MEASUREMENTS ON THE FIRST 20-CELL DEFLECTOR SECTIONS FOR A SUPERCONDUCTING RF SEPARATOR

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Summary

Experimental results on the first 20-cell Nb deflector sections for an S-band superconducting RF separator are given. A sequence of surface treatments including electropolishing, anodizing and high temperature UHV-annealing has allowed to obtain repeatedly high field Q-values up to $1.8 \cdot 10^9$ and peak magnetic fields up to 400 Oe. This corresponds for the operating mode ($\pi/2$) to deflecting fields of 2.6 MV/m and to electric peak-fields of 14 MV/m. With the same surface treatments we have obtained in a 4 cell test deflector a Q-value of $2.5 \cdot 10^9$ and a peak magnetic field of 850 Oe which corresponds to a peak electric field of 30 MV/m. A new method for localizing cells with high surface resistance in multi-cell cavities has been applied successfully. It also has been tried to localize the cells where a magnetic breakdown takes place. Perturbation measurements have been performed for a large number of modes and it is shown that the fabrication tolerances ensure a sufficient field-flatness in the $\pi/2$-mode. A movable RF coupling system using a bellow as an outer conductor and a new type of RF joint are shortly described.

Introduction

At Karlsruhe a superconducting RF particle separator is currently under construction[1] which will be installed in a particle beam with an intercavity distance of 80-90 m allowing separation of kaons and antiprotons in the range of 10-30 GeV/c.[2] The design frequency of the separator is 2855 MHz (S-band) and its two iris loaded and uniform periodic niobium deflectors are operated in a $\pi/2$-standing wave mode. Each deflector has an effective length of 2.74 m corresponding to 104 cells. It is intended to reach deflection fields of at least 2 MV/m corresponding to magnetic peak fields at the surface of 310 Oe. In order to avoid safely a thermal breakdown during operation at these field levels, a minimum quality factor $Q_0 = 5 \cdot 10^8$ has to be reached. Experiments on several test-deflectors[1,3-6] allowed us to fix all parameters, the fabrication and welding techniques and the surface treatments to be applied. As a UHV-treatment at temperatures around 2000°C seems essential for obtaining sufficiently good performances it was decided to assemble each deflector from 5 sections of about 60 cm length which can be heat treated in the existing high-temperature UHV-furnace. The fabrication of the first deflector at Siemens, Erlangen has been finished and we report in the following on experimental results obtained with the first 20-cell sections (called hereafter D1 - D5). In Fig.1 the geometry of the deflector cells is shown.

1. The experimental layout for cold measurements; surface treatments.

For the low temperature measurements on the deflector sections we have used the expe-

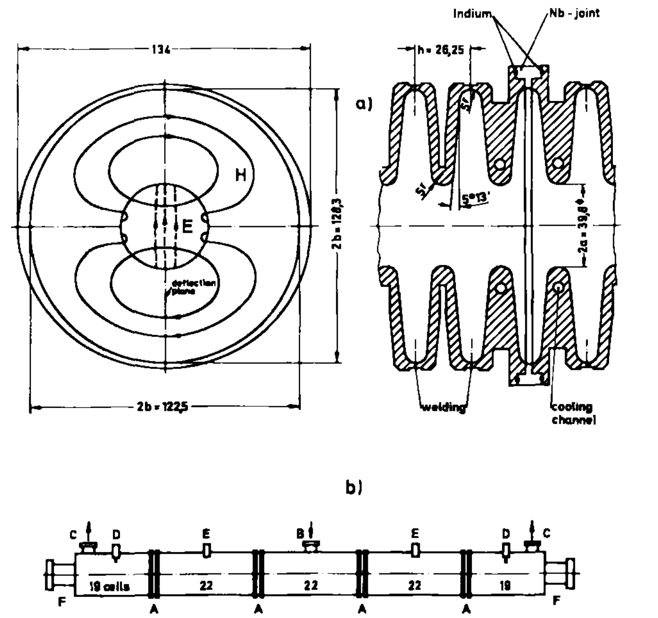

Fig.1a: Geometry of the normal cells and a joint cell of one deflector section. Some field lines are indicated. For mode stabilisation the cells have an elliptical cross-section.
1b: Schematic layout of one deflector assembled from 5 sections. A: RF joints, B: RF-in, C: RF-out, D: fine tuner, E: coarse tuner, F: beam tube

