IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

PERFORMANCE OF THE KARLSRUHE SUPERCONDUCTING PROTON LINEAR TESTACCELERATOR

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Abstract

The advantage of the superconducting solution for rf accelerators in comparison to a normalconducting version is the drastic reduction of rf power requirement and hence reduced operating cost due to the much lower rf power losses at a comparable or higher accelerating field. The Karlsruhe group is the only one which studied in detail the acceleration of protons with superconducting resonators. Over the past several years a superconducting proton testlinac as a model accelerator has been completed. A review of the testaccelerator operation is given. The aim has been reached to demonstrate the feasibility of acceleration of protons for both high and low velocities. An energy of 4.5 MeV with a beam current of 150 µA (100% duty cycle) was obtained and accelerator performance has been tested. This includes more than 1000 hours of high field operation of the superconducting resonators and more than 3000 hours operation of the cryogenic system. Energy gradients of 1 - 2 MeV/m have been obtained reproducibly over the past several years without any degradation and without additional surface treatments after installation of the resonators into the accelerator.

Introduction

The aim of this paper is to review the operation of the superconducting proton linac at Karlsruhe [1-5]. The linac project was started [6] at Karlsruhe in 1970 as a pilot project for a larger proton accelerator. It has been a basic research and development program for the applicability and feasibility of rf superconductivity on a technical scale. It gave rise to several other programs in this field [7,8], i.e. the rf separator for CERN [9], a test section of a postaccelerator for the Heidelberg tandem accelerator [10], a test resonator for storage rings [11] and a test section for heavy ion post acceleration at Saclay [12].

An important feature of the superconducting accelerator is due to the fact that the rf losses in resonators can be reduced by 5 to 6 orders of magnitude, thus allowing continuous operation and acceleration of a continuous beam without any problems.

Technical reasons led to the development of the concept of short independently-phased resonators. The use of modular construction reduces fabrication cost and at the same time increases the overall reliability. Short sections are necessary for handling during surface treatment because this includes thermal treatment in a vacuum furnace of reasonable size and several devices for chemical treatment.

Therefore, an important difference of the superconducting linac to a conventional proton linac is given from the beginning, this linac is an array of short independently-phased resonators. Hence the velocity profile is established only by phasing instead by increasing the lengths of successive accelerator units. A short resonator can effectively accelerate a wide range of velocities. A linac formed of such resonators is exceedingly flexible with regard to the mode of operation and hence can cope with a change of performance of the resonators, without loosing the property of phase stability. A possible failure of one or more of the resonators to provide the design accelerating field will reduce the maximum beam energy only, but the linac can continue to accelerate the beam. On the other hand, this provides a direct method to vary the energy of the output beam over a large range by programming the field levels of the individual resonator, and adjusting the correct resonator phases.

Accelerator Description

A plan of the superconducting testlinac is shown in Fig. 1.

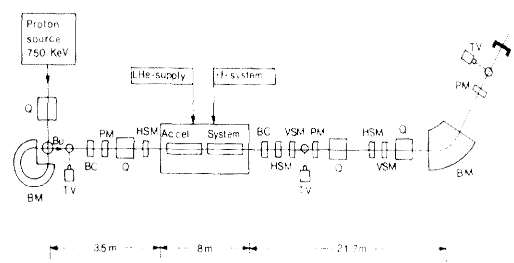

Fig. 1: Plan view of the superconducting proton accelerator
BC: beam current monitor; BM: bending magnet; BV: 4-gap-buncher; F: Faraday-cup; HSM: horizontal steering magnet; VSM: vertical steering magnet; Q: quadrupol; PM: position monitor; TV: television beam monitor.

The injector is a conveniently used Cockroft-Walton-cascade, the injection energy is 750 keV. The injection system [13-15] delivers a chopped and tightly bunched beam with less than 1% of the particles inbetween. The proton bunches have a length of 40 nsec (22° at 90 MHz) and a total energy spread of 3.8% up to beam currents of 400 µA. The normalized emittance at the accelerator input is 2.7π•cm•mrad with also about 1% of the beam outside. A general view of the linac cryostat is shown in Fig. 2. The cryostat contains the super-

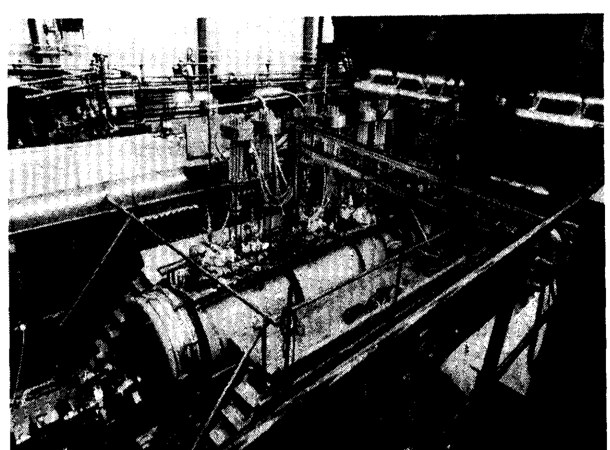

Fig. 2: General view of the linac cryostat from the high energy end. The cryostat has a diameter of 1.5m, the electronic tuners for each resonator are mounted on top of the cryostat.

conducting accelerating system, focussing and beam di-

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agnostic elements, helium storage vessels and an array of coaxial rf coupling lines. The electronic tuners for each resonator are mounted on top of the cryostat, as well as the devices for cooling down and warming up and the safety valves. The cryostat is connected to the large 300 W refrigerator allowing operation at a temperature of 1.8 K with superfluid helium II. The main parameters of the superconducting proton linac are given in table 1.

TABLE 1
Parameters of the Superconducting Proton Linac

energy range	0.75-4.5 MeV
max. beam current	150 μA
energy resolution	2.5%
operating temperature	1.8 K
electrical length	5 m
technical length	8 m
focussing	s.c. quadrupoles
total cooling power	200 Watts at 1.8 K
total rf power (without beam)	1.4 kW
max. beam power	0.675 kW
energy gradient	1-2 MeV/m
operating frequency	90 / 720 MHz
type of acc. structure	Helix / Alvarez
structure material	niobium
diameter of the structure	0.2 / 0.29 m
modular length	0.5 / 0.25 m
beam aperture	4.5 / 2.0 cm

The basic idea of the cryostat design was to use a double vacuum system, avoiding leaks between the beam vacuum in the accelerating system and the helium bath [16,17]. Liquid helium is guided in cooling channels only in particular into the helices which are connected to the storage vessels. The schematic layout of the cryostat is shown in Fig. 3. Cooling is achieved by heat

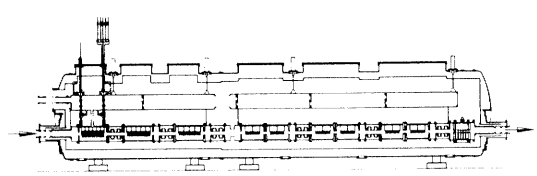

Fig. 3: Schematic layout of the linac cryostat

transfer in helium II without mass transport, i.e. only by the 'internal convection' mechanism of superfluid helium [18]. In the mean time it has become almost certain that the use of 4.2 K cooling instead of 1.8 K cooling is preferable for operation of superconducting low-frequency structures, because there is no further gain in surface quality and breakdown field level operating at lower temperatures [19]. Operating at 4.2 K will reduce refrigeration cost more than 50%. But the cryostat design for the linac did not allow to change the mode of cooling.

The accelerating system consists of nine helix-resonators with a total electrical length of 4.8 m operated at 90 MHz and one Alvarez-resonator of 0.25 m length running at 720 MHz. Quadrupole focussing with small superconducting lenses is used (gradient 30 T/m, length 30 cm, aperture 6 cm). The stray magnetic fields of the solenoids are clamped by superconducting lead shields. A module of the helix resonators is shown in Fig. 4. The outer cylinder has a length of 50 cm and a diameter of 20 cm, it contains two niobium helices with a length of 13.3 cm each (this corresponds to $\beta = 0.08$ at 90 MHz). The helices have a radius of 3.2 cm and are made of niobium tubing. With the exception of the first three all the other helix resonators have been built identically, thus are exchangeable within the linac. The helix design was made in such a way [20-22] as to keep the peak fields at the helix below 16 MV/m and to minimize power dissipation.

