MEASUREMENTS AND IMPROVEMENTS OF THE TIME STRUCTURE OF A SLOWLY EXTRACTED BEAM FROM A SYNCHROTRON

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Abstract

The slow extraction from the heavy ion synchrotron SIS at GSI is performed by tune variation or transverse rf excitation. The beam is quite sensitive to any tune variation, e.g. caused by ripple of the magnet's power supplies. Besides measurements of the spill structure with integration times from μs to ms region it is shown that the intensity variation of the extracted beam is significantly smoothed when a partially bunched beam is extracted. This is independent of the the stored current. The measurements are compared to a Monte-Carlo simulation. The interesting role of the chromaticity is shown.

1 INTRODUCTION

For most fixed target experiments at the GSI heavy ion synchrotron a slow extraction via tune variation or transverse rf knock out is used. To get an extraction time of several seconds the relative tune variation towards the 3^{rd}-order resonance is about 10^{-3} s^{-1}. This slow tune change is disturbed by the variation of the magnetic field due to power supplier ripples having a main network related 50 Hz (and harmonics) frequency characteristic. Therefore, the extracted current is strongly modulated and this should be taken into account for any rate consideration for the experiments. Moreover for the cancer therapy, where an active scanning of the pencil beam is used [1], this modulations have to be measured precisely to control the deposited dose within the human tissue. By bunching the beam with the rf cavity at a harmonics of the revolution frequency, a much smoother spill structure can be created. This is due to a time dependent momentum deviation $\Delta p(t)$ of the single particles and its coupling to the tune spread $\Delta Q(t)$ via the chromaticity $\Delta Q(t)/Q = \xi \cdot \Delta p(t)/p$. This is an alternative approach to rf-channeling [2] or slow acceleration [3], where neither additional hardware nor dynamic software control is needed. We show relevant measurements for low and high current and interpret them with the help of a Monte-Carlo simulation.

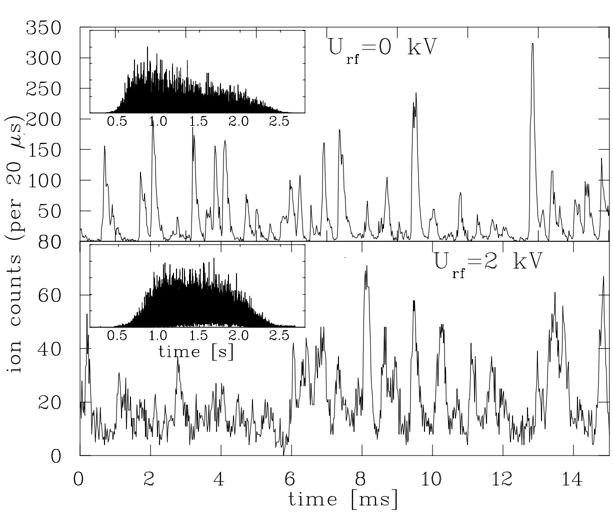

Figure 1: Typical time structure of a spill extracted by tune variation without bunching (top) and improvement by a 2 kV bunching voltage (bottom). The full spill-signal of the 300 MeV/u C^{6+} beam is drawn in the insert.

2 COMPARISON OF TIME AND FREQUENCY DOMAIN SIGNALS

To get a reliable view of the extracted current one needs a fast and non-integrating detector system in connection to a high rate data acquisition system. For low current measurements we use a plastic scintillator where single particles up to an average rate of a few 10^6 s^{-1} are counted [4]. For high currents we use a cryogenic current comparator (CCC), that measures the magnetic field of the ions [5]. The full spill is recorded with a time bin of 20 μs. The chromaticity used at SIS is $\xi \sim -1$ and the momentum spread is typically $\Delta p/p = 5 \cdot 10^{-4}$. The top of Fig.1 shows a typical time spectrum by means of a tune variating extraction with a carbon beam used for the cancer treatment. One can see a clear over-modulation or 'chopping' of the beam and a steeper rise of the peaks compared to the falling edge as expected [3]. The average current amounts about 1/15

