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COLLECTIVE LINEAR ACCELERATION OF IONS

by

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1 - Introduction

The rapid development of high-energy physics has led to a number of discoveries of great importance. Yet the most fundamental laws of the world of elementary particles can apparently be ascertained and understood only when accelerators are built that yield particle fluxes of hundreds and thousands of GeV. In this paper we demonstrate the possibility of achieving a new principle of charged-particle acceleration, based on the utilization of collective interaction.

The idea of this method, put forth several years ago by V.I. Veksler[1], consists in using to accelerate ions the fields produced in the interaction of a bunch with a jet of electrons by the flux of electromagnetic radiation or inside a two-component bunch. To achieve a collective acceleration, we must create a charged two-component bunch consisting of electrons moving in an external field along closed trajectories and positive ions captured into the electron bunch. The number of ions should be relatively small. If the density of electrons in the bunch is sufficiently great, the electric field confining the ions to the electron-bunch surface may also be made very strong. By virtue of this it becomes possible, with the aid of any electromagnetic fields, to accelerate as a whole an electron bunch containing captured ions to very high energies.

Our calculations show that even now it is entirely possible to achieve experimentally systems in which an accelerating field acting upon ions will reach several million volts per cm. Hence this new approach permits us to anticipate obtaining protons with energies up to hundreds of GeV and higher by relatively much simpler and less expensive means than can be done by the presently known methods.

A model of such an accelerator, for a proton energy of 1 GeV, is now under construction at Dubna.

2 - Obtaining a charged annular bunch

One of the main problems in building a coherent accelerator is that of obtaining a charged bunch. Investigation of various ways of doing this has shown that the simplest is to produce the bunch in the shape of a ring containing relativistic electrons and ions at rest.

The electrons are injected into a weak-focussing field, usual for accelerators, on a large-radius orbit. Then, owing to the adiabatic growth of the magnetic field the ring is compressed to the required dimensions. This compression, of course, is accompanied by an acquisition of energy on the part of the beam. The amplitudes of the particle oscillations around the instantaneous orbits become damped, and the ultimate ring cross-section may turn out fairly small. Ions are introduced into the ring in the final state by injecting a certain amount of neutral gas. We have examined various aspects of the steady state of an electron ring and the process of its adiabatic compression. Taking into account that the time intervals of interest to us are much shorter than the duration of the Maxwellizing process in the transverse direction, and that the particle densities are relatively low, we pursued our study as an approximation of the self-consistent field, without allowing for the collision integral.

Specifically, as a first approximation, where the energy spread in the beam equals zero, the motion of a test particle in a unified field is described by the equations:

$$\frac{d}{dt}(\gamma_\perp \dot{\rho}) + \gamma_\perp \omega^2 \left[(1-n)(1-\mu P) - \mu\left(\frac{4R^2}{\gamma_\perp^2 \beta_\perp^2 R^2 g(b+g)} + \frac{P}{2}\right)\right]\rho = 0$$

$$\frac{d}{dt}(\gamma_\perp \dot{z}) + \gamma_\perp \omega^2 \left[n(1+\mu P) - \mu\left(\frac{4R^2}{R^2 \gamma_\perp^2 \beta_\perp^2 b(b+g)} + \frac{P}{2}\right)\right] z = 0$$

where: $\rho = r - R$; $\omega = \beta_\perp \frac{c}{R}$; β is the velocity; $\gamma_\perp = \frac{1}{\sqrt{1-\beta^2}}$;

g and b are the torus semiaxes in the r and z directions, respectively (referred to the radius of the ring); and $\mu = \frac{\nu}{\gamma_\perp}$,

where $\nu = \frac{e^2 N_e}{2\pi R m_e c^2}$.

The adiabatic invariants of these equations will be:

$$\gamma_\perp R \beta_\perp \frac{a_\rho^2}{R^2} \sqrt{(1-n)_{ef}} = J_\rho \, ,$$

$$\gamma_\perp R \beta_\perp \frac{a_z^2}{R^2} \sqrt{n_{ef}} = J_z$$

where a_ρ and a_z are the oscillation amplitudes in the laboratory system.

It is easy to show that, if the ring dimensions during acceleration remain invariant in the natural system, the effective field acting upon the ions in the ring is: $E_{eff} = \dfrac{2\,e\,N_e}{\pi R^2\,(g + b)}$

Using the adiabatic invariants, we can obtain, with certain assumptions, a simple dependence of E_{eff} on the initial conditions: $E_{eff} \approx 30\,H\sqrt{\gamma_{\perp 0}}$, where H is the final field (H being expressed in Oe, E in V/cm).