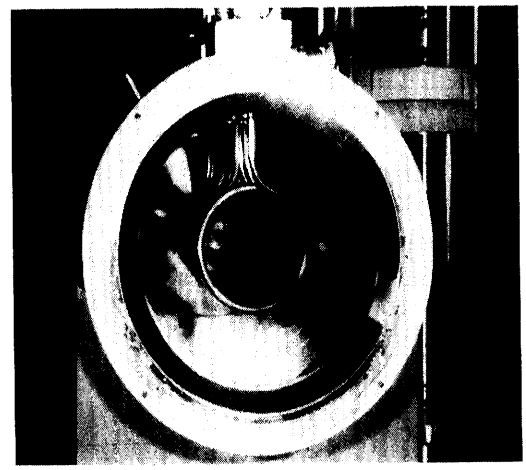

Fig. 4: Module of niobium helix resonators

Surface treatments applied to the finished resonator had to be repeated several times with intermediate measurements of the superconducting properties in a laboratory set up [23]. Electropolishing more than 50 μm was usually followed by annealing in order to lower the hydrogen content (2 h, 1200°C, 10^{-5}-10^{-8} Torr). Oxipolishing and anodizing were done in most cases as a final treatment. The surface treatment was continued until the design field levels could be exceeded by a safety margin.

The Alvarez resonator [24] is a 5 cell unit with an outer diameter of 29 cm and a bore diameter of 2 cm, it had been designed for 720 MHz, β=0.1 and E_{acc}=2MV/m.

The resonance frequency is tuned by mechanical deformation of the endplates. No fast tuner is needed because the mechanical construction provided excellent stability.

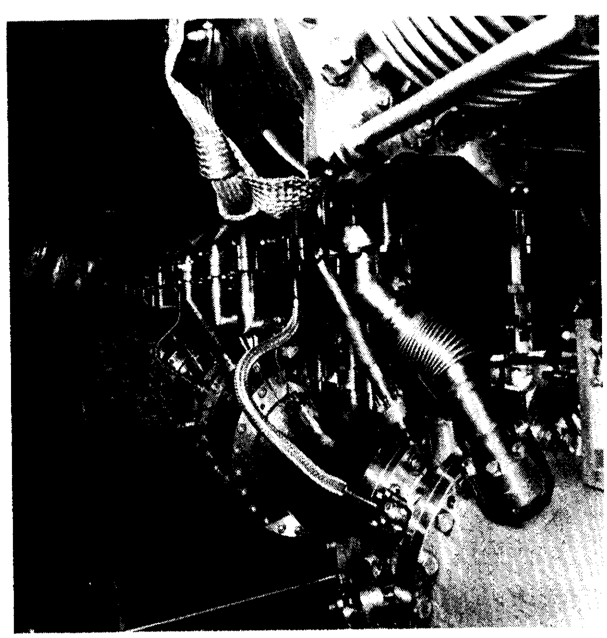

Fig. 5: View into the cryostat

The output beam is guided through a beam transport system (Fig. 1) and analyzed in energy with a 40° magnetic spectrometer (designed energy resolution 0.2%).

The rf system of the helix part consists of nine 90 MHz units with broadband 1 kW amplifiers. The rf field in the helix resonator is established using a rf positive feedback (lock in loop) and an amplitude control loop. A fast electronic tuning is necessary to eliminate any frequency modulation (usually 1-2 kHz peak to peak) within the tuning range of 2-3 kHz. A PIN-diode tuner was developed [25,26] which acts as a voltage-controlled reactance (VCX) and controls the rf phase by modulating the rf frequency by the necessary amount. The modulation cycle is being controled by the phase error signal. In addition, the tuning control signal is fed back to the amplitude modulator in order to damp the frequency vibrations of the helix [27,28].

Accelerator Operation

Several tests have been made with the assembled linac. The cooling system was operated for more than 3000 hours [29,30] without any leak problems. Typical cooling times for the refrigerator, the helium transfer lines and the cryostat (2 tons of stainless steel, 0.5 tons of niobium) from room temperature to 1.8 K with a subsequent filling with 500 l of He II were about 60 hours. A cooldown characteristic is shown in fig. 6.

