STATUS OF SUPERCONDUCTING RF CAVITY DEVELOPMENT

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Summary

The scope of accelerator applications of RF superconducting devices is briefly discussed from a historical perspective. Current projects and development activity are outlined.

Introduction

For several reasons, a brief historical review seems appropriate at this time. The twenty-fifth anniversary of the first acceleration of beam with a superconducting cavity will occur shortly [1,2,3]. Also, the scope of accelerator applications of superconducting radio-frequency (SRF) devices has, within the last few months, begun to increase rapidly [4] - to the point that it seems likely that early expectations for this technology will largely be fulfilled.

Since the object is to accelerate beam, a simple one parameter measure of the technology is the total of how much beam has been accelerated. Figure 1 shows the total accumulated voltage in tests and/or operation of superconducting accelerating cavities with beam, up to the time indicated, as reported in the open literature [4-35]. This parameter has been divided into two terms: first, the subtotal for electron accelerating velocity-of-light structures, and second the subtotal for low-velocity, ion accelerating structures. To restate: each of these terms represents as a function of time an integrated, accumulative total voltage produced by SRF hardware and demonstrated with beam.

High-velocity Accelerating Structures

Until recently, the high-velocity branch has been dominated by the SC linac at Stanford (Figure 1 - A). This pioneering machine until quite recently provided more than half the voltage ever produced for SRF acceleration of electrons [5,6,8,10]. Only with the installation of the first half of the SC cavities for the upgrade of KEK in late 1988 has the Stanford linac been superseded (Fig 1 - E) [4].

The modest increase in voltage from 1975 to 1988 results primarily from beam tests of short superconducting sections in circular electron accelerators, starting at Cornell (Fig 1 - B), and, more recently, the series of beam tests at CERN, Cornell, DESY, and KEK (Fig. 1 - D) [11,22,24,25,26,29].

Also, included is the electron linac under construction at Darmstadt the first elements of which operated in 1984 (Fig. 1 - C) [28].

Except for the Darmstadt machine there has been a hiatus in accelerator construction. This has at least partly been due to the difficulty in achieving in an actual accelerator the electric field gradients obtained in early tests of small SC cavities. Compared with low-velocity applications, the prospective electron accelerator applications of SRF are to relatively large machines with stringent performance criteria. Consequently, much of the long term development of basic SRF technology has been driven by high-velocity applications.

The major technical problems overcome in the years since first operation of the Stanford linac include

1. Reduction of electron-loading caused by multipacting by appropriate choice of cavity geometry.

2. Reduction of thermal-magnetic instability by increasing the thermal conductivity of the cavity walls.

3. Reduction of field-emission induced electron loading by developing cleaning and handling techniques.

These, and numerous other advances, have over the past decade more than doubled the accelerating gradients available in high-velocity structures [36]. As a result, construction of several major machines is in progress. The recent rapid increase in voltage of high-velocity machines indicates that the technology is sufficiently mature to support these efforts.

Low-velocity Accelerating Structures

The first acceleration of an ion beam occurred at Karlsruhe in 1972 (Fig 1 - F) [7]. At this time, independent development efforts at several laboratories were aimed at building superconducting heavy-ion linacs.

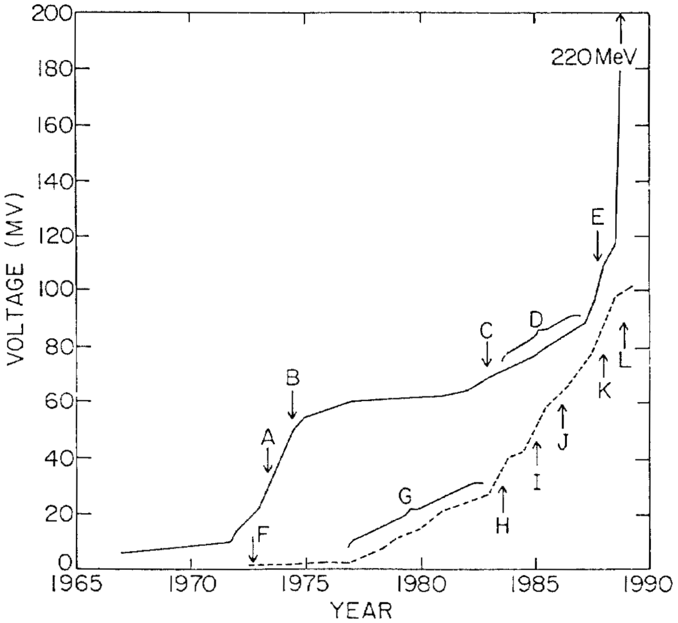

Figure 1. Total voltage achieved in beam tests of superconducting RF accelerating structures as a function of time. The solid line represents velocity of light electron accelerating structures. The dashed line represents low-velocity, ion accelerating structures. For an explanation of the various lettered points see the text.

