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STOCHASTIC COOLING AND STORAGE TESTS WITH OXYGEN IONS IN LEAR.

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ABSTRACT

O^{8+} and O^{6+} ions were stored in LEAR [1] during a machine experiment session. The aim was to obtain some hints on the lifetime of heavy ion beams in a good cooling ring vacuum, and to test cooling and stacking of ions.

Stochastic cooling was used to compensate the beam decay due to multiple scattering on the residual gas, which is the most important effect on lifetime. An equilibrium momentum spread of less than $5 \cdot 10^{-4}$ was measured thus proving the efficiency of stochastic cooling for multiply charged ions. With the vacuum conditions of LEAR ($2.6 \cdot 10^{-12}$Torr gauge reading with a residual gas of 90% H_2), measured beam lifetimes are 25 minutes for O^{6+} at 7.2 MeV/u and 600 minutes for O^{8+} at 11.5 MeV/u.

These numbers set favorable limits for low energy ion storage rings.

1. INTRODUCTION

A machine experiment session was performed with O^{8+} and O^{6+} beams in LEAR, profiting from the availability of these ions from LINAC 1 [2]. These studies were prepared in collaboration with the MPI-Heidelberg and GSI-Darmstadt who are commissioning heavy ion storage rings, and with the lead ion project group at CERN, which is interested in the feasibility of a low energy accumulator and in the measurement of charge exchange cross-sections.

Stochastic cooling was used to compensate beam decay due to multiple scattering on the residual gas. This is the first time that heavy ions have been stochastically cooled. The low injected beam current (about 5µA of O^{8+} or O^{6+} ions) made it difficult to perform some operations which were routinely done on p^{+} and $\bar{p}$ beams, such as orbit and tune measurements, or absolute current monitoring. However, the relative change in current could be deduced from the longitudinal Schottky scans. In this way, the beam lifetimes were measured under various conditions and longitudinal stochastic cooling could be set up. Transverse stochastic cooling was put on "blindly", using nominal computed settings and observing the improvement of the beam lifetime.

2. O^{8+} TESTS

2.1 Beam properties.

O^{8+} ions were delivered by the LINAC I at 147.4 MeV/c/nucleon (11.5 MeV/nucleon kinetic energy), corresponding to the magnetic field needed for 294.9 MeV/c protons. The measured momentum spread was $\Delta p/p \approx \pm 3.0‰$ just after injection. The number of coasting particles was estimated to be about $4.0 \cdot 10^{6}$.

2.2 Lifetime measurements and stochastic cooling.

Initial beam lifetime measurements indicated a lifetime of 200 to 250 minutes. After stochastic cooling was tuned (Figure 1) the lifetime rose to 600 minutes. Only short time was available for the experiment and the adjustment of the cooling system was delicate due to the low beam intensity, but we believe that in the conditions where 600 minutes were measured, was the transverse cooling correctly adjusted to eliminate beam heating mechanisms.

2.3 Multi-injection.

Some multi-injection tests were performed with O^{8+}. The coasting beam is first bunched on harmonic 1, then harmonic 2. The first harmonic is then decreased, and the bunched beam occupies one of two 2nd-harmonic buckets, the second being empty. A beam is then injected in the empty bucket, using the coasting bunch signal to synchronise the injection kicker magnet. After injection, the beam is adiabatically debunched and strong momentum cooling is applied for a couple of minutes, before the whole process can be resumed. Although a noticeable current increase indicated that the principle worked, the kicker synchronisation was not stable enough to increase the intensity with stacking by more than a factor 4, because of the weak coasting bunch signal.

3. O^{6+} TESTS

3.1 Beam properties.

O^{6+} ions were delivered at 115.6 MeV/c/nucleon (7.2 MeV/nucleon kinetic energy) by the LINAC I, corresponding to the magnetic field needed for 308.4 MeV/c protons (almost the usual momentum that 50 MeV protons have - 308.6 MeV/c). The momentum spread and current were the same as for O^{8+}

3.2 Lifetime measurements and stochastic cooling.

Depending on cooling conditions, the measured lifetime was between 19 and 25 minutes (Figure 2). It is remarkable that, as for O^{8+} the momentum cooling was quite efficient, reducing the initial momentum spread to 0.5‰ in 4 minutes (Figure 3).

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3.3 Multi-injection.

