MULTIPLE SHOT AND MULTIPLE CHANNEL OPERATION OF THE CPS FAST EJECTION SYSTEM

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1. General

In 1963 a mobile small aperture kicker magnet in straight section 97, together with a mobile septum magnet a quarter or a betatron wavelength downstream in straight section 1, provided fast ejection[1] into the south experimental hall. One could eject either 1 or all 20 circulating proton bunches. This system served mainly the neutrino experiment and later the g-2 experiment, when facilities had been extended to 1-5 bunches or 17-20 bunches. In a later stage, other fast ejection channels were installed using stationary septum magnets in straight section 58 (1965)[2] and straight section 74 (1967)[3], serving the 2 m hydrogen bubble chamber in the east experimental area, respectively the 1 m heavy liquid bubble chamber in the neutrino area. An improved, radiation resistant version of the kicker magnet, permitting remote field polarity inversion, was installed in 1967[4]. Channel 1 was dismantled in 1968 but may possibly be replaced by a channel starting from straight section 2. Channel 16, for ejection towards the ISR[5] is scheduled for first operation in 1970.

The rapidly growing demand for fast ejection (more channels, more experiments, double pulsing of the B. C.) made more efficient beam sharing between different channels necessary. Since the new generation of fast kicker facilities, under development elsewhere in CERN, proved to be a longer term project, it was decided in 1967 to rebuild the old systen[6], aiming for installation in the summer shut down of 1968. This has been accomplished and the facilities are in operation since October 1968[7].

The new system, popularly called "Operation Straight Flush„ permits ejection of up to 3 bursts into the same or different channels during the same accelerator cycle (multiple shot). The energy and timing (interdependent), the number of bunches to be ejected and the kicker magnet field polarity may be chosen for each shot. The minimum time interval between bursts is 150-200 ms, depending on energy. The programme may also be varied from cycle to cycle (sequencing).

These new kicker magnet facilities permit to serve all existing and presently planned fast extraction channels (Fig. 1) and to cover all demand, probably for a few years to come.

Due to the numerous possibilities thus created, their use needs some experimenting and their full exploitation will be accomlished only gradually. Also, due to growing complexity of beam sharing schemes the urgent need for a complete and coherent beam diagnostic system is reconfirmed.

This programme required building completely new delay line pulse generators and spark gaps, incisive modification of the high voltage charging supply and construction of programmable controls for the latter, a new control and interlock system and, last but not least, a flexible programming and timing system to be able to take full advantage of the new facilities.

2. Kicker magnet

A central part of the fast ejection system is a mobile small aperture kicker magnet[4] of 20×22 mm^2 useful aperture, located in the accelerator vacuum system which is locally enlarged to a tank. The magnet is moved by a hydraulic servoactuator outside the tank over a connection shaft sliding through a seal.

The kicker magnet is of the delay line type with 10Ω characteristic impedance and 85 ns filling time. The inductances given by ferrite rings, and the vacuum dielectric plate capacitors between the ferrite rings have the coaxial structure of Fig. 2, the aperture being cut out of rings and plates. There are two magnet units, powered independently, fixed to a central support. The magnet may be excited up to 3000—3500 A, resulting in 0.12—0.14 Tm kick strength.

Mechanical switches, located right under the vacuum tank permit to commutate the current and hence the field direction, thus avoiding flashover difficulties encountered elsewhere with reversal of voltage polarity.

3. Delay line pulse generators

Each of the two delay line magnet units is powered through 80 m long transmission cables by a separate delay line pulser (Fig. 3), using a spark gap switch (front gap). A second spark gap (tail gap) may connect the other end of the pulse forming network to a matched dumping resistor. By appropriate timing of these gaps the pulse length going to the kicker magnet may be varied between 0.1 and 2.1 μs. The RC section at the front gap gives a short rise time to the pulse, the third gap (clipping gap) gives a short fall time by short circuiting the line at the relevant moments[8]). The construction is illustrated in Fig. 4. The two pulsers may be operated simultaneously or separately.

The spark gaps are of the three electrode swinging cascade type[9] with an annular electrode shape to reduce the influence of erosion. The gaps are triggered by 30 kV Marx pulse generators, the overall jitter being typically 12 ns.

The pulse forming networks may be charged to 30—70 kV within 150—200 ms by a H. V. supply with ignitron switches in the primary circuit. A start pulse opens the ignitrons for full wave charging. When a voltage derived from a H. V. divider is equal to the programmed reference voltage, the phase cut angle jumps to the other side of the sine wave and the voltage is then held constant to within $1^0/_0$ by a servoloop.

4. Electronic controls

A **program sequencer** (Fig .5a) gives a synoptic display of the beam sharing scheme in case the program is varying from pulse to pulse. During accelerator operation this program sequencer is a slave of the main accelerator programmer; it then receives timing signals from the latter and retransmits them to the ejection system. During accelerator stops the program sequencer can generate autonomous programs for system test runs.

The **kick and bunch selectors** (Fig. 5b) permit selection of the ejection parameters for each of the ejection areas programmed on the sequencer panel. The proton bunches are labelled earlier in the accelerator cycle such that it is possible to choose the first bunch and the number of bunches to be ejected for each of the subsequent shots.

The **pre-and post-pulse units** (Fig. 5c) are preset scalers generating trigger pulses locked to the ejection pulse, before respectively after ejection. If the ejection moment is changed, the pre-and post-pulses follow automatically, maintaining the preset time interval before or after ejection. These pulses serve to synchronize the septum magnet pulse, the closed orbit deformations, RF beam steering perturbations, monitoring oscilloscope triggers, RF separators. The pulses are also available to experimental groups.

