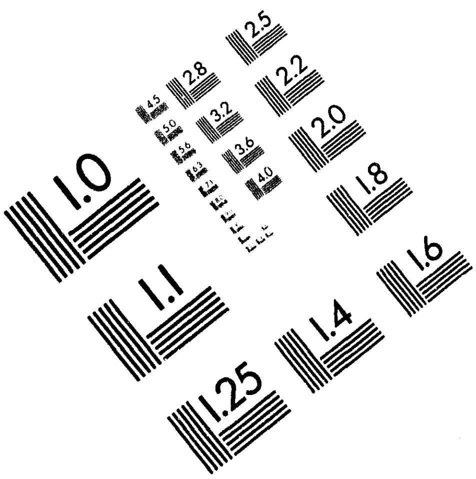

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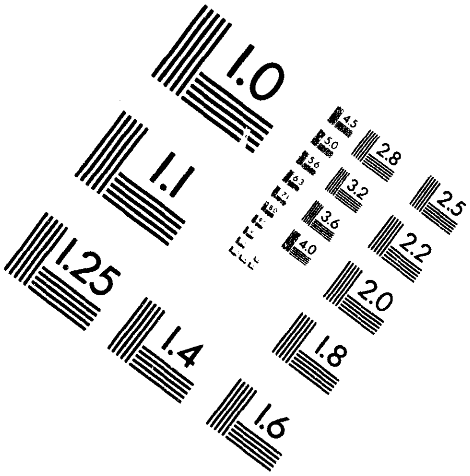

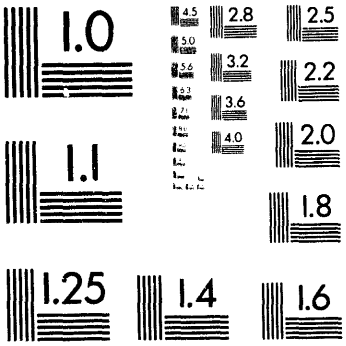

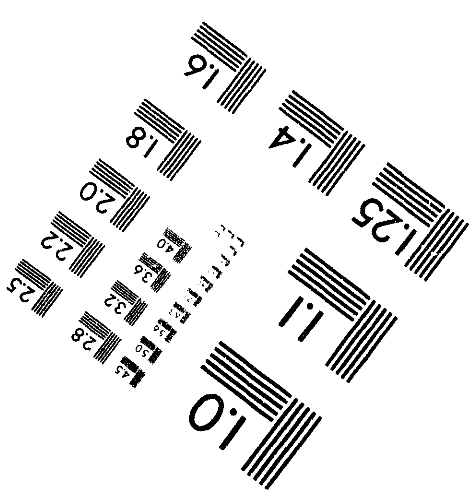

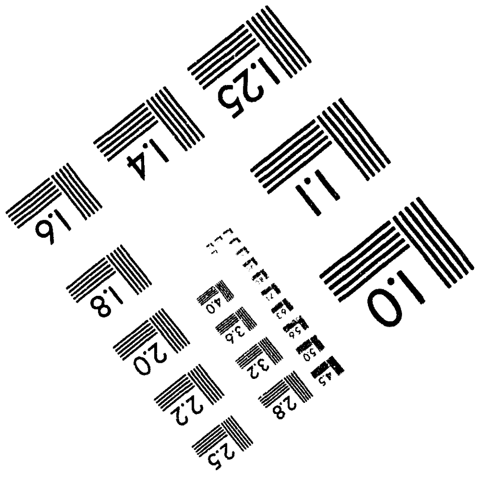

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Overview of Superconducting RF Technology and its Application to High-Current Linacs

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Abstract. Superconducting linacs may be a viable option for high-current applications such as copious neutron production like that needed for transmutation of radioactive waste. These linacs must run reliably for many years and allow easy routine maintenance. Superconducting cavities operate efficiently with high cw gradients, properties which help to reduce operating and capital costs. However, cost effectiveness is not the sole consideration in these applications. For example, beam impingement must be essentially eliminated to prevent unsafe radioactivation of the accelerating structures, and thus large apertures are needed through which to pass the beam. Because of their high efficiency, superconducting cavities can be designed with very large bore apertures, thereby reducing the effect of beam impingement.

