SRF TECHNOLOGY CHALLENGE AND DEVELOPMENT

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Abstract
SRF technology for particle accelerators is in continuous evolution, providing a large variety of high gradient- low loss resonators with large apertures, suitable for many different beam current and energy regimes. Recent development was aiming not only at highest gradient and Q but also at improving field quality, reliability and cost reduction for large production. The SRF R&D effort, once concentrated mostly in the high energy electron machines, is increasingly focused to heavy ion linacs, energy recovery linacs and also to cavities for special applications. A concise overview of the present state of the art will be given, with emphasis to very recent publications.

INTRODUCTION

Superconducting (SC) technology is nowadays the first choice for large accelerators, after a development lasting several decades and still ongoing [1][2][3]. Well known advantages over normal-conducting (NC) one are: low rf losses, leading to energy savings, reduced rf system cost, possibility of cw or long pulse operation at high gradient; large beam aperture, leading to low beam losses, low wakefields, low beam impedance for Higher Order Modes (HOM). Moreover, some new applications like Energy Recovery Linacs (ERL [4]) would not be possible without SC technology. Of course there is a price to pay: high quality factor Q reduces the cavity rf bandwidth, making it difficult to provide reliable phase- and amplitude-lock; HOMs have a long lifetime and must be damped with additional couplers; SC operation makes cavities more prone to quench due to NC transition of even a small area, and make multipacting (MP) problems more severe; SC technology implies the use of more expensive materials, more strict cleanliness and vacuum requirements; cryogenic cooling technology is technically more difficult and more expensive than water cooling. However, due to high gradient and unique capabilities, the overall construction and operation cost of SC technology can be lower than NC one in many applications, becoming the main one in present large accelerator projects.

The goal of SC cavity development is to produce close-to-ideal resonators characteristics:

- High gradient, up to the fundamental limits of their SC materials;
- High Q in the desired resonant mode (only);
- High shunt impedance for the desired resonant mode (only);
- No multipacting;
- Stable resonant frequency determined only by the tuner position;
- Ideal axially symmetric field distribution (or planar for deflecting cavities);
- Possibility of coupling a large amount of rf power without affecting the resonator properties.

R&D on SC resonators is pushing not only for high gradient and Q, but also for overall efficiency, beam quality, reliability and low cost. Activities are involving numerous laboratories and institutions, and the impressive progress reached so far is moving the new accelerator specifications to higher and higher levels. However, there is still way to go to reach ultimate performance and there are still physical aspects which have not yet been fully understood and which are subject of an active and productive research.

MAIN RESONATOR TYPES IN USE

The evolution of SC resonators has selected a few main resonators types, finally excluding some of the early successful types, like spiral and split ring ones. Development of new geometries, or the use of old geometries for new applications, is still ongoing. R&D, initially focused mostly on cavities for high energy electron machines, is now devoted in a large part also to low beta cavities for ion linacs, which performance (normalized to the different cavity parameters) is steadily approaching the ones of elliptical cavities.

The main resonator geometries in use for particle acceleration can be classified as follows (a good introductory description can be found in [5][6]):

- Elliptical cavities ($\sim 0.6 \le \beta \le 1$) widely used in high beta machines, both linear or circular, for electron and ions;
- Quarter-wave resonators (QWR, $\sim 0.02 \le \beta \le 0.16$), with 2 or 4 gap, used in several low beta ion linacs in operation and in new projects;
- Half-Wave resonators (HWR, $\sim 0.09 \le \beta \le 0.5$), of Coaxial or Spoke type. Until now, only a few coaxial HWRs (and no Spoke) are in operation, but hundreds of such cavities are going to be installed in several new ion linac projects;
- CH resonators ($\sim 0.02 \le \beta \le 1$), multigap Spoke cavities widely studied and prototyped, not yet in operation but proposed in several projects too. β=1 multi-spoke have been recently proposed also for electron acceleration [25].

It should be noted that other, less common types of resonators are presently in use:

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- Split ring (low-β), widely used in the past and now being replaced by QWRs, but still working in a few heavy ion linacs;
- Superconducting RFQ: two units are in operation at the Legnaro heavy ion linac.

Other new SC geometries are being developed for beam deflection [26] (e.g. Crab cavities, in use) and HOM damping (e.g. SC photonic band gap resonators) [7].

A special class of SC cavities, which peculiarities will not be treated here, is the one of SRF guns [8], where the resonator is strictly integrated with a high brightness electron source. This successful technology is rather new and expanding.

