# THE RF SYSTEM OF A 700 MeV CYCLOTRON

A. A. Glazov, V. A. Kochkin, L. M. Onishchenko,
I. M. Poĭfe, M. M. Semenov, I. V. Tuzov, E. Shvabe

Joint Institute of Nuclear Research, Dubna
(Presented by A. A. Glazov)

The accelerating system of the 700 MeV cyclotron must ensure a continuous acceleration of protons with a current up to 1 milliamp at the maximum radius. It is also necessary that the energy attained by the accelerated protons per revolution be the maximum possible under a technically and economically feasible application of high-frequency power supply to the accelerating electrodes. The determining factors in the selection of an accelerating system are the configuration and the structure of the region where particles are accelerated, and the design of the accelerator electromagnet.

Special features of the accelerator considered here (a strong-field device with little variation in the magnetic field intensity and with a high degree of helicity) are the small height of its accelerating region (Figure 1), no variation of airgap along the azimuth and only insignificant airgap variation along the radius ($2h_{min}$ = 146 mm, $2h_{max}$ = 220.4 mm) with the maximum airgap at the mean radius. Such a construction of the working zone precludes the application of simple cavity resonators as accelerating systems, even when operating at high order harmonic frequencies. This is so because the vertical height of the resonator should be equal to about one half the wavelength of the accelerating voltage and the period of proton revolution in the cyclotron field should be 83.3 nanoseconds ($f = 1/T = 12$ Mc). It is also impossible to use a multi-electrode (three or more) accelerating system for work at harmonic frequencies ["short frequencies" in the original text] with the existing design of the proton accelerating region. In fact, at a frequency equal to twice the frequency of proton revolution, the radius of the accelerator has to be four times larger than the wavelength of the accelerating voltage. Besides, it may not be technically feasible to build a console over three meters long containing carrier components located in a small interpolar gap and still meet the stringent requirements for size and uniformity of the gap between the accelerating electrode and the chamber.

The only practical and expedient solution in this case is an accelerating system which makes use of the resonance characteristics of short-circuited quarter-wave lines (at a frequency equal to the frequency of proton revolution) with dees made in a simple shape, i.e., a system used in cyclotrons. This system here differs from the conventional cyclotron systems in that the dees must in this case be treated as lines with distributed parameters and not as capacitances concentrated at the stub ends. The reason for this is that the diameter of the accelerator pole piece is larger than a quarter wavelength, even during operation at fundamental frequency. Another distinguishing feature here is the very small interpolar spaces at very large dee dimensions, i.e., a very low characteristic impedance of the dee lines.

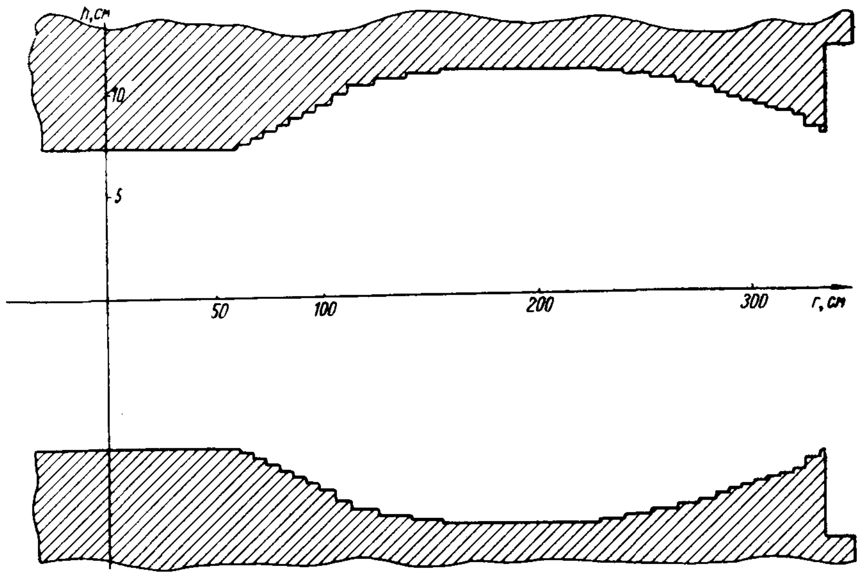


Figure 1

The accelerating voltage, which determines the energy attained by the protons during a revolution, is limited by the breakdown between the chamber and a dee (in the case where the interpolar spaces are small as is characteristic of the accelerator described here). In order to raise this voltage it is at the same time necessary to reduce the physical height of the dee to a minimum while the aperture made for the beam should be at least 50 mm. This construction can be realized by placing the copper plates of the dee leaves together with the attached tubes for cooling water on frames stretched between bars, U-shaped in the plan view, brought out through the airgap of the magnet. In this way the physical height of the dee will not exceed 80 mm and the minimum space between a dee and the metal lining of the chamber will be 30 mm.

The maximum energy attained by the protons should be at least 400 kV/rev, when limitations with respect to phase shift are taken into account at prevailing accuracies of the law of increase of the mean field. Experience in cyclotron operation shows that the maximum amplitude of the high-frequency dee voltage can reach about 100 kV at a 30 mm gap between the dee and the chamber. Thus, in order to ensure the necessary accumulation of energy, the accelerating system of the cyclotron must consist of two dees, and the angle of proton flight inside the dees must be approximately 180°. At the same time, the space charge factor with the consideration of the r-f nature of the beam amounts to about 20 percent according to measurements made on prototypes of the cyclotron. Macroscopically, the beam is continuous in time.

