SUPERCONDUCTING RF CAVITY TECHNOLOGY*

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Abstract

Large-scale application of superconducting rf (SRF) cavities to electron and ion accelerators is in progress at many laboratories around the world [1]. In the last few years over 70 meters of niobium cavities have been built for high energy physics storage rings and nuclear physics recirculating linacs. In acceptance tests, these structures reach an average accelerating field of 9 MeV/m with Q values over $2x10^9$. Attractive future application possibilities to high luminosity storage rings (B-factories) and free-electron lasers are discussed. Research towards higher gradients continues. With a new, furnace based preparation technique, several single cell cavities (10 cm active length) now reach surface fields corresponding to accelerating fields of 25 MeV/m, with the record value of 30 MeV/m at Q's of $2x10^9$. This performance level is attractive for future application to a TeV Energy Superconducting Linear Accelerator (TESLA). An SRF TeV linac eliminates the need for ultra high peak power sources, allows a low rf frequency (1-3 GHz), long (msec) RF pulse lengths, and substantially reduces the long and short range wakefield problems that exact tight tolerances for alignment and jitter. We also briefly review the status of materials other than bulk Nb.

Operating SRF Systems

Linac Boosters for Heavy Ions

To provide precision beams of heavy ions for nuclear physics research, SRF linacs have been one of the most successful applicatons of SRF technology. 5 facilites are operating, utilizing over 180 resonators (~50 meters). The first facility (ATLAS) started operation in 1978. Completed heavy-ion accelerator facilities now provide beams with mass up to 100 atomic units and energies up to 25 MeV/nucleon. These are ATLAS, SUNYLAC, Saclay, U. of Washington and Florida State U.

Split ring, modified helix and, recently, quarter wave resonators are used. The on-line gradient average is 2 - 3 MeV/m. Apart from economy, the SRF linac preserves the excellent beam quality from the tandem because of the stable cw operation, in addition to the general desirability of a cw beam for experiments.

Storage rings

To increase the energy of e^+e^- storage ring colliders, accelerating systems must provide voltages that increase as the 4th power of the beam energy to make up for energy losses from syncrhotron radiation. In this application, SRF cavities pose many advantages over normal conducting copper structures. They can be economically operated at accelerating voltages of ~5-10 MeV/m compared to 1 - 2 MeV/m for copper structures. With copper systems, a large fraction of the available rf power is dissipated in the walls of the structure, whereas with SRF cavities, most of the rf power can be available for the beam, allowing higher beam energies.

The presence of an accelerating structure has a disruptive effect on the beam, and the associated impedance limits the maximum current for high luminosity. With the higher voltage capability, SRF systems can be shorter, reducing the overall impedance, allowing higher beam currents. In copper cavities, the need to provide the maximum accelerating voltage for minimum rf dissipation leads to structure geometries with small beam holes and re-entrant irises, i.e high impedances. SRF cavities can have large beam holes and smoother iris geometries which are more suitable for higher beam currents. Both single and multi-bunch instability problems are greatly reduced through use of SRF cavities.

Prototype structures for storage rings have been developed by CERN, Cornell, DESY and KEK. Between 1982 and the present these structures have been tested extensively in the storage rings CESR, PETRA, SPS, and the accumulation ring TAR at KEK with steady progress The maximum current stored was 69 mA.

A full scale accelerating system of 32, 5-cell, 500 MHz niobium cavities (~50 meters) is now operating in TRISTAN at KEK, raising the beam energy from 27.5 to 32 GeV [2]. It uses a 6.5 Kwatt helium refrigeration system. The average accelerating gradient achieved in the horizontal cryostat tests without beam was 7.5 MeV/m. Routine measurements on the performance in the ring over 600 days showed no degradation in all but 4 cavities. The structures were operated cold at ~5 MeV/m for over 7000 hours, and with over 5000 hours of physics runs. The maximum current stored was 13 mA.

