Smoothing of the slowly extracted coasting beam from a synchrotron

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Abstract

Slow extraction of beam from synchrotrons or storage rings as required by many fixed target experiments is performed by controlled excitation and feeding of a structural lattice resonance. Due to the sensitive nature of this resonant extraction process, temporal structure of the extracted beam is modulated by the minuscule current fluctuations present on the quadrupole magnet power supplies. Such a modulation lead to pile-ups in detectors and significant reduction in accumulated event statistics. This contribution proposes and experimentally demonstrates that by introduction of further modulation on quadrupole currents with a specific amplitude and frequency, the inherent power supply fluctuations are mitigated leading to a smoothening of the beam temporal structure. The slow extraction beam dynamics associated with this method are explained along with the operational results.
Controlled slow extraction of beam from synchrotrons and storage rings is required by a host of “target experiments” as well as hadron cancer therapy based on charged particle deposition on tumours [1]. The extracted beam is also referred to as “spill”. The extraction procedure is performed in two steps: a) exciting a lattice resonance and b) feeding the driven resonance by moving the betatron tunes of individual particle towards it. While most synchrotron facilities drive the horizontal third order resonance for slow extraction using sextupolar fields [2], there exist a few variants of resonance feeding mechanisms (under operation) such as quadrupole driven [2], betatron-core driven [2], or RF knock-out [3, 4]. During the design phase, the choice of resonance feeding mechanisms is determined by extraction parameters such as beam energy, instantaneous momentum spread, total spill period and macro-shape of spill as requested by experiments as well as the ability to swiftly interrupt the extraction process [2, 4]. The accelerator users typically assume particle count distribution in the spill for their given measurement bins to be solely governed by Poisson statistics. However, with experience, most facilities and users have realized that the minuscule ripples and noise ($\Delta I/I \approx 10^{-5}$) on currents supplied to focusing magnets i.e. quadrupoles lead to significant temporal modulation of the extracted spills. These modulated spills are detrimental to statistics obtained by the experiments, where as much as 2/3rd of the delivered beam has been reported by experiments to be unusable [5]. Any improvements on the power supply side are either technologically unfeasible or would lead to long disruption in the operation of the facility. Similarly, the hadron cancer therapy synchrotrons are also designed with an assumption of uniform spill delivery and reliability of the dose delivery is limited by non-uniformity of the spill and efforts are undergoing to improve the spill [6].

In order to deal with spill non-uniformities, the primary resonance feeding mechanisms in most facilities have been augmented by other techniques. One of first such techniques found in literature was proposed at CERN [7], where the resonance feeding mechanism is assisted by a longitudinal stochastic noise, such that the particles are fed at a speed faster than the separatrix modulation induced by power supply noise. This "stochastic extraction" method reduced the effect of power supply ripples and is shown to work well for very long (in range of several minutes to hours) extraction times [8, 9]. Other ideas also involved some form of longitudinal gymnastics such as "rf phase displacement" [10], "rf channelling" [2] and bunched beam extraction [11] which all reduce the effect of power supply ripples at the cost of high frequency modulation of the spill. Although these techniques reduce low frequency
modulations on the spill, they actually hinder experiments which rely on smooth structure at time scales smaller than the revolution times. Spill smoothing based on feedback systems [12] is non-trivial to operate given that the slow extraction transfer function consists of a large (dynamic) delay in the order of ms between particle extraction and its measurement in the spill. Feedback/servo systems have thus shown improvement only in low frequency or macro-spill regime (< 50 Hz) [13] and limited success is reported in literature for micro-spill (> 50 Hz) [14].

In this report, we take a new view of the problem of uneven spill structure by primarily influencing the particle transit time, i.e. the time required by the particle to reach the electrostatic septum after it first becomes unstable. Consequently, the instantaneous variation of transit times for particles with different initial phase space co-ordinates and momenta being extracted at that same time instant referred to as ”transit time spread” is also modified. It led us into developing a new technique based on controlled tune modulation in correlation with the transit time. This technique while smoothing the spill structure against power supply ripples, does not introduce any significant additional longitudinal structure at higher frequencies. The first application of this technique is with the quadrupole driven resonance feeding mechanism, where the effect of power supply fluctuations on spill are expected to be the strongest [2]. The recently concluded High Acceptance Di-Electron Spectrometer (HADES) experiment [15] reported 50% increase in recorded events compared to previous campaigns [5] as a direct result of these investigations.