rimental layout shown in Fig.2. The sections are hanging vertically inside the cryostat. They are connected to a coupling unit with the help of an RF joint of the same type as will be used later on for the assembling of the different sections to form one deflector.[7] During the first experiments the coupling unit was situated above the sections but it turned out that there is a danger of dust or small particles falling from the movable coupling lines into the first (coupling) cell of the coupling unit. Therefore, we changed the layout by coupling from below as it is shown in Fig.2. The pumping of the structure is always done via a pumping line and a bend from below. This pumping system has several advantages. It avoids dust particles falling from above into the sections. At the beginning of cooling down for a cold measurement, it acts as a cryopump for the sections and at the same time as a trap for degassing products (or leaks) from the upper warm part of the vacuum system. Rough-pumping of the system is done by using a turbo-molecular pump. Once a vacuum of the order of 10^{-5}Torr is obtained, pumping is continued with an ion-pump which is normally not exposed to atmospheric pressure. Many experiments on test-deflectors[1,3-5] have led us to a sequence of surface treatments which allow to reach reliably Q-values and magnetic peak fields in excess of what has been assumed a lower limit for the application at CERN. The sequence has been described in ref.5 and we list here only the surface treatments applied to each section

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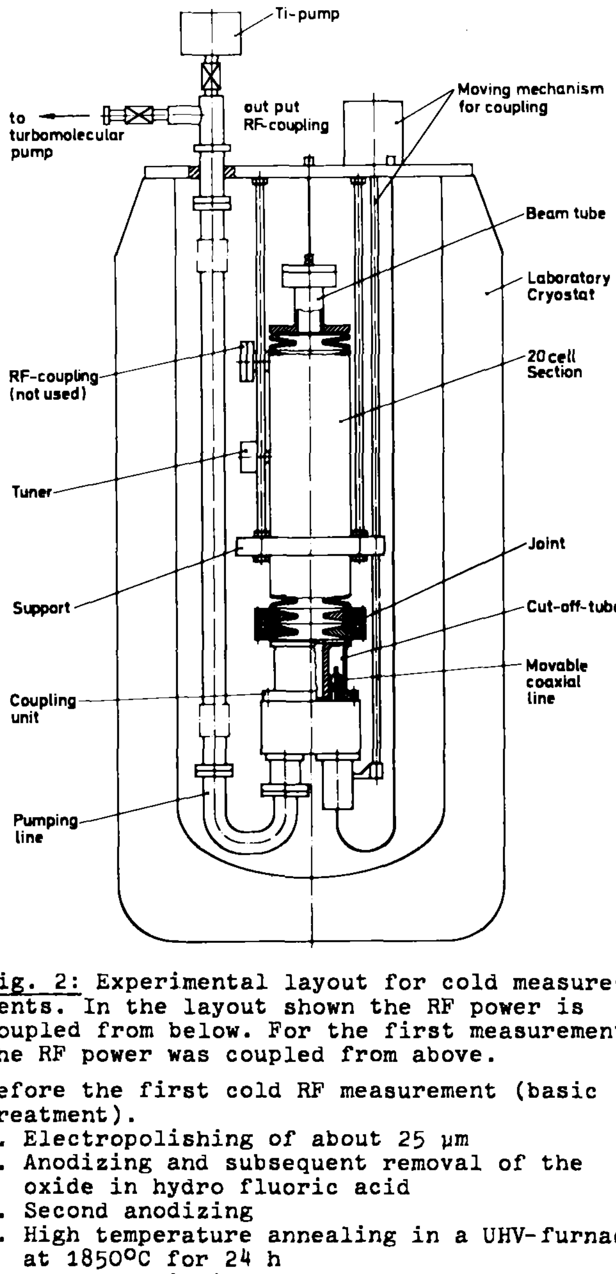

Fig. 2: Experimental layout for cold measurements. In the layout shown the RF power is coupled from below. For the first measurements the RF power was coupled from above.

before the first cold RF measurement (basic treatment).

1. Electropolishing of about 25 µm
2. Anodizing and subsequent removal of the oxide in hydro fluoric acid
3. Second anodizing
4. High temperature annealing in a UHV-furnace at 1850°C for 24 h
5. Electropolishing of about 75 µm
6. Anodizing as in point 2 and 3
7. Second high temperature annealing as in point 4.