An **interlock system** protects ejection channels, kicker magnet and pulse generator in case of failures. There are general interlocks and area interlocks. The general interlocks switch off the power supply of the high voltage pulse generator in conditions of alarm from vacuum, temperature, pressure, overvoltage and overcurrent detectors in the kicker magnet or pulse generator. The area interlocks inhibit the firing of the pulse generator at ejection channels, in which ejection is forbidden by personal protection. There are other area interlocks in case of improper ejection into an area: if the pulses of the two kicker magnets are not equal (pulse balance), if the spark gap pressure does not correspond to the high voltage (pressure-HV balance) or if the field inverters are not in the correct position.

A **monitoring system** permits to display all fast high voltage signals of the kicker magnet and pulse generators as well magnetic kick and some low level signals on an oscilloscope for systems check out. Another scope may display slow signals such as the H. V. charging process or the kicker magnet movement.

A **hydraulic programmer** (Fig. 6) generates an electric analog signal that is followed by the electrohydraulic servosystem[10] moving the kicker magnet. The cycle is first composed of voltage steps, then smoothed by a filter and modulated onto the 400 c/s carrier wave of the feedback system.

5. Operational experience

Since its first functioning in October 1968 the system has been in constant operation mostly in the double shot mode or in the triple shot mode. A number of machine development sessions have been held in order to exercise through some of the numerous new possibilities, which have by no means been exhausted. There possibilities are only gradually being discovered and included in the accelerator program, which has shown a growing complexity and diversity over the last year. The possibilities are expected to be fully exploited only some time from now.

The diagrams of Fig. 7 illustrate the complexity of beam sharing schemes as practised to date.

Figs. 8, 9 and 10 give typical oscillograms taken at a machine development session, during which three partial fast ejections were made at 200 ms intervals at 19.2 GeV.

The extraction efficiency at present varies with accelerator stability and operational care and attention, but is lower in the average than in the old days of single shot ejection. The principal causes for this may be (I) larger beam diameter due to growing accelerator intensity, (II) a bit marginal rise and fall time and intensity of the kick, (III) growing complexity of beam sharing schemes. The first two causes can not easily be avoided and may possibly be coped with by a new generation of ejection equipment in some years from now. The fhird (and not the least) cause may be reduced by operator training, and more and well chosen beam diagnostic equipment.

As a whole, the system has been working surprisingly well, considering the short construction and testing time of hardly one year. This is borne out by the fact that 3 months after start-up the responsibility for the system was transferred to the very efficient MPS ejection maintenance team and since that date the construction team has never been bothered with requests for help.

