RADIO-FREQUENCY SYSTEM FOR THE 680 MEV PROTON SYNCHROCYCLOTRON

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Summary

The following are general considerations governing the preliminary calculations, experimental investigations and mechanical design of the radio-frequency system for a synchrocyclotron accelerating protons up to 680 Mev (Institute for Nuclear Problems of the USSR Academy of Sciences) as well as electrical and mechanical data.

The planning of high-power synchrocyclotrons calls for the solution of a number of problems involved in the development of electrical and mechanical designs for an rf resonant system and methods of exciting rf oscillations in it over a wide frequency range. The components of the rf system should be chosen so as to make tuning within the necessary frequency range possible and avoid excessively high currents and voltages in those components which limit the accelerating rf voltage and lower the reliability of the accelerator in operation. The problems also have to be solved of avoiding parasitic oscillations and effecting coupling of the rf oscillator with the resonant system.

With the increase of energy W of the accelerated particles, the difficulties in design become greater. This increase requires a greater frequency change of the accelerating rf electric field. At the same time, a number of parasitic oscillation frequencies of the resonant system approach the working frequency range.

1. *Resonant system*

Let us consider a system consisting of a dee, a transmission line and a variable condenser (hereinafter termed a "frequency variator") the capacity of which changes during the accelerating cycle from C_{min} to C_{max} in accordance with the necessary working frequency change from f_{max} to f_{min}. The dependence of $\alpha_c = C_{max}/C_{min}$ on the energy of accelerated protons is shown in Fig. 1. It is assumed here that we have the simplest idealized system in which the dee and the transmission line can be regarded as a homogeneous line, i.e., one whose characteristic impedance does not change along its length. For any value of W, and hence for the necessary frequency ratio $\alpha_f = f_{max}/f_{min}$, an optimum line length is chosen at which the required capacitance ratio α_c is minimal. The curve shows that for accelerating protons up to energies of about 400 Mev the required capacitance ratio α_c lies in a practically feasible region ($\alpha_c \approx 25$). With a further (even slight) energy rise, the required value for α_c rises sharply and this makes the use of the hypothetical simplest system impossible. In synchrocyclotrons designed for accelerating protons up to energies exceeding 400 Mev, therefore, the rf resonant system is made more complicated so as to reduce the required capacitance ratio of the frequency variator and make it possible to tune the system in the given frequency range.

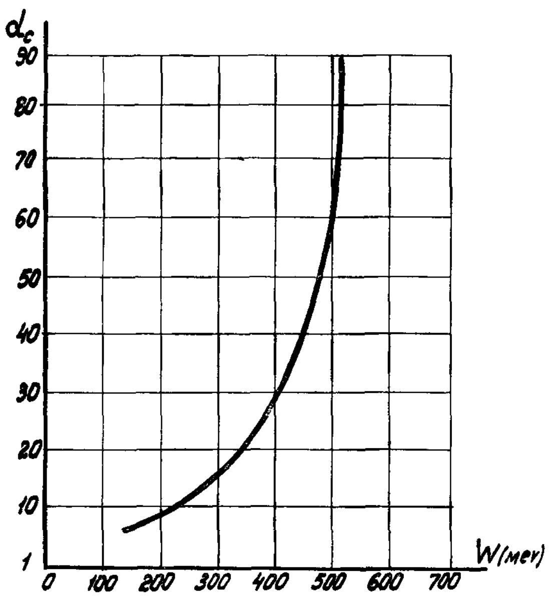

Fig. 1.

For example, if it is necessary, with the variator in question, to widen the system frequency range towards higher frequencies, an inductance L_p can be connected in parallel to the variator. Connection of an inductance L_s in series with the variator widens the range towards lower frequencies.

Widening the system frequency range can also be achieved by using a non-homogeneous transmission line the characteristic impedance of which changes along its length in the specified manner.

In designing a synchrocyclotron rf resonant system account has to be taken of the usual non-homogeneities of the characteristic line impedance and lumped inductances (e.g. inductance L_p due to "metal insulators" supporting the resonant system parts), which can substantially affect the working conditions of the system.

