USSR ACADEMY OF SCIENCES,
B.P. KONSTANTINOV NUCLEAR PHYSICS INSTITUTE, LENINGRAD

SYSTEM FOR INCREASING THE PULSE-DURATION OF THE PROTON BEAM IN THE 1 GeV SYNCHROCYCLOTRON OF THE LENINGRAD NUCLEAR PHYSICS INSTITUTE OF THE USSR ACADEMY OF SCIENCES

N.K. Abrosimov, R.P. Devyaterikov, A.G. Kotov,
A.V. Kulikov, G.F. Mikheev and N.N. Chernov

Translated at CERN by B. Hodge
(Original: Russian)
Not revised by the Translation Service

(CERN Trans. Int. 73-5)

Geneva
February 1973

Sent to Zh.T.F.

A combined system has been designed for the 1 GeV LNPI synchrocyclotron for increasing the duration of the internal and external proton beam macro-pulse, and for fast single-revolution beam spill onto an internal target.

In order to increase the duration of the beam (beam stretching) the slow acceleration principle is used, additional acceleration being given by a Cee-electrode (1-4). The fast-single revolution spill is effected by using a pulsed deflector to divert the protons vertically on to an internal target situated above or below the median plane (5-6).

Because of the design of the Cee-electrode and its power supply, these two systems can be used in combination, so that they can operate simultaneously with any desired sequence.

A distinctive feature of the stretching system is the comparatively high beam-capture efficiency of the Cee-electrode during the acceleration mode, with a sufficiently high duty factor for the cycle, which is obtained by frequency and phase synchronization between the basic accelerating system and the generator of the Cee-electrode. By chosing the optimum frequency programme for the Cee-system, the shape of the macro-pulse of the stretched beam was practically rectangular. The system incorporates a narrow-band resonance power amplifier, with synchronous frequency tuning, and in this way it has been possible to reduce substantially the RF power of the system.

The present paper describes the beam stretching system.

DESIGN OF THE Cee-ELECTRODE

The design and location of the Cee-electrode in the chamber of the accelerator is shown in Figure 1. To ensure that the Cee-electrode can operate simultaneously as an accelerating electrode for beam stretching and as a deflector for beam spill, it has been designed in the form of two split copper plates (2). The angular coverage of the plates is 60°, the width 250 mm, and the ejection radius R = 3165 mm.

Each of the plates is attached to the side-wall of the chamber (5) by means of three rod-type holders (7, 9). The central rods (9) act simultaneously as voltage inputs to the Cee-electrode. The side-rods are separated from the plates by ceramic insulators (4). The attachment system of the Cee-electrode is designed to enable the radial and vertical position of the plates to be adjusted without destroying the vacuum in the chamber. The plates are free to move over a distance of 40 cm in the radial direction, and the distance between the plates may be varied between 6 and 18 cm. The components for adjusting the plates are equipped with position indicators (6).

The design of the Cee-electrode insulators enables the system to operate as a deflector with a pulse voltage of up to 100 kV on the plates. Hollow ceramic insulators (13, 15) are used on the central supports. To prevent the vacuum seals from being broken by corona discharge, the cavities of the insulators are filled with an inert gas. It is possible to cool the inputs and the plates of the Cee-electrode with water.

Figure 2 shows a photograph of the wall of the vacuum chamber of the accelerator from the side of the holders and inputs to the Cee-electrode. The protective cover has been removed.

A simplified basic diagram of the output cascade of the stretching generator and pulse generator for the spill is shown in

Figure 3. The plates of the Cee-electrode (1) are connected with the output cascade L5 of the RF generator for the stretching system, by means of two feaders (2, 3) in the form of RKG-15-type cables. To ensure that the equipment was kept away from the radio-active zone and to reduce the amount of screening from the accelerator's magnetic field, it was decided to use 12.5 m feeders, which corresponds, for a beam-ejection frequency f_K = 13.4 MHz, to the excitation of an oscillation mode of $4x\lambda/4$, as shown in Figure 3 (4). Tuning of the resonance frequency is effected by a variable inductance with a ferrite core (8). The plates of the Cee-electrode are used at the same time as a pulse deflector for single-revolution spill of the beam. The pulsed voltage is produced by a thyratron generator L_{1-4} with an output ferrite transformer (7). The output coil of the transformer, which consists of the central cores of the feeders, made in such a manner that the system provides an in-phase accelerating voltage to the plates in the stretching mode and an out-of-phase pulsed voltage in the spill-mode. At the same time it is possible to prevent any coupling between the pulse-and RF generators.

FUNCTIONING OF THE SYNCHROCYCLOTRON IN THE BEAM STRETCHING MODE

The operating principle of the accelerator in the beam stretching mode is illustrated in Figure 4, in which the following are shown: f_D is the frequency programme of the basic accelerating system of the synchrocyclotron; f_C is the frequency programme of the Cee-electrode. U is the modulating voltage for controlling the frequency generator of the Cee-electrode. The main frequency programme is interrupted by means of the anode manipulator, (dashed curve). The generator of the Cee-electrode operates continually. Both frequency programmes are in phase with each other in the range of beam capture during acceleration by the Cee-electrode. When the frequencies of the basic programme f_D and the initial frequency of the Cee-electrode f_1 come close together at a moment of time t_1, the frequency of the Cee-electrode generator is captured by the frequency of the main generator, and during an interval of time $t_1 - t_2$ both generators operate in phase. At a moment in time t_2, when the frequency of the basic programme reaches a value of f_K , corresponding to the optimum radial position of the beam in relation to the Cee-electrode, the voltage from the main generator is switched off and an avalanche for forming the saw-edge current is switched on to control the generator frequency of the Cee-electrode. The interval $t_2 - t_3$ and the slope of the dependence $f_c(t)$ can be varied at will within a wide range. The lowest frequency of the generator f_3 corresponds to the end of beam ejection (13.3 MHz). The total deviation in the $t_2 - t_3$ range is 250 kHz.

