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FIRST ELECTRON COOLING OF HEAVY IONS AT THE NEW HEIDELBERG STORAGE RING TSR §

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Abstract The new Storage Ring TSR at the Max Planck Institut in Heidelberg is the first ring in operation to store and electron cool heavy ions up to 30 MeV/u at a charge to mass ratio of q/A=0.5. Commissioning of the ring started middle of 1988 with the accumulation of 73.3 MeV $^{12}C^{6+}$ beams. In first tests end of 1988 electron cooling of $^{12}C^{6+}$ beams could be demonstrated by the momentum compression of rf-stacks from $\Delta p/p=0.018$ to values of $\Delta p/p=2 \cdot 10^{-4}$ within 3 seconds at intensities of about $2 \cdot 10^{9}$ ions. Low intensity beams ($\leq 10^{7}$) were cooled to $\Delta p/p = 4 \cdot 10^{-5}$. Applying cooling during injection resulted in intensities of 18mA ($3 \cdot 10^{10}$ ions) stable and cooled, showing extreme collective effects in the Schottky noise spectrum with an irregular behaviour with respect to the expected $\Delta\omega \sim \sqrt{N}$ scaling law. Cooling of p, $^{12}C^{6+}$ and $^{28}Si^{14+}$ beams was performed with differences in obtainable momentum spread explainable by intra beam scattering. Lifetimes of cooled beams range from 36 h for 21 MeV protons to 4100 s for 140 MeV $^{12}C^{6+}$ ions at average ring pressures of $\leq 8 \cdot 10^{-11}$ mbar.

INTRODUCTION

The Heidelberg Heavy Ion Test Storage Ring TSR[1] is a 55.4 m circumference

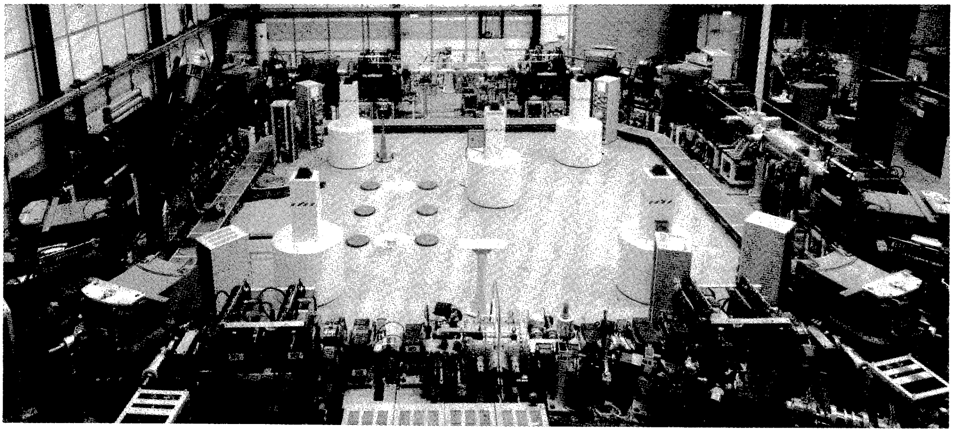

FIGURE 1 The Heidelberg Test Storage Ring for Heavy Ions TSR. The Electron Cooler can be seen in the left straight section.

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low energy cooler ring with four fold symmetry, see Figure 1. The injection line from the MP-Tandem Postaccelerator Combination[2] can be seen in the lower right of the photograph guiding the beam to the electrostatic septum. The electron cooler is situated in the left straight section, the experimental area in the background, and the rf-cavity at the right side.

Details of the TSR layout are described elsewhere[1] and can be identified to some extent in Figure 2 showing the floor plan of the ring. Deflection is accomplished by eight 45 degree C-shape magnets (maximum magnetic rigidity $B \cdot \rho = 1.5$ Tm). Always two dipoles with inbetween horizontally focussing quadrupoles constitute the center of one focussing period, which is completed on both sides by quadrupole doublets and half the long straight sections. In the main optical mode of the TSR two periods are operated antisymmetric forming one of the two superperiods of the machine.

