THE SUPERCONDUCTING SEPARATED–ORBIT CYCLOTRON TRITRON

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The Tritron is the prototype of a superconducting separated–orbit cyclotron. It will increase the energy of the ions from the Munich MP–tandem by a factor of 5. The ion beam is guided by 241 superconducting channel magnets with alternating field gradients along a fixed spiral orbit with almost 20 turns (turn separation 40 mm). Radially neighboring channels are joined into 12 flat sectors. In each second of the 12 intermediate gaps a superconducting cavity (170 MHz, PbSn on copper) is inserted. In the remaining six intermediate gaps rows of beam position probes are installed. The assemblage of the whole system is completed. The commissioning of this new type of cyclotron is going on.

1 Introduction

There is an increasing demand for proton beams with currents of 10 mA, e.g. for accelerator driven spallation neutron sources[1]. Cyclotrons are accelerators especially adequate for particle beams with high average intensity. The development of cyclotrons for the greatest possible beam intensities is a challenge, which calls for a re–examination of the present designs. In view of the high beam power a basic demand on the design is to keep beam losses as small as possible. This requires strong focusing power and high accelerating voltages at injection and extraction.

Up to now all cyclotrons are dominated by the magnetic system. The height of the magnets always is large compared to that of the field volume really needed for bending and focusing. All magnetic flux is returned outside of the extraction radius with big yokes occupying valuable space. The rf–acceleration system and the injection / extraction elements are squeezed into narrow gaps, limiting the maximum accelerating voltages respectively the turn separation and thus the beam current at extraction. The condition of isochronism restricts the axial focusing power strongly. It excludes longitudinal focusing completely. As one consequence among others low harmonic numbers h of the rf–frequency with respect to the revolution frequency are preferable, causing the rf–cavities to have big extensions. Under those limiting conditions it is hard to optimize the rf–system without serious compromises concerning the accelerating voltage, the peak fields, and the dissipated energy.

To overcome the problems, F.M. Russell proposed already in 1963 the principle of the separated–orbit cyclotron (SOC)[2]. However to put this idea into action superconductivity was needed. In 1983 a superconducting SOC was proposed[3]. For this project big superconducting rf–cavities for acceleration of many parallel beams with high accelerating voltages had to be developed as well as superconducting channel magnets for bending and focusing. The Tritron is a rather small prototype of a superconducting SOC with almost 20 turns, which presently is coming into operation.

2 The principle of the SOC

In a SOC, the particles are guided by magnetic structures along a locally fixed spiral path with the given turn separation much bigger than the radial beam width. Each of the field levels and radial gradients of neighboring orbits can be chosen basically independently, incorporating strong transverse focusing by alternating gradients as in a synchrotron.

The bunches can be guided well centered along the design path by a proper field setting, based on informations from beam position probes. If the velocity v_0 of the bunch would increase in proportion to the mean orbit radius r_0 (by adequate accelerating voltages per turn), then the center of the bunch would move isochronously with constant revolution frequency f_{rev}, and the field values at the spiral orbit would vary according to the condition of isochronism as in the case of an isochronous cyclotron. However the fields for off–center particles generally will be non–isochronous due to the free choice of the radial gradients of the fields. The revolution frequency of off–center particles will vary. The relative variation is given by the variations of the velocity and of the radius r:

$$\frac{\Delta f_{rev}}{f_{rev}} = \frac{\Delta v}{v_0} + \frac{\Delta r}{r_0} \qquad (1)$$

The $\Delta v/v_0$ – term is dominating as long as $\beta = v_0/c$ does not approach 1 too near. Equation 1 leads to longitudinal oscillations of the off–center particles with respect to the central one as in the case of a synchrotron, if the slope of the accelerating voltage as function of the phase is positive. It is the local non–isochronism of the fields which causes the longitudinal focusing.

The adequate effective accelerating voltage per turn needed to keep the mean velocity in proportion to the mean orbit radius r_0 is given by

$$V = \frac{A\,m_0 c^2}{Q\,e} \cdot \beta^2 \cdot \gamma^3 \cdot \frac{\Delta r_0}{r_0} \qquad (2)$$

Here $A\,m_0$ is the mass and $Q\,e$ the charge of the ion, and Δr_0 is the increment of r_0 per turn, the mean turn separation. V is a given function of r_0 due to the fact, that the turn separation is fixed, unlike the situation in conventional cyclotrons. Because β is proportional to r_0 (at least on average), V has to increase also in proportion to r_0 (in non-relativistic approximation $\gamma = 1$). The amplitude of the accelerating voltage per turn V_0 has to exceed the voltage V somewhat, to stay with the phase sufficiently far from the maximum, where the slope is vanishing. Assuming this phase φ_0 to be constant, the amplitude V_0 will be a given function of r_0 as $V(r_0)$. Then, if the bunches are injected with a phase φ slightly different from φ_0, the whole bunches execute coherent synchrotron oscillations due to the longitudinal focusing, consisting in phase oscillations with respect to φ_0, in velocity oscillations with respect to v_0, and in radial oscillations of the bunch centers with respect to r_0. The radial variations Δr_{coh} can be suppressed by proper field corrections of course, so that merely phase–energy oscillations will remain. The suppression of Δr_{coh} makes possible that the phases of the centers of the bunches stay bound to the given phase φ_0 as long as they don't exceed the limiting phase, where $V(\varphi) = V_0$ and the slope of the voltage becomes zero. The incoherent synchrotron oscillation numbers of the off–center particles with respect to the bunch center are typically $Q_{inc} \approx 0.2$ per turn. The coherent synchrotron oscillation numbers are somewhat larger: $Q_{coh} \approx 0.3$ per turn, because of the vanishing $\Delta r / r_0$ – term in Equ. 1.

