LOW AND MEDIUM BETA SC CAVITIES

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Abstract

The use of low- and intermediate-beta superconducting cavities, once confined to low current heavy ion linacs, is steadily increasing in accelerators. The progress in this technology allowed a significant increase in cavity performance during the last 10 years; a large number of resonators, with different geometries, frequencies and gap numbers have been built for a large variety of applications and the development is still going on. The main boost is given by new projects of radioactive beam facilities and high power proton accelerators worldwide. While the advantages of SC resonators, compared with normal conducting structures, are rather well established in high-beta linacs, this is not always the case at low-beta. The choice of the optimum transition beam energy in a linac, where superconducting cavities should replace the room temperature ones, requires a careful evaluation that depends on the linac specifications.

INTRODUCTION

The first superconducting (SC) low-β resonators have been conceived for low intensity, cw Heavy Ion (HI) beams in the 70's, typically for rf boosters of Tandem accelerators. The nearly zero beam loading and the cw beams made superconducting linacs very attractive for this application: differently from Normal Conducting (NC) ones, SC cavities can reach very high gradient with a rather low power, and fit naturally cw operation. Their usual geometries, with only 2÷3 accelerating gaps, allow a linac structure (ISCL, Independently-phased Superconducting Cavity Linac) that is suitable for acceleration with different velocity profiles and different A/q beams. In the beginning, mainly cavities with β~0.1 have been developed, with different shapes. Some have been successfully used in real accelerators: Helix, Quarter-Wave, Split-Ring (for a review of SC heavy ion boosters till 1998, see, e.g., ref. [1]). It is interesting to note that, at present, all operating superconducting low-β linacs still belong to the HI booster category; in two cases (ANL, in operation, and LNL, under commissioning) the Tandem was replaced by a superconducting low-β linac injector. Some of the early heavy ion linacs have been shut down and nowadays the resonators in operation are either of the QWR or Split-Ring types.

The HI booster resonators have some special features:
1. Low frequency, typically 40÷160 MHz. This implies a relatively large size and, consequently, problems of mechanical stability;
2. Absence of beam loading. This implies, for resonators with typically Q~10^8÷10^9, a very narrow resonance bandwidth, < 1 Hz.

This makes difficult to keep these cavities locked in amplitude and phase to an external frequency. This can be done by means of moderate overcoupling, to widen the resonance bandwidth by lowering external Q (thus without loading the cryogenic system).

In addition to careful mechanical design of the resonators, essentially 3 techniques are being used to stabilize the cavity center frequency against He pressure fluctuations, Lorenz force detuning and microphonics:
1. Mechanical slow tuning in feedback
2. Electronic fast tuning [2]
3. Mechanical damping of dangerous modes [3].

A very promising technique, recently implemented in elliptical intermediate-β cavities [4] and demonstrated also in QWR ones [5] is fast tuning with piezoelectric actuators.

The trend, in low-β SC boosters for heavy ions, is to use only QW cavities, which have shown extremely good performance. The achieved gradient on-line, in 25 years, has moved from 2 to 6 MV/m, still increasing. A new element is presented by the introduction of SC RFQ's.

NEW APPLICATIONS

SC low-beta cavities for high brightness proton beams have been proposed in the 90's; this resulted in the study of new geometries, like Half-Wave Spoke and Coaxial types [6]. However, the real new boost for the low-β cavity development came recently from new projects of SC HI drivers and boosters for Radioactive Ion Beam (RIB) facilities (for a review see, e.g., [7]) and high intensity proton accelerators (for a review see, e.g., [8]). They extended the required β out the traditional SC resonators range and, due to the high current specifications (~0.5 ÷100 mA), beam loading and space charge problems became an issue. This development evolved on one side extending to higher frequency and β the HI cavities, on the other side doing the opposite operation with the existing β=1 multi-cell elliptical ones.

Among these new accelerators, at least three (SNS, SARAF and JPARK) are already under construction and a much larger number has been studied and proposed.

STATE OF THE ART

Most of the low- and intermediate-β resonators have only a few accelerating gaps, thus a large velocity acceptance. The cavity types can be somehow grouped in 4, partially overlapping classes of β_0, bearing in mind that a 2-gap cavity with optimum velocity β_0 can accelerate efficiently up to more than $2\beta_0$.

The typical state-of-the-art surface peak electric and magnetic fields E_p and B_p is about 60 MV/m and 120 mT

in the all β range. The lower the β_0, the higher are usually E_p/E_a and B_p/E_a due to the sometimes complicated resonator geometries; this is the main limitation in the maximum accelerating gradient for low-β cavities.

