Recent Results on Equilibrium Temperatures and Cooling Forces with Electron Cooled Heavy Ion Beams in the ESR

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Abstract

Electron cooling of heavy ions over the whole mass range has been performed in the storage ring ESR. Measurements of the longitudinal cooling force for a variety of ions have revealed a significant deviation from the Q^2-dependence for small relative velocity. Measurements of the equilibrium beam properties of cooled heavy ions evidenced that the achievable phase space density is determined by a balance between cooling and heating by intrabeam scattering. Calculations of the corresponding intrabeam scattering rates for a U^{92+} beam are compared with the cooling rates of the electron beam concluded from the cooling force measurements.

1 INTRODUCTION

The ESR storage ring [1] offers the unique opportunity to perform experiments with stored and cooled bare ions up to Uranium. The phase space volume of the ion beam is reduced by an electron cooling system [2]. In combination with an rf stacking scheme it allows repetitive injection in order to accumulate beam currents up to certain limits. For light ions transverse instabilities causing particle losses are observed at high intensity, whereas for the heavier ions the limits are given by recombination losses due to REC (radiative electron capture) with electrons in the cooling section. Below the maximum ion currents the beam properties are determined by an equilibrium between cooling and heating by intrabeam scattering [3]. The crucial quantities for the understanding of this balance, the heating rate due to intrabeam scattering and the cooling rate provided by the electron beam, have been studied in detail.

2 COOLING FORCES

The power of the electron cooling system for a certain ion species is characterized by the cooling force with which the electron beam compresses the phase space volume of the ion beam. The longitudinal cooling force of the ESR electron cooling system has been measured as a function of the ion velocity in the comoving rest frame. The two methods of simultaneous heating with white rf noise and fast change of the accelerating voltage with a delayed measurement of the the ion beam response are well adapted to the regime of small and large relative velocities [3].

The ion beam intensity was reduced to less than 100 μA in order to reduce detrimental effects of the ion beam temperature. The electron current was 50 mA in all heating measurements and 250 mA for the high voltage stepping method. Fig. 1 summarizes the results for various ions over the whole velocity range accessible by the two methods. The linear part of the cooling force up to 2000-3000 m/s is followed by a broad maximum of the cooling force around 10^4 m/s corresponding to a longitudinal electron beam temperature of 0.5 meV approximately. The magnitude of the maximum value is likely to be limited by transverse velocity components $v_\perp^* \simeq 2-4\cdot 10^4$ m/s which are due to the ion temperature and the magnetic field quality. With further increase of the relative velocity an almost linear decrease of the cooling force is found in a regime which is mainly dominated by the transverse electron temperature. For relative velocities in excess of 10^6 m/s the velocity dependence approaches the asymptotic case of a v^{*-2}-decrease.

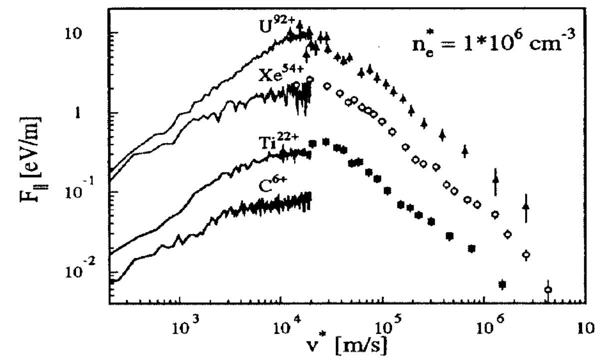

Figure 1: Cooling forces normalized to an electron density $n_e^* = 1\cdot 10^6$ cm^{-3} as a function of the relative velocity (typical kinetic energy 250 MeV/u).

The absolute accuracy of both cooling force measurement methods is 20 % typically. This allows also a determination of the dependence on the ion charge of the longitudinal cooling force. Basic theoretical considerations lead to a Q^2-dependence, but more elaborate concepts [5], [6] predict for small relative velocities an increase with $Q^{1.5}$ which has also been observed experimentally [7], [8].

