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R.F. BEAM RECOMBINATION ("FUNNELLING") AT THE CERN PSB BY MEANS OF AN 8 MHZ DIPOLE MAGNET

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Introduction and Summary

For filling the Antiproton Accumulator ring, the beam in the PS must be concentrated within one quarter of its circumference. A first step is to inject as much beam as possible into two groups of five PS buckets each occupying one quarter of its periphery. For this purpose, beams from the 4-ring injector synchrotron (PSB) are recombined in pairs by means of an RF dipole magnet which permits longitudinal interleaving of successive bunches. Each PSB bunch being slightly under 180° in length, two of them can fit into a (stationary) PS bucket. It is shown that the use of a sinusoidal deflecting field instead of the ideal square wave results in only a modest growth of the transverse emittance of the recombined beams. The increase of longitudinal emittance by a factor of ~ 3, inherent to the scheme is also acceptable for the PS machine. We discuss the beam dynamics aspects, the construction of the 8 MHz, 250 gauss meter deflecting magnet and the experimental results.

RF Recombination Scheme[1]

In the CERN PS complex, antiprotons are produced by an intense proton beam at 26 GeV/c which has to match the circumference of the Antiproton Accumulator (a quarter of the PS). The first stage of the beam concentration process takes advantage of the four ring structure of the 800 MeV synchrotron injector (PSB) (5 bunches per ring, each one quarter of PS circumference). Beams from pairs of rings are recombined prior to PS injection thus filling only 10 of the 20 PS buckets. One way of doing this is to add the beams in the vertical plane by means of a thin double-septum magnet ("vertical addition")[2]; this was used for a while but was abandoned as it led to excessive transverse emittance and therefore beam losses. At present we use only two rings[3] with nearly 10^{13} ppp each. RF recombination[4] (figure 1) would make available the full four-ring intensity of the PSB. -The various PSB-PS recombination and transfer schemes are sketched in figure 2.

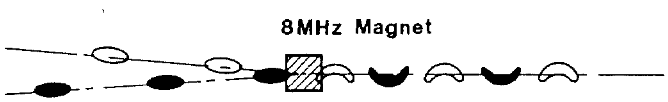

Fig. 1: Bunches from two accelerators recombined onto a common axis by a sine-wave deflector.

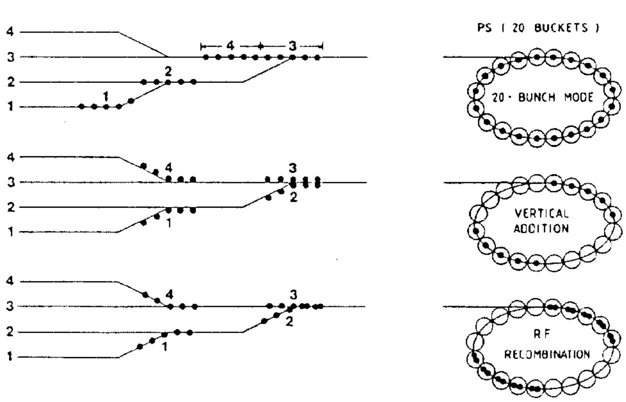

Fig. 2: Schemes for recombining the four PSB rings.

Deflector design[5]

A careful comparison of the total energy stored by an electric or a magnetic deflector suggests that for $\beta \sim 1$ magnetic deflection is the most economical. The specifications for a magnet were then as follows:

Particles	: 800 MeV protons
Peak deflection	: ± 5 mrad (vertical)
	Bl = 244 gauss meters
Frequency f	: 8.03 + 0.1 MHz
Overall length	: ~ 1.5 m
Effective length	: l = 1.2 m
Aperture height	: h = 55 mm
width	: w = 100 mm
Pulse repetition rate	: ~ 1.2 pps

The duty factor of ~ 10^{-3} is effectively determined by the build-up time of the device: beam is present for a maximum of 2 μs per pulse.

Magnet Construction

The induced voltage per turn V_1, independent of length for a given deflection, tends to determine the general type of magnet construction. Here

$$V_1 = 2\pi fhBl = 67.5 \text{ kV}$$

which suggests a one-turn magnet.