With the same principle as used for O^{8+}, but using the first RF harmonic to drive the kicker synchronisation (Figure 4), it was possible to inject 20 shots, leading to a factor 10 increase in intensity (Figure 5).

4. VACUUM CONDITIONS

The results of the gas analysis performed at three different locations in the machine can be found in Table 1 [3]. The average pressure deduced from the gas analysis was $6.1 \cdot 10^{-12}$Torr. The average pressure measured on the gauges all around the machine was $2.6 \cdot 10^{-12}$ Torr (uncorrected). The gauges readings corrected with the average gas composition is included in Table 2 [3]. The corresponding corrected average is $4.5 \cdot 10^{-12}$Torr.

5. ESTIMATION OF THE CHARGE-EXCHANGE CROSS-SECTIONS

At the pressure of $5.0 \cdot 10^{-12}$Torr (N_2equivalent for scattering) as deduced from Table 1, the multiple scattering lifetime (emittance increase by 10πmm.mrad) for O^{8+} ions at 145 MeV/c is estimated to be at least 500 minutes. Hence the observed decay constant of 200-250 minutes probably includes other loss mechanisms, whereas the value of 600 minutes, obtained with "good machine conditions" could in principle include multiple scattering and/or charge exchange, thus setting a lower limit of 600 minutes to the latter effect.

For O^{6+} at 115 MeV/c the expected multiple scattering lifetime is again at least 500 minutes and the observed 25 minutes decay time is in all probability dominated by charge exchange. For the residual gas pressure of $5 \cdot 10^{-12}$Torr ($n \approx 1.9 \cdot 10^{5}$ molecules/cm^3), the total charge exchange cross-section ($\sigma = \frac{1}{\tau n \beta c}$) to fit the measurements is $\sigma = 3 \cdot 10^{-20}$cm^2 for O^{8+} ($\tau = 3.6 \cdot 10^{4}$s, $\beta = 0.156$), and $\sigma = 10^{-18}$cm^2 for O^{6+} ($\tau = 1.5 \cdot 10^{3}$s, $\beta = 0.121$). Both values are lower than those obtained from [4] which, assuming pure H_2 as residual gas, yields $\sigma = 1.5 \cdot 10^{-19}$cm^2 for O^{8+} and $\sigma = 5.0 \cdot 10^{-18}$cm^2 for O^{6+} under the conditions of the experiment. It should be mentioned however that [4] only deals with ions heavier than oxygen. On the other hand, Schlachter's formula [5] for fully stripped ions leads to a much lower cross-section for O^{8+} ($\sigma = 5 \cdot 10^{-21}$cm^2) for the gas composition given in Table 1.

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Table 1: Results from gas analysis with mass spectrometer.

[3]
RGA 103

Molecule	Percentage	Partial pressure(Torr)
H_2	87.6	$3.1 * 10^{-12}$
He	2.8	$1.0 * 10^{-13}$
CH_4	7.4	$2.6 * 10^{-13}$
N_2	1.5	$5.4 * 10^{-14}$
Ar	0.7	$2.4 * 10^{-14}$
Total	100	$3.5 * 10^{-12}$

RGA 301

Molecule	Percentage	Partial pressure(Torr)
H_2	83.0	$7.7 * 10^{-12}$
CH_4	7.0	$6.6 * 10^{-13}$
H_2O	4.0	$3.8 * 10^{-13}$
N_2	6.0	$6.0 * 10^{-13}$
Total	100	$9.3 * 10^{-12}$

RGA 402

Molecule	Percentage	Partial pressure(Torr)
H_2	94.4	$5.3 * 10^{-12}$
CH_4	2.85	$1.6 * 10^{-13}$
H_2O	1.24	$7.0 * 10^{-14}$
N_2	1.42	$8.0 * 10^{-14}$
Total	100	$5.6 * 10^{-12}$

AVERAGE

Molecule	Percentage	Partial pressure(Torr)
H_2	87.01	$5.3 * 10^{-12}$
He	0.54	$3.3 * 10^{-14}$
CH_4	5.91	$3.6 * 10^{-13}$
H_2O	2.46	$1.5 * 10^{-13}$
N_2	3.94	$2.4 * 10^{-13}$
Ar	0.13	$8.0 * 10^{-15}$
Total	100	$6.1 * 10^{-12}$

Table 2: Corrected reading of the machine gauges.

