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SOME RESULTS ON THE COMPLEX ADJUSTMENT AND START-UP OF THE IHEP PROTON SYNCHROTRON

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INTRODUCTION

The 70 GeV proton synchrotron was constructed on the basis of a project drawn up by a number of scientific research and design organizations.

The Institute of Theoretical and Experimental Physics of the State Committee for the Use of Atomic Energy (ITEP) was responsible for the physics part of the project. The D.V. Efremov Scientific Research Institute for Electro-Physical Apparatus of the State Committee for the Use of Atomic Energy was responsible for the magnet and its power supply system, the vacuum chamber and the injection equipment. The RF systems controlling the acceleration process and the generation of the accelerating field, and also the radiotechnical measurement and beam observation systems were developed by the Radiotechnical Institute of the USSR Academy of Sciences.

The state design institute Tyazhpromelektroproekt (Heavy industry electrical design) designed the general purpose electronic equipment and the cable connections. The accelerator building complex was designed by the State Union Design Institute of the State Committee for the use of Atomic Energy. The accelerator construction was generally supervised by the USSR State Committee for the use of Atomic Energy. The adjustment of the separate systems and the complex adjustment and start-up of the accelerator were carried out by the Institute of High Energy Physics of the State Committee for the Use of Atomic Energy (IHEP) and those responsible for the acceleration system. The main work on the beam was done by IHEP with the participation of the Radiotechnical Institute of the USSR Academy of Sciences.

The construction of the accelerator was begun in 1961, and by the beginning of 1967 all the main structural and assembly work for the accelerator project had been completed[*]. By September 1967 the individual systems were adjusted and on 14 October the accelerator was commissioned.

The parameters of the IHEP proton synchrotron were repeatedly published at different stages of the project[1-5].

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*) In the first stage of construction of the accelerator, until the formation of IHEP in 1963, the work was coordinated by ITEP.

Main parameters of the IHEP proton synchrotron

Parameter	Value
Number of magnet units	120
Number of super-periods in the magnet structure	12
Structure of the period	FODO
Length of equilibrium orbit	1483.7 m
Radius of curvature of orbit in magnet unit	194.1 m
Mean radius of orbit	236.2 m
Core length of normal magnet unit	10.42 m
Core length of short magnet unit	9.30 m
Length of long straight section	4.87 m
Length of medium straight section	2.62 m
Length of short straight section	1.27 m
Distance to the hyperbola asympote in magnet unit	43.8 cm
Number of betatron oscillations per turn:	
radial	9.72
vertical	9.65
Useful section of vacuum chamber:	
radial	17.0 cm
vertical	11.5 cm
Injection energy	100 MeV
Magnetic field at injection	76 Oe
Transition energy	~8 GeV
Maximum particle energy	76 GeV
Maximum magnetic field on orbit	13000 Oe
R.F. harmonic number	30
Amplitude of accelerating voltage	370 kV
Frequency of accelerating voltage:	
upon injection	2.6 MHz
at the end of injection	6.05 MHz
Acceleration time	2.6 sec
Cycling time of accelerator	7 sec
Design intensity	10^{12} protons/pulse

I. ADJUSTMENT OF ACCELERATOR SYSTEMS

The commissioning of the accelerator was preceded by a long period of assembly and complex adjustment of the separate systems. Below we give a short description and the results of the adjustment of the main systems of the proton synchrotron excluding the linear accelerator-injector, which was commissioned on 28 July, 1967.

1. RING MAGNET

The magnet of the proton synchrotron consists of 120 magnet units, each of which consists of five stacks, encompassed by a general winding. The stacks are made of 2 millimetre silicon steel sheets, and the profile of the sheet was stamped without subsequent machining.

The stacks of each unit are fixed to a supporting block and can be moved in a horizontal and vertical direction. The supporting block, in turn, can also be adjusted by means of special jacks.

The main magnet winding is made of aluminium conductor with a cooling water channel. A general view of part of the ring tunnel with magnet units installed appears in Fig. 1.

a) Water-cooling system

The magnet water-cooling system had to remove about 2×10^7 kcal/hour, produced in the winding when the magnet is in operation. The coolant of the cooling system has to have an electrical resistance of not less than 5×10^5 Ωcm, so that the loss currents passing through it do not lead to distortion of the azimuthal distribution of the magnetic field.