At CERN [3], a 6.8 meter active length SRF system has been operated in LEP using an 800 watt refrigerator. The accelerating structure consists of 4 x 4-cell 350 MHz Nb cavities, connected to a single 1 Mwatt Klystron. Tested individually, the cavities reach > 5 MeV/m, and together were operated at 4.7 MeV/m, storing 2.5 mA beam current (LEP design current = 2x3 mA). 20 more cavities are ordered.

To increase the energy of the SPS injector for LEP from 20 to 21.8 GeV, an SRF system of 2 x 4-cell, 350 Mhz, Nb/Cu cavities has been installed. Off-line tests reached 6.7 MeV/m and the on-line average gradient achieved was 4.9 MeV/m [4].

SRF Systems Under Construction

Heavy Ion Boosters

Argonne [5] is presently replacing the tandem by a new injector based on Nb quarter-wave resonators, specially designed to accelerate very low velocity ions, provide a higher beam current and extend the mass range up to uranium ions. Argonne is also providing Nb split-ring resonators for a booster at Sao Paolo, Brazil. JAERI in Japan in constructing 40 Nb quarter-wave structures. Several other laboratories are planning and protyping resonators for future boosters.

Storage Rings

Based on successful storage ring beam tests and installations in TRISTAN and LEP, plans are underway to install a complete SRF system to raise the LEP energy to 100 GeV using more than 320 meters. At DESY, construction is in progress to install 16 cavities (4 cells, 500 MHz) in HERA to raise the energy of the electron ring and reduce the polarization time [6].

Recirculating Linacs

Nb cavities are replacing normal conducting systems in medium energy (4 GeV) electron accelerators for nuclear physics. When completed in 1994, CEBAF will use 180 meters of Nb cavities [7]. In addition to lower overall power consumption, SRF cavities offer special advantages for nuclear physics electron accelerators in the form of high average currents (1-2x100 μA), continuous beams (100 % duty cycle) and excellent beam quality. In a cw superconducting machine, the rf phase and amplitude can be controlled very precisely, resulting in an energy spread of $2x10^{-5}$, vs. $2x10^{-3}$ typical for a competitive normal conducting linac with a pulse stretcher. A low transverse emittance is also essential to minimize the background events due to beam halo. For a given desired average current, a cw machine can have lower peak currents which reduces the emittance degrading interaction of the beam with the cavity and vacuum chamber. For CEBAF, the expected emittance is 10^{-9} m-rad at 1 GeV, as compared to $2x10^{-7}$ m-rad for a normal conducting option.

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The Cornell cavity design was chosen for CEBAF because it exceeded the performance and higher mode damping requirements, and was proven in a beam at CESR. In the industrial prototyping stage, 10 cavities were produced by various companies and tested at Cornell U and Wuppertal U. In acceptance tests, the average gradient was 10 MeV/m and the average Q was 7×10^9 at 2 K, far exceeding the machine design specifications of 5 MeV/m and Q = 2.4×10^9. Industrial and in-house (CEBAF) production of cavities has started. The average of first 10 cavites is Eacc = 9 MeV/m [7]. A full scale cryo-module comprising 8 cavities was tested, reaching an average gradient of 7.5 MeV/m and acceptable Q.

Progress continues on the installation of a 130 MeV recirculating linac by a Darmstadt/Wuppertal collaboration. In Saclay, France, a machine (ALS II) [8] similar to CEBAF is under planning. SRF facilities have been installed, 1.5 GHz 1-cell and multi-cell cavities tested, and a pilot accelerator section is underway.

Future Applications.

B-Factories

Recently SRF cavities are under consideration for advanced storage ring colliders in the B-quark energy range (5 GeV + 5 GeV) with a target luminosity of 50 - 100 times CESR's world record of 10^{32} per cm^2 per sec. Such machines call for very high beam currents (amps). Therefore low impedances are a must. To provide tighter focussing needed for higher luminosity, another feature exploited is the use of very short bunches, e.g. $\sigma_l < 1$ cm, calling for even higher voltages. As for other storage ring applications, SRF cavities offer high accelerating voltage with low impedance at substantially reduced wall plug power.