[3]

Gauge	Corrected reading(10^{-12} Torr)
101	3.63
102	12.07
103	3.21
105	2.62
106	1.01
201	4.82
203	1.40
206	5.63
301	10.05
303	4.63
305	4.63
307	1.81
401	4.43
403	5.03
405	4.22
406	2.41
Average	4.48

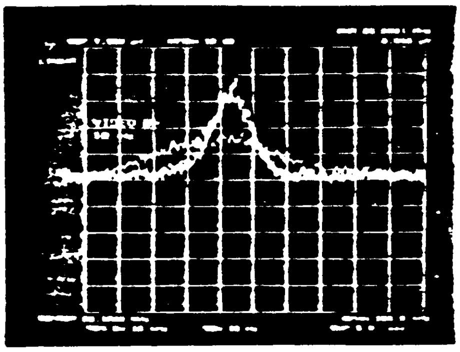

Figure 1: Cooling of O^{6+} beam. Momentum distribution after injection and after 4 minutes of stochastic cooling. The vertical scale is the square root of the particle density, the horizontal scale is the beam momentum ($\Delta p/p = 5 \cdot 10^{-4}$/div).

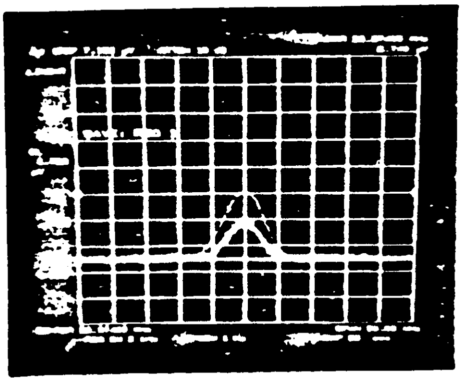

Figure 2: Lifetime of O^{6+} beam. Evolution of the momentum distribution during the lifetime measurement process (19 minutes).

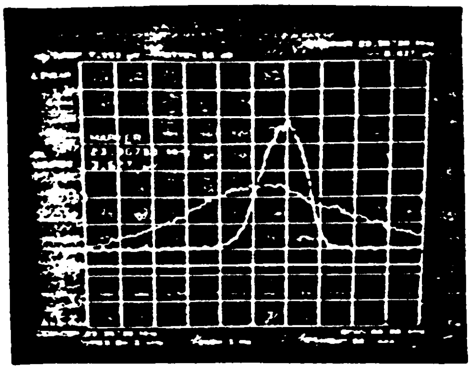

Figure 3: Momentum cooling of O^{6+} ions. Same as Figure 1, but horizontal scale is $\Delta p/p = 2.5 \cdot 10^{-4}$/div.

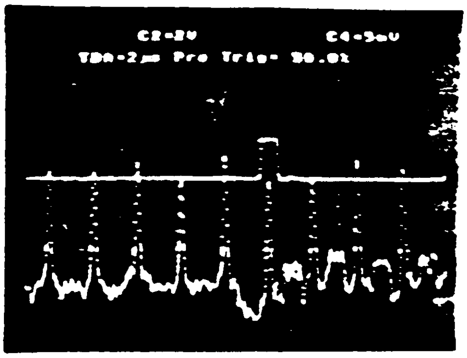

Figure 4: O^{6+} Multi-injection. The upper trace is the kicker signal, the lower trace is a sum pick-up signal. Before the injection, one can see the short bunch every two second harmonic bucket. After the injection, the gap is filled by the incoming beam.

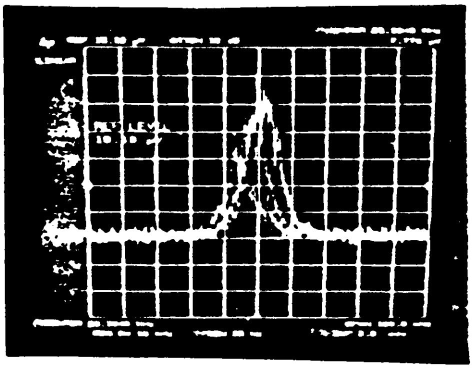

Figure 5: Multi-injection of 20 O^{6+} shots: momentum phase space. The lower trace corresponds to the first injection, the middle one to the 10th, the upper one to the 20th. The maximum intensity is reached after 20 shots. The intensity increase factor is of the order of 10 (the spectrum analyser output is proportional to the square root of the intensity).

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