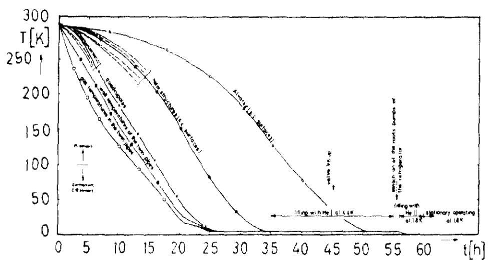

Fig. 6: Cooldown characteristic of the linac

The total refrigeration power required at 1.8K was about 200 watts:

transfer lines	35 watts,
precryostat and linac transfer line	16 watts,
linac cryostat	69 watts,
rf losses and beam losses with an output beam current of 150μA	80 watts.

Low-level multipacting was processed away after a few hours of maintaining low rf fields to the resonators in a manner similar to that applied in laboratory experiments. After processing cw energy gradients of 1-2 MeV/m, which correspond to peak electric fields of 16 MV/m and peak surface magnetic fields of 50 mT, were achieved. This corresponds pretty well to the design values and was reproduced several times in long term experiments. Table 2 presents some of the data taken within the last two years.

TABLE 2
Niobium Helix Performance, E_{acc} in MV/m

	design	f.s.t.	lab.	Nov. 77	Jun. 78	Nov. 78
W1	0.94	Nov. 75	1.06	1.03	1.02	1.03
W2	1.4	Feb. 77	1.6	1.4	1.4	0.85*
W3	1.7	Feb. 77	1.8	1.3	1.5	1.3
W4	2.2	Jul. 77	2.5	1.7	2.1	2.1
W5	2.2	Aug. 77	2.7	2.0	2.2	2.0
W6	2.1	Jun. 77	2.5		2.2	2.0
W7	2.1	Feb. 78	2.8		2.1	2.0
W8	2.2	Mar. 78	2.9		2.3	2.2
W9	2.0	Apr. 78			2.5	2.0

* The surface of W2 was contaminated in June 1978 due to a leaky rf window

It should be pointed out that the final surface treatment (f.s.t.) applied to helix W1 was done in November 1975. Since that time, the superconducting properties show no significant degradation. Further should be pointed that the achievable field strengths were close to the design values throughoutthe total operation time. Some resonators showed clearly that electron emission was the dominant effect of field limitation, but it became not quite clear whether the observed field limitations occured inside the resonators or at the low temperature end of the rf coupling lines. The achievable fields in long term experiments are somewhat lower as the best values taken in the laboratory.

In summary, it has been proven that the necessary energy gradients for a superconducting accelerator are obtainable reliably over long periods. Temperature cycling did not affect the superconducting properties.

The rf system has been operated at design field level with phase synchronisation to a common master oscillator for a total period of more than 1000 hours. The phase error of $< 1^{\circ}$ and the remaining amplitude error was well within specifications. No principle problem occured during long term operation. Due to instrumentation problems we had several interruptions. The rf amplifiers should be mentioned, i.e. the only way to get a satisfactory stable operation of the commercial rf amplifiers was a reduction of output power. This did not affect the rf operation at the designed field level. Another trivial problem was due to failures of power supplies for the pindiode tuners. These failures and other reasons for interruptions were eliminated during operation. One remaining problem dealing with the complicated operation of a full scale accelerator was some sort of discharges at the low temperature end of some of the coupling lines.

Beam experiments were started with low beam currents of about 10 μA. At first, the energy gradient of subsequent helix resonators was determined by measuring the energy of the proton beam. The maximum energy gain was found setting the phase between rf field in the resonator and the reference phase. In this way the right velocity profile was established by phasing which was observed by the minimal energy spread. It has been demonstrated that maximum transmission of the input beam is strongly dependent on phasing. Some of the results are presented in table 3 and compared to the expected values.

