SPIRAL FACILITY : FIRST RESULTS ON THE CIME CYCLOTRON OBTAINED WITH STABLE ION BEAMS

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Absract : SPIRAL, the R.I.B facility of GANIL, includes in particular a low energy beam transport, an axial injection and a K = 265 compact cyclotron (CