COMMISSIONING OF THE TRITRON

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Abstract

The TRITRON is the prototype of a separated orbit cyclotron with both magnets and rf-cavities superconducting. Recently it was demonstrated, that the principle works as anticipated. The 6 large cavities of the reentrant type for the acceleration of 20 parallel ion beams (170 MHz, PbSn on Cu, indirectly cooled, no separate vacuum) operate well above the design values (5 MV/m, Q_o>5 10^8).

Introduction

Cyclotrons are accelerators especially adequate for providing ion beams with high average intensity. In recent years an increasing demand for particle beams with average currents of more than 10 mA arose, for instance for the production of high neutron fluxes, for accelerator driven nuclear power plants, and for transmutation of nuclear waste (1).

The key to a high power / low loss cyclotron operation is a strongly increased accelerating voltage per turn, resulting in a turn separation of several cm instead of mm. There are three substantial reasons for this. First the longitudinal intensity limit in cyclotrons is proportional to the third power of the average voltage per turn. Second the extraction is facilitated in the region most critical for beam losses. Finally the large turn separation makes the use of independent magnetic channels with alternating gradients possible, resulting in both strong transverse and longitudinal focusing.

The required high accelerating voltages can be obtained with superconducting rf-cavities, because here the maximum voltage is limited by field emission, and not by cooling the dissipated heat as in conventional cavities. In view of the high acceleration voltages used the saving of dissipated rf-power is an additional advantage of superconductivity.

The total radial width of the magnetic channels is equal to the turn separation. A magnetic channel consists of a frame of steel with superconducting coils inside (window frame type magnet with bedstead type ends of the coils). Due to the high current density in the superconducting coils the width of the coils (3mm) is negligible compared to that of the steel frame and the window for the beam. Neighbouring channels can be combined to form a flat sector. By this the space is not occupied by big masses of steel, and the shape of the rf-cavities can be optimized. The stray field of the magnetic channels are of sufficiently short range, so that the rf-superconductivity of the cavities will not be influenced. The principle of this type of cyclotron was proposed already in 1963, though with non-superconducting elements at that time (2). However superconductivity is needed in order to realise this new concept.

