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KERNFORSCHUNGSZENTRUM KARLSRUHE GMBH

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A LINEAR POSTACCELERATOR WITH SUPERCONDUCTING HELIX RESONATORS FOR MEDIUM MASS IONS

PREPARATORY EXPERIMENTS AND CONCEPTUAL DESIGN

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Abstract

The concept is presented of a linear accelerator equiped with short superconducting resonators as accelerating elements. Saving high-frequency power remarkably reduces the operating costs as compared with normal conducting resonators. Booster systems of this type can be used to further accelerate medium heavy ions having passed an MP tandem after their charge state has been increased.

The design confirms and gives shape to the projects covered by a study of 1973 on the performance and cost of a superconducting booster accelerator. The design parameters are the result of experience gathered with a 1 m long test section developed at the Institute für Kernphysik of the Karlsruhe Nuclear Research Center. This test section was investigated from June 1976 until February 1977 with the heavy ion beam of the MP tandem of the Max-Planck Institut für Kernphysik, Heidelberg in four acceleration and three irradiation experiments as well as during 1000 h of cryo-operation in total and 500 h of high field operation of the resonators. The results of these experiments and in particular the experiences obtained with the test section in the everyday operation of a tandem accelerator facility will be summarized.

The system described is of the modular type and can be extended. The design presented as an example is based on the construction of four units yielding an effective accelerating voltage of 9.4 MV. A total of 32 superconducting helical resonators are fed individually at an operating frequency of 108.5 MHz. Phase controls ensure the synchronization of the individual elements. The refrigeration capacity of 200 W at 4.4 K is transferred by two-phase flow of helium and by bath cooling. The mains power consumption of the linear accelerator is 200 kW. The necessary capital investments amount to 4.4 million DM, the operating costs (excluding personnel and depreciation) to about DM 60 per hour for an annual 3000 h of operation.

Ein supraleitender Wendel-Nachbeschleuniger für mittelschwere Ionen

Experimentelle Vorarbeiten und Entwurf

Zusammenfassung

Es wird das Konzept eines Linearbeschleunigers vorgestellt, der kurze supraleitende Hochfrequenzresonatoren als Beschleunigungselemente enthält. Durch Einsparung an Hochfrequenzleistung wird eine deutliche Reduzierung der Betriebskosten gegenüber normalleitenden Resonatoren erreicht. Ein derartiger Nachbeschleuniger ermöglicht es, nach einem MP-Tandem mittelschwere Ionen nach Erhöhen ihres Ladungszustands wirksam weiterzubeschleunigen.

Der Entwurf bestätigt und konkretisiert die in einer Studie 1973 zusammengefaßten Projektionen über Leistung und Kosten eines supraleitenden Nachbeschleunigers. Die zugrundegelegten Parameter wurden aus Erfahrungen mit einer im Institut für Experimentelle Kernphysik des Kernforschungszentrums Karlsruhe entwickelten 1 m - Teststrecke gewonnen, die von Juni 1976 bis Februar 1977 am Schwerionenstrahl des MP-Tandems des Max-Planck-Instituts für Kernphysik, Heidelberg in vier Beschleunigungs- und drei Bestrahlungsexperimenten sowie während insgesamt 1000 h Kryobetrieb und 500 h Hochfeldbetrieb der Resonatoren untersucht wurde. Die Ergebnisse dieser Experimente und insbesondere die Erfahrungen mit der Teststrecke im "Alltagsbetrieb" an einer Tandembeschleunigeranlage werden zusammenfassend dargestellt.

Das beschriebene System ist modular und erweiterungsfähig. Der hier als Beispiel aufgeführte Entwurf geht von der Errichtung von vier Einheiten aus, die eine gesamte durchfallene Spannung von 9.4 MV liefern. Insgesamt 32 supraleitende Wendelresonatoren werden bei einer Betriebsfrequenz von 108.5 MHz individuell gespeist. Phasenregelungen sorgen für Synchronisation der Einzelelemente. Die Kälteleistung von 200 W bei 4.4 K wird durch Zweiphasenströmung von Helium und Badkühlung übertragen. Die Anschlußleistung des Linearbeschleunigers ohne Strahlführungs- und Strahlpräparationseinrichtungen beträgt 200 kW. Hierfür belaufen sich die Investitionen auf ca. 4.4 MDM, die Betriebskosten (ohne Personal und Abschreibung) bei einer jährlichen Betriebszeit von 3 000 h auf ca. 60 DM/h.

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1. Introduction

Tandem accelerators with terminal voltages around 12 MV are increasingly used in many accelerator laboratories to accelerate medium heavy ions. In order to expand the accessible range of energy many laboratories are actively interested in booster acceleration of the ions in a flexible linear accelerator which, typically, should supply a voltage gain of 10 - 15 MV up to a mass number A ~ 80 with good beam quality and at low operating costs.

In the course of prototype work on a superconducting proton linear accelerator helical resonators have been developed at the Institut für Experimentelle Kernphysik Karlsruhe (IEKP) which lend themselves also to the acceleration of heavy ions. Accordingly, members of IEKP, the Heidelberg Max-Planck-Institut (MPI H) and the Institute of Applied Physics of the University of Frankfurt in 1973 drafted a "Study for the Design of a Booster Accelerator for Medium Heavy Ions with Superconducting Helical Resonators"[1] which furnished the basic data. Estimates in that study indicated that 44 helical resonators could generate an accelerating voltage of 13 MV (6 MeV/N for $^{79}Br^{26+}$ at an injection energy of 1.77 MeV/N). In order to achieve maximum flexibility, i.e., availability of the installed voltage over a broad range of particle velocities, the resonators should be operated electrically independent of each other so that the velocity profile for ions over a wide range of masses can be set by a suitable choice of rf phases.

Since there was interest both at MPI H and IEKP to test this concept, which promised to be associated with remarkably lower operating costs than a normal conducting accelerator at comparable capital costs[1], under everyday conditions and, in particular, to check the handling capability and the reliability of the rf superconduciton technology applied, both institutes agreed upon the construction of a superconducting test section and its operation with the heavy ion beam of the MP tandem at the MPI H.

This joint venture was implemented between mid-1974 and early 1977. The test section with two resonators in a cryostat and the respective high frequency system was developed and constructed at IEKP. Between mid-1976 and early 1977 the test section (fig. 1) was installed in the beam path of the MP tandem at MPI H. A summary of the experiences accumulated during this test operation and the result of the beam experiments will be given in Chapter 3.

After this comprehensive preparatory work the concept of a superconducting booster can now be cast into more precise terms. As a practical example for application, Chapter 4 describes a booster with an effective accelerating voltage of 9.4 MV. The expenditure involved in the construction and operation of such a unit is summarized in Chapter 5.

The general interest in using rf superconductivity for heavy ion boosting and the present state of the art are evident from developments of niobium split ring resonators (Argonne[3]), lead split ring resonators (Pasadena and Stony Brook[4]) and niobium re-entrant cavities (Stanford[5]). A comparison and a survey of these studies is given in [6].

2. Boosters for Tandem Accelerators

2.1 Objectives of Boosters

Over the past 10 or 15 years electrostatic tandem accelerators in particular of the MP-type [7] have helped in many accelerator laboratories to create decisive experimental bases for heavy ion physics. Together with highly specialized sources for negative heavy ions these machines have become integral parts of the experiments, much more so than in experiments with light particles, or have influenced the generation of other, comprehensive equipment, such as magnetic spectrometers, large area detector systems and time-of-flight systems. A number of tandem accelerator laboratories have thus become centers of heavy ion physics.

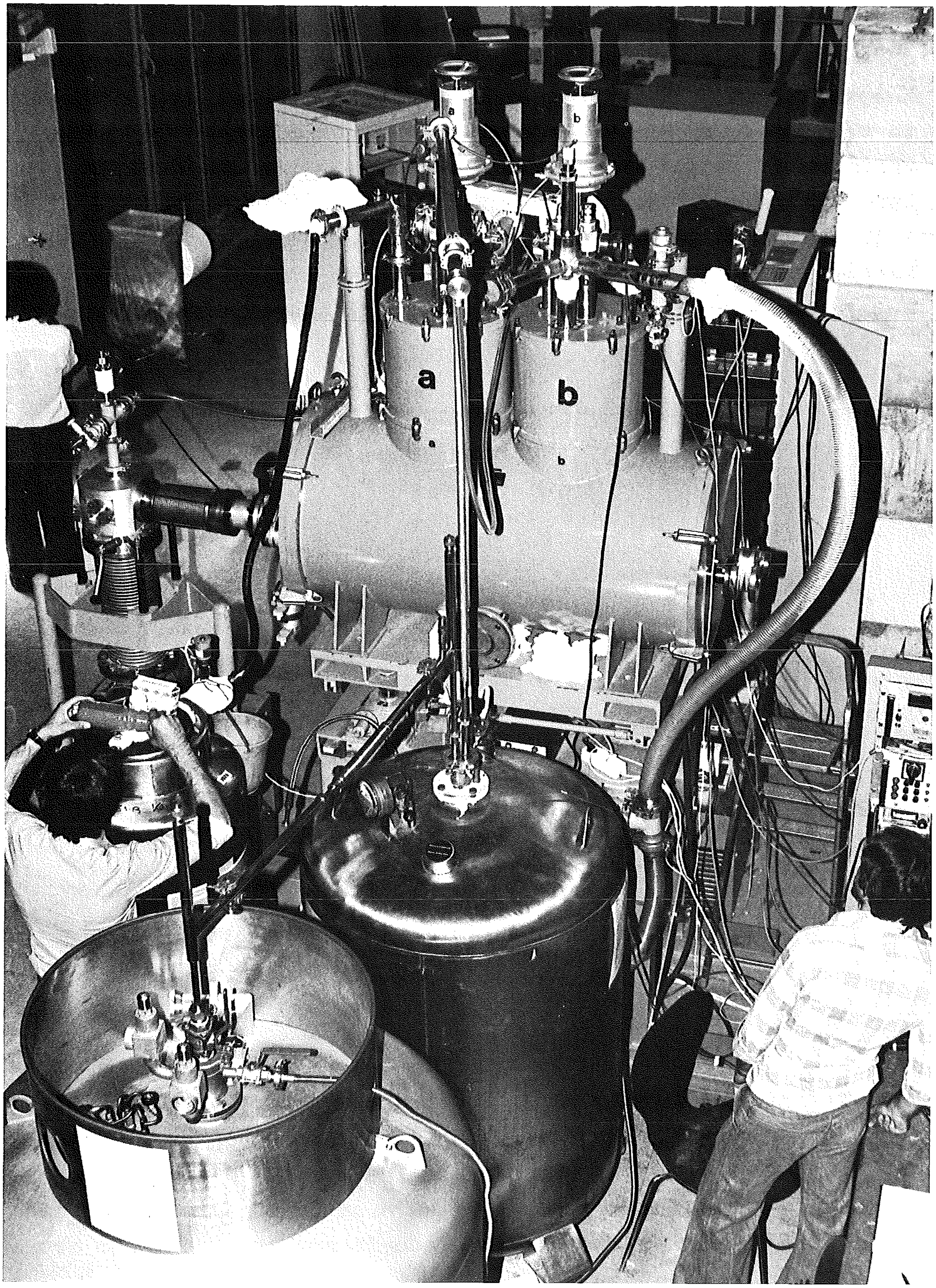


Fig. 1: Test section of a superconducting ion booster

The terminal voltage of the original MP accelerator was limited to levels below 10 MV which proved to be an obstacle in the attempt to extend experiments into the range of heavier ions. Thus, each of the ten tandem accelerators in this category had to undergo upgrading programs[8] in recent years which raised the terminal voltages, from about 10 MV into the range of 12 - 13 MV. With ions up to mass numbers of A 20 MP tandem accelerators are now able to overcome the Coloumb barrier of very heavy nuclei; for heavier projectiles of higher masses the accelerating voltage is still insufficient (fig.2).

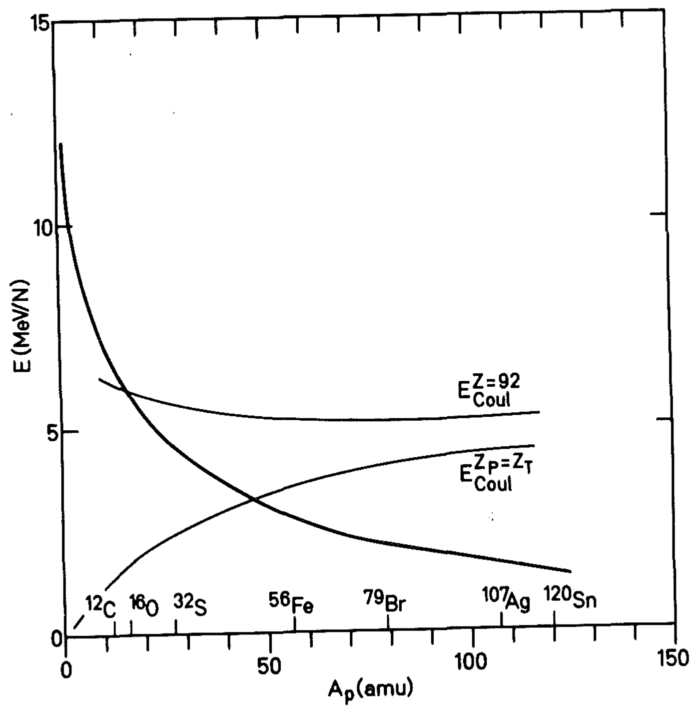


Fig. 2: Final energies of a MP tandem upgraded to a terminal voltage U_T=12 MV expressed in MeV/nucleon as a function of the mass of the projectile, A_p. The diagram also shows the Coulomb barriers for an Uranium (Z_T=92) target and a target having the same atomic number as the projectiles ($Z_p = Z_T$)

Studies [1,9,10] published 1972 to 1976 indicated that an increase in ion energies to approx. 6 MeV/N up to a mass number A ~ 80 would open up a broad field of experimental possibilities without, at the same time, infringing upon the area of very heavy projectiles, in which existing large accelerators (such as e.g. the Unilac) (or the superhilac) would offer more advantageous and experimental conditions.

