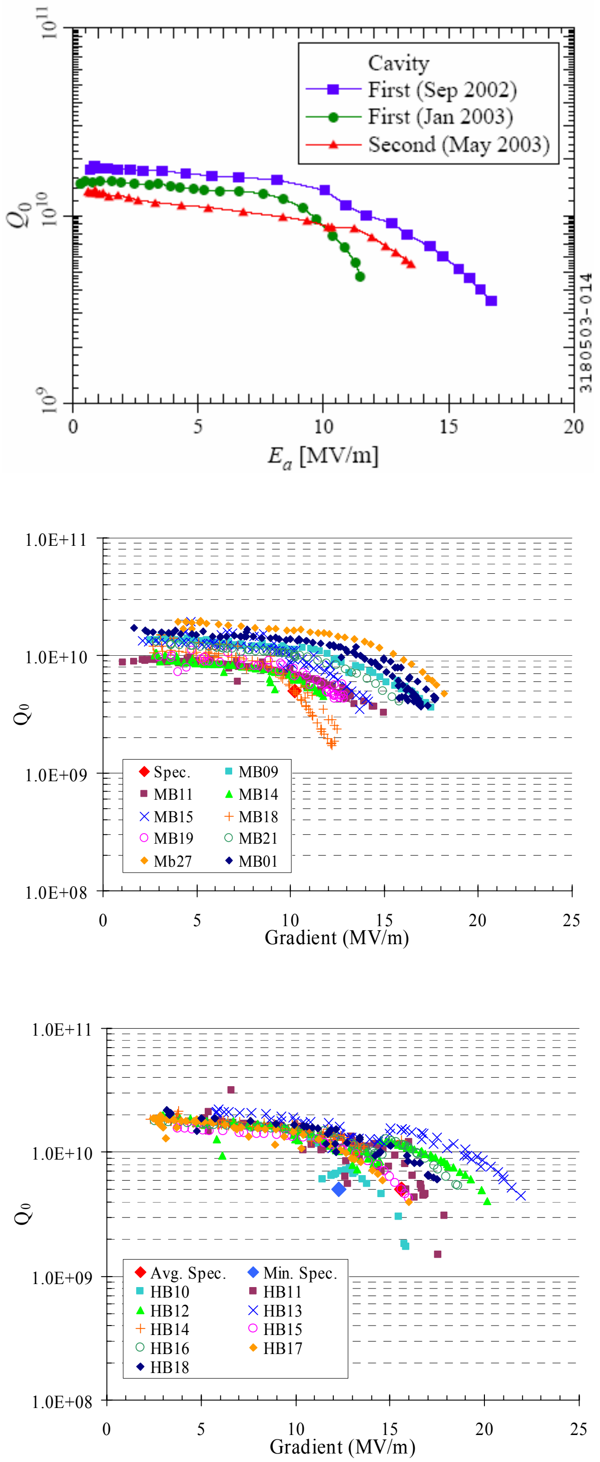

Figure 16: Experimental results for TM-class 805 MHz elliptical cavities. Upper: β=0.47 [43]; center: β=0.61 [52], lower: β=0.81 [52].

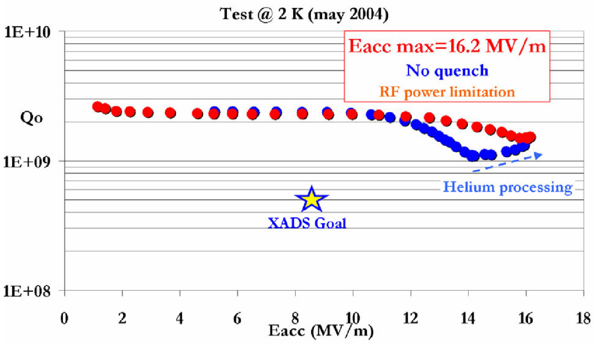

Figure 17: Q-curve for a single-spoke, 352 MHz, β=0.35 cavity [29].