BLOCK DIAGRAM OF THE BEAM STRETCHING SYSTEM

Figure 5 shows the block-diagram for the stretching system. Because of the substantial effect of the circulating beam on the resonance system of the Cee-electrode, the generator is made in the form of a master oscillator (10) and a resonance power amplifier (11). The ferrite variators (6 and 7) are magnetized by the current pulse from the amplifier (4), producing the variation in frequency in accordance with the selected law. In order to obtain the necessary law of variation in frequency over a period of time the current is shaped by a generator which produces a stepped voltage (2) providing an approximation of the random function $U(t)$ in 15 consecutive time intervals. Smoothing of the synthesized pulse is effected in the integrator (3). Synchronization of the beam stretching system with the basic programme of the accelerator is effected by a frequency-mark unit (7). The master oscillator (10) is synchronized with the main RF generator (12) of the synchrocyclotron by means of units 5, 8 and 9.

THE GENERATOR OF THE Cee-ELECTRODE

The design of the generator is shown in Figure 6. The master oscillator L_1 and the resonance power amplifier L_2 are designed using GU-5A lamps. The natural resonance frequency of the master oscillator can be varied by means of the ferrite variator L1, which is designed with 4 M200HH-type coils measuring 180 x 110 x 20 mm. The resonance frequency of the anode contour of the output power amplifier L_2 can be varied by means of the ferrite variator L2 (16 analogue coils). Both variators can be magnetized synchronously with saw-shaped current pulses from the final cascade of the current amplifier. In order to obtain the frequency deviation at 250 kHz for a mean frequency of 13.4 MHz, it is necessary to have a magnetization current amplitude of $\sim$ 10 A. The magnetization windings L 1 and L 2 consist of 20 and 30 turns respectively.

In order to obtain the optimum transition mode from proton-acceleration by the Dee-system to acceleration with the Cee-electrode, the master generator L1 is synchronized with the main RF generator of the synchrocyclotron in the region of the transition point. Synchronization is effected by communicating the main frequency signal from the generator of the Dee-system to the master oscillator of the Cee-electrode. Tuning of the optimum phase-difference between the voltages of the Dee - and Cee-electrode is effected by an adjustable delay line, designed on the basis of a selection of sections of coaxial cable, connected by means of hermetic contacts. The contacts are controlled from the accelerator control desk. Unit 5 controls the moment of switching on and off of the synchronization signal which passes through the control unit (9).

A negative shift of up to 2.5 kV is communicated to the plates of the Cee-electrode. In the nominal operating mode, the amplitude of the volatge on the Cee-electrode is 1.5 - 1.7 kV, which corresponds to a generator power output of 0.4 - 0.6 kW.

CURRENT-SHAPER FOR CONTROLLING THE FREQUENCY PROGRAMME OF THE Cee-ELECTRODE GENERATOR

The block-diagram of the current shaper for obtaining the required law of frequency deviation in the Cee-electrode generator is shown in Figure 7. Figure 8 shows the voltage profiles at various points.

The input pulse (1), which corresponds to the reference mark for the end of the main RF programme of the synchrocyclotron, sets in operation, by means of the control trigger, the master oscillator G, the frequency of which may be adjusted within a wide range. The pulses of the G generator reach the input of the binary 4-digit counter, which consists of triggers T1-T4.

The counter is connected to a logic decoder with 16 output wires. On each of the wires, there appear in succession rectangular voltage pulses of a duration $T = 1/f_r$, where f_r is the frequency of the generator G. These pulses enter the gates K1-K15, the loading of which is provided by the potentiometers R1-15. The output signals of the potentiometers are combined in a linear summator, which has a system for regulating the output signal (R).

In this way the total pulse (V) is a combination of 15 consecutive discrete sets. By changing the amplitude of each step individually, it is possible to reproduce a single pole analogue signal of practically any desired form.

The pulse from the 16 wires of the decoder (IV), corresponding to the initial state of the counter, arrive to release the controlling trigger, thus completing the operating cycle of the generator.

The total pulse (V) passes through the integrator and arrives at the d.c. amplifier, which has a differential input. The stability of the amplifier with an induction loading (the magnetization coils of the ferrite variators L1 and L2) is ensured by a combined feedback.

The output power of the 300 W amplifier at maximum current in the load is 10 A.

The initial value of the frequency f_1 of the Cee-electrode generator is determined by the amplifier's output current when the output signal of the summator is zero. Adjustment of the initial output current is effected by the multi-turn potentiometer R_{I1} .

