EXTRACTION FROM THE JÜLICH 90 MeV-^d^ AEG-ISOCRHERONOUS CYCLOTRON

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Summary

The Jülich Isochronous Cyclotron had its acceptance tests for the internal beam in March 1968. The beam extraction has been performed since June 1968. At present all extraction elements are in operation and the measurements of the external beam properties will be continued. The specifications of the external beam have been fixed in a contract with the user of the machine in October 1968.

The original design of the machine was for 55-90 MeV deuterons. Similar to the Karlsruhe Cyclotron, the RF-system was designed as a 3-Dee-system, located in the valley sector of the pole plates. For an operation in the 3W-mode the resulting RF-range is 20-30 MHz. According to this, we get 32.5-45 MeV protons in the 3W-mode, 67.5-135 MeV 3He^+, and 90-150 MeV alphas. The operation in the 6W-mode has been tested successfully for protons and deuterons. The design of the magnetic guiding field has been based on the demand for a high quality beam extraction. In order to avoid saturation effects in the iron and as a consequence nonlinearities in the extraction region, we kept the magnetic field relatively low. The maximum average field, hill and valley fields are 13.0, 19.2 and 7.0 kG respectively. There are 12 trim coils arranged on the hill sectors, which are suitable for independent isochronous and harmonic field corrections.

As a result of the high energy gain per turn of 200 keV for 90 MeV deuterons, the turn separation (3.5 mm) at the extraction radius is sufficient for an extraction at \( \gamma = 1 \). We have scaled orbits in the whole particle and energy range. The beam measuring equipment consists of four remotely controlled differential probes (see fig. 1), one of these at an azimuth of 90° is also used for high current measurements.

If the turns are separated from each other, the amplitude of the coherent oscillation can be taken from the current density measurement. As an example fig. 2 shows the current density vs. radius, measured with a 0.5 mm differential probe. From this figure we found a radial coherent amplitude of 1.7 mm. For greater radii where the individual turns cannot be seen, the coherent amplitude was determined by using shadow measurements. In each case the coherent amplitude was found to be less than 2.0 mm. The originally measured beam eccentricities of about 3 mm were compensated by the trim coils.

The phase width of the internal beam indicated by 12 phase probes depends on the ion capture conditions and lies between 30° and 50° (basis width).

The beam extraction system

The basic design of the extraction system is to provide a sufficient turn separation with a short electrostatic deflector, so that the deflected beam is free of ionic beam extraction. Additionally, a focusing element guides the deflected beam through the fringing field. According to this, the extraction system consists of three main elements (fig. 1):

1. An electrostatic deflector operating with a maximum field strength of 90 kV/cm and covering an azimuthal width of 25°.
2. A pair of totally screening compensated iron channels, positioned inside a Dee-sector, each 31 cm in length.
3. A focusing channel forming the fringing field of the following hill sector, combined with a second deflector for the correction of beam position.

Electrostatic deflector

The electrostatic deflector has to provide a turn separation of 30 mm at the entrance of the following weakening channel. The top of fig. 3 shows a vertical section of the electrodes. The high voltage electrode is made from chromium plated copper, rounded with a radius of about 4 mm at its outer edges. The electrodes are mounted on two araldite supports, which have an opening for water cooling, vacuum sealed by small o-rings. The height of the electrode is 16 mm. A pair of stainless steel sheets prevents arcing towards the trim coils. The septum is a 0.2 mm tungsten foil, pressed against the water cooled support. This arrangement has been tested without beam whereby tungsten was found to be the optimal material to prevent arcing. In tests we have learned about the rather difficult and misterious techniques of araldite. The horizontal aperture of the deflector is given by the resulting turn separation of 2.6 mm for \( \gamma = 1.09 \) and a radial amplitude of 2 mm. We chose 3 mm aperture at the deflector entrance and 5 mm at the exit, resulting in a maximum voltage of 32 kV. With such an arrangement we measured more than 80% transparency of the deflector. Yet the foil has been dented to a small extent for internal...
currents exceeding 10 μA. This denting reduces the transparency. To prevent this effect we arranged small carbon pieces (5 mm width in beam direction and 0.2 mm depth in the median plane) in front of the tungsten foil just outside the electric field (bottom fig. 3). The radial position of these pieces is defined by the septum support. We have tested these carbon pieces up to 16 μA beam current without recognizing any change. At higher current extraction the problem is to avoid heating of the tungsten septum.

