EXPERIMENTS ON ELECTRON COMPENSATION OF PROTON BEAM IN RING ACCELERATOR

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There is enough reason to expect that the limitations of the circulating current in the accelerators due to the betatron frequency shift by the self-field may be overcome by the electron compensation of beam space charge. The stability problem has been treated previously (1-3). The compensated beam is stable with respect to plasma wave excitation with wavelengths significantly smaller than beam transverse size. There exist stability regions for larger wavelengths[1,2]; some of the instabilities may be eliminated by proper choice of accelerator parameters (e.g., longitudinal instability). A number of incoherent instabilities (especially transverse) may be suppressed by the external feedback systems. During accumulation some instability regions may be passed through. Keeping in mind a significant hydrodynamic rigidity of the circulating beam it may be expected that a proton current increase may occur by the electron compensation methods. An effective compensation is considered possible in betatron regime as well as in synchrotron regime with very high harmonic numbers. The necessary density of electron gas may be produced by the circulating proton beam ionization of residual gas.

On the experimental setup[4] where a limited current has previously been obtained in the resonance regime experiments on electron compensation of proton beam in betatron regime have been started. A hollow copper coil has been installed in the vacuum chamber with a constant guide field (Fig. 1). Protons with current up to 300 μa at the energy 1 MeV are injected by the charge-exchange method. During the injection period protons lose 200 ev per turn in the charge-exchange hydrogen jet. The induced electric field between the coil ends compensates this energy loss. The coil is supplied by the pulse current generator that provides for nearly constant voltage (up to 200 volts) in 200 μsec. (Fig. 4e). The cavity has an oval cross-section with axis 4x3cm^2. The radius of middle orbit is 42 cm. Four rectangular sections in the coil are foreseen to place the magnetic shields, hydrogen jet and the measuring devices. The measured average hydrogen pressure inside the coil within the operating interval of time is equal (as a rule) to 5×10^{-5} torr.

The first experiments were carried out with axial symmetric magnetic field ($n = 0.6$). The number of protons stored in quasibetatron regime is defined by the inward spiralling time and makeup 5.5×10^{10} at maximal injection current. Longitudinal instability of beam has been observed in this case. Fig. 2 shows the oscillogram of circulating current (a) and HF signal from the ring induction probe (b). The HF signal consists of revolution frequency harmonics. Longitudinal instability arises at the beginning of the accumulation process when the energy spread in the beam is still small rapidly developing to full bunching. The total number of bunched particles does not increase, very often dropping to negligible amounts when accumulation continues. Longitudinal bunching is accompanied by radial broadening testified by a signal from the outer target (Fig. 2c). The reduction of radial aperture brings about a decrease of accumulated current. The threshold number of particles N_κ depends upon injection current I and relative energy losses per turn ε. When a relative energy spread of injected protons is equal to $\pm 5 \times 10^{-3}$ the threshold for instability is equal to $N_\kappa = 8 \cdot 10^8$ ($I = 8.5$ μa, $\varepsilon = 2.3\ 10^{-5}$) and $N_\kappa = 10^{10}$ ($I = 300$ μa, $\varepsilon = 1.5\ 10^{-4}$). The above parameter dependence is in good agreement with the "negative mass" theory.

In a quasibetatron regime a relaxation of the number of compensating electrons was observed. When the intensity of the proton beam was constant (Fig. 3a) the beam potential increased sharply in 1 μsec and then slowly decreased in 8-10 μsec (Fig. 3b, 3g). In such cases a loss of electrons was observed by the collector situated over or under the beam (Fig. 3c, 3d).

