Improvements in Materials and Fabrication -Large Scale Production and Testing-*

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ABSTRACT

Several laboratories around the world are presently involved in large scale construction projects utilizing superconducting cavities. The reasons for this multitude of activities are a matured technology based on better understanding of the phenomena encountered in superconducting cavities and the influence of material properties and quality assurance measures.

At KEK a string of 32 five-cell 508 MHz niobium cavities has been assembled for Tristan, and since autumn of 1989 many thousand hours of operations experience exist now with this system.

CEBAF has started the production of its nearly 200 m long(338 cavities) superconducting accelerator section. The successful acceleration of electrons to 45 MeV in the front-end-test provided a glimpse into the complexity of such a system.

CERN and DESY are also building superconducting cavities on a large scale, and at Darmstadt much experience has been gained with a recirculating linac. At several laboratories plans for future applications of superconducting cavities in B-factories, linear colliders, or free electron lasers exist. This paper gives an overview of the present construction projects and discusses some of the difficulties associated with the transition from a laboratory scale to large scale project.

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INTRODUCTION

The remarkable properties of superconductors are caused by the condensation of charge carriers into Cooper pairs below the critical temperature T_c. In contrast to the dc case, where the dc-resistance of a superconducting material is zero below T_c, superconductors show a finite electrical resistance below T_c if subjected to an alternating electromagnetic field. The electrical resistance decreases exponentially with temperature below the critical temperature and reaches zero at zero temperature. This behavior is described by the microscopic theory of Bardeen-Cooper-Schrieffer (BCS), and for frequencies $f = \omega/2\pi$ small compared to the energy gap frequency (700 GHz for niobium) and for temperatures $T < T_c/2$, the surface resistance is proportional to the number of normal electrons (quasi-particles) excited thermally across the energy gap Δ and can be expressed by

$$R_{BCS} = \omega^2/T \times exp - (\Delta\ /kT_c)(T_c/T) \qquad (1)$$

The Q-value of an rf cavity made out of a superconducting material is then given by

$$Q_{BCS} = G/R_{BCS} \qquad (2)$$

with G being a geometrical constant depending only on the geometry and field configuration in the cavity. The wall losses in such a cavity are then given by the surface integral of the magnetic field

$$P_W = 1/2 \times R_{BCS} \times \int H^2 dS \qquad (3)$$

According to equation (1), an accelerating L-band-cavity made out of niobium and operating at a temperature of 1.8K would dissipate about 10^6 times less power than a copper cavity at room temperature at the same frequency and field level. It is this enormous reduction in power losses in cavities which has made the use of superconductivity in accelerators so attractive and which led to its first application at Stanford University two and a half decades ago.[1] Of course, in reality, the picture is not as glamorous as painted, and the reduction in power consumption is not as dramatic.

First, the surface resistance does not decrease indefinitely with decreasing temperature as given in (1), but is limited by a temperature independent residual resistance as shown in Figure 1. This residual resistance - despite some theoretical and experimental work[2] - is not completely understood, but is considered to be caused by frozen-in magnetic flux, defects in the superconductor, debris, dust or contamination on the superconducting surface, or features of the metal-oxide interface.

Secondly, the power dissipated in the superconductor has to be removed at low temperatures with low efficiency refrigerators, which reduces the factor of a million in power savings to roughly a factor of 1000. Nevertheless, the remaining improvements over normal conducting materials is significant enough to have attracted accelerator designers over the years. The pioneering work, which was done at HEPL, SLAC, BNL, Cornell, and KfK Karlsruhe, has flourished with an ever increasing number of laboratories getting involved in rf-superconductivity applications to Heavy Ion Boosters, Storage Rings, Nuclear Physics Instruments or FEL's.

Common to all these applications is the desire to take advantage of the low rf losses in superconducting cavities. This feature also permits accelerating cavities to be very simple iris loaded structures, because optimization of the shunt-impedance R/Q is not essential anymore.

Rf-superconductivity offers additional advantages depending on its application as listed below:

Recirculating Linacs

Continuous beam, high average current, and excellent beam quality due to precisely controllable rf phase and amplitude (energy spread of 2×10^{-5} *vs* 2×10^{-3} normal-conducting)

Storage Rings

Due to energy losses caused by synchrotron radiation (forth power of beam energy) electron-positron storage rings have to continuously provide billions of volts for acceleration. Superconducting niobium cavities can be economically operated at three to five times higher gradients with negligible wall losses and nearly all of the rf power supplied to the accelerating system is used for the acceleration of the beam. In contrast, in normal conducting systems (LEP,TRISTAN) a large fraction of rf power is dissipated in the structure walls. Higher gradients obtained in cavities with large beam holes result in shorter acceleration systems, reducing the disruption of the beam by beam-cavity interactions and permitting therefore higher beam currents. The same arguments are true for the recent consideration of SRF-cavities for B-factories (high luminosity requires high beam currents, low impedance).

Linac Boosters for Heavy Ions

Preservation of beam quality because of stable cw operation, low energy spread, operations costs.

Free Electron Lasers

Superconducting acceleration systems like rf linacs and storage rings offer the excellent beam quality (low emmittance, small energy spread) needed for strong spatial overlap of the laser beam with the electron beam; also tunability over a broad range of wavelength.

Linear Colliders

Low peak power, lower frequency of structure, reduced transverse wakefield effects, relaxed requirements for "final focus". Challenges are capital cost reduction by increasing gradients and decreasing manufacturing costs for acceleration system.

The potential advantages of rf-superconductivity over conventional room temperature technology have been recognized for a long time, and the pioneering efforts at HEPL/Stanford University and at KfK in the early 1970 have contributed to the present blossoming of projects and plans for implementation of new systems. The R&D efforts in both laboratories contributed to the understanding and elimination of fundamental problems in subsequent years:

a) Resonant electron loading ("Multipacting") was eventually eliminated in subsequent years by appropriate choice of cavity geometry.[3,4,5,6]

b) Thermal stabilization of cavities was accomplished by increasing the thermal conductivity of the wall material, when temperature mapping techniques had shown that cavity limitations were caused by heating of the cavity walls and simulation calculation had verified the experimental results.[7,8]

c) The importance of field emission ("Non-resonant electron loading") was investigated and reduction of field emission induced electron loading was achieved by developing appropriate cleaning and handling methods.[9]

This fundamental understanding has it made possible that - in a laboratory environment - astonishingly consistent and extremely high values for Q-values and field gradients have been achieved, which are getting closer to the fundamental limitation of the superconducting material (BCS-resistance, critical field). To preserve these outstanding cavity performance in a production environment is the challenge for the future and it will be discussed later in this paper.

