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EVOLUTION OF THE RF SYSTEM OF THE CPS BOOSTER SINCE THE BEGINNING OF ITS OPERATION

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Summary

Since the first beams were accelerated in 1972, the RF system has performed very satisfactorily. In particular, the simple air-cooled design of the cavity and final amplifier[1] has proved to be very trouble free in operation.

As the beam intensities gradually reached and then exceeded the design value of 2.5×10^{12} protons per ring, a number of improvements were introduced to cope with the increased beam loading and to permit the special beam gymnastics that have been found useful at the highest intensities.

Modifications include: i) provision for reducing the Q of the cavity during trapping; ii) an improved system for synchronizing the four rings prior to ejection; iii) measures taken to control longitudinal instabilities; iv) safety precautions to protect the cavity and amplifier against transients.

Control of cavity Q

The PSB is unusual in that the RF cavity voltage is determined by the energy spread of the injected beam rather than by the requirements of the acceleration itself. Thus a voltage of 12 kV is needed although the energy gain per turn is only ∿ 1 keV, leading to a stable phase ϕ_s of ∿ 5°.

If we represent the combination of amplifier and cavity[2,3] as in Fig. 1a, where tube anode resistance and capacitance have been absorbed into the cavity conductance G and susceptance B, then for a beam of 2.5×10^{12} protons per ring the fundamental components of the currents are roughly as shown in Fig. 1b. During

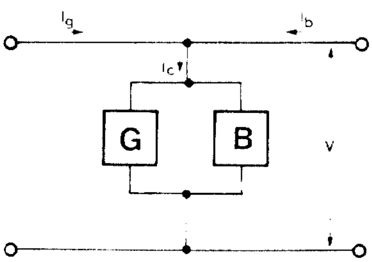

Fig. 1 a)

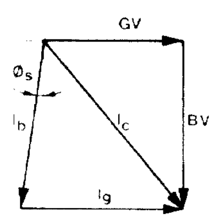

Fig. 1 b)

acceleration, I_b changes by a little more than the ratio of frequencies (3 to 8 MHz), while I_g increases by a factor of ∿ 2 due to the change of losses in the ferrites, so that the proportions of the vector diagram do not alter very much during the cycle. It is obvious from inspection that any variation of beam intensity is mainly "seen" and compensated by the cavity-tuning loop (controlling B). On the other hand, changes of I_g, which is controlled by the AGC, have a strong effect on the phase of the cavity relative to the beam. This cross-coupling of the loops[4], while appreciable, is still acceptable at full cavity voltage. However, for effective adiabatic trapping we need to start with a cavity voltage of the order of 1 kV. At the start, with the beam unbunched, there is no problem; but the fundamental component develops rapidly and soon we have something like Fig. 2 where we show the phase of $I_g \neq 0$, suggesting that the tuning loop may not quite follow the rapid rise of I_b.

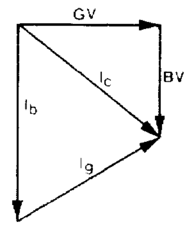

Fig. 2

With proportions such as these, the AGC can no longer control the cavity voltage, and in fact it fluctuates during the early part of the rise (Fig. 3a). In order to restore control we increase G by pulsing the standing current through the tube for the duration of the voltage rise (∿ 500 μsec). Measurements indicate that we can change the Q of the cavity from ∿ 80 to ∿ 45 by this procedure. The result is a clean voltage rise (Fig. 3b) for up to 3×10^{12} pp ring. While this technique is very simple to implement, it has its limits owing to the "constant current" character of the tetrode. If it is necessary to go further, we shall use the second (spare) tube as a load.

