# OVERVIEW OF TEM-CLASS SUPERCONDUCTING CAVITIES FOR PROTON AND ION ACCELERATION

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### *Abstract*

Superconducting (SC) TEM-class cavities have been developed at institutions worldwide for cw and pulsed proton and ion linacs. New geometries spanning nearly the full velocity range from 0.1 < v/c < 0.8 include co-axial quarter and half-wave and single and multi-spoke cavities. Optimized designs have large beam acceptance, high shunt impedance and good microphonics properties. Rapidly improving clean surface processing techniques have been applied to TEM cavities where achieved surface fields and rf losses are comparable to the best results achieved in elliptical cavity designs. Recent results for a three-spoke cavity following hydrogen degassing after fabrication show very low rf losses even at high accelerating fields and open the possibility for substantially reduced effective cryogenic load in 2 K, rather than the historically used 4 K, operation. At present performance levels, SC TEM-class cavities constitute the technology of choice for most ion linac applications requiring cavities up to or beyond v/c=0.6.

## INTRODUCTION

Superconducting (SC) cavities have low rf losses, typically of the order of 10 Watts per active meter of accelerating structure, or roughly 100 times less than copper structures in cw operation. Similarly, modern TEM cavities offer high accelerating gradients (≥7 MV/m) and high real estate gradients (≥2 MV/m) both for low particle energies ~5 MeV/u up to several hundred MeV/u.

In pulsed operation SC structures may still offer critical advantages. The large bore diameter, typically 3-5 cm for TEM cavities, provides large transverse acceptance while the low frequencies, 50-350 MHz, result in large longitudinal acceptance. This is important for high power linacs where beam losses should be $\leq 1$ Watt/meter. In addition, SC cavities are short (~1 m) and independently powered so that, with modern controls systems, the cavity array may be retuned if one or more become inoperable. This high degree of fault tolerance is required for applications such as the accelerator driven transmutation of nuclear waste (ADS) where reliability is crucial. Finally, SC linacs have the flexibility of operations, such as multi-charge state and multi-ion acceleration, which is simply not possible with any other readily available technology.

## CAVITIES

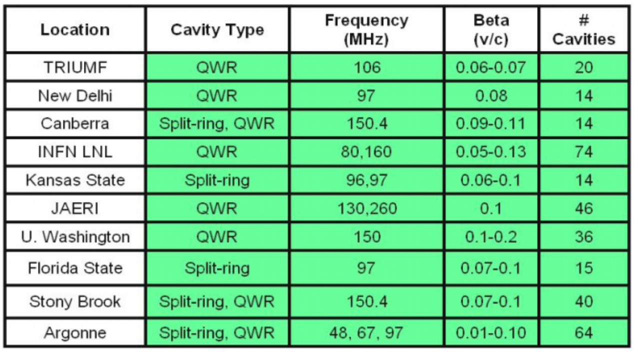
Superconducting (SC) TEM-class cavities, so referred for the electromagnetic modes resembling the TEM-modes of a coaxial transmission line, have been operated in ion linacs worldwide for three decades [1]. Several excellent recent reviews are available [2-4]. This discussion focuses on today's state-of-the-art TEM structures.

Existing TEM-class cavities are either quarter-wave ($\lambda/4$) as in Figure 1 or half-wave structures ($\lambda/2$) as in Figure 2 with frequencies ranging from ~50-800 MHz and typical dimensions of $0.1 \leq l \leq 1$ m. Spoke cavities, a type of $\lambda/2$ structure, have one or more central conductors oriented perpendicularly to a cylindrical outer housing and are easily extended to multiple cells per cavity.

To date, the operating temperature for all TEM-class cavities has been ~4 K since lower temperatures would have offered no practical benefit. It is noted that SC elliptical-cell cavities, used in mostly in electron linacs

Figure 1: Quarter-wave cavities. Clockwise from top left; ANL 97 MHz $\beta$=0.07,0.1, Stony Brook 150 Mhz $\beta$=0.06, 0.1, New Dehli 97 MHz $\beta$=0.1, ANL 425 MHz $\beta$=0.155, INFN-LNL 160 MHz, ANL 115 MHz $\beta$=0.15.