The present technology is mostly based on bulk niobium. At LNL, however, high performance 160 MHz QWRs have been built also with Nb sputtered on OFHC Cu substrate. The Pb-plating and the Nb explosive bonding on Copper techniques are not considered competitive anymore, although cavities of this type are still in operation. The resonator treatment includes of course all the state of the art procedures, like high temperature baking, electropolishing (EP) and high pressure water rinsing (HPR). However, in low-β cavities top performances have been obtained by means of nothing more than the standard chemical polishing (CP). This can be related to the relatively small area exposed to peak fields in the low-β geometries, and in the low BCS resistance related to low frequencies.

Very low-β **(~0.01÷0.04).** This range is covered by 4-gap QW resonators and SC RFQs. The Cu-Nb, 48 MHz 4-gap QWR's at ANL, that allowed replacement of the Tandem accelerators, are working since many years [1]. The mechanical stability problems of these resonators, related to their large size and large load capacitance, have been completely solved by an electronic fast tuner and, later, by the addition of a LNL-type mechanical damper in the cavity stem. ANL proposed, for RIA, 4-gap QWR's made of bulk Nb [13].

LNL chose a different approach and built superconducting RFQ's presently under commissioning [9]. Two resonators give 4.66 MV in 2.13 m, resulting in a good real-estate gradient up to β=0.035; an ANL-type fast tuner is used to achieve reliable phase-lock in these geometrically complicated cavities.

Low-β **(~0.03÷0.2).** This range is covered mainly by 2-gap QWRs and HWRs. Split-ring cavities are not being proposed anymore for future projects. QWR's are very efficient, cost-effective and high performance resonators, and they represent the best choice for frequency around 100 MHz. They can achieve reliably 6 MV/m and they can work, sometimes with mechanical dampers, without the necessity of fast tuners [10]. Niobium QWRs are working at LNL, NSC New Delhi [11] and are being installed in ISAC-II at TRIUMF [12]. They are foreseen also in RIA [13], SPIRAL-II [14] and EURISOL [39].

High performance QWRs have been built at JAERI with explosive-bonded Nb on Cu [1] and at Legnaro with Nb sputtering on Cu [15].

The main QWR's drawback is the presence of electric and magnetic dipole field components, which cause beam vertical steering [16] and increase with resonator rf frequency. For QWRs, however, proper shaping of the gap profile or proper misalignment of the resonator can provide effective compensation [17]. Cavities with dipole compensation have been built at MSU [31], LNL [18] and ANL [13]. Quadrupole components, although less dangerous, can be corrected in a similar way, preventing

beam emittance growth [19]. Above approximately 160 MHz, the best dipole compensation can be obtained with the more symmetric HWR shape. Cancellation of dipole and quadrupole field components is particularly important in high current proton-deuteron accelerators with space charge, like SARAF [20]. Here, 176 MHz HWR cavities with β_0=0.09 (fig.5) and 0.15 are under testing, similar to the ones proposed by ANL for RIA [13].

Figure 1. The 106 MHz TRIUMF-ISAC II QWRs, the 161 MHz QWR with steering correction developed by MSU and LNL, and the 97 MHz QWR at NSC.

Intermediate-β **(~0.1÷0.5).** This is the range where most of the effort was done in the last 10 years. The aim is to find a high current, ~350 MHz SC proton linac design starting from β~0.1: these are the typical frequency and output β of high intensity proton RFQs. All this development finally merged with the ongoing one for RIB facilities.

A 1-gap reentrant cavity with β_0>0.1 for was built and tested at LNL [23], with the aim of using it for a fault tolerant linac section. Reentrant cavities give about 0.6 MV with 7 W in 13 cm flange-to-flange. They have cylindrical symmetry and provide an ideal field profile and large acceptance, but they are rather sensitive to Lorenz force detuning.

An opposite approach is going on at the University of Frankfurt, where a 19 gap, β_0=0.1 SC CH cavity prototype is under construction [21]. Compared to QWRs, this kind of structure puts severe requirements in achieving good alignment, field flatness, tuning and final surface finishing; however, it could allow an extremely compact linac [22]. The fixed beam velocity profile is not a problem since only one type of beam is used.

A 4-gap structure with parallel stems, called "Ladder cavity", is under construction at LNL [42]; this structure could join compactness and efficiency for high current beams with 0.1<β<0.2.
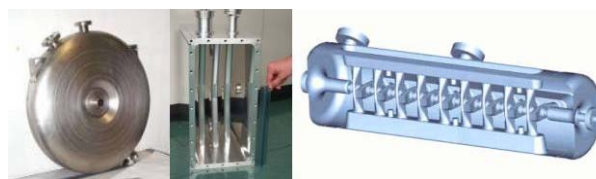

Figure 2. Reentrant, Ladder and multi-gap CH structures.

