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LARGE APPLICATIONS AND CHALLENGES OF STATE-OF-THE-ART SUPERCONDUCTING RF (SRF) TECHNOLOGIES

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ABSTRACT

Various applications of superconducting radio-frequency (SRF) accelerating structures in many fields around the world are introduced. These applications consist of high energy physics, nuclear physics, free electron lasers, energy amplifiers, nuclear materials and the treatment of radioactive wastes. A review of recent development of SRF technologies is presented. We also briefly discuss the future prospects of SRF technologies and applications.

INTRODUCTION

Due to the great attraction of SRF cavities (quality value Q higher than Cu by $\sim 10^5$ and accelerating fields Eacc higher than Cu by an order of magnitude in continuous wave (CW) mode), tremendous efforts have been contributed to the development of SRF technology for four decades. In the 1960s, SRF cavities were basically the delicate devices of scientists pursuing potential applications at a few high prestige laboratories. In the 1980s, many laboratories and industrial partners joined the development efforts that resulted in the production of higher RRR (250) of Nb materials and overcoming of multipacting, field emission (FE) and thermal breakdown (TB). At the present time, a total of about 1,000 m of SRF structures with associated large cryogenic systems (multi-kW refrigerators both at 2K and 4K) have been operated successfully at many laboratories around the world.[1-5]

SRF cavities' applications are rapidly extended from the traditional high energy physics and nuclear physics to free electron lasers,[6,7] nuclear materials,[8] the treatment of radioactive wastes and energy amplifiers.[9] Several new applications with a total of more than 20 km of SRF cavities, such as TESLA,[10] APT, JAERI, etc. have been proposed.

The new proposed and ongoing projects have presented more challenges to the SRF cavities and associated systems that will definitely stimulate new momentum of SRF technology development.

In this paper, I will briefly introduce the advantages of SRF cavities and challenges facing the implementation of these advantages in applications. I will then present a variety of SRF applications with a summary of the existing, ongoing and proposed projects. Finally, I will discuss the status and future development of state-of-the-art SRF accelerating cavities in light of the applications.

ADVANTAGES AND CHALLENGES

Advantages of SRF Technologies

The technical advantages of superconducting RF (SRF) accelerating cavities over conventional RF approaches are: (1) the quality values Q of SRF cavities are about 10^9–10^{10} (surface RF resistance Rs 10^5 times lower than that of Cu cavities) as shown in Fig. 1, and (2) accelerating gradients are around 10–25 MV/m in continuous wave (CW) mode, an order of magnitude higher than Cu cavities in CW, as shown in Fig. 2.[11] The benefits of SRF cavities in large scale applications can be summarized as follows:[12-14]

Produce Very High Quality, High Energy Particle Beams. The high Q value allows for us to use large aperture structures operating at lower frequencies (a few hundred MHz) with CW mode (or long macro-pulse length). The large aperture has a beneficial consequence of substantially reducing shunt-impedance, and thereby transverse and longitudinal wake-field effects, leading to relaxed accelerator alignment tolerances.

Reduce Operational Cost. Superconductors have a RF resistance (BCS contribution plus a residual RF resistance) below the critical temperature Tc. The high Q value of SRF cavities presents very low RF wall losses (lower peak power requirements) and low operational costs (net gain is still several hundred times after accounting for the refrigeration

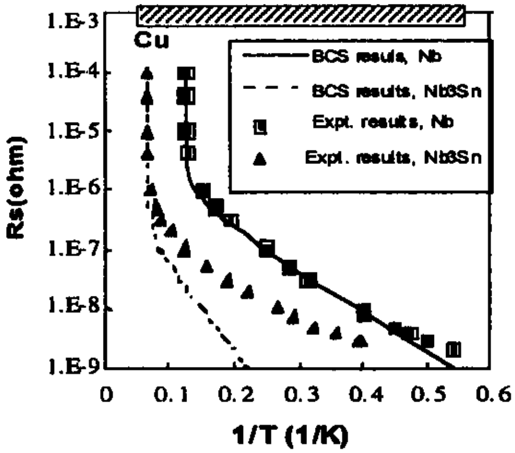


Figure 1. A comparison of surface RF resistances between Cu and Nb (also Nb_3Sn).

