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LOW FREQUENCY DUTY FACTOR IMPROVEMENT FOR THE CERN PS SLOW EXTRACTION USING RF PHASE DISPLACEMENT TECHNIQUES

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Summary

The slow extraction spill from synchrotrons is modulated by residual ripple on the power supplies of magnetic elements. Stochastic RF methods[1,2] were proposed in the past to improve the poor duty factors of very long extractions (several minutes). Another method, based on RF phase displacement principle is presented here. It is particularly suitable for standard spill lenghts of the order of 1 sec. This operationally simple technique has been studied, tested and implemented on the CERN-PS and has improved the low frequency duty factor from 67 % to 98 % typically for up to 600 ms spills.

Introduction

The frequency domain analysis of slow extraction spill from synchrotrons can be divided in two parts, namely :

i) a high frequency part : ranging from a few tens of kHz (machine revolution frequency) up to several GHz results essentially from the longitudinal beam characteristics, i.e., longitudinal density discontinuities caused by the debunching procedure and (or) beam-chamber interactions (coupling impedances and resonances of bellows, flanges, etc.).

ii) a low frequency part : ranging from 0 to a few kHz and more precisely characterized by the mains 50 Hz fundamental with all its harmonics up to 600 Hz. (The 600 Hz components are by far the most important at the PS). This strong modulation is very disturbing for the "down the line" physicists and the situation was improved by the method proposed here, derived from the RF phase displacement theory.

Principle of the method

The low frequency duty factor F can be defined as

$$F = \frac{\left[\int_{T_s} S(t)\ dt\right]^2}{T_s \int_{T_s} S^2(t)\ dt} \tag{1}$$

where T_s = spill duration and calling N the number of ejected particles :

$$S(t) = \frac{dN}{dt} = \frac{dN}{dQ}\frac{dQ}{dt} = \frac{dN}{dQ}\dot{Q}_o \left(1 + \frac{\dot{Q}_V}{\dot{Q}_o}\right) \tag{2}$$

where Q = betatron number

$\dot{Q}_o$ = mean particle velocity towards the resonance (in Q space)

$\dot{Q}_V$ = varying velocity due to the power supply ripple

combining equations (1) and (2) yields

$$F = \frac{1}{1 + \frac{1}{2}\left(\frac{\dot{Q}_V}{\dot{Q}_O}\right)^2} \tag{3}$$

valid for $\dot{Q}_V \leq \dot{Q}_O$.

for one particular ripple frequency ω and corresponding ripple amplitude r, equation (3) can also be written as

$$F = \frac{1}{1 + \frac{1}{2}\left(\frac{\omega r}{v_o}\right)^2} \tag{4}$$

with $$v_o = \frac{\Delta p}{p}\frac{1}{T_s} \tag{5}$$

$\frac{\Delta p}{p}$ = total beam momentum width $\left(= \frac{1}{\xi_H}\frac{\Delta Q}{Q}\right)$

ξ_H = horizontal chromaticity

From equation (4) we can see that in order to increase F, for a given ripple amplitude r, one has to increase v_o, the speed (in Δp/p space) at which the beam crosses the ejection resonance. Equation (5) shows that for a given T_s, v_o is larger if one increases the beam momentum spread Δp/p, which is usually done during debunching.

To further increase v_o locally, near the resonance, one can use RF phase displacement techniques. Feeding RF cavities with an unmodulated fixed frequency voltage on a flat-top field B, one creates buckets with sin ϕ_s related to the magnetic field slope $\dot{B}$ (generally small) through the following formulas:

the energy gain per turn $[\Delta E]_1$ is

$$[\Delta E]_1 = eV \sin\phi_s \tag{6}$$

and $$[\Delta E]_1 = \frac{dE}{dt}\frac{2\pi R}{\beta c} \tag{7}$$

where V = peak RF voltage, R = machine radius and for a constant frequency

$$\frac{dB}{B} = \frac{\gamma^2 - \gamma_{tr}^2}{\gamma^2}\frac{1}{\beta^2}\frac{dE}{E} \tag{8}$$

equations (6), (7) and (8) yield

$$\sin\phi_s = \frac{2\pi R\ \dot{B}\rho}{V}\ \frac{\gamma^2}{\gamma^2 - \gamma_{tr}^2} \tag{9}$$

where ρ = bending radius $\left(= \frac{E\beta}{ceB}\right)$ and $\gamma_{tr} = \frac{E_{tr}}{E_o}$ (E_{tr} = transition energy; E_o = rest energy).

