THE HEIDELBERG HEAVY ION TEST STORAGE RING TSR

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Summary

A heavy ion test storage ring (TSR) is under construction at the Tandem-Post-accelerator combination of the Max-Planck-Institut für Kernphysik in Heidelberg. The ring will store ions up to a magnetic rigidity of 1.5 Tm corresponding to about 30 MeV/u for a charge to mass ratio of 0.5. The TSR is specially designed to investigate the electron cooling of heavy ions. The availability of a combination of partially and fully stripped heavy ions together with a cold intense electron bath (I - 1.0 A typically) of adjustable relative energy will provide unique possibilities for atomic physics investigations. The general layout of the TSR as well as the status of the major components is described. First injected beams are expected for late 1987.

General description

The Heidelberg Heavy Ion Test Storage Ring TSR [1] is an experimental facility for accelerator-, atomic- and nuclear physics now under construction at the MP-Tandem Postaccelerator combination [2]. The TSR is built in close cooperation with the GSI Darmstadt and working groups of the Physics Institutes of the Universities of Heidelberg, Gießen, and Marburg. Its main purpose is to study many still open questions related to electron cooling of heavy ions [3]. At the same time it will be a very valuable research tool for a large variety of atomic physics experiments especially investigating the interaction of free electrons and photons with fully or partially stripped heavy ions

The storage ring is located in a newly built addition to the existing hall of the accelerator complex as depicted in Fig. 1. The beam transport system of the post-accelerator will be extended by about 12.0 m into the new hall to facilitate the coupling to the ring. The injection transport starts with an achromatic system with two 45-degree dipole magnets. The injection proper consists of a 45-degree dipole, a thick magnetic septum and an electrostatic septum.

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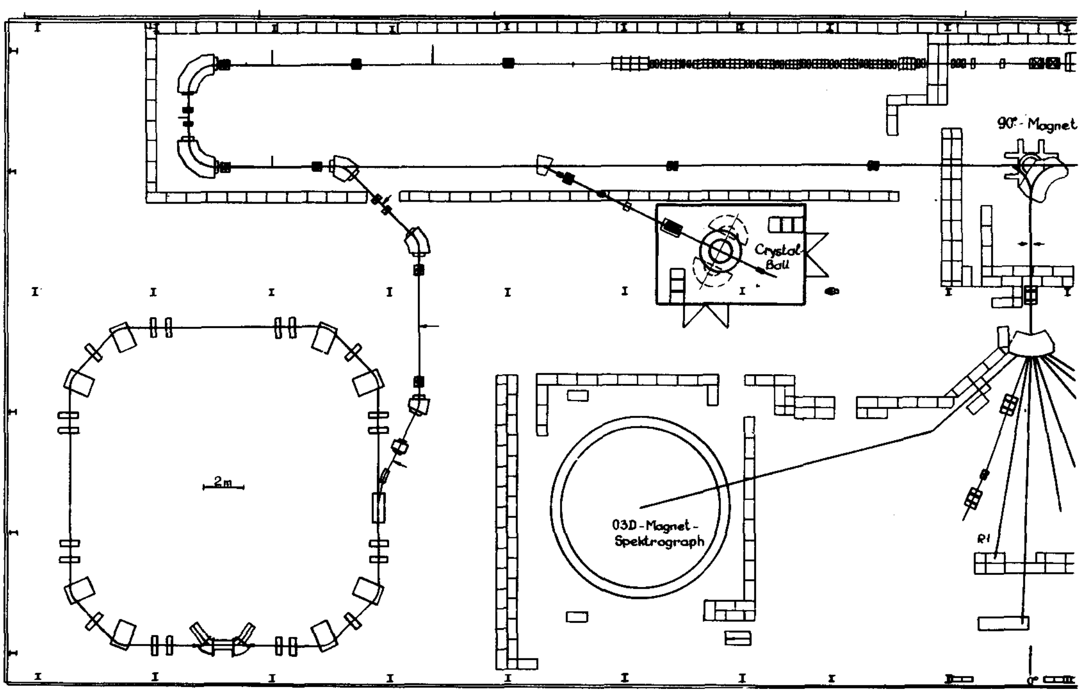

Fig. 1 Floorplan of the Heidelberg heavy ion postaccelerator and the Storage ring TSR. The beam transport of the Linac will be extended to facilitate injection.

Fig. 2 shows the layout of the TSR , Table I lists the basic parameters. The maximum magnetic rigidity possible is with $B \cdot \rho$ = 1.5 Tm only slightly higher than the rigidity of the beams delivered by the postaccelerator, which are typically 1.1 Tm ($^{12}C^{6+}$ 15 MeV/u, $^{127}J^{47+}$ 8 MeV/u).