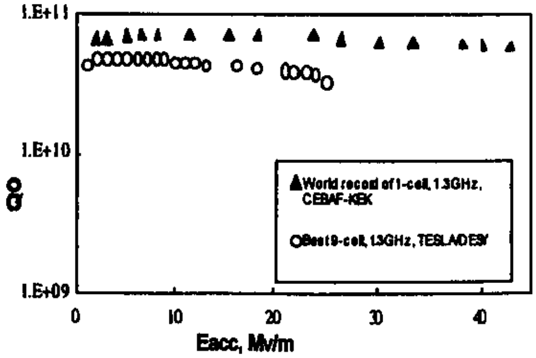


Figure 2. The overall RF performance of an one-cell and a 9-cell cavities.

cost of an SRF cavity system).

Reduce Accelerator Size and Construction Cost. The high accelerating gradients make it possible to greatly reduce the construction cost and also the sizes of accelerators.

Technical Challenges

Continuously Push Performance to the Theoretical Limits.

(A) Major technical efforts are focused on overcoming the most serious obstacles, field emission (FE) and thermal breakdown (TB), which prevent from reaching the theoretical performance limits (40-50 MV/m for Nb cavities[14,15]).

(B) Some applications require the SRF cavities to carry very high electron or proton beams (~1000 mA). The high input power (sub-MW/cavity) challenges designs of the power couplers and HOM couplers.[16,17]

(C) Procedures need to be identified for transferring the good performance of SRF cavities obtained in a test environment to an industrial mass production and regular operation.

Demonstrate Cost Effectiveness. A cost effective design of SRF systems must be demonstrated. The TESLA collaboration at DESY has a long-term goal of reducing the construction cost to from the current level of $40,000/MV to $2,000/MV by: (1) increasing Eacc, and (2) reducing cryomodule cost (Fig. 3).

STATUS AND PROSPECTS OF SRF APPLICATIONS

The large-scale applications of SRF accelerating cavities have rapidly grown and have clearly demonstrated the technical advantages in long-term operations during the last ten years. Previously SRF cavities were mainly used in electron and heavy ion accelerators. The SRF cavities are now used to accelerate proton beams in many proposed large applications. The scales of SRF accelerators have developed from a few cavities to several hundred meters of SRF structure with hundreds of cavities. Based on these successes, some proposed applications, such as the TESLA 500-GeV $e^+ e^-$ collider, would utilize about

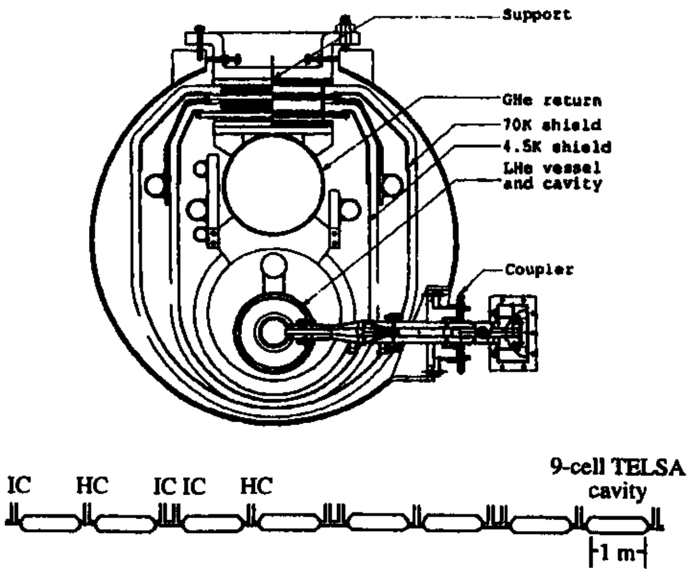


Figure 3. The cross-section of a TESLA cryomodule and arrangement of 8 9-cell cavities.

20,000 SRF cavities in two 10-km-active-length linacs with a superfluid liquid-He (LHe II) inventory of about 95,000 kg.[12] A brief summary of various SRF applications is presented herewith.

SRF Structures in Successful Operation

TRISTAN at KEK (Japan). TRISTAN[2] was the first large scale application of SRF cavities in the world. It consists of 32 5-cell Nb cavities in 16 cryostats (Fig. 4A), 8 high power 508 MHz RF systems and one 6.5 kW LHe refrigerator. Energy gain per pass is 0.24 GeV. It has successfully served high energy research for 7 years.

HERA at DESY (Germany). Since 1992 the HERA electron storage ring has been equipped with 16 superconducting (SRF) and 84 normal-conducting cavities (both 500 MHz)[3] as shown in Fig. 4B. The cavities have a total of about 30,000 hours of beam operation time. Energy gain per pass is 0.08 GeV.