SPOKE Half-Wave resonators of different β_0, from 0.15 to 0.35 have been built at ANL[43], IPNO Orsay

[40] and LANL [41]. They could reach very high gradient and have demonstrated excellent mechanical stability. Spoke cavities with bore diameter up to 60 mm have been successfully built, making this cavity type one of the best candidates for all-superconductive, high power proton accelerators (HPPA).

Figure 3. Spoke resonators: LANL (β=0.2), IPNO (β=0.35), and ANL double Spoke (β=0.4).

Spoke resonators can also be constructed with more than 1 spoke, giving multi-cell cavities. A 2-Spoke cavity prototype with β=0.4, made at ANL, could reach 3.4 MV acceleration with 20 W [13]; 3-Spoke prototypes are under development. Also 4-Spoke cavities have been proposed, for the new APT design at LANL [28].
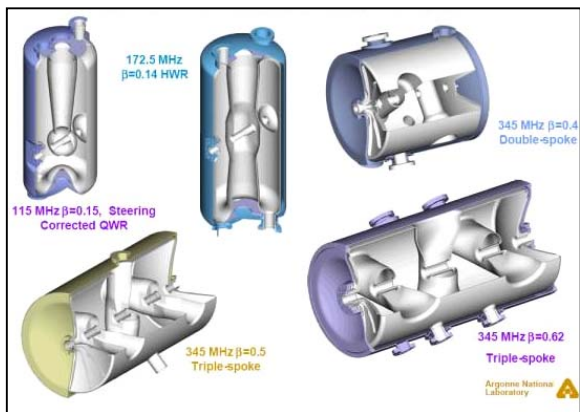

Figure 4. Low-, medium and high-β structures being prototyped at ANL for RIA.

Coaxial 2-gap HWRs have been built with β_0 up to about ~0.3 (thus efficient up to about β=0.5÷0.6). More compact than 2-gap Spoke cavities, they have usually lower shunt impedance but they can be more cost effective and mechanically stable, with comparable performance. A 322 MHz, β_0=0.28 HWR has been recently built and tested at MSU for RIA [31], and a 352 MHz, β_0=0.3 one at LNL for the project SPES [29].

Figure 5. Coaxial HWRs from LNL-SPES (352 MHz), MSU-RIA (322 MHz) and ACCEL-SARAF (176 MHz).

Both cavities provided above 1.2 MV with 10 W at 4.2K with a real estate length below 30 cm. The MSU cavity, however, is planned to work at 2K at higher E_a. Differently from most Spoke and coaxial HWRs, tuned by beam port displacement, the SPES cavity uses an independent piston tuner on the cavity side. This is insensitive to helium pressure changes and requires moderate force, allowing tuning of very stiff cavities.

High-β **(~0.4÷0.8)**. This beta range is covered by 700÷805 MHz elliptical multi-cell cavities working at 2 K, that use a technology originated in electron accelerators. Suitable cryomodules are nowadays fully developed; resonators offer high gradients and a large transverse acceptance, due to the large available aperture (~80÷100 mm). The 805 MHz, β_0=0.61 and 0.81 cryomodules produced for SNS, with design gradient of 10 and 16 MV/m with $Q_0 > 5 \times 10^9$, respectively, have shown excellent results [30], still improving after introduction of EP in the standard treatment. The MSU-Jlab β_0=0.47, 6-cell resonator of the same family exceeded by far the RIA design requirements [31]. CEA Saclay and CNRS Orsay made a 700 MHz, β_0=0.65 5-cell resonator that reached 19 MV/m with Q_0~10^{10} [34]. Successful resonators have been built also at JAERI [32], LANL [33], and INFN Milano.

ANL proposed, for the RIA project, 3-Spoke cavities with β_0=0.5 and β_0=0.62 working at 345 MHz [35] (see fig. 4). These cavities, larger in size compared to multi-cell of the same β, will have a bore diameter of 40 mm. Extrapolation from the 2-Spoke cavity results suggests a possible operating gradient of 9.5 MV/m at 4.2K. The lower number of cells (4 instead of 6) and the lower frequency, compared to the MSU-Jlab β_0=0.47 cavities, seem to provide better longitudinal acceptance and lower number of cavities for the RIA driver, reducing the overall linac cost. Similar arguments have been put forth also for the new APT design at LANL [28]. The calculations assume the capability of routine operation at E_p=27.5 MV/m (rather conservative), and B_p=83 mT (rather challenging) for the 3-Spoke cavities but only 58 mT for the elliptical ones. According to different calculations done at MSU [36], however, the claimed advantages would disappear, if also the same B_p limit is used for both types of cavities. This discussion is still open to new results.

