AXIAL INJECTION IN THE ORSAY PROJECT OF A SUPERCONDUCTING CYCLOTRON AND IN THE MEDICAL CYCLOTRON MEDICYC

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Summary

Central geometry compatible with an axial injection has been designed for two cyclotrons : the Orsay project of a superconducting cyclotron ($K_B = 600$, $K_F = 220$ and $R_e = 0.87$ m) and the medical cyclotron MEDICYC ($K_B = 60$, fixed RF frequency = 24 MHz) now under construction. A design was achieved to fulfil for each case the following requirements : on axis injection, constant geometrical set-up compatible with the various harmonic modes, vertical electrical field components less than 25 kV/cm in the inflector. General considerations on forbiden ρ-band (ρ = injection radius) are given, which establish clearly the matching conditions of a certain central region to one of the usual inflector types : spiral, mirror, hyperboloid. Thus a mirror has been set up for the first case, and a spiral type, allowing higher injection energy, for the second case. Acceptances in the superconducting cyclotron has been deduced, showing the need of an external source with good emittance and a careful design of the beam transport along the axis of the cyclotron.

1. Introduction

With the advent of highly stripped heavy ions sources such as ECR[1] or EBIS[2], axial injection has become an attractive way to produce ions for acceleration in cyclotrons and eventually synchrocyclotrons.

Moreover the use of external sources shows other advantages over usual internal sources[3] : possibility of using cumbersome sources like duoplasmatron for light ions, obtaining of higher and better vacuum leading to a reduction of both sputtering and sparking, selection of one charge state, possibility of using an external buncher.

In this paper two studies will be reported. The first one deals with the design of an axial injection system for the Orsay superconducting cyclotron project[4], [5], based on some requirements on which we will elaborate later on. In the second study, we have used the same approach as in the first study, to design the central region of the medical cyclotron $K_B = 60$ MEDICYC[6], now under construction for the Centre Antoine Lacassagne at Nice (France). In this later case we have set some criteria to be used in order to choose the inflector type adapted to the desired injection energy.

2. Basic requirements and parameters for an axial injection

As it has been pointed out by G.H.Ryckwaert[3], axial injection systems have usually to be fitted in existing cyclotrons, so that "a priori" requirements are difficult to achieve (see for example the M.S.U. study for the K=800 cyclotron[7]). This was not the case for the two projects discussed here, for which it was possible to design a central geometry compatible with the following requirements :

a. the external beam should be injected along the magnetic axis of the cyclotron down to the entrance of the inflector, in order to prevent radial magnetic field components to act on the beam. One also avoids in this case any deflection plates along the entrance beam tube.

b. the injection energy should be not too low, in order to minimize space charge effects and to obtain the best emittance possible from the external ion source. This requirement is very important in the case of MEDICYC in which high current proton beam in the mA region are expected. Moreover, in the case of a superconducting cyclotron high injection energy is also desirable in order to achieve the largest possible injection radius at least of the same order as the R.F accelerating gap distances near the centre.

c. the horizontal electrical field components appearing in the central region should not exceed 100 kV/cm. It turned out again that in the case of a superconducting cyclotron, high dee voltage is necessary in order for the ion trajectories to easily move off the centre and keep clear of the various obstacles during the first turn (e.g. dummy-dee posts, inflector housing, R.F shields).

d. the vertical electrical field component E_z in the inflector, should not exceed a value of the order of 25 kV/cm, in order to prevent sparking along the direction of the magnetic field B_o.

e. the operation mode should be of "constant geometry" for each harmonic. Moreover it was found useful not to have to modify the central region and therefore to design it in such a way to ensure compatibility with each of the harmonic modes (h = 2, 3, 4 in the case of the Orsay project, h = 1, 2 in the case of MEDICYC).That is to say that the first R.F accelerating gap (puller) is kept untouched.

f. the dees and the inflector should be electrically shielded with respect to each other.

Assuming a constant magnetic field B_o in the median plane around the centre, it is easy to show[8] that the equation of motion of an ion of charge state Z_i and mass number A is completly determined by 3 parameters :

- the harmonic rank h,
- the ratio $p' = p/V$ where $p = \frac{Z_i}{A} B_o^2$ and V the peak voltage on each dee,
- the electrical phase when the ion is for example at the exit of the inflector in the median plane of the cyclotron.