The coherent phase focusing works even if the given phase φ_0 is not a constant but a function of r_0, so that $V_0(r_0)$ needs not to be strictly proportional to $V(r_0)$. The only restriction on $V_0(r_0)$ is, that it should not contain strong harmonics of Q_{coh} to avoid resonance problems.

Due to the longitudinal focusing the harmonic numbers h can be rather high. From this the rf–frequency and thus the size of the cavity can be matched much better to the basic dimensions, the injection and extraction radius.

As a result it can be concluded, that the introduction of magnetic structures with individual field settings and gradients along a given spiral path offers strong focusing in both transverse and longitudinal directions, and that the involved large turn separation of the order of several cm disposes of the injection and extraction problems. For this accelerating voltages an order of magnitude larger than those in conventional cyclotrons are needed. Therefore the starting point of the whole design has to be the rf–system.

3 Superconductivity for SOCs

There are two classes of problems, which finally limit the maximum accelerating voltage attainable in rf–cavities: cooling problems and field emission of electrons.

The dissipated power in the walls increases as V_{max}^2 and may become too large, simply because of cooling problems. These problems can be overcome by using superconducting cavities. Rf–superconductivity imposes new conditions on the design, which can be met in general however.

1. The cavities must not be exposed to magnetic fields larger than $\approx 10^{-4}\ T$.

2. Particular geometries (as parallel walls and real spherical shapes) may cause severe resonant secondary electron emission (multipacting) at different rf–field levels, which may be difficult to overcome.

3. The quality factor of unloaded superconducting cavities is of the order of 10^9. Therefore the time constant of energy variations of the cavity system is extremely long ($\approx 10^{-1}$sec). It may become comparable to the period of the mechanical vibrations of the cavity, so that resonant exchange between the energy of the rf–field and the vibrations may occur. The cavity should be rigid. The supports should be placed at the nodes of the fundamental vibrational mode of the cavity. Tiny deformations of the cavity may cause the rf–frequency to be out of resonance. Variations of the forces acting on the cavity should be avoided. Sensitive tuning systems are needed.

4. The tuning range of the rf–frequency is rather limited due to the stiffness. Therefore superconducting cavities have to be operated at fixed frequency, and with a superconducting SOC only a certain number of fixed beam energies can be obtained corresponding to the range of harmonic numbers h. However due to the longitudinal focusing the range of h is rather big (typically $15 \ldots 55$), the relative distance of successive energy levels is small, and it can be reduced additionally by stimulating coherent energy oscillations[4].

5. The dissipated heat –though several orders of magnitude less than in conventional cavities– should be kept small, because it has to be cooled by a refrigerator with a cryogenic efficiency of the order of $\approx 2 \cdot 10^{-3}$. Therefore the cavity should

be designed with the volume of the electrical field as small as possible (restricting it mainly to the acceleration gap), and with the volume for the surrounding magnetic flux large, forming a big torus around the gap region.

If cooling problems can be excluded, then the maximum accelerating voltage is given by the effective electrical peak field at some place in the cavity and by the width of the accelerating gap.

The magnetic structures have to fit in the space left by the cavities. The most space-saving structures are superconducting channel magnets, consisting of narrow superconducting cable beams on the left and right of the particle beam within a cold rectangular channel of steel (window frame type). If the magnetization of the steel stays below saturation ($B \leq 1.9\ T$), the ampere-turns of the coils per mm height of the window is less than 1510 A/mm, corresponding to a cable width of 3 mm at an overall current density of $\approx 500\ A/mm$. The width of the cable beams is small compared to the total width of the channel, which corresponds to the turn separation Δr_0. The magnetic flux between the two cable beams in the window is returned immediately in the adjacent steel frame, so that voluminous yokes are avoided. The total width of the steel yoke is about the same as the width of the window. The range of the stray field is of the order of the height of the window. In a distance of a few cm in front of the ends of the channels the stray field can be made to stay below the critical limit for the superconducting cavities by means of mirror plates. The total height of the channel magnets needs not to be more than about three times the height of the window. Radially adjacent channel magnets can be combined to form extremely flat sectors. These sectors restrict the rf-cavities only marginally.