STRETCHED BEAM PARAMETERS

Figure 9 shoes dependence of the intensity of the stretched pulse of the ejected proton beam on the coefficient for momentary filling T/T_M. T is the duration of the beam macro-pulse, and T_M is the modulation period of the fundamental frequency programme. The initial point on the graph (I/Imax. = 1) corresponds to operation of the accelerator without the beam stretching system (duration of beam $\sim$300 microsec. T/T_M = 1.4%). Transition of the beam from acceleration by the Dee-electrode to acceleration by the Cee-electrode is achieved with an efficiency of almost 100%, but the exponential drop in intensity as the temporary filling coefficient increases may be related to the shorter life of the beam because of inhomogeneity in the magnetic field in the region of the regenerative ejection system of the accelerator. The maximum coefficient of the momentary filling of 45-50% is at present time restricted by the value of the relation of the non-working part of the programme to the modulation period on account of the influence of the following cycle of the basic programme on the mode of acceleration by the Cee-electrode when the frequency of the basic programme is close to double the output frequency. When using the mode with omission of acceleration cycles, the coefficient of temporary filling may be considerably increased. Operation of the stretching system without operation in phase with the basic programme leads to a reduction in the mean intensity by 10-15% with at the same time a considerable impairment of the stability of intensity from one cycle to the next. The dependence of the intensity of the stretched beam on the relative phase shift between voltages on the Dee- and Cee-electrode is shown in Figure 9. This dependence is well-explained by the process of capturing the beam phase volume in the separatrix of the Cee-system.

The time-distribution of the stretched beam intensity in the individual cycles, and the overall distribution over a long period, is shown in Figure 10. The full reproducibility of the shape of the overall distributions of the stretched beam proves the high stability of the system. The fluctuations in intensity in the individual acceleration cycles does not exceed the limits of statistical deviation. In the macro-structure of the pulses, a micro-structure is preserved corresponding to the frequency of particle revolution.

The oscillogram in Figure 11 shows (from top to bottom): the envelope of the RF frequency of the basic programme of the synchrocyclotron; the current shape for frequency modulation of the Cee-system (the point UP on the block-diagram, Figure 7); the ejected beam of the synchrocyclotron - the signal from the photo-multiplier located in the main accelerator hall; the peak at the end of the RF programme corresponds to the background from beam scattering on the components of the ejection system.

The time scale of the oscillograms is 3 msec/graduation.

The oscillograms shown in Figure 12 illustrate the behaviour of the shape of the stretched beam when there is a variation in the amplitude of one of the steps of the overall pulse of the current modulator (point U on the block-diagram, Figure 7). The time scale is 2 msec/graduation.

In conclusion the authors wish to thank the staff of the Accelerator Division who took part in the designing, assembly and tuning of the beam-stretching system, namely: V.K. Volkov, V.V. Lavrov, A.S. Prokrovskij, A.A. Timofeev and V.I. Shalmanov.

---ooOoo---

References

1. A. Cabrespine, J. phys. et radium, 2I 5. 332, 1960.
2. M.H. Foss, R.W. Findley, A. Suzuki, NIM 29, 2, 282, 1964.
3. K.M. Growe, Conf. on high energy cyclotron improvements (Williamsburg, USA, Febr. 6-8, 1964), p. 108.
4. CERN Synchro-cyclotron Users Handbook, v. I (1967).
5. I.P. Scanlon, G.H. Stafford, J.J. Thresher, P.H. Bowen, RSI, 28 10, 749, 1957.
6. I. Rainwater, W.W. Havens, Jr., I.B. Garg, RSI, 35, 3, 263, 1964.
7. R.P. Devyaterikov, A.V. Kulikov, V.V. Lavrov, G.F. Mikheev, Control system of the FTI Synchrocyclotron. Proceedings of the Second All-union Conference on Charged Particle Accelerators, Vol. II, 234-236, 1972.

Manuscript received by the Publishing Department: 25/IX/1972.

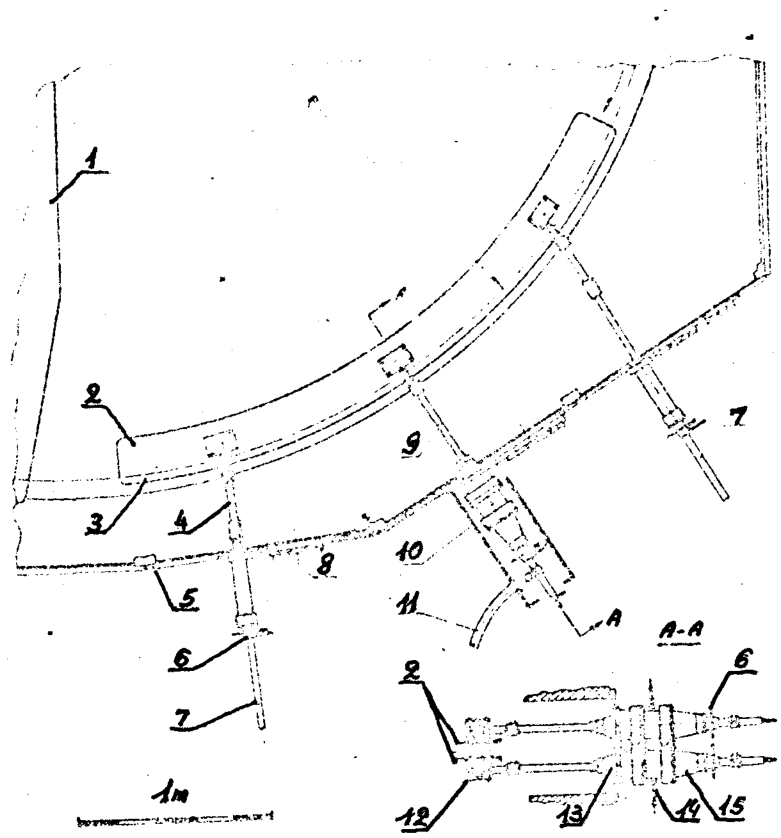


Fig. 1. Design and layout of the Cee-electrode in the accelerator chamber.

