HIGH GRADIENT SUPERCONDUCTING RF STRUCTURES

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Abstract

Superconducting (s.c.) RF structures for the acceleration of electrons have been known for over 30 years (HEPL, Stanford). More than 10 years after their successful start a new generation (i.e. standing wave, π-mode cavities), made from niobium and operated at frequencies between 352 MHz and 3 GHz, was established at accelerators being operated for high energy physics (CERN, DESY, KEK) as well as nuclear physics (CEBAF, Darmstadt) experiments. Although the HEPL s.c. cavities were limited to a 10% duty cycle and the 2nd generation now allows continuous wave operation, the increase of the accelerating gradient was remarkably small with respect to the > 50 MV/m limit given by the physics of RF superconductivity.

Thirty years ago HEPL cavities reached about 2 MV/m; 15 years later DESY cavities achieved 4 MV/m. And the large 338-cavity CEBAF installation is based on a 5 MV/m gradient, the commissioning of the accelerator being less than 10 years ago. Since 1992 the TESLA (TeV Energy Superconducting Linear Accelerator) collaboration has studied the fundamental problems in cavity fabrication as well as operation. Last year an 8 mA electron beam was successfully accelerated in a 15 MV/m module containing 8 s.c. 9-cell cavities. Two more modules (20 to 25 MV/m) will be installed. From recent cavity tests a gradient of 25 MV/m can be taken as state of the art. Cavity production, preparation, and installation was remarkably improved, a prototype linac (TESLA Test Facility Linac) for a large linear collider shows good performance.

1 RF SUPERCONDUCTIVITY AND LINEAR ACCELERATORS

In 1961 Banford and Stafford [1] at Harwell proposed the feasibility of a superconducting proton linac, and have carried out experimental measurements on lead and niobium at 400 MHz using quarter-wavelength hairpin resonators. Similar measurements were started by Susini [2] and others at CERN and the University of Lausanne on lead and niobium surfaces at 300 MHz using a capacitively-loaded coaxial resonator. Here the interest was in building a s.c. separator. Also in 1961, a program was started at Stanford University to measure the properties of superconductors in a microwave cavity at 2856 MHz [3]. This program started the pioneering work for the application of superconducting RF structures for the acceleration of electrons.

The Stanford cavity was about 14 cm in diameter by 14 cm in length and was resonant at 2865 MHz in the TE011 mode. In this mode there is no current flux across the joints between the cavity side wall and the two end plates, so that the quality factor Q is independent of these joints. Several types of tin and lead surfaces were measured. Electroplated surfaces gave the highest Q's. A residual resistivity was always observed as T approached zero. Today we know from the theory of RF superconductivity that this is not due to improper cavity fabrication but can be explained by the BCS theory of superconductors. Nevertheless, material properties are limiting the achievable accelerating gradient. We characterize the state of the art material by the so-called RRR (residual resistivity ratio) which is a direct measure of the thermal conductivity.

At the 1963 International Conference on High Energy Accelerators in Dubna the Stanford group published a very preliminary design of a 20 GeV - 10% duty cycle superconducting accelerator. This at a time at which no real cavity has ever been built. The remarkable numbers were an assumed length of 3000 m corresponding to about 10 MV/m (active/total length ratio of 66%), and a power dissipated in the walls of the structure of 200 kW average, i.e. 100 W/m; the forward power was claimed to be 2 MW average, so that the total beam power of 1.8 MW average corresponded to almost 100 μA average electron beam current. Ref. [4] can be used to compare this design with the actual TESLA design [5] for a 500 GeV c.m. linear collider.

Based on the TE011 measurements the Stanford group designed and built the first two accelerating cavities, one TM010 and one 2 π/3 mode cavity. In 1965 an accelerating gradient of 3.7 MV/m was reached at an unloaded Q_o of $2.5 \cdot 10^8$ [6]. The cavity was electroplated with lead and operated close to 2856 MHz. Radiation exceeding 100 mR/h provoked the optimistic statement *The radiation provides indirect evidence of strong accelerating fields*. The explanation for the field emission limit was a possible local enhancement of the electric field by a factor 200 caused by sharp projections on typical surfaces [7]. Today we use enhancement factors of

100 to 1000 to explain the level of field emission using Fowler-Nordheim theory.

During the discussion of a LINAC 64 conference paper [8] the author felt that *the present state of knowledge of RF superconductivity was sufficiently discouraging to abandon further work on a superconducting proton linac*. Suelzle from Stanford wrote almost 10 years later *lower-than-expected accelerating gradients have necessitated the re-evalution of the energy objectives* [9]. The hope for getting roughly 14 MV/m in a 6-meter long, 1300MHz accelerating structure was not fulfilled. By the end of 1972 the 1300 MHz structures were limited to 3 MV/m. But the first superconducting electron linac was commissioned. It produced an 8 MeV, 250 μA beam with 12 keV · deg (FWHM) and a transverse emittance of less then 1 π mm mrad. Today the HEPL accelerator is used to drive different undulators and produce Free Electron Laser radiation in the infrared.