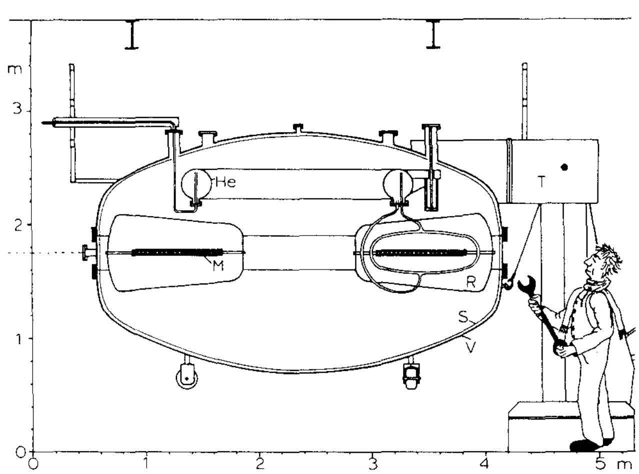

Figure 1: Cross section of the Tritron cryostat. V: vacuum vessel, S: 80K-shield, M: magnet sector, R: rf-cavity, He: helium reservoir, T: support.

4 The Tritron project

Based on the preceding considerations the Tritron was designed[5,6,7]. The main purpose of this project is to introduce the technology of superconducting cavities and channel magnets in cyclotron design and to demonstrate the feasibility of the separated orbit cyclotron. When the project was started it was unknown, if superconducting cavities of the type needed, would operate at all. In order to keep the accelerating voltage per turn low, the turn separation, respectively the width of the channel magnets were chosen as small as possible ($\Delta r_0 = 40\ mm$). Due to the resulting small aperture of the magnets ($d = 10\ mm$) the Tritron will not be suited to accelerate beams with high currents.

Fig.1 and 2 show cross sections of the Tritron. The ions are injected from a MP-tandem by three superconducting channel magnets at a radius of 66 cm and extracted after almost 20 turns at a radius of 145 cm. The energy gain factor will be ≈ 4.9, e.g. a $^{12}C^{6+}$ beam will have a maximum energy of 20 MeV/u, protons about 43 MeV. Each of the 12 magnet sectors consist of 20 or 19 channel magnets. Six sector-shaped rf-cavities, operating at 170 MHz provide for the accelerating voltage. The radial and axial beam positions are measured by wire scanners installed in each second intermediate sector. In addition, an array of 20 small superconducting axial steerer magnets is positioned in three of the intermediate sectors.

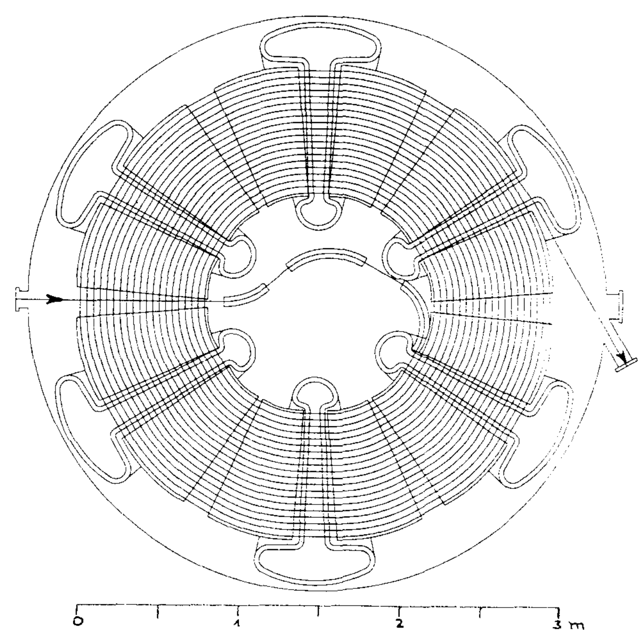

Figure 2: Horizontal cross section of the Tritron. The diameter of the vacuum vessel is 3.6 m.

Each magnet sector consists of two steel sheets, each 30 mm thick, with curved slots every 4 cm (see Fig. 3 to 5). All pieces from steel are Ni plated to avoid rust. The coils consist of 2 x 13 windings of a Rutherford–type cable, including a separate gradient winding in each half–coil. The half–coils were wound directly into the slots and then vacuum impregnated with epoxy in situ. A copper profile shields the coil from beam losses. Flat disc springs between the copper profile and the coil prevent the coil from cracking of from the steel[8].

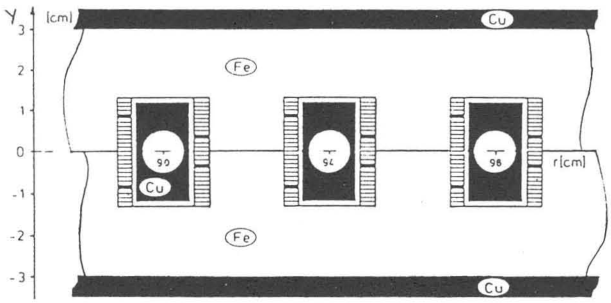

Figure 3: Radial cross section of three channel magnets.