While one might have obtained some reduction in stored energy by using ferrites, the necessity of leaving a rather large distance between the core and the conductors would have limited their usefulness. We decided to dispense with ferrites altogether which brought the following advantages:

- simplicity of the air-cored design
- avoidance of delivery delays
- reduction in vacuum pumping requirements.

On the debit side, it is possible that the air-cored design requires slightly more RF power, but with our low duty cycle the extra mean power is of no importance. Providing the necessary peak power is also no problem.

Having decided on a single turn magnet, one still has the choice between what one may call a single-ended or double-ended arrangement (figure 3). We chose the double-ended structure which has the advantage that all voltages are halved. The current in the conductors is of course the same in either case, ~ 3400 A. This basic structure must be tuned, supplied with RF drive and balanced with respect to ground.

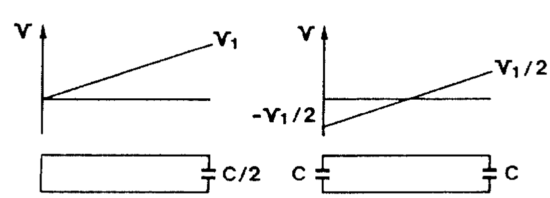

Fig. 3: Voltage distribution for single and double ended arrangements.

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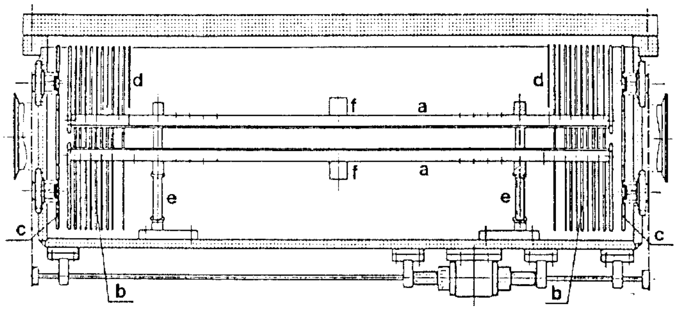

Fig. 4: Longitudinal section of the deflector.
a - main conductor, b - capacitor stack, c - motor driven tuning plate, d - balancing capacitor, e - alumina supports, f - copper support and heat conductor.

RF drive can be provided in a number of ways. We chose what appeared to be the simplest, attaching the tube anode directly to an appropriate point on one of the resonant lines (via a vacuum feed-through and DC blocking condenser). This is shown schematically in figure 6. To maintain balance to earth inspite of the loading by the tube anode capacity, four adjustable earthed metal plates form the capacities C_1-C_4. Finally the whole system is fine tuned to resonance by two motor-driven plates, one at each end (C_5-C_8), which do not alter the balance to ground. The various parameters work out as follows:

C ~ 2000 pf
Q ~ 1000
P ~ 110 kW (peak power)
τ ~ 20 μs (time constant)
T ~ 300 μs (pulse duration).

The construction is shown in figures 4 and 5.

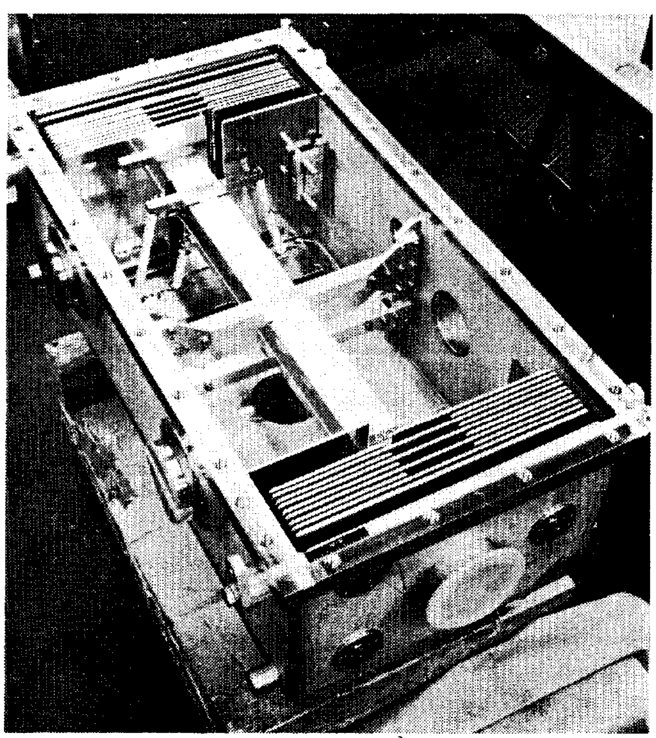

Fig. 5: View of magnet with cover of vacuum tank removed.

