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PERFORMANCE OF A SUPERCONDUCTING 65-CELL-STRUCTURE IN X-BAND

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ABSTRACT

For superconducting accelerator application a 65-cell X-band structure of o.51 m length, with increasing phase velocity β_ϕ ($.52 \leq \beta_\phi \leq .94$) was developed and constructed. After careful chemical tuning, electropolishing, and UHV-annealing, Q-values of $1o^9$, and an accelerating field of 3.9 MV/m have been reached with a bath temperature of 1.8 K. This field corresponds to a peak electric field of 44 MV/m and a peak magnetic field of 83 mT. A set-up of specially prepared resistors and X-ray detectors showed that the quenching breakdown ocurred in the cell with the highest fields, without electron loading. Together with an 8o keV gun and beam focusing elements the structure has been operated as a small superconducting accelerator in the 2 MeV region.

I. INTRODUCTION

For several years design studies for an experimental superconducting linear accelerator for electrons have been carried out at Wuppertal. After reaching an accelerating field of 8 MV/m in a 3-cell 8 GHz niobium structure operating in the $\pi/2$-mode[1] we decided to study the possibility of electron acceleration with cylindrical disc loaded structures of that frequency. The gun energy of the experimental accelerator has been chosen at 8o keV. Because of this low electron energy the capture section requires a special design to accelerate the electrons up to an energy of about 1 MeV to enter an accelerator section which has a phase velocity of $\beta_\phi = 1$[2].

II. DESIGN AND FABRICATION

The correlation between fabricating tolerances and field flatness in a structure shows that $\pi/2$-mode operation is superior to π-mode for a large number of cells. We have therefore chosen the $\pi/2$-mode. This mode also offers the advantage of flange connections in the unexcited cells. These flanges allow to subdivide the structure into parts which makes fabrication and surface treatments easier. Besides by the type of structure, the frequency and the operating mode the capture section is especially influenced by the low gun energy of 8o keV. This requires a phase velocity $\beta_\phi < 1$ to capture and accelerate the electrons. We have attempted to meet this requirement by a structure whose phase velocity β_ϕ increases progressively with the velocity β_e of the accelerated electrons[3] and which fulfills the adiabatic condition $\beta_e = \beta_\phi$ by a suitable choice of the accelerating field strength. A design accelerating field of E_{acc}= 2 MV/m has been chosen. For a structure length of 5o cm the boundary conditions require 33 steps of phase velocity β_ϕ for an optimum energy gain of the captured electrons. The 33 phase velocities determine the iris distances of the 65 cells. With the programm LALA[4] the diameters and the other parameters of the different cells have been calculated for an iris thickness of 2 mm and an iris aperture of 15 mm. The accelerator structure has been built from two subsections of 25 cm length with flanged endcells. These substructures can be tested separately and are joined together to the 65-cell structure. The geometrical and the electromagnetic properties of the two substructures (S37, S31) and the flanged structure (S65) are listed in Table 1.

The field flatness is very important for multiple cell accelerator structures. The influence of fabricating tolerances on eigenfrequency and field flatness of

Table 1: Geometrical and rf-parameters of substructures S37, S31 and accelerator structure S65

	S37	S31	S65
Number of cells	37	31	65
Total length (mm)	268	275	51o
Diameter Ø (mm)	$34.6 \leq Ø \leq 32.7$	$32.7 \leq Ø \leq 32.4$	$34.6 \leq Ø \leq 32.4$
Gap of cells l(mm)	$2.94 \leq l \leq 6.32$	$6.24 \leq l \leq 6.86$	$2.94 \leq l \leq 6.86$
Range of β_ϕ	$.52 \leq \beta_\phi \leq .88$	$.88 \leq \beta_\phi \leq .94$	$.52 \leq \beta_\phi \leq .94$
G (Ω)	125	157	14o
r/Q (Ω/m)	23oo	36oo	32oo
E_p/E_{acc}	11.3	5.1	11.3
B_p/E_{acc} (mT/MV/m)	21.36	8.5	21.36

r/Q is the relative shunt impedance, E_{acc} the accelerating field, E_p the peak electric field, B_p the peak magnetic field, G the geometric factor.

