RECENT DEVELOPMENTS IN LOW AND MEDIUM BETA SRF CAVITIES

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Abstract

Several high power proton and ion linac projects based on superconducting accelerating technology are currently under study and drive an important worldwide R&D effort on superconducting cavities, especially for low and medium energy linacs. Multi-cell elliptical cavities, single or multi-spoke cavities, half-wave and quarter-wave superconducting cavities have been developed at many laboratories and institutions and continue to extend the state-of-the-art for this class of cavities. This talk reviews recent developments and results for SC cavity performance for low and medium beta SRF cavities. The ongoing effort on reduced beta elliptical cell cavities is not discussed. A brief overview of associated hardware required for use with of low- and mid-beta cavities including rf power couplers and fast and slow tuners is presented.

INTRODUCTION

From the first use of superconducting (SC) structures as accelerating cavities in the 1960's up until the last decade, the field of SC accelerating cavities was based on two distinct types of cavities developed independently by separate groups of scientists and engineers and for different applications. The low-velocity structures, used in proton and heavy-ion linacs and mostly for low energy nuclear physics studies accelerated ions up to about 10% the speed-of-light, β~0.1. Geometries are all some variation of a quarter-wave resonator operated in the lowest resonant mode, resembling a TEM mode of a coaxial transmission line. At the other end of the velocity range elliptical cell structures have been used for the acceleration of electrons (leptons) moving with β~1. Modes of these cavities resemble pillbox modes and use the TM_{010} pi–mode for particle acceleration.

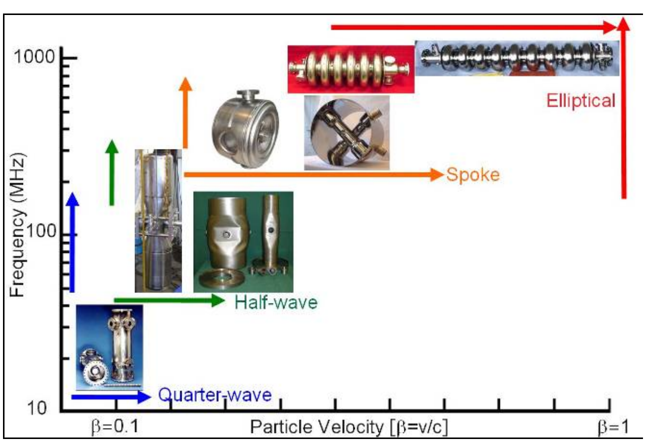

Figure 1: Superconducting accelerating structures spanning the full range of beta as required for acceleration of ions to high energies.

However, over the past decade there has been new interest in accelerating ions up to high velocity for a variety of applications. Consequently, new structures have been designed and prototyped both to extend upward the range of beta for TEM cavities and to extend downward the range for elliptical cavities. Some examples intermediate beta structures are shown in Figure 1.

APPLICATIONS

It is interesting to note that almost all of the early linacs based on low-beta SRF cavities are relatively small machines with a dozen to a few dozen cavities used to provide modest beam currents for heavy-ions nuclear physics or related studies. With a couple of exceptions, cavity frequencies are clustered near 100 MHz, and the maximum beta is around β~0.1. A list of the existing and proposed linacs using SC quarter-wave cavities is shown in Figure 2. Time ordered from bottom to top, the list shows ATLAS the first SC ion linac (1978) and proposed quarter-wave based linacs at the top.

Though at present no half-wave or spoke cavities ($\lambda/2$ structures) are used to accelerate ion beams, this will change shortly with the commissioning of the SARAF [1] half-wave linac at SOREQ. Several other proposed or planned SRF linacs, many of these large and including several cavity geometries, will use $\lambda/2$ structures to accelerate ions in the intermediate velocity region of $0.2>\beta>0.5$. Examples of proposed half-wave and spoke cavity applications are shown in Figure 3.

