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BEAM CONTROL

Schnell reported on beam control design and apparatus.

1. Introduction

A programmed frequency system like the one used in the early stages of the CPS acceleration cycle will always show frequency errors. Unfortunately, the admissible frequency tolerances are very tight in the CPS (10^{-6} in the neighbourhood of transition), making it impossible to carry through the whole acceleration solely with the frequency programme.

2. Frequency Correction and Beam Control

Adiabatic frequency errors, i.e. errors that develop slowly compared to the synchrotron oscillation frequency, can be corrected by a simple beam controlled frequency correction servosystem. In such a system, the error signal from a radial pickup electrode, measuring the radial position of the beam, is used 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 easily corrected in this way. A more sophisticated kind of beam control seems therefore advisable, which derives the accelerating wave from the bunched beam itself. For example, the beam feedback shown in fig. 1 can be used to do this.

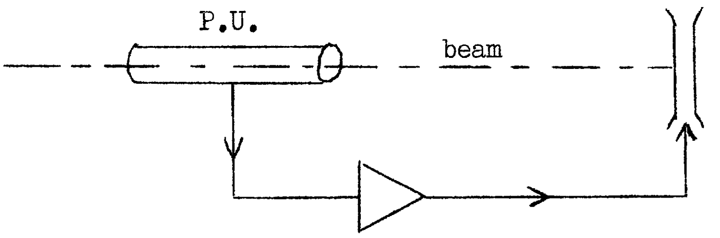

fig. 1

A phase pickup electrode provides an RF signal of the same frequency and phase as the rotating bunches. This signal is amplified and used directly to drive the accelerating stations. However, the unavoidable transit time from the P.U. to the gap (via amplifiers and cables) would cause untolerable variation of phase shift with frequency. In one case, this phase shift would move more than 10 times around 360° during acceleration.

Two methods have been proposed to avoid this:

a) The phase shift can be compensated by an electronic phase shifter which may be programmed and/or servocontrolled by a radial P.U. signal. This method is used in the Brookhaven AGS.

b) An automatic servocontrolled system can be used to keep the phase between P.U. and gap constant. This system, shown in its basic form in fig. 2, has been designed for the CPS.

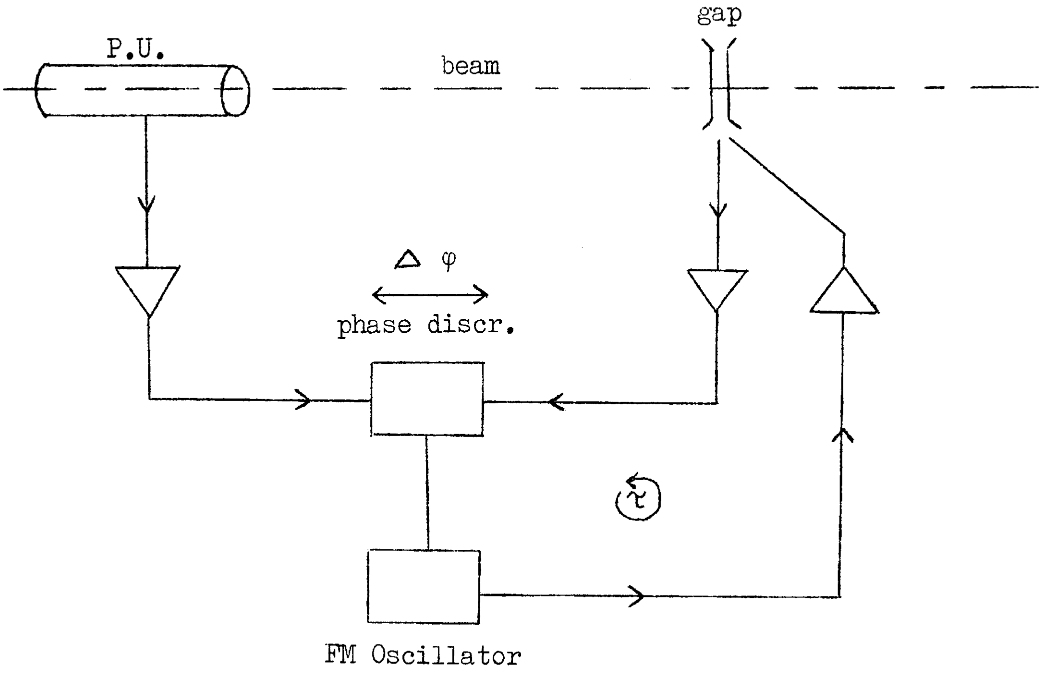

fig. 2

A phase discriminator measures the phase error between P.U. and gap. (The two channels to the inputs of the discriminator must have equal phase shift over the frequency range). The error signal acts on the frequency $\dot{\varphi}$

of an FM oscillator which feeds the cavity. An automatic phase correction (APC) servoloop is thus formed. Actually, the system may be considered as a special amplifier with frequency independent phase properties and providing feedback.