Figure 2: Spoke cavities. Clockwise from top left; ANL 805 MHz $\beta$=0.28, IPN-Orsay 352 MHz $\beta$=0.35, Jülich 760 MHz $\beta$=0.2, ANL 350 MHz $\beta$=0.63, LANL 350 MHz $\beta$=0.17.



| Location | Cavity Type | Frequency (MHz) | Beta (v/c) | # Cavities |
|---|---|---|---|---|
| TRIUMF | QWR | 106 | 0.06-0.07 | 20 |
| New Delhi | QWR | 97 | 0.08 | 14 |
| Canberra | Split-ring, QWR | 150.4 | 0.09-0.11 | 14 |
| INFN LNL | QWR | 80,160 | 0.05-0.13 | 74 |
| Kansas State | Split-ring | 96,97 | 0.06-0.1 | 14 |
| JAERI | QWR | 130,260 | 0.1 | 46 |
| U. Washington | QWR | 150 | 0.1-0.2 | 36 |
| Florida State | Split-ring | 97 | 0.07-0.1 | 15 |
| Stony Brook | Split-ring, QWR | 150.4 | 0.07-0.1 | 40 |
| Argonne | Split-ring, QWR | 48, 67, 97 | 0.01-0.10 | 64 |

Figure 3: Facilities based on TEM-class cavities.

with velocity $v/c=\beta\sim1$, generally require 2 K operation due to the higher cavity frequencies, mostly $\geq$800 MHz, and the higher associated BCS losses which increase with the square of the cavity frequency.

SC proton and heavy-ion linacs for 10 MeV/u (v/c~0.1) (see Figure 3) and SC electron-beam linacs for higher energies up to several GeV (v/c~1.0) have operated for decades. However, starting in the past decade many applications requiring new structures at intermediate velocities were proposed. A list of projects using TEM cavities, shown in Figure 4, includes both cw and pulsed hadron linacs for the rare isotope production, intense spallated neutrons for nuclear waste transmutation (Accelerator Driven Systems) and pulsed proton beams for neutrino physics studies.

Cavities required for these SC linacs span most of the full velocity range (0.1<v/c<1.0) and would use quarter-wave, co-axial half-wave, and spoke-loaded TEM cavities, as well as, $TM_{010}$ elliptical-cell cavities for ion velocities v/c~0.6 and higher.

## HIGH-PERFORMANCE CAVITIES

### *Fabrication*

Any of the dozens of major and minor cavity fabrication steps which include material procurement, handling, machining, forming, welding and final surface processing will impact cavity performance. Likewise, fabrication procedures and quality assurance techniques have advanced dramatically over the past three decades leading to much improved SC cavity performance.

Recently fabricated TEM-cavities have been designed mostly using PC-based 3D simulation codes such as MAFIA, Microwave Studio, and ProEngineer/ANSYS [5]. High-purity (RRR~250) bulk niobium, usually in the form of 2-4 mm thick sheets and available from several vendors, is the material of choice for parts fabrication.

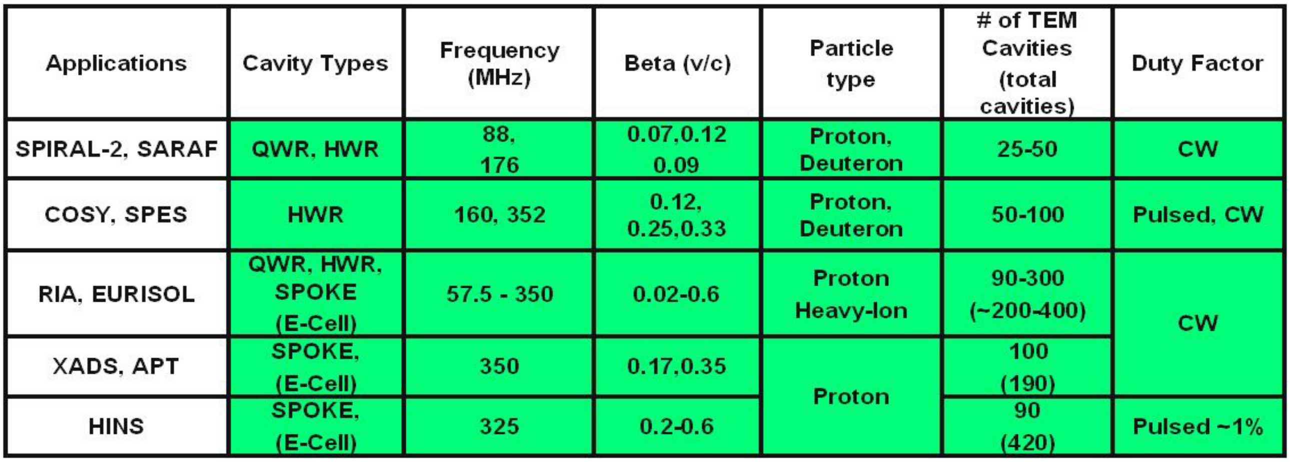
Hydroforming or deep-drawing techniques are used to produce nearly any desired geometry and in large quantities if needed. Cavity shapes, and in particular the loading elements are tailored to minimize both the peak surface electric and magnetic fields (see *e.g.* [6]). A peak surface electric field of 3 MV/m for one MV/m of accelerating gradient ($E_{PEAK}/E_{ACC} = 3$) is typical for an optimized TEM cavity. Similarly for magnetic fields, the range for optimized designs is $B_{PEAK}/E_{ACC} = 6\text{-}8$ mT/MV/m.