IMPROVEMENTS IN MATERIALS AND FABRICATION

Since the last workshop at KEK two years ago most of the efforts in the various laboratories has concentrated around improvements of cavity performance with respect to higher gradients. A twofold approach was followed by

a) improving the surface treatment methods

b) minimization of $E_p/E_{acc}-$ ratio.

a) Improvement of surface treatment methods

This effort concentrated mainly on high temperature heat treatment in the presence of titanium as a protection and/or getter material to reduce field emission. Excellent cavity performances have been reported by Cornell University,[10] the University of Wuppertal[11] and Saclay,[12] and accelerating gradients above 25 MV/m have been reported not only for single cell cavities but also for multi-cell structures.

Conventional rinsing methods have been refined by improvement of the ultrapure water quality, by monitoring resistivity and/or particle content of the rinse water and by using ultrasonic agitation at higher temperatures and for longer periods of time. Gradients as high as 18 MV/m in a 5-cell production cavity[13] and $E_p > 50$ MV/m in a single cell 1500 MHz cavity[14] have been measured at CEBAF. At Cornell University field emission studies showed that many emission sites in the cavities were caused by indium dust generated during the handling of the cavities and could be eliminated by subjecting the surfaces to a one-hour nitric acid soaking prior to chemical processing.[15] At Los Alamos the "soaking" technique has already been used for a long time and the average peak surface fields improved from 33 MV/m to 48 MV/m with a record value of 78 MV/m[16] (Figure 2).

High-peak-power - processing was further pursued at Cornell University and resulted in further improvements of cavity performance after a furnace treatment with Ti. In a 9-cell S-band niobium cavity a record gradient of 19.5 MV/m with a Q-value of 4×10^9 was measured.[17]

Table 1

Laboratory	Cavity type	Treatment	Gradient
KEK	508MHz,5-cell	ep	E_{acc},15 MV/m[18]
CERN	352 MHz,4-cell	bcp	E_{acc}, >10 MV/m
CORNELL	1500MHz,1-cell 1500MHz,9-cell	ht ht,hpp	Ep, 60 MV/m E_{acc},19.5 MV/m
SACLAY	1500MHz,5-cell	bcp	E_{acc},18 MV/m
Wuppertal	3GHz,1-cell 3GHz,5-cell 3GHz,9-cell	ht ht ht	E_p,70 MV/m E_{acc}, 22 MV/m E_{acc},16 MV/m
Los Alamos	3GHz,1-cell	bcp	E_p, 78 MV/m
CEBAF	1500MHz,1-cell 1500MHz,5-cell	bcp bcp	E_p, 52 MV/m E_{acc},18 MV/m
DESY	500 MHz,4-cell	bcp	E_{acc},8.5 MV/m[19]

Table 1 summarizes the best results obtained in the various laboratories.

b) Cavity Shape Optimization

This activity was mainly triggered by the efforts to demonstrate that a superconducting linear collider with gradients > 15 - 20 MV/m is not utopic anymore and can be tackled in the near future. Two prototype shapes (Figure 3) with ratios of $E_p/E_{acc} \cong 2$ have evolved in a CORNELL/DESY/WUPPERTAL/DARMSTADT and a KEK/CEBAF collaboration. Whereas the latter collaboration is still in the early stages, the CORNELL-led efforts have produced several multi-cell cavities both at L- and S-band frequencies with outstanding performances (> 19 MV/m) after heat-treatments.

A major problem with high purity niobium surfaced in 1989/90, when several laboratories discovered that the achievable Q-values and gradients could significantly degrade by the cooldown conditions. This problem of the "European Q-disease" will be the topic of a review talk at this workshop.[20] At CEBAF, it led us to re-investigate the usefulness of anodic oxide layers on the niobium surfaces as an alternate surface treatment method.

c) Fabrication Experiences

Four 9-cell S-band cavities and two 6-cell L-band cavities have been fabricated at Cornell without machining steps at the irises and equators, eliminating some essential cost contributions in cavity fabrication.

Main improvements in the fabrication of the CEBAF-cavities were made in deep drawing more complicated pieces, which reduced the number of components and welds, resulting in cost reductions. At this time, INTERATOM has fabricated > 150 cavities with ≈ 2 km of electron beam welds without problems. The materials of four manufacturers as specified (grain size, elongation, recrystallization, etc.) did not cause any manufacturing problems.

An interesting, new welding technique for cavities was introduced by the French company TECHMETA. Rather than welding the cavities from the outside with a full penetration weld, the electron beam is deflected by a 90° bending magnet located inside a cavity. Figure 4 shows the arrangement, which provides excellent beam quality over a distance of 3 m.[21]

At CERN, C. Hauviller[22] has successfully hydroformed single cell copper cavities at 350 MHz and 1500 MHz with subsequent niobium coating. The process was also applied to 3" diameter × 1/8" niobium tubing supplied by CEBAF, but failed due to non-uniformity of the starting material caused by the tube-drawing process.

Nevertheless, such a process, which has been investigated earlier at Cornell and DESY, could potentially reduce cavity manufacturing costs significantly.[23]

d) Material Improvements

The University of Wuppertal is collaborating with two Russian Laboratories on exploring niobium of higher purity as is presently commercially available (RRR > 300). GIREDMET has supplied niobium of RRR = 520 with very low Ta-content and the niobium supplied by the Institute of High Energy Physics in Protvino had RRR = 800. After Ti-treatment at 1350° the RRR values exceeded 1500. Single cell S-band cavities have been fabricated from these materials, and it will be very interesting to evaluate the performance of these cavities.[17]

The mechanical properties of the Protvino material has been measured by G. Rao at CEBAF at room-temperature and at 4.2K. At room-temperature the yield strength is 9600 psi and the elongation is 46.6%; at 4.2K the material fractured at 83000 psi at a maximum elongation of 6.5%. At CEBAF we were also interested in the temperature dependence of the mechanical properties of the niobium used for the cavity manufacturing, because during cooldown of the cryostats pressure excursions might occur subjecting the cavities to unusual load conditions. Figure 5 shows the first set of data obtained with RRR > 300 Fansteel material. Noticeably, there is a minimum in the elongation at about 100K, the same temperature, which is most devastating to the Q-value of cavities made from high purity niobium, if they are held at this temperature for several hours.[24]

LARGE SCALE APPLICATIONS OF SUPERCONDUCTING CAVITIES

At the present time superconducting cavities are used on a large scale in two areas: in storage rings and as nuclear physics instruments.

a) Storage Ring Applications

The interest in the application of superconducting cavities in storage rings started in the late 1970's and a series of beam tests of such devices have been conducted at KfK, Cornell, DESY, KEK and CERN. The outcome of these developments and experiments confirmed the expectations in the technology and has paved the way for three large scale projects at KEK, DESY and CERN as indicated in Table 2.

