FERRITE MODULATION SYSTEM DESIGNED FOR OPERATING A FIXED-FREQUENCY CYCLOTRON IN AN FM MODE

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I. INTRODUCTION

During the past twenty years fixed-frequency cyclotrons have shown wide utility in many laboratories of the world. In 1955-1956 cyclotrons with electromagnets of 1200 mm pole diameter[1] were designed and serially constructed in the Soviet Union, with which protons can be accelerated to energies in the region of 12.6 MeV.

In 1955 A. A. Naumov(*), L. M. Nemenov and V. S. Panasyuk investigated the feasibility of increasing the energy range of protons accelerated in this cyclotron up to 30 MeV by operating it in a frequency-modulated (FM) mode. To modulate the dee circuit frequency they suggested using a ferrite-cored inductance, the existing cyclotron equipment being maximally utilized.

Calculations made on the basis of the Bohm and Foldy paper[2] indicate that in a cyclotron of 1 200 mm pole diameter, and with the magnetic field uniform to within $\sim 2\%$, the necessary frequency deviation at approximately 30 MeV is $\sim 5\%$. The capture efficiency with an accelerating voltage of 25 kV is $\sim 10\%$.

To check experimentally the operation of this device, the necessary radiotechnical equipment was fabricated together with the additional ferrite-loaded system applicable to the 1.5 m cyclotron of the Atomic Energy Institute. Because of the limited time available for experimenting with the cyclotron, it was decided that the equipment tests should be performed using the magnetic field and frequency parameters normally used for deuteron acceleration[3]. In this case, the frequency deviation should be 1.8%. When the acceleration voltage is 25 kV, the rate of frequency variation is 1.34×10^{10} sec^{-2} and the capture efficiency is $\sim 17.4\%$.

II. UTILIZATION OF THE MAIN EQUIPMENT AND CHOICE OF AN FM SYSTEM FOR THE CYCLOTRON DEE CIRCUIT

In the Soviet Union, RF multi-stage oscillators of 120-150 kW power are widely used to drive cyclotron dees. In an FM mode of acceleration, the dee voltage can be reduced to 20-30 kV, resulting in a saving of RF power which can be used for broadening the oscillator passband. Naturally in this case the broadening of the passband takes place at the expense of decreasing the oscillator efficiency, but this fact is not considered to be an important defect for the following reasons:

1. The construction of an oscillator specially intended for acceleration in an FM mode would involve substantial expenditure on design and fabrication.
2. In order to install new equipment it is necessary to have extra space which is not always available with devices that are already in operation. Furthermore, it is not justifiable to allow an expensive piece of equipment like the fixed-frequency cyclotron to stand idle.

In a synchro-cyclotron attention should be given mainly to the method of frequency modulation and to the efficiency of extraction of ions from the source. One of the dees is grounded in this case, and the cyclotron resonance corresponding to the ungrounded dee is driven by the RF supply. Since the size of a dee is small in comparison with the wavelength of the RF voltage, the usual dee circuit design can be used. Thus the dee circuit can be used practically without any reconstruction.

(*) A. A. Naumov was, for various reasons, unable to take part in the further experiments.

The method of frequency modulation should be considered in detail. Because of the high RF voltages and modulation frequencies, mechanical modulators of whatever type would not be sufficiently stable or reliable. Although a reactance tube can be used for frequency modulation it appeared to be unsuitable for economic and technical reasons.

The application of a ferrite modulation system magnetized by alternating current of a frequency which is defined by an acceleration cycle frequency is a more convenient technique. By suitably connecting this system to the dee circuit, the dee resonance frequency can be changed(*).

To connect the modulation system to the dee circuit in a simple manner, inductive coupling could be considered. However, with the partial coupling achievable in practice, it is not possible to obtain the required frequency variation with minimal currents in the variable inductance. It is therefore better to connect the variable inductance directly to the cyclotron dee.

In the case under consideration, the variable inductance was made in the form of a short-circuited co-axial ferrite-loaded line connected to the dee by an insulated spacer. In this study we have used ferrites developed and manufactured in 1956-1957. At that time ferrites with a high permeability ($\mu \sim 1000$) at frequencies of the order of 10 Mc were as a rule of rather poor quality. In a strong RF field such ferrites usually overheat and deteriorate. For this reason ferrites of lower permeability have to be used. On the other hand, to reduce the magnetizing current, it is desirable to use ferrites of high permeability. A permeability of $\mu = 20$-50 is probably an optimum value under these circumstances [5].