STATE OF THE ART

High Gradient Frontier

The main boost to the high gradient has been given by the progress in SC material (Niobium) and surface treatment development. The main limitations on the sustainable peak electric and magnetic fields come by field emission onset and Q degradation at high fields.

Field emission is mainly caused by contamination of the rf surface by dust and inclusion of foreign material, as well as local field enhancement due to surface roughness. Good surface quality is now obtained starting with very pure material and applying a series of surface treatments - degreasing, grinding, chemical polishing (BCP) and/or Electropolishing (EP), high pressure rinsing – and assembly clean rooms. Foreign materials removal and re-cristallization can be obtained by firing the cavity at very high temperature, taking advantage of the very high melting temperature of Niobium. EP can produce a very smooth surface compared to BCP, and is presently considered slightly superior, although more expensive, to BCP for maximum performance. Very smooth surfaces can be obtained also by means of Centrifugal Barrel Polishing (CBP) followed by a "light" BCP or by EP. Other techniques to eliminate surface defects, like e.g. laser bombardment [9], have been proposed and are under development.

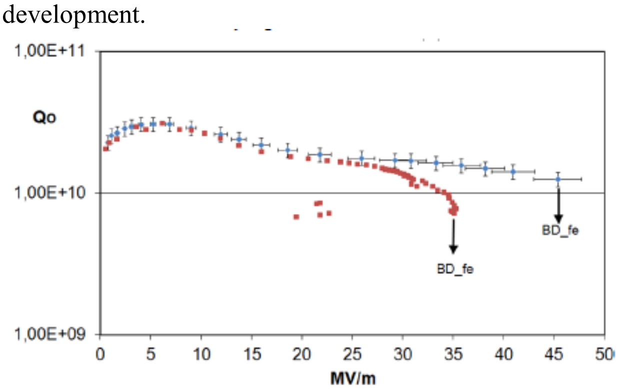

Figure 1: Performance at 2K of ILC type, large grain Niobium nine-cell cavity at DESY, reaching 45 MV/m gradient after Electropolishing [28].

Q degradation at high field causes cavity overheating and creation of hot spots, triggering NC transition and cavity quench. Thus the maximum achievable gradient is in a large part determined by the cavity Q, even in pulsed operation. The maximum peak fields reached in vertical test with the best single cell elliptical resonator are now E_p~130 MV/m and B_p~200 mT [10], close to the physical limits of Nb determined by critical magnetic field. Multicell cavities performances are usually slightly below these values. Recently, large grain 9 cell cavities treated with EP could approach them and exceed E_a=45 MV/m [21]. Nevertheless, realistic specifications for production cavities are presently not exceeding E_p~60 MV/m and B_p~110 mT in elliptical cavities for the possible future ILC machine, and E_p~35-45 MV/m and B_p~70-90 mT for existing accelerators or funded construction projects.

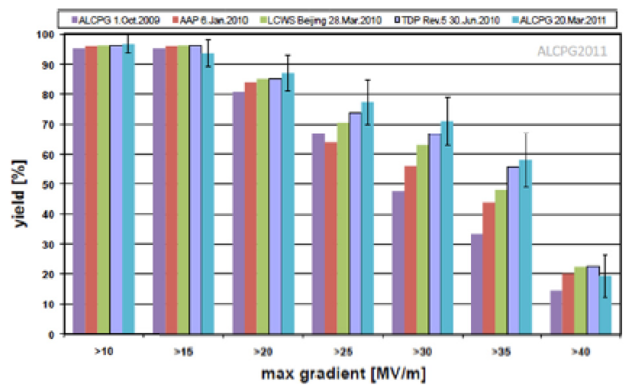

Figure 2: Maximum gradient evolution of ILC nine-cell cavites built by industry for DESY, Cornell, Jlab, KEK and FNAL [30].

High Efficiency Frontier

High efficiency of SC resonators is pursued mainly by increasing the cavities Q, especially at high field. Q slope, i.e. the observed change of Q at different gradients, although not fully understood, is generated by several well known causes like hydrogen precipitation in the Nb (Q disease), surface contamination by foreign materials, trapped magnetic field creating NC areas, and even surface roughness which creates local peak magnetic field enhancement and overheating. Even in this case, material purity and surface cleanliness are of utmost importance both for reduced rf losses and for efficient heat removal from the rf surface due to improved thermal conduction. Q disease is now completely cured by heat treatment in vacuum at 600-800 °C, which removes Hydrogen from the Nb bulk. It was shown that cavities made with large crystal grain and single grain Nb material, with smoother surface and less grain boundary extension, have better thermal conductivity, reduced magnetic field trapping and smoother H_p distribution, resulting in a very high Q. Low rugosity, obtained CBP, contribute to increase the Q even in cavities treated with EP [24]. A final "mild" thermal treatment at 120 °C, although through a mechanism which is not completely clear, was demonstrated to reduce the BCS resistance and the high field Q slope [2], and is now part of the standard procedure of cavity thermal treatment together with the one for the cure of Q disease.

