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THE CERN PROTON SYNCHROTRON ORBIT DISPLAY

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In this paper, the automatic orbit display of the CERN proton synchrotron, which is now in operational use, is described. It makes use of 40 electrostatic pick-up stations which provide the fast analog signals. These signals are processed, digitized and fed into the IBM 1800 computer which calculates the corresponding beam positions. The system is able to follow the trajectory of one particular bunch during more than one machine turn. A description of the electronic circuitry, including synchronization, acquisition and calibration subsystems, is given. By using various comparative methods, the results of which are presented, the accuracy of the whole system has been determined.

INTRODUCTION

The first proposal for an automatic orbit acquisition and display system at the CERN Proton Synchrotron (PS) was made by Barbalat as early as 1965.(1) A detailed project was then developed and the first trials on the machine were reported at the 1967 High Energy Accelerator Conference.(2) However, some difficulties were encountered during the realization of this first project and it was found desirable to modify some items of the system. This paper presents the second generation of orbit display which has been in operational use on the PS since 1969.

The originality of the system is due to the sampling technique used. In fact, the system measures the trajectory of one particular bunch, following it around the machine. This technique gives roughly the same accuracy as the averaging (slower) methods(3,4) used up to now, but in addition it allows a wide variety of measurements to be made (for instance trajectories of kicked bunches). In order to separate the closed orbit and some possible coherent oscillations of the bunch, we need to measure the position of the beam during more than one turn, approximately $Q+1$ betatron wavelengths (Q is the number of betatron wavelengths per turn).

The system makes use of 40 electrostatic pick-up (PU) stations,(5) eight of which are used for second turn measurements. The position information is obtained from voltages induced in the electrodes after two operations: difference between voltages on two opposite electrodes and normalization with respect to intensity. The difference operation is performed on fast analog signals whereas the division operation between difference and sum information of the same PU station is made on digitized signals by the PS IBM 1800 computer.

The general block diagram of the system is represented in Fig. 1 and all the descriptions below may be referred to it.

1. DESCRIPTION OF ONE MEASURING CHANNEL

1.1. *Pick-up station and transmission system*

Every pick-up station is of the combined type, having two pairs of electrodes, one for radial and one for vertical measurements. Their compactness (7 cm long) allows them to be installed in the pumping manifolds. Signals are transmitted on 75 Ω cables through four cathode followers (head amplifiers) located very close to the electrodes.(6) Moreover, a summing resistor network inside the head amplifier provides the so-called 'sum signal' proportional to the intensity.

The two pairs of difference signals and the sum signal are fed into three identical differential amplifiers(7,8) located in the machine ring but in a radiation-shielded area. Those amplifiers, having a remote gain control facility (the variable resistance element is an integrated chopper transistor 3N87) are bandwidth- and gain-matched in order to ensure as far as possible equal transmission characteristics for signals coming from the same pick-up.

An improvement of this scheme is foreseen in the future (1972), which avoids the need of active elements near the electrodes(9) and will then be able

