

# Recent Developments at the Heidelberg Heavy Ion Cooler Storage Ring TSR \*

M. Grieser, D. Habs, R. v. Hahn, C. Ellert, C.M. Kleffner, J. Liebmann, R. Repnow,  
D. Schwalm, M. Stampfer, A. Wolf

MPI für Kernphysik und Physikalisches Institut der Universität Heidelberg,  
W-6900 Heidelberg, Germany

E. Jaeschke

BESSY, W-1000 Berlin, Germany

S. Papureanu

IFIN Bucharest, Romania

## Abstract

The Heidelberg Heavy Ion Storage Ring has been in operation since 1988 and is routinely used for atomic physics experiments. Electron cooling is used to reduce the phase space of the stored beam and for accumulation, which has resulted in stored intensities of up to  $3 \cdot 10^{10}$  particles. At these intensities transverse coherent instabilities have been observed. These transverse oscillations of the beam can be damped with an active feedback system. For acceleration and deceleration of ions, a novel accelerating resonator as well as an induction accelerator were built and installed in the TSR. In this paper recent developments at the TSR are reported.

## 1 INTRODUCTION

The Test Storage Ring TSR constructed at Max Planck Institut für Kernphysik for accelerator, atomic and nuclear physics studies is in operation since May 1988 [1]. The 55.4 m circumference ring with the maximum magnetic rigidity of 1.5 Tm receives light to heavy ions up to iodine from a 12 MV tandem Van-de-Graaff and normal conducting RF linac combination. Ion beam intensities of a few  $\mu\text{A}$  or less are limited by the modest output of the negative ion sources as well as by the stripping processes necessary for acceleration.

Accumulation in the TSR can be accomplished with a combination of multiturn injection and electron cooling stacking [2] -called ECOOL stacking. With ECOOL-stacking, intensities were enhanced by factors of several thousands compared with single turn injection, for example with  $^{32}\text{S}^{16+}$  ( $E=195$  MeV) an intensity multiplication factor of  $N \approx 4000$  was obtained. ECOOL stacking can also be combined with RF stacking [3]. With this method, a current of 18 mA for  $^{12}\text{C}^{6+}$  ions ( $E=73.3$  MeV) was reached. In table 1, the achieved intensities and lifetimes are listed for various ion species. The lifetimes were measured in the range of  $4\text{-}6 \cdot 10^{-11}$  mbar. For protons a lifetime of 60 h could be reached. One sees that with  $^9\text{Be}^+$  and  $^7\text{Li}^+$ , only a relatively low current can be stored because ECOOL-stacking is not efficient with these ions due to the short lifetime and small cooling force.

Table 1: *Energies, currents and lifetimes of some ion beams stored in the TSR.*

Ion	Energy [MeV]	Intensity [ $\mu\text{A}$ ]	lifetime [sec]
p	21	3300	220000
$^7\text{Li}^+$	13	12	48
$^9\text{Be}^+$	7	2	16
$^{12}\text{C}^{6+}$	73	18000	7500
$^{28}\text{Si}^{14+}$	115	960	540
$^{32}\text{S}^{16+}$	195	1500	450
$^{35}\text{Cl}^{17+}$	202	650	370
$^{63}\text{Cu}^{26+}$	510	110	240
$^{80}\text{Se}^{25+}$	480	110	204

## 2 THE FEEDBACK SYSTEM

With optimized electron cooling, currents up to 2 mA could be stored stably, limited by the onset of transverse coherent instabilities. The highest intensities of 18 mA  $^{12}\text{C}^{6+}$  beam only could be accumulated by misalignment of the electron beam with the ion beam. An active feedback system was installed in the TSR [4] to damp the transverse coherent oscillations of the beam. In figure 1 a schematic illustration of the feedback system is shown. The coherent beam oscillations are detected by a beam position monitor. The pickup signals from each electrode are first fed into an impedance transformers(IT), then subtracted with a hybrid. The difference signal is proportional to the collective beam oscillation. A closed orbit suppressor (COS) has been built into the preamplifier stage which allows a compensation of the differential pick-up output signal at any position of the closed orbit such that a closed orbit off center results in zero output signal. An output amplification stage with a total gain of 17.4dB amplifies the difference signal before being sent to the feedback delay stage. The feedback delay consists of a long doubly shielded cable which has a length such that the electronic delay time matches the time of flight of the particles from the pickup to the kicker. The power stage of the feedback loop consists of two 10W amplifiers with continuously adjustable

\*Work supported by BMFT

gain from 0 to 62 dB. The kicker consists of parallel electrodes. The useful bandwidth of the feedback electronics ranges from 40 kHz to 80 MHz.

