IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

PRODUCTION OF BEAMS WITH HIGH LINE-DENSITY BY AZIMUTHAL COMBINATION OF BUNCHES IN A SYNCHROTRON

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Summary

Simultaneous acceleration of several beams in the same machine by several RF fields of slightly different frequencies was already considered a long time ago[1,2]. As they rotate at different frequencies, the bunches will periodically coincide in azimuth, thus producing beams of high local line density. Bunches rotating at different frequencies can be produced either outside the machine (e.g. in the injector) or even inside by appropriate modulation of the RF cavities. These techniques will be used in the p-$\bar{p}$ project at CERN. A high line-density proton beam, necessary for antiproton production, is obtained in the CPS by azimuthal combination, either at the injection or at the ejection level. On the other hand, the antiproton bunches in the SPS must be azimuthally combined before storage in order to achieve the design luminosity. Computer simulation and RF manipulations of these procedures, as well as experimental results already obtained at the CPS, are presented.

1. Bunch behaviour when submitted to two RF waves

We assume that two sets of bunches, called B_1 and B_2, having different energies are circulating in the same machine. Each beam is hopefully held bunched by its own RF wave of frequency f_1, f_2 respectively. The question is to see whether bunches B_1 feel only the frequency f_1 and vice-versa. Intuitively we know that if the frequency difference is large the frequency f_2 is far from being synchronous with bunches B_1 and its effect will be small. More precisely the total RF wave can be considered as the wave f_1 strongly modulated in amplitude and phase (100% modulation) at the difference frequency $\Delta f = f_2 - f_1$. From this, one expects a large effect when the ratio $\alpha = \Delta f/f_s$ (f_s: synchrotron frequency corresponding to one wave) becomes of the order of unity. It has been shown[2] that an approximate condition for beam independence is that the buckets do not touch, which, for stationary buckets, corresponds to the condition $\alpha > 4$. A computer simulation has been made in order to evaluate the bunch distortions as a function of α and the bunch size[3]. The bunch is assumed to be matched at the beginning of the process. Fig. 1 shows a typical case $\alpha = 4$, for various bunch sizes. The condition $\alpha > 4$, already mentioned, does not correspond to a sharp threshold, even for small bunches. Distortion increases rapidly for larger bunches.

Estimates for much longer drifting periods have been obtained in an experiment on the SPS machine. On a 10 GeV/c "flat bottom" two RF cavities were used to hold the bunches (almost full buckets) at frequency f_1, while the third cavity was powered at frequency f_2. Bunch emittance was estimated from the height of a wide band pickup electrode signal. Small blow-up after 50 synchrotron periods is obtained for $\alpha = 5.6$, while for $\alpha = 4.4$ the effect of frequency f_2 appears clearly after a few periods.

2. Combination of two bunches

When drifting the two sets of bunches periodically coincide in azimuth, which doubles the local line density. This high line density beam can be used directly, for instance to produce short and intense bursts of secondary particles ($\bar{p}$) after fast ejection. The bunch pairs can also be combined in a single large bucket at a frequency $(f_1 + f_2)/2$. Here, the critical parameter is the final beam emittance. Minimum blow-up requires a small frequency separation and relatively small bunch distortion, which are unfortunately two contradictory requirements.

a) First example, CPS injection[4,5]

Bunches B_1 are produced in one CPS booster ring (or possibly by two CPS booster rings vertically recombined[4])) whose RF frequency is set to f_1. A group of five CPS cavities is driven by f_1, with the proper phase and amplitude to match bunches B_1. Bunches B_2 coming from another booster ring are trapped in the same way (5 cavities, f_2). Bunches B_1 and B_2 are separated by at least one RF period and must drift by 5(+1,-0) RF periods to be superimposed. As the bunch area to bucket area ratio is small (8 mrad/18 mrad) the expected bunch distortion is little. By counting an integer number of periods of the difference frequency $f_2 - f_1$, one generates a trigger pulse which starts the combination. All ten RF cavities are then connected to the normal phase loop system and their voltage set to the maximum (20 kV) to provide maximum acceptance ($\sim$ 50 mrad). In order to avoid phase transients, the phase lock system is presynchronized on f_1 during the drifting period. If frequencies f_1 and f_2 are held constant the two beams spiral inwards because of the rising magnetic field which limits α to about 5. They can also be programmed to give no radial displacement which allows more flexibility.

