# The Superconducting Tritron Magnets *

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*Abstract*

The Tritron project is a study of a new type of cyclotron, a superconducting separated-orbit cyclotron with a MP-tandem as injector [1,2]. It shall increase the ion energies by a factor of $\approx 5$. The ion beam will be guided by 238 superconducting window-frame magnets with alternating gradients along a spiral orbit with almost 20 turns. The spiral consists of 30°-arcs and drift lengths between them. The turn separation outside the channel magnets is $\Delta R =$ 40 mm. Radially neighbouring channels are joined into 12 flat sectors (see figure 1). In each second of the intermediate gaps a superconducting cavity respectively a line of radial beam position probes is inserted [3].

## I. MAGNET DESIGN

The specific features of the Tritron design are the strong focusing in both transversal and in the longitudinal direction. The working line in the stability diagram can be put far from the stability limits. There is no energy limitation due to resonance lines, which are crossed very fast without disturbances. The tolerances for the gradients are rather high. The injection is made simply by three superconducting channel magnets, for extraction no element at all is needed. In principle several rings of the Tritron type with increasing radii could be combined to achieve specific energies of the ions up to several 100 MeV/u. The magnets and cavities are cooled indirectly (thermal siphon technique), no bath cryostat is needed. The whole machine is hanging in a vacuum vessel consisting of two shells (diam. 3.6m). There is no special vacuum chamber neither for the beam nor the rf-cavities. The mass of a cavity is $\approx$ 450 kg, and that of a magnet sector $\approx$ 150 kg. The refrigerator power is 10 kW at 300 K and 155 W at 4.6 K.

The 12 magnet sectors are identically apart from the normalized field gradients $\left|\frac{\partial B}{\partial r} \cdot \frac{1}{B}\right| = +\ 3.6\ \mathrm{m}^{-1}$ and $-\ 4.9\ \mathrm{m}^{-1}$. All channels of a sector have the same normalized gradient, the first sector after the 90°-injection magnet is radially defocusing. The pole edges are not tilted. All sectors consist of 20 channels except the last two, where the $20^{th}$ channel is removed to give space for injection and extraction respectively. The bending radius of the innermost channels is 430 mm. It increases from turn to turn by $\Delta R$ = 26.94 mm. The distance between neighbouring channels at the ends of the channels is 40 mm (turn separation). The bending angle is 30°, the sector angle 20°.

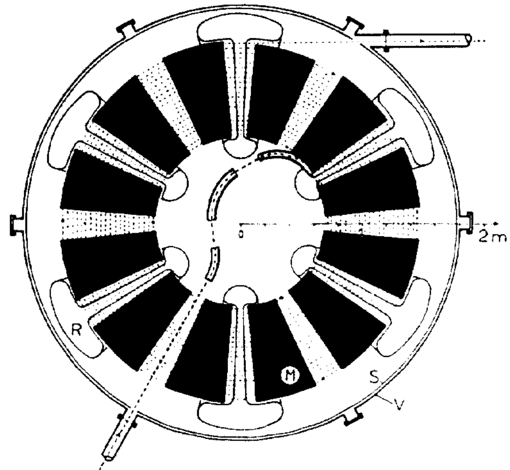


Figure 1: Horizontal cross section of the Tritron: M magnets, R cavities, V vacuum, S 80K-shield.

Each sector consists of two steel sheets, each 30 mm thick, with curved slots every 4 cm (width 22 mm, depth 15.5 mm, see figure 2). The maximum induction is limited by the saturation of the steel to about 2 T. Thus the overall current density of the superconducting coils can be chosen $\geq$ 600 A/mm$^2$, and the radial width of the coil can be made small compared to the total width of the channel. The coils consist of 26 windings of a Rutherford-type cable (0.69 x 2.88mm$^2$, 14 strands, diam.each 0.4 mm and 54 filam., Cu/NbTi = 1.4, 2 insulating layers of glass cloth with prepreg, each 0.1 mm thick). The half-coils are wound directly into the slots by a computer controlled winding

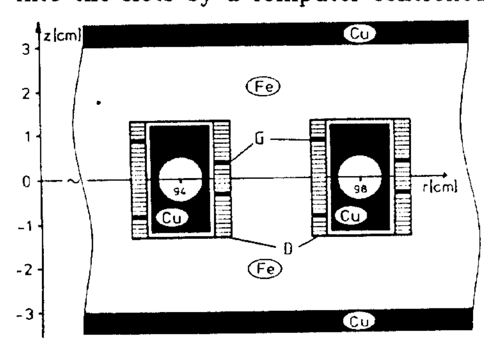


Figure 2: Cross section through a magnet sector with two adjacent channels. G gradient windings, D insulation layers, Cu copper shields.

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machine with a rate of 3 to 5 half-coils per day and then vacuum impregnated with epoxy. A copper profile with a bore (diam.11 mm) for the beam shields the coil from beam losses. Flat disc springs between the copper profile and the coil prevent it from cracking from the steel.

