THE PS 200 MHz RF SYSTEM
PRESENT SITUATION AND FUTURE PROSPECTS

by

D. Boussard

SUMMARY

The 200 MHz RF system which is installed in the PS was originally intended to provide some adequate RF structure on the beam at injection in the SPS. Since then it has been used for other purposes and, in particular, it has allowed operation of the PS at very high intensities. A review of the present uses of the system is given, together with a brief technical description. In order to match the SPS intensity programme, a "bunch-into-bucket" transfer technique is proposed, which will lead to an extension of the RF system up to eight cavities. The proposal described here was approved at a PS-SPS meeting held last February. The conclusions of this meeting are attached to this paper as an appendix.

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APPENDIX
THE PS 200 MHz RF SYSTEM - PRESENT SITUATION AND FUTURE PROSPECTS

Following the results of last Autumn's experiments, the 200 MHz RF system installed in the PS for several years will be extended and modified in order to allow bunch-into bucket transfer to the SPS. This seems to be a good opportunity to summarize the knowledge we have gained with this system over the past years, and to extrapolate as to the situation expected in the near future.

1. The various uses of the 200 MHz RF system

a) 200 MHz premodulation of the ejected beam. This is the use for which the system was originally built. It was recognized that the debunching-rebunching process being better performed in the SPS in the case of a single injection, the SPS closed orbit instrumentation would be blind at the crucial moment of injection. By making some 200 MHz structure present on the beam at injection the PU sensitivity is restored at least during the debunching time (= 1 ms at 10 GeV/c). At 10 GeV/c the 200 MHz cavity is driven by the 21st harmonic of the normal PS RF frequency, \( h = 420 \) but one can produce an RF structure on the beam by using any multiple of the revolution frequency. This was the case for the 3.5 GeV/c ejection experiments in which the cavity was driven by the 433rd harmonic of the revolution frequency (not a multiple of the normal RF frequency). Nevertheless, this is a potentially unstable situation at high intensity due to the impedance of the cavity.

b) Controlled blow-up

When the 200 MHz cavity is driven by a multiple of the normal RF frequency, a very strong non-linearity is produced inside the bucket (large spread in rotation frequency around the stable point). This strongly speeds up the natural filamentation process which converts any non-adiabatic manipulation into a longitudinal blow-up of the beam. It also overrides the effect of the self forces which tend to prevent the natural filamentation from occurring. Experimentally, one indeed observes that the 200 MHz RF system produces non-oscillatory smooth bunches with some amount of longitudinal blow-up.
This effect was deliberately used on a 1 GeV (kinetic) intermediate flat-top 50 ms long where the 200 MHz cavity is driven by the 24th harmonic of the normal RF frequency (8.31 MHz). By controlling the ratio of the two RF voltages (8.31 MHz and 200 MHz) one can easily adjust the amount of blow-up required (from 7-8 mrad to about 20 mrad). This operation is absolutely essential at high intensity (above $10^{13}$ p.p.p) to prevent longitudinal instabilities and pass transition without beam losses. It has been shown to be very useful for another application (filling the ISR with a beam of controlled longitudinal emittance)\(^1\). This facility (blow-up on a 1 GeV flat-top) is now used on all the PS cycles.

Nevertheless, the mechanism of the blow-up remained somewhat mysterious until recently because no obvious non-adiabatic process could be identified. Finally, it turned out that the phase noise of the low frequency master oscillator (8.31 MHz) multiplied by 24 was the real cause of the blow-up\(^2\). Similar results can be obtained with a noiseless generator (the beam itself) properly modulated in phase by an external generator (frequency about 1 kHz). This new technique, more flexible and more powerful, will become operational after the 1978 shut-down.

c) **RF scanning experiments**

One can measure the energy spread of a debunched beam by scanning an empty bucket through it. This technique works better with a high-frequency RF system (the scanning time is inversely proportional to the harmonic number). A study of the energy distribution of the beam depending on the debunching conditions, has been performed on a 24 GeV flat top\(^3,5\). It has shown the correlation between the slow-extraction spill shape and the energy distribution. Although non-operational at present, this measurement technique can be nevertheless useful in all cases where a debunched beam circulates in the machine (debunching-rebunching at 10 GeV/c for instance).