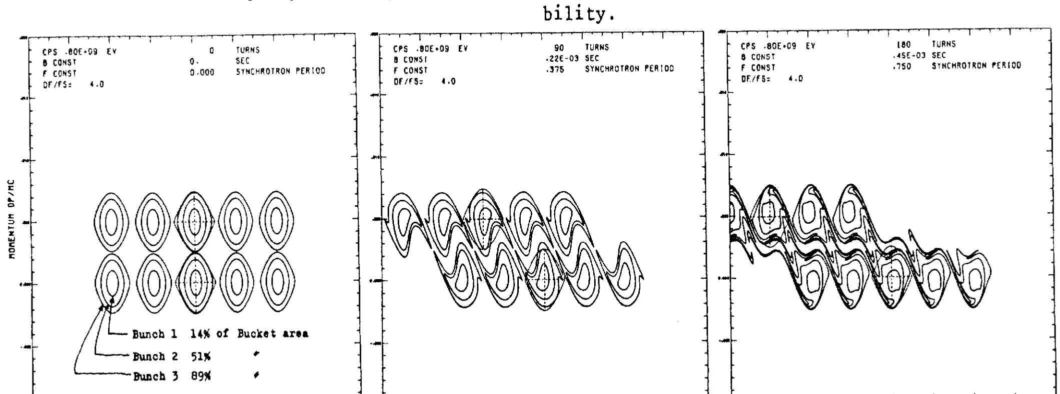

Fig. 1 - Bunch distortion during drifting ($\alpha = 4$) (concentric lines correspond to various bunch sizes)

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Figure 2 shows a mountain range display of the bunch drifting and combination. It is worth noting that even during the drifting period where the phase loop is not operative, the RF cavities are properly compensated against beam loading[6]. Optimum frequency separation was found to be about $\alpha = 5$, which gives the minimum final emittance ($\approx$ 40 mrad). The RF gymnastics work correctly, even for the highest injected intensities ($\approx 10^{13}$ ppp), but a still unexplained beam loss occurs above $\sim 6 \cdot 10^{12}$ ppp injected. A microwave instability developing while the bunches filament in the large bucket is a possible candidate to explain this beam loss, but further studies are necessary.

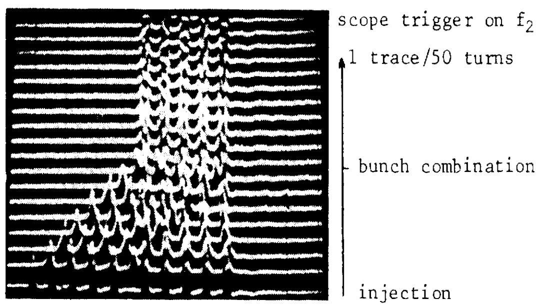

Fig. 2 - CPS 800 MeV injection

b) Second example

In the CERN $p\bar{p}$ project, the antiprotons are injected in the SPS under the form of 12 equispaced bunches. At the storage energy (270 GeV flat top) these bunches are combined in pairs to obtain the design luminosity. The reason to inject 12 bunches instead of 6 is a lack of bucket area at low energy. Adjacent bunches are first separated in momentum as described in chapter 3, up to a large enough frequency difference ($\alpha \approx 10$). Just before they superimpose in azimuth, their energy difference must be reduced in order to minimize the final beam emittance. During this period (approaching), no phase lock system can be used. The two frequencies f_1 and f_2 are programmed linearly (df/dt = constant).

A number of computer simulations have been made to optimize the parameters α, df/dt and V_{RF} in order to achieve the minimum bunch area after combination. The phase space plots corresponding to the optimum case are shown in Fig. 3 and the relevant parameters are given below:

Bunch area	(rad)	initial	0.630	final	2
Bucket area	(rad)	"	1.3	"	2.9
RF voltage	(MV)	"	1.2	"	5.5
df/dt	(kHz/s)	"	13.8	"	0
α		"	10	"	3.3

Approaching time 25 ms

3. Frequency separation

Up to now we have assumed that the two sets of bunches are circulating in the machine at two different energies. To arrive at this situation one can use the injector as described for the 800 MeV CPS injection, but it is more attractive to separate in energy bunches which are already rotating on the same orbit.