For each harmonic mode, a constant trajectory will therefore be achieved if one keeps the parameter p' constant, which means adjusting V proportionnaly to the value of p , typical of an ion, its charge state and its energy.

3. The case of the Orsay superconducting cyclotron project

The Orsay project has been designed to accelerate not only heavy ions but also light ions[5] (protons from 127 to 207 MeV, $^3He^{++}$ from 186 to 390 MeV), for which axial injection from a duoplasmatron source becomes the only solution, if one excludes internal P.I.G. source. Ions heavier than carbon will be radially injected from the Orsay M.P Tandem upgraded to 15 MV. Axial injection system will also allows the use of highly stripped ion sources.

The main characteristics of this project are reported in table 1.

$K_B = 600$, $T_{max} = K_B \frac{Z_i^2}{A}$ for $\frac{Z_i}{A} \leq 0.37$

$K_B = 111$

$K_F = 222$, $T_{max} = K_F \frac{Z_i}{A}$ for $\frac{Z_i}{A} > 0.37$

3 magnetic sectors

3 electrical dees opening 60°

Average magnetic field : $\bar{B} = 1.75$ to 4.05 Teslas

Extraction radius : 0.87 m

R.F range : 24 to 62 MHz

Harmonic modes : 2, 3, 4

Dee voltage peak : 100 kV

No internal source

Axial and radial injection

Table 1. Main characteristics of the Orsay project of a superconducting cyclotron.

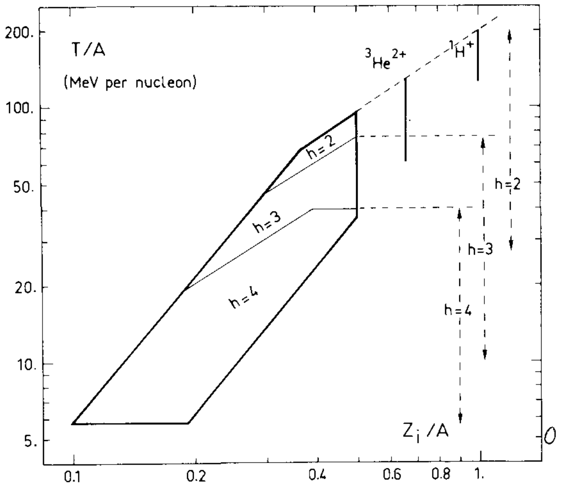

Fig.1 - T/A, Zi/A diagram, taking into account limitations due to the resonance $\nu_r+2\nu_z=3$ and $\nu_z \geq 0.1$. Three regions are delimited for each harmonic mode due to the radiofrequency range (24-62 MHz) and to the condition $E_z \leq 25$ kV/cm.

Taking into account the real (T/A, Zi/A) diagram (see fig.1) and the frequency range from 24 to 62 MHz, one obtains for each harmonic mode the maximum value for $p = \frac{Z_i}{A} B_o^2$:

h = 2 p = 4.404
h = 3 p = 3.930
h = 4 p = 2.693

All these values correspond to the a dee peak voltage V = 100 kV, so that the 3 equations describing the constant ion motion in the central region are fully determined.

Although various type of inflectors are possible (see § 4.1), the choice was made on an electrostatic mirror for reason of simplicity and compactness.

h	ion	$\frac{Z_i}{A}$	Energy (MeV/A)	B_o (Tesla)	$\frac{Z_i}{A} B_o^2$	V (kV)
$2^{a)}$	proton	0.9928	207.4	2.04	4.127	62.2
$2^{a)}$	$^3He^{++}$	0.6634	130.1	2.55	4.314	98.0
$2^{b)}$	$^{20}Ne^{7+}$	0.35	63.	3.55	4.404	100.0
$3^{b)}$	$^{40}A^{9+}$	0.23	27.	3.65	2.994	76.0
$4^{b)}$	$^{84}Kr^{10+}$	0.12	8.	3.87	1.786	66.3
$4^{b)}$	$^{131}Xe^{17+}$	0.13	9.5	3.89	1.966	73.0

a) from duoplasmatron
b) from ECR (ref.1)

Table 2. Characteristics of some typical ions accelerated in the Orsay project from an external source.

