NEW CYCLOTRON CONCEPTS

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Summary

By analogy with the development of conventional cyclotrons the next step in evolution of superconducting cyclotrons will be the separated sector cyclotron with superconducting magnets. At Munich the feasibility of such a machine has been studied (SuSe). This work has led to a new design of flat, superconducting sector magnets, which makes feasible the Tritron: an inexpensive separated sector cyclotron with transversal and longitudinal focusing as in a synchrotron (similar to SOC), which could be supplied with superconducting accelerating cavities. A Tritron with r_1 = 70 cm, r_2= 150 cm, E_1 = 5 MeV/u, E_2 = 22 MeV/u for Q/A = 0.5 is proposed, approved and partly funded.

The SuSe-Tritron Concept

Among the many types of heavy-ion accelerators, cyclotrons are most suitable for high precision experiments with light and medium heavy ion beams of high intensities and energies up to several 100 MeV/u. The largest existing conventional system is GANIL/Caen with T_{max} = 100 MeV/u for ions with specific charge Q/A = 0.5. The most advanced system under construction is the set of superconducting compact cyclotrons MSU I and MSU II at East Lansing/Michigan. This facility will accelerate heavy ions up to 200 MeV/u.

There are several aspects of high quality, high intensity ion beams of energies above 200 MeV/u up to about 1 GeV/u in research and applications, which justify some effort to further development of cyclotrons. Some of these topics are: studies of nuclear reaction mechanisms and of nuclear structure, production of exotic nuclei by projectile fragmentation, medical applications, π - meson factories and neutron spallation source.

Apart from the last three topics, for energies above ~1 GeV/u synchrotrons combined with storage and cooler rings and internal targets may become increasingly attractive because of a much more efficient use of the beam power. The cooler ring in Bloomington/Indiana and the SIS 18/ECR project at GSI/Darmstadt illustrate this development. For all high intensity, external target operation the cyclotron concept will be superior to the synchrotron system of course, at least for energies below ~1 GeV/u.

At Munich a project study was performed on a superconducting separated sector cyclotron [1] (SuSe) as a booster for the existing 13 MV-tandem to achieve at least the π-production threshold in free nucleus-nucleus collisions at about 300 MeV/u. From two reasons this type of cyclotrons was chosen. First, due to the fact that part of the returning magnetic flux can be led through the intermediate sectors by proper adjustment of the cross section of the iron yoke, the azimuthal field variation can be made large enough to provide easily the axial focusing forces even for the fastest particles. Secondly, the open design allows the installation of large cavities with extreme high accelerating voltages, thus providing clean injection and extraction, which are essential in order to achieve good beam properties.

A superconducting prototype sector coil of the magnets has been built and was tested, the accelerating cavities were developed, and a new type of superconducting channel magnets without stray field as injection elements for SuSe were designed. We will report on these topics in more detail below.

During the SuSe project study it became clear that it would be preferable to subdivide the system into two coupled accelerators instead of one. There were two reasons for this change in concept. First, originally it was planned to inject at a mean radius $\bar{r}_1$ = 40 cm and to extract at $\bar{r}_2$ = 240 cm, thus increasing the energy by a factor of up to ~60. But this design turned out to be not practicable because of space problems in the central region. Therefore it was decided to enlarge the injection radius to $\bar{r}_1$ = 75 cm, but to keep the extraction radius at $\bar{r}_2$ = 240 cm. Then an intermediate accelerator with an energy increase by a factor of four is needed (22 MeV/u for Q/A = 0.5). Secondly, there is no chance of getting a large system as SuSe funded within the scope of universities at the present financial situation, but a less expensive accelerator would be supported.

On the search for a new, cheaper cyclotron design one should reduce the cost of the most expensive parts of it, the magnets. The SuSe magnets including the cryogenic equipment e.g. would cost about 75% of the total accelerator and is by no means balanced to the rest. The new magnet design should improve the poor ratio of the field volume really needed for bending the particles to the field volume produced in the magnets (for SuSe this ratio would be less than some 10^{-3}). Instead of leading the returning magnetic flux from the particle orbits over long distances to the outside yoke, the flux lines should be kept as short as possible. This may be achieved by narrow window-frame magnets along the separated orbits with superconducting coils in order to keep the turn separation moderate. Then one gets an accelerator similar to the separated orbit cyclotron SOC, which was proposed first already 20 years ago [2,3].