There are major development challenges ahead to advance the capability of the present generation of storage ring SRF cavities to carry the needed amps of current. New fundamental and higher mode couplers with higher power capability have to be developed. Higher modes need to be damped heavily ($Q_l < 100$). An attractive approach to meet these needs is to distribute the input and output powers over a large number of single cell cavities each equipped with couplers. A possible B-factory parameter list calls for an input power/cell of 500 Kwatts, a total HOM power loss of 15 Kwatts/cell.

Free Electron Lasers

The first free electron laser (FEL) at 3 micron wavelength was demonstrated with the electron beam from the superconducting linac (SCA) at Stanford University [9].

Among the many candidate drivers considered for FELs, the rf linac is in principle suitable for a broad range of laser wavelengths from infra-red to visible to ultraviolet. For short wavelength FELs, good beam quality and high peak currents are essential features. For reasons discussed in connection with nuclear physics accelerators, SRF linacs excel in both beam emittance and energy spread. For example at 90 MeV, an emittance of 10^{-8} πm-rad and an energy spread of 3×10^{-4} were achieved in the SCA.

A linac driver offers high extraction efficiency and therefore higher average power. In the SCA experiment at 1.6 microns, more than 1% of the beam energy was converted to laser energy as compared to 0.001% [10] in storage rings. For high efficiency, energy recovery in a SRF linac has been demonstrated in principle at the SCA [11]. The overall system efficiency, defined as photon power out/rf power supplied to the beam was increased by a factor of 10.

At INFN (Italy) [12] as well as at JAERI (Japan) [13], infra-red FELs are under construction using 500 MHz HERA and TRISTAN storage ring cavities. Modern SRF structures can handle much higher peak currents than the SCA as shown in storage ring beam tests (> 1000 amps).

Pilac

Los Alamos is considering adding 500 - 920 MeV to its pion linac using SRF cavities. Because the pion deacys rapidly, higher gradients are desirable. The laboratory has acquired SRF technology, and is testing Nb cavities at 3 GHz and 805 MHz. A momentum compactor cavity (402.5 MHz) for the low energy pion beam was ordered from industry and a gradient of 6 MeV/m was achieved. A PILAC technical workshop will be held at Los Alamos following this conference. Nb cavity applications are also forseen in upgrades to LAMPF and compact FELs.

Superconducting Linear Colliders

The most promising technique for producing e+e- interactions in the TeV energy range is the linear collider. In contrast to existing applications discussed above, the rf must necessarily be pulsed to keep the refrigerator associated capital and operating cost of such a large machine affordable. Although pulsed, a high duty cycle (few %) retains many of the inherent advantages of the superconducting approach discussed below.

TESLA Workshop A 4-day Workshop on a TeV Energy Superconducting Linear Accelerator (TESLA) was held at Cornell University on July 23 - 26, 1990. The purpose of the meeting was to work on an improved parameter list for TESLA, discuss related accelerator physics issues, explore ideas on improving gradients and on developing accelerating structures/cryostats suitable for TESLA, review costs, advance ideas for cost reduction, and arrange collaborations for work on TESLA issues. About 70 scientists participated from the laboratories at Argonne, BNL, CEBAF, CERN, Cornell, Darmstadt, DESY, Fermilab, IHEP Protvino, INFN (Frascatti, Genova, Milano), KEK, Lawrence Livermore, Los Alamos, Saclay, SLAC, Stony-Brook, and Wuppertal. Several cavity manufacturing firms were also present.

A staged approach to TESLA was considered reasonable (Table 1). However the starting energy is a function of High Energy Physics (HEP) interest and of progress in developing higher gradients in SRF cavities. Linear colliders have the advantage that, if a suitable site is selected, the length can be extended periodically.

