RELATIVISTIC STABILIZED ELECTRON BEAM

II. BRIEF REVIEW OF EXPERIMENTAL WORK

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(presented by A. A. Naumov)

The formation of a stabilized electron beam requires ring currents of relativistic electrons thousands of times greater than the betatrons currents so far known. A number of methods to produce strong electron currents have been suggested and qualitative calculations made which show that further investigations should be conducted in two directions.

The first line of investigation relates to methods of reforming plasma formed in some way or other into a ring beam of relativistic electrons. The conditions necessary for plasma electrons to be accelerated by the electric field conflict with those for discharge ignition. Hence special ring gas discharges have to be selected which proceed in a sufficiently high vacuum. Several possibilitities are now being considered for electron acceleration in gas discharges of various types (in a high-frequency ring gas discharge excited in a chamber with a strong toroidal magnetic field, in a ring gas discharge produced by an inductive electric field, in an ironless betatron-type set involving a very high potential difference per turn, etc.).
Special mention should be made of a system employing the principle of so-called ion rain. This is a betatron set in which a ring ion source is located over an equilibrium orbit. The source injects fast ions into the volume of the chamber along the magnetic field. Due to ionization of the residual gas, the ion charge is compensated by electrons, and the strong ion structure thus formed on the equilibrium orbit makes it possible, by means of the inductive field, to accelerate the compensating electrons which originally had thermal velocities.

Experiments on reforming plasma into a beam of relativistic electrons, were conducted with units of various kinds, and the results obtained show that the plasma electrons are accelerated under certain conditions. As this work is far from complete however, it could not be included in the present paper.

The second line of investigation consists of accumulating fast electrons in a large volume and then accelerating them and pulling them into a ring beam of relativistic electrons.

Experiments were made using betatron-type sets with a greatly enlarged chamber providing for preliminary accumulation of the electrons. Closed beams of relativistic electrons were obtained having a circulating current far exceeding that obtained in the betatrons so far known. We shall deal with these experiments in fuller detail, as we hope, on the basis of the results obtained, to develop in the near future a betatron set which would provide ring beams of relativistic electrons with currents ranging from 30 to 100 amp. A set of this kind may be of interest in itself as it would provide a pulse of electrons with high beam peak intensity.

The success in obtaining strong currents in betatron sets using the accumulation principle is due to the fact that the effectiveness of injection increases substantially when the volume charge in the region of the orbits close to the electron gun is reduced. For this purpose, fast electrons are injected at small radii into a large ring chamber with a constant magnetic field. The electrons are accelerated by the inductive electric field until a continuous spiral of electron current fills the whole chamber. From that moment on, the guide field grows in accordance with the flux in the central core, so that the betatron ratio 2 : 1 is realized inside the chamber. At this value, the electrons are accelerated and attracted to the equilibrium orbit.*

Here are brief data on the experimental betatron accumulation set designed by a group of research workers and engineers including E. A. Abramyan, I. E. Bender, L. N. Bondarenko, G. I. Budker, A. A. Naumov, S. N. Rodionov, I. M. Samoilov, L. I. Tokarev, and L. I. Yudin.

Figure 1 shows the lay-out of the set.

An inductive electric field is produced in the system by means of a laminated core (1) and shielded yoke (2), with an excitation winding (3).

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* We have recently learned that the same principle has been employed in a special iron betatron[1].