this complex structure has been examined at a brass model by systematic disturbance of excited and unexcited cells and measuring the deviation of the frequency and the field profile. To achieve the required field flatness (better than 1o%) the fabricating tolerances of the cells have been fixed to ±.o2 mm by LALA calculations and these measurements. The machined parts, each consisting of an iris (2 mm thickness, 15 mm aperture) and two half cells (1 mm wall thickness), have been fabricated from bulk niobium and assembled by electron beam welding from outside. Thus a welding seam is in the center of each cell, except for the end cells with the cut-off tubes of 6 cm length. Figure 1 shows the 65-cell accelerator structure.

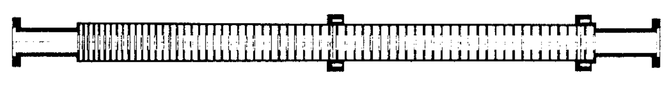

Fig. 1: The 65-cell accelerator structure with increasing phase velocity

III. SURFACE TREATMENTS AND RF-MEASUREMENTS

Electropolishing (EP), chemical polishing (CPT), anodizing (A) and high temperature annealing (HTA) are well established methods for the treatment of niobium cavities to achieve clean and smooth surfaces, which are important for the surface losses and the maximum supportable field. For the described accelerator structure two additional requirements had to be met. The resonant frequencies of the two substructures had to be equal and the field flatness had to be within the given bounds. Measurements of frequency and field profile have shown that the substructures could not be fabricated with sufficient dimensional precision for both having the frequency within the required tolerance and a field profile with the desired accuracy. We first tried to find a optimum preparation sequence by applying some combinations of the different surface treatments to S37 before eliminating the unflatness of the structures. The rf-tests were carried out in horizontal and vertical laboratory cryostats, according to a procedure described elsewhere[1]. Some of the results are shown in Table 2.

After machining and electron beam welding structure S37 has been electropolished (EP) to remove a damage layer of 1oo µm. The procedure resulted in a surface resistance of 518o nΩ at 1.8 K. This value could be reduced by a factor of 5 by HTA at 14oo°C at a vacuum of $1o^{-6}$ Torr. The following treatment has been a combination of EP (2o µm) and HTA (6 hrs 14oo°C, $1o^{-6}$Torr) resulting in a surface resistance of 49o nΩ at 1.8 K. The

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Table 2: Performance of the substructures S37 and S31, and of the accelerator structure S65.

Treatment	d	T K	Q_o $1o^9$	R_s nΩ	Q_L $1o^9$	E_{acc} MV/m	B_p mT	B
S37 EPI(2o µm),	2	1.6	.22	348	.21	1.27cw	27.1	q
A(35V),HTA (6 h	8	1.4	1.33	93	.9o	1.5ocw	32.	q
19oo°C,$1o^{-8}$Torr)	2o	1.5	1.o2	122	.71	1.5ocw	32.	q
S31 EPI(5o µm)	7	1.3	.44	358	.41	2.27cw	19.5	q
A(35V),HTA (6 h	33	1.4	.64	26o	.41	2.6cw	22.3	q
19oo°C,$1o^{-8}$Torr)	4o	1.4	.61	26o	.55	3.3	27.9	q
S65 CP-tuned								
EPI (2o µm)	2	1.8	.4o	35o				
A(35V),HTA (6 h	21	1.6	.6o	232	.5o	3.38cw	72.2	q
194o°C,$1o^{-8}$Torr)						3.57	76.3	
	27	1.6	.66	21o	.58	3.66	78.2	q
with beam	33	1.4	1.o4	134	.83	3.61cw	77.2	q
loading	135	1.8			.77	3.83cw	81.9	q
	154	1.8			.85	3.9ocw	83.3	q

