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ABSTRACT

In the framework of antiproton physics at CERN, a new Low Energy Antiproton Ring (LEAR) is being designed. In the basic mode, it will serve as a beam stretcher giving spill times in the region of an hour. The spill $\phi(t)$ must, of course, have a good duty factor $\langle \phi \rangle^2 / \langle \phi^2 \rangle$. A method employing "stochastic extraction" has been studied theoretically and tried out at the CERN PS (~ 9 s flat top) where an extremely good duty factor has been achieved, showing that much longer spill times will be practicable. The pulse length can be varied within wide limits given by the ripple, the momentum acceptance and the intermodulation distortion of the amplifier chain for the noise power. In addition, another method has been found effective which uses empty buckets. These methods need no servo system and both can easily be applied to other synchrotrons.

1. WHAT IS ULTRASLOW EXTRACTION ?

Conventional slow extraction is normally made by creating a resonant condition and sweeping the beam slowly across the resonance (or the resonance across the beam). The coarse spill rate $\phi(t)$ can be controlled easily by acting on the sweeping speed v_0 . A more delicate problem is caused by the current ripple of the bending and tuning elements. Passive and very sophisticated active methods are employed to attenuate the resulting spill structure. But common to all these methods so far is that the shape of the circulating beam - density $\psi = dN/d(\Delta p/p)$ as a function of fractional momentum $\Delta p/p$ - behaves as a rigid body which is moved in time average into the resonance. This mechanism provokes a hard resonance edge all the time. For a continuous spill, it is then necessary that the beam edge is never repelled from the resonance due to ripple. This condition is for one significant ripple frequency ω

$$v_0 \geq \omega r \quad (1.1)$$

and yields a duty factor F

$$F = \langle \phi \rangle^2 / \langle \phi^2 \rangle = \left(1 + \frac{1}{2} \left(\frac{\omega r}{v_0} \right)^2 \right)^{-1} \quad (1.2)$$

where r is the ripple amplitude, to be measured in the same units as v_0/ω , preferably in $\Delta p/p$. The equals sign in (1.1) limits the validity range of (1.2) and the resulting duty factor of 2/3 may be taken as a convenient cut between good and bad duty factors. As a numerical example, we find a spill duration of $T_s \approx 1$ s taking, say, $\omega = 2\pi \cdot 100$ Hz, $r = 5 \cdot 10^{-6}$ and $(\Delta p/p)_{\text{beam}} = a = 3 \cdot 10^{-3}$ in $v_0 = a/T_s$ as typical values. Since for LEAR¹⁾ we aim at T_s as long as many minutes, it is evident that improving the existing method is inadequate, rather an entirely new principle should be found which could be called ultraslow extraction.

In 1978, Simon van der Meer²⁾ suggested the use of filtered RF noise around the resonance which provides a diffusion constant D within a limited $\Delta p/p$ range. Indeed, individual particles will now execute a random walk, the beam distribution then ceases

to behave as a rigid body but tends to fill up any voids so that discontinuities of the spill rate can no longer occur.

2. WHAT IS THE DUTY FACTOR IN THE PRESENCE OF NOISE?

Let $x = \frac{\Delta p}{p}$ axis counted from the nominal resonance. The Fokker-Planck equation for the particle density $\psi(x, t)$ is

$$\frac{\partial \psi}{\partial t} = \frac{\partial}{\partial x} \left(D \frac{\partial \psi}{\partial x} - v_0 \psi \right) = - \frac{\partial \phi}{\partial x} \quad (2.1)$$

A stationary solution ψ_0 must have a flux ϕ_0 independent of x and is for $v_0 \geq 0$; $\phi_0 \geq 0$; $x \leq 0$

$$\psi_0 = \frac{\phi_0}{v_0} \left(1 - \exp v_0 \int_0^x \frac{ds}{D} \right) \rightarrow - \frac{\phi_0}{D_0} x \text{ for } \begin{cases} v_0 \rightarrow 0 \\ D \rightarrow D_0 \end{cases} \quad (2.2)$$

