THE BEAM DIAGNOSTICS SYSTEM, SERVING THE SERPUKHOV FAST EJECTION

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Summary

A set of beam transformers measures the intensity of each bunch, circulating or ejected. Five electrostatic pick-ups measure the radial position of one selected bunch. Secondary emission grids and luminescent screens give the profile and position of the beam at relevant points. Gated radiation detectors monitor beam loss in the ejection area. All signals are digitalized and fed to a minicomputer on line. Readout is via nixies, CRT analogue displays, pen recorders and a teletype. Statistics can be made over a chosen number of acceleration cycles.

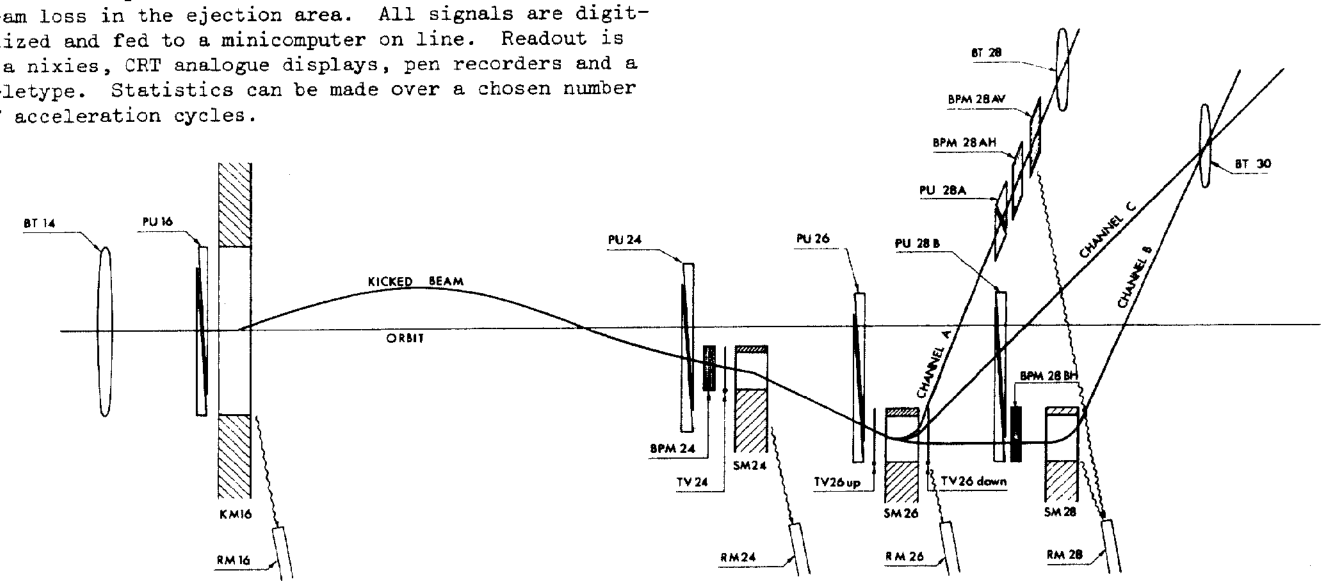

Fig. 1. Ejection area. KM: kicker magnet; SM: septum magnet; BT: beam transformer; PU: electrostatic pick-up; BPM: beam profile monitor (H/horizontal and V/vertical); TV: luminescent screen, monitored by television; RM: radiation monitor. Numbers indicate the straight sections where components are mounted.

Introduction

The fast ejection system[1,2] for the Serpukhov 70 Gev proton synchrotron was made by CERN and installed and commissioned jointly at the Institute for High Energy Physics (IHEP) at Serpukhov, USSR, as part of the collaboration between the two Institutes.

Experience with the CPS showed the desirability of installing, simultaneously with the ejection, a beam diagnostic system designed specifically to yield all relevant data on ejection performance. This should shorten the usually lengthy setting up times, increase average efficiency which tends to drop during routine operation, and provide a record of performance. Also, since different parties were responsible for commissioning of a number of strongly interlaced systems (accelerator, ejection, proton beam transport, RF separated beam, bubble chamber), it seemed appropriate to be completely clear about beam conditions at the interfaces between ejection and accelerator on one hand, and ejection and beam transport on the other. Knowing the vulnerable nature of such instrumentation and its relative novelty in the USSR, some redundancy has been incorporated and the hardware and software have been kept as modular and conceptually simple as possible.