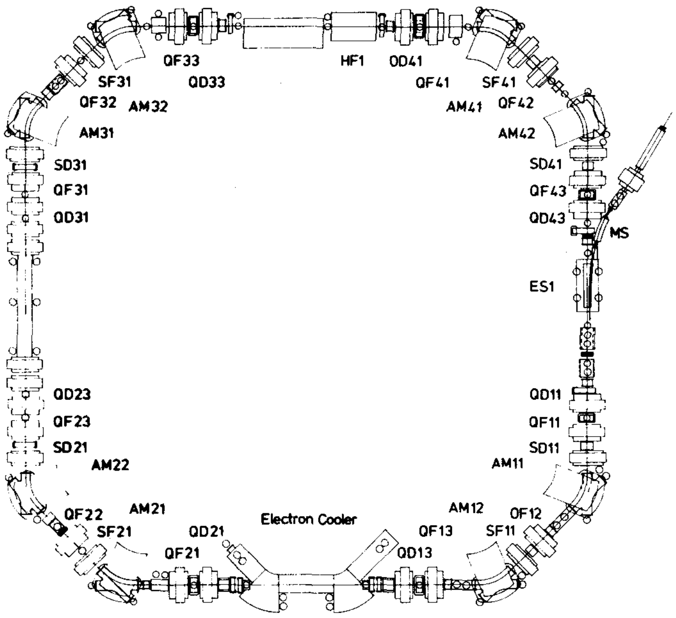

Fig. 2 Layout of the heavy ion test storage ring TSR with its main components. Th AMX deflection magnets, QDX and QFX quadrupole lenses, SFX and SDX sextupole lenses, HF1 stacking cavity, ES1 electrostatic septum, MS magnetic septum.

Table I

Basic parameters of the TSR

Magnetic rigidity B x p	1.5 Tm
Number of stored ions N	10^{10}
Circumference C	55.4 m
Mean radius R	8.8 m
Straight sections SS	4 × 5.2 m
Focussing period FP	QDFOBOFOBOFDQ
Superperiodicity S	2; 2 × (FP, -FP)
Betatron-Tune Q_x, Q_y	2.42, 2.25
Natural chromaticities Q'_x, Q'_y	-3.44, -5.5
Transition energy γ_{tr}	2.89
Vacuum P	$<10^{-11}$ Torr

The storage ring has a fourfold symmetry, its circumference is 55.4 m. Deflection is accomplished by eight 45 degree C-shape magnets (labeled AM11 to AM42 in Fig. 2). Always two dipoles with inbetween horizontally focussing quadrupoles (QFX2) form the center of one focussing period, which is completed on both sides by the quadrupole dubletts QDX1, QFX1 and QFX3, QDX2 and half the long So one focussing period has the structure FP-QDFBOFOBFDQ. In the main operation mode of the ring two antisymmetric focussing-periods (FP,-FP) form one of the two superperiods.

Fig. 3 shows the betafunctions β_x, β_y and the dispersion D [5] plotted for half the ring. The dispersion is set to zero in two long straight sections of the TSR, while it is finite and

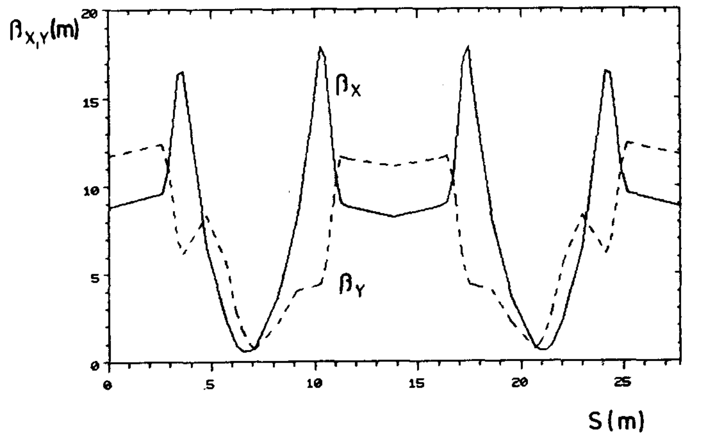

Fig. 3 a) Betafunctions β_x and β_y as calculated by the program MAD [5] for one superperiod of the TSR.

