# Ion Beam Acceleration and New Operation Modes at the TSR Heidelberg *

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*Abstract*

A newly designed radio frequency cavity was used at the storage ring TSR in Heidelberg to accelerate stored $^{12}C^{6+}$ ($E_0 = 73.3$ MeV) beams. It was possible to accelerate about 90% of the stored particles by more than a factor of three in kinetic energy ($E_{fin} \approx 240$ MeV). A new operating mode of the machine close to the transition energy was also investigated. Up to 10 $\mu A$ $^{12}C^{6+}$ and protons could be stored, however the beams were susceptive to longitudinal instabilities. For 21 MeV protons ($\gamma = 1.02$) a $\gamma_{tr}$ parameter of 1.04 could be reached. A new method to produce a beam of polarized ions, based on spin selective attenuation by a polarized atomic hydrogen target was successfully proved with 23 MeV protons. To minimize losses of the beam particles the TSR was operated in the low-beta- mode. After one hour a beam polarization of 0.014 was achieved.

## 1 INTRODUCTION

The Test Storage Ring TSR [1] installed at Max Planck Institut für Kernphysik is used for accelerator, atomic and nuclear physics experiments. The 55.4 m circumference ring with the maximum rigidity of 1.5 Tm receives heavy ions up to iodine from a 12 MV Van de Graaff and a normal conducting RF linac combination. Electron cooling is used to reduce the phase space of the stored beam and for accumulation [2], which resulted in stored intensities up to 18 mA $^{12}C^{6+}$ ions ($3 \cdot 10^{10}$ particles ). 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 60h could be reached. To study dissociative recombination processes [3] between molecules and electrons, $HD^+$ (E=2 MeV) molecular ions were stored with a beam lifetime of 5s at $1 \cdot 10^{-10}$ mbar.

## 2 BEAM ACCELERATION

For acceleration and deceleration of ions a $\lambda/4$ resonator [4] filled with 20 ferrite rings was developed. 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 magnetic quadrupole shown in figure 1.

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

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

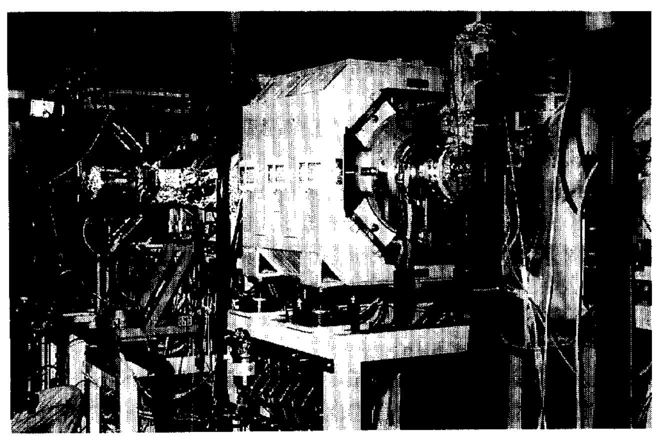

Figure 1: *The ferrite loaded quadrupole resonator.*

Each magnetic pole has a coil of 5 windings. In contrast to conventional design the magnetization coils are completely outside the rf- field of the resonator. The resonator can be operated in a frequency range of 0.8 to 7 MHz. This resonator was used to accelerate stored $^{12}C^{6+}$ ($E_0 = 73.3$ MeV) beams without phase feedback loop. It

*Work supported by BMFT under contract No. 06HD525I





0-7803-1203-1/93$03.00 © 1993 IEEE

was possible to accelerate the stored particles by more than a factor of three in kinetic energy ( $E_{fin} \approx 240$ MeV) corresponding to an increase of the revolution frequency of 0.7707 MHz to 1.394 MHz with particle losses of less than 10%. Consider into account saturation effects all magnetic fields were changed synchronously. Particle losses during the acceleration depends on the resonator voltage. Figure 2 shows the fraction of ions stored after the acceleration.

