NEW RF EXERCISES ENVISAGED IN THE CERN-PS FOR THE ANTIPROTONS PRODUCTION BEAM OF THE ACOL MACHINE

R. Garoby
PS Division, CERN, 1211 Geneva 23, Switzerland

Summary

The new antiproton collector machine (ACOL)[1] presently under development at CERN, requires the highest possible proton intensity (more than 10^{13} protons per pulse) in one quarter of the PS circumference, and a guaranteed bunching factor, for its $\bar{p}$ production beam: possibly less than 25ns bunches, 105 ns apart. The present 26 GeV longitudinal merging technique [2], cannot meet these specifications, so that new quasi-adiabatic processes had to be imagined [3].

First, before transition energy, a "bunch pair merging" operation reduces from 10 to 5 the number of bunches, with a moderate blow-up, by slowly bunching the beam on half the initial harmonic number. Then, on the high energy flat top, the length of circumference occupied by the bunches is halved, by a technique tentatively named "bunch batch compression". This is basically a slow increase of the RF harmonic number seen by the beam, implemented by operating part of the existing cavities stepwise at increasing harmonic numbers (10,12,14,16,18 and finally 20).

Computer outputs are presented, together with machine experiment results.

High intensity bunches in the CPS

The ACOL project demands more than $2 \cdot 10^{12}$ protons per bunch on the target, at 26 GeV. Since this figure is the present record intensity of the CPS injector (PSB), one must merge bunches during the cycle.

Various techniques have been invented for that purpose, and the "26 GeV longitudinal merging" [2] is actually applied in routine operation. Unfortunately, the resulting "bunches" are badly adapted to any further bunch compression process, especially at the highest intensity, because their emittance is large and their distortion important. Therefore two new techniques, which may eventually be combined, are under investigation.

The first does the bunch merging near injection energy. One inserts the bunches of one PSB ring between the bunches of another, using a high frequency dipole magnet in the transfer line [4], and injects then 2 bunches per RF bucket (on $h_{PS} = 20$). After filamentation, only 5 "super-bunches" are left. Experiments have shown that strong microwave instabilities develop during filamentation, leading to losses at the beginning of acceleration. With the present set of harmonic numbers ($h_{PSB} = 5$, $h_{PS} = 20$), the situation is only marginally improved. However studies are going on.

The second technique allows one to merge bunches at any energy. It is an application of a scheme conceived by I. Bozsik et al. [5], and is related to some beam manipulations performed at Fermilab [6].

Merging pair of bunches

While the beam is bunched on $h = 20$, an $h = 10$ RF signal is prepared, whose buckets would be centered in the middle of the ones on $h=20$. The voltage on $h = 10$ is then "slowly" increased, and decreased on $h = 20$. Figure 1 represents the RF voltages seen by

Figure 1

RF voltages and buckets during the merging process.

the beam, and some trajectories in the longitudinal phase space (for static parameters) as a function of time. Two trajectories are drawn, which divide the phase plane into 3 not-communicating zones:

- 1) the outermost region, corresponding to uncaptured particles.
- 2) the intermediate layer, whose trajectories are periodic in $1/10$ th of a revolution (except for $t = 1$).
- 3) the innermost kernel, whose trajectories are periodic in $1/20$ of a revolution (but absent when $t = 4$ at the end of the manipulation).

Starting on $h = 20$, one can see that the $h = 20$ periodic structure gently disappears, finally leaving only the one on $h = 10$. This is equivalent to a quasi-adiabatic debunching ($h = 20$)/rebunching ($h = 10$) process. According to Bozsik et al.'s computations, the emittance blow-up is lower than 10 %, when the merging time is greater than 5 synchrotron periods (which, in their case, is the same in the initial and final states). They also show that the result is almost independent of space charge repulsion.

Merging will be done on the 3.5 GeV flat top, below transition. The 10 initial contiguous bunches on $h = 20$ ($1/2$ of a CPS turn), each one with an emittance $\epsilon_{10} \leq 0.4$ eVs, are finally combined into 5 contiguous bunches on $h = 10$, with an emittance:

$$\epsilon_{11} = 2 \times \epsilon_{10} > 0.8 \text{ eVs}$$

x being the blow up factor of the process.

Crossing transition energy

Actually, bunches of 1.5×10^{12} protons, and $\epsilon_1 \leq 0.6$ eVs, are accelerated across transition energy in the CPS, without either losses or blow-up, thanks to the gamma-transition jump scheme [7]. Using the somewhat pessimistic scaling law that N_b/ϵ_1 (N_b = number of particles per bunch) has to be kept constant [7,8], one can estimate that the "super-bunches", containing up to $N_b = 4 \times 10^{12}$ protons must have an emittance: $\epsilon_1 \leq 1.6$ eVs. This allows a blow up factor (x) of 2.

So the standard CPS technique for blowing up the longitudinal emittance [9], using the 200 MHz RF system can be applied to smooth up the process.

High energy operations

Bunches batch compression

5 contiguous bunches on $h = 10$, arriving on the 26 GeV flat top, occupy a length L on the machine circumference:

$$L = 4 \times (C/10) + l_b \quad \text{with } C = \text{CPS circumference} \\ l_b = \text{bunch length}$$

Since $l_b < (C/10)$, because bunch emittance ($\epsilon_1 = 1.6$ eVs) is smaller than bucket acceptance ($A_1 = 13.5$ eVs @ $V = 40$ kV, $h = 10$), it is possible to capture these 5 bunches in 5 contiguous buckets of a higher harmonic RF h' , as long as $L < 5 \times (C/h')$. Moreover, by changing the RF voltages in a continuous fashion, a contour of constant surface in the phase plane also evolves in a continuous way. Consequently, a slow enough evolution of the voltages can provide a quasi-adiabatic increase of the harmonic number. That method has to be applied 5 times, to cover the following series of harmonic numbers: 10, 12, 14, 16, 18, 20.

