# THE USSR ACADEMY OF SCIENCES' 6 METRE SYNCHROCYCLOTRON

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**(presented by V. P. Dzhelepov)**

## 1. *Introduction*

The construction of big energy accelerators of heavy particles became possible after the discovery by V.I. Veksler (1944) and McMillan (1945) of the principle of phase stability for circular resonance accelerators.

To promote research in the physics of high energy particles and acquire experience in the synchrocyclotron method of acceleration, a 5 m. synchrocyclotron was completed and put into operation in 1949 at the Institute of the Nuclear Problems of the USSR Academy of Sciences. In this machine deuterons were accelerated up to energies of 280 Mev and α–particles up to energies of 560 Mev. In 1950, protons were obtained with it with an energy of 500 Mev [1,2,3]. The construction of the accelerator was preceded by experiments on an operating model which helped to clear up a number of points related to its development and operation [4].

The study of the operation of the completed 5 m. synchrocyclotron, and the experience accumulated in the research conducted with it permitted its reconstruction in 1953 and an increase in the energy of accelerated protons to 680 Mev. The average current on the extreme orbits amounted in this case to 0.3 μA.

During its reconstruction, a new vacuum chamber was built, the diameter of the magnet poles was increased to 6 m. and a new high-frequency resonant system was developed. With the 6 m. synchrocyclotron, intensive beams of positive and negative π mesons with an energy up to 400 Mev and neutrons with an energy as high as 600 Mev can be obtained. With slight alteration of some parts of the high-frequency resonant system, it would also be possible to obtain deuterons with an energy of 420 Mev and α-particles with an energy of 840 Mev [5, 6].

## 2. *Magnet*

As known, the space-stable motion of ions in the magnet gap is confined to a zone where the magnetic field index

$$n = -d\ln H/d\ln R \leqslant 0.2 \quad ,$$

since at $n = 0.2$ a parametric resonance is observed between the free vertical and radial oscillations of accelerated ions.

As a result of the limited vertical dimensions of the dee aperture, the zone of the parametric resonance appearance determines the maximum radius of the magnetic field region in operating accelerators in which ion acceleration is actually possible. For this reason considerable attention has been given to solving the problem of increasing the radius of stable orbits of accelerated ions to the maximum.

When the diameter of the magnet poles was 5 m., they were constructed as one-piece soft iron discs. The 6 m. diameter pole pieces are constructed of several parts welded together.

The pole pieces serve simultaneously as the top and bottom covers of the vacuum chamber installed in the gap between the magnet poles. The gap between the pole-pieces in the centre of the chamber amounts to 600 mm. and the magnetic field intensity in the centre of the vacuum chamber to 16,600 Oersted. The magnet is 18 m. long, about 10 m. high and weighs some 7,000 tons. The magnet core is made of ordinary carbon steel.

The magnet excitation windings are made of copper bars and are air-cooled. The power of the DC generator, required to produce the rated magnetic field intensity amounts to some 1.000 kW. The current running through the windings of the magnet is stabilized within ± 0.1 per cent.

Very laborious computation and experimental work was carried out to correct the magnetic field configuration in the zone of particle acceleration. In addition to using ordinary shims at the periphery of the pole pieces, much work was done to make the surface where the radial component of the magnetic field equals zero coincide with the mean geometric plane of the accelerating chamber.

Correction of the magnetic field configuration called for the development of special apparatus for fine magnetic measurements such as:

(*a*) an instrument for measuring the radial drop in magnetic field intensity [1];

(*b*) an instrument for determining the azimuthal asymmetry of the magnetic field [7];

(*c*) devices for determining the position of the surface where the radial component of the magnetic field is equal to zero.

Thanks to research work and correction of the magnetic field configuration of the 6 m. synchrocyclotron, it was found possible to extend the radius of the zone ensuring the space stability of accelerated ion motion up to 279 cm.

Additional asymmetric power input to the magnet excitation windings from a separate regulated generator is used in the synchrocyclotron and allows the position of the accelerated particle orbit plane to be changed in the course of the accelerator operation. This is used when selecting the optimum operation conditions *.

The radial drop in the magnetic field intensity from the centre to the extreme orbits, which is necessary for focusing the particles in the vertical plane, is chosen to be equal to 4.9%. Displacement of the magnetic centre of the extreme orbits does not exceed 2 cm. Provision has been made by thorough correction of the magnetic field configuration of the accelerator for the acceleration of protons to the energy of 680 Mev [8].

Steel cones have been installed in the centre of the pole pieces to achieve better focusing conditions at the initial stage of acceleration.

Provision has also been made for a relatively rapid change in the polarity of the magnet poles (in 15 minutes) to improve the conditions of extracting $\pi^+$ and $\pi^-$ mesons of various energies through the collimators mounted in special openings in the side post of the magnet.