T is the bath temperature, Q_o the unloaded and Q_L the high field quality factor, R_s the surface resistance, B the breakdown mechanism, q is quenching, d the days of pumping time, h the hours of HTA treatment.

first experience with electropolishing (EP) has shown an unexpected increase of the eigenfrequency of the structure, caused by an enhanced polishing action at the discs of the structure. To avoid this we modified the electropolishing device[5]. Using this method (EPI) and the sequence of treatments listed in Table 2, a surface resistance of 93 nΩ and a Q_o-value of $1o^9$ could be achieved. This corresponds to a residual resistance of 65 nΩ. Despite of the low surface resistance an accelerating field of only 1.5 MV/m could be reached. The field was limited by quenching in one of the cells. The structure was operated in various modes of the pass band to gain more understanding of the relation between the unflatness and the achievable field. Thereafter field profile measurements were carried out for almost all pass band modes. The field flatness of the fundamental mode was found to be 3o%. In the other modes of the pass band strong excitations of individual cells were observed at a low average field level. The field measurements during the cold test were corresponding to the assumption that quenching always occurred in the most excited cells. It therefore could be expected that in a well balanced structure higher accelerating fields could be reached.

After applying to S31, (which showed a more balanced field profile), the final sequence of surface preparation technique, electropolishing (EPI), anodizing (A) and heat treatment (HTA) at 19oo°C, the test listed in Table 2 has been carried out. The surface resistance of 26o nΩ, at 1.4 K obtained with magnetic shielding, is a factor of 5 lower than in the test at the same temperature without shilding. This confirmes the importance of an accurate magnetic shielding. At pulsed rf-operation an accelerating field of E_{acc}= 3.3 MV/m and a loaded Q-factor of $6 \cdot 1o^8$ could be reached. This field value was about 25% higher than the field of 2.6 MV/m at cw operation. As expected, the required accelerating field could be achieved.

The next step was the adjustment of the field flatness by treating the substructures individually to reach the required field profile and a common eigenfrequency. On account of the special geometry of the structure the only correction to the field profile could be done by chemical tuning (CPT). Using this method, the field flatness of the structure has been adjusted by individual tuning of various cells. After each polishing process of a cell the change of the field profile and the eigenfrequency of the substructures have been measured to find the correlation with the polishing time. By this method the unflatness in the structures S37 and S31 could be reduced to less than 1o%.

After the heavy CP during tuning procedure an EPI treatment had to be applied in order to reduce the effect of grain boundary etching. 2o µm has been removed from the surface of S37, and the eigenfrequency of this part has determined the reference frequency to which S31 had to be adjusted. This has been done by successive electropolishing (EPI) until the required field flatness of the assembled structure S65 was obtained[6]. The structure parts S37, S31 and the choke flange with the cut-off tube have been anodized at 35 V and high temperature fired at 194o°C for 6 hours at a vacuum better than $1o^{-8}$Torr. The treated parts have been preserved under vacuum at $1o^{-7}$Torr, and the final assembly has been done in a dustproof room before mounting the structure on the horizontal accelerator cryostat. At the working temperature of 1.8 K the eigenfrequency of the accelerator structure was 8o49.269 MHz. The achieved fields and quality factors are shown in Table 2. An unloaded Q of $1o^9$ and a residual resistance of 134 nΩ have been measured at 1.4 K, the lowest temperature which could be reached. At a loaded Q of $8 \cdot 1o^8$ an accelerating field of 3.9 MV/m has been reached at cw operation in the π/2-mode. The corresponding peak surface electromagnetic fields are E_p= 44 MV/m and B_p= 83 mT. The field was limited by a self-pulsing breakdown.