Further improvement of the terminal voltage does not seem to be possible at present in the existing MP tandem, given the present geometries of the tank and the column and given also the present state of the art in the field of accelerator tubes. The desired improvement in energy can thus be achieved only by means of a booster to further accelerate the ions having obtained a higher charge state in a second stripper which follows the MP tandem. Although, in principle also cyclotrons and electrostatic accelerators can be used as boosters, most accelerator projects in the planning or construction phases use radiofrequency linear accelerators [11]. Linear accelerators are most attractive for these purposes especially because of the low capital costs and the modular design capability of these machines.

2.2 Requirements for Tandem and Booster

The combination of a linear accelerator with an electrostatic tandem accelerator first of all results in a number of additional requirements for the tandem accelerator system itself:

The generation of negative heavy ions which, if possible, should supply all elements, including rare isotopes, in the desired range of masses with intensities of typically 5 μA, is now ensured by the development and the improvements achieved in recent years in the field of sputtering ion sources [12,13,14].

The need to couple a dc machine to an rf-accelerator gives rise to the requirement for an efficient beam pulsing system to compress a maximum fraction of the dc intensity into a small range ($\Delta\phi = \pm 5^{\circ}$) within the longitudinal acceptance of the boosters in order to maintain a good beam quality, as mentioned later.Special systems yield up to 80% [15]. The phase range of $\Delta\phi = \pm 5^o$ at an operating frequency of approx. 100 MHz corresponds to a pulse width of $\Delta t_p \sim$ 250 ps, which value has been underrun by far[16]. To maintain the phase coherence, an isochronous beam transport system has been developed and tested[17]. In addition, type, thickness and positions of the two strippers, i.e. the terminal stripper within the tandem and the post-tandem stripper have to be optimized, because energy straggling and angular straggling as the ions pass through the gas duct or the foil are mechanisms ultimately determining the beam quality of the overall system[18].

Extending the range of masses up to A 80 also requires improvements to be made in the vacuum system of the tandem accelrator and in the beam guide system, which must ensure a high vacuum better than 5 x 10^{-7} Torr to avoid decharging losses in excess of about 5%.

The main <u>requirements to be met by the booster</u> relate first to the energy gain, which should be sufficient for a broad range of masses (A_p = 12 - 80) in order to overcome the Coulomb barrier, and second, to the preservation of the excellent beam quality of the MP tandem accelerator.

The effective accelerating voltage necessary to boos the heaviest ions planned beyond the Coulomb barrier (fig. 2) is exclusively a function of the choice of the charge states in the two strippers with the terminal voltage given. Since stripping twice will greatly reduce the beam intensity finally available already in the most frequent charge states (fig. 3), higher cahrge states can be chosen only where a reduction in intensity in favor of the final energy can be tolerated[19].

The voltage required to accelerate ^{79}Br beyond the Coulomb treshold is in the range of 13 to 20 MV for various charge states ($Q_2 = 20^+ \dots 26^+$). The peceding study[1] has been based on the value of 13 MV.

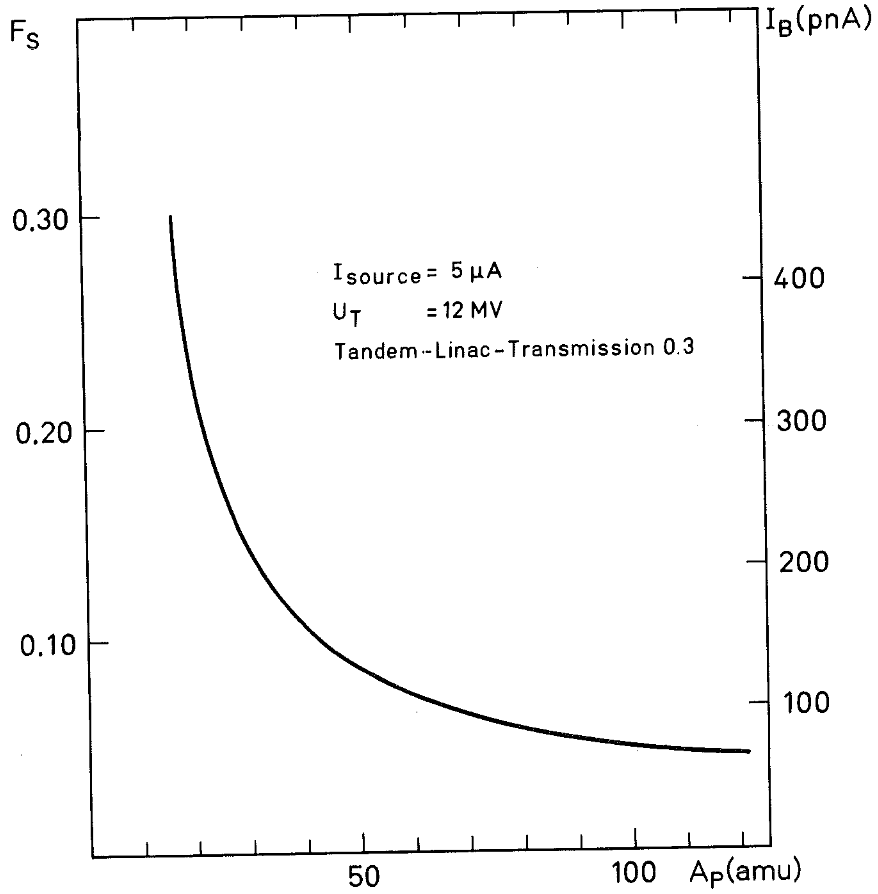


Fig. 3: Fraction F_s of the intensity transmitted by the MP tandem which can be injected into the booster after stripping twice. I_B is the current available when choosing the most frequent charge state in the two strippers.

This paper describes in chapters 4 and 5 in more detail a minimum version of a booster with an accelerating voltage of 9 - 10 MV. This, after all, opens up a range of masses up to approx. A_p = 40 (e.g., ^{40}Ca is brought to 6 MeV/N with 10 MV at full intensity). As the system is modular, extrapolation of parameters and expenditures can easily be made for a larger accelerator.

Since a considerable part of the heavy ion experiments are coincidence experiments, it is important that the acceleration voltage be available as a continuous voltage (cw).

Since the voltage offered by the booster should be efficiently useful over a broad range of masses at different charge states and also with different terminal voltages of the MP tandem accelerator, a flexible acceleration structure is necessary. This flexibility can only be achieved by short resonators, whose effective acceleration voltage only weakly depends on particle velocities. For adaption to the particle velocity the rf phases of the different resonators must be independently set which at the same time would also allow the final energy to be varied continously.

The second main criterion to be met by the booster refers to the beam quality: The combined tandem-linac accelerator system must largely preserve the excellent beam quality of the MP tandem machine with a radial emittance E_r 5 mm mrad and an energy monochromaticity W/W $2x10^{-4}$. These are the main aspects for deciding on focusing in the booster (see Chapter 4.2) and on the amplitude and phase stability requirements for the individual resonators (see Chapter 3.1.2).

3. Preparatory Experiments

In order to generate reliable basic information for the design of a superconducting booster meeting the criteria outlined in Chapter 2.2 a short booster section was built and tested with the heavy ion beam of the MP tandem accelerator. This test section consisted of a cryostat with beam tube connections, two niobium helical resonators, two rf supply and control systems, and the respective cryogenic and vacuum systems [20].

The component development and the contributing experiments are outlined in Chapter 3.1 below, while beam experiments are described in Chapter 3.2. A summary of the most important operating experience is offered in Chapter 3.3.

3.1 The Superconducting Booster Test Section

3.1.1 Resonators

Choice of Resonator Parameters

Initial planning was based on the positive experience accumulated at IEKP on short superconducting helical resonators made of niobium. During the construction phase of the test section other designs of superconducting structures (e.g., split rings) with higher acceleration capabilities for heavy ions were proposed[21, 22]. Because of the necessary development period, however these structures were no longer considered for the test section.

In the parameter studies of short helical structures $\lambda/2$ resonators with resonance frequencies of 54 and 108 MHz were studied alternatively, with the following criteria being taken into account:

1. The resonator frequency was to be a multiple of the fundamental frequency (6.78 MHz) of the pulsing system installed in the MP tandem accelerator.

2. A chain of identical resonators was to accelerate ions of mass numbers between A = 12 and 80 with, if possible uniformly high voltage gain.

3. For optimization it was requested that the number of identical resonators needed to accelerate $^{79}Br^{26+}$ from an injection energy of 1.77 MeV/N to an final energy of 6 MeV/N should be a minimum.

4. Modulation of the resonance frequency by vibrations should be minimized.

5. In order to avoid influences of electrons on the resonator properties, a peak electric field of E_{max} = 16 MV/m at the helix surface should not be exceeded in continuous operation.

6. The resonators should be manufactured as simply as possible.

7. The dimensions of the resonators should be as small as possible in order to facilitate handling during fabrication and, especially, during the subsequent preparation steps (see paragraph on surface treatment).

Criteria 2, 6, 7 and, in particular, 4 led to a decision in favor of the 108 MHz resonator, although the voltage gain of a 54 MHz resonator would have been approx. 1.5 times higher and would thus have meant a smaller number of units.

In order to determine the most favorable parameters, first of all a modified sheet model [23,24] was used to optimize the accelerating field E_{TW} relative to the peak electric surface field E_{max}. These calculations apply only to infinitely long helices, because end effects are not being taken into account. In order to consider the influence of end effects upon the axial field, resonator models were built in which the values derived from the modified sheet model served as basic parameters. The electric axial field was measured in these models by perturbation technique, and the transit time factor as a function of ion energy was derived from the result [25]. With these experimental values taken into account the helical parameters were modified stepwise in such a way that the number of resonators necessary to accelerate $^{79}Br^{26+}$ from 1.77 MeV/N to 6 Mev/N became a minimum.

Table I contains the parameters of a λ/2 helical resonator at 108.48 MHz optimized in this way. The diameter of the helical tube is 1.0 cm. The resonator has an overall length of 30 cm. At the design field the magnetic surface field attains a maximum of 62 mT. The design field is defined by a maximum electric surface field of E_{max} = 16 MV/m. The final number of windings was found by setting the resonance frequency.

Table I: Optimum parameters for a λ/2 helical resonator at 108.48 MHz for the acceleration of heavy ions

Helix diameter	64.8 mm
Pitch of helices	16.5 mm
Length of helices	136.2 mm
Resonator length (flange to flange)	296 mm
At design field level:	
Reactive power PQ	117×10^6 VA
Maximum accelerating voltage at optimum injection phase (β = 12%)	312 kV
frequency shift by radiation pressure	26 kHz

In order to prevent a peak of the electrical surface fields the diameter of the outer tank was selected to be 15 cm (2.3 x the diameter of the helix) and the distance between a helix and the end plate was chosen to be approximately equal to one radius of a helix. Fig. 4 is a schematic diagram of such a resonator.

The resonator is characterized by particularly small dimensions orthogonal to the beam axis and by its low volume. These characteristics have a positive influence on the fabrication of the resonators and the surface preparation and facilitate assembly and adjustment of the resonators in the cryostat.

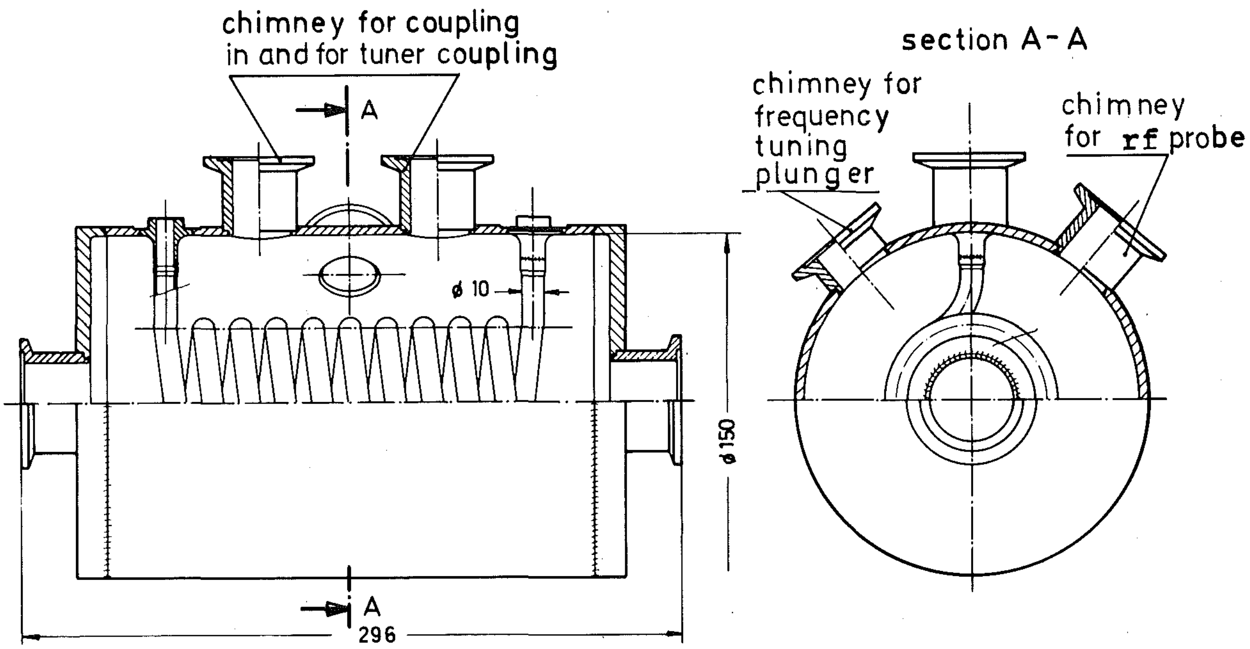


Fig. 4: Schematic of the $\lambda/2$ helical resonator

Fabrication of Test Resonators

A total of three $\lambda/2$ helical resonators of the same geometry (Fig. 4) were built[26]. Each of the helices was wound from a 10 x 1 mm Nb tube and welded into an outer tank rolled out of a Nb sheet. All welds were made by the TIG technique (inert gas welding). This allowed the fabrication costs to be greatly reduced relative to the electron beam welding technique applied previously. There is no integer number of windings of the helix; the desired resonance frequency was set instead by stepwise bending back of the helix supports and measuring the eigenfrequency in an external model tank. The remaining frequency error of less than ± 100 kHz could be corrected by a Nb plunger penetrating into the resonator. In order to accumulate experience for industrial series fabrication, one resonator was completely manufactured by W.C. Heraeus, Hanau [27]. IEKP was merely responsible for the surface treatment and for frequency adjustment. The measured results are comparable with those obtained from the resonators[26] fabricated in the laboratory workshops.

