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DESIGN AND STATUS OF AN EXPERIMENTAL SUPERCONDUCTING LINEAR ACCELERATOR FOR ELECTRONS

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ABSTRACT

We report on the design and status of a small superconducting linear accelerator for electrons in the 3 MeV range. It is operated at 8 GHz. Primary goals are: a high energy gradient by choosing a high frequency, a working temperature of 4.2 K by using Nb_3Sn, and to gain information about the performance of multicell structures at 8 GHz. At present the 80 keV electron gun, the vacuum beam line, and the cryostat are set up. A three cell Nb_3Sn covered cavity was used for the first experiment with the accelerator and a beam of 1 μA was accelerated to 160 keV. The performance of four 30-cell Nb-accelerating structures operated in the π/2-mode and the observed field limitations around 2 MV/m are analysed. Higher field values (up to 8.8 MV/m) were achieved in structures of a smaller number of cells.

I. INTRODUCTION

Superconducting rf accelerating structures hold the promise to make continuous wave electron accelerators possible. Experimental work in rf superconductivity carried out during the past decade in several laboratories (for a recent review see ref. 1) has shown that high shunt impedances, corresponding to Q-values of about 10^9, can be achieved in superconducting niobium structures in the frequency range from 100 MHz to about 10 GHz. Unexpected field limitations, however, have been observed and the results obtained in single cell cavities indicate that the breakdown field increases with the operating frequency. Because of these observations we have started to develop accelerating structures at 8 GHz. After reaching an accelerating field of 8 MV/m in a three cell 8 GHz structure operated in a π/2-mode (2) we decided to set up an experimental superconducting accelerator for electrons to test the possibility of electron acceleration with multicell structures of that frequency and to study the related problems. Niobium and Nb_3Sn are planned to be used as materials. The latter because of the hope to operate superconducting accelerators at 4.2 K.

II. GENERAL ARRANGEMENT

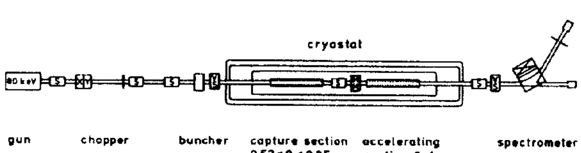

Fig.1: Schematic layout of the experimental accelerator (S = focusing solenoid; VS = viewing screen; MM = microwave monitor)

Figure 1 shows the schematic layout of the experimental accelerator. The electrons are produced in a 80 keV gun and pass through a microwave chopper, which selects bunches of 6^o phase spread. This chopper is only used if an electron beam of small energy spread is to be produced. If higher currents are needed the rf structure of the beam is created by a bunching cavity. The capture section is a niobium cavity with 65 cells. It has a phase velocity varying between β = 0.53 and 0.95, is operated in a π/2 standing wave mode, and has a design accelerating field of 2 MV/m. The electrons leave the capture section with an energy of 1.05 MeV and enter the accelerator section, which has 59 cells and a phase velocity of β = 1.0. Depending on the achievable accelerating field in this structure the electron beam will be accelerated up to 2 or 4 MeV. The beam energy is analysed in a small magnetic spectrometer. Focusing solenoids, steering magnets, optical viewing screens, and one microwave position monitor are also part of the beam line.

III. CHOICE OF PARAMETERS

Table 1 gives the characteristic parameters of the accelerator and its components. Because of the experimental character of this accelerator parameters like the beam energy or the beam current are of minor importance. They are given in table 1 only as a design guide line.