1. Dee
2. Cee-electrode plates
3. Edge of the electromagnet pole
4. Ceramic insulators
5. Walls of the vacuum chambers
6. Plate position indicators
7. Rod-holders
8. Inspection windows
9. Rod-inputs
10. Protective cover
11. Feeder cables
12. Hinged attachment system for plates
13. Internal insulators
14. Connecting pipes for gas supply
15. External insulators

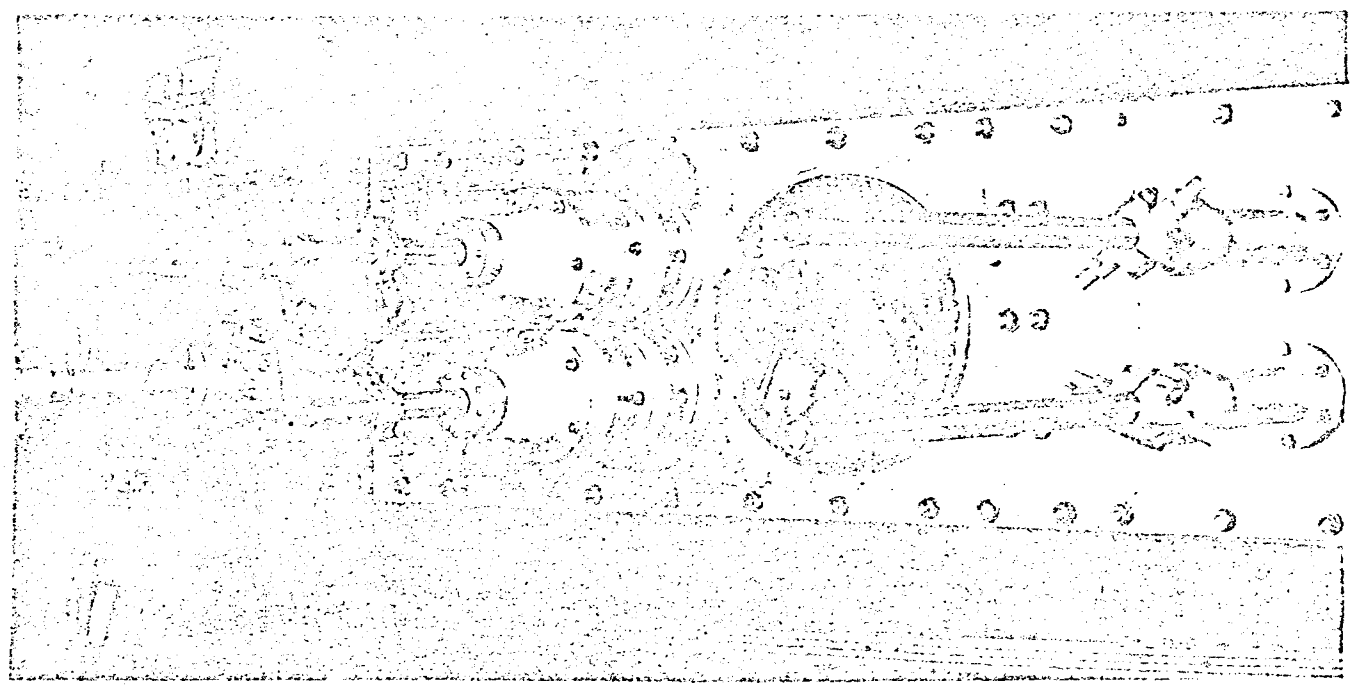
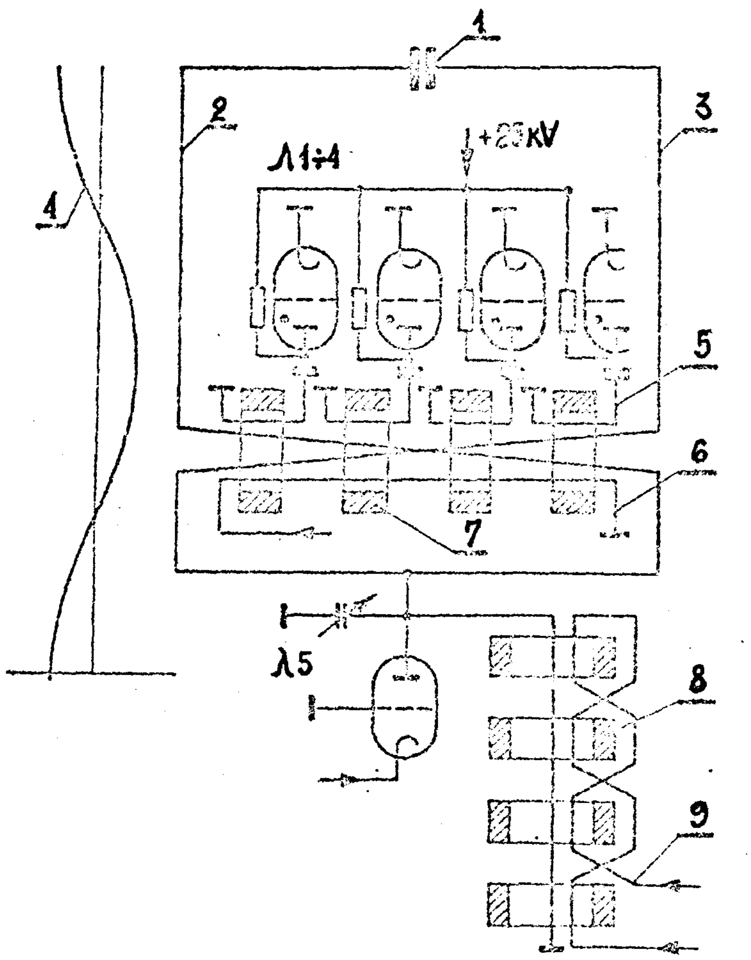