By applying a shunting inductance L_p the current through the variator is increased in practice, limitation to relatively great values of this inductance is necessary. A decrease in the inductances causes a rapid rise of current through the variator, whereas the decrease in the capacitance ratio α_c is comparatively slow.

The limitation in inserting a series inductance L_s can be effected in practice by increasing the variator voltage. Until relatively small inductances L_s are used, the necessary variator capitance ratio α_c decreases considerably while the variator voltage rise is small. The use of large inductances is inadvisable, as it leads to a considerable voltage rise, whereas the capitance ratio α_c decreases only slightly.

The same limitations occur when using a non-homogeneous line. In a quarter-wave short-circuited line (fig. 2) having a characteristic impedance change in two steps, the greatest change in the natural line wave-length occurs when the length $l_1 = l_2 = l/2$.

The natural line wave-length decreases when the characteristic impedances ratio $W_1/W_2 > 1$ and increases when the ratio $W_1/W_2 < 1$. This is true also in the case of a half-wave line loaded by the variator at its end.

The varied voltage distribution along such a resonant system at the upper and lower frequencies of the working range makes it possible to take advantage of the inhomogeneity of the line both for shortening λ_{min} and for increasing λ_{max}. To solve the first problem, it is necessary for that part of the line which lies for the shortest wave-length of the working range, near the voltage node, to have a lowered characteristic impedance. The second problem would be solved if the mean characteristic impedance value of that part of the line which lies near the current loop at λ_{max} exceeds that of the other parts of the line. These conditions are fulfilled if the line consists of at least 3-4 homogeneous parts each having different characteristic impedances. With the increase in the inhomogeneity of the line, the variator voltage increases as does the current through the line. It should be noted that the use of a non-homogeneous line gives a greater voltage rise on the variator and a greater current increase through the line itself than when other methods are used. By choosing a corresponding relationship between the separate parts of the line, a relative decrease in the variator voltage can be obtained at the expense of current increase.

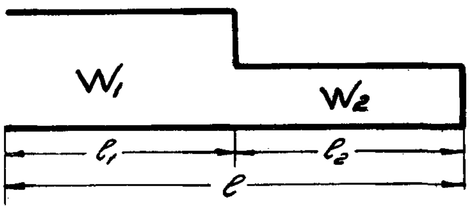

Fig. 2.

An analysis * leads to the following conclusions: Any method used for making the rf system frequency range broader depends on one of the three simplest methods considered above (or a combination of them). Corrections are made in all of them of the frequency dependence of the reactance in respect of the variator. When this dependence approaches the frequency dependence of the lumped inductance reactance, the necessary variator capacitance ratio is decreased and the frequency range widens.

Any method involving the widening the system frequency range makes its working conditions more arduous, as this increases the voltage on the variator or the current passing through it, while the current passing through the line may increase as well. These factors may limit the value of the accelerating voltage. It is more expedient to insert lumped inductances, both shunting the variator and in series with it, than to use an equivalent quarter-wave short-circulated line. The use of the latter requires a greater variator capacitance ratio α_c or a voltage increase on the variator (or a current rise through it).

If a series inductance is inserted in the resonant system, using a variator for tuning over frequency ranges that are necessary for accelerating both protons and deuterons, the voltage on the variator will be greater than when accelerating particles of one kind only. It is therefore advisable when going over from accelerating protons to deuterons, to install various simple additional parts in the resonant system and so have the possibility of working at moderate voltages on the variator.

The use of a non-homogeneous line or an inductance connected in parallel to the variator, makes it possible to have a system where $l/\lambda_{min} > 0.5$. Their use is essential in synchrocyclotrons with high particle energies and a large-sized magnet. The Academy of Sciences' synchrocyclotron accelerating protons up to 680 Mev was a case in point.

* A detailed analysis of an rf system has been made by B. I. Poliakov in his thesis, 1955.

A non-homogeneous line can be more advantageous under such conditions than an inductance connected in parallel to the variator. The losses in the variator and especially in the inductance connected paralled to it are thereby reduced. There is no need to design intricate bypass condensers for use for high currents. In addition, the sub-harmonic frequency of the system approaches the lower working frequency at a small inductance L_p. The use of a non-homogeneous line raises the frequency of parasitic transverse oscillations of the dee and removes it from the working range. In fact, the part of the line having a lower characteristic impedance is placed on the dee itself, where it is connected to the transmission line. For transverse oscillations, the part of the dee having lowered characteristic impedance lies near the voltage node for those oscillations.