Surface Treatment and Conditioning

The surfaces of the helical resonators were prepared by the usual techniques: electropolishing, chemical polishing, oxy-polishing and baking in a high vacuum furnace. In the electropolishing and chemical polishing steps, films in the order of 100 µm are removed from the surfaces. Oxypolishing is carried out to remove a surface layer of only 0.1 µm Baking is performed in the high vacuum furnace at temperatures $T \sim 1150\ ^{o}C$ and a pressure $p < 10^{-6}$ Torr, each for a period of approx. 2 h. This removes stresses in the material and the hydrogen dissolved in niobium during the electropolishing process.

The following treatment steps are suggested for mass fabrication:

After winding the helix is stress annealed together with the winding mandril and subsequently bent into its final form. Afterwards, about 100 μm is electrolytically removed from the surface of the helix. Approx. 100 μm is also removed from the surfaces of the other parts of the resonator. Since these components are not exposed to high fields, the faster, but less exactly controlled procedure of chemical polishing is recommended for these steps. After welding the parts together, the resonator is electropolished another 50 to 60 μm and finally baked. Once a resonator has attained high rf fields, it is sufficient to oxypolish the resonator, if the rf properties deteriorate, perhaps as a result of surface contamination.

After termination of the surface preparation the resonators are rinsed in methanol and fitted together under dustfree conditions. Next, the system is evacuated and the beam openings on both sides are plugged. After insertion of the stack of resonators into the cryostat the plugs can be removed through locks under a vacuum so that further venting of the resonators is eliminated.

During commissioning, after surface preparation, the resonators are conditioned in order to overcome field limitations caused by electrons. The multipacting thresholds initially present at low field levels (E_{max} ~0.1 MV/m) will definitively disappear after a short period of operation. Limitations at high field levels (E_{max} > 10 MV/m) can be shifted towards higher field values by conditioning the resonators in a diluted helium atmosphere[26].

Also after contamination (see Chapter 3.3) this method of conditioning will result in an increase in the attainable field level. The time required for conditioning varies between a few minutes and several hours.

High Frequency Couplings

Each resonator contains three capacitive rf couplings. The rf input coupling and the coupling for the elctronic tuner consist of superconducting Nb pins cooled by a helium chamber each. It was not possible to optimize the heat streaming to the low temperature side, because the necessary parameters (such as dimension of the electronic frequency control (see Chapter 3.1.2) had not been determined right away. Fig. 5 shows one of the resonators used with the He cooling chambers assembled. The rf output probe is a normal conducting Cu pin.

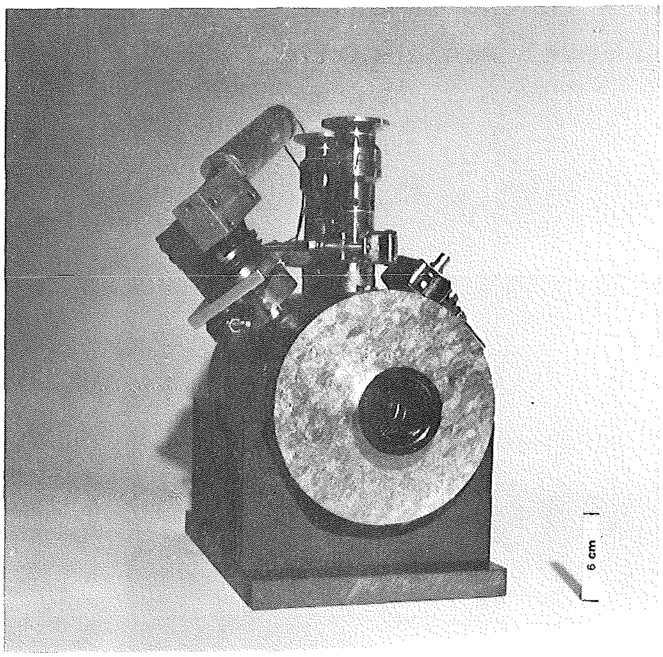


Fig. 5: Nb helical resonator assembled with two coupling line cooling chambers (top), the output coupling probe (right) and the frequency correction plunger drive (left)

Frequency Correction

Frequency tuning at helium temperatures is achieved by a movable superconducting Nb plunger penetrating into the resonator. The offset position of that plunger is used to balance out the influence of fabrication tolerances upon the resonance frequency. The tuning range of the plunger is sufficient, despite the frequency shift by radiation pressure of typically 30 kHz at design level, to permit synchonous operation of several resonators at different field levels. A Nb plunger (Fig. 6) moved by a gear motor, which is flanged onto the resonator by means of Nb membrane bellows, has been successfully tested in a separate experiment [2,28]. Together with a tuning offset of 50 kHz and a tuning range of 55 kHz no influence on the attainable field level was observed.

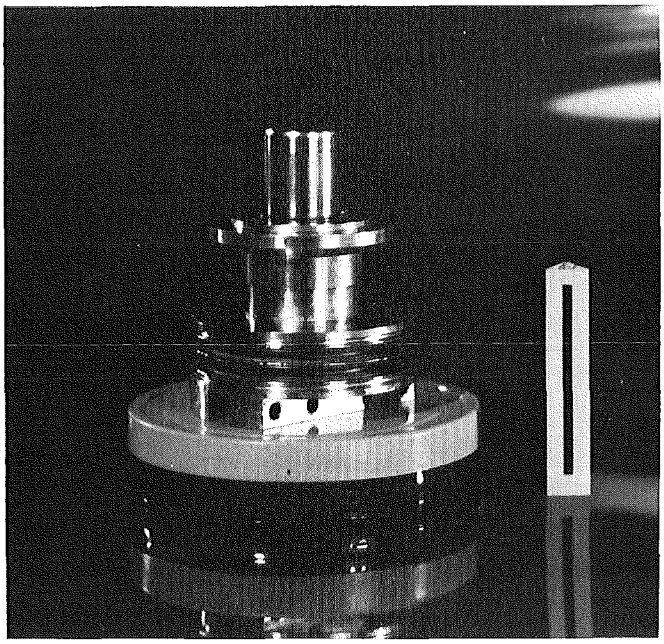


Fig. 6: Nb plunger for frequency correction with Nb membrane bellows

3.1.2 High Frequency Supply and Control Systems

According to the requirements to be met by phase and amplitude stabilities (Chapter 2.2), as opposed to the inherent frequency instability [31] of the resonators used, the rf systems necessary for each individual resonator must perform the following three functions:

a) Feeding the superconducting resonator with rf power at its resonance frequency.

b) Amplitude stabilization of the accelerating rf voltage.

c) Synchronization of the phase of the accelerating rf voltage.

Performing these functions separately has proved to work satisfactorily already in an earlier rf system [32] developed for the superconducting proton linear accelerator. Correspondingly, the rf system in the facility described in this paper is also arranged in the following three loops.(Fig. 7):

a) A self-excited rf feedback loop in which the frequency is determined by the resonator. This allows the extremely narrow band resonator to be fed despite the self-detuning caused by the field forces (radiation pressure).

b) An amplitude control loop limiting amplitude errors to <1%.

c) A phase control loop which uses a fast, electronically actuated tuning element [33] to balance out the frequency variations brought about by mechanical environmental influences (vibrations) in such a way, that a constant phase relation (synchronization) can be maintained relative to a common reference oscillator and, between the individual resonators [34]. In this case a phase deviation $<1^{\circ}$ is permissible.

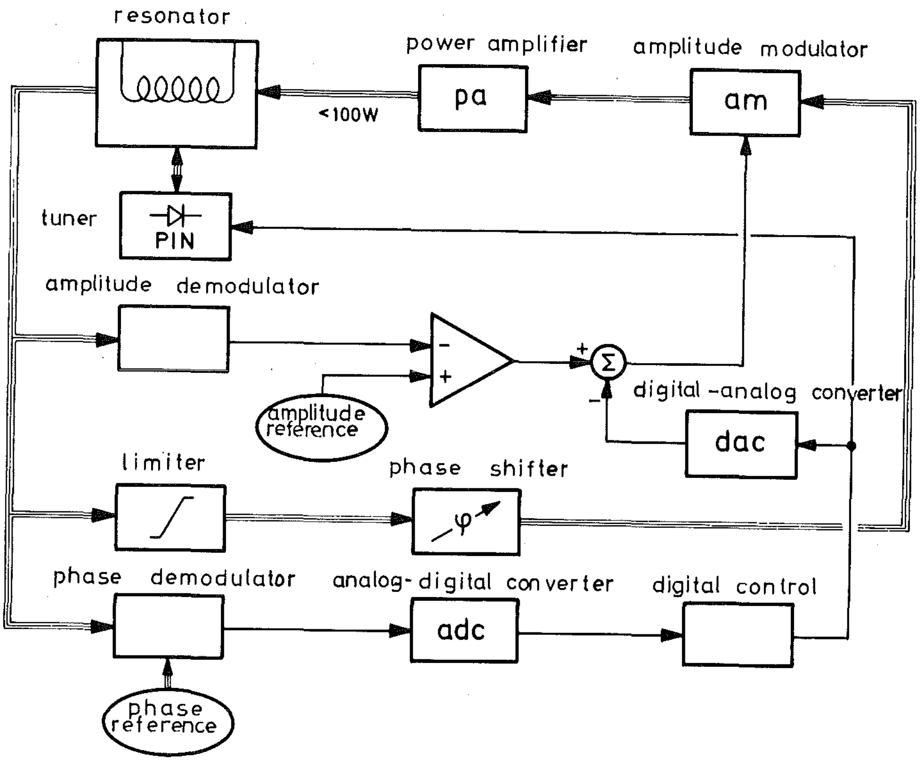


Fig. 7: High frequency control system

An additional forward control acting upon the amplitude control loop from the phase control loop allows a compensation of the ponderomotoric instability [31] of the superconducting helical resonator. In this way an attenuation of the excessive frequency oscillations caused by mechanical helical resonances can be achieved.

The test section was equiped with two rf systems designed in accordance with Fig. 7. The necessary rf power was supplied by wide band amplifiers with 100 W output power each. The rf system, whose control modules together with the frequency control element are shown in Fig. 8, consumpts a mains power of <1 kW.

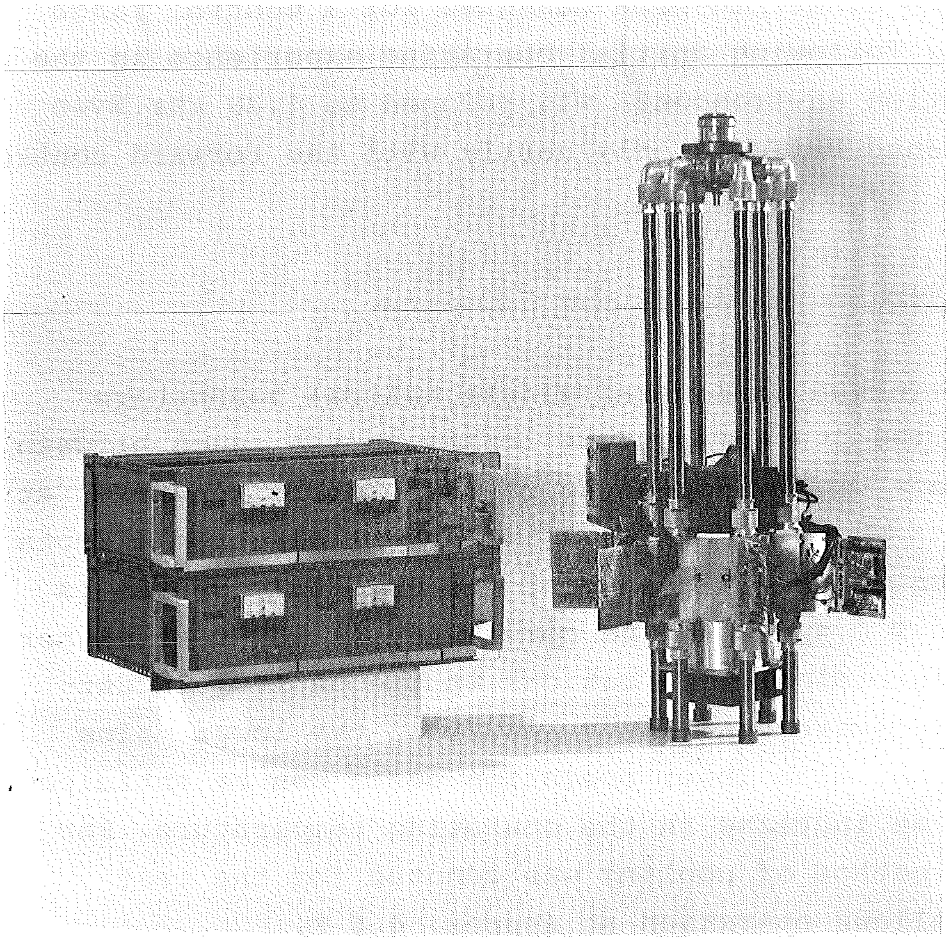


Fig. 8: Control electronics (left) and electronic tuner (right)

In order to facilitate the simultaneous operation of a number of accelerator resonators (see Chapter 4), automation of the manual control functions is necessary. The amplitude loop, in which a PIN diode modulator [35] acts as a control element, was included into the automation of the system by an automatic starting funtion, an automatic operation monitor and a digital amplitude reference input [36].

The phase control loop uses a variable reactance as a frequency control element, which can be switched in 6 steps by means of PIN diodes and which is arranged outside the cryostat[37].
Originally, this tuner had been designed for a control range of 2 kHz which, following initial operating experience in the final installation environment, was reduced to 1.36 kHz. Even this control range was used only partly with the forward control in effect.

