ACCELERATION, DECELERATION AND BUNCHING OF STORED AND COOLED ION BEAMS AT THE TSR, HEIDELBERG

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Abstract

Several experiments at the heavy ion storage ring TSR have shown the feasibility of wide range, efficient acceleration and deceleration. The newly developed method of mass selective acceleration enables an effective separation of ion species with relative mass differences of $\frac{\Delta m}{m} = 3.7 \cdot 10^{-4}$. Parabola shaped short bunch lengths were measured for an electron cooled 50 MeV $^{12}C^{6+}$ ion beam in the space charge limit. To overcome the space charge limit the TSR was operated at a momentum compaction of $\alpha = 1.57$.

RF ACCELERATION

The heavy ion storage ring TSR, installed at the Max-Planck-Institut für Kernphysik, is used for accelerator, atomic and molecular physics experiments. The TSR storage ring has a circumference of 55.42 m and can receive heavy ions from a 12 MV tandem van-de-Graaff and a normal conducting RF linac combination. Light positive and negative ions with mass to charge ratio $\frac{A}{|q|} \leq 9$ are provided by the high current injector. Heavy positive molecules are available from the Pelletron. Up to now the TSR is mainly used for experiments performed at injection energy. The widely tunable range of the TSR resonator opens up the possibility to accelerate and decelerate ions. Recent experiments have shown the feasibility of acceleration and deceleration. For ramping the magnetic fields the newly developed DAC cards as well a DSP driven synthesizer card were used. The generated functions to ramp the magnets can be directly calculated from the rigidity, taking into account the measured saturation effects of the TSR magnets. The user front end used for the ramp calculation is written in Mathematica. Only with the calculated functions for the power-supply currents and the calculated rf frequency it was possible to accelerate a $^{12}C^{6+}$ beam from 73.3 MeV to 362 MeV. The measured ion current during this acceleration process is shown in fig. 1. The ion current rises as the revolution frequency is increased during the ramp. From the final rf frequency and the stored ion current at the final energy an efficiency of 98% for the acceleration process can be calculated. The efficiency is the ratio of the ion number reaching the final energy, to the injected ion number. In these tests a record magnetic rigidity for an ion beam in the TSR of 1.57 Tm was achieved, significantly above the rigidity of 1.4 Tm realized in any previous beam time. The ramping time of 7s in the present case was limited by the voltage induced in the correction windings on the iron

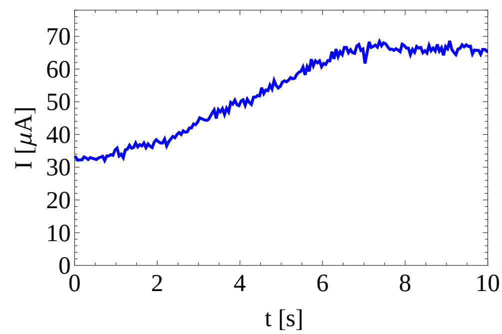

Figure 1: Ion current during acceleration of $^{12}C^{6+}$ ions from 73.3 MeV to 362 MeV. After 7 s the maximum rigidity of 1.57 Tm was reached.

cores of the TSR main magnets, which had to kept below 6 V for proper operation of the power supplies presently in use. The high efficiency was achieved by pre-cooling the ion beam with the electron cooler before starting the ramp.

