INTERMEDIATE-VELOCITY SUPERCONDUCTING ACCELERATING STRUCTURES*

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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). 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 properties of these intermediate-velocity structures, the status of their development, as well as present an over view of the medium-energy superconducting ion accelerator designs being developed world-wide.

OVERVIEW OF MEDIUM-ENERGY ION ACCELERATORS

Medium-energy superconducting ion accelerators can be grouped into three broad categories: high-current cw, high-current pulsed, and low-to medium current cw.

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].

The main technical issues and challenges 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 collaboration between several laboratories [4], or the proposed European Spallation Source. A different application, although with similar beam parameters, is the 8 GeV injector linac at Fermilab [5].

The main technical issues and challenges 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 [6]. 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 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
- Cavities with large velocity acceptance (few cells)
- Cavities with large beam acceptance (low frequency, small frequency transitions)

ACCELERATING STRUCTURES

The majority of the superconducting structures that are being developed for medium-energy accelerators fall into two categories: those based on $\lambda/2$ resonant transmission line modes (TEM-like) and those based on a transverse magnetic (TM) mode [7-9]. The former can be of either the coaxial half-wave or spoke geometry, the latter are compressed versions of the familiar "elliptical" geometry used in high-energy accelerators.

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TEM-class cavities

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) [10, 11], and the spoke geometry (mostly in the medium-velocity region) [10, 12]; the latter having the advantage of being able to be used as a building block for longer multi-gap structures [13-16]. 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 [15]. A number of laboratories worldwide are now involved in the development of spoke cavities [14-26].

Fig 1: Examples of single-, double-, and triple-spoke cavities [11, 16, 26].

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 cavities have been designed and tested for β's as low as 0.47 [27-35].

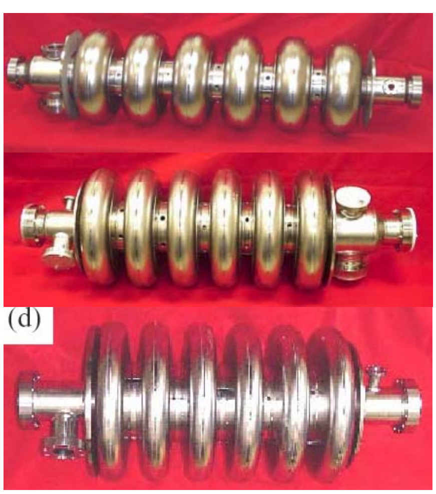

Figure 2: Examples of β=0.81, 0.61, and 0.47 elliptical cavities [27, 35]

DESIGN CONSIDERATIONS

General considerations

Intermediate-velocity ion accelerators 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

- 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 3 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.

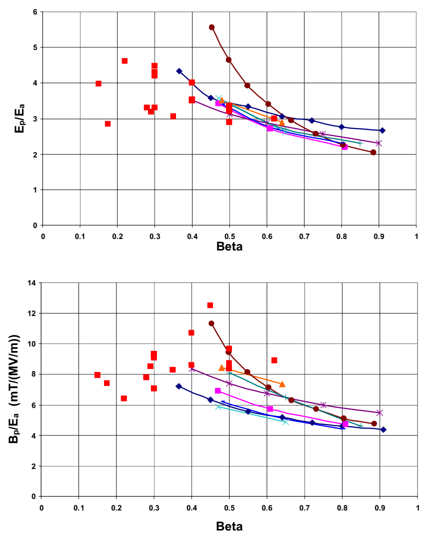

Figure 3: Peak surface electric field (upper) and magnetic field (lower) normalized to accelerating field. Data points joined by lines are for TM-class structures, isolated points (red squares) are for TEM-class structures.

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).

$$P = \frac{E^2 l^2}{R_s\ R_{sh}} R_s \tag{1}$$

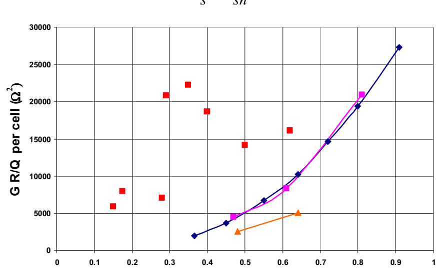

Figure 4: Product of shunt impedance and surface resistance (R_{sh} R_s) per cell or loading element.

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. 4 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.

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.

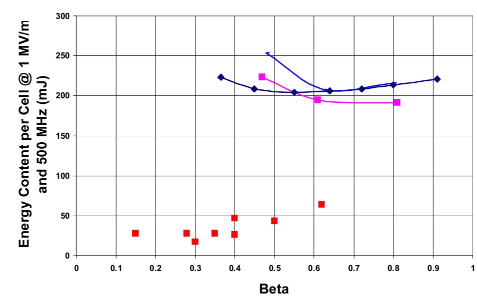

Figure 5: Energy content per cell or loading element at 1 MV/m for 500 MHz structures.

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 [36].

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. 6 left). In some cases there is a dominant single-frequency driving term and the probability density would have the characteristic double maximum (Fig. 6 center). If the probability density is measured over a long time it sometimes can be represented by the sum of 2 gaussians (Fig.6 right); 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 [37].

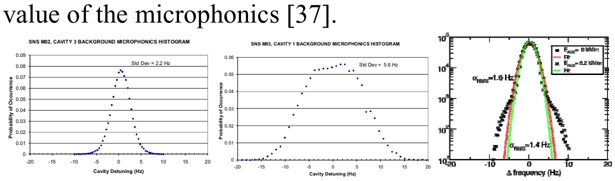

Figure 6: Probability density of microphonics. Left: Gaussian; modes driven by noise [36]. Center: bimodal; modes driven by single-frequency term [36]. Right: dual Gaussian; non-stationary driving term [38].

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 have shown large variations between supposedly similar cavities [39]. 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 form a few 10s to several 100s Hz [39]. 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 [40]. 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 [41].

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 [39], while TEM-class cavities show a response at only a few high-frequency modes [38].

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 shown in Fig. 7 (upper). For the TEM-class cavities Fig. 7 shows results for a 345 MHz, β=0.4, double-spoke from ANL (lower left) [16]; and 352 MHz, β=0.35 single-spoke from Orsay (lower right) [25].

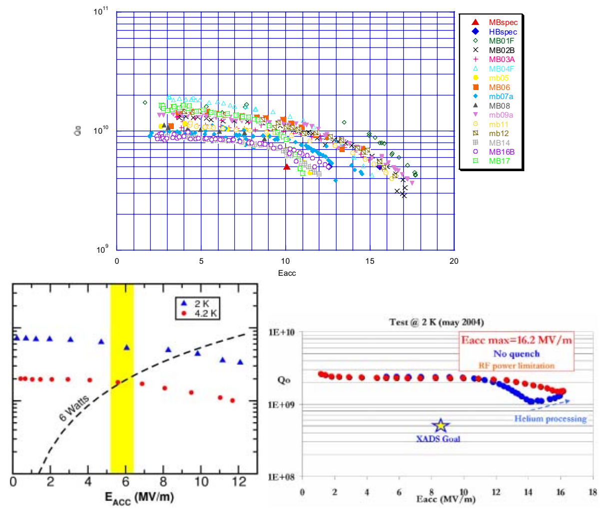

Figure 7: Experimental results for TM-class elliptical cavities (upper) and TEM-class spoke cavities (lower).

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