SENSITIVITY OF PROBES USED TO MEASURE THE ELECTRON CURRENT IN A BETATRON

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Calibration of the probes (consisting of a magnetic loop, turns on the accelerating chamber, and an electrostatic signal electrode) used to measure the current circulating in the accelerating chamber of the 15 MeV betatron is reported for various phases of the acceleration. The calibration was carried out in the working part of the accelerator with a current of electrons which had undergone a single revolution in the chamber. Results found in a calculation of the sensitivity and other probe characteristics are reported. A method is described for measuring the current involved in the acceleration by means of turns on the chamber and an electrostatic deflection of electrons. Recommendations are given for the use of probes to adjust a betatron.

Analysis of electron capture in acceleration, of the acceleration itself, and of the operating efficiency of a betatron requires measurement of the current circulating in the accelerating chamber. Various methods are available for measuring this current: 1) a method involving measurement of the charge of the electron beam when it is scattered on a target [1, 2]; 2) the magnetic-induction method, based on measurement of the voltage induced in the turns by the magnetic flux produced by the circulating electron beam [3, 4]; and 3) the method based on measurement of the voltage induced in an electrostatic signal electrode in the accelerating chamber by the charge of the accelerated beam [5].

Measurement of the currents circulating in an induction accelerator during various stages of acceleration rests on a determination of the probe sensitivity and capabilities.

Results of the Calibration of the Magnetic-Induction Probes and the Signal Electrode. Discussion of Results

The probes were calibrated with the current of electrons which had undergone a single revolution in the accelerator chamber and which struck a baffle covering the entire chamber cross section; Fig. 1 shows the probe arrangement in the accelerating chamber. Electrons from injector 2 complete a single revolution in chamber 1 and strike baffle 3 behind the injector. The signal from the baffle is fed through RK-75 coaxial cable loaded by 75 Ω to the input of a DSO7 dual-trace oscilloscope. Signals from the magnetic loop 4, the turns on the chamber 5, and the electrostatic signal electrode 6 are alternately fed to the second oscilloscope input. A grounded screen 7 in front of the signal electrode prevents electrons from striking it. The maximum current to the baffle was 25 mA, at an injection energy of 10 kV and an induction current of 500 mA.

Table 1 shows the basic characteristics and the calculated and experimental sensitivities of the magnetic-induction probes used to study electron capture in acceleration and acceleration itself. The sensitivity and other probe characteristics were calculated by the procedure described in [6], where the output voltage of the magnetic-induction probe was given as

$$U(t) = \frac{W\overline{\Phi}_m}{10^8\tau} \cdot \frac{\eta}{\sqrt{\eta^2 - 1}} \left[e^{-(\eta - \sqrt{\eta^2 - 1})\Theta} - e^{-(\eta + \sqrt{\eta^2 - 1})\Theta}\right] = \frac{W\overline{\Phi}_m}{10^8\tau} \cdot f(\eta, \Theta), \tag{1}$$

S. M. Kirov Tomsk Polytechnical Institute. Translated from Izvestiya Vysshikh Uchebnykh Zavedenii, Fizika, No. 9, pp. 106-110, September, 1970. Original article submitted September 8, 1969.

TABLE 1. Basic Characteristics of the Magnetic-Induction Probes

Characteristic	Units	Probe	
		turns	magnetic loop
Inductance	$L \cdot 10^{-6}$ H	69	241
Resistance	r, Ω	1,1	51
Capacitance	$C \times 10^{-12}$ F	65	70
Number of turns	W	8	1200
Pulse rise time	$\tau_f \times 10^{-9}$ sec	70	120
Sensitivity:			
a) calculated	mV/mA	10,5	1,0
b) experimental	mV/mA	12,0	1,6

where

$$\omega^2 = \frac{1}{LC};\ \tau = \frac{L}{R} + rC;\ \gamma = \frac{r}{R};\ T_i \doteq \frac{1}{\omega\sqrt{2\gamma+1}};$$

$\Theta = t/T_i$ is the reduced time; $\eta = \tau\omega/2\sqrt{2\gamma+1}$; L is the probe inductance; r is the resistance of the probe winding; C is the probe capacitance; R is the load resistance; W is the number of turns in the probe winding; $f(\eta, \Theta)$ gives the shape and magnitude of the probe signal; and $\overline{\Phi}_m$ is the average magnetic flux linking the probe winding when a beam I passes along the center of a toroidal core with a permeability μ:

$$\overline{\Phi}_m = 0.2Ib \ln \frac{r_2}{r_1} \approx 0.2I\mu \frac{S}{r_{av}}. \tag{2}$$

Here b is the core width; and r_1, r_2, r_{av}, and S are the outer, inner, and average radii and the cross-sectional area of the core.

From Eq. (1) we see that with $\eta > 1$ the process is aperiodic, while with $\eta < 1$ it is oscillatory. Choice of optimum values of L, W, and R in our case reduces to finding the optimum value of η, at which a maximum probe sensitivity would be achieved for a specified pulse rise time. It should be noted that the requirements of a maximum sensitivity and a minimum pulse rise time are conflicting.

Experimental results are shown along with the results of approximate calculations in Table 1 for the following load resistances: R = 560 Ω for the turns and R = 750 Ω for the magnetic loop.

The turns in the chamber were made of PÉLShO conductor, 0.33 mm in diameter; the average turn diameter was 270 mm, and the winding spacing was 6-8 mm. Table 1 shows the turn inductance in the working gap of the 15 MeV betatron; the turn inductance in air was 28.0 ± 0.3 μH. The magnetic loop consists of PÉLShO wire 0.12 mm in diameter on a hardboard strip 1.8 × 26 mm in area and 240 mm long.