The results confirm the philosophy: the beam was ejected close to the theoretical trajectory and conserving the accelerator emittance one day after completion of the installation. The first run started a few days later and was highly efficient. Four months later, the responsibility for operation and maintenance has been transferred to IHEP personnel. Above all: discussions about "who is causing what" have been virtually non-existent.

After installation, accelerator beam intensities were typically around 10^{12} protons per cycle. The beam is divided in 30 bunches at intervals of 165 ns, each about 20 ns long and of roughly triangular shape in time.

The field in the kicker magnet KM16 (Fig. 1) should rise and fall between the passage of subsequent bunches. It can thus deflect sequential groups of 1 up to 30 bunches into the aperture of septum magnet SM24 which moves close to the central orbit shortly before ejection and which bends the beam into the stationary septum magnet SM26. The latter acts as switch, directing the beam into channel A, channel C or, when not powered, into channel B through the stationary septum magnet SM28. The system allows 3 ejections per acceleration cycle, each time ejecting a different number of bunches at different times and energies, into anyone of the 3 external channels.

The detectors and their uses are the following:

* Three beam transformers (BT). One is placed upstream of the fast ejection system and one at each exit window. They measure the charge of each proton bunch and permit to calculate the circulating beam intensity before and after each ejection shot, the ejected-beam intensity and the ejection efficiency for each proton bunch. This yields an accurate account of the proton distribution between the three channels and allows adjusting the rise and fall time of the kicker magnet field between passage of bunches.

* Five electrostatic position pick-ups (PU). One is placed upstream of each ejection magnet and one at the

exit window of channel A in straight section 28. They permit to follow the radial position of any chosen proton bunch, circulating or deflected. This yields the closed orbit and the ejection trajectory and their possible instabilities. It also allows fine adjustment of the rise and fall time of the kicker magnet.

* Three beam profile monitors (BPM). One is mounted on the upstream end of the moving septum magnet SM24, the second is placed at the exit window of channel A in straight section 28 and the third, also in straight section 28, is on the trajectory going to channel B. All give the horizontal density distribution of the beam and BPM28A gives in addition the vertical one. These yield the position of the beam behind the septum of SM24, the accelerator beam emittance, the position of the beam at the exit window and the ejected-beam emittance.

* Four radiation monitors (RM), one place downstream of each ejection magnet, detect losses of beam in the ejection area, discriminating between fast and slow radiation bursts, between shots and between the four monitors. This yields information about possible beam interception by ejection equipment and allows to localize it, distinguish between deflected or circulating beam and to identify the responsible shot.

* Three luminescent screens, one mounted upstream on the moving SM24 two others upstream and downstream of SM26, are monitored by TV cameras. They are composed of fixed luminescent frames, outlining the contours of the magnet apertures, and movable solid screens which can fill those apertures. These yield a coarse corroboration of some PU and BPM data and position and size of the beam at the exit of SM26.

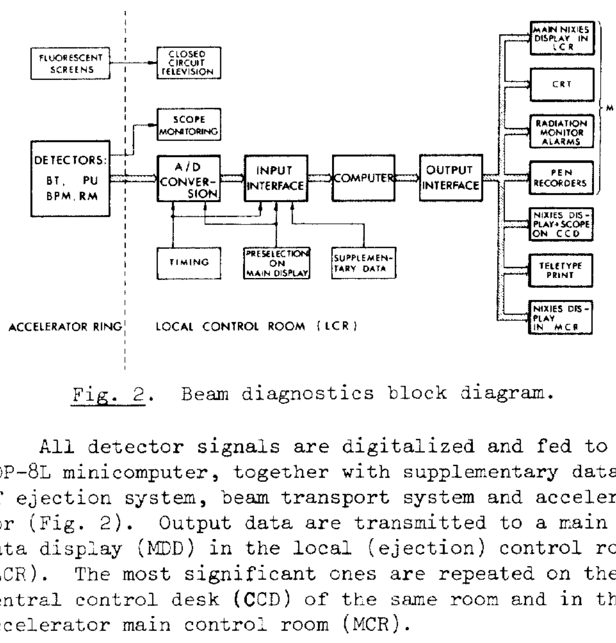

Fig. 2. Beam diagnostics block diagram.

