AGOR CENTRAL REGION DESIGN

J.P.Schapira*, A. Le Goff and R. Brizzi

AGOR project, Institut de Physique Nucléaire, 91406 Orsay Cedex, France

ABSTRACT

The shape of the AGOR central region has been determined by electrolytic tank measurements, and three dimensional calculations. The resulting design is compatible with the three harmonic modes of operation (h = 2,3,4) and the use of only two spiral inflectors. In the worst case, natural beam centring is 3.5 mm. By combining two correcting coils, which produce a h = 1 magnetic field component, much better centring is achieved at 25 cm. Taking into account all the correlations introduced by the axial magnetic field, the buncher and the inflector, the calculated cyclotron acceptance turns out to be compatible with the expected emittances of beams from multicusp light ion source and from usual ECR sources.

The Orsay Groningen project AGOR of a compact superconducting cyclotron is designed to accelerate light ions as well as heavy ions in a large range of energies[1].Ion beams will be axially injected, at low energy, from ion sources through an axial injection line described in ref.2. Light ions (hydrogen and helium) will be produced in a multicusp type ion source[3], whereas an ECR type of source will be used for heavy ions. The axial injection line has also been designed to transport polarized light ion beams. The present paper will present the actual (and hopefully final) design of the cyclotron central region, which in many respects differs from the preliminary designs reported in refs. 2 and 4.

GENERAL REQUIREMENTS

The central region design has taken into account various constraints concerning space availability, ease of operation and maintenance. These general goals have led to the following requirements:

- The beam is injected along the magnetic axis of the cyclotron, minimizing problems with radial magnetic field components and steering devices. Only focussing elements are therefore used at this stage[2].

- The central region is unique and compatible with the 3 harmonic modes h of operation. Only 2 different spiral type inflectors[5] will be used, one for h=2 and the other for h=3,4 injecting in two different "tunnels" located in the first dee nose (fig. 1).

- For each harmonic mode, the orbits are constant, independent of the type of ion and its energy. Therefore, all the voltages (ion source, buncher, inflector and dee) are set proportional to $Z_i/A.\ B^2$, where Z_i/A is the charge to mass ratio of the ion and B the isochronous field. In addition the electrical field strengths on the inflector and on the dee have voluntarily been limited to around 30 kV/cm in the vertical direction parallel to the magnetic field, and 100 kV/cm in the horizontal direction. Electrical gaps are at least 10 mm wide.

- Special care has been taken to minimize the capacitances between the RF accelerating electrodes. The inflector housing provides such an isolation (see fig.1).

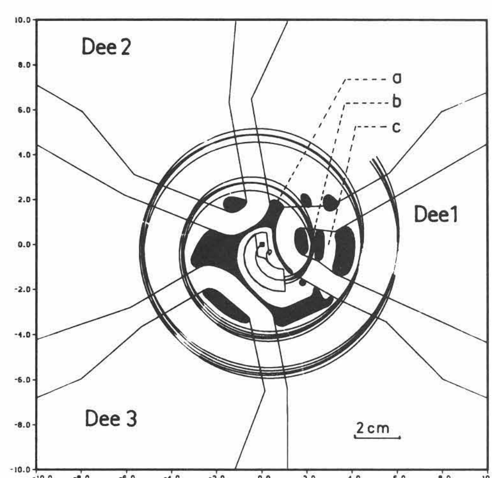

Fig. 1 : AGOR central region, with the inflector h = 2 : a) inflector housing; b) injection hole for h = 2; c) injection hole for h = 3,4.

ELECTRICAL FIELD MEASUREMENTS AND ANALYSIS

The purpose of the study is to design a central region (dee noses, posts, inflector housing) such that injected beams coming out of the inflector have the following properties:

a- to get round the various obstacles in the median plane;

b- to be sufficiently focused in the vertical direction in order to go through a dee aperture of 16 mm;

c- to achieve an acceptance compatible with the emittance expected from the ECR ion source;

d- to be nearly centred after a few turns;

e- to cross the electrical gaps at the correct phase so that maximum energy gain is achieved after a few turns during the subsequent acceleration process.