Table 2

Laboratory	**KEK**	**DESY**	**CERN**
Project	TRISTAN	HERA	LEP
Frequency[MHz]	508	500	352
Structure	5-cell	4-cell	4-cell
Material	Nb	Nb	Nb/Nb-Cu
# of cavities	32	16	24/176
Operating T	4.2K	4.2K	4.2K
Design field	5 MV/m	4 MV/m	5 MV/m
Q at design field	2×10^9	2×10^9	3×10^9

<u>KEK</u>

The installation of the 32 cavities into TRISTAN was completed in summer 1989. The performance of the electropolished cavities was excellent when tested in a vertical cryostat with an average gradient of 10 MV/m.[25] The average value of the maximum accelerating gradients after installation of the cavities into the horizontal cryostats was 7 MV/m without beam. In 1990 TRISTAN was operated at an average current of 12 mA at 29 GeV, during which the cavities had been kept cold for about six months. Except for some accidental damages on four cavities due to leaks in the input coupler system (vacuum leaks) and two non-understood degradations, the remaining cavities have kept their performance without degradation during many thousand hours of operation.

In the mean time, four additional cavities have been fabricated and tested with an average gradient of > 9 MV/m in their vertical tests. One of these cavities exhibited the highest gradient ever achieved with a cavity of such dimensions (Figure 6).

LEP

About two hundred 4-cell 350 MHz cavities in modules of four cavities per cryostat will be installed into LEP by 1994 to raise the beam energy beyond 90 GeV. 32 of the cavities are fabricated from niobium sheet metal; 168 will be niobium sputtered on copper to take advantage of the higher thermal stability and the lower manufacturing costs.

Industry (CERCA) is building 20 of the 32 sheet metal cavities. The first four cavities have been delivered and after initial QA problems, the cavities perform satisfactorily in the horizontal tests and are presently assembled for installation in the tunnel[27] (Figure 7). Three modules - 1 sheet niobium, 2 Nb/Cu -fabricated in house, are already installed. The average gradient of the Nb/Cu - modules is 5 MV/m in the laboratory with a best value for an individual cavity of 9.7 MV/m.[26] Contracts for fabrication of Nb/Cu cavities have been placed to three companies and the technology transfer has started.

HERA

A total of 12 niobium cavities (6 cryostats) (Figure 8) have been installed in HERA a few weeks ago; they have been tested prior to installation with an average gradient of > 6 MV/m. These cavities in conjunction with the normal-conducting acceleration system provided in the recent run of HERA a total of 29 GeV in smooth operation. An additional 32 cavities might be added to the existing system, if the operating experience stays positive.[28] The HERA-cavities suffered in the early stages from the Q-degradation problem; different chemical treatment procedures have been investigated to avoid the solution of hydrogen in the high purity niobium, and together with more rapid cooldown of the cavities these efforts have been successful to some extend.

b) Nuclear Physics Application

Besides the Heavy Ion projects, which make use of low β-structures and which will be discussed in another talk,[29] there exists presently several prototype projects at Saclay, INFN and Los Alamos and construction projects at Darmstadt and CEBAF. Details of these projects will be presented at laboratory talks and posters.

SACLAY

Five 5-cell cavities have been manufactured and tested in a vertical configuration with gradients ranging from 8 to 17 MV/m. During the assembly sequence into the cryostats, these cavities are twice subjected to exposure to dry nitrogen gas, which does not seem to degrade the cavity performance. In the production module Q-values $> 5\times10^9$ and gradients > 5 MV/m have been achieved; the field gradients were restricted to these values due to operations conditions and not to cavity limitations.[30]

DARMSTADT

The original 20-cell structures of the 130 MeV accelerator, which were made from reactor grade niobium, are being replaced with structures from RRR=280 niobium. The very first of these cavities exhibited a gradient of 6.7 MV/m (compared to an average of 3 MV/m for the reactor grade cavities), but during a slow warm-up of the accelerator to intermediate temperatures severe Q-degradations were encountered. Subsequent modules were routinely hydrogen degassed at the University of Wuppertal, the degradation phenomenon disappeared, and the average gradient is 5.4 MV/m. After two recirculations a beam energy of 75 MeV was achieved.[31]

CEBAF

CEBAF received until now a total of 138 cavities from INTERATOM and 16 cavities were built in house. These cavities are chemically treated at CEBAF, assembled in a class 100 clean-room into hermetically sealed cavity pairs and tested in a vertical configuration. When exceeding CEBAF's design values of $E_{acc} = 5$ MV/m and Q(2K,5 MV/m)> 2.4×10^9, the cavity pairs will be installed into cryostats. Until now 48 different cavities have been tested. Of the 48 cavities, 45 exceeded CEBAF's design values in the first test, three on the second processing:

- Q-values up to 2.4×10^{10} have been achieved with an average Q-value of 8×10^9 at 5 MV/m
- Gradients as high as 18 MV/m have been measured with an average gradient of 9.5 MV/m

Statistics of the measurements are shown in Figures 9 and 10.

Despite the excellent cavity performances, only 14 pairs out of a total number of 60 pairs tested have been used for cryomodule assembly because of various problems:

- Through leaks on gate valves (8) - problem corrected with MDC-valve*
- Bonnet seal leak on gate valve (3) - corrected with MDC-valve
- Problem on rf probe in cold test(short) (1)- corrected
- Low Helium level - cavity was warming up (3)- corrected
- Leak at cavity flange/e–beam weld-inhouse cavity (2)-corrected
- Misalignment of pair (1)- corrected
- Insufficient Nb-removal (2)- corrected
- Leaks at various flanges, preferentially window-flange
- Through leaks through window ceramic

The major problem of leaks have resulted in a series of investigations and changes in the procedures:

The mechanical rigidity of the square flanges was increased, the flange deflection was investigated both experimentally and computationally, the bolt torques and spring washer assemblies were reevaluated, a reduction of the thickness of the indium and the placement of the gasket closer to bolts is considered, the creep behavior of the indium was evaluated, the QA-procedures for the flange surface finishes were tightened,

* MDC Vacuum Products Corporation

and it was found that chemical surface treatment of metal surfaces after mechanical polishing is essential.

In a thermal cycle test (10 cycles) of an assembly incorporating these procedures in the most troublesome window-flanges, leak rates as low as 10^{-15} torr ℓ/sec at 2K were measured with 0.04" indium wire seals.

There exists confidence that strict adherence to the established procedures will eliminate the leak problem and that the temporary production slippage will be made up with anticipated construction completion at the end of FY 1993.

During 1990/1991 it was demonstrated that pair assembly and pair test rates, and cryo-module assembly and test rates can be achieved to support this schedule.

SUMMARY OF EXPERIENCES

a) Large scale production of cavities by industry seems to be no problem, if sufficient support is offered. Several companies have acquired the capability to manufacture modules in accordance with specifications, ranging from 5 - 10 MV/m.

b) The capability to provide fully tested units by industry is very limited and expensive; nevertheless, several companies like Mitsubishi Heavy Industries, Interatom, Dornier and Cerca have provided partial services.

c) Technology transfer to the extent of "ready-to-use" accelerating sections has not been demonstrated yet.

d) The cavities produced by industry perform very well after proper surface treatment and assembly at the user's facilities and average gradients close to 10 MV/m have been achieved in the vertical test cryostats.

e) In no laboratory have the vertical test results been duplicated under running conditions with beam. The deviations range up to factors 2 or 3. This was in some cases due to operations conditions, in some cases due to cavity performance.

