ACCELERATING IONS WITH SUPERCONDUCTING RESONATORS, OPERATED AT A TEMPERATURE OF 4.4 K

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Abstract

A superconducting section of a post-accelerator adding 0.5 MV of effective energy gain per charge to ions preaccelerated by an MP tandem is presently tested in the beam line at Heidelberg. ^{32}S ions of two different charge states with intensities up to 2 μA were accelerated in cw operation.

The two helically loaded cavities are independently phased to a reference line by use of pin diode tuners. The rf system provides an excellent stability of the accelerating field: the amplitude was kept constant within 5×10^{-4} and the phase error remained within 5×10^{-3} radian pp.

A forced flow of subcritical helium at a temperature of 4.4 K was advantageously used to cool the resonators. Total cooling power for continous operation of the section amounted to 9 W where only about 1 of rf power was dissipated by one superconducting cavity at the designed field level.

Introduction

A development program was started in 1974 by the Institut für Experimentelle Kernphysik des Kernforschungszentrums Karlsruhe (IEKP) and the Max-Planck-Institut für Kernphysik Heidelberg (MPI) on resonators both normalconducting (MPI) and superconducting (IEKP) in view of designing a postaccelerator, adding ~10 MV of effective voltage gain to ions preaccelerated by the 13 MV upgraded MP tandem. High flexibility of efficiently accelerating ions of arbitrary charge and mass up to mass 80, preservation of the high beam quality defined by the preaccelerator and pulsing system and coarse and fine tuning of the target energy were of particular importance in the design and led to the concept of short accelerator cavities independently phased [1].

Though these demands can be fulfilled by normalconducting resonators as well as by superconducting ones, operation at reduced cost is expected from a superconducting system. As comparative proposals were intended to be drawn up by the end of 1976, the R&D-work on the superconducting postaccelerator was confined to building and testing of a prototype section based on components with sufficient operating experience. Consequently helically loaded λ/2-resonators and rf systems using a pin diode tuner as control elements for the cavity phase where used, components which had been tested under more stringent demands in the superconducting proton accelerator at Karlsruhe. In spite of the short development time, some essential improvements could be introduced which simplify design and fabrication and further reduce capital and operating costs. These developments are discussed within the following sections.

The test section

Two helically loaded niobium resonators, having an inside length of 23 cm and a diameter of 16 cm, are housed in a cryostat of about 1.2 m length (fig. 1). An aperture of 4 cm clearance throughout the cryostat allows for an ion beam to pass along the axis of the system. Three rf lines (power input, reactance line and reference probe) connect the resonators to the electronic units. Helium is continously fed from a pressurized 500 l tank via a low loss transfer line into the cryostat. Helium vapor is compressed into a 200 bar storage. A motor truck service provides for discharge of gas bottles and refill of up to 1000 l per week of liquid at the low temperature plant of the IEKP, 50 km distant from the experiment. Though all installations for low pressure 1.8 K operation were provided in the cryostat and helium recovering

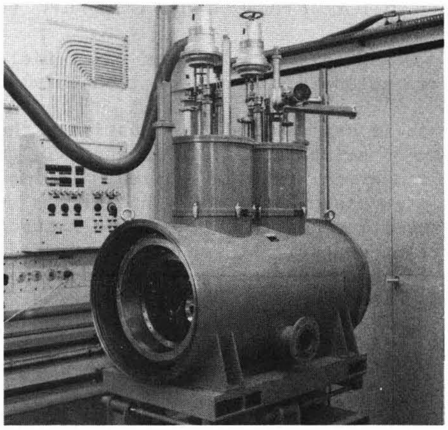

Fig. 1:
Cryostat for beam operation of two helix resonators equipped for experiments with alternatively 4.4 K forced flow or 1.8 K superfluid cooling

system, the test section has been operated exclusively at 4.4 K as this more advantageous cooling method could be applied without any difficulties (see below).

The superconducting resonators

The design of the helically loaded resonators was described in detail in an earlier publication [2]. The most essential parameters are repeated in table I.