Formed niobium cavity parts are welded together under high vacuum, typically $1\times10^{-6}$ Torr or better, using an electron beam. Welded cavities intended for operations are housed inside an integral helium jacket constructed from stainless steel, titanium or niobium. Liquid helium is fed by gravity into the jacket and cools the SC cavity surface by conduction through the thin-wall niobium.

### *Chemical Processing*

The present state-of-the art in surface preparation of SC rf cavities calls for the removal of at least a ~100 μm thick damaged layer resulting from niobium forming and machining. Electropolishing [7] (EP) has been used with SC cavities since the early 1970's and has been used to produce smooth surfaces free of major defects. The other widely used technique for damaged layer removal is buffered chemical polishing (BCP), which produces a manifestly rougher surface than EP when used on fine-grained (~50 micron) niobium material.

In elliptical-cell cavities treated with BCP the measured accelerating fields are somewhat lower than those achieved with EP [8]. Similarly, most TEM-class cavities treated with EP exhibit less Q-slope and lower rf losses, particularly at high gradients [9], than those treated with



| Applications | Cavity Types | Frequency (MHz) | Beta (v/c) | Particle type | # of TEM Cavities (total cavities) | Duty Factor |
|---|---|---|---|---|---|---|
| SPIRAL-2, SARAF | QWR, HWR | 88,<br>176 | 0.07,0.12<br>0.09 | Proton,<br>Deuteron | 25-50 | CW |
| COSY, SPES | HWR | 160, 352 | 0.12,<br>0.25,0.33 | Proton,<br>Deuteron | 50-100 | Pulsed, CW |
| RIA, EURISOL | QWR, HWR, SPOKE (E-Cell) | 57.5 - 350 | 0.02-0.6 | Proton<br>Heavy-Ion | 90-300<br>(~200-400) | CW |
| XADS, APT | SPOKE, (E-Cell) | 350 | 0.17,0.35 | Proton | 100<br>(190) | |
| HINS | SPOKE, (E-Cell) | 325 | 0.2-0.6 | | 90<br>(420) | Pulsed ~1% |

Figure 4: Proposed or funded projects using TEM cavities.

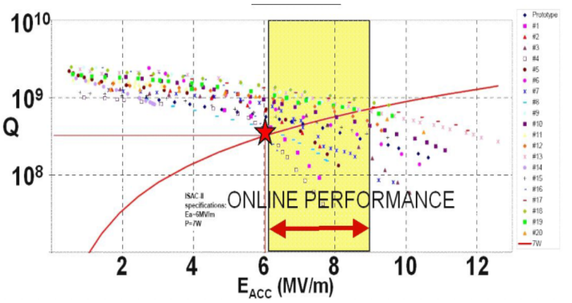


Figure 5: Today’s state-of-the-art for online performance at TRIUMF based on 20 quarter-wave resonators.