In fact a technical study[9] performed at Orsay has shown that with such a mirror covered with stainless steel wires it was possible during 35 hours, to bend a beam of 20µA of $^{14}N^{1+}$ using a vertical electrical field of 25 kV/cm and a magnetic field of 0.6 Tesla, without any damage due to sparking.

3.1 Centre design compatible with the 3 harmonic modes. The design of the central geometry has been developped in two steps. The first one was based on a simplified model[10] in which the six R.F accelerating gaps are straight with a uniform electrical field (100 kV/cm at maximum) and a gap of 1 cm wide. Three types of computing programs have been developped to calculate the ion trajectory within this 2-dimensionnal model. The first one, BORDN, calculates all the sets of initial conditions on the edge of the first R.F accelerating gap (puller), for which the orbits centre converges to the machine centre after a certain number of revolutions. A set of initial conditions is defined by :

- the injection radius ρ (or the injection energy),
- the position of the centre of curvature at the injection on the edge of the first R.F accelerating gap,
- the electrical phase.

The second program UNJAU is an automatical search program, which used the data file generated by BORDN in order to tilt the two first R.F accelerating gaps in such a way that a set of initial conditions matches the characteristics of a mirror simultaneously for the 3 harmonic modes. At this point some constraints are built in UNJAU : mirror electrical field limitation (E_z < 25 kV/cm), transit time in the mirror less than 110° in order that the trajectory at the exit of the mirror is not too grazing. Finally the third one, ORBINI, calculates the orbit for a certain geometry and a set of initial conditions. The preliminary results of these calculations, reported in ref. 10 showed that it was possible by just tilting the two first R.F accelerating gaps to design a central geometry common to the 3 harmonic modes.

These results have then been used as a starting point for building a model of the central region (scale 5 : 1) for electrolytic tank measurements. In three minor modifications of this model, the final central geometry was fixed for the reference trajectories corresponding to the 3 harmonic modes (fig. 2). It became thus possible to design two permanent pullers, for h = 2,3 and h = 4 respectively in the central region of the Orsay project. On the other hand it is worth pointing out that the trajectories were calculated directly from the equipotential lines (and not from the electrical

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field) taken during the electrolytic tank measurements (program AGORA[11]).

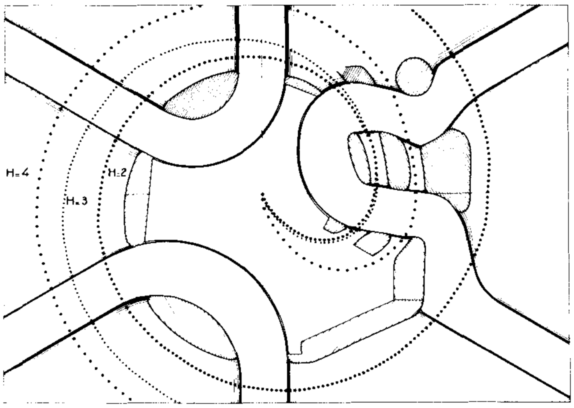

Fig.2 - Central region and the three trajectories h = 2,3 and 4 calculated by AGORA, from the electrolytic tank measurements.

The axial injection parameters deduced from this study are reported in table 3.

Parameters :	h = 2	h = 3	h = 4
$p = \frac{Z_i}{A} B_o^2$	4.404	3.930	2.693
Ion source parameter :			
Maximum injection voltage (kV)	23.8	22.7	29.8
Mirror parameters (see ref. 8):			
Transit angle (deg)	102.9	109.3	95.1
Injection radius (cm)	1.058	1.095	1.514
Max. elongation[a)] (cm)	0.28	0.30	0.38
Grazing angle[a)] (deg)	28.	26.	30.
Mirror inclination[b)] (deg)	41.1	40.5	41.6
Max. Ez (kV/cm)	25.0	21.8	23.7
Central geometry parameters :			
Gain in the first R.F gap[c)]	76.	72.	79.
Gain in the second R.F gap[c)]	71.	86.	86.
Off. centering in X (mm)[d)]	1.2	0.	0.6
Off. centering in Y (mm)[d)]	-0.3	0.	1.2

a) with respect to the entrance/exit plane ;
b) with respect to cyclotron vertical axis ;
c) in percent of the dee voltage peak ;
d) OXY are the machine axis (see fig.4).

