REMARKS ON THE PHASE LOCK SYSTEM OF THE CERN PROTON SYNCHROTRON

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1. INTRODUCTION

A programmed frequency system like the one used in the CERN Proton Synchrotron (CPS) during the early part of the acceleration cycle will always show frequency errors. The accuracy of the CPS programme system is of the order of 10^{-3}. The admissible frequency tolerances, on the other hand, are very tight, making it impossible to carry through the whole acceleration process with the frequency programme.

If there were only adiabatic frequency variations, i.e. errors that develop slowly compared to the synchrotron oscillation period, one could use the signal from a radial position pick-up electrode to correct the accelerating frequency. However, non-adiabatic frequency errors such as caused by hum, noise and transients in the programme, and in the automatic tuning system of the cavities cannot be corrected in this way. The more radical kind of phase locked beam control[1, 2] seems therefore essential, where the accelerating wave is derived from the bunched beam itself.

The simplest system of this kind is shown in Fig. 1. A phase pick-up electrode provides an RF signal of the same frequency and phase as the rotating bunches. This signal is amplified and used to drive the accelerating stations. However, the unavoidable transit time from the pick-up electrode to the gap

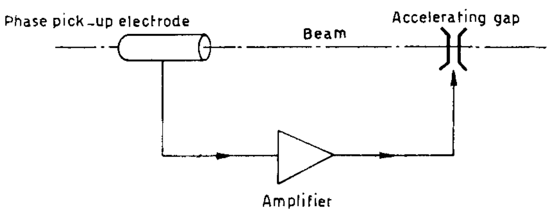

Fig. 1 Direct beam feedback.

(via amplifiers and cables) causes an intolerable variation of phase shift with frequency. In the case of the CPS this phase shift amounts to more than 20π during acceleration. To overcome this difficulty we keep the phase between pick-up electrode and gap constant by means of a servo system.

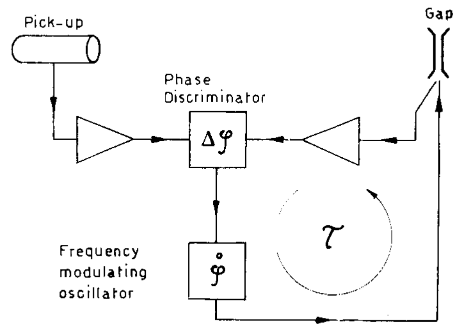

Fig. 2 Automatic phase control system.

This system is shown in its basic form in Fig. 2. A phase discriminator measures the phase error between pick-up electrode and gap. (The two channels to the inputs of the disciminator must have equal phase shift over the frequency range.) The error signal acts on the frequency $\dot{\phi}$ of an FM oscillator which feeds the cavities. An automatic phase correction (APC) servo loop is thus formed, locking the accelerating wave to the rotation of the bunches.

Under ideal conditions such a system ensures that the centre of azimuthal charge distribution of the bunch passes the gap at a fixed phase ϕ_s with respect to the accelerating voltage.

In general there remains still an error in energy gain per turn, causing the bunch to move radially. This is corrected by a second servo loop, in which the voltage from a radial pick-up electrode acts either on the accelerating voltage V_m or on the stable phase ϕ_s in order to correct the energy gain per turn ($eV_m \cos \phi_s$) and to keep the bunch inside the vacuum chamber. This sytem is called the radial control system.

2. DYNAMIC PROPERTIES OF THE AUTOMATIC PHASE CORRECTION LOOP

The most important problems for the design of the APC system are connected with its dynamic properties. The requirements are :

a) To avoid coherent bunch oscillations there must be considerable loop gain in the system, at the synchrotron frequencies.

b) The system must operate over the entire frequency range covered during the accelerating process.

c) It must be able to carry out the phase jump at transition, sufficiently fast and without dropping out of synchronism.

d) It must, of course, be stable.