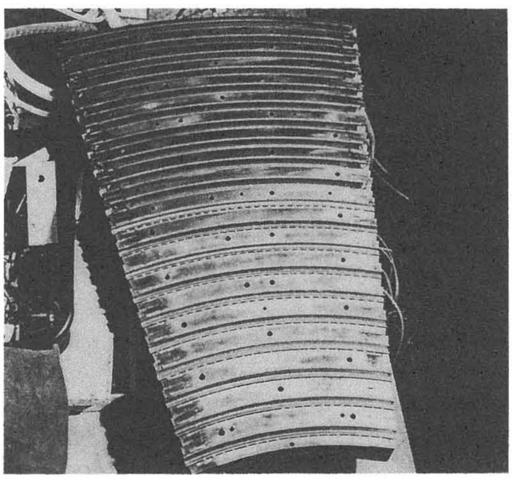

Figure 4: Lower half of a magnet sector, seen from above.

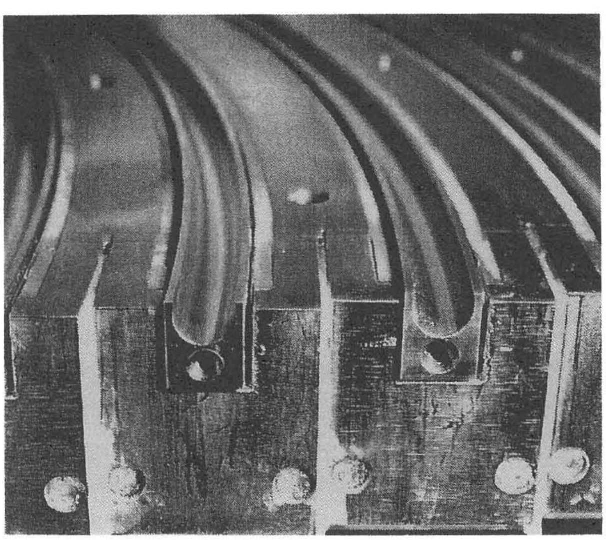

Figure 5: Lower half of a magnet sector, seen from the exit side.

The rf–cavities are made from copper, electroplated with PbSn (some 10^{-3} mm) as superconductor [9,10] (see Fig. 6 and 7). The total radial length is 123 cm. The gap has a radial length of 80 cm, the gap width increases from 62 mm at the first beam hole to 128 mm at the last. The cavity is operated in the fundamental mode at a fixed frequency of 170 MHz, corresponding to harmonic numbers of about 14 to 55. The radial voltage characteristic V_{gap} and the electric field distribution in the gap is shown in Fig. 8. The design voltage at the last beam hole was 0.53 MV with an unloaded quality factor $Q_0 = 3.6 \cdot 10^8$ corresponding to a dissipated heat of 6 W per cavity. This voltage was obtained with $Q_0 \approx 10^9$ typically. The maximum voltage observed at the last beam hole was 1.2 MV, corresponding to a maximum field in the gap of more than 10 MV/m. More details about the magnets and the cavities were published earlier[5...10].

In Table 1 general design data of the Tritron are listed.

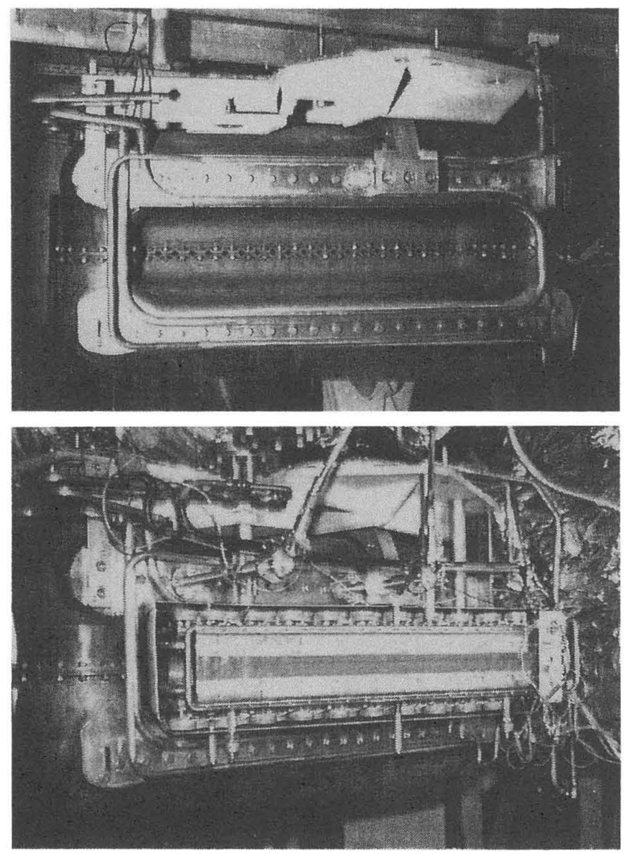

Figure 6: Side view of a cavity with cooling pipes, hanging under a supporting platform. The cavity and the adjacent magnet sectors are adjusted together. Then the whole unit –one of six in total– is put into the cryostat. At the bottom photo a magnet sector is installed. The beam holes are closed by an adhesive tape to protect the cavity temporarily from dust. Variable rf–power couplers and sapphire rods as slow fine tuners are put to the upper cavity half between the cooling pipes, with the driving linkages visible.