A compilation of the cooling forces for bare ions stored in the ESR for different relative velocities as a function of the ion charge reveals significant deviations from the Q^2-dependence (Fig. 2). At small relative velocities in the linear part of the cooling force a fit to the data results in a $Q^{1.37}$-dependence. In the intermediate regime an exponent close to 2 is found, but for large relative velocities the exponent slightly decreases which might be caused by

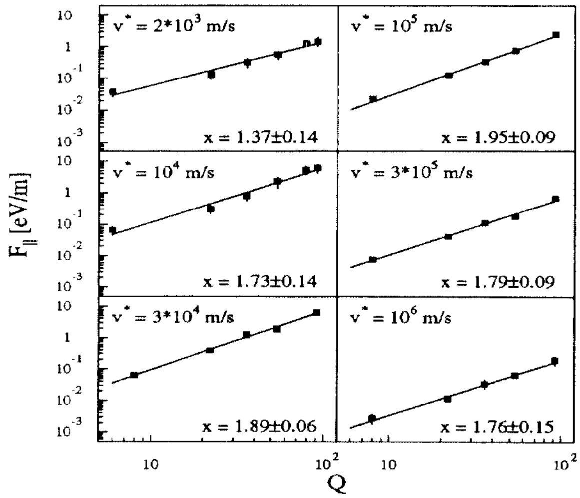

Figure 2: Cooling forces as a function of the ion charge. Relative velocity as indicated in the viewgraph. Data were fitted according to $F_{\parallel} \propto Q^{x}$.

a reduced Coulomb-logarithm. From these results it follows that for hot ion beams especially at high energy one benefits most from the higher charge of heavy ion, whereas for cold ion beams with small relative velocity components the cooling force is reduced for high ion charges.

3 EQUILIBRIUM TEMPERATURES

Storage and cooling of heavy ions and nondestructive diagnosis of stored ion beams are standard operational procedures in the ESR [4]. After a storage time of few seconds the process of phase space compression by electron cooling is completed and the phase space volume of the ion beam remains constant. The cooling rate of the electron beam and the heating rate which is dominated by intrabeam scattering in the dense ion beam determine the occupied phase space volume. The cooling rate is basically proportional to the electron current, but also all kinds of velocity components in the comoving reference frame either due to ion beam emittance and momentum spread or associated with the electron beam temperature will affect the cooling force. The intrabeam scattering rate is connected with the six-dimensional phase space density of the ion beam and the specific ion optics of the storage ring.

Measurements of emittances and momentum spreads as a function of the number of stored particles for various species of bare ions stored in the ESR and cooled with an electron current I_{el}= 250 mA are shown in Fig. 3. An increase of the phase space volume with the number of stored ions is evident. The power scaling $\epsilon \propto N^{a}$ for the increase of the two-dimensional subspace area of the phase space volume ($\epsilon = \epsilon_x, \epsilon_y, \delta p/p$) is listed in Table 1. Variations of the exponent a are certainly caused by slightly differing cooling conditions. The dependence of the equilibrium values on the ion charge is not very pronounced.

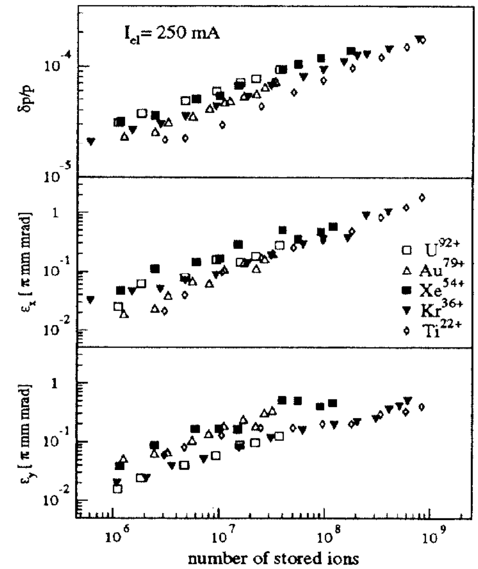

Figure 3: Momentum spread and emittances of a cooled heavy ion beams as a function of the number of stored ions.

ion	Ti^{22+}	Kr^{36+}	Xe^{54+}	Au^{79+}	U^{92+}
$\delta p/p$	0.40	0.30	0.32	0.35	0.30
ϵ_x	0.68	0.58	0.50	0.70	0.66
ϵ_y	0.27	0.47	0.50	0.46	0.65

Table 1: Exponent a of power scaling $\epsilon_x, \epsilon_y, \delta p/p \propto N^{a}$

Ion beam emittances and momentum spread as a function of the cooling power of the electron beam are shown in Fig. 4 for the case of a beam of bare Uranium. The equilibrium beam emittances decrease proportional to $I_{el}^{-\alpha}$ with $\alpha = (0.25 - 0.50)$ and the momentum spread proportional to $I_{el}^{-0.30}$. Again the variations are larger for the transverse emittances also observed for other ion species. The increased cooling rate for higher electron currents allows for stronger compression of the phase space volume of the ion beam.