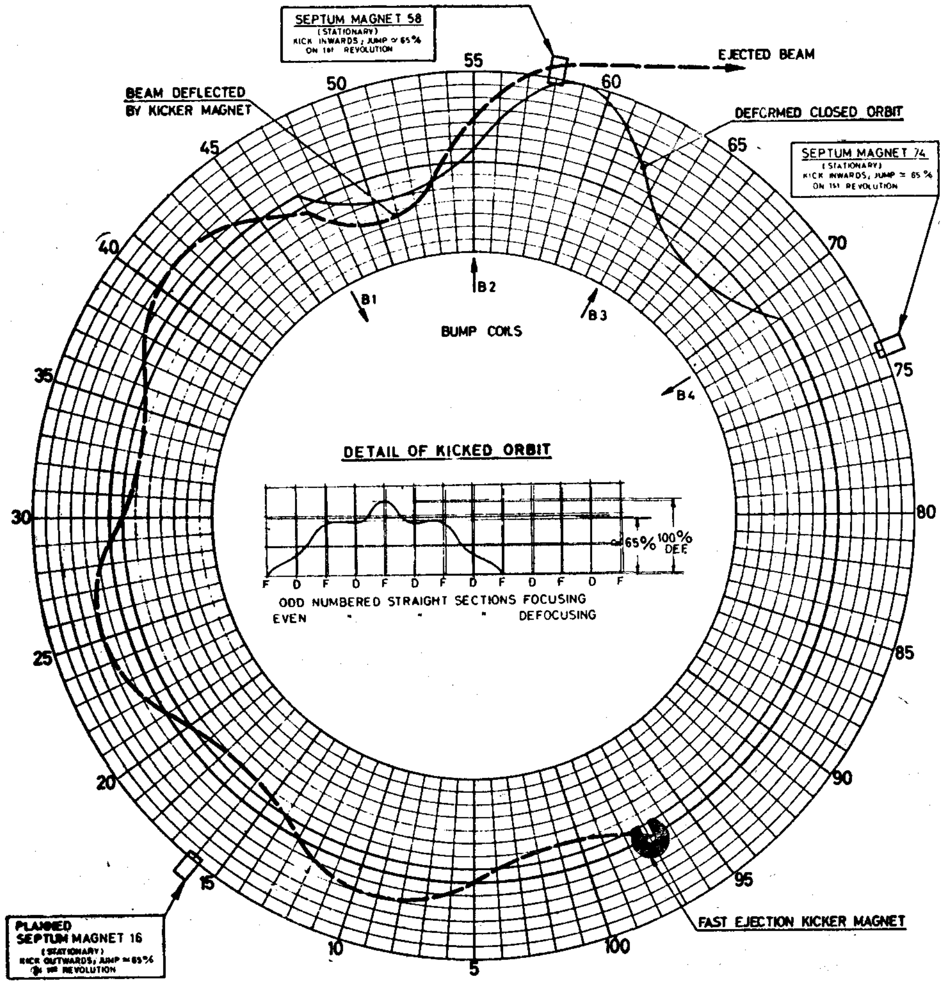

Fig. 1. **Fast ejection channels of the CPS** Presently existing channels are 58 and 74; channel **16** towards the ISR and West Hall is planned for 1970. All channels use stationary septum magnets. Example of ejection into channel 58: average closed orbit position is displaced a bit outward, A local closed orbit distortion (bump), centered around straight section **59**, is created by a double pair of backleg windings B1, B2, B3, B4. This places the beam in front of the septum magnet. The kicker magnet deflects the beam inwards, creating a betatron oscillation of enough amplitude to jump the septum. For a subsequent shot of the kicker magnet into another channel the previous bump is suppressed and a new one is created near the septum magnet of that channel.

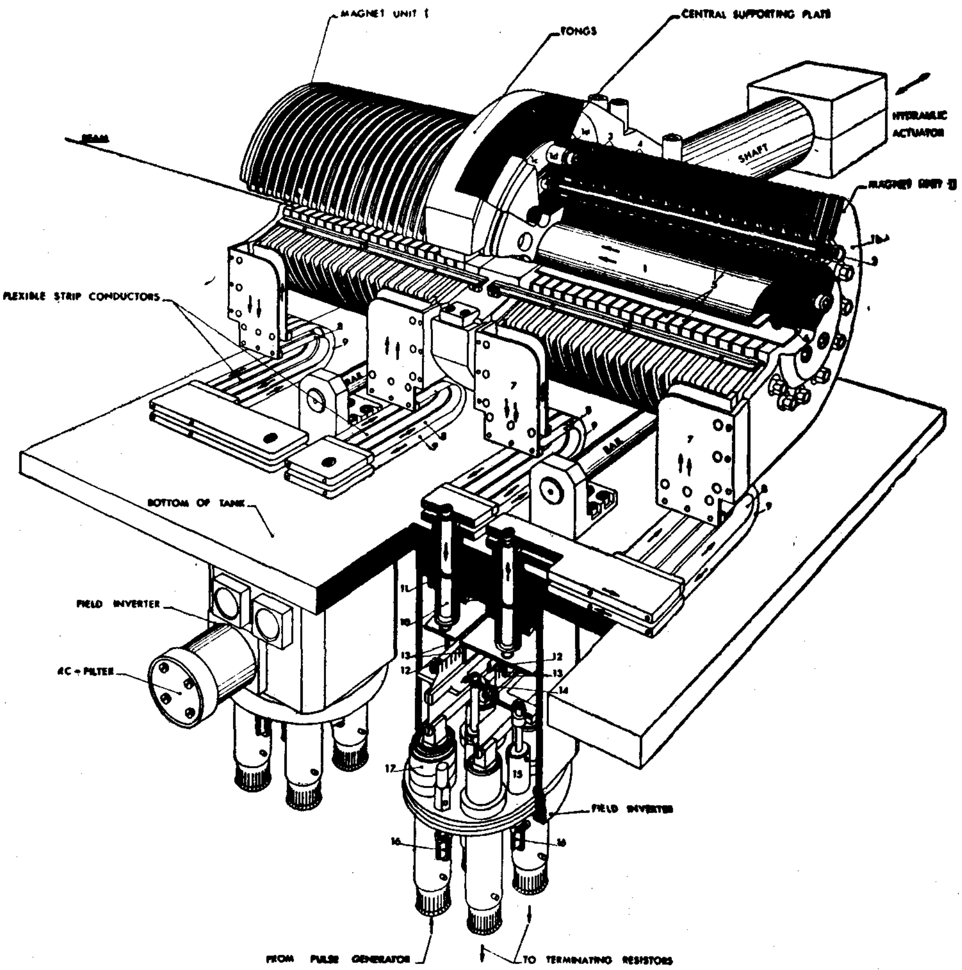

Fig. 2. **Perspective view and partial cut of the kicker magnet** (1) inner conductor with (1 a) inner flange and (1 b) outer flange: (2) outer conductors, (1 c), (2 c) rings cast into central supporting plates; (1 d), (2 d) stubs welded onto rings, (3) large, thin capacitor plates of inner conductor; (4) small, thick capacitor plates of outer conductors; (5) ferrite rings, borne by inner conductor; (6) profile‘alignin ferrite rings (7) plates supporting flexible strip conductors, (8) flexible strip conductors connected to inner conductor; (9) flexible strip conductors connected to outer conductor; (10) inner conductor of coaxial traversal connected to inner conductor of magnet unit; (11) earthed outer conductor connected to outer conductor of magnet; (12) moving contact of field inverter; (13) fixed contacts of field inverter; (14) moving bypass contact; (15) pneumatic cylinders actuating field inverter; (16) pressurized air connections to cylinders; (17) electrostatic pickup ring for observation of incoming pulse; (18) long pickup loops for observing time dependence of magnetic kick.