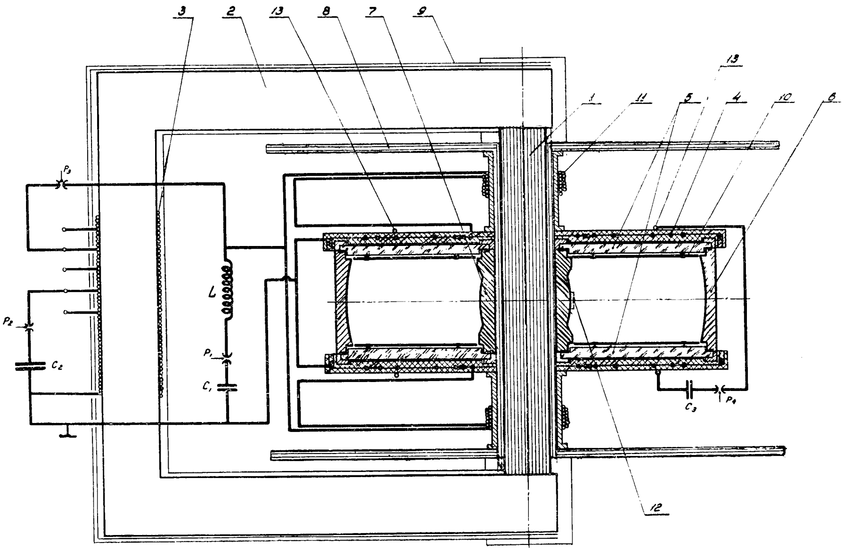
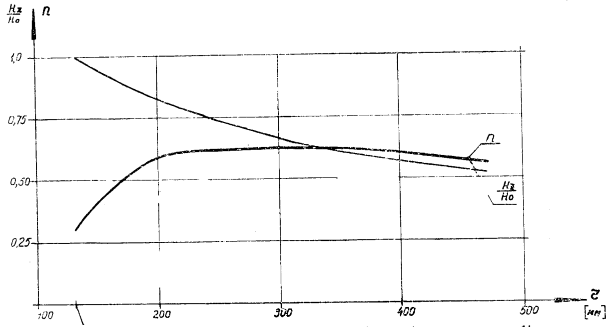


Fig. 1. Diagram of betatron set with preliminary electron accumulation.
1. Core; 2. Yoke; 3. Yoke winding; 4. Guide field winding; 5. Vaccum chamber covers; 6 and 7. Outside and inside chamber walls; 8. Shielding; 9. Yoke shielding; 10. Glass disc; 11. Back turns; 12. Electron gun; 13. Beam deflection winding.

The guide field is produced by means of windings (4) fastened to the covers (5) of the vacuum chamber. The chamber covers are made of special glass. The number of turns and the arrangement of the windings are so selected as to provide a focusing field in the region of the median plane at all radii inside the camera. Besides, for the same purpose the duralumin walls (6 and 7) which form the cylindrical box of the vacuum chamber have an inside curvature equal to that of the magnetic field lines.

Figure 2 gives the values of the vertical field component (H_Z) and the index (n) as a function of the radius obtained in the first version of the set.

The inductive electric field produced by the flux in the core must penetrate the chamber. For this purpose each of the latter's metal walls have two slots which prevent the formation of shorted turns. The slots are filled with a thick rubber layer providing a vacuum seal and reliable insulation.



gun radius H_0 magnetic field intensity at gun radius

Fig. 2. Vertical component of magnetic field and logarithmic index as a function of radius.

The dispersion fields of the core and of the yoke which penetrate into the chamber are greatly weakened by means of specially designed split shields (8 and 9, fig. 1) which envelop the magnetic conductor.

Shields (10) consisting of aquadag-coated glass discs, serve to shield the interior of the chamber from the electrostatic fields induced by the windings, and to protect the chamber covers from electron bombardment.

The windings creating inductive and guide fields in the set may have independent power supply. Special windings, (11) whose turns have the direction opposite to that of the main windings (4) are designed to prevent interaction between the systems that induce the guide and accelerating fields respectively. The field of compensating windings (11) has little influence on the shape of the field in the working volume of the chamber.

The electron gun (12) is mounted on the inside cylinder of the chamber and provides electron injection in a narrow angle tangentially to the circumference.

As explained above, electron injection should take place when there is a constant magnetic field. To simplify the design of the set, use was made of quasi-constant fields induced by low frequency currents which arise at an oscillatory discharge of capacitor C_1 through the supporting windings (4) and a special choke L. The fields necessary for electron acceleration and displacement of the equilibrium orbits are also induced by discharge currents of the respective capacitors.

The set operates in the single-stroke pulse range. The sequence of the main processes in each cycle of acceleration is illustrated by the curves in fig. 3.

After the capacitors C_1, C_2, and C_3 are charged, the spark-gap P_1 is ignited, thus closing the discharging circuit of capacitor C_1. The magnetic field induced by windings (4) begins to grow sinusoidally. After 650 microsec., when the field in the chamber reaches its maximum value, the injector is switched on. The discharging circuit of capacitor C_2 is closed across winding (3) by means of spark-gap P_2. The arising inductive electric field provides electron acceleration in an unrolled spiral. The energy of the injected electrons and the size of the guide fields are so selected as to produce small radial oscillations which make it possible to reduce the inductive electric field necessary for catching the greater portion of the gun-injected electrons. About 1 microsec. after the beginning of the electron acceleration, the electrons reach a probe placed on the final radius. From this moment on, the entire working space in the region of the chamber median plane is filled with accelerated electrons. Their further acceleration under betatron conditions can now begin. For this purpose, current is fed from winding (3) by means of the spark gap P_3 to the system of windings (4) and (11).