All detector signals are digitalized and fed to a PDP-8L minicomputer, together with supplementary data of ejection system, beam transport system and accelerator (Fig. 2). Output data are transmitted to a main data display (MDD) in the local (ejection) control room (LCR). The most significant ones are repeated on the central control desk (CCD) of the same room and in the accelerator main control room (MCR).

Beam monitors

Beam Transformers[3]

Bunch-by-bunch intensity measurement is chosen rather than more precise overall measurement since, together with the CRT analogue display, this constitutes a very powerful operational tool.

The transformers must show the bunch structure of the beam, which acts as primary winding. The secondary winding consists of two parallel sections of 6 turns each, wound on a toroidal permalloy-tape core. BT14 has an opening of 205 mm and is mounted around an insulated section of the accelerator vacuum chamber. It is made of 10 µm thick tape, whereas BT28 and BT30, with an opening of 75 mm, have a tape thickness of 30 µm to make them magnetically comparable with BT14. The transformers are connected via long low-loss coaxial cables with the analogue-to-time converters (ATC).

The signals pass first through remote-controlled attenuators. The electronic switch (Fig. 3) connects one of the external transformers during ejection and the internal one before and after. Next, the base-line between bunches is accurately reset to zero. This circuit also drives a low impedance line to which 30 gates are connected, one for each bunch.

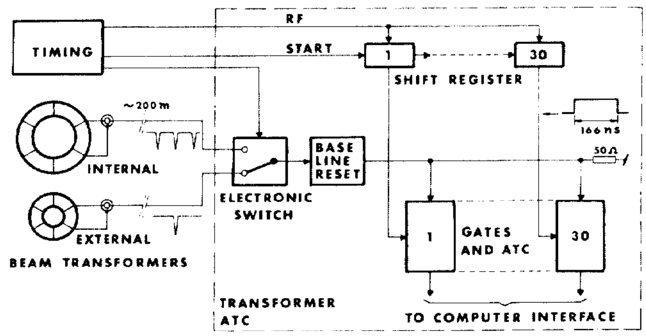

Fig. 3. Beam transformer A/T conversion.

The gates are controlled by a shift register. A start pulse injects a logical 1, which travels down the register and opens sequentially the gates. The bunch transmitted through a gate is stretched and serves to charge a capacitor, which is then discharged by a constant current. For the duration of the discharge, an output pulse is generated which is sent to the computer interface. To prevent reflections in the distribution line, the whole ATC is built very compact and fits into a 4-unit wide NIM plug-in.

In 30 sequential intervals of 165 ns, corresponding to the RF buckets, BT14 measures the circulating bunches 160 µs before and 165 µs after ejection. The ejected bunches are measured by BT28 or BT30 in the corresponding intervals. The appropriate external transformer is selected by a coaxial reed switch, which can automatically be commutated between ejection shots from a shot-channel correlator.

The internal transformer was calibrated by comparing the sum of the measurements of the 30 bunches with the machine intensity. The two values continued to agree within 3 % over a period of several months. The precision of the ejection efficiency measurement is about 2 %.

Electrostatic pick-ups[4]

The deflection of single or small numbers of bunches in fast ejection makes it imperative to measure large displacements of one single bunch with a precision of, say, 1 mm. This in contrast with conventional closed orbit measurements where integration times may be large, displacements smaller and absolute precision better.

The PU's are of the type described by Sherwood[5]. They are essentially rectangular stainless steel tubes, separated by a diagonal cut. They are 200 mm wide, 106 mm high and 120 mm long, except for PU28A at the exit window, which is smaller.

Since for the bunched beam at ejection times a large time constant is not necessary, the signals from the electrodes are directly fed to long low-loss coaxial cables and are therefore strongly differentiated. Such signals are difficult to digitalize but the method has also several advantages: no active components in the radioactive zone, signals with a fixed base-line and reduced sensitivity for stray particles.

