

Beam dynamics in newly designed cyclotrons at Ion Beam Applications

S.Zaremba, M.Abs, E.Conard, L.Hardy, Y.Jongen, M.Ladeuze
 Ion Beam Applications, s.a.
 Chemin du Cyclotron, 2
 B-1348 Louvain-la-Neuve, Belgium

and G.Lannoye
 Centre de Recherches du Cyclotron, Université Catholique de Louvain
 Chemin du Cyclotron, 2
 B-1348 Louvain-la-Neuve, Belgium

INTRODUCTION

After the commercial success of the first 30 MeV H^- cyclotron CYCLONE 30 Ion Beam Applications s.a. developed, built and produces three other types of cyclotrons destined for a production of a large variety of radioisotopes. The current status of all these projects is presented elsewhere [1, 2, 3, 4]. This paper briefly presents different aspects of theoretical calculations and a comparison with measurements of finished accelerators.

The well known high intensity 30 MeV H^- cyclotron is reviewed. A new central region geometry is proposed in which H^- and D^- ions can be accelerated on fourth and eighth harmonic modes respectively.

The isochronous magnetic field shaping results and beam dynamics calculations for a new 10 MeV H^- and 5 MeV D^- CYCLONE 10/5 cyclotron are discussed. The central region of this cyclotron is designed to operate with two internal, nearly 180° apart, ion sources permanently installed in the cyclotron [4].

Preliminary calculations of the magnetic field and a stripping extraction system in a 18 MeV H^- and 9 MeV D^- CYCLONE 18/9 cyclotron are outlined.

Magnetic field calculations and measurements, the central region and extraction system calculations in a classical 3 MeV D^+ CYCLONE 3D cyclotron are described.

CYCLONE 30

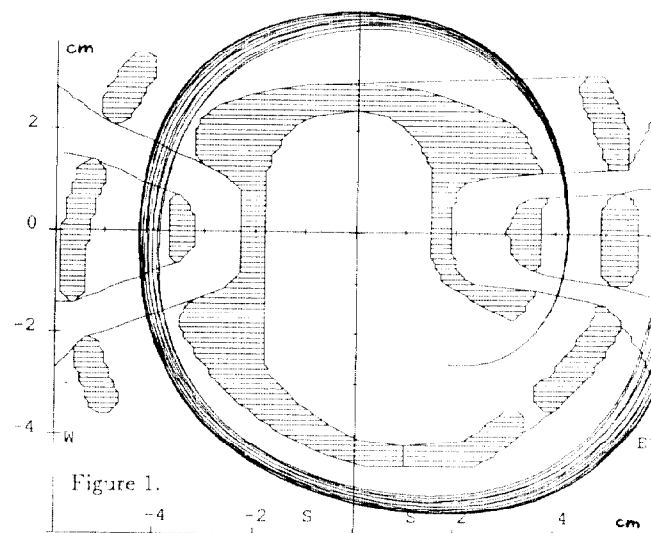
A detailed description of the 30 MeV H^- CYCLONE 30 was presented previously [5]. All important parts of CYCLONE 30 such as the magnet structure, the RF system, the axial injection system and the central region have been initially designed for the acceleration of H^- ions only. An increasing interest of radioisotope producers in accelerated D^- ions encouraged us to review certain elements of the cyclotron to provide the acceleration of D^- ions. It is evident that eventual changes of CYCLONE 30 should be as small as possible, compatible with actual requirements and without any degradation of existing performance.

It would be possible to use the existing axial injection line and the spiral inflector [6] for D^- ions if an injection voltage is equal to a half of the injection voltage for H^- (nominally 28 kV). A constant orbit mode operation for both types of ions in the existing central region is possible using dee voltages at the same ratio as injection voltages. The cyclotron continue to work with the same RF frequency for both types of ions but the harmonic mode changes from 4 for H^- to 8 for D^- ions.

Detailed calculations of D^- trajectories in the existing cyclotron central region have shown that:

- the time of passage by first two accelerating gaps is too long (low value of a transit time factor, too small energy gain or even deceleration);
- too large an azimuthal distance between first two accelerating gaps of the dee (close to 45° which is an optimum for H^- beam).

