THE TRITRON - A SUPERCONDUCTING CYCLOTRON WITH SEPARATED ORBITS

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ABSTRACT

The Tritron project is a feasibility study of a new type of cyclotron, a superconducting separated orbit cyclotron for quasi-continous ion beams with small emittances, in principle for specific energies of hundreds of MeV/u, overcoming different limitations of other cyclotrons by its outstanding features. First the concept is presented, then the status of the Munich project. The cryogenic system is operating. Almost all components of the beam transport system exist. The first two superconducting rf-cavities have exceeded the design voltage and quality factor considerably. The magnetic fields of superconducting test channels were investigated. The computer controlled winding machine is operating and all components for the production of the 240 channel magnets exist.

THE TRITRON CONCEPT

The Tritron concept is based on the magnet design: the beam is guided with strong focusing along the spiral orbit by superconducting channel magnets with alternating gradients as in a beam transport system (fig. 1). The channel magnets are joined to flat sectors, leaving a maximum of space between each second sector for optimizing the shape of the rf-cavities with respect to the radial voltage characteristic, peak field and losses. Due to the short range of the magnet stray fields the cavities can be superconducting too. In the remaining intermediate sectors beam probes will be installed to control the radial position.[1]

The specific features of the Tritron concept are:

- Strong focusing in both transversal directions: no limitation of the energy by lack of axial focusing.
- 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.
- Strong longitudinal focusing, because the magnetic field needs not to be exactly isochronous. Thus no increase of the effective phase-space volume occurs: no energy or radial spreading, no flat-topping system.
- Due to the longitudinal focusing high harmonic numbers can be used, causing rather dense energy levels for fixed rf-frequency. The gaps between can be filled partly by excitation of azimuthally fixed coherent synchrotron oscillations.
- The injection is made simply by three channel magnets. For extraction no element at all is needed: no electrical deflectors, no septum magnets. Several rings with increasing radii can easily be combined without loosing intensity.
- Both the magnets and the cavities are cooled indirectly (thermal siphon), thus avoiding complicate bath cryostats. There is no special vacuum chamber for the beam. The total mass is rather low. The total power consumption is moderate.

A list of general data of the Tritron is given in table 1.

THE SUPERCONDUCTING CAVITIES

The Tritron will be the first cyclotron without any space restrictions on the design of the rf-cavities due to the magnets. Because of the constant turn separation (4 cm) the energy increase per turn has to be approximately proportional to the radius, resulting in a voltage amplitude across the gap of $U_1 \approx 270$kV at the innermost and ~ 530 kV at the last turn. This can be realized effectively with a wedge-shaped gap of ~ 85 cm length for the 20 parallel beam holes and with a radially increasing gap width from 6 cm to 12.8 cm. Then the transit time factor is almost independent of the radius. The electric field is surrounded by the magnetic rf-field with a rather big cross-section, which is reduced somewhat in the central part. Thus a wedge-shaped reentrant-type cavity results of total length ~ 120 cm, operated in the fundamental mode TE 101 at a fixed frequency of ν_{rf} = 170 MHz (see fig. 2). The electric field is almost independent of the radius (within ~ 10%), the voltage increases approximately linearly (see fig. 3). The geometry constant G=94Ω [2] shows, that the shape is favorable with respect to losses. It is about four times the G-value of a λ/4-resonator and ~1/3 of that of a spherical cavity. The magnetic rf-peak field at the surface is rather small ($< 10^{-2}$T) as well as the ratio of electric peak field to maximum gap field (< 1.5).