Proton Ion Medical Machine Study (PIMMS) [2] provides a comprehensive account of the slow extraction process. Here we discuss only the aspects relevant for this paper and try to utilize the PIMMS notations wherever possible. Figure 1(a) shows the stable phase space area for the considered one dimensional third order slow extraction mechanism. The triangular shape is a characteristic of third order resonance described by Kobayashi theory [16]. \( \vec{X} \equiv (X, X') \) is a phase space vector with the normalized coordinates with \( X = \frac{x}{\sqrt{\beta_x}} \) and \( X' = \sqrt{\beta_x}x' + \frac{\alpha_x}{\sqrt{\beta_x}}x \). where \( \alpha_x, \beta_x \) are the Twiss parameters. The size of phase space area is defined by unstable fixed points of betatron motion and is given as

\[
A_{\text{stable}} = \frac{4\sqrt{3}\pi^2}{3} \left( \frac{\varepsilon Q}{S_v} \right)^2,
\]

where \( \varepsilon_Q = 6\pi(Q_m - Q_r) \) is the difference between machine and resonance tunes. \( S_v \) is the strength of a virtual sextupole created by an arrangement of \( N \) sextupoles governed
by the relation, $S_v \cdot e^{3i\psi_v} = \sum_n S_n e^{3i\psi_n}$ with the normalised sextupole strength of the $n^{th}$ sextupole $S_n = \frac{1}{2} \beta_{x,n}^2 (k_2 L)_n$ and the phase advance $\psi_n$ between the considered location which is usually that of the electrostatic septum and the location of the $n^{th}$ sextupole, where $\psi_n$ corresponds to the third integer tune of the resonance $Q_r$ and $\psi_v$ determines the orientation of the stable phase space. The Steinbach diagram in Fig. 1(b) shows the

FIG. 1: (a) Schematic showing stable phase space area modulation due to power supply ripples for any specific tune and the particle transit towards the septum. (b) Steinbach diagram showing the spread in transit times due to amplitude and momentum distribution of fed particles.
separation of stable and unstable area as a function of particle momentum $\Delta p$. The slope of separating line is, $\left|\vec{X}\right|/\Delta p \propto (Q_r \xi)/(p_0 S_v)$ where $\xi$ is the chromaticity in the plane of extraction and $p_0$ is the momentum of zero amplitude particle at resonance tune $Q_r$. In quadrupole driven extraction, the stable phase area is slowly shrunk with time by moving the machine tune $Q_m$ towards resonance $Q_r$ such that the particles (starting from larger amplitudes/action) leave the stable area and traverse towards the extraction septum. Upon crossing the electrostatic septum, particles obtain a kick such that the particle trajectory passes through another magnetic kicker, thus spilling it out of the synchrotron. For a particle with a certain amplitude $\left|\vec{X}\right|$, the transit time is primarily determined by the distance to resonance $\varepsilon_Q$ at which the particle becomes unstable, which in turn is directly proportional to the strength of resonance $(S_v)$ as shown by Eq. 4.17 in \cite{2}

$$T_{tr} \propto \frac{1}{\varepsilon_Q}$$  \hspace{1cm} (2)

For a particle beam with a given emittance and finite momentum spread, there is corresponding spread in transit times. This is also schematically shown in Fig.\cite{1}(b). The transit time spread scales with the "mean" transit time $T_{tr}$

$$\Delta T_{tr} = \frac{dT_{tr}}{d\varepsilon_Q} \Delta \varepsilon_Q \propto \frac{1}{\varepsilon_Q^2} \Delta \varepsilon_Q$$ \hspace{1cm} (3)

as discussed in \cite{17}. The spiral step growth at any time step is given as a function of sextupole field strength and coordinates in the previous time step $(X_0, X'_0)$ as $\Delta X_1 \propto S_v X'_0 (3^{1/4} \sqrt{A_{stable}/2} + 1.5 X_0)$.  

The fluctuations of $A_{stable}$ shown in Fig.\cite{1} are dominated by the field ripples of quadrupole and sextupole magnets. The modulations in size of the stable phase space area for independent quadrupole and sextupole ripples is estimated as,

$$\delta A_{stable} = 2 A_{stable} \left( 6\pi \left| \frac{\delta Q_m}{\varepsilon_Q} \right| + \left| \frac{\delta S_v}{S_v} \right| \right)$$ \hspace{1cm} (4)

$\delta \varepsilon_Q = 6\pi \delta Q_m$ because $Q_r = \text{const}$. If we assume that quadrupole and sextupole fluctuations are of the same order, i.e. $|\delta Q_m/Q_m| \sim |\delta S_v/S_v|$, the contribution of the quadrupole ripples has a larger influence since $|\varepsilon_Q| \ll Q_m$ so that $|\delta Q_m/\varepsilon_Q| \gg |\delta Q_m/Q_m|$ resulting in $|\delta Q_m/\varepsilon_Q| \gg |\delta S_v/S_v|$ as also observed at GSI SIS-18 and CERN SPS \cite{19}.