LEP II at CERN (Switzerland). Development of SRF cavities for more than 15 years yielded a gradual increase of the beam energy in LEP.[4] The majority of the 230 SRF cavities (352 MHz) are based on thin niobium films sputtered on a copper substrate. Energy gain per pass is 2.2 GeV. Fig. 4C shows a CERN SRF cryomodule.

CEBAF at Jefferson Lab (USA). The accelerator is designed for nuclear physics. It has a superconducting injector linac and two parallel superconducting main linacs containing 338 SRF cavities.[18] All cavities are a 5-cell design with waveguide couplers. The cavities operate at a frequency of 1.5 GHz and 2 K. The accelerator can simultaneously deliver beam to three experimental halls after 1-5 passes through the main linacs (re-circulation) for energies up to 4 GeV. Fig. 4D is the CEBAF cryomodule.

S-DALINAC at Darmstadt (Germany). It was designed for a free electron laser and has operated since 1990 with 8 20-cell SRF cavities (3 GHz) in 5 cryomodules.[6]

ATLAS at Argonne (USA). The heavy-ion linac of SRF quarter-wavelength SRF cavities began operation in 1978 and has operated and expanded continuously.[5]

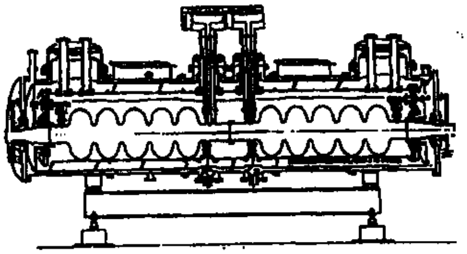
ALPI at L.N.L (Italy). ALPI was completed in 1990 with 97 SRF quarter-wave resonators for heavy-ion acceleration.[19]

Stanford University (USA), SUNY-StonyBrook[20] (USA) and Saclay (France) have all contributed to the developments of SRF technologies for many years.

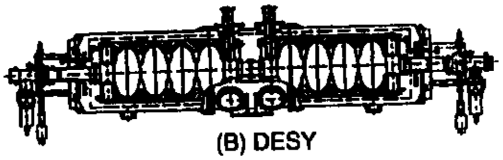
SRF Structures Under Development or Construction

TESLA-TTF at DESY (Germany). The TESLA (TeV Electron Superconducting Linear Accelerator) Collaboration is an international R & D effort towards the development of an e^+e^- linear collider with 500 GeV center of mass for multiple purposes: high energy physics, nuclear physics and laser technology. The TESLA Collaboration is building a prototype TESLA test facility (TTF) of a 500 MeV superconducting linear accelerator (~100 m) to establish the technical basis[12]. The collaboration will develop 20 km of active SRF accelerating structures at a frequency of 1.3 GHz and 25 MV/m if TESLA is finally approved (Fig. 5).

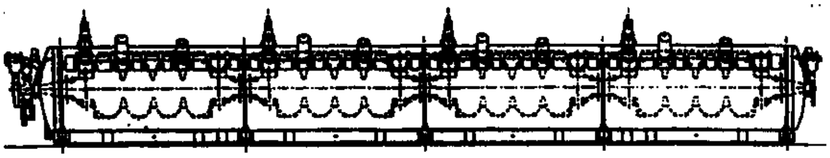
B-Factory at KEK (Japan). The B-Factory is designed mainly to search for the famous CP violation. It consists of 20 single-cell 500 MHz accelerating cavities as shown in Fig. 6. The very attractive feature of its SRF structures[21,22,23] is the capability of carrying very large beam current (300-1,000 mA), high input power (~300 kW per cavity) and very high HOM power extraction of 12 kW per cavity.



(A) KEK



(B) DESY



(C) CERN

(D) CEBAF

Figure 4. Cryomodules of the representative SRF structures in successful operation.

CESR-II at Cornell University (USA). Similar efforts for SRF development as KEK-B (but smaller scale) have been carried out at Cornell University for many years.[24]

IR/UV-FEL at Jefferson Lab (USA). A 1-kW demonstration continuous-wave infrared free electron laser[7] is being developed and will be operated in 1998. It uses the 1.5 GHz CEBAF cryomodules in both injector and linac shown in Fig. 7.

Proton Linac at JAERI (Japan). It will be the first large scale SRF proton linac in the world for both a nuclear waste transmutation facility and a neutron scattering facitity.[25] It will have 304 SRF cavities in 8 different β (0.45 - 0.89) regions of 699-m length as in Fig. 8.