Both systems a) and b) , if they work ideally, ensure that the centre of gravity of the bunch passes the gap at a fixed phase φ_s with respect to the accelerating voltage. Such systems are called phase lock systems.

There will be, in general, an error in energy gain per turn, causing the bunch to move radially. This is corrected by a second servoloop, in which the voltage from a radial P.U. electrode acts on either the accelerating voltage V_m or on the stable phase φ_s to correct the energy gain per turn ($e\ V_m \cos \varphi_s$) and keep the bunch inside the vacuum chamber. This is called the radial control system.

3. Design of the Automatic Phase Correction Loop

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

To avoid coherent bunch oscillations there must be considerable loop gain in the system.

The system must be able to carry through the frequency variation during the accelerating process.

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

It must, of course, be stable.

a) Loop Gain

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 are:

α) An ideal integration implied by the fact that the error signal out of 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 cavity with its tuning system is very complicated, but there are two limiting cases:

i) If the cavity automatic tuning system still works perfectly at frequencies ω where $\mu \ll 1$, the cavity has no influence at all.

ii) If the cavity automatic tuning system stops working at frequencies well below the unity loop gain frequency of the APC loop, the cavity behaves like a fixed frequency circuit. Assuming a small modulation index, so that only first order side bands have to be taken into account, the influence of a fixed resonant circuit (tuned to the carrier frequency) on phase modulation is that of a simple time constant

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

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 $\frac{k}{p}$ expresses the integration and $\left[k = \frac{\dot{\varphi}}{\Delta \varphi}\right]_{\text{static}}$ gives the overall sensitivity of the phase discriminator-FM oscillator set. The second factor expresses the time delay; one has $\tau \approx 2.7$ μs of which 1.7 μs 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 cavity. It is given by $T = 1.6$ μs , $b/2 = 100$ kc/s.

To improve the system a correcting network has been included between the phase discriminator and the FM oscillator. This network 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 $|\mu(p)| < 1$ for $p\tau \geqslant \frac{\pi}{2}$ leads to a modulation frequency of unity loop gain $f_1 = \omega_1/2\pi \leqslant 90$ kc/s. The adopted value is $f_1 = 30$ kc/s including a margin of 6 db and a small additional allowance for the automatic tuning system of the cavity.

The correcting network is also used to provide an increase of loop gain faster than 6 db/oct below f_1.

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

b) Preprogramming

With $k' = k/360 = 50$ kc/s, 100° variation of stable phase would be necessary for a frequency variation of 5 Mc/s for example. Preprogramming of the frequency proves therefore necessary. Such a preprogramme is in fact available from the Hall computer - master oscillator chain. Its accuracy is of the order of $\pm$ 10 kc/s at top frequency, causing $\pm 1/5^\circ$ of phase variation, which is perfectly acceptable. The adding of the programme and APC signal is done behind the FM oscillator, in terms of frequency by mixing. To obtain the sum frequency isolated from difference and carrier frequencies, a double mixing scheme is used. The programme frequency f_p is added to an auxiliary frequency f_o (30 Mc/s) in a first mixer, $f_p + f_o$ is filtered out by a band filter and then again mixed with the frequency from the FM oscillator in a second mixer. $f_p + \dot{\varphi}$ is obtained from the second mixer, filtered out by a low pass filter and fed to the cavity.

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 systems and might possibly phase modulate the accelerating wave with the synchrotron frequency in a dangerous way.

There is another way of providing a frequency preprogramme. Out of the P.U. electrode one obtains 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. The signal from the P.U. electrode is however very distorted, possibly noisy and of variable amplitude and it has to be "cleaned" by an AVC system and a selftracking filter before it can be fed through the mixer chain to 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 , as it is anyhow available.

c) Switching

An electronic switch has been designed to switch between programme and beam control signal. During the programmed acceleration the APC loop serves only to lock the accelerating gap voltage to the programme. Two versions of the electronic switch have been developed, one using tubes and the other diodes. The switch can be switched over to beam control at any desired moment by the master timer. The automatic device switches it back when the beam intensity drops below a certain value.

