TRITRON - A SUPERCONDUCTING CYCLOTRON WITH SEPARATED ORBITS

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The Tritron is designed to be be used as a booster for the existing MP-Tandem at the Accelerator Laboratory of the Universities of Munich [1]. It will be able to increase the ion energies by a factor of 4.9, eg a $^{12}C^{6+}$ beam will have a maximum energy of 21 MeV/u.

In Fig. 1 cross sections of the Tritron are shown. The main parameters are summarized in the table. The cryostat has a diameter of 3.6 m. The beam is injected at a radius r_1= 66 cm and extracted after almost 20 turns at r_2= 145 cm. The turn separation is Δr = 4 cm. Each of the 12 superconducting flat magnet sectors has 20 channels of the window frame type (Fig.2). In each channel the field is adjustable individually by means of superconducting switches across the magnet coils [2,3]. There are alternating gradients from one sector to the other to get strong focusing in both transversal directions. Six superconducting resonators operating at 170 MHz are used to accelerate the beam along the 20 parallel orbits. The maximum voltage at injection is $U(r_1)$= 270 kV, at extraction $U(r_2)$= 520 kV per cavity. To get longitudinal focusing, the bunches have to cross the resonators at a rf-phase with increasing voltage, resulting in ~ 0.2 synchrotron oszillations per turn.

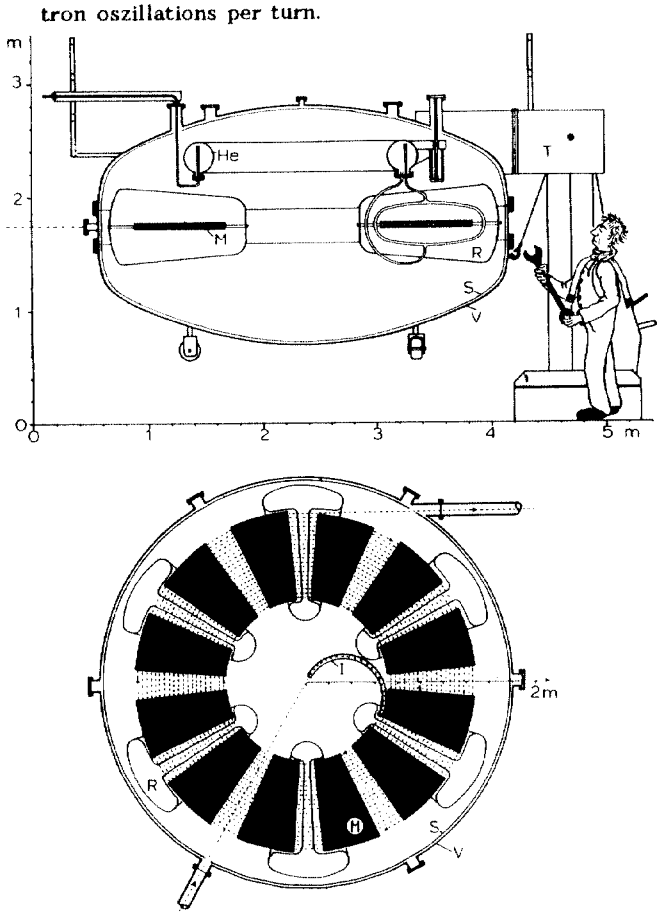

Fig. 1: Cross sections of the Tritron.
M: Magnets; R: Resonators; I: Injection magnet; V: Vacuum vessel; S: 80 K shield; He: liquid helium reservoir;
T: support; Ion beam: dotted.

