THE RELATIVISTIC ISOCHRONOUS CYCLOTRON AT KARLSRUHE

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A relativistic isochronous cyclotron at the Nuclear Research Centre at Karlsruhe was built by the research institute of the AEG.

After design studies from 1958 to 1959 the construction of the cyclotron vault and the necessary laboratories began in spring 1960. The cyclotron proper was completed in the summer 1962. After a trial period for the separate main parts the planned energy of 55 MeV for deuterons was attained in October 1962. The maximum deuteron current, measured up to now, is more than 200 μA. As we have no targets for intensities in this range the arc voltage of the ion source is pulsed to facilitate the measurement.

Main Features

The following are, in sum, the main features of the Karlsruhe cyclotron.

1. The magnetic field structure is of the Thomas type with radial 60° sectors and a period of 120°.
2. The acceleration system is housed in the valleys of the magnet pole shoes. It consists of three star-connected quarter-wave resonators.

From this conception follows the mode of the construction of this cyclotron : the gap between the hills of the pole shoes could be freely chosen so small (only 8 cm) because no specific space is wanted for acceleration purposes. It is only within this narrow air gap that the magnetic field increases radially, step by step. By this means we compensate for the relativistic mass increase. As little as 1000 watt will control within the limits of 0.3% the kidney-shaped trimming coil system.

The periodicity of the acceleration system is three times the cyclotron frequency. Such a system makes use of six acceleration gaps per turn instead of two gaps for the one- or two-dee system. The result is an energy gain per revolution of six times the RF amplitude, if the ions pass every gap at optimum phase displacement. In our case that means six times 40 KeV or 240 KeV per turn.

The relatively high frequency of 33 Mc/s makes it possible to use a central quarter wave transforming line. The purpose is to fix the three resonators in the centre of the machine and to adapt the RF generator to the acceleration system by a voltage transform ratio 1 : 4.

The Karlsruhe cyclotron is equipped with control and measuring systems to satisfy all operational and safety needs. The current of the exciting coils is inherently stabilised for a constancy better than 1 in 10 000, the voltage stability of the RF generator is 1 in 1 000. Insulation break downs within the acceleration system are interrupted in time by a rapid electronic circuit breaker. The self-excited RF system is automatically tuned under the guidance of a quartz controlled frequency transmitter, and the three quarter-wave resonators are timed automatically, either separately or together, over a range of ± 1,5%. To avoid multipactoring, a booster generator working with a wobbled frequency is used.

There is a sampling oscillograph with five pick-up electrodes fixed at the end of each trimming coil range which serves to compare the phase angle of the ion pulse with that of the RF frequency. This measurement is made continuous for each radius by means of a special radially moved sampling target. An automatic adjustment of the trimming coils according to the phase angle between ion pulse and RF is in preparation.

Further characterisitic data are : the magnet weight 280 metric tons; the pole diameter is 225 cm or 88 in.; the edge of the pole shoe has a Rose shim, the maximum isochronous radius is about 105 cm; and the amplitude of the first harmonic in the radial direction is about 4 cm.

The Livingston type of ion source is located 2.4 cm from the centre of the machine. The arc voltage may be continuous or pulsed. The tuning of the RF system is arranged by moving the short circuit, in our case, turning diaphragms of the quarter-wave resonators. The Q-factor of the RF system is about 7000, the peak voltage 40 kV, the power losses are 18 kW, and the maximum power output of the RF generator is 70 kW.

The vertical section , Fig. 1, shows the upper and lower magnet yokes with the two pole shoes; the main exciting coils, consisting of copper conductors of 19 by 19 mm with a hollow centre for cooling water; and the trimming coils, situated only at the hills of the pole shoes and made of turns of 10 mm by 0.2 mm anodised aluminum. Further visible are parts of the vacuum chamber, which is constructed of non-magnetic steel plates; the quarter-wave resonator; the turning diaphragm, constructed of 0.2 mm copper foil, with the corresponding drive gear; the inner conductor; and the transforming line, with the RF feeder.