In general, no irreversible degradations in long term running periods have been reported.

f) We all know that superconducting cavities are very sensitive to handling; slow and controlled exposure to atmospheric nitrogen after tests is successfully exercised in various laboratories. The approach of hermetically sealing cavities after assembly does not seem to be a bad idea either. Cavity pairs at CEBAF have survived - without degradation in performance - cross-country trips in trucks, transatlantic flights in 747's and cutting out of helium vessels.

g) Nevertheless, the fact that the excellent performance in vertical tests have not fully materialized under operating conditions raises the question of how one can preserve these excellent results especially in the light of linear collider requirements.

h) It seems necessary to apply much more stringent quality control in the future than is presently applied; a very conscientious, knowledgeable and dedicated staff is needed. This might not be realistic if one talks about many kilometers of high performance cavities. Therefore the "human" factor has to be minimized by introducing robotic systems, compatible designs and less elaborate processing and assembly procedures. We should be alert to learning from mass production industries such as the automobile, semi-conductor, space, or food/pharmaceutical-industries.

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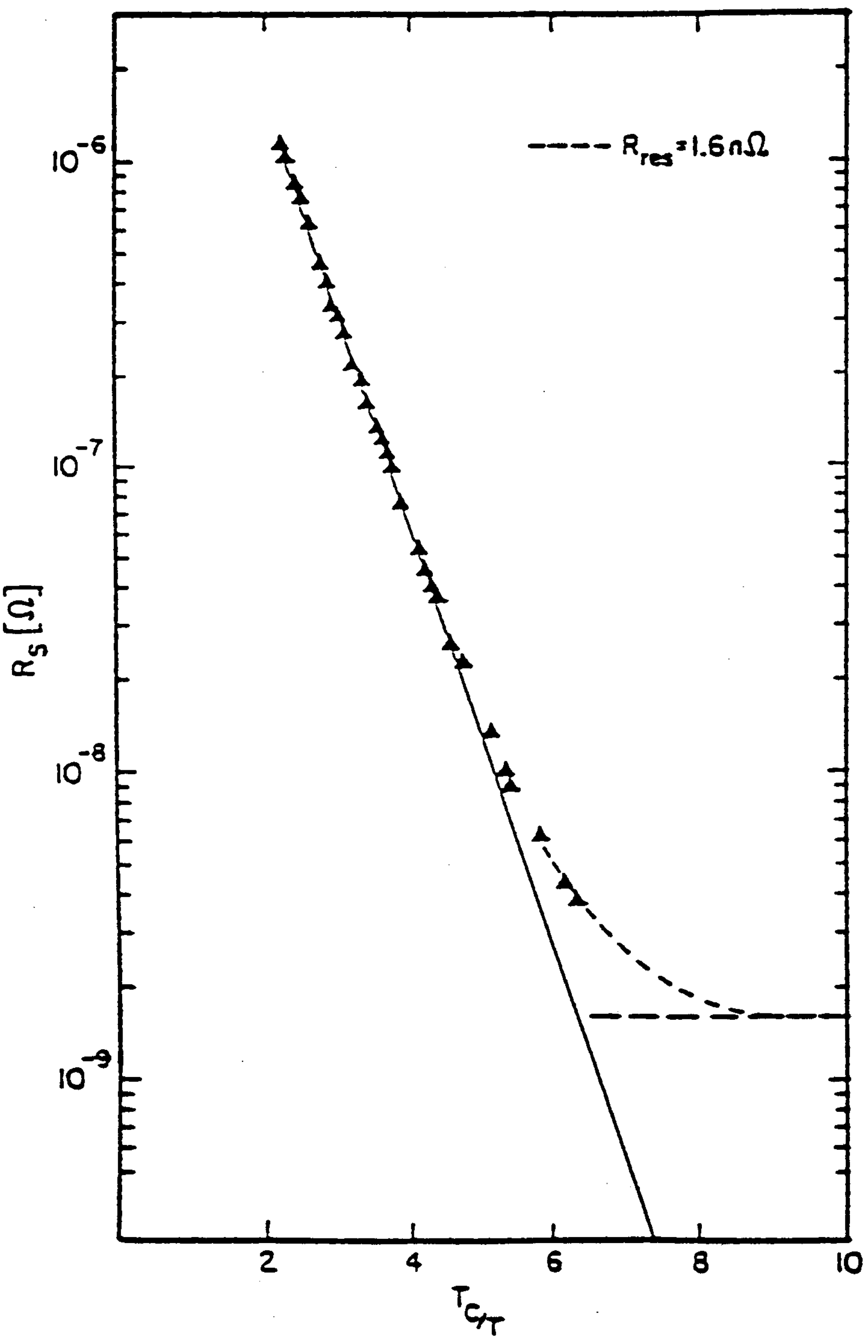