2 S.C. CAVITIES FOR STORAGE RINGS

The somewhat disappointing results from Stanford certainly have de-emphasized the search for high gradients. But in the late 70's the use of s.c. cavities in storage rings was considered. Here gradients of a few MV/m were sufficient. Important were instability thresholds - an adequate damping of higher order modes (HOMs) for multiturn operation was needed. Tests in existing storage rings led to promising results as reported [10-11]. Today we can find 352-MHz cavities in LEP as well as 500-MHz cavities in HERA. The first Workshop on RF Superconductivity, organized in 1980 by the Kernforschungszentrum Karlsruhe (KfK), summarized all activities aiming for the use of RF superconductivity for acceleration of ions as well as electrons.

While all first β=1 cavities were of cylindrical symmetry, i.e. a pill box with slightly smoothed out edges, one can find the first spherical resonators around 1980. According to [12] the Genoa / Italy 3-cell C-band structure was built in spherical geometry because of easier manufacturing. The result was amazing, the comparison of the maximum accelerating field shows the remarkable gradient of 8 MV/m. Somewhat later the spherical geometry was found to be the best in order to avoid multipacting. The high radiation levels in the HEPL tests were not only caused by simple field emission but by resonant electron emission, i.e. multipacting.

Within a short time the five laboratories being the driving forces towards high gradient β=1 structures, CERN, Cornell, DESY, KEK, and Wuppertal, concentrated on the spherical geometry. The E_{peak}/E_{acc} ratio was optimized to be about 2 for any geometry. Some cavities had a wall section being exactly perpendicular to the cavity axis (remains of the old pill box). Later the elliptical geometry was found to be best because of easier chemistry and water cleaning. The resonator frequencies and the number of cells varied from 352 MHz / 4-cell (CERN) to 3 GHz /5 & 20-cell (Cornell; Wuppertal - for the S-DALINAC / Darmstadt).

A significant frequency dependence of the maximum obtainable accelerating field could not be found. The choice of frequency was determined by the need to combine the cavity operation with other normal conducting structures or by the existence of klystrons. For most of the listed cavities the maximum number of cells was chosen from HOM calculations. The need to damp HOMs and to have sufficient coupling between the input coupler and the cavity led to slightly different designs.

3 HIGHER GRADIENTS, LOCALIZED DEFECTS, AND HIGHER RRR

For many years the design goal for superconducting structures was about 5 MV/m. This was based on experience with multicell cavities. Nevertheless, the goal of high gradients was never forgotten since the BCS theory predicted maximum gradients of almost 50 MV/m at 2 K. Considerable effort has been devoted to the understanding of surface defects. Larger defects could be localized and sometimes even eliminated by grinding. In 1979 the technique of temperature mapping was developed at CERN and it was demonstrated that well localized defects were one of the prime causes of quenching [13]. Over the years these temperature mapping devices have been improved, and more diagnostics like X-ray diodes and RRR measuring devices using eddy current induced by small coils have been introduced.

Cornell pointed out that the threshold for thermal instabilities could be increased if the thermal conductivity, i.e. the RRR of the cavity wall is improved. In a close collaboration with industry the RRR value for the used Nb material was raised from typically 40 (corresponding to a heat conductivity λ = 10 W/(m·K) at 4.2K) to values between 150 and 200. To increase the RRR even further yttrification at about 1250^{o}C was used at Cornell. Later the use of 1400^{o}C UHV baking in the presence of titanium vapor was established.

The combination of eliminating defects and using higher RRR has guaranteed a more reliable way towards accelerating fields of 5 to 10 MV/m in multicell cavities. As examples one can quote results from CEBAF prototype cavities which reached 6-8 MV/m, a single cell KEK 500 MHz cavity (RRR 80) with 7.6 MV/m, the first CERN LEP prototype cavity (4-cell, 352 MHz) with 7.5 MV/m, and last but not least one 20-cell 3GHz cavity for the S-DALINAC which reached 7.8 MV/m after the preparation at Wuppertal. Cornell was able to reach really high gradients in 1.5 GHz single cell cavities: 22.5 MV/m. Wuppertal followed with 23.1 MV/m for a 3 GHz single cell structure.