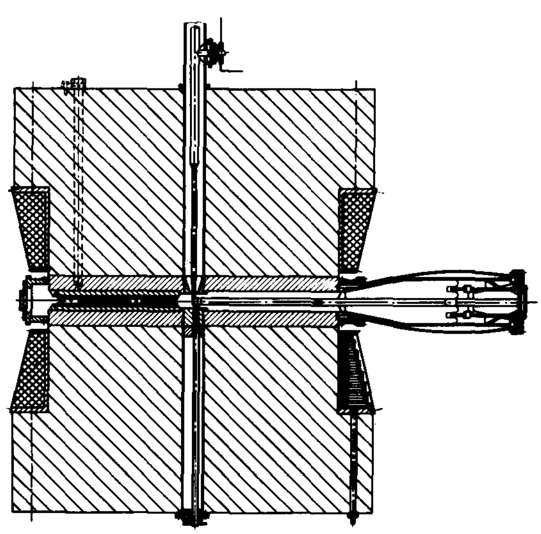

Fig. 1 Vertical section of the Karlsruhe cyclotron.

The pole shoes serve at the same time as the upper and lower cover of the vacuum chamber. Without lifting the yoke the complete chamber unit can be dismantled by means of a special rail trolley.

The ion source is brought into the vacuum chamber from below. For adjustment it can be moved in two directions and be turned about its axis.

The horizontal section, Fig. 2, shows the complete acceleration system with the three quarter-wave resonators, the six acceleration gaps, and the vacuum chamber with the connection for the oil diffusion pump of 8000 liters/s capacity.

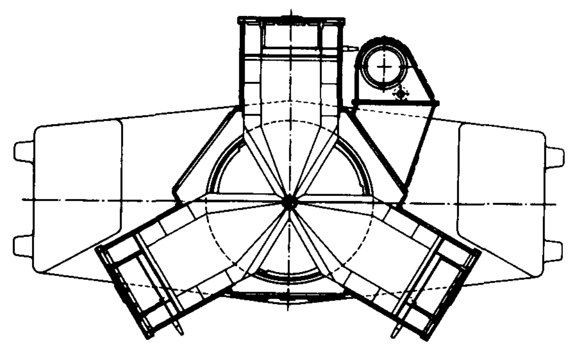

Fig. 2 Horizontal section of the Karlsruhe cyclotron.

A picture of the cyclotron within the vault is shown in Fig. 3. In front is one of the remote-controlled target changers. The high frequency generator is on top of the magnet, along with a second pumping set comprising an oil diffusion pump of 250 l/s capacity to evacuate the transforming line. Two of the three extensions of the vacuum chamber for the quarter-wave resonators, the main exciting coils, and a vessel for deaerating the cooling water can also be identified.

The target arrangement is shown in Fig. 4. The three front targets are remotely controlled from the operation room. The middle unit allows an automatic transfer of targets from the laboratory along a special target trail.

Measurements

The first experiments were performed with H_2^+ ions to avoid high activities in the machine. A surprising result was that at a vacuum of some 2 x 10^{-6} torr about 15% of the hydrogen molecules of the first turn reached the full radius. Another result was that the axial spread of the beam in no case exceeded the slot height of the ion source.