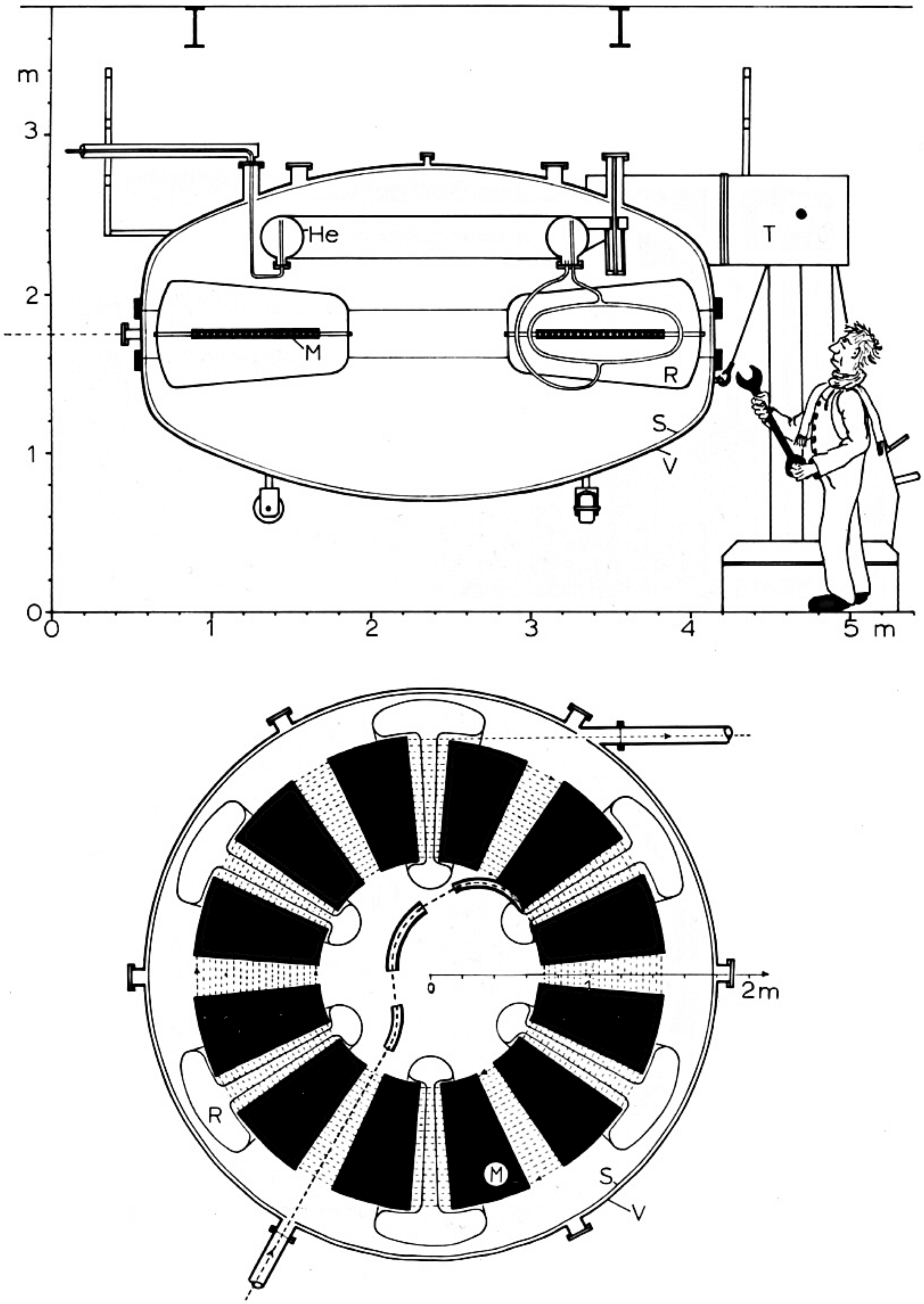

Figure 1. Cross sections of the TRITRON cryostat. V: vacuum vessel, S: 80 K-shield, M: magnet sector, R: rf-cavity, He: helium reservoir, T: support

The TRITRON

According to the preceding considerations a small prototype of a separated orbit cyclotron, the TRITRON, was designed at the Beschleunigerlaboratorium of the University of Munich and the Technical University of Munich (3,4). The purpose of this project was to study the beam dynamics of such a machine theoretically, to develop the technology, and to demonstrate the feasibility of the principle of this new type of cyclotron. It is a rather small machine with the existing MP-tandem as injector, thus not a high current prototype device.

Figure 1 shows cross sections of the TRITRON. The injection radius is 66 cm, the extraction radius 145 cm, the energy gain factor is about 5. Six sector-shaped rf-cavities (170 MHz) with 20 beam holes provide an acceleration voltage of 3 MV on the last turn. When the project was started it was unknown whether superconducting cavities of the type needed would operate at all. In order to keep the acceleration voltage low, the turn separation was chosen as small as possible (40 mm) resulting in an aperture of the magnetic channels of only 10 mm. Altogether 240 channel magnets with alternating gradients are arranged in 12 flat sectors, guiding the beam along 20 turns. Arrays of 20 small superconducting axial steerer magnets are positioned in three of the intermediate sectors. The radial and axial beam positions are measured by wire scanners installed in each second intermediate sector. The whole machine is hanging on a torus-like liquid helium reservoir under the upper half of the cryostat (diameter 3.6 m). The cavities and magnets are cooled indirectly by pipes connected to the torus. An additional pipe system for forced helium flow provides the cooling from 300 K to 4.5 K. The insulating vacuum of the cryostat is the same as for the beam, there is no separate vacuum chamber. Therefore the cavities are floated by normal laboratory air each time the cryostat has to be opened.