Table 3. Axis injection characteristics (deduced from the electrolytic tank measurements).

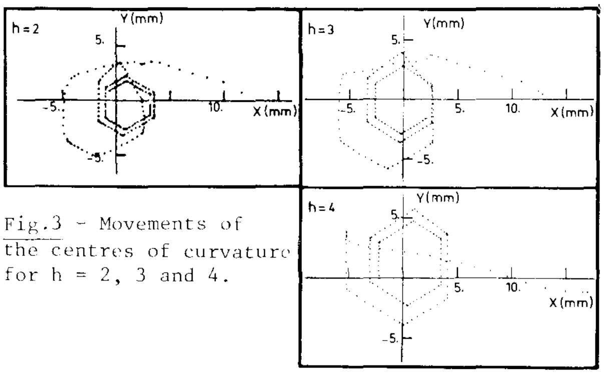

Fig.3 - Movements of the centres of curvature for h = 2, 3 and 4.

The centering of the orbits, as shown on fig.3 of the order of 1 mm can be considered as satisfactory.

3.2 - Geometrical and phase-energy acceptances for the horizontal motion in the central region:

The acceptance for the horizontal motion in the central region is defined at the entrance of the mirror in the phase space ($x_o x'_o\ y_o\ y'_o$, $\delta\tau_o$, $\frac{\delta\rho}{\rho}$) corresponding to the physical plane E $x_o y_o$(see fig.4). Here $\delta\tau_o$ and $\delta\tau_1$ stand for the orbital phase.

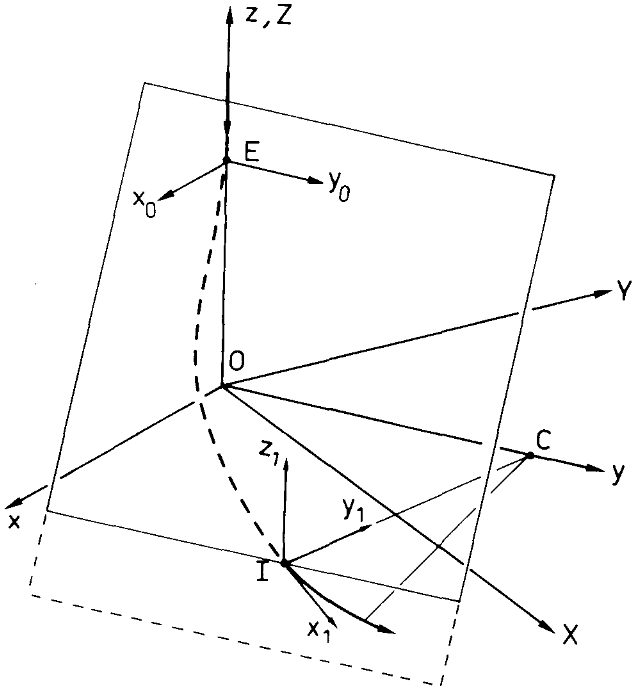

Fig.4 - System of axis for the central region calculation. OXYZ : machine axis. Oxyz : mirror axis(ref. 8). E : mirror input. I : mirror output. C : centre of injection circle.

It takes therefore the mirror into account as well as the various obstacles of the central region. The transfer matrix of the mirror[7,8] gives a set of initial conditions for the trajectory program AGORA in the plane Iy_1z_1 (the vertical movement z is not considered here):

$$y_1 = -s.x_o + c.y_o + 2s.\rho y'_o$$

$$y'_1 = -c.\frac{x_o}{\rho} - s.\frac{y_o}{\rho} + (c-st).y'_o - t.\ \frac{\delta\rho}{\rho}$$

$$\delta\tau_1 = (\frac{\gamma}{s} - c).\frac{x_o}{\rho} - 2s.x'_o - s.\frac{y_o}{\rho} + \delta\tau_o$$

where $\gamma = \frac{\tau}{2}$, $s = \sin\gamma$ $c = \cos\gamma$ $t = tg\gamma$ and τ the mirror transit angle.