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The space $\Delta\phi$, in RF radians, between buckets, that is the distance between the head of one bucket and the tail of the preceeding one (see Fig. 1) is given by

$$\Delta\phi = 2\pi - |\phi_{2e} - \phi_{1e}| \tag{10}$$

where the values of ϕ_{1e} and ϕ_{2e} are obtained from the equations[3]

$$\sin\phi_{1e} = \sin\phi_s \tag{11}$$

and

$$\cos\phi_{2e} + \phi_{2e}\sin\phi_s = \cos(\pi - \phi_s) + (\pi - \phi_s)\sin\phi_s \tag{12}$$

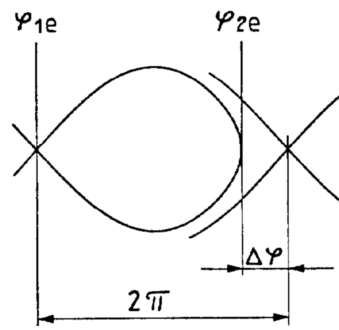


Fig. 1: RF buckets

For $\sin\phi_s \ll 1$ ($\phi_s < 10^o$) one can easily find

$$\Delta\phi \simeq 2\sqrt{\pi|\sin\phi_s|} \tag{13}$$

If a combination of flat-top slope and quadrupole ramping can be found in order to fix the frequency of the extraction resonance, after adjusting the RF frequency exactly at this value (buckets sitting on the resonance), the particles are pushed by the decreasing flat-top field through the "holes" between the buckets. Resonance position in frequency domain is checked by Schottky scan measurements. The particle speed v_o, at resonance crossing is thus increased by a factor K which can be easily derived from the conservation of phase space as

$$K = \frac{2\pi}{\Delta\phi} \tag{14}$$

Again for $\sin\phi_s \ll 1$, combining eq. (9), (13) and (14) yields

$$K = \sqrt{\frac{\pi}{|\sin\phi_s|}} = \sqrt{\frac{V\,T_s}{2R\,B\rho\,\Delta p/p}} \tag{15}$$

and

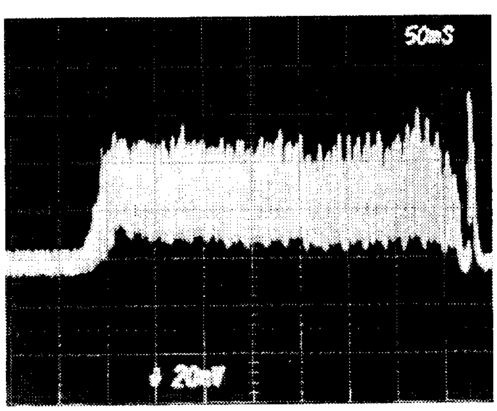
$$F = \frac{1}{1 + \frac{1}{2}\left(\frac{\omega r}{Kv_o}\right)^2} = \frac{1}{1 + \frac{R\;B\;\rho\;T_s}{V\;\Delta p/p}\;(\omega r)^2} \tag{16}$$

Application to the PS slow extraction

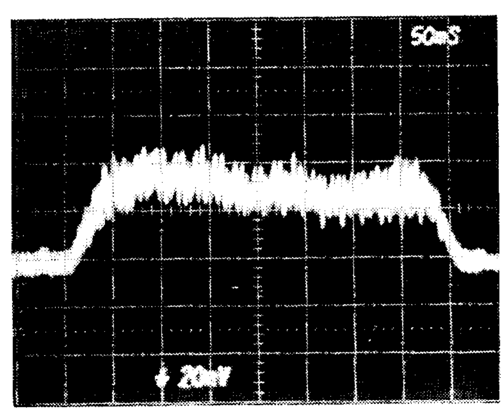
Since the middle of 1980, we are using two of the existing eight 200 MHz cavities to improve the PS slow extraction duty factor. These cavities had been installed primarily for the 200 MHz prebunching prior to extraction to SPS but had been lying idle due to the long shut-down (1 year) of this machine.