A few years later the standard material for s.c. cavities was RRR 280. The first multicell cavities reached again higher gradients but shortly after the installation of the first 20-cell cavity in the S-DALINAC the enthusiasm was damped by a new phenomenon. After keeping the cavity at temperatures just above nitrogen temperature (70 - 100K), which can happen in a linac installation, the quality factor dropped, the cryogenic losses were increased by a factor of 10. Darmstadt and DESY found the Q-degradation (sometimes also called Q-disease) at about the same week. Months later it was clearly identified as a clustering of hydrogen and therefore creation of normal conducting niobium hydride areas [14]. For increasing the RRR of the Nb material the oxygen was removed with the disadvantage that the hydrogen is not chemically bound anymore. A cooling of the acid during chemical polishing is necessary to avoid high hydrogen concentration in the niobium. Otherwise Niobium hydride areas start to grow. Baking at temperatures above 750^{o}C can cure the problem.

4 THE STATUS BEFORE TESLA

At the LINAC 92 Conference R. Sundelin presented a good overview about the state of the art in s.c. cavity production [15]. Assembly in clean rooms was standard, the Cornell group had improved gradients using high peak power processing, and CERN used high pressure water rinsing to suppress field emission in the LEP cavities which are made from copper but sputter coated with Nb. The number of superconducting cavity operating hours in larger installations increased substantially.

Table 1:
S.c. cavities in operation as known at the time of the LINAC 92 Conference, i.e. before the start of the TESLA program. The CEBAF installation was ongoing at a rate of 16 cavities per month.

	Nbr.of	Cav.	MHz	m	MV/m
MACSE	5	5-Cell	1500	2.5	6.5
S-DALINAC	10	20-Cell	3000	10.0	5.9
HERA	16	4-Cell	500	19.2	3.6
HEPL				30.8	3.0
TRISTAN	32	5-Cell	508	47.2	6.6
CEBAF	106	5-Cell	1497	53.0	7.6
LEP	12	4-Cell	352	20.4	3.7

The achieved accelerating gradients of the different machines are listed above. The CEBAF installation was ongoing at a rate of 16 cavities per month.

5 CEBAF AND LEP INSTALLATION

The CEBAF recirculating superconducting electron linac at Jefferson Lab went in full operation and is now using 330 s.c. cavities operating at 2.0 K. The operation frequency is 1497 MHz. Four pairs of the 0.5-m-long cavities are contained in one cryomodule but each cavity is separately powered by one 5 kW klystron. According to [16] the distribution in the accelerating gradients has its maximum at about 7.5 MV/m with a spread of 5 MV/m FWHM. The principal limitation of the installed cavities is electron field emission and associated phenomena, such as X-ray production, charging and arcing at the cold ceramic RF window, and anomalous 2 K heat load. This affects about 80% of the cavities. Only 12% of the cavities are limited by quench. The average quench limit is at 13 MV/m.

The cavity operation in CEBAF has been quite stable and reliable. In 1997 the maximum energy delivered to the nuclear physics experiments was 4.4 GeV at a beam current of 115 μA. The RF could have supported 5.6 GeV with a five pass beam delivery. In-situ RF-helium processing of the cavities was tested and yielded an additional 41 MeV/pass. Jefferson Lab intends to upgrade the machine to the 6-8 GeV region by this method. Further steps towards higher electron beam energy are described elsewhere [17]. The Jefferson Lab Free-Electron Laser installation can operate above 10 MV/m.

In 1997 CERN operated 240 s.c. cavities in LEP. Out of the 240 cavities 16 were made from solid niobium and 224 were sputtered Nb/Cu cavities. The operation frequency is 352 MHz, the nominal operating field 6 MV/m. Eight cavities are grouped each and driven by one klystron. Two klystrons are connected to one HV power converter. According to [18] the overall performance of the s.c. RF system was good during the 1997 operation period. The average operational gradient of the 224 Nb/Cu cavities was 5.9 MV/m even though some cavities were limited at lower gradients. The four solid Nb modules were running at about 3.6 MV/m (nominal gradient 5 MV/m).

6 THE TESLA R&D EFFORT

Since 1991 the international TESLA collaboration [19] is following an approach to a 500 GeV linear collider using superconducting accelerating cavities. Altogether 35 institutes from nine countries are developing linac components as there are s.c. accelerating structures, couplers, cryostats, RF sources, beam diagnostics etc. The TESLA Collaboration tries in a joint effort to increase the usable accelerating gradient to more than 25 MV/m. A test facility, located at DESY with major components flowing in from members of the collaboration, is going to establish a well-developed collider design. The status of this design work is described elsewhere [5].

The TESLA Test Facility (TTF) includes cavity preparation and testing as well as the final test of cavities in a linac installation [20]. About 25 standard 9-cell 1.3 GHz structures operating in the pi-mode have been prepared and tested. Out of the first production series eight cavities were taken for the assembly of one TESLA cryogenic unit, the TTF module #1.