The effect of fluctuations on the measured spill structure is illustrated in Fig.\cite{2}. The dashed line in Fig.\cite{2}(bottom) show the controlled shrinkage of stable phase space area
FIG. 2: Bottom: Stable phase space area modulation due to inherent power supply ripples (black solid lines) and when external ripples are introduced on quadrupoles (red dotted lines). Middle: Spill just after crossing the separatrix, Point A in Fig. 1. Top: Spill at the measurement location, Point B in Fig. 1 after convolution with transit time distribution.

as it is performed with time, while the solid black line depicts the undesired modulation $\delta A_{\text{stable}}$ due to quadrupole field fluctuations for particles with a specific momentum. The nature of fluctuations is similar irrespective of particle momentum although the absolute stable phase space area is different for different momenta as indicated in Fig. 1(b). As the stable area shrinks, particles are "released" and their relative counts are shown in Figure 2 (middle) shortly after crossing their respective momentum dependent separatrices denoted
by point $A$ (also shown in Figure 1). Following that, the higher frequency components above a certain cut-off frequency given by $f_{\text{cut}} > 1/\Delta T_{tr}$ are filtered due to convolution with the instantaneous transit time distribution $\Delta T_{tr}$ while the particles traverse from point $A$ to the point $B$ (top) which can be seen as the point of ”spill measurement or user experiment”.

Our first approach towards spill smoothening looked at influencing the transit time spread. As evident from Eq. 2 and Fig. 1(b), the transit time spread $\Delta T_{tr}$ can be increased by reducing the $\varepsilon Q$ which in turn is performed either by reducing the sextupole fields $S_v$ [17, 18] or reducing the beam emittance. This is demonstrated by comparing three scenarios with a 300 MeV/u $C^6+$ beam with mean rate of $2 \times 10^6$/s. Case (1) is that of a ”typical” working point in terms of sextupole strength $S_v = 11.0 \ m^{-1/2}$ optimized for minimizing beam losses and nominal beam emittance of 15 mm-mrad , second (case 2) is that of reduced sextupole strength $S_v = 5.5 \ m^{-1/2}$ for nominal injection beam emittance of 15 mm-mrad, and the third (case 3) is for a small emittance of 4 mm-mrad at the lower sextupole setting $S_v = 5.5 \ m^{-1/2}$. These are compared against their respective power spectra in Fig. 3. It is clear that, for the last case, the $f_{\text{cut}}$ is the lowest as the higher frequency fluctuations are curbed and results in the best (smooth) micro-spill structure. Another important observation is that the transit time spread increases as $\varepsilon Q$ approaches zero towards the end of spill, and thus the duty factor or quality of spill is improved. The “duty factor” [2, 18] $F$ is defined as the ratio $F = \langle N_p \rangle^2/\langle N_p^2 \rangle$ where $N_p$ is the number of particle counts per measurement time $T_m = 10 \ \mu s$, and each duty factor is calculated over 1000 such measurements (10 ms). Notably, some studies took an exactly opposite strategy of increasing the sextupole fields $S_v$ and distance to resonance $\varepsilon Q$ for micro-spill improvement [20]. The limitation of our first approach is that both the sextupole strength and beam size cannot be arbitrarily reduced without effective loss is statistics for the experiments. As discussed earlier, lower sextupole strength results in a smaller spiral step $\Delta X$, which below a certain threshold leads to losses on the septum wires. Similarly, reducing the beam size at multi-turn injection synchrotrons typically results in lower intensities, and thus effective loss in event rate for experiments. Transverse beam cooling also needs significant time and thus is not a viable option for experiments relying on large cumulative statistics. Therefore, a new technique independent of sextupole strength and beam emittance was developed and is discussed next.