Fig. 2. Accelerator chamber seen from the side of the Cee-electrode.



<u>Fig. 3</u>. Simplified basic diagram of the output avalanches of the Cee-electrode generator and pulse generator for the spill.

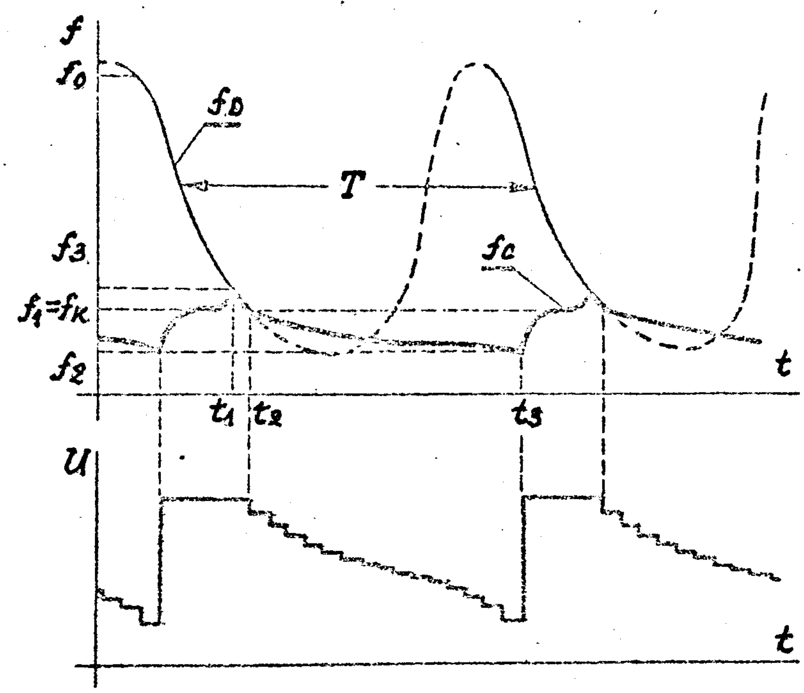
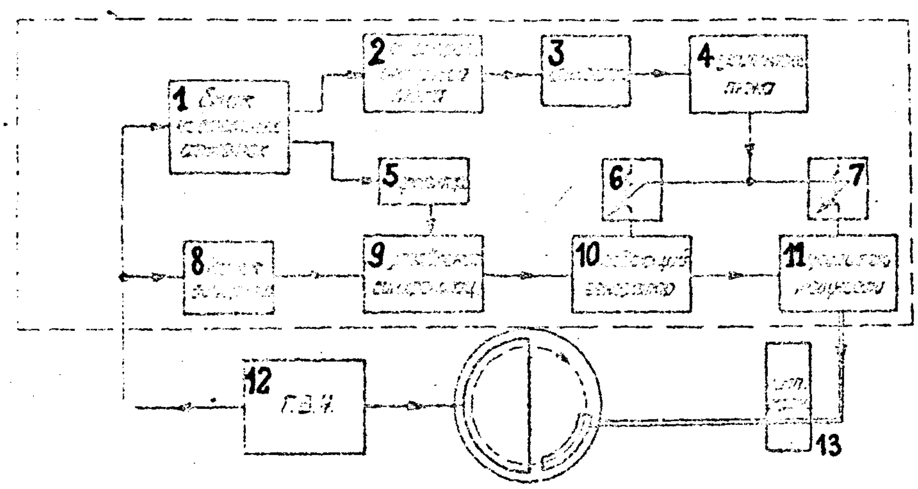
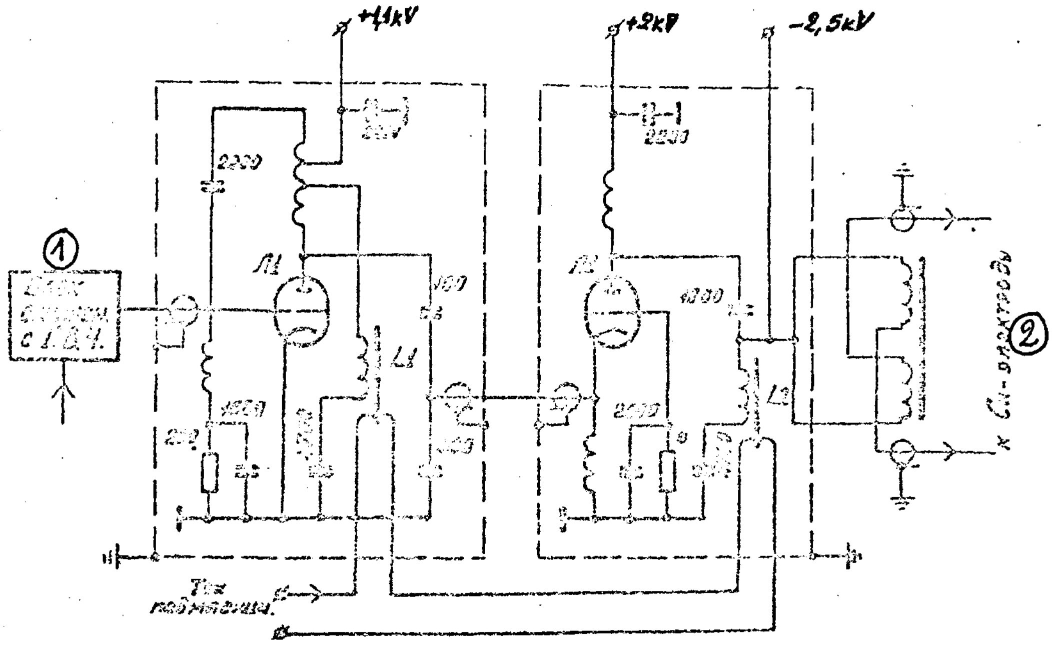