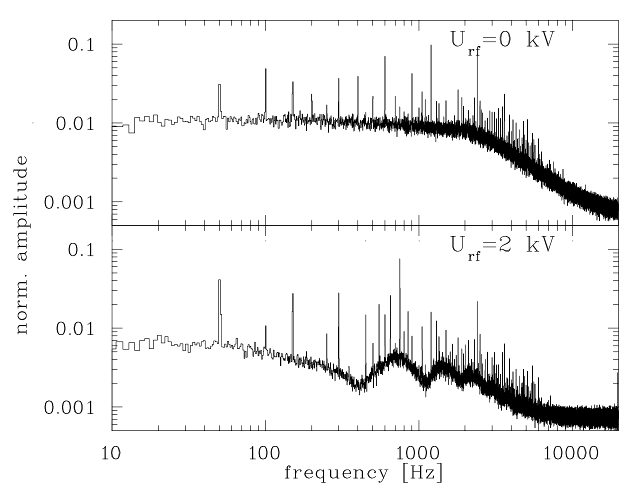

Figure 2: Fourier transformation of of the signals displayed in Fig.1 averaged over 10 Spills; without bunching (top) and with bunching (bottom).

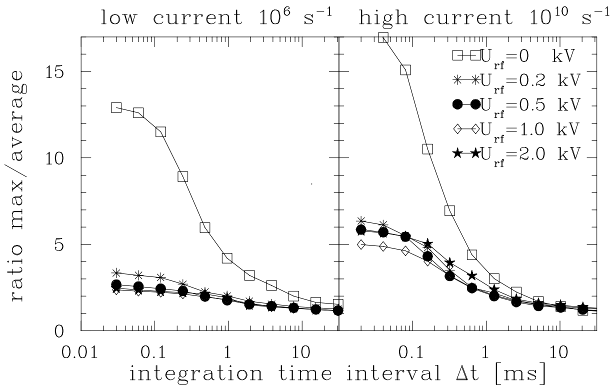

Figure 3: The ratio of maximum-to-average current for a 300 MeV/u Ar^{18+} beam using various bunching voltages as a function of the integration time. Results for low current ($\sim 10^6$ s^{-1} using a scintillator) on the left and high current ($\sim 10^{10}$ s^{-1} using the CCC) are displayed.

of the peak current (within 20 μs integration time). By extracting a beam, which is bunched inside the synchrotron by about 1/4 of the voltage used for acceleration, the time structure is changed in a sense that the over-modulation vanished completely (see Fig.1 bottom). The peaks have still the same rise time, but the breaks disappear due to the time dependent tune of a single particle caused by the synchrotron oscillations, as explained in detail below.

As a typical result the Fourier transformation of the time signal is displayed in Fig.2 for both cases. 50 Hz related lines are visible having a width below 1 Hz reflecting the characteristic of the power supplies of the magnets. In the cases shown, the 600, 750, 1200 and 2400 Hz lines are most prominent. But more important are the non-coherent contributions up to about 10 kHz in the unbunched beam. The position of this shoulder is lowered by the bunching. In addition the amplitude for low frequencies is about a factor of two smaller. Both changes reflect the vanishing over-modulation in the time domain. Having a bunched beam, the synchrotron frequency and it's harmonics are clearly visible at about 700 Hz for 2 kV bunching voltage. For this bunching voltage the contribution is low, but for higher voltages the peak value increase up to a factor of ~ 5 for $U_{rf} = 5$ kV. This might give some restrictions of this method.

Another characterization more suited for the specification from the experimentalists is the variation of the maximum-to-average ratio within a certain time. A typical result from a measurement using a Ar^{18+} beam is shown in Fig.3. Here the low current results fit well to the high current results, showing the independence on any space charge effects (for a transversal uncooled beam). For an unbunched beam, the maximum-to-average is about 10 to 20 on the 20 μs scale and decreases between 0.1 and 3 ms to about 2. With bunching the ratio is as much as a factor 5 lower for short time bins, but shows the same time characteristic as for unbunched beams. This improvement appears for quite low bunching voltages, but can even be increased with higher bunching factors.