Extended studies using different programs, and among them, the code for calculations of an electric potential distribution in three dimensions [7] and particle trajectories in a varying electric field and a static magnetic field [8] ended with a design of a new central region geometry presented in figure 1.



The azimuthal distance between first two accelerating gaps is about 30° , which is the optimum for both types of ions in the chosen geometry and gap dimensions have been reduced in a horizontal and a axial plane to increase the energy gain. It was also noticed that the optimum dee voltage to accelerate D^- ions is about 40 kV, which is very different from the theoretical half (25 kV) of the nominal dee voltage for H^- (50 kV).

Calculations have confirmed that a change of the azimuthal distance between first two accelerating gaps diminishes a phase acceptance for protons from 60° to $40-50^\circ$ so one can expect a certain reduction of the current intensity with respect to actual performances. The phase acceptance for D^- is similar.

Different isochronous magnetic field shapes for H^- and D^- ions are obtained by use of movable magnetic elements placed in two opposite valleys. The difference between both isochronous magnetic fields starts to be significant from a radius 300 mm and at the extraction radius of 750 mm it increases to 270 Gauss. The isochronous magnetic field for D^- corresponds to movable elements placed in the bottom of valleys. A rotation and a fixation of movable pieces close to the cyclotron median plane produce the isochronous magnetic field for H^- . All required magnetic fields are achieved by an iterative method described in [9]. A second harmonic imperfection of the magnetic field is created by the installation of movable pieces which influences the beam acceleration. Experience shows that relatively high amplitudes of the second harmonic of the magnetic field (up to 1 kGauss) do not deteriorate cyclotron performance [10].

CYCLONE 10/5

This medical cyclotron is based on the same principle as CYCLONE 30 [5] and its current status can be found elsewhere [1,2,4]. CYCLONE 10/5 has four magnetic sectors, their azimuthal length varies between 54 and 57°. The diameter of the magnet poles is 800 mm with a vertical aperture of 50 mm from the cyclotron center up to radius 50 mm, for larger radii the vertical aperture is 30 mm. The RF acceleration system is similar to that of CYCLONE 30, two 30° dees and a nominal dee voltage 30 kV, working with a frequency of 40.4-41.5 MHz.

CYCLONE 10/5 will be equipped and will operate with two internal ion sources permanently installed in the cyclotron. One ion source will provide H^- ions accelerated on the second harmonic mode and the second ion source, installed about 180° apart, will produce D^- ions accelerated on the fourth harmonic mode. A design of the one cyclotron central region which is compatible with the acceleration of two distinct ions on different harmonic modes was the most difficult problem to solve. A layout of the finally accepted solution is presented in figure 2. The design of the central region of the cyclotron assumed that a change of the type of accelerated ions should be done by switching on another ion source and switching off the one which works. This simplicity of the functioning was not obtained because dee voltages should be changed. Finally accepted dee voltages are: 32 kV for H^- and 28 kV for D^- ions.

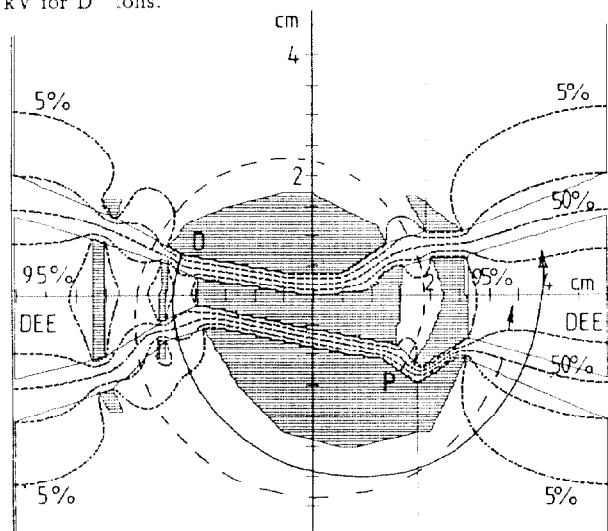


Figure 2. CYCLONE 10/5 - General layout of the central region, dashed line - H^- trajectory, full line - D^- trajectory, equipotential lines of 5, 25, 50, 75 and 95 per cent of the dee voltage amplitude are also marked.