The coolant used is demineralized water obtained in desalting plant with ion-exchange resins. At the output from the plant the resistance of water is 2×10^6 Ωcm, which considerably exceeds the required value.

b) Magnet power supply

The ring magnet is excited through ignitron rectifiers from four motor-generator sets with flywheels. On the a.c. side the generators are connected in a ring circuit. The rectified voltage from the coupled sets is fed separately into the upper and lower magnet windings. The amplitude of the sum current of upper and lower windings is 10,000 A and the peak power supply is 100 MW. Figure 2 is a view of the ignitron rectifier hall.

During the start-up of the accelerator, the same parameters of the magnetic field cycle were used as for carrying out magnetic measurements on an assembled magnet. The following time characteristics were obtained for the cycle during the adjustment process:

Rise time of current	2.45 sec ± 20 msec
Decay time of current	1.93 sec ± 20 msec
Flat top	2.57 sec ± 30 msec

The variation of the rise time of the magnetic field does not exceed ±0.5%. This is achieved by using a filter with booster capacitance.

c) Magnetic measurements

On the basis of measurements of the magnetic characteristics of the stacks, carried out both on a special bench in the factory, and on the IHEP bench, the stacks were arranged in magnet units. The measurements made it possible to arrange the stacks and units round the ring in such a way that the resonance harmonics in the magnetic field (for example, the 10th harmonic) were considerably attenuated.

Owing to the low level of the injection field (76 oersted) and the high sensitivity of the shape of the orbit to small external fields, loss currents, etc., in order to obtain the final information on the magnetic characteristics of the ring magnet (including stray fields in the straight sections) measurements were made of the magnetic characteristics of an assembled magnet of the accelerator under rated excitation conditions. The measurements confirmed that the magnetic field characteristics were satisfactory (for example, the r.m.s. field dispersion in magnet units at injection level did not exceed 0.15%, and in medium and high fields it was less than 0.04%).

Processing of the results of the measurements[5)] showed that even without correction of the magnetic characteristics distortion of the equilibrium orbit did not exceed ±6 cm upon injection.

d) Geodetic measurements

The magnet units were installed with reference to a special geodetic network, including 60 reference marks with uniform azimuthal distribution.

During the period before start-up, the stability of the geometrical position of the ring magnet units was measured. The programme included measuring the vertical and horizontal displacement of the magnet units and also determining possible deformation of the magnet units themselves. It was established that deformations of the ring magnet did occur as a result of a series of factors. The most important reasons for deformation were: the installation of concrete shielding in the experimental hall (settling of the magnet units of up to 1.5 mm); excavation of ground in the immediate vicinity of the magnet units for the construction of new experimental halls (elevation of the units by 1.5 mm); additional subsidence round the whole length of the ring; variations in the hydrothermal conditions in rock layers serving as a foundation for building work.

Processing of the above measurements shows that such considerable displacement of the magnet units leads to distortion of the equilibrium orbit of not more than ±7 mm. This is explained by the evenness of the deformation and the practical absence of harmonics in the resonance range.

e) Correction system

The systems for correcting the field of the ring magnet serve to regulate the main characteristics of the magnetic field determining the operation of the accelerator. Corrections to the shape of the equilibrium orbit, horizontal and vertical, the frequencies of the betatron oscillations, the non-linearity of the magnetic field and other parameters can be carried out during the whole accelerating cycle up to the maximum magnetic field strength. There are additional correcting systems specially for the injection field region including passive correction of the residual field in all magnet units, correction of the equilibrium orbit per section (20 sections) and correction of the transients occurring in the magnet winding. The latter are due to the fact that the magnet represents a long line in which a transient process occurs when the power supply is switched on, considerably distorting the azimuthal distribution of the magnetic field.

In order to correct the vertical component of the magnetic field, additional windings are used, placed in each magnet unit in the same casing as the main winding. Correction of the other parameters of the magnetic field (gradient, median plane, non-linearity of the field), is carried out by means of special windings placed on the pole surfaces of the magnet units.

2. INJECTION SYSTEM

The injection system serves to transport the proton beam from the injector to the accelerator ring and to place the particles in the equilibrium orbit. It consists of a matching channel and injection device. A block diagram of the injection system is given in Fig. 3.

a) Matching channel

The optical part of the channel consists of 10 quadrupole lenses, two kicker magnets and five correctors, which match the emittance of the beam from the linear accelerator to the acceptance of the synchrotron. On account of the great length of the channel (about 80 metres) the design chosen was not the widely spread system of triplet quadrupole lenses, but a channel-type system consisting of alternate focusing and defocusing lenses. Part of the input channel can be seen in Fig. 1.