The present state-of-the art for low-beta SRF linacs in routine operations is the ISAC-II [2] heavy ion linear accelerator in operation at TRIUMF since 2006. The accelerator presently consists of 20 SC quarter-wave cavities similar to the INFN-Legnaro design based on relatively simple coaxial niobium tubes. Cavities have two beta values, β=0.057 and 0.071, with each cavity

Location	Cavity Type	Frequency (MHz)	Beta (v/c)	# Cavities
Spiral-2/Ganil	QWR	88	0.07,0.12	26
MSU FRIB / MSU Re-Acc	QWR	80.5	0.04, 0.085	112
CERN	QWR	101	0.76, 0.12	30
Triumf	QWR	80	0.06-0.07	20
New Delhi	QWR	97	0.08	14
Canberra	Split-ring, QWR	150.4	0.09-0.11	14
INFN Legnaro	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, 72, 97	0.01-0.10	64

Operations & Upgrades	Under construction	Planned	No longer operating

Figure 2: Superconducting rf linacs based on quarter-wave cavities.

Applications	Frequency (MHz)	Beta (v/c)	Particle type	# of Spoke or HWR Cavities (total cavities)	Duty Factor
SARAF	176 (HWR)	0.09, 0.15	Proton, Deuteron	42	CW
MSU FRIB	322 (HWR)	0.285, 0.52	Proton to Heavy-Ion	224 (336)	CW
Project X	325 (Spoke)	0.2-0.6	Proton	93 (445)	Pulsed
Eurisol	176, 352	0.09-0.3	Proton, Light ion	108	CW
ESS	352 (Spoke)	0.35, 0.59	Proton	Up to 126	Pulsed
IFMIF	175 (HWR)	0.094, 0.17	Deuteron	42	CW

Under construction	Planned	Under consideration

Figure 3: Superconducting rf linacs using half-wave or spoke cavities.

providing approximately 1 MV of accelerating potential. An expansion of ISAC-II using β=0.11 quarter-wave cavities fabricated locally by PAVAC is underway and will add another 20 MV of gradient using 20 cavities. The ISAC-II cryomodule is assembled in the clean room in order to reduce particulate levels and permits operation with fairly high values of electric field on the cavity rf surface, ~35 MV/m. While state-of-the-art in terms of real estate gradient, new features and techniques such of highly optimized geometries, baking, electropolishing, isolated cavity rf space and lower temperature operation leave room for major improvements for this range of beta.

Some of these techniques will be used for low beta linacs under construction today. The SPIRAL-2 [3] SC linac is currently under construction at GANIL. This linac is being built using the two cryomodule types, a low-beta module housing one β=0.07 cavity, and a high beta module housing two β=0.12 cavities. The design accelerating field of the SPIRAL-2 QWRs is E_{ACC}=6.5 MV/m (L_{eff}=0.41 m.), which, for β=0.12 cavities, corresponds to an accelerating voltage of more than 2.5 MV per cavity. The relatively higher performance compared to operating cavities is due largely to substantially reduced surface fields from EM design optimizations. The cryomodule design also incorporates clean assembly and separate cavity and insulating vacuum space. Operation at these levels would represent a substantial advance for low beta linac performance.

At Argonne an energy upgrade [4] of the ATLAS heavy ion linac at ANL uses a new cryomodule containing seven 109 MHz β=0.15 quarter-wave SC cavities. Design features to improve cavity performance include, clean room assembly, separate cavity and insulating vacuum spaces, reduced peak surface fields based on an improved geometry, and rf surfaces prepared using electropolishing rather that the more common buffered chemical polishing (etching). In single cavity tests of 6 of the 7 cavities, the average gradient was E_{ACC}=10.2 MV/m (L_{eff}=0.25 cm) or an average of just over 2.5 MV/cavity. Operations in ATLAS will be at a slightly lower gradient corresponding to 2.1 MV/cavity due to limitations of the VCX fast tuner. Operation at these levels would be an important advance for this class of cavity, however, it also highlights the need for an alternative fast tuner, such as a fast mechanical tuner, that does not limit cavity field performance.

At Soreq NRC, the Soreq Applied Research Accelerator Facility (SARAF) [1], is currently under construction and will include a superconducting cryomodule housing six β=0.09 half-wave resonators (HWR) with 3 SC solenoids The second phase of the project will include 5 additional SC modules. The choice of the half-wave structure was based on the low beam steering inherent with the HWR, however, solutions to this issue with quarter-wave cavities have since been developed [5]. The cavity string for SARAF, designed and built by ACCEL (now Varian), uses clean assembly and an isolated cavity vacuum space. The planned accelerating voltage/cavity of 0.86 MV is similar to values for cavities at similar beta in routine operations today.