Small posts in the central region serve to diminish a real width of accelerating gaps and to create optimal azimuthal distances between them.

The isochronous magnetic field has been obtained after few iterations of the procedure described in [9]. The figure 3 presents the calculated phase slip for the finally accepted isochronous field for H^- and D^- ions.

The optimum excitation current for H^- ions is 175 A. The isochronous magnetic field for D^- ions is obtained by an increase about 10 A of the main coil excitation current. This corresponds to a change of the RF frequency of less than 0.9 MHz. For higher excitation currents the gradient of the magnetic field drops due to differences of the iron saturation between the cyclotron center and the region in the vicinity of the sector external edges.

The extraction of ions from CYCLONE 10/5 will be done by

the stripping method using eight stripper foils. Only positions of two stripper foils placed at different azimuths of a one sector and particle trajectories after the stripping up to a target have been calculated. Stripper foils will be placed in the magnetic sector at azimuth 22° and 55° with respect to the symmetry axis of the valley. Other stripper foils are placed correspondingly using the four-fold rotational symmetry of the magnet.

Targets will be installed directly on the cyclotron vacuum chamber inside the magnet yoke at the azimuth about 49° and 91° with respect to the defined previously symmetry axis of the valley.

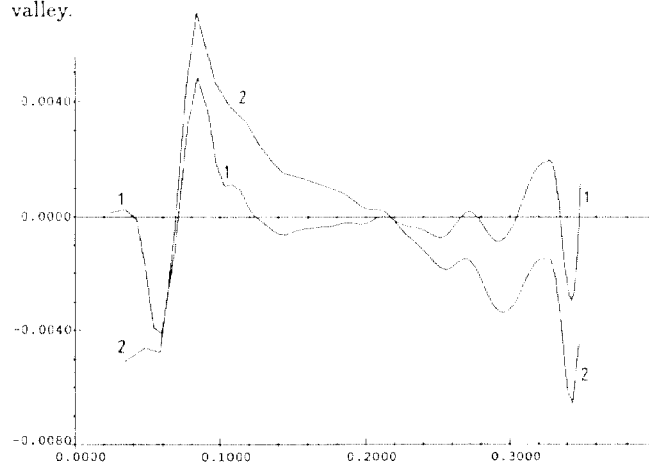


Figure 3. CYCLONE 10/5 - Phase slip (turn/turn) for H^- (1) and D^- (2) as a function of radius (m).

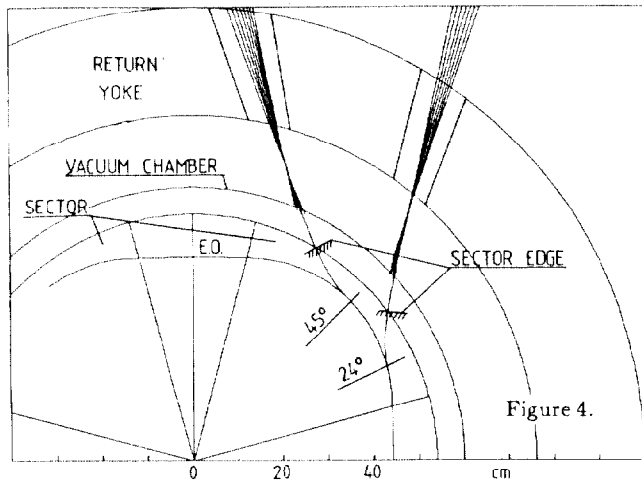
CYCLONE 18/9

This cyclotron is at the conceptual design stage so only certain number of preliminary calculations have been performed. The current status of this project is found in [1]. CYCLONE 18/9 will be an extended version of CYCLONE 10/5 [1,2,3,4]. The diameter of the magnet poles is 1080 mm, the vertical aperture is identical, the upper yoke and the return yoke are 50 per cent thicker than in CYCLONE 10/5. An excitation coil uses the same current value also the RF acceleration system is identical. The main difference between them lies in the extraction system. Small dimension targets will be installed in this case outside the magnet yoke.