Fig. 1: R(T) vs Tc/T

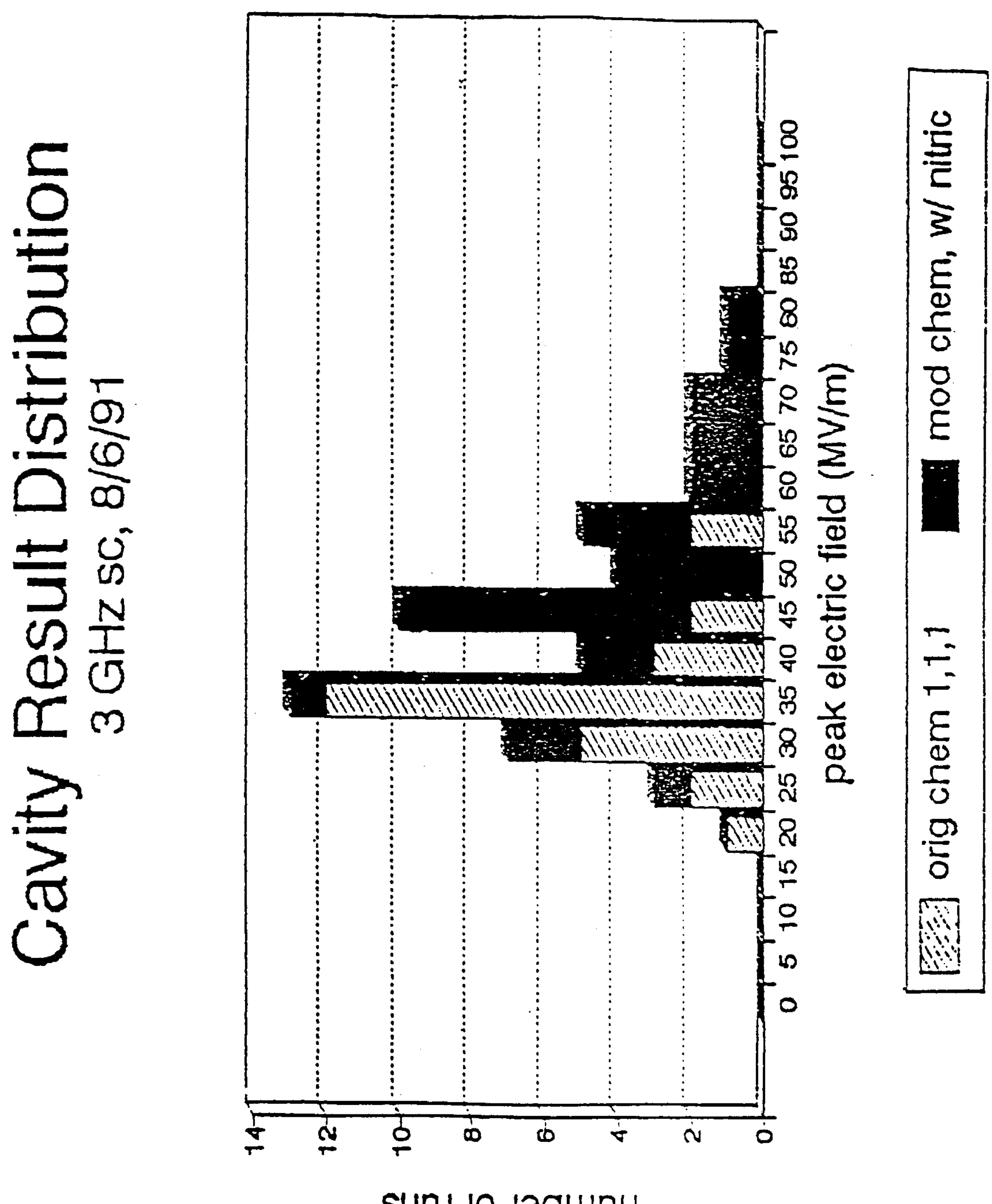
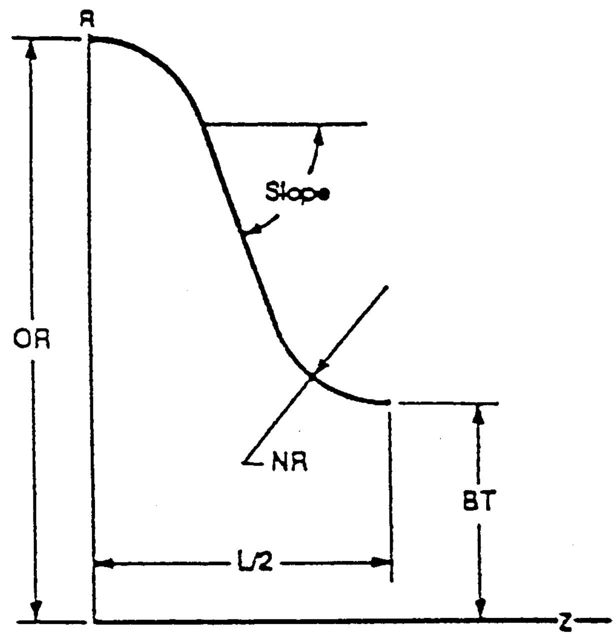


Fig. 2: Histogram of S-band single cell results from Los Alamos

TESLA - CAVITIES



Parameter	Cornell	KEK
Frequency [MHz]	1500	1300
OR (Radius)	9.48cm/9.43 cm	10.33 cm
Beam Tube (Radius)	3.56 cm	3.80 cm
Slope [degree]	70	75
L/2	4.93 cm	5.78 cm
Coupling	1.8 %	2.66 %
E_p/E_{acc}	2.1	2.22
R/Q per cell	89 Ohm	108 Ohm
H_p/E_{acc}	57 G/MV/m	43.1 G/MV/m