d) **Rebunching experiments**

In the case of multibatch injection in the SPS, it is more interesting to change harmonic number in the PS rather than in the SPS. (The beam current in the PS does not increase with the number of batches, and the impedance of the SPS 200 MHz travelling wave structures can be avoided). The usual stability criterion indicates that a low energy is better ($\eta/\gamma$ factor) at constant
emittance. Therefore, low-energy \((T = 1 \text{ GeV})\) experiments have been performed first, with the normal RF system. They have shown that the change of harmonic number is possible at 1 GeV with a moderate blow-up (8 to 20 mrad) and a good capture efficiency \((> 95\% \text{ at } I_p = 10^{13})\) \(^6\).

At high energy the same results can be theoretically obtained by increasing the emittance of the beam like \(\sqrt{\gamma/n}\) (60 mrad at 10 GeV/c corresponds to 8 mrad at \(T = 1 \text{ GeV}\)). This is now possible in a clean way by using the 200 MHz system to blow up the beam emittance as indicated in 1(b). As a result, similar performances can be achieved at 10 GeV/c, with the normal RF system\(^7\): capture efficiency \(> 95\% \text{ at } I_p = 1.1 \cdot 10^{13}\) emittance growth from \(\approx 60 \text{ mrad}\) to \(\approx 120 \text{ mrad}\).

This very interesting result shows that one can envisage bunch-into-bucket transfer with fixed tune 200 MHz cavities and it opens the field of recapture experiments with the present 200 MHz RF system.

It is interesting to mention that clean debunching conditions (at 1 GeV as well as at 10 GeV) are necessary to achieve these results. Compensation of all normal PS cavities was the key to solving the debunching problems as well as the RF low-energy difficulties. In order to arrive at a fully-operational situation up to the highest intensities, a considerable effort at understanding still has to be made.

On December 8th 1977, we made the first trial to recapture the debunched beam at 10 GeV/c with the 200 MHz RF system. The RF voltage available was \(\approx 80 \text{ kV}\) giving an acceptance of 70 mrad only. Under these conditions, the capture efficiency at \(I_p = 1.2 \cdot 10^{13}\) was \(\approx 75\%\), not significantly different from the figure obtained with the normal RF system adjusted to give the same acceptance\(^2\). There is no sign of unexpected problems when recapturing the beam at 200 MHz.

Nevertheless, during this experiment we encountered several problems:

- lack of RF voltage to provide enough acceptance and fully recapture the beam (one single 9.5 MHz cavity provides 150 mrad).

- lack of flexibility of the low-level RF circuitry. The cavities have to perform different tasks during the same cycle; they have to be precisely put in phase when working together, etc.
- difficulty in measuring the capture efficiency. When recapturing with a 9.5 MHz cavity, the bucket area is big enough to permit splitting between the trapped and the untrapped part of the beam. This gives an accurate measurement of the capture efficiency, but takes some time (50 to 100 ms). The other technique (used during this experiment) compares the amount of RF structure with the d.c. beam current. It takes no time, but is less precise and requires a very good high-frequency instrumentation.

In order to pursue the 200 MHz recapture experiments and arrive at a bunch-into-bucket transfer, we have to improve the present situation in these three directions.

2. Present situation of the 200 MHz system

There are at present (end 1977) two cavities installed on a frame in SS6. This frame can house four such cavities, for which 4 feeder lines (3\(\frac{1}{8}\))" are installed between SS6 and the North Hall platform. A third cavity was assembled in December 1977 by the PS RF section and will be installed during the shut-down. In Spring 1978 three cavities, together with their associated power amplifiers, will therefore be available. We shall now give the relevant parameters for one cavity.

a) RF voltage.

The maximum RF voltage is limited ultimately by the gap insulator breakdown. The ceramic window has been tested up to 75 kV which represents the maximum voltage per cavity. The other limitation is the maximum current (which is proportional to the RF field strength) which flows in the PIN diodes when they are on\(^8\). At present we limit the voltage to 50 kV for this reason.