A similar switch is used at the other branch of the phase discriminator to switch in a phase delay of $2\ \varphi_s$ (120°) at transition. As the frequency has very nearly reached its final value, a very simple phase shifter can be used. It can simply be a piece of cable, but a variable RC phase shifter has been prepared for experiments. The transition switch is triggered from the transition timer and works nearly simultaneously ($\sim 1\ \mu s$), giving the required step function in phase to the APC loop. The latter answers with a smooth transient of 30° overshoot and about $50\ \mu s$ total time. It seems noticeable that the system does not jump out of synchronism although the original phase step function exceeds the range of the phase discriminator.

The phase discriminator works around 90°. The desired value of $\varphi_s = 60^\circ$ (before transition) is obtained by proper choice of the position of the P.U. electrode and cavities at the orbit. A variation of at least $\pm 20^\circ$ can however be made in the phase discriminator.

d) Phase Drifts

One reason for phase drift are the unequal frequency dependent phase shifts in the two channels leading to the phase discriminator. Another reason could be amplitude variations, especially of the beam P.U. signal. A third reason are frequency drifts which cause phase drift via k' . Finally, φ_s should be measured in principle with respect to the phase stable particle in the bunch, but the P.U. can only see its centre of gravity of charge; as stable point and centre of gravity differ when the bunch is not symmetric, there results some drift in space.

Various measures have been taken to counteract phase drifts. Firstly, all individual units in the two chains have been adjusted to equalness in phase within ± 1 o/o. 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 FM oscillator uses an inversely biased silicon diode as variable capacity; this method is very convenient as the high sensitivity (0.7 Mc/s/volt) permits a direct connection between the anode circuit of the 6BN6 and the capacitive diode, the correcting filter network being included there. The stability of this oscillator when freely running with a fixed bias voltage is a few times 10^{-4}, causing only a few tenths of a degree phase variation. Finally, as the 6BN6 coincidence tube measures zero crossings of the incoming waves whereas the centre of gravity of the bunch coincides with the peak of induced voltage, an integrator is used on both sides of the 6BN6 to convert peaks into zero crossings.

4. The Radial Beam Control System

The radial P.U. stations are provided for the automatic correction of beam position. They are roughly 1/2 betatron wavelength apart to provide coarse averaging of the beam position around the orbit. The output of each P.U. electrode is connected to a differential amplifier whose output is proportional to beam deviation. However, a phase sensitive (synchronous) detector is necessary to restore the sign of a deviation in the detected output voltage. To do this, a voltage proportional to the sum of the voltages induced in both halves of the P.U. 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 2 diodes and a coaxial push-pull transformer. It gives about ± 5 V for ± 5 cm of beam deviation.

To avoid the influence of beam intensity on the output of the synchronous detector an AVC amplifier is included in the reference signal path and an identical amplifier of variable gain in the difference signal path, receiving the same controlling voltage. Variations of the difference and sum signal due to beam intensity variation are thus reduced while keeping variations due to radial displacement unchanged. A beam intensity variation of 100:1 results in an output variation of about 3:1.

During programmed acceleration the bunch must be able to carry out radial variations if it is to keep in synchronism with the programme frequency. During that time the synchronous detectors are therefore switched off with 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 magnet unit (computer room), and auxiliary voltages to steer the beam for experiments.

The output has then to correct $V_m \cos \varphi_s$, the energy gain per turn. In principle, one can act on φ_s or on V_m. The former solution has been rejected, mainly because of the necessity to reverse the sign of the error signal at transition. The accelerating voltage has therefore to be controlled. The following system has been adopted, as direct control of the voltage over the gap is not feasible: the 16 cavities are divided into two groups of 8 each and a variable phase shift δ is introduced between them. The net accelerating voltage seen by the protons is therefore $V_m = V_{mo} \cos \frac{\delta}{2}$, where V_{mo} 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.

5. Progress Status

All main items are built in final form and tested individually. The main parts of the APC system have been provisionally assembled and tested successfully with one cavity and with programmed frequency. The transition phase jump has also been studied and outphasing was tried with a dummy summing network without cavities.

Some auxiliary equipment has still to be built and everything has to be mounted on the final racks, to be installed in the Control building, and cable connections have to be made. Everything should be ready by September 1st, 1959.

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E.R.

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