Fig. 4. Frequency programme of the accelerator (f_D), Cee-electrode (f_c) and shape of the voltage which provides the frequency programme of the Cee-electrode.



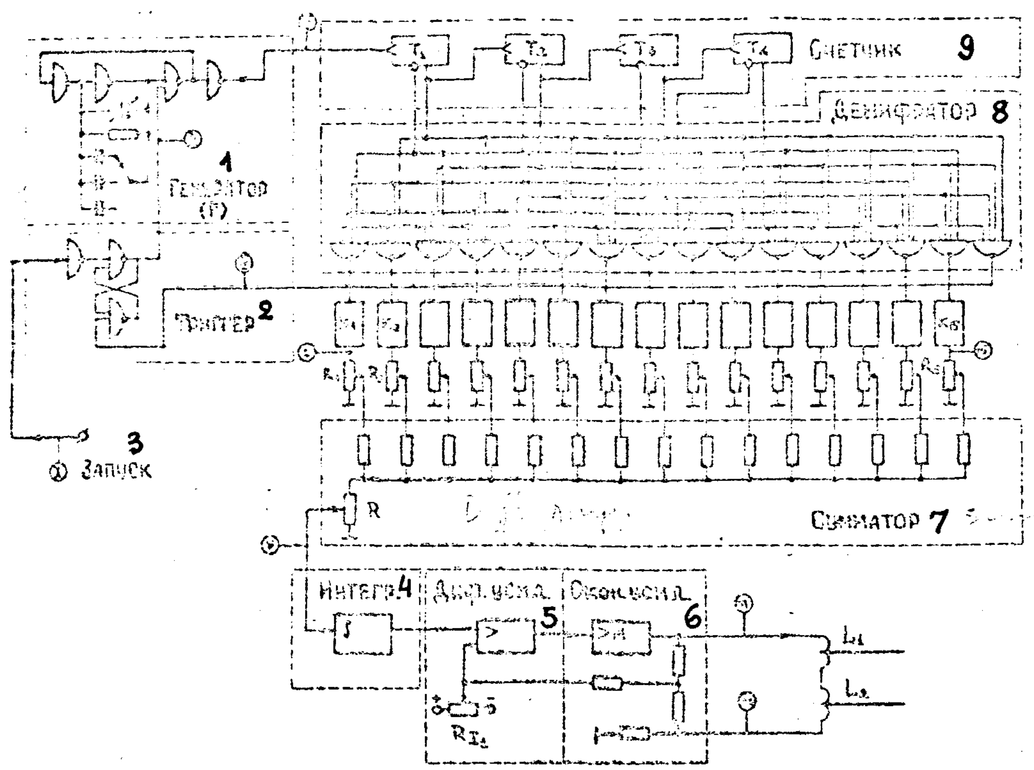
<u>Fig. 5</u>. Block-diagram of the beam-stretching system.

1. Frequency-mark unit
2. Current-pulse shaper
3. Integrator
4. Current amplification
5. Shaping
6.
7.
8. Delay line
9. Synchrocyclotron control
10. Master oscillator
11. Power amplifier
12. RF generator
13. Pulse tran.



<u>Fig. 6</u>. Basic diagram of the Cee-electrode generator.

1. Unit providing synchronization with RF generator
2. To the Cee-electrode



<u>Fig. 7</u>. Block-diagram of the current shaper for controlling the frequency programme of the Cee-electrode.