SRF Structures in Proposal and Consideration

APT at LANL (USA). The SRF accelerating system is designed for production of 3-kg/yr tritium. The linac will have 402 SRF cavities of about 1-km length and will be operated at 2 K. Prototype cavity was tested.[26]

Energy Amplifier at CERN (Switzerland). It was proposed by Bowman and Rubbia that it is possible to sustain a nuclear fission chain reaction under sub-critical conditions by providing the required balance of neutrons with a steady flow of neutrons from the spallation of an intense beam of protons on a solid target[9]. This method has a advantage of the safer operation since the chain reaction, if needed, can be easily controlled by acting on the proton accelerator. A superconducting linac has been proposed as the

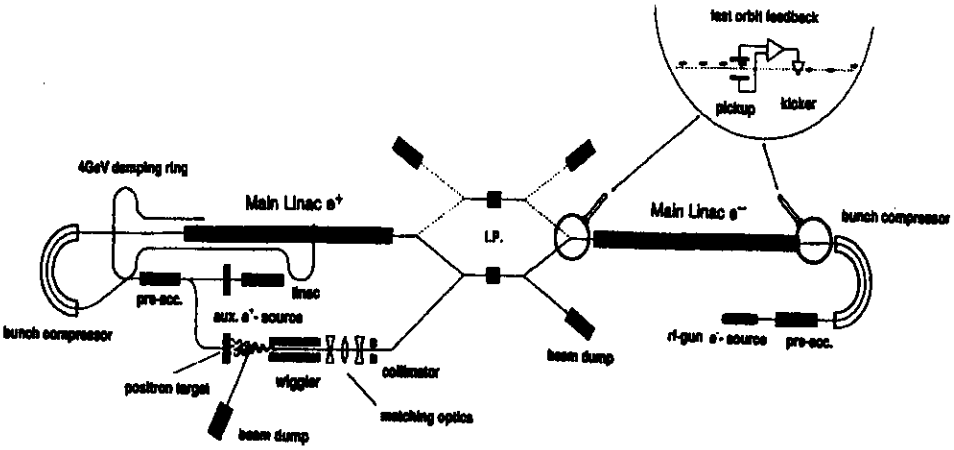


Figure 5. An overall layout of TESLA-500.

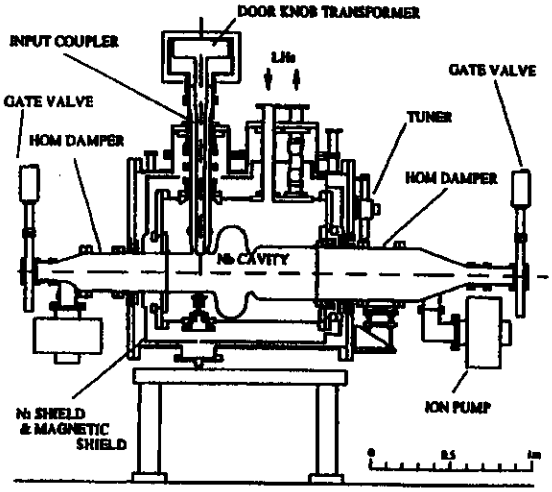


Figure 6. The layout of a cryomodule for the KEK-B SRF cavity.

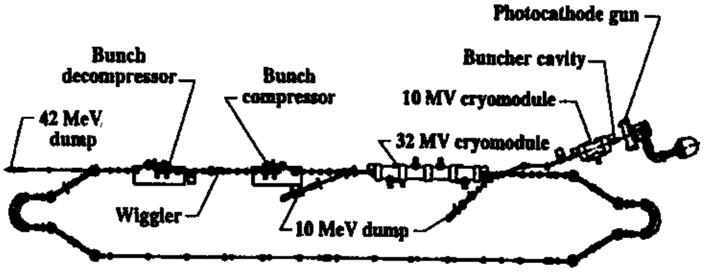


Figure 7. A schematic layout of the Jefferson Lab 1-kW IRFEL.

proton beam accelerator (Fig. 9) which drives a nuclear plant based on the concept of the energy amplifier. An example based on the net generation of 400 MW is described. This requires a proton beam energy of 1 GeV with a continuous beam current of 10 mA, corresponding to a beam power of 10 MW. Two frequencies, 360 and 805 MHz, have been considered for the linac design.

Neutron Source (Europe)[27] **and Muon Collider (USA)**[27] are other potential users of large scale SRF structures (not introduced here).