The dynamic solution should be found by imposing an oscillating boundary where $\psi(x, t) = 0$. Instead, it is easier to superimpose on ψ_0 a diffusion wave ψ_ω and to interpret the amplitude of the resulting zero as the ripple amplitude r , in a sense reversing cause and effect. $\psi_\omega = \hat{\psi}_\omega \exp(\mu x + i\omega t)$ put into (2.1) yields for $D_0 \omega \gg v_0^2$: $\mu = \pm \sqrt{i\omega/D_0}$ and

$$\psi_\omega = \hat{\psi}_\omega \exp \left(\frac{x}{\lambda} + i \left(\frac{x}{\lambda} + \omega t \right) \right) \text{ with } \lambda = \mp \sqrt{2D_0/\omega} \quad (2.3)$$

where the sign is selected such that it belongs to a wave moving away from the resonance with the phase velocity $|v_\omega| = |\lambda|\omega = \sqrt{2D_0\omega}$ and the damping length λ . The zero of the total density $\psi = \psi_0 + \psi_\omega$ has in first approximation the amplitude $r = D_0 \hat{\psi}_\omega / \phi_0$ which modulates the flux $\phi = -D \frac{\partial \psi}{\partial x} \Big|_{\psi=0}$ with an amplitude $\frac{\phi_\omega}{\phi_0} = \frac{\sqrt{2} r}{\lambda}$ yielding a duty factor³⁾

$$F = \left(1 + \left(\frac{r}{\lambda} \right)^2 \right)^{-1} = \left(1 + \left(\frac{\omega r}{v_\omega} \right)^2 \right)^{-1} = \left(1 + \frac{1}{2} \frac{\omega r^2}{D_0} \right)^{-1} \quad (2.4)$$

Comparison with (1.2) shows that $v_\omega/\sqrt{2}$ replaces the former sweeping speed v_0 , but clearly v_ω can be kept large also for a long spill. A few times of what is needed for a duty factor $F = \frac{2}{3}$, namely $D_0 \approx \omega r^2$, should suffice for an acceptable spill structure.

3. SOME EXPERIMENTS WITH THE CERN PS

Two slightly different schemes were tried. The goal of the first experiments was to demonstrate the feasibility of stochastic extraction in the most simple way. We maintained the set-up for normal extraction, but at 10 GeV/c (instead of the usual 24 GeV/c) and on a flat top length of 1.5 s (instead of 0.4 s). Then we added noise (20 kHz bandwidth) around the 420th harmonic of the resonance revolution frequency with our high Q 200 MHz cavities which are normally used for bunching the beam prior to transfer to the SPS. The carrier frequency was tuned suitably to follow the field decay which moves the beam into resonance. When switching on and off the noise, one sees the improvement of the duty factor. The effect was artificially enhanced by generating additional 50 Hz and 100 Hz field ripple. In doing so, we improved the (deteriorated) duty factor from 20% to almost 90%. The scheme has the disadvantage that the momentum of the extracted beam changes in time.

In a second experiment, we tried extraction on a 9 s flat top at constant field.

In order to make the servo system for the coarse spill rate redundant, we first performed a flattening and widening procedure by applying noise of narrow bandwidth (20 kHz) for 300 ms around the beam without interfering with the resonance and so made the beam shape "rectangular" (Fig. 1a). We then switched to wider noise (40 kHz) and simultaneously reduced the carrier frequency (by ~ 30 kHz) so that the high frequency edge of the noise spectrum coincided with the previously created low frequency edge of the beam. Extraction now follows a programmed linear sweep of the carrier frequency in an obvious way (Fig. 1b). Also shown (Fig. 2) are the circulating currents and the spill structure for stochastic extraction and normal extraction for which, of course, we reintroduced a field decay. The duty factor for stochastic extraction is of the order of 99%.

