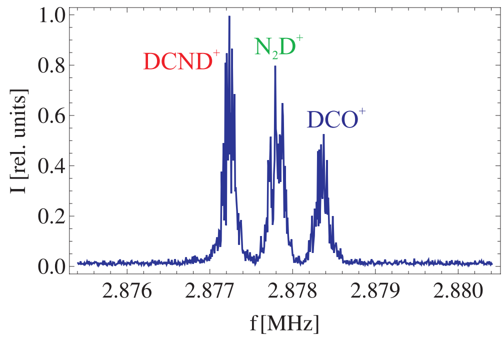

Figure 2: Measured Schottky Spectrum of a molecular ion beam, consisting of three ion species with a mass of 30 u.

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

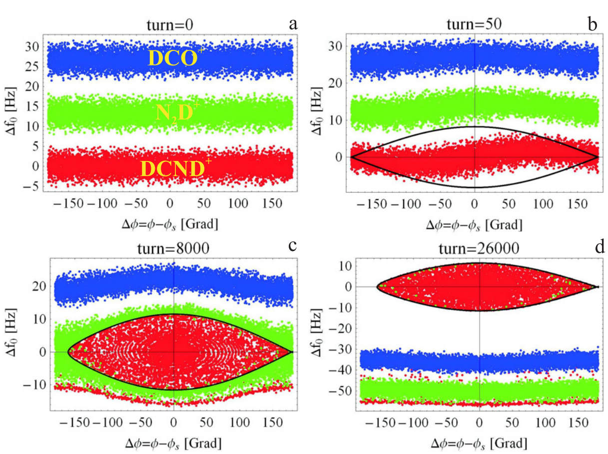

Figure 3: Illustration of mass selective acceleration in the longitudinal phase space. The size of the separatrix given by the resonator voltage and synchronous phase is shown as a black curve.

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 ($\geq$ 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 with 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

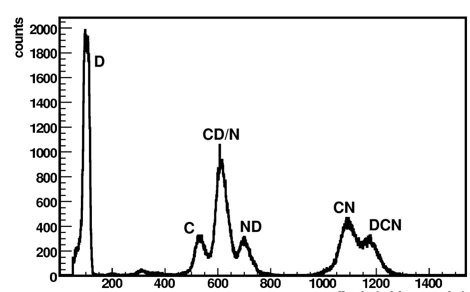

Figure 4: Pulse height spectrum of a finely segmented surface barrier detector for neutral fragments from reactions of DCND$^+$ with residual gas. The spectrum shows peaks corresponding to mass 2, 12, 14, 16, 26 and 28. Coincident pulses yield a sum of up to mass 30 (DCND).

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 $I = 45$ μA. The resonator voltage was set to 795 V. Also shown in fig. 5 is a parabola fit function (red line),

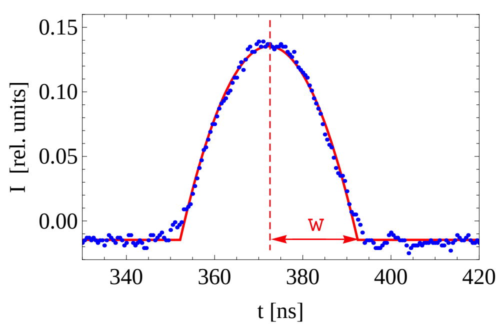

Figure 5: Measured electron cooled longitudinal ion beam ($^{12}C^{6+}$, $E = 50$ MeV) profile. The width of the parabola profile is defined by w.

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 $E_{\|}(\Delta\phi)$, seen by one ion, can be assumed to be constant during one turn and the space charge voltage can be defined by $U_s(\Delta\phi) = E_{\|}(\Delta\phi)\cdot C_0$, 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 $E_{\|}(s)$ can be calculated from the charge line density $\lambda(s)$ of the bunch by the following formula [1]:

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

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 $|s| \leq w_s$, 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 $U\cdot\sin(\Delta\phi+\phi_s)+E_{\|}(\Delta\phi)\cdot C_0 = 0$, 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 would be 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