Geometrical acceptance has been calculated assuming $\delta\tau_o = \frac{\delta\rho}{\rho} = 0$. Moreover one has assumed, for the sake of simplicity, that the x_o, y_o movements were decoupled at the mirror entrance, although this is not generally the case (the cyclotron axial field up-stream couples these two motions). The phase-energy acceptance has been calculated assuming a trajectory reference ($x_o = y_o = x'_o = y'_o = 0$). The results for each harmonic are shown in fig. 5. Only ion sources of very good emittance are able to match the fairly small geometrical acceptance lying between 100 and 200 π mmx mrad. Yet a recent review[13] indicates that it should be possible to achieve a normalized emittance of the order of $\varepsilon_N \approx 0.15$ π mmxmrad with duoplasmatron and high charge states sources.

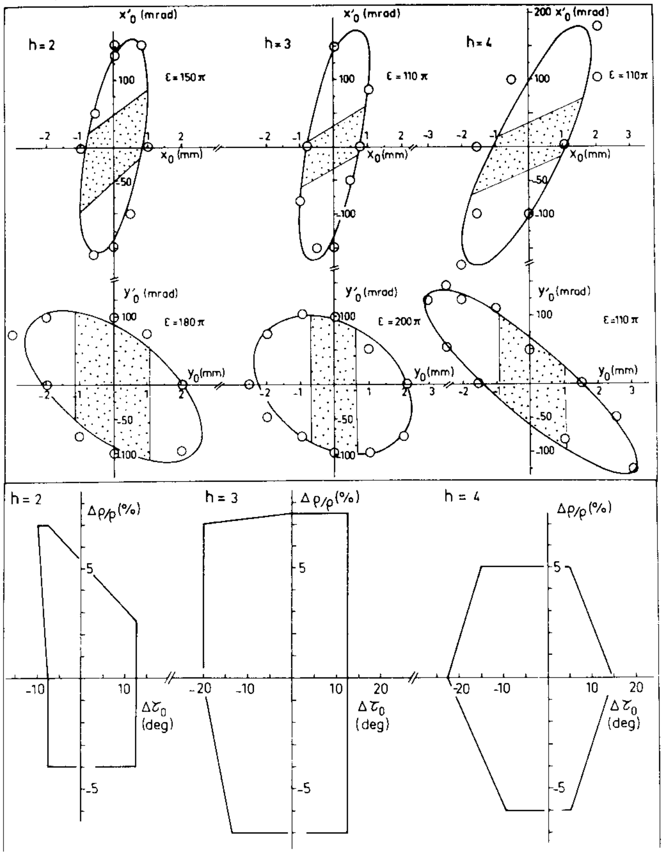

Fig.5 - Region of geometrical and phase-energy acceptances, calculated at the inflector entrance (see fig.4) The shaded area correspond to a R.F phase spread of ± 10° due to the response of the mirror to the beam geometrical emittance.

In this case the emittance injected in the cyclotron would be in the range of 20 -100 π mm x mrad depending on the energy per nucleon, matching the acceptance of the cyclotron. Nevertheless careful design of the transport system through the axial magnetic field[12] is necessary to avoid the degradation of the injected emittance through the injection tube. A solenoid can be used near the entrance of the yoke to focus the beam in a region where the axial field is low (specially in the proton case) and to match the emittance at the entrance of the inflector[7,8,10,12].

With regard to the large phase-energy acceptance, it appears possible to use a buncher above inflector. Because a mirror introduces a large phase spread in phase due to the geometrical size of the beam, it seems pointless to built a buncher with high performances (± 10° R.F phase seems good enough).

4. The case of the medical cyclotron MEDICYC

The medical cyclotron MEDICYC[6] has been designed to operate at a fixed radiofrequency value of 24 MHz. Two harmonic modes will be used : h = 1 for 60 MeV protons (ρ = 2.460, V = 50 kV) and h = 2 for 30 MeV deuterons (ρ = 1.230, V = 30 kV). Because fairly high intensities must be injected for neutrontherapy , the highest injection energy possible compatible with $E_Z < 25$ kV/cm has been looked for, in the same way as in the case of the Orsay project. For this purpose we have transcript the basic programs of the first 2-dimensionnal analysis to the case of MEDICYC (two electrical dees with an opening of 75°).