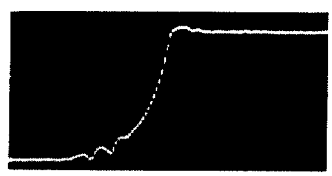

Fig. 3 a)

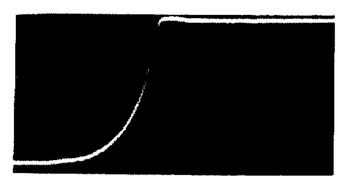

Fig. 3 b)

Synchronization

The four PSB rings have fully independent acceleration and beam control systems. Once full energy has been reached, the bunches of the different rings must be brought to the correct phase relationship so as to be evenly distributed, after recombination and transfer, around the PS ring. This is obtained by phase-locking the bunches to a common reference oscillator, prior to ejection. The process must be smooth to avoid uncontrolled dilution, but it must not be too slow (available time ≈ 25 msec).

The original design of the sync system[5,6] included a three-step approach; frequency sync, coarse phase sync, fine phase sync. At each step in the process it is difficult to avoid a transient in the phase between bunches and cavity (ϕ_b-ϕ_c) which can cause longitudinal dilution. The frequency sync scheme has been replaced by that of Fig. 4; a single analogue meter measures the frequency Δf which is present at the output of the phase discriminator used for fine phase sync. The residual frequency error can be brought down to a few Hz (limited essentially by the offset of the frequency meter, designed for a range of a few kHz). The pull-in range required for the phase sync is then very small and can be covered in one step.

In practice, an intentional offset of about 300 Hz has been introduced because from the moment the order to close the phase sync loop is given, the actual closing is delayed until $\phi_b - \phi_r = 0$ (to avoid the switching transient). The maximum delay thus introduced is $1/(f_b - f_r)$. It was decided to limit the maximum waiting time to about 3 msec, which requires an offset of about 380 Hz (Δf_0 in Fig. 4). Switch S1

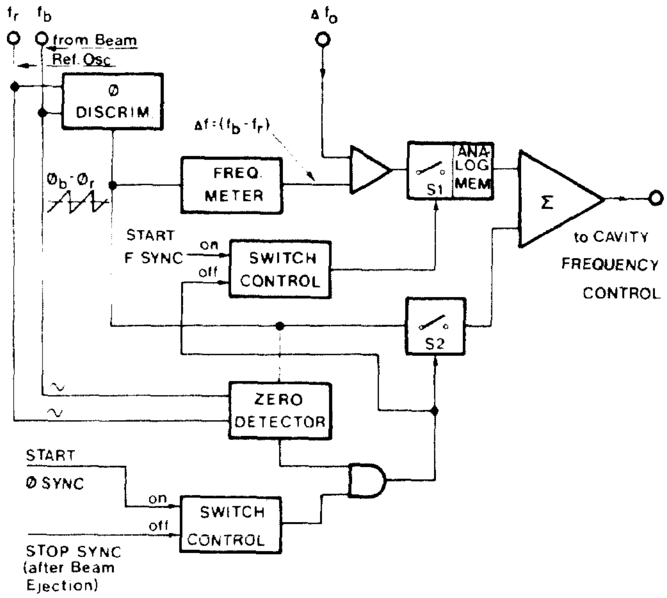

Fig. 4

is closed by a pulse "START F SYNC". It is opened at the same time that S2 is closed (first zero crossing of $\phi_b - \phi_r$ after the "START ϕ SYNC" pulse). The last value of the frequency correction is memorized in an analogue memory. The output of the ϕ discriminator crosses zero for $\phi_b - \phi_r = 0$ and $\phi_b - \phi_r = \pm 180°$. A coincidence circuit acting on f_b and f_r gates out the "fake" zeros from the zero crossing detector. The total pull-in range of the sync system has been limited to ±10 kHz as a trade-off between maximum allowable df/dt and time required for sync. The range of radial correction possible (±6 mm) is amply sufficient in practice.

A limiter has been introduced on the correcting signal to limit $(df/dt)_{max}$ without reducing the loop gain too much. The sync time therefore consists of a constant speed approach plus an exponential one to Δf_0. Figure 5 illustrates the operation: scope triggered at "START F SYNC". Initial $\Delta f \approx +3.2$ kHz (Fig. 5a) and -3.2 kHz (Fig. 5b). The transients on $\phi_b - \phi_c$ are those causing dilution. Although still measurable at the beginning of ϕ SYNC, they are very small both in amplitude and duration.