Before assembly of the optical components, magnetic measurements were made and the lenses were shimmed, which made it possible to widen substantially the region of uniform gradient. The lens power supplies ensure long term stability of the gradient and field to within ±0.5% in the lenses and correctors and ±1% in the kicker magnets. The beam optics were calculated for the matching channel and the injection trajectory in the stray magnetic fields. The channel was calculated so as to obtain in addition to the matching a beam cross-over of minimum dimensions at the debuncher (the debuncher is located between lenses L_5 and L_6 in Fig. 3).

b) Injection device

The injection device consists of one pair of electrostatic plates and four pairs of pulsed plates (respectively E_1 and E_2-E_5 in Fig. 3).

The power supplies of the plates are made so as to ensure both one-turn and three-turn injection of particles into the accelerator. In the latter case transient orbit distortion is produced locally by means of pulsed plates. The stability of the power supply voltage of the electrostatic plates is ±0.1% and of the pulsed plates ±0.5%. For one-turn injection the fall time of the voltage on the pulsed plates does not exceed 0.3 μs.

3. VACUUM SYSTEM

The accelerator vacuum chamber is made of Mark 1X18H10Г 0.4 mm thick corrugated stainless steel with an elliptical cross-section with 115 × 195 mm axes. The whole chamber is divided by section valves into 20 sections, which can be pumped down separately. Aluminium seals are used for the majority of the connections. HЭM-300 titanium sputter ion pumps with a pumping speed of 300 ℓ/sec are used to sustain the operating vacuum.

In all there are 132 of these pumps in the ring chamber and injection channel.

In order to obtain the forevacuum and start up the titanium pumps in each of the 20 sections, there is a pumping station including a BH-1MГ forevacuum mechanical pump with a semi-conductor trap and a BH-2MГ pump.

Before assembly, all the joints of the chamber and the vacuum equipment underwent preliminary vacuum tests on a bench. Preliminary tests contributed to a considerable extent to the successful performance of the assembly and start-up adjustment work. It took 4 months to assemble the chamber and vacuum equipment, carry out the adjustment and obtain the operating vacuum of $(2\text{-}4) \times 10^{-6}$ Torr.

Operating experience with the vacuum system over several months showed that the rated vacuum could be achieved by operating half the NEM-300 pumps installed, which proves the satisfactory vacuum seal and low degassing rate of the chamber walls.

4. RF SYSTEM

In the period before the accelerator start-up, work was done to adjust the RF systems generating the accelerating field and controlling the acceleration process, and the radiotechnical measurement and beam observation systems. The adjustment was carried out in three stages: separate tuning of the various systems by means of simulators, complex adjustment together with other systems of the accelerator and tuning of the apparatus under proton accelerating conditions.

a) System generating the accelerating field

Proton acceleration is carried out by means of 54 accelerating stations located in straight sections between the magnet units. Figure 4 is a photograph of one of these stations. Each station ensures an amplitude of the accelerating voltage of about 7 kV and the accelerated particles receive an energy increase of 190 keV per turn with normal values of the equilibrium phase (30°) and the magnetic field rise rate (6,500 oersted/sec). The accelerating stations are resonance amplifiers with automatic tuning of the output circuit by magnetization of the ferrite. The frequency of the programmed FM master generator is synchronized to change with the strength of the magnetic field in the accelerator magnet gap in the 2.6-6.1 MHz range. The automatic control system of the FM generator ensures following the frequency law with an accuracy of 10^{-4}-10^{-6} by means of the information on the radial-phase motion of the accelerated beam. When adjusting the RF system the greatest attention was paid to the system generating the accelerating field, since in the laboratory tests the accelerator working conditions could not be completely reproduced. In order to tune the FM master generator with the beam frequency control system a radiotechnical beam model was used. Work was done to increase the response rate of the ferrite resonators of the accelerating stations after the RF voltage is switched on.

b) <u>System controlling the acceleration process</u>

The synchronization of the main systems of the accelerator and of the measuring and control devices is carried out by pulses at the start of the magnetic cycle and at fixed values of the magnetic field strength. Magnetic field detectors are placed in a magnetic measuring block, the winding of which is series connected with the winding of the accelerator magnet. Measurements showed that the stability of these pulses is better than $\pm 1.5 \times 10^{-4}$ over a long period.

c) <u>Radiotechnical measurement system</u>

In the process of operating the accelerator, the initial and final value of the frequency of the accelerating field, the intensity of the accelerated particle beam, the position in time of the control pulses, etc., are automatically measured in each accelerating cycle. The indications of the instruments are recorded on a digital signal panel.