Let $\mu(p)$ be the loop gain for a steady state phase modulation with angular frequency ω and $p = j\omega$. The parameters determining the loop gain then are :

α) An ideal integration, introduced by the fact that the error signal produced by the phase discriminator acts on the time derivative of phase rather than on phase itself.

β) A time delay τ for transmission around the loop, caused by cables, RF amplifiers and the necessary ripple filters between phase discriminator and FM oscillator.

γ) The influence of the accelerating cavities. The behaviour of the accelerating cavities with their automatic tuning system is very complicated, but in a rough approximation it is possible to neglect the influence of the automatic tuning and to treat the cavities as fixed resonant circuits. Assuming a small modulation index, so that only first order side bands have to be taken into account, the effect of a fixed resonant circuit (tuned to the carrier frequency) on phase modulation can be described with a single time constant

$$T = \frac{1}{\pi b} \qquad (b = \text{bandwidth of the circuit}).$$

The system has been designed under this latter assumption and it was found experimentally that it also works satisfactorily with the actual cavity.

Altogether one obtains

$$\mu(p) = \frac{k}{p} e^{-p\tau} \frac{1}{1+pT}.$$

The first factor k/p expresses the integration and $k = \left[\frac{\dot{\phi}}{\Delta\phi}\right]_{\text{static}}$ gives the overall static sensitivity of the phase discriminator-FM oscillator combination. The second factor expresses the time delay; for the CPS one has $\tau \approx 2.7\,\mu$s, of which $1.7\,\mu$s is caused by the RF amplifiers and cables, corresponding to 500 m electrical length around the loop. The last factor expresses the influence of the cavities. It is given by $T = 1.6\mu$s, $b = 200$kHz.

To improve the servo properties of the system a correcting network has been included between the phase discriminator and the FM oscillator. This network has two functions :

a) It corrects for the influence of the cavity by providing a term $1+pT$, so that the loop gain becomes

$$\mu(p) = \frac{k}{p} e^{-p\tau}.$$

The stability condition

$$|\mu(p)| < 1 \qquad \text{for } p\tau \leq \frac{\pi}{2}$$

leads to a modulation frequency f_1 of unity loop gain,

$$f_1 = \frac{\omega_1}{2\pi} \leq 90\text{kHz}.$$

The adopted value is

$$f_1 = 30\text{kHz},$$

including a safety margin of 6 db and a small additional allowance for the automatic tuning system of the cavities.

b) The correcting network also provides an increase of loop gain faster than 6 db/oct. below f_1. In this way it was possible to achieve

$$k = 100\omega_1 \quad \text{or} \quad k' = k/360 = 50\frac{\text{kHz}}{\text{degree}}.$$

The system has been tested and found to be stable with the above parameters. One finds

$$|\mu(p)| \approx 7 \quad \text{at} \quad 7.8\text{kHz}$$

(synchrotron frequency at injection), and

$$|\mu(p)| \approx 1000 \quad \text{at} \quad 300\text{Hz}$$

(typical synchrotron frequency after transition).

3. PREPROGRAMMING

With $k' = k/360 = 50$ kHz/degree, a carrier frequency variation of 5 MHz would cause a change of 100° in stable phase. Hence, preprogramming of the carrier frequency proves necessary. Such a preprogramme is in fact available from the frequency programme generator. Its accuracy is of the order of ± 10 kc/s at top frequency, causing a $\pm 1/5°$ variation of the stable phase, which is perfectly acceptable. The adding of programme frequencies and APC error frequency is done by mixing. In order to isolate the sum frequency from difference and carrier frequencies, a double mixing scheme is used. The programme frequency f_p is added to an auxiliary frequency f_0 (30 MHz) in a first mixer. f_p+f_0 is filtered out by a band pass filter and then again mixed