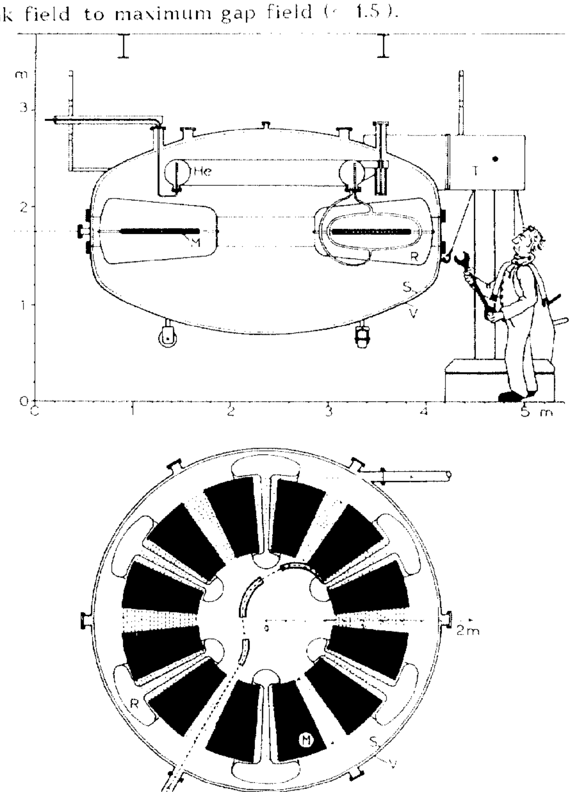

Fig.1. Tritron cross sections. M magnets, R cavities, v vacuum vessel, S 80K shield, He liquid He reservoir, T support.

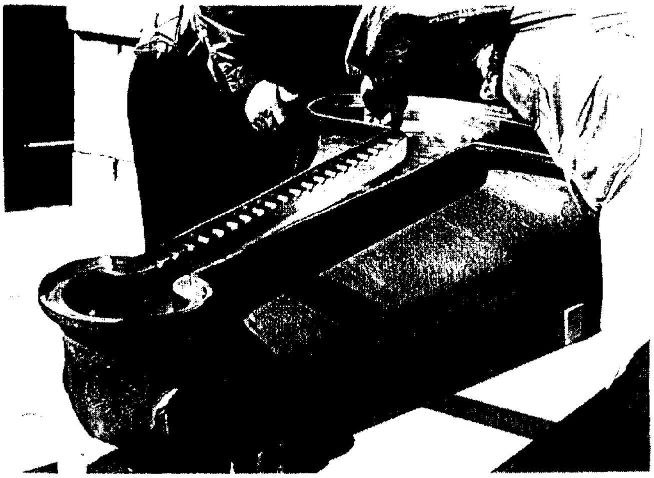

Fig.2. One half of a cavity

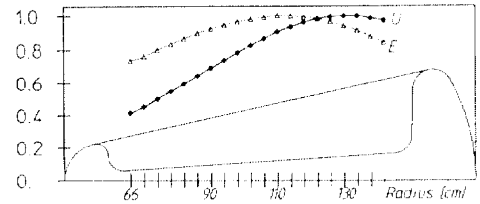

Fig.3. Voltage and electric field characteristic in relative units and half of the cross section of the cavity

The surface resistance of superconducting rf-cavities is the sum of R_{BCS} according to the BCS-theory and the residual resistance R_{RES}. R_{BCS} is approximately proportional to ν^2_{rf}. At the rather low frequency of 170 MHz R_{BCS} is extremely small (for Pb, PbSn or Nb). Thus R_{RES} is practically dominating. R_{RES} is independent of the temperature. Therefore the temperature of the cavities needs not to be below ~ 5K.

Each cavity consists of two halves, which are screwed together in the orbital plane. No current will cross the joint. The cavities are produced galvanoplastically from copper (~10mm) and PbSn (~5µm) as superconductor on the inner surface. Due to the good thermal conductivity of the copper the cavities can be cooled indirectly by two cooling pipes with liquid helium. Moreover the size of hot spots on the surface, caused from dielectric losses of dust particles e.g., is much smaller than in cavities with worse thermal conductivity. This is of special importance for the Tritron cavities, which cannot be handled under clean room conditions nor be operated in a separate vacuum.

