SIMULATION STUDIES OF LONGITUDINAL RF-NOISE AND PHASE-DISPLACEMENT ACCELERATION AS DRIVING MECHANISM FOR THE MEDAUSTRON SYNCHROTRON SLOW EXTRACTION

U. Dorda, EBG MedAustron, Wiener Neustadt, Austria
A. Wastl, H. Schönauer, M. Benedikt, CERN, Geneva, Switzerland

Abstract

MedAustron is a synchrotron based hadron therapy and research facility located in Austria currently entering the installation stage. It is an implementation of the CERN-PIMMS design which proposed induction acceleration by a betatron core to the beam into the third-order slow resonant extraction. Primarily in order to increase the accelerators flexibility towards future irradiation schemes but also as back-up options, two alternative extraction driving mechanism have been studied: Longitudinal RF-noise and phase displacement acceleration. The advantages as well as the corresponding limitations are explained, analytical estimates and particle tracking results performed with the 2D tracking codes LONG1D and a specifically developed Python based simulation code are presented.

INTRODUCTION

In order to allow for the foreseen active scanning of the beam over the tumor, a very stable, low intensity, spill has to be delivered by the extraction from the synchrotron. The MedAustron accelerator complex is based on the CERN-PIMMS study [1], which uses a betatron core to accelerate the beam into a third order resonance. Alternative extraction methods have been studied in order to be able to deliver shorter spills down to 0.1 s for non-clinical purpose, as back-up and to ensure flexibility for possible new irradiation strategies. In order to allow for the change of the extraction scheme to be transparent to the other machine set-up, the alternative extraction scheme must be capable to increase the momentum of the stack by $\Delta p/p = 5 \cdot 10^{-3}$.

The simulations results presented in this papers are studying the longitudinal beam dynamics of RF-noise and phase-displacement acceleration. As soon as a particle reaches a given momentum offset it is assumed to be immediately extracted via the horizontal slow resonant extraction. In reality the required momentum deviation at which the particle gets extracted is a function of the horizontal amplitude as well. This aspect is identical to the betatron acceleration and related intensity smoothing was studied extensively in [1].

The MedAustron RF-system operates at harmonic number h = 1 with a maximal RF-Voltage of $V_{max,RF} = 5kV$.
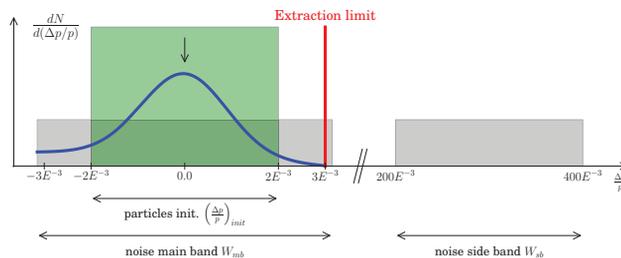

Figure 1: Main and side-band of the filtered white noise applied to the particles in order to excite the diffusion process. The initial particle distribution is indicated in pale green, the distribution after some time in blue.

RF NOISE

Longitudinal RF-noise was proposed and analytically described as a possible driving mechanism for third order slow resonant extraction in [2]. Individual particles perform a random walk in the longitudinal phase-space and diffuse into the resonance. The diffusion process is determined by the band-width and amplitude of the applied RF-noise. As a minimum band-width W, the frequency spectrum corresponding to the beam momentum spread and the resonance must be covered ("*main-band*" in Fig. 1). If the band-width is too small, the flux of extracted particles will show an unwanted modulation. In this case, noise outside the beam spectrum must be added ("*side-band*"). In case of a time-wise constant noise excitation, the extracted beam current follows an exponential decay in time with a time constant $\tau = -(\frac{\pi}{2Q'W_{mb}})^2 D$ where Q' is the chromaticity. The diffusion constant D is given by $D = \frac{1}{2W_{total}}\left(\frac{Q'V_N}{\beta pT}\right)^2$ where V_N is the rms noise voltage, T the revolution period and W_{total} the total band-width of the noise signal.

Simulation Results

A dedicated 2D single particle tracking code was developed and used to simulate the case of a coasting $300 MeV$ proton beam with an initial momentum spread of $\frac{\Delta p}{p} = 4 \cdot 10^{-3}$ (uniformly distributed). This corresponds to a main-band band-width of 4.0 kHz. In order to include margins and the resonance, a band-width of 5.0 kHz was used (equivalent to $\frac{\Delta p}{p} = \pm 3.15 \cdot 10^{-3}$).

An analysis of the RF-voltage applied to one particle in consecutive turns indicated that adding a side-band of 400

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kHz band-width shifted 800 kHz from the main-band suppresses the correlation in the time domain within the interesting time scales. Figure 2 shows the change in the momentum distribution of the beam as a function of time ($U_{RF,RMS} = 4.6$ kV).