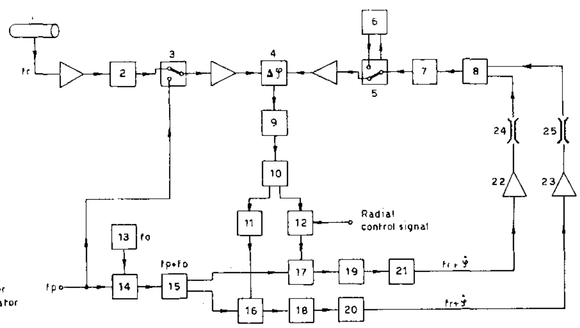

Fig. 3 Automatic phase control system, detailed block diagram.
1. phase pick-up electrode.
2, 7. AVC ampl.+integrator
3. progr.—beam control switch
4. phase discriminator
5. transition switch
6. transition phase setting
8. Summing network
9. filter+correcting network
10. FM oscillator
11. fixed phase shifter
12. electr. phase shifter
13. Quartz oscillator 30 MHz
14, 16, 17. mixers
15. bandpass filter 32-40 MHz
18, 19. low pass filters
20, 21. distribution amplifiers to 8 accel. stat. each
22, 23. power amplifiers (8 each)
24, 25. acc. gaps.

with the frequency from the FM oscillator in a second mixer. $f_r+\dot{\phi}$ is obtained from the second mixer ($f_r = 20$ times revolution frequency of beam), filtered out by a low pass filter and fed into the cavities (see Fig. 3).

Special care has been taken to avoid " cross beats ". These are beat notes between various harmonics of all the associated sum, difference and carrier frequencies, which occur easily in such non-linear systems and might eventually phase modulate the accelerating wave in a dangerous way.

There is another way of providing a frequency preprogramme. The pick-up electrode gives in fact f_r, the true revolution frequency, which is certainly the best programmed frequency one can imagine. Connecting it to the input of the first mixer permits to dispense entirely with the programme generator once acceleration has started and clean bunches have been formed. The signal from the pick-up electrode is, however, very distorted, possibly noisy and of variable amplitude. It has hence to be " cleaned " by an AVC system and a self-tracking filter before it can be fed through the mixer chain into the cavities. A very simple self-tracking amplifier has in fact been prepared for such an experiment, but at least in the beginning we shall normally use f_p, since it is available anyhow.

4. SWITCHING

An electronic switch is necessary to switch between programme acceleration, which is necessary for trapping and bunching, and beam controlled acceleration. Its position is shown in Fig. 3. During programmed acceleration the APC loop remains closed and serves only to lock the accelerating gap voltage to the programme. The switch can be switched over to beam control at any desired moment during acceleration.

A similar switch is used in the other branch leading to the phase discriminator. It allows to switch in a phase delay of $2\phi_s$ (120°) at transition. As the frequency is already very nearly constant at transition, a very simple phase shifter can be used. It could be simply a piece of cable, but a variable RC phase shifter has been prepared for the initial experiments. The transition switch is triggered from the transition timer and works nearly instantaneously ($\sim 1\ \mu s$), giving the required step function in phase to the APC loop. The latter answers with a smooth transient of 30° overshoot and about 50 μs total time.

5. SETTING OF STABLE PHASE AND PHASE DRIFTS

The phase discriminator operates around 90° phase difference between its two inputs. The desired value of $\phi_s = -60°$ (before transition) is obtained by proper choice of the mutual positions of pick-up electrode and accelerating cavities along the orbit. In addition, a variation of at least $\pm 20°$ can be made by adjusting the phase discriminator.

One reason for possible drifts in stable setting are unequal frequency dependent phase shifts in the two channels leading to the phase discriminator. Another reason could be amplitude variations, especially of the beam pick-up signal. A third reason are frequency drifts in the different oscillators. Finally, ϕ_s refers to the phase stable point within the bunch, but the pick-up electrode can only see the centre of azimuthal charge distribution of the bunch. These positions do not coincide if the bunch is not symmetric, i.e. for large phase oscillation amplitudes.