The two-dee accelerating system with a 180° angle of proton flight between dees can be built in several different ways. Variants of the dee design for an accelerator system were investigated theoretically and experimentally at the Joint Institute of Nuclear Research (OIYaI) and the Scientific-Research Institute of Experimental Atomic Physics (NIIEFA); namely, semicircular dees closed up over the distance of short arcs near the axis of symmetry, partially rectangular homogeneous dees and partially rectangular dees with variable characteristic impedance. Of all the possible designs considered here, the accelerating system in the form of a rectangular line with an increased characteristic impedance outside the airgap of the electromagnet has the best characteristics in terms of losses, excitation and ease of construction (Figure 2).

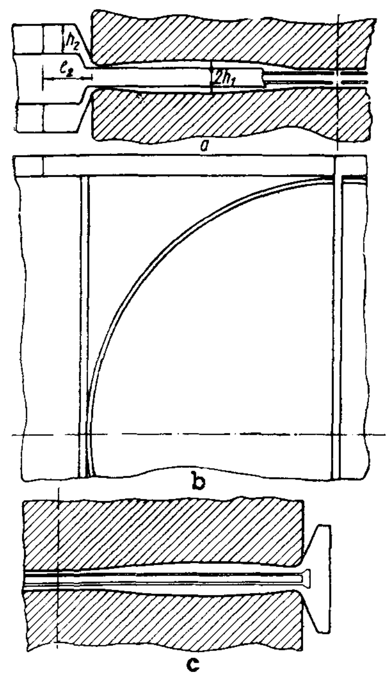


Figure 2. Accelerating system of a cyclotron in the form of a rectangular line:

(Views: a -- side view; b -- top view; c -- front view).

The widened gaps between inside conductor and surface conductor of the line outside the electromagnet make it more convenient to insert the loop coupling it to the generator. The natural frequency of the system can be easily regulated by controlling the gap width. The short-circuiting jumper parallel to the dee shoulder and of the same length prevents any transverse oscillations, even when the excitation system is not located on the axis of symmetry.

Calculations and measurements made on prototypes have shown that, at a gap $h_2$ = 20 cm (see Figure 2), the length $l_2$ of the section beyond the magnet is about half a meter and the system can be easily placed in between the vertical arms of the electromagnet yoke -- which is very convenient from the structural point of view, and for setting up a protective means against radiation effects. It also follows from calculations that for the system shown in Figure 2 the high-frequency power losses in copper amount to about 1000 kW and the maximum current flowing through the shorting shunt is of the order of 60 kiloamps.

It is standard practice to add to the calculated losses an amount which accounts for the nonideal copper surface, here 20 percent above the losses for ideal copper. Thus, the power required by the accelerator system for a beam of 1 milliamp must be (without considering losses in the shorting shunt) about 2 MW. The contact losses in the short-circuiting device are uncertain and vary with wear. Under unfavorable conditions these losses may come close to the total remaining losses in the system. The significance of this shorting shunt and especially the power losses in its contactor device were determined by setting up a full-size dummy cyclotron accelerator system (Figure 3). The voltage distribution along the accelerating edge, the position of the shorting shunt $l_2$, the Q-factor and the high-frequency power losses P were measured at maximum dee-ground voltage of 100 kV; the results are as follows:

| $V_{center}$, in relative units | $V_{side}$, in relative units | $l_2$, cm | Q | $P_{dee}$, kW |
|---|---|---|---|---|
| 1 | 0.98 | 46 | 2100 | 1200 |

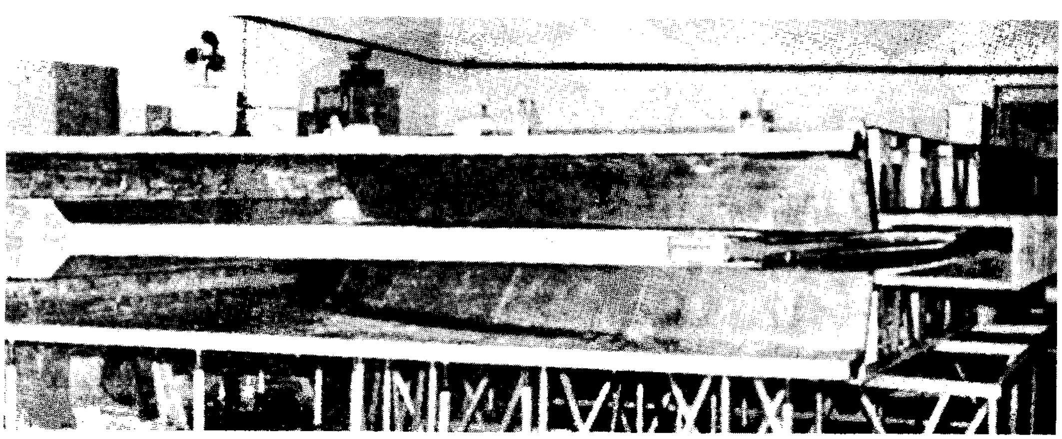

Figure 3. Dummy model of the accelerating system of a cyclotron.

The high-frequency supply for the accelerator is provided with extra reserve power in view of the fact that the losses in the short-circuiting device are not constant and also because the current-carrying surfaces have a tendency to deteriorate with time (oxidation, oil accumulation) whereas their repolishing is made difficult by the radiation hazards.

The supply for the accelerating system comes from two identical power amplifiers with common excitation. Each delivers 2 MW of power to a matched load. Their output must be arranged in such a manner that either one generator can operate both dees or each of the generators can operate its own dee. The design of such a high-frequency supply system for an accelerator has already been worked out.

It may be said in conclusion that the accelerating system selected here meets the requirements set forth. The radio-frequency engineering and the mechanical design carried out at the OIYaI and the NIIEFA, and also the prototype models of the various accelerator system components, have shown that the construction of this system is feasible and that the scheme as well as its basic parameters were judiciously chosen.