High frequency ripples with amplitudes larger than the inherent ripples are introduced on the quadrupole power supplies with a technique discussed in [18], which leads to a modulation
of machine tune $Q_m$ and therefore the stable space area as marked with dotted red lines in Fig. 2. The spill smoothing works as follows; due to large tune modulation at the introduced frequency, particles from the stable phase space area are periodically released. However, due to the relation of introduced frequency with the transit time, some of the released particles are captured back due to expansion of stable area in the other half of the cycle. The lower frequency inherent ripples are not able to "feed" on the particles, and are thus strongly suppressed in spill. The choice of introduced frequency $f_{ext}$ should be comparable to the mean transit time $f_{ext} \approx 1/T_{tr}$ such that only a portion of the released particles are recaptured in the expansion phase and thus are available for release during the next ripple cycle. If $f_{ext} \gg 1/T_{tr}$, the particles would not be able to follow the fast oscillations of stable area and no periodic release of particles at the introduced frequency will occur and thus spill quality is as if only the inherent ripples are present. Expectantly, no improvement was experimentally observed for those cases. Further constraint on the introduced frequency is that, it should be above the cut-off $f_{ext} > f_{cut} = 1/\Delta T_{tr}$ in order to utilize the "washing out" effect due to transit time spread as discussed earlier. Since, both the transit time and transit time spread are related to each other as shown earlier in Eqs. 2 and 3, along with all the constraints discussed above, the optimal frequency found both experimentally and in simulations is just above the cut-off frequency in the spill spectra. For case (1) discussed in Fig. 3, the optimal exciting frequency is approximately 7.5 kHz while for case (2), it is found to be $\approx 4$ kHz. Further, in a quadrupole driven extraction process, where $T_{tr}$ varies during the extraction, the exciting frequency should follow it during the extraction. The amplitude of excitation should be significantly higher than the inherent ripple amplitude such that it forces the particle release ahead of inherent ripples. On the other hand, it should be low enough such that not all particles released in the previous cycle are captured and the length of spill is not affected due to associated tune modulation. The optimal value found was a factor of 5-10 times higher than the inherent ripple amplitude which corresponds to 1 – 2% of total current change during the slow extraction tune ramp in our experiment.

Figure 4 shows the spill spectra and duty factors with and without tune modulation for a high energy beam of 1.58 GeV/u $Ag^{45+}$ corresponding to the highest rigidity at SIS-18 for the HADES experiment [15]. In this case, the duty factor does not improve from start to end of extraction (unlike shown in Fig 3). The reason for that stems from the insufficient voltage on the electrostatic septum at the highest SIS-18 rigidity. Insufficient kick from the
septum leads to loss of particles with smaller spiral step $\Delta X$ (or larger transit time) and thus the effective transit time spread distribution $\Delta T_{tr}$ remains roughly the same for the whole extraction. In Fig. 4 (top), the wiggly shape of spectrum in the “passband” is due to transit time dependent septum losses. This also results in a spill quality of $F \approx 0.2$ which is worse than the ones obtained at lower energies. A sweep of excitation frequency from 5 kHz to 3.8 kHz was introduced in order to account for the transit time variation during extraction. As a result, all the lower frequency components are suppressed by $\approx 10$ dB in the power spectra shown in Fig. 4 (top). This led to a factor 2.5 improvement in the duty factor and a much smoother spill as shown in Fig. 4 (middle and down respectively) although the introduced frequency of $\approx 4$ kHz is a much smoother spill is clearly visible. The HADES experiment reported an increase by a factor of 1.5 in cumulative statistics. The corresponding event rates (courtesy of HADES collaboration) are shown in Fig. 5.

The tune modulation technique for spill smoothing described in this report is operationally straightforward and immediately renders itself to other facilities and experiments facing issues with micro-spill non-uniformity. In summary, the steps to be followed are; an estimate of the transit time from the cut-off frequencies at the start and end of spill is made from the spill spectrum. A frequency sweep between the two cut-off frequencies with an amplitude of 1% of the quadrupole current change due to tune ramp during extraction is introduced. Finally, some empirical tweaking of amplitude and frequency should be performed to obtain the optimal smoothing. As a next step, waveforms other than a simple sinusoid for the introduced tune modulation will be studied. On a longer term, particle amplitude dependent external tune modulation using non-linear fields could be beneficial.

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FIG. 3: Comparison of beam spill (bottom), its duty factor (middle) and the power spectra (top) for case (1) stronger sextupole strength and large emittance, case (2) weaker sextupole strength and large emittance and case (3) weaker sextupole strength and small emittance.
FIG. 4: Comparison of beam spill (bottom), its duty factor (middle) and the power spectra (top) with and without external modulation of tune.
FIG. 5: The event rate registered in the HADES detector with and without tune modulation. (Courtesy: J. Pietraszko and M. Traxler from the HADES collaboration).