I. INTRODUCTION

Questions regarding the design of linear accelerators with high duty factor for the long-term production of high-current ion beams center as much on beam physics as on hardware. The pervasive concern is whether dynamical phenomena which generate a diffuse halo of beam particles can be sufficiently controlled to limit radioactivation induced by beam impingement to safe levels. For example, as indicated in Section III below, the maximum tolerable amount of beam impingement is of the order of 0.03 nA/m for 1 GeV protons. The heat load associated with this level of impingement is 30 mW/m. The rf losses on a superconducting cavity will be ~20-40 W/m, and therefore radioactivation is by far the dominant concern related to beam impingement on superconducting structures. This concern is equally important for copper accelerators. Because shunt impedance is of less concern in superconducting cavities, they can be designed to operate at low frequency and with large bore-hole apertures to mitigate impingement. These constitute additional degrees of freedom which are available in the design of high-current linacs. In Section IV below, we provide four generic superconducting cavity geometries designed specifically for use in these high-current linacs.

II. SUPERCONDUCTING ACCELERATORS

Superconducting accelerators now have a long history which spans almost 20 years [1-8]. Both low-velocity ion (and proton) accelerators and high-energy electron accelerators have been developed and are operating. With the exception of a few high-energy electron accelerators, all of them have been low current machines where the power delivered to the beam was much smaller than the rf power which would have been required had the accelerator been normal-conducting. The main driver in the development of superconducting accelerators has been the substantial reduction of electrical power required to achieve the beam energy. As the beam current is increased the rf power delivered to the beam also increases and, if the current is sufficiently high, even a normal-conducting accelerator becomes beam loaded. Thus, for very

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high-current beams, the relative reduction in power provided by superconductivity is not large, while the absolute reduction remains approximately the same.

Another important characteristic of superconducting cavities and accelerators is that they can sustain high cw gradients. This usually translates into accelerators which are substantially shorter than their normal-conducting counterparts and a corresponding reduction in construction and capital costs. As the beam current is increased, however, the maximum operating gradient will not be set by the maximum value that can be sustained by the cavities but by the maximum amount of rf power that can be transmitted by each coupler from room temperature to cryogenic temperature. For accelerators of the ATW class it is expected that, indeed, the couplers would limit the achievable gradient otherwise attainable but that it still would be higher than that of a normal-conducting accelerator.

Superconducting accelerators (especially at low velocity) have traditionally been built from a large number of small, independent accelerating cavities. The main reason is that those accelerators had to be able to accelerate particles with widely different charge-to-mass ratio and thus had to be able to tailor their velocity profile to the particle to be accelerated. This feature had the added advantage that each cavity could be operated at its optimum field value instead of at a predetermined design value. Additionally, these accelerators displayed very good reliability and availability since they could operate in the presence of a number of local point failures-- all that was needed was to readjust the phase and amplitude of the cavities past the failure point. This enhanced reliability could be of major importance in accelerators of the ATW class which must provide high availability. The amount and location of point failures that can be tolerated would, however, be dependent on the beam current and would be determined by detailed beam dynamics studies. Preliminary studies on a deuteron accelerator for IFMIF indicate that loss of a cavity or focusing element could be tolerated while maintaining a reasonable bunch size and beam emittance.

While all the previous considerations have been crucial for low-current superconducting accelerators and may still be important for high-current accelerators, the main advantage that the superconducting technology may have for the latter is in offering a way to reduce beam loss and activation of the accelerator, thus possibly allowing hands-on maintenance instead of the required remote maintenance when beam loss exceed a certain value. Because the surface resistance of superconductors is a quadratic function of frequency, it is usually more efficient to design superconducting accelerators for lower frequencies than one would for normal-conducting ones. Thus a large bore size is often a natural feature of superconducting structures. Additionally, since optimizing the shunt impedance of a superconducting structure is not an overarching consideration as it is in the case of normal-conducting structures, at a given frequency, the former can be designed with much larger apertures than optimal, further reducing the mount of beam impingement.

III. LIMITS ON PERMISSIBLE RADIOACTIVATION

Studies of the amount of beam impingement that can be tolerated while still allowing hands-on maintenance have been done in the case of 35 MeV deuteron accelerators. Typically, dose rates of the order of 2 mrem/h, 30 cm from the accelerators and 24h after shutdown are obtained for beam losses of the order of 1 nA/m for either copper or niobium [9].

For high-energy proton accelerators, detailed calculations are much more difficult to perform. Neutron yields increase with higher Z for proton bombardment; the range of 1 GeV protons in both niobium and copper is of order 40 cm,[2] and, because the wall thickness of the cavities is much less than the range, radioactivation of niobium should be slightly more, but comparable to, that of copper. Thus, for a proton beam, the current loss in both niobium and copper needs to be less than 0.2 nA/m at 200 MeV, and less than 0.03 nA/m at 1 GeV, to be under 2.5 mrem/hr at a distance of 1 m from the linac one hour after shutdown [10].