The acceleration cycle ends (beam not ejected in these particular pictures) at $t \approx 32$ msec. The traces beyond are meaningless for the present discussion.

The new sync system uses substantially fewer electronic modules than the former one, giving an appreciable improvement in operational ease and reliability. Since its initial adjustment, it has required no repair and virtually no readjustment on any of the four rings.

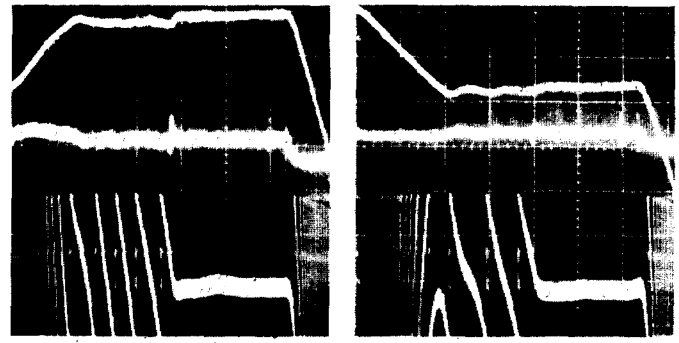

Fig. 5 a) Fig. 5 b)

Upper = Beam radial position ΔR; 1 mm/div
Middle = $\phi_b - \phi_c$; 10°/div.
Lower = $\phi_b - \phi_r$; 100°/div.
Time = 5 msec/div.

Longitudinal damping

Under certain conditions, various types of longitudinal instabilities develop in the PSB. While theoretical and experimental work [7,8] is under way to describe, understand, and find means to prevent them, it has been found experimentally that a certain amount of "bucket shaking", i.e. phase modulation of the accelerating voltage, can stop the growth of the instabilities and control, within limits, the longitudinal emittance of the beam. The main effect of this modulation is probably a redistribution of protons within the bunches, although the stabilization mechanism is not yet fully explained.

The facility for applying the phase modulation has been provided and has been instrumental in reaching and surpassing the design intensity of 10^{13} ppp in the machine.

Modulation at about the synchrotron frequency is most effective on stability, while modulation at about twice the synchrotron frequency increases the bunch length. The optima for frequency and amplitude depend on beam intensity and linac energy spread. The amplitude is of the order of a few degrees (stable phase angle during acceleration ≈ 5°).

During the first part of acceleration (≈ 200 msec) a signal is applied to stabilize the beam and is adjusted for the operating conditions of the machine. The optimum frequency ranges normally from 4 to 4.5 kHz. During the end of acceleration (≈ 300 msec) the same frequency is applied and its amplitude adjusted for the required bunch length. As the synchrotron frequency falls to about 2 kHz at the end of the cycle, the same frequency is adequate enough to act as double synchrotron frequency. Separate controls on the four rings allow bunch length equalization between rings and adaptation to the PS demands.

Above $\approx 2.2 \times 10^{12}$ ppp/ring, the adjustment for stability becomes somewhat critical, and can be eased by bunch lengthening already early in the cycle. This is obtained by permanent application of a 7 kHz, small amplitude (≈ 1°) modulation, which is effective when the synchrotron frequency approaches 3.5 kHz, early in the cycle, and has no appreciable effect elsewhere. The final bunch length adjustment is obtained with the second application of the 4 kHz signal. Figure 6 shows a simplified block diagram of the module used (one module per ring). The timing circuitry, not shown in the figure, switches S1 into position A for ≈ 200 msec, B for ≈ 60 msec, C for ≈ 300 msec, then B until the beginning of the next acceleration cycle (total acceleration time ≈ 580 msec).

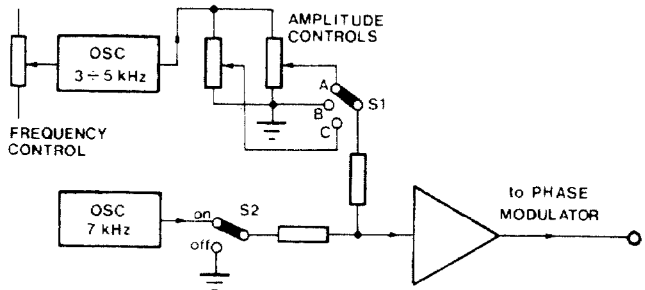

Fig. 6

Switch S2 (manual) is OFF only when low intensities are used. The 7 kHz signal, useful at high intensities, is harmless at medium intensities, and somewhat detrimental below $\approx 2 \times 10^{11}$ ppp/ring.