We adduce the numerical estimates: $\gamma_{\perp 0} = 7$; $H = 2 \times 10^4$ Oe; $E_{eff} = 1.5 \times 10^6$ V/cm, and the final radius is 5 cm. Then as the initial dimensions of the beam we get $2\,q_0 R_0 = 8$ mm *, and as the total number of electrons $N_e = 0.8 \times 10^{13}$. Increasing the number of particles introduced from the injector makes it theoretically possible to raise E_{eff} up to several MV/cm. The example considered is for the state in which there is no energy spread in the beam. For the state with an energy spread, the beam parameters do not change significantly.

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* Translator's Note: The Russian at this point becomes partially illegible. Also, the JINR English translation changes the Russian $N_e = 0.8 \times 10^{13}$ to $N_e = 0.86 \times 10^{13}$.

The task of the injection is to produce an electron ring with a large number of particles and, as the cited example shows, fairly rigid parameters. As electron injector we use a linear induction accelerator capable of providing an electron pulse current of 200 A at a voltage of up to 3 MV. Study of several types of injector revealed the possibility of using an iron shielding channel with a current wall that compensates the distortion of the magnetic field in the region of particle motion.

To assure "missing" of the beam at the instant of injection, a sharply rising magnetic field is created so that the instantaneous-orbit circuit interval exceeds the beam dimensions.* In the case of the model this increment amounts to about 0.8×10^9 Oe/sec.

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* Translator's Note: The wording of the Russian is a little ambiguous here. The reference seems to be to "the interval (or period) for (or during) a circuit of the instantaneous orbit."

Investigation of the resonance phenomena during beam compression permitted selection of an optimal relation of the magnetic-field index to the radius, so that dangerous passage through resonances was avoided. This relation was achieved by special positioning of the constant and pulsed magnetic-field coils.

The model examined by us assumes the creation of an intense annular beam of charged particles with the aid of weak focussing. We know that in systems of this type a longitudinal instability may develop. Detailed calculations of this phenomenon, taking account of the influence of the shield, have shown that for selected values of the electron beam's initial parameters---with allowance made also for the particles' actual energy spread---such instability does not arise. We investigated too the stability of a two-component ring with respect to plasma oscillations. The analysis revealed that with injection of ions at the end of the compression the system dimensions do not admit of development of this kind of instability. On the basis of the calculations performed, an experimental apparatus was built. The measurements made on this apparatus have confirmed the correctness of our ideas and the possibility of producing a bunch with parameters close to those calculated.

3 - Extraction of the ring

At the end of the compression process the ring of particles finds itself squeezed between two magnetic mirrors. To extract the ring, a system is created that displaces the ring as a whole a distance of 40 cm, after which the ring enters the accelerating-focussing system. In addition to moving the ring over to the extraction system, we have the superimposed requirement of ion confinement within the ring and compensation of the Coulomb electron repulsion. To expel the ring from the median plane, we placed two supplementary windings 18 and 20 cm from it. The current in those starts to rise at the end of the compression process. Now forces arise that act upon the ring in the z-direction. The ring begins to move, and the velocity of its motion is determined by the rise of the current in the windings. If the current in the supplementary windings rises linearly, the magnetic well becomes deformed, specifically, it moves away from the median plane with a gradual loss of depth.[x] Placing the coils of the confining-field system at the appropriate distance from the median plane assures, over the entire region, gradients not exceeding 10 Oe/cm, which does not conflict with the condition for confinement of the ions within the ring. The ring's final velocity on extraction is 0.2 C.

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x The ring's subsequent motion occurs with acceleration in a decaying magnetic field. Compensation of the Coulomb repulsion in the final stage of extraction is achieved with a supplementary focussing system.

4 - Acceleration of the ring

In selecting means for accomplishing the further stages of acceleration one must take a number of conditions and circumstances into account. The most important of these are:

1) One of the chief problems of collective acceleration is the dynamics of combined acceleration of heavy ion particles and an electron bunch. According to this method, as a result of accelerating the electron bunch the ions should acquire a velocity equal to that of the electrons, whence their energy would be $\frac{M}{m_{\perp}}$ times greater than that of the electrons. For simple physical reasons, however, it is clear that a combined motion of ions and electrons, owing to the difference in their masses, is possible not with arbitrarily large external fields that accelerate the bunch as a whole. The ions are accelerated by the electron bunch's electric field until they are inside the bunch, but this condition may be violated with sufficiently great accelerations of the bunch owing to the influence of the inertial forces acting on the ions.