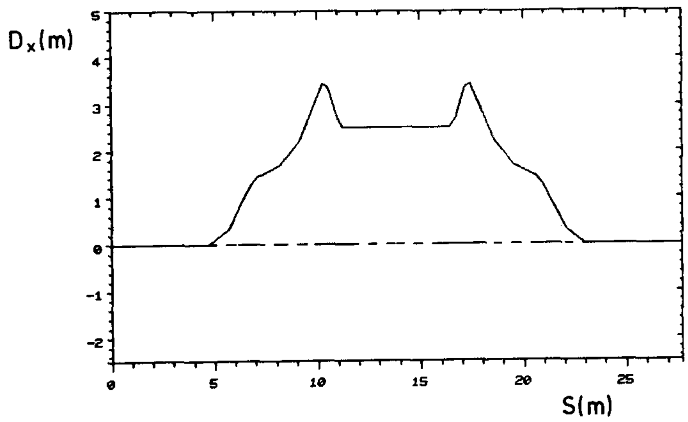

Fig. 3 b) Dispersion function D_x for one superperiod of the TSR.

adjustable to values around 2 m in the remaining two. The sections without dispersion are reserved for the electron cooler and the RF-system, while injection and experimental setups are to be found in the dispersive straights. The small dispersion and the large apertures of the ring elements will allow a "multichargestate operation". The principle of this mode can be seen from Fig. 4, which shows closed orbits through one superperiod for ions,

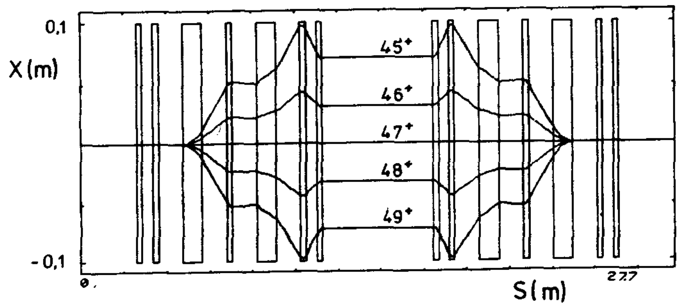

Fig.4 Closed orbits for particles deviating in momentum by $\Delta p/p$ = 0.02 simulating different charge states of ^{127}J.

that differ in momentum by steps of p/p- 0.02 from the momentum of the nominal particle. These steps correspond to differences of one chargestate for $^{127}J^{+}$ ions. It can be realized, that particles, that undergo chargechanging processes in non-dispersive sections, as for example in the electron cooler, will not be lost. If chromatic corrections by sextupole- and higher multipole families can be successfully performed, this feature of the TSR will be extremely valuable as chargechanging processes are the dominant loss mechanism in a heavy ion storage ring. Fig. 5 shows preliminary results of chromaticity corrections using two sextupole and two octupole families.

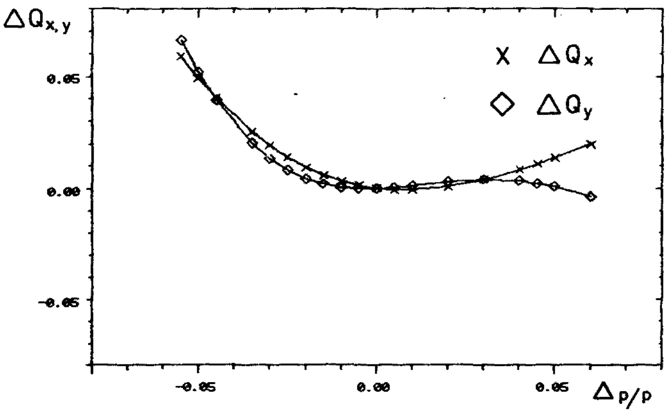

Fig.5 Results of chromaticity corrections by two sextupole and two octupole families. Plotted are tuneshifts Q_x and AQ_y vs. momentum deviation p/p.

Accumulation of ions in the TSR is done by a combination of two stacking methods, multiturn injection into the horizontal betatron phase space and RF-stacking into momentum space. Four bumper magnets displace the closed orbit towards the electrostatic septum (ES1), a ferrite loaded cavity (HF1) changes the momentum of the multiturn stacked beam by typically p/p - 0.03 thus clearing the space at the septum for further consecutive multiturn operations. Using pulse mode operated sputter sources [7] for negative ion injection into the MP-tandem will result in a total number of accumulated ions between 10^{10} for light ions (^{32}S) and 10 for heavy ones (^{127}J). For this a measured horizontal emittance of the postaccelerated heavy ion beams of E_x - 1.5 πmmmrad and an available horizontal acceptance of 120.0 πmmmrad is assumed as well as a measured momentum spread of p/p - 0.0005 together with a momentum acceptance of p/p - 0.03. Taking into account bunching efficiencies, losses in two strippers, transmission losses in the HP-Tandem and efficiencies in the two stacking processes gives equivalent numbers of turns between 50 for ^{12}C and about 500 for ^{127}J.