TABLE I

DESIGN VALUES OF SUPERCONDUCTING HELIX RESONATORS

operating frequency	108.48 MHz
peak surface field strength	16 MV/m
accelerating field strength related to helix length	2.3 MV/m
energy gain per charge at optimum velocity	300 KV
rf-cavity loss	1 Watt
stored energy	0.16 J
frequency shift by radiation pressure	~30 kHz

Fabrication of the resonators has been greatly simplified: a single wall housing is made out of 4 mm niobium sheet (fig. 2)

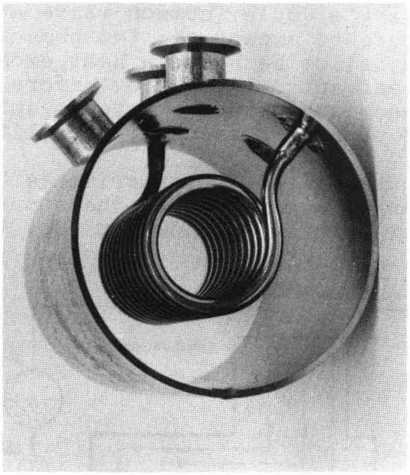

Fig. 2:
Helically loaded λ/2 resonator before welding the endplates to the cylindrical part. Simple construction and small dimensions (16 cm dia) characterize the design.

The helix, made out of 10 mm o. d. tubing, is wound on a mandril and stress relieved at 1100° C in a vacuum furnace. Inner surfaces of the parts are electropolished ~100 μm before welding. The helix length is adjusted in an rf test measurement to compensate for fabrication tolerances to give the correct frequency within typically 0.2 MHz. (Further frequency correction is done by adjusting the pitch of the helix and by a small niobium plunger in the cavity wall. The remaining error is typically 2 ÷ 3 kHz.) The helix ends are welded to the cylinder and the resonator is finally closed by welding the end plates to the center part. TIG-welding is used throughout all fabrication steps. Electropolishing the complete resonator by ~50 μ is followed by a 1200° C bakeout to reduce the hydrogen content formed during the electropolishing process. Final treatment is alternatively oxipolishing or electropolishing a few μm. If in a subsequent low temperature test thermomagnetic breakdown was found as an effect of field limitation further electropolishing and outgassing were applied.

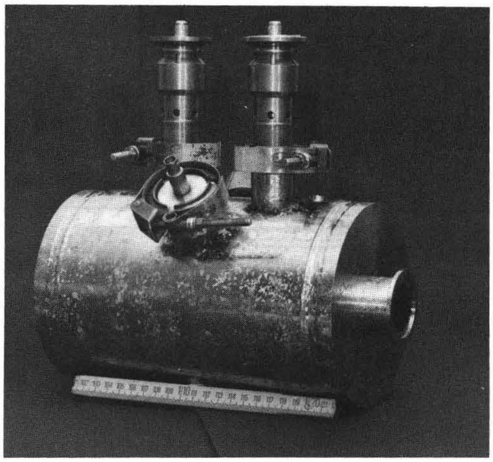

Fig. 3:
Coupling probes and coaxial lines are mounted to the resonator with the aid of standard clamps giving a very reliable low temperature seal.

A resonator treated the way described will show a high Q (10^8-10^9) over a wide range of field strength being ultimately limited only be electron loading effects. Laboratory experiments with the two resonators fabricated for the test section showed after preparation maximum field strengths of 20 to 25 MV/m (peak surface field). Surface preparation of the first resonator (A) was finished last January. More than 10 temperature cycles, intermediate storage under either vacuum or laboratory air, and high field operation for >100 h did not make a repeated surface preparation necessary.

During the first period of beam tests the maximum field strength which could be maintained in stable operation was limited to the design field strength due to electron loading. We attribute this behavior to difficulties during assembling and to the poor vacuum (~10^{-5} Torr) during this experimental period. Rinsing with methanol (resonator B) and oxipolishing (resonator A) proved to be sufficient means to restore the good performance of the resonators. In the tests recently started with a vacuum of $<10^{-6}$ Torr, more than 20 MV/m could be obtained in stable operation.

rf system

A combination of control loops for amplitude, and phase is used to stabilize the accelerating field to a reference line[3]. Phase between accelerating field and reference line is controlled by a variable reactance using pin diodes as fast switches[4]. This system, successfully tested for the superconducting proton linac at Karlsruhe, was modified for the demands of our cavities and further improved. The development includes reduced size, modular technique and remote control of amplitude and phase reference values. Semiconductor elements are used throughout the system including the final amplifiers. Some parameters of the system are given in table 2.