We intend to carry out experiments to determine what exactly the safe limit for the PIN diodes current is. If the present current turns out to be the maximum allowable, one could consider slightly modifying the PIN diode system, i.e.

- install six diodes per line instead of 4; or
- reduce the coupling with the cavity (new position of the coupling rods).
One must nevertheless check that the flexible cable between the cavity and the PIN diodes will stand an increased power (in the 6-diode case).

b) Impedance and required RF power

The impedance of the cavity, defined so as to relate the voltage on the gap to the losses in the cavity, is determined by the R/Q factor and the measured bandwidth. The R/Q factor, which depends only upon the geometry of the resonator, has been measured by perturbation techniques. The best value (including the transit time factor) is:

$$R/Q = 39 \Omega.$$  

The Q of the cavity (unloaded Q) can be adjusted by an auxiliary loop in the cavity coupled to a 50 Ω load (50 kW). By rotating the loop one alters the coupling with the load and hence changes the Q of the cavity. At present, the unloaded Q is about 1500 which gives an impedance of ~60 kΩ.

From this value, it follows that the RF power necessary to provide 50 kV is about 20 kW. For this setting of the loop, half the power goes into the 50 kW load, and most of the rest into the cables for the PIN diode system. The power amplifier attached to each cavity is capable of delivering 25 kW and can therefore provide 50 kV per cavity even taking into account the feeder line losses and some imperfect matching. If one wishes to run at 75 kV per gap with the same power, the impedance of the cavity must be approximately doubled.

c) Beam loading problems

When the beam is bunched at 200 MHz it will give a reactive load to the cavity (no acceleration). For low frequency cavities this is compensated (at least at the RF frequency) by the tuning loop and the amplifier still sees a resistive load. In the fixed tune 200 MHz cavities, the amplifier itself must accept the reactive part of the load. It is thus essential to minimize the beam-induced voltage.

The impedance seen by the beam is not simply the impedance defined above (60 kΩ). The output impedance of the power amplifier, transformed by the input coupling loop, comes in parallel with the cavity impedance.
6.

Seen from the load, the power amplifier is far from being matched\(^3\) (the measured reflexion coefficient is \(> 0.9\)). Depending upon the length of line, it can be either a very high or a very low impedance (1100 \(\Omega\) down to 2 \(\Omega\)). Therefore, by properly choosing the length of line between the amplifier and the cavity, one can minimize the beam-induced voltage (at a fixed frequency).

A preliminary experiment\(^2\) has shown that one can at least gain a factor 5 on the impedance seen by the beam by properly adjusting a trombone inserted between the power amplifier and the cavity.

3. A proposal for a bunch-into-bucket transfer from the PS to the SPS

a) Required 200 MHz RF voltage in the PS

We know that we must provide at least a bucket area of 120 mrad to recapture a beam of \(\approx 1.1 \cdot 10^{13}\) p.p.p with more than 95\% efficiency. Nevertheless, some safety margin is necessary for several reasons:

- provision for higher intensities in the PS (1.34 \(\times\) \(10^{13}\) already reached)
- possibility of measuring the beam emittance (bunches less than \(360^\circ\) long) and the capture efficiency in the PS. Although this argument seems a bit artificial, we think that it is essential to decouple the two machines as much as possible, and to specify unambiguously the properties of the ejected beam (emittance and capture efficiency).
- provision for tolerances during the transfer. This point is examined in more detail in 3(d).

We propose an operational bucket area of 150 mrad which corresponds to 400 kV at 200 MHz. The corresponding RF voltage in the SPS for a matched transfer is 1720 kV. The ejected bunches of 120 mrad would then be 4 ns long leaving a base line of 1 ns between them.