As expected the position of the beam center remains unchanged and the distribution widens due to diffusion until the first particles reach the extraction limit. As particles are continuously removed from the distribution once it reaches the extraction limit, the particle density on the right side is reduced, causing the position of the beam center to be shifted to the left side. The diffusion process continuously re-populates the right side and consequently particles keep moving into the resonance. As expected no particles are found outside of the main-band at any time. As the beam
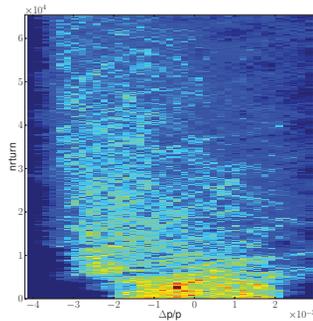

Figure 2: 2D histogram of the particle density in $\frac{\Delta p}{p}$ space over time/turns. The extraction limit is set to $\frac{\Delta p}{p} = 3 \cdot 10^{-3}$.

center is not oscillating and the re-population of the right side continues, one can deduce that the noise band-width is chosen sufficiently wide. Figure 3(a) shows the number of stored particles as a function of time for different ratios of $V_N^2/W_{total} \propto \tau$. The exponentially assumed decay proceeds faster the higher this ratio. As expected a constant noise voltage does not result in a linear progression. Figure 3 shows the decay of the number of stored particles for the case of $V_N^2/W_{total} = 30$ (black curve). The exponential fit (red) to this data gives a time constant of $\tau = -1.1 \cdot 10^{-5}$ s. This curve is proportional to the extraction rate ($\frac{d}{dx}e^x \propto e^x$) and therefore the time constants may be compared to the one obtained from the analytic formula for the time constant of the decay of the extraction rate $\tau = -0.89 \cdot 10^{-5}$ s.

PHASE DISPLACEMENT ACCELERATION

In order to perform phase-displacement acceleration, empty RF-buckets are created just above the longitudinal phase-space area covered by the beam ("stack"). Next, the bucket energy is decreased adiabatically so that the bucket traverses the beam phase space area forcing the latter to move upwards. This method was successfully applied in the CERN ISR to accelerate coasting proton beams from 26.6 to 31.4 GeV [3] by ≈ 200 sweeps (12kV) through
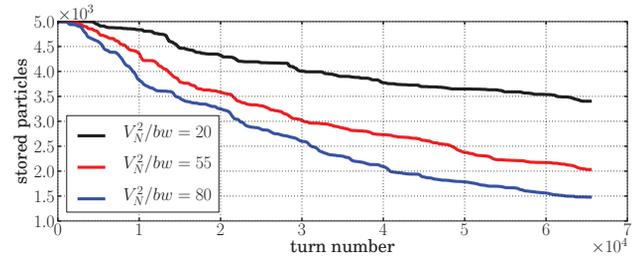
(a) The decay of the stored beam current is in all thee cases of different V_N^2/W_{total} smooth. As expected, a higher ration of V_N^2/W_{total} increases the spill flux.
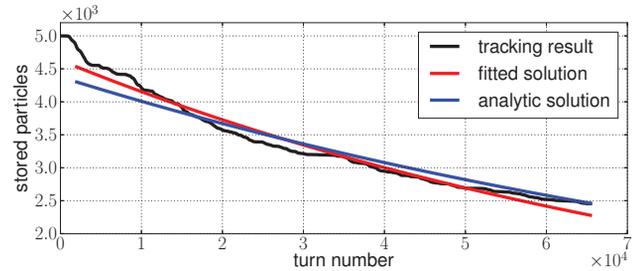
(b) Case of a noise side-band of $W_{sb} = 400kHz$ and $U_{RF} = 3.5kV$: The simulation results (black) and the exponential fit (red) correspond well to the analytic solution.

Figure 3: The stored beam current as a function of time for various noise configurations.
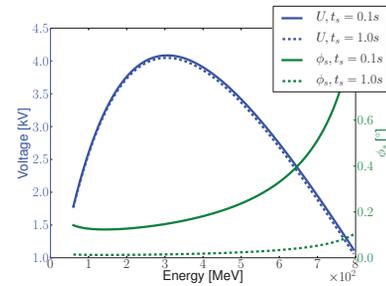

Figure 4: The RF voltage of a single RF-bucket required to accelerate the whole proton-stack by $\Delta\frac{\Delta p}{p} = 5 \cdot 10^{-3}$ within 0.1/ 1 second as a function of energy.

the stack. In [1] it is also proposed to use multiple empty bucket sweeps as an alternative extraction driving mechanism.

The MedAustron RF-system could be used for the case of one single bucket without any modifications using the frequency program of the LLRF system.

The particle tracking code LONG1D [4] was used to simulate the acceleration with one or multiple buckets.