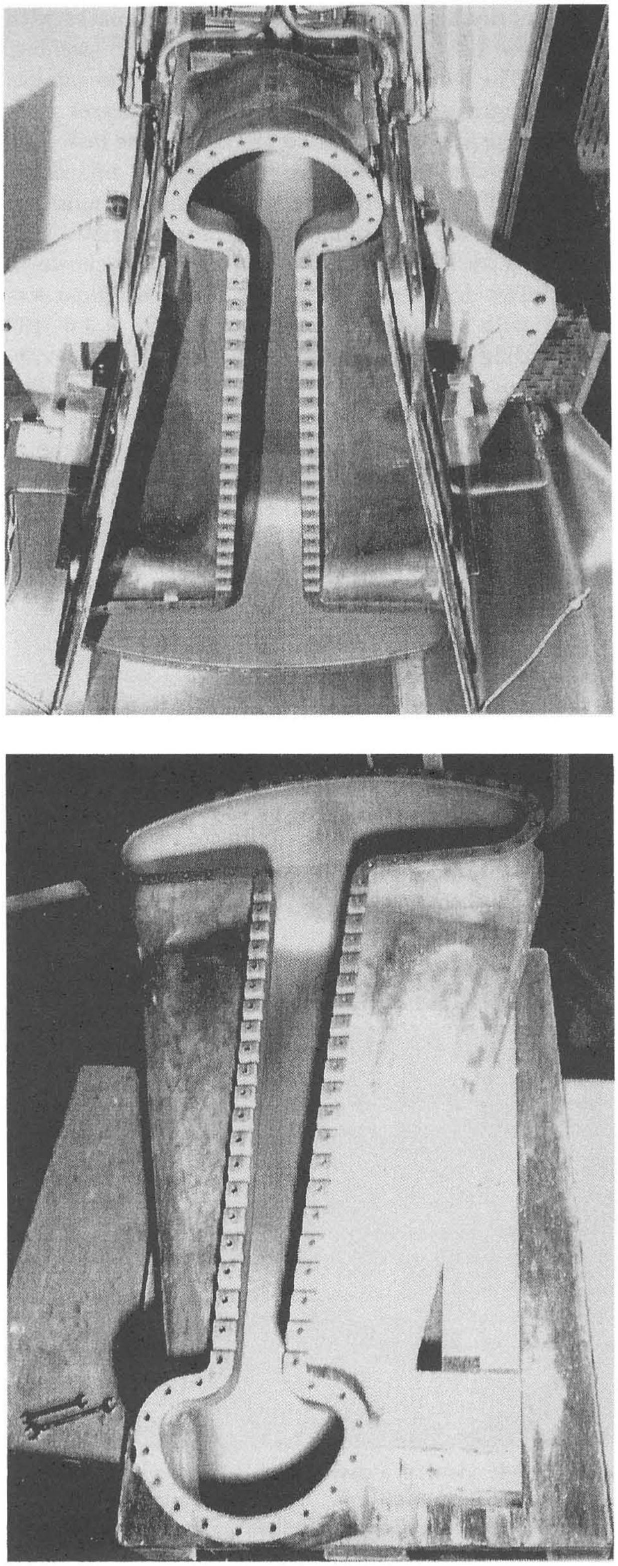

Figure 7: Two cavity halves before being screwed together in the horizontal plane of symmetry. The upper half is hanging on the supporting platform. The view is from below. No special clean room conditions are needed!

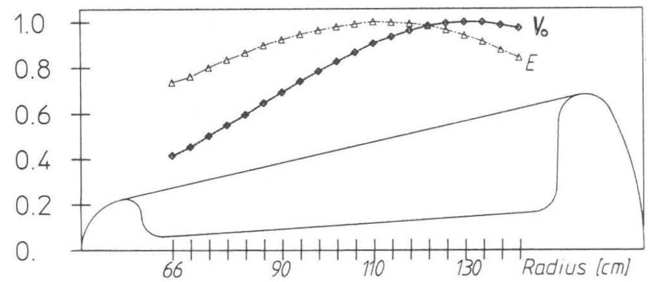

Figure 8: The radial characteristic of the amplitudes of the electrical field E and voltage V_0 of the cavities.

The whole machine is hanging under a torus–like helium reservoir on the upper half of the cryostat (Fig. 9 and 10). The cavities and magnets are cooled indirectly by pipes connected to the torus (thermal siphon cooling). To cool down from 300 K to $\approx$ 4.5 K helium gas is forced to flow through a second pipe system connected in series with heat exchangers in the refrigerator (155 W at 4.6 K). It takes about 100 h to cool the total mass of about 7 tns to 4.5 K. The stand–by load on the 4.5 K level is less than 50 W. The insulating vacuum of the cryostat is the same as for the beam, there is no separate vacuum chamber. Due to the good cryopumping the pressure in the cryostat generally is $\leq$ 10 Pa. A complete cycle –consisting of evacuation, cooling from 300 K to 4.5 K, heating from 4.5 K to 300 K, and pressurization– takes $\approx$ 7 days.

5 The status of the commissioning

Early in 1994 all components of the Tritron were finally produced, but not yet tested except for prototypes. After having assembled the complete machine, the different parts were taken into operation step by step. The system consists of a multitude of components, each of which has to be in order.