Mass Selective Acceleration

Acceleration of molecular ions has been applied in experiments bringing, among others, D_3O^+ beams from 2 MeV at injection to final energies of 4.2 MeV within 2.5 s. Singly charged molecules are produced in a Penning ion source located at the 2 MV terminal of the Pelletron. Besides heavy singly charged molecules, like $DCND^+$, the ion source produces several other ion species such as N_2D^+, DCO^+ etc., with equal masses of 30 u. Due to the fact that the relative mass difference of two neighboring ion species, like $DCND^+$ and N_2D^+, is only $\Delta m/m = 3.7 \cdot 10^{-4}$, the desired molecule ions ($DCND^+$) can neither be separated with the separation dipole of the ion source nor with the magnets of the transferline guiding the ion beam to the TSR ring. The Schottky spectrum of the injected molecular ion beams, taken at the 44^{th} harmonic of the revolution frequency, is shown on fig. 2. The peaks in the spectra correspond to the different ion species. Because the energy of each ion type is the same, given by Pelletron voltage and the ion charge, the frequency splitting Δf/f can be calculated, in the non-relativistic approach, with following formula: $\frac{\Delta f}{f} = -\frac{1}{2}(1+\alpha)\frac{\Delta m}{m}$, where α is the momentum compaction of the storage ring, describing the change of the closed C_0 orbit length by variation the momentum p of the ions: $\alpha = \frac{\Delta C_0/C_0}{\Delta p/p}$. In the standard mode of the TSR the momentum compaction factor $\alpha = 0.1$ results in

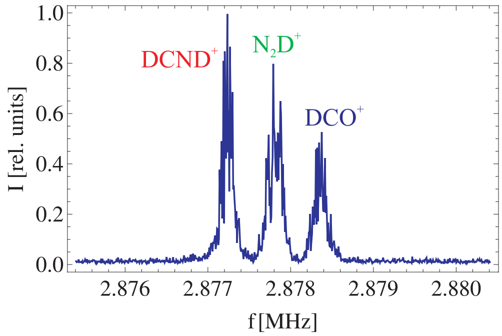

Figure 2: Measured Schottky Spectrum of a molecular ion beam, consisting of three ion species with a mass of 30 u.

a frequency splitting of 581 Hz at f=2.878 MHz, shown in fig. 2. The width of each peak in the spectrum is determined by the momentum spread ($\sigma_p/p \approx 3 \cdot 10^{-5}$) of the injected beam, which is quite small, yielding in a clear separation of the mass peaks. With mass selective acceleration the desired ion species, for example DCND$^+$, can be separated from the other type of ions. The procedure is explained in fig. 3. Mass selective acceleration can be described in the longitudinal phase space, defined by the frequency deviation $\Delta f_0 = f_0 - f_s$ and phase deviation $\Delta\phi = \phi - \phi_s$ of an ion, with a revolution frequency f_0 and rf phase ϕ. The revolution frequency of the synchronous particle is given by f_s and its rf phase is ϕ_s. After multiturn injection, which takes place at a resonator voltage of $U = 0$, three frequency bands are formed in the phase space (fig. 3 a). The width of each frequency band is given by the measured momentum spread of the injected beam. After injection the resonator

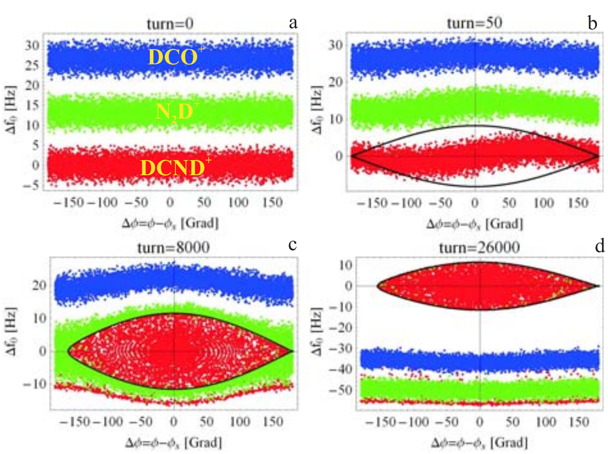

Figure 3: Illustration of mass selective acceleration in the longitudinal phase space. The size of the separatrix given by the resonator voltage and synchronous phase is shown as a black curve.