Electric stress. The physical dimensions of the main capacitors depend strongly on the acceptable electric stress. In this instance we chose a gap of 6 mm for ~ 40 kV (peak), a stress slightly below the Kilpatrick limit. After machining, the aluminium alloy plates were lightly cleaned with a fine emery belt sander and chemically degreased. No voltage holding problems occurred and conditioning was extremely rapid.

Mechanical stresses. For a voltage difference of 34 kV, the mean force between plates is ~ 70 N/m^2 during the pulse. While this is not very large, the unbalanced force at the ends of the stack results in some small deformations, causing a detuning of the order of $\pm 2^0$, which is just within acceptable limits in our case. The magnetic force between the two main conductors is negligible compared to their weight.

Associated Equipment (figure 6)

For the sake of simplicity DC is applied to the anode of the final tube, with pulsing controlled by the grid. Gain is ~ 100. The driver is in a remote equipment room. AVC and tuning are quite conventional. Thermal drifts are very slow and accurate phase control has presented no problem.

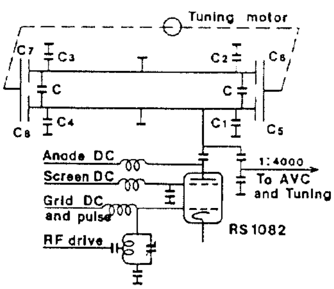

Fig. 6: Schematic diagram of resonant system and final tube.

Beam Dynamics Aspects[6]

Deflection. If the bunch length is short with respect to the bunch distance, it is only the sine-wave deflector's peak value which matters. However, in our case, bunch lengths of almost 180° lead to a strongly varying deflection along the bunch, with the bunch centre overdeflected, and the edges strongly underdeflected. A simple relation between peak ($\hat{\theta}$) and effective ($\bar{\theta}$ = weighted average) deflection is readily found under the (simplifying) assumptions: (i) a bunch length of 180°; (ii) the line density function is a half sine-wave; (iii) no acceptance restriction downstream:

$$\bar{\theta} = \hat{\theta}\,\frac{\pi}{4}\,\cos\phi$$

where ϕ is the phase between deflection and bunch (usually $\phi = 0$ for typical "funnelling" applications). For $\phi = 0$, the bunch center experiences an overshoot of 27%, whereas the low density edges are almost not deflected at all. The case $\phi \neq 0$ is interesting for our particular application where two PSB bunches have to fit into one PS bucket which is easier if they are somewhat closer than 180°, at the expense of more overshoot for a given effective deflection (figure 7).

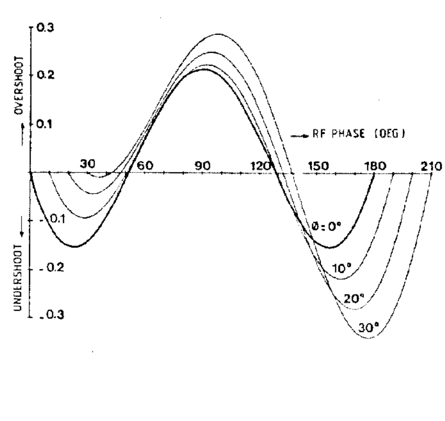

Fig. 7: Weighted relative overshoot along the bunch (ϕ = phase between sinusoidal deflector and bunch)

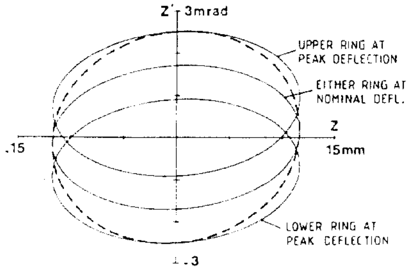

Fig. 8: Over-deflected bunch centres at RF dipole exit, and "enclosing" ellipse (broken line).