To further minimize charge changing losses for heavy ions in the TSR stringent vacuum requirements have to be fulfilled. The use of special grade stainless steel (316 LN), firing to 920°C and heating the assembled system to 300°C will ensure an operating pressure well below 10^{-11} Torr. Fig. 6 shows the results obtained in a 10 m long vacuum test section pumped by 2 ion getter pumps (65 1/s) and 4 Ti-sublimators. The ultimate pressure after 200 hours was 2.10^{-12} Torr.

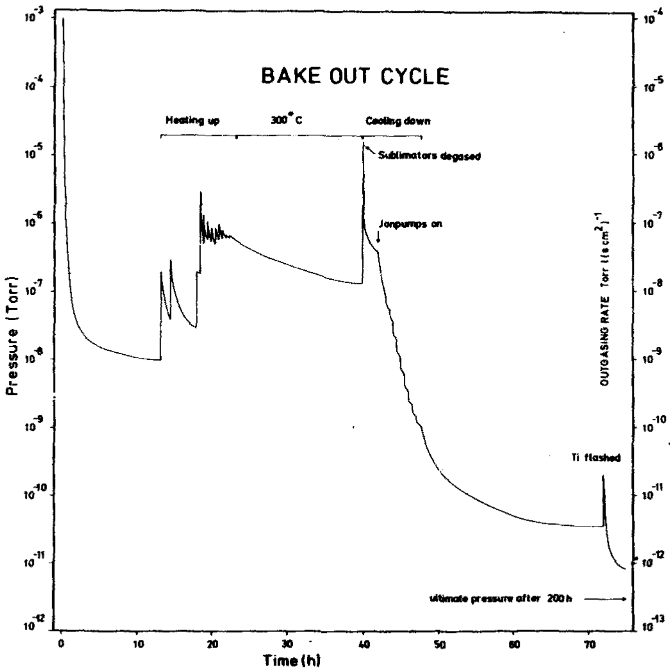

Fig. 6 Pressure and outgassing rate during a typical bakeout cycle of the vacuum. The final pressure obtained after 200 hours is $2\cdot10^{-12}$ Torr.

Status of major components

In the following section parameters and status of the major components of the TSR are described:

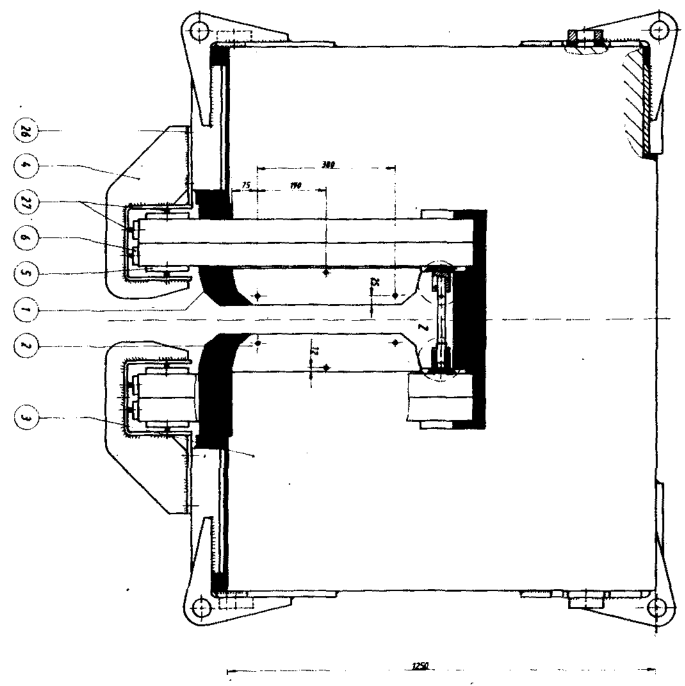

Fig. 7 Construction drawing of the TSR dipole magnet.

Dipole Magnets

The deflection magnets of the TSR, which have been designed with the help of the POISSON program [8], are eight curved 45 degree C-shape magnets with their yokes oriented to the inner side of the ring. A construction drawing can be seen in Fig. 7, the parameters are listed in Table II. The pole shoes are plane parallel without any shimming, as the computer simulations showed that the homogeneity over the full gap volume could not be ensured over the dynamic range of the magnet (0.2-1.3 T) by one simple shim form. A prototype of this laminated magnet (Fig. 8) was built in the workshops of MPI and carefully measured. The series production has started in industry.