TABLE 1

Characteristic parameters of the accelerator

General	Beam energy [MeV]	3.3
	Maximum c.w. current [μA]	20
	Operating frequency [GHz]	8.055
Gun	Voltage [kV]	80±.08
	Current [μA]	150
Chopper	Output bunch phase spread [^{o}]	6
	Microwave power input [W]	45
Accelerating units (General)	Mode	π/2
	Diameter of iris opening [mm]	15
	Quality factor (design)	$0.5\cdot10^9$
	Operating temperature [K]	1.8
Capture section	Range of β	0.53<β<0.95
	Number of cells	65
	Shunt impedance [Ω/m]	10^{12}
	E_{acc} (design) [MV/m]	2
	H_p/E_{acc} *) [mT/(MV/m)]	17.75
	E_p/E_{acc}	9.96
	Power loss in the cavity walls [W]	2
	Total microwave power input [W]	22
Accelerating section	Length [m]	0.56
	Number of cells	59
	Shunt impedance [Ω/m]	$1.98\cdot10^{12}$
	E_{acc} (design) [MV/m]	5
	H_p/E_{acc} *) [mT/(MV/m)]	7.35
	E_p/E_{acc}	4.5
	Power loss in the cavity walls [W]	7.1
	Total microwave power input [W]	63
Cryostat	Length/diameter [m]	3.5/.4
	Length/diameter of helium tank [m]	2.5/.22
	Total standby heat load [W]	2.2
	Total refrigeration power [W]	20

*) E_{acc} = accelerating field; H_p = peak surface magnetic field; E_p = peak surface electric field

The most important components of the accelerator are the superconducting structures which will be described later. The characteristic parameters of the electron gun, the microwave chopper and buncher, and of the cryostat are given in Table 1. These devices will not be discussed in detail. The use of niobium structures at X-band frequencies requires a working temperature of 1.8 K. Experiments with Nb_3Sn multicell cavities (3) show that at 4.2 K accelerating fields in the 4 MV/m range can be achieved. Aside of the working temperature

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and other parameters of minor importance the choice of the operating frequency has to be analysed. For frequencies below 1 GHz the costs for the accelerating structure and the necessary cryostat increase rapidly. For frequencies higher than 1o GHz the beam hole becomes too narrow to guarantee a safe handling of the electron beam. An optimum frequency choice inside this interval is a compromise between conflicting observations. The surface resistance of an ideal superconducting resonator decreases with the square of the frequency and therefore the shunt impedance of a superconducting accelerator structure increases linearly. This asks for a low frequency and the first superconducting electron linac at Stanford is in fact operated at 1.3 GHz (4).

Measurements on single cell superconducting cavities carried out in several laboratories in the last years (1) have shown, however, that the achievable accelerating fields increase with increasing frequency. In a two cell π-mode structure at 8.6 GHz 21.8 MV/m have been achieved recently at Cornell (5). These experimental observations may well be explained by the frequency dependence of field limiting electron multipacting phenomena in superconducting cavities. Especially one side multipacting (6 - 8) leads to limiting fields which increase linearly with the frequency of accelerating structures comparable in shape. Field limitations can also be caused by surface imperfections which can lead to magnetic thermal breakdowns (9) and one "bad cell" can spoil the field gradient of a whole structure. We have therefore chosen relatively short accelerating units. The capture section (fig. 2) and the accelerator section are built from two units of approximately 27 cm length. The units are flanged together by a choke flange.

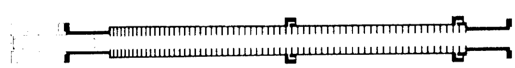

Fig. 2: Capture section with increasing phase velocity

At the design frequency of 8 GHz a beam hole of 1.5 cm is still tolerable because the optimization of the shunt impedance by the choice of an appropriate geometry is not a major design criterion for a superconducting structure. The field flatness of the accelerating field, however, is an important concern at high frequencies. The tolerance requirements for a structure operated in a π-mode increase with the square of the number of cells in one section. We have therefore chosen the π/2 mode. In this mode the tolerances asked for increase only linearly with frequency. This mode also offers the advantage of unexcited cells and flanges like the ones shown in fig. 2 are possible. The microwave power is coupled into each of the two sections of the accelerator via a coaxial probe cut-off coupling system (fig. 2), the inner conducter of which is a hollow tube and is passed by the beam. The capture section determines the frequency of the accelerator. The accelerator section is tuned to that frequency mainly by electropolishing. In addition piezoelectric and motor driven tuners will fine adjust the resonant frequency of the accelerating section to the reference frequency. The tuners will deform thin walled portions of the structure. Phase and amplitude in each section are monitored by an output coupling probe similar to the input coupler and located at the other end of the sections. These signals are used for feedback stabilization. The microwave chopper or buncher and the superconducting structures are driven by three travelling wave tube amplifiers. The available power of 14o W limits the beam current to about 2o μA. The design Q value for the structures is $o.5\cdot 1o^9$. For Q's of this magnitude field limitations caused by a temperature increase at the inner walls of superconducting structures are not expected for accelerating fields below 1o MV/m.