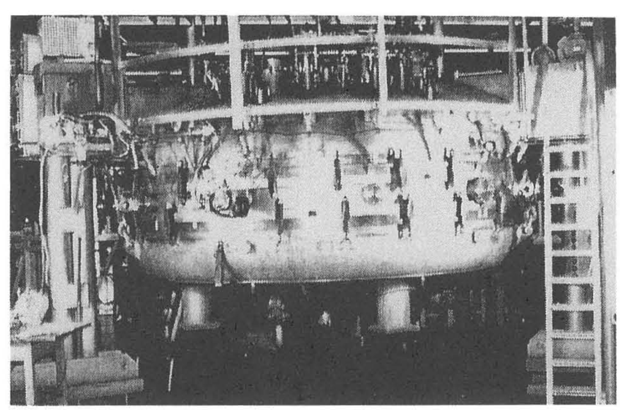

Figure 9: The Tritron cryostat. All connections are made through flanges on the upper half. The lower part can be removed.

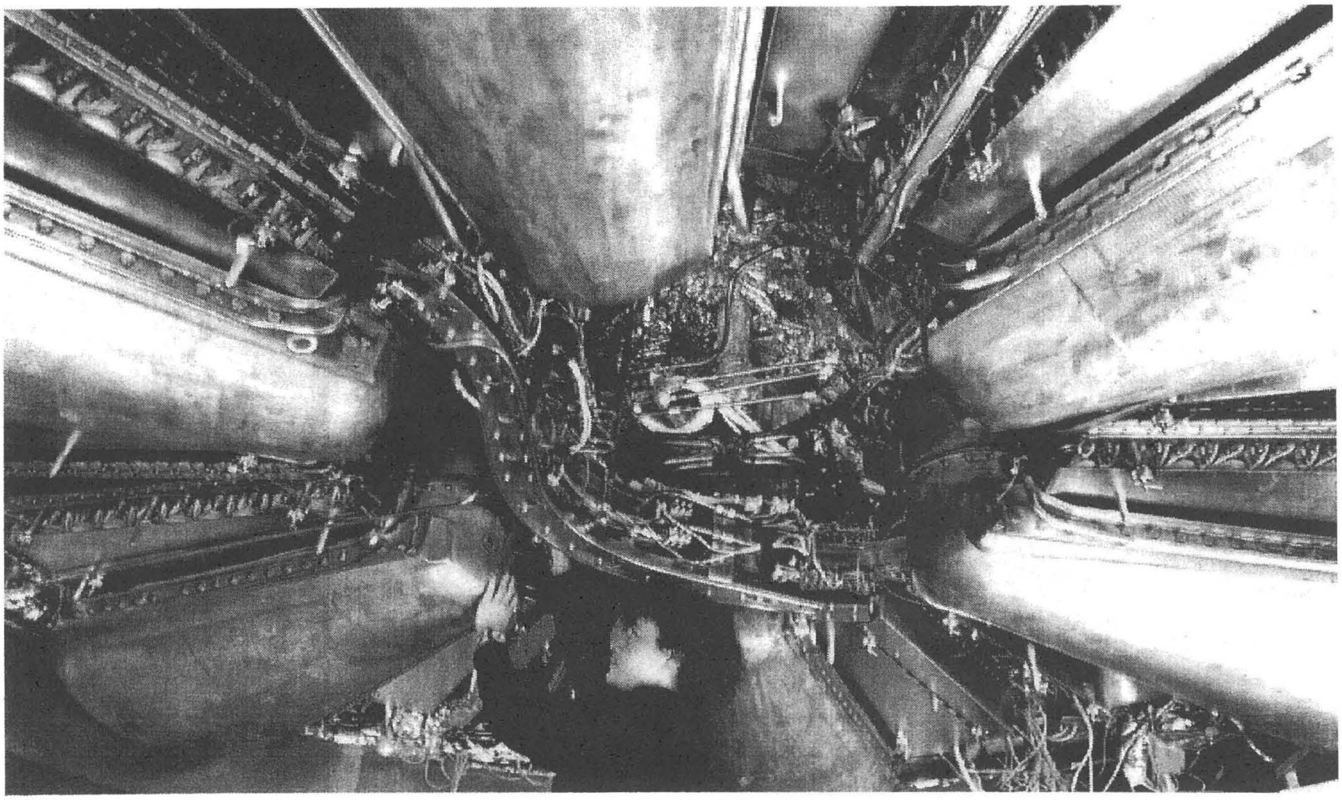

Figure 10: View from below into the Tritron cryostat with the complete machine assembled. The beam comes from the upper left corner and is injected by three channel magnets, positioned on the double–curved support above the lady.

1. The 241 superconducting coils are subdivided into 482 half–coils. All half–coils are connected in series with just one power supply. Each half–coil is connected by superconducting joints to a superconducting switch, which can be turned normal conducting by means of a resistive heater. Individual currents in a channel can be achieved by turning both switches of the corresponding half–coils superconducting, when the design current is reached. All further variation of the current from the power supply –the excess current– will be bypassed by the switches. The system contains in total almost 1000 superconducting joints and 500 switches with heaters (stuck on with epoxy), which have to be able to transport excess currents of at least 140 A. The resistance of each of the 500 normal conducting joints connecting succeeding half–coils should be $\leq 10^{-8}\Omega$.