Fig. 3: TESLA cavity shapes: CORNELL, KEK

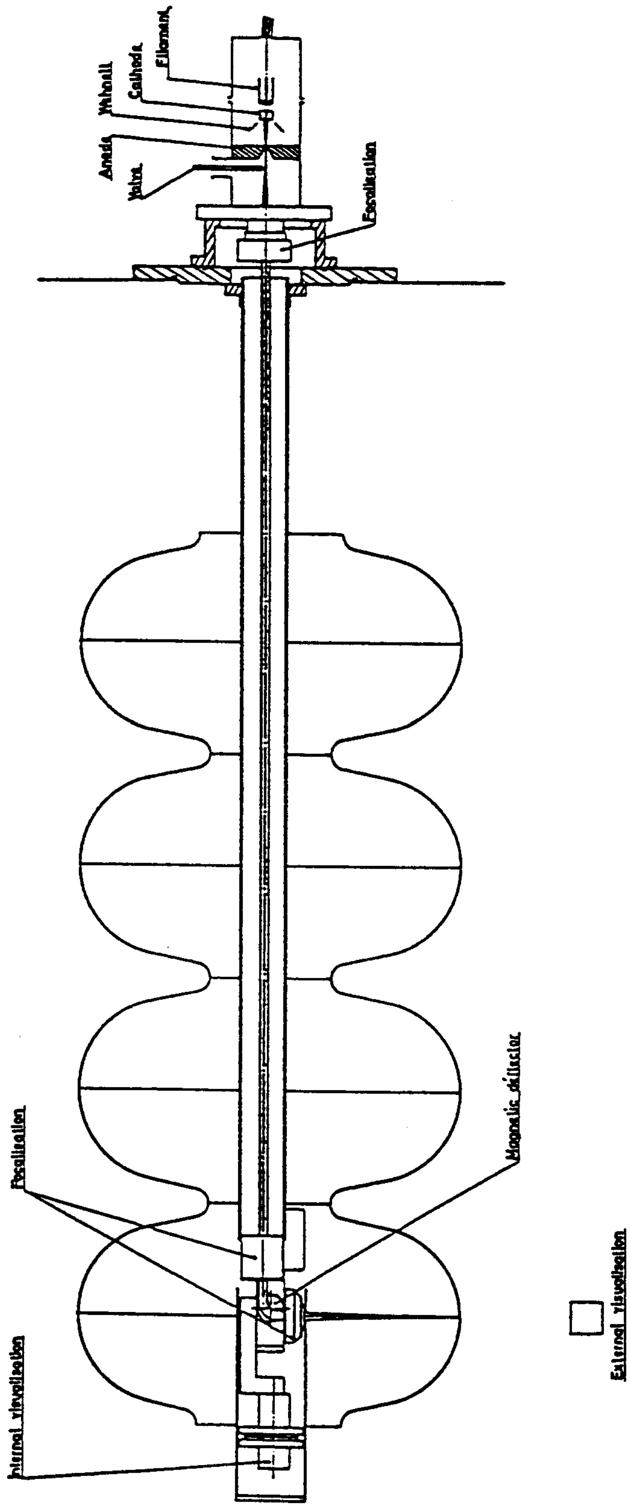


Fig. 4: Inside welding of cavities by TECHMETA

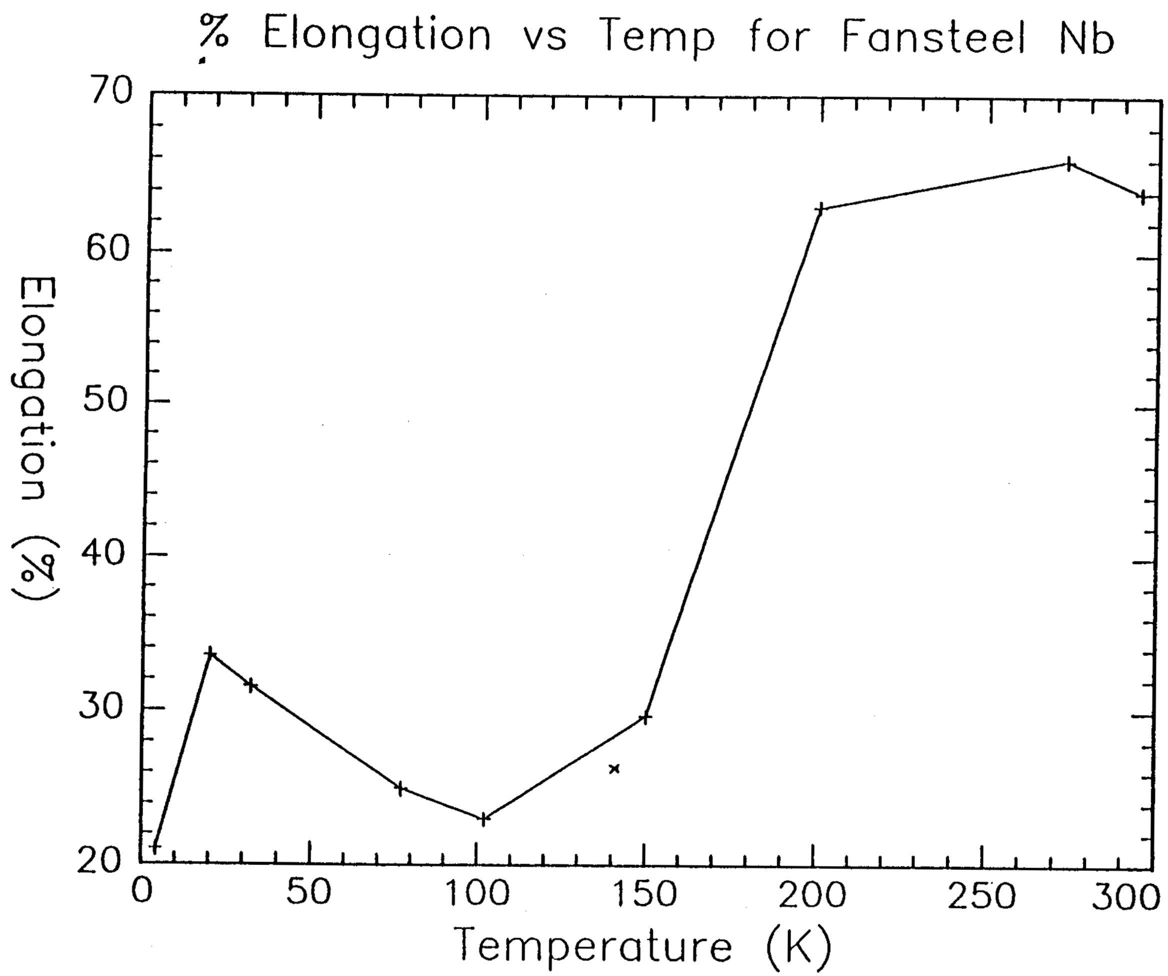


Fig. 5: **Elongation of high purity niobium as a function of T**