1. Generator
2. Trigger
3. Start
4. Integrator
5. Diff. Amp.
6. Final amplifier
7. Summator
8. Decoder
9. Counter

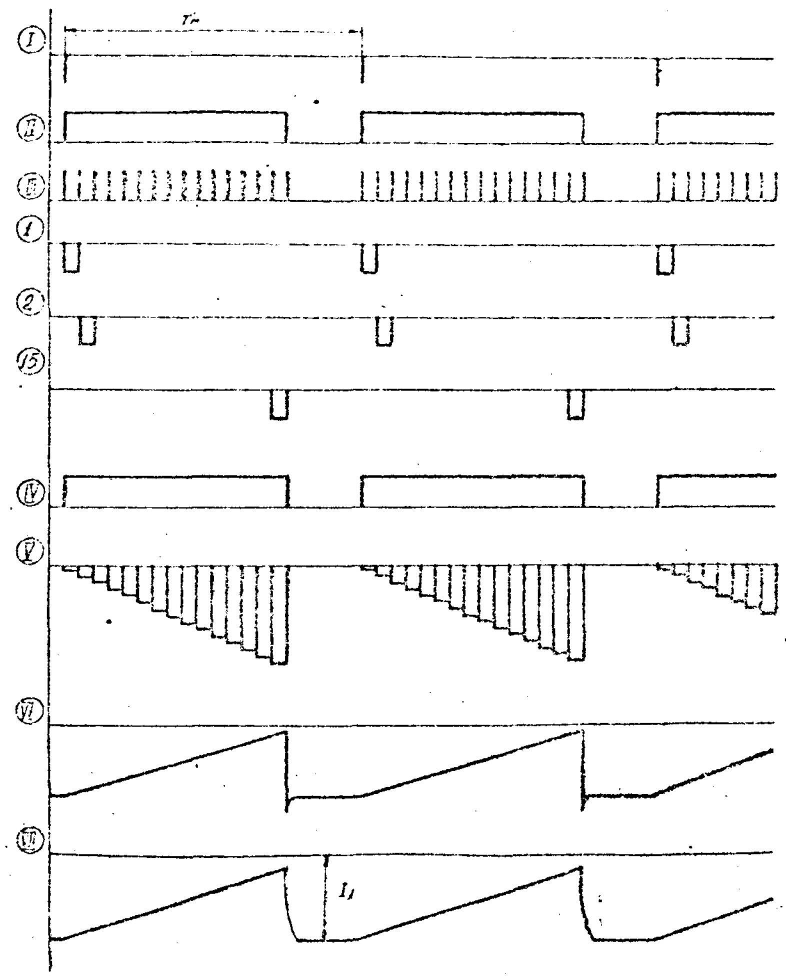
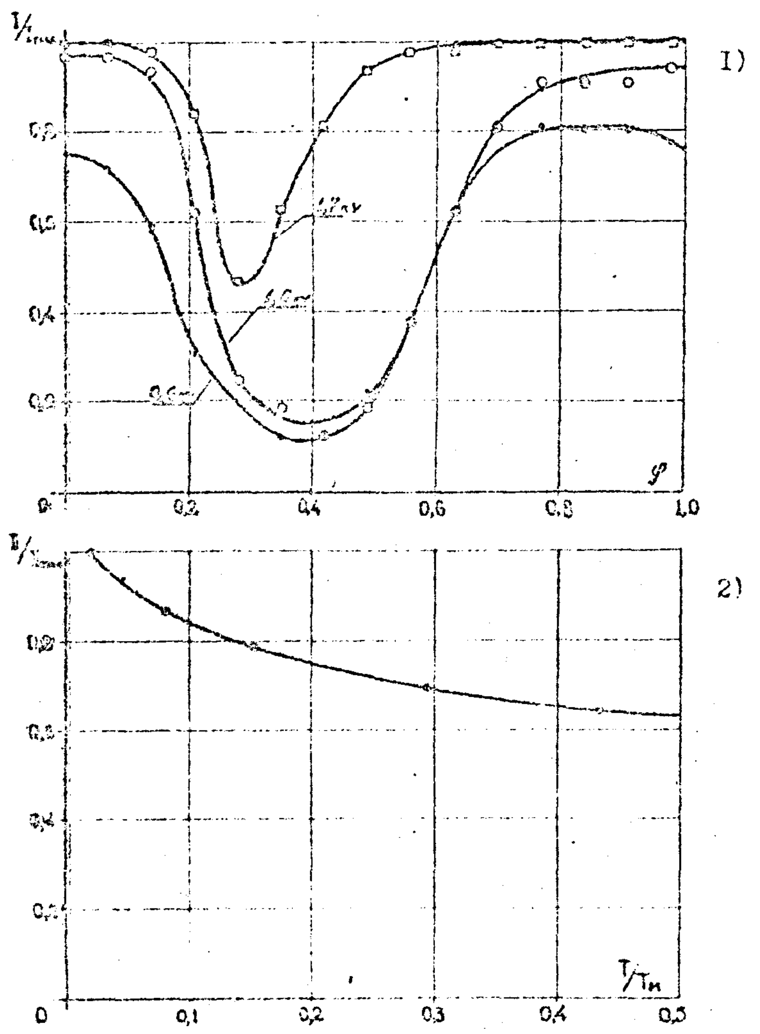


Fig. 8. Voltage-profiles of the current-shaper.



<u>Fig. 9</u>. Dependence of the relative intensity of the stretched beam on

1 - the relative phase-shift between the voltages on the Dee- and Cee-electrode;

2 - the coefficient of time filling.