The beam intensity can at present be modulated on a pulse to pulse basis between two preset values. Each module has therefore two sets of frequency and amplitude control (not shown in Fig. 6) preset for the two

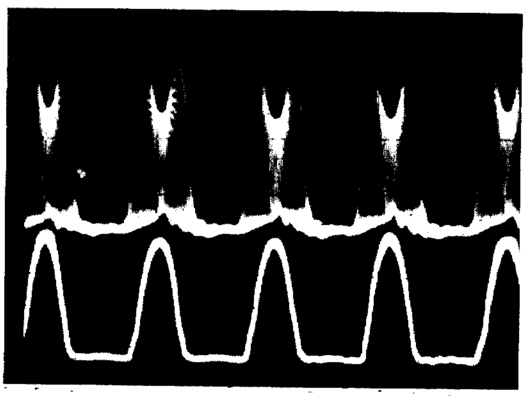

Fig. 7

intensities and switched in as required. In future, when more sophisticated schemes of intensity modulation will be introduced, computer-controlled modules will have to replace the present ones.

Figure 7 shows the effect of the phase modulation on the stability. Beam intensity 2×10^{12} ppp/ring. Upper trace: no stabilization applied. Lower trace: stabilizing signal applied and optimized.

Safety

A particular problem appears at the time of ejection. Although the beam disappears, it is still "seen" by the phase control loop because of the high Q of the tunable filter that extracts the fundamental frequency from the bunch signal. The phase error between the decaying tunable filter output and the cavity gap is amplified by the full open-loop gain and applied to the cavity, causing a large frequency transient which cannot in general be followed by the cavity tuning circuit. When the phase error seen by the loop reaches a preset threshold ($\approx 100°$), a veto circuit opens all loops at the proper point (the control inputs to the oscillator driving the cavity) but by this time the transient has had time to develop.

A remedy has been found by opening the phase control loop about 1 µsec before ejection. At this time the beams are synchronized, and their inertia prevents any significant phase drift during 1 µsec.

Another problem appears in case of failure of a high intensity beam to be ejected when it should. All control loops, save cavity tuning and AGC, were open in this case 2 msec after ejection time by a reset pulse. (If the beam is ejected, the veto circuit opens them 2-3 µsec after ejection.) With the loops open and the beams circulating, it will drift radially under the action of the decreasing magnetic field and/or the decaying loop correction signals, which return to zero with the loop filters' time constants. If during the drift the phase between beam and cavity varies too rapidly for the AGC and tuning loop to follow, the normal vector diagram of Fig. 8a may vary and go through the configuration shown in Fig. 8b. For high beam

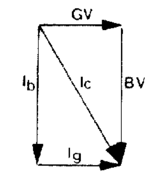

Fig. 8 a)

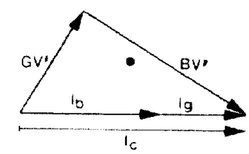

Fig. 8 b)

currents, V' can be as much as $V\sqrt{2}$, which might lead to voltage breakdown in the cavity. If the phase control loop is kept closed, fast phase variations are prevented, and slow variations limited by phase stability. The tuning loop and AGC will track, until the beam is scraped by scrapers in the vacuum chamber and the current drops below the threshold of the tunable filter. The veto circuit will then open the loops and the remaining beam will be lost in an uncontrolled way.

A command is sent to close the phase loop again, 5 µsec after the ejection time. The veto circuit will prevent its execution if the beam has been ejected: if not, the loop will close and most of the beam will be lost in a "controlled" way.

The chamber is protected by beam scrapers, and this occurrence being rare, induced radioactivity is not a problem.

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