4. LIMITATIONS

There are, however, a number of limitations. In the second scheme we can expect a constant spill rate for a constant tuning rate of the carrier frequency only if the density inside the noise region remains small compared to the density of the unperturbed beam. According to (2.2) and referring to Fig 1b, we need $D_0 \gg v_0 b$. For relatively short spills, this condition can be more stringent than $D_0 > \omega r^2$. On the other hand, it is a disadvantage to have D_0 too large for two main reasons:

- i) at the edge of the noise the ripple generates diffusion waves. In order to ensure enough damping when they arrive at the resonance, b must contain at least several wavelengths, but λ increases as $D_0^{1/2}$ (2.3).
- ii) a large D_0 implies more noise amplification and thus leads to more intermodulation distortion, i.e. due to the non-linearities of the power amplifiers we shall find a larger fraction of undesired diffusion D_u outside the selected bandwidth. The resulting beam loss on the other side must remain tolerable. As the ratio of the undesired flux tends to a fraction of the order $\sqrt{D_u T_s} / a$ of the intended flux, we might signify the practicable range of T_s by the inequality

$$\frac{a^2}{D_u} \gg T_s \gg \frac{a^2}{D_0} \quad (4.1)$$

For completeness, we mention the dependence of D_0 in $\frac{\Delta p}{p}$ space on machine parameters if produced with bandwidth Δf at one appropriate harmonic of the revolution frequency

$$D_0 = \frac{1}{2} \frac{\overline{\Delta x^2}}{\Delta t} = \frac{1}{2\Delta f} \left(\frac{V_{rms}}{2\pi R B\rho} \right)^2$$

where $2\pi R$: machine circumference
 $B\rho$: magnetic rigidity of the beam.

5. ADDITIONAL POSSIBILITIES

Although we have demonstrated the feasibility of a good duty factor for a 10 s spill, the extrapolation to, say, 1000 s is still a challenge. Since uncontrollable slow drifts of the magnetic field and of the carrier frequency could become critical for the coarse spill rate, it is certainly beneficial to avoid too low a v_0 . This can be arranged by

splitting up the stochastic flattening into various intermediate steps, each followed by a stochastic extraction process as described, but v_0 being augmented by the number of steps. A somewhat larger momentum acceptance is needed and a more complicated program for the carrier frequency. At very long spills also the intermodulation distortion has more time to degrade the distribution outside the applied bandwidth. Our LEAR ring will be equipped with a stochastic cooling system. This might be used to reduce the deterioration of the distribution in this momentum region and so restrict losses to the inside. We then, of course, can no longer rely on a basically programmed procedure but need the help of beam observation (Schottky scans, etc.) at least when passing through a learning period. Spill durations as long as envisaged for LEAR are unlikely to be interesting for most other accelerators, but a moderate increase of spill length or the improvement of a poor duty factor might.

During our experiments an additional method has been tried successfully^{5,6)} which was even more efficient than stochastic extraction for a normal spill length (≈ 350 ms). Again an RF system is employed, but without noise. The frequency is programmed such that (empty) buckets are centred around the resonance in momentum direction. The particle flux is forced in between the slowly moving ($\Gamma = |\sin \phi_s| \ll 1$) buckets where the average speed in $\Delta p/p$ direction is so increased from v_0 to $\sqrt{\pi/\Gamma} v_0$. Ideally, the duty factor (1.2) increases

$$\text{from } F = \left(1 + \frac{1}{2} \left(\frac{\omega r}{v_0}\right)^2\right)^{-1} \quad \text{to} \quad F = \left(1 + \frac{1}{2} \frac{\Gamma}{\pi} \left(\frac{\omega r}{v_0}\right)^2\right)^{-1}$$

if a restriction is ignored due to possible insufficient bucket height compared to the width of the resonance. Since Γ is proportional to v_0 this duty factor falls eventually to an unacceptable value but at a significantly longer spill time than without RF.

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Fig. 1a) Flattening

NOISE SPECTRUM

BEAM SPECTRUM

Horizontal : 10 kHz/div.
Vertical : 10 dB/div.

Fig. 1b) Extraction

NOISE SPECTRUM

BEAM SPECTRUM

Horizontal : 10 kHz/div.
Vertical : 10 dB/div.

NORMAL EXTRACTION

(Spill signal inverted, sorry)

STOCHASTIC EXTRACTION

Horizontal : 1 s/div.

Fig. 2 Circulating currents (upper traces) and spills

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