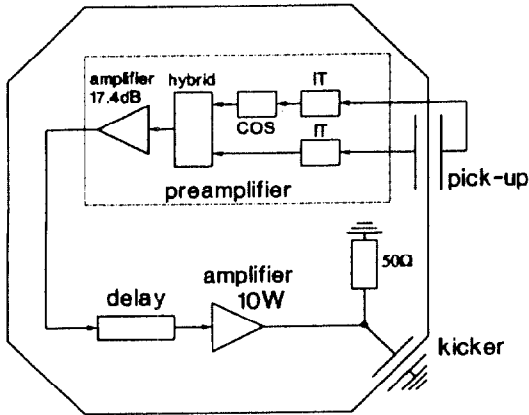


Figure 1: Block diagram of the transverse feedback system (COS=closed orbit suppressor)

A series of measurements was made to investigate the stability limits of a  $^{12}\text{C}^{9+}$  beam at 73 MeV with the transverse feedback system in operation. The beam was accumulated using ECOOL stacking resulting in stable currents of 1 mA. By continued injection of particles, the circulating beam current could be increased up to 5.5 mA, but particle loss occurred rapidly because the beam began to oscillate coherently with increasing amplitude. Near total loss of the beam occurred as the beam hit the vacuum chamber wall. With the feedback system acting to stabilize the beam, currents up to 9 mA ( $1.5 \cdot 10^{10}$  particles) have been accumulated and stored stably while being cooled with the electron cooler. When the feedback was turned off the current dropped rapidly. With the horizontal system only the beam could be stabilized up to approximately 2.2 mA. With only the vertical system active, the beam was again stable up to 9 mA. Figure 2 shows transverse Schottky spectra at the 11<sup>th</sup> harmonic of the revolution frequency (a) without feedback at 1 mA and (b) with feedback at 5 mA. A reduction of the lower sideband amplitude in figure 2 indicates the damping of the beam oscillations.

### 3 THE SYNCHROTRON RESONATOR

For acceleration and deceleration of ions, within the rigidity limits of the ring, an rf resonator [5] was developed and installed in the TSR. The  $\lambda/4$  line resonator filled with 20 ferrite rings is shown in figure 3. The variation of the resonance frequency is realized by changing the permeability of the ferrites with a d.c. magnetic field created by an external quadrupole. Each magnetic pole has a coil with 5 windings. In contrast to conventional designs the magnetization coils are completely outside the rf field of the resonator

A 10 kW transmitter has been built for the resonator. At maximum input power, a resonator voltage of 5 kV was

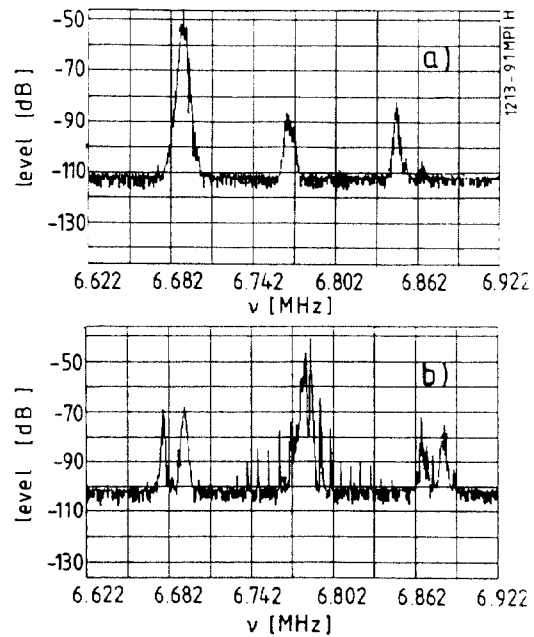


Figure 2: Transverse Schottky spectrum showing the betatron sidebands due to the coherent oscillation without feedback (a) and with feedback (b)