It is common to most field limiting phenomena that they are caused by or result in an excessive power dissipation at well localized spots. Different diagnostic techniques for locating these heat sources have been indispensable to elucidate breakdown mechanisms[7]. To detect local heating of the structure a set-up of 2o specially prepared carbon resistors has been used[6]. Four resistors are arranged equidistant around a selected cell and are pressed against the surface by a ring of teflon. Five rings have been mounted along the structure. A fast electronic read-out and data acquisition system has allowed parallel and serial displaying of the resistor voltages and processing of the sampled data. Operating the structure in the accelerating mode the resistors at the first cell have indicated heat pulses at quenching. Bath temperature at this test was 1.9 K, and the peak magnetic field was limited at 79 mT. A maximum temperature change of ΔT(R1)=64o mK was shown by R1(on top of the cell) 8 ms after the breakdown. At R2 and R4 (right and left side of the cell) the maximum ΔT(R2)=13 mK and ΔT(R3)=2.7 mK has been reached 12 ms later. At this time the temperature measured by R1 was reduced to the half maximum value. With these data the spot could be localized near resistor R1. Using the measured temperature changes the heat flux from the spot has been estimated to 1oo mW/cm^2 at the outside surface of the cell. The rings mounted on cells 43 and 44 have shown heat pulses of ΔT = 2o µK synchronous to the applied rf-signal. No X-ray intensity has been detected by collimated NaJ-detectors situated outside the cryostat. Operating the structure in the 57/66 π-mode NREL has been observed and heat pulses have been measured at cell 43 in coincidence with field dependent X-ray intensity. Synchronous with the building up of the field in the cavity the temperature measured by the resistors increased. At maximum field the maximum temperature changes were reached, and at the same time X-ray intensity was indicated by the NaJ-detectors. At a peak field of E_p= 46 MV/m (B_p=82 mT) the maximum energy of the observed bremsstrahlung was 27o keV. At a bath temperature of 1.9 K the resistors have indicated temperature changes of ΔT(R1)= 3.5 mK, ΔT(R2)= 5 mK and ΔT(R3)= 7.1 mK. Using this temperature distribution the heat source resulting from the impacting electrons from field emission could be localized in the vicinity of R3. This loss mechanism is not observed in the fundamental accelerating mode, where the maximum accelerating field was determined by the quench in cell 1.

IV. EXPERIMENTAL SUPERCONDUCTING ACCELERATOR

The most important component of the experimental accelerator is the described superconducting structure. The characteristic parameters of the accelerator cryostat[8] and the beam line components will not be discussed in detail.

The schematic arrangement of the experimental accelerator is shown in fig. 2.

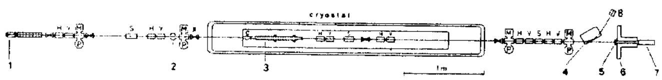

Fig. 2: Schematic layout of the experimental accelerator. 1) gun, 2) prebuncher, 3) accelerator structure, 4) bending magnet, 5) bremsstrahlung converter, 6) lead collimator, 7) γ-detector, 8) faraday-cup, X) vacuum s.t. valve, H) and V) steering dipoles, S) solenoid, M) viewing screen, P) ion getter pump, C) rf-coupling probe.

The gun (AEG A61-12oW/2 TV tube) is flanged to an electrostatic preaccelerating unit. At 8o keV a dc beam current between o.1 and 3o μA can be used. The operating time of a gun system was about 4oo hours at a vacuum of typical $1o^{-7}$ Torr. Mechanical alignment of gun, accelerator structure and drift section has been accomplished by means of a laser beam, before the cryostat was assembled. The microwave power is coupled into the cavity through the beam tube via a coaxial probe cut-off system (inner diameter 9 mm). The coupling of the structure to the microwave system can be changed from outside the cryostat by moving the center conductor of the coaxial probe with a remotely controlable device. Beam guidance is done by horizontal and vertical steering coils. The injected beam is focused to the entrance of the superconducting accelerator structure by a solenoid. A similar system with superconducting coils, made from niobium-titan, serves to steer the accelerated beam inside the cryostat (fig. 3).