3.1.3 Cryosystem

Experiments performed on several single helical resonators indicated that the low temperature losses in the range between 4.2 and 1.8 K are weakly dependent on temperature. Instead, at a field of >16 MV/m, temperature independent electron effects are dominant. Now, the efficiency of the cryogenic system is approximately $\sim T^{-1}$ and also its complexity is lower at higher temperatures; accordingly, reductions in the capital investment for the cryosystem and, as a result of the lower mains power consumption, also lower operating costs can be anticipated to result from an increase in the operating temperature. For this reason, a method of cooling was adopted for the test section which allows operation at approx. 4.4 K.

Resonator Cooling

The cooling of the resonators utilizes the evaporation enthalpy of liquid helium. This technique uses the heat transfer at high temperature constancy both in the cooling ducts (turbulent two-phase flow) and in the hlium bath of the cryostat (bath cooled by nucleate boiling). The heat flow densities from the helices to the coolant amount to only some 10^{-2} Wcm^{-2}, which is so low that also the wall-coolant temperature gradient is only a few hundredths of a degree K.

The helium-liquid-vapor mixture entering the cryostat is first passed through a heat exchanger for condensation of the vapor fraction and for flow quieting. Next the helium passes alternately through a helix, condenser, helix etc. and, in the test section, after leaving the second helix, is expanded to the pressure of the cryostat bath in an expansion valve (fig. 9). The flow through this valve is controlled by a helium level probe in such a way as to hold the helium level constant. The flow through the helices is therefore determined by the overall evaporation losses in the helium feed line, the helical resonators and in the cryostat. (A heat input of 1 W will evaporate about 1.4 L of He/h at approx. 4.4 K). A high liquid fraction within the helices is ensured by the fact that the heat input to the cryostat bath is higher than within the helices. The condensers connected in between resonators also ensure that the vapor generated in the helices is at least partly reliquefied. Condensation of the vapor in addition greatly reduces the pressure losses in the helical section[38]

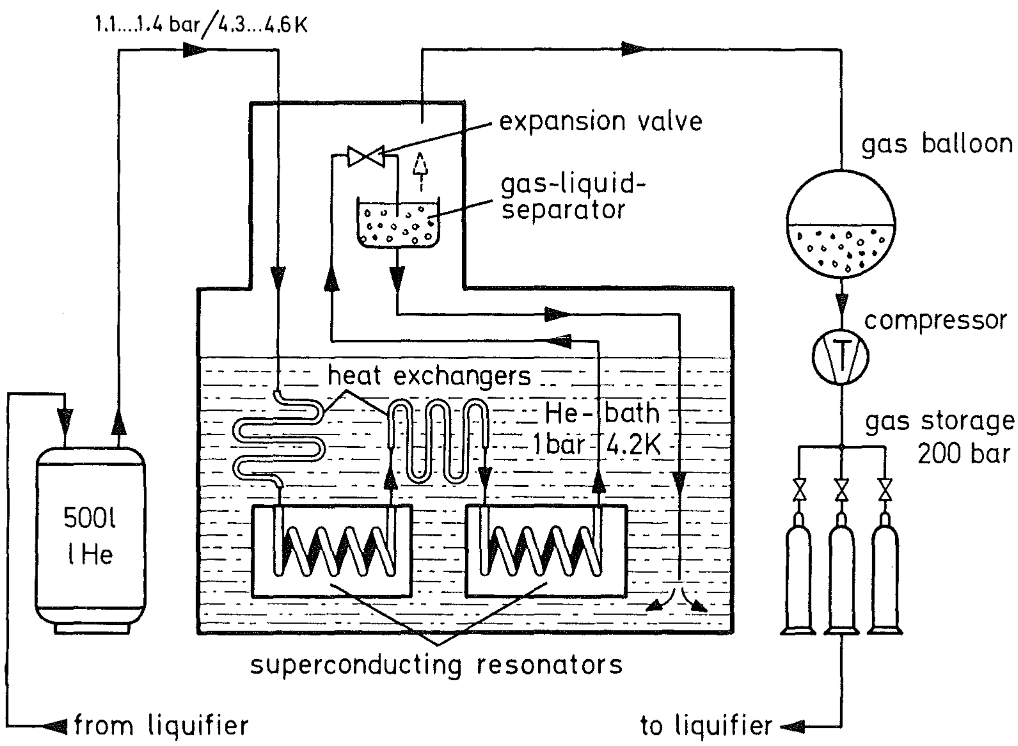


Fig. 9: Cooling circuit diagram in the test cryostat

Preliminary Experiments

The method of cooling outlined above was tested in a prototype cryostat (Fig. 10) with a resonator model and, subsequently, with an original resonator[22] . These investgations showed that stable operating conditions are attained even at high vapor contents, both with respect to flow and temperature stability and frequency stability of the resonators. The maximum temperature increase between the inlet and the outlet of a helix was only 0.2 K at 90% vapor fraction. Measurements performed with a microphone installed inside the gas room and a dynamic pressure transducer in the two-phase region did not indicate any oscillations in the helium cooling circuit at flows up to 4 g/s and feed pressures around 1 - 1.6 bar. No influence on the frequency of the helical resonators was found. These experiments demonstrated that superconducting accelerating sections of this type can be advantageously and reliably operated at approx. 4.4 K, i.e. with boiling He I or He I liquid-vapor mixtures at a slight overpressure relative to the atmosphere.

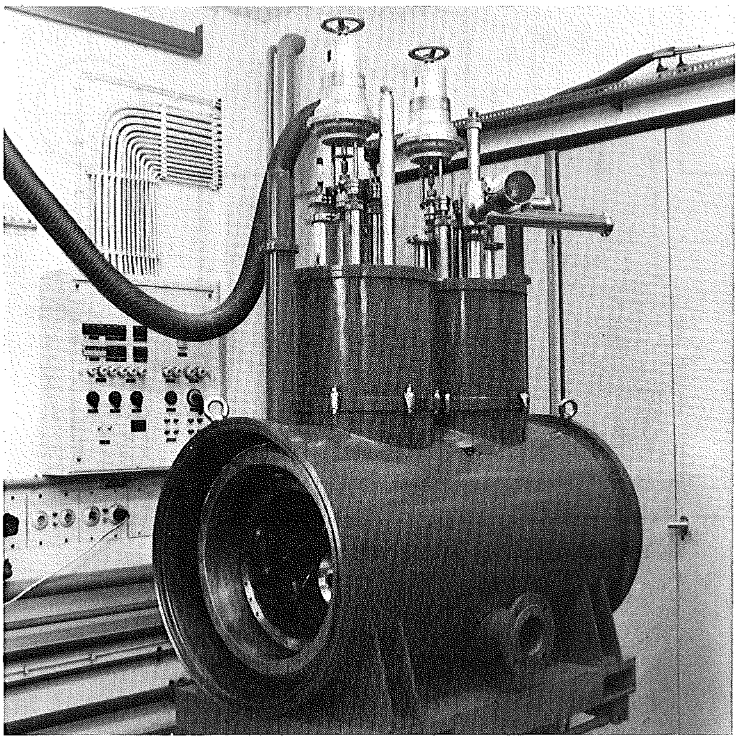


Fig. 10: Test cryostat with internals.

3.2 Beam Experiments in the Test Section

After completion of the test section at the IEKP it was transported to the MPI and operated there in a beam line of the MP tandem accelerator. The experiments covered the period between June 1976 and January 1977. In connection with the beam experiments extensive experience was to be accumulated with respect to the performance and reliability of this section of a superconducting booster which was representative in its main components.

3.2.1 Acceleration Experiments

In order to verify the accelerating voltages of the individual resonators calculated on the basis of perturbation measurements, sulfur ions of different charge states and with different injection energies were accelerated through the test section[22]. The energy increment at particle velocities in the range between approx. 6 and 10% of the light velocity corresponded to the calculations as represented for a resonator in Fig. 11. This also directly confirms the relatively broad velocity acceptance of the helices in a beam experiment. Acceleration both of a continuous and a pulsed beam showed no indications of any repercussions of the beam upon the two resonators operated in the synchronous phase mode at design field.

3.2.2 Irradiation Experiments

No information had previously been available about the effects of high energy heavy ions hiting the surface of rf superconductors. Merely radiation damage in DC superconductors had been studied in sufficient detail, e.g., in its effects upon the critical temperature. In rf superconductors modifications were expected in the metal-oxide boundary which could lead to additional rf losses or to a change in the electron emission properties. In order to bridge this information gap, two irradiation experiments were carried out[39,2] :

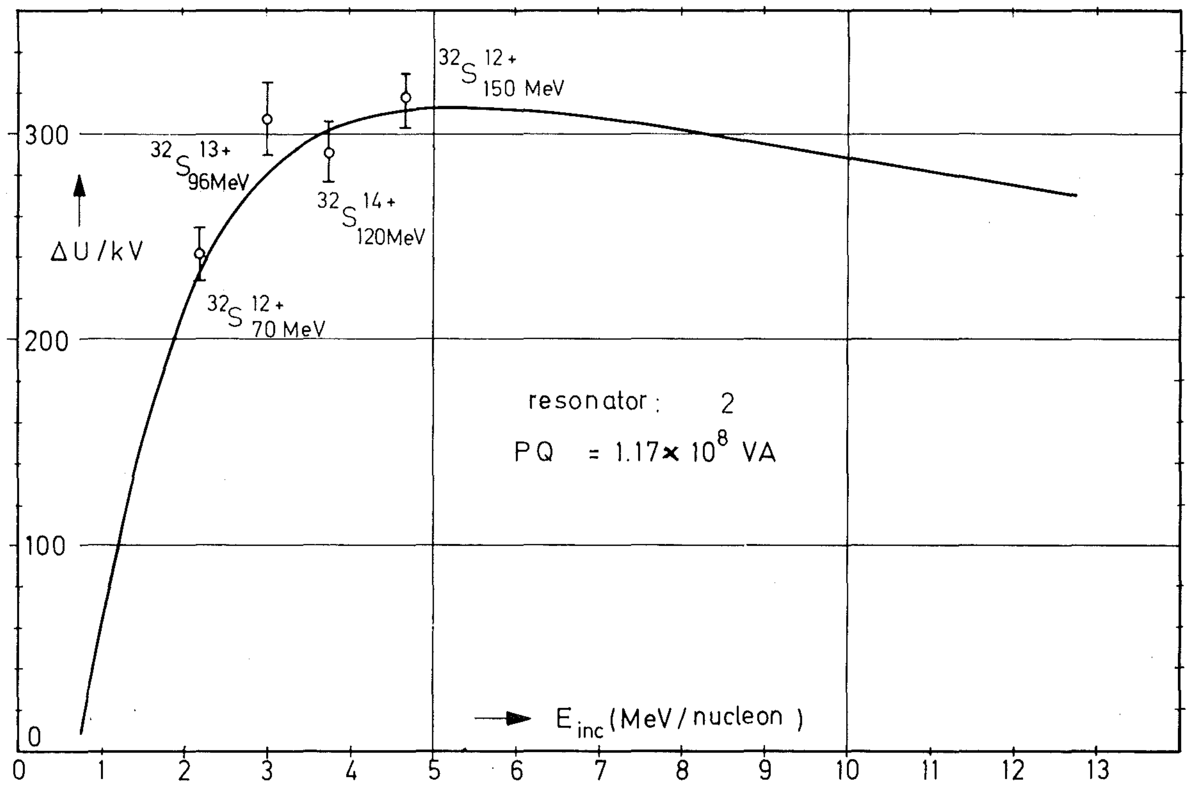


Fig. 11: Maximum potential difference of a resonator as a function of the injection energy. ⫯ measured points. The solid curve was calculated from perturbation measurements

a) A resonator was irradiated in situ at a working temperature of 4.4 K. For this purpose, a 100 MeV $^{20+}$Ni-beam of 1 pnA was deflected at the input end of the cryostat and scattered over an area of approx. 12 cm^2 of the inner side of the helix. On the basis of measurements of the temperature rises at the end of the helix both the beam power absorbed by the helix and the radiation induced changes in rf losses were estimated. After a total dose of 1.4 x 10^{14} ions changes were observed neither in the superconduction losses nor in electron emission.

b) In order to achieve more defined irradiation conditions along with a higher dosis and better measurement resolution when observing superconduction properties, resonator 3 in another experiment was exposed to a 99 MeV ^{68}Ni beam at room temperature. The superconduction properties were studied in subsequent measurements in a laboratory setup. Even after irradiation with a total of 2.6 x 10^{15} ions distributed over an area of 12 cm^2 (i.e., 2,2 x 10^{14} ions/cm^2) the change in resonator losses was within the limits of measuring uncertainties. At the same time, no negative effect on the maximum field level after irradiation was observed.

The expected total of any particle irradiation as a result of scattering from diaphragms or residual gases, which also can only reach the inside of the helices, is far below the dose applied in these studies even in long-term operation of an accelerator with a adequate choice of diaphragm apertures.

3.3 Operating Experience

In order to explain the amount of practical experience underlying the draft of a superconducting booster design outlined in Chapter 4 below, first of all the most important operating experiences with the test section will be summarized which have been obtained over 1000 hours of cryo-operation at 4.4 K, including 500 h of high field operation, 200 h of synchronous operation of both resonators at the design field, and 40 h of beam acceleration time.

Resonators

a) The three test resonators attained a surface electric field of 20 to 30 MV/m after completion of the surface treatment outlined in Chapter 3.1.1, like four earlier $\lambda/2$ helical resonators manufactured at IEKP [30,40] and accordingly exceeded by far the design level of 16 MV/m. The attainable field levels were limited by electron emission.

b) Continuous operation over up to 300 h at design field did not deteriorate the resonator performance.

c) It was possible to verify experimentally the expected acceleration properties of the resonators (ΔU = 312 kV per resonator).

d) The rf losses in the resonators were typically 0.7 watts, but always < 1 W.

e) Frequent temperature cycling between 4.4 K and 300 K did not impair the superconducting properties.

f) Irradiation of a surface region with a multiple of the dose to be expected in accelerator operation over many years did not lead to any measurable damaging effect.

g) Bad vacuum conditions or breakdowns of the vacuum in the room temperature part of the beam tube increased the electron emission rate especially of the resonator in the immediate vicinity, thus reducing the maximum field level, but even in the worst case 80 % of the nominal field strength could still be attained.

h) Simple wet chemical treatment (oxipolishing) ensures that the initial condition of the superconducting surfaces remains reproducible even after major contamination.