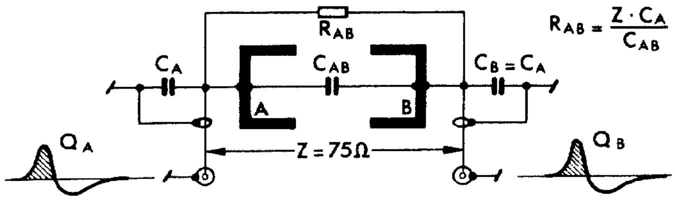

Fig. 4. Pick-up equivalent diagram. C_A and C_B are 76 pF for the large electrodes. The interelectrode capacitance C_{AB} is kept small (2 pF) by mounting an earthed strip, 1 cm wide, between the electrodes. R_{AB} makes the measurement frequency independent.

The signal from each electrode is digitalized separately. Only the positive part Q_A and Q_B of the differentiated signal (Fig. 4) is measured. The signal passes first a remote controlled step attenuator (Fig. 5). A fast diode gate opens to let the selected bunch through. This bunch passes a current amplifier with a high output impedance. The hot carrier diodes D1 and D2 allow the positive part of the differentiated pulse to charge C1. The differential amplifier A2 charges capacitor C2 to the voltage of C1. Amplifier A3 generates an output pulse for the duration of the discharge of C2.

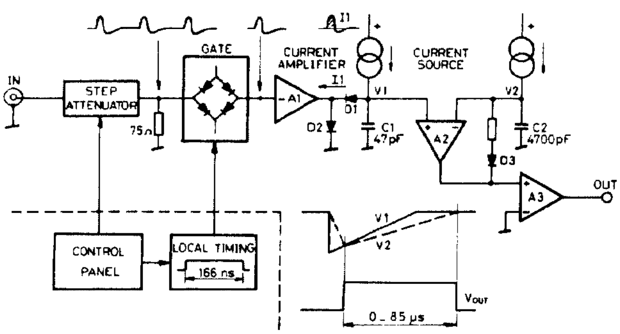

Fig. 5. Pick-up analog-to-time conversion.

In good working conditions and with a stable accelerator beam, statistics were obtained over several hundred shots, with RMS deviations of the measured position of less than 0.3 mm and this for all PU's. The absolute precision is better than 2 mm everywhere, as long as the beam does not touch the electrodes.

Beam Profile Monitors

The BPM's consist of grids of 16 aluminium foil strips, 2 mm wide, 3 mm apart, 25 µm thick, sandwiched between two solid foils at +200 V potential w.r.t. the strips. The latter are soldered at both ends to connection leads on a printed circuit frame, giving the sandwich mechanical stiffness.

BPM24 is mounted upstream on SM24 and hence moves with it. It is collapsable and when turned into the deflected beam path, it covers the magnet aperture and the first strip is in line with the septum. Signals and controls pass through flexible strips. BPM's in straight section 28 are stationary. Since they are placed between the main magnet coils, they are shielded against a magnetic field of about 0.15 T by a thick armco yoke.

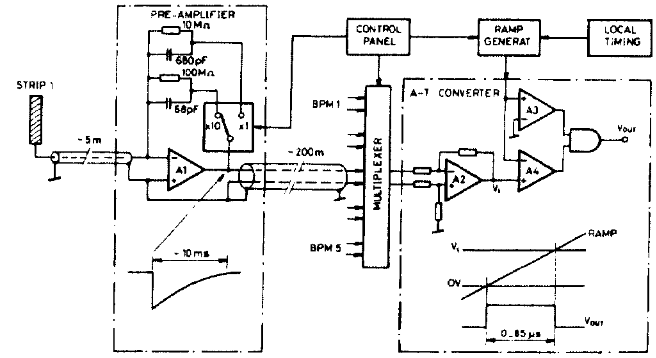

Fig. 6. Beam profile monitor A/T conversion.

When the BPM is placed in the beam path, electrons are set free by protons striking the strips. Charge sensitive preamplifiers (Fig. 6) are situated in the accelerator basement, where the radiation level is moderate. Reset is automatic, due to the resistor in parallel with the feedback capacitor. The gain is remote controlled. The 16 outputs go through a shielded multicore cable to the multiplexer. There one BPM, out of maximum five, can be connected to the ATC. In the ATC a linear ramp is generated, 0.5 ms after ejection. This ramp crosses the zero line and the signal line. An output pulse is generated between these two crossings. The 16 pulses are sent to the computer interface.