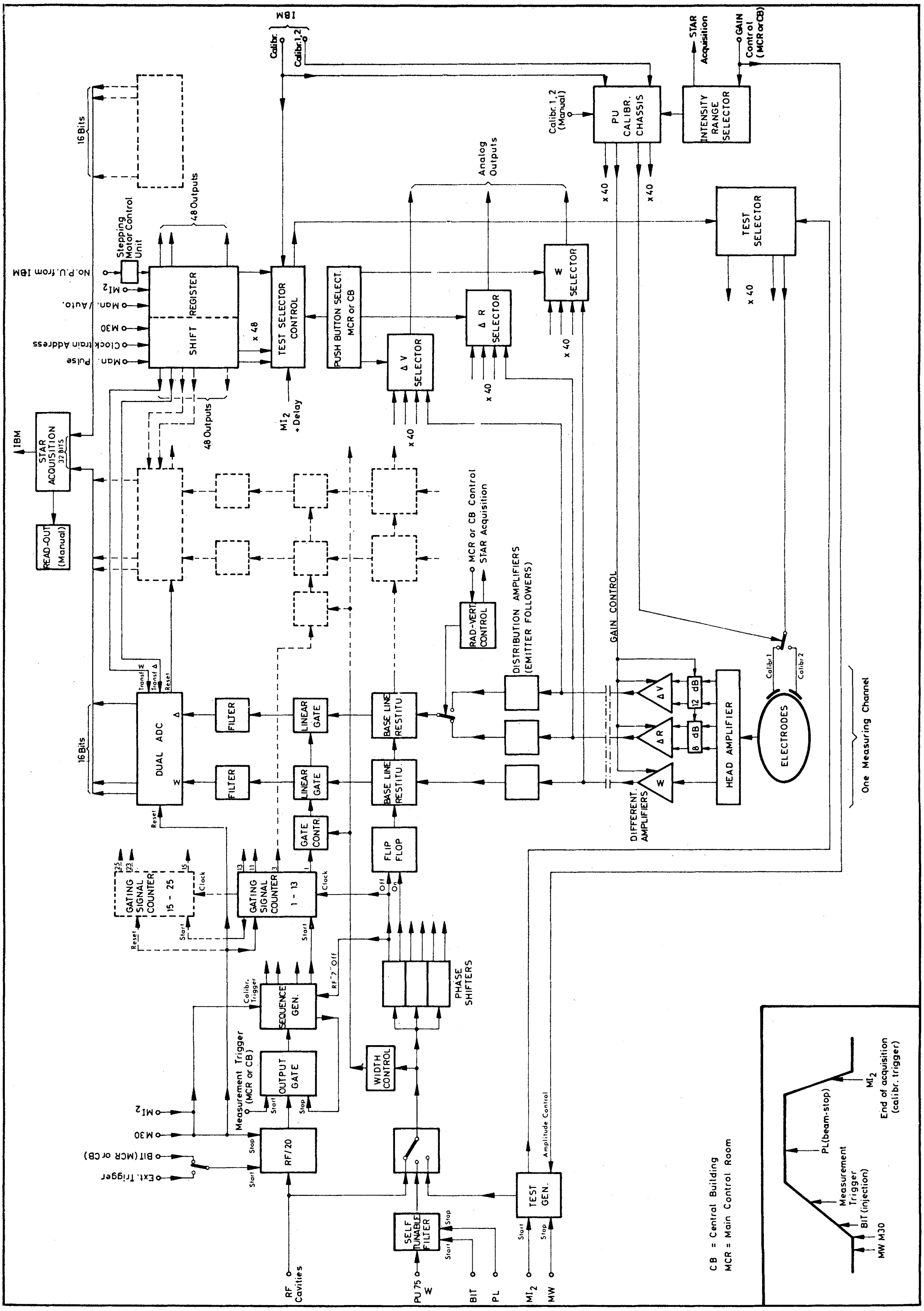

FIG. 1. General block diagram of the automatic orbit acquisition and display system at the CERN PS.

to cope with the expected increase in beam intensity and radiation level.

Signals are transmitted through low loss cables of equal electrical length (for synchronization purposes) to the centre of the ring where they are distributed via emitter followers(10) both to the digital display system and to the selectors for direct observation on oscilloscope.

The overall bandwidth of the transmission system is about 40 MHz.

1.2. *Base line restitution*

As the pick-up signals are ac-coupled, it was found to be interesting to clamp their base line to zero in order to ease digitizing and polarity detection problems.

By short-circuiting the switch S (Fig. 2) during a fraction of the time interval between pulses (restitution time), one clamps the base line of the signal to zero and therefore restores the dc component of the signal. The following amplifier (emitter follower with offset compensation) simply acts as an impedance matching circuit. For the switch S, we make use of a balanced diode bridge (hot carrier diodes) driven by a differential amplifier.(11)

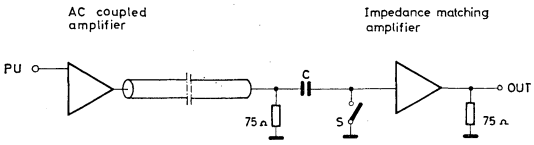

FIG. 2. Principle of base line restitution.

The accuracy of this circuit is better than ±1 per cent of full signal range (±1.5 V) for a dc base line shift. Clamping is effective for base line variations as fast as 80 kHz (-3 dB point).

The timing signals required to open and close the switch are provided by the synchronization circuits. The special arrangement of the PU stations in the PS strongly simplifies the synchronization problems. The pick-up stations can be arranged into four groups:

Straight sections:	3–13–23 . .	93
	5–15 . . .	95
	7–17 . . .	97
	10–20 . . .	100

and within each group the distance between stations is exactly two rf wavelengths. Therefore the same timing signal may be used for all the stations of the same group (PU signals are in phase).