Where a considerable degree of correction is required, a combination of two or three of the above methods is advisable. This can give a sufficiently large widening of the frequency range without any substantial increase in the variator voltage and current through the variator or transmission line. This combined correction enables each of the described methods to be used precisely where it is most effective.

Use is made in the resonant system of the Academy of Sciences synchrocyclotron of the above combination of correction methods.

2. *Eliminating parasitic oscillations*

One of the main problems in putting the rf system of a high-power synchrocyclotron into operation is the elimination of parasitic oscillations.

The oscillatory circuit of the synchrocyclotron is a system with distributed constants having considerable transverse dimensions. The resonant system becomes complicated by a number of reactive circuits, which are determined by the type of rf oscillator and coupling circuit used, as well as by some of the mechanical parts of the system. There are also resonant cavities in the system. All this leads to an abundance of parasitic resonant frequencies which can be near and even within the working frequency range.

If effective measures are not taken beforehand, the starting-up process of the synchrocyclotron rf system becomes very difficult. The elimination of one parasitic oscillation often leads to the excitation of another and can affect the working conditions of the oscillator in part of the working frequency range.

While working out the rf system for the 680 Mev synchrocyclotron, special attention was paid to the following:

1. In designing the resonant system and in choosing the circuit and design of the elements coupling the rf oscillator with the resonant system, steps were taken to remove the nearest parasitic resonant oscillations from the working frequency range.

2. No self-excitation of the rf oscillator could take place at frequencies lying outside the working range, due to the use of a special rf oscillator circuit.

3. The resonant system should be symmetrical and the point where the rf oscillator is coupled with the system should lie on the axis of symmetry. This is a measure to avoid the effect of a number of possible parasitic resonant frequencies corresponding, say, to transverse oscillations of the dee, transverse oscillations of the variator and vacuum chamber cavity oscillations. Nevertheless, if the resonant frequencies corresponding to these oscillations differ even by a few megacycles from the highest working frequency, this can affect the working conditions of the rf oscillator and the value of the accelerating voltage.

Various possible kinds of oscillations nearest to the working frequency range are briefly described below. Capacitive coupling is used between the rf oscillator and the resonant system of the 680 Mev synchrocyclotron. The frequencies of longitudinal oscillations of the system are defined by the parameters of the resonant system, by the coupling circuit and by the rf oscillator output reactance. To raise the frequency nearest the working range, the coupling circuit inductance, the capacitance of parts of this circuit relative to the ground and the output capacitance of the rf oscillator must be reduced as much as possible. The output capacitance of the rf oscillator is defined by the capacitance and inductance of the vacuum tube leads and by the parts of the feed-back circuit.

The frequency of transverse dee-oscillations is defined primarily by the dee diameter; it depends also on its shape and on other resonant system elements connected to the dee. As already shown, the use of a non-homogeneous line makes the frequency rise of these oscillations possible. It is also raised somewhat if the dee angles are slightly cut off.

The resonant frequency of the oscillations of the vacuum chamber cavity where the dee is installed may be near the working range. The frequency of these oscillations depends mainly on the chamber dimensions in the horizontal plane; it is somewhat lower than for a hollow parallelepiped of the same size because of the dee and the dummy dee located inside the chamber. To make the excitation of these oscillations more difficult, the dee has to be installed in the vacuum chamber as symmetrically as possible. The frequency of these oscillations can be increased by changing the shape of the dummy dee, by using special plates for changing the configuration of the resonant cavity, etc.

It is comparatively easy to change the resonant frequencies defined by the external design elements (e.g. supports of resonant system parts, by-pass condensers, etc.).

The above-mentioned measures and the use of a wideband rf oscillator made the starting-up process of the synchrocyclotron rf system much easier.

3. *Rf oscillator circuit*

In an idealized rf oscillator circuit such as the Colpitts oscillator circuit, the frequency range of the generated oscillations is unlimited. Parasitic oscillations can therefore arise at frequencies outside the given range. It is known that any limitations of frequency range in a real circuit are due to the inductance of vacuum tube electrodes, their leads and external connecting conductors. The character of the reactance of the parts of a similar oscillator circuit depends on the frequency. For some frequency ranges, it leads to a break of the phase balance necessary to produce self-excitation of the oscillator.