Weakening Channel

The purpose of the compensated iron channels is to transport the beam to the pole edge. The two identical channels consist of an hollow iron tube of 9 mm inner and 20 mm outer diameter (fig. 4) and a compensation coil with 16 windings having a cross-section of 4 x 4 mm² and 2 x 2 mm² for water cooling.

Theoretically the magnetic field inside the tube is homogeneous, on the outside dipole field. In practice homogeneity is realized for inner diameters of less than 10 mm. The field strength is zero from 5 to 6 kG and about 150 G at a 7 kG valley field. The field distortion caused by the iron tube was measured and the arrangement of the windings has been chosen as to compensate the dipole field at the last orbit.

For a field bump of 0.1 %, produced by the weakening channels, the resulting eccentricity of the orbits has been estimated to be less than 0.16 mm. Fig. 4 shows the bumps produced by different compensation currents. Using a current 5.7 % to low, the orbit shift has been measured to be about 1 mm while we estimated a 1.3 mm shift at V = 1.08.

Since the field gradient depends on the compensation current, the adequate current can be indicated by a gradient probe (fig. 4). This probe consists of a small steel pin (1 mm diameter, 15 mm high), which is fastened with ball bearings. It indicates an upper and lower limit for the compensation current in the control room. This indicator is helpful for operating the machine.

At the channel entrance two targets are positioned, having an aperture of 8 mm for the beam. In this way it can easily be seen, if the deflector voltage and the channel position match.

Focusing Channel

The focusing channel is the only optical element of the extraction system. To avoid nonlinearities of the magnetic field, a special profile of the iron channel has been developed. The channel is composed of two parts, the first channel is defocusing and the second one is focusing in the horizontal direction.

Fig. 5 shows the vertical iron section of the channel and the normal field gradients as a function of the distance from the channel, for different beam energies. The negative and positive gradient curves correspond to the defocusing and focusing parts of the channel respectively. The combination of the defocusing and focusing channel is convenient for several reasons. At first, the variation of the phase volume at a given target point, due to the variation of the magnetic field, can be kept small. Secondly by varying the length of both channels it is possible to vary the orientation of the phase volume without changing position and angle of the extracted beam.

The properties of the channel were determined in a model, scale 1 : 73, we found, that the extraction angle changes about 0.5° in the desired energy range. This effect can be compensated by an additional electric field with a maximum of 25 kV/cm, inside the channel.

The entrance of the channel is positioned according to a beam penetration spot in a foil. The channel exit is movable and is adjusted for maximum extraction efficiency.

Results of beam measurements

Fig. 6 shows the total beam current as well as the current density, measured at two different azimuths for energies of 65 and 75 MeV. The most important results given in fig. 6 are the beam transparency and the current distribution of the deflected beam. The transparency of the electrostatic deflector, and the screening channel together with the deflector, is 75 % and 73 % respectively.

In the 65 MeV case the horizontal beam width is 2 mm PWHM behind the deflector (θ = 90°) and 3 mm PWHM between the weakening channels (θ = 150°).

The result can be compared with General Orbit calculations made for the low energy case. The fact, that the current density curve shows no fluctuations in the extraction region, indicates that a total precessional mixing exists. Consequently we started the calculations with eigen-ellipses, according to a radial amplitude of 2 mm. The continuum in energy was simulated by supposing five neighbouring eigen-ellipses with different energies.