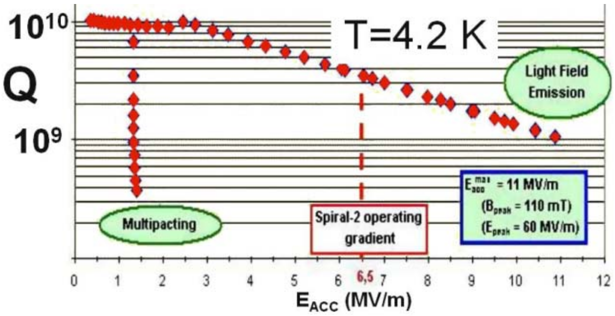


Figure 6: Measured Q-curve for a Spiral-2 88 MHz $\beta$=0.12 quarter-wave resonator from IPN-Orsay.

BCP. It is noted, however, that several well performing TEM-cavities have been produced using only BCP.

At ANL EP has been the standard surface treatment for more than three decades for low-$\beta$ TEM-class cavities. A variation on the EP technique has recently been used successfully at ANL. This was required since modern cavities are usually designed with no demountable joints and with sufficiently small access ports so that the (inner) rf surface is no longer accessible for EP after final electron beam welding. Instead, the niobium sub-components are heavily electropolished individually and then welded together. A brief ~5 minute BCP is then used to remove any residues from welding. The resulting surface has been shown to be much smoother than is achieved using only a heavy BCP treatment [10]. The same approach has also recently been proposed for use with the ~1000 elliptical cavities required for the XFEL.

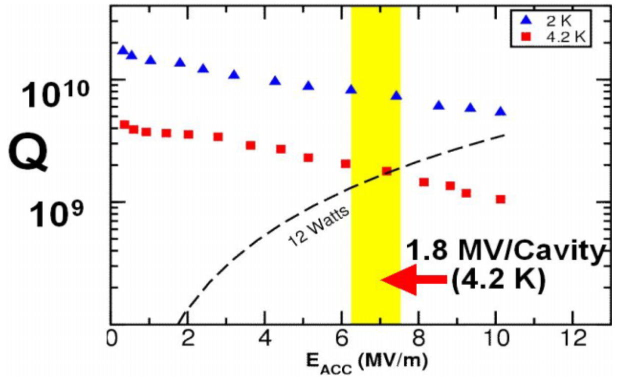


Figure 7: Measured Q-curves for a RIA 172 MHz $\beta$=0.25 half-wave resonator from ANL.

### *High-pressure Rinsing and Clean Assembly*

A major advance in SC cavity performance was achieved in the early 1990’s at laboratories such as KEK, DESY and JLab with the introduction of high-pressure water rinsing and clean room assembly. The goal is to remove and prevent contamination with particulates, which are known to cause field emission. These techniques have been adapted for TEM-cavities at Argonne [11] and elsewhere.

High-pressure water rinsing using filtered (to 0.1 µm or better) deionized water in a (class 100 or better) clean area for at least one hour is now required practice for reliably achieving accelerating gradients ≥10 MV/m. Similarly, final assembly of the cavity together with the power coupler and the vacuum system hardware must also be performed in a suitable, class 100 or better, clean area.

Little data exists on the maintenance of cleanliness in long-term linac operations. The best demonstration to date is FLASH at DESY [12] which uses separate cavity and cryogenic vacuum systems to maintain cleanliness. The linac has operated with dozens of clean SC elliptical cavities starting in the year 2001 with surface gradients exceeding $E_{PEAK}$>50 MV/m ($E_{ACC}$=25 MV/m) and no performance degradation.

## COLD TEST RESULTS

This section presents examples of today’s state-of-the art performance for different classes of TEM cavities. The accelerating length for measured Q performance curves has been defined to be $\beta\lambda/2$ per cell.

### *Quarter-wave Cavities*

In 2006 a set of twenty quarter-wave cavities with $\beta$=0.057 and 0.071 based on the INFN-LNL design was commissioned at Triumf [13]. This linac constitutes today’s state-of-the-art in terms of online performance and is the first TEM-cavity linac to use most of the clean room techniques discussed in the previous section. Single cavity test results are shown in Figure 5. together with the indicated range of performance online.

New quarter-wave geometries have been developed at IPN-Orsay, ANL, MSU [14-16] and elsewhere for velocities somewhat higher ($\beta$≥0.15) than previously used. Test results for a quarter-wave cavity developed for Spiral-2 at IPN-Orsay are shown in Figure 6 and are among the best achieved to date. This cavity has low rf losses ($R_{RES}$=1.5 nΩ at low fields) and a useful accelerating gradient (rf power~25 Watts) at 10 MV/m. Future linacs based on these new cavities will use separate cavity and cryogenic vacuum systems to preserve cavity cleanliness as done for elliptical-cell cavity linacs. The first TEM-cavity cryostats using separated cavity and cryogenic vacuum systems are being installed at both ANL and Soreq.