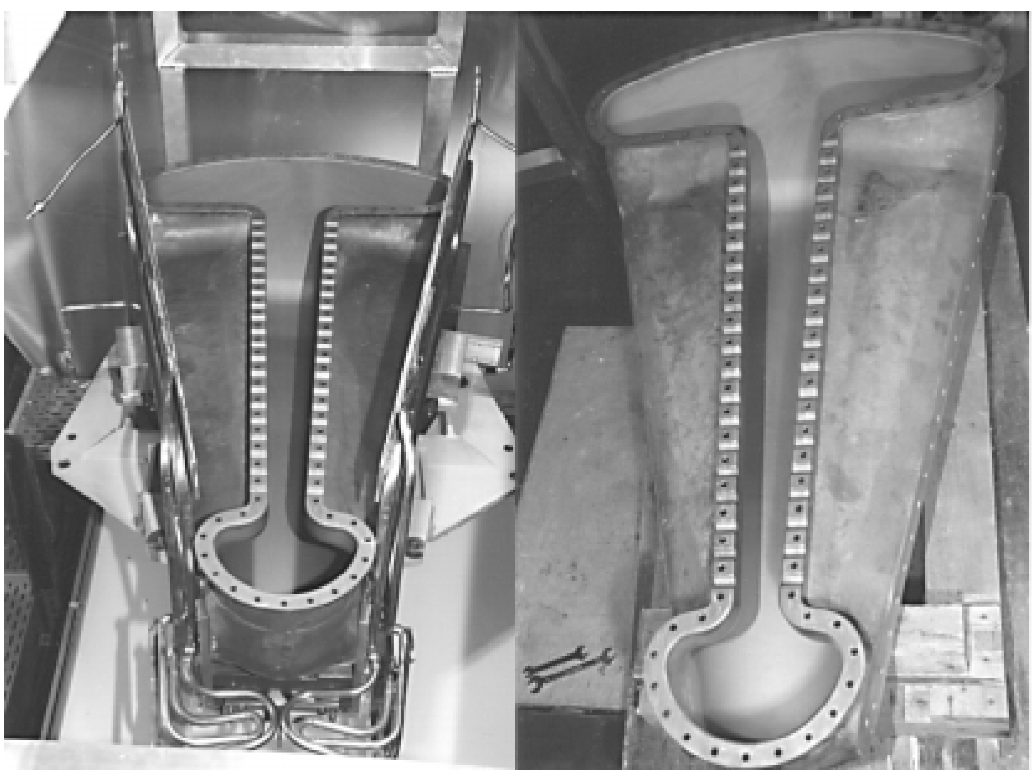

Figure 2. Two halves of a cavity, the left showing the O-shaped cooling pipes on both sides attached.

The cavities (see Figure 2) are described in detail elsewhere (5). They are produced by an electroforming technique from copper and then electroplated with a thin layer (<5 10^{-3} mm) of $Pb_{96}Sn_4$, which becomes superconducting below 7.5 K. Each cavity consists of two halves, connected in the plane of the particle orbits. No rf-currents should cross the flat joint in the fundamental mode. The total length of the cavity is 1.233 m. The gap width is 62 mm at the first orbit, and 128 mm at the last. The maximum E-field is at the 13th beam hole, the maximum voltage at 18th hole. The diameter of the beam holes is 13 mm. The ratio E_{peak}/E_{max} is less than 1.5.

