RESULTS OF THE TRITRON - PROJECT

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Abstract

The TRITRON is the prototype of a separated orbit cyclotron with superconducting rf-cavities and magnets. Recently it was demonstrated, that the principle works as anticipated. The magnets and rf-cavities operate very stable, reproducible and reliable. The main goals of the project were achieved. After a review of the conception of the TRITRON and the technical design results of the commissioning are reported.

1 INTRODUCTION

Cyclotrons are accelerators especially adequate for providing ion beams with high average intensity. In recent years an increasing demand for particle beams with average currents of more than 10 mA arose, for instance for the production of high neutron fluxes, for accelerator driven nuclear power plants, and for transmutation of nuclear waste [1].

The key to a high power / low loss cyclotron operation is a strongly increased accelerating voltage per turn, resulting in a turn separation of several cm instead of mm. There are three substantial reasons for this. First the longitudinal intensity limit in cyclotrons is proportional to the third power of the average voltage per turn. Second the extraction is facilitated in the region most critical for beam losses. Finally the large turn separation makes the use of independent magnetic channels with alternating gradients possible, resulting in both strong transverse and longitudinal focusing.

The required high accelerating voltages can be obtained with superconducting rf-cavities, because here the maximum voltage is limited by field emission, and not by cooling the dissipated heat as in conventional cavities. In view of the high acceleration voltages used the saving of dissipated rf-power is an additional advantage of superconductivity.

The total radial width of the magnetic channels is equal to the turn separation. A magnetic channel consists of a frame of steel with superconducting coils inside (window frame type magnet with bedstead type ends of the coils). Due to the high current density in the superconducting coils the width of the coils (3mm) is negligible compared to that of the steel frame and the window for the beam. Neighbouring channels can be combined to form a flat sector. By this the space is not occupied by big masses of steel, and the shape of the rf-cavities can be optimized. The stray field of the magnetic channels are of sufficiently short range, so that the rf-superconductivity of the cavities will not be influenced. The principle of this type of cyclotron was proposed already in 1963, though normalconducting at that time [2]. However superconductivity is needed in order to realise this new conception.

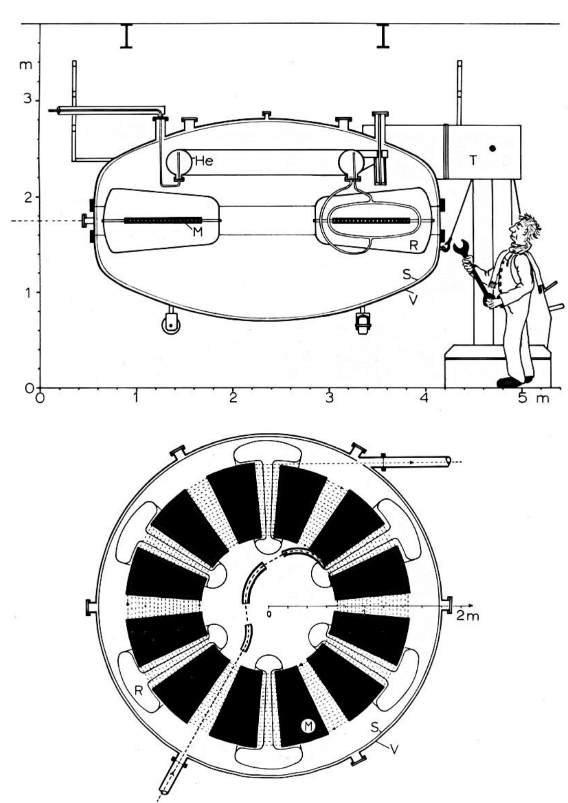

Figure 1. Cross sections of the TRITRON cryostat. V: vacuum vessel, S: 80 K-shield, M: magnet sector, R: rf-cavity, He: helium reservoir, T: support

2 THE TRITRON

According to the preceding considerations a small prototype of a separated orbit cyclotron, the TRITRON, was designed at the Beschleunigerlaboratorium of the

University of Munich and the Technical University of Munich [3,4,5]. The purpose of this project was to study the beam dynamics of such a machine theoretically, to develop the technology, and to demonstrate the feasibility of the principle of this new type of cyclotron. It is a rather small machine with the existing MP-tandem as injector, thus not a high current prototype device.