IV. PERFORMANCE OF THE ACCELERATING STRUCTURE

Before the multicell accelerating structures were fabricated we have carried out numerous tests with one to nine cell 8 GHz cavities to investigate methods of surface treatments and the technique of the preparation of Nb_3Sn surfaces. After the machining and electron beam welding all niobium structures are electropolished according to the procedure used by Siemens (1o) to remove a damage layer of 1oo μ and to achieve smooth surfaces. The final treatment always consisted in UHV firing at 19oo °C. For the preparation of Nb_3Sn surfaces the vapor deposition technique was used (3). Table 2 gives a series of results obtained so far with the small test cavities and the multicell accelerating units.

TABLE 2

Performance of multicell superconducting cavities

Cavity-mode (material)	Q_{res} (T[K])	E_{acc} [MV/m]	breakdown mechanism
1 cell TM_{o1o} (niobium)	$1o^{1o}$ (1.3)	13 [1)]	(e^-)quenching
(Nb_3Sn)	$5\cdot 1o^8$ (4.2)	11 [1)]	(e^-)
3 cell π/2 (niobium)	$7\cdot 1o^8$ (1.3)	8.8	quenching
(Nb_3Sn)	$7\cdot 1o^7$ (4.2)	5.5	(e^-)thermal
9 cell π/2	$5.2\cdot 1o^8$ (1.5)	3.2	quenching
(niobium)	$1.2\cdot 1o^8$ (1.5)	4.3	(e^-)thermal
(Nb_3Sn)	$9.5\cdot 1o^7$ (4.2)	3	thermal
31 cell π/2	$1.1\cdot 1o^8$ (1.8)	2.6	(e^-)quenching
(niobium)	$2.8\cdot 1o^8$ (1.8)	2.2	(e^-)quenching
31 cell π/2 (niobium)	$1.3\cdot 1o^8$ (1.8)	2.3	(e^-)thermal
31 cell π/2 o.9 <β< o.95 (niobium)	$3.7\cdot 1o^8$ (1.8)	2.o	(e^-)quenching
37 cell π/2 o.5 <β< o.9 (niobium)	$1.3\cdot 1o^9$ (1.6)	1.3	(e^-)quenching

1) Half the maximum electric field on the axis

The tests were carried out in laboratory cryostats according to a procedure described in (2). The observed field limitations are discussed in the next chapter. There is a tendency that high residual Q's are harder to obtain in multicell structures than in single cell cavities. This fact is explained by the increased probability of surface imperfections and contaminations in larger structures. The expected Q for ideal Nb_3Sn surfaces at 4.2 K is in the range of $1o^9$(11). Our results are about a factor of 1o lower and more experimental research has to go into the Nb_3Sn preparation technique, although the obtained accelerating fields at 4.2 K are already comparable to those of niobium cavities at 1.8K.