a) Phase excursion

At constant magnetic field, bunches B_1 will be accelerated at a stable phase $+\phi_s$ and bunches B_2 decelerated at a stable phase $-\phi_s$. This, of course, implies that the RF wave can be phase modulated at a frequency corresponding to the distance between bunches B_1 and B_2. As seen later, the process must be fast; therefore a phase lock system is necessary to impose the stable phase $\pm\phi_s$ without dipole oscillations. This is still possible as the bunches B_1 and B_2 are still separated in azimuth and the corresponding pick-up signals can be properly gated. During the process, the phase excursion $\Delta\psi$ between bunches B_1 and B_2 increases parabolically at constant ϕ_s and constant RF voltage. When a frequency separation α is reached (α expressed for stationary buckets at the same RF voltage) one has

$$\Delta\psi = \frac{1}{4 \sin \phi_s} \alpha^2 \qquad (1)$$

Obviously $\Delta\psi$ must be smaller than the $B_1 - B_2$ initial distance, which shows that ϕ_s must be large (ϕ_s is limited by the minimum area of the moving bucket), and hence df/dt. α must be sufficient to ensure the two beams' independence ($\alpha \approx 4$ to 10). From there ϕ_s is returned to zero with the phase lock system, which afterwards is no longer necessary. The RF cavities are simply powered with the two frequencies f_1 and f_2.

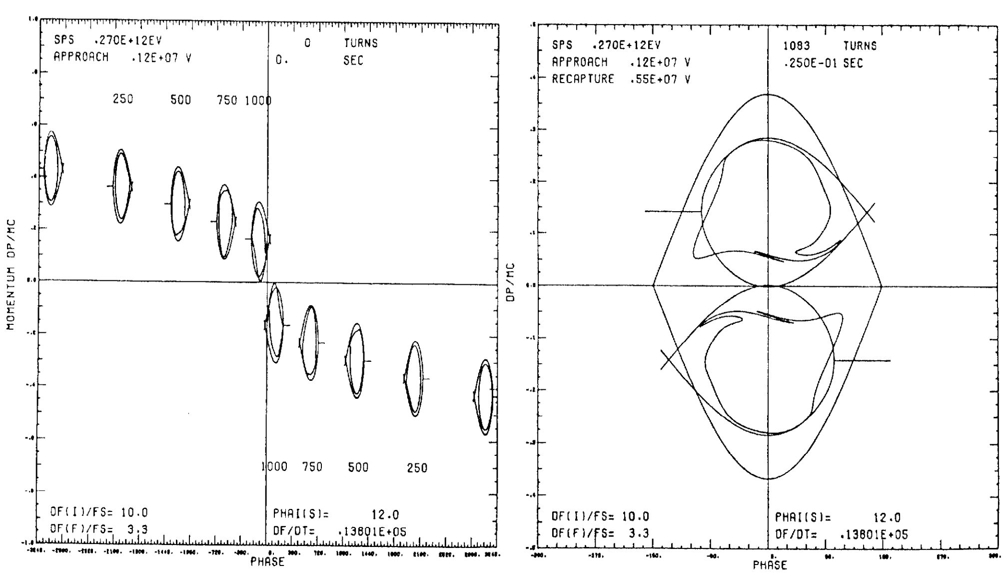

Fig. 3 - SPS 270 GeV bunch approach and combination

In the SPS at 270 GeV the initial B_1-B_2 distance is 385 RF periods (1925 ns). For $\alpha = 10$ and $\phi_s = 30^o$, $\Delta\psi = 8$ RF periods, which is negligible. The RF cavities (travelling wave structures) have a filling time of $\simeq 700$ ns, much smaller than the B_1-B_2 distance at the end of the process. Therefore, no particular problems are expected in this case.

b) Practical example of frequency separation

In the CPS, $\bar{p}$ production requires an intense beam filling only one quarter of the CPS circumference. A possible scheme is to combine 2 × 5 bunches at the ejection energy (26 GeV) thus avoiding the problems of acceleration of very intense bunches.