The number of cavities required to provide 400 kV depends on the design of the PIN diodes system. With the present design (50 kV/cavity) 8 cavities are necessary, whereas an improved PIN diode design could bring this number down to 6. In any case, some extra straight section space should be made available to house the new cavities, preferably near the North Hall wall.
b) Required power

The RF power required is determined by the amount of beam loading tolerable. We propose to equip each cavity with a trombone which can at least reduce the impedance of the cavity down to about 12 kΩ (60 kΩ/5). This figure will be doubled if we run the cavity at 75 kV for the same power. The beam-induced voltage at $10^{13}$ p.p.p (< 1 A peak at 200 MHz) would be less than 24 kV giving an equivalent detuning angle of 17°. We have checked that the power amplifier could still work under these conditions although with a reduced maximum output.

It would be preferable to stay at the present situation (60 kΩ, 50 kV per cavity) which gives a smaller detuning (13°).

In any case, we think that one 25 kW power amplifier per cavity is perfectly adequate with the help of the variable length technique (at fixed frequency).

c) Low-level and instrumentation

A basic requirement for the 200 MHz low-level system is to provide a facility to put the cavities properly in phase. This is best achieved by comparing the beam and cavity phases, or, in other words, by using a rudimentary beam control system. In order to measure the capture efficiency one should move the beam radially, in a controlled way. Some form of radial control, including a 200 MHz radial pick-up, must therefore be constructed. This means that a complete beam control system working at 200 MHz is necessary, including monitoring and control of the power and tuning of the cavities. This part of the project should not be underestimated, although one can make an extensive use of already-developed modules, because the system has to perform several tasks in the same machine cycle with all the pulse-to-pulse modulation problems.

A good on-line measurement of emittance and capture efficiency requires at least a very high frequency pick-up electrode. It would be desirable to install in the PS a pick-up similar to the one in use in the SPS (AEW, resistive wall type, BW = 3 to 4 GHz), and presumably some high-frequency electronics attached to it.
A remark about the measurement of capture efficiency by moving the beam radially at constant magnetic field: some frequency variation must be allowed (50 kHz corresponds to 37 mm radial displacement at 10 GeV/c) and therefore one should not reduce the bandwidth of the cavity too much (50 kV per cavity is better from this point of view).

d) **Synchronization at transfer**

Bunch into bucket transfer means both phase and momentum matching between the two machines. Phase matching requires some form of RF link between the PS and the SPS. A coaxial cable has already been pulled from BA3 to the PS for this purpose. From previous experiments it is expected that the short-term stability can be as good as a few degrees of 200 MHz RF phase. Long-term drifts can be automatically corrected by special circuits using the beam as a reference. If difficulties arise, an optical fibre link would provide the required phase stability.

As the PS and SPS RF frequencies are equal (via the phase link) and locked to a reference oscillator, the momentum matching depends only on the jitter of the PS and SPS magnetic fields. The best estimates at present, which are consistent with the observations, are $\pm 10^{-4}$ for both machines (after the shut-down).

This corresponds to an equivalent momentum jitter in the SPS of $\pm 1.74 \times 10^{-4}$. When compared to the bunch height: $\pm 1.68 \times 10^{-3}$ (120 mrad bunch in 150 mrad bucket) this is a rather small value. Nevertheless, the matched bucket (150 mrad in the SPS) is not much higher: $\pm 1.76 \times 10^{-3}$, and some particles may fall outside the bucket depending on the magnetic field jitter.

One can overcome this difficulty by injecting into a larger bucket (we have enough RF voltage in the SPS) at the expense of some blow-up. Nevertheless, one must realize that an emittance modulation of the various batches will result, which may be annoying (during slow extraction for instance).

This problem can be solved in a cleaner and more elegant way if, RF-wise, we can treat the various batches independently. They can be brought to their desired energy and phase in an adiabatic way (during the process the phase excursion is only about $2\pi$ RF radians). This of course
implies some sophisticated electronics and the possibility to fully modulate the RF power amplifiers at the revolution frequency. Note also that, due to the filling time of the RF cavities in the SPS, such a technique is not compatible with the five-batch transfer, but will be better used with the 3 x 3 turn transfer scheme.

There is another possibility which requires less phase modulation on the RF system, but may nevertheless give some blow-up. The phase and energy oscillations of each batch (injected into a large bucket) which are due to momentum errors can be decomposed into the normal modes of oscillation of the beam \( m = 1, 2, 3 \); dipole, quadrupole), and can be damped by a specialized feedback system (rather complicated).

e) PS repetition time

The debunching-rebunching process takes some 10 GeV flat-top time. It will thus lengthen the 0.65 s minimum repetition time of the PS which has a flat-top of zero duration. From the experimental results, it seems adequate to consider 50 ms to make the adiabatic reductions of the 9.5 MHz RF voltage, then 15 to 20 ms for proper debunching and a few ms for recapture at 200 MHz. If one wishes to separate the trapped and the untrapped part of the beam, the 200 MHz RF bucket must no longer be stationary. For a moving bucket area of 132 mrad at 400 kV \( (\phi_s = 3^\circ) \) the splitting rate between the two parts of the beam is as high as 2.7 mm/ms (this is the same whether the radius or the frequency of the trapped beam is kept constant).

Hence, it would only take some extra ~ 20 ms to completely separate the uncaptured particles from the rest of the beam. It is therefore very attractive, as an operational procedure, to consider the removal of non-trapped particles from the extracted beam. This can be done by ejecting on a ramp of the magnetic field (preferably downwards) at constant RF frequency in such a way as to bring the beam into the centre of the vacuum chamber at the moment of ejection. The untrapped particles could be eliminated by a specialized dump target in the PS, or by some form of ejection. The additional jitter in B field at ejection due to the SPS revolution clock frequency (0.07 G) is negligible.
In any case, the minimum cycle time of the PS would be around 0.75 s, which is somewhat unfortunate because it falls into the dangerous region for the PSB power supplies.

4. **Summary of parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of operating RF cavities</td>
<td>8</td>
</tr>
<tr>
<td>RF voltage per cavity</td>
<td>50 kV</td>
</tr>
<tr>
<td>RF power per cavity</td>
<td>20 kW</td>
</tr>
<tr>
<td>RF cavity impedance</td>
<td>60 kΩ</td>
</tr>
<tr>
<td>Impedance seen by the beam, per cavity</td>
<td>&lt; 12 kΩ</td>
</tr>
<tr>
<td>Unloaded Q of cavity</td>
<td>1500</td>
</tr>
<tr>
<td>Maximum bucket area ($\phi_S = 0$)</td>
<td>150 mrad</td>
</tr>
<tr>
<td>Bucket area at ejection ($\phi_S = 3^\circ, V_{RF} = 400$ kV)</td>
<td>132 mrad</td>
</tr>
<tr>
<td>Bunch area after recapture 1)</td>
<td>120 mrad</td>
</tr>
<tr>
<td>Bunch length at ejection</td>
<td>4 ns</td>
</tr>
<tr>
<td>Bunch height at ejection</td>
<td>$\pm 1.68 \cdot 10^{-3}$ $\Delta p/p$</td>
</tr>
<tr>
<td>dB/dt at ejection</td>
<td>0.324 T/s</td>
</tr>
<tr>
<td>Rate of radial displacement of the untrapped particles</td>
<td>1.81 mm/ms</td>
</tr>
<tr>
<td>Duration of the debunching-rebunching-transfer process</td>
<td>100 ms (maximum)</td>
</tr>
<tr>
<td>Estimate of spread in emittance from batch to batch in the SPS 2)</td>
<td>120-160 mrad</td>
</tr>
</tbody>
</table>

1) For $I_p = 10^{13}$ and > 95% capture efficiency.

2) Due to B field jitter, without sophisticated electronics.

This note is the result of many MD sessions on the PS, followed by discussions amongst the participants. I wish to associate them with the presentation of our team work, and I think that the above proposal also reflects their opinion.
REFERENCES

1) ISR performance report, Controlled blow-up of the bunch area in the PS and ISR stacking efficiency, 13th May 1977.

2) Compte rendu No. 58 des séances d'études sur le PS et le Booster, to be published.

3) D. Boussard, MD Note MPS/SR/MD 72-9.