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A method of thermal treatment has been recently developed for material purification and recristallization by means of an induction furnace [11]. With this method, induction currents heat directly the cavity, which is kept in vacuum, to very high temperature in a very short time, without the need of a furnace with additional heaters that might cause cavity contamination from the furnace itself. First results have shown a significant improvement in Q, although not yet in maximum achievable gradient. An induction furnace is used even to bake a cavity in N atmosphere, producing a high T_c NbN layer on the rf surface to increase Q [12].

The SC resonators technology is now able to produce elliptical resonators with very low residual surface resistance (down to ~1 nohm at low field) and little Q-slope up to the maximum fields, although in production cavities a large safety margin both in gradient and in Q is still required [13][14]. In low-β QWR and HWR cavities, with lower rf frequency, although Q slope is still more pronounced than in elliptical ones, the minimum obtainable residual resistance is rather low as well. Maximum reported peak fields in cw mode are E_p~80 MV/m and B_p~140 mT.

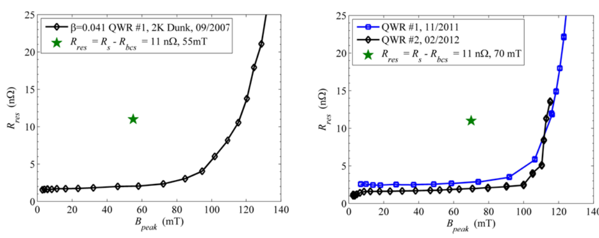

Figure 3: Surface residual resistance vs. peak magnetic field at 2K of the 80.5 MHz prototypes for the ReA3 linac at MSU [16]. Left: β=0.047 QWR; right: β=0.085 QWR. The stars represent the accelerator design specifications.

R&D low-β cavities is very active with continuous progress in cavity performance [15][16][17].

Another way to increase efficiency is optimization of cavity geometry. This is probably reaching the ultimate limits in elliptical cavities, but in low-β resonators the progress still has some margin. QWRs and HWRs with extremely well optimized geometries, which include conical inner and outer conductors, have been produced with valuable reduction of the E_p/E_a and B_p/E_a values, at the price of an increased construction cost which can be compensated by the possibility of larger operation gradient.

Beam Quality Frontier

Beam quality can be affected by SC resonators if the field distributions or their time dependence possess unwanted components. QWR fields typically include a dipole component which causes a phase dependent beam steering; this can be in most cases eliminated or significantly reduced by cavity displacement from its geometrical axis. Proper shaping of the beam ports and drift tubes can also eliminate steering while keeping the cavity on axis.

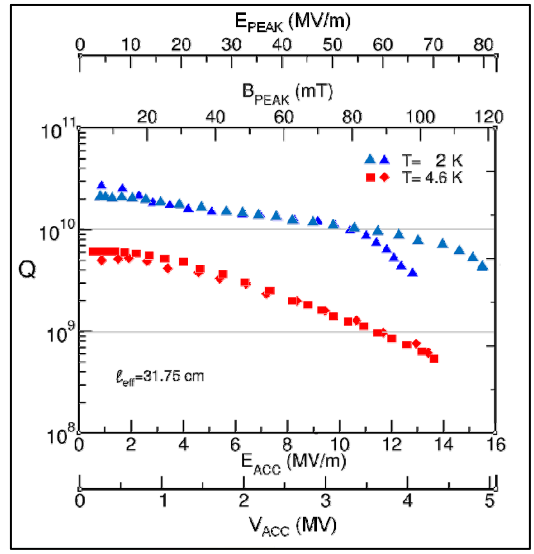

Figure 4: Performance of the ANL, 72 MHz doubly-tapered low-β Quarter-Wave Resonator [15].

HWRs fields have quadrupole components which can cause phase dependent focusing with opposite sign in the vertical and horizontal transverse planes. This effect, neglected in the past for its low strength, has recently become a potential source of emittance growth in new high intensity linacs and is being minimized by geometrical shaping of cavity drift tubes and beam ports [18].