Nevertheless, this factor cannot be used to eliminate oscillations of any frequency outside of the given range if the above-mentioned circuit parameters are chosen deliberately.

Otherwise, many frequencies of the natural oscillations which are not of the fundamental type not only come close to the working range but by changing in dependence with the working frequency cover a very wide frequency range. In this connection, a solution had to be found to the problem of completely eliminating parasitic oscillations while at the same time ensuring easy adjustment of the feed-back value in the given range.

In the special limited frequency band rf oscillators circuit (see fig. 3) the interelectrode capacities and the inductances of the electrodes and their leads have been used, while circuits $L_5 C_5$ and $L_7 C_7$ are connected in series between the anode and cathode lead as well as between cathode and grid leads. The outer resonant system, in which rf oscillations are to be excited, is connected to points "a" and "b".

As shown in the detailed analysis * a circuit, of this kind, if its parts are correctly chosen, can satisfy the phase requirements of self-excitation in the given frequency range only. In this range it is possible to adjust the feed-back coefficient within wide limits even in the immediate neighbourhood of the highest frequency beyond which parasitic resonant frequencies of the oscillatory system may exist.

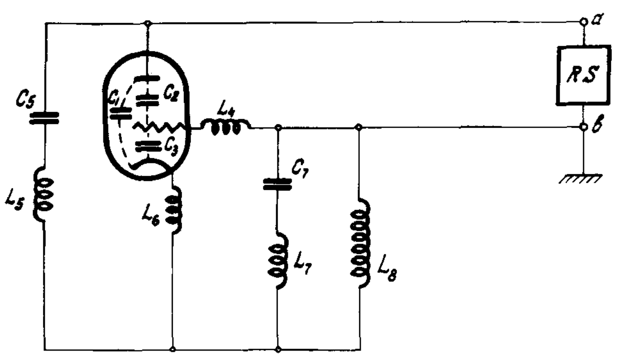

Fig. 3.

* See foot-note on p. 420.

The operation of the circuit can briefly be described as follows: near the frequency $f_r = \frac{1}{2\pi\sqrt{L_7 C_7}}$ and above it the feed-back coefficient becomes negative and remains so at all higher frequencies. This is because the signs of the reactances of the anode and grid feed-back circuits at frequencies higher than f_r remain opposite to each another due to the fact that the resonant frequencies at which the change of the reactance sign takes place are so chosen as to be equal in these circuits.

This assertion that feed-back coefficient remain negative at all higher frequencies holds strictly true only where there is some limitation of the value of the interelectrode capacities ratio Caf/Cag. This is practically always the case in modern high power oscillator triodes.

Disregarding the effect of the cathode choke coil L_8 at higher frequencies, comparatively simple quantitative relationships can be obtained among the parts of the circuit for which the phase balance requirements are satisfied for a given frequency range only. The analysis also shows that due to the presence of cathode inductance L_6 these requirements are not critical; and this makes the practical adjustment of the rf oscillator easy.

At frequencies below the working range the cathode choke coil L_8 together with other parts of the circuit ensure the breaking of the phase requirements for self-excitation. This may be necessary if there are parasitic sub-harmonic resonant frequencies in the system produced by the connection of parallel inductances to it (e.g. metal supports).

It also follows from the analysis that the feed-back coefficient values in the lower and upper parts of the working frequency range can be adjusted independently of each other; this is vital advantage.

In the rf oscillator for the 680 Mev synchrocyclotron two water-cooled power triodes of the Ty-12 type are used. Copper-plated steel anode water-jackets are used which serve at the same time as supplementary magnetic shielding for the triodes.

The stoppage of rf oscillations during the non-working part of the frequency modulation cycle is effected by means of a specially designed pulsing device using thyratrons. This device affects the triodes grid circuit of the rf oscillator.

The rf oscillator provides its normal power at the frequency of 26.5 mc., whereas no oscillations could be generated even at the frequency 28.0 mc., corresponding to the second harmonic of the lowest frequency of the resonant system. The adjustment of the rf oscillator feed-back is effected by changing C_7 and L_7.