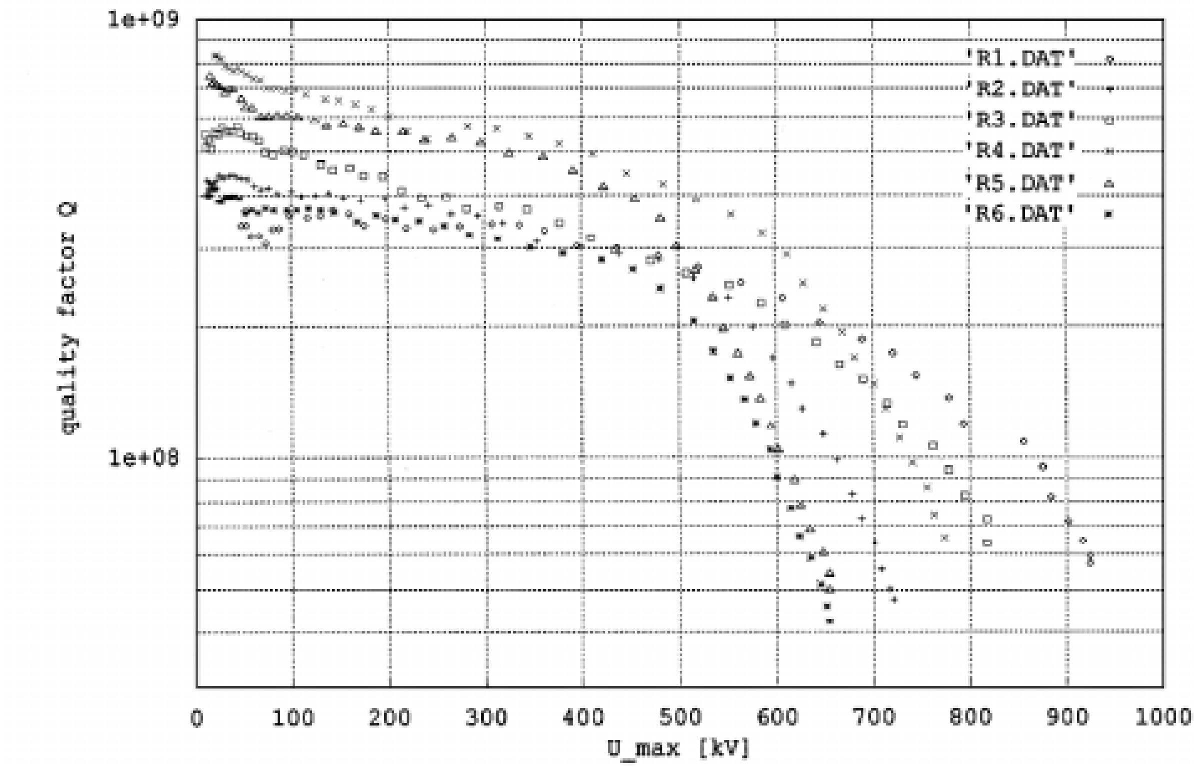

Figure 3. Quality factors of the six cavities versus the voltage amplitude at the last beam hole, with the antennas strongly coupled as under realistic beam conditions.

Though not being handled under special clean room conditions the quality of the cavities stayed constant during a period of several years after the original electroplating procedure. Typical curves of the quality factors versus the rf-voltage at the last beam hole are shown in Figure 3. The various curves were taken with the cavities loaded differently by coupler probes. At voltages of 500 kV the dissipated heat per cavity is about 5 W. In order to remove multipactoring at all levels the cavities have to be conditioned with rf-pulses each time they had been exposed to air. Coarse tuning is made by mechanical deformation, fine tuning by sapphire rods (slow) and piezoelectric actors (fast). An electronic control system provides for stability of phases (1^{o}) and amplitudes (10^{-3}). The reproducibility is of the same order. Actual phase and amplitude settings are made by observing the shift of the radial position of the beam half a betatron-oscillation downstream of the cavity.

The currents of the 240 magnetic channels have to be adjusted individually according to the respective momentum of the central particle of the bunch. This is accomplished by just one single power supply by bypassing the difference of the current of an individual channel and the main current in controllable superconducting switches across each coil. The fields are reproducibly correlated to the currents in the coils. There are neither leakage effects of the currents in the superconducting switches, nor hysterese effects of the steel, nor magnetization effects of the superconductor, nor cross talking effects from neighbouring channels observed ($dB/B<10^{-4}$). Once the optimum field settings for a certain injection energy is found on the first two turns e.g. (with the cavities switched off), it can be used for further runs without any variations. The beam will appear immediately at the end of the second turn again with good transmission, as soon as the proper injection energy has been chosen, even if the magnets had been warmed up in the meantime. This stable and reproducible tuning facilitates the beam funneling considerably.