Initial calculations of an approximate azimuthal length of magnetic sectors have been done using, among others, the program POISSON [11]. Results served for a design of an initial sector shape. They confirmed that the saturation of iron is acceptable in all of magnet system except sector corners close to connection points between sectors and the magnetic upper yoke where the magnetic field is about 24-27 kGauss. It was also verified that it is not possible to create the isochronous magnetic field for H^- and D^- ions using the method proposed for CYCLONE 10/5 because the maximum difference between average values of the isochronous fields is 130 Gauss. The system of movable pieces, similar to the one chosen for CYCLONE 30, will be adopted.

The position of stripper foils has been fixed at an azimuth of 24° and 45° with respect to the symmetry axis of the valley crossed by the beam before entering in the sector. Preliminary calculations of the beam optics between the stripper foil and targets confirm that it will be impossible to obtain a beam spot on the target with a diameter about 10-12 mm without additional beam optics correction elements because of the length of the trajectories between stripper foils and targets that is 700-900 mm. The magnet fringing field has a focusing effect in the radial plane and the defocusing effect in the axial plane. The edge of the magnet

creates another lens effect also focusing in the radial and defocusing in the axial plane. Movable pieces having specially designed shape are foreseen to change lens effects of the magnet edge, to obtain necessary focusing in the axial plane and diminish overfocusing effects in the radial plane. Figure 4 presents schematically beam trajectories after stripping and necessary angles of the sector edges.



CYCLONE 3D

CYCLONE 3D 3 MeV D^+ , two 90° dees, first harmonic operation mode, classical cyclotron is destined for Positron Emission Tomography systems. Current status of this project is presented in [1,2,3,4].

A perfect rotational symmetry of CYCLONE 3D allowed to make a precise design of a magnet shape using two-dimensional POISSON program. Several runs determined the shape of the magnet poles that are flat up to the radius 206 mm. There are small shims (height 1 mm) between 206 mm and the radius 235 mm which is the end of the tapered magnet pole, a total radius of the sector is 268 mm. A vertical aperture of the magnet is 50 mm then reduced to 48 mm between shims. The vertical aperture of dees is 14 mm which is the maximum taking into account a mechanical rigidity of dees and a necessary insulating distance with respect to magnet poles.

A shape of the magnetic field measured in the cyclotron is in a perfect agreement with the calculated magnetic field after a normalization with respect to the field in the center of the magnet. It was noticed that a real excitation current necessary to obtain the required magnetic field is always 1-2 percent higher than theoretical. The difference can be explained by the difference of a magnetic permeability in the iron.

CYCLONE 3D is equipped with an internal ion source [4]. A central region design, presented in figure 5, was relatively easy because of the homogeneous magnetic field in the central region and more than enough of available space to put necessary elements.

Equilibrium orbit calculations made after the last mapping of the magnetic field in the cyclotron have shown that using higher excitation currents it will be possible to accelerate deuterons up to 3.5-3.6 MeV. Axially the beam is weakly focused, values of an axial betatron frequency ν_z are close to zero but positive and one can expect relatively large amplitude of axial oscillations.

Calculations of an extraction system have been performed for these values of kinetic energy. The extraction system consists of an electrostatic deflector with the azimuthal length of 60° . There

is no element to increase the turn separation prior to extraction, it was estimated that the turn separation due to the kinetic energy gain per turn (2.5 mm before extraction, the dee voltage is 30 kV) is sufficient. The septum has a 8° long V-shaped cut at the deflector entrance to facilitate heat dispersion. The gap dimension between the septum and the high voltage electrode is 4 mm at the entrance of the deflector and 10-12 mm at the exit. The optimum position of the deflector has been found and initial experiments have shown that an extraction efficiency up to 40 per cent is attainable.

Relatively large beam dimensions required on target (100 mm in the radial and 10 mm in the axial plane) do not demand any additional beam correction element along the beam path after the deflector. Big radial dimensions of the beam are obtained by the defocusing effect of the magnet fringing field. Calculations confirmed that the beam is strongly overfocused in the axial plane and this effect could be dangerous when the beam has big axial dimensions before extraction. The shape of the beam spot in the axial direction is dependent on a radius. Axial dimensions on target varies up to 30 per cent comparing target edges.

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