Photos 1 and 2 show typical pick-up and timing signals whereas the effectiveness of the clamping is demonstrated on photos 3 and 4 (taken near injection where the base line is strongly displaced).

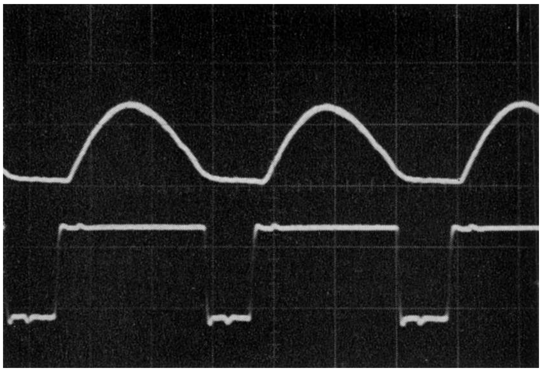

PHOTO 1. Injection

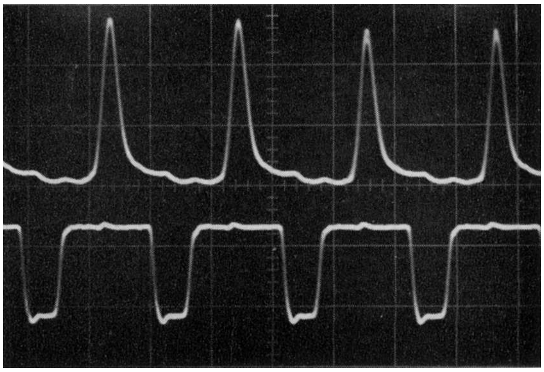

PHOTO 2. High energy

PHOTOS 1 and 2. Base line restitution. PU and clamping signals.

1.3. *Linear gates and filters*

In order to select the desired bunch, two linear gates per channel are used, one for the sum signal, the other for the difference signal (a switch in the clamping circuit allows the selection between radial and vertical difference signals). Those gates described in Ref. 12 have 2.5 nsec rise time and very little pedestal and transients.

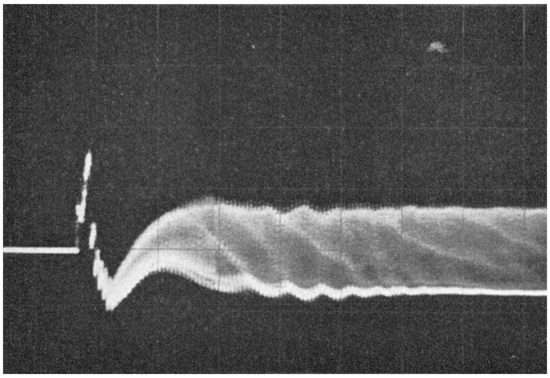

PHOTO 3. Without restitution.

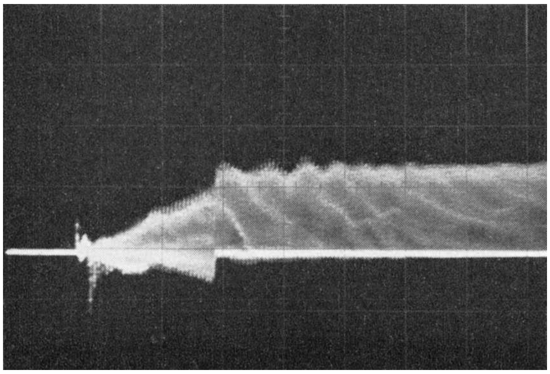

PHOTO 4. With restitution.

PHOTOS 3 and 4. Base line restitution. Sum signal just after injection. Sweep: 100 μsec/cm (restitution starts about 200 μsec after injection).

The radial (or vertical) position of the selected bunch is determined by the *ratio* of the difference and sum signals, and therefore is not altered if both these signals are filtered in the same way. Two identical filters follow the linear gates and perform three functions:

(i) Increase the pulse rise time (> 15 nsec) in order to reduce the requirements on the Analog-to-Digital Converter (ADC).

(ii) Compensate the pulse height variations during the acceleration cycle (resulting from bunching factor and frequency changes) for a better use of the ADC dynamic range.

(iii) Adapt the output level of the linear gate (±1.5 V) to the ADC input level (±3 V).

These filters are of the Bessel type (3 elements) and are carefully matched by differential techniques.