2. There are in total 62 superconducting axial steerer magnets, also equipped with superconducting switches.

3. More than 120 probes for the radial and axial beam positions are installed.

Table 1: General design data of the *Tritron*

Injector	MP-tandem (14MV)
Energy gain factor	$\simeq 4.9$
Injection radius	0.66 m
Extraction radius	1.45 m
Turn separation	40 mm
Number of turns	19.8
magnet data:	
Number of magnet sectors	12
Number of channel magnets/sector	20 (19)
Bending angle per channel	30°
Sector angle	20°
Bending radius ρ_1, ρ_{20}	430 mm, 942 mm
Geometrical aperture	10 mm
Maximum magnetic induction	
sector channels	1.7 T
3rd injection channel	2.4 T
Normal.radial gradients $\frac{\partial B}{\partial r}\cdot\frac{1}{B}$	$3.6\ m^{-1}$, $-4.9\ m^{-1}$
Betatron oscillation numbers Q_x	1.2 ... 1.6
Q_y	0.8 ... 1.7
Synchrotr. oscill. numbers (incoh:)	$\simeq 0.2$
cavity data:	
Number of cavities	6
Fixed rf–frequency	170 MHz
Harmonic numbers	$\simeq 14 - \simeq 55$
Total radial length	1233 mm
Radial gap length	$\simeq 0.85$ m
Gap width injection/extraction	62 mm / 128 mm
Aperture of the beam holes	13 mm
Maximum gap voltage	0.53 MV
Maximum accelerating field	4.7 MV/m
Peak field to maximum gap field	< 1.5
Unloaded quality factor	$3.7 \cdot 10^8$
Dissipated power per cavity	6 W
Surface resistance	$2.5 \cdot 10^{-7}\Omega$

4. The rf–couplers and tuners of the cavities have in total 24 driving linkages with universal joints.

5. The total length of helium cooling pipes is of the order of 300 m, there are about 120 tube fittings (Swagelok, stainless steel).

Though all components had been manufactured as carefully as possible, a small number of elements may fail. Some percentage of the superconducting contacts could not be loaded to the design current of 140 A and had to be replaced. Some heaters of the switches cracked off, when cooled down. The insulating layers of the superconducting cables connecting the two halves of a sector broke at some places, where they had been squeezed too heavily, causing short–circuits. Some of the normal joints were imperfect, so that the dissipated heat turned the coils normal conducting at low current values. Different other hidden paths of heat flowing onto the magnets had to be tracked down and blocked. Due to the special properties of materials at low temperatures some of the universal joints of the drivers of the rf–couplers seized up, and cables of the probes broke, when they were bent back and forth frequently. Some of the tube fittings, leaking at low temperatures, had to be identified and tightened. Though all those failures were trivial, it took quite a number of cooling cycles to eradicate them finally. In addition some time consuming problems had to be overcome, which however were not specific to the special design of this machine, as failures of the refrigerator and of the beam guiding system e.g..

Finally various unexpected difficulties occurred, caused by the complex interaction of the different subsystems. As soon as somewhere in the magnet system a quench is detected, the power supply will be switched off. Then the voltage across each half–coil is given by $I \cdot R_{shunt}$, where I is the current and $R_{shunt} = 0.5\ m\Omega$ is the shunt resistor protecting the coil from overvoltage. Because of the series connection of all coils maximum voltages of 240 V arise already at $I = 1\ kA$. Under unfavorable circumstances these voltages may lead to arc–discharges, which can destroy the current leads, if most of the magnetic field energy (in total 20 kJ at 1 kA) is dissipated locally. This indeed occurred until additional overall shunt resistors were put in parallel, thus reducing the maximum voltage considerably.

Another unexpected problem concerned the frequency tuning system of the rf–cavities. The original system consisted of a coarse tuning by mechanical deformation ($\Delta f \simeq 50\ kHz$) and a fine tuning by sapphire rods, moved into the rf–field ($\Delta f \simeq 300\ Hz$). The driving linkage of the coarse tuning system between the wall of the cryostat and the cavity represents a rather rigid joint. Thus a force acting on the cavity (the driving force for the fine tuning sapphire rod e.g.) reacts upon the coarse tuning and causes a certain detuning. Correlated to the rotations of the driving linkage of the sapphire rod the rf–frequency varied periodically with an amplitude of 25 Hz. This effect could be reduced by an order of magnitude, when the driving linkage of the sapphire rod was decoupled almost completely from the cavity. Nevertheless the remaining variations would be still too strong to be accepted in the computer frequency control system. In addition other mechanical influences on the system (by the position probes e.g.), have to be compensated by a fast fine tuning system. For this purpose piezoelectric tuners were installed. A strong Cu–frame clasps the piezoactor and the cavity, causing a frequency shift of up to about 300 Hz at 4.5 K. With this device, frequency deviations with amplitudes of several Hz can be corrected as well as the frequency shift due to the pressure by the rf–field ($\leq 200\ Hz$). The control of the piezo tuners is incorporated in the existing rf–amplitude and phase control system.