Various measures have been taken to counteract phase drifts. Firstly, all individual units in the two chains have been adjusted to equating in phase within $\pm 1°$. Secondly, the phase discriminator works with a 6BN6 gated beam coincidence tube giving good amplitude rejection; in addition there are AVC amplifiers in each channel keeping the output variations to 2 : 1 for input variations of 100 : 1. Thirdly, the stability of the FM oscillator when running freely with a fixed bias voltage is a few times 10^{-4}, causing only a few tenths of a degree phase variation. The FM oscillator uses as variable capacity an inversely biased silicon diode. This method is very convenient since the high sensitivity (0.7 MHz/volt) permits a direct connection between the anode circuit of the 6BN6 and the capacitive diode via the correcting filter network. Finally, since the 6BN6 coincidence tube measures zero crossings of the incoming waves, whereas the centre of azimuthal charge disribution of the bunch coincides with the peak of induced voltage, an integrator, consisting of a pentode working into a capacitive load, is used on both sides of the phase discriminator to convert peaks into zero crossings.

6. THE RADIAL CONTROL SYSTEM

Two radial pick-up stations separated by approximately ½ betatron wavelength are provided for the automatic correction of radial beam position. Each pick-up electrode is connected to a differential amplifier (Fig. 4) whose output is proportional to beam deviation times beam intensity. A phase sensitive (synchronous) detector is necessary to restore the sign of the deviation in the output voltage. To do this, a voltage proportional to the sum of the voltages induced in both halves of the pick-up electrode is taken out of the differential amplifier at its input, amplified separately and used as a reference voltage for a synchronous detector. The synchronous detector uses a standard circuit with two diodes and a coaxial push-pull transformer. It gives about ± 5 V for ± 5 cm of beam deviation.

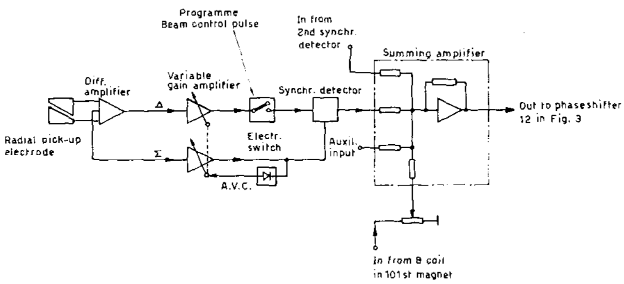

Fig. 4 *Radial beam control system.*

In order to eliminate the influence of beam intensity on the output of the synchronous detector, two additional amplifiers are introduced: an AVC amplifier in the reference signal path and an identical amplifier of variable gain in the difference signal path, the latter receiving its controlling voltage from the AVC amplifier. Variations of the difference and sum signal due to beam intensity variation are thus reduced while variations due to radial displacement remain unchanged. A beam intensity variation of 100 : 1 results in an output variation of about 3 : 1.

During programmed acceleration the bunches must be able to carry out radial excursions in order to stay in synchronism with the programme frequency. The synchronous detectors are then switched off by an electronic switch in the RF signal path.

The two synchronous detectors are followed by a summing amplifier to sum up the error signals, a preregulating voltage out of a $\dot{B}$-coil in the 101st (reference) magnet unit and auxiliary voltages to radially steer the beam for experiments.

The output of the radial control system has to correct the energy gain per turn $V_m \cos \phi_s$. In principle, one can act on ϕ_s or on V_m. The former solution has been rejected for the time being, mainly because of the necessity to reverse the sign of the error signal at transition. Since direct control of the gap voltage in the accelerating cavities is not easily feasible, the following method has been adopted [3]. The 16 cavities are divided into two groups of 8 each, and a variable phase shift δ is introduced between the signals feeding both groups. The net accelerating voltage seen by the protons is therefore $V^m = V_{m0} \cos \delta/2$, where V_{m0} is the sum of the absolute values of the total voltages developed by each group of cavities. V_m can be controlled by an electronic phase shifter varying δ. To avoid the complications of a frequency independent phase shifter, this phase shifter has been placed directly at the output of the 30 Mc FM oscillator of the APC system, where the frequency is nearly constant. The final arrangement of APC loop and outphasing is shown in Fig. 3.