voltage was increased linearly in 1.5 ms to $U = 10$ V, capturing the stored ion beam into the rf bucket, enclosed by the separatrix (compare fig. 3 b). To accelerate the ions, the synchronous phase was increased from 0^o to 1^o. In the calculation a time of 200 ms was used to simulate the shift of the synchronous phase. In the experiment the same shift was carried out in 0.5 s, by changing the derivative of the rf frequency $\frac{df}{dt}$ from 0 to 0.45 MHz/s, following the magnetic rigidity $B\rho$ of the DCND$^+$ ion beam. The longitudinal phase space during the synchronous phase shift is displayed in fig. 3 c. At turn=26000 displayed in fig 3 d the synchrotron phase is already 1^o. The ions outside the bucket, created in the bunching process (fig 3 b), taking place during the first 1.5 ms, are not accelerated and keep their energy. In fig. 3 c the rf bucked, filled with DCND$^+$ ions, moves through the N_2D^+ ion beam without capturing a N_2D^+ ion. There are only a few N_2D^+ ions inside the DCND$^+$ bucket, caused by the bunching process taking place in the first 1.5 ms. To avoid a trapping of any undesired ions, the resonator voltage has to be slightly decreased. Due to the small energy spread of the injected ion beam a reduction of the resonator voltage is possible. However, a small energy drift of the Pelletron will cause an energy error that cannot be balanced by the bucket size if the resonator voltage is decreased. In fig. 3 c,d it can be seen that some DCND$^+$ ions are not captured in the bucket, because the resonator voltage was increased too fast. For that low ion beam velocity $\beta = 0.012$ a slower voltage increase (≥ 5 ms instead of 1.5 ms) would be more adequate. During the acceleration process the energy difference of the ion bucket to the non accelerated undesired ions is increasing with time. Since the magnetic field of the storage ring is matched to the DCND$^+$ ions, the false ions will hit the vacuum chamber of the storage ring during the acceleration process, due to the limited momentum acceptance of the storage ring. After 2 s acceleration time a pure DCND$^+$ ion beam reaches the final energy of E=3 MeV. At this energy the neutral reaction products from collisions

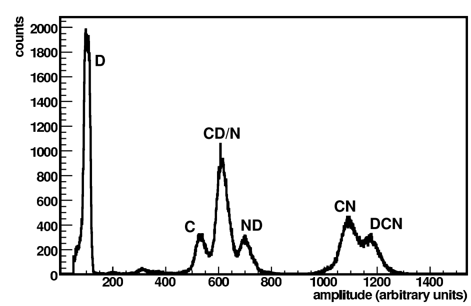

Figure 4: Pulse height spectrum of a finely segmented surface barrier detector for neutral fragments from reactions of DCND$^+$ with residual gas. The spectrum shows peaks corresponding to mass 2, 12, 14, 16, 26 and 28. Coincident pulses yield a sum of up to mass 30 (DCND).

of DCND$^+$ with residual gas (mostly H_2) were observed using a finely segmented, energy-sensitive surface barrier detector. These collisions lead to dissociation into neutral and charged or only neutral fragments. The corresponding pulse height spectrum is shown in fig. 4. Changing the rf start frequency to an integer multiple of the revolution frequency of the simultaneously stored N_2D^+ or DCO^+ beam allows to separate also N_2D^+ or DCO^+ ions.

Deceleration

In a first test devoted to the deceleration of highly charged ions, a reduction of the beam energy by a factor of > 6, from 73.3 MeV to 11.8 MeV (1 MeV/u), could be achieved readily with an efficiency of 68%, corresponding to a rigidity decrease from 0.71 Tm to 0.28 Tm. Formerly deceleration tests using the rf-booster were much more difficult and resulted in beam losses of several order of magnitudes. This feature now considerably widens the operating range with highly charged ions, produced at the MPIK accelerators, for new stored ion beam experiments planned at the TSR.

SHORT ION BUNCHES

For efficient ion beam deceleration small initial longitudinal bunch lengths, obtained by bunched beam electron cooling, are required. Even smaller longitudinal bunch lengths are necessary for experiments with a reaction microscope in a storage ring. Tests therefore were performed with 50 MeV $^{12}C^{6+}$ ion beams using the 6^{th} harmonic for bunching. A bunched ion beam profile obtained with simultaneous electron cooling, measured with a capacitive pick-up, is shown in fig. 5. The intensity of the $^{12}C^{6+}$ ion beam with $E = 50$ MeV used for this measurements was $I = 45\ \mu$A. The resonator voltage was set to 795 V. Also shown in fig. 5 is a parabola fit function (red line),