Bunches B_1 and B_2 (five bunches each) are diametrically opposite in the CPS ring allowing maximum ψ ($\psi_{max} = 5 \times 2\pi$). α can be chosen low ($\alpha = 4$), because no further combination is necessary: the two beams are simply fast ejected as soon as they coincide in azimuth. Equation (1) shows that $\Delta\psi$ can be made smaller than ψ for reasonable values of ϕ_s($\phi_s = 45^o$ gives $\Delta\psi = 0.9$ RF periods).

In order to overcome the problem of the limited bandwidth of the CPS cavities which would not permit any modulation at the revolution frequency, we tuned the cavities differently (using ferrite bias). Two of the four cavities related to bunches B_1 are tuned at the usual RF frequency (harmonic number h = 20), the other two being tuned at h = 19 and h = 21. By a proper choice of the relative phases of the RF waves, one can synthesize a 100% amplitude modulated wave, whose maximum is sitting on the bunches B_1. The h = 19 and h = 21 cavities are diametrically opposite in the ring such that a pure amplitude modulation seen by the beam appears as a pure phase modulation on the sum of the four cavity voltages (with equal delays). Sideband frequencies are generated from the h = 20 signal (division and addition), care being taken to ensure synchronization with bunches B_1. The remaining four cavities are arranged in the same way to give maximum voltage on bunches B_2. This scheme does not ensure complete independence of the two beams during the splitting period, because only one side-band of the phase modulation spectrum is generated. However, computer simulations have shown that the resultant bunch distortion is small in this case.

Fig. 4 shows a schematic diagram of the circuitry of the two phase-lock systems working on bunches B_1 and B_2 during the frequency splitting phase (switch S_3 down). Switch S_1 is operated at the revolution frequency and selects B_1 and B_2 phases. The stable phase

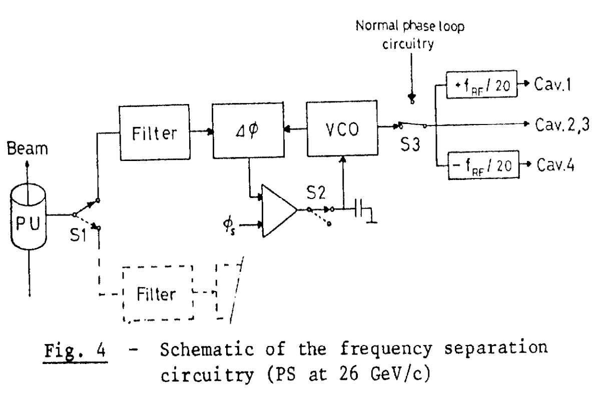

Fig. 4 - Schematic of the frequency separation circuitry (PS at 26 GeV/c)

ϕ_s is programmed as an offset of the phase discriminator. When $\alpha = 4$ is reached, switch S_2 is opened, keeping the RF frequencies f_1, f_2 constant, without phase lock.

Fig. 5 shows a mountain range display of the bunch superposition on a 26 GeV/c flat top. Satisfactory operation has been achieved up to an intensity of 8×10^{12} ppp.

Fast ejection of the azimuthally superimposed bunches has also worked correctly.

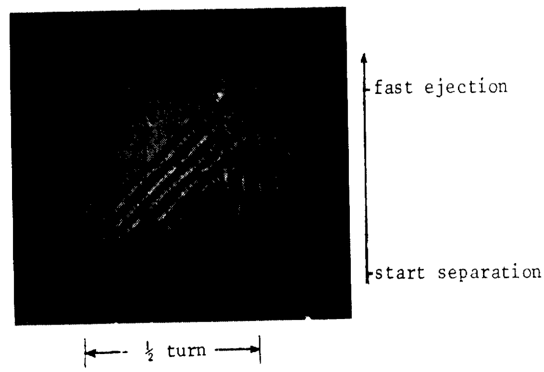

Fig. 5 - Frequency separation in the PS at 26 GeV/c

Conclusion

Several bunch superposition techniques have been estimated by computer simulation, and hardware implementation realized. A very interesting field of application of these new techniques is the CERN $p\bar{p}$ facility where they have demonstrated their efficiency in sophisticated beam manipulations, requiring only small electronic hardware.

Acknowledgements

The CPS experiments have benefited from the collaboration of many people, especially R. Cappi, J.P. Delahaye, J. Jamsek, P. Lefèvre, J.P. Ruinaud and G. Roux.

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