5. BEAM OBSERVATION SYSTEM

In the accelerator the beam parameters are measured both in the accelerating process and when ascertaining the particle dynamics in the first turn.

a) Beam observation in the first turn

The beam position and its shape in the input channel and in the accelerator chamber during the first turn are determined from its image on screens or grids covered with a scintillating compound. The observation is carried out by means of television apparatus from the main desk of the accelerator. The sensitivity of the apparatus makes it possible to observe 10^8 particles. In all there are 60 screens and 36 television cameras in the accelerator (including the input channel). The screens are installed with an accuracy of ±2 mm. In order to measure the beam intensity in the input channel, induction current detectors and a Faraday cylinder are installed.

b) Beam observation during acceleration

In the accelerating chamber there are 85 pairs of slotted electrostatic induction electrodes, for determining the position of the equilibrium orbit in the acceleration process. This quantity of electrodes makes it possible to obtain satisfactory information on the deviations of the orbit from the axis of the chamber in the radial and vertical directions (on the average there are 9 observation points for one betatron oscillation). The accuracy of measurement of the position of the orbit in the chamber at an intensity of $10^{10}\div 10^{12}$ protons per pulse is $0.1 \times X \pm 1$ mm (X is the deviation of the beam from the axis of the chamber).

There is also apparatus designed for measuring the azimuthal distribution of particles in separate bunches, the frequency of the betatron oscillations and a series of other values determining the particle dynamics in the accelerator.

II. START-UP OF THE ACCELERATOR

When commissioning the accelerator, the final aim was to obtain accelerated protons with the design energy. The problem of obtaining a high intensity accelerated beam was not posed.

1. METHOD OF START-UP

Beams of two types were used for injection when starting up the accelerator. At first, testing was done with a narrow, low intensity proton beam, sufficient however for it to be accurately observed. Such a beam is very convenient for the adjustment of the magnet optics of the matching channel and especially when studying the injection of particles into the ring accelerator and the motion of the protons in the first turn. Furthermore, at an intensity of 10^8 protons per pulse the residual radioactivity, immediately after the accelerator was switched off, remained at a low level. This was important, since it was necessary to carry out a series of fitting and adjustment jobs during the accelerator start-up.

A narrow 100 MeV proton beam was shaped by a collimator with an aperture of 3×3 mm^2, installed in the output of the linear accelerator-injector. The current from the injector was artificially lowered to 3-5 mA.

Tests with a beam of considerable intensity were begun only after protons were regularly circulating in the chamber, at the stage of beam acceleration with automatic frequency control of the accelerating voltage.

A chart of the separate stages of start-up of the accelerator is of interest:

1.	Beginning of work with beam	28 August 1967
2.	Putting beam through matching channel	1 September 1967
3.	Injecting beam into accelerator ring	2 September 1967
4.	Obtaining first turn and beam circulation	17 September 1967
5.	Capture into accelerating regime	5 October 1967
6.	Acceleration up to critical energy	7 October 1967
7.	Acceleration up to design energy	14 October 1967

The intervals between stages 3-4 and 4-5 were mainly occupied in the preparation of the vacuum system of the accelerator ring and the RF acceleration system respectively.

2. RESULTS OF THE START-UP

The first turn of protons in the accelerator chamber was obtained without magnetic field correction, but distortion of the trajectory reached ±5 cm in the radial direction and ±2 cm in the vertical direction. Passive correction of the magnet units together with correction of the field of the injection unit, where the non-standard part of the vacuum tank is located, made it possible to reduce the value of the radial distortion to ±2.5 cm. Figure 5 is a photograph of the beam image on a screen located immediately after the injection point of the beam into the accelerator chamber. The image at the edge of the screen is of the in-going beam and the one in the centre is of the beam completing the first turn (on the left the spot from the lamp illuminating the screen).

In the absence of accelerating voltage the beam injected into the chamber deviates in the magnetic field which increases in time towards the inner wall of the chamber. The deviation interval for the IHEP accelerator under circulation conditions is about 3.5 mm. Figure 6 shows an oscillogram of the signal from an induction electrode under circulation conditions. Circulation during 20 turns shows that distortion of the equilibrium orbit upon injection does not exceed ±3 cm, which agrees with the trajectory measured in the first turn.