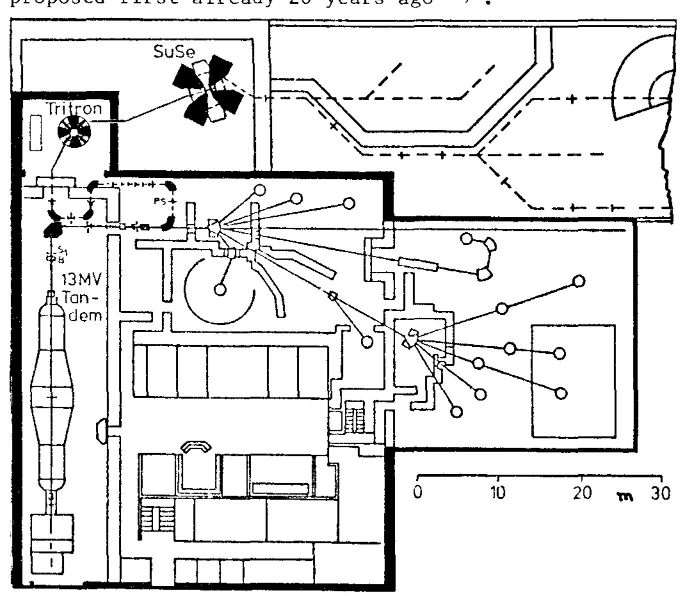

Fig. 1: Plan view of the Munich Accelerator Laboratory
Existing buildings
Planned extensions

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As in a conventional cyclotron the magnetic field at the central orbit has to fulfil the condition of isochronism. But in contrast to cyclotrons the radial gradient of the field in the channels may be set at will as in synchrotrons. From this it follows:

a) The axial focusing problems are irrelevant.
b) Even longitudinal focusing will occur.
c) The betatron frequencies may be kept constant.

Clearly one has to pay for these advantages with an increased expense for accelerating voltage. So there are typical features of a cyclotron, a synchrotron as well as a linac. Therefore we call it Tritron.

More details of the Tritron, which shall serve as intermediate accelerator between the tandem and SuSe, are given below. The Tritron will be installed in existing buildings of the Munich Accelerator Laboratory, a plan view of which is given in fig. 1. The Tritron is expected to cost about 2.5 M$, it is partly funded by the Federal Government of Germany.

The Project Study on SuSe

SuSe consists of four sector magnets and two accelerating cavities positioned in opposing sector gaps. A plan view of SuSe according to the original concept with $\bar{r}_1 = 40$ cm is given in fig. 2. Some significant features of SuSe and of some typical beams are summarized in tab. 1.

The Sector Magnets

Each sector magnet consists of a pair of superconducting main coils with two layers of superconducting trim coils between them, cold iron pole pieces inside the coil cases, and a large warm iron yoke. Fig. 3 shows a cross section of the magnets, tab. 2 gives some data.

The critical point for the design of the main coils is the central region. The coil width has to be small (6.5 cm) to keep sufficient space for the cavities between the magnets. The height must not be much more than the distance of the two sides of the sector coil in the tip of the coil (≲40 cm) in order to produce the field efficiently. Thus the current density must be as high as ~85 A/mm², so cryostatic stability of the superconductor is ruled out. The coil case is cast in one piece, made from AlSi9Mg. It divides the coil into three parts (see fig. 4). The outward directed electromagnetic forces, which try to make the coil more circular, are taken up by beams, which are fixed to the coil case by axial bolts. The cable (see fig. 5) is insulated by one layer half overlapped glass/capton/glass sandwich tape. The insulation of the potted coils is matched so that the Al-coil case prestresses the coil, when cooled from 300 K to 4.5 K. The coil case is cooled by means of two pipes with forced flow of two phase helium at 4.5 K, 1.2 bar. Thus all heat from outside is screened. The helium inside the cable serves as a heat sink in case of small heat inputs inside the coils.