Fig. 1 shows cross sections of the TRITRON. The injection radius is 66 cm, the extraction radius 145 cm, the energy gain factor is about 5. Six sector-shaped rf-cavities (170.7 MHz) with 20 beam holes provide an acceleration voltage of 3 MV on the last turn. When the project was started it was unknown whether superconducting cavities of the type needed would operate at all. In order to keep the acceleration voltage low, the turn separation was chosen as small as possible (40 mm) resulting in an aperture of the magnetic channels of only 10 mm. Altogether 240 channel magnets with alternating gradients are arranged in 12 flat sectors, guiding the beam along 20 turns. Arrays of 20 small superconducting axial steerer magnets are positioned in three of the intermediate sectors. The radial and axial beam positions are measured by wire scanners installed in each second intermediate sector. The machine is hanging on a torus-like liquid helium reservoir under the upper half of the cryostat. The cavities and magnets are cooled indirectly by pipes connected to the torus. An additional pipe system for forced helium flow provides the cooling from 300 K to 4.5 K. The insulating vacuum of the cryostat is the same as for the beam, there is no separate vacuum chamber. Therefore the cavities are floated by normal laboratory air each time the cryostat has to be opened.

The cavities [6] are produced by an electroforming technique from copper and then electroplated with a thin layer (<5 10^{-3} mm) of $Pb_{96}Sn_4$, which becomes superconducting below 7.5 K. Each cavity consists of two halves, connected in the plane of the particle orbits. No rf-currents should cross the flat joint in the fundamental mode. The total length of the cavity is 1.233 m. The gap width is 62 mm at the first orbit, and 128 mm at the last. The maximum E-field is at the 13th beam hole, the maximum voltage at the 18th hole. The diameter of the beam holes is 13 mm. The ratio E_{peak}/E_{max} is less than 1.5.

Though not being handled under special clean room conditions the quality of the cavities stayed constant since the original electroplating procedures during the years 1990 to 1992. Typical curves of the unloaded quality factors versus the rf-voltage at the last beam hole are shown in Fig. 2. At voltages of 500 kV the dissipated heat per cavity is about 5 W. In order to remove multipactoring at all levels the cavities have to be conditioned with rf-pulses each time they had been exposed to air. Coarse tuning is made by mechanical deformation, fine tuning by sapphire rods (slow) and piezoelectric actors (fast). An electronic control system provides for stability of phases (1^o) and amplitudes (10^{-3}). The reproducibility is of the same order. Actual phase and amplitude settings are made by observing the shift of the radial position of the beam half a betatron-oscillation downstream the cavity.

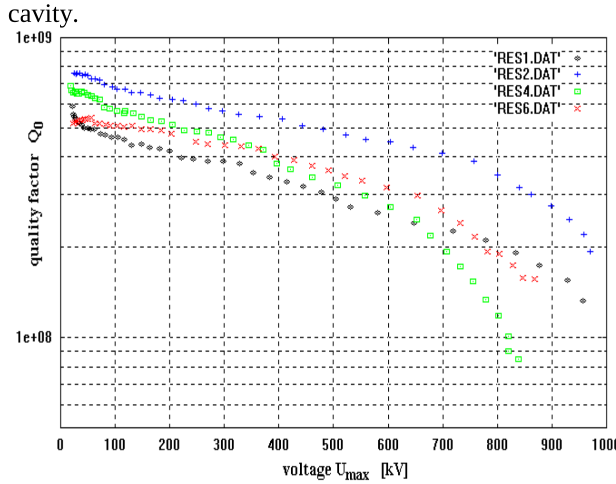

Figure 2. Typical curves of the unloaded quality factor of the Tritron cavities versus the voltage amplitude at the last beam hole.

The currents of the 240 magnetic channels have to be adjusted individually according to the respective momentum of the central particle of the bunch. This is accomplished by just one single power supply by bypassing the difference of the current of an individual channel and the main current in controllable superconducting switches across each coil. The fields are reproducibly correlated to the currents in the coils. There are neither leakage effects of the currents in the superconducting switches, nor hysterese effects of the steel, nor magnetization effects of the superconductor, nor cross talking effects from neighbouring channels observed ($\Delta B/B<10^{-4}$). Once the optimum field settings for a certain injection energy is found on the first two turns e.g. (with the cavities switched off), it can be used for further runs without any variations. The beam will appear immediately at the end of the second turn again with good transmission, as soon as the proper injection energy has been chosen, even if the magnets had been warmed up in the meantime. This stable and reproducible tuning facilitates the beam funneling considerably.

3 THE COMMISSIONING

All components of the TRITRON work very reliable, which can be seen from the fact, that the cryostat was kept cooled below 80 K at least since January 1997 except for three short warm ups for minor repairs of (1) broken wires of some probes, (2) problems with the driving linkage of a rf-antenna of one cavity, and (3) a broken piezoelectric actor of the fast fine tuning system of one cavity. Since January 1997 the TRITRON project had in total 10 weeks of beam time from the tandem injector. For all tests $^{32}S^{+14}$-ions were injected with typical currents of 10 pnA and an energy of 40.3 MeV (corresp. to h = 47), a relative energy spread of $8 \cdot 10^{-3}$, and a bunch length of 200 ps. Due to the small geometrical aperture of the channel magnets (10 mm) the injection phase and energy of the beam has to be stable within ±1° resp. $\pm 4 \cdot 10^{-5}$. Most of the beam time was needed to prepare the tandem to fulfil these requirements.