As the TSR is set up at a tandem linac combination intensities of injected beams are low even with pulsed sputter ion sources. Therefore an elaborate injection scheme[3] using multiturn injection and rf-stacking had to be used to fill the horizontal and longitudinal phase space. Due to the good beam quality of the injector ($\Delta p/p \sim 10^{-4}$, $\varepsilon_{x,y} \sim 1.5\pi$ mm mrad) and the large horizontal ($a_x = 120\pi$ mm mrad) and longitudinal ($\Delta p/p = 0.03$) acceptances of the ring as much as 40 equivalent turns can be accumulated horizontally and up to 30 multiturn batches stacked longitudinally[4] resulting in a total current of 7 mA $^{12}C^{6+}$ ($1 \cdot 10^{10}$particles).

TSR was constructed in the years 1985 to 1988 with a first beam stored in May 1988. After the installation of an electron cooler it has become the first heavy ion cooler ring world wide. Since end of 1988 its unique experimental possibilities in accelerator-, atomic-, plasma-, and nuclear physics are beginning to be exploited[5].

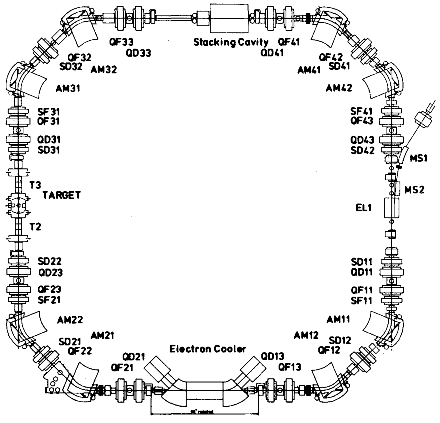

FIGURE 2 Floor plan of the TSR showing its major components. The labels A MX designate dipoles, QDX and QFX quadrupoles, SFX and SDX sextupole lenses, MSX and ELX magnetic and electrostatic injection septa.

THE ELECTRON COOLER

The electron cooler is located in one of the four long straight sections of the storage ring. It's basic structure and the position of the various components can be seen in Figure 3. The main parameters are listed in Table I. Further details of the design especially of the gun, collector and magnet system are given elsewhere[6].

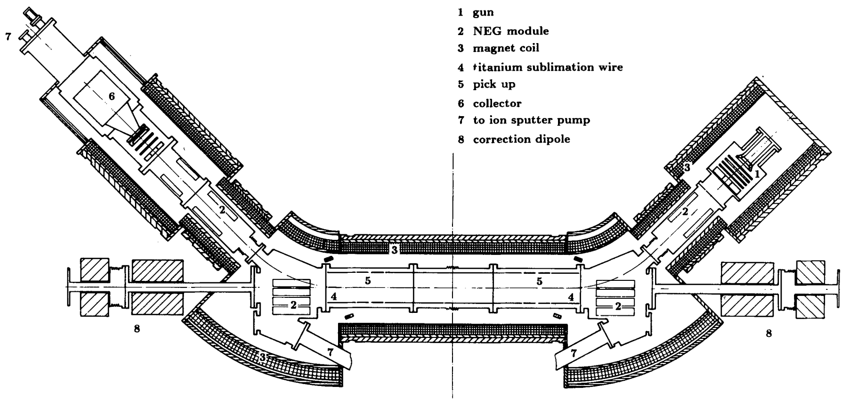

FIGURE 3 Cut drawing of the TSR electron cooler showing the gun(1), the NEG pump modules (2), the solenoidal and toroidal magnets(3), the titanium sublimator pumps (4), the position pick ups (5), the collector (6), pumping ports (7) and the correction dipoles on the ring axis (8).

Although the length of a straight section in the TSR is 5.2 m, the space needed for the toroids and correction magnets to compensate the closed orbit deflection in the toroid magnets themselves limits the length of the cooling solenoid to 1.5 m. The aperture dimensions were determined by the requirement to run the TSR in a variety of modes which called for a horizontal beam clearance of +/- 100mm in all parts of the ring. As the β - functions in the cooling straight section are β_x= 5m and β_y= 2m a maximum horizontal beam emittance after injection of 120 π mm mrad calls for a diameter of the electron beam and thereby for that of the cathode of 50 mm.