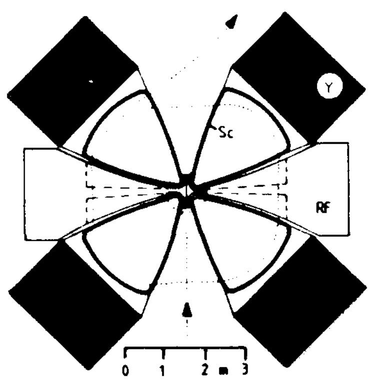

Fig. 2: Top view of SuSe. Sc: superconducting coil, Y: iron yoke, RF: accelerating cavity

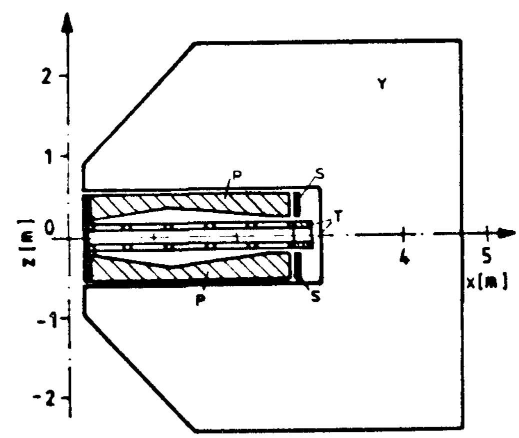

Fig. 3: Cross section of a magnet. S: main coil, Y: yoke, T: trim coil, P: cold iron pole piece

Tab. 1: Main features of SuSe

Injection radius $\bar{r}_1$	0.4 m (0.75 m)
Extraction radius $\bar{r}_2$	2.4 m
Average field at $\bar{r}_2$	2.25 T
Sector angle per magnet	≈50°
2 accelerating cavities	TE 101 mode
Resonant frequency range	59....74 MHz
Harmonic operation modes	5.,6.,...16
Max. accel. vol. per turn at $\bar{r}_1$	500 kV
Max. accel. vol. per turn at $\bar{r}_2$	2 MV
Beam separation at $\bar{r}_1$	>9 mm
Beam separation at $\bar{r}_2$	>2.5 mm

Ion	$^{1}_{1}H^{1}$	$^{3}_{2}He^{2}$	$^{12}_{6}C^{6}$	$^{32}_{16}S^{15}$	$^{58}_{28}Ni^{21}$	$^{197}_{79}Au^{94}$
T [MeV/u]	500	450	300	246	126	25
$\varepsilon_{x,y}$ [πmm mrad]	0.11	0.11	0.13	0.16	0.17	0.41
ΔT/T [10^{-4}]	2.0	1.0	1.0	1.7	2.3	3.1
bunch [psec]	33	22	16	17	19	46
intensity [pnA]	5000	1000	3700	18	10	1

Tab. 2: Some data of the magnets

Weight	~300 tn
Stored energy	≲25 MJ
Max. field at r = 2.5 m, z = y = 0	4.8 T
Max. field at the conductor	6.6 T
Gap height	8 cm
Main coil:	
Total weight	~2 tn
Coil case	AlSi9Mg
Total height	382 mm
Active height	294 mm
Active width	65 mm
Overall current density	≲84 A/mm²
Ampere turns	≲1.6 · 10^6 A
Number of double pancakes	23
Number of turns	598
Current in the cable	≲2675 A
Min. bending radius of cable	68 mm
Magn. pressure, radial	≲12 N/mm²
Magn. pressure, axial	≲20 N/mm²

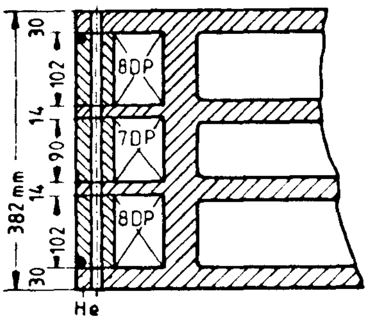

Fig. 4: Cross section of the coil. DP: double pancakes, He: liquid Helium

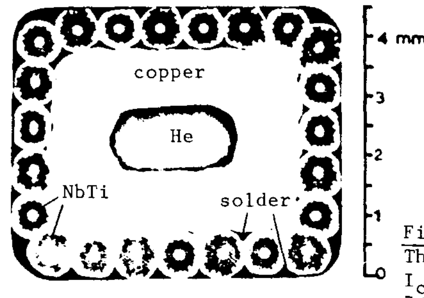

Fig. 5: The SuSe-cable. $I_c \lesssim$ 4300 A at 4.5 K, 7 T.