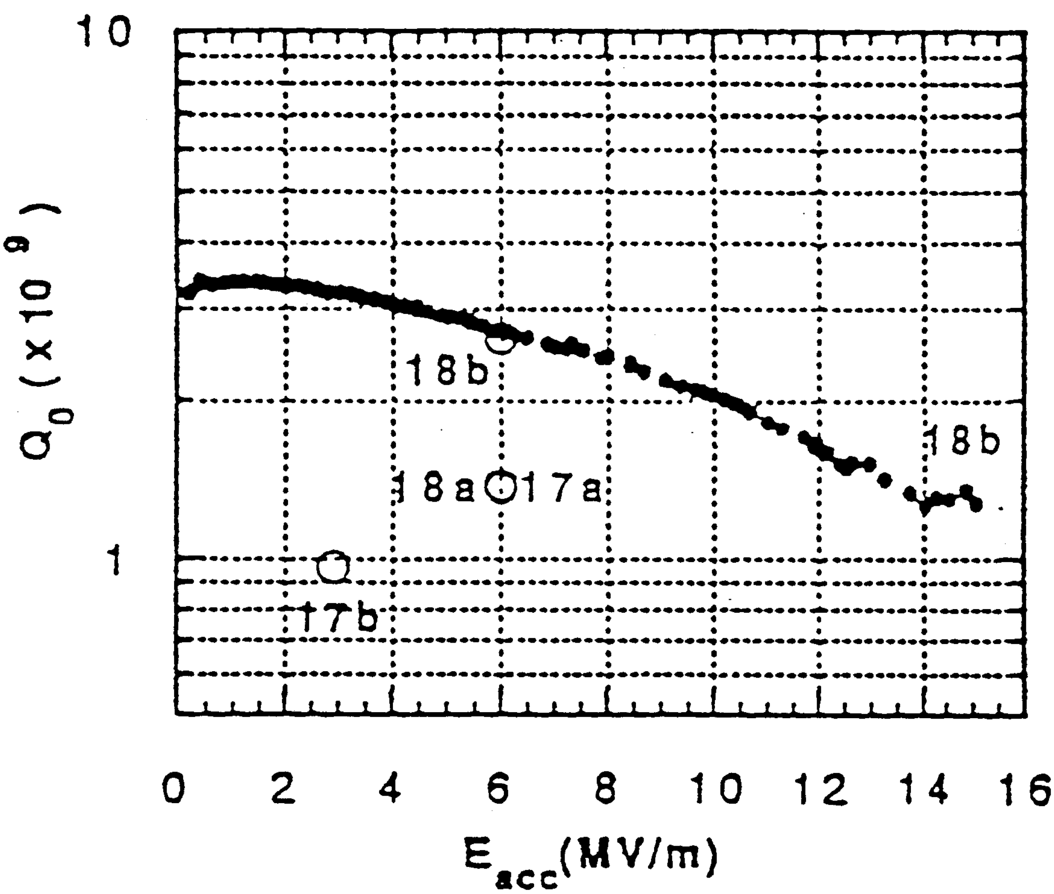


Fig. 6: Best result obtained with an electropolished 500 MHz-cavity at KEK

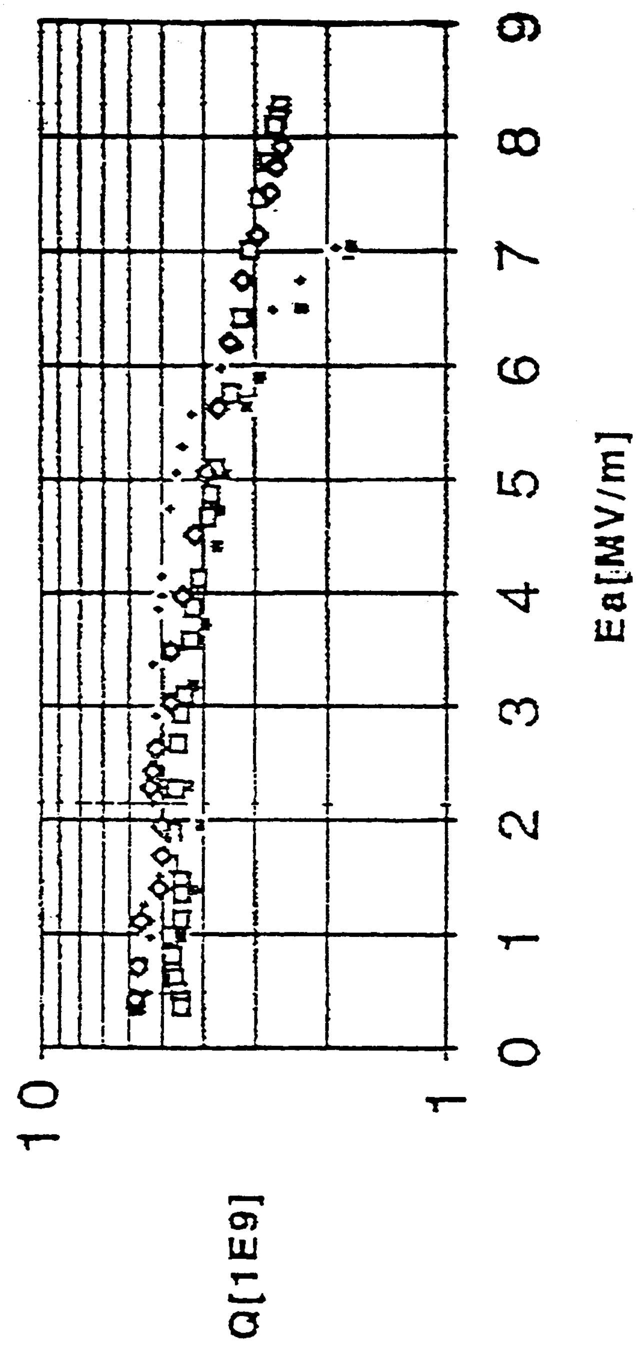
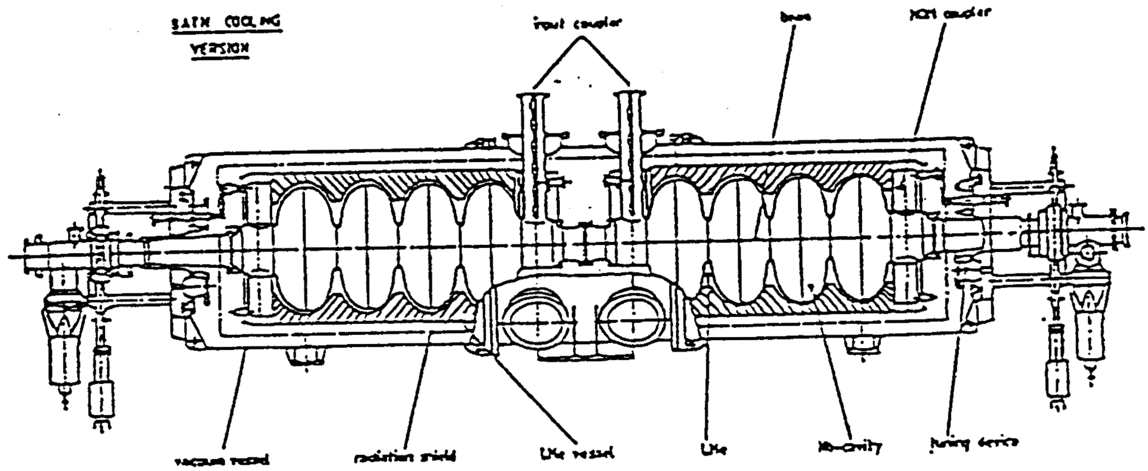