It was intended to use lithium-zinc ferrites of the type Φ-20 with $\mu = 20$, but for technical reasons the permeability of the ferrites actually manufactured was only between 7 and 10. For subsequent calculations of the variable inductance we used the ferrite characteristics shown in Fig. 1. From the relation between Q and B, where $B = rH$, μ as a function of H may be determined. The ferrites were manufactured in the form of toroidal rings with an inner diameter of 87 mm, an external diameter of 137 mm and a

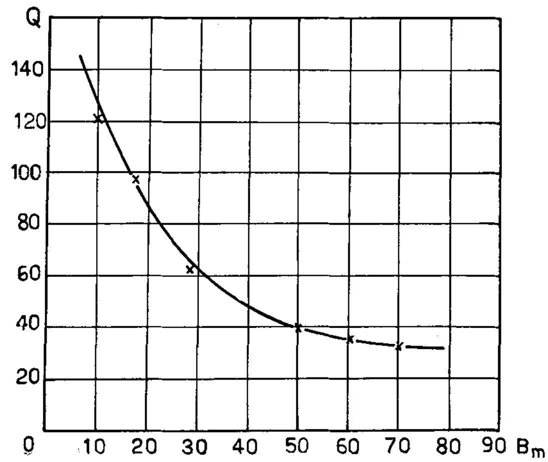

Fig. 1 The Q factor as a function of RF induction.

ihickness of 15 mm. The rings were placed on the inner conductor of a special co-axial line. The external diameter of the line is made large enough (600 mm) to give the required characteristic impedance (160 ohm). The electrical length of the line takes into account both the characteristic impedance of the cyclotron circuit and the possibility of obtaining the magnetizing current necessary for a given frequency deviation. As a matter of interest, at a frequency of 9.8 Mc, the electrical length of the line is 40°, corresponding to a geometrical length of 2 000 mm. In such a line, specific losses in ferrite are of the order 2.5 W/cm^3 when the dee voltage is 25 kV. In order to make the frequency deviation 3 %, the permeability should be changed by 35 %. This is possible when the peak magnetizing current is $\sim$1500 A.

The modulation system and its connection to the cyclotron are shown in a simplified form in Fig. 2. The dee junction element is a copper connector. To reduce the coupling circuit inductance, the connector is placed close to the external cylinder of the cyclotron resonance line. The gap between the connector and the cylinder wall is determined only by considerations of breakdown strength. It is of the order of magnitude 8-10 mm. The corresponding coupling circuit inductance is less than 0.5 μH. The junction connector passes from the vacuum chamber through the insulated spaces. The inner conductor and the dee junction connector are cooled by water circulating

(*) By the end of the design development a publication came to our notice in which the operation of an induction ferrite-modulated cyclotron is reported [4].

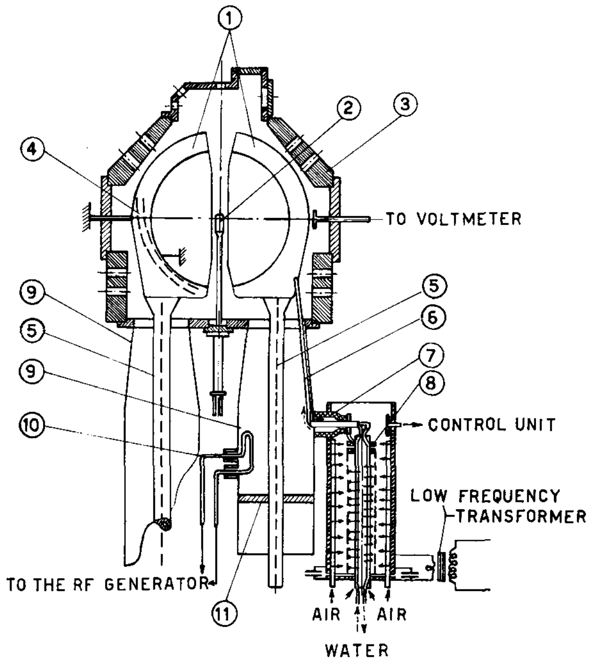

Fig. 2 Schematic diagram of the connection of a ferrite-loaded line to the cyclotron dee circuit.
1) dees
2) arc ion-source
3) acceleration chamber
4) deflector
5) dee stem
6) connector
7) insulated spacer
8) toroidal ferrite ring
9) outer conductor
10) coupling loop
11) shorting bar