After the high temperature treatment the sections are carefully flooded with dry and clean N_2 inside the furnace, then brought under a protective plastic cover to a dust-free glove box where they are assembled with the coupling unit and where all extra flanges are mounted under streaming clean air. Finally the sections are connected to the pumping system.

Whenever the sections have been exposed for longer periods to air or protective gases an additional treatment is applied before the following cold measurement. This consists of an electropolishing of about 10 µm, an anodizing and a high temperature annealing (as in point 4). The treatment described above also is applied to the coupling units. As they cannot be mounted immediately after the last high temperature treatment to a 20-cell section, they are stored for a few days under clean air or in a stainless-steel box which is evacuated to about 10^{-2}Torr. Before assembling with the sections they are flooded eventually with dry and clean nitrogen gas and then stored inside the dust free box.

2. The dependence of Q-values on modes and bad cells[8]

In the course of low temperature measurements on the 20-cell sections we have found not only unloaded Q-values well below the theoretical values at 1.8 K but also a mode dependence of the unloaded Q exceeding greatly the normal 20% variation which is predicted by theory and measured at room temperature. This is explained by localized regions where the surface resistance is greatly increased. The Q-value of an RF cavity is defined by the relation

$$\frac{1}{Q} = \frac{P_o}{\omega W} = \frac{\frac{1}{2}\int RH^2 dS}{\omega W} \tag{1}$$

with $\omega = 2\pi f$, and
f: frequency of the mode used
W: stored RF energy inside the cavity
P_o: RF power absorbed inside the cavity
H: magnetic field amplitude
R: surface resistance.

If the quality factors in a multi-cell cavity are dominated by the RF losses of one bad cell one can write[8]

$$\frac{1}{Q_{i,k}} = K_i' \frac{(H_{i,k})^2}{W_k} \tag{2}$$

where $Q_{i,k}$ is the quality factor determined by the RF losses in cell "i" and for the mode "k", $H_{i,k}$ is the magnetic field amplitude at the bad region of cell "i" and for the mode "k", W_k is the stored energy for the mode "k", K_i' is a constant independent of mode (but not of cell number!).
In our disk loaded waveguides we expect that bad regions are located mainly at the weldings, the RF joints and the holes for tuning and RF coupling. All these regions are situated inside the slot region where the deflecting mode is described well by a TM_{110} coaxial mode and where losses are due to the magnetic field components H_θ and H_r. On the other hand, in a disk loaded waveguide the longitudinal electric field component E_z can be easily measured by pulling a perturbating needle parallel to the axis of the waveguide and in the disk hole region. It has been shown[8] that there exists for every point inside the slot region a proportionality between $H_{i,k}$ and the maximum of the electric field component E_z inside the disk hole region of cell "i" and for the mode "k". We therefore may write

$$H_{i,k} = K\, E_{z\,i,k} \tag{3}$$

where K, for a given point, is independent of mode and cell number. By combining (2) and (3) one gets

$$\frac{1}{Q_{i,k}} = K_i \frac{(E_{z\,i,k})^2}{W_k} \tag{4}$$

where the constant K_i is again independent of mode. Formula (4) is convenient for calculating the mode distributions for any bad cell "i". One obtains for every "i" a characteristic $1/Q_i$-distribution and one can try to fit the low temperature Q-distributions by one distribution or by a superposition of distributions thereby identifying the position of the bad cell(s). The only free parameter for this fit is the value of the constant K_i and in many cases it was possible to get a good fit with a single distribution showing that the Q-value was determined mainly by one bad cell. In Fig.3 and Fig.4 a few fits are illustrated.

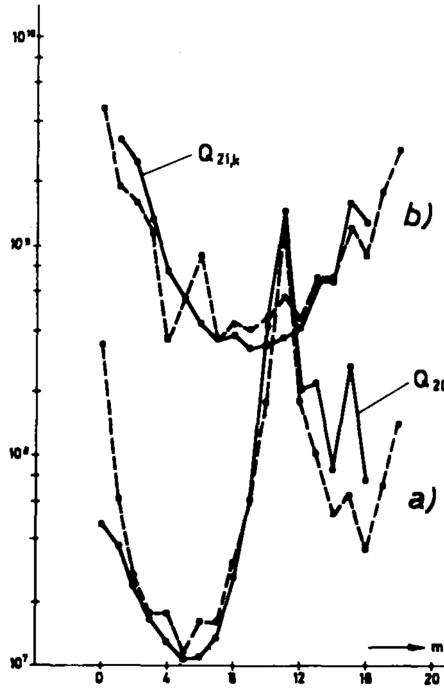

Fig.3: Fit of the measured mode dependence in D5 for the unloaded Q-values at low temperatures (dashed line) with the calculated values (full line).
a) coupling from above, bad joint. Fit for the joint cell.
b) coupling from above, better joint. Fit for the coupling cell.