In order to capture the protons into the accelerating regime, the protons were injected into the chamber with the RF accelerating voltage switched on. When using programmed acceleration without automatic frequency control of the accelerating field by the beam, 4.4 GeV protons were obtained. After the automatic frequency control was switched on and the moment of phase jump of the accelerating field in the region of the transition energy was matched, the protons were accelerated up to the maximum energy -- 76 GeV. The optimum regime was obtained by accelerating the protons practically in the mean radius of the accelerator. The system controlling the accelerating field frequency was switched on 1 msec after the beginning of acceleration. Particle losses after the completion of beam shaping did not exceed 50%. About 15% of the protons injected into the chamber were captured into the accelerating regime. The maximum beam intensity with a maximum energy of 76 GeV upon start-up of the accelerator reached 1.0×10^{10} protons per pulse*).

In conclusion the writers wish to express their sincere thanks to the many members of the staff and all who took part in the adjustment of the systems and the start-up of the accelerator.

*) Later, as a result of studies made on the accelerator and the improvement of a series of parameters of the systems, the intensity of the accelerated beam was increased to 1×10^{12} protons/pulse.

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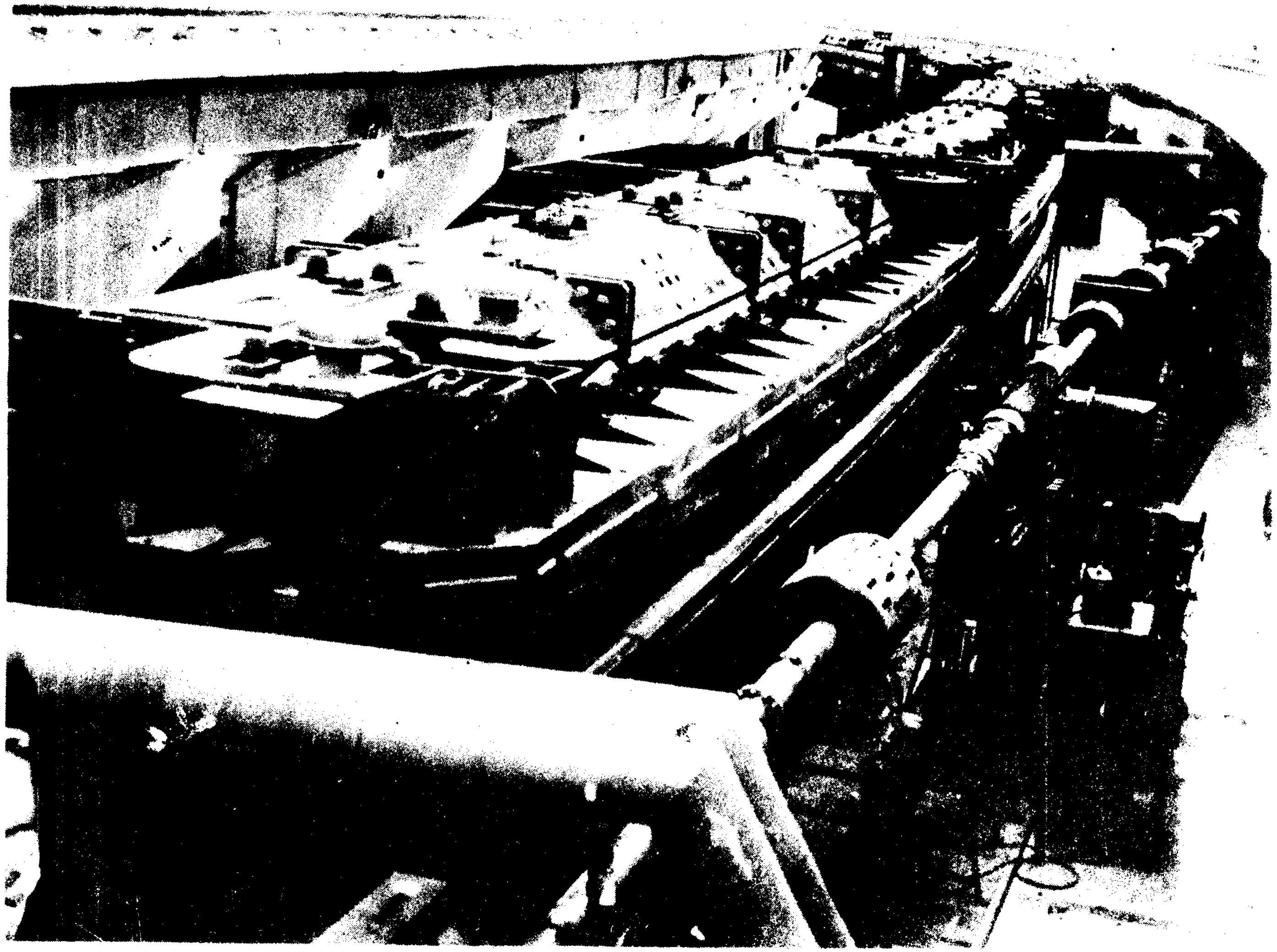