### 3. *The resonant system and the rf oscillator*

The design of the rf system was chosen to provide an accelerating voltage of 15 kV, while the natural oscillation frequency of the system when accelerating protons changes from 26.5 Mc. to 13.6 Mc. It was originally intended to place the metal rotor of the variable condenser (frequency variator) in the region of small intensity magnet field in order to avoid considerable eddy currents, but it was later judged inexpedient to move the variator into region of stray field in view of the consequent lengthening of the resonant system. It was therefore installed at a place where the field intensity is about 600-800 Oersted and provided with strong magnetic shielding. As a result, the field intensity inside the shield is less than 30 Oersted. Even for such conditions, however, the distance from the centre of the magnet poles to the frequency variator is approximately equal to half of the shortest wave-length of the working range. For this reason, it became necessary in order to tune the system in the predetermined frequency range to raise the upper frequency of the natural oscillations of the system by means of a special choice of the characteristic impedance of the system and also by selecting a design which would give the shortest path of the current along it. The widening of the frequency range at its lower end was effected mainly by raising the characteristic impedance of the system near the frequency variator. The part of the line in direct proximity to the variator may be defined as a lumped inductance.

The rf resonant system consists of a dee, a dummy dee, the variator and a line connecting it and the dee. Near the variator, the line is of a coaxial cylindrical form and is connected to the dee by means of a smooth passage.

The variator rotor made of 6 discs having 10 blades each is fixed on insulators inside the inner stem of the coaxial line and is electrically connected to the latter by a multi-cylinder condenser (consisting of 6 pairs of cylinders) having a capacity of 20,000 $\mu\mu$F. The stem with the rotor is held by three metal supports radially located near the centre of gravity. To increase the reactive resistance of the supports in a wide frequency range, they are made of special water-cooled steel pipes in the form of cylindrical spirals which are copper-plated to reduce high-frequency losses. Their inductance is connected in parallel to the line and raises the upper frequency of the working range to a certain extent.

This design of high-frequency resonant system has made it possible, despite the wide range of working frequencies, to have relatively small values of current and voltage on the variator. It has been possible in consequence to obtain an accelerating peak voltage over 15 kV and a repetition rate of the acceleration process of about 100 cps.

The multicylinder condenser effectively shunts the ball-bearings of the rotor and the contact brush protecting them. The latter takes the form of a bronze split ring enveloping the steel shaft of the rotor. Whereas the maximum current passing through the variator is as high as 3,000 amp., the current flowing through the bearings and contact brush does not exceed 100 amp. This ensures stable operation of the variator during 10,000 hours without replacing the bearings.

Thanks to the rotor design, variable capacitive coupling can be effected between the rf oscillator and the resonant system and optimum values obtained for the variable impedance of the system in the wide range of frequencies used.

The self-excitation of parasitic oscillation has been fully eliminated by the application of a new type of rf "band"

* A change in the position of the orbit plane permits a gradual decrease by many thousand times in the extracted proton beam intensity, as may be necessary when making certain experiments.

