FIRST OPERATION EXPERIENCE OF A PILOT CW SUPERCONDUCTING ELECTRON ACCELERATOR*

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Summary

We report on the first operation of a small superconducting linear accelerator which serves as a pilot project for the Darmstadt Superconducting Recyclotron. A five cell niobium accelerating structure operated at 3 GHZ was used to accelerate a chopped 200 keV electron beam to an energy of 850 keV. The Q value of the structure and its accelerating field remained at $4 \cdot 10^9$ respectively 5.7 MV/m during one year. Design, fabrication and test of the accelerating structure are discussed. A description of the pilot accelerator including its gun, chopper, and cryostat is given.

Introduction

Recent advances in the understanding of field limitations in sc accelerating structures[1-4] have led us to propose the construction of a superconducting recyclotron[5], which will replace the Darmstadt normal conducting linear accelerator DALINAC[6]. This continuous wave (cw) electron accelerator is designed for an electron beam of 130 MeV with an energy spread of about 10^{-4} and a cw current of 20 μA. From the point of view of sc structures the most important design parameter is the accelerating field of 5 MV/m.

The funding of this project was granted in the fall of 1981. In order to test the superconducting accelerating structures, the most crucial components of the planned 130 MeV superconducting recyclotron, and to gain experience with superconducting technology a pilot accelerator has been set up. The pilot accelerator is described as well as its operation and performance.

Superconducting Accelerator

The main components of the superconducting cw accelerator are shown in fig.1. The electron gun produces a continuous electron beam with a maximum kinetic energy of 250 keV. This beam is chopped at the accelerator frequency (3GHz). The helium cryostat is designed to house a 5-cell accelerating structure (capture section) plus one 20-cell accelerating structure (standard section for the 130 MeV recyclotron). Behind the cryostat Mott-scattered electrons from a thin (15 μg/cm^2) ^{12}C foil can be detected by a cooled silicon surface barrier detector to determine the energy of the accelerated electron beam.

The operating frequency (f) of the superconducting structure can be chosen in a range of about 0.5 to 10 GHz. Accelerating fields in access of 5MV/m have been reached in the above frequency range. The experimentally reached rf losses per MV and meter of accelerating structure show a minimum[7] around 3 GHz. Furtheron, we have chosen niobium for the material of the superconducting structures which at 3 GHz enforces due to the temperature dependence of the surface resistance of Nb an operating temperature of 2 K. At this temperature a quality factor Q of the structure of $3 \cdot 10^9$ can be achieved.

The use of a spherical or elliptical cavity design is an efficient way to suppress electron multipacting. For ease of fabrication the spherical design was adopted. The chemical surface treatments with highly reactive chemicals, the high temperature annealing above 1100°C and the mechanical manipulations to finish a structure after welding, ask for a length of the structure not very much longer than one meter.

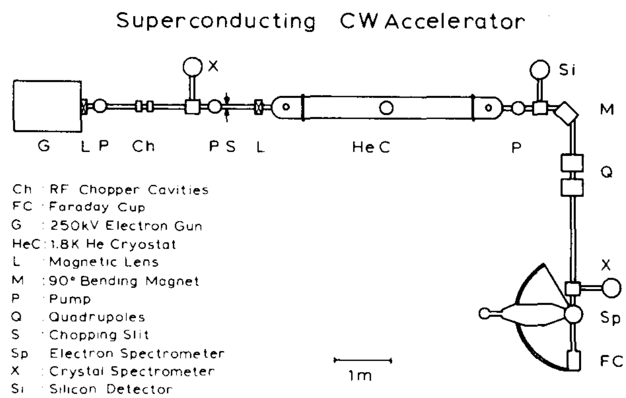

Fig.1 Floor plan of the pilot cw superconducting accelerator.

In order to achieve a small ratio of the surface electromagnetic field to the accelerating field the π mode operation of the standing wave accelerating structures was acquired which has also the advantage of the highest specific shunt impedance r/Q per unit length. To reduce its sensitivity against tuning errors a strong cell to cell coupling is required, which can be achieved by a large iris aperture. The accuracy in the manufacturing process of a single cell asks for a cell to cell coupling factor of 4.1% resulting in an iris diameter of 35 mm. This large opening is beneficial to ease the coupling to the higher order modes excited by the beam.

The diameter of the cut-off tube was chosen to allow the propagation of TE_{11} waves with frequencies above 3.5 GHz. A sufficient and simple loading of the deflecting modes can therefore be accomplished by probes in the cut-off tubes. Because of their large diameter the length of the cut-off tubes has to be 14 cm to reduce the rf losses of the fundamental mode at normal conducting parts to a negligible amount.

The small superconducting accelerator described in this paper contains a 5-cell accelerating structure. This cavity is shown in fig.2 and its rf parameters are given in table I.

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TABLE I

CHARACTERISTIC rf PARAMETERS

Normalized shunt impedance r/Q	20 Ω/cm
Geometry factor G	293 Ω
Field enhancement factor E_p/E_{acc}	3.0
Field enhancement factor H_p/E_{acc}	4.2 mT/(MV/m)
Cell to cell coupling factor	4.1 %

The fabrication of the cells is done in several steps. First, a disk (Ø 150 mm) of 2 mm Nb sheet material is formed by deep drawing to an ashtray like cup. Then the cups are stress annealed at 1100°C. At next the iris aperture is deep drawn. After a short chemical

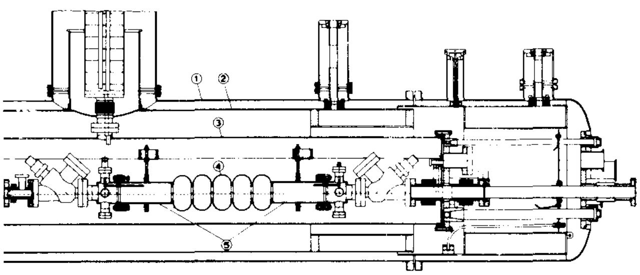

Fig.2 Cross section of half of the 5m long helium cryostat with the 5-cell accelerating structure including vacuum jacket (1), LN_2-cooled radiation shield (2), LHe vessel (3), niobium cavity (4) and cut-off tubes with rf couplers (5).

polishing (10 μm) the cups are welded together by an electron beam and the resonant frequencies of the individual cells are measured. Our present experience resulting from measurements on more than 30 cells shows that about 90 % of all cells are within an interval of 3.5 MHz around the design frequency appropriate for this fabricational step. This places an upper limit for the variations of the main diameter D of ±45 μm. Individual chemical polishing (50 μm - 100 μm) reduces the frequency deviations to less than 300 kHz. Before the final welding the five cell structure is set up to measure its field flatness.

After welding the five cell structure was chemically polished and tested in a vertical bath cryostat following conventional procedures. A temperature mapping system was used to detect regions of increased rf losses in the structure. The structure then was pressurized with dry nitrogen and equipped with straight through valves for its later accelerator application. Prior to its shipment it was tested in the horizontal accelerator cryostat at Wuppertal and showed no significant reduction in its performance. It was transported to Darmstadt under vacuum, mounted in the accelerator cryostat and a first test of its superconducting features did not show any changes compared to the results achieved at Wuppertal.

The helium cryostat of the pilot accelerator has been designed at Wuppertal and was built in the workshop of the institute at Darmstadt. A cross section of part of the cryostat with a 5-cell accelerating structure installed is shown in fig.2. The outer vacuum jacket is fabricated from stainless steel and has a length of 5 m and a diameter of 0.4 m. Inside, a liquid nitrogen cooled radiation shield (aluminum) is provided to keep heat losses low. The liquid helium vessel (stainless steel) has a usable length of 3.5 m and an inner diameter of 0.20 m. Both the radiation shield and the helium vessel are wrapped by 20 layers of aluminized mylar foil (superinsulation) and 5 layers of glassfibre cloth to reduce radiation losses. Standby losses of the cryostat at 4.2 K amount to 2.1 W corresponding to a liquid helium evaporation rate of 3 l/h.

Accelerator Operations and Results

The superconducting 5-cell accelerating structure used in the accelerating tests has been mounted in the cryostat for one and a half years. In this period six tests have been performed to improve the beam transport system and the beam position monitors and to compare experimental beam energies with the results of calculations. After each test the cryostat was warmed up to room temperature and taken apart to allow for minor changes in the beamline, like installation of correction coils, a position monitor etc. The accelerating structure was always kept under vacuum to prevent a contamination of the niobium surface. The unloaded Q of about $4 \cdot 10^9$ and the maximum effective accelerating field (E_{acc} = 5.7 MV/m) at 1.8 K remained unchanged in all tests.

The beam from the electron gun is in the velocity range of β = 0.7 - 0.74 for injection voltages between 200 kV and 250 kV, respectively, whereas the 5-cell accelerator section is a β=1 structure. Therefore, calculations of the kinetic energy of the electrons in this structure for various combinations of injection phase and accelerating field have been performed using field distributions as determined from computer codes LALA[8] and SUPERFISH[9]. In fig.3 the result of such a calculation for an accelerating field of 5 MV/m and injection energies of 200 keV and 250 keV at optimum injection phase is shown.