TABLE 1
Possible TESLA Machines Depending on HEP Interest

Energy (GeV) Linac	Lumin. (cm^{-2} sec^{-2}) $\times$ 10^{33}	Length (km Linac)	Gradient (MeV/m)	Beamstr-ahlung δ	Physics
50	2.6	3.3	15	.006	Z-Factory
150	1.8	7.5	20	.003	Top Fac.
250	2	10	25	.006	≡ NLC
500	5.1	16.7	30	.09	≡ JLC,TLC
750	10	18.8	40	.62	≡ TLC-1.5

Parameter Philosophies In the past, several different approaches have been used to develop a parameter set for a superconducting TeV linear collider. In one approach, Sundelin [14] adopted beam parameters for the final focus and the source as in the SLC, with the philosophy that these are demonstrated. A design luminosity ~10^{33} cm^{-2}sec^{-2} was achieved in a 2 TeV CM SRF linac without calling for major developmental efforts in areas such as very small spot size at the interaction point and accompanying very low emittance at the source. In another approach, Rubin et al [15] considered a 1 TeV CM machine with L ~8×10^{33} cm^{-2}sec^{-2}, and adopted all the advances in source and final focus that a normal conducting TLC would count on, such as flat beams of aspect ratio 100, final vertical spot size of σ_y = 2.2 nm, source emittances ε_y = 0.05 μm, and very short bunch length, σ_y = 70 μm. A low frequency SRF linac was substituted for the high frequency, high gradient normal conducting linac.

At the TESLA workshop, a middle road was followed to take further advantages offered by an SRF linac which allows higher beam powers by virtue of its higher efficiency. Thus it was possible to reach L = 5×10^{33} cm^{-2}sec^{-2} in a 1 TeV CM machine and relieve the final focus spot size to σ_y ~100 nm, use smaller aspect ratios (~ 25) and larger source emittances with SLC like bunch length. In

Table 2, we present one of the TESLA parameter sets generated and compare it with the corresponding normal conducting machine (NLC), as well as with the SLC.

TABLE 2
Comparison of Possible Parameters Between TESLA-1/2 and Normal Conducting (NLC & SLC) Linear Colliders.

	TESLA-1/2 1990	NLC	SLC	Units
General				
CM Energy	1	1	0.1	TeV
Luminosity 10^{33}	2	2	.002	$cm^{-2}sec^{-1}$
Length/linac	10	2.6-5.2	3.0	kmeters
Source				
Particles/bunch	4.2	0.7-1.2	5	10^{10}
Bunch Length	2	.07-.1	1	mm
emittance x/y	25	100	1	
emittance y(ε_n)	1	.0185	15	µm
Final Focus				
β_x	19.5	28	7.5	mm
β_y	5	0.087	7.5	mm
σ_y	101	2.4-3.6	1463	nm
σ_x	998	162-420	1463	nm
D_y	8.65	17	0.7	
H	1.79	2	2	
Beamstr. energy spread δ	0.006	.11	.001	
Beamstr. parameter Υ	0.02	0.2		
Linac				
RF Frequency	1.5	11.4	2.86	GHz
Accel. Gradient	25	50-100	17	MV/m
Q	$8x10^9$	10^4	10^4	
Q_L(HOM)	10^5-10^6	20	10^4	
Rep Rate	20	120-360	120	Hz
RF Pulse Width	1598	0.06-.08	.9	µsecs
Bunches Per Pulse	400	10	1	
Bunch Spacing	1200	1.8	(18)	meters
Tolerance		26	100	µm
Peak Power/length	0.04	120-240	60	Mwatts/m
Total peak power	400	$6.2x10^5$		Mwatts
Beam Power/linac	13.4	0.6-1	0.05	Mwatts
Wall Power	75	50 -100	26	Mwatts
Efficiency(%)	18	1	0.2	

Attractive Features of TESLA The TESLA parameters provide a significantly smaller beamstrahlung induced energy spread, δ, (by a factor of 18 for Table 2) improving the physics potential, especially in cases such as a Toponium factory. The beamstrahlung parameter Υ is substantially lower, drastically reducing backgrounds due to the electron-positron pairs generated by beamstrahlung photons. A larger beam size σ_y makes it easier to bring the beams into collision. The large bunch length, σ_z, eliminates the need for bunch compression. The smaller ratio of horizontal /vertical emittance reduces coupling between the two planes which can dilute emittance.