1 Empty Bucket

Figure 4 shows the RF-voltage required to accelerate the beam with a single sweep into the resonance. In all cases, the required voltage is well within the RF-systems capabilities and the synchronous phase is sufficiently small to not give raise to scattering [5]. The case of a 60 MeV proton beam-stack being traversed within 150 ms by a single

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$U_{RF} = 2kV$ bucket was simulated (Fig. 5). It validates that the sweep is sufficiently adiabatic (synchrotron period is 0.5ms) and not scattering occurs. Figure 7 shows that the

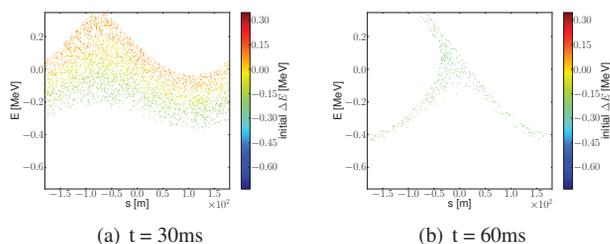(a) t = 30ms   (b) t = 60ms

Figure 5: Longitudinal phase-space at two time instances during the 1 bucket empty bucket acceleration. The coloring encoding indicates the particles initial energy.

extracted beam current as a function of time is for the better part a smooth curve and validates that almost the complete beam is extracted.

6 Empty Buckets

As an alternative, the case of six smaller buckets crossing the stack time-shifted was investigated. Figure 6 shows the longitudinal phase-space at when six empty buckets are sweeping within 25 ms spaced in time by 8 ms. In this configuration, the buckets almost touch each other: Figure 6(b) shows the situation where the first bucket is already completely submerged in the stack while the second one is just entering the stack. Figure 6(c) shows the situation just before the first bucket reaches the lower end of the stack. The high synchronous phase and the closeness of two consecutive buckets cause a significant distortion of the bucket-shape. In Fig. 6(d), the second bucket is reaching the lower end of the stack. Comparing its bucket shape to the first one at its start (Fig. 6(b)), shows that the closeness of the neighboring buckets has altered its shape/ reduced its area. While the concept still holds even in this extreme case, it's efficiency is significantly reduced.

Figure 7 shows the circulating beam current for various options of 6 buckets. The red curve indicates the case of 6 buckets with $U_{RF} = 250V$ spaced by $\Delta t = 20$ ms sweeping through the stack within $t_s = 30$ ms. As there are moments when no bucket is located at the very top of the stack, there are pauses in the decrease of the circulating beam current. While this pulsing is smoothened by the dynamics of the horizontal 3rd order slow resonant extraction (which is not included in this simulation model), the spiral step (and thereby the extracted beam profile) is a function of the particle energy and thus a function of time in this case. This can be avoided by increasing the sweep-time t_s and decreasing the spacing Δt between two buckets (blue line). A configuration for a perfectly smooth extraction was found for a longer extraction duration (green curve).

Given the simplicity and compatibility with the existing RF-system the method of one single bucket will be studied in the machine.

(a) t = 0   (b) t = 10ms

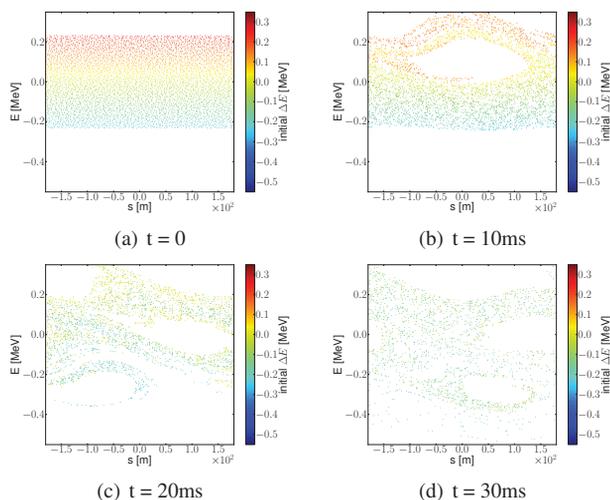(c) t = 20ms   (d) t = 30ms

Figure 6: Longitudinal phase-space at various time instances during the multiple-empty bucket acceleration, The coloring encoding indicates the particles initial energy.
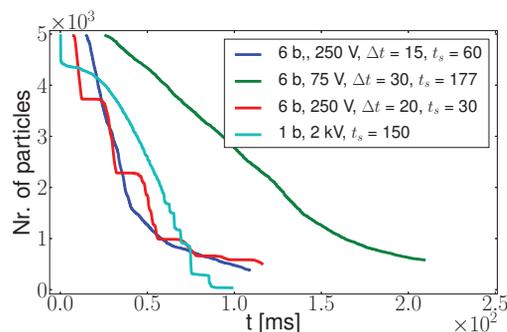

Figure 7: Various different cases of the circulating beam current as a function of time.

ACKNOWLEDGEMENTS

REFERENCES

[1] P. J. Bryant *et al*, "Proton-Ion Medical Machine Study (PIMMS)," CERN, Geneva, CERN-PS-2000-007-DR (2000).

[2] S. van der Meer, "Stochastic extraction, a low-ripple version of resonant extraction," CERN, Geneva, CERN-PS-AA-78-6 (1978).

[3] E. Ciapala & S. Myers & C. Wyss, "Phase displacement acceleration of high intensity stacks in the CERN ISR," CERN, Geneva, CERN-ISR-BOM-OP-RF-77-13 (1977).

[4] S. R. Koscielniak, "The LONG1D Simulation Code," Proc. 1st EPAC (1988).

[5] E. W. Messerschmid, "Scattering of particles by phase displacement acceleration in storage rings," CERN, Geneva, CERN-ISR-TH-73-31 (1973).