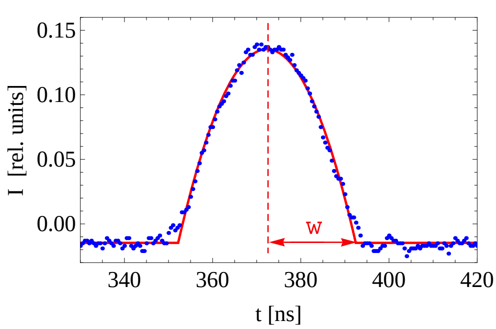

Figure 5: Measured electron cooled longitudinal ion beam ($^{12}C^{6+}$, $E = 50$ MeV) profile. The width of the parabola profile is defined by w.

which represents the data very well. A bunch length, defined in fig. 5, of $w = 20$ ns can be obtained from the fit. This bunch length is space charge limited. In the space charge limit the voltage of the resonator $U_i(\Delta\phi) = U\sin(\Delta\phi + \phi_s)$ each ion is passing through is compensated by the longitudinal space charge voltage of the ion beam. For bunching, in the TSR standard mode, where the slip factor $\eta = \frac{\Delta f_0/f_0}{\Delta p/p}$ is positive, the synchronous phase used for bunching is $\phi_s = 0$, where f_0 is the revolution frequency of an ion and p describes its momentum. Because the synchrotron oscillation is a very slow process compared to the revolution time, the longitudinal electrical field $E_\parallel(\Delta\phi)$, seen by one ion, can be assumed to be constant during one turn and the space charge voltage can be defined by $U_s(\Delta\phi) = E_\parallel(\Delta\phi)\cdot C_0$, where C_0 denotes the circumference of the storage ring. The ion phase $\Delta\phi$ is related to the longitudinal position s in the bunch: $\Delta\phi = -\omega\frac{s}{v_s}$, where ω is the angular frequency of the resonator and v_s the velocity of the synchronous particle, located in the center of the bunch at s=0. Ions in front of the synchronous particle ($s > 0$) arrive at the resonator gap earlier than the synchronous one, therefore there is a negative sign in the formula. The longitudinal electrical field $E_\parallel(s)$ can be calculated from the charge line density $\lambda(s)$ of the bunch by the following formula [1]:

$$E_\parallel(s) = -\frac{1+2\ln(\frac{R}{r})}{4\pi\epsilon_0\gamma^2}\frac{\partial\lambda(s)}{\partial s}. \qquad (1)$$

The constant ϵ_0 is the absolute permittivity and γ is the relativistic mass increase (for TSR energies $\gamma = 1$). R denotes the radius of the beam tube ($R = 0.1$ m) and r is the average beam radius, defined by twice the two σ_r value ($r = 2\sigma_r$) of the transverse beam width. A parabola density profile is the only longitudinal charge line distribution, for an electron cooled ion beam with $\Delta\phi \ll 2\pi$ ($\sin(\Delta\phi) = \Delta\phi$) , which compensates the resonator voltage $U_i(\Delta\phi)$ for each ion, independent of its phase $\Delta\phi$. The parabola charge line density $\lambda(s)$ can be calculated from the number N_B of particle in the bunch:

$$\lambda(s) = \frac{3N_BQ}{4w_s}(1 - \frac{s^2}{w_s^2}) \qquad (2)$$

for $|s| \le w_s$, with $\int_{-w_s}^{w_s}\lambda(s)ds = N_B\cdot Q$. The charge of an ion is Q and w_s describes the bunch length in meters, related to the bunch length w in seconds, $w_s = v_s\cdot w$, defined in fig. 5. If $U_i(\Delta\phi)$ is completely compensated by the space charge voltage $U\cdot\sin(\Delta\phi+\phi_s)+E_\parallel(\Delta\phi)\cdot C_0 = 0$, the synchrotron oscillation of each particle in the bunch is freezed. This condition leads finally to the longitudinal space charge limit. For a beam, having a parabola longitudinal charge line density, the space charge limit is given by following formula:

$$w = C_0\sqrt[3]{\frac{3(1+2\ln(\frac{R}{r}))I}{2^4\pi^2c^4\epsilon_0\gamma^2h^2\beta^4U}}\,. \qquad (3)$$