While the experience outlined under a) - f) above fully met our expections, the way in which the maximum field level of the resonators were affected by vacuum breakdowns in the adjoining beam vacuum system at room temperature constituted the only major defect in operation, which will be commented upon for this reason:

1. In the laboratory experiments, these and similar resonators were frequently vented, which did not affect the maximum field level in any way.

2. Venting experiments using purified gases were performed on laboratory resonators [40], but did not result in any irreversible changes in the superconducting properties.

3. During assembly the resonators were sealed by valves or plugs. In that time the pressure rose to values $> 10^{-6}$ bar. No influence was found upon the maximum field level attainable after conditioning (Chapter 3.1.1).

4. Damage was caused exclusively by leaks and pump failures, respectively, in the adjoining room temperature beam vacuum system.

5. The ultimate pressure of the two turbomolecular pumps of 2×10^{-9} and 10^{-9} bar respectively, was barely sufficient.

6. One contaminated resonator was completely regenerated by flushing with methanol.

From these observations it must be concluded that the contaminations were caused by dust or oil vapor In the limited experimental period it was not possible to exchange the vacuum system. For the superconducting booster design care was taken to ensure fast separation of the beam vacuum in case of a failure in the room temperature part of the system (Chapter 4.4.1)

Rf System

a) The triple control system with the additional amplitude forward control was stable in operation. Mechanical excitations were sufficiently attenuated, even blow of a hammer against the cryostat did not upset synchronization.

b) Short-term variations of the resonator fields remained below $\pm$ 0.2 % in amplitude and below $\pm$ 0.45° in phase.

c) The long-term variations observed were due to a temperature dependence of the demodulators used.

d) The control range of the electronic tuners of 1.36 kHz was only partly used at a typical frequency deviation of 200 - 500 Hz peak-to-peak.

e) The output power of the rf amplifiers of 100 watts was sufficient up to 10% above the design field level even if the tuner reaches the edges of the frequency control range.

f) Automatic starting and monitoring of the rf control system functioned reliably together with a digitally controlled amplitude reference.

Cryosystem

a) The losses in the prototype cryostat, amounted to 4 W in continuous operation at a constant helium level without rf applied and 8 W when operating both resonators at design field.

b) A mutual thermal feedback of the two heated helices was not found even after a breakdown of the rf field in a resonator in which a heat pulse of approx. 0.15 Ws is generated.

c) The pressure drop over the entire section including the transfer line amounted to $<$50 mbar. At this differential pressure the necessary flow could still be achieved.

d) Pressure instabilities which could have led to a detectable modulation of the resonator eigenfrequency were not observed.

4. Engineering Concept of a Superconducting Helix Booster

As a result of the weak dependency of the transit time factor on the injection energy per nucleon the helical resonator tested in the test section can be used over the entire length of a booster without any change in geometry. The final energy of 6 MeV/N required in the study for a mass number of approx. 80 leads to the need for at least 48 resonators with an effective accelerating voltage of 13 MV. However, the draft outlined below is limited to a booster with 32 resonators and an accelerating voltage of 9.4 MV, which is the minimum solution capable of future extension. Further reduction of the number of resonators would not be adequate because of the fundamental expenditure involved in terms of superconducting technology. An optimum length of the cryostats, as a compromise between cryolosses and ease of handling, is found by combining eight resonators with two focusing elements (Chapter 4.2) in the same cryostat. The attainable final energies for ions in the range of masses of interest, $A_p \angle 80$ amu, for boosters with 4 and 6 of those cryostat modules, respectively, corresponding to the 32 and 48 resonators, respectively, is indicated in a comparison with the final energy of the MP tandem accelerator and the Coulomb **barriers** in Fig. 12.

The booster concept is based on series production of the resonators and the respective rf systems tested in the experiments mentioned above. A factor of special importance is the reliability of the vacuum system (Chapter 4.4), which is to prevent damage to superconducting surfaces. The cryostats with the transfer line (Chapter 4.5) and the cryogenic system (Chapter 4.6) were redesigned in the light of the dimensions of the overall system.

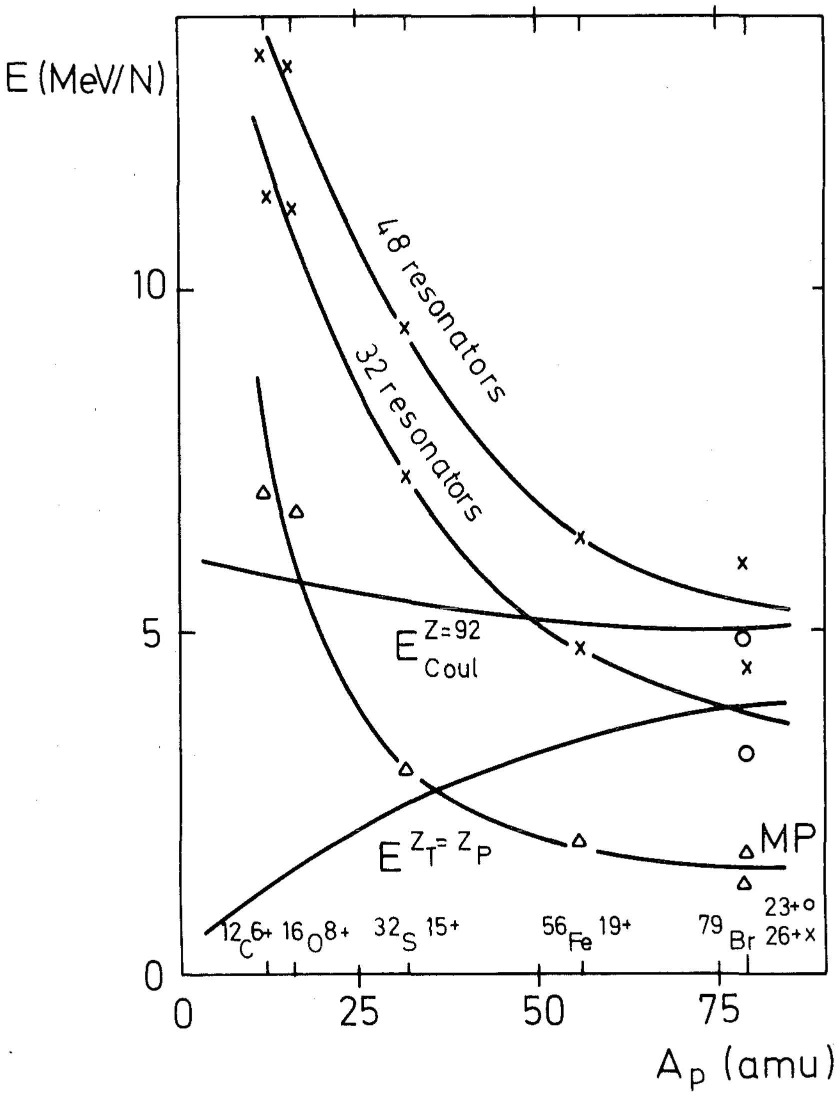


Fig. 12: Final energies of the superconducting booster with 32 and 48 resonators, respectively, compared with the injection energies from the MP tandem accelerator and the Coulomb barriers as function of ion masses.

4.1 Resonators

Now that it has been possible to manufacture the two test resonators at IEKP and the third one commercially by means of an inexpensive welding technique and without any problems, and surface preparation has turned out to be reproducible, no difficulties are expected to occur in series fabrication of these resonators. The resonator design proper can be used without any modifications; merely the rf coupling lines should be simplified.

4.2 Focusing and Beam Dynamics

Magnetic quadrupoles and solenoids can be used for focusing in a superconducting booster. The simplest possibility would be to use conventional normalconducting quadrupoles.However, this solution has the disadvantage for a superconducting helical booster that the cryostat would frequently have to be interrupted by room temperature sections. Moreover, positioning (to an accuracy of ± 0.1 mm) must be carried out through the aperture of the accelerator under complete venting conditions, which means that verification and correction of the setting after startup would entail problems. The use of superconducting quadrupoles is expensive, because of the relatively complicated coils, and leads to major drawbacks in adjustment. For this reason, the use of superconducting solenoids is the most adequate solution, if the necessary field strengths are sufficiently low to ensure safe operation.

The refraction capability of a solenoid is given by

$$f_{solo}^{-1} = \frac{\bar{B}_z^2 \, l_{solo}}{(2\, p_o)^2} \, e^2 \, \zeta^2 \tag{1}$$

where $\bar{B}_z$ is the field strength of the solenoid averaged along the axis, l_{solo} the effective length of B_z, p_o the nominal pulse, and ζ the charge state of the ions to be accelerated. The solenoid serves to focus the beam of a finite emittance ε and for compensation of the defocusing of the beam during acceleration. Defocusing by a helix obeys the following relation:

$$\delta = r'/r = - \frac{\pi}{2} \frac{\zeta e E_o T}{W_o \beta_o \lambda} \, l_W \sin\phi_s \tag{2}$$

where E_o is the maximum axial field strenth, T the transit time factor, W_o the kinetic energy, $\beta_o = v_o/c$ the relative velocity, l_W the effective helical length, and ϕ_s the synchronous phase.

Studies of the application of solenoids in superconducting heavy ion accelerators [41, 42] resulted in values for $B_z^2\ l_{solo}$ between 1 and 6 T^2m for beam rigidities of the order occurring for a booster connected to a tandem. These values correspond to field strenths between 2 T and 6 T in an effective solenoid length of 15 cm. Since these calculations correspond to estimates of extreme values ($\cos\mu = +1$ and -1) and do not present any precise information about the acceptance, calculations have been performed in a strictly periodical approximation [43] for a symmetrical cell consisting of four helices and one solenoid.

Fig. 13 shows the results for $\cos\mu$ and the acceptance as a function of the field strength B_{solo}. Agreeement with the estimates in [41, 42] is good. The acceptance of approx. 7 cm mrad at 5 T is completely sufficient.

The technical implementation of a solenoid has also been studied theoretically in [41] and experimentally in [42]. This in particular offers a possibility of shielding the magnetic field to less than 0.16×10^{-4} T at a distance of 10 cm. This value is far below the critical field strength, which means that safe operation of superconducting high frequency resonators close to the solenoids is possible.

The next important question refers to the beam dynamics and the beam quality of a superconducting helical booster. Without requiring detailed calculation, information on this point can be gained from calculations for a booster with spiral resonators [44]. Since the field distributions on the axis of

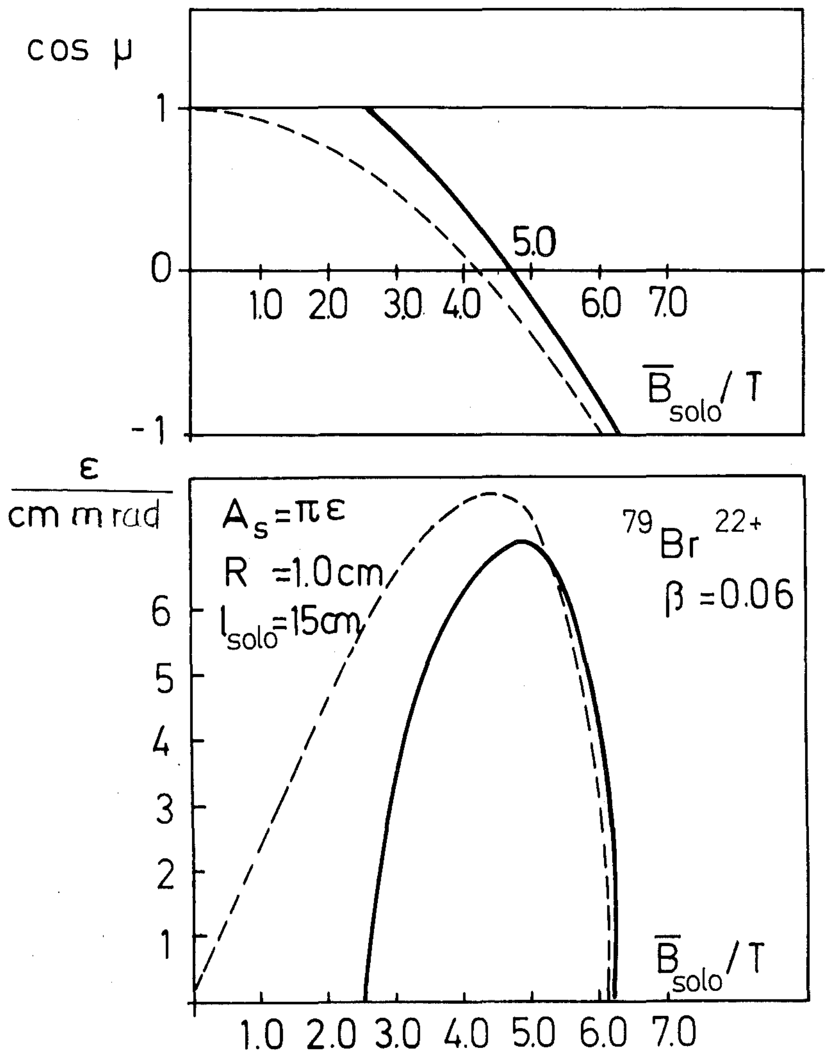


Fig. 13: cos μ and the acceptance $\varepsilon = r\,r'$ in the case of solenoid focusing as a function of the field strength $\bar{B}_{solo}$, calculated for a symmetrical cell in periodical approximation with a radius of aperture of 1 cm and an effective solenoid length of 15 cm. The dashed curve was calculated with $\delta = 0$ (without defocusing by acceleration), the solid curve with $\delta = 1.59$ mrad/cm (143 MeV, Br^{22+}, $\beta = 0.06$).

$\lambda/2$ helices and spiral resonators and, hence, the behavior of the transit time factor are similar, the results can be extrapolated to the case of longitudinal emittance. This also applies to the radial emittance, because coupling between longitudinal and radial phase spaces can be neglected, as a result of the high injection velocity downstream of the tandem, and the strictly periodical approximation it is sufficient to calculate the acceptance.

The typical longitudinal emittance downstream of a pulsing system of $\varepsilon_1 = \Delta W \Delta\phi = 3.5^{\circ}$ MeV is accelerated without distortions (the shape of the envelope remains elliptical) and enlargement, respectively, if the beam is bunched to $|\Delta\phi| \leq 7^{\circ} \hat{=} \pm 200$ ps. The limits for the phase stabilities of the individual helices in these cases were assumed to be $\pm 1^{\circ}$ and for the nominal phase $\phi_s = -20^{\circ}$. Also the maximum radial emittance of $\varepsilon_r = r\ r' = 0.8$ cm mr is accelerated without distortions. Quadrupole focusing calculations [45] carried out on a superconducting quadrupole doublet for 4 and 5 helical resonators, respectively, arrive at comparable results.

In summary it can be stated that a superconducting helical booster for heavy ions can be implemented with solenoid focusing and would retain the good beam characteristics of the tandem beam.

4.3 RadioFrequency Systems

The control system for rf supply and stabilization of the resonators has turned out to be reliable during operation of the test section. The simultaneous operation of a multitude of these systems is greatly facilitated by the automatic startup and monitoring of each individual system. Flexibility of the booster is ensured by computer control of the amplitude and phase references.

An interface for the digital amplitude input is available. A digital phase reference system presently under development at IEKP can be integrated.

For series fabrication the temperature dependence of the amplitude demodulator should be reduced by means of a thermostat and the control range of the electronic tuner should be narrowed down to 1 kHz, as a result of which the avaiable rf power is sufficient to exceed the design field level in the resonator by 30 %. In addition, a cost saving simplification of the electronic tuner is possible as a result of the reduction in the frequency control range.

4.4 Vacuum Systems

Beam Vacuum

In order to protect the superconducting surfaces from contamination, not only extreme cleanliness must be observed in the whole beam vacuum compartment (absence of dust and oil), but special requirements must be imposed also with respect to a failsave beam vacuum. This is being taken into account in the following concept of the beam vacuum system:

Pump sets for the beam vacuum may be turbomolecular pumps with a pumping speed of 70 $l\ s^{-1}$, which are installed at the end of the accelerator and in the intermediate spaces of the cryostats. In case of failure (overheating, power failure) each pump is separated on the intake side by a pressure controlled valve. If the pressure were to rise to values $> 10^{-9}$ bar as a result of pump failure or leakage, those pressure controlled valves among the valves installed in the beampath at all inputs and outputs of the cryostats will close which are closest to the alarming sensor. In addition, each pressure rise will cause the valves at both ends of the accelerator to be closed. In order to avoid damage due to breakdowns of the vacuum in the extended beam tube system of the experimental area or the tandem, fast acting valves are installed at both ends of the accelerator which are initiated by pairs of pressure sensors installed upstream at specific distances. Fig. 14 is a schematic representation of the layout of the beam vacuum systems.

Insulating Vacuum

The insulating vacuum is generated for each cryostat by a separate high vacuum turbomolecular pump of 250 l s^{-1} pumping speed. It is known from experience, that sufficient insulation of the cryostats is provided if a pressure $<10^{-8}$ bar is attained at the intake ports.

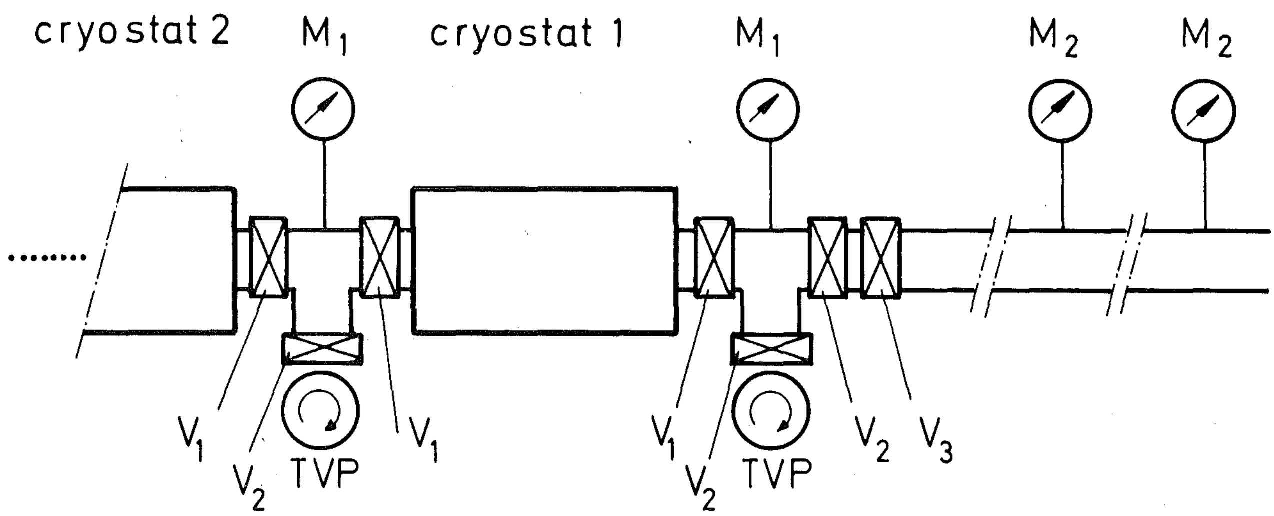


Fig. 14: Beam vacuum system.

V_1, V_2: Pressure controlled valve.
V_3: Fast acting valve.
M_1: Pressure sensor, controls adjacent valves V_1.
M_2: Pressure sensor, controls V_3.

4.5 Cryostats and Helium Transfer Lines

The cooling concept for the booster is based on the application of a method of cooling proven in the test section (Chapter 3.1.3).

Cooling of Resonators

In accordance with the layout of the test section the eight resonators contained in a cryostat will be fed in series. In this way, the whole mass flow is put through, with the advantage of improved heat transfer and without any problems of uniform distribution, which would exist if several units were connected parallel, and a high cooling reserve is created for excess heat flux densities. Calculations of the pressure drops[38] show that in the most disadvantageous case pressure drops of <200 mbar can be expected at a flow rate of 2 gs^{-1}.

Cooling of rf Coupling Lines

Cooling the rf coaxial lines does not offer any problems, because of the low rf current; the design must be optimized together with the detailed design of the cryostats. In making assumptions about the cooling capacity, it was assumed that all the heat generated in these lines (<1 W per resonator) flows into the helium bath. Methods to further reduce the heat input at 4 K have been proven and can be taken into account in the design.

Requirements to be Met by Cryostats

The cryostats in which the acceleration structures are to be cooled must be very effectively insulated against heat, must be extremely leaktight also after many temperature cycles and, in case of defects of structural or cryostat components, must be easily accessible for disassembly and assembly purposes. The criteria of high reliability, the possibility of quick repair of defects together with low operating costs and low capital costs are contradictory and admit a number of design possibilities.

Cryostat Concept

The concept proposed in this study has been designed primarily to offer high availability of the acceleration section. It is based on a breakdown of the acceleration section into four equal subunits (cryostats with eight identical helical sections each which, if necessary, can be cooled down or warmed up and assembled or disassembled independently, while the other three cryostats are operated with the refrigerator undisturbed. This leads to the following advantages:

- Errors can be detected and removed more easily by the arrangement of the system in this way. This reduces potential downtimes.

- While one defect is being repaired, operation of the other cryostats can be continued. There is no need for unnecessary warming up and cooling down of the whole accelerator. This helps to save operating costs and avoids stresses upon the material caused by frequent temperature cycling.

- A cryostat may be replaced by a beam tube with normal conducting focusing elements, which allows 75% of the performance of the accelerator to be kept available.

The specification that each cryostat must be capable also of independent operation not only demands a subdivision of the cryostat system (beam vacuum, 4 K helium compartment, 80 K helium compartment, insulating vacuum), but also one external line system each for the 4 K and 80 K loops with the respective connecting lines to the cryostats and with thermally insulated valve units for low-loss separation of a defective cryostat from the rest of the cold system. Moreover, additional connections and facilities are needed for separately cooling down and warming up the cryostats.

The cryostat components require a large number of feed-throughs from the helium compartment to room temperature level. In order to be able to assemble these feed-through there are lateral hatches in the individual shells of the cryostat extending over the entire length. The cold seal fo the hatch in the helium tank requires extrapolation of the experience available at IEKP.

The details of the schematic design of the cryostat can be seen from fig. 15 and 16. Each acceleration section consists of 8 helical resonators approx. 300 mm long, 2 superconducting solenoids of the same length, 1 inlet heat exchanger and 7 condensers. The helium tank is suspendid on tensile bars with low heat conduction which may be equipped with adjusting mechanisms to align the structure in the beam. The domes accommodate the rf coupling lines, the expansion valve and electric measuring cables. Feed and removal of the helium will be from the side of the transfer line system extending parallel to the cryostat chain, through an additional dome in which also the two-way valve is located. The entire helium tank is surrounded by a superinsulated cold shield maintained at 80 to 100 K temperature by means of helium gas. The use of the cold shield reduces to at least 1/6 the heat to which the helium tank is exposed both through the insulation and the stainless steel connections between the outer tank and the inner tank. In order to be able to keep the superconducting structures and the cold flanges at temperatures < 100 K over prolonged downtimes another cooling coil, which can be cooled by LN_2, will be installed (" stand by cooling"). This cooling system avoids increasing operating cost and material stresses caused by repeated warming up to room temperature.

Concept of the Helium Transfer Lines

The system of transfer lines connects the cold box of the refrigerator with the cryostats by means of one 4 K and one 80 K main line each and the corresponding bypass lines. The length of the main lines is approx. 10 m each, that of the connecting line to the cold box is approx. 16 m.

Legend

1 Cold box, superinsulated
2 Low temperature heat exchanger
3 Expander
4 J - T expansion valve
5 4 K feed and return line
6 80 K feed and return line
7 Compressor of the refrigerator
8 Gas cooler
9 Suction and pressure buffer
10 Pressurized helium storage vessel
11 Gas balloon
12 Storage compressor
13 Warm gas from cryostats
14 Thermally insulating shutoff devices
15 Two-way valve for cooling down
16 Heat exchangers (recondensers)
17 Gas separators
18 LHe level control
19 Helium bath, 4.4 K, 1.2 bar
20 Safety valve
21 LHe tank
22 80 K cold shield
23 Vacuum tank of cryostat
24 Focusing solenoid
25 Helical resonator

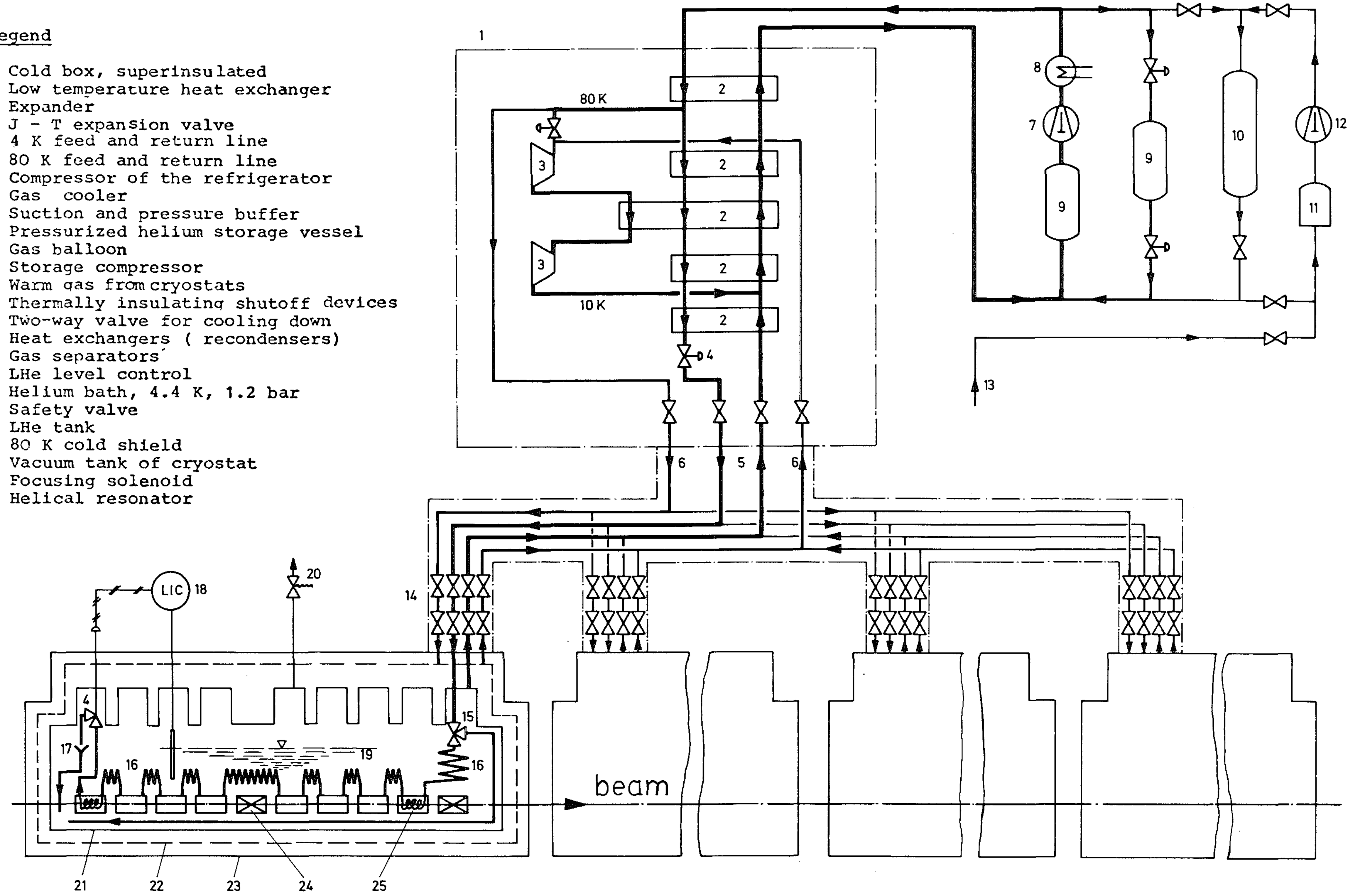


Fig. 15: Cryogenic flowsheet of booster system with helium refrigerator and cryostats.