Other proposed or planned facilities requiring relatively large numbers of low- and mid-velocity cavities such as Facility for Rare Isotope Beams (FRIB) at MSU [6] and Project X at FNAL will likely need to use all of the techniques discussed above.

RECENT DEVELOPMENTS

Field Performance

Remarkable test results for the first of three types of SC spoke resonators (β=0.2, 0.4 single-spokes and a β=0.6 triple spoke) have been demonstrated recently at Fermilab [7]. The cavities were prototyped and tested for use in the front end section of a high intensity proton linac. Cavities were fabricated using well known forming, machining and electron beam welding techniques from high RRR 3 mm niobium. Bare niobium cavities at β=0.2, one each from Roark and Zanon, were delivered to Fermilab. Buffered chemical polishing (BCP) on both cavities was performed with 1:1:2 BCP at T~15-17°C. For the second (Roark) cavity an improved system for BCP of the cavity surface was used to provide better uniformity of the acid

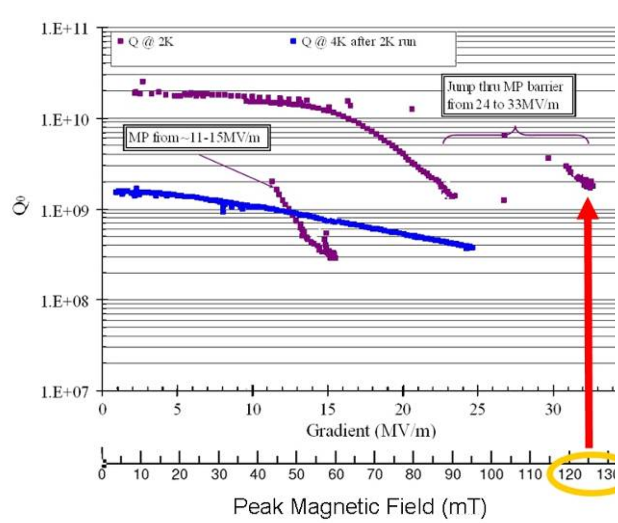

Figure 4: Fermilab/Roark single spoke cavity with E_{ACC}=33 MV/m. V_{ACC}=4.5 MV, physical length = 0.33 m.

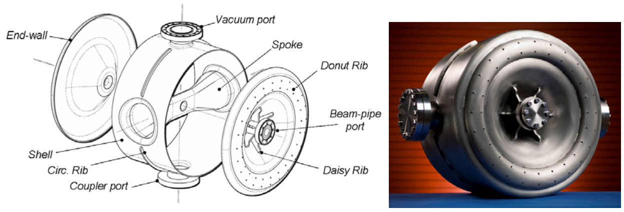

Figure 5: Optimized single spoke cavity with E_{PEAK}/E_{ACC}=2.56 and B_{PEAK}/E_{ACC} =3.87 mT/(MV/m).

circulation over the cavity surface and, thus, more uniform removal. Final surface preparation was performed using high-pressure de-ionized water for rinsing and clean room assembly at Argonne before transfer to Fermilab for testing. Cold test results are shown in Figure 4.

At the maximum gradient, (E_{ACC}=33 MV/m, L_{eff}=0.135 m) the total voltage is 4.5 MV. With an overall physical length along the beam axis of only 0.33 m, the 'real estate gradient' is comparable to values for higher beta (elliptical cell) cavities. This performance is due both to the optimized shape and to the absence of any large fabrication defects as evidenced by the achieved peak magnetic field of B_{PEAK}~125 mT. This constitutes roughly a factor of two increase in real performance relative to other cavity prototypes in this velocity region.