The guide field begins to change in time by much the same law as the flow in the central core. The accelerating electrons are attracted to the equilibrium orbit.

Electron acceleration continues for about 100 microsec. At a pre-set moment, the capacitor C_3 is discharged with the aid of the spark-gap P_4 across counter-connected windings (13). As a result, the median plane of the magnetic field is shifted upwards and the accelerated electrons are ejected on to a special probe located over the equilibrium orbit, where the current pulse (see fig. 3) and the corresponding γ-radiation pulse are recorded. Below is a brief description of the main components of the set which are the result of special development work.

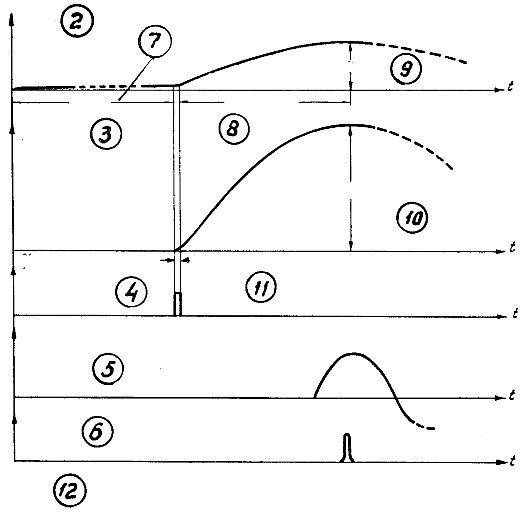


Fig. 3. Curves illustrating operation of the set.
2. H-field in chamber; 3. B magnetic induction in core; 4. $I_{inj.}$ — current injected by gun; 5. $H_{eject.}$ = field of deflecting windings; 6. I = current to target; 7. 650 μ sec; 8. $t_{accel.}$ = 100 μsec; 9. H = 340 gauss; 10. B = 14,000 Œrsted; 11. $t_{accumulation}$ — 1 μ sec; 12. All values given in diagram are out of scale.

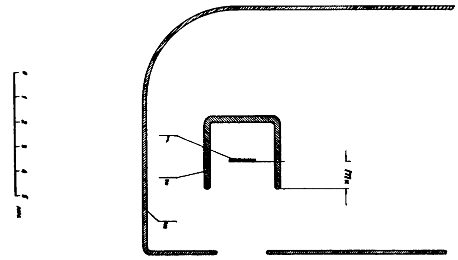


Fig. 4. Electron optics of injector system.
1. Cathode (tungsten tape 0.1 × 1.0 × 26 mm.); 2. Control electrode (Wehnelt cylinder), height 20 mm. Made of tantalum 0.3 mm. thick; 3. Anode (stainless steel) 0.15 mm. Anode output diaphragm 20 mm. high.

Electron injector

The lay-out of the injector and its electron optics is given in fig. 4. The gun has a direct-filament tungsten tape cathode (1) to which the control electrode (2) is coupled. If the assembly is properly done, the system provides electron beams of a half angle of ± 1°. To ensure longer life of the tungsten tape and reduce the heating of surrounding objects, a pulsed supply of the cathode is provided with temperatures so forced as to ensure emission of up to 10 amp/cm^2. The main elements of the injector are housed in the inside cylindrical wall of the chamber.

Shielding

When developing the set, a number of shielding systems were investigated and applied which in the first place protect the cavity of the accelerating chamber from alternate magnetic stray fields and in the second place ensure penetration into the chamber of the inductive electric field necessary for the electron acceleration.

The shielding consists of a system of insulated copper surfaces, the gaps between which offer high resistance to the magnetic flux.

Penetration through the gaps between the flux shields is partially shunted; this particularly weakens the field in the chamber. Shielding systems have been developed which provide a ten thousand-fold weakening of the field.