Peak RF Power Because losses are so low, SRF cavities can be filled slowly, drastically reducing the peak rf power demand over a copper linac, for e.g., from 240 Mwatts/meter to 40 Kwatts/meter as in the above example.

Higher efficiency Because the energy can be stored for long pulse lengths, many hundreds of bunches can be accelerated, increasing the overall conversion efficiency from ac power to beam power.

Low rf frequency The inclination towards higher rf frequencies in normal conducting linacs makes the wakefield effects very serious, the number of power feed points per unit structure length very large and the rf pulse lengths very short. Because of low losses, SRF cavities can store energy efficiently, allowing the use of low rf frequency (1.5 - 3 GHz). At these frequencies, transverse wakefield effects are substantially reduced, relaxing requirements on alignment tolerances and injection jitter. With reduced longitudinal wakefields, the energy spread after acceleration is smaller, so that the energy bandwidth of the final focus can be made narrower, permitting larger final quadrupole apertures, and precluding the need for crossing angles and related complications.

Rf pulse length and bunch spacing Because SRF cavities can store energy efficiently, the rf pulse length can be many thousand times longer than for copper cavities. A large number (several hundred) of bunches can then be spaced far apart from each other (km), eliminating the possibility of wrong bunches running into each other at the collision point. With the large bunch spacing and lower wakefields, the damping requirements on the higher modes are considerable relaxed. To avoid multibunch instabilities, normal conducting colliders require very heavy damping ($Q_L < 10$) for the transverse higher modes of the accelerating structure because of the close spacing (3 meters) of the bunches within the short rf pulse length. With this close a spacing, many bunches are present at the same time in the interaction region, making a crossing angle necessary, which complicates the final focus system, and places severe requirements on the final focus quadrupoles.

For the TESLA workshop, the program LINACBBU was used to calculate the transverse blow-up factor for each bunch in 200 bunch train with 1 µsec between bunches ($1.4x10^{10}$ population). For 1.5 GHz Cornell/CEBAF SRF cavities, it was found that Qext < 10^6 yields a transverse blowup factor of only 1.2 [16]. SRF cavities for storage rings need $Q_L \sim 10^4$. The reduced damping requirement can be advantageously used to lower structure costs by increasing the number of cells per structure and by reducing the number of couplers per module.

Challenges for TESLA The capital cost of TESLA is dominated by the structure. Thus the major challenges are to increase the gradients and lower the costs. Progress towards the first is discussed in the next section. Substantial progress has been registered towards lowering structure costs [17]. Polarized cells have been developed to orient deflecting modes so that a single coupler can damp both polarizations of transverse modes. Nb polarized cavites at 1.5 and 3 GHz have been built and tested to show that no multipacting occurs from the polarizing shape distortions. Cavity fabrication procedures have been simplified. Machined steps are eliminated at cavity weld joints and new parameters developed that allow all cylindrically symmetric welds to be performed in one pump-down of the weld chamber. Calculational tools have been developed to predict the Qext achievable by a coupler placed on the beam-pipe past the end cell. Predictions are that in the highest impedance mode families, increasing the number of cells to 10 still allows tolerable Qext values.

Towards Higher Gradients

The present state of the art of gradients achieved with structures for electrons is shown in Fig. 1. Achieved gradients in off-line tests on more than 70 meters of structures average close to 9 MeV/m. Key aspects responsible for this outstanding performance are the anti-multipactor cell shape, high thermal conductivity Nb to stabilize against premature breakdown of superconductivity and clean surface preparation to ensure low field emission.