Although the coarse spacing of 3 mm between strips proved adequate for the beam sizes of somewhat less than 10 mm during commissioning, the system may be upgraded to provide twice the present resolution.

Radiation Monitors

Ionization chambers (IC) are used as radiation detectors. They are filled with pure argon at a pressure slightly above atmospheric. The sensitive volume is about 1 litre and the collection times are 500 µs for the positive ions and 3 µs for the electrons. The collected charge is roughly proportional to the number of protons lost in the straight sections monitored.

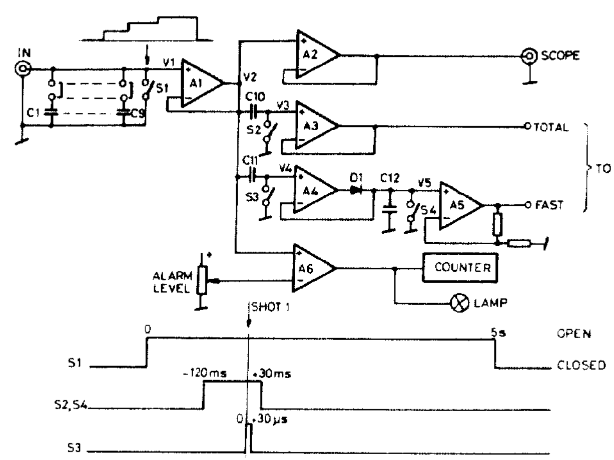

Fig. 7. Radiation monitor A/T conversion.

The signals from the IC, integrated over the whole acceleration cycle, are displayed on a scope (Fig. 7). Separate channels, gated by reed relay S2 (slow) and by electronic switch S3 (fast) produce voltages proportional to the increment of the integrated radiation signal, i.e. respectively the "total" and the "fast" radiation bursts produced around the ejection moments. Signals from these channels go to ATC's and the computer. To be comparable, the fast component is multiplied by 2, since only electrons may be collected in this interval. An analogue discriminator lights an alarm lamp and advances a counter if the total radiation of the acceleration cycle exceeds a preset level.

Computer Interface

The analogue signals of the beam detectors are A/T converted, chopped by a 3 Mc/s clock and stored in 55 counter registers of 8 bits. Of these registers 30 are assigned to receive the 30-bunch intensities before, during and after ejection, and the others to receive first the pick-up informations and thereafter the informations of the preselected beam profile monitors plus the radiation monitors. One register transmits to the computer the time order of the ejection shot. So for each shot there are 5 data transfers to the computer (detail in Fig. 8) which occupy sequential memory locations. Informations pertaining to different shots are stored in different memory groups. The adopted one-cycle stealing technique allows a minimum repetition time of 150 μs for each data transfer (A/T conversion + 55 DMA).

Every 250 μs a single output DMA for CRT is requested. Program controlled transfers (IOT transfer) are used to read from 36 parallel registers of 12 bits the data coming from various points of the ejection control room and to transfer output data to the displays (Table 1).

BCD output data, stretched to about 10 μs, are transmitted in parallel with their addresses over twisted-pair cable to the ejection control room and over coaxial cables towards the MCR.

Table I

Input and output informations of the computer.
The transfer mode is given together with the symbols used in the print.

	Input	Output
Beam detectors (data break input)	Beam transformers	- Beam intensity at ejection time (BIMINT)
		- Shot intensity and efficiency (SHTINT, SHTEFF)
		- Internal and external bunch efficiencies for CRT (**)
		- Internal and external selected bunch efficiency (BNCEFF)
	Pickups	Selected bunch position (PU 16, 24, ...)
	Radiation monitors	Slow and fast radiation levels
	Beam profile monitors	- Beam position and diameter of selected BPM
		- Beam profile on CRT (**)
Selection on MDD (IOT inputs)	Shot-channel correlation (*)	Channel of ejection (CHAN.)
	Selected bunch (*)	Bunch (not) in the shot
	BPM selected (*)	
	Selected number of acceleration cycles for statistics (TTCYCL)	
	Statistics or single cycle (*)	
	Print	
Supplementary date (IOT inputs)	Transformers upstream and downstream the beam transport system	Beam transport efficiency
	Target charge	Degree of focusing on the target
	B train	Ejection energy
	SM 24 position	SM 24 position relative to the vacuum chamber centre (SM 24)
	First ejected bunch (FSTEJB)(*)	
	Number of ejected bunches (*) (NEJBNS)	
	Beam transformer attenuation (*)	
	Beam on	Number of acceleration cycles with beam intensity higher than a selected value (CYCLES)
	CRT option	
	Clock	Data and hour of the print
	Cycle hold	
	Radiation monitor levels	Radiation alarms