4. *Design of the resonant system*

Fig. 4 gives the circuit diagram of the rf system for the 680 Mev synchrocyclotron.

Fig. 5 shows the selected design lay-out, with all the above considerations taken into account.

The frequency variator (1) has a multiblade rotor (2) with its shaft (3) fixed on insulators (4) inside the transmission line stem connecting the rotor to the dee. The rotor is electrically connected to this line by means of a coaxial multicylinder condenser (5) having a large capacity.

The rotor of the variable coupling condenser (6) is rigidly attached to the ungrounded rotor of the frequency variator. This provides for the excitation of the resonant system on its axis of symmetry. At the same time, it allows an optimum degree of coupling for the rf oscillator and the resonant system over the whole working frequency range.

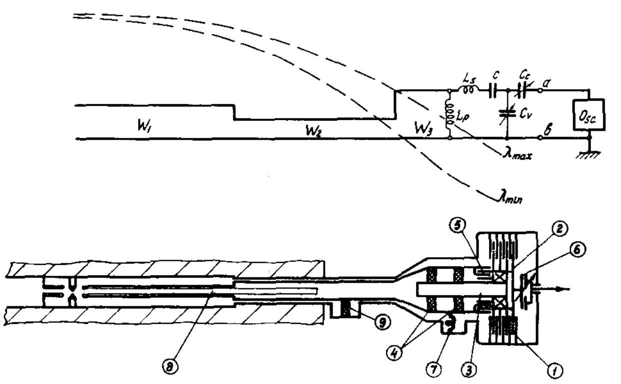

Fig. 4. et 5.

Thanks to this design, the inductance and initial capacitance of the variator rotor are relatively low. In the design in question, the problem of protecting the bearings from strong rf currents is successfully solved by the bearings being shunted by the coaxial condenser (5). In this way, a current 100 A less than the maximum rf current of 3,000 A running through the variator passes through the ballbearings and the bronze brush protecting them. The coaxial shunting condenser is of great importance for reliable operation of the system at a high accelerating peak voltage.

The variator design and the selected shape of the dee and the transmission line, with its smooth passage connection to the dee, all ensure a minimum increase in their equivalent electric length. The resonant system itself is designed as a non-homogeneous line 5.2 m. long; the value of the series inductance L_S is mainly determined by the design of the passage from the transmission line to the variator. As a result of the use of supports made in form of cylindrical spiral springs (7), a relatively high inductance of the latter is connected in parallel to the system. The use of metal supports was considered desirable in order to increase the reliability of the system, and the form of cylindrical spirals was chosen to increase their inductive reactance over the whole frequency range.

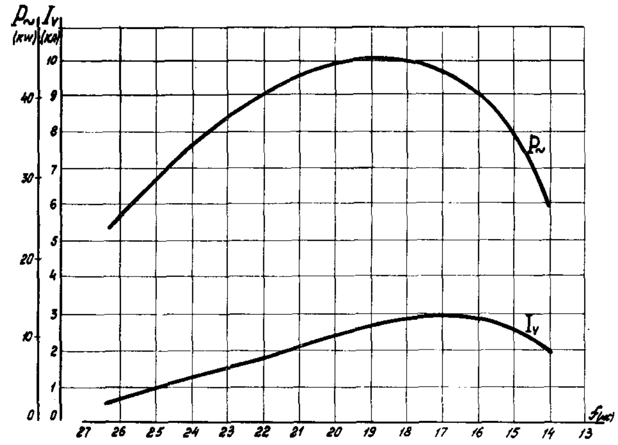

Fig. 6.

In the design described above, the stem holding the variator rotor is supported by three such springs. The dee (8), which is 6 m. in diameter, is supported by two pairs of insulators (9).

The resonant system is designed to permit operation in the frequency range required for accelerating deuterons also. It was necessary for this purpose to increase the characteristic impedance of the resonant system near the current loop.