Table II.

Basic parameters of th

Magnet type:	C shape
B_{max}	1.3 T
Deflection radius ρ	1.15 m
Gap height g	80 mm
Deflection angle φ	45 degrees
Poleface angle $\varepsilon_1 = \varepsilon_2$	22.5 degrees
Useful aperture	200 mm × 55 mm
Homogeneity in useful aperture B/B	2×10^{-4}
Mechanical length L	880 mm
Lamination	1 mm transformer steel (1400-100 A)
Iron weight	12.8 t
Copper weight	0.835 t

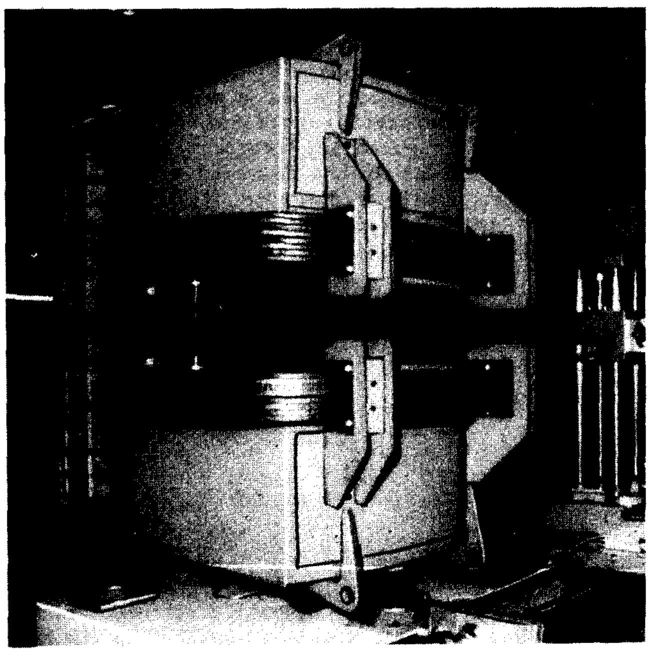

Fig. 8 Prototype of the TSR dipole during field mapping.

Quadrupole lenses

Without a possible low beta insertion the TSR needs a total of 20 quadrupole lenses which are grouped in alltogether 5 families. As the parameters of these families are not too different, only one type of quadrupole will be used in the ring because of cost reasons. Fig. 9 shows a photograph of the prototype built at MPI, Table III lists the basic parameters.

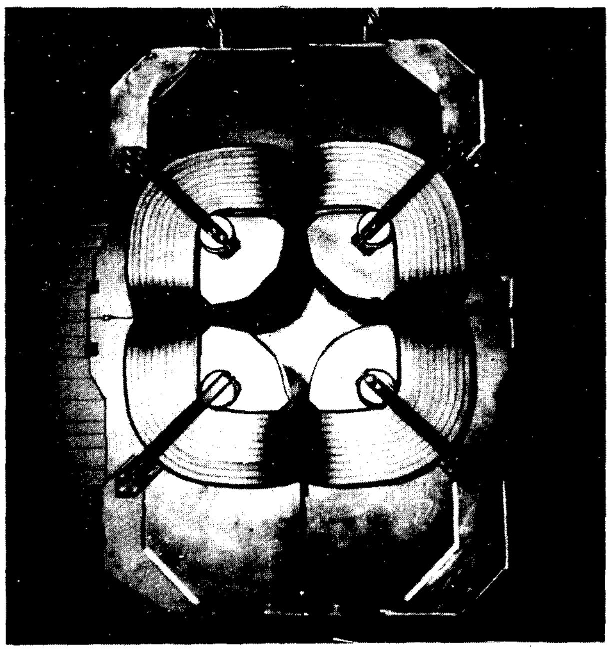

Fig. 9 Prototype of the TSR quadrupole magnet built at MPI.

Table III.

Basic parameters of the TSR quadrupole lenses

Magnet type	"figure of eight"
Gradient g	7.5 T/m
Magnet length L	0.25 m
Aperture radius r	0.1 m
Useful aperture a	200 × 100 mm
Lamination	1.0 mm transformer steel (1400-100 A)
Iron weight	1.9 t
Copper weight	0.36 t

The useful aperture has been enlarged to +/- 105 mm by shimming the pole edges with the simple shim shown in Fig. 10. In this diagram the ratio of integrated gradient at a given aperture position to integrated gradient at the lens center is plotted. A value of at most +/- 1.5 10^{-3} of this ratio ensures the optical properties needed. Measurements of the harmonic contents of the fields have been done by a rotating coil (Morgan coil [9]) and were analyzed according to the expression

$$B(r,\varphi) = \sum_n n a_n r^{n-1} \cos n \cdot \varphi \quad (1)$$

The ratios of the coefficients a_n to the quadrupole coefficient a_2 are given in Table IV.