4.1 - Method of choosing an inflector and 2-dimensionnal calculations.

Three inflector types are a priori candidate to match each set of initial conditions (ρ, X_c, Y_c where C is the centre of the injection circle) obtained in the way described in § 3.1, at each point of the edge of the first R.F accelerating gap. The types of inflector usually considered are the spiral[14], mirror and hyperboloid[15] one. Because one wants the entrance of the inflector to be on axis, the quantity $\xi = \frac{OC}{\rho}$ (where O is the centre of the machine) deduced from the initial conditions, is now typical of only one inflector type. In fact it is easy to show that whatever ρ can be : $0 < \xi < 1$ corresponds to a spiral type, $1 < \xi < \frac{\pi}{2}$ to a mirror type, and $\xi = 1.741$ to an hyperboloid type (refs.8,14,15).

In the case of the two first inflectors, the value of ξ is related to the transit angle τ , so that the inflector is completely defined when ρ and ξ are given. Because the hyperboloid is at fixed transit angle $\tau = \frac{\pi}{2}\sqrt{6}$, there is a unique value for ξ . The inflector is rotated around the machine vertical axis to let the centre of its exit circle to coincide with the point C related to the choosen set of initial conditions. The range of ξ values which do not satisfy the conditions $E_Z < 25$ kV/cm or for which the inflector exit point is beyond the first R.F accelerating gap are of course forbidden. In the case of the mirror, the upper limit $\frac{\pi}{2}$ corresponds to a totally grazing output angle and is not physical. A value ξ_{max} (mirror) = 1.172 corresponding to τ = 110° appears to be more realistic and has been choosen somewhat arbitrarly in this work. These simple considerations show that for a given geometry there are ρ- forbidden bands in which it is not possible to match the corresponding set of initial conditions which insures proper orbit centering, to any of the three usual inflector types.

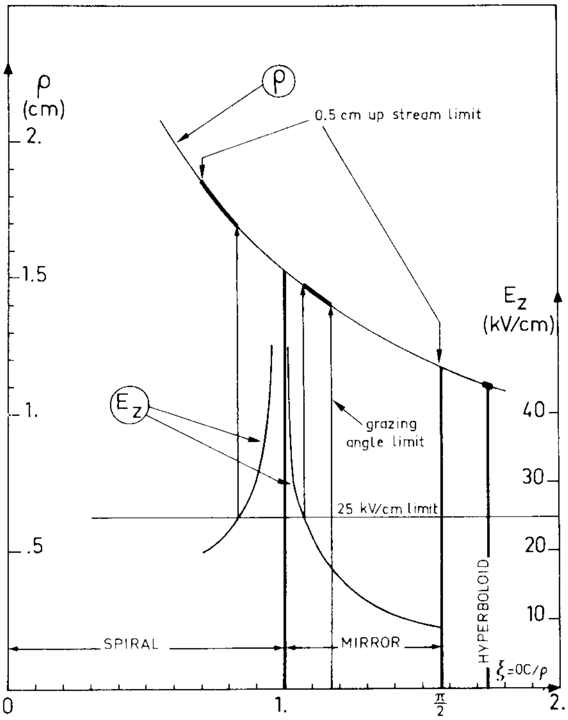

Fig.6 - Curve $\rho = f(\xi)$ corresponding to h = 1 for which further orbit centering is achieved, in the case of the 2-dimensionnal analysis for MEDICYC. On clearly sees the allowed ρ- allowed bands and the corresponding inflector types.

The central geometry of MEDICYC has also been designed with the constraint that the entrance point on the first R.F gap should be the same for the two harmonic modes (one single puller). This condition was not possible unless the two first R.F gaps were tilted like in the Orsay project. The result of BORDN (adapted to MEDICYC) for the choosen 2-dimensionnal geometry is shown on fig. 6 where the curve $\rho = f(\xi)$ corresponding to h = 1 is represented with the allowed ρ- bands. It is clear that high injection energy is achieved only with a spiral type of inflector whereas the hyperboloid matches to the smallest ρ possible value. The mirror does not appear convenient not only because of lower ρ value matching but also because the grid might not be suitable for high current.