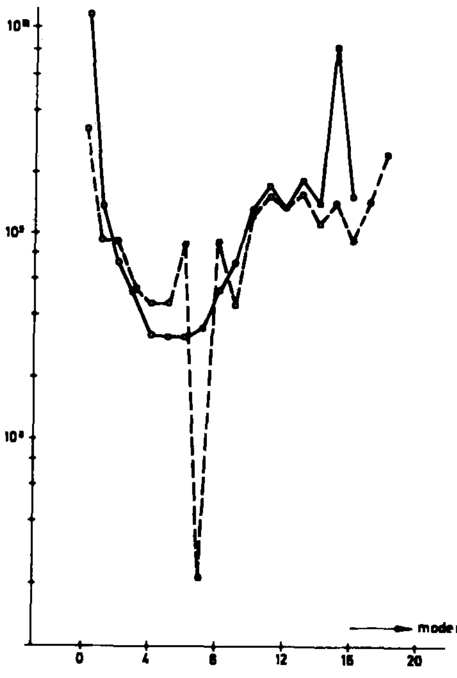

Fig.4: As Fig.3, good joint, coupling from below. Fit by a superposition of contributions from the joint- and the coupling-cell. The deep minimum for k=7 is not understood.

3. Results of cold measurements

In Table I some results of cold measurements are given. For more details see ref. 9.

Table I: Some experimental results for the $\pi/2$-mode

$Q_0 \cdot 10^{-9}$ at low field	$Q_0 \cdot 10^{-9}$ at H_p	H_p (Oe)	Remarks
		D 1 + M	(20 cells)
0.72	0.54	385	additional treatment*
2.5	1.6	400	warmed up and joint re-tightened.
2.2	1.8	390	4 weeks under vacuum
		E + D 3 +	M (24 cells)
1.6	>0.72	330	additional treatment
		D 5 + M	(20 cells)
0.72	0.5	340	additional treatment
1.25	1.2	370	warmed up and joint re-tightened
	Test deflector (4 cells)		
3.6	2.5	850	additional treatment

*before the additional treatment (10 µm electropolishing, anodizing, high-temperature annealing) each deflector has been submitted to a basic treatment (see chapter 1);coupling always from below.
M: coupling unit (2×1/2 cell)
E: end unit with beam hole (2×1/2 cell)

Q-values

Whenever possible we have measured the Q-value for all modes of a section (Fig.3 and Fig.4). As the mode dependence is in all cases largely exceeding the calculated range for a uniform surface resistance the analysis of the preceding chapter was applied in order to localize cells with bad regions. As an example of such an analysis we choose the first measurements on D1 and D5 which were done by coupling from above. It turned out that for both deflectors the first cooling down cycle after a surface treatment and assembly did not give very high Q-values. An analysis of the mode dependence of Q showed that this was always due to a bad RF joint (Fig.3a). After a warming up and a retightening of the joint the Q-values improved but the analysis of the Q-distribution showed for both deflectors bad regions in the coupling cell (Fig.3b). After a dismounting of the section D1 a few small metallic particles were found lying in this cell. These particles presumably had fallen into the cell from the coupling region above. Therefore, in the next experiments the sections were turned by 180° in order to couple from below. The mode-distributions obtained after this change show an additional improvement and are described essentially by a superposition of contributions from the joint- and coupling-cell (Fig.4). The contribution from the coupling cell now could be explained by the fact that before assembling the coupling sections are stored for a few days under vacuum or air. This storage period and the following exposure to air may give an increase of the surface resistance of the coupling cell.
At very low Q-values one always is limited by thermal breakdown but there is no consistent relation between Q and the breakdown field levels. In fact such a relation cannot be expected as long as very inhomogeneous surface

resistances are found. Once the Q-values at high fields exceed our design value of $5 \cdot 10^8$ we are no longer limited by thermal breakdowns and we are always able to reach magnetic field levels above our design value of 310 Oe. We finally note that our deflectors showed only a moderate multipacting (a few hours at most) and a degradation of Q-values towards higher fields not exceeding 50% of the low-field values. The multipacting barriers are always restored by a warming-up cycle under vacuum.