through tubes soldered to them. The ferrites are cooled by air circulating both through the holes in the inner conductor and through special tubes in the inner wall of the outer conductor. The outer conductor is a steel cylinder faced with copper sheet. Its wall thickness is 5 mm. The steel cylinder serves also to shield the ferrites from the magnetic leakage field of the cyclotron. The magnetizing current transformer is connected between the outer and inner conductors of the modulation line, which is short-circuited for RF current by blocking capacitors at its end. The cyclotron resonant system in the FM mode is fed from two oscillator feeders by an ungrounded coupling loop.

III. BLOCK DIAGRAM OF EQUIPMENT

The block diagram of the equipment used for operating the cyclotron in the FM mode is shown in Fig. 3. The circuit operates in the following way. A low frequency sinusoidal voltage from the output of the audio frequency oscillator XI goes to the amplifier XII at the output of which arises the current necessary for magnetizing the ferrite. The time required for one period of magnetizing current corresponds to two periods of the dee circuit frequency variation.

When the RF oscillator is in an extraneous excitation mode the frequency of the master oscillator should coincide with that of the dee circuit during the acceleration cycle. Frequency coincidence is provided by a "program" device X in which both doubling of the frequency of the audio oscillator XI and selection of the proper amplitude and phase take place. The controlling voltage is applied to the reactance tube VII of the master oscillator IV. The automatic centre-frequency control of the oscillator IV is secured by a phase discriminator VIII. Automatic frequency control serves to reduce variations of the dee voltage amplitude when there is a slow detuning due to heating of the ferrites and the dee circuit components. Slight variations of the centre-frequency of the acceleration voltage in the FM mode affect slightly the current of accelerated ions, and must be compensated by the magnetic field.

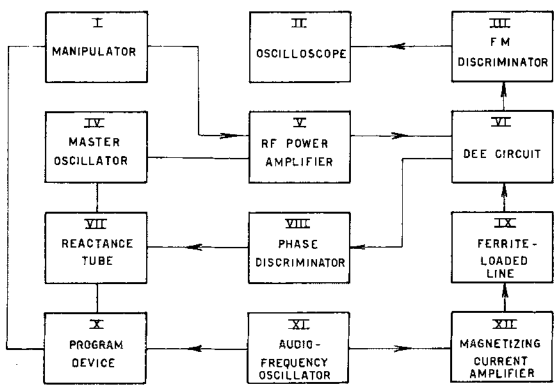

Fig. 3 Block-diagram of the FM system

To decrease the temperature of the ferrites, the RF oscillator is usually put in only for the period of acceleration by means of the switch I. The voltage controlling the reactance tube is also used for triggering this switch which affects the third and fourth stages of the RF power amplifier V.

The calibrated FM discriminator III shows the frequency deviation, the input discriminator voltage being supplied from the dee circuit VI by a special potential divider. Apart from the FM discriminator, there is also an AM detector.

Fig. 4 shows the schematic diagram of the magnetizing current amplifier. The unit consists of a pre-amplifier, a driver stage and a power amplifier. The commercially available amplifier *Y*-50 is applied to the input transformer of the driver stage. For the driver stage, a cathode-loaded push-pull amplifier of four type-80 tubes is used.

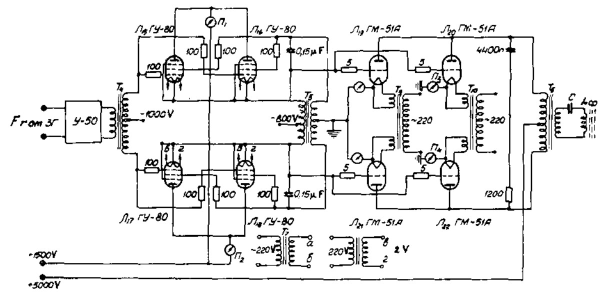

Fig. 4 Magnetizing current amplifier

The output class B_2 amplifier uses four modulator triodes of the ГМ–51A type ($Л_{19}$, $Л_{20}$, $Л_{21}$, $Л_{22}$). The primary winding of the output transformer is shunted by an RC circuit, considerably reducing the amplitude of transformer transients arising from random overvoltages. The secondary winding of the transformer consists of two turns connected to the ferrite magnetizing circuit.