Phase and amplitude lock stability is also important and is related to mechanical stability of resonators against Lorentz force detuning (LFD), He pressure fluctuations and mechanical noise from environment and cryomodule components, like mechanical tuners. SC cavities with high loaded Q (e.g. the ones with low beam loading, or the ones of ERL where rf coupling is minimum) are exposed to amplitude and phase instabilities because of their reduced rf bandwidth. In addition to careful mechanical design, mechanical dampers are used in QWRs to reduce detuning from mechanical vibrations. Stable He pressure is required for high Q applications. Because of its reduced pressure noise, operation at 2K can be preferable compared to operation at 4.2K also for low frequency resonators where the BCS surface resistance is very low also at 4.2K [16]. Fast tuners can be used to counteract detuning. Electronic ones can work in feedback up to the frequency of dangerous mechanical modes of resonators; however, they require a large reactive power which is usually limiting the maximum cavity gradient in operation. Fast piezoelectric tuners can work in feedback to correct vibrations up to a few tens of Hz, becoming unstable at higher frequencies. However, with repetitive detuning signals like the ones caused by LFD in pulsed operation, they can be used in adaptive feed-forward mode allowing acceptable phase and

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amplitude jitter also in high gradient SC pulsed machines [19].

Beam quality is preserved also by limiting higher order modes excited by the beam. The large aperture for the beam which is possible in SC resonators allows keeping shunt impedance for beam induced HOMs rather low. However, the high Q of SC cavity modes tend to build up very strong HOMs that cause beam degradation up to beam break up. Different techniques have been developed in the past to extract and damp HOMs through dedicated rf couplers or through the cavity beam pipes covered with resistive materials (see, e.g., [27] for an updated review). A possible alternative, proposed two decades ago, is the introduction in the lattice of a special cavity (photonic band gap type) for HOM extraction and filtering and simultaneous acceleration. A similar cavity has been recently prototyped in a superconductive version and tested with promising results [7].

High Reliability and Low Cost

High reliability is needed especially in applications where beam trips and cavity failures can damage the accelerator system or the beam target, as in Accelerator Driven Systems (ADS) and in any high intensity machine. Reliability and availability is of course a system characteristic which involves all components. Concerning resonators and accessories, high reliability is pursued, especially in large projects, by refining the design, the construction and assembly procedures, improving intermediate and final quality control checks, performing long validation tests before production. High reliability can be demanding in terms of cost. However, in some cases, it requires design simplification which leads to cost reduction. In some projects, resonators reliability is more important than maximum performance, and a large design safety margin is kept in specifications for machine operation. In this case, at the price of a slight reduction of maximum performance, considerable savings can be made in the cavity cost by simplifying the mechanical design, the cavity surface treatments and the assembly procedure.

Cost reduction can be accomplished also with the development of resonators technologies different from bulk Niobium. Nb sputtering on Copper, successfully applied e.g. in the LEP elliptical cavities and in some of the Legnaro QWRs, is still an active field, although its results are still below the ones that can be obtained with bulk Nb. Thin film technology is looking for materials with higher critical temperature T_c compared to Nb, aiming for higher cavity gradients and higher Q. One way is thin film deposition of NbN alloys on the rf surface. This would give the possibility of operating cavities at 4.2K with a Q similar to the one of Nb at 2K. Higher Q than with Nb was already demonstrated in several cases (e.g. recently in [11]) but, until now, at a significantly lower gradient.

Another development line is aiming at production of SIS (Superconductor-Insulator-Superconductor) multilayer coatings on Nb cavities [20]. Covering the Nb rf surface with layers of superconductor with higher T_c than Nb, with thickness lower than the penetration depth and alternated with thin layers of high thermal conductivity, low rf loss insulator material, it is possible to shield the underlying Nb from the rf magnetic field and increase the maximum gradient before cavity quench. This new technology, recently proposed [29] and still at an initial stage of development, seems to be a good candidate for moving the future cavities gradients beyond the ones achievable with pure Nb.

CONCLUSIONS

Superconducting resonators technology is becoming the standard choice in new particle accelerators and it is in a continuous progress. Cavity design and production techniques leading to high performance are well under control. Although some fundamental questions in SC cavity behaviour are still without a final answer, the achievable operation gradient is in a continuous progress. The techniques which have been developed for elliptical cavities and gave spectacular results, are steadily being extended to SC low beta resonators which nowadays represent an important driving force in the field. New important applications for SC cavities have been proposed and are close to being implemented. New ways are being studied to break the fundamental limits of the present bulk Nb technology.

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