Peak magnetic fields and breakdown field levels

Peak field levels between 350 and 400 Oe have been obtained repeatedly in the 20 cell-deflectors. This corresponds to electric peak fields between 12.5 and 14.3 MV/m and to deflecting fields between 2.3 and 2.6 MV/m, the design value for this latter being 2 MV/m.* We have tried to localize during a low temperature measurement the cells where breakdowns occur. If one assumes that the breakdowns are caused by the weldings or by bad regions near the weldings the method described in ref.8 may be applied. We use formula (3) in order to obtain for the mode "k"

$$\frac{(H_{i,k})^2}{W_k} = K^2 \frac{(E_{z_{i,k}})^2}{W_k} \qquad (5)$$

This may be written with the relation (1)

$$(H_{i,k})^2 = \frac{K^2}{\omega} \frac{(E_{z_{i,k}})^2}{W_k} \cdot P_{O_k} Q_k \qquad (6)$$

If one replaces in formula (6) P_{O_k} by the RF power at which a magnetic breakdown occurs in the mode "k" and Q_k by the corresponding low temperature Q-value and $(E_{z_{i,k}})^2/W_k$ by the value obtained from a perturbation measurement one can determine with the K-value of a given but arbitrary point in the slot region the magnetic field level corresponding to this breakdown. If for different modes the magnetic field levels are equal for a given cell "i" one can suspect that the breakdown occurs somewhere in the slot region of this cell and if it is assumed that the breakdown takes place at a definite point e.g. at the welding region one may determine with the corresponding K the critical breakdown field-level H_{crit}. During one low temperature measurement we have found two possible cells where the breakdown levels are nearly equal for three different modes. We therefore suspect that the field levels were limited by a magnetic breakdown at the weldings of these cells.[10]
We mention another simple method of localizing RF breakdowns in multi-cell deflectors lying horizontally in a He-bath. By raising the He-temperature slightly above the λ-point (2.17 K) we were able to see directly a bubble production in the He-bath which sets in when a breakdown with sufficient energy production occurs. In a 4 cell test-deflector a breakdown occuring at a peak field level of the order of 200 Gauss and a stored energy of 1/100 Wsec could be clearly localized.

*We have obtained recently in a 4 cell test deflector magnetic peak fields of 850 Oe with a corresponding quality factor of $2.5 \cdot 10^9$.

4. Coupling system and RF joints

Coupling system[11]

The RF power is fed to the cavity by a system using a vertically movable coaxial transmission line with the center conductor acting as a probe in a circular waveguide below cut-off and an off-center aperture coupling to the magnetic field of one deflector cell (Fig.5). In the layout used previously (Fig.5a) sliding spring contacts were used so to avoid radiation of RF power between the outer conductor of the movable coaxial line and the cut-off cylinder. As there was a danger of small metallic pieces rubbed off from the (niobium) cut-off cylinder and falling inside the deflectors and, at high power levels, of excessive currents across the contacts we replaced the sliding contacts by a bellow forming the outer conductor of the movable coaxial line (Fig.5b). It was found experimentally that the impedance of the bellow was not changed by more than ±1% over the moving range of the bellow (± 5 mm for a normal length of 50 mm). From measurements with a prototype coupling system using a stainless-steel bellow and an inner conductor made of copper we anticipate that the coupling losses with a niobium conductor cooled by HeII will be negligible for the working conditions we foresee with 3m-deflectors (unloaded and loaded Q-factor $\geq 5 \cdot 10^8$ and $5 \cdot 10^6$ respectively).
In order to reduce even more the coaxial line losses we intend to replace the stainless-steel bellow in the final version by a niobium bellow. The dependence of the coupling coefficient and the coupling losses on the

