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THE FEASIBILITY OF USING THE PS AS AN INJECTOR FOR "PROJECT B" RF PROBLEMS

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1. General

General aspects of using the PS as an injector for the reduced 300 GeV machine[1] are discussed in Ref.[2]. This note is intended to summarize implications given by requirements of the 180 MHz rf system[3] proposed for the 300 GeV main ring. We concentrate on the following aspects:

Bunch area considerations

Transition aperture

Debunching at high intensity.

Our conclusions are to be found at page 10 of this note.

2. Bunch Area Considerations

Some characteristics of the travelling wave rf system[3] scaled down to the 879 m radius of MR 32 are listed in Table 1. It is noted that the bucket area provided by the rf voltage has a broad minimum in the 35 GeV region ($\gamma \simeq \sqrt{3}\,\gamma_{tr}$). The minimum value is about 0.17 ($(\frac{\Delta p}{m_o c})$ x rf radians). Including some safety factor it is therefore required that the bunch area is smaller than say 0.15 to avoid spill out.

We note in passing that injecting from a fast booster the bunch area would be 0.01 - 0.02 which is safe below this limit.

Assuming adiabatic trapping, the bunch area is determined by the momentum spread of the injected beam:

$$A = 4\pi \left(\frac{\Delta p}{p}\right) \times (\beta\gamma)_{inj} , \qquad (1)$$

where $2\Delta p$ is the total momentum spread at the base of the distribution.

Table 1 - Some Parameters of a 180 MHz rf System

Center frequency: f_o	=	184.3 MHz
Frequency swing	=	$\frac{f_{max} - f_{min}}{f_{min}} = 5.5 \times 10^{-3}$ (8 GeV injection)
Harmonic number: h	=	3400
Peak voltage per turn: U	=	4 MV
Acceleration rate	=	150 GeV/s
Bucket area (minimum at $\approx \sqrt{3}\,\gamma_{tr}$)		$A \approx 0.17$ rad ($\frac{\Delta p}{m_o c} \times$ rf radians)
Total length of structure	=	2 × 20 metres
Total input power	=	2 × 0.7 Megawatts

The requirement to have $A < 0.15$ will therefore impose a limit on the acceptable momentum spread. Some method to reduce $\Delta p/p$ to about 10^{-3} or lower will probably have to be used at 10^{13} p/p.

Reduction of the momentum spread in the PS is uneconomic because it increases the debunching time in the main ring (Table 2). In addition ejection schemes using the PS fast kicker need a gap of at least 65 ns between adjacent bunches, and therefore tight bunching. This is to avoid loss during rise of the kicker field.

A solution to reduce the momentum spread is the use of a "debuncher cavity" installed in the main ring. This cavity would be used to turn the injected bunches by 90° in phase space. Its action is similar to that of the debuncher used between Linac and PS.

Table 2 - Debunching Time in Main Ring neglecting Space Charge

1/h gives the fraction of the circumference around which the beam has to debunch.

Transfer momentum	Debunching time (in sec) for $\Delta p/p = \pm 10^{-3}$		
	h = 1	h = 5	h = 20
10 GeV/c	1.5	0.3	0.080
12 GeV/c	2.7	0.54	0.140
14 GeV/c	5.1	1.05	0.260
16 GeV/c	12.4	2.5	0.620
18 GeV/c	370	74	18.4
20 GeV/c	18.8	3.7	0.940
22 GeV/c	10.6	2.1	0.530
24 GeV/c	7.9	1.6	0.400
26 GeV/c	6.6	1.3	0.330
28 GeV/c	5.9	1.2	0.290

Assuming that the 20 PS bunches are uniformly distributed around the main ring, the debuncher would work at about 1 MHz fixed frequency ($f = 9.5$ MHz × 100 m/879 m). Only a moderate voltage is required for debunching. Assuming $\frac{\Delta p}{p} = \pm 2 \times 10^{-3}$, we find that a peak voltage

$$U = \frac{\pi}{2} \times 938 \text{ MV} \times \left(\frac{\Delta p}{p}\right)^2 \frac{h\eta}{\gamma} (\beta\gamma)^2 \leq 6 \text{ KV}$$

is sufficient for debunching at energies between 12 and 28 GeV. The debunching time is the same as for free debunching (Table 2).

Although from the rf point of view a small bunch area is preferable, we will see in section 4 that a rather large bunch area is required to ensure debunching.

3. Aperture at Transition

Apertures required to accommodate momentum spread at transition in the main ring are listed in Table 3. In the last column we list the aperture which remains for closed orbit distortion when these transition apertures plus the beam radius ($E_H = 1\ \pi$ μradian metres at transition corresponding to $E_H \approx 2\ \pi$ μradian metres at 8 GeV) are subtracted from the 47.6 mm quoted in Ref.[4].