EM Design

It is often assumed that the relatively lower gradients for low beta structures are due to a necessarily complicated design with inherently less favorable EM parameters. An example contrary to this is provided in Figure 6. showing the optimization of the B-field in a very low beta (β=0.025) "bifurcated" four-gap quarter-wave structure [8], generally similar to an older cavity design that has been used in ATLAS for nearly two decades. Peak surface magnetic fields in the updated design are reduced by a factor of 3 and are similar to the best values achieved for any SC cavity as shown in Figure 7. Other cavity EM parameters, including surface electric field, shunt impedance and geometrical factor are likewise

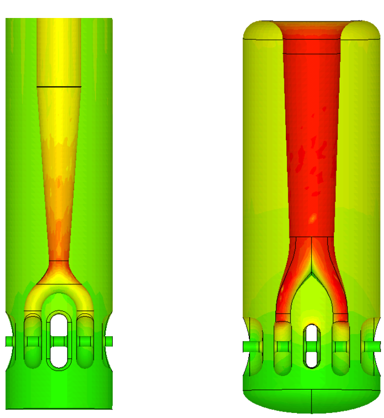

Figure 6: Optimized β=0.025 four gap cavity (right) with B_{PEAK}/B_{ACC}=4.3 mT/(MV/m), 3X lower compared to an existing ATLAS cavity (left). The red center conductor (right) indicates the uniformly distributed magnetic field

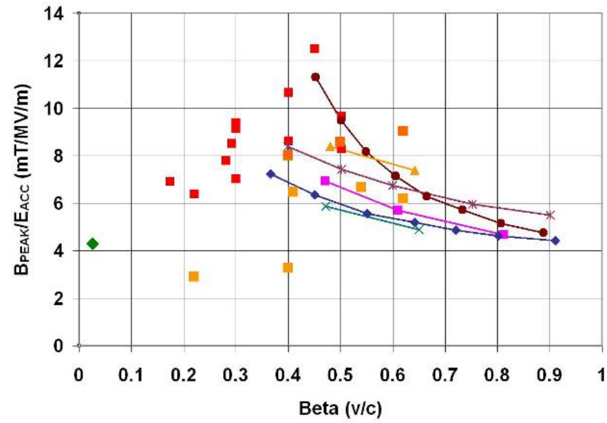

Figure 7: Design peak surface B-fields for elliptical (lines), spokes (squares) and a quarter-wave (diamond) [9]. Lower is better.

favorable (see Table 1).

The recent Fermilab single-spoke design along with this low-beta quarter wave design study strongly suggests that these optimizations are possible for most low- and mid-beta cavities. Likewise, with today's modern 3D EM simulation codes and well established and cost effective fabrication techniques (*e.g.* die hydroforming) the continued use of unoptimized geometries is an unnecessary sacrifice.

2 Kelvin Operation

In addition to very high field performance discussed above, it has also been demonstrated that very low surface resistances of ~5 nΩ can be achieved in low and medium velocity TEM cavities particularly when operating at 2 Kelvin. So far, at operational field levels (~10 MV/m, 80 mT) such low losses have only been achieved through the use of electropolishing of the cavity rf surface and hydrogen degassing. This is consistent with results from elliptical cell cavities, where the high quality factor at high gradients is best achieved when cavities are electropolished and baked.

All quarter-wave, half-wave and spoke cavities built to date were initially intended for 4 Kelvin operation, however, the results for 350 MHz triple-spoke cavities with β=0.5 and β=0.62 after hydrogen degassing at 600°C show an rf surface resistance 10 times lower in 2 K

Table 1: Optimized EM parameters compared to old design for a β=0.025 four gap cavity.

Parameter	Units	ATLAS	Optimized
E_{PEAK}	MV/m	5.04	3.41
B_{PEAK}	Gauss	117	43
Length, L_c	cm	24.638	26
U	mJ	221	150
G	Ω	13.8	18.1
R/Q_0	Ω	900	1486
β_G		0.025	0.026

operation than in 4 K [10]. Even with the increased cost of 2 Kelvin refrigeration of roughly ~3.5 times (both capital and operating), this nonetheless represents a major opportunity for cost savings for cw SRF linacs.

COUPLERS, TUNERS

Coupler and tuner design for SRF cavities offers the opportunity for creativity since the options often more varied than for the SRF structures themselves. However, it seems that the design for all ancillary systems ought to be guided by the following: (1) provide ample, not just adequate, range or capability (obviously at a reasonable cost); (2) do not needlessly sacrifice cavity performance. Below a brief overview of solutions is presented, some of these proven and other yet do be fully demonstrated.