At 1.5 - 3 GHz , the best 5-cell and 6-cell accelerating structures from four different labs reached surface electric fields between 33 and 40 MV/m (Fig. 2) with the standard chemical surface treatment. In structures with reduced Esp/Eacc = 2.1, of which the Cornell structure in Fig. 2 is one example, these results correspond to Eacc = 16 - 19 MeV/m. Thus several labs have now provided existence proofs for Eacc > 15 MeV/m in full scale accelerating structures.

Field emission is recognized to be the dominant obstacle to reaching higher fields. Efforts to reduce field emission by using a UHV furnace treatment in the final stages of surface preparation have made steady progress. Using solid state gettering with Ti, techniques have been developed that simultaneously improve the Nb thermal conductivity and provide a cleaner RF surface. With heat treatment at 1400 - 1500 C, 1.5 GHz single cells tested at Cornell, now reach much higher fields that cavities with standard preparaton (Fig. 3) The average surface field is 50 MV/m at Q values above 10^9, with 60 MV/m as the record best value (Fig. 4). With the new heat treatment at Wuppertal, 3 GHz single cells have reached Esp = 70 MV/m, and a 5-cell, 3 GHz structure reached Esp = 67 MV/m. These values correspond to Eacc = 24 - 32 MeV/m (Fig. 4).

Exploration has started on an alternate technique to overcome field emission using pulsed high power for processing emitters. With pulses up to 1 msec long and power between 2 and 50 Kwatts, the onset of field emission in 1-cell, 3 GHz cavities was moved up from Esp = 20 - 30 MV/m to fields of Esp = 36 - 40 MV/m. Recently, in a 9-cell, 3 GHz accelerating structure, pulsed processing was used to process emission from Eacc = 10 MeV/m, Q = 10^9 to Eacc = 15 MeV/m. Q = $5x10^9$.

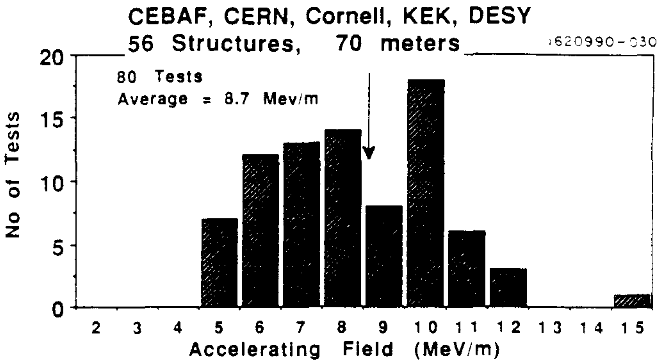

Fig.1 Present state of the art in gradients achieved in high purity Nb structures.

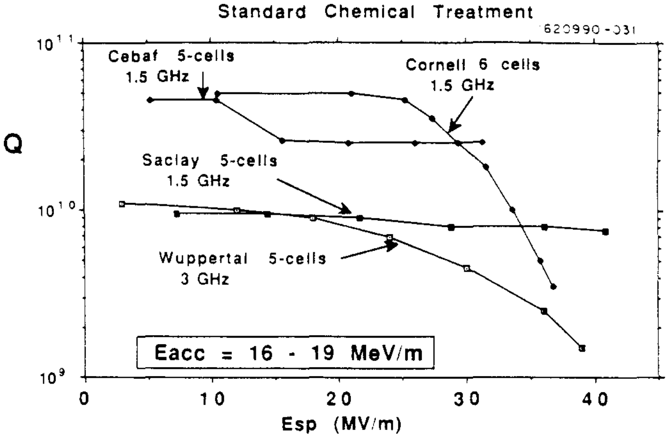

Fig.2 Existence proof provided by several labs in multi-cell structures for Eacc > 15 MeV/m.