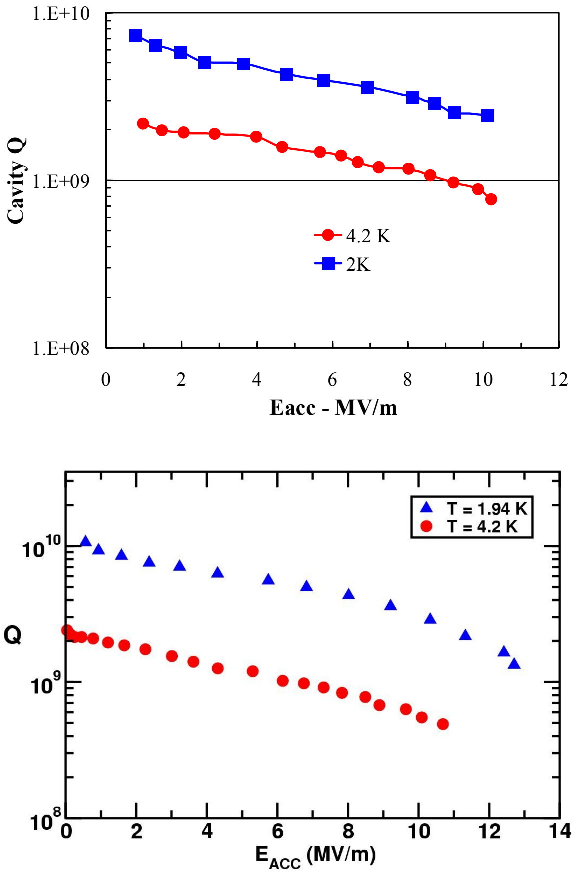

Figure 18: Experimental results for triple-spoke 345 MHz cavities. Upper: β=0.50 [31], lower: β=0.63 [32].

CONCLUSIONS

The development of superconducting cavities for proton and ion linacs has seen constant progress for more than 3 decades: new geometries are being developed for new applications for low to high currents, the whole velocity range from <.01c to c has been covered, and the performance is steadily improving.

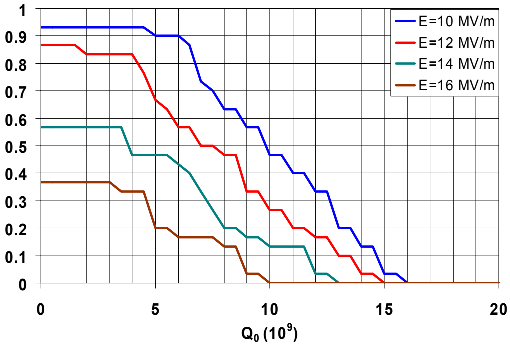

Figure 19: Fraction of 30 VTA tests of β=0.61 cavities exceeding a Q_0 at various operating gradients.

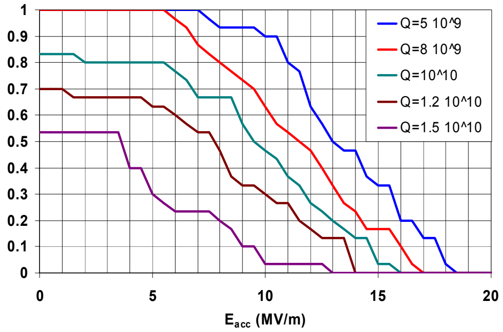

Figure 20: Fraction of 30 VTA tests of β=0.61 cavities exceeding a gradient at various Q_0.

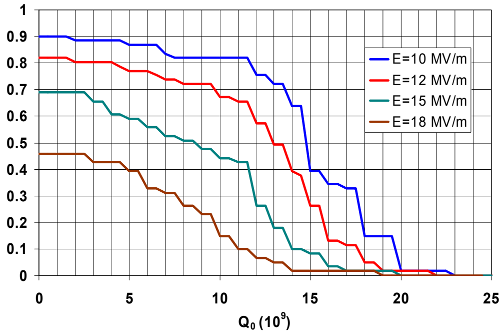

Figure 21: Fraction of 61 VTA tests of β=0.81 cavities exceeding a Q_0 at various operating gradients.

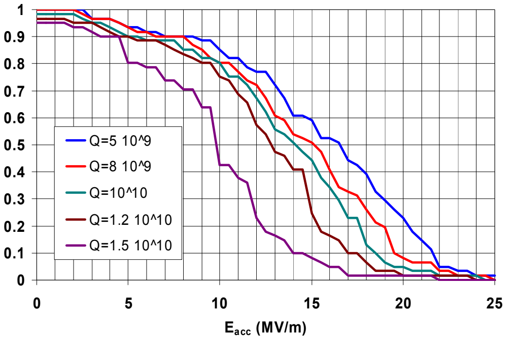

Figure 22: Fraction of 61 VTA tests of β=0.81 cavities exceeding a gradient at various Q_0.

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