(*) Ejection parameters and parameters modifying the statistics

(**) Data break output

The computer interface is straightforward and home made since at the time when decisions were taken, early in 1969, this seemed the right thing to do.

Computer Software

The computer program occupies about 95 % of the 8K memory locations of the PDP-8L computer. Assembler language was adopted for easy understanding and for quick manipulation through the teletype ASR-33 during first operations.

Interrupt signals from the timing (Fig. 8) initialize the program each acceleration cycle (INT 3), start at each shot the calculation of the 30 internal and external bunch efficiencies for the CRT (INT 4) and start program controlled input transfers and other calculations after the last shot (INT 5). INT 5 is not essential and was included for more safety.

Check is done if previous calculations are terminated.

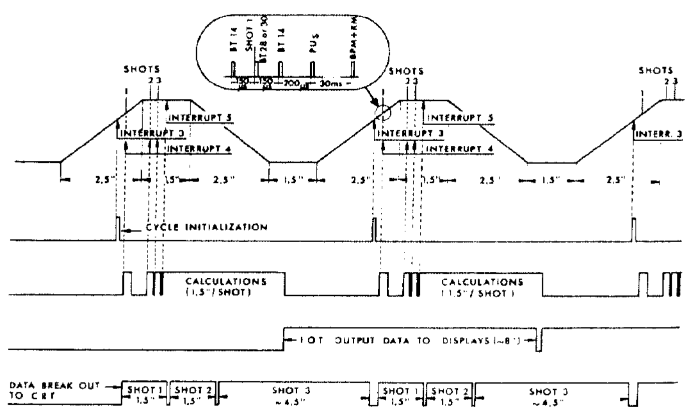

Fig. 8. Accelerat. cycle and computer synchronization.

Shot-by-shot outputs to CRT are program delayed up to 1.5 s to allow visualization on CRT. Duration of all calculations is about 1.5 s/shot and after their execution output data are transmitted, grouped per shot to the various displays every 35 ms and preceded by a label for shot identification. Stored data pertaining to another selected acceleration cycle are also transmitted (cycle hold). Parameter values and their squares may be accumulated during a preselected number of cycles and thereafter statistics (mean values and standard deviations) are printed out (Fig. 9).

If differences occur in the ejection parameters (Table 1), statistics are interrupted and the results up to that cycle are printed out. A software monitor controls re-entries and time sharing between calculations and printout. A few tables facilitate the inclusion of other beam detectors and minimize the computing time. Programs for maintenance and debugging are included.

Displays

All output data, except the CRT, are issued under program control over a common bus, in parallel with their address and preceded by a shot identification. Any of these data may be selected from the bus by address decoders in the display units.

A main data display (MDD) is located amongst the ejection system control racks in the ejection control room (which is situated in the ejection building and far away from the accelerator MCR). A display control panel on the MDD permits display selection. A fixed summary of these data is remoted displayed on a central control desk (CCD) of the same ejection control room and in MCR.

The MDD comprises (a) 8 nixie digital display units, (b) 3 pen recorders, (c) a control panel, (d) 24 radiation alarm level selectors and (e) the CRT analogue display. The CCD has a summary of the nixie displays for 3 shots and a small repetition of the CRT. The MCR receives only the nixie summary.

There are two types of nixie units: (i) triple ones with fixed address to be chosen by jumpers on the printed circuit and (ii) dual ones with variable address to be selected by digi-switches on the front panel. The pen recorder drivers are variable address nixie units followed by a DAC. The recorders are for medium term monitoring, e.g. search for infrequent irregularities, correlation of two variable parameters, etc. Nixie units and pen recorders display a collection of data for one of the three shots, chosen on the display control panel.