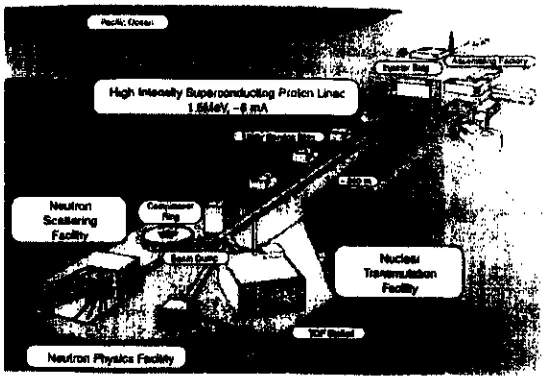


Figure 8. Plan of a facility layout for Proton Linac at JAERI (Japan).

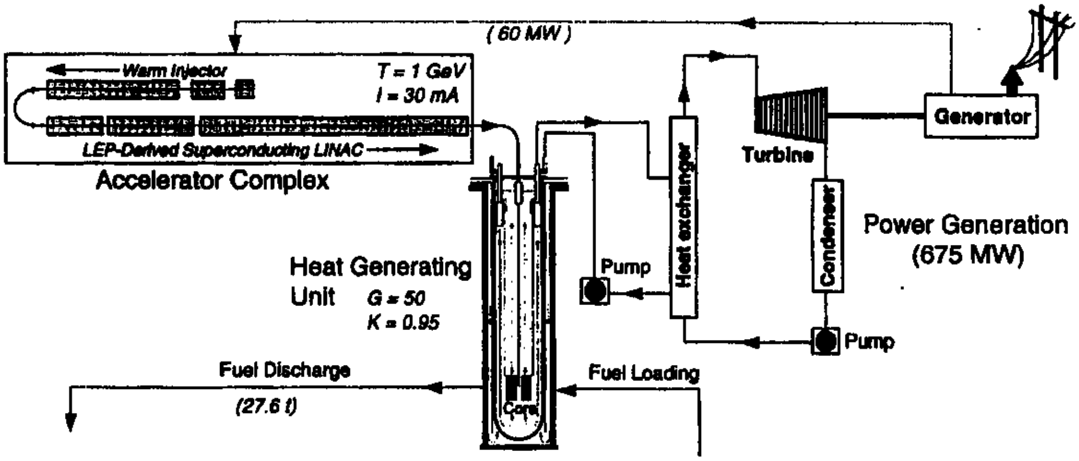


Figure 9. An energy amplifier with an SRF linac.

STATE-OF-THE-ART SRF TECHNOLOGIES

Two principal measures of cavity performance are the accelerating gradient Eacc and the unloaded quality value Qo. The performance highly depends on physical shapes, materials, cavity preparation and post processing, and the operational environment. Jefferson Lab's CEBAF and TESLA-TTF are used herewith as examples to introduce the representative achievements of the state of the art SRF technologies. Finally, table 1 summarized the status of SRF developments.

Cavity Performance Before HPR, HPP & HT

The 338 5-cell cavities installed in CEBAF were fabricated and processed using the best SRF technologies developed in the 1980's, such as cavity design, mid-high RRR industrial NB sheets, cavity-fabrication by electron-beam welding and class 100 clean room assembly. Fig. 10 shows the overall statistics of the accelerating gradients reached in 324 5-cell SRF cavities[28] at Q0 above 3×10^9. However, the high pressure rinsing (HPR), high RF power processing, (HPP) and high-temperature Ti-purification (HT) were not available.

Cavity Performance After HPR, HPP & HT

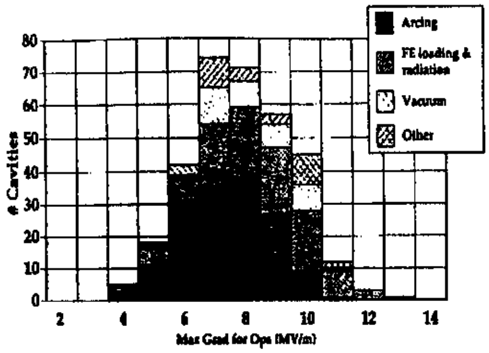


Figure 10. Performance of the CEBAF cavities in operation.