In the central region, the above properties depend almost entirely on the shape and the phase of the electrical field in the gaps, whereas magnetic means (bump, harmonic h=1 component) are used to achieve better characteristics for the properties d) and e).

The electrical field distribution in the 6 accelerating gaps has been measured in an electrolytic tank on a 5:1 scale model of the central region. Measurements have extended to 15 cm from the centre and simply extrapolated from this point to 40 cm. The probe consisting of a tungsten wire (diameter= 0.1 mm, active length= 0.5 mm) measures the electrical potential in a point of coordinates x,y,z, where z=0 refers to the cyclotron median plane, materialized in the tank by the water surface. By presetting the potential to a certain percentage of the total electrode voltage, one records the positions x,y, where the probe detects this potential (using a Wheatstone bridge type of device). Therefore equipotential horizontal lines are constructed and stored in a computer for subsequent analysis and trajectory calculations. Up to 15 equipotential surfaces (each defined by 3 horizontal lines measured at z=0, 5.5 and 7 mm in machine coordinates), ranging from 5 to 95% of the total dee voltage, have been measured in each of the 6 accelerating electrical gaps.

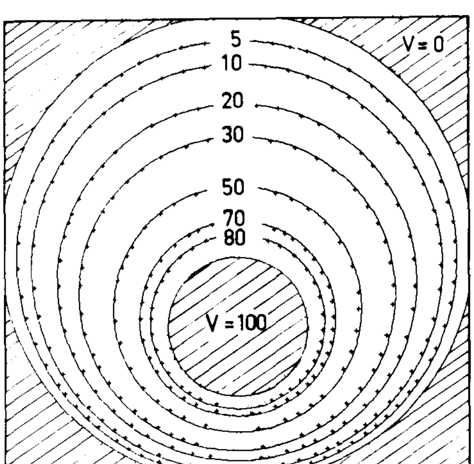

Fig. 2 : Electrolytic tank measurements for two off-centred cylinders : comparison between measured points (cross) and theoretical circles.

The performance of these tank measurements has been tested on the equipotential network generated by two off-centred and parallel cylinders for which there exists an exact analytical solution. As shown in fig. 2, the experimental points (crosses), measured by the probe, fit the theoretical circles to within 0.2 mm (machine scale). Each equipotential surface, defined by 3 horizontal cuts, is analysed by the program TRAFIT in terms of a set of parametric equations $x = X(t,z)$, $y= Y(t,z)$. These functions, used in the orbit code AGOMAG, are constructed from a polynomial least square fit in t of each cut and a Lagrange interpolation in z^2.

For the first two injection gaps, a 3-dimensional calculation of the potential distribution, using the finite-element code MODULEF[6], has given similar results as those obtained by the electrolytic tank measurements and has been used in the orbit calculations.

TRAJECTORY CALCULATIONS: PROGRAM AGOMAG

The ion trajectory is calculated from the exit of the inflector through these equipotential surfaces, using a concept of "discretization" first proposed by P. Mandrillon[7]. This concept supposes that the network of the 15 equipotential surfaces in each gap is stationary (e.g. their position is independent of the phase). This hypothesis is strictly true only for h=3, because the 3 dees are in phase. For the two other harmonics, this is very nearly true because of the high degree of RF shielding obtained. This point has been checked with tank measurements, by observing virtually no displacement (less than 0.2 mm in machine scale) of the equipotential line 5% (the most sensitive) when one changes the voltage ditribution on the two non adjacent dees. In the discretization concept, the action of the electrical field occurs only at discrete points located between 2 successive equipotential surfaces. According to conservation laws, changes in energy and in direction take place only at these points, between which the particle moves freely in the magnetic field. The treatment, performed by the program AGOMAG, is therefore purely geometric, and is analogous to a problem of successive refractions in optics.