Timing signals for opening the gates are provided by the synchronization circuits. A voltage controlled monostable circuit (one per channel) determines the opening time of the gates, which varies from 180 nsec at injection down to 70 nsec at high energy. The common voltage which controls all these circuits is roughly proportional to the rf period and is provided by a special circuit (width control), the principle of which is described in 2.1 (frequency independent phase shifter).

1.4. *Analog to Digital Converter*

This circuit, of the pulse height to time converter type, is an improved version of the circuit described in Refs. 2 and 13. A capacitor C (Fig. 3) is charged up to the peak amplitude of the pulse through a feedback linearized diode. In order to handle fast pulses, the feedback amplifier requires special care (very fast transistors, compact wiring, loop compensation techniques). A temperature compensated current source discharges the capacitor during a time which is proportional to the pulse height.

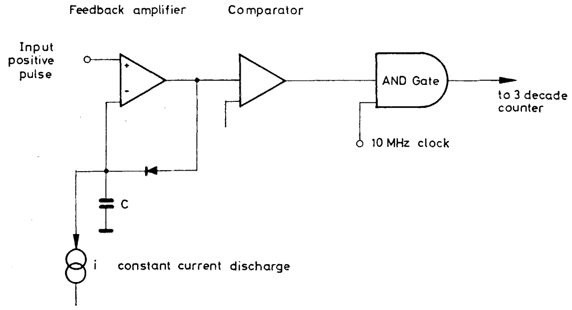

FIG. 3. Schematic of the analog to digital converter.

Two such circuits, one of them being preceded by an inverting amplifier, are associated in order to handle positive or negative signals.

The discharge time interval detected at the output of the amplifier is shaped to TTL logic levels by a comparator and digitized by a 10 MHz clock pulse train counted in a 3-decade integrated circuit counter.

Auxiliary logic circuits compare the time intervals coming from the positive and negative circuits and provide the polarity information as well as an error detection (when the base line restitution fails, large positive and negative components are both present in the signal). Overrange detection is also provided.

Conversion time for ±3 V pulses is 100 μsec and the linearity of the circuit reaches ±1 per cent for pulses having more than 10 nsec rise time.

Two identical bipolar ADC's are used for digitizing sum and difference signals.(14) The 16 output bits (12 for the 3-decade number, the remaining four allocated to sign, error, overrange and manual or IBM control data) are transferred to the IBM 1800 computer in parallel, using 'wired or' techniques and sequential transfer.

2. SYNCHRONIZATION

The purpose of the synchronization circuits is to provide timing signals required by the clamping and the gating circuits. As already mentioned (see 1.2) the particular arrangement of the PU stations around the ring permits a simple scheme to be used. Only three different timing signals are required for the synchronization of the clamping circuits (note that the signals from groups 5–15 . . . and 10–20 . . . have the same rf phase).

On the other hand, the distance between two consecutive PU stations belonging to the same group is two rf wavelengths, which means that the time of flight of one bunch is two rf periods. Therefore sequential opening of all the gates is possible by counting techniques, using as clock signals the timing signals for clamping circuits.

2.1. *The rf clock signals*

During acceleration the clock signal is derived from the beam itself by using the sum signal of one particular PU station (PU 75). In order to ensure synchronism throughout the cycle (variable frequency), one has to match both the delays and the phase shifts of the bunch signal channel and of the timing signal channel.

The sum signal of PU 75 is transmitted through a cable shorter than the normal transmission cables, in order to allow pure delay compensation, to a self-tunable filter(15) which takes out the fundamental rf component of the bunch signal. Three frequency independent phase shifters,(16) driven by this beam derived rf signal and acting as pure phase shifts, are used to provide three rf clock signals for each PU group.

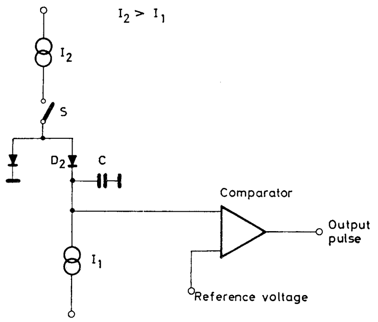

FIG. 4. Schematic of the phase shifter.