The system is designed to operate in a heavy ion ring in which low energy fully or even partially stripped ions as heavy as ^{127}J are to be stored with lifetimes on the order of minutes. Therefore a residual gas pressure of 10^{-11} mbar or better had to be maintained also in the cooler where high gas loads from gun and collector are present. Besides the precautions in assembling the vacuum chambers from specially cleaned, vacuum fired and 300°C bakeable components a high pumping speed is necessary which is supplied by 34 NEG modules (15 000 l/s) two 400 l/s and one 60 l/s sputter ion pumps.

The obtainable pressure depends on the collection efficiency for the electron beam but can be kept in the 10^{-11} mbar range for currents of 1 A.

The magnetic field which holds the electron beam on its way from the gun to the collector is produced by five solenoidal and two toroidal coils designed for a maximum induction of B=0.3 T in order to be able to study cooling with a strong magnetic friction force. The field quality in the main cooler solenoid which is essential for a low electron temperature is ensured by precision winding as well as by powering 7 sets of correction coils. This way the mean square fluctuations of the field direction $\sqrt{\langle B_t^2 / B_l^2 \rangle}$ were reduced to less than $4 \cdot 10^{-5}$ both horizontally and vertically for an effective length of the cooling region of 1.2 m.

TABLE I Basic Parameters of the Electron Cooler

Gun Perveance	[µP]	0.4 — 6.7	adjustable
Electron Energy	[keV]	1.0 — 20.0	
Electron Current	[A]	≤ 1.0	
Transverse Temperature	[eV]	≤ 0.3	
Max. Induction	[T]	0.3	
Cathode Diameter	[cm]	5.0	
Effective Cooler Length	[m]	1.2	

ELECTRON COOLING OF HEAVY ION BEAMS

Electron cooling[7] up to recently only applied to protons is known to produce brilliant particle beams with extremely small momentum spreads, where the obtainable equilibrium value is determined only by the balance of the friction force exerted by the cooling electrons and the heating due to intra beam scattering, scattering in the residual gas or internal targets.

Electron cooling of heavy ions is besides the exciting new possibilities in atomic physics of special interest, as the high charge of the ions does deeply influence the cooling process itself. Theory predicts an increase of the

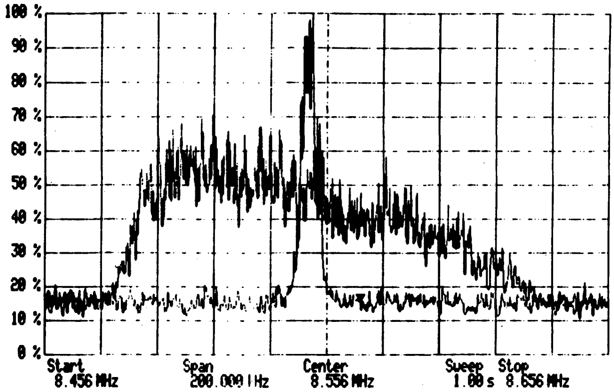

FIGURE 4 Schottky noise spectrum of a rf-stacked 73.3 MeV $^{12}C^{6+}$ beam before and after cooling. The initial momentum spread is reduced from $\Delta p/p = 0.018$ to $\Delta p/p = 2 \cdot 10^{-4}$ in about 3 s.

cooling force with charge proportional to Z^2 and by this a decrease of the cooling time $\tau_c \sim A/Z^2$. Under otherwise comparable conditions intrabeam scattering however will due to its Z^4/A^2 dependence result in higher equilibrium momentum spreads. At the TSR it is for the first time possible to investigate the electron cooling for a large variety of ions in almost all possible charge states.

Most of the systematic investigations have been performed up to now for $^{12}C^{6+}$ beams at an energy of 73.3 MeV corresponding to an electron energy of 3.3 keV matching the ion velocity. The cooler gun was set for a perveance of 1.66 μP yielding a current of 350 mA.