The reactance of the output transformer load is compensated by means of a capacitor bank. The Q factor of the magnetizing circuit is of the order of 10. The program device (see Fig. 5) consists of a low frequency phase shifter, a frequency doubler, a non-linear network and an output amplifier. The bridge circuit phase shifter permits continuous control of the low-frequency phase shift in the range from 0° up to 170°. The frequency of the sinusoidal voltage is doubled by a full-wave rectifier and then applied to the input of the non-linear network, allowing final adjustment of the controlling voltage curve shape.

The network consists of $Л_3$, and $Л_4$ diodes and the resistances $R_3 - R_6$ in series with them. The shaped voltage from the network output goes to the $Л_5$ tube of the low-frequency amplifier and then to the $Л_6$ tube of the output cathode follower. From the cathode follower the controlling voltage is applied to the amplifier grid of the reactance tube.

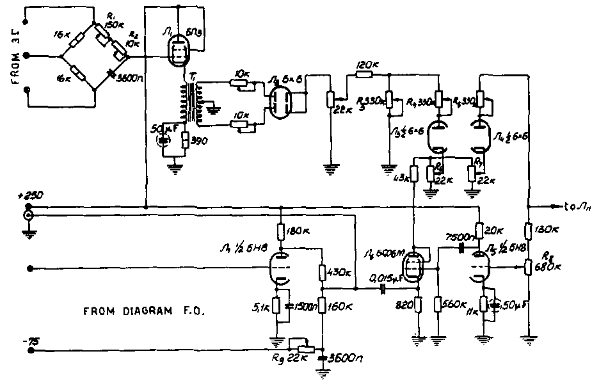

Fig. 5 Program device

IV. ION ACCELERATION

For deuteron acceleration experiments, an arc source of ions has been chose. The ions were extracted by one dee only. To eliminate the detection of C^{12} ions(*) as well as induced RF noise, all the measurements were made with a shielded probe[6]. The shielded probe electrode could be connected either to a type HO-1 oscilloscope or to an ion current integrator[7] by means of a shielded cable. In the former case the pulse current was determined and in the latter case the average current. The current sensitivity of the ion current integrator was $\sim 4.2 \times 10^{-11}$ A.

As pointed out above, the dee voltage was 25 kV. The deuteron acceleration experiments were made with a magnetic field strength of 12.8×10^3 oersted. The wavelength of the RF oscillator was 30.6 m. The deuteron energy at the 650 mm radius with the magnetic field uniform to 0.9% was 16.6 MeV. To accelerate deuterons in a fixed-frequency mode up to

(*) C^{12} ions are produced due to the presence of oil vapour. They are accelerated in a third subharmonic mode up to the radius of 650 mm at a dee-to-ground voltage of 16 kV.

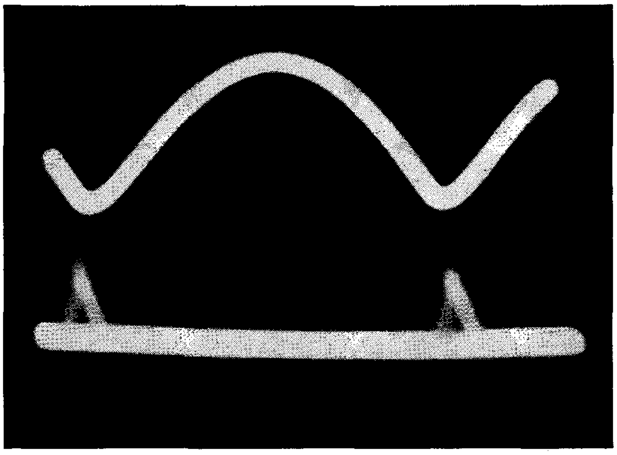

Fig. 6 Synchro-cyclotron current pulse oscillogram (lower curve). Frequency-time curve (upper curve).

the 650 mm radius, the accelerating voltage would have to be not less than 70-80 kV. It is estimated that with fixed-frequency deuteron acceleration at a dee voltage of 25 kV, the maximum radius could not exceed 500 mm.