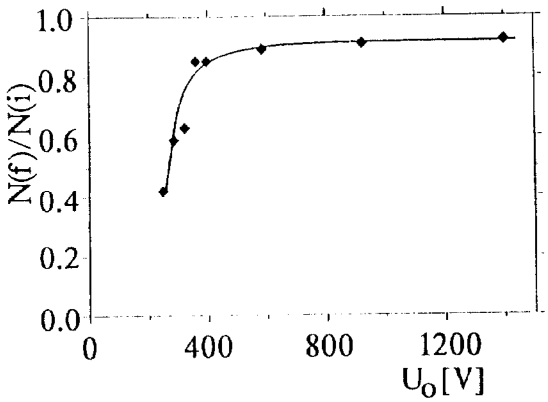


Figure 2: *Fraction of ions stored after acceleration from 73.3 MeV to 240 MeV for different acceleration voltages.*

The maximum attainable energy for $^{12}C^{6+}$ was about 300 MeV corresponding to a rigidity of 1.44 Tm.
Electron cooling was applied at a carbon energy of 130 MeV to decrease the momentum spread after acceleration from $8 \cdot 10^{-3}$ to $1.5 \cdot 10^{-4}$. With electron cooling a horizontal and a vertical beam diameter of about 1 mm was obtained.

## 3 THE LOW-BETA MODE

The application of internal atomic beam targets or storage cells demands a $\beta$-function at the position of the target to be as small as possible to increase the acceptance angle: In order to achieve these requirements the TSR is operated in the low-beta mode. This mode was used to produce a polarized proton beam (E=23 MeV). The new polarization method is based on spin selective attenuation in a polarized target [6]. Electron cooling was used to compensate heating and energy losses in the target. The longitudinal B-field (0.02 T) in the cooler was compensated with two correction solenoids. The target consists of a Teflon coated storage tube of 11 mm diameter and 250 mm length, cooled at 100 K. To determine the target density the deceleration of the stored proton beam without electron cooling was measured. A typically value of $6 \cdot 10^{13} H_1/cm^2$ for a target polarization of 0.8 was achieved. The beam lifetime of the protons was about 5 h without and about 30 minutes with polarized gas. These measurements result in an acceptance angle at the target of 4 mrad. A proton beam of typically 0.8 mA was accumulated with electron cooling stacking. After one hour storage time a polarization of the remaining beam (about 100 $\mu$A ) of 0.014 could be measured [6].

The calculated horizontal ($\beta_x$) and vertical ($\beta_y$) $\beta$-functions and the dispersion function (D) of the low-beta-mode obtained with the computer code MAD [5] are shown in figure 3. The calculations predict $\beta$-functions of $\beta_x$=0.8m and $\beta_y$=0.8m at the target position.

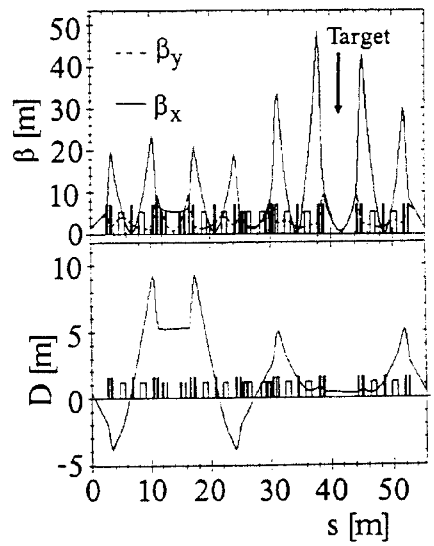


Figure 3: *Calculated $\beta$-functions and dispersion of the low-beta mode.*

## 4 OPERATION OF THE TSR CLOSE TO THE TRANSITION ENERGY

A new operation mode close to transition energy was also investigated, since for sufficient small currents and strong cooling intra beam scattering (IBS) is expected to be strongly suppressed, as already observed for protons in the NAP-M storage ring at Novosibirsk [7]. This is especially of great interest for the laser cooling experiments performed at the TSR.
This mode can be obtained by increasing the dispersion function in the dipole magnets up to 8.8 m. The calculated dispersion function and the $\beta$ functions are shown in figure 4. The properties of this mode were investigated in a few beam times with $^{12}C^{6+}$ (63 MeV,73 MeV) and protons (21 MeV). Table 2 shows a comparison between typically measured and calculated ring parameters. $\bar{\beta}$ is the average value of the $\beta$-function of a quadrupole family. This measurements were done at $\gamma_{tr}$=1.1.