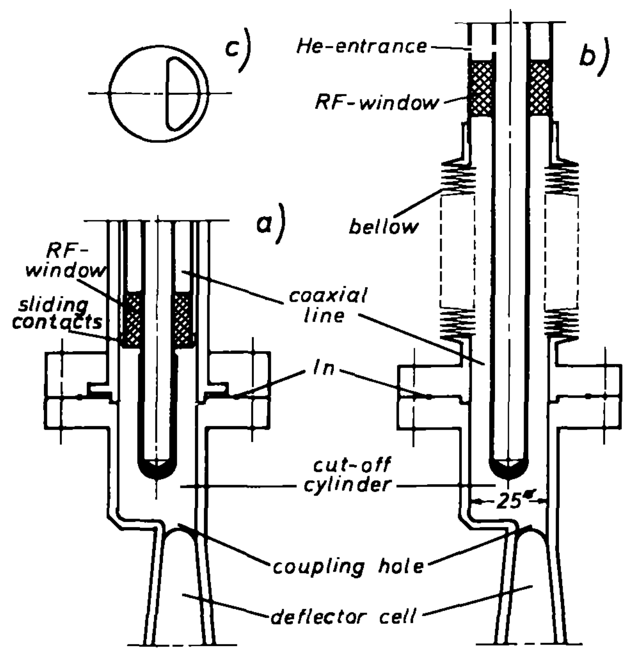

Fig.5: RF coupling system. Only the vacuum-tight lower part is shown.
a) old layout with sliding spring contacts
b) new layout with bellow
c) shape of the coupling hole.

distance of the inner conductor from the coupling hole shows that the coupling coefficient is dominated by a TM_{01}-mode and, at very small distances, by a TM_{03}-mode whereas the largest contribution to the coupling losses stems from a TM_{11}-mode. One therefore can try to optimize the system by giving the coupling hole an adequate shape. As a result of theoretical calculations and RF measurements the shape of the coupling hole shown in Fig.5c has been adopted.

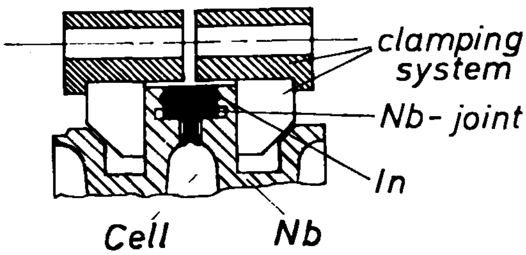

Fig.6: Layout of RF joint

RF joints[7]

The 3m deflectors will be assembled from 5 sections by using RF joints of the type shown in Fig.6. The RF contact is obtained by a specially shaped niobium ring and vacuum tightness is insured by two indium-joints. Before mounting the joint is chemically polished or cleaned in hydrofluoric acid. This type of joint has been used by now many times and turned out to be reliable and easily exchangeable. No remachining of the end flanges of the sections is necessary. Its RF performances have been tested both in a simple cavity and during the measurements on the different deflector sections and it was found that the joint - which normally is placed at a field-free cell of the deflectors - does not deteriorate the Q-value of the deflectors below the design value of $5\cdot10^8$ even for modes where it is submitted to nearly the full RF current. This will simplify considerably the frequency tuning requirements on the different sections of a deflector.

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D. Gray, Rutherford High Energy Laboratory: Dr. Kuntze mentioned the cost of the refrigerator. We have seen niobium with these low Q's at 1.85°K. One might think that perhaps one could get the same Q and field values with niobium at 4.2°K. Carne operated a cavity 1.2 m long at 1.2 GHz and he found that he could achieve a Q of about 10^8 and a field of 2.5 MV/m at both 1.85° and 4.2°K.

Kuntze: I completely agree with you as far as different actual accelerating structures are concerned because we are already in the region of 10 nano-ohms, which we reach sometimes at 4.2°K. However mechanical considerations introduce additional constraints. With the helix we have to use super fluid helium for cooling to avoid bubbles. We do not see much improvement between 4.2° and 1.8° in actual structures. In small test resonators we get an improvement of 50 to 80 between 4.2° and 1.8°.

Gray: You get 2.5 MV/m in actual structures ?

Kuntze: Yes. It's not necessary to reduce the surface resistance to a tenth of a nano-ohm.

L. Bollinger, Argonne National Laboratory: We have recently tested a helix with a bare surface at both 1.8°K and also 4.2°K to an accelerating field in excess of 3 MV/m. There is almost no difference in the Q for these two temperatures. Therefore, in planning a small heavy ion energy booster we are planning to operate at a temperature in the neighborhood of 4.2°K and using forced flow.

A. Schwettman, Stanford University: Temperature dependence of Q is strongly dependent on frequency. Now, Kuntze at Karlsruhe and the group at Argonne are talking about helical structures which operate at frequencies on the order of 100 MHz where there is very little difference between the Q at 4.2°K and 1.8°K. For the electron accelerator structures at 1.3 GHz the Q of our structure at 4.2°K would be about 3×10^8 whereas the Q that we achieve at 1.9°K is 7×10^9, a factor of more than 20. The conclusion that you reach depends very strongly on the operating frequency.