The measuring probe was shielded with an aluminium foil of 360 μ thickness, thus indicating the synchro-cyclotron currents without background.

After it was clear that the shielded probe at the 650 mm radius did not detect ion currents, FM deuteron acceleration experiments were started. The average synchro-cyclotron current at the 650 mm radius with 0.5% frequency modulation was 0.1 μA with 1.0% it was 0.4 μA and with 1.8% it was 1.1 μA. The ion current measurements of a synchro-cyclotron pulse with 1.8% frequency modulation made with the oscilloscope showed approximately 30-35 μA. In the oscillogram of Fig. 6 the lower curve shows the position of the synchro-cyclotron current pulse relative to the frequency-time curve (the upper curve).

The design of the shielded probe does not permit detection of the total beam current since the shield wall and the gap needed to insulate the electrode from the shield are of the order of 1.5 mm, and, as a result, part of the beam is lost. To estimate the proportion of the beam lost in this way, an additional experiment was started. The measuring electrode was shielded with a copper foil of 350 μ thickness, which was irradiated by an accelerated deuteron beam. By measuring the distribution of induced activity in the foil, one can estimate the proportion of the beam lost as well as the radial oscillation amplitude. The measurements have indicated that the radial oscillation amplitude is $\sim$4 mm. The lost part of the beam decreases the ion current detected by the shielded probe by 2-3 times. The radial oscillation amplitude observed is such that part of the beam could presumably be extracted from the acceleration chamber if a pulsed detector were used. All the synchro-cyclotron current values given above do not take into account the attenuation of the ion beam by the shield.

V. CONCLUSION

1. Experimental studies with the 1.5 m cyclotron of the Atomic Energy Institue shows the feasibility of the ferrite-loaded line method of accelerating in an FM mode. Thus, using the main equipment of the Y-120 cyclotron, it is possible to accelerate in an FM mode at rather low cost.

2. With synchro-cyclotron acceleration the average deuteron current obtained at the 650 mm radius was 2-3 μA. The synchro-cyclotron pulse current was of the order 60-90 μA.

3. Two ferrite-loaded lines connected in parallel have an advantage over a single line. In this case one can use a multi-turn magnetizing winding, the current being correspondingly decreased.

4. Ferrites with high permeability and low RF losses have been developed recently. The application of such ferrites will permit development of a ferrite modulation system of smaller size and lower magnetizing power.

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PASSAGE OVER TRANSITION ENERGY BY MEANS OF STOCHASTIC ACCELERATION

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In alternating gradient machines, passage over transition energy gives rise to the loss of phase stability. To overcome this difficulty an acceleration system should be found which will work only because there is a transition energy, that is an energy for which the revolution time of the particle around the machine is independent of energy, and consequently constant during a certain time.

A scheme for the acceleration, which does not need phase stability, is the stochastic system, and is discussed in R. Keller's paper presented at this Conference (see p. 187). The limitation of this system is the bandwidth of acceleration frequencies which must be used. It is then precisely at transition energy that this system will be efficient as the acceleration frequency is stationary in this region. We will examine the energy range which can be covered around transition energy with a given frequency bandwidth. We will study the mean acceleration time needed to bring the particles from minimum to maximum energy, and the distribution function of the particles with radius, which will present a sharp peak towards the higher end.

A magnetic field in which a particle would have a revolution period independent of the orbit radius should have the following form :

$$eB = m\frac{v}{r} = m\frac{2\pi}{T} = \frac{m_0}{\sqrt{1-\frac{v^2}{c^2}}}\frac{2\pi}{T} = \frac{m_0 2\pi}{T}\frac{1}{\sqrt{1-\left(\frac{2\pi r}{cT}\right)^2}}$$

where T is constant.

At transition energy the actual magnetic field is in fact tangential to such a curve.

It is easily found that the total energy E divided by the rest energy is equal to

$$\frac{E}{m_0c^2} = B\frac{eT}{2\pi m_0} = \frac{1}{\sqrt{1-\left(\frac{2\pi r}{cT}\right)^2}}$$