### *Coaxial Half-wave Resonators*

SC coaxial half-wave resonators have been developed as prototypes at ANL, INFN-LNL and MSU [17-18] for

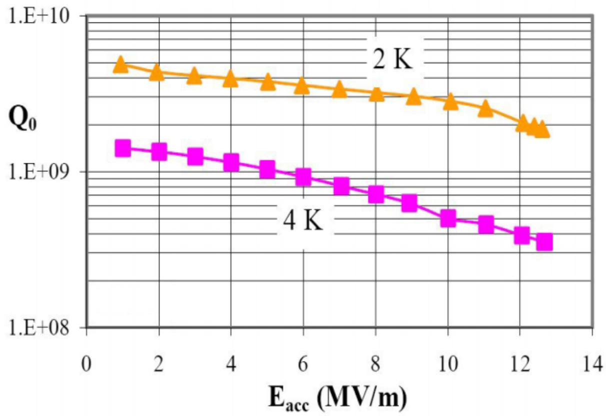


Figure 8: Q-curve test results for a 350 MHz $\beta$=0.175 single-spoke cavity developed at LANL.

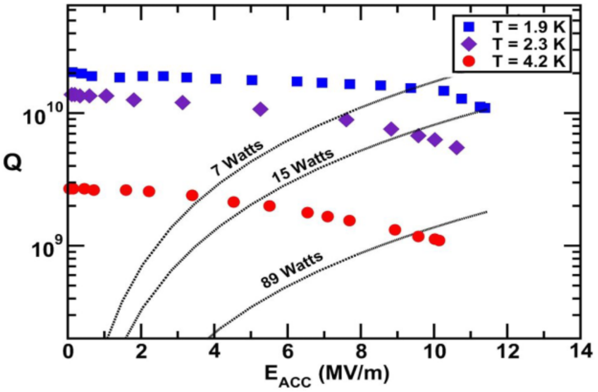


Figure 9: Q-curves and lines of constant rf power for an ANL 345 MHz $\beta$=0.63 triple-spoke cavity. At T=2 K, only 7 Watts rf power produces a gain of 7 MV/cavity.

proposed radioactive ion beam facilities and are being installed for the first time in a SC linac at SARAF with cavities fabricated in industry by ACCEL.

Today's half-wave cavities range in frequency from $f_0$=172-350 MHz and have an accelerating velocity range from 0.1<v/c<0.3. Cold test results, as shown in Figure 7, have demonstrated high accelerating gradients and low rf losses for this class of cavity.

### *Single-spoke Resonators*

The world's first SC spoke cavity, an 850 MHz, $\beta$=0.28 resonator, shown top-left in Figure 2, was developed in the early 1990's as part of work on Neutral Particle Beams for weapons [19]. In the mid-1990's a pair of single-spoke resonators for RIA (not shown) with $f_0$=350 MHz and $\beta$=0.29 and 0.4 were built, tested and then later high-pressure rinsed and assembled in a clean room to achieve accelerating gradients of more than 10 MV/m. More recently single-spoke cavities have been developed at LANL [20], and IPN-Orsay [14] for high-current and/or high beam power applications. These include a $\beta$=0.15 352 MHz cavity developed by IPN-Orsay for EURISOL, a pair of $\beta$=0.175 350 MHz cavities developed at LANL for AAA and a $\beta$=0.35 352 MHz cavity from IPN-Orsay for XADS.

Test results for one of the two LANL cavities are shown in Figure 8 indicating useful accelerating gradients above $E_{ACC}$=10 MV/m. Other single-spoke cavities at LANL, IPN and ANL have all achieved accelerating gradients exceeding 10 MV/m with comparably low rf losses.

### *Multiple Spoke Cavities*

Multi-spoke cavities have been developed at Argonne as R&D RIA [21]. These structures span the previously undeveloped velocity region up to the region for existing elliptical-cell cavities and operate at $f_0$=345 MHz with peak velocities of $\beta$=0.40, 0.50 and 0.63. A three-spoke cavity but with a reduced frequency of 325 MHz and a further optimized EM design, are part of the baseline design for the HINS proton driver at Fermilab. Multi-spoke cavities are also under development at FZJ (Jülich).