In an increasing number of experiments the extraction is done by an excitation of betatron amplitude by a transverse electric field with a noise characteristic on the betatron side band ('knock out method' [6]). We find the same type of improvements due to bunching as described for the tune variation. In this sense both methods are equal, but the knock out method has the big advantage, that the beam optics, and therefore the transverse beam properties, are constant during the extraction.

3 COMPUTER SIMULATION AND EXPLANATION

For numerical calculations of the slow extraction process with a bunched beam a code using Monte-Carlo method has been written. The betatron oscillation and nonlinear resonance of the beam are analyzed in the normalized horizontal and vertical phase space. Thin lens approximation is used for treatments of the effects of the nonlinear magnetic field and the high frequency perturbation field according to [6]. The accelerator is not considered in detail, but phase advances between the important elements (2 sextupoles, electrostatic septum ES) are taken into account. The horizontal phase advance $\Delta\mu(t)$ per revolution for every particle with tune Q is not a constant, but depends on the particle's momentum deviation $\Delta p(t)$ and the chromaticity ξ of the ring:

$$\Delta\mu(t) = (Q + \xi \cdot \Delta p(t)/p) \cdot \pi$$

Due to the bunching, the time dependent momentum deviation is calculated solving the differential equation for the longitudinal motion [7] to get the time dependent momentum oscillating with the synchrotron frequency.

In order to limit computer time and to have a sufficiently large number of extracted particles, only a small fraction of a beam is generated which occupies the region close to the resonance line. The momentum is described by a Gaussian distribution of $5 \cdot 10^{-4}$ total width. The sextupole field strength is chosen to have a separation of the particles at ES of 7-9 mm and the horizontal tune difference to the 3^{rd}-order value of $5 \cdot 10^{-3}$ is set to produce a separatrix area in which the beam with an emittance of 20π mm mrad can be contained. Several numerical simulation have been made using 655.000 particles and an extraction length of 20.000 turns equals ~ 20 ms. The speed of the resonance line moving to the beam is $\Delta Q/\mathrm{turn} = 2 \cdot 10^{-8}$. The tune ripple frequency is chosen randomly in the range of 0.4-10 kHz and the corresponding amplitude for 100 % modulation of the extracted beam is automatically calculated in the range of $dQ/Q = 3 \cdot 10^{-7} - 7 \cdot 10^{-6}$ [3]. The parameters used in the simulation correspond to the 300 MeV/u C^{6+} beam where measurements are displayed in Fig.1 to 2.

The calculated time profile for an unbunched beam is shown in Fig.4a. Like in the experimental case, the beam is over-modulated. The intensity of the particles on the unstable separatrix branch is modulated if the tune varies (e.g. due to the ripples on the magnets power supplies). Such an

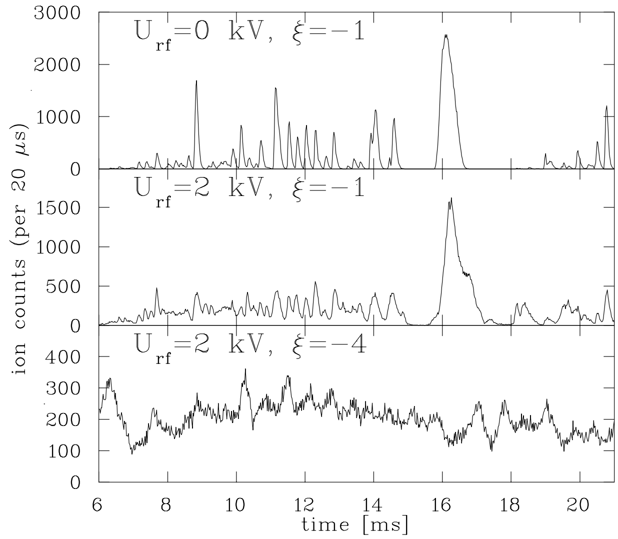

Figure 4: Simulated time structure of a spill extracted by tune variation without bunching and chromaticity $\xi = -1$, like at SIS (top), with bunching using 2 kV (middle) and improved structure using bunching and $\xi = -4$ (bottom).