The principle of these phase shifters is as follows: During one period of the input signal the voltage across the capacitor C (Fig. 4) charged by a constant current source I_1 varies linearly (Fig. 5). During the next period it is rapidly discharged through S, which is closed, and its voltage clamped to zero by the diodes D_1, D_2 (Fig. 4). A reference voltage proportional to the rf period is generated by a similar circuit followed by a low pass filter. A comparator detects the crossing of reference and ramp voltages and defines every two rf periods an output pulse. From simple geometrical considerations it follows that the phase shift between input and output pulses is frequency independent.

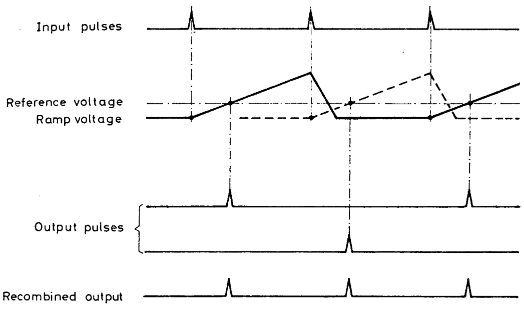

FIG. 5. Phase shifter waveforms.

The system is duplicated in order to handle the next rf period and the two output pulses are recombined to restore the input frequency. Accuracy of 7° is obtained within the 3 to 10 MHz input frequency range.

During the dead time of the machine cycle, a cavity-derived clock signal is used for prepositioning the phase shifters reference voltages at injection. Also, during calibration process (see 4.1) a clock signal derived from the calibration generator is used instead of the machine derived timing signals.

Two phase shifters per PU group provide two rf pulse trains which define the beginning and the end of the base line restitution time (see photos 1 and 2).

2.2. *The gating signals*

The timing signal which stops the restitution time (see 1.2) is used as a clock for a synchronous counter with multiple decoders.(17) The output pulses from this counter are the 1st, 3rd, 5th . . . 23rd clock pulses. They open sequentially the linear gates corresponding to one PU group. Twenty clock pulses correspond to one revolution (the harmonic number is 20), therefore the two last pulses (21st and 23rd) are used for measurements during the beginning of the next turn.

For wiring convenience, each counter (one per PU group) is split into two chassis which contain also the associated monostable circuits and filters. The same clock signal is used for groups 5 to 15 . . . and 10 to 20 . . . but the latter has a counter which decodes the even numbers (note that the time delay between PU 5 and PU 10 is just one clock period). Those counters which make use of the fast 'emitter coupled logic technique' (MECL) have very little delay and jitter.

The four counters are triggered by four 'start' signals arranged in such a sequence that the gates of pick-up stations 3, 5, 7, 10, 13 . . . are successively opened. A special logic circuit produces these four signals from the different clock pulses and a 'trigger' signal which defines the instant of measurement.

In order to know precisely the measured bunch, the trigger signal must be put in phase with the revolution frequency. We use for this purpose a logic circuitry (MECL technique), the main item of which being a synchronous divide-by-20 counter, which selects the desired bunch, and possibly the desired turn (near injection).(17) Moreover, this circuit provides accessory signals: ADC and gating signal counter reset pulses, and a trigger pulse for the oscilloscope.

3. DATA ACQUISITION AND CONTROLS

3.1. *Data transmission*

Just after (100 μsec) the measurement has been triggered, all the information is stored in the memories of the 96 ADC (48 channels, 8 of them devoted to the second turn measurements, having each one sum and one difference memory). During the dead cycle of the machine, all these data are sequentially transmitted to the IBM 1800 computer through the STAR (Système de Transmission Adressé Rapide)(18,19) data transmission system.

Sequential reading of all the data is obtained by sending transfer pulses successively to all memories. In fact, during computer acquisition via the STAR system two memories are read at the same time because the input of the STAR system may accept 32 bits (double precision mode) which matches well the 2 × 16 bits of two memories.

Thus the 8 ADC chassis are split into 2 groups of 4, within each of them, the 16 bits are paralleled using 'wired or' technique. Data are then transferred directly to 'Data Group' of the STAR system.

Transfer pulses are produced from an 'address' pulse and a clock train (transmitted from the IBM 1800 computer via the STAR system) by a special shift register circuit. This shift register normally has 96 successive positions, but it can be split by special signals into two separate shift registers each having 48 positions and being driven in parallel by the clock pulses. This possibility permits speeding up the data acquisition by a better use of the 32 bits of the STAR system.

On the other hand, the '96 positions mode' is used for slow, manual control of the shift register and direct reading of data on a read-out display.