Systematic investigations have shown [3], that PbSn with ~2% Sn has several advantages compared to pure Pb: the R_{BCS} - surface resistance is two times smaller; the critical temperature (7.4K) is somewhat higher; it can be easier deposited electrolytically, and it is more stable, when it has to be exposed to the laboratory air during many weeks.

Presently two cavities have been tested, two more are ready for being PbSn-plated. Fig. 4 shows the unloaded quality factor of the first two cavities as a function of the voltage U_{20} at the last beam hole, respectively of the maximum electric field at the 13th beam hole. It was taken at a temperature of ~5K in a magnetic background field of $0.5 \cdot 10^{-4}$T. The maximum Q-value corresponds to a surface resistance of $10^{-7}\Omega$ (averaged over the total surface of ~3 m^2), which is about a factor of 5 more than the BCS-surface resistance at 5K and 170 MHz. Two curves belonging to constant heat dissipation are given. The data were taken about half a year after the PbSn layer was produced. The cavities had been exposed to the laboratory air without protective gas for several months, opened twice for surface inspections and closed without special dust free conditions. The maximum voltages were limited by field emission. The calibration was made by observing the energy gain of electrons from a ^{207}Bi source. Oscil- lations of the frequency caused by acoustic noise were less than 10 Hz. No ponderomotoric oscillations occured. Initial resonant electron emission (multipacting) at low field levels could be overcome after few minutes of operating the cavities in pulsed mode at a high power.

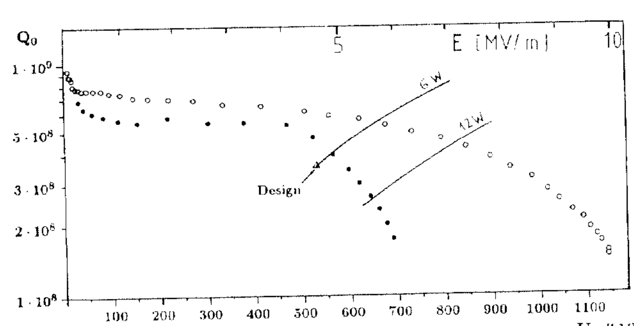

Fig.4. The unloaded Q_0 value of the first two Tritron cavities versus the maximum gap field at the 12th hole respectively the gap voltage at the last hole. Temperature 5K, background field 0.5G. In addition the design value and two lines of constant dissipated heat are shown.

THE MAGNETS

The Tritron magnets were designed to keep the field volume and the steel mass as small as possible. Each turn of the spiral orbit is guided separately by narrow window-frame magnets of total radial width of 4 cm (Fig. 5). The maximum induction is limited by the saturation of the steel to about 2T. Thus the overall current density of the superconducting coils can be chosen ≥600A/mm^2, and the radial width of the coil is small compared to the total width of the channel. The coils consist of 26 windings of a Rutherford-type cable. Two of them generate the field gradient. The coils are wound in situ by a computer controlled winding machine and then vacuum inpregnated with epoxy. A copper profile with a bore (Ø 11mm) for the beam shields the coil from beam losses. Flat disc springs between the copper profile and the coil prevent the coil from cracking off the steel frame. 20 neighbouring channels (30° bending angle each, no pole edge rotation) form one sector (sector angle 20°), which consists of two halves connected in the orbit plane. The magnets are indirectly cooled by cooling pipes on copper shields.

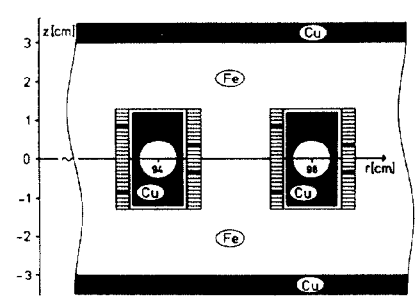

Fig.5. Cross section through a magnetsector showing two adjacent channels, G gradient windings, D insulation layers.