To demonstrate the feasibility a main coil was built by BBC/Mannheim and is tested now at Munich. Since October 1983 it is held cold below ~20 K with two interruptions for modifications. The refrigeration to 80 K with liquid N_2 takes ~4 to 5 days, then ~560 l liquid He are needed to achieve ~10 K (cold mass ~2 tn). The coil can be kept below 10 K at a helium flow of ~4 l/h.

The maximum current was 2800 A, which is more than the design value (limit: power supply).
No training has been observed so far. First of all the behaviour during a quench was studied. Then there were observed three shorts caused during the manufactoring of the coil. The influence of these shorts on the operation of the coil was examined. Furthermore first measurements of deformations due to electromagnetic forces were performed. These three topics will be discussed in more detail.

Fig. 6a) shows the current decrease after an artificial quench at I_o = 1310 A. After disconnecting the current supply (switch S in fig. 6b)) the current first decreases very fast (time constant $\tau_S \approx 0.6$ sec) to ~60 % of I_o, then the decrease slows down with $\tau_L \approx 7$ sec corresponding to the inductivity of the coil $L \approx 1$ H and the shunt resistor $R \approx 0.28\ \Omega$. Corresponding to the fast current decay in the coil a large current is induced in the coil case, which acts as a circuit with good coupling to the coil. The share of current depends strongly on the resistivity of the Al-alloy, while τ_S is determined mainly by L/R and the coupling of both circuits. This effect has several advantages. First, due to the fast current redistribution the whole coil quenches, thus hot spots in the coil are avoided. Secondly, the current in the coil itself is reduced. Last, the coil as well as the coil case is heated more uniformly, so thermal stresses are reduced. After the artificial quench at 2800 A the temperature of the coil raised to ~50 K. When the coil is energized with a rate $\dot{I} \leq 400$ A/h the heating due to induced currents in the coil case is negligible.

The shorts in the coil were detected by measuring the resistance of each double pancake in dependence of the temperature. Three shorts each across one turn were found, all in that part of the coil, which was manufactured first. It is likely that these shorts are positioned at the cross over of the innermost winding of the double pancakes. Because there was not sufficient space for the last double pancake in the first part of the coil, the double pancakes already completed were compressed by force afterwards. The second and third part of the coil were wound more carefully already from the beginning.

The shortened turns act as secondary circuits with good coupling to the coil. When energizing the coil opposing currents are induced in the shortened turns, which decay with a time constant given by the resistance R_S of the shortened turn. One of these turns has a time constant of ~4 min., from which follows $R_S \approx 10^{-8}\ \Omega$. If the magnetic flux increases too fast (due to an enhanced charging voltage across the coil) the heat produced in R_S may not be drawn off fast enough, or the opposing current may exceed the critical limits of the superconductor. Then the shortened turn may quench and cause a quench of the whole coil as well. Therefore the current rate has to be quite low, e.g. at I_o = 2800 A about $\dot{I} \lesssim 100$ A/h.

In order to measure the deformations of the coil due to electromagnetic forces different probes were installed. First results show quite good agreement with simple estimations. The maximum deformation of the central part of the coil was 0.08 mm at I_o = 1000 A. The deformations of the two other parts were about half of this value.

The RF-System of SuSe

The accelerating voltage at the extraction radius has to be at least 2 MV per turn at the extraction radius in order to achieve 2.5 mm turn separation. From space and power consumption reasons, a conventional dee system would not be appropriate. Therefore two wedge shaped cavities are chosen driven in the TE101-mode (length 3.2 m, height 2.4 m, width from 10 cm to 2 m, see fig. 2). The voltage is radially increasing with the maximum at the extraction radius. The frequency variation from 59 to 74 MHz corresponding to harmonic numbers 5 to 16 is achieved by changing the gap between the capacitively loaded accelerating lips inside the cavity. This technique has two advantages. First, at narrow gap the frequency is low and the transit time factor high, as it is needed for slower, heavier ions, which are accelerated at high harmonic numbers. Second, the cavity with wide gap is well adapted for the fast, light ions, which are accelerated at high frequencies

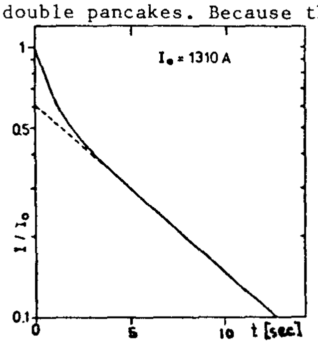

Fig. 6a): The current decrease after an artificial quench at I_o = 1310A.