Fig. 1 View of part of the ring tunnel in the beam injection region

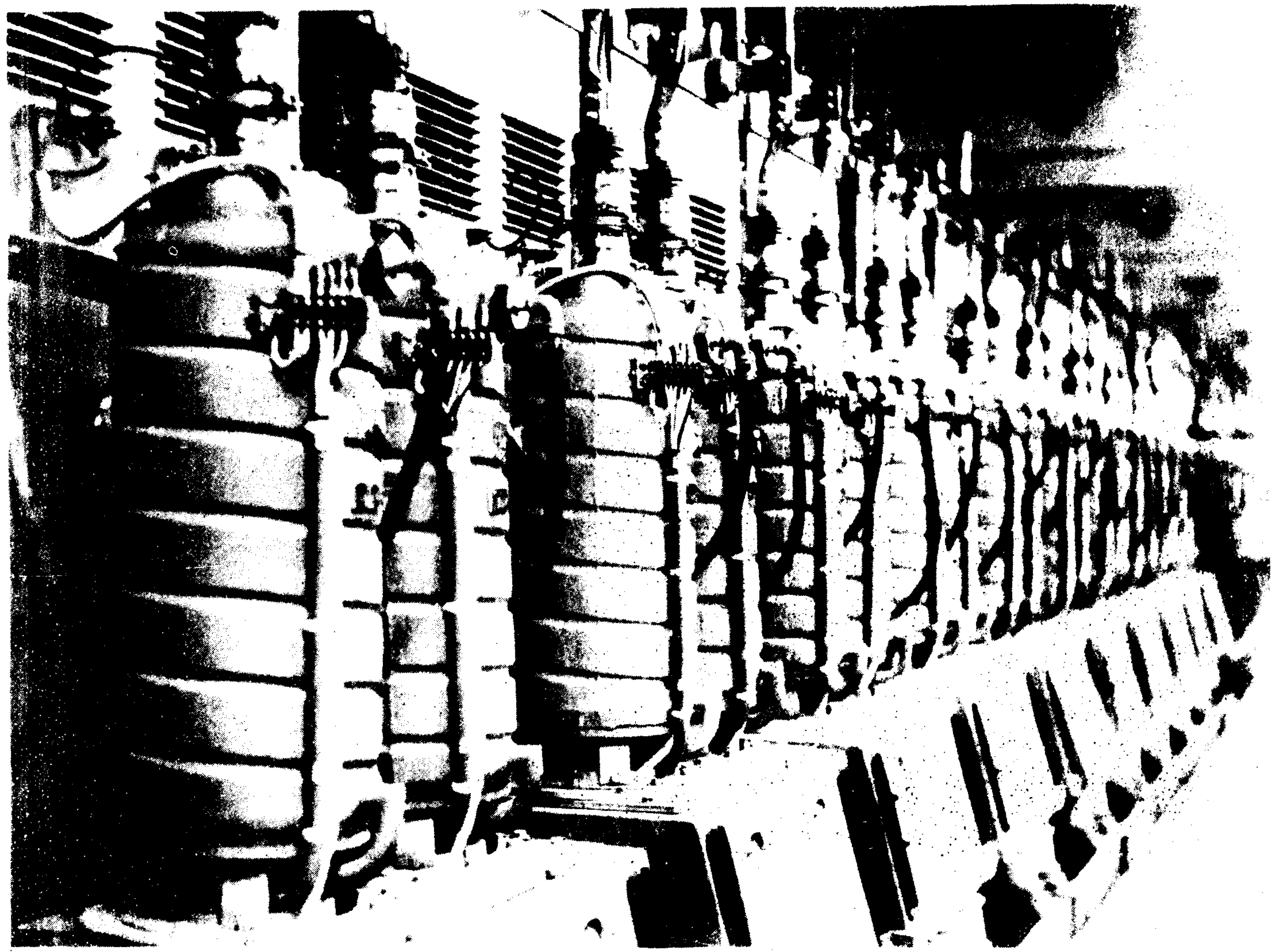
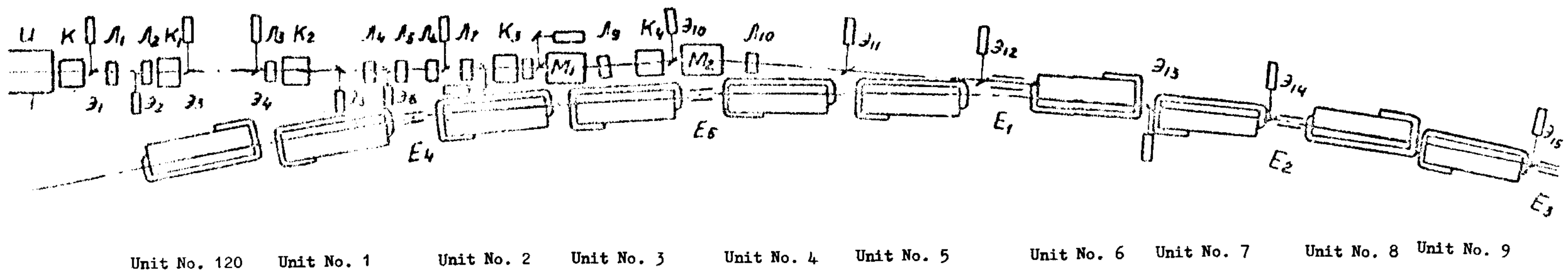