Almost immediately after aligning the electron beam parallel to the ion beam and establishing full overlap cooling was observed. Most spectacular was the situation depicted in the Schottky noise spectra of Figure 4, when a 1.8 mA ($3 \cdot 10^9$ $^{12}C^{6+}$- ions) coasting beam accumulated by the combined stacking method with a large momentum spread of $\Delta p/p = 0.018$ was cooled within 3 s to an equilibrium value of $\Delta p/p = 2 \cdot 10^{-4}$.

Analyzing the Schottky lines of high intensity cooled beams ,- see Figure 5-, a double peak structure becomes visible.This splitting is due to two plasma waves[8] propagating pararallel and antiparallel on the circulating beam. The behaviour is observable, when the particle number N exceeds a critical value

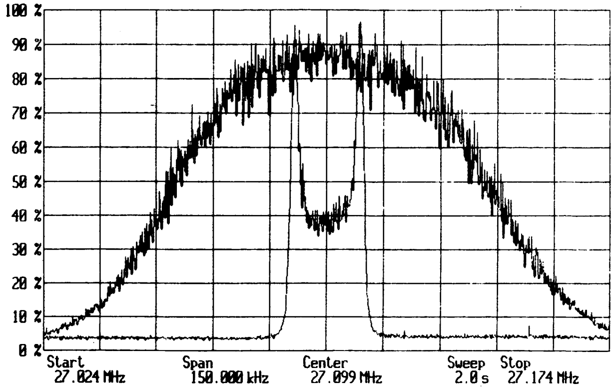

FIGURE 5 Schottky noise spectrum for an uncooled 2.6 mA beam of 140 MeV $^{12}C^{6+}$ (broad distribution). Cooling to equilibrium produces collective effects. The strong signal suppression is evident as the gaussian spectral form is changed into a double peak structure,

$$N > N_{crit} = \frac{4\pi \cdot T_{\parallel}}{Z^2 \cdot e^2 \cdot \omega_0} \cdot \left[\frac{\mathrm{Im}(Z_n)}{n} \right]^{-1} \qquad (1)$$

where Z and ω_0 are chargestate and revolution frequency of the beam; $T_{\parallel}$ is the longitudinal temperature and Z_n the longitudinal coupling impedance. The peak splitting is proportional to $\sqrt{N}$ whereas the momentum spread can only be obtained from a parameterized analysis of the spectrum form.

For particle numbers $N \ll N_{crit}$ the width of the then gaussian noise spectrum is a direct measure of the momentum spread $\Delta p/p$ as

$$\frac{\Delta p}{p} = \frac{1}{\eta} \cdot \frac{\Delta\omega_n}{\omega_n} \qquad (2)$$

where the η-parameter is 0.9 for the TSR, ω_n the n-th harmonic of the revolution frequency and $\Delta\omega_n$the full width frequency spread at $1/\sqrt{2}$ maximum signal amplitude.

Systematic investigations of achievable momentum spread as a function of the number of stored particles were performed for $^{12}C^{6+}$ (73.3 MeV), $^{28}Si^{14+}$ (115 MeV) and protons (21 MeV). The results are summarized in the diagram of Figure 6. Although the three types of ions could not be cooled at the same particle velocity, the strong influence of ion charge on intra beam scattering can clearly be seen with the ratios in momentum spread scaling for Si : C : p approximately as 7 : 4 : 1 .

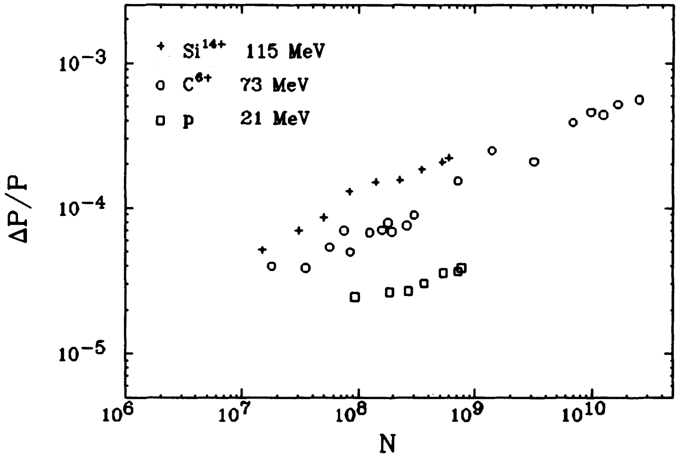

FIGURE 6 Momentum spread of cooled ion beams as function of the number of stored particles and ion charge. Equilibrium values increase from protons to Si-ions due to intra beam scattering.