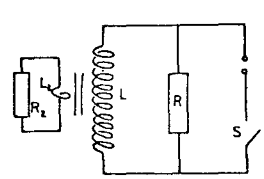

Fig. 6b): Circuit diagram of the coil and the coil case.

and low harmonic numbers and need the highest voltage. As the gap is wide the electric field remains at moderate values.

The cavities were optimized with respect to the power consumption by means of the computer code CAV3D for the calculations of three-dimensional cavities [4] and measurements on several models. Due to the bad mesh size the accuracy of the computer code is not sufficient to replace the measurements completely. But it is a valuable tool for getting informations about the effect of changes of the cavity shape, which would be difficult to predict otherwise. As a result of these investigations the power consumption of the two cavities would be in total about 700 kW at a maximum voltage of 1 MV each for the SuSe-design with small injection radius and about 400 kW for the new version with $\bar{r}_1 = 75$ cm respectively.

Superconducting Channel Magnets

Superconducting channel magnets without stray field [5] are essential for the injection and extraction system of SuSe. These magnets have to produce inductions of up to 2 T in a background field of ~2 T inside a narrow channel with a cross section of 1 x 1 cm² along the ion path. Because they are located in the vicinity of the circulating particles they must not produce significant stray fields in a distance of a few cm. A simple coaxial line with a cylindrical inner conductor and a coaxial outer conductor has no field outside but in between. However, due to the 1/r dependence of the inside field a coaxial magnet would not be suitable in general. Nearly any gradient is attainable, e.g. $\partial B/\partial x = 0$, if the cross sections of the inner and outer conductors are chosen in a proper manner. The inner conductor consists preferably of a bundle of parallel wires, which return on the outer conductor thus forming loops. There always exists a current distribution on the outer conductor which makes the field outside vanishing. This can be seen, if one thinks for a moment the outer conductor being a superconducting foil. Switching on the inner current there are surface currents induced in the foil, which hinder the magnetic flux from penetrating through it. The current distribution can be calculated by a fitting program with the wire positions as variables and the fields as goal of the fit (outside zero, inside the useful channel certain values). A superconducting septum magnet without stray field for the SuSe injection system (see fig. 7) is under construction.

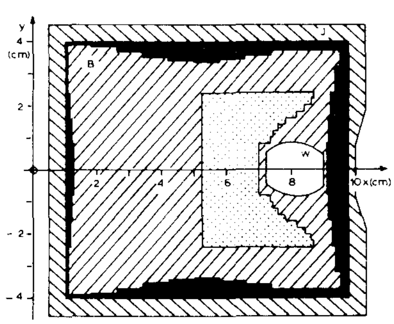

Fig. 7: Cross section of a superconducting septum magnet.

j = ±220 A/mm², $I_{tot} = 257$ kA turns, for $7 \leq x \leq 9$ cm: $B_y(x,0) = 2$ T.

The Tritron

As explained above between the tandem and SuSe an intermediate accelerator is needed, the Tritron. The Tritron is a separated orbit cyclotron with 12 sector magnets of 20° azimuthal width, consisting of 20 superconducting window-frame magnets arranged as neighbouring arcs. These 20 channel magnets can be gathered in one flat sector, which is produced by milling almost concentric slots every 4 cm in two sheets of iron and putting them together face by face, after having wound the coils inside (see fig. 9). The injection radius is $r_1 = 70$ cm, the extraction radius $r_2 = 150$ cm, so the factor of energy gain of ions will be somewhat more than 4 (maximum energy for protons: ~43 MeV , for ions with Q/A = 0.5: ~ 21 MeV/u). The total accelerating voltage of 3 MV per turn in maximum shall be provided by six superconducting cavities in every second intermediate sector (azimuthal width: 10°). Cross sections of the cavities (reentrant-type, TE 101-mode) are shown in fig. 8, which gives an overall view of the total design. The magnets and cavities (total weight <3 tn) hang on a torus shaped 500 l helium reservoir inside a large vacuum vessel (Ø 3.6 m). When the lower half of the vessel is removed immediate access is given to all parts of the machine. Thus complicated cryostats as well as vacuum chambers for the particles are avoided.