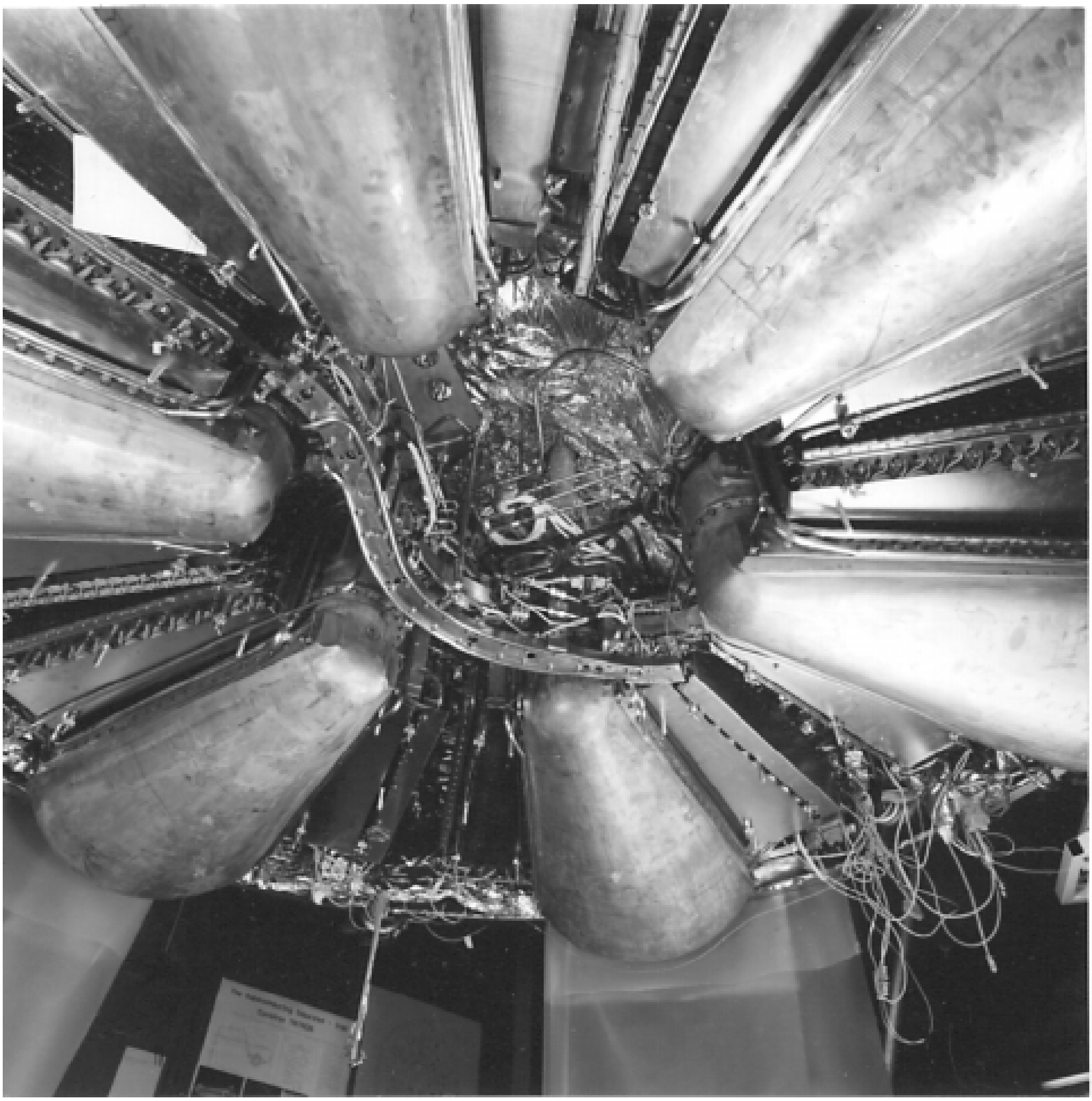

Figure 4. View from below into the TRITRON cryostat with the complete machine assembled.

Present Status

All components of the TRITRON were installed in the cryostat and have been ready for use for about one year (see Figure 4). The cryostat has been kept cooled at least below 80 K since January 1997, with only one warm up needed for minor maintenance work during one day. This demonstrates the high reliability of all components. Most of the test runs during summer 1997 were used to stabilise the injection phase (to 1^o) and momentum (to $3\ 10^{-4}$) of the beam from the tandem. Additional control systems had to be implemented into the existing ones. In July the adjustment of the phases and amplitudes of the cavities started, to make the beam enter the second turn at the second hole of the first cavity with a proper phase to guarantee continuous acceleration on the following turns. On September 12th all phases and amplitudes were adjusted in a proper manner to accelerate a sulfur beam, starting with an energy of 40.3 MeV. The beam was guided for the first time along 6 turns with continuously increasing energy. Though neither the phase space ellipses were matched to the acceptance ellipses nor the field settings of the magnets were optimized the beam passed through 75 channel magnets and had finally an energy of 72 MeV. The currents in the channels respectively the Br-values follow a straight line with small deviations. These deviations show two oscillations corresponding to two coherent synchrotron oscillations with the expected number 0.5 per turn. The observed betatron-oscillation numbers and momentum compaction factor were in agreement with theory as well.

Conclusions

The results of this first test run demonstrate that the principle of a separated orbit cyclotron works as anticipated. In the near future the beam dynamics will be studied in more detail, and the transmission will be improved by proper field settings. The experience of the last year proves a very stable, reproducible and reliable operation of all components. Based on the good results of the superconducting cavities future separated orbit cyclotrons can be planned with enlarged turn separation, say 10 cm, which would leave a geometrical aperture for the beam of about 5 cm. This would make the acceleration of high intensity beams with low losses possible.

This project was carried through completely within the frame provided by a university laboratory. Much of the development work was done by 24 students working for their Diplom, and five PHD students. The project was funded by the German Federal Minister of Research and Technology (BMFT) under the contract number 06 TM 189, and by the State of Bavaria.

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