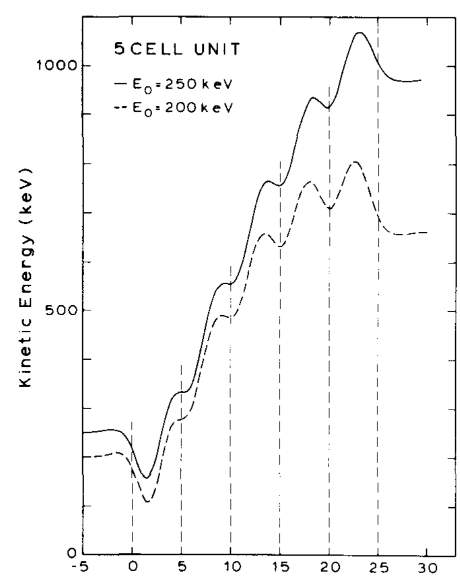

Fig.3 Calculated beam energy in a 5-cell preaccelerating structure for two injection energies. The effective accelerating field is 5 MV/m in both cases. The vertical dashed lines indicate the location of the irises.

Two results should be noticed:

i) The fact that the accelerating field penetrates into the cut-off tubes on both sides of the structure decreases the injection energy by almost 100 keV, which results in a less effective acceleration.

ii) The phaseslip of the electrons which is increased by the aforementioned effect causes a low efficiency towards the end of the structure (in the region between 15 cm and 25 cm). Increasing the injection energy improves this situation (as can be seen by comparing the full and the dashed curve in fig.3) but injection energies in excess of 250 keV result in an insufficient bunching by the preaccelerator section.

So far, acceleration tests have been performed at injection energies up to 200 keV. Four typical spectra of Mott scattered electrons from a 15 µg/cm^2 ^{12}C foil taken with a cooled Si-detector are displayed in fig.4. The spectrum on top was taken with the direct beam from the electron gun with no acceleration field present. Applying accelerating fields of 3.2, 4.3 and 5.7 MV/m yields energies of the Mott scattered electrons of 350, 565 and 845 keV, respectively. A ^{209}Bi source with electron energies between 480 keV and 1050 keV was used for the energy calibration of the Si-detector.

In fig.5 calculated energies for the electron beam after being accelerated by the 5-cell structure are shown as a function of the effective accelerating field for three injection energies. The experimentally determined energies

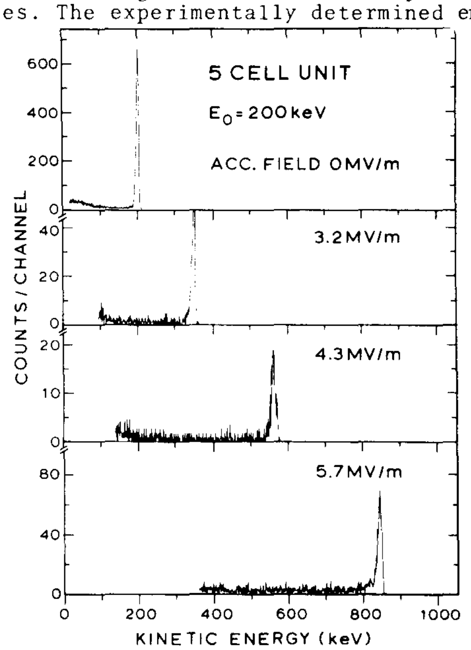

Fig.4 Energy spectra of Mott-scattered electrons on ^{12}C for different accelerating fields. Note, the maximum obtained accelerating field is 5.7 MV/m.

are extracted from the spectra of Mott-scattered electrons. The corresponding values for the effective accelerating field were calculated from rf power measurements. At the injection energy of E_0 = 200 keV there is satisfactory agreement with the calculated values. Note, that the maximum accelerating field of 5.7 MV/m is the highest field ever achieved with a superconducting multicell structure operated in an accelerator.

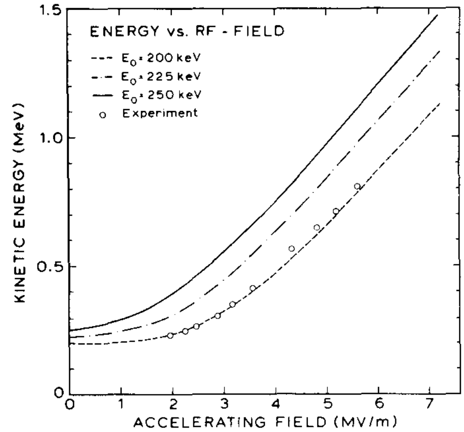

Fig.5 Comparison of calculated beam energies at the end of the 5-cell preaccelerator for three injection energies with measured values determined from the Mott-scattering spectra. All measurements were performed at 200 keV injection energy.

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