In this method, only the direction $\vec{n}$ of the electrical field (not its value) has to be known; two successive numerical differentiations are not required, as is the case in the usual method [8] which deduces the field outside the median plane from the z=0 potential distribution.

RESULTS: HORIZONTAL MOTION

All the central geometry properties depend primarily on the harmonic mode h, and will therefore be presented for 3 typical beams h=2,3 and 4 reported in tab.1.

The position and the shapes of the different posts, crossing the median plane, have been determined by successive modifications of the 5 : 1 scale model of the central geometry[4], using wax, coated with a conducting paint and added to the parts to be modified; this technique allows a quick change of the electrode shape. The injection dee nose geometry is crucial, because it determines wether the trajectories clear the inflector housing and the dee posts, as well as the quality of initial beam centring. In that respect, the "boomerang" shape of the right hand side post at the exit of the inflector (case h=3,4) has been found useful to force the centre of curvature to go upward during the first turn. On the other hand, the gaps have been tilted in angle, so that the beam crosses at a later phase, giving vertical phase focusing. At 10 cm, all the electrical gaps match to their normal angle; as a consequence, each dee is made of 2 parts which are connected at 10 cm, the dee nose and the dee itself, allowing easy mechanical modifications, if necessary. A Typical beam for h=2 is shown in fig.1 .

RESULTS: BEAM CENTRING

Because of the above mentioned constraints, one cannot achieve a natural centring better than 3.5 mm for h=4. Among the 15 correcting coils wound around the hills and used for isochronism, a special linear combination C23 of the coils C2 and C3, vanishing after 25 cm, was found to be efficient for producing a magnetic field component h=1 which recentres the beam progressively up to 25 cm, where 3 centring probes will be located. As a result, centring better than 1 mm is achieved at 25 cm (fig. 3). The most difficult ion to recentre is the one for which Z_i/A and the E/A are the lowest (case h=4). This is due to the poor natural centring, to the fact that ν_r stays very near to 1 and that the form factor of C23 changes sign at R= 13.5 cm. Due to the high current in C2 needed in that case, this correcting coil is used only for centring and not for isochronism.

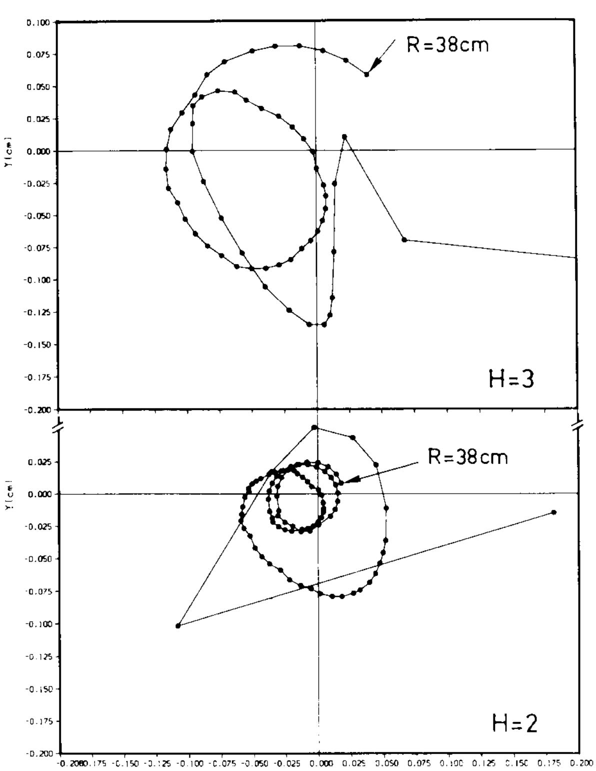

Fig. 3 : Beam centring at R = 25 cm for h = 2 and h = 3, using an harmonic one magnetic field component (see text).