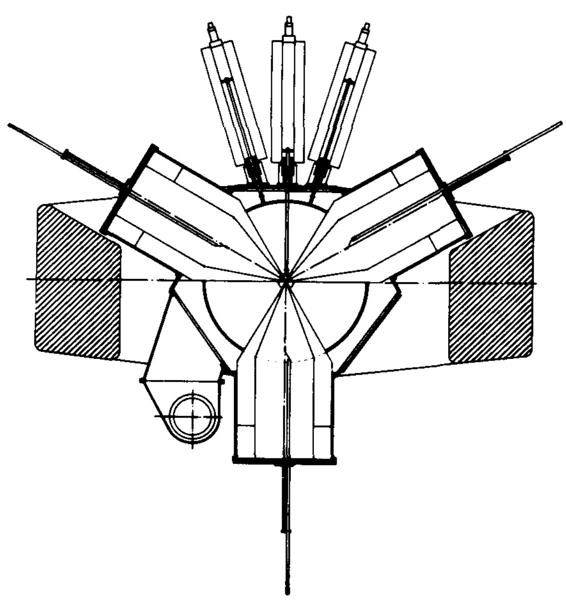

Fig. 4 Target arrangement.

The total current plotted versus radius is shown in Fig. 5. With deuterium, no beam loss was observed from the first turn, in our case that is the fourth acceleration gap, to full radius. The lower curve chows the measured H_2^+ current. All measurements were performed with an ion current up to 5 μA at maximum energy. With a double target it was possible to measure total current and beam density in the same run.

The beam current density up to 2/3 of full radius is plotted in Fig. 6.