The bunch length w in formula (3) is determined by the beam intensity I , the resonator voltage U, the number of bunches h in the ring and the beam velocity β in units of the speed of light c. If the space charge voltage $|U_s(\Delta\phi)|$ of the ion beam were larger than $|U_i(\Delta\phi)|$, the magnitude $|\Delta\phi|$ of each ion would increase by the repelling space charge force, resulting in an increase of the bunch length. On the other hand a larger bunch has a smaller space charge voltage $|U_s(\Delta\phi)|$, thus the ion starts to oscillate. These oscillations $\Delta\phi$ will be damped by the electron cooler, bringing back the beam to the space charge limit. Therefore an electron cooled ion bunch in the space charge limit is stable. With an average transverse beam seam size σ_r=1 mm, the bunch length w can be calculated. Fig. 6 shows the measured bunch length w as a function of resonator voltage U as well the theoretical prediction (red curve). As it is shown in fig. 6 the calculated function agrees very well with the fit to the data ($w \sim U^{-0.34}$), blue line. At the

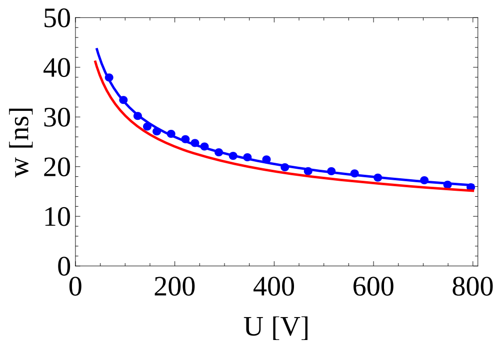

Figure 6: Measured bunch length w for an electron cooled $^{12}C^{6+}$ ion beam ($E = 50$ MeV, $I = 20$ μA) as a function of the resonator voltage. The red curve is a calculation, where formula (3) was used.

same number of bunches $h = 6$, the bunch length w was measured as a function of the beam intensity, shown in fig.7. The resonator voltage used in these measurements was $U = 795$ V. A fit through the data, blue curve, gives an exponent of 0.31, which is slightly less than the predicted value of 1/3. Furthermore the bunch length w was

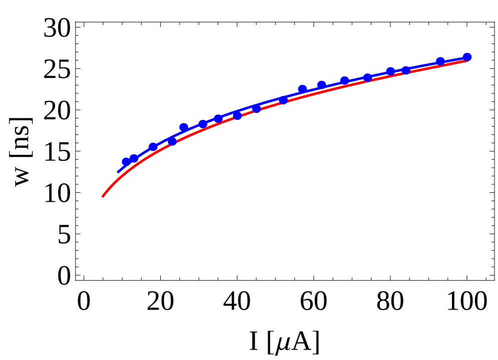

Figure 7: Measured bunch length for an electron cooled $^{12}C^{6+}$ ion beam as a function of the ion intensity. The resonator voltage used in this measurement was $U = 795$ V. The red curve is a calculation using formula (3).