The calculations show that this limitation is expressed as

$$E \leq \frac{m_{\perp}}{M} \frac{eN}{\pi a R},$$

where a is the ring's inside radius, M the ion mass, and $m_{\perp} = m_e \gamma_{\perp}$.

So for the bunch parameters obtained for the accelerator model the external field should not exceed 10-20 kV/cm.

2) In contrast to ordinary linear accelerators, in our case we accelerate a single dense electron bunch whose total charge is great, so that the natural current of the accelerated electrons places a heavy load on the accelerating system.

Taking these circumstances into account, we selected as accelerating element a single-gap resonator. For such an acceleration system we calculated the possibilities of the bunch's picking up energy. Since in our case the resonator is traversed once by a bunch (ring) bearing a large charge and having relativistic or nearly relativistic velocity, retardation is essential in such a system, whence the usual quasi-static calculation of the energy balance is inadequate. Significant radiative losses of energy by the bunch may occur within the system. The resonator's accelerating field may be diminished through the load imposed by the current of accelerated electrons.

Our electrodynamic calculation of a model of a cylindrical resonator shows that that the bunch's main energy losses are due to excitation of TM waves, the largest contribution being that of the waves corresponding solely to the radial harmonics. Precise numerical calculation of the energy picked up in the resonator has shown that there is a very real acceleration of a bunch bearing a charge of 10^{14} e from β values of about 0.1 to as close as one likes to 1.

Because of the discreteness of the external field, however, using a string of resonators to accelerate the bunch will not result in the maximum possible energy increment along the length, so in our accelerator we adopted a combination system consisting of a sequence of resonators and a specially varying magnetic field. To elucidate the effect of such a system, we make two prefatory observations:

1) In the motion of a ring of particles having azimuthal velocity in a field decaying adiabatically from H_1 to H_2, the ring's longitudinal velocity increases and its azimuthal velocity decreases. These variations are linked to the magnetic-field gradient via the simple relation $\frac{\gamma_{z2}}{\gamma_{z1}} \approx \sqrt{\frac{H_1}{H_2}}$.

2) When the ring moves in a rising field, the reverse process occurs.

Indeed we utilized these well-known circumstances to create our accelerating system. Along the resonator length a rising magnetic field is produced so that at the accelerating electric field's maximum amplitude the longitudinal velocity increases as required to confine the ions. The electric field's remaining energy is devoted to increasing the rotational energy of the electrons in the ring. In the interval between the resonators the energy stored in rotational motion is converted into translational motion of the ring. Calculation of the motion of particles in such a system has demonstrated the possibility of obtaining a prescribed accelerating gradient continuous over the length of the accelerator. Here, on an average, the magnetic field remains constant and such as is required for confinement of the annular bunch.

5 - Focussing of a charged ring undergoing acceleration

In extracting a ring from a potential well, one is faced with the problem of focussing it in the longitudinal direction. This problem remains when it comes to accelerating the ring. The ring's transverse inner radius is kept constant, at the same time as the outer radius, by the longitudinal magnetic field. Theoretically, external focussing is unnecessary if the self-focussing condition ($N_i = \frac{N_e}{\gamma_\perp^2}$)

is fulfilled[2,3], but even in this case, for simple physical reasons, a potential well is needed to eliminate instabilities, particularly the hydrodynamic ones. We consider that external fields must be used to create a potential well sufficient to compensate the space-charge forces. We have looked into different ways of focussing a moving ring longitudinally. Some of these ways (focussing by radiation in decelerating structures, by a magnetic-field gradient and helical magnetic fields) will not be discussed here, because their use, at least in a model, would involve either technical or theoretical difficulties, e.g., intense deceleration of the ring in the focussing system.

In the space between the resonators, waveguide systems can be used for focussing. As the calculations have shown, it is possible to make a system in which the accelerated ring would be in a phase with the field where the amount of energy picked up would equal zero. Usable for focussing are the retarded E-waves and H-waves created by disk-loaded or spiral waveguides. Our estimate of the focussing action indicated that, to focus a ring with the parameters adopted for our accelerator model, an electric-field peak value of 40 kV/cm would suffice.