4 INTRABEAM SCATTERING RATES

The measured equilibrium values are related to heating rates calculated by computer codes which were developed to simulate intrabeam scattering in a specific ion optical lattice. Two different codes, one following the Piwinski formulae [9], the other starting from a Fokker-Planck approach [10], were applied to determine the intrabeam scattering rates in all three degrees of freedom. The results for the longitudinal rates show systematic variations with the beam parameters and are also stable with respect to small changes of the equilibrium values. In Fig. 5 the longitudinal heating rates for the equilibrium values of Fig. 3 are shown as a function of the number of stored ions. The decrease with the particle number can be explained by increasing velocity spread of the ion beam - both longitudinally and transversely - for more intense beams. The

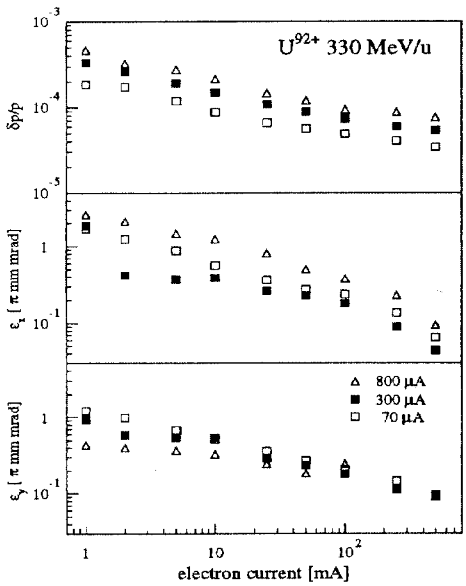

Figure 4: Momentum spread and emittances of a cooled U^{92+} 330 Mev/u beam as a function of the electron current for three ion beam intensities.

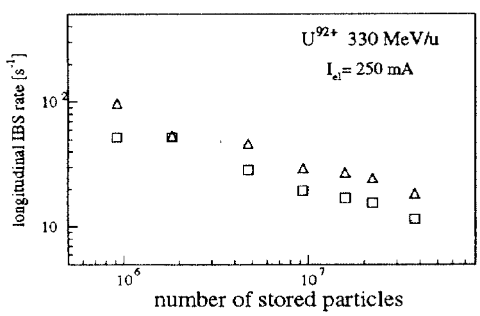

Figure 5: Calculated longitudinal intrabeam scattering rates for U^{92+} cooled with a 250 mA electron beam. Squares are calculated from [9], triangles from [10].

relevant velocity components in the comoving rest frame are on the order of some 10^4 m/s. From Fig. 1 one can easily see that in this regime the cooling force is decreasing with the relative velocity.

For the transverse heating rates small variations of the input values of the transverse emittance can cause large changes of the rate, sometimes even resulting in negative rates, i.e. cooling. In some cases similar heating rates for the horizontal and vertical rates were calculated as one expects from the fact that the cooling rates are of similar magnitude, but sometimes the two transverse rates even had opposite signs.

Calculations for the experimental values of Fig. 4 when the cooling rate is varied by means of the electron current are shown in Fig. 6. The heating rate is increasing more than linearly indicating that the expected linear increase with the electron current is intensified by stronger cooling forces resulting from reduced velocity components of the

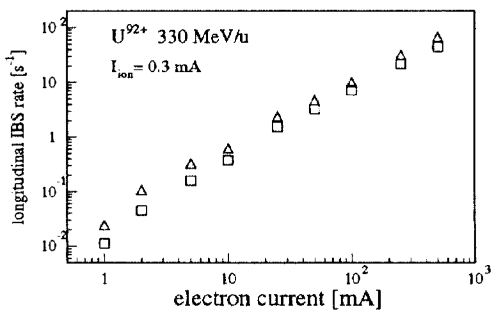

Figure 6: Calculated longitudinal intrabeam scattering rates for U^{92+} (300 μA) cooled with varying electron current. Squares are calculated from [9], triangles from [10].

ion beam.

The same tendency is observed for the transverse cooling times which are typically an order of magnitude larger than the longitudinal ones. The reason for the afore-mentioned ambiguities in the calculation of the transverse times which are common to both computer codes is unclear.

The calculated heating rate of 3.8 s^{-1} for [9] and 4.4 s^{-1} for [10], when a beam of 40 μA U^{92+} is cooled by an electron beam of density $n_e^* = 1 \cdot 10^6 \mathrm{cm}^{-3}$, can be compared with the ring averaged cooling rate from the measured cooling force. The cooling force for U^{92+} from Fig. 1 corresponds to a longitudinal cooling rate of 8 s^{-1} averaged over the velocity range that corresponds to the longitudinal particle distribution. This is considered a satisfactory agreement between heating rate calculations and cooling rate measurements.

5 REFERENCES

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