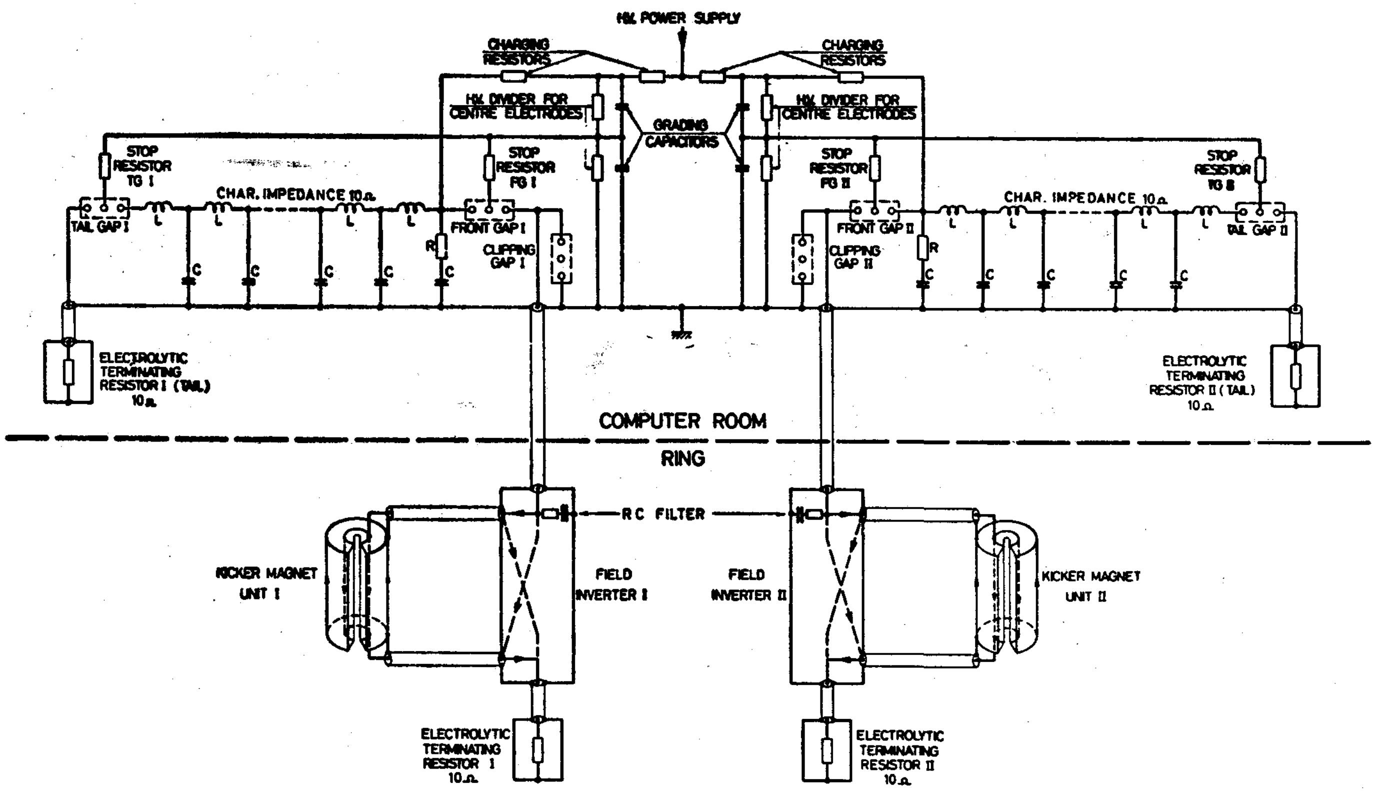

Fig. 3. **Simplified diagram of the H. V. pulse circuits** The kicker magnet consists of two units, each with a mechanical field inverter, permitting inversion of the current. Each unit is excited by its own line type pulser. The pulse duration can be adjusted by relative timing of front gap, tailgap and clipping gap.