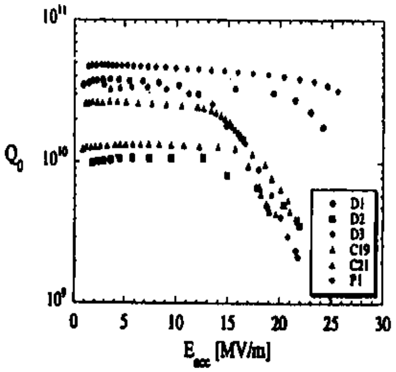


Figure 11. Performance of the TESLA cavities after HPR & HT

The TESLA collaboration utilized almost all the technical experience developed to date. It adds the high pressure water rinse, a 5 MW klystron for high power processing on cavities and couplers and high temperature Ti-purification in an ultra-high vacuum oven into a new infrastructure.[28] The design goal for the gradient is Eacc > 15 MV/m at a quality factor of Q> 3x10^9 for a pulse length of 800 μs. The majority of them exceeded the specification of 15 MV/m. Several cavities reached 25 MV/m at Q> 1x10^{10} in cw mode (as shown in Fig. 11) and up to 30 MV/m in pulsed mode.[11] The first cryomodule with 8 9-cell cavities in it reached Eacc > 12 MV/m). Cornell, KEK, Wuppertal and Jefferson Lab (through collaboration) have also conducted HT, HPP and HPR, and reached the Eacc region of 15-25 MV/m (multi-cell) and 20-40 MV/m (one cell).

Table 1. State of the Art SRF Cavities: Performance

Laboratory	JLab	CERN	DESY	KEK	KEK	Cornell	Dmst.	TESLA
Project	CEBAF	LEP II	HERA	TRISTAN	B-Factory	B-Factory	Dalinac	(DESY, etc.)
f, MHz	1497	352	500	508	508	500	3000	1300
Structure	5-cell	4-cell	4-cell	5-cell	1-cell	1-cell	20-cell	9-cell
Materials	Nb	Nb/Nb-Cu	Nb	Nb	Nb	Nb	Nb	Nb
Cavities	338	24/216	16	32	16/20	4	8	33
T, K	2	4.5	4.2	4.2	4.2	4.2	1.8	1.8
Eacc (at D)	5MV/m	5-6	4	5	10/14	5-6	6-8	15/25
Q at D-E	2.4x10^9	3-4x10^9	2x10^9	2x10^9	1-2x10^9	1x10^9	1x10^9	3x10^9
V(1-P), GeV	0.845	2.2	0.08	0.24	in AR	in CESR	0.085	0.5
Coupler, kW	1.75/5	125/280	65/300	70/200	400/800	200/325	0.5	200, Pulse
I, mA	0.2	6-7	30	15	570	220	1.7, Pulse	

Couplers for Very High RF Power and Beam Current

In several new applications (APT, B-Factory, sub-MW FEL, etc.), the SRF cavities need to handle with a very high beam current (300 - 1000 mA). Such a cavity requires its input coupler transferring several hundred-kW RF power into the cavity and each HOM coupler extracting a 10-kW scale of HOM RF power out of the cavities. The coupler design, cooling arrangement, and the ultra-high vacuum are all challenging tasks. There have been two types of high power input coupler designs:[16,17] coaxial type design (CERN, DESY, KEK) and waveguide type (mainly Cornell). Both have successfully transferred several hundred-kW RF into cavities. A single cell cavity with a cylindrical large beam pipe was designed to propagate HOMs toward the beam axis and damp them by ferrite absorbers bonded on the inner surface of beam pipes (KEK, Cornell). The absorber was made by the HIP (Hot Isostatic Press) method and tested up to 12 kW RF power.

Cryogenic Systems for SRF

The dissipated power in cavities has to be removed at 4 K. In order to further reduce the surface resistance Rs, SRF cavities with frequency larger than 1 GHz use He II as cryogen at 1.8K - 2K. It requires maintaining a pressure below 1.6 kPa on the heat sink of a 1.8 K cryostat system. Bringing the saturated vapor up to atmospheric pressure thus requires compression ratio exceeding 80, i.e. four times higher than that of refrigeration cycle for normal He at 4.2 K.

In a small-laboratory cryostat, this can be done by standard roots or rotary vacuum pump handling the very low pressure GHe. This technique may be pushed to larger scale. For instance, DESY has developed a large pumping station to reach 100-200 W at 2K for the TESLA-TTF SRF structure. However, 300 W at 2K is a commonly accepted limit for this technology. The alternative process is to perform compression of the vapor at low temperature, i. e., at the highest density. The pumps and recovery heat exchangers get smaller in size and less expensive. The pumping must be non-lubricated and non-contaminating, which seriously limit the choice of technology. Hydrodynamic compressors of the centrifugal or axial-centrifugal type have been used in large scale systems. Their limited pressure ratio imposes the arrangement of multistage configurations. Fig 12 shows the practical ranges of application of the different pumping techniques[29]. Fig. 13 is a block diagram of the 2 K and 4.8-kW (plus 12 kW of 50-K shield refrigeration) refrigerator at Jefferson Lab for the CEBAF SRF linac system.[30] It also delivers 10 g/s LHe to the end station. Four cold compressors with an inlet temperature of 3 K and magnetic bearings are utilized in the refrigeration cycle. It is the first multi-kW superfluid LHe cryogenic system in the world, and it has been successfully operated for three years.