The goal for the accelerating gradient was set to 15 MV/m average (to be compared with the 1992 state of the art given in table 1) at an unloaded quality factor $Q_o=3\cdot10^9$. This goal was reached with module #1. Although some cavities are limited below 15 MV/m the maximum achieved electron energy was 125 MeV in short macropulses and 105 MeV in 800 µs long macropulses. The overall performance is limited by the weakest cavities since all eight cavities are driven by one common klystron and the RF forward power is equally split. Details about the operation can be found in [21].

7 THE FIRST TTF CAVITY PRODUCTION

About 25 cavities from 4 different manufacturers were tested in a vertical test cryostat. The average gradient was 19.2 MV/m at $Q_o > 3\cdot10^9$. 14 cavities showed $E_{acc} > 20$ MV/m, 3 cavities showed $E_{acc} > 28$ MV/m. The last 9 cavities delivered and tested had a clearly increased gradient of 24.3 MV/m at $Q_o > 3\cdot10^9$. Figure 1 shows the test results as a function of time. Maximum gradients are plotted as well as the usable gradient defined by the onset of increased cryogenic losses. Some of the very first cavities had maximum acceleration voltage being almost high enough for TESLA 500 but the strong field emission limited the usable gradient.

During 1996 the first group of cavities was tested. High pressure rinsing with ultraclean water reduced the field emission but most of the tested cavities were limited around 13 MV/m. The reason was found to be an insufficient cleaning after the preparation for electron beam welding of the equator. Since summer 1997 another 11 cavities were tested. The average maximum gradient is almost 25 MV/m. Field emission is still an issue and limits the usable gradient to roughly 22 MV/m. Nevertheless, all four manufacturers were able to produce cavities with gradients above or close to 25 MV/m. The gradient of the best TESLA 9-cell cavity is above 30 MV/m. Figure 2 shows the horizontal test result. This cavity is going to be used in the second cryogenic module.

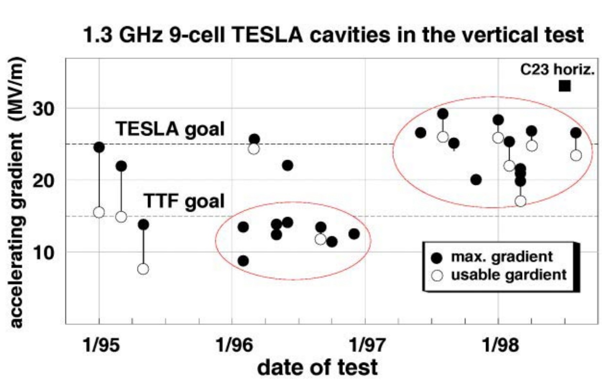

Fig. 1: Vertical test of 1.3 GHz 9-cell cavities.

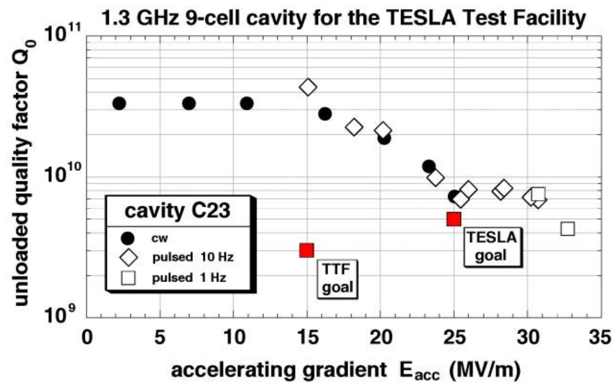

Fig. 2: The best TESLA 9-cell cavity measured in a horizontal test cryostat. For this test the cavity is equipped with the main RF input coupler and the HOM couplers.

8 OUTLOOK

The goal for the second TTF Linac module being just in the assembly phase is 20 MV/m. The third module is expected to reach 25 MV/m. All three modules will be used for a Free Electron Laser experiment in the UV [22]. Further modules will be built to finalize the design of accelerating units of the large TESLA machine [23]. Being installed in the TTF Linac they will finally drive a VUV free-electron laser. Therefore a new cavity production was started. A total number of 26 cavities is expected to be at DESY by end of 1998. The material for all cavities was scanned for inclusions of other metals. A special eddy current scanning apparatus was developed.

Single cell cavities have reached 40 MV/m accelerating field [24]. The members of the TESLA collaboration and also Jefferson Lab as well as KEK are still improving the gradients of resonators made from solid niobium. Electropolishing is studied again in order to smoothen the inner surface. High pressure water rinsing is the most successful method to decrease field emission. Nevertheless, the installation procedure of all RF couplers seems to be a main issue.

With the aim to decrease the cavity production costs two new fabrication methods are studied. Spinning of cavities is described elsewhere [25]. Hydroforming of multicell cavities is also under investigation. Both methods allowed the production of L-band single-cell cavities with accelerating gradients above 20 MV/m. A slightly decreasing Q vs. E_{acc} is not understood. Multicell-cavities are underway and will be measured next.

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