Because the beam is running only a few mm apart from the coils, the tolerances for the channels and especially for the cable positions are extremely tight. For uniform distribution of the cables a homogeneous field is obtained, as far as saturation effects can be neglected. Two single windings of the same cable as the main coil but without current produce the field gradient. The inner and outer parts of these gradient windings have different distances from the central plane of symmetry. The field in the channel far from the ends was calculated with the code POISSON. The gradient windings will produce higher order field contributions in addition to the linear term. Beam dynamic investigations have shown, that sixtupole terms would reduce the dynamic aperture most seriously. The average quadratic term has to stay below $\left|\frac{\Delta B}{B}\right| < 5 \cdot 10^{-3}$ in a distance of 4 mm from the central orbit. The gradient windings produce negative quadratic terms, if their distance from the central plane is small, and positive, if they are positioned near the gap edges. By a proper choice of the distances the gradient as well as a certain value for the quadratic term can be adjusted within tolerances given by the discret variation due to the cable thickness. Corrections can be made by inserting insulation layers between the cables at a proper position. At the ends of the coils a strong local negative sixtupole term stems from the region, where the half-coils spread apart. These contributions were analysed experimentally by means of integral flux probes and differential Hall probes. The position of the gradient windings and the additional insulation layers are adjusted in such a way, that the resulting integral sixtupole term is small enough.

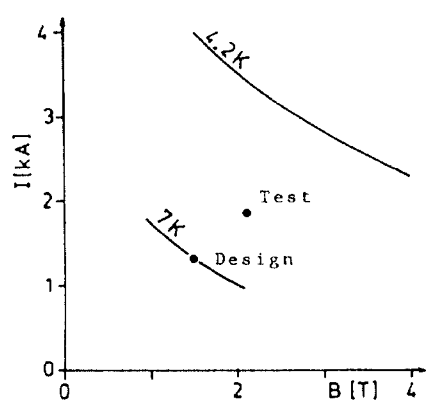


Figure 3: The critical data of the Tritron-cable, design value and best test result.

In order to guide the beam along the central orbit the current of each of the 238 channels has to be adjusted individually. The difference between maximum and minimum current of all channels is less than ≈ 170 A. All main coils will be connected in series. Each half of a main coil has a superconducting switch with superconducting contacts in parallel, which will be toggled to the superconducting state as soon as the appropriate current of the coil is achieved. Further variation of the current from the power supply will be shared between the switch and the coil according to the ratio of the inductances ($\leq 10^{-3}$). The switches are made of superconducting wires (hairpin shape) with the copper matrix etched off along ≈ 3 cm, which can be heated above the critical temperature with ≈ 2 mW by means of an Allen–Bradley resistor, glued on the filaments. The filaments at the ends of the switch wire are mixed with those of all strands of the coil cable and pressed within a copper tube ($\approx 5 \cdot 10^4$ N/cm$^2$) to form the superconducting contacts.

## II. EXPERIMENTAL RESULTS

So far five magnet sectors are wound, potted and partly connected to protection resistors and superconducting switches. Ten channels were investigated extensively at temperatures below 5 K with results as summarized below.

- No magnet channel had to be trained. The maximum currents were limited by the current leads and the current supply respectively. Currents above ≈ 2000 A were achieved corresponding to a field level of ≈ 1.9 T, far above the original design value of 1.4 T (see fig.3).

- The stray field 35 mm in front of the end plates at the ends of the channels is less than $5 \cdot 10^{-5}$ T, which is sufficiently small, so that the superconducting cavities won't be disturbed (see fig.4). The stray fields beside the steel yoke at very high currents (> 1600 A) due to saturation can be shielded by steel sheets (2 mm thick) in a distance of 2 mm.

- In fig.5 the relative variation of the field integrated along an arc with radius as that of the channel center is shown as function of the radial position x from the center for two different magnet channels. The sixtupole contributions at $|x| = 4$ mm are less than $1.5 \cdot 10^{-3}$ of the central field, this is 1/3 of the critical value.

- The current setting by means of the superconducting switches was tested successfully. The maximum current of all switches was at least 230 A, which is above the design value. The switching times in both directions were less than 0.5 sec. When changing the switch current by 120 A, the relativ field variation in the corresponding magnet was less than $\approx 2 \cdot 10^{-4}$.