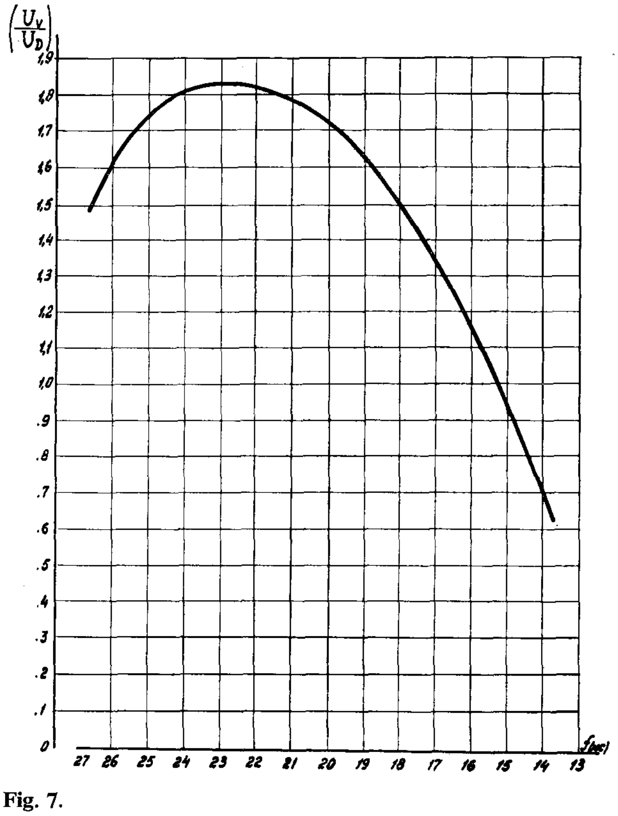

Fig. 7.

In developing the above system, the designer had to solve a number of difficult problems, as illustrated by the following : the inductive reactance of the supports (7) must be high enough over the whole frequency range of the rf system to ensure that excessively high currents do not pass through the variator and the supports of the system. The supports must also be of adequate strength, since the variator rotor, weighing about 0.8 tons, rotates at a speed of 600-700 r.p.m. The rotor working in vacuo must be effectively cooled, as about 5 kW rf power is dissipated on it. The variator rotor has a diameter of 1,080 mm. and consists of 6 discs, each with 10 blades.

5. *General data on the rf system*

The rf system has the following characteristics :

The working frequency range is from 26.5 to 13.6 mc.;

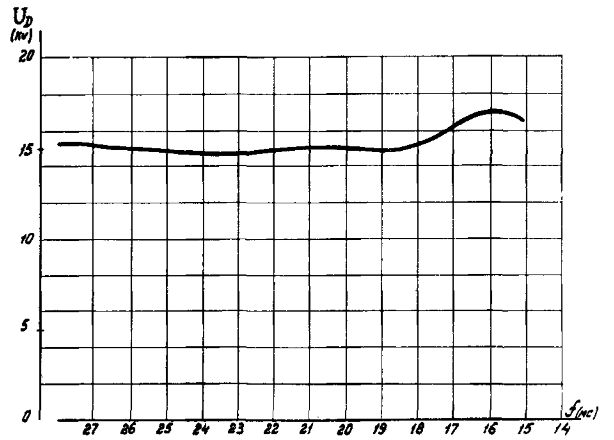

Fig. 8.

The average power input of the rf oscillator is about 50 kW; this power is about half as much if pulsed.

Figs. 6 and 7 give the frequency dependence of the rf power $P_{\sim}$ dissipated on the resonant system of the current I_V passing through the variator at a dee peak voltage $U_D = 15$ kV, and of the ratio U_V/U_D where U_V is the peak voltage on the variator.

The curve in fig. 8 shows the change of U_D as a function of frequency.

The peak voltage in gaps between the blades of the stator and rotor of the variator does not exceed 30 kV a quite permissible value at a gap of 3 mm. The variator capacity changes from 200 to 3200 pF; the capacity of the multi-cylinder condenser is 20,000 pF. The latter consists of 6 pairs of cylinders with 1 mm. gaps between their surfaces; the voltage at these gaps does not exceed 1.5 kV.

In operation, the rf system for the 680 Mev synchrocyclotron gives peak accelerating voltages of 15 to 20 kV. The frequency sweep from 26.5 mc. to 13.6 mc. about 100 times per second.

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