3.2. *Data display*

Data transmitted to the IBM 1800 computer are processed on-line in order to deliver in the Main Control Room the PS orbit information. First of all, the unprocessed data are displayed on cathode ray tube alphanumeric display (Selenia) in order to be able to check quickly the transmission system and some points which may appear as doubtful.

Then the computer calculates the beam positions from sum and difference data, taking into account calibration coefficients (see 4.3). The betatron amplitude function enters also in the calculations in order to display normalized displacements in equivalent millimeters, and to provide the mean radial position.

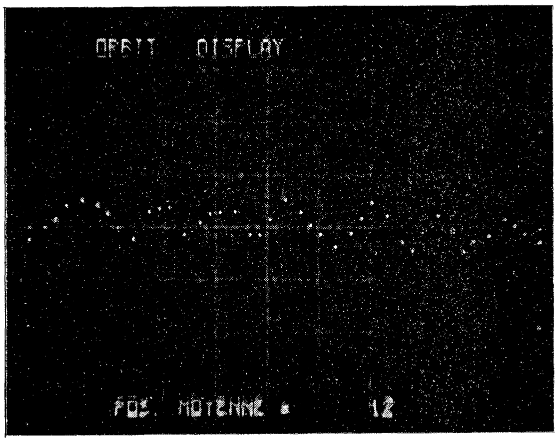

PHOTO 5. A typical orbit display on the memory scope.

Numerical results and orbit figure can be obtained by the IBM line printer which indicates also the mean radial position and the conditions of measurement.

Another possibility, which proved very useful, is the orbit plot on the memory scope associated with the computer (photo 5). This plot may be displayed in various places in the Main Control Room through a TV link.

Some automatic tests are provided in the computer software to reject bad measurements. In particular the sum signals must lie within a predefined range.

3.3. *Controls*

Controls needed for the PU data display operation are available either in the Main Control Room (mode AUTO), or in the centre of the ring (mode MANUAL) where almost all the electronic circuitry is located.

In order to cope with the various possible intensities accelerated in the PS, the PU amplifiers have a remote gain control (see 1.1). A four position selector allows the choice of four intensity ranges, which can be arbitrarily chosen by voltage adjustment. For one of them, namely the most commonly used, the gains of all the PU amplifiers are adjusted in such a way that analog signals are exactly calibrated (difference and sum signals are exactly equal for a 2 cm displacement). This simplifies the interpretation of PU signals viewed on an oscilloscope. For the other ranges, the calibration is not exact (because one wants to avoid too many independent settings) but calibration factors are automatically taken into account by the computer for orbit display.

Moreover, calibrated attenuators (8 dB radial, 12 dB vertical), at the input of radial and vertical difference amplifiers can be remotely switched off, which allows a magnified scale to be used for measuring small orbit deviations.

PU selection for analog observation is performed by remote controlled 40 position coaxial selectors.

Radial or vertical orbit selection is obtained by relays at the input of the clamping circuit.

The choice of the selected bunch depends either on the preset state of the divide-by-20 counter (local control) or on the timing of the start signal at injection (remote control).

In addition to the normal trigger inputs, special fast trigger inputs are available for special purposes (for instance one can use ejection linked trigger signals for kicked bunch observations).

4. CALIBRATION

An automatic calibration facility using the IBM 1800 computer is associated with the PS orbit acquisition system. This gives a substantial improvement of the overall accuracy of the system and moreover simplifies maintenance problems of this large electronic system by systematic fault detection.

4.1. *Calibration generator*

The calibration generator is designed to provide pulses which, as much as possible, look like beam signals. The repetition frequency is 7 MHz (intermediate value between 3 MHz and 9.5 MHz respectively injection and high energy frequencies) and the half-sine-shaped pulse is approximately 70 nsec long. In order to compensate cable distortions between the centre of the ring and the PU stations a special differentiator circuit is used at the output of the generator.(20) The simulation of the 1.5×10^{12} proton beam requires generator output voltages as high as 30 V and needs high-power, high-frequency output circuits. The 4 position output attenuator is coupled to the 4 remote gain control selector for the best use of the dynamic range of the circuits.

The generator is triggered every machine cycle, during the dead time of the cycle. The duration of the calibration pulse train defined by start and stop pulses is nevertheless limited by one shot circuits in order to prevent overheating of components.

A synchronous timing pulse train delivered by the generator is used for synchronization purposes during the calibration process. Note that the frequency of the calibration signal is constant, which means that phase shift and delay are equivalent. Therefore we simply use the phase shifters (see 2.1) with separate reference voltages, switched on every dead time of the machine cycle, in order to put calibration and timing signals in the correct phase.