In June 1995 a beam of $^{32}S^{14+}$–ions of 40 MeV was injected for the first time into the complete Tritron. The cavities were not operating because the beam could not yet be bunched. The beam was guided from one position probe to the next by adjusting the magnetic fields of the channels in between. Some of the axial steerer magnets were used for moderate axial corrections. The beam passed the three injection magnets and the succeeding 31 channel magnets along the innermost 2.6 turns. All channel magnets –even those without beam– were operating at the same time with currents up to 1020 A (about 0.6 of maximum). The technique of individual current setting in the channels by means of the superconducting bypass switches was tested successfully. The fields in the three injection channels and following 31 channels with the switches superconducting stayed stable, when the current in the switches was changed by $\pm 120\ A$. No effects on the beam positions were observed.

Each position probe consists of a frame at the end of a pendulum with two pairs of tungsten filaments ($5 \cdot 10^{-3}\ mm$ thick, distance $\approx 13\ mm$). One pair is approximately vertical directed to measure the radial coordinates, the other is tilted to obtain the axial position. The beam passes generally in between. When the filaments are moved into the beam, the change of the resistance of the filaments due to the temperature variation is detected. Typical signals vice the position of the frame are shown in Fig.11 (in arbitrary units). The left half of the diagram was taken, when the frame was moving from the rest position to the left side. Both right filaments crossed the beam. The positive peak indicates an increasing resistance. Maximum resistance was achieved, when the signal crossed the zero line. The negative part of the signal reflects the drop of the resistance due to cooling by radiation and heat flow along the filaments to the frame. Then the frame was moved back to the rest position without registering the resistance, and after a stop of a few seconds it was moved to the opposite direction, taking the right part of the diagram. After a detailed analysis of the signals one can learn the coordinates of the center of the beam and the dimensions of the cross section. From the shift of the signals as function of the magnet current it can be concluded possibly, if the beam is scraping somewhere the beam tube. This method can be used also to check the calibration of the probes.

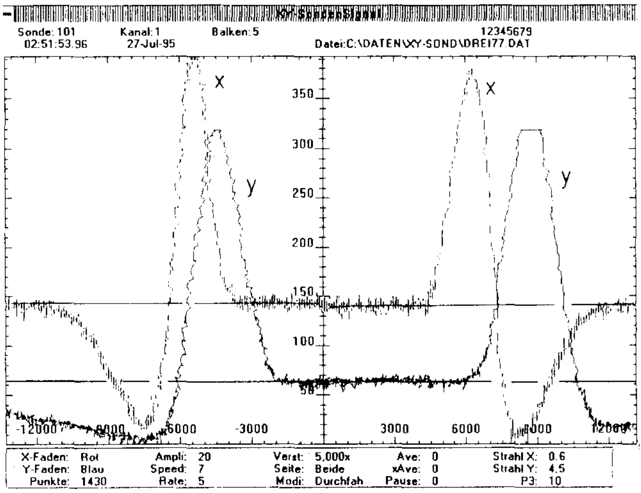

Figure 11: Typical position probe signals, taken at the end of the first turn with an injected beam current of ≈ 10 nA. The beam is centered rather well in the radial direction, however it is some mm above the plane of symmetry. The right part of the y-signal is cut because of overflow. The cooling rate is less for the y-filaments because of their length due to the tilt.

The probes except those along the injection path had not been tested previously. The switches controlling the points of return of the frames had to be adjusted due to the results of the first tests with beam. Therefore only the first half of the signals of most of the probes could be used for the position analysis up to recently. As a consequence the centering proceedure of the beam during the very first tests was by not perfect, so that the intensity was lost almost completely after 2.6 turns.

Nevertheless some further interesting results can be extracted from the first test runs. The beam dimensions correspond rather well to the expected values of some mm. Investigations of the optical properties of the magnets were started successfully by stimulating betatron oscillations. When operating the first cavity at a rather high voltage level, the expected horizontal spreading of the unbunched beam was obtained downstream. No influence of stray–fields of the magnets on the cavities was observed so far.

Very recently the buncher in the beam transport system to the Tritron was taken into operation finally. The drivers of the position probes were adjusted during the late shut–down. The commissioning is going on.

Major milestones of the Tritron project are shown in Table 2. The total costs –including those for buildings, beam transfer, refrigerator and salaries except those for six permanent positions– were about 12 MDM corresponding to approximately 8 M$(US). On the average about 15 people were involved full–time during 11 years (5 physicists, 2 engineers, 5 technicians and 3 students).

Table 2: Milestones of the Tritron development.

1982	May: Very first idea for the Tritron.
1983	December: Internal, quite preliminary proposal.
1984	April: Approved by Accelerator Research Committ. Development work starts
1987	July: Final funding.
1989	Design values exceeded by two rf–cavities.
1990	Start of final magnet production.
1992	Last channel magnet wound and potted. Last cavities electroplated with PbSn.
1993	June: Beam along first half turn.
1994	Preliminary assemblage. Test of subsystems.
1995	June: Commissioning starts. Beam along 2.6 turns.

Acknowledgements

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