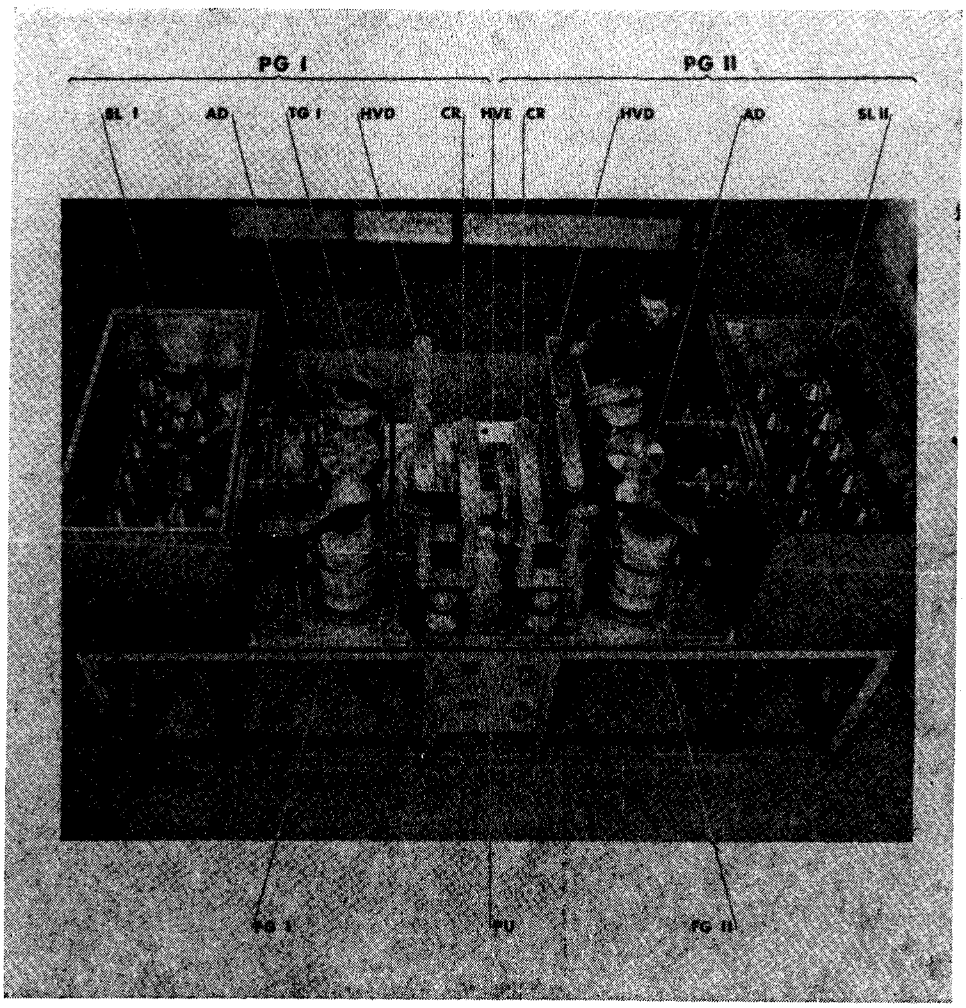

Fig. 4. **Delay line pulse generators being assembled for life tests**

PG=pulse generator; SL=storage line; FG=front gap; TG=tail gap; AD=RC section for steep, pulse front; HVD=high voltage divider for center electrode of spark gaps; CR=charging resistor; HVE=high voltage entry from power supply; PU=air pressure unit for sparkgap.

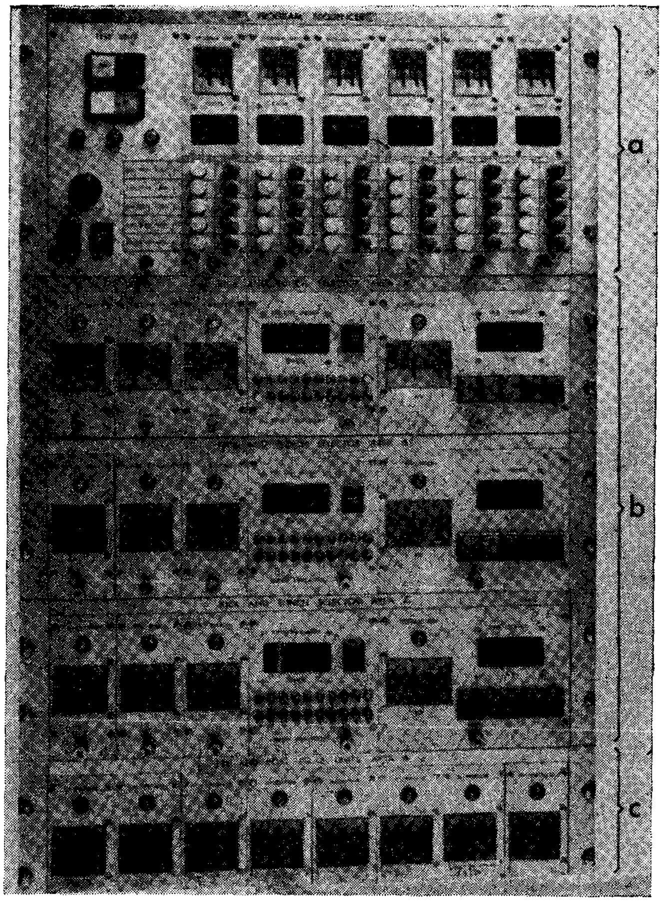

Fig. 5. **Programming and timing**

a) Program sequencer

The programs are repeated for a preselected number of acceleration cycles, with Nixies displaying the counted cycles. In each program unit the ejection areas are switched on with the left-hand knob, and the right hand light flashes when the high voltage pulse generator is triggered. After completion of the preselected cycles, the next program unit is started; the last program unit restarts the first unit. For tests during stops of the PS accelerator, the test unit simulates the M-train, RF and RF/20 signals. The test cycle time can be varied between 0,5 and 3,3 sec.

b) Kick and Bunch selector

The M-ejection unit counts the M-pulse train and provides a selection of the ejection energy. The first bunch unit selects the first bunch to be ejected, and the ejected bunches unit selects the total number of bunches to be ejected. The ejection energy in calculated from the main magnetic field, and is displayed by Nixies. The line voltage is preselected, sampled immediately before ejection and displayed. Push, buttons under the line voltage display select the lines to be pulsed and the polarity of the magnetic kick.

c) Pre-and post-pulse units

For synchronization of auxiliary ejection operations or phycics experiments to the ejection moments a number of units is allocated to each area. Example: a number of 23 programmed on a pre-M-pulse unit of area A, results in a trigger pulse 23-M-pulses before the ejection M-pulse of area A. The M units are for rough timing the RF units have max. 1—2 ns jitter with respect to the first ejected bunch.