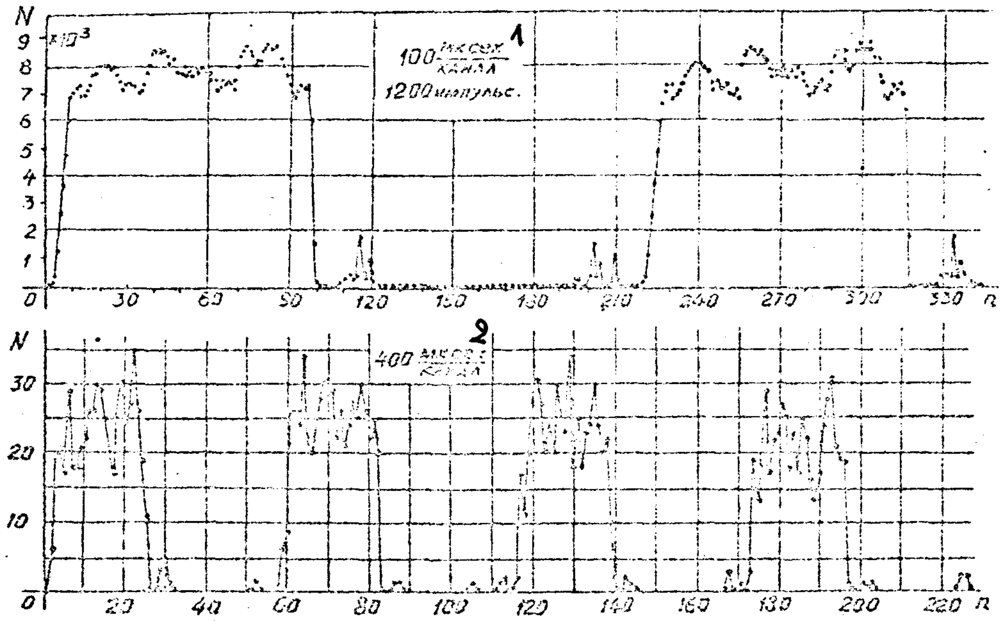


Fig. 10. Distribution in time of the intensity of the ejected stretched beam.

1. 100 $\frac{\text{microsec.}}{\text{channel}}$

   1200 pulses

2. 400 $\frac{\text{microsec.}}{\text{channel}}$

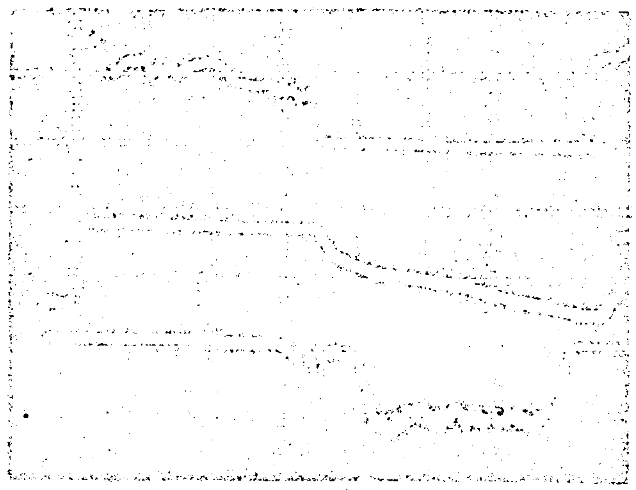


Fig. 11. Oscillograms (from top to bottom):

- envelope of the RF voltage on the Dee;
- shape of the current controlling frequency-modulation of the Cee-electrode;
- shape of the macro-pulse of the ejected stretched beam.

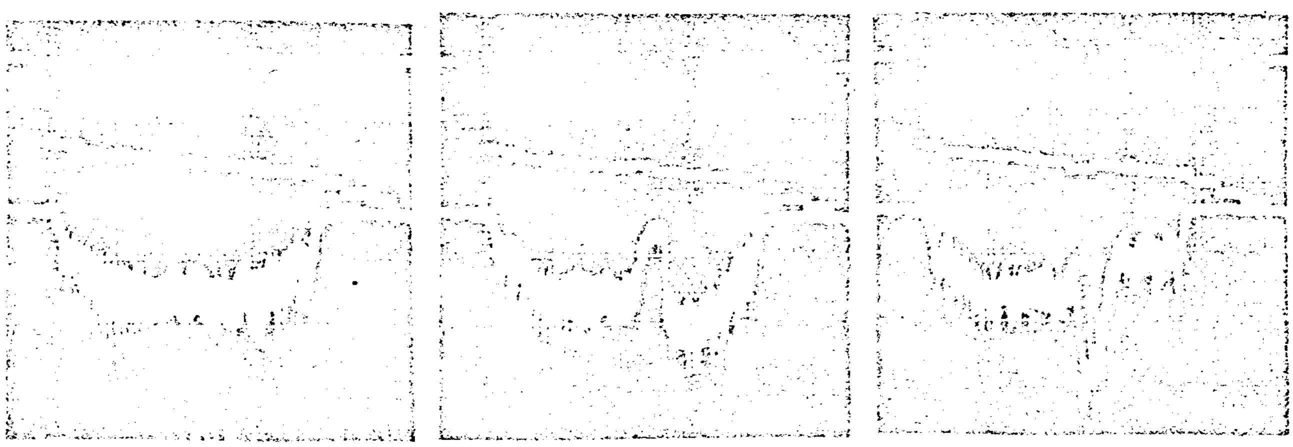


Fig. 12. Behaviour of the shape of the stretched beam when the amplitude of one of the "steps" of the control voltage is changed.