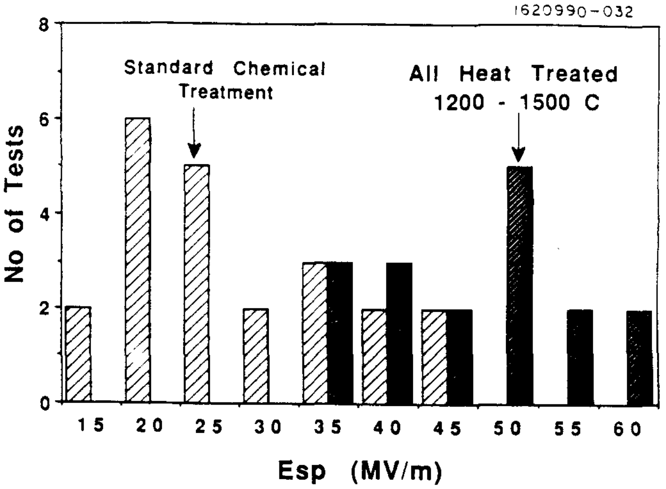

Fig.3 A comparison between heat treated and chemically treated (standard) 1-cell, 1.5 GHz cavities prepared by Cornell

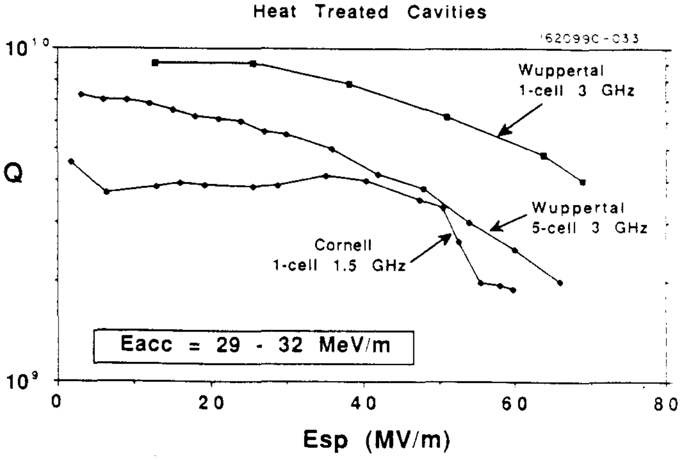

Fig.4 Best Q vs. T on heat treated 1-cell and multi-cell structures.

Basic Studies in RF Superconductivity

With the newest heat treatment techniques, average surface magnetic fields of 1200 Oe, with a maximum of 1500 Oe have been reached in 1.5 GHz, 1-cell cavities. A Nb cavity operating near the theoretical limit set by the critical magnetic field (2000 Oe) needs to support an rf surface electric field ~100 MV/m. A basic question is whether a Nb surface under any condition will tolerate this value. In a specially designed "mushroom" shaped cavity at Cornell [18] and in an "RFQ-type" cavity at Argonne [19], cw surface rf electric fields of 145 MV/m were demonstrated without breakdown, while a pulsed (1 msec) field of 210 MV/m was reached in the RFQ.

Using a high speed temperature mapping system, extensive studies have been carried out on the nature of emitters in rf cavities, under various surface treatments. Results show that, like emitters studied with dc fields, emissive areas are randomly distributed between 10^{-8} to 10^{-12} cm^2, and β values fall between 100 and 400, with a distribution increasing sharply for lower β values. The density of emitters is about 0.2/cm^2 at 40 MV/m with standard surface treatment, falling by a factor of 10 with heat treatment, which also shifts the distribution of β down by a factor of 2. Clean air, water and methanol are proved not to bring emitters in cavities. Chemical residues or minute impurity inclusions remain as possibilities to be investigated, other than debris introduced by improper cleaning or assembly procedures. Condensed gases are shown to enhance emission from potential sites, and He processing is shown to be effective against the associated emission.