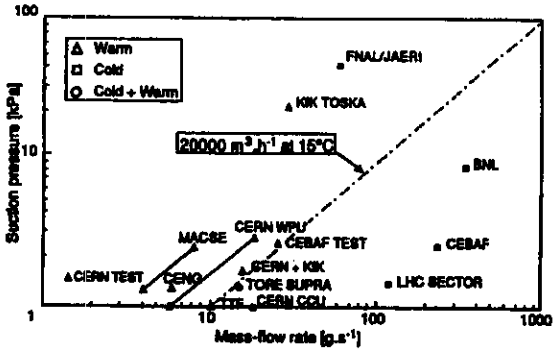


Fig. 12. Application range of the low-pressure He compressors.

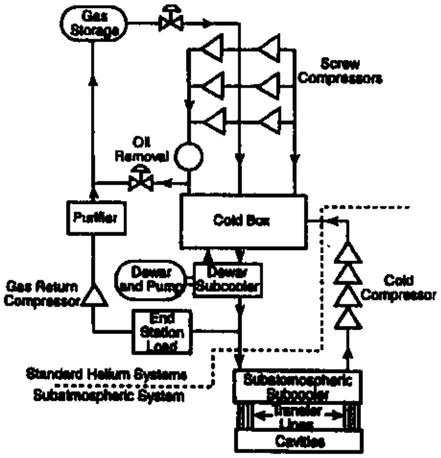


Fig. 13. A block diagram of the Refrigerator for CEBAF SRF Linac.

APPROACHES TOWARD THEORETICAL LIMITS

SRF cavities have successfully operated at many accelerators. However, they still do not reach the theoretical limits. Using a rule of thumb that 40 Gauss (4 mT) is equivalent to 1 MV/m accelerating gradient in cavities with the TESLA shape, the theoretical limit for Nb given by Bsh is then about 50 MV/m. Great efforts have been contributed to reaching theoretical limits in many laboratories around the world.

Increased Cavity Thermal Conductivity

Cavities with Thin Sputtering Nb Film on a Cu Substrate. The main advantage of thin sputtering Nb film on a Cu substrate is the much higher thermal conductivity of Cu than Nb that significantly reduces the risk of cavity thermal breakdown.[4,14] The 230 cavities for LEP II with the techniques have been constructed and reached Eacc ~6 MV/m. However, the Q-value of these cavities decreases faster with RF power than with conventional niobium sheet cavities. To eliminate Q-degradation, the coating process parameters such as layer thickness (1-2 μm), noble gas mixture, coating temperature, and substrate treatment are studied.

Cavities with Very High RRR Solid Nb Sheets. Industry is now able to provide Nb sheet with RRR (RRR = R(300K)/R(4K)) of 250 (thermal conductivity ~ $RRR^{1/2}$) for cavity fabrication. Cavities using these sheets produce a range of TB at ~15 MV/m. Higher RRR of > 500 is desired for reaching a Eacc > 25 MV/m. Currently the way to increase RRR (>500) is to employ Ti-solid state gettering.[31, 32, 33, 34]

Defeating FE and TB

Understanding and Locating FE & TB. The main approach to understand and locate the FE and TB of cavities is to study the hot spots (T) and X-ray (R) generated on the cavity surfaces during RF operation. Several fast and high resolution T-R mapping systems[35, 36] for cavities have been developed and successfully identify and characterize the TB and FE (Fig. 14). These cavity tests are backed by many sample tests: SEM, SIMS, TEM, scanning Auger, RRR, Tc, and AFM (Fig. 15). Examinations of Nb sheets become very important before making cavities.

Preventing FE and TB Sources. Cleaning techniques similar to those utilized in the semiconductor industry are used to remove potential contamination for FE and TB from the cavity's RF surfaces. Cleanliness during chemical etching, water rinsing (high purity water of 18 MΩ-m) and clean room have played an important role in achieving higher Eacc. The very high pressure (80 bar) water rinsing (HPR) device developed by CERN[37] is very helpful in removing foreign particles and is adopted by many labs.