It is noted that this aperture is insufficient to accommodate a beam of 0.15 rad bunch area even if closed-orbit distortions are corrected to zero. For 0.1 rad bunch area, 5.8 mm half aperture would be left for closed-orbit distortions which is marginal but perhaps sufficient if one relies on orbit correction. One would therefore conclude that

i) additional horizontal aperture has to be provided, or
ii) one has to go to bunch areas $A \lesssim 0.1$ rad,

if one has to go through transition in the main ring. Going to Table 4, condition ii) would require injection below 9 GeV/c for $N = 10^{13}$ or below 14 GeV/c for $N = 10^{12}$ to ensure debunching.

Table 3

Semi-aperture in mm required to accommodate momentum spread at transition in MR 32[4]

All apertures quoted at maximum β_H and for $\alpha_p = 6.75$, $f_{rf} = 180$ MHz, $\dot{E} = 150$ GeV/s, $\gamma_{tr} = 19.3$, $\phi_s = 45^o$. The remaining aperture is evaluated under the following assumption: $E_H = 1\ \pi$ μrad metres at transition, $a_H = 47.6$ mm total horizontal half aperture.

Bunch area	Aperture for momentum spread		Aperture in mm remaining for c.o. distortions
	low intensity	3×10^{13} p/p*	
0.02 (fast booster)	14.2	18.5*	≥ 19
0.1 (PS)	31.7	31.7	5.8
0.15 (PS)	38.8	38.8	(-1.3)

*Assuming compensation by "rf mistiming" at transition.

4. Debunching in the Main Ring

Some of the proposed transfer schemes[2)] consist in the transfer of a bunched beam. The simplest scheme would produce 20 PS bunches concentrated in a fraction of the main ring circumference, the more refined schemes would distribute 20 or a higher number of PS bunches evenly around the main ring.

Some other schemes consist in the transfer of a beam which has already been debunched in the PS.

With the transfer of a bunched beam there are 2 possibilities: either one leaves the main ring rf system on during transfer, and only those protons are trapped which happen to fall inside a main ring bucket (roughly 1/3 of them); most buckets would be empty. Or, the beam is first debunched (with or without blow-up), and subsequently the rf system is switched on and the beam is rebunched at the main ring harmonic number (= 3400).

The first of these possibilities would give serious instantaneous beam loading, unless the beam intensity is low.

Let us then look at the second possibility - debunching and rebunching. Debunching will only be possible if Δp is large enough and the coupling impedance $|Z|$ seen by the beam is small enough. What really matters is rather $|Z|/h^*$, where h^* is the harmonic number of the perturbation. From Ref.[5] we use the information that the coupling impedance of the rf structure dominates the situation completely, at several harmonic numbers h^* around h = 3400. Unfortunately, the debunching of a certain bunch structure in the presence of a coupling impedance at a much higher harmonic number is an unsolved theoretical problem. We shall therefore use Keil and Schnell's criterion[6], which says that a beam which is already debunched will be stable against self-bunching at harmonic number h^* if

$$\frac{|Z|}{h^*} \leq \frac{0.7\,\pi}{2} \; \frac{E_o}{e} \; \frac{|n|}{I_o \gamma} \left(\frac{\Delta p}{m_o c} \right)_f^2$$

Here, $(\Delta p)_f$ denotes the <u>full</u> width at <u>half</u>-height of the distribution. We shall assume that this approximately equals the half-width at base, that is, $(\Delta p)_f = \Delta p$ as used in Eq. (1).

During the debunching process, some sort of double beam structure containing both the old and one or several new ($\simeq$ 3400) harmonic numbers will probably develop.

It does not seem likely that the self-bunching criterion under these conditions is much more stringent than the one given above, although this point remains to be studied.

The largest value of the coupling impedance Z which may be seen by the beam equals on eighth of the shunt impedance of the rf-structure at mid-band[7]

$$|Z|_{max} = \frac{n}{8} \; \frac{2\pi f_o}{V_g} \; \frac{R}{Q} \; L^2$$

For n = 2 structures of length L = 20 m each, group velocity $V_g = 0.088\ c$ and R/Q = 580 Ω/m we obtain

$$|Z|_{max} = 2.55\ M\Omega \;.$$

With the harmonic number h* = h = 3400 we find

$$\frac{|Z|_{max}}{h^*} = 750\ \Omega$$

This value of $|Z|/h^*$ we then substituted into the stability criterion, along with $N = 10^{13}$ or $N = 10^{12}$, and we solved for $(\Delta p/p)_f$. The results for some injection energies are shown in Table 4, together with the corresponding bunch areas A after adiabatic trapping (relation (1), p. 2). We note that with $N = 10^{13}$, the bunch area A required to assure debunching is larger than the initial 0.15 imposed by bucket area for all transfer momenta larger than about 11 GeV/c. For all transfer momenta larger than about 9 GeV/c, the required area is larger than the critical 0.10 imposed by horizontal aperture at transition, so one would have to transfer below 9 GeV/c. With $N = 10^{12}$, one could transfer either above 24 GeV/c, or below 14 GeV/c.