The following proceedure was used to adjust the magnet currents and the rf-cavity voltage phases resp. amplitudes in the TRITRON in a manner, that steady acceleration would result:

- 1. Still without voltage in the cavities, the currents of all magnets on the first two turns are adjusted to get the beam well guided to the end of the second turn.
- 2. The first cavity is switched on with a rather high voltage. The beam will be accelerated or deaccelerated according to the effective phase of the cavity voltage at the passage of the bunches. An energy shift causes betatron oscillations of the whole bunch, which can be detected as radial position shift most sensitively half a betatron oscillation downstream of the cavity (0.4 turn). By this method both zero phases can be determined. From the radial broadening of the beam the (focusing) zero phase with increasing voltage can be distinguished from the defocusing one. Furthermore the radial broadening possibly gives informations about the tilt of the longitudinal phase ellipse. Finally the actual phase setting of say 60° with respect to the focusing zero phase is put on the cavity.
- 3. The currents of all magnets downstream of the cavity are increased by a precalculated value, which corresponds approximately to a specific velocity increase of the bunches according to an isochronous motion. Then the voltage amplitude of the cavity has to be adjusted until the beam is well centered again in the succeeding channels.

The same proceedure has to be applied to the remaining cavities. If the last cavity has been set, the beam has to be funnelled by adjusting the currents of the magnets on the succeeding turns. If the specific energy gain per cavity on the first turn had been chosen appropriate to the injection energy, the momentum of the bunches resp. the bending power (*Br)* of the magnets will increase approximately linearly with the magnet number. However, generally the specific energy gain will be missed and the energy of the bunches will execute coherent oscillations with respect to the ideal course. At the worst there will be no steady acceleration at all. Then the phases and amplitudes of the cavity voltages have to be adjusted again starting with a different specific energy gain.

Following this proceedure the beam was guided along several turns with continuously increasing energy. Up to now the beam passed through 75 channel magnets to a maximum of six turns, finally having an energy of 72 MeV. The currents in the channels respectively the *Br*-values follow a straight line with small deviations. These deviations show two oscillations corresponding to two coherent synchrotron oscillations with the expected number 0.5 per turn (see Fig. 3). The observed betatron-oscillation numbers and the momentum compaction factor were in agreement with theory as well. In continuing to more turns the main problems are caused by different longterm instabilities of the tandem, which make the funneling process through the narrow channels along many turns difficult. This is not a principal limitation, but a consequence of the conservative design of the TRITRON as a prototype machine with rather small turn separation and narrow geometrical aperture. Based on the good results of the superconducting cavities future separated orbit cyclotrons can be planned with enlarged turn separation, say 10 cm, which would leave a geometrical aperture for the beam of about 5 cm. This would reduce the requirements on the stability of the injector considerably and make the acceleration of high intensity beams with low losses much easier.

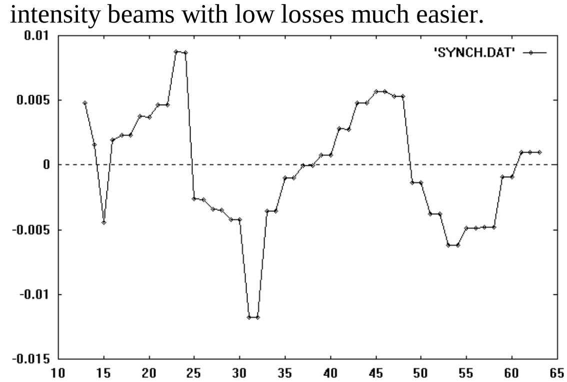

Figure 3. The relative deviations from linear increase, *ΔBr/(Br)*, versus the magnet number of turn 2 to 5, showing two coherent synchrotron oscillations.

4 CONCLUSIONS

The results of the test runs demonstrate, that the principle of a separated orbit cyclotron works as anticipated. The beam dynamics corresponds to theory. The experience of the last year proves a very stable, reproducible and reliable operation of all components. No aging effects were observed during a period of more than six years. This concerns particularly the superconducting switches and joints of the magnet system, and the superconducting cavities, which are handled under normal laboratory air conditions.

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REFERENCES

[1] H. Niefenecker, Nuclear Physics News, 4 (1994) 21.
[2] F.M. Russell, NIM 23 (1963) 229.
[3] U. Trinks et al., NIM A244 (1986) 273.
[4] U. Trinks, CAS-Proc. CERN 96-02, 187.
[5] U. Trinks, Proc. 14th Conf. on Cyclotr.and Appl., CapeTown 95, p 20, World Scient.,Ed:J.C. Cornell.
[6] T. Grundey, J. Labedzki, P. Schütz, U. Trinks, Nucl.Instr.and Meth. A306 (1991) 21.