For focussing the beam in our accelerator model, however, we use a system based on utilization of the image forces on an anisotropic surface. When a charged bunch passes near the shielding surface, an electromagnetic field is produced. Detailed analysis of this field has shown that, when certain shield parameters (dielectric permeability, distance from ring) are selected, the conditions for stability in the longitudinal direction can be assured. Here stability along the large radius is automatically preserved. Experiments with a straight beam have shown the correctness of this line of reasoning, and have made it possible to build such a system in an accelerator.

So we have shown the theoretical possibility of building all the systems for a new type of accelerator. A model of such an accelerator, for a proton energy of the order of 1 GeV, is currently under construction at Dubna. All the main systems are built and adjusted. They are shown in Figures 1-4: linear induction accelerator, chamber for producing the annular bunches, and the accelerating system. The extraction and acceleration of annular bunches are presently being worked on. We plan to complete tuning of the model by early 1968.

In conclusion, we tabulate the model's basic parameters and the tentative parameters for a 1,000 GeV accelerator.

	Energy	Proton intensity per cycle	Number of cycles per sec.	Length of accelerator	Number of resonators
Model	1 GeV	10^{11}	1	15 m	4
Projected accelerator	1,000 GeV	10^{12}	10-100	1,500 m	3,000

Participants in the designing of the different systems were O.A. Kolpakov, V.N. Mamonov, Yu.V. Muratov, Yu.L. Obukhov, and Yu.I. Smirnov.

R e f e r e n c e s

1) V.I. Veksler: Atomnaya energiya, no. 5 (1957).

2) G.I. Budker: Atomnaya energiya, no. 5 (1956).

3) Bennett: Phys. Rev., 98, 1584 (1955).