Fig. 2 General view of the ignitron rectifier room



Symbols:

Ц - injector
$Л_{1-10}$ - lenses
$К_{0-4}$ - correctors
$Э_{1-15}$ - screens
$Е_{1-5}$ - inflector plates
$М_{1-2}$ - kicker magnets

Fig. 3 Diagram of particle injection

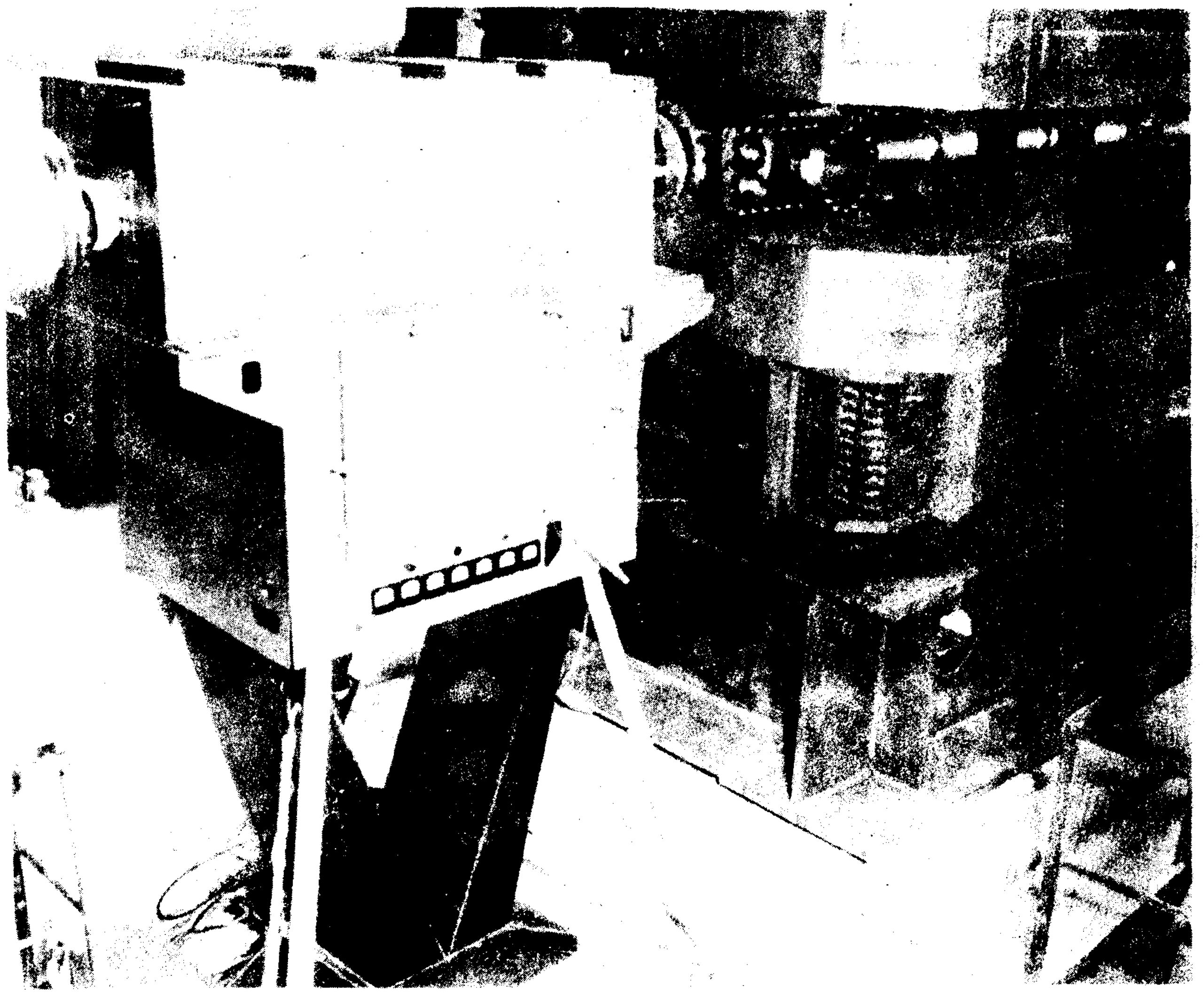