TABLE II

PARAMETERS OF THE RF-SYSTEM

amplitude control loop	
loop gain	100 dB
unity gain frequency	50 kHz
phase control loop	var. controlled reactance with pin diodes
number of steps (diodes)	6
step width	250 Hz
switching frequency	100 kHz
rf power	50 Watts ave., 100 W peak
amplitude stability (measured DC to 1 MHz)	$< 5\times10^{-4}$ pp
phase stability, measured	$< 5\times10^{-3}$ rad pp

The values of field stability, given in table 2, were obtained with a frequency modulation of ~500 Hz_{pp} by ambient vibrations mainly induced by rotating pumps unflexibly connected to the cryostat. No means of screening the vibrations were applied.

The cooling system

Measurements on the temperature dependence of breakdown field strength and cavity losses had been carried out in an earlier experiment with a helically loaded resonator whose axis was vertically positioned in a helium bath to allow for a self-acting flow by the thermosyphon effect. Only a very weak dependence of the superconducting properties on temperature was found for $T < 4.2$ K, which suggested the application of a higher cooling temperature.

As the capital cost of a 4.2 K refrigerator is estimated to be about 50% of a machine delivering superfluid helium at 1.8 K, and as the overall efficiency of the cooling process increases proportional to temperature, essential cost reduction is expected for an accelerator cooled at temperatures ≥ 4.2 K.

However it was feared that instabilities often encountered in a two-phase flow of subcritical helium might impede the control of a defined flow and might interfere with the frequency stability of the resonator. A further experiment with a helix dummy having the configuration of our helix resonators but heated by a dc current and cooled by forced subcritical helium of adjustable mass flow was carried out. Temperature sensors at the entrance and exit of the helix tubing showed that the temperature rise along the tube remained within 0.2 K when the vapor content in the flow was kept below 90% (mass fraction). These observations are in accordance with measurements of de la Harpe et al.[4]. The total flow rate was varied in this experiment from 6 to 22 l/h. A heat load of up to 15 Watt was thus removed in stable operation from a single helix, whereas the maximum heat capacity in a helix of our geometry in a superfluid bath would be limited to about 2 Watt.

Using a Joule Thomson valve at low temperature to expand the two phase flow into the helium bath and a heat exchanger to calm and subcool the flow before entering the heated path were found to be sufficient means to supress pressure instabilities.

These preceeding experiments led to the arrangement applied in the superconducting test section as shown in fig. 4.

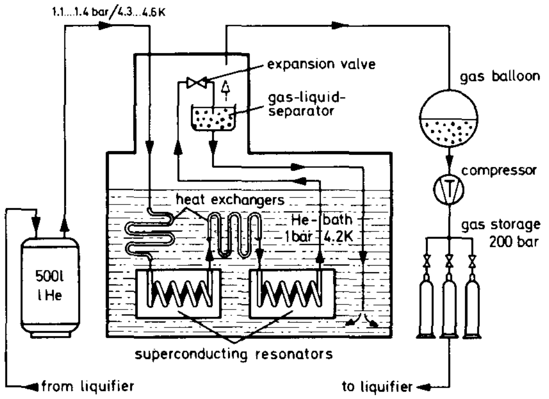

Fig. 4:
Flow diagram for operation with a forced flow of subcritical helium.

The two helically loaded resonators are passed in series by a flow of helium the rate of which is controlled automatically by an expansion valve to keep the helium level of the surrounding bath constant. The necessity that liquid helium must be fed to the helium bath, to compensate for the evaporation rate caused by cryostat losses, ensures an efficient cooling of the resonators, as a minor fraction of liquid in the flow maintains stable temperatures within the resonators.

Subsequent tests with our superconducting resonators confirmed that the flow through the helix could be varied in wide limits without influencing either the frequency stability or the breakdown field.