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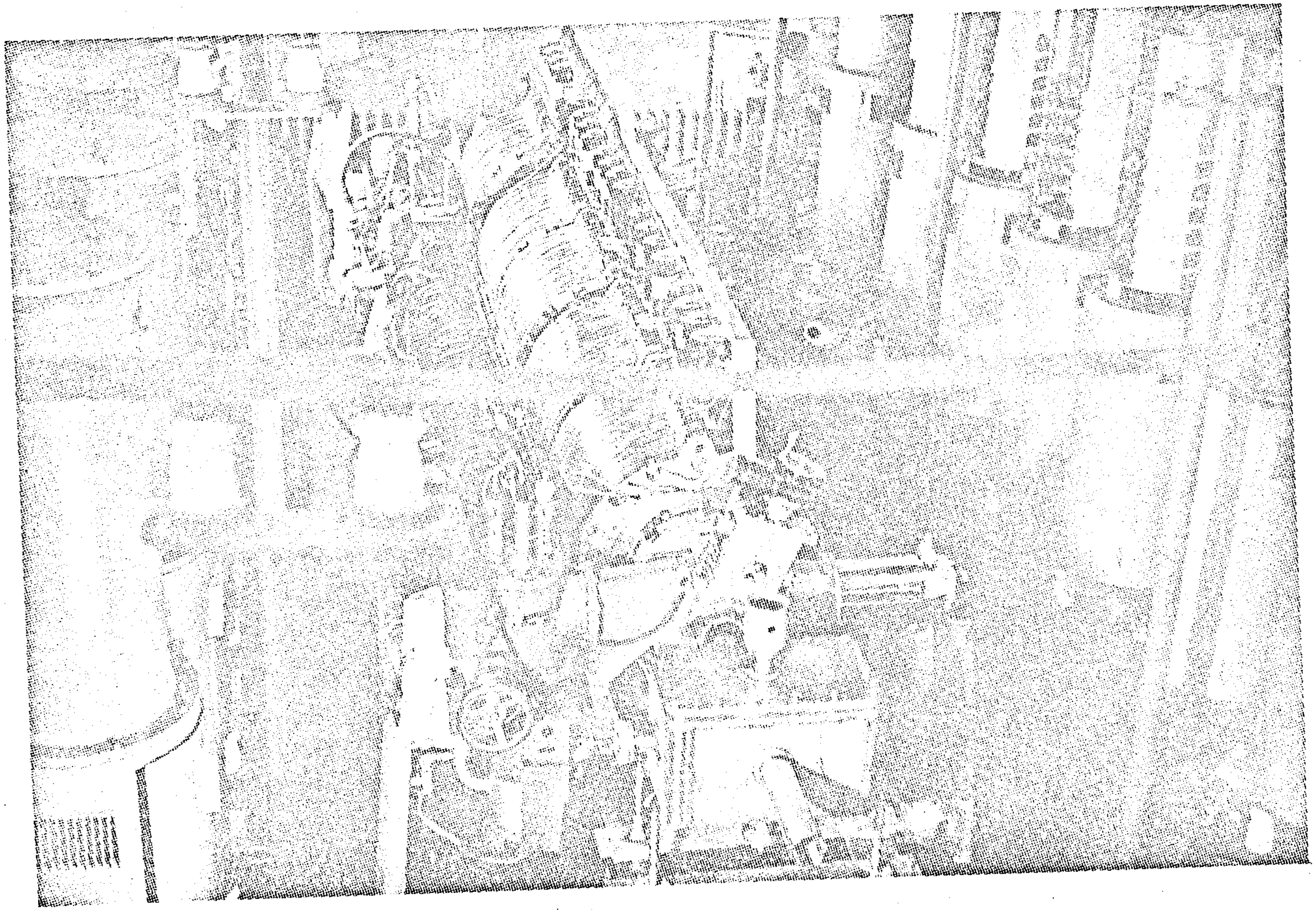
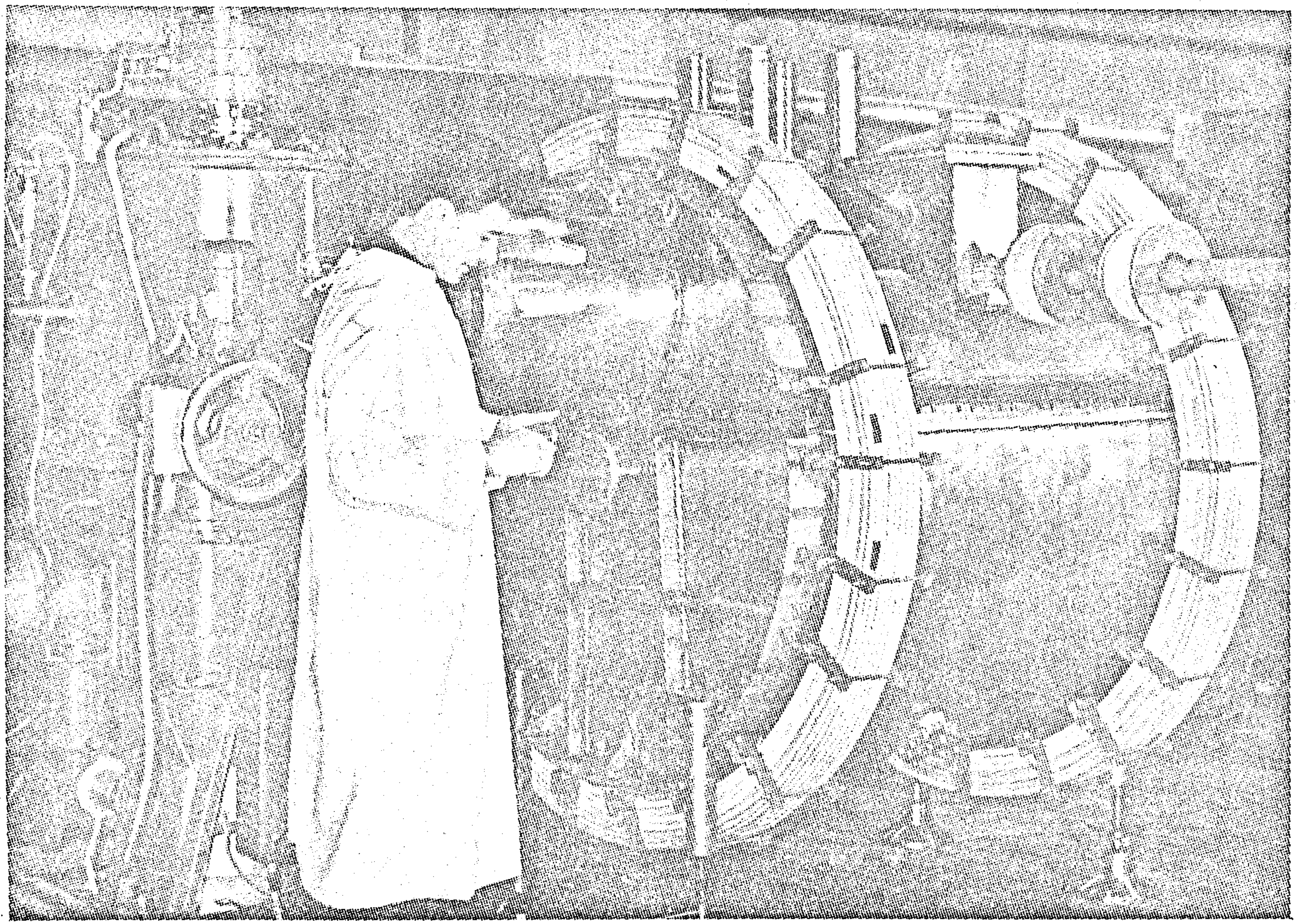