measured as a function of the rf frequency for a $^{12}C^{6+}$ ion

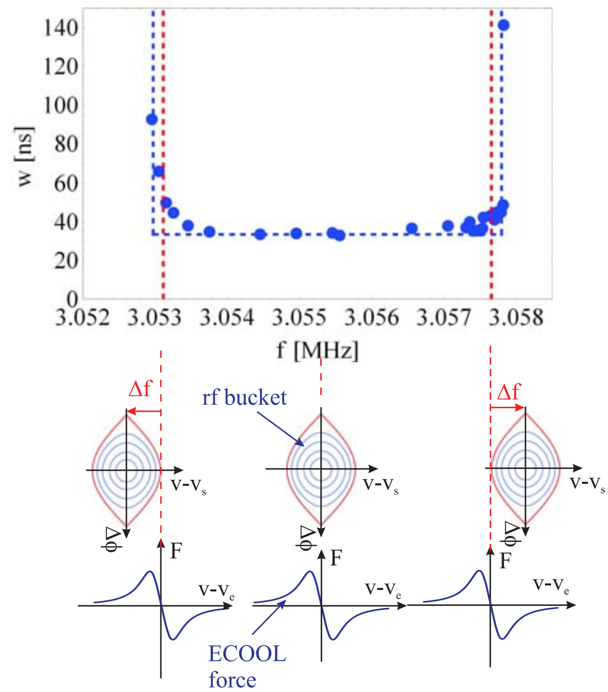

Figure 8: Measured bunch lengths for an electron cooled $^{12}C^{6+}$ ion beam as a function of the rf frequency f. Also shown is the explanation of the bunch length increase at large frequency shifts.

beam with $E = 50$ MeV. The result of these measurements are displayed in fig. 8. The voltage used in this measurement was $U = 96$ V and the ion current was $I = 20$ μA. As it can be seen in fig. 8 the bunch lengths are constant, around $w = 33$ ns, in a relatively wide frequency range. On the borders the bunch lengths are increasing rapidly. There is a deviation from the parabola bunch shape if the bunch length is larger than $w = 90$ ns. Outside the boundaries, blue marked vertical lines in fig. 8, there are no observed ion bunches. This behavior can be explained also with fig. 8. If the rf frequency f is changed, the velocity v_s and the revolution frequency f_s of the synchronous particle, which has to fulfill the equation $f = h \cdot f_s$, is modified. This means that the rf bucket, where the synchronous particle is sitting in the center ($v = v_s$), is shifted with respect to the velocity v_e of the electron beam. The cooling force of the electron cooler tries to shifts the ion velocity v to the electron velocity v_e. If the electron velocity v_e comes to the outside of the rf bucket no bunching is possible, due to the missing closed orbits in the longitudinal phase space around the synchronous particle. The experimental values found for the two limits are $\Delta f_l = \pm 2.37$ kHz, which is close to the bucket height $\Delta f_b = 2.27$ kHz calculated with: $\Delta f_b = \frac{1}{C_0}\sqrt{\frac{2|\eta|hQU}{\pi m}}$, where m is the mass of an ion. In fig. 8 the bucket size (red lines) are also shown. The small frequency difference between the vertical blue and red dashed lines can be explained by the momentum spread of the stored ion beam.

Bunch Lengths at Negative η

The ion bunch length can be decreased by increasing the resonator voltage U or by decreasing the intensity I of the stored ion beam. But for both quantities there are practical limits. The intensity limit is given by the experimental requirements, whereas the voltage is limited by the maximum voltage of the resonator, which should not exceed in our case 5 kV. To decrease the bunch length further the space charge limit has to be overcome. Because the synchrotron frequency f_{sy} fulfills the following relation: $f_{sy} \sim \sqrt{\eta \cos(\phi_s)}$, bunching is done at $\phi_s = \pi$ for $\eta = \frac{\Delta f_0/f_0}{\Delta p/p} < 0$, to obtain a real synchrotron frequency. If the beam is bunched at $\phi_s = \pi$, the voltage $U_i(\Delta\phi)$, seen by one ion, has the same sign as the space charge voltage, thus the space charge of the ion beam $U_s(\Delta\phi)$ cannot compensate $U_i(\Delta\phi)$. A negative η parameter means that particles with larger momentum than the central particle need more times T ($T = 1/f_0$) for one turn compared to the central one. A negative slip factor η can be achieved by increasing the length of the closed orbit for an ion having a positive momentum deviation. The length of the closed orbit C_0 can be described by the momentum compaction α of the storage ring, defined in the subsection mass selective acceleration. To avoid the space charge effect, the TSR was set to α=1.57, which is consistent with $\eta = -0.57$, for 50 MeV $^{12}C^{6+}$ ions. An α paramer of 1.57 results in an average dispersion $\bar{D}_x = 13.8$ m in the TSR main dipole magnets. At this setting bunch length measurements for an electron cooled 50 MeV $^{12}C^{6+}$ ion beam were performed. A longitudinal ion bunch profile taken at a beam intensity of $I = 1.3\ \mu$A and at a rf frequency f=3.053 MHz is shown in fig. 9. In constrast to the profile measured at the space