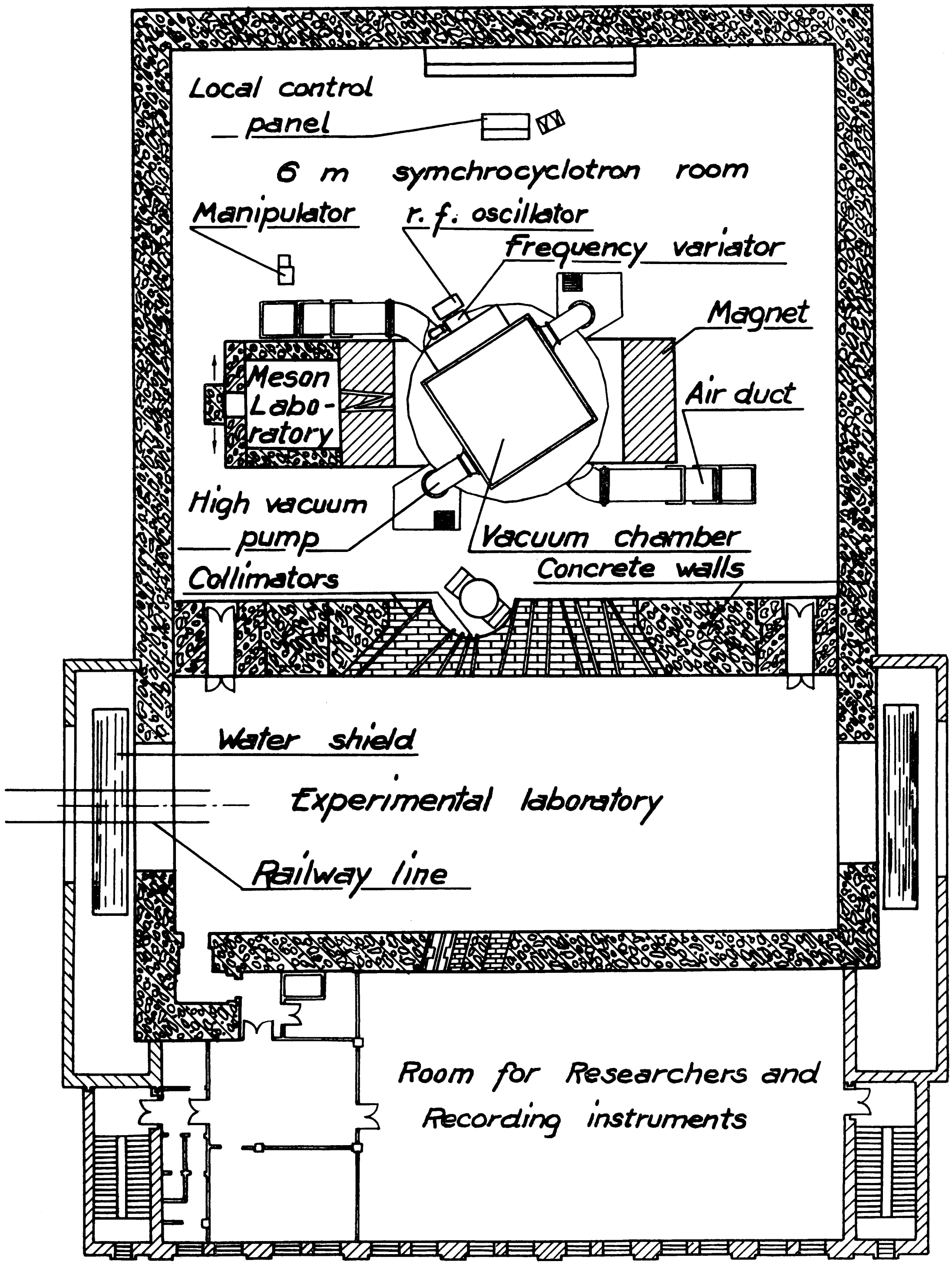


**Fig. 1.** Plan view of the 6 m. synchrocyclotron.

oscillator in which the positive feedback is effected only in the predetermined frequency range. This allows control within wide limits of the absolute value of the feedback coefficient in direct proximity to the upper and lower frequencies of the working range. The system makes use of series LC circuits connected between the anode and cathode lead, and between the grid and cathode leads of two uhf triodes of the Gu-12A type with grounded grids; the inductance of the triodes leads, their inter-electrode capacities and the cathode chocke coil are also used.

The operation of the resonant system as well as the circuit diagram of the rf oscillator are dealt with in greater detail in a separate paper [6].

The rf oscillator can be stopped during the non-working part of the frequency modulation cycle by means of a specially designed pulsing device using thyratrons [9] and acting on the grid circuits of the rf oscillator. Other conditions of operation are also possible under which the acceleration cycles follow at a repetition rate several times lower than that of the frequency modulation. It is also possible to accelerate a single bunch of particles when a signal is sent from the Wilson chamber or from some other metering instrument. The operating conditions are controlled by means of a special timing device [10] which ensures a rigid time sequence of pulses controlling the voltage to the ion source, pulsing device and other circuits. It also enables the operation of various nuclear research instruments to be synchronized with that of the synchrocyclotron. All the above processes fit in with the cycle of frequency modulation of the rf oscillator exciting the resonant system. Rf voltage is switched on before every acceleration cycle by means of a photo-electric system where a ray of light falling on a multiplier phototube is intersected by the frequency variator rotor blades.

## 4. *Vacuum system*

The stable operation of the synchrocyclotron and the current intensity of the accelerated ion beam are determined to a considerable extent by the air pressure in the vacuum chamber and in the frequency variator housing. The accelerator vacuum chamber has a form of a rectangular parallelepiped of $675 \times 675 \times 100$ cm$^3$.

The chamber is assembled of brass plates 100 mm. thick. The steel covers of the chamber simultaneously serve as pole pieces. All the joints of the vacuum chamber are vacuum-sealed by means of rubber gaskets.

When the chamber has been properly conditioned, the minimum pressure of the residual gas amounts to $2.10^{-6}$ mm. Hg. The working gas being delivered to the ion source, the pressure in the chamber does not exceed 6 to $7.10^{-6}$ mm. Hg. The total volume to be pumped, consisting of the interconnected volumes of the vacuum chamber, the resonant line and the frequency variator housing, amounts to about 35 m$^3$. The vacuum chamber is evacuated by two oil vapor jet pumps with a total capacity of 80,000 litres per second at a pressure of $1 \times 10^{-5}$ mm. Hg. The frequency variator housing is evacuated by an additional pump with a capacity of about 10,000 litres per second at a pressure of $1.10^{-5}$ mm. Hg.