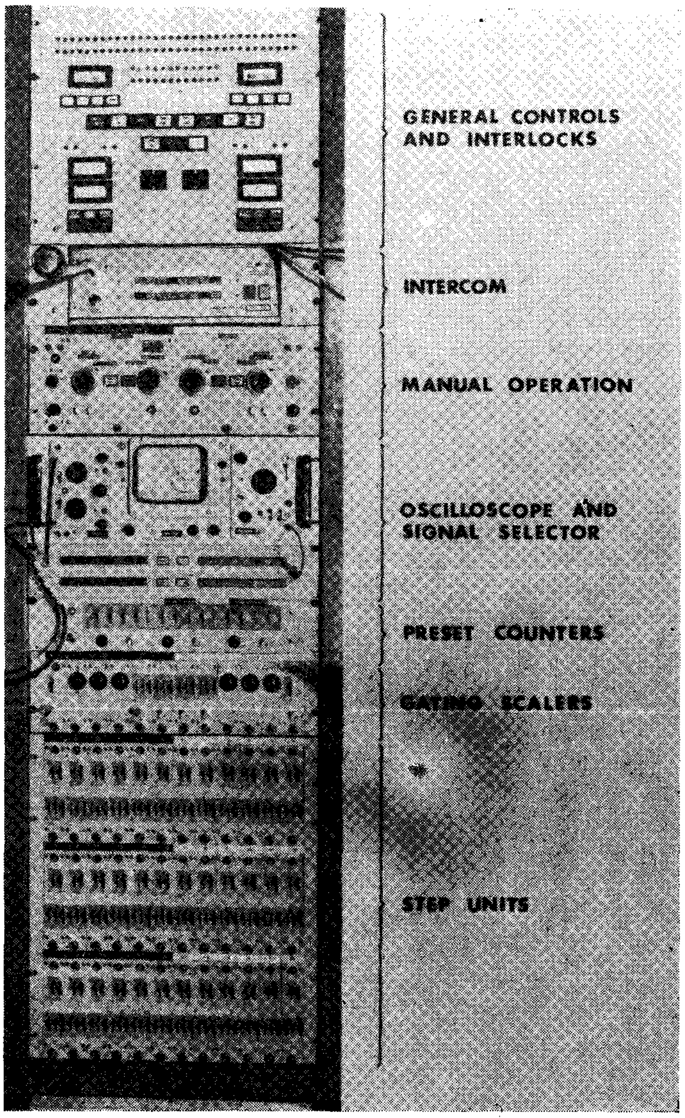

Fig. 6. **Hydraulic servoactuator controls and programmer**

The program is an electrical analog signal first composed in steps by the step units, then smoothed by a filter and modulated on the carrier wave of the servosystem. Each step unit is a preset counter combined with preset voltage generator. At the chosen *M*-pulse the *analog signal* assumes the voltage preselected on the unit, until the next unit takes over in the same way. The cycle may be advanced or delayed as a whole by the gating scalers which let the M-train through at chosen moments.