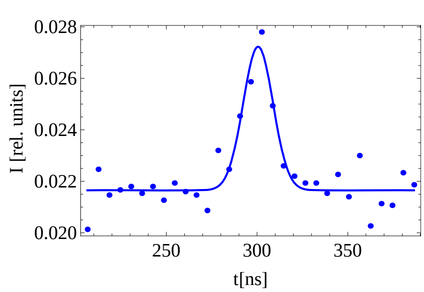

Figure 9: Measured ion bunch profile ($I = 1.3\ \mu A$) at $\eta = -0.57$. A resonator voltage of 10 V was selected.

charge limit, this profile can be described with a Gaussian distribution. At the intensity of $I = 1.3\ \mu$A a beam width σ=8 ns was determined. The measured beam widths σ as a function of the rf frequency f for different resonator voltages U are shown in fig. 10. After the measurements at resonator voltages of U=10 V and U=19 V the electron energy was increased slightly, resulting in a shift of the red

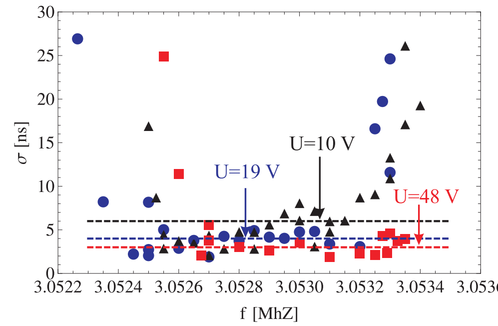

Figure 10: Measured bunch length as a function of the rf frequency f at $\eta = -0.57$. The beam intensity was between 0.5-1.5 μA.

data points to higher frequencies compared to the measurements at 10 V and 19 V. As it can be seen in fig. 10 the bunch length σ decreases with the applied resonator voltage U. At U=48 V bunch lengths of $\sigma \approx 3$ ns were measured. To compare this Gaussian bunch length σ with the parabola bunch length w obtained at the space charge limit, the parabola bunch length has to be converted to a corresponding length σ_w of a Gaussian distribution, having the same half width. A parabola and a Gaussian distribution have the same half width if the relation: $\sigma_w = \frac{w}{2\sqrt{\ln(2)}}$ is fulfilled. For 50 MeV $^{12}C^{6+}$ ions the space charge limit is given by: $w[ns] = 62.1\frac{I[\mu A]^{0.31}}{U[V]^{0.34}}$. This equation gives for $I = 0.5\ \mu$A and U=48 V a corresponding Gaussian bunch length σ_w=8 ns, which is a factor 2.7 larger than the measured bunch length ($\sigma \approx 3$ ns) at $\eta = -0.57$.

CONCLUSION AND OUTLOOK

Ramping of the TSR storage ring is now routinely used to accelerate a stored ion beam to the rigidity limit of the storage ring. With the method of mass selective acceleration simultaneously stored ion species with relative mass differences down to $\frac{\Delta m}{m} = 3.7 \cdot 10^{-4}$ can be separated. For a bunched electron cooled ion beam ($^{12}C^{6+}$, $E = 50$ MeV), a bunch length of $w = 3.1$ ns at $h = 6$ and $I = 0.1\ \mu$A can be anticipated in the TSR standard mode ($\eta > 0$), sufficient for the experiments with an internal gas jet target and a reaction microscope. To overcome the space charge limit the TSR was operated at a momentum compaction of $\alpha = 1.57$. In this mode shorter bunch lengths compared to the standard mode were achieved, if the same intensity and resonator voltage U are used. But currently the maximum voltage which can be applied to the beam, at $\eta = -0.57$, was limited to approximately $U \approx 50$ V. At higher resonator voltages almost no storage of a cooled bunched ion beam was possible. To improve this situation further investigations are necessary.

REFERENCES

[1] A. Hofmann, CERN yellow report, CERN 77-13, page 143 (1977).