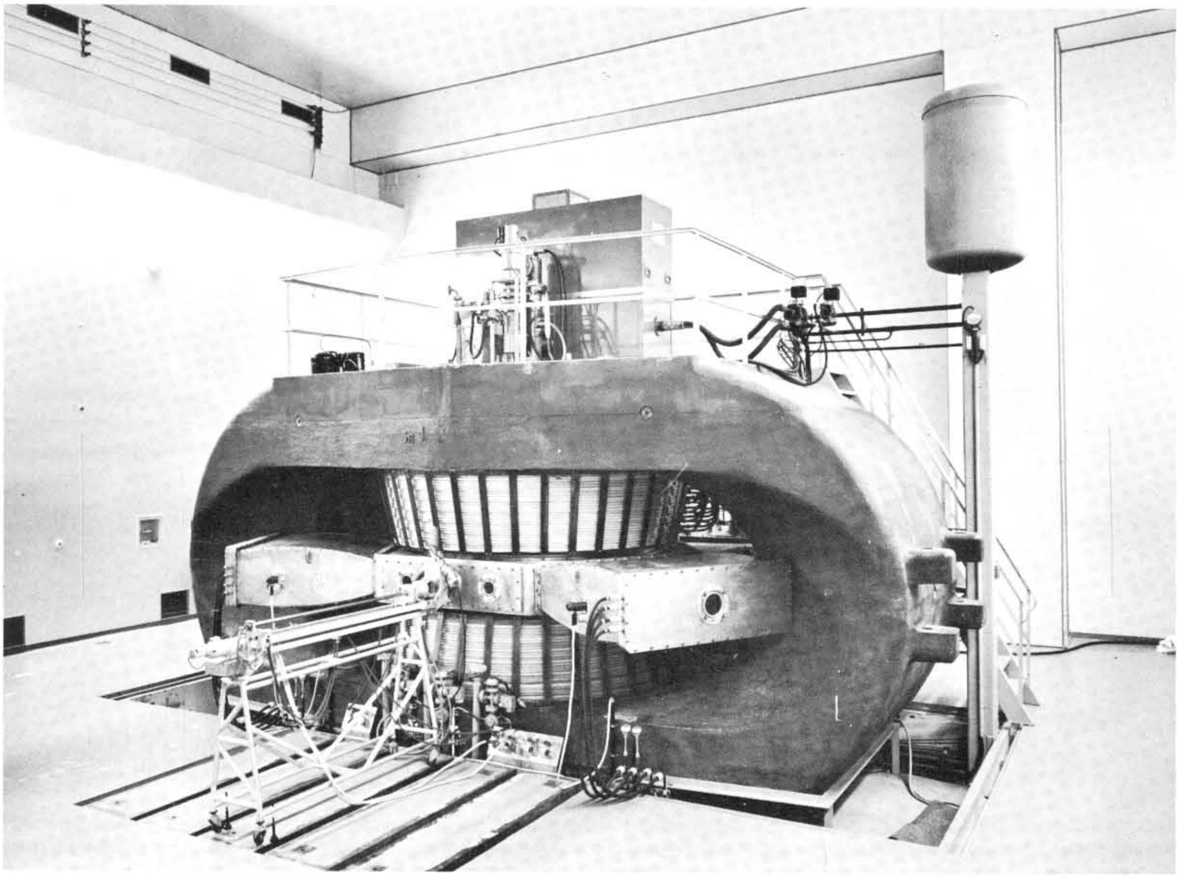

Fig. 3 Photograph of Karlsruhe cyclotron in vault.

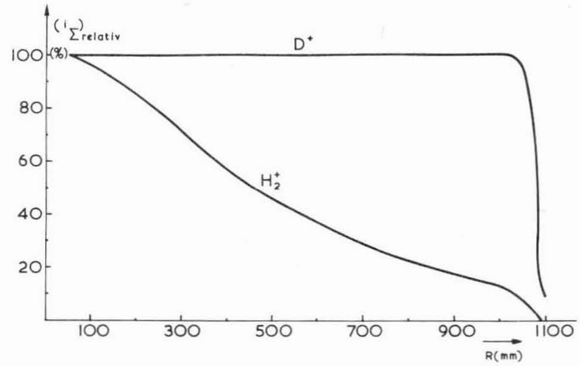

Fig. 5 Total current versus radius.

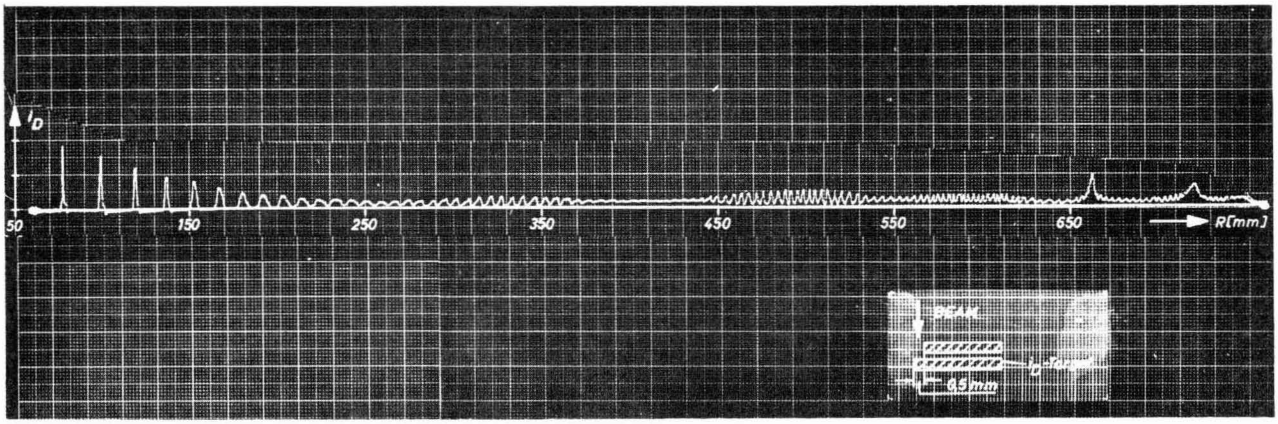

Fig. 6 Beam current density to 2/3 full radius.

At these measurements the target was 0.5 mm wide. One can recognize besides the good separation of the single orbits a periodical structure of the current density versus radius.

Fig. 7 shows three of these plots of beam current density up to full radius of the machine, also measured with the 0.5 mm target on the azimuth. One can recognize, too, a separation of single orbits nearly up to full radius, and the periodic oscillation of beam current density. Out of the number of turns in such a period we have determined ν_r. There is a good agreement between the values of ν_r gained out of the theoretical field configuration and the values of ν_r determined out of density periods of different plots.