Tritron design data

Injektor		13 MV tandem
Max. energy	H^{1+} (Q/A= 1)	40.7 MeV
	S^{16+} (Q/A= 0.5)	21 MeV/u
	I^{33+} (Q/A= 0.26)	5.7 MeV/u
Energy gain factor		~ 4.9
Injection radius r_1		66 cm
Extraction radius r_2		145 cm
Turn separation Δr		4 cm
Number of turns		19.8
Harmonic number		17 - 50
Number of magnet sectors		12
Number of cavities		6
Magnet sector data:		
Number of magnet channels		20 (19)
Sector angle		20°
Minimum bending radius ρ_1		430 mm
Maximum bending radius ρ_{20}		942 mm
Maximum magnetic field B_{max}		1.4 T
Radial grandients $\frac{1}{B}\frac{\partial B}{\partial r}$		3.6 m^{-1}, -5.2 m^{-1}
Dimensions of the supercond. cable		0.7 x 2.9 mm^2
Number of strands		14
Strand diameter		0.4 mm
Strand material	Cu/NbTi	1.35
Maximum cable current I_{max}		1300 A
Cavity data:		
Gap width at injection d_1		60 mm
Gap width at extraction d_{20}		130 mm
Rf-frequency		170 MHz
Maximum accelerating field E_{max}		5.2 MV/m
Maximum voltage at r_2		0.50 MV
Stored Energy U		1.8 J
Dissipated power P		6 W
Quality factor (unloaded) Q_o		$3 \cdot 10^8$
Beam power		≤ 200 W
Geometry factor G		60 Ω
Surface resistance R_s = G/Q_o		$2 \cdot 10^{-7}$ Ω

The cryosystem

The vacuum vessel consists of two half shells. The lower half can be removed. Inside the vessel is a torus like helium reservoir (~270 l), which supports the resonators and the magnets. The operating temperature will be 4.5 K. The cavities are made of copper covered with a thin superconducting layer of PbSn. Due to the good thermal conductivity of copper cooling by pipes can be used. The superconducting magnets will be cooled by thermal bonds to the cavities. There is no special vacuum system for the beam. At 4.5 K a pressure of $2 \cdot 10^{-7}$mbar was measured. The stand-by losses of the cryostat are less than 5 W.

The magnets

The magnet sectors consist of two steel sheets (each 3 cm thick) with slots every 4 cm (Fig.2). Aside from the coils to generate the alternating gradient the sectors are mechanically identical. The window inside the coils has a height of 28 mm and a width of 15 mm. Epoxy resin is used to bond the coils to the steel sheets. Because of the mechanical stresses caused by quenching the coils have to be supported by flat springs. Each half coil is protected by a parallel resistor ($1 \cdot 10^{-4}\Omega$), resulting in passive thermal quench protection.

Four channels were prepared and tested until now. Three of them have separate coils to generate the field gradient. A maximum current of 1840 A was achieved without any training. The design value is 1300 A corresponding to B= 1.4 T. The effective magnetic length is in good agreement with TOSCA field calculations. Measurements of the field gradient gave a value of $\frac{1}{B}\frac{\partial B}{\partial r} = 3.5\ m^{-1}$. Nonlinear deviations of the field are less than $5 \cdot 10^{-4}$ in a region of ± 3.5 mm around the channel center. The stray field at the cavitiy location is less than 10^{-3} T.
Higher order components in the field expansion, which may be caused by inhomogenities of the current density in the coils, the gradient layers, edge effects, or saturation of the iron, can lead to transversal instabilities of the beam. Calculations with particle tracking codes showed that the field deviations due to the sextupole terms have to be less than $\Delta B/B = 3 \cdot 10^{-3}$. This limit is much more than the sextupole terms measured so far at different locations of several channels.

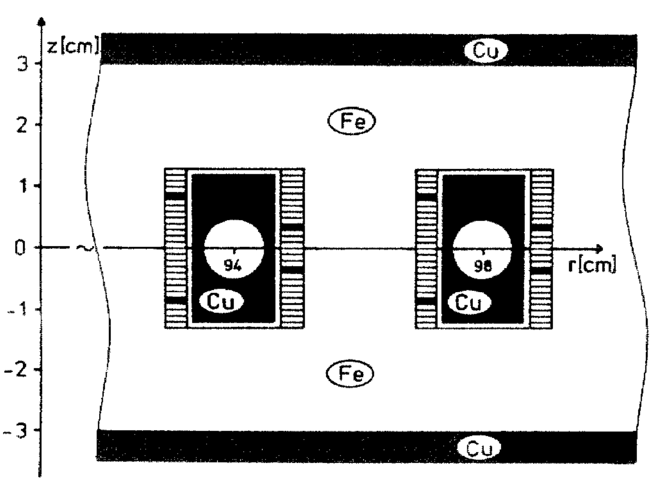

Fig. 2: Vertical cross section through a magnet sector showing two radially adjacent channel magnets. The superconducting cable is of Rutherford-type. Two extra turns (indicated black) made of the same cable are used as gradient layers.