- In fig.6 the normalized gradient $\left|\frac{1}{B} \cdot \frac{\partial B}{\partial x}\right|$ for one channel is shown as function of the current in the main coil. The gradient was measured with Hall probes, moved radially in the plane of symmetry, azimuthally positioned in the centre of the channel. The gradient windings had no current. The diagram shows the results of two runs with different curves for currents below

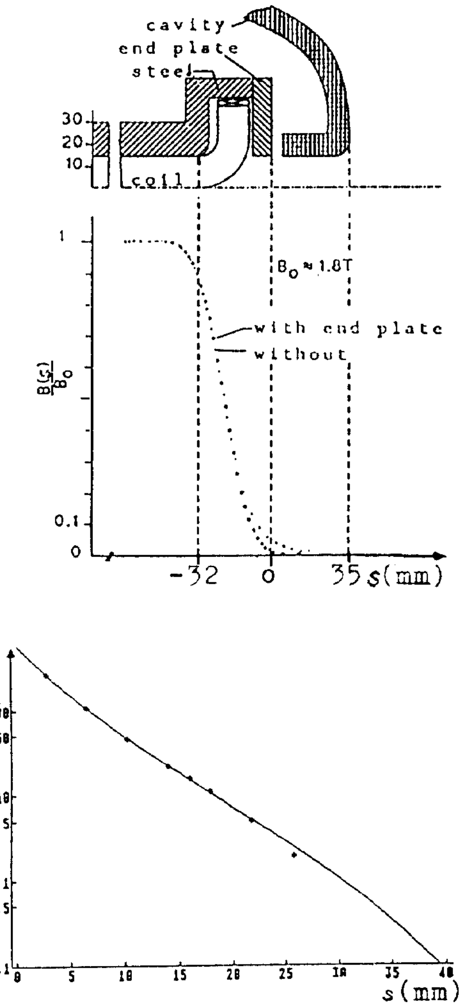


Figure 4: Relative induction along the orbit at the end of the channel, measured by Hall-probes, respectively the absolute field value as function of the distance of the end plate (central field 1.8 T).

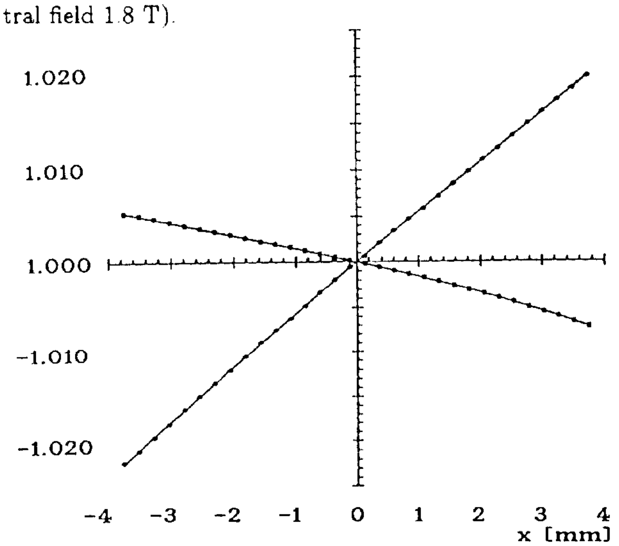


Figure 5: Variation of the normalized field integral as function of the radial distance from the center of the channel for two channels, I = 1500A

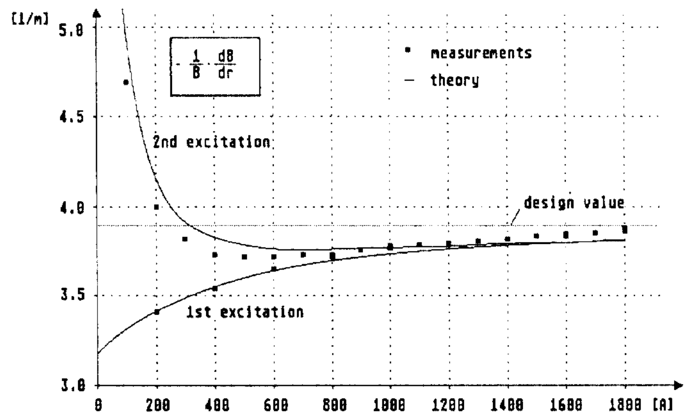


Figure 6: The normalized gradient in the centre of a channel as function of the current in the main coil.

1000 A. At both runs the gradient was measured starting with zero current and increasing it step by step. The lower part of the curve was taken, when the coil was energized initially after it had been normal conducting. The upper part was observed during a second excitation. The dependence of the gradient on the current and (below 1000 A) on the preceding excitation cycles is caused by persistent screening currents in the superconducting filaments, induced during changes of the field. All features of the curve of fig.6 were reproduced by model calculations, starting with the external magnetizing fields at each filament, calculating the resulting screening current distribution, replacing it by a pair of currents with the same magnetic moment and observing their contributions to the original field in the plane of symmetry. The Tritron magnets will be operated at currents of at least 500 A. Then the variation of the gradients due to the magnetization effects of the superconductor is about 5 % . This is comparable to the fluctuation of the gradients due to uncontrollable nonuniformities of the coils. Field calculations using the code POISSON gave a normalized gradient of ± 3.9 m , indicated by the broken line in fig.6. The variation of the gradient of the order of some percent is of no serious consequence for the beam dynamics in the Tritron. The sextupole components showed no current dependence, in agreement with the theoretical calculations.

*References*


[1] U. Trinks et al., Nucl. Instr. Meth., A244, (1986), 273

[2] U. Trinks, Nucl. Instr. Meth., A287, (1990), 224

[3] P. Schütz et al., The superconducting cavities for the TRITRON, in this issue