Fig. 4 Straight section with one of the 54 accelerating stations

Fig. 5 Photograph of the beam image on a screen located in straight section 7

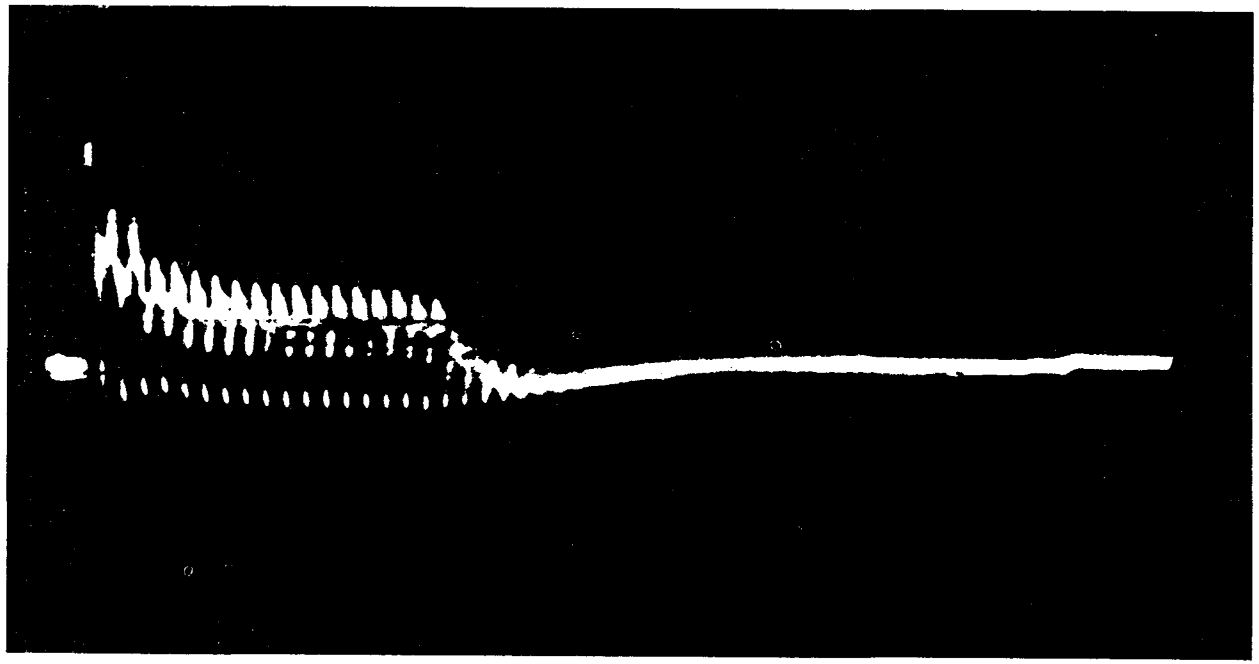


Fig. 6 Oscillogram of beam circulation in the accelerator chamber