Destroying FE Sites in Situ. Despite how well a job is performed to eliminate FE, there is always a possibility that particles escape removal and stay on cavity surfaces. Therefore a technique that can eliminate the emitters in situ is highly desirable. The techniques are high power processing (HPP) developed at Cornell University[38] and He-processing[34, 39]. During HPP a high power RF pulse is applied to the cavity in situ and eliminates the FE through an explosive process which destroys the remaining FE emitters. During the processing the cavity operates in the FE region in the pressure of a partial He gas just below discharge, causing a reduction of the electron loading. At DESY an HPP facility (4 MW, 2 ms) has been used successfully in raising Eacc. At Jefferson Lab He processing is currently applied to SRF cryomodules in the CEBAF linac to gain Eacc.

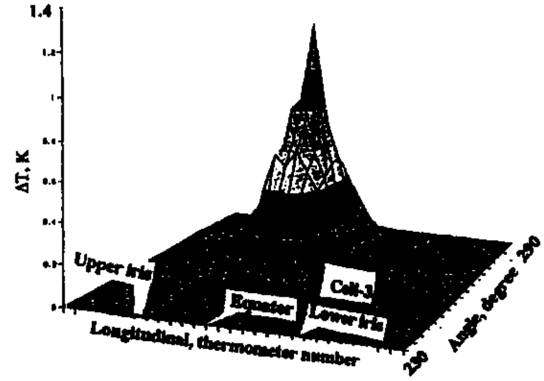


Figure 14. Identification of a TB location m at 12 MV/ (Eacc) on a TESLA cavity surface.

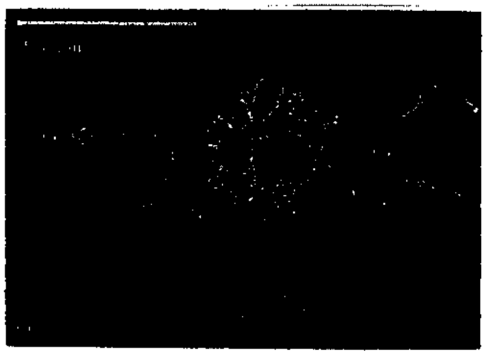


Figure 15. An emitter remained active at the field of Epk=17 MV/m.

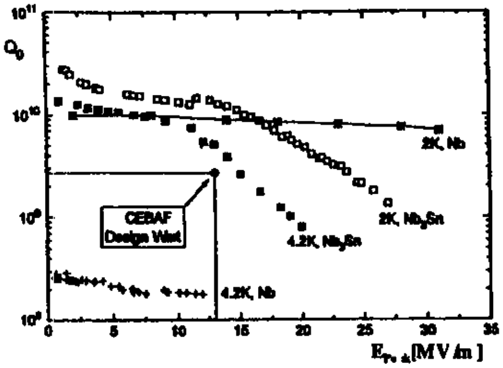


Figure 16. Initial results from a Nb_3Sn cavity.

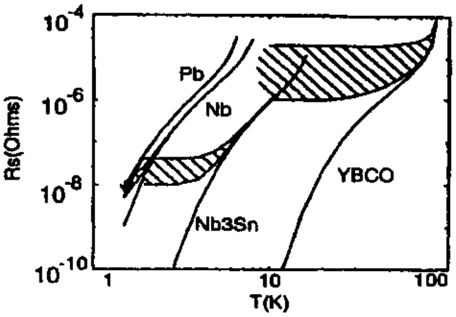


Figure 17. Surface resistances as functions of the temperatures for several LTc and HTc materials.

New Materials Other Than Nb for SRF Cavities

The limit magnetic field in RF is Bsh. The Bsh of Nb_3Sn is about 400 mT, which represents 100 MV/m of Eacc. Several cavities with Nb_3Sn coating on solid Nb sheet have been developed and tested by a collaboration of Wuppertal Univ., CEBAF, etc. Fig. 16 is the initial results[11]. It shows some encouraging results that an Nb_3Sn cavity can be operated at 4 K with an acceptable Q and Eacc of CEBAF design while Nb cavity must be operated at superfluid He (2K).

Materials with a high-enough BCS energy gap 2Δ would allow a considerable reduction of the BCS surface resistance. According to the BCS theory, Δ is related to the critical temperature $\Delta = 3.5\ KT_c$. Therefore, superconductors with a higher critical temperature than niobium are possible candidates for cavity applications as shown in Fig. 17. Among them are the well-known "old" high-T_c superconductors NbN (17 K), Nb_3Sn (18.5 K), and "new" high-T_c superconductors such as $YBa_2Cu_3O_{7-\delta}$ (T_c = 93 K), which have also been studied or discussed for possible RF applications.[40]

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