In the following sections the magnets, the superconducting cavities and some aspects of the beam dynamics of the Tritron are discussed.

The Tritron Magnets

The bending radius of the magnets was chosen quite large not only to keep the accelerating voltage moderate, but also to meet the demand for a field far below saturation of iron (<1.5 T). So the permeability of iron Fe + 1.8 % Si at 4 K is $\mu > 3000$. Then the width of the return yoke can be made as small as the window width. To get the coil width small (<3 mm), the current density has to be about 400 A/mm² , which is easily attainable because of the low magnetic field. The coils are potted and cooled through the iron. Of the remaining channel of 16 mm width about 12 mm can be used for the ion beams. As the tandem supplies the Tritron with beams of excellent quality, this width will be sufficient. In order to protect the superconducting coils from heating by beam losses a copper tube inside the channel serves as shield (see fig. 9).

The field gradient in the channels will be constant, the axial focusing is achieved by edge focusing (tilt 4°). The field is homogenous within ~10^{-4}, if the height of the window in the iron is constant and the coils with uniform current density fit the window height without gaps. If there are gaps of about 0.1 mm between the coils and the upper and lower border of the iron frame, then the field increases from the center towards the radial limits of the window by ~10^{-3}. This sextupole term can be used to compensate for the corresponding term of the stray fields at the entrance and exit of the channels.

Though there are in total 240 single channel magnets, only one power supply is needed, if all the coils are connected in series, each with its own (cold) shunt resistor and a superconducting switch in parallel. If the current in one coil has to be changed say from I_1 to I_2, first the current supply is set to I_1, then the switch is made normal conducting, now the current supply is set to the new value I_2, and the procedure is terminated by switching back to the persistent current mode. From magnetic field calculations by means of the code POISSON it follows, that the coupling of neighbouring channels is weak: a 3 % change of the field in one channel causes a change of less than 10^{-4} in the adjacent ones (at 1.5 T).

The Tritron Acceleration Cavities

The large turn separation of the Tritron leads to a considerable reduction of the cost for the magnetic bending system, on the other hand it causes enhanced effort at the accelerating system. At injection an accelerating voltage of about 1.4 MV, at extraction of about 3 MV per turn is needed. From considerations concerning the maximum electrical field, the transit time factor (gap width <10 cm) and the total power consumption the total number of cavities has to be at least