All four lines (feed and return lines of the 4 K and 80 K loops could be arranged in parallel in one common vacuum tube, and the heat input to which the 4 K lines are exposed could be reduced by the introduction of a 80 K coldshield. The interconnecting lines should be equiped with thermally insulating, tight shutoff devices. For instance, two conventional cold valves could be evacuated if a cryostat had to be separated from the rest of the system.

Cooling down of the Circuit

When cooling down the whole circuit with the four cryostats connected in parallel by proper actuation of the two-way valve, the helium gas is first passed through the helium tank rinsing the resonators and the superconducting solenoids from below ("spray nozzle"). This makes for faster and more uniform cooling of the "large masses", the helices in the resonators cooling with some delay. In this way, impurities in the beam vacuum will condense on the beam tubes and the wall of the resonator, but not on the helical surfaces exposed to high field strengths. The uniform mass flow distribution to the cryostats is brought about by temperature monitoring of the tank and the structure and by proper setting of the valves. Subsequently the cryostats are filled each with approx. 200 l of helium one after the other.

Cooling the system from room temperature to operating conditions will take about two days. This process may be accelerated, e.g. by the following measures:

- liquid nitrogen path within the cold box
- additional expansion machine
- addition of stored liquid helium.

Warming up and Cooling down of a Cryostat

Separate warming up of each individual cryostat is possible after evaporation of the liquid helium by means of a heater and a blower attached to the cryostat. Couling down could be achieved by precooling with LN_2 to 80 K and, subsequently, by feeding lHe from a separate transport vessel. Switching over to the refrigerator circuit is practicable as soon as a low liquid level is reached inside the helium tank.

Table II: Main data, cryostats

Cryostats:	Number	4
	Type	He I bath cryostat
	Operating temperature	4.4 K
	lHe content	approx. 200 l
	Resonator cooling	two-phase He I, approx. $2 gs^{-1}$
	Outer diameter	800 mm max.
	Outer length	3800 mm
	Height of beam tube	1750 mm
	Height of dome cover	approx. 2350 mm
	Cryostat losses	$\leq$ 12 W
	Heat input by internals	< 18 W

4.6 Refrigerator

Cooling Capacity

Table III is a compilation of the cooling capacity expected.

Table III:

Basic cryostat losses	12 W/cryostat	48 W
Resonator losses including rf lines	16 W/cryostat	64 W
Focusing elements	2 W/cryostat	8 W
Transfer line system with valves		50 W
Reserve capacity for control and safety		30 W
Total cooling capacity		200 W

A more accurate calculation of the cooling capacity can be made only after the detailed designs of cryostats and transfer line systems have been completed. The true cooling capacity may therefore deviate from this information by approx. ± 10%. The additional cooling capacity at the level of 80 K for cold shields of cryostats and transfer lines is approx. 500 W.

Schedule of Operation of the Refrigerator

The capacity requirements can be met by proven standard systems manufactured by various companies. These systems consist of the three main components, i.e. helium compressor, cold box and control console. They operate by the following principle (fig. 15): The helium gas compressed in the compressor is cooled to operating temperature within the vacuum insulated cold box. For this purpose a large portion of helium gas, following precooling in countercurrent flow heat exchangers, is branched off for the precooling circuit proper and expanded in expansion machines almost isentropically to a level below the inversion temperature of helium (Claude process) while, at the same time, performing work. To the precooling circuit the heat is transferred by various heat exchangers in a countercurrent flow from the actual useful flow which is isenthalpically expanded in various steps (valves) below the inversion temperature and fed to the cryostats (Joule-Thomson process). The "low pressure" expansion to working temperature returnes to the compressor through the heat exchangers in a flow countercurrent to the medium pressure helium gas.

Design Alternatives

The helium refrigerator system presently in the market differ mainly in the type of precooling and the type of machinery used (compressors, expansion machines). Plants with liquid nitrogen precooling (cascade principle) operate at a lower mains power consumption and lower mass flow rate using piston expansion machines. For annual operation times in excess of some 2000 h these plants are competitive only if an additional cryogenic system is used (cryogenerator according to the Philips-Stirling method), as far as operating costs are concerned. This additional system requires more capital costs and additional mains power. More modern systems use expansion turbines with gas bearings. These machines have practically no wear, are very reliable and require little maintenance. If two units are connected in series, they provide a cooling capacity both at approx. 80 K (1st stage) and approx. 10 K (2nd stage). The slightly lower efficiencies of turbines compared with piston expansion machines hardly matter in view of the generally higher availability.

Helium compressors are mostly multi-stage dry-type compressors for oil-free compression of the helium gas. No sufficient operating experience has as yet been available in the use of screw type compressors with oil separators attached. A comparison of the basic data for refrigerators with lN_2 precooling received in early 1977 (without cryogenerator, with two piston expansion machines, dry-type compressor with piston rings)and a refrigerator using only helium as a coolant (two expansion turbines connected in series with gas bearings, dry type compressor with labyrinth piston) boils down to the following statement (see also[47]): the "efficiencies" of these refrigerators (mains power consumption per Watt guaranteed at 4.4 K) vary, depending on the process employed and the manufacturer, between

0.5 and 0.6 kW/W,

and the capital cost for the installed plant, based on the guaranteed refrigeration capacity at 4.4 K, vary between

5 and 6 TDM/W.

A helium purification system is integrated in the cold box. For storage of the whole helium inventory (when the plant is warmed up to ambient temperature) the compressor of the refrigerator and, failing this, a smaller storage compressor with a gas balloon is used to feed the gas into a pressurized helium storage system with a capacity of 1000 standard m^3.

Modern design of refrigerators will be good for continuous operation over several 1000 h. The operating experience so far available has confirmed their reliability[48]. Major maintenance jobs can be carried out within the two weeks of annual downtime.

<u>Main Data</u>

The basic parameters for a refrigerator of the 200 - 250 W category are listed in Table IV.

Table IV: Parameters of the refrigerator

Cryogenic capacity in refrigeration mode at 4.4 K	200 - 250 W
Liquefaction capacity (alternative)	50 - 60 l/h
Cryogenic capacity at 80 K	approx. 500 W
Power consumption	100 ÷ 170 kW
Refrigeration by use of	2 piston expansion machines + precooling with lN_2 or 2 expansion turbines
Compressor - mass flow rate - final pressure	approx 500 1000 std.m^3/h approx. 12 - 30 bar
Cooling down time of the refrigerator	2 - 4 h

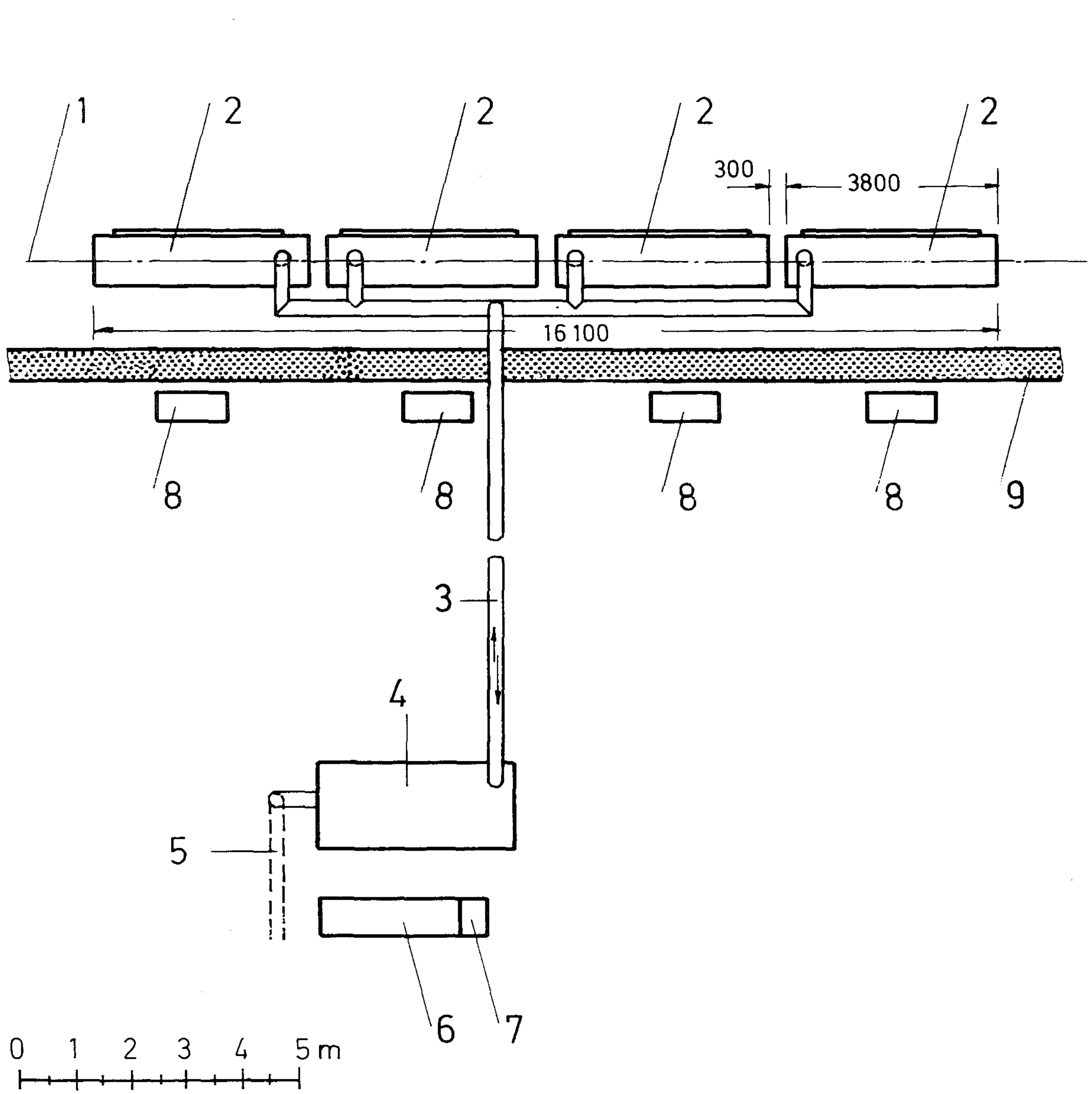
4.7 Implementation

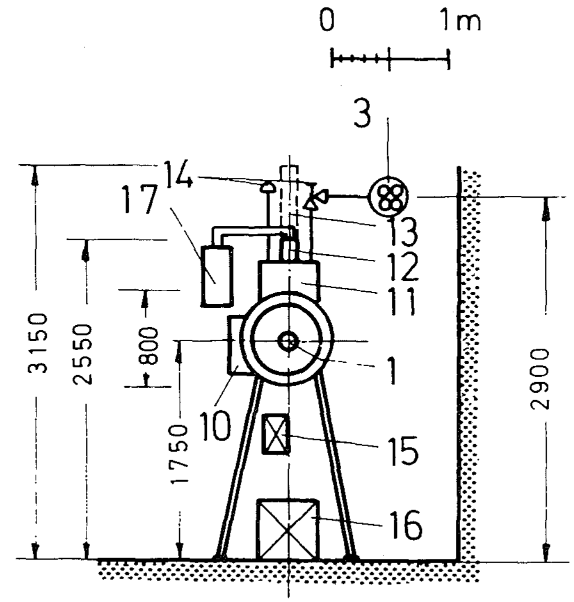
In order to demonstrate the space requirement of a superconducting booster with 32 helical resonators the major boundary conditions are listed below which are pertinent to the installation of the linear accelerator and the necessary supply systems.

In this thinking it is assumed the linear accelerator will be set up in a closed radiation protection vault, while all supply facilities, which can be installed remote from the accelerator, are accessible outside the for maintenance and repair at any time. To avoid cryogenic losses it is necessary to place the cold box of the cryogenic system as close to the cryostats as possible in order to make for short cryolines, while the components connected with the cold box by warm lines can be installed also at greater distances. Vibrations caused by the compressors are supressed by erecting these machines on separate foundations outside the accelerator building.

The four cryostats with an overall length of approx. 16 m are installed in the beam axis downstream of the rebuncher and beam matching section close to the wall of the radiation protection vault so as to save a maximum of space (Fig. 16). The cryo-distribution line is run sideways above the cryostats, where also the valves and fittings are located. An inner height of the radiation protection vault of 3.15 m will be sufficient for assembly of the rf coupling lines at a beam axis height of 1.75 m. The resonators are easily accessible through the assembly openings in the sides of the cryostats. The pumps for the insulating vacuum and the beam vacuum are located underneath or between the cryostats.

The cold box contains the low temperatures heat exchangers, the expanders, the purifier and the valves. It is set up outside the vault in a space as close to the cryostat as possible together with the switchboards for the cryogenic





cross section of cryostat

Legend

1 Beam axis
2 Cryostats
3 Helium transfer lines
4 Cold box with expander and purifier
5 Warm connecting lines to the compressor building
6 Switchboard for cryogenic system
7 Control console for vacuum pumps
8 Rf control units
9 Radiation protection vault
10 Lateral opening
11 Dome
12 Rf coupling lines
13 Extension height for coupling lines
14 Cold valves
15 Rf amplifier
16 Vacuum pumps
17 Electronic tuner

Figure 16: Space requirement of a superconducting booster with 32 resonators

system and for the vacuum pump rigs so as to allow good accessibility, also for a crane.

An overall length of 16 m has been planned for the cryo-lines from the cold box to the distribution line of the cryostats. This length is still acceptable because of the use of an 80 K radiation shield.