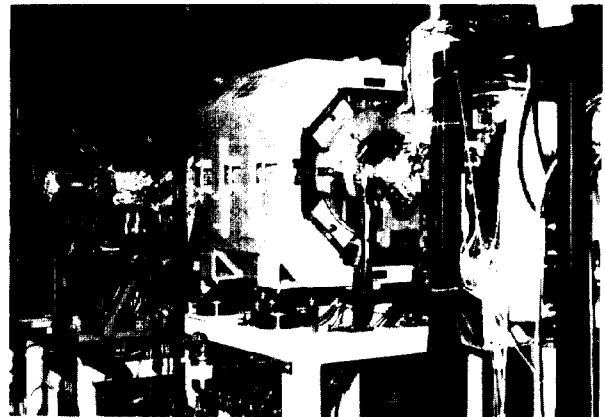


Figure 3: The new quadrupole ferrite loaded resonator

obtained. The resonator can be operated in a frequency range from 0.5 to 8 MHz. Figure 4 shows the dependence of the resonance frequency on the bias current for different loading capacities, parallel to the acceleration gap.

As shown in figure 4 a frequency variation of about 7 MHz was achieved with a loading capacity of 190 pF and a bias current of only 160 A. A frequency variation of more than 2MHz per second was obtained.

### 4 THE INDUCTION ACCELERATOR

In contrast to the rf resonator, the induction accelerator [6] is a device for varying the energy of the coasting beam. The scheme of the induction accelerator is shown in figure 5. A toroidal iron core encloses the stored ion beam. A time varying current through the  $n_1$  primary windings produces a varying magnetic flux inside the iron, which in-

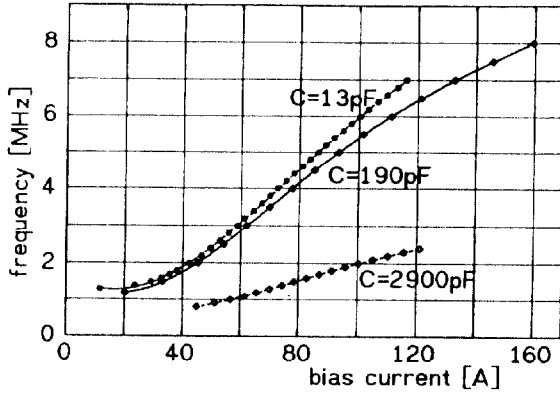


Figure 4: Resonance frequency versus bias current for different loading capacities.

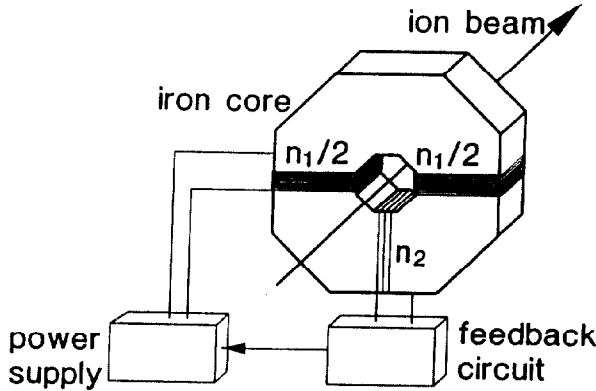


Figure 5: Principle of the induction accelerator ( $n_1$  and  $n_2$  denoting the number of turns of the primary and secondary coil)

duces an electric field to accelerate the ions. The induced voltage in the  $n_2$  secondary windings is fed into a feedback system. This feedback system regulates the primary current.