IV. SUPERCONDUCTING STRUCTURES

1. General considerations

Geometries of low-velocity superconducting resonators generally incorporate an inner conductor which provides a TEM-like accelerating mode [11]. The center-gap to center-gap distance in these structures is of order $\beta\lambda/2$, where $\beta = v/c$ is the beam velocity, and λ is the rf wavelength. For velocities less than ~0.1c and frequencies of several hundred MHz, this distance becomes too small for practical resonators, and this consideration is a principal motivator for superconducting RFQs which provide proton energies to ~8 MeV [12]. For proton energies ranging from 8 MeV to 2 GeV, the corresponding velocity range is $\beta = 0.1\text{-}0.9$. Superconducting resonators have recently been developed for frequencies in the range 350-850 MHz and optimized for velocities up to $\beta = 0.3$. Off-line experiments with these structures have yielded high accelerating gradients [13,14]. Of these structures, the easiest to fabricate is the spoke resonator shown in Fig. 1. This geometry is also modular, for several units can be stacked together to make a multigap cavity. For these reasons, we use the spoke as the baseline geometry for superconducting cavities to be used in high-current linacs.

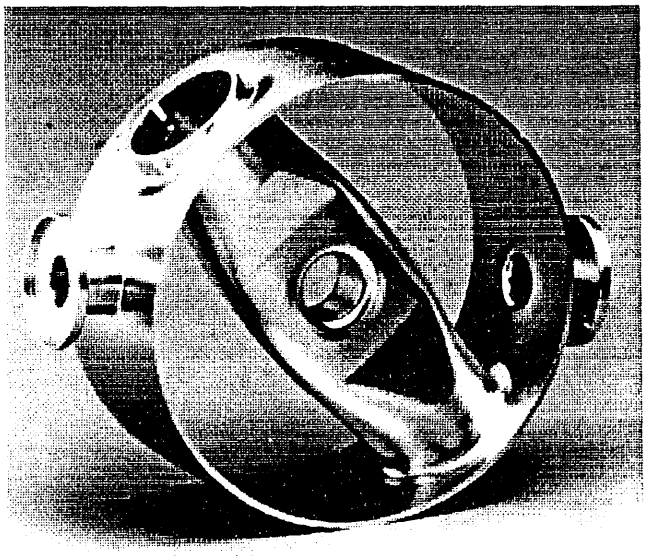

Figure 1. 850 MHz, $\beta = 0.28$, 2-gap spoke resonator prior to the welding of the end plates.

The choice of frequency hinges on a number of considerations. One of them is the ability to provide large-bore apertures for the beam, and this favors lower frequencies and larger cavities. Large bores also provide lower transverse shunt impedances which reduce cumulative beam breakup. The availability of rf power is a second concern.

On the other hand, it has been inferred from numerical simulations that high frequencies mitigate emittance growth by lowering the charge per bunch [15]. This is a major consideration when emittance preservation is crucial. For most of the high-current applications, however, emittance growth is a concern only in connection with halo formation and beam transport. A detailed understanding of the effects of bunching on high-current beams is a fundamental building block for the design of these linacs, and this will be the topic of future investigations.

One possible strategy for achieving high currents is to combine two beams by funneling them together at a relatively low energy, a process which doubles the rf frequency. To achieve large bores and use a common frequency for rf power amplifiers, we shall assume the linac operates at 350 MHz, and that prior to funneling, the frequency is 175 MHz.

2. Large-bore superconducting cavity geometries

As shown in the examples of Figs. 2 and 3, the spoke geometry can be adapted to span a wide velocity range. For high velocities it becomes more practical to introduce single-cell structures like that shown in Fig. 4, or multicell structures like that shown in Fig. 5. The properties of these large-bore geometries, which were calculated with MAFIA in the case of the spoke resonators and SUPERFISH in the case of the "elliptical" cavities, are given in Table 2 below. In the Table, resonators #1-#4 refer to the 175 MHz, $\beta=0.125$ spoke, the 350 MHz, $\beta=0.45$ spoke, the 350 MHz, $\beta=0.45$ single-cell, and the 350 MHz, $\beta=0.8$ two-cell, respectively.

Compared to two-gap spoke resonators, two-cell "elliptical" cavities generally have higher shunt impedances and lower rf surface fields. They are also comparatively simple and easy to fabricate. However, for a given frequency, these structures are also much larger than the spoke, and are likely to be less mechanically rigid.

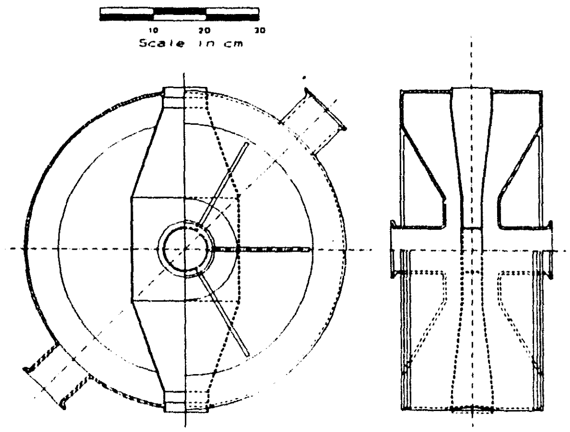

Figure 3. 175 MHz, $\beta=0.125$, 2-gap spoke resonator.