4.2. *Calibration signal selection*

Calibration signals are capacitively coupled to the electrodes through small adjustable coupling capacitors.(5) They are adjusted in such a way as to produce an equivalent beam displacement which is well known (3.2 cm radial–3.6 cm vertical) and calibrated in the laboratory. Two thermal (mercury) relays, insensitive to the stray magnetic field of the main magnet, connect the calibration signal on one pair of electrodes (one radial, one vertical), on the other, or on both in order to simulate positive, negative and zero displacements. The latter is used only for balancing the cathode followers which have a remote gain control facility. The relays are switched either by manual or by computer control.

The output of the test generator is coupled to the PU stations via a 40 position test selector which makes use of coaxial relays. This selector can be driven either by push button selectors, or by the shift register (see 3.1) for automatic calibration purposes.

During the calibration process (dead time of the cycle) the shift register (which is in its '96 position mode', see 3.1) is positioned on the desired channel by auxiliary clock pulses. Those pulses can be either manually or computer generated; in this case information is transmitted by the STAR system and pulses are delivered by circuits normally used for driving stepping motors. Therefore the same shift register is used both for PU data acquisition and selection of the channel to be tested. As we would not like to prevent the orbit acquisition during calibration (which is rather long), the shift register has to perform both tasks within the same machine cycle. This implies an intermediate memory between the shift register and the test selector because of the slow response of the coaxial relays. This memory (test selector control) is only an array of 40 D flip flops, and its contents is renewed each machine cycle.

4.3. *Acquisition*

The zero errors of the measuring channels, which are mainly due to the clamping circuits, are computerized exactly like beam signals. One has just to trigger the measurement when no beam is present. The computer informs the operator if some channels have zero errors larger than a given tolerance or rejects the PU station if the error is very large.

Positive or negative calibration factors (note that they may differ because the ADC's have two separate positive and negative circuits) are selected by the computer at the beginning of a test process. Then the shift register is positioned (during the dead time) to the number which corresponds to the channel to be tested. Therefore the test selector and the data transmission system are ready for acquisition of test signals.

Ten measurements, taking ten machine cycles, are performed for every channel. The computer is then able to average out all these data and to calculate calibration factors from sum and difference averaged values as well as standard deviations (useful for maintenance purposes).

Out of range signals and calibration factors are automatically eliminated, and the operator is advised of the fault. Then, the next channel is automatically tested and the process goes on up to the last station. Next the same process repeats for the other polarity.

Calibration factors corresponding to positive or negative signals, to radial or vertical measurements and to the four intensity ranges are stored in the computer memory and used for automatic correction of orbit display.

Other simplified routines are also available, which permit, for instance, the calibration of only one channel.

5. RESULTS AND CONCLUSIONS

During the development of the system a large number of comparative beam measurements have been made using both the conventional oscilloscope technique and this new automatic display. The aim was mainly to prove that digitizing the PU signals was possible without losing accuracy.

More severe tests are comparisons between PU data and position information given by other means. Absolute position measurements using internal targets, although they confirm PU data, are not very interesting because only a limited number of pick-ups can be tested. The most interesting technique is to produce a well known bunch trajectory perturbation.

Two well-located dipoles which are an integral number of half betatron wavelengths apart are used to produce between them a sinusoidal perturbation of the closed orbit which is measured by the orbit display system. Deviations from the theoretical values were obtained from a large number of perturbations (up to 40 mm peak to peak betatron oscillation amplitude) and their root mean square value is about 1 mm. This value represents roughly the statistical *measured* accuracy of the whole system.

It is also possible to obtain the accuracy by measuring coherent betatron oscillations excited by a kicker magnet normally used for ejection purposes and carefully calibrated. These measurements, extended over 5 Q betatron oscillations (5 turns) gave the same results.

Another method is to vary the mean radial position of the beam (for a given magnetic field) and to compare the average beam displacement given by the orbit display, and the shift of the revolution frequency. We performed these tests both at low and high energy (+20 to −20 mm displacements) and their results confirm the 1 mm accuracy figure of the system.

In conclusion, although the authors are well aware that the system could have been designed more simply and cheaply (some historical reasons played a certain role here), the orbit display, which went into operation more than one year ago, has proved very useful for the experiments on the PS as well as for normal running of the machine.

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