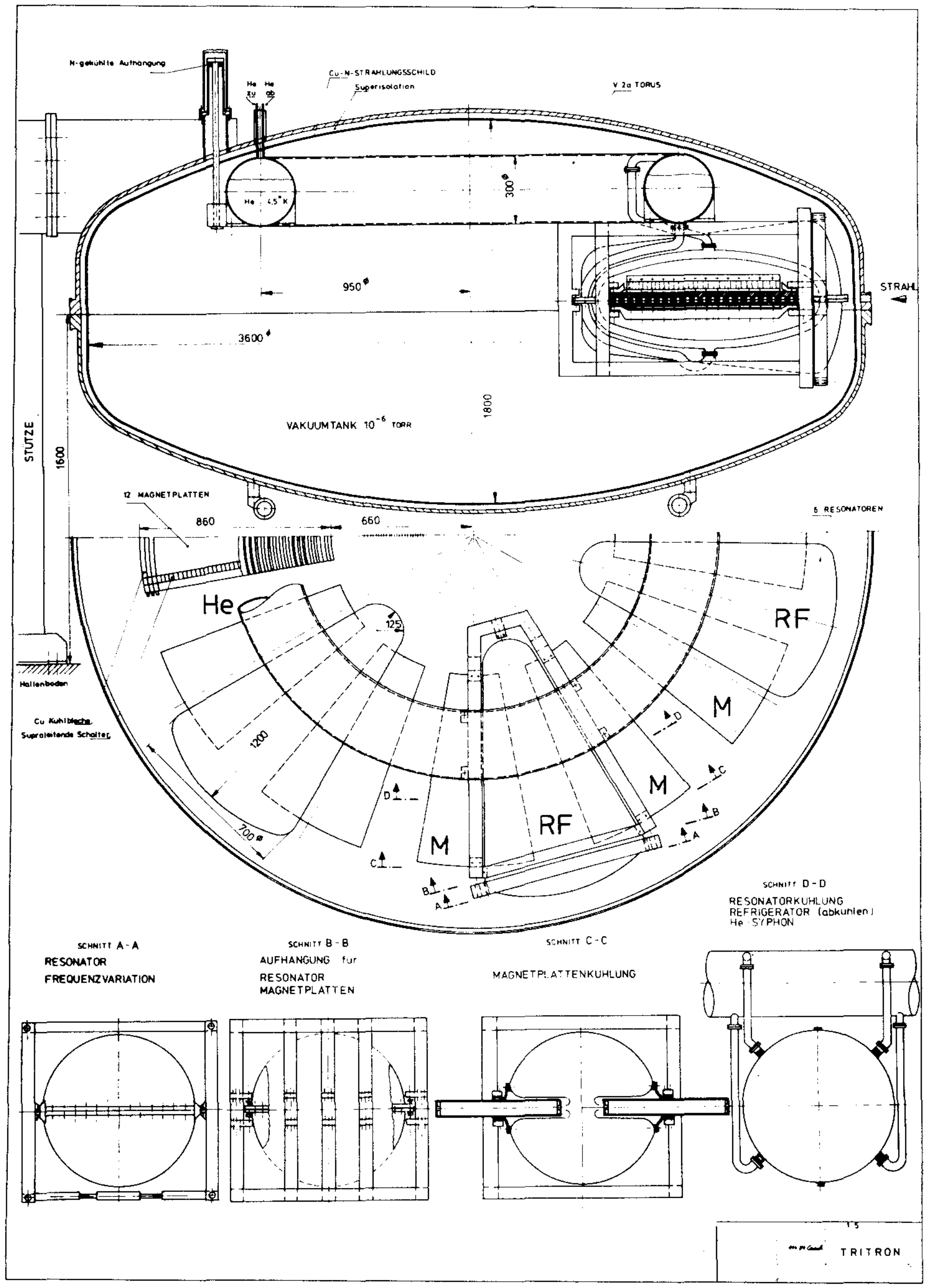

Fig. 8: Technical view of the Tritron.

Above: vertical cross section with vacuum vessel, 80K - shield, He-torus, accelerating cavity in supporting frame and sector magnet.

Centre: half plan view with magnets (M), cavities (RF) and the He-torus (He).

Below: several azimuthal cross sections,
A-A: frame for frequency variation
B-B: supporting structure
C-C: cavity with two magnets
D-D: cooling system of the cavity hanging on the He-torus.

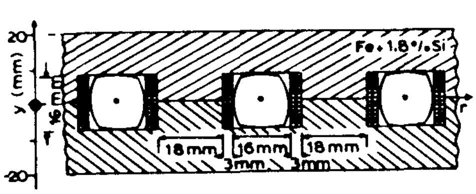

Fig. 9: Cross section of a superconducting Tritron magnet. B_{max}=1.5T, average current density 400 A/mm², iron yoke cold (4.5K).

six. Because there are needed at least four additional intermediate sectors between the magnets for the installation of beam probes as well as the injection and extraction system, the Tritron consists of in total 12 sector magnets and the same number of sector gaps.

The wedge shaped cavities have a length of 120 cm and a height of 70 cm (see fig. 8). The cavities are capacitively loaded by the accelerating lips, which enclose partly the flat sector magnets. The frequency is about 170 MHz corresponding to quite high harmonic numbers ≥19, which are acceptable because of the longitudinal focusing. As consequence the frequency range of the cavities has to be only about ±3 %. It may be achieved by simply pressing the cavities in azimuthal direction, thus changing the gap distance and the capacity respectively (without sliding contacts).

Because the power consumption of six conventional cavities would amount up to ~300 kW in total, and because this power would be produced in direct vicinity to the superconducting sector magnets, the cavities are planned to be superconducting as well. RF-superconductivity works only, if the magnetic background field is far below the critical field for the superconductor (for Nb: <1.9 T, for Pb: <0.8 T). Because of the short range of the stray fields of the magnets this condition is fulfilled for the Tritron.