We have measured the radial distances from peak to peak of the plots shown above and we have drawn up these values versus the number of orbits. There is a periodical change in these radial distances.

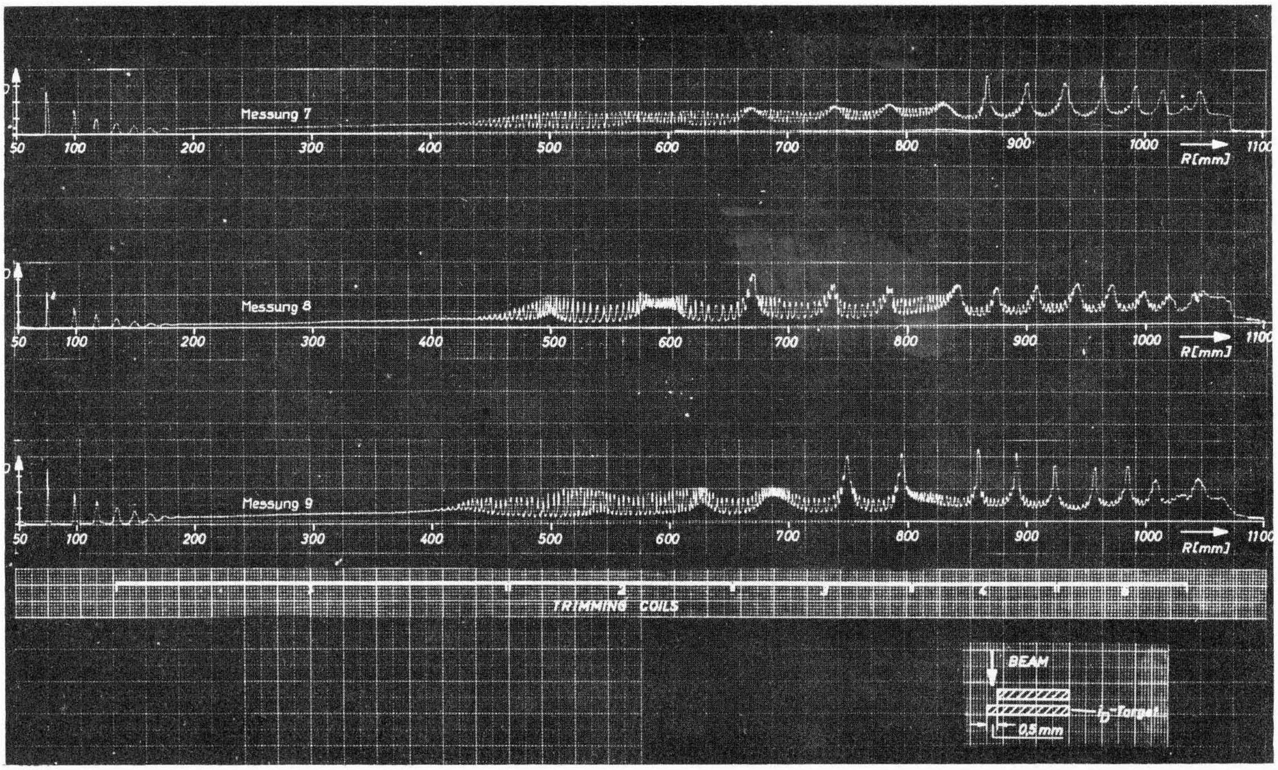

Fig. 7 Beam current density to full radius.

In following a simple model concept, we derive the amplitudes of the radial betatron oscillations from the difference between the largest and the smallest distances from peak to peak. This model implies that there is a precession of the radial betatron oscillations, and that the oscillation of the measured orbit distances will be compared with the average distances resulting from the energy gain per turn.