When relaxation occurs beam compensation decreases to 30-60%. The presence of an ion flow on the outer collector proves it (Fig. 3f, 3e). Sharp changes of compensation occur synchronically in the whole beam if the total number of particles exceeds 7×10^9. The above mentioned oscillations are not observed when the beam is bunched with linear density modulations more than 1% (Fig. 3g, 3h). When proton bunching is considerable, compensation is close to zero. This is proved by the current on the ion collector with a retarding potential being close to compensating bunched beam potential (Fig. 3m, 3a). The oscillograms (Fig. 3k, 3l) show beam potential with and without energy spread of injected protons. Beam potential with no energy spread and with bunching at the beginning of accumulation is approximately twice the beam potential when relaxations take place. When proton current is less than the relaxation threshold and energy spread is large, beam compensation is close to 100%.

Proton capturing into betatron regime is illustrated in Fig. 4. At high injection current (a) the circulating current (b) increases non-linearly. An increase in proton losses on inner (c) and outer (d) targets was observed. The longitudinal instability develops from the start which is proved by the signal from the ring induction probe (e). The depth of the linear density modulations of protons at the beginning of accumulation is close to 1. At the end it is about several tenths. In the longitudinal bunching spectrum the maximal amplitude has the 18th mode followed by a significantly reduced 10th mode. A relatively small maximum is present within the region of the 50th mode. When the number of injected particles is near 3×10^{11} the number of accumulated particles does not exceed 9×10^{10} because of longitudinal instability. The increase of injected proton energy spread keeps back the appearance of instability (4f), significantly reducing beam bunching. The efficiency of injection, though, does not increase significantly due to the increase of the initial betatron oscillations.

The initial energy spread ± 2.5% permitted 10% increase of the number of accumulated particles. Of greater efficiency is the proton energy spread that appears during accumulation at the expense of non-synchronization of the accelerating voltage. This permitted the number of particles captured into the betatron regime to increase up to $1.5x10^{11}$.

Further experiments were carried out in alternating gradient magnetic field (number of cells = 4, momentum of compaction $\alpha = 0.7$, $\nu_r = 1.15$, $\nu_z = 0.76$). In the quasibetatron regime a vertical spillout of proton accumulated current (Fig. 5a, 5c) was observed. Simultaneously the current on the inner target decreased sharply (b). During the spillout the vertical beam oscillations (d) were registered by the induction probe. Of greatest intensity are oscillation modes 6 and 11. Modes under 6 were not observed. The time before the instability begins decreases with the increase of residual gas density and injection current. When hydrogen pressure changes from 10^{-5} to 10^{-3} torr ($I = 250\mu a$) it decreases from 60 to 20 μsec. The accumulation of protons in the betatron regime is restricted by vertical beam instability. The limit circulating current depends upon accumulation rate and residual gas density. The limit number of particles is equal to 5×10^{10} with the pressure 2×10^{-5} torr and injection current 250 μa. When the pressure of the residual gas rose, circulating current pulsations (Fig. 6b) and vertical proton losses (Fig. 6a) were observed.

The following conclusions are drawn from the above studied processes. The excitation of the vertical oscillations is connected with an interaction of a circulating beam with a plasma produced by residual gas ionization. Longitudinal bunching was not observed when operating with magnetic fields when $\alpha < 1$.

In future a suppression of coherent vertical oscillation and an increase of intensity limit is expected.