V. FIELD LIMITATIONS

Many reasons like for example the increase of the shunt impedance of superconducting structures with decreasing frequency, the reduced tolerance requirements, the larger aperture to pass the electron beam and the smaller number of electron beam welds per unit length favor low frequencies in the design of superconducting accelerators. Only the experimentally observed increase of the accelerating field with increasing frequency has guided us to design an experimental accelerator with an operating frequency of 8 GHz. So far, however, high fields have only been reached at X-band frequencies in one or two cell structures excited in the TM_{010} or π-mode. This frequency dependence of the maximum accelerating field can be explained by a special form of electron loading known as one side multipacting. This field limiting mechanism was observed in superconducting structures and quantitatively explained for the first time by the Stanford group (6). Our measurements, given in table 2, show that in fact in single cell and even in three cell cavities high fields can be obtained. There is, however, a definite reduction in the maximum field as the number of cells increases. The field levels in the 2 MV/m region obtained in the multicell accelerating units are comparable to the results obtained at Stanford at 1.3 GHz and also similar to the field levels achieved in the CERN superconducting seperator (12) which is operated at 2.85 GHz. These low fields even at 8 GHz are extremely disappointing at first sight. Two side multipacting inside the choke flanges cannot be responsible for the observed phenomena. The choke flange has been tested in TM_{010} mode single cell cavities and the threshold for multipacting was 2o mT for the magnetic field at the flange location. In the accelerating units this field is about an order of magnitude lower.

At present we only have strong hints for the explanation of our results. The phenomenon of one side multipacting is fairly well understood in single cell cavities excited in the TM_{010} mode. Electrons starting from the outer diameter of cylindrical cavities are bent back by the magnetic rf field and accelerated by a generally small electric rf field perpendicular to the cavity wall. If the electrons gain more than about 1oo eV, they can cause secondary emission and thereby multiply to an avalanche. At low magnetic surface fields (less than 2o mT at 8 GHz) only multipacting of high order is possible and mainly the electric field determines the multipacting threshold. In TM_{010} cavities electric surface fields at the outer diameter can be generated by large beam holes. This is also true for multicell structures. In addition, however, field distributions considerably different from a TM_{010} excitation have to be considered. Especially in the π/2-mode significant electric surface fields are present inside the so called unexcited cells. These will be enhanced and magnetic fields are added due to an imperfect field flatness of the standing wave in the multicell cavity. These distortions are caused by mechanical tolerances and can also lead to enhancements of the electric surface fields inside excited cells. The field flatness decreases with an increasing number of cells per structure and therefore the probability for one side electron multipacting increases. Practically all our measurements showed multipacting limitations (indicated by (e^-) in table 2) which could be overcome by field processing. But also the final limiting field breakdowns, which are characterized in table 2 by "quenching", are most likely caused by electron multipacting. Sometimes electron multipacting and quenching have been observed simultaneously. Quenching can be caused if the electron cloud which increases from rf cycle to rf cycle transfers enough energy from the cavity field to a small portion of the cavity wall, to raise its temperature, until it becomes normal conducting and leads to a field breakdown. We therefore assume that one side multipacting is responsible for our field limitations. The phenomenon of one side multipacting in multicell structures has yet to be analysed in detail to confirm this hypothesis.

VI. FIRST ACCELERATOR TEST

To test the main components of our experimental accelerator we have done an accelerating experiment using a three cell structure covered with Nb_3Sn, the performance of which is contained in table 2. After overcoming severe difficulties of guiding a very low energy electron beam through the whole accelerator a current of 1 μA was accelerated from 8o keV (gun energy) to 16o keV. The energy of the beam was analysed in a small magnetic spectrometer. No Q degradation of the Nb_3Sn layer was observed after several days of operation. The cryostat showed very low losses as given in table 1. The time needed for warming up the cryostat to replace inside components and for the successive cool down was about 2 days.

VII. CONCLUSION

We have reported about the design criteria for a small superconducting experimental linear accelerator for electrons operated at 8 GHz. A first experiment was carried out using a three cell Nb_3Sn accelerating structure to test the major components of this accelerator. Measurements on the multicell structures, fabricated from niobium showed field limitations at surprisingly low accelerating fields between 2 and 2,6 MV/m. We assume that these field limitations are caused by one side multipacting. This kind of electron loading is favored in multicell structures by field configurations, which are not found in single cell cavities.

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