For the standard PS operation values of B = 1.15 T, $\Delta p/p = 4.10^{-3}$, $T_s = .4$ s, V = 10 kV and 600 Hz ripple frequency with 3.10^{-6} of relative amplitude, a duty factor improvement from 67 % for no RF to 98 % with RF has been achieved.

Fig. 2 (a and b) and Fig. 3 (a and b) show the spill shape and the spill frequency spectrum respectively without and with RF.

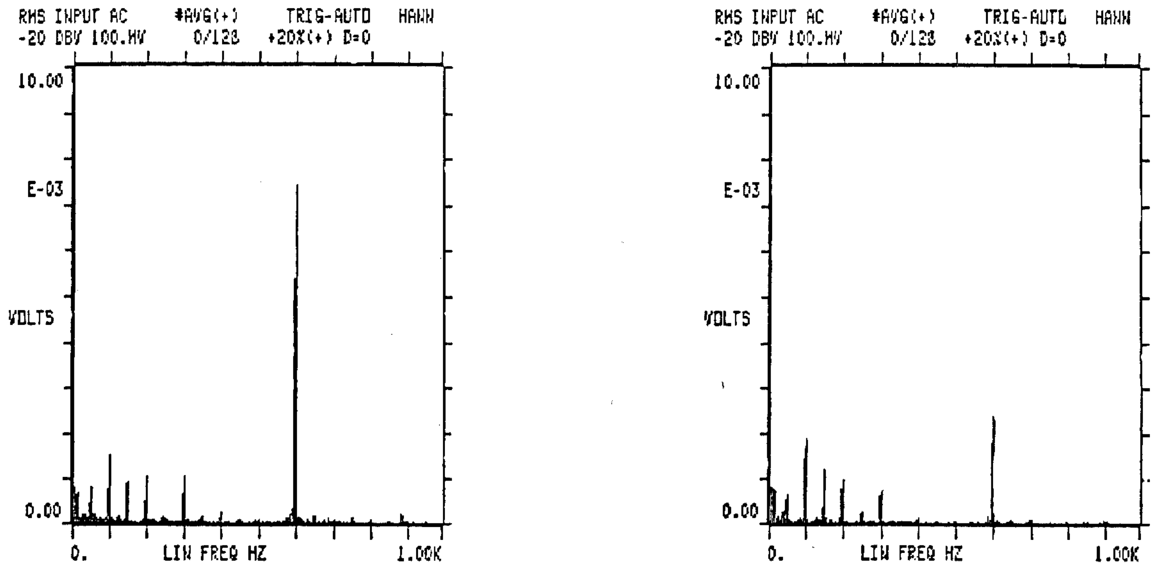


a) RF off



b) RF on

Fig. 2 : Slow extraction spill (50 ms/div.)



a) RF off

b) RF on

Fig. 3 : Spill frequency spectrum

(horizontal : 100 Hz/div; vertical : linear)

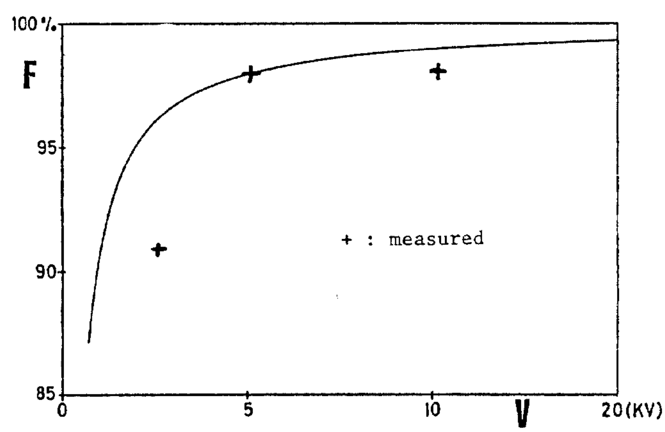


Fig. 4: Duty factor F versus RF voltage V

Fig. 4 shows duty factor F versus RF voltage V with the other parameters values as mentioned above.

Conclusions

For very long spills, the method presented here is probably less effective than the stochastic techniques. Nevertheless, for "standard" (T_s < 1 s) spill lengths it has the advantage of hardware and operational simplicity and it turns out to be more efficient. Up to now we have not been able to measure the VHF spill structure component. However, we have had no adverse comments from the physicists whose counting rates are usually well below this frequency.

Acknowledgements

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