RESULTS: VERTICAL MOTION

Vertical focusing depends chiefly on the electrical phase when the beam is crossing the gaps (phase focusing) and also on the curvature of the equipotential surfaces at the gap entrance (geometrical focusing). Concerning the first effect, vertical focusing is increased when the particle crosses the gaps at a phase later than the equilibrium one which corresponds to the maximum energy gain (phase 0 on fig. 4.). This is achieved by tilting the gaps away from the beam (fig.1) and by requiring the magnetic field (including correction coils contribution) to produce the proper phase shift per turn[9], such that a late starting time can be chosen. The first correcting coil C0 creates the necessary magnetic bump needed to bring the phase back at its "equilibrium" value after few turns. In addition, the vertical acceptance is also increased by reducing the dee aperture to 10 mm at the fourth gap entrance on a radial distance covering the first turn only, before the vertical amplitude becomes too large. This can be expressed through an average electrical ν_z on 5 turns of the order of 0.2, yielding a reasonable vertical acceptance, as seen below.

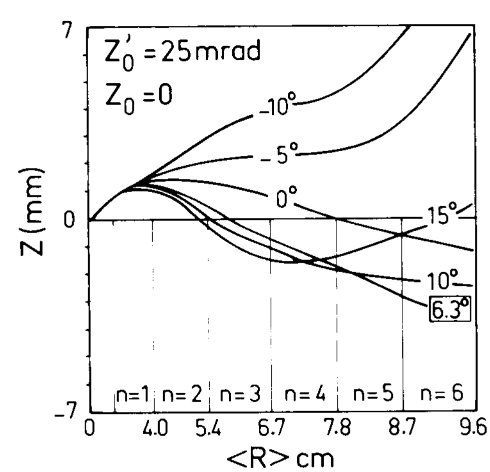

Fig. 4 : Vertical focusing during the 6 first turns versus starting phase, with no magnetic vertical focusing (B = const.).

RESULTS: CENTRAL REGION ACCEPTANCE

The central region acceptance in a 6-dimensional phase space has been determined by retaining those particles which do not hit the lower and upper parts of the dee ($|z|<7$ mm) as well as the various obstacles crossing the median plane (inflector housing, posts) during a certain number of turns corresponding to a complete vertical oscillation (around 12 turns). Initial conditions are defined at the exit of the inflector by uniformly randomizing inside a 6-dimensional phase space hypercube. The program AGOACC tracks these particles and stores the 6 initial and final coordinates of those which are not lost. This approach yields the "intrinsic" central region acceptance, expressed at the inflector exit, in the sense that it does not take into account any correlations between the 6 initial coordinates introduced by optical elements located up-stream on the injection line, such as the axial field of the cyclotron, the buncher and the inflector.

A more realistic approach is to determine the "real" cyclotron acceptance at a point located somewhere upstream, before any transverse or phase-energy coupling occurs. This is achieved in the same way as above. Finally, the corresponding acceptance may be further reduced to take into account some restrictions, the most important one being the beam size at the inflector entrance.

These results are summarized in table 1. One observes that for the "real" acceptance, the beam size is kept reasonable at the inflector entrance, whose dimensions are 5mm by 10 mm. For harmonic h=2, the "real" acceptance is approximately three times larger than the measured emittance of light ion beams delivered by the multicusp ion source[3] and is of the same order for heavy ions from an ECR ion source, taken as roughly equal to 300 mm.mrad at 20 kV[10].

In conclusion, this study shows that this central geometrical set-up, despite all the requirements mentioned above and a fairly small dee aperture of 16 mm, should have a reasonable transmission, even for heavy ion beams delivered by ECR type source. Ultimate beam centring is achieved by means of an acceptable h=1 magnetic pertubation, even in the extreme case of very heavy ion beams at their lowest possible energies.