Alternate Materials to Bulk Nb

Nb/Cu [20] The chief motivation in developing Nb/Cu cavities is to provide increased stability against thermal magnetic breakdown. Other advantages are Nb material cost savings and the elimination of magnetic shielding allowed by the lower sensitivity to the earth's magnetic field. The possibility of hydroforming the base copper cavities for further cost reduction is also under exploration.

Several full scale LEP style cavities have been tested. Early coatings gave disappointing performance attributed to the presence of foreign particles, which when buried under the Nb, produce blisters in the film. Weld areas were also found to be trouble spots. Improved cleanliness before coating and improved welds with an internal e-b gun were found to ameliorate coating quality reproducibility problems. Strict adherence to an elaborate sequence of procedures is essential.

At low field, Q values of 10^{10} and, at 5 MV/m, Q values of 5 - 7 x 10^9 were obtained in the best of the Nb/Cu cavities. Unlike bulk Nb, losses are observed to increase with increased field even before field emission losses start. The best cavity reached 9.4 MV/m after 10 hours of rf processing. Sputter coated cavities have also been studied at 500 and 1500 Mhz. The residual resistance was found to scale with f^2, increasing from 4 nΩ at 0.35 GHz to 100 - 200 nΩ at 1.5 GHz [8].

Nb_3Sn [21] Nb_3Sn is a promising material because of its higher Tc and higher theoretical rf critical magnetic field (~4000 Oe). Compared to Nb cavities, Q improvement factors of ~200 are achieved at 4.2 K. Q values close to 10^{10} have been measured at 4.2 K over 1 - 3 GHz cavities. The residual resistance is observed to scale as f^2 [8].

Cavity Q values are sensivite to the cool down rate because of trapped magnetic flux generated by thermoelectric currents. Q values are also observed to drop permanently if there is a local breakdown, again attributed to thermoelectric currents. Residual losses increase with increasing field, for e.g. at 3 GHz, 140 to 470 nano Ω was observed between low fields and Eacc = 10 MeV/m. Typical accelerating fields for low purity base Nb are 5 MV/m, while best accelerating field values at 4.2 K and 3 GHz are ~10 MeV/m using medium purity Nb (RRR = 160).

High Temperature Superconductors [22]. The new superconductors offer important potential advantages: the rf critical field is likely to be more than 4 times higher than for Nb, suggesting the future possibility of gradients as high as 200 MeV/m and operating temperatures as high as 77 K.

To be competitive with Nb for accelerator application at the same rf frequency, the surface resistance of a high temperature superconductor (HTS) may be as high as 10^{-5} Ω (as compared to 10^{-7} Ω for Nb) because of the increased overall refrigerator efficiency.

Observed properties of bulk sintered ceramics fall far short of the minimum desirable values. For example, at 500 MHz, best values are 10^{-4} ohms at 77 K, increasing with frequency as f^2. Moreover, the resistance increases rapidly with increasing rf surface magnetic field, to 10^{-3} Ω at few Oe and to 10^{-2} Ω at 20 Oe. Oriented bulk ceramics show lower losses at low fields in the good orientation.

High quality crystals and thin films show significantly lower resistance and better behavior with increasing field. At 6 GHz and 90 Oe, the resistance of the crystals remained below 5×10^{-4} Ω at 20 K, showing that the high resistance of the bulk ceramics at high fields is also not an intrinsic property of HTS.

At this performance level, HTS films are attractive for passive electronic applications, such as multipole band-pass filters, but not for accelerators

CONCLUSIONS

RF superconductivity has become an important technology for particle accelerators. Practical structures with attractive performance levels have been developed for a variety of applications. Over 100 MVolts have been installed in accelerators for heavy ions and over 300 MVolts for electron accelerators [23]. Experience in these machines shows that high accelerating fields with low rf losses can be maintained for operationally significant lengths of time. Substantial progress has been made in understanding field limitations and in inventing cures through better cavity geometries, materials and processes. The technical and economic potential of RF superconductivity makes it an important candidate for future advanced accelerators at both the luminosity as well as the energy frontiers.

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