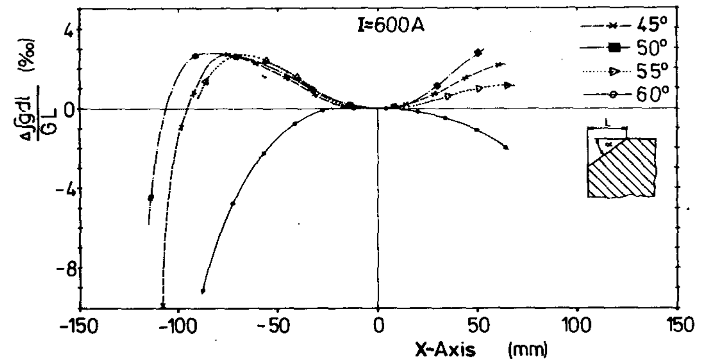

Fig. 10 Length-integrated gradient at horizontal position x divided by the integrated gradient at the lens center. The geometry of the simple poleend shim can be seen in the insert. The final shape selected is $\alpha = 45$ degrees and L = 15.0 mm.

Table IV

Harmonic coefficients a_n normalized to a_2 at different excitations

I(A)	a_3/a_2 (1/m)	a_4/a_2 (1/m^2)	a_5/a_2 (1/m^3)	a_6/a_2 (1/m^4)
210	$5.1\ 10^{-5}$	$4.6\ 10^{-6}$	$7.3\ 10^{-7}$	$<1.8\ 10^{-7}$
430	$1.5\ 10^{-4}$	$3.6\ 10^{-6}$	$6.5\ 10^{-7}$	$<1.1\ 10^{-7}$
840	$2.2\ 10^{-4}$	$4.0\ 10^{-6}$	$6.8\ 10^{-7}$	$<5.2\ 10^{-7}$

The Magnetic Septum

The magnetic septum (MS in Fig. 2) has to deflect the ion beam by 20 degrees and to transport it close to the storage ring. Due to the proximity to the closed orbit stray fields must The magnet, that does fulfil the requirements, is shown in Fig. 11. It has a radius of curvature of 2.08 m and a length of 0.7m. Having a laminated yoke and watercooled coils, it is as well suited for pulse as for DC operation. The construction of the magnet allows an easy separation of the upper and lower yoke to remove these parts from the vacuum chamber and by this facilitates the bakeout of the latter. Measurements with a hallprobe show an effective length of 0.750 m and a homogeneity of $\Delta B/B < 1.3\ 10^{-3}$ over a range of +/- 11 mm around the beam axis. The stray field at the location of the stored beam is only 2.1 G at the maximum field of 4.5 kG. The electrostatic septum (ES1) following in the injection line has to deflect the beam by 9 degrees. It will use a thin metallic foil instead of the usual wire arrangement, and is designed for a maximum electric field of E - 8.0 MV/m.

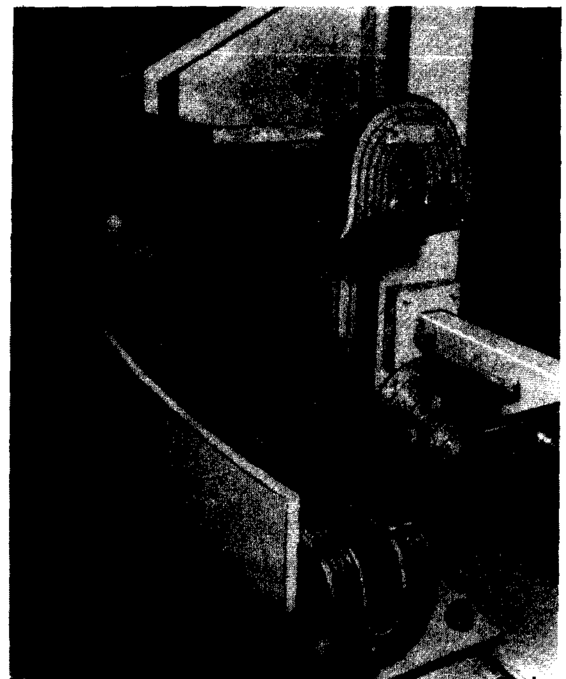

Fig. 11 Photograph of the magnetic septum of the TSR; upper and lower poles moved to extreme positions.