At the medium radius of the machine we found amplitudes from 2 to 6 mm, and less than 2 mm at full radius. According to this model these amplitudes of betatron oscillations result from an eccentricity of the orbits. The eccentricity may be produced by poor adjustment of the ion source or errors in the magnetic field. It is possible that at certain positions of the ion source the centre point of all orbits deviates by 3 mm from that of the machine. With only a few measurements we cannot say that it is only the position of the ion source which is responsible for the eccentricity of the orbits. On the other hand we can study the influence of the first harmonic of the magnetic field. In the upper plot in Fig. 7 all the currents of the three trimming coils of the first range were equal. The other two plots of Fig. 7 show that the trimming coils of the first range were excited differently, that a first harmonic was produced. The first harmonic was displaced 120°, comparing the middle of the lower plot. One can see a remarkable change of beam current density versus radius. A 0.1% change in the field strength of the first harmonic resulted in radial betatron amplitudes of up to 9 mm.

This range of measurements could not yet be finished because the cyclotron has to be completed to a fixed time table. But we hope that we can finish these measurements later. Besides these measurements the cyclotron was used for radiation experiments. In the course of these, the cyclotron with the exception of the target support was activated to only a low level. Towards the end of February, all experiments were stopped. At that time the necessary changes in the extraction system were began.

The extraction system, Fig. 8, begins with a short septum situated in the strong magnetic field sector. The radial electric field strength is 80 kV/cm. By this means the beam is deflected by 18 mm where it enters the magnetic channel. By means of further magnet shims not shown in this figure, the deflection can be increased to about 35 mm. The field gradient between the strong and weak magnet sectors lies mainly in the direction of the beam. Along the shims in the weak magnet sector there is a strong field gradient at a right angle to the direction of beam. The gradient can be positive or negative according to the location of the shimes to the beam. The edge of the following strong field sector is shifted radially in such a way that it lies parallel to the last isochronous orbit. At this corner of the strong field sector the magnet channel begins; it will be built in such a way that the beam is guided by alternating field gradients. With this field gradient in the magnetic channel as well as along the shims we may expect a good optical quality of the external beam.

The foregoing description of the Karlsruhe cyclotron was no more than a short survey. Comprehensive details will be published later.

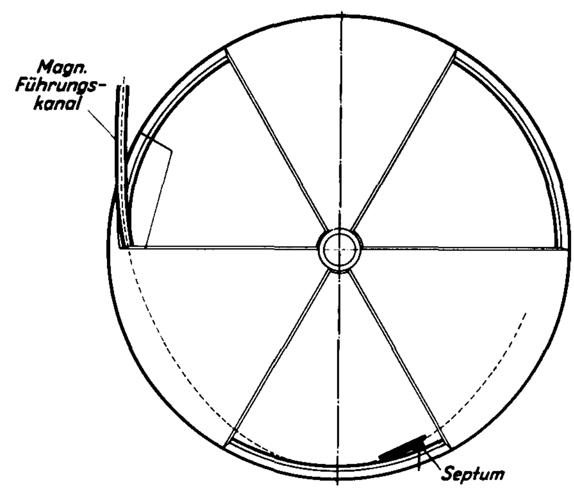

Fig. 8 The extraction system.

DISCUSSION

LIVINGSTON : Did you measure the level of radioactivity?

KÜLLMER : At 10 μA we measured 50 R/h at 2 m from the target.

LIVINGSTON : I would like to express admiration for the very beautiful curves of current density versus radius. Have you attempted to get rid of this sharp peaking by relocating the ion source?

KÜLLMER : We can move the ion source only within a range of 2 mm. We think the peaks of beam density are due to an excentricity induced by a first harmonic of the magnetic field near the ion source.

WATERTON : Where does voltage breakdown occur in the RF system?

KÜLLMER : Breakdown occurs only near the ion source.

LAPOSTOLLE : Does the machine use the defining and focusing system which was designed for it?

KÜLLMER : Yes, the machine has six slits on the first turn. Each acceleration gap has it own slit.