The signal electrode was an aluminum plate 22 mm wide and 40 mm long, held at a radius of 160 mm in the chamber. The equilibrium orbit of the 15 MeV betatron has a radius of 135 mm.

Using known equations for the sensitivity of the signal electrodes [7, 8] and experimental data [9] showing that the probe shape has little effect on its sensitivity and characteristic, we derived the following equation for a plate-shaped electrostatic signal electrode:

$$U_e = \frac{KlK_e}{C_e\Pi} Q, \tag{3}$$

where U_e is the voltage on the electrode; Q is the circulating charge; l is the electrode length; K_e is the screening coefficient; Π is the length of the equilibrium orbit; C_e is the total capacitance of the electrode and the entrance to the measurement apparatus; and K is a correction factor. In $K_e = \alpha/2\pi$, the angle α is that subtended by the signal electrode at the center of the beam. The factor K takes into account both the shape of the zero-potential surfaces adjacent to the signal electrode and the fact that a voltage is induced in electrode not only by electrons opposite it, but also by electrons in front of it and behind it.

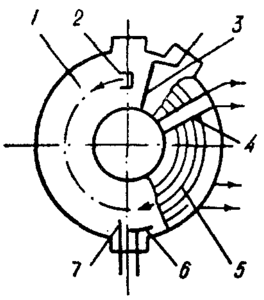

Fig. 1

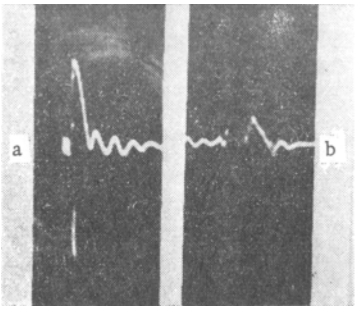

Fig. 2

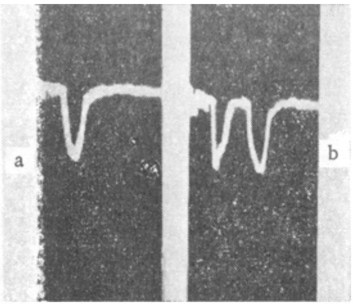

Fig. 3

Fig. 1. Probe arrangement in the accelerating chamber.

Fig. 2. Oscillograms of the voltage taken from the turns in the chamber. a) Transient current; b) accelerated current.

Fig. 3. Oscillograms of the voltage from the signal electrode, recorded during the calibration.

The signal-electrode voltage U_e can be related to the beam current I by

$$U_e = \frac{K l K_e}{C_e \cdot 5.96 \cdot 10^7 \sqrt{U}} I, \tag{4}$$

where U is the electron injection voltage. In our case we have $l = 4$ cm, $K_e = 0.1$, and $C = 50 \cdot 10^{-12}$ F. Calibration of the signal electrode yielded K = 1.5. Substituting these values into Eq. (4), we find

$$I = 5 \cdot 10^{-3} \sqrt{U} \cdot U_e. \tag{5}$$

At an injection voltage of U = 10 kV and a load resistance of R = 75 Ω, we find a signal-electrode sensitivity of 2.1 mV/mA; the sensitivity of the probe consisting of turns on the chamber is 12.0 mV /mA, and that of the magnetic loop was only ≈1 mV/mA. The turns on the chamber are apparently to be preferred because of their high sensitivity. The turn sensitivity measured agrees well with that calculated (Table 1).

Measurements can be made with magnetic-induction probes only after the conductors are shielded and all possible paths by which interference can reach the measurement apparatus are blocked by capacitances. Much noise is produced by, e.g., the power-line and heater windings of the transformers in the injection circuit, by the last cascade in the synchronization circuit, etc.

Magnetic probes were used to measure the circulating current at the time of injection (a transient current) [3, 4]. It has not previously been possible to use the magnetic-induction method to measure the current captured in acceleration because of the interference caused by operation of the bias circuit. By using electrostatic deflection of electrons, we were able to significantly reduce the interference and use the turns to measure the current captured in acceleration. Figure 2 shows oscillograms of the voltage taken from the turns. The negative part of the pulse (a) corresponds to an increase in the current in the chamber, while the positive part of the pulse corresponds to a decay of this current. The transient current had an amplitude of 35 mA, and the injection voltage was 18 kV. The positive pulse in Fig. 2b corresponds to deflection of the current; here its level is 3 mA. Oscillogram 2b was photographed at a scale 10 times as large as that in Fig. 2a. The electrons were deflected by supplying a high-voltage pulse to the signal electrode; the voltage was 6 kV, supplied 40 μsec after the beginning of injection.

Figure 3 shows oscillograms of the voltage from the signal electrode recorded during the calibration. Figure 3a corresponds to capture of electrons in acceleration at the peak of the injection pulse, while Fig. 3b corresponds to capture at the fronts.

CONCLUSIONS

The most sensitive of our probes is a probe consisting of turns on the accelerating chamber, along the perimeters of the electron orbits. We found that a transient current exists in the chamber and reaches a large value when electrons are no longer captured in acceleration and when there is thus no bremsstrahlung x radiation, which is usually used to adjust betatrons. It is easy to adjust the betatron for maximum radiation by using the maximum signal from the probes. In this adjustment method, the betatron gives a maximum radiation during the very first operation of the electron-deflection circuit.

In this study, we: 1) found a logical way to choose probe parameters and evaluate their sensitivity and other characteristics; 2) calibrated probes (consisting of turns, a magnetic loop, and an electrostatic signal electrode) with the current of electrons completing a single revolution in the accelerating chamber of a betatron; 3) proposed a method for adjusting the betatron on the basis of the maximum probe signal without operating the electron-deflection circuit; and 4) measured the current captured in acceleration by a magnetic-induction pickup, by cutting off the current in the accelerating chamber.

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