Optics. In reality, the downstream machine has a limited acceptance, and the optimum overshoot will depend on the ratio of the emittance of the incoming beam to the acceptance of the downstream machine. In our case this ratio is almost 2 and an overshoot of 25% was about optimum, i.e. beam at $\pm$ 37° was given the ideal deflection and beam at $\pm$ 53° is missteered by the same amount. Beam within $\pm$ 53° is thus fully transmitted, the remainder is transmitted in slowly diminishing proportions, reaching ~ 40% at the bunch extremities. The vertical emittance ellipse of the recombined beam has then a different shape and must be matched to the downstream machine. This is illustrated in figure 8 which shows the high-density central parts of the bunches, overdeflected upwards for e.g. ring 3, and downwards for ring 2, as they leave the RF dipole. The broken line ellipse almost encloses both but is larger and has another aspect ratio. Optimum matching, taking into account all relevant parameters, clearly would require extensive computer studies. In the light of experimental results, we expect that the gain in transmission efficiency, over the simple approach presented here, would be marginal.

Experimental Results

Recombination. The RF recombination scheme was tested in early 1984, and later the beams were injected into the PS machine. Depending on the vertical emittance of the beams to be recombined, the required effective deflection varies from $\pm$ 2.6 (ε_v = 15 $\pi\mu$radm) to $\pm$ 4 mrad (ε_v = 30 π). With the RF dipole set to a peak deflection of 4 mrad, the effective deflection was found to be ~ 3.2 mrad; the difference signal of one bunch, observed on an electrostatic position monitor downstream of the device (figure 9a), compares well with figure 7, ϕ = 0° (RF dipole and bunch in phase). Figure 9b shows the same signal when recombining ring 3 (bunches 1, 3, 5, 7, 9) and ring 2 (the other bunches). It corresponds to ~ 5 mm overdeflection of bunch centres for a beam half-size of ~ 20 mm, about as expected.

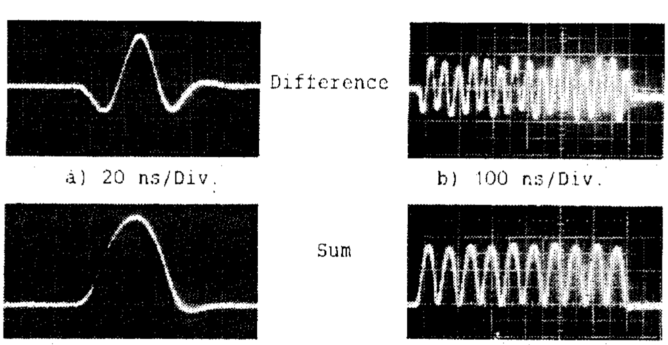

Fig. 9: Sum and difference signals on a position monitor downstream of the RF dipole, for one bunch (a), and rings 3+2 recombined, five bunches each (b).

Injection into the PS[7]. In the first tests done with beams injected into the PS, there were intensity losses of ~ 25% between the PSB rings and the PS (after a few turns), and a further 10% in the PS due to non-captured protons, at moderate beam intensity (~ 3.10^{12} p/PSB ring). Transmission was improved by: (i) reducing the dipole's effective deflection angle from 3.2 mrad to ~ 2.6 mrad while of course decreasing the angle between the incoming beams (the pulsed double-septum magnet, left over from the "vertical addition" mode, figure 2, allows this operation); (ii) changing the matching into the PS according to figure 8; (iii) reducing the distance between pairs of bunches to be injected into one PS bucket, from 180° to 160°; (iv) better longitudinal matching in the PS by voltage reduction. By these measures, the overall efficiency was raised from ~ 65% to ~ 85%.

High Intensity. Not surprisingly, a severe intensity limitation appeared in the PS. Studies done with two Booster rings gave the following results:

PSB 2 rings accelerated	1,18 10^{13} p/p
PS entry	1,08 10^{13} p/p
PS after capture losses	$\leqslant$ 0,77 10^{13} p/p.

This limit corresponds to $1,55.10^{12}$ p/PS bucket which is marginally lower than the one experienced with one PSB bunch transferred to a PS bucket. Although the scheme opens the possibility of twice this intensity per PS bucket, it was not put into operation so far, but studies are under way to understand[8] and possibly overcome the PS intensity limit so as to provide more $\bar{p}$ for the future Antiproton Collector[9].

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