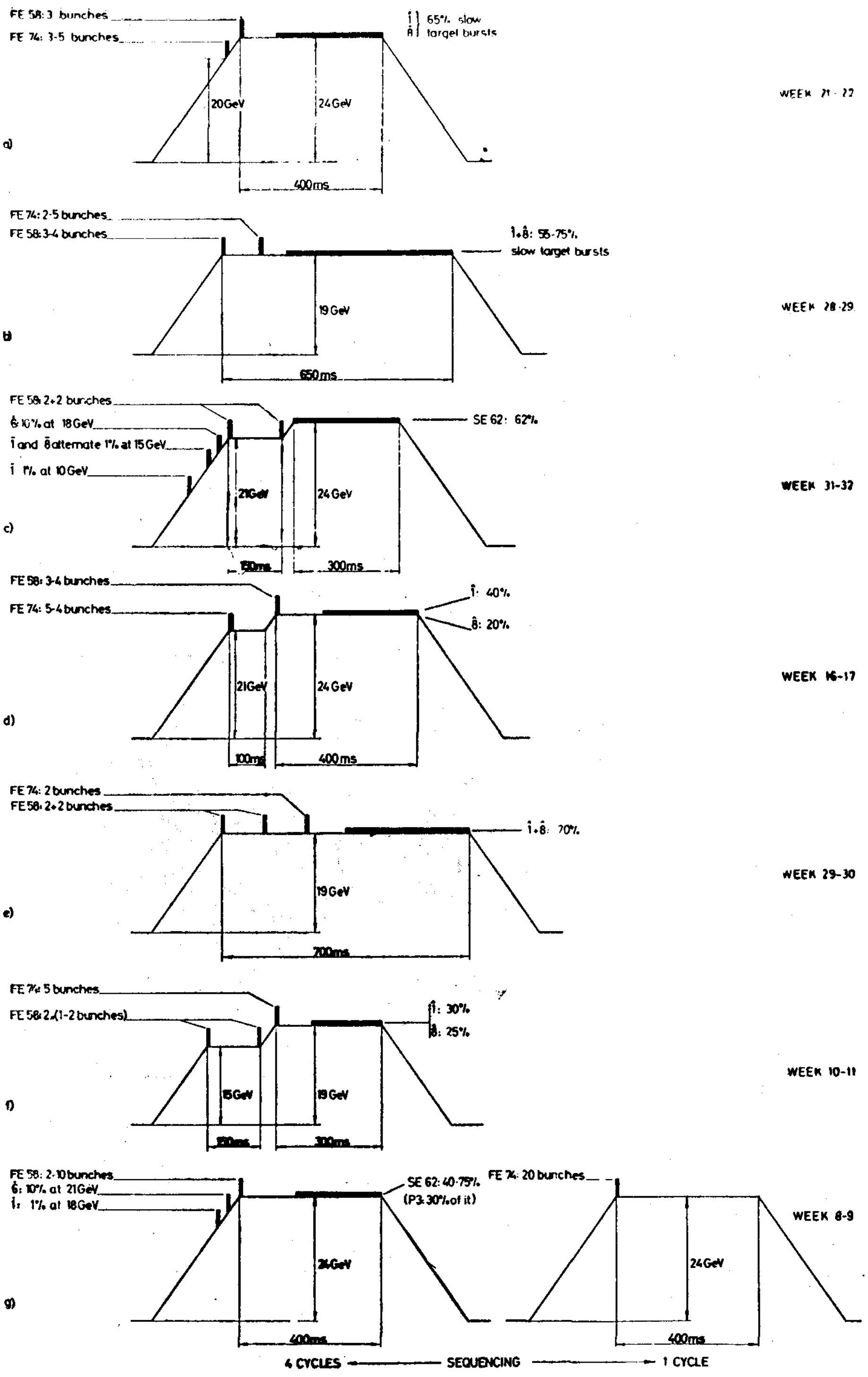

Fig. 7. **Typical Beam sharing schemes:**

FE 58 means fast ejection into channel 58, etc. SE 62 means slow ejection into channel 62. n means a short burst on target n. $\bar{n}$ a medium burst, $\hat{n}$ a long burst.

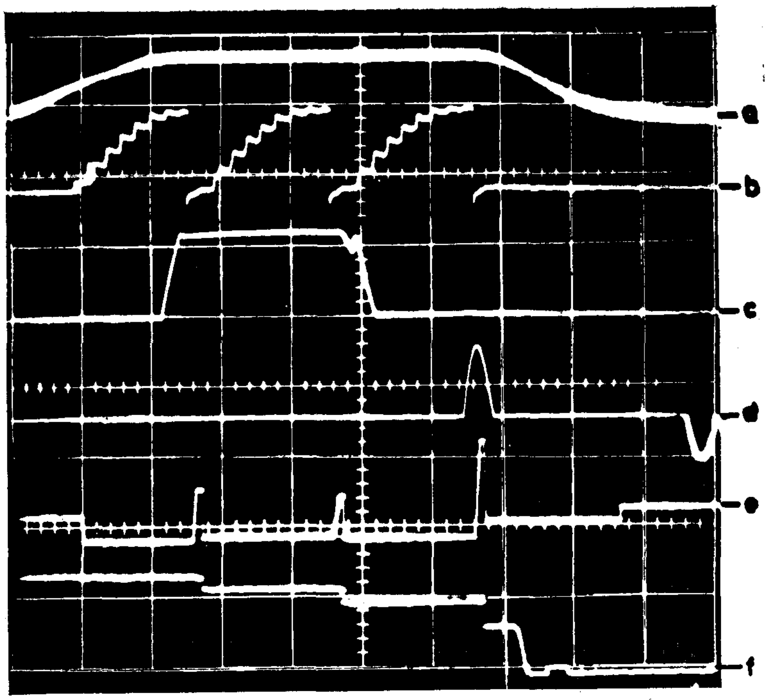

Fig. 8. **Triple fast ejection:**

Two shots are ejected into the bubble chamber channel and then one shot into the neutrino channel, all in intervals of 200 ms at 19.2 GeV/c. The oscillogrammes (100 ms/div) show

a) kicker movement
b) line voltage
c) bump current during ejection into bubble chamber channel
d) bump current during ejection into the neutrino channel
e) RF-perturbations
f) internal beam current trafo

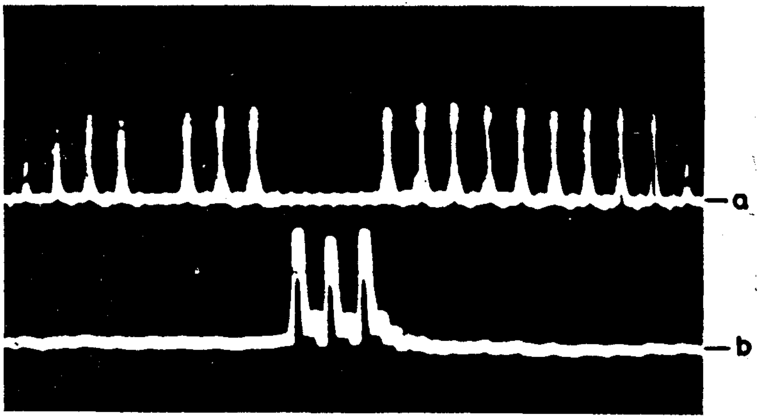

Fig. 9. **Second shot of triple fast ejection:**

The oscillogramme a) shows the bunch structure with 105 ns from bunch to bunch of the internal beam just after the second shot, 1 bunch having bean ejected by the first shot and 3 bunches by the second shot. The oscillogramme b) shows the three ejected bunches of the second shot passing the bubble chamber channel.