Parameters :	h = 1	h = 2
Radio frequency (MHz)	24.	24.
$p = \frac{Zi}{A} B^2_o$	2.640	1.230
Particle	proton	deuteron
Final energy (MeV)	60.0	30.0
Ion source parameter		
Injection voltage (kV)	33.4	15.6
Spiral inflector parameters$^{a)}$		
$\xi = OC/\rho$	0.67	0.77
k value$^{a)}$	1.156	0.950
Transit angle$^{a)}$ (deg)	208.1	171.0
Injection radius (cm)	1.677	1.620
Max. E_z (kV/cm)	17.2	10.1
Central geometry parameters		
Peak voltage on the dee (kV)	50.	30.
Gain in the first R.F gap$^{b)}$	78.4	81.0
Gain in the second R.F gap$^{b)}$	77.1	83.9
Off. centering in X$^{c)}$ (mm)	0.4	0.7
Off. centering in Y$^{c)}$ (mm)	0.	0.

a) see ref. 14 ; b) in per cent of the dee voltage peak ; c) O X Y are the machine axis (see fig.4).

Table 4. Axial injection characteristics for MEDICYC (deduced from electrolytic tank measurements).

4.2 - Electrolytic tank measurements and final calculations. The structure of the two first R.F gaps has been deduced from the above 2-dimensionnal results, together with the set of initial conditions h = 1 and 2 satisfying a spiral type of inflector and leading to the same entry in the first R.F gap. Whereas the set for h = 2 was exactly the same as in the 2-dimensionnal analysis, the one for h = 1 had to be slightly modified to properly centre the orbit. Because the displacement of the centre of curvature is parallel to the accelerating gap, it was found necessary to bring the second gap, i.e. the equipotentials nearly parallel to the X axis to push the centre of orbit towards the centre of the machine. This shape was obtained by introducing posts in the dee and the dummy dee with the drawback of having fairly large radial electrical field components acting on the trajectory at the exit of the second R.F gap (see fig. 7).

At this stage, this study is dealing only with the central geometry, the ion source and inflector parameters (tab. 4), compatible with all the basic requirements discussed above for an axial injection. A standard high intensity, good emittance ($\varepsilon_N \cong 0.15\pi \times 10^{-6}$ m x rad) duoplasmatron source will be used in this system. Axial injection line based on one (or more) solenoidal coils and one simple buncher, beam transport calculations, vertical motion around the median plane and geometrical as well as phase-energy acceptance calculations, are now undertaken, for this system has to be put into operation by the end of 1985.

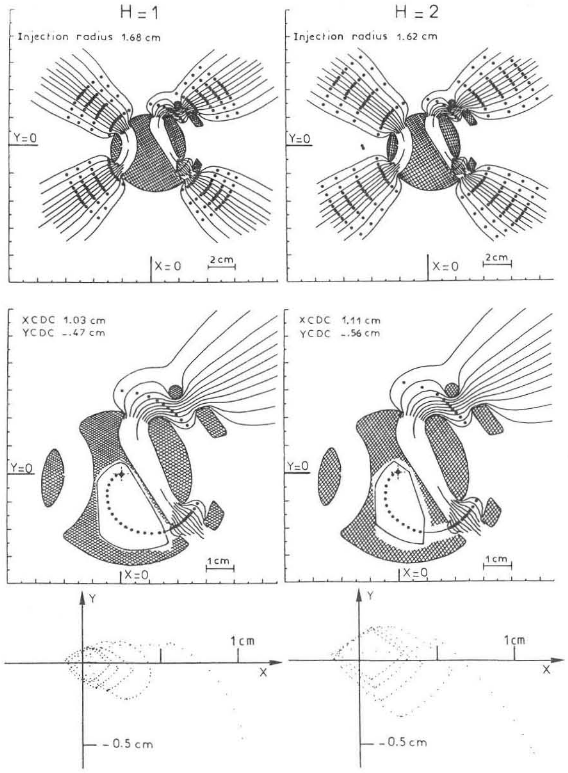

Fig.7 - Reference trajectories for MEDICYC (case h = 1 and 2) as deduced from electrolytic tank measurements and movements of the centres of curvature. The spiral inflectors are represented inside the radiofrequency shield.

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