TABLE 3
Energy Gain in the Linac

	E_{acc}(MV/m)	T_i (MeV)	T_o (MeV)	ΔT_{exp} (keV)	ΔT_{theor} (keV)
W1	0.94	0.75	1.122	372	373
W2	0.76	1.122	1.450	328	291
W3	1.04	1.450	1.714	264	382
W4	1.83	1.714	2.118	404	365
W5	1.80	2.118	2.505	387	432
W6	1.62	2.505	2.931	426	445
W7	1.66	2.931	3.385	454	473
W8	1.96	3.385	3.789	404	532
W9	1.60	3.789	4.287	498	520

The agreement between measured and calculated values of table 3 is good. Thus the rf measurements of the field strengths have been verified independently. In other beam experiments it was possible to increase the maximum energy of the output beam only by phasing. A maximum beam energy of 4.5 MeV was obtained with the same resonator field levels as table 3. The calculated energy is 4.58 MeV in this case which is extremely close to the measured value. The energy resolution of the 4.5 MeV-beam was measured to be 114 keV or 2.5%. This clearly indicates the effect of phase damping due to the acceleration process, because the energy spread of the input beam was 3.8%. To test the energy resolution of the magnetic spectrometer an unchopped beam of 750 keV has been measured, the result was 8×10^{-4}. The energy spectrum obtained from the 4.5 MeV proton beam is shown in fig. 7.

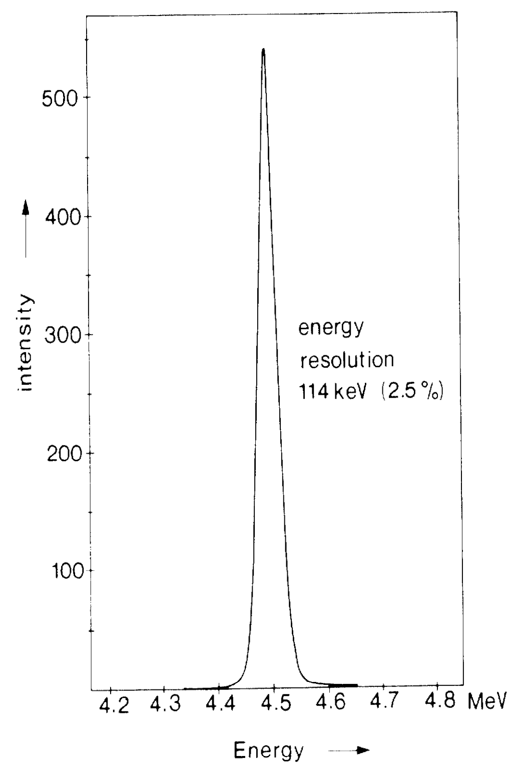

Fig. 7: Measured energy spectrum of the 4.5 MeV proton beam

The operation of the focussing system with the six superconducting quadrupoles has been nearly as expected, with the exception of the fact that we have been unable to extract more than 85% of the input beam. Beam current is lost at known positions as indicated also by the enhanced helium losses.

The accelerator has been designed to operate with beam currents as large as 100 µA. While most of its operation has been with currents of about 10 µA, we were able to accelerate and extract a beam current of 150 µA from a 176 µA input beam. The beam loss was measured in the helium tank. The rf power transferred to the beam in each resonator was directly measured as a crosscheck for the accelerated beam current. The agreement within the experimental error limits was excellent. In addition, beam profile and beam position along the accelerator have been measured.

The stability of the linac was excellent as demonstrated by the observation that the machine could be shut down for several hours or even days and the beam would reappear at the target, without any adjustments, when the accelerator was turned back on.

Acknowledgement

Many people were involved in the work done at Karlsruhe; it is therefore not possible to thank everybody individually. We would like to thank specially our refrigerator crew for their untiring effort during the accelerator runs. In particular we would like to thank G. Hochschild, J.E. Fricke, K. Mittag, L. Szecsi and J.E. Vetter from Karlsruhe for their contributions to the linac during design and construction. The surface treatments of the helix resonators and the laboratory measurements were mainly done by B. Messerschmidt, N. Münch and G. Westenfelder. H. Lotz and H. Heckfuß did all the mechanical assembly of the cryostat and the cryogenic system. P. Grundel, H. Oppermann and G. Redemann were responsible for the maintenance and operation of the proton injector, the beam transport and diagnostic system and the complete installations. P. Schlick was involved in the set-up of the rf system. F. Schürrer and R. Vincon took care of the Alvarez resonator, surface preparations as well as rf measurements.

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