The flow rate to maintain a constant helium level in the system was found to be about 7 l/h (~5 Watt of cooling power) without feeding rf to the resonators. This value includes the transfer losses generated in the line from the storage tank to the cryostat. The pressure drop at this flow rate was mainly generated across the JT-valve whereas a Δp of <50 mbar was deduced from measurements of saturation temperatures across the system of heat exchangers and helices.

Beam experiments

A d. c. beam of ^{32}S ions was injected from the MP tandem into the superconducting test section to measure the energy gain of the resonators separately and in combined phase locked operation. Energy analysis of the beam was made by measuring the total energy of ions scattered by a 100 µg/cm^2 gold foil about 1 m downstream from the resonators with a surface barrier detector at an angle of 15°. The spectrum obtained from a 120 MeV $^{32}S^{+14}$ beam without post-acceleration is shown in fig. 5.

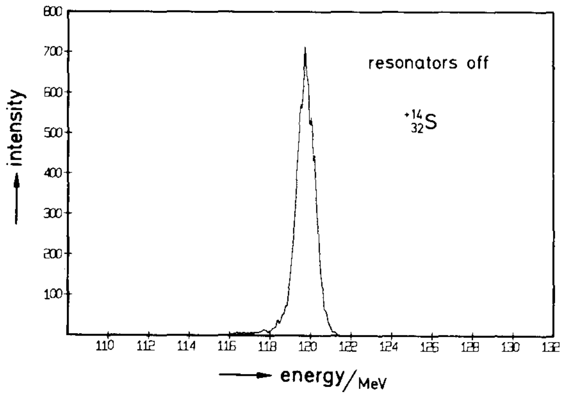

Fig. 5:
Energy spectrum of a $^{32}S^{+14}$ beam as measured with a semiconductor detector. Resonators are switched of.

Operating the cavities separately at the design field resulted in spectra one of which is shown as an example in fig. 6.

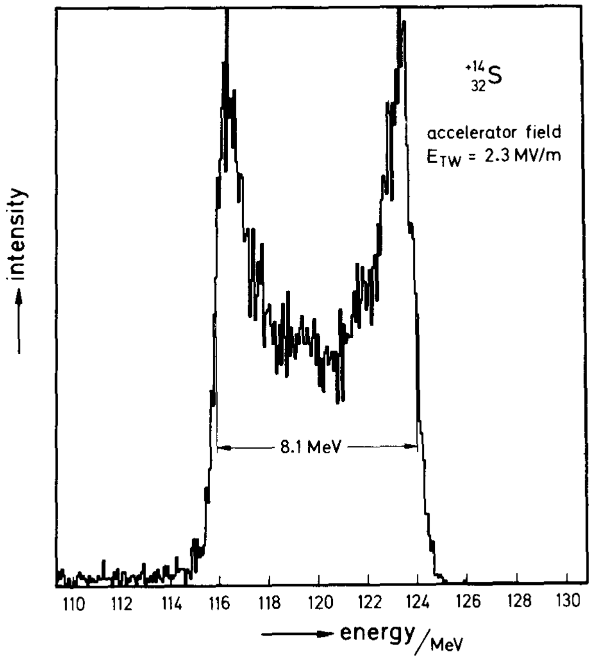

Fig. 6:
The spectrum of fig. 5 is broadened to a width of 8.1 MeV by action of one resonator operated at the designed accelerating field strength of 2.3 MV/m.

As the energy spread is still small compared to the injection energy, the spectrum can be assumed to be symmetric, resulting in an energy gain of half the total width (4.05 MeV), or an energy gain per charge of 290 kV.

Similar measurements were carried out with $^{32}S^{+12}$ ions at 70 MeV and at 150 MeV to determine the velocity acceptance of the cavity. The measured values are shown in fig. 7 and were found to be in excellent agreement with calculations based on a field profile measurement (fig.7).

In a subsequent test both resonators were phase locked to a reference. The energy spread introduced to a $^{32}S^{+14}$ beam of 120 MeV injection energy by operation of the combined resonators amounts to 14 MeV corresponding to a total voltage drop of 500 kV (fig. 8). This value is somewhat smaller than the sum of the maximum values obtained with the single resonators for the following reason: The resonant frequencies of the cavities were not perfectly matched at the design field due to a tuning error of the resonant frequencies. Consequently the field strength in one of the resonators was lowered to operate at a smaller value of static frequency shift where the cavity frequencies coincided. An adjustable plunger is being developed to compensate for such tuning errors.