The Stacking Cavity

Rf-stacking of the multiturn injected batches requires the operation of a tunable accelerating cavity with only modest requirements on acceleration voltage. Fig. 12 shows a cavity salvaged from the ISR ring, that has been modified by the addition of 4 ferrite rings (type 4L2 Valvo) and a coarse tuning by manually adjustable vacuum capacitors. Coarse tuning is possible between 1.0 and 10.0 MHz, fast electronic tuning by magnetizing the ferrites can be done over a range greater than 5% at any set frequency. At a power input of less than 1 kW, accelerating voltages of 1kV can be obtained. A regulation system, modulating the excitation current of the ferrites according to the frequency ramp with a risetime of less than 1 msec and stabilizing phase and amplitude has been successfully tested.

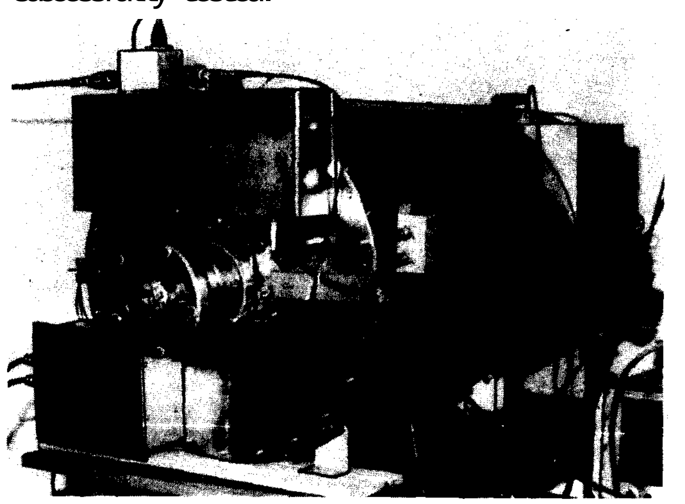

Fig.12 The former ISR cavity modified as stacking cavity for the TSR.

The Electron Cooler

For the first operation phase of the TSR an electron beam of about 1 A at an energy of typically 7 keV corresponding to the magnetic rigidity of ions of approximately 1 Tm is needed. Optimization and design of the electron gun and collector have been done with the program EGUN [10]; results of such computer simulations can be seen in Figs. 13 and 14.

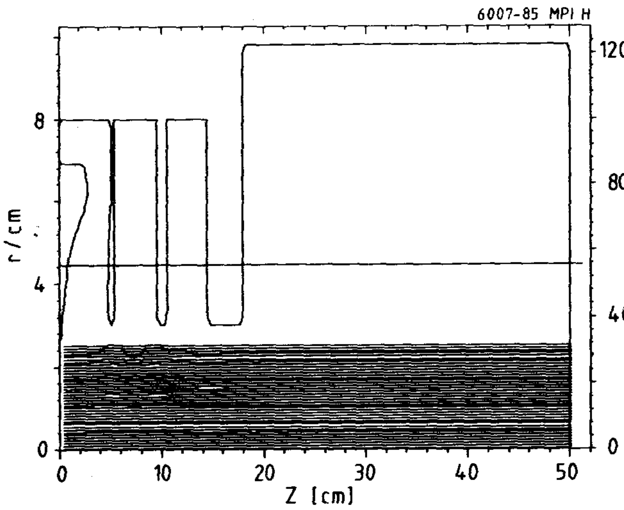

Fig. 13 Radial-axial cut through the electrode configuration of the electron gun. Plotted are electron trajectories as calculated by the program EGUN [10] and the axial magnetic field.

The gun cathode is a 50 mm diameter flat dispenser type in Pierce geometry. It is followed by a set of alltogether 5 cylindrical anode electrodes the potential distribution of which can be changed to give different perveances. Furtheron a specific potential distribution has to be set together with a correct solenoidal field to minimize the transverse electron temperature E_t. Applying this resonant focussing [11], a value of $E_t = 0.25$ eV can be obtained at an energy of 7 keV, a perveance of 1.67 μP, and a solenoid field of B = 0.05 T.

The collector geometry is shown in the computer result of Fig.14. It does resemble the construction used at the NAP-M storage ring [12]. The electron beam is finally stopped in a large cylindrical collector vessel with an entrance aperture of 70 mm. It is decelerated resonantly by an electrode configuration mirrorsymmetric to the cathode anode geometry and finally accelerated towards the collector, the potential of which is slightly positive compared to the potential of the gun. A rapidly decreasing magnetic field in the collector region, adjustable by two smaller correction solenoids, does diverge the electron beam over a large part of the collector surface thus reducing the power per unit area.