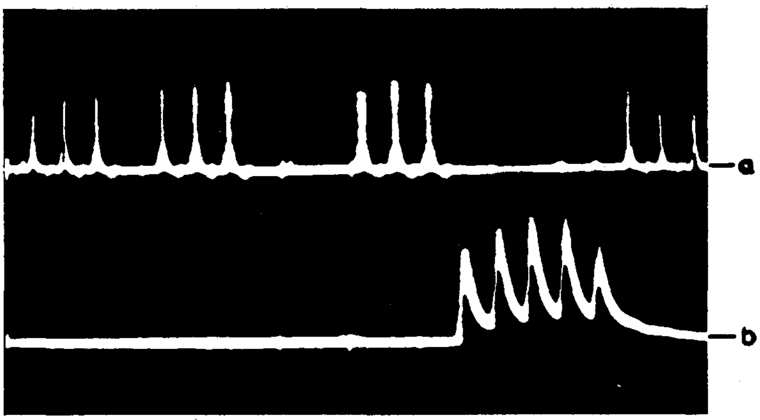

Fig. 10. **Third shot of triple fast ejection**

The oscillogramme a) shows the bunch structure with 105 ns from bunch to bunch of the internal beam just after the third shot, 1 bunch having been ejected by the first shot, 3 bunches by the second shot and 5 bunches by the third shot. The oscillogramme b) shows the 5 ejected bunches of the third shot in the neutrino channel.

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ДИСКУССИЯ

Столов: Во время работы вывода в течение одного цикла меняется ли давление в разрядниках при разных уровнях энергии выводимого пучка?

Kuiper: No. Originally we thought of doing this, but development of a fast programmable pressure regulation proved too tedious for the time we had, so we dropped it. Later, the pressure range, over which the gap switches reliably was increased so that it is now possible to work at different voltages without pressure changing. Also, at half the maximum voltage or less one may pulse only one of the two kicker magnet modules, giving only half the maximum kick or less. It is even possible to work at different energy levels without voltage change. One then chooses the voltage for the maximum energy and accepts bigger deflection for the shots with lower energy, which one compensates by placing the beam further away from the septum by r. f. steering. Voltages change is a convenience rather than an absolute necessity.

Водопьянов: Что показывает Ваш опыт работы с разрядниками? Каково число срабатываний одного разрядника?

Kuiper: The present spark-gaps have now $\sim 10^7$ shots and have not failed. They may need cleaning after, say, $3 \cdot 10^6$ shots indicated by instabilities. The figure may be pessimistic since we did open, then occasionally also for other reasons or by wrong suspicion and so we do not yet know how long they can really work before giving trouble.

Казанский: Какова стабильность характеристик выведенного пучка; разброс по импульсам и интенсивности от импульса к импульсу?

Kuiper: Momentum precision is about 0,1%. It is given by ejection timing essentially a time-pulse, and the reproducibility of the magnet cycle. Stability is fairly good and more dependent on the accelerator than on ejection (varying beam position, varying filling rate of bunches). Exceptions: I bunch operation, because of mentioned marginal rise and fall time. Also, at the higher energies, when the beam does not jump the septum with enough margin at 20 GeV and good operation the R. M. S. Fluctuation may be estimated to be typically ±5% for single bunch ejection and ± 2% for 5 bunches ejection.

Blumberg: a. What type of orbit deformation: dipole or backleg?

b. Is it half wavelength or $3\lambda/2$?

c. What is duration?

Kuiper: Orbit deformation are made over 3/2 betatron wave length, created by backled windings on 4 pairs of magnet units. The duration of their excitation current pulse depends on the particular operational scheme, the rise and fall time may be 20—50 msec.

Agoritsas: Could you please give the pulse shape and the characteristics of your delay line generator for a shot of one bunch? i. e. rise time, fall time, duration and ripple on the flat top.

Kuiper: With correct adjustment of the system the rise time for, say, 5 bunches is $\sim$100 nsec to 90% and then another $\sim$100 nsec to 100%. Ripple on the flat top is less than 5% peak to peak, fall time is $\sim$100 nsec to 10%, there after there is some remaining ripple. For single bunch ejection the rise time and fall time are essentially the same but there is no clear "flat„ top. The kick is short of triangular with a rounded off peak. The voltage must be increased because of the 90%.

Barbalat: For the slow extraction eficiency measurement we calibrated our detectors with the fast beam and it was possible to set up a fast ejection with practically 100% efficiency. But this needed of course rather long and delicate adjustment.

Столов: При эффективности вывода 90%, что является причиной потерь?

Kuiper: It has been shown repeatedly that it is possible to obtain 100% ejection efficiency with "careful" operation. However, during "normal" operation in shifts the efficiency in general drops. Reasons are: 1) rise and fall time of the kick are marginal to that, when synchronization is incorrect, the first and the last chosen bunch may be on the rise, respectively fail of the kick and a part of these bunches interacts on the septum 2) at the higher energies the kick strength becomes marginal and as we go up all bunches may start interacting with the septum. Presently we work up to 20 GeV. 3) The beam has grown thicker over the years and hence neads a larger kick. Moreover it is now more or less filling the good field region of the kicker magnet. At incorrect beam to magnet position the outer particles may obtain less than nominal kick: 4) We must also face the fact that beam sharing schemes have grown so complicated that they just require more care and understanding than a few years ago. 5) The beam diagnostics is still often insufficient or partly out of order, which does not make it simpler for the operation.

Адо: Что можно сказать о надежности системы вывода?

Kuiper: Do not know the exact figures by heart, but statistics in terms of operation hours are extremely good.

Neale: When J work at CERN several years ago, quite often one of the 20 bunches was missing due to fault injection. Do you still have this problem? If so how can you make sure that you do not eject the missing bunch?

Kuiper: Yes, the "inflector bunch„ it still incomplete, typically 0÷30%. It depends on operatien and may be 100% when carefully adjusted. The inflector have a marginal turn-off time. Since the bunches are labelled earlier in the cycle one can choose a specific bunch and there is no risk of "ejecting the missing one". Of course this is essential for multiple shot operation.