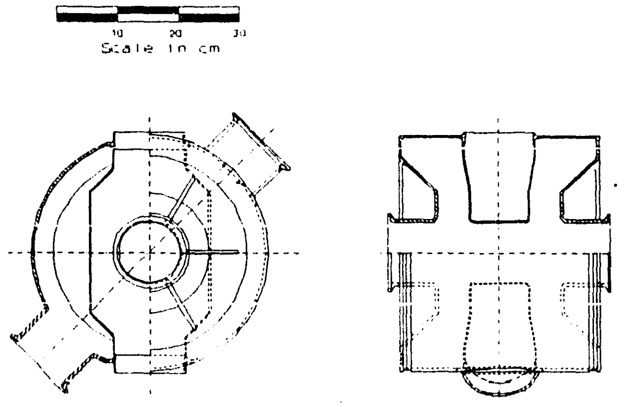

Figure 2. 350 MHz, $\beta=0.45$, 2-gap spoke resonator.

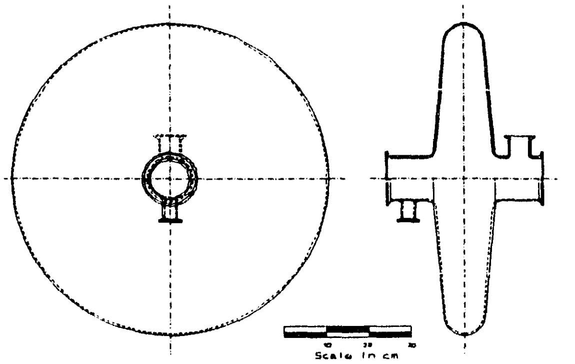

Figure 4. 350 MHz, β=0.45, single-cell TM_{010} resonator.

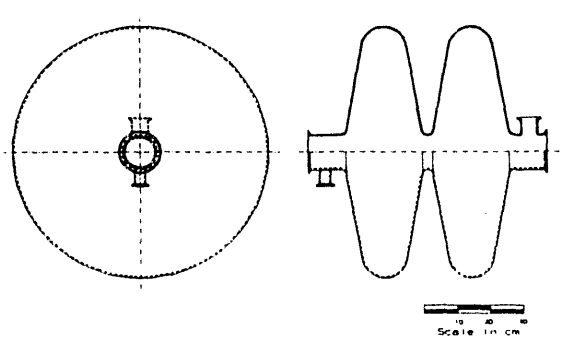

Figure 5. 350 MHz, β= 0.8, 2-cell TM_{010} resonator.

Table 1. Comparison of resonator properties.

	#1	#2	#3	#4
B_p/E_{acc}[G/(MV/m)]	122	125	41.6	35.9
R_{sh}^* (10^5 MΩ)	1.3	1.5	1.2	6.7
R_{sh}/Q (Ω)	47.1	121	51.3	205
P (W)*†	2.73	9.65	9.0	14.5
ΔV (MV)†	0.6	1.2	1.0	3.1
Diameter (cm)	60	38	74	76

*Assumes BCS R_s at T = 4.2 K, †At E_{acc} = 6 MV/m.

It remains to be determined where to transition from the spoke geometry to multicell structures in a full linac design. It is also of interest to determine the optimum number of gaps or cells for each structure. Beam dynamics and the availability of rf power influence this question. The required lattice period of focusing elements will be shorter at lower velocities. A requirement that the linac be operable when one or more structures have failed will place an additional constraint on structure length. The amount of rf power which may be input to the cavity will be limited by the capability of the coupler, and this places the most stringent restriction on structure length in high-current linacs.

V. CONCLUSIONS

Radiofrequency superconductivity offers a number of advantages for high-current, high-duty-factor linacs, among these is the ability to open up the cavity apertures to mitigate beam impingement and its associated radioactivation. The cavities also may be expected to operate at a higher real-estate gradient than their normal-conducting counterparts. There are no known show-stoppers for rf superconductivity in these applications; the associated beam physics is beginning to be understood [16-18], and appropriate accelerating structures have been designed.

An important uncertainty in the design of these linacs is the projected capability of rf power couplers. Coupler development and continued beam-physics research are key components of the development path. A more important and fundamental component, however, is a high-current ion-beam test of superconducting structures [13].

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