RF parameters, as a function of time, are shown in Figure 2 (but with a normalized time scale, where one unit is the duration of one harmonic step).

Figure 2

RF Parameters during batch compression.

To avoid dead times, due to the finite tuning rate of ferrite cavities, one has to split them in 3 groups (A,B,C), each with independant voltage, phase and frequency programs. Peculiar phase plane trajectories are represented in Figure 3, as a function of time. The origin corresponds to the center of the central bunch, which does not move during the process. The stable region around it has the largest acceptance, and the lowest one is obtained in the farthest region from the origin. The separatrix of that last one, at each moment, is drawn in Figure 3 (for static RF parameters). This maximum bunch emittance presents local minima during the process (Figure 4), but no bottleneck: the absolute minimum is attained in the final state ($A_1 = 4.8$ eVs @ $V = 40$ kV, $h = 20$).

A comfortable margin remains between this value and the estimated bunch emittance ($\epsilon_1 \approx 1.6$ eVs @ $4 \cdot 10^{12}$ protons).

Evolution with time of the distance, in azimuthal degrees, between extreme and central stable phases is also drawn in Figure 4.

3 D DISPLAY OF MAXIMUM EMITTANCE TRAJECTORIES.

Hmin=10 Hmax=20 Delta H=2
Vmin= 40.0 KV Vmax= 40.0 KV Normalized Delta t = .05

Figure 3

3 D display of phase plane trajectories during batch compression.

Estimating a blow up factor 1.05 for each harmonic step, the final bunch emittance is :

$$\epsilon_{12} = (1.05)^5 \times \epsilon_1 \approx 2 \text{ eVs}$$

TIME EVOLUTION OF DISTANCE BETWEEN BUNCHES AND OF THE MAXIMUM EMITTANCE OF EXTREME BUNCHES.

Figure 4

Longitudinal parameters during batch compression

Final bunch compression

Starting from $V = 40$ kV, $h = 20$, the voltage is suddenly increased to $V_1 = 200$ kV, and bunches are ejected after $1/4$ of a turn in the bucket. Ejected beam parameters are then:

- 5 contiguous bunches on $h = 20$.
- ideally up to 4×10^{12} protons per bunch.
- 25 ns bunch length.
- less than $4 \cdot 10^{-3}$ total $\Delta p/p$

Discussion

High intensity problems: experience will tell whether exotic coupled bunches mode instabilities, or intolerable microwave instabilities develop during the process. However, initial and final bunches are stable against microwave instability (computed threshold : $Z/n \approx 100 \Omega$ for a measured impedance $Z/n \approx 20 \Omega$). On the other hand, beam loading of cavities has to be treated on 6 different harmonic numbers. Two measures are designed to act against it:

- voltage reductions are obtained by progressively counterphasing cavities, each cavity voltage being kept at its maximum.

- a development program has been launched to reduce cavity impedance, using local RF feedback loops.

Hardware implications: since 3 differently tuned groups of cavities could conveniently be organized during a recent machine shutdown, two main hardware developments remain.

1) the low level RF system and its associated controls.

2) the improvement of the cavity amplifier chains (local RF feedback).

Low level equipment has been designed and is presently under fabrication. Concerning high level hardware, measurements have been done on a test cavity, and study is now at the design stage.

Experiments

Because of low level hardware availability, only partial tests have been done until now (during December 83 and August 84), making use of only two groups of cavities. Intensity was low (2×10^{12} protons or 1/10 of the aim), and all steps of the process happened at the same energy, on a 3.5 GeV flat top [10]

Figure 5 : P.U. signal during experiment

Figure 5 is a mountain range display of a longitudinal P.U. signal. Time increasing from the bottom to the top of the photograph, one clearly sees the beam structure going from 10 bunches to 5 (bottom half of the photograph), and the 5 bunches being squeezed in less and less space. The experiment was stopped at $h = 14$, because of hardware problems.

For the "bunches pair merging", at least 20 ms were necessary to reduce the voltage on $h = 20$ from 40 kV to 0 kV, while 50 ms were mandatory for increasing up to 40 kV the voltage on $h = 10$ (≈ 20 synchrotron periods). For the "batch compression", 20 ms (or almost 8 synchrotron periods) were sufficient for each step in harmonic number (10 to 12, and 12 to 14), but no lower value was tested.

Resulting blow up factors were 1.76 for the merging, and 1.21 for the limited batch compression, but these numbers can probably be reduced, because some

200 MHz phase modulated voltage was continuously applied to "smooth up" the results after very brief RF adjustments.

Hardware modifications proved necessary, and hints for the design of the complete low level system revealed. Moreover, proof of the principle has been established, and preparation is now going on for further experiments.

Conclusions

The set of techniques described has the great advantage to provide merged bunches, on the original harmonic number, with a very small degradation of the longitudinal phase space density of particles. It is matched to the needs of the ACOL $\bar{p}$ production beam, but the AA could readily benefit of it, as soon as it is available (because of expected process reliability, and of the small $\Delta p/p$ of the ejected beam). Moreover, sophistication is still possible and, for instance, 20 PSB bunches could theoretically be merged into 5, by applying two successive sets of "bunches pair merging/batch compression". But verdict of full scale experiments has to be obtained, especially concerning the problems related to high beam intensities.

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