Because the beam is running in a distance of a few mm from the coil, 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. The gradient windings will produce higher order field contributions in addition to the linear term. Quadratic terms have to stay below $|\Delta B/B| < 5 \cdot 10^{-3}$ in a distance of 4 mm from the central orbit. Rather strong quadratic contributions occur at the entrance and exit of the channel. They can be compensated by symmetrical inserted insulation layers at the top and bottom of the coil.

In order to guide the beam along the central orbit the current of each channel has to be adjusted individually. The difference between maximum and minimum current of all channels is less than ~ 170A. 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 switched 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 ~ 3cm, which can be heated above the critical temperature with ~ 2mW by means of an Allen-Bradley resistor, glued on the filaments with epoxy (switch on/off times < 0.3 sec). 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 (~ $5 \cdot 10^4$ N/cm^2) to form the superconducting contacts.

The gradient windings of the radially focusing channels are without current, those of the axially focusing channels will be connected in series.

In total seven channel magnets have been tested. No training was needed. The maximum currents were limited only by the current leads respectively the current supply. Currents of more than 1800A were achieved, which is ~20% above the design value. The stray fields 35mm in front of the end plates of the channels are less than $5 \cdot 10^{-5}$T and will not impair the superconducting cavities. The quadratic field contributions were investigated carefully by means of Hall probes (differentially) and superconducting induction loops (integrally). The admissible limits could be observed. At currents above 500A the quadratic term is independent of the current, while the gradient seems to vary due to magnetisation effects of the steel and/or superconductor. This variation of some 10^{-2} can be tolerated. The field change of a channel with both switches superconducting was measured when the currents I_0=1000A in both neighbouring channels were varied by ±100A. The relative change was less than $\pm 3 \cdot 10^{-4}$.

CONCLUSIONS

The main purpose of the development of a small superconducting separated orbit cyclotron in Munich is to demonstrate the feasibility of this type of cyclotron. The encouraging test results of the first two superconducting cavities indicate, that possibly these cavities will not limit the range of application with respect to ion masses and energy. Rather the last injection channel (90°) may cause a limitation by the lack of bending power, because the bending radius of 30cm is smallest in the whole machine. The channels along the first turn of the spiral orbit have bending radii of 43cm.

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Table 1 Tritron design data

Injector		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/extraction radius		66 cm/145 cm
Turn separation Δr		4 cm
Number of turns		19.8
Harmonic number		17-58
Number of magnet sectors		12
Number of cavities		6
Magnet sector data:		
Number of magnet channels		20 (19)
Sector angle/bending angle		20° / 30°
Bending radius		430 mm/942 mm
Maximum magnetic field B_{max}		1.4 T
Radial gradients $\frac{1}{B}\frac{\delta B}{\delta r}$		3.6 m^{-1}, -4.9 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}		1400 A
Cavity data:		
Superconductor		PbSn on Cu
Gap lenght		~ 90 cm
Gap width		60mm....128mm
Rf-frequency		170 MHz
Maximum field E_{max}		4.6 MV/m
Maximum voltage at extraction		0.53 MV
Dissipated power P		6 W
Quality factor (unloaded) Q_o		$3.7 \cdot 10^8$
Geometry factor G		94 Ω
Surface resistance $R_s = G/Q_o$		$2.5 \cdot 10^{-7}$ Ω
Betatron osc.numbers Q_x		1.2....1.6
Q_y		0.8....1.7
Synchrotron osc.numbers		~ 0.2
Total weight		~ 10 tn
Total power		~ 400 kW
Refrigerator power		150W at 4.7 K

[1] U. Trinks, "Superconducting Cyclotrons", Nucl. Instr. and Meth. A287 (1990) 224-234
[2] Calculated with the 3-D code MAFIA. From the Q-value measured before electroplating with PbSn a value of 84 Ω was derived.
[3] L. Dietl, U. Trinks, "The Surface Resistance of a Superconducting Lead-Tin Alloy", Nucl. Instr. and Meth. A284 (1989) 293-295