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The first such heavy-ion linac started operation at Argonne in 1978 (Fig. 1 -G) [18,19,21,23,31]. Although the Argonne linac until 1987 constituted more than half of the total voltage for the low-velocity branch, at present no one machine can be said to dominate this field, since a number of SC ion accelerators have become operational over the last several years. The principal machines are at the following institutions: SUNY Stony Brook (Fig 1 - H), Florida State University (Fig. 1 - I), University of Washington (Fig. 1 - J) and CEN Saclay (Fig. 1 - K) [27,32,33,34]. These accelerators are intended for nuclear structure and atomic physics studies, which typically require a variety of ions, very low beam currents, and high beam quality.

Until recently, all the low-velocity machines have been booster linacs used to boost the energy of beams from electrostatic accelerators. In early 1989, however, a superconducting injector linac was added to the Argonne linac, replacing the tandem injector, and making it the first stand-alone SC heavy-ion linac (Fig. 1 - L) [35,41].

Application of SRF to low-velocity, low-current ion accelerators has been for several reasons more straightforward than for high-velocity machines.

The required SC slow wave structures operate at 50 - 150 MHz, and at such low frequencies the problems of thermal-magnetic instability in SC cavities is greatly reduced, because of the decrease in both SC and normal-state surface resistance with decreasing frequency.

Also, the variable velocity profile required to accelerate a variety of ions has led to linac designs consisting of an independently-phased array of short resonant cavities. Thus the basic SC element is small and relatively inexpensive.

Another consequence of independent phasing is that the flexibility of the linac tuning can be used to accommodate resonator malfunction or variations in resonator performance. Any level of performance can be useful, there is no well-defined minimum useful accelerating gradient.

Also, because of the low shunt impedance of normally conducting slow-wave structures, the high shunt-impedance of superconducting structures is particularly advantageous in the low beam-current accelerators required for nuclear structure studies.

For these reasons the low-velocity branch of SRF has been characterized by a number of independent development efforts, many of which have resulted in useful machines. The steady growth of voltage of this class of machine will, if presently planned projects are executed, continue at much the same rate well into the next decade.

Current Status of Some Major Projects

High-velocity Accelerators

CEBAF - 12 5-cell, 1700 MHz niobium cavities produced by five different vendors have been tested at accelerating field levels of $5 < Ea < 12$ MV/m. Cavity production has started with an expected delivery rate of 12 cavities/month by the end of 1989. Some 330 such 5-cell units will be produced over the next several years for the CEBAF recirculating linac [37,38].

CERN - 4-cell, 350 MHz niobium cavities have been developed for use in the LEP storage ring. Also 4-cell cavities of Nb sputtered onto copper have been operated at Ea > 5 MV/m with $Q=6\ 10^9$. A 4-cell structure has been operated on line at accelerating field levels up to Ea = 7 MV/m for more than 7000 hours with no performance degradation [39].

DESY - following prototype tests of a 500 MHz, 4-cell niobium cavity with beam at gradients Ea > 5 MV/m, sixteen such cavities and necessary cryostats will be delivered from a commercial vendor in 1989 for installation, as a pilot project, in the HERA storage ring [40].

KEK - now contains the largest SRF accelerator with the successful tests with beam of 16 5-cell, 500 MHz cavities late in 1988. The RF cavities can presently operate at an average maximum gradient of 6.8 MV/m. With beam, the cavities have provided up to 110 MV of accelerating voltage. An additional 16 5-cell cavities will be installed in the first half of 1989 [4].

Low-velocity Accelerators

Argonne - A very-low-velocity, 12 MV injector linac using 48 MHz, niobium interdigital structures is currently under construction. A prototype section was successfully operated with beam in early 1989. The SC interdigital cavities have operated with beam at gradients up to Ea = 4.4 MV/m [35,41].

SUNY Stony Brook - the existing superconducting booster linac is being upgraded with the addition of sixteen Pb electroplated onto copper quarter-wave resonators [42].

JAERI - a heavy-ion linac is being built with 130 MHz niobium quarter-wave resonators. Prototype SC quarter-wave cavities have been operated at gradients Ea = 6 MV/m [43].