The measured value of the dispersion function $D(s)$ at the location of the beam profile monitor was $D_{BPM}$ = 6m compared to the theoretically value of 8.8 m calculated with the computer code MAD [5], thus, confirming the need of generally much bigger values for $D(s)$ than for the standard operation mode at $\gamma_{tr}$ = 3.1.
Using a beam profile monitor and a Schottky pick-up equilibrium values of the emittances and the momentum spread for an electron cooled 63 MeV $^{12}C^{6+}$ beam and a 21 MeV proton beam were measured. The transverse blow-up of the ion velocity distribution after switching off the elec-

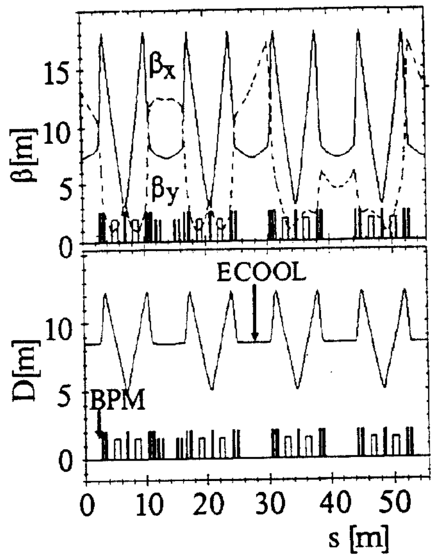


Figure 4: *Calculated Twiss parameters of the mode with* $\gamma_{tr} \approx 1$.

Table 2: *Calculated and measured Twiss parameters of the mode with* $\gamma_{tr} \approx 1$.

| | Experiment | Theory |
|---|---|---|
| $Q_x$ | 1.1 | 1.11 |
| $Q_y$ | 3.39 | 3.42 |
| $\gamma_{tr}$ | 1.1 | 0.99 |
| $\beta_{x,1}, \beta_{y,1}$[m] | 3.7,12.3 | 8.6,13.5 |
| $\beta_{x,2}, \beta_{y,2}$[m] | 8.9,5.4 | 18.2 ,4.7 |
| $\beta_{x,3}, \beta_{y,3}$[m] | 2.4 ,2.3 | 3.0,2.5 |
| $\beta_{x,4}, \beta_{y,4}$[m] | 21.4,3.9 | 18.2,3.0 |
| $\beta_{x,5}, \beta_{y,5}$[m] | 10.1,7.9 | 8.6,8.6 |

tron cooler was also investigated to determine IBS heating rates. Experimental data were compared with theoretical predictions by calculating the equilibrium and blow-up with a suitable IBS computer code [8], which describes the measurements in the standard mode very well. In the $\gamma_{tr}$-mode however, the measured equilibrium emittances were about one order of magnitude higher in the case of 63 MeV $^{12}C^{6+}$ and 21 MeV protons than predicted by the calculations. The experimental blow up of the horizontal and vertical emittances after switching off the electron cooler are also much too high than predicted by IBS. These measurements are shown in figure 5 together with the theoretical curve.

One reason for this strong heating could be a first order resonance as a requirement for the operation near the transition energy is $Q_x \approx \gamma_{tr} \approx 1$, where $Q_x$ is the horizontal tune. Because of the large dispersion function in the cooler section (D=8.8 m) it was very difficult to optimize the electron cooler. These insufficiencies can be avoided

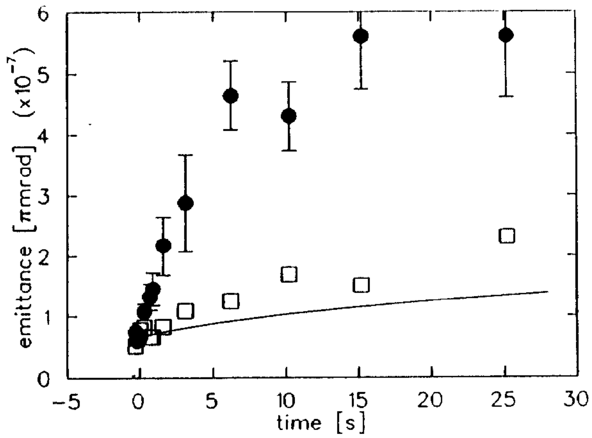


Figure 5: *Experimental horizontal (•) and vertical (□) blow-up of 21 MeV protons, measured at 7 μA.*

with an improved ring setting.

## 5 ACKNOWLEDGMENT


We would like to thank the technicians of MPI for their work which made these experiments at TSR possible.


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