4) Compte rendu No. 52 des séances d'études sur le PS et le Booster, PS/OP/BR Note 77-4.

5) R. Cappi, University of Modena, Thesis (1976-77).

6) Compte rendu No. 56 des séances d'études sur le PS et le Booster, PS/OP/BR Note 77-8.

7) Compte rendu No. 57 des séances d'études sur le PS et le Booster, PS/OP/BR Note 77-9.

8) D. Boussard, Les manipulations RF avant le transfert continu vers le SPS, SPS/RF/DB/bs/76-30.

9) W. Pirkl, Matched feeder vs tuned system, PS/LIN/Note 76-4.
SUMMARY OF A MEETING ON THE PS 200 MHz SYSTEM AND DECISIONS TAKEN

(9th February 1978)

Present:

SPS
Y. Baconnier
H. Beger
D. Boussard
M.C. Crowley-Milling
B. de Raad

PS
D. Bloess
E. Brouzet
J. Gareyte
M. Georgijevic
P. Germain

J. Jamsek
P. Lefèvre
G.L. Munday
G. Nassibian
G. Plass

The meeting was called jointly by the two Division Leaders in order to go ahead with this problem. A similar meeting had been organized already in September 1977. Its outcome was to encourage the continuation of experiments in the PS.

A review of the present situation was given by D. Boussard. The only possible solution for satisfactory multibatch transfer, as foreseen by the SPS intensity improvement programme, is a change of harmonic number in the PS to allow bunch-to-bucket transfer from the PS to the SPS.

Originally it was thought that debunching followed by recapture at 200 MHz would be best done at an energy of 1 GeV in the CPS. This would have necessitated a 200 MHz accelerating system with mechanically-tuned cavities (10% frequency swing) to accelerate from 1 GeV to 10 GeV. Experiments carried out in the autumn of 1977 have shown, however, that after a controlled blow-up of the emittance at 10 GeV, it is possible, at 10 GeV, to achieve debunching and recapture with an efficiency of about 90% which is as good as has been achieved at 1 GeV.

Consequently the mechanically-tuned cavities have been abandoned and it is now proposed to change the harmonic number in the CPS at 10 GeV with eight fixed-tuned cavities of the present 50 kV execution. These will be located in SS6 (six cavities) and in SS8 (two cavities). The power amplifiers will be in the North Hall. There was general agreement about this proposal which was accepted by both Division Leaders.
At the start-up in February 1978 there will be three cavities installed in the CPS, with three amplifiers on the platform in the North Hall. These will be used in SPS machine development studies for double batch injection by means of bunch-to-bucket transfer. The fourth cavity and 4th amplifier will be installed in the one-week shutdown in July 1978. These four cavities will be used to increase the SPS intensity from July 1978 onwards by using double batch transfer operationally.

The remaining four cavities and four amplifiers will be completed in the second half of 1978 and will be installed in the shutdown of early 1979, so that the complete system will be operational at the start-up in February 1979.

Whereas the present three amplifiers are installed on a platform in the North Hall, the final eight amplifiers will be installed on the floor of the North Hall. CPS will study (J. Jamsek) how the installation and move of the amplifiers can be organized without interrupting the operational use of the 200 MHz system.

The cavities, amplifiers and other components will be constructed and paid for by SPS, while the installation will be handled by FS. After further study of the installation problems, it will be settled between the two divisions as to which contribution will be paid from the SPS budget for the installation of the system.

The time needed for RF gymnastics on the 10 GeV flat-top would bring the minimum repetition time of the PS to about 750 msec, which is in the forbidden zone of repetition times for the PSB power supply. As no tricks to reduce this seem obvious at present, it may be necessary to increase the repetition time to about 830 msec to be on the other side of the forbidden zone. This would also allow us to increase an SPS injection energy to about 12 GeV (P. Lefèvre). However, these matters do not need to be settled now and one should in any case go ahead with the programme aiming at 650 msec repetition time for the PS complex.

G.L. Munday asked the PS experts (P. Lefèvre, E. Brouzet, A. Krusche) to study the problem of getting rid of the uncaptured protons before extraction towards the SPS.