The total energy change  $\Delta E$ , of the ions of charge  $Q$  and revolution frequency  $f$  passing the induction accelerator is given by the following formula :

$$\Delta E = Qf\Delta\Phi$$

Where  $\Delta E$  is essentially determined by the flux change  $\Delta\Phi$  created in the iron core by the change of the primary current. The maximum flux change allowed by the saturation field strength  $B_{sat}$  of the ions is  $\Delta\Phi_{max} = 2 \cdot A \cdot B_{sat}$ , where  $A$  is the cross section of the core. For example, with  $B_{sat}=1.5$  T and  $A=0.124$  m<sup>2</sup>, the maximum energy shift of  $C^{6+}$  beam at 73.3 MeV is 1.4 MeV.

This device was used to measure the velocity dependence of the friction force of the electron cooling. The cooling force  $F_e(v_r)$  was balanced with the induction force  $F_{ind}$  of the accelerator:  $F_e(v_r) + F_{ind}=0$ . The ion velocity  $v_r$  relative to the average velocity of the electrons could be measured with Schottky noise analysis. The measured cooling force for deuteron ions ( $E=12.2$  MeV) at a solenoid magnetic field of 403 G is shown in figure 6 after normalizing

to an electron density of  $10^8$  cm<sup>-3</sup>. The expected linear dependence of the friction force of  $v_r$  is observed for the low velocity points (dashed straight line). In the high velocity region, there is clearly a deviation from the  $1/v_r^2$  dependence of the simple model as predicted by the more detailed theory [7].

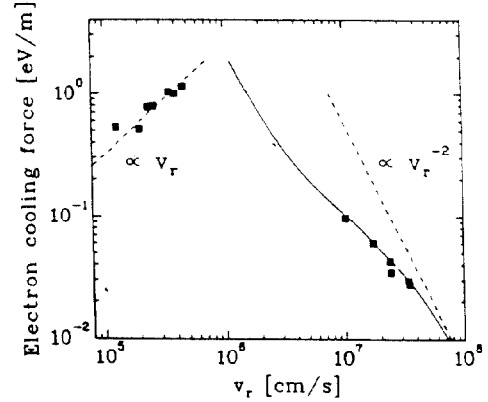


Figure 6: Longitudinal electron cooling force as a function of the longitudinal relative velocity  $v_r$  between the ions and electrons.

## 5 ACKNOWLEDGEMENT

We gratefully acknowledge the skillful and enthusiastic work of the technicians at the Max-Planck-Institute.

## 6 REFERENCES

- [1] E. Jaeschke, D. Krämer, W. Arnold, G. Bisoffi, M. Blum, A. Friedrich, C. Geyer, M. Grieser, D. Habs, H. W. Heyng, B. Holser, R. Ihde, M. Jung, K. Matl, R. Neumann, A. Noda, W. Ott, B. Povh, R. Repnow, F. Schmitt, M. Steck, E. Steffens, The Heidelberg Test Storage Ring for Heavy Ions TSR, Proc. European Particle Accelerator Conf., Rome, 1988, ed S. Tassari (World Scientific, Singapore, 1989), vol. 1, p. 365
- [2] M. Grieser, D. Habs, R. v. Hahn, C. M. Kleffner, R. Repnow, M. Stampfer, E. Jaeschke and M. Steck, Advanced Stacking Methods Using Electron Cooling at the TSR, 1991 IEEE Particle Accelerator Conference, San Francisco, vol. 5, p. 2817
- [3] G. Bisoffi, M. Grieser, E. Jaeschke, D. Krämer and A. Noda, Radio Frequency Stacking Experiments at the Heidelberg Test Storage Ring, Nucl. Inst. and Meth. A287 (1990) 320.
- [4] M. Stampfer, diploma thesis, Heidelberg 1992.
- [5] M. Blum, M. Grieser, E. Jaeschke, D. Krämer, S. Papureanu, A New Type of Acceleration Cavity for the Heidelberg Test Storage Ring, 1990 European Particle Accelerator Conference, Nice.
- [6] Ch. Ellert, D. Habs, E. Jaeschke, T. Kambara, M. Music, D. Schwalm, P. Sigray and A. Wolf, An Induction Accelerator for the Heidelberg Test Storage Ring TSR, submitted to Nucl. Inst. and Meth., Section A.
- [7] A. Sørensen and E. Bonderup, Nucl. Instr. and Meth. 215 (1983)27.