REMARKS ON SUPERCONDUCTIVITY AT LOW-β

After SNS, the superiority of SC linacs over NC ones is rather well accepted in the accelerator community above, say, β=0.5. This is not yet the case for the low and medium beta range, where NC resonators could do the job as well. The optimum borderline between NC and SC is sometimes not easy to define at low beta. There are a few, well known aspects to be considered in the evaluation:

Beam A/q - Short, independently phased SC resonators with large velocity acceptance are ideal for accelerating

efficiently different A/q beams with different velocity profile. For NC cavities, long DTLs with fixed velocity profile is often the only possible choice, due to shunt impedance problems (the construction and operation cost of short NC modules can be significantly higher): this implies that all beams will have the final velocity of the worst A/q one.

Pulsed vs. CW - Cw operation is ideal for SC structures; NC resonators prefer low duty cycle, pulsed operation. Pulsed operation causes time dependent Lorenz force detuning, which makes difficult to keep high-Q, SC cavities locked to a fixed frequency (this, however, can be managed by means of fast tuning systems). This is not an issue for NC cavities with much lower Q. SC structures can operate at high gradient without problems of cooling; NC ones are limited in maximum operating gradient by water cooling efficiency.

Figure 6. The 5-cell, β_0=0.65 CEA/CNRS cavity and the SNS cryomodule.

Low vs. high beam current - SC cavities are ideal for low current beams, where efficiency is dominated by rf losses. In the high beam loading limit, NC and SC linacs have comparable efficiency. SC cavities, however, have the advantage of a larger aperture that can reduce beam losses even at low beta. Moreover, the maximum achievable current, in a linac, cannot be increased indefinitely due to space charge and rf losses problems: for very high average currents (e.g. 100 mA) cw operation is mandatory. Apparently, this calls for all SC linacs; on the other hand, they have rather long focusing periods compared to DTLs, causing beam dynamics problems at low energy that can limit the real-estate gradient. For example, the new 100 mA APT design based on SC Spoke resonators foresees, in the 90 m long, 6.7÷43 MeV section, an average real estate gradient of only 0.4 MV/m [28]. From this point of view, low-gradient, cw NC structures, like the IPHI-DTL prototype [37] are still competitive at high current.

Reliability issues - Reliability can have different importance for different kinds of projects. In ADS systems, for example, a beam-off time above ~1 second can cause nuclear reactor damaging. This level of reliability is hardly achievable with the present technology. A dedicated effort for developing a FMEA (Failure Mode and Effect Analysis) method to assess SC linac reliability is going on for the XADS-PDS project [38]; difficulties come from the lack of available data about reliability of components, which are often unique or new prototypes. In a qualitative approach, the SC technology has many useful features like large aperture, modularity, and some fault tolerance. One case is the SC low-β linac based on short reentrant cavities (giving a maximum of 0.6 MV each); tolerance to a single cavity fault, in this case, is paid by a large number of required resonators. Using, e.g. spoke resonators (1÷2 MeV/cavity), less cavities are required but fault tolerance can be obtained only by adding real-time calculations and adjustment of cavity parameters. Although these techniques have not yet reached reliable and applicable solutions, the knowledge in this field is rapidly evolving.

Construction and operation cost - Even for low-β proton beams SC linacs can be cost effective. In the studies for the EURISOL, 5 mA cw proton driver [39], a comparison between NC and SC option between 5 and 85 MeV was done, showing a similar construction cost. The operation cost of a SC linac, however, was estimated to be 2 M€/year lower than for a NC one. Pulsed operation of the NC linac would of course reduce this gap, as well as higher beam intensity requirements.

CONCLUSIONS

After two decades of use in heavy ion boosters, the range of applications of low- and intermediate-β superconducting resonators is significantly increasing. Strong development is pushed by new high power proton and heavy ion linac projects. Different cavity geometries from 1 to 19 gap, suitable for different beam energy, A/q and current, have been developed. Attention is being paid to cancellation of higher-order field components to prevent beam emittance growth. Low- and intermediate-β cavities reach nowadays more than 60 MV/m and 120 mT peak fields in every beta range, and approximately half of these values are considered reliable in operation. Some projects have even higher specifications. In the high current applications, however, beam dynamics constraints can limit significantly the real estate gradient of SC linacs below β~0.3, making the NC choice still competitive.

ACKNOWLEDGMENTS

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