In addition to (1) selecting the shot for nixies and pen recorders, the control panel permits to (2) chose the bunch to be measured for each shot, (3) assign the ejection channel, i.e. external BT, to each shot (a switch allows remote control from the ejection programming system), (4) the BPM to be displayed and (5) its amplification. For the teletype, it allows to (6) select the single cycle or statistics mode and for the latter (7) the number of cycles. It also permits to (8) initiate the printout immediately. A cycle-hold knob, acting on the computer program, permits to freeze all digital data of one accelerator cycle indefinitely, so that all 3 shots may be called for examination. A light signals when a bunch selected to be measured is not programmed in the ejection shot, in which case the closed orbit position is measured otherwise the ejection trajectory. An error lamp signals overflow of the interface counters or too low beam intensity in the accelerator.

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PROGRAM BIDONE (VERSION 17/02/72)
20/04/1972   04H 19M

SHOT     1
CHAN.    A
FSTEJB   003
NEJBNS   001
SELBNC   003
CYCLES   + 41.0
ENERGY   + 69.5   +   .0    GeV
BIMINT   + 12.6   +   .6    10^11 ppp
SHTINT   +    .3  +   .0    10^11 ppp
SHTEFF   + 93.6   +   .4    %
BNCEFF   + 93.6   +   .4    %
SM24     - 21.7   +   .2    mm
PU16     +    .6  +   .1    mm
PU24     - 21.1   +   .3    mm
PU26     - 96.8   +   .4    mm
PU28A    -  1.9   +   .2    mm
BPM      24H
  POS    -  5.5   +   .1    mm
  DIAM   +  6.7   +   .1    mm
TTCYCL   + 74.0
```

Fig. 9. Print-out of statistics (mean values and standard deviation) accumulated during 41 single shot ejections. Symbols are explained in Table 1.

In the statistics mode the teletype prints mean values and RMS variations of the main beam data of three shots. In the single shot mode, it prints a coherent set of beam data for each shot, including internal and external efficiencies of all bunches.

The radiation alarm panel allows selection of a level for each radiation monitor, separately for each of the 3 shots and for "total radiation" (time window 150ms around ejection) and "fast radiation" (time window 30 μs after ejection). The corresponding lamp lights and an acoustical signal is issued when a level is exceeded. This permits localization of beam interception by ejection equipment, to distinguish between the three shots

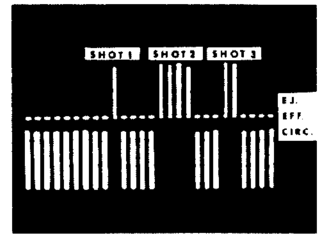

Fig. 10. CRT analogue display.

and whether the deflected beam or the circulating beam is the cause.

The CRT analogue display shows two rows of 30 vertical bars, giving respectively the efficiencies of the ejected bunches and the ones remaining in the accelerator thereafter. In the ideal case the rows are complementary (Fig. 10). Alternatively the CRT can display the beam profiles for three shots of the monitor chosen on the control panel (Fig. 11). The height of each bar is then proportional to the number of protons intercepted by the corresponding strip of the BPM.

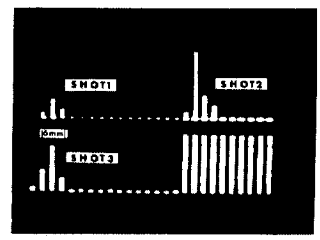

Fig. 11. CRT analogue display. Beam profiles from BPM24

Conclusions

In addition to what is said in the Introduction, the four months of operational experience proved the layout and choice of detectors and displays to be a lucky one and their functioning highly satisfactory. One can really grasp all relevant parameters, one has some cross checks in case of doubt and the displays have a convenient flexibility and are easily and intuitively interpretable.

Acknowledgements

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References

1. B. Kuiper, B. Langeseth, K.P. Myznikov: Proc. Int. Conf. High-Energy Accelerators, Yerevan 1969, Vol. I, p. 549.
2. R. Bossart et al. Proc. of 8th International Conference on High-Energy Accelerators, CERN 1971, p. 116.
3. J.H. Cupérus. To be publ. in Particle Accelerators.
4. J.H. Cupérus. To be publ. in Rev. of Sci. Instrum.
5. A.J. Sherwood, IEEE Trans. on Nucl. Sci., Vol. 12, No. 3, p. 925 (1965).