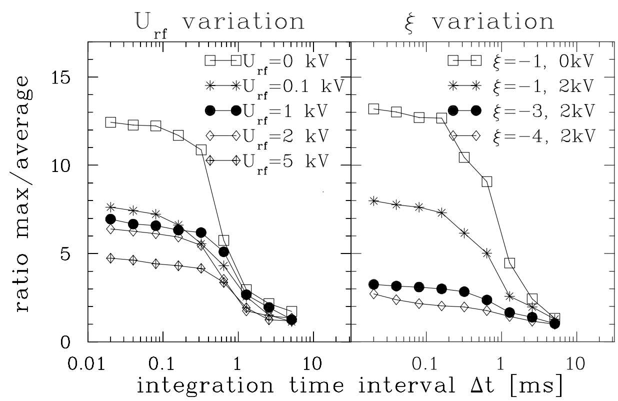

Figure 5: The ratio of maximum-to-average current as calculated for a 300 MeV/u C^{6+} beam as a function of the integration time. On the right $\xi = -1$ (corresponding to the normal SIS setting), on the left the proposed improvement for different ξ are shown.

intensity modulation may be described in a Steinbach diagram, as shown in Fig.6, as 'stripped resonance bands' with increasing amplitude over the time the particles need to proceed from the unstable region outside of the separatrix to the position of the ES. The slope of these resonance bands are given by the chromaticity. The time profile of the extracted beam current can be obtained by summing up the projection of these stripes, leading to a strong modulation in case of small chromaticity and momentum spread.

For a bunched beam this situation is changed, see Fig.4b. In this case at a definite time all particles with amplitudes on the resonance line do not become unstable simultaneously as in the case of an unbunched beam. Now the time to reach the unstable region depends on the momentum of the particle because of the synchrotron oscillation that causes a time dependence of the momentum. In the Steinbach diagram it is seen that a particle with a certain momentum deviation can move back to the stable region. Such a particle performs excursions into the stable region during several

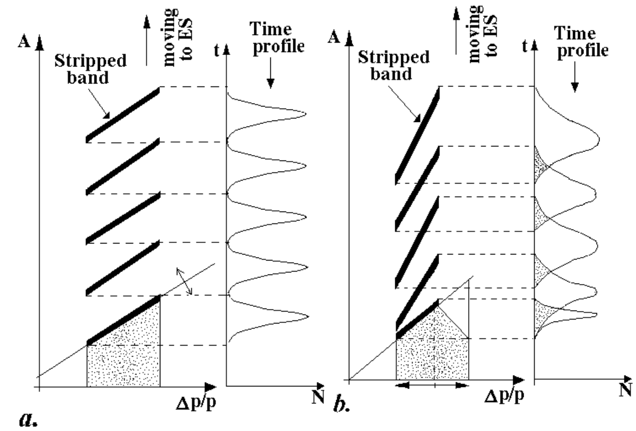

Figure 6: Steinbach-diagram to visualize that the flux of particles is obtained by summing over the 'strip profiles' without bunching (left) and with bunching (right).

synchrotron periods, while the particle betatron amplitude will be increased enough to reach finally the ES. This additional velocity component results in an increased slope of the stripped band equivalent to an enhancement of the chromaticity. The calculation shows that the delay of the particles with maximum momentum deviation for bunched beam ($U_{rf} = 2$ kV) is about 10-12 time more compared to the unbunched beam. Such time delay of some fraction of the particles results in an improvement of the spill quality (Fig.4 and 5). It is even improved with increasing rf-field due to the stronger focusing of the momentum close to the resonance line as has been also measured.

The correspondence between measurement and calculation is quite good taking experimental uncertainties and numerical simplifications into account.

It is clear that overlapping of the stripped bands will be higher if the angle of this bands are increased resulting in an improvement of the spill quality. Fig.4c shows the calculated time profile of the extracted beam with the same rf voltage as before but with different horizontal chromaticity of $\xi = -4$. The results for the spill quality depending on chromaticity are shown in Fig.5. Measurements have to be done to verify that an even higher spill quality is possible.

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