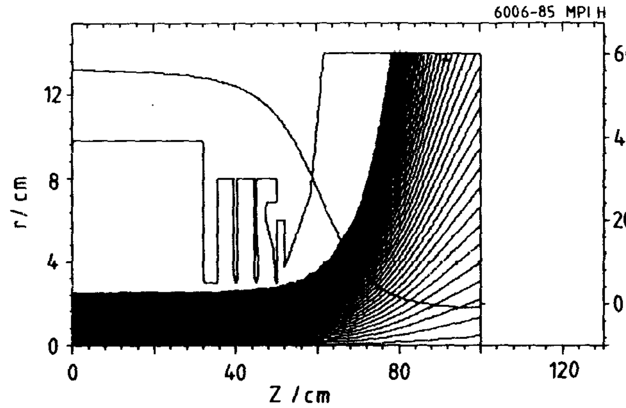

Fig. 14 Radial-axial cut through the electron collector showing trajectories of decelerated electrons as calculated by the program EGUN.

Tracking secondary electrons from the place of origin in the collector shows, that these are normally reflected by the magnetic field and the biased collector aperture except when the momentum vector is exactly in the opposite direction to that of the incident particle. For test of the major components of the electron cooler a straight experimental set up is being assembled, that can be seen in Fig. 15. In a 1.5 m long solenoid of 0.4 m inner diameter the gun, the collector and a diagnostic section will be tested under realistic conditions. Due to the stringent vacuum require-

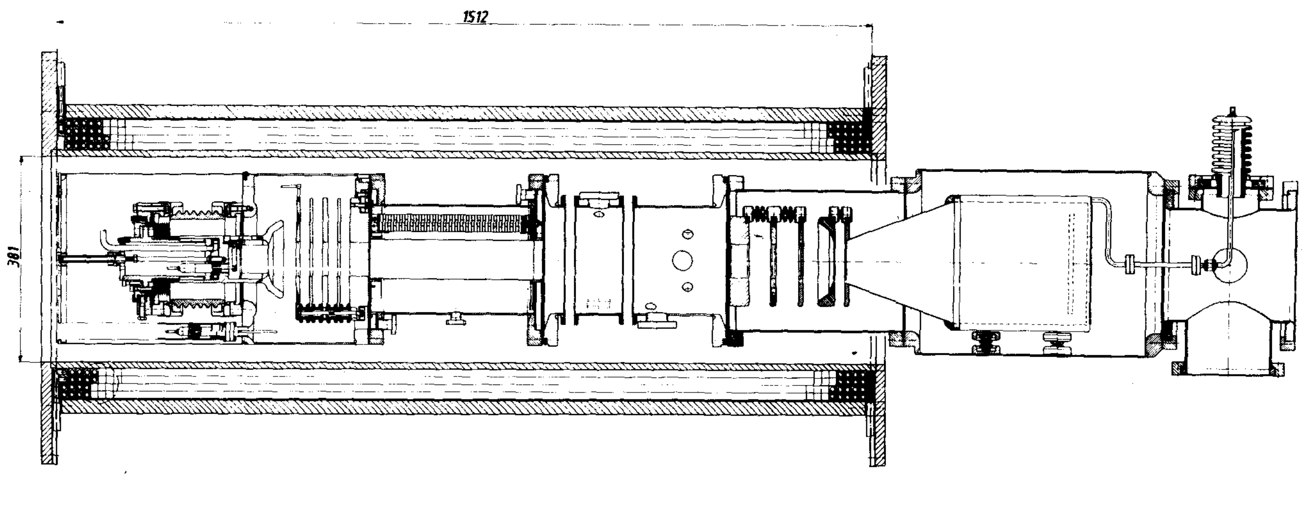

Fig. 15 Layout of the straight electron cooling test section.

ments in the TSR thorough investigations of vacuum properties of materials and pumping possibilities will be done. Non-evaporable getter pumps and titanium sublimators will be used to keep the pressure in the test section with running beam below 10^{-11} Torr.

Status and Time Plan

The major magnetic components of the TSR (dipoles and quadrupole lenses) are being produced in industry to be delivered and assembled by the end of 1986. They immediately will be installed at their ring positions in the newly built addition to the experimental hall. Completion of the ring and first tests to inject beam are anticipated for late 1987.

Acknowledgements

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Discussion

D.Bohne. You use a strong solenoid field to have the high efficiency of the ring. So you need the correction of chromaticity.

E.Jaeschke. You can compensate easily by quadrupoles.