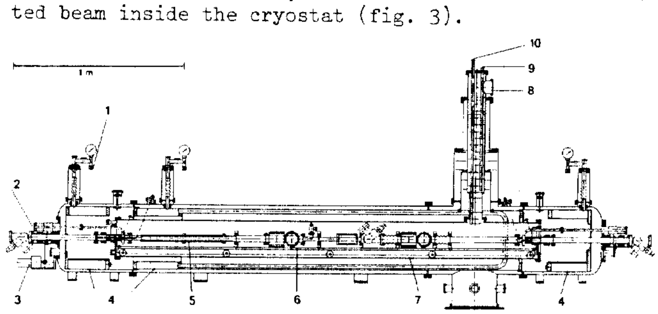

Fig. 3: Cryostat with accelerator structure and beam guidance system. 1) N_2 relief valve, 2) rf-wave guide, 3) adjustable rf-coupling system. 4) 77 K heat shielding, 5) accelerator structure, 6) mounting bench, 7) Helium vessel, 8) He gas return line, 9) LHe transfer line, 1o) cable entry.

The position of the injected and accelerated beam is monitored by beryllium oxide screens and can be observed at a tv monitor.

The main objective of the accelerator test was the actual use of a high frequency superconducting structure to accelerate electrons and to gain operating experience. In this first test a prebuncher was not used. The electrons are continually injected and only electrons within a phase interval $\Delta\phi$ around a synchronous phase have been captured and could gain a maximum energy. To determine the energy of the bremsstrahlung produced by the accelerated electrons copper and tantal foils have been used as conversion targets. Electrons have been injected at 86 keV and their kinetic energy due to acceleration has been measured as a function of the accelerating field. The data taken at various runs are shown in Fig. 4.

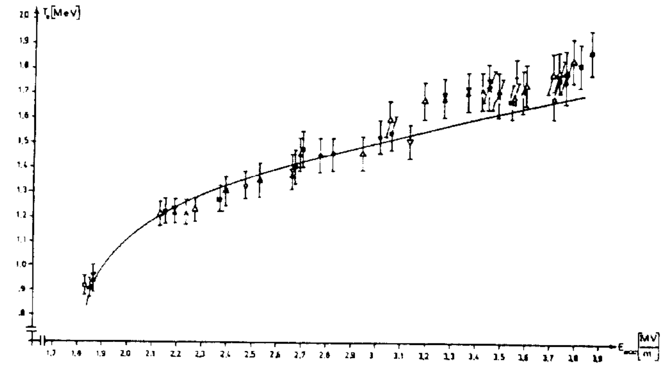

Fig. 4: Electron energy gain versus accelerating field

The quoted error is due to the uncertainty in the maximum energy of the bremsstrahlung spectrum of not monoenergetic electrons. The drawn curve is based on energy gain calculations of an electron injected with an optimum phase relation and accelerated along the axis of the structure. During the accelerating experiments the injected current was limited to 1μA. At an accelerating field of 3.9 MV/m and cw-operation electrons have been accelerated from 86 keV to 1.9 MeV.

V. CONCLUSION

We have reported on the design and the performance of a 65-cell π/2-mode X-band accelerator structure with progressing phase velocity, and an accelerating experiment using this structure. At cw-operation and an accelerating field of 3.9 MV/m electrons of 86 keV (gun energy) have been accelerated up to 1.9 MeV. Elimination of the field unflatness and application of a sequence of surface treatments was decisive to achieve a peak electric field of 44 MV/m and a peak magnetic field of 83 mT. The 65-cell structure reached the performance of a 3-cell structure of the same design and frequency. For a 8 GHz structure with constant phase velocity $\beta_\phi = 1$ which is operated in the π-mode these peak fields would correspond to an accelerating field of 16 MV/m.

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