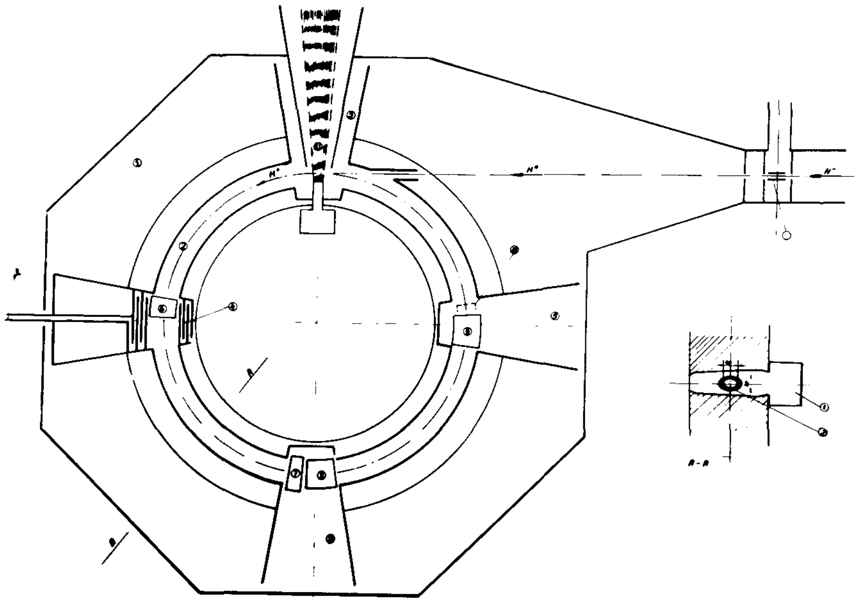

Fig. 1 A layout of the experimental setup

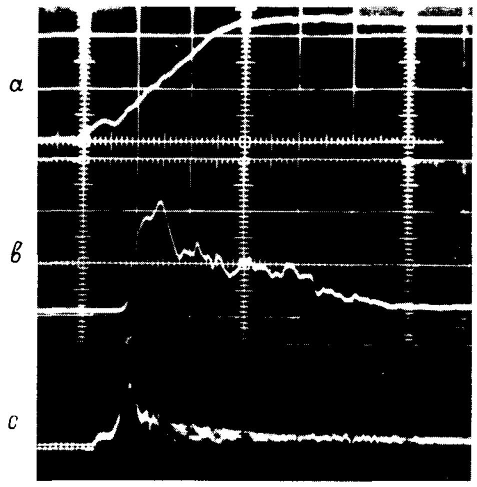

Fig. 2 Time scale 10 μsec per division

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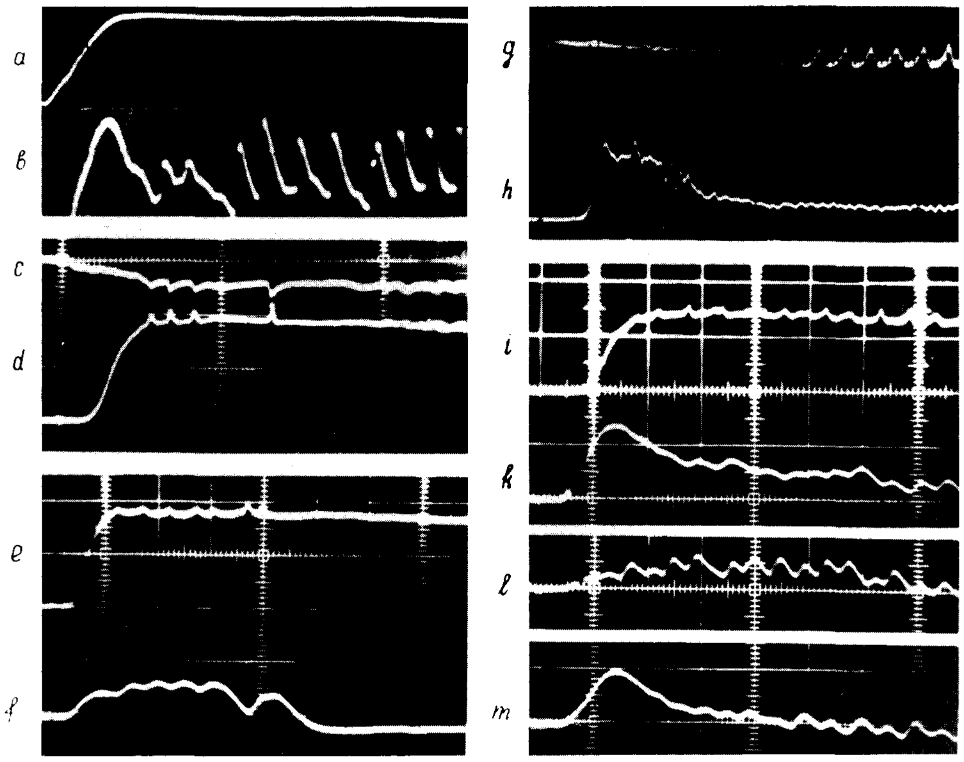