Neglecting particle losses in the septum, fig. 7 shows the development of the radial phase space. The phase volume entering the electrostatic deflector occurs at θ = 65°. There is a continuous increase of the phase volume with time, combined with an increase of the radial beam width from less than 2 mm at the deflector entrance, to 5 mm at the screening channel exit. There, the effective phase space of the ion burst is about 15 mm mrad.
The profiles of the extracted beam have been investigated by using beam penetration spots. At the entrance of the focusing channel the horizontal and the vertical beam width were found to be 9 mm and 3 mm respectively. The foil located at the focusing channel exit showed a circle shaped beam of 5 mm in diameter. One of the purposes in the design of the magnetic guiding field was to get a fixed orbit geometry in the extraction region for the whole energy range. As a consequence the beam measurements showed, that the position of the extraction elements could remain unchanged for all investigated energies.

This is an interesting aspect for handling of the beam extraction. A given target point outside the machine can be met by adjusting only the deflector voltage inside the focusing channel.

Precessional Extraction

To get an information on the possibility of a high current extraction, we made a test in July 1968, using the precessional extraction. Among the elements of the extraction system, only the electrostatic deflector was available and inserted in the cyclotron.

The experiments were prepared by calculations on the beam dynamics in the extraction region. The main result of the calculations, using the measured data of the magnetic field, was, that a field bump of 5 G produced a sufficient turn separation of 6 mm at \( \gamma = 0.95 \). The total phase shift of the final 50 turns was calculated to be less than 450°.

Corresponding to the turn separation of 6 mm the radial aperture of the electrostatic deflector has been enlarged up to 3 mm. The high current test was carried out for a deuteron energy of 57 MeV, requiring a deflector voltage of 35 kV. The deflector entrance was positioned in such a way, that the beam extraction occurred at \( \gamma = 0.95 \).

We started the experiment by centering the internal beam. To find a suitable field bump, we varied the azimuth of the precalculated 5 G-bump in steps of 15°, every time measuring the total beam current and the current density. Furthermore the transparency of the electrostatic deflector was optimized by adjusting its exit and secondly by introducing a small first harmonic at the inner radius range.

The radial width of the deflected beam was 4 mm FWHM measured at \( \Theta = 90° \) (behind the electrostatic deflector) and 8 mm FWHM at \( \Theta = 150° \). The most interesting result of the high current test was, that the deflector transparency of 90% was constant for the total examined current range. According to this result, the septum showed no damage after the test. The high current experiment was stopped at a deflected beam current of 1 mA only to avoid a troublesome activation of the machine.

A comparison between the results of the precessional extraction and the extraction at \( \gamma > 1 \) shows, that the radial width of the extracted beam is larger in the first case. Additionally for the precessional extraction the General Orbit Code calculations yielded an increased beam emittance by a factor of two. Since, for the Jülich cyclotron high beam quality considerations outweigh high current considerations in importance, we chose the extraction at \( \gamma > 1 \).

Conclusion

During the next weeks, the beam matching will be performed in cooperation with the Jülich Institute of Nuclear Physics (Prof. Dr. C. Meyer-Börnike). To obtain the suitable shape and orientation of the horizontal and vertical phase-ellipses, the length of the focusing and the defocusing part of the magnetic channel will be adjusted. The beam properties, i.e. emittance and energy resolution, will be measured at first for deuterons and alphas. The beam extraction will be finished in August this year.

References


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Fig. 1: Horizontal section with beam extraction system

Fig. 2: Measured current density vs. radius
vertical section

vertical section

deflector entrance plan view schematic

1. high voltage electrode
2. septum (tungsten foil)
   0.2 mm
3. araldite
4. water cooling
5. stainless steel plates
6. septum support
7. carbon plates (0.2 mm)

Fig. 3: Electrostatic deflector

Fig. 4: Top: Vertical section of the weakening channel with gradient probe. Bottom: Magnetic field produced by the weakening channel for three different compensation currents.

Fig. 5: Vertical section of the focusing channel and the corresponding field gradients. Top: Horizontal defocusing part. Bottom: Horizontal focusing part.

Fig. 6: Total current and current density vs. radius measured at two azimuths.

Fig. 7: Motion of the extracted ion burst in the radial phase space shown at four azimuths.