Couplers

The various combinations of inductive and capacitive, fixed and variable rf power couplers have been developed recently for low- and mid-beta cavities, suitable for 1-5 kW rf power [3,11]. Generally, the choice of inductive or capacitive couplers must be made based on the application and cavity type. For example, with clean cavities, coupling from the top of the cavity is generally and rightfully avoided. This leads naturally to the choice of a capacitive coupler for use with a "bottom coupled" quarter-wave resonator.

The choice for fixed or variable coupler, though, application dependent should consider both the rf conditioning and operational requirements since the former bears critically on the final cavity performance. The author asserts that nearly all of the present low- and mid-beta cavities benefit substantially from high-power pulse conditioning with at least a couple of kilowatts of rf power into the cavity. This capability ought to be designed into the coupler along together with the operational requirements. Considering the high cost of rf power, the increased complexity of the variable coupler may justified. Additional benefits of the variable coupler include better overall ease of use and the possibility to effectively condition low-level multipacting. Recent examples of fixed and variable capacitive couplers are shown in Figure 8. Reference [12] reports on an improved 20 kW version of the fixed capacitive coupler.

Tuners

Important considerations for slow tuner design include tuning range, sensitivity, response time, physical size,

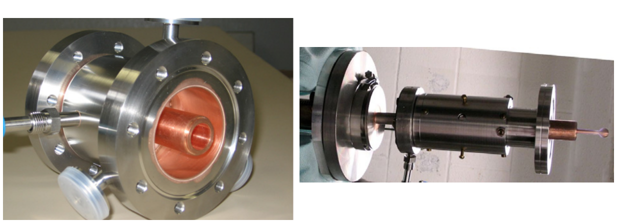

Figure 8: Fixed capacitive cw power coupler (left) for 5 kW from IPN and a 50 dB variable capacitive coupler from ANL.

serviceability, reliability (# moving parts), effect on cavity performance and, as always, cost.

TRIUMF reports on an operational cavity tuner mechanism based on a motor driven linear actuator [2] with a penetration through the lid of the cavity cryostat, extending downward to a flexible tuning plate on the bottom of the cavity. It is noteworthy that this single device can be operated so as to compensate for frequency deviations at rates up to 30 Hz. Michigan State University proposes to use a related scheme that penetrates from the bottom of the cryostat and drives a tuning plate with both a motor and a fast mechanical piezoelectric element [13].

For slow tuning in Spiral-2, IPN has developed a high RRR niobium plunger [14] which penetrates into the rf space. The device does cause modest rf losses of ~10% which might be reduced with further development.

At Argonne slow tuners for quarter-wave cavities use a helium gas driven pneumatic bellows [15] to squeeze the cavity near the beam axis. The design is compact, sensitive and reliable and has only one moving part (the bellows).

Fast tuners are required generally on linacs with low to moderate beam currents and when overcoupling is not used. These are less well developed for present low- and mid-beta cavities. The variable reactance (VCX) fast tuner at ANL is reliable and cost effective, however, it requires a separate penetration into the cavity rf space and has limiting switching power and frequency range and is thus not recommended for high-gradient cavities. Other mechanical fast tuners based on piezo or magnetrictive elements developed at places such as MSU, SARAF/ACCEL and ANL/Energen appear promising but are yet to be demonstrated in routine operations.

CONCLUSION

There are many well developed SRF structures covering the low and medium velocity range so that, together with elliptical cell cavities, established solutions are available for the entire velocity range. Several new projects using mostly long established designs for $0.1<\beta<0.2$ are proposed or under construction. However, scientists and engineers working on low and medium velocity cavities have been hesitant to adopt new techniques and solutions, some of these to be had at relatively low risk and with the potential for real cost savings. Areas where major gains (factors of 2-3) are still to be had with modest effort include increased gradients through better EM design for overall reduced linac size and reduced refrigeration and RF power costs. The realization of these savings could drive new applications (*e.g.* radioistopes for medicine) requiring low and medium beta accelerating structures.

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