Accelerating cavities

The 6 wedge-shaped reentrant type resonators consist of two half shells which are connected by screws in the horizontal plane. They are fabricated by electroplating copper onto a fibre glass mould (wall thickness ~ 10 mm). Two halfs have just been delivered waiting to be coated with PbSn (Fig.3) .

Fig 3: One half shell of a resonator made by electroplating copper (wall thickness ~ 10 mm). The shell is shown after the electroplating process was finished. Some machining still has to be done to get a flat plane at the top. Also the beam holes and holes to house the screws in the top central plane have to be drilled. The cooling pipes and the support structure will be attached to the flat planes on the right and the left.

So far a test cavity welded and soldered out of copper sheets was used to get some preliminary informations. It has approximately the same shape and size as the Tritron resonators. Several tests showed that the pipe cooling works well. After each evacuation of the cavity electron multipacting was observed at low field levels. However, it disappeared after some minutes of rf-processing with modest rf-power (~50W) and did not reappear until the cavity was exposed to air. Oscillations of the resonance frequency caused by acoustic noise were less than 50 Hz. No ponderomoric oscillations were observed.
So far the maximum accelerating field was 5.4 MV/m, limited by field emission. This exceeds the design value. It was measured directly by observing the energy gain of electrons from a ^{207}Bi emitter. The quality factor was $Q_o = 4.2 \cdot 10^7$ which is 7 times less than the design value. The reason is probably the imperfect cavity surface with its welding and soldering seams (pores and discontinuities) and a PbSn layer which was not homogeneous. At some places copper showed up. Therefore the electroplating electrodes have to be improved. A reentrant type 500 MHz cavity with rotational symmetry showed much better results. It was electroplated with PbSn in the same electrolyte as the test cavity [4].

Beam dynamics

The magnets represent a beam transport system guiding the bunches along the spiral orbit. Their fields will be adjusted to keep the beam centered. Due to the alternating gradients the betatron oszillation numbers range from $Q_x = 1.2$, $Q_y = 0.9$ at injection to $Q_x = 1.6$, $Q_y = 1.9$ at extraction.

In order to get a steady acceleration, the injection energy must correspond to a revolution frequency at injection, which is almost a subharmonic of the rf-frequency. With a proper choice of the injection phase between 0^o and 90^o (increasing accelerating voltage), the bunch is longitudinally focused. Therefore the revolution frequency starts to oszillate around the value for the subharmonic of the rf-frequency. This leads to incoherent synchrotron oszillations of the ions with respect to the bunch center ($Q_{sinc} = 0.2$, typical radial amplitude < 0.5 mm for $\Delta p/p < 2 \cdot 10^{-3}$). In addition the bunches will execute coherent synchrotron oszillations with Q_{sco} somewhat less than Q_{sinc}. The radial amplitude of these azimuthally fixed coherent synchrotron oszillations is suppressed by the magnet field setting, which oszillates azimuthally corresponding to the energy oszillations. The central phase of the coherent synchrotron oszillations changes automatically according to the radial voltage characteristic of the resonators and the needed energy gain. A typical central phase curve starts at about 55^o at injection and ends at 65^o passing a minimum of 45^o [5].

Due to the rather large accelerating voltage per turn, the longitudinal focusing is not very small compared to the radial focusing. As a consequence the coupling between the radial and the longitudinal motion cannot be neglected. To get a stable motion the radial focusing strength has to be sufficiently strong [6], excluding a weak focusing scheme.

Present status

The erection of the concrete shielding and the installation of the power cables and the cooling water pipes is almost finished. The cryostat was completed last year, a refrigerator with a cooling capacity of 150 W at 4.5 K will be installed during summer. A new power supply for the magnets just has arrived. The computer controlled winding machine to manifacture the coils of the 20 channel magnet sectors is near completion. First tests with superconducting switches across the magnets were successful. When a switch was superconducting, a change of the current from the power supply $\Delta I = 140$ A caused a change of the current in the magnet coil of $3.3 \cdot 10^{-3} \cdot \Delta I$, given by the ratio of the switch inductivity to the coil inductivity. The field stability was $\Delta B/B < 5 \cdot 10^{-4}$ within 15 minutes. The first resonator made by electroplating will be covered with PbSn in July.

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[3] R. Savoy, Thesis TUM 1988.

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[6] G. Hinderer, Proc. 11th Int. Conf. on Cyclotrons and Applications, Tokyo 1987, p. 215.