Because of the separate foundations required for the compressors a compressor building dimensioned approx. 6 x 12x5 m^3 must be installed a suitable distance (e.g., 30 m) away from the cold box. It contains the refrigeration compressor, the helium storage compressor, the 15 m^3 gas vessel, the mains distribution and the compressor switchboards. Close to the building the pressure storage for 1000 Standard m^3 helium and the suction and pressure buffers for the cryogenic compressor are set up. The installations leading to the cold box for warm helium and electric supplies are run in a shaft. The distance between the cryostat and the compressors (approx. 45 m) counteracts the transmission of mechanical vibrations.

The rf control units combined for one cryostat each are installed behind the wall of the radiation protection vault. The rf power amplifiers are housed in the cryostat racks.

5. Expenditure in Construction and Operation

This section is to demonstrate the time and personnel requirement connected with the construction of a superconducting booster following the concept outlined in Chapter 4. The capital and operating cost are based on quotations submitted by industry and on experience obtained at IEKP in setting up and operating low temperature systems. The information is restricted to the booster. The measures necessary to fit the injecting MP tandem accelerator, the beam transport and matching system the computer control system for the overall facility, the beam diagnosis system and radiation protection measures are not taken into account in the costs quoted here.

Although the complete booster could be set up by industry, optimum costs could be achieved by having the institution interested in this construction participate as much as possible. In particular the design documents for the components should be supplemented by the staff of the institute. The future operating personnel of the accelerator should be called in already at the assembly stage.

5.1 Construction

Component Fabrication

(a) Cryogenic System

An industrial standard type refrigerator can be used.

(b) Line System

The pipeline system for 80 and 4.4 K helium should be manufactured by industry on the basis of planning documents.

(c) Cryostats

The containers should be manufactured by industry on the basis of fabrication drawings. Instrumentation and internals will be added on site.

(d) Superconducting Resonators

A bid has been received from a manufacturer about the fabrication of 50 resonators of the type described above. A series production specimen has furnished good results (Section 3.1). The contribution of the instute comprises surface treatment, testing of the properties and fitting the necessary additional components, such as frequency correction plungers and coupling pins and lines.

(e) Radio Frequency Supply and Control Units

Some components (power supply, amplifier,converter) are industrial standard products. The arrangement in circuits, fabrication of the housings, etc. can be carried out both at workshops of the institute and by smaller special companies. Testing and adjustment work will be the responsibility of personnel from the institute.

(f) Superconducting Solenoids

The superconducting solenoids of the type required will be manufactured by industry.

Time Schedule

The time schedule for the construction of the superconducting booster is shown in Fig. 17. After a planning phase of six months component fabrication will last well into the third year of construction. Whilst the cryogenic equipment determines the shortest possible time for implementation, fabrication of the resonators and rf control units has been extended accordingly in order to avoid excessive peak personnel requirements. Assembly and component tests are carried out in the third stepwise commissioning is performed in the fourth year of construction Under the most advantageous conditions of component fabrication and by employing additional personnel during the test and construction phases, the time schedule can be shortened so that commissioning of the accelerator is possible towards the end of the third year of construction.

Staffing

The employment of personnel of various qualifications during the period of construction is shown in Fig. 18. A distinction is made between project personnel (38 manyears) and non-project personnel (14.5 manyears). The latter category comprises

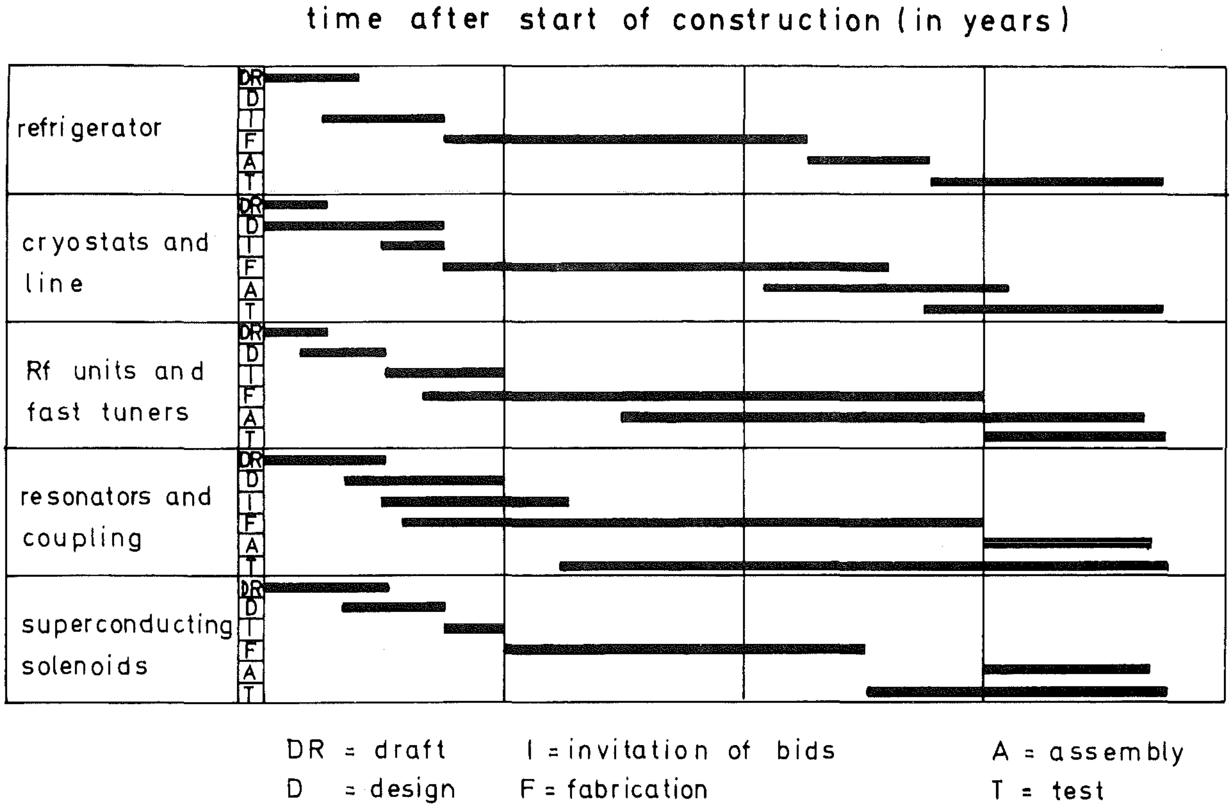


Fig. 17: Time schedule for construction of the superconducting booster

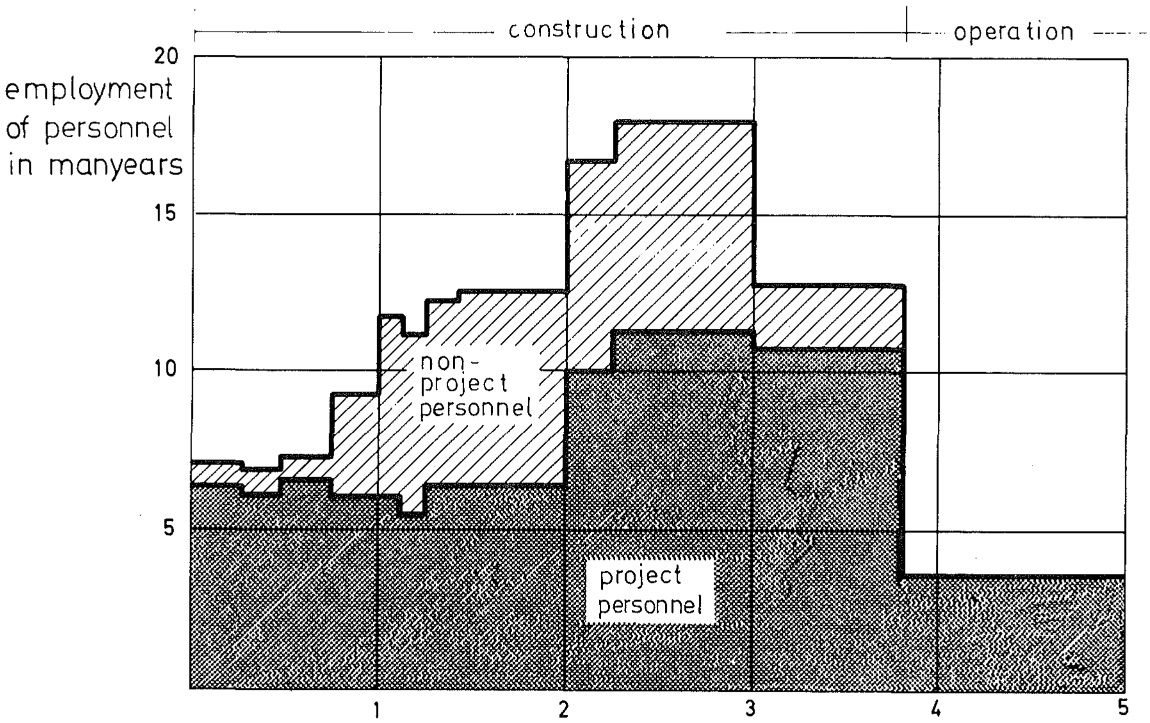


Fig. 18: Employment of personnel during construction and operation of the superconducting booster.

personnel in the workshop and outside personnel, respectively. The activities to be performed by personnel with special experience in the cryogenic field and in rf superconductivity are estimated to amount to 15 manyears and have been taken into account in the estimates.

During the period of operation the personnel requirement will decrease to 3.4 manyears/year (fig. 18)

5.2 Operation

An annual operating period of 3000 h is assumed, with one operating cycle taking at least four weeks. Downtimes of up to approx. 2 weeks are bridged by precooling of the accelerator by means of liquid nitrogen (see Chapter 4.5). During longer outages heating to room temperature is economically more favorable. During the cooling period of operation the cryogenic system must be monitored by an operator. This is not necessary in the steady-state mode of operation. Fault signals in the control room of the injector tandem, which is manned around the clock, and one operator standing by for emergency action are sufficient.

Some components of the accelerator, such as vacuum pumps, measuring systems, valves and parts of the cryogenic system need regular maintenance. This may be performed during operation and in an annual outage period of approx. 2 weeks. For the cryogenic system a maintenance contract should be signed with the supplier.

Minor repairs will be carried out by the operating crew of the accelerator. Major assembly work needs the support of trained personnel of the institute. Work on the cryogenic system will be monitored by personnel of the manufacturer (see operating costs).

Even in case of failure of an accelerator element operation of the accelerator can be continued. Correction of the phase relations of the other resonators may be necessary. Major breakdowns leading to failures of a whole section may be remedied by heating only the cryostat involved. If the repair of such failure takes more time, the section involved may be replaced by a beam tube with normalconducting focusing elements.

5.3 Capital Costs

The capital costs listed represent the state as of late 1976. The cost estimate quoted for the cryogenic system is based on a bid for a comparable system. The costs of cryostats and transfer lines are estimated in the light of experience accumulated at IEKP in the construction of various cryogenic systems. One bid has been submitted for the superconducting resonators. The prices of superconducting solenoids were obtained from ANL[49]. The costs of the rf supply and control units are partly based on list prices of the components used, partly on calculations made by extrapolating from the items available.

The capital investment per MV of accelerating voltage amounts to TDM 516 according to costs of 1/1977. This means that they are still below the levels projected in the study[1] composed in August 1973 [1] (538 TDM/MW, prices of 1973).

Capital Costs

A. Cryogenic System

Refrigerator (250 W at 4.5 K and 500 W at 80 K)	1300 TDM
Storage compressor and helium pressure storage	200 "
Purifier	50 "
Accessories, measuring equipment, automation	100 "
Subtotal A:	1650 TDM

B. Cryostats, Lines, Vacuum

Helium lines 80 K and 4.4 K	200 TDM
4 cryostats of 4 m each, 45 TDM/m	720 "
Racks	50 "
Measuring and control systems for cryostats	100 "
Vacuum pumps	200 "
Automatic valves, beam path	100 "
Subtotal B:	1370 TDM

C. Superconducting Components

32 resonators	288 TDM
Tuners, coupling lines, etc. matching the resonators	160 "
Completion of the systems for surface treatment and annealing	50 "
8 focusing elements (superconducting solenoids) including power supplies at 12.5 TDM each	100 "
Subtotal C:	598 TDM

D. RadioFrequency and Control Systems

32 rf supply and control units from rationalized fabrication at 20 TDM each	640 TDM
Central testing unit	50 "
Subtotal D:	690 TDM
Aggregate total:	4308 TDM

5.4 Operating Costs

In the list of operating costs outlined below an annual operation of the cryogenic system of 3000 h was assumed, which would be available about 80% for boosting purposes on the basis of an operating cycle of four weeks of continuous operation. Personnel costs and depreciation are not included. The costs of electricity and cooling water are estimated at the rates charged large customers in 1977. The maintenance costs for the refrigeration system are based on information from the manufacturers. The helium losses are values taken from experience in the long term operation of the cryogenic systems of IEKP[50]. The sum total of the operating costs of DM 59.90/h corresponds to the estimate in the study[1].

Booster Operating Costs (excluding depreciation, interest and personnel)

A. Consumption

a) Power Costs	
0.2 MW x 130 DM/MWh	26 DM/h
b) Cooling Water	
20 DM/MWh x 0.15 MW	3 DM/h
c) Instrument Air	
20 std.m^3/h x 0.06 DM/std.m^3	1.20 DM/h
d) Helium Gas Losses	
0.07 std.m^3/h x 15 DM/std.m^3	1 DM/h
Consumption Cost Total	31.20 DM/h

B. Maintenance and Repair, Other Working Stocks

a) Cryogenic Unit

Cryogenic unit maintenance contract	7 TDM/a
Spare parts, auxiliary materials for cryogenic unit	10 "
Special repair + general revision	15 "
	32 TDM/a

b) Other Components of the System

2%/a of the capital costs of 2.7 MDM	54 TDM/a

Maintenance Cost Total	86 TDM/a
which, at 3000 hours of operation per annum corresponds to	28.70 DM/h

Operation Cost Total (for 3000 h/a of operation of the cryogenic system)	59.90 DM/h

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