Table 1: CENTRAL REGION CHARACTERISTICS

Harmonic rank:	h=2	h=3	h=4
General parameters:			
$Z_i/A.B^2$ (max.)	4.463	2.958	2.058
energy range (MeV/A)	23.- 200.	9.9- 72.	5.8- 9.9
Spiral inflectors:			
magnetic radius (mm)	12.61	16.15	16.15
electrical radius (mm)	25.03	24.58	24.58
rotation angle (deg.)	-173.954	-161.907	-156.807
electrical gap (mm)	5.	5.	5.
electrode length (mm)	10.	10.	10.
Reference beams:	Proton	$^3He^{++}$	$^{136}Xe^{13+}$
Z_i/A	0.993	0.666	0.096
final Energy (MeV/A)	200.	62.	5.8
source voltage (kV)	31.1	29.5	21.8
buncher voltage (kV)	0.785	0.999	1.082
inflector voltage (kV)	12.4	12.1	8.1
dee voltage (kV)	73.6	59.5	50.4
isochronous field (Tesla)	2.000	1.880	4.070
Centring:			
natural centring (mm)	1.0	2.3	3.5
max. h=1 amplitude (G)	1.8	8.2	59.8
final centring at 25 cm (mm)	< 0.3	< 0.7	< 0.3
Vertical motion:			
magnetic bump a r= 0 (G)	321.	296.	381.
phase delay (RF deg.)	6.3	5.2	10.6
"Intrinsic" acceptance $^{a)}$ **:**			
horizontal (mm.mrad/π)	290.	290.	205.
vertical (mm.mrad/π)	130.	160.	130.
RF Phase (deg.)	+/-20.	+/-20.	+/-20.
"Real" acceptance $^{b)}$ **:**			
transv. plane (mm.mrad/π)	90.	100.	110.
1/2 beam size $^{c)}$ (mm)	1.2	1.5	1.3
1/2 RF phase width (deg.)	20.	20.	25.
1/2 hor. size $^{a)}$ (mm)	1.8	1.8	1.5
1/2 hor. divg. $^{a)}$ (mrad)	100.	100.	100.
1/2 vert. size $^{a)}$ (mm)	1.5	1.5	1.5
1/2 vert. divg. $^{a)}$ (mrad)	75.	60.	50.

a) at inflector exit; b) before Z = 3.4 m; c) at inflector entrance.

*Work jointly supported by the "INSTITUT NATIONAL DE PHYSIQUE NUCLEAIRE ET DE PHYSIQUE DES PARTICULES" (IN2P3), France and by the "STICHTING VOOR FUNDAMENTEEL ONDERZOEK DER MATERIE" (FOM), Netherlands.

REFERENCES

1) H. Schreuder, "The AGOR cyclotron past the half-way mark" invited paper at this conference.
2) J.P. Schapira, S. Brandenburg and P. Mandrillon, "Axial injection system for the superconducting cyclotron AGOR", in Proc 11 th Int. Conf. on Cyclotrons and their Applications (Tokyo, 1986),p.495.
3) M. Malard, A. Serafini, L. Hablot, J.P. Schapira and S. Gustafsson, "AGOR axial injection, using a positive light ion multicusp source", paper presented at this conference.
4) J.P. Schapira and P. Mandrillon, "Axial injection in the Orsay project of a superconducting cyclotron and in the medical cyclotron MEDICYC", in Proc. 10 th Int. Conf. on Cyclotrons and their Applications (East Lansing, 1984), p. 332.
5) J.L. Pabot, Thesis 1968, Grenoble University, France.
6) M. Bernadou et al., MODULEF : a modular finite elements library, (INRIA, Paris 1985).
7) P. Mandrillon, IPNO-GTA/85-01 Report, Orsay, France.
8) F. Marti et al., "Design calculations for the central region of the NSCL 500 MeV superconducting cyclotron", Proc. 9th Int. Conf. on Cyclotrons and their Applications, (Caen 1981),p. 465.
9) B. Launé, private communication.
10) AGOR, Cyclotron design report, October 1986.