Lifetime of stored beams at an average residual gas pressure in the 10^{-11}mbar range is dramatically increased when cooling is applied to protons ,- 3 h to 36 h -, but lowered when 140MeV $^{12}C^{6+}$ ions are cooled,- 5 h to about 1 h. The decrease in the case of fully stripped carbon can be explained by Radiative Electron Capture in the cooler region being the dominant process. The increase in proton lifetime shows, that heating in the residual gas by multiple scattering is well counterbalanced by electron cooling for these low charge particles.

ACCUMULATION OF HIGH INTENSITY BEAMS BY COOLER STACKING

In order to increase the number of stored particles beyond what is possible by using the combined multiturn injection - rf-stacking method electron cooling was applied already during the injection phase to compress the phase space occupied by the injected beam.

The multiturn injection is operated in this mode with the standard parameters, while the rf-cavity is set to decelerate the multiturn batches by only 1.5 % in momentum. When the energy of the cooling electrons is chosen to drag the ions to a momentum slightly below the momentum of the beam after deceleration, and when the repetition rate of the rf-stacking process is set equal to the cooling time constant, the injected batch is cooled before the next one arrives, thus clearing acceptance and increasing injection efficiency.

A maximum of 18 mA $^{12}C^{6+}$ions ($3 \cdot 10^{10}$) could be stored and cooled , a factor of three more than ever achieved without cooling. The splitting and the form of the Schottky noise spectrum are extreme,- see Figure 7.

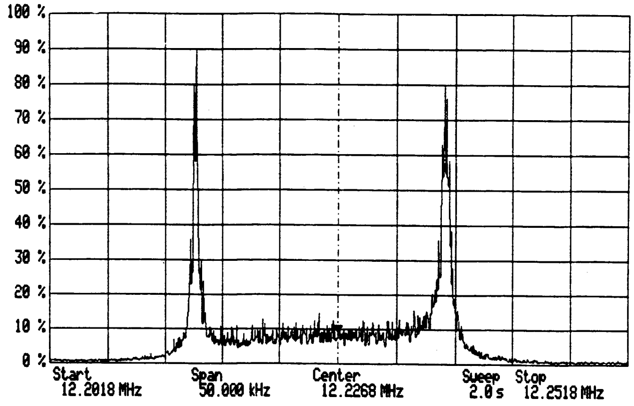

FIGURE 7 Schottky noise spectrum of a 73.3 MeV 15 mA $^{12}C^{6+}$ beam.

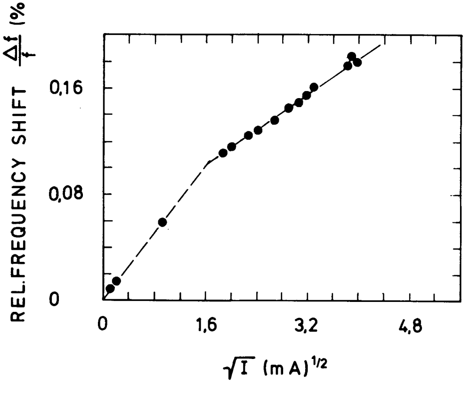

FIGURE 8 Frequency splitting in the Schottky noise spectra plotted versus the square root of the stored intensity. At currents of 4 mA the slope changes indicating a "phase transition" of the cold beam.

In Figure 8 the frequency splitting at the 28th harmonic is plotted against the square root of the stored intensity. Up to currents of about 4mA the splitting follows Parkhomchuks scaling[9]

$$\Delta\omega \sim \sqrt{(\mathrm{Im}(Z_n/n))} \cdot \sqrt{N} \qquad (3)$$

whereas at higher currents the slope of the curve significantly changes. A hint that at this threshold the beam undergoes a "phase transition" comes from the observation, that above 4 mA the beam behaves more "quietly", with no transversal oszillations detectable, which at lower currents often led to beam losses.

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