Q-curves for the ANL $\beta$=0.63 triple-spoke cavity are shown in Figure 9. At T=4 K, $P_{IN}$=89 Watts to achieve an accelerating gradient of 9.4 MV/m ($E_{PEAK}$=27.5 MV/m). X-ray measurements indicated no field emission out to the highest accelerating fields.

In an effort to increase performance the $\beta$=0.63 triple-spoke cavity was baked in a high-vacuum furnace for 10 hours at 600 $^{o}$C in order to remove hydrogen introduced during fabrication. Hydrogen contamination is known to decrease cavity performance. Before re-testing, a light (5 μm) buffered chemical polish (etch) and high-pressure rinse were performed. Subsequent performance at 4 K was little changed, however, rf losses at 2 K were reduced dramatically (~5x). After baking only 7 Watts of rf power were required for 9.4 MV/m operation at 2 K. Even considering the ratio of helium refrigerator efficiencies for these temperatures, $\varepsilon_{4.2K}/\varepsilon_{2K} \approx 3.5$, the performance at 2 K as shown in Figure 9, suggests that 2 K operation should be explored for future TEM-cavity linacs. Results should be confirmed in other TEM-cavities and additional baking is planned at ANL.

## APPLICATIONS

Large projects based on $\geq$100 TEM cavities have been proposed. The cw Rare Isotope Accelerator (RIA) SC linac [21] includes each of the main class of TEM cavities and relies on essentially all of the merits of SC rf structures. Wall plug power for helium refrigeration of only ~13 MW compares to ~500 MW rf power required for a comparable room temperature linac.

SC cavities for RIA provide the only available means of multiple-charge state acceleration as required for high-power uranium beams. Uranium is limited to ~3 particle μA in today's state-of-the-art ECR sources and the large transverse and longitudinal acceptance achieved with SC cavities and, particularly, with SC spoke cavities, makes this technique possible. Also, due to the broad cavity velocity acceptance and independently adjustable cavity phase, the linac is retunable for lighter ions, such as protons, with energies up to 1 GeV.

SC TEM-cavities may offer advantages in pulsed linacs. High-power pulsed linacs require large acceptance, as possible with SC structures, to maintain low beam losses $\leq 1$ Watt/m. The proposed pulsed 8 GeV SC proton driver linac for HINS [22] uses existing SC cavity designs taken from development for the ILC and RIA. The baseline design uses spoke cavities from 10-410 MeV/u including two types of single-spoke cavity ($\beta$=0.2, 0.4), and a triple-spoke cavity ($\beta$=0.6). Cavities operate at 325 MHz, the fourth subharmonic of 1300 MHz and the frequency of existing klystrons developed for JPARC. The high real estate gradients (>3 MV/m) achievable using using clean room techniques, makes SC structures economical in pulse mode down to energies of 10 MeV/u or lower.

## OTHER CONSIDERATIONS

Microphonic induced frequency shifts in TEM-cavity linacs with moderate beam currents, as for proposed RIB facilities, are generally larger than loaded cavity bandwidths. In modern TEM cavities the problem is somewhat mitigated by rigid mechanical designs.

For example, the spoke cavity, composed of a cylindrical outer housing with intersecting spokes supported at both ends has excellent stability [11] and may be designed with minimal sensitivity to helium pressure changes. The co-axial half-wave geometry may be designed with similarly good mechanical properties.

Quarter-wave cavities can be susceptible to vibrations, however, recent designs have incorporated a passive mechanical vibration damper developed at INFN-LNL to damp microphonics with excellent results. For all TEM cavities, VCX, piezoelectric or magnetostrictive fast tuners are either demonstrated or well advanced. Pulsed operation of TEM cavities has yet to be demonstrated but is the subject of ongoing studies at ANL and FNAL.

## CONCLUDING REMARK

Superconducting TEM cavities required to fill in the full velocity range required for proton and heavy-ion linacs have been developed. These cavities have large acceptance, low rf losses, good mechanical properties, and operate at high accelerating gradients. TEM-cavities should represent the technology of choice for many of today’s intermediate velocity hadron linac applications.

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