The cavities consist of OFHC-copper sheets (6 mm thick), which are electroplated with lead as superconductor and cooled by two helium pipes. For frequencies less than 200 MHz the surface resistance does not decrease much more below 4.4 K, thus cooling with boiling helium is sufficient. From three reasons lead instead of niobium was chosen. First, on account of the large dimensions of the Tritron this technique is relatively simple and cheap. Secondly, the thermal conductivity of lead is nearly as good as that of copper and at least 10 times better than that of niobium. A good thermal conductivity helps considerably to hinder the spreading of normal conducting spots on the superconducting surface. Thirdly, the shape of the Tritron-cavities can be optimized with respect to the maximum magnetic and electrical fields, so that the superior critical data of niobium become irrelevant.

The development of superconducting cavities at Munich was startet with a somewhat smaller test cavity of rotational symmetry (see fig. 10). The diameter is 44 cm, the length of the accelerating gap 10 cm. The frequency in the TM010-mode is 490 MHz. The cavity consists of two shells with the seam along the line, pressed of 6 mm thick copper sheets. After polishing a quality factor of 34000 was measured, which corresponds to the value calculated by the code SUPERFISH. Then a layer of lead was electroplated on the copper shells. First measurements of the quality factor in the superconducting state are ~$5 \cdot 10^7$, about 40 times less than the theoretical maximum value. This difference may be explained partly by imperfections of the surfaces and partly by the fact, that the RF-currents cross the seam. To avoid these losses, the Tritron cavities will have the seam only in the plane of the particle orbits. Then in the ideal case of perfect symmetry no currents at all cross the seam. The maximum voltage attained in the test resonator at the first experiment was 440 kV, limited by the RF-power supply.

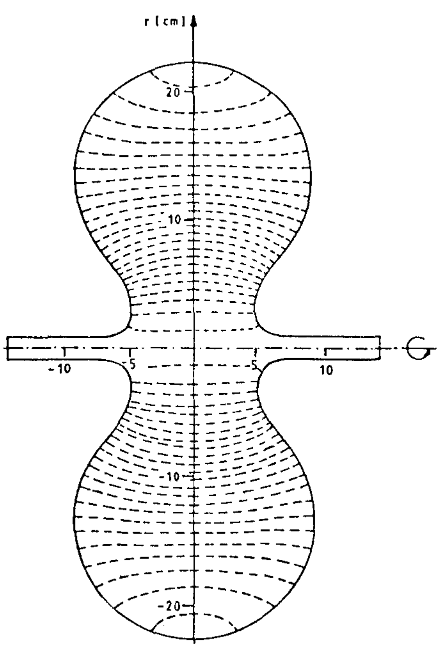

Fig. 10: The superconducting test cavity with electrical field lines.

Beam Dynamics in the Tritron

The free aperture for the ion beam in the magnet is only 12 mm in width. Thus the beam has to be well centered throughout the whole machine. The constant turn separation of $\Delta r = 4$ cm requires a well defined energy gain per turn depending on the radius. This energy gain can be achieved by choosing the proper central (synchroneous) phase with respect to the RF. This leads to a certain phase curve $\phi_s(r)$, which is obtained by small shifts of the phase from turn to turn, realised by a corresponding shift of the revolution frequency. This is produced by small ($<10^{-3}$)deviations from the isochroneous fields for the central particle. In order to get longitudinal focusing, ϕ_s has to stay between 90° and 180°. Computer calculations for a sinusoidal dependence of the accelerating voltage $U_o(r)$ with $U_o(r_2) = U_{max}$ have shown a typical phase shift from ~140° at r_1 to ~110° at r_2.

Due to the longitudinal focusing non central particles oscillate with a synchrotron frequency of about 0.1 to 0.5 per turn (thus in total ~5 to 8) in the longitudinal and radial phase space. For the expected longitudinal phase space of the injected beams the corresponding radial width is less than ~±3 mm.

The radial and axial betatron frequencies are in the range of 0.8 per turn. The betatron motions are superposed to the synchrotron oscillations, which leads to a total beam width of less than ±4 mm. More details about beam dynamics and tolerance problems are given in an internal report [6].

This work is based on the contributions of all members of the SuSe group, which consists of about 20 people. Thanks to all of them.

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