Fig. 7: Results of 352 MHz production cavities of CERN/CERCA



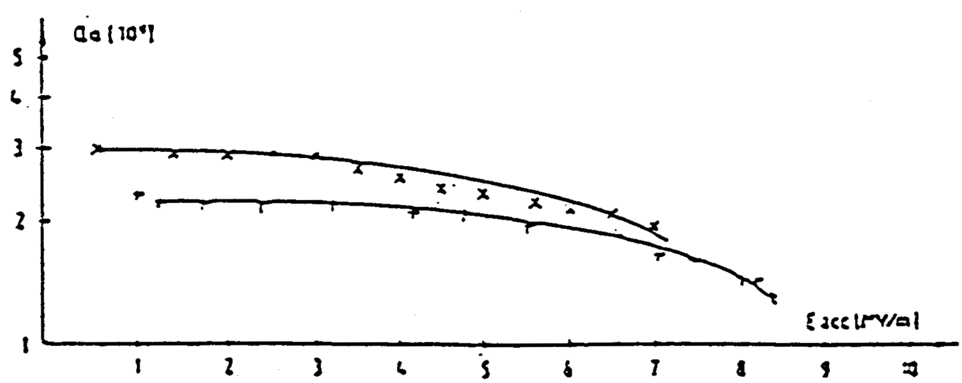


Fig. 8: DESY cryostat and Cavity Performance

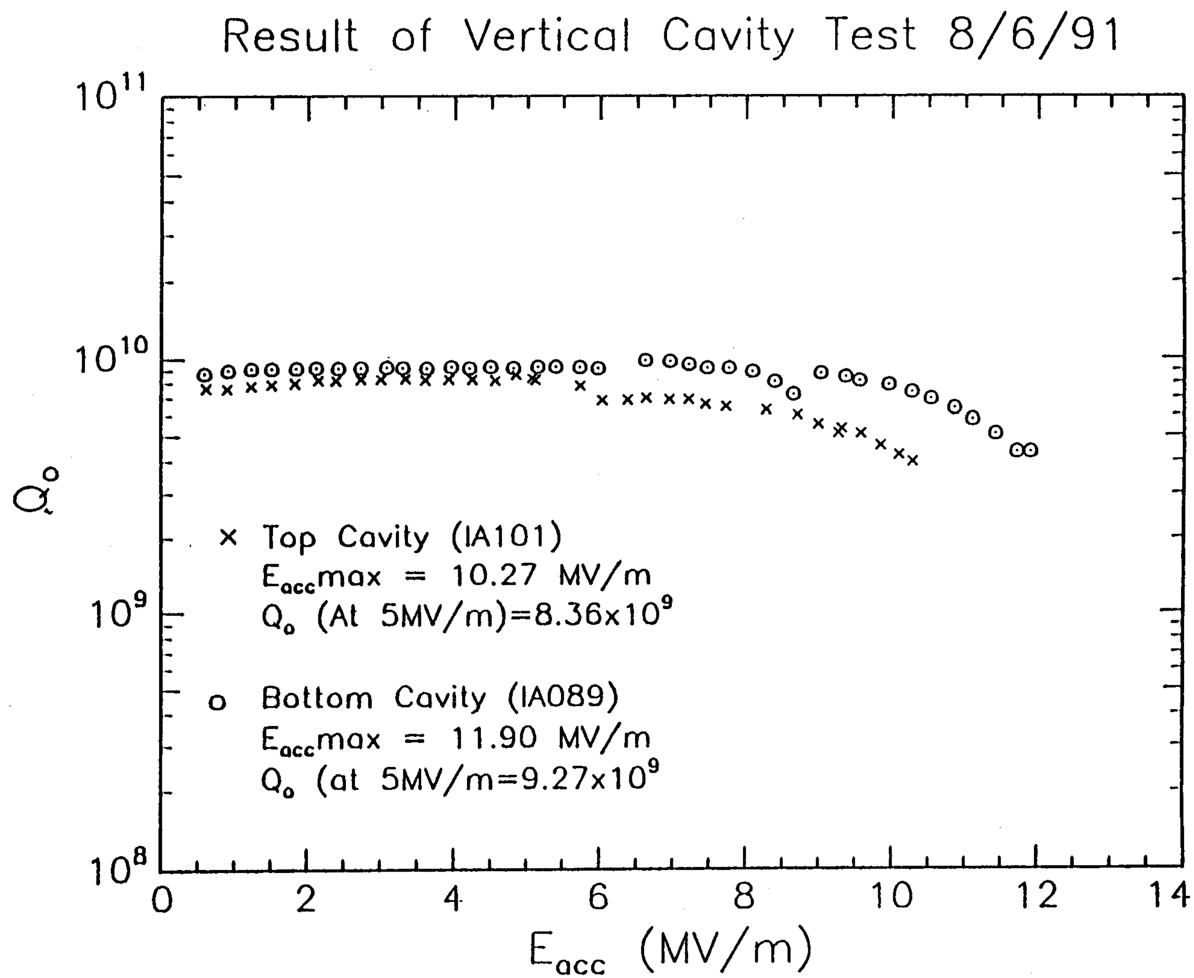


Fig. 9: **Typical Q_0 vs. E_{acc} for CEBAF cavity pair**

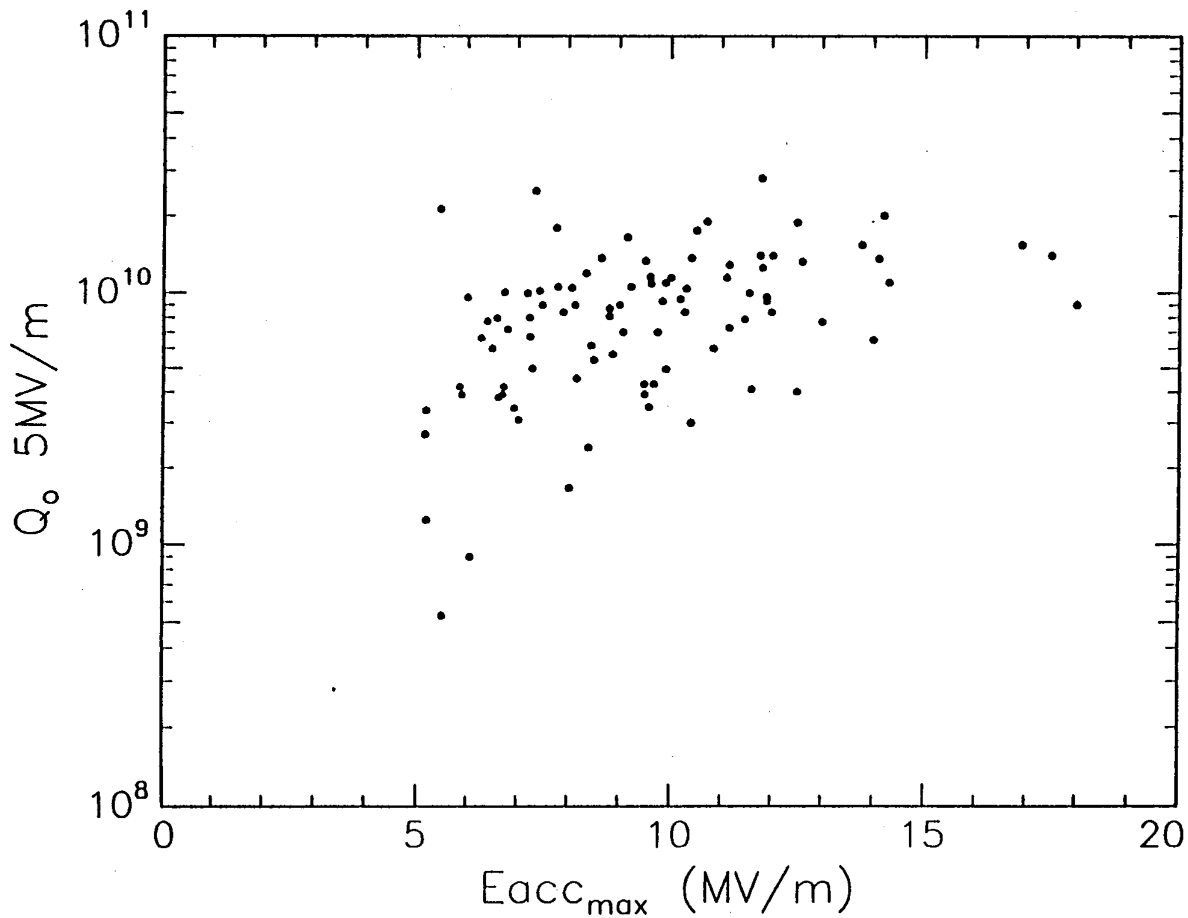


Fig. 10: CEBAF results Q(5 MV/m) vs. E_{acc}, vertical cryostat