Figure 1: Linear induction accelerator



Translator's Note: This unidentified photograph, taken from the JINR English translation, does not appear in the Russian original. On the other hand, Figure 2 in the Russian, showing the "Chamber for producing annular bunches," is not duplicated in the translation. This apparently is a different photograph of the said chamber.

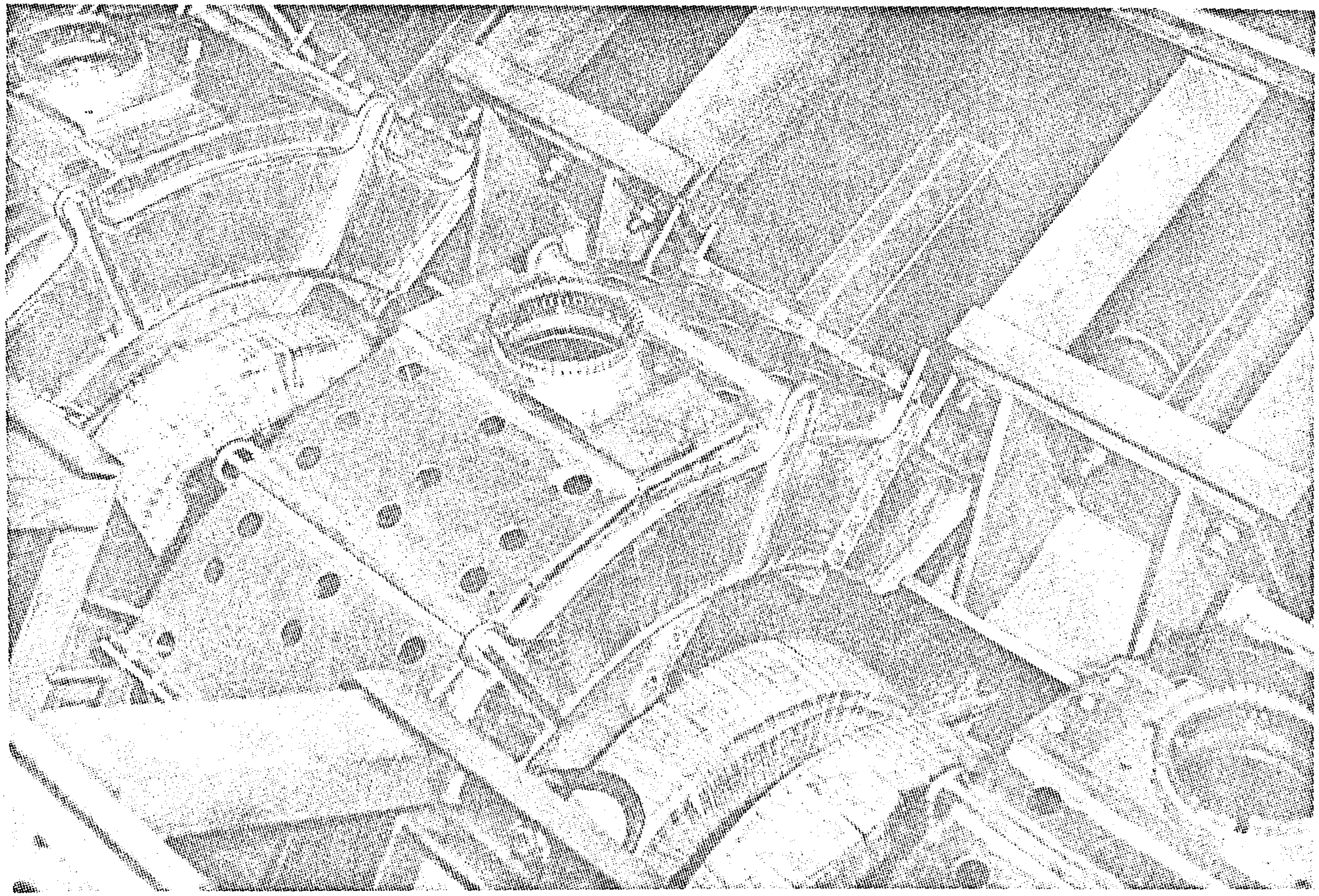


Figure 3: System of accelerating resonators

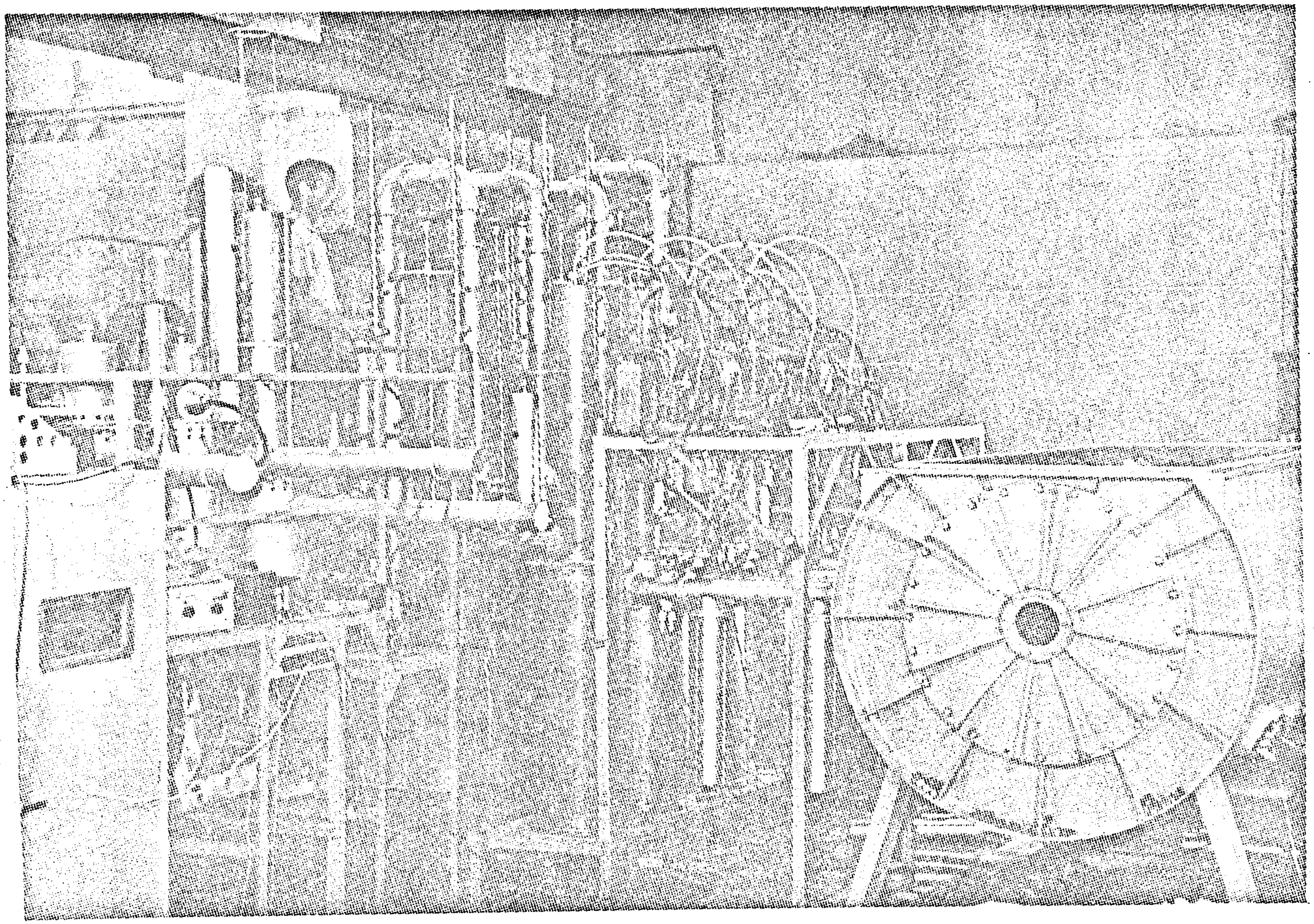


Figure 4: General view of high-frequency system