A special low-frequency rf system for the debunching would help if one matched the bunches into stationary buckets. It is not clear whether such a system would help against the instability if one attempted complete debunching. In fact the growth rate of the selfbunching effect is of the order of 2 ms, whereas typical debunching times for $\Delta p/p = \pm 10^{-3}$ are ∿ 100 ms (Table 2).

One might think of deliberately increasing the momentum spread and then debunch by a debuncher system as described in section 2 of this report. By adequate gymnastics* the time interval within which particles of all momenta have a Δp smaller than the threshold value can in fact be reduced to only a few milliseconds. However, a sizeable fraction of the particles will have a momentum spread smaller than the threshold Δp

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*We are indebted to W. Hardt for suggestions concerning this point.

p	γ	$N = 10^{13}$		$N = 10^{12}$		
GeV/c		$\Delta p/p$	A	$\Delta p/p$	A	
8	8.58	0.82×10^{-3}	0.088	0.26×10^{-3}	0.028	These A's should be smaller than 0.10
9	9.64	0.90×10^{-3}	0.109	0.28×10^{-3}	0.034	
10	10.70	0.99×10^{-3}	0.133	0.31×10^{-3}	0.042	
12	12.83	1.21×10^{-3}	0.195	0.38×10^{-3}	0.062	
14	14.95	1.54×10^{-3}	0.289	0.49×10^{-3}	0.091	
16	17.08	2.23×10^{-3}	0.479	0.71×10^{-3}	0.151	
18	19.21	11.47×10^{-3}	2.769	3.63×10^{-3}	0.876	
						$\gamma_{tr} = 19.3$
20	21.34	2.46×10^{-3}	0.660	0.78×10^{-3}	0.209	These A's should be smaller than 0.15
22	23.47	1.76×10^{-3}	0.519	0.56×10^{-3}	0.164	
24	25.60	1.46×10^{-3}	0.470	0.46×10^{-3}	0.149	
26	27.73	1.28×10^{-3}	0.446	0.40×10^{-3}	0.141	
28	29.86	1.16×10^{-3}	0.435	0.37×10^{-3}	0.138	

Table 4

for a much longer time. One might argue that these particles will self-bunch with a momentum spread comparable to the threshold value listed in Table 4.

This bunch structure would then become apparent once the debunching process has brought down the momentum spread of the whole bunch to a comparable value. Obviously, this question needs further study and it may well be that the above conclusions are pessimistic.

If the frequency of the main rf system would be lowered, its power consumption and, hence, its coupling impedance Z kept constant, the momentum spread required for stability would increase with $h^{*-\frac{1}{2}}$. Since the bucket area for given voltage also scales with $h^{*-\frac{1}{2}}$ the situation is unchanged with respect to overflow from the bucket but worse with respect to horizontal aperture at transition. Thus, it is not advantageous to lower the frequency unless it can be lowered to such a low multiple of 1 MHz (bunch frequency for 20 bunches, evenly distributed around the main ring) that direct trapping of the PS bunches becomes possible. This, however, seems impracticable, since the cavities would have to be filled with ferrite in order to make their dimensions at all reasonable. At 4 MV per turn this would lead to prohibitive power loss and cooling difficulties.

Conclusion

The main difficulty, at least with those transfer schemes that rely upon debunching and rebunching in the main ring, seems to be the tendency of self-bunching under the influence of beam induced fields. Either the beam may not debunch, or rebunch itself at a wrong frequency, or, if sufficient momentum spread is arranged to make the beam debunch, the new bunch area after rebunching is so large that most of the beam may be lost out of the buckets at $\sqrt{3}\,E_{tr}$. For transfer below the main ring transition, the required bunch area is somewhat smaller, but a new limitation turns up:

one is limited by horizontal aperture when going through transition in the main ring.

According to the debunching criterion which we have used although it may not be exactly correct in this case, one is just at the limit of thes constraints for 10^{13} protons per pulse and 8 GeV (kinetic, corresponding to 9 GeV/c) transfer energy. This happens to be the same minimum energy for which we would want to build the rf system anyhow, in view of the later addition of a fast cycling booster injector. The coupling impedanc leading to self-bunching difficulties comes almost entirely from the rf accelerating structure itself. Hence, an active feedback system decreasi the effective coupling impedance by about an order of magnitude may well be feasible in spite of the high harmonic number. Bearing this in mind one may conclude that the bunch-by-bunch transfer of 10^{12} protons per pulse at 8 GeV kinetic energy is quite safe. The same process with 10^{13} protons per pulse may well be possible but cannot be guaranteed at present.

Transfer schemes which rely upon transfer of a beam which is debunch in the PS, or already rebunched there at the main-ring frequency, may suffer less from these difficulties.

References

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