Acknowledgement

The author wishes to thank Prof. Ch. Schmelzer for his criticism and for many useful discussions.

LIST OF REFERENCES

1. Johnsen, K. and Schmelzer, C. Beam controlled acceleration in synchrotrons. CERN Symp. 1956. *1*, p. 395-403.
2. Green, G. K. Phase transitions in the alternating gradient accelerator. CERN Symp. 1956. *1*, p. 103-5.
3. Schmelzer, C. Note on the amplitude regulation of the accelerating voltage. CERN PS (*) RF Note 5. November 1956.

DISCUSSION

COURANT: Do you have a provision in your beam control system so that you can adjust the radius of the beam and have the radial position somewhere else than in the middle of the aperture?

SCHNELL: Yes. This is done simply by adding a voltage to the error signal from the radial pick-up.

VASIL'EV: What is the threshold intensity for the CERN beam control system?

GABILLARD: The threshold sensitivity on the phase electode is about 10^7 protons per pulse.

SCHNELL: For the radial electrodes the threshold for 1 cm displacement is about 10^8 protons per pulse. The figures are valid for a bandwidth of 30 MHz.

SCHMELZER: In the phase lock system described by Schnell, the radial correction signals influence the amplitude of the accelerating field. There is a second method, which will be used in Brookhaven, and which is also foreseen in the CERN design. There the radial position error controls the stable phase angle. At first sight it looks as if these two methods were equivalent. There is however a slight difference: whereas the second method needs a sign reversal of the radial error signal at transition, the first does not. On the other hand the second method may be of advantage for some experimental purposes. This is, when the beam is to be kept at constant energy for some time. At the desired energy the guide field must be kept constant and the stable phase angle shifted to 90° (measured from the crest of the RF wave). With the radial position error correcting the stable phase sitting, the RF system will accelerate or decelerate such that the beam stays in the middle of the vacuum chamber. The energy variation is then only due to the residual variation of the guide field.

SCHNELL: In this connection I like to mention that we can vary the setting of the stable phase angle in the phase discriminator itself by at least ±20°.

LINGJAERDE: I would like to ask Mr. Vasil'ev what sort of phase discriminators they use. Whether they use diode coincidence devices or gated tubes as we do at CERN?

VASIL'EV: We usually use ring type coincidence discriminators.

BLEWETT, J. P. (to Schnell): Can you tell me at what stage you detect when you are taking the difference? Do you detect on the pick-up electrode difference amplifiers?

SCHNELL: We amplify the difference in RF and then detect in a phase sensitive detector using the sum signal as reference.

TURNER: Vasil'ev just mentioned that he integrated his individual pulses, if I heard correctly. Would he like to comment on this?

VASIL'EV: This is described in our report.

GREEN: It has been our general experience that the bandwidth needed to observe the shape of the pulse is considerably wider than 5 MHz. At least 50 MHz is needed to display the shape of the bunch and some numerical calculations were made

(*) Internal memorandum not generally distributed but possibly available from author.

recently which show why this is. Smith at the Cosmotron took a hypothetical distribution of protons at every 3° along the phase axis in the phase-momentum plane and then computed their motion with the proper differential equations, proton by proton, on a digital computer. The computer was instructed that if a proton reached the limit of oscillation, it was thrown out. At various times the distribution of the remaining protons was plotted. At time zero the particles are injected and are uniformly distributed in angle with no radial deviation. As the beam becomes bunched, with hypothetically perfect acceleration the angular distribution of the protons takes a series of crazy shapes which faintly resemble the familiar smooth shapes but which have considerable fine structure and vary with time. With wide band amplifiers on the Cosmotron (50-100 Mc bandwidth) we see these. There is a second interesting thing in the calculation. This is really the reason I brought it up. Smith determined the centre of gravity of the bunch of protons and plotted it as function of time. I don't remember the exact shape and unfortunately I do not have the graphs. The phase centre of gravity varied with time rather irregularly for 10 to 20 phase oscillations. I am a little uncertain, but I believe the worst amplitude was about 0.05-0.1 radians, rather large. The radial centre of the gravity of the bunch also wobbled with diminishing amplitude. However the motions of radial and phase centres did not correspond in any simple fashion. The reason for bringing this up is that I have always been rather an advocate of injecting directly into phase lock, and Smith has been against it. I think he has a little the better of the argument.