Kansas State - a 12 MV booster linac built with niobium split-ring resonant cavities is nearing completion [44].

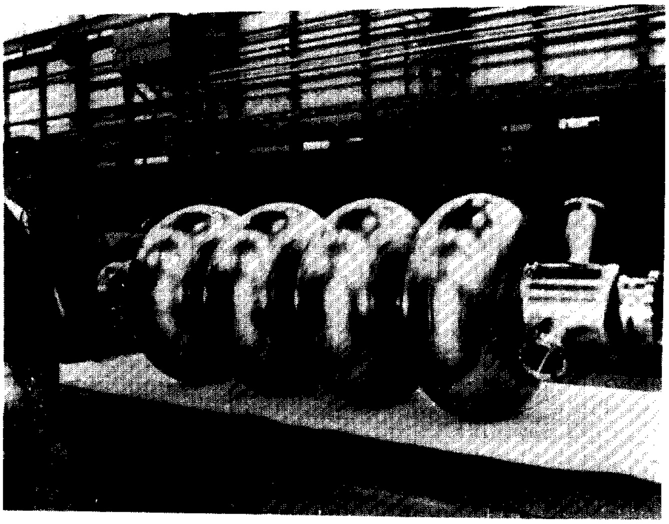

Figure 2. Niobium 352 MHz 4-cell cavity for the CERN LEP storage ring.

Figure 3. Niobium and Copper-niobium parts for several 48 and 72 MHz interdigital low-velocity resonators for the Argonne Positive Ion Injector (PII) project.

Legnaro - a 40 MV booster linac is planned and SC quarter-wave cavities using lead electroplated onto copper as the superconducting material are being developed [45].

Sao Paulo - a booster linac based on niobium split-ring resonant cavities is planned [46].

Development of SC RF Technology

In addition to the accelerator projects mentioned above, several laboratories are actively working to develop high-field superconducting RF technology both generally and also focussed on particular applications such as linear colliders [47].

Pushing the limits of Niobium

Studies are ongoing to understand the causes of electron-loading, and also to push the maximum fields obtained in accelerating structures. In recent work at Cornell, heat-treating to clean the cavity interior surface of 1700 MHz niobium 5-cell resonators has yielded an average peak surface electric field of 40 MV/m, with the best results above 50 MV/m [48]. These field levels are among the highest ever achieved in niobium cavities, and represent an increase of roughly a factor of three over currently obtained operational field levels.

In recent years, high thermal conductivity of the cavity wall has been established as an important parameter in achieving high accelerating field levels [49,50]. An appreciable increase in the accelerating field levels in the niobium 8 GHz 20-cell cavities of the Darmstadt electron linac has resulted from vacuum furnace gettering performed by the group at the University of Wuppertal [51].

At Wuppertal, high fields (Ea = 10 MV/m) and high Q ($3\ 10^8$) at 4.2 K have been obtained in Nb_3Sn, single cell cavities at 3 GHz [52].

Development of High-Tc Oxide Rf Superconductors

A number of laboratories are studying the high-field RF properties of the high-Tc oxide superconductors [53]. The bulk of available data is for YBCO material.

In polycrystalline (sintered bulk ceramic) material, surface resistance Rs at low field levels more than a factor of ten less than copper at 77 K is typical, but Rs increases rapidly with increasing surface magnetic field levels. Even so, such materials have been observed to superconduct in RF surface magnetic fields above 600 Gauss [54].

The group at Cornell has observed Rs below 10^{-3} ohms at 6GHz and 77 K in bulk single crystal YBCO samples; also, these samples show no degradation of Rs with surface magnetic field up to 93 Gauss [55].

The group at Wuppertal has observed Rs below 10^{-2} ohms at 87 GHz and 77 K in YBCO epitaxial films grown on barium titanate crystals by laser ablation [56]. This surface resistance is more than a factor of ten less than for copper at the same frequency and temperature.

The results to date show that the oxide superconductors have intrinsic characteristics that could be useful in high-field applications. A major remaining problem is to develop means to fabricate entire RF cavities with these materials.

Figure 4. Final assembly in a clean room of a pair of 500 MHz 5-cell Niobium cavities for installation on the TRISTAN storage ring at KEK.

Conclusions

A long period of development of superconducting velocity-of-light accelerating structures is coming to fruition with the construction of several major superconducting accelerators. The number of superconducting heavy-ion linacs continues to grow steadily. While the scope of accelerator applications of superconducting RF technology continues to expand, recent developments in materials and processing techniques show that the full potential of the technology has not yet been reached.

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