HIGH-CURRENT IRON-FREE BETATRONS

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Abstract

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1. The present communication is devoted to work undertaken with the aim of obtaining intense ring beams of high-energy electrons. The conditions for successful realization of the potential capabilities of the induction method of accelerating large electron currents and the simplicity of the accelerator installation determined the choice of an iron-free version of the betatron. The advantages of completely iron-free betatrons have been noted repeatedly (see, for example, ([1], [2])). Attempts to construct such accelerators are known ([3]–[6]). The maximum currents achieved up to the present time amount to several amperes at an energy of 2 MeV ([7]).

Below we describe pulsed iron-free betatrons in which circulating currents of ~ 90 A were obtained ($2 \cdot 10^{12}$ accelerated electrons in one acceleration cycle) at electron energies up to 100 MeV*. Several designs of iron-free accelerators were created, one of which is shown in Fig. 1.

2. For forming an axially symmetric betatron field, the simplest system is one of circular turns with radial transitions. Such an electromagnet can be calculated with satisfactory accuracy. However, the use of circular turns in iron-free electromagnets intended to obtain sufficiently strong, rapidly varying magnetic fields encounters difficulties in obtaining a field with small azimuthal inhomogeneities. The investigations carried out made it possible to create an electromagnet which, along with good symmetry of the magnetic field and a large relative width of the stability region, provides the possibility of obtaining a high magnetic-field intensity. The electromagnet is formed by two flat spirals connected by a central solenoid with a gap in its middle part. With such a construction of the electromagnet, it is possible to distinguish the contribution of the fields of the solenoid and of the flat spirals to the total distribution of the magnetic field, which makes it comparatively simple to control the position of the equilibrium orbit by relatively changing the currents in these parts of the electromagnet. By the corresponding arrangement of the spiral turns, by selecting their number, pitch, and the ratio of turns in the spirals and in the solenoid, the known betatron stability conditions were fulfilled with satisfactory symmetry of the magnetic field. The azimuthal static inhomogeneity in the plane of the equilibrium orbit does not exceed 0.5%. To a considerable extent it is due to the influence of the supply buses. In such an iron-free electromagnet there are practically no phase inhomogeneities

Fig. 1.

Figure 1: Fig. 1.

of the magnetic field. The relative dimensions of the stability region in the radial and axial directions are, respectively:

$$\Delta r/r_0 \approx 0.7 \qquad \Delta z/r_0 \approx 0.6,$$

where r_0 is the radius of the equilibrium orbit. The index of the magnetic-field decrease in the region of the equilibrium orbit is equal to $0.4 \div 0.5$.

Electromagnets of this type were used in betatrons with equilibrium-orbit radii of 3.9; 7.8; 11.7; and 23.4 cm.

* The first operating designs of the accelerators were realized in 1957.

3. The accelerator electromagnets were powered from capacitor energy-storage banks. Depending on the parameters of the circuit, the acceleration time can vary over wide limits ($10^{-5} \div 10^{-2}$ sec). The maximum magnetic-field strength is determined by the energy of the power source and by the mechanical strength of the electromagnet structure. The latter factor limited the magnetic-field strength at the equilibrium orbit to a value of $\sim 2 \div 4 \cdot 10^4$ oersteds. The field in the region of the central solenoid is then equal to $1 \div 2 \cdot 10^5$ oersteds. The limitation of the maximum electron energy associated with their radiation braking in strong magnetic fields, owing to the short acceleration time and the considerable dimensions of the stability region, plays a secondary role in this case.

4. Large pulsed currents in the windings of air-core electromagnets do not preclude the possibility of using them in accelerators designed for operation at industrial frequency and higher. The low inductance of an air-core electromagnet makes it possible to reduce ohmic losses in its winding by shortening the duration of the acceleration cycle. Under certain conditions, the power dissipated in such an electromagnet may be less than the total losses in a betatron with an iron magnetic circuit for the same energy. Operation of an air-core betatron ($r_0 = 3.9$ cm) at a frequency of 25 Hz (acceleration time 13 μsec) confirmed the possibility and expediency of using such accelerators at frequencies up to several kilohertz. A certain complication of the power-supply circuit is more than compensated by the high average intensity, simplicity, and compactness of the accelerator.

Fig. 1.

5. The absence of a quantitative theory of the process of electron capture into the betatron regime and the ambiguity in the interpretation of experimental results made it necessary to investigate the optimal conditions

for injection in air-core betatrons. The influence on electron capture of the parameters of the injection pulse (shape, duration, amplitude*), the strength of the vortex electric field, the electrostatic potential on the conducting coating of the chamber, and the number of injection pulses in one cycle was studied. The possibility of increasing the circulating–

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* Data up to 300 keV are given in Ref. (8).

of the electron current by means of additional magnetic focusing and compensation of the space charge of the injected electrons. The injection parameters were chosen with account of the experimental results obtained. Owing to the large dimensions of the stability region, it proved possible to increase the distance between the cathode and the end face of the injector to a value of $\sim 0.17 r_0$ without any noticeable decrease in the intensity of the accelerated-electron beam. This made it possible to carry out internal injection of electrons with energies up to 250 keV by means of an ordinary Kérst-type injector with increased interelectrode spacings. For injection of electrons with an energy of 500 keV, an electron gun with three accelerating gaps was used, providing at the output a current of $\sim$ 50 A in a pulse of duration $5 \cdot 10^{-7}$ sec. The electron beam was introduced into the stability region by means of an electrostatic inflector. In a number of cases, the introduction of electrons into the inflector was carried out through a channel shielding the magnetic field of the accelerator. In the injectors, directly heated tungsten cathodes or heated tantalum cathodes were usually used. In some investigations a cold cathode was used, which provides large pulse currents and operates satisfactorily when the pressure varies in the range $10^{-3} \div 10^{-7}$ mm Hg (9). The injectors were powered from pulse cascade transformers, pulse-voltage generators (10), and cable transformer lines (11).

6. To displace the beam of accelerated electrons onto the target, systems have been developed which provide radiation pulses with durations from hundredths of a microsecond to several tens of microseconds. In betatrons with $r_0 \leqslant 11.7$ cm, rapid dumping of electrons is accomplished by an azimuthal perturbation of the magnetic field by means of a low-inductance winding. In accelerators with $r_0 = 23.4$ cm, a "double dump" system has been used, with a preliminary slow change in the radius of the equilibrium orbit and subsequent rapid displacement of the electron beam onto the target. This method facilitates the production of very short radiation pulses with a duration equal to a time of $\sim$ 10 electron revolutions ($\sim 5 \times 10^{-8}$ sec). In addition, the beam structure is preserved during the displacement process. The necessary synchronization is achieved through the use of highly stable switches (12).

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