Spark gaps

To ensure proper coupling of the capacitor banks to the windings in acoustically shielded boxes, graphite spark-gaps were constructed with a special ignition system; forced air ventilation was switched on after every operation cycle. The spark-gaps are designed for switching currents of over dozens of kiloamperes in circuits with voltages up to 50 kV and ensure accuracy of switching time within ± 0.1 microsec.

Power supply and control circuits

The general lay-out of the power supply system is shown in fig. 5. Rectifiers for charging the capacitor banks provide repetition of operation cycles every 30 sec.

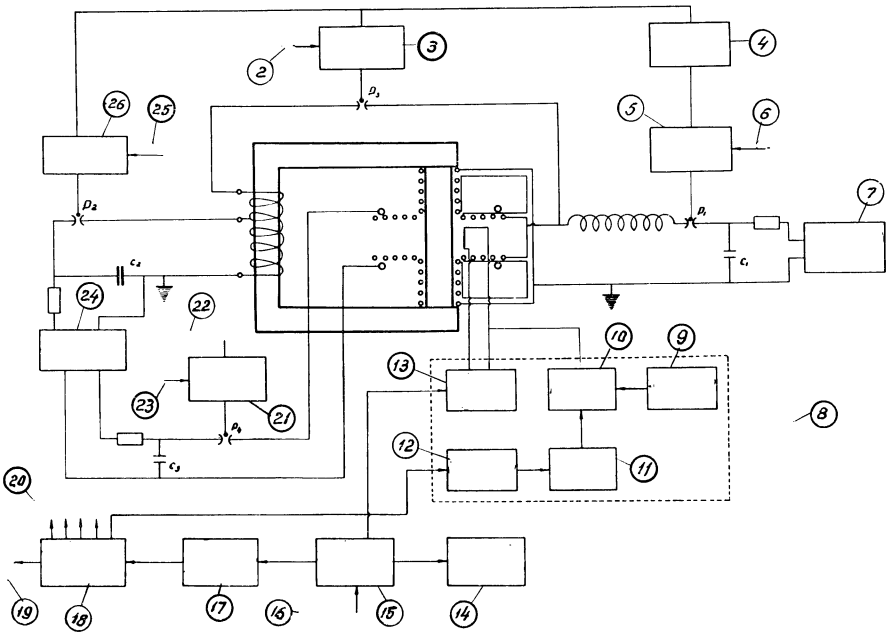


Fig. 5. Block diagram of betatron. 2. From control generator; 3. Ignition system; 4. Ignition system rectifier; 5. Ignition system; 6. From control generator; 7. Rectifier 6 kV; 8. Gun power supply unit; 9. Rectifier 30 kV; 10. Modulator; 11. Master oscillator; 12. Mixer; 13. Gun cathode filament; 14. Spark gap cooling system; 15. Timing relay unit; 16. Start; 17. Circuit synchronization block; 18. Control generator; 19. Sarting of meter; 20. To ignition systems; 21. Ignition system; 22. From rectifier; 23. From control generator; 24. Rectifier 50 kV; 25. From control generator; 26. Ignition system.

Voltage is supplied to the injector in pulses during the working periods and the conditioning which precedes each working pulse. The gun voltage amplitude may vary from 10 to 30 Kv, while the pulse range lies between 0.5 and 50 microsec.

A control generator regulating the switching time of any unit of the system is used for controlling spark-gap ignition time and for switching on the working pulse of the gun and auxiliary equipment. At every working cycle, a timing relay unit switches in the gun filament, the conditioning pulses and the ventilation of the spark-gap, and also starts the control generator.

Vacuum system

The chamber is pumped off with an oil diffusion pump with a capacity of 2,000 litres per second.

When liquid nitrogen traps are employed, the vacuum in the chamber reaches 2×10^{-6} mm. Hg.

Results of experimental work on betatron set

Experimental work is now being done on accumulation and acceleration of electrons without compensation of the volume charge. At the equilibrium radius, 10 amp. of electron current was obtained with an energy of 3 Mev. The dependence of beam intensity on the injected electron energy is being investigated. Accumulated current and the energy of accelerated electrons are to be considerably increased in the immediate future.

On the basis of the results obtained, a pulsed betatron set is being developed which will provide ring currents of the order of 100 amp. with an energy of over 10 Mev.

LIST OF REFERENCES

1. Gund, K. Ein leicht bewegliches 15 Mev Betatron. Stahl und Eisen, *73*, p. 710-3, 1953.