Fig. 3 Time scale 20 μsec per division

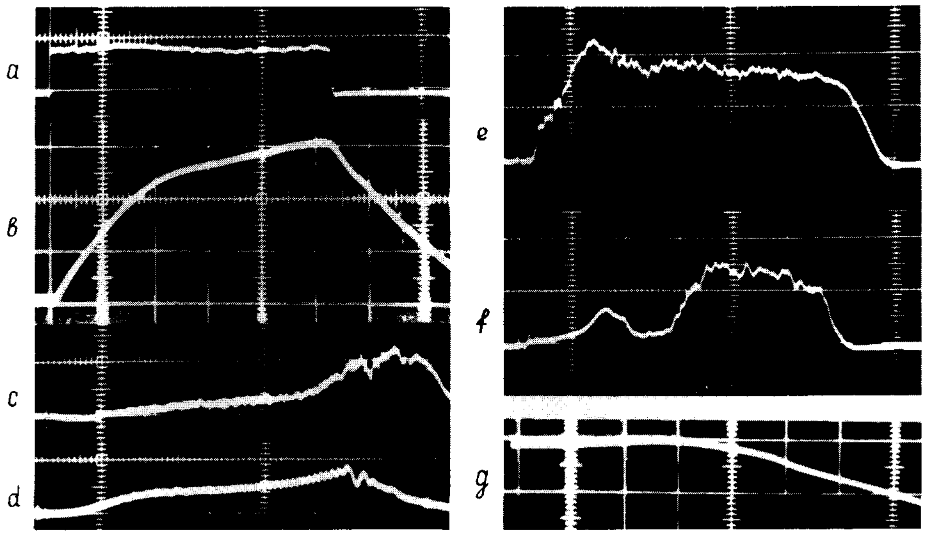

Fig. 4 Time scale 50 μsec per division

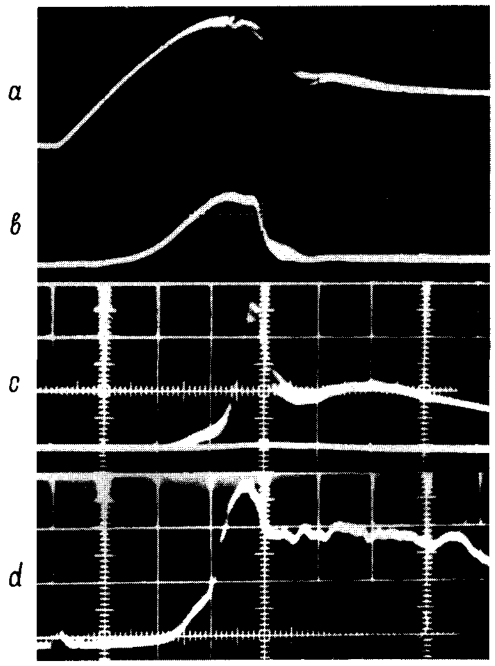

Fig. 5 Time scale 20 μsec per division

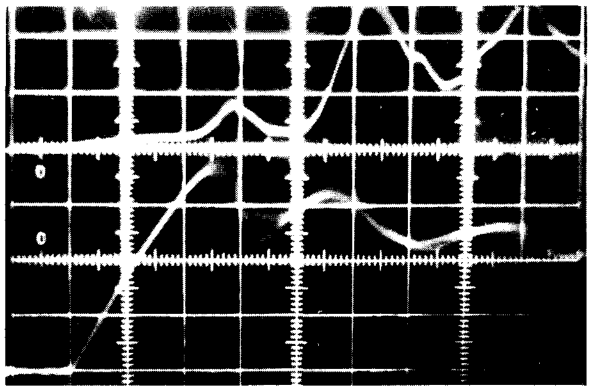

Fig. 6 Time scale 20 μsec per division