The other thing I wanted to comment on was: Vasil'ev showed a phase comparison system which he fed to an oscilloscope. You might find it interesting to connect that signal back to your oscillator. We have done this in the Cosmotron. It diminishes the coherent phase oscillations and considerably improves the beam intensity. It might take out the step in intensity which you have.

SCHMELZER: This is essentially the system used in CERN.

GREEN: It is that system, but without the d. c. response. It goes down to 800 cycles.

TAILLET: We have observed at Saclay almost similar wave shapes as Green has discussed.

SCHAFFER: This fact is very important in the case of an electron synchrotron, because we have a very heavy beam loading and we transmit almost all of the RF power into the beam. That means that there is a reaction of the beam on the RF system.

GREEN: This won't bother you. The fine structure which I discussed will be smoothed out by your high Q cavities. These are changes of shape within one bunch and at a very high frequency referred to the revolution frequency. The interesting thing is that in the centre of charge variations go on for several phase oscillations so I think one must programme that long.

SCHMELZER: This effect of filamentation will disappear completely if you inject with a momentum spread equal to or larger than the momentum acceptance range, provided that you have a constant particle density.

GREEN: Yes.

SCHMELZER: There is another effect which makes initial programmed acceleration desirable. The azimuthal centre of charge deviates from the position of the phase stable point due to non-linear effects at large phase oscillation amplitudes. The effect becomes negligible if the maximum peak to peak amplitude of phase oscillations is less than about one third of the phase acceptance region.

GREEN: But automatically compensated by the radial control.

SCHMELZER: Yes.

GREEN: About what is the general current in the synchrophasotron in particles? What is your average experience of protons per pulse at 10 GeV?

VASIL'EV: I think it is about 10^9.

GREEN: In your picture, you have a large drop in intensity, and then a small drop. Do you know why that second small drop occurs?

VASIL'EV: I don't remember about this step, but over all the cycle there is about 10 times loss.

GERMAIN: Coming back to the accuracy of the RF programme of Vasil'ev, I was a little astonished to hear the figure of 1.5×10^{-6} accuracy. Is this right? I should also like to ask what is the influence of the remanent field on this accuracy, because if you start with a coil and then integrate, you must take into account the remanent field. And is it sufficiently stable to achieve this high accuracy?

VASIL'EV: We have a special system for measuring the remanent magnetic field. This system contains several tens of peaking strips to measure the remanent field in all magnet units.

GERMAIN: May I ask what is the remanent field?

VASIL'EV: It is of the order of 20 to 30 G.

GERMAIN: A second question. What is the influence of rate of rise of B on the frequency programme?

VASIL'EV: The stability of rate of change of B is about 1 or 2% and our system keeps the accuracy within tolerances.

GERMAIN: And what about the delay introduced by these peaking strips to measure the remanent field?

VASIL'EV: The delay in the peaking strips is not large, about 15 μsec.

ADDITIONAL PAPERS

The following papers, related to the subject of this session, were not read but are included in the Appendix.

Andreev, V. G. Application of the method of successive approximations to a calcultation of cavity resonators for linear acceleration of protons. see p. 626

Polyakov, B. J. Experiment on excitation of power oscillations on meter waves in a toroidal cavity resonator placed in vacuum. see p. 670