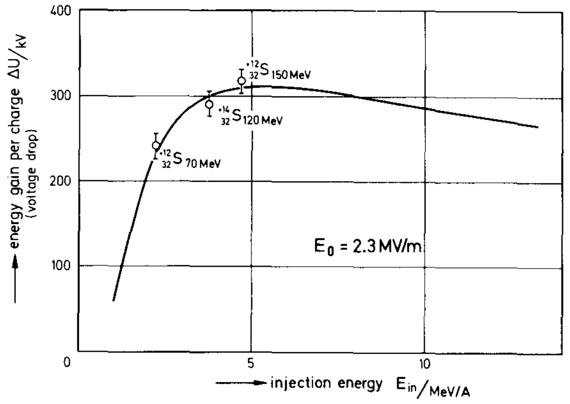

Fig. 7:
Measured energy gain per charge for three beams of different specific injection energies (velocities) agrees well with the calculated curve derived from a field profile measurement. The broad velocity acceptance of the resonator is demonstrated.

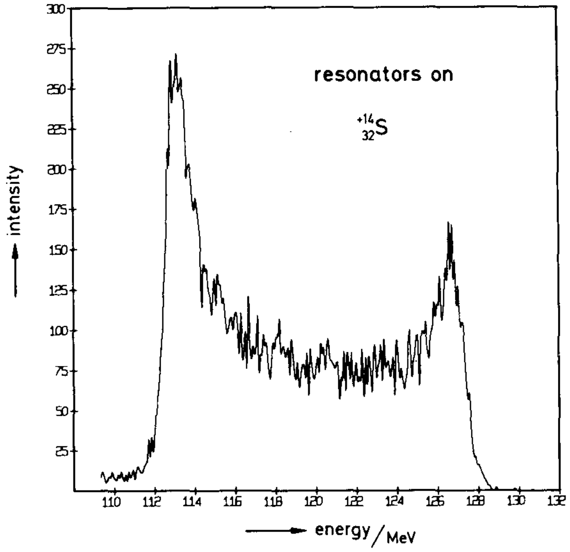

Fig. 8:
Two resonators in phase locked operation yield a spectrum widened by 14 MeV corresponding to a voltage drop of 0.5 MV.

Conclusions

Extended experience has been gained in constructing and operating superconducting $\lambda/2$ helix resonators to be used as accelerating elements in a heavy ion postaccelerator.

Small dimensions and simplicity of construction yield fabrication at low cost (4000 $ per element including material). Operated at a conservative value of peak electric field of 16 MV/m, 300 kV of voltage drop are obtained from a single resonator. The cavity loss of 1 Watt at 4.2 K keeps the cooling power low: 15 Watt are estimated to be required per MV of voltage drop. Using 4.4 K forced flow operation a capital cost of 2000 $ per cold watt is expected for the refrigerator system. The total power consumption per MV will amount to less than 15 kW, comparing favorably with normalconducting solutions.

A stored energy of 0.5 J per MV of voltage drop and a frequency vibration of 500 Hz_{pp} keep the tuning requirements in reasonable limits. Using pin diode tuners as variable reactances a reactive power of 2 kVA per MV has to be installed. The necessary maximum rf input power of about 300 W per MV can be obtained using transistor power amplifiers of high lifetime.

The test program carried out at present aims at gaining more experience under realistic conditions given during operation in the beam line of a complex accelerator system. Acceleration of pulsed beams and long-term operation at the design field strengths are projected.

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DISCUSSION

G.J. Dick, CalTech: Were the phase and amplitude stability numbers obtained at high operating fields?

Vetter: The stability values were obtained at the design field level at highest amplitude loop gain.

Dick: Was the dissipation measurement also made with the stabilizing system in operation?

Vetter: Dissipation in the cavity walls amounted to less than one watt per resonator. The additonal low temperature fraction of the rf line losses was measured to be ∿ 0.7 watts, though this part of the losses is not yet optimized.