H. Lengeler, CERN: I would like to confirm fully what Schwettman is saying. For similar cavities at the same frequency, we also have an improvement of at least a factor of 20 between 1.8 and 4°K.

Kuntze: It's a question of economy. A refrigerator for 4.2°K is very much less expensive than 1.8°K so if one can live with the Q value at 4.2°K I think one should give it a chance.

T. Khoe, Argonne National Laboratory: What experience have you had with indium seal joints ?

Kuntze: Very good.

Khoe: What is the best surface treatment of the indium joint region ?

Kuntze: The cavity structure is electro-polished before we put it together and then sometimes it is anodized and fired. I see no difference in the joint region. Structures should be fired. It depends upon the frequency as Alan Schwettman said.

M. Green, Lawrence Berkeley Laboratory: This is a question that I would like to direct to both Schwettman and Kuntze. How important is temperature stability in the accelerator ? Is this an argument in favor of the superfluid helium refrigeration system ?

Schwettman: I would have to answer that we've not experimentally studied that question because we already have good temperature stability. But there would be several things that might be considered. First, with our feedback circuitry which samples both the amplitude and the phase of the r.f. fields temperature stability is not so important. Also, there will always be some advantage in reducing magnetic breakdown in having as low a temperature as possible. The question is not the stability of the thermal environment but how big a ΔT you have at the conducting surface at its operating temperature. The question of temperature stability is probably less important than we originally thought.

Kuntze: With the helix, I think temperature stability might be really essential because we have bubbles. The helix is mechanically a very weak structure and bubbles in the helium vibrate the helix. So far we haven't tried to run it at 4.2°K. We were just able to run it at a fixed frequency at 1.8°K.

Bollinger: The point of Tat Khoe's remark was that we have recently gotten some evidence that occasionally at the joint there is a failure to have a good r.f. contact. Cornell has found that, also. The way in which you treat the surface at the joint can be quite important.

Kuntze: We haven't done any special treatment.

T. Nishikawa, National Laboratory for High Energy Physics: I would like to mention the preliminary result on NbN cavities done by the staff at KEK. Using NbN cavities they got a Q of about 10^7 at 4°K.

Kuntze: It may be important to go to another superconductor with a substantially higher H_c and this would be the case of NbN as Dr. Nishikawa said.

M. Tigner, Cornell University: I'd like to comment about the surface treatment. In single cells we have gotten Q's of 5×10^9 and fields of 10 to 15 MV/m with no heating, not even to annealing temperatures. We just machined and electropolished it and then chemically polished and anodized it.

Kuntze: In my opinion, firing is needed in actual big accelerating structures where cleanliness is harder to obtain than with small cavities. We got good results with r.f. separator structures only if we put them in the furnace for final treatment. These are 60 cm sections and together with the 3 meter section we need the furnace for cleanliness.

G. Loew, Stanford Linear Accelerator Center: If you want to get beyond the barrier of 3 or 4 MeV/meter is the only hope right now to try nitride compounds and if so, is anybody trying ?

Kuntze: Yes, Japan is trying. At KEK they have fabricated the first NbN cavities and work has also been done at SLAC. Brookhaven is trying Nb_3Sn. Could Dr. Hahn comment ?

H. Hahn, Brookhaven National Laboratory: Since we are extremely limited in funds and personnel, everything goes extremely slowly. The procedure to generate Nb_3Sn was to put a small piece of tin in a cavity, to close it off, and to heat it to 900°C. In this procedure we don't know exactly what we are generating, but we did detect the Nb_3Sn pattern with x-rays. We measured the Q's and they were in the middle range and we were able to see something like 120 gauss. Now, at the same time I would like to mention that we are working on a NbTi cavity to establish if type-II materials have a limit H_{c1} or not. We chose NbTi because this is the easiest material to handle and still have all of the properties of very high conductivity.

Kuntze: I would like to put a question to Dr. Sarantsev. Unfortunately, I have no information about the work in Russia which is going on in this field, but I know that there has been work in the past on different super-conductors. Do you know something about it ? At Dubna and Kharkov work has been done in this field.

V. Sarantsev, Joint Institute for Nuclear Research: There have been no results.