To freeze out the oil vapours, some of the baffles in the high-vacuum pumps are cooled to a temperature of - 20 °C.

The vacuum seals used ensure that the rise of pressure in the vacuum chamber (due to leaks and degassing of inner surfaces) amounts to 0.2-0.3 micron per hour.

When there is fore-pressure in the vacuum chamber ($10^{-3}$ mm. Hg.), the operating vacuum in a conditioned accelerator is attained in 25 to 30 minutes after the vacuum valves of the oil vapour jet pumps have been opened.

The vacuum chamber is fitted with various devices enabling targets to be introduced into the chamber and installed at a predetermined radius. These operations are effected at distance without disturbing the operating vacuum conditions in the chamber.

## 5. *Ion source and extraction of particles*

A conventional arc source with a hot tungsten cathode is used as the ion source in the synchrocyclotron. A cold cathode source is also used very successfully. A much greater stability of the ion current can be reached in the latter case at normal intensity. The discharge in a source with a cold cathode is produced by the rf electric field of the dee due to the secondary electron emission of a beryllium or aluminium cathode.

It has been possible to bring a proton beam out of the vacuum chamber having an intensity of 5 to 7% of the circulating beam current. The extraction is effected by exciting radial oscillations of accelerated particles in the zone of the extreme orbits and throwing protons into a magnetic channel [11]. In addition, a considerable number of neutron beams and charged $\pi^-$ mesons of both signs are brought out. The extraction of each beam is effected by means of special devices fitted in the accelerator. This operation is fully described in a separate paper [12], in which the beam parameters are also given.

## 6. *The layout of the accelerator equipment*

The entire synchrocyclotron equipment is housed in two buildings. The main one houses the equipment which cannot be placed at a great distance from the synchro-cyclotron on account of its operating conditions. In the same building are laboratories where experimental and recording apparatus for research purposes are placed along the extracted beams.

To ensure the most favourable conditions for research work with accelerated particles, the synchrocyclotron room is separated from the main laboratories by two concrete protection walls with respective thicknesses of 4 and 2 m.

thick as well as by a 1.5 m. thick concrete ceiling. The 4 m. wall separating the accelerator room from experimental laboratory has an embrasure provided with collimators for the passage of the particle beams.

The electric power equipment, the water-cooling devices for the various parts of the resonant system, the rf oscillator valves and the control equipment for all the circuits and units of the accelerator are housed in the second building.

7. *The control system for the synchrocyclotron*

The staff must not remain in close proximity to the synchrocyclotron when in operation because of radiation danger. The remote control of the synchrocyclotron and of its equipment is effected by a shift engineer and a technician from the central control room in the second building.

A number of special devices for automatic and remote control are provided for this purpose.

Experience has shown that the synchrocyclotron and all its parts operate for several thousand hours with little time loss for inspection or repair of its equipment.

8. *Principal trends of nuclear research*

The research programme for the Institute's synchrocyclotron includes a detailed study of the followng three classes of nuclear processes with nucleon energies of 380-660 Mev:

1. Elastic scattering of protons by protons, of neutrons by protons and of neutrons by neutrons.

2. Formation of charged and neutral $\pi^-$ mesons in collisions of nucleons with nucleons.

3. Interaction between $\pi^-$ mesons and nucleons.

Experimental study is also performed on interaction of nucleons and $\pi^-$ mesons with atomic nuclei. These investigations are beyond the scope of this communication and are described in separate papers.

*Conclusion*

Nuclear research in the field of energies up to 700 Mev is regularly carried out on this synchrocyclotron—at the moment the largest accelerator of this type in the world—by ten physical and chemical institutes of the USSR Academy of Sciences.

It operates regularly for 100 to 105 hours a week and permits investigations with 13 extracted beams of high energy protons, neutrons and $\pi^-$ mesons.

Its construction was the result of many years' work by scientists, engineers and designers, and a large number of factories, especially in the electrical industry plants, shared in manufacturing its equipment.

The development of various systems of the 6 m. synchrocyclotron involved a great deal of research and development work in physics, electrical engineering, radio engineering, electronics and vacuum engineering. This was a help in anticipating most of the various difficulties attending the starting-up period; but some of them became apparent and were overcome only during the initial period of operation.

It is quite evident that the synchrocyclotron method of acceleration is highly advisable in a definite region of particle energies. The experience of synchrocyclotrons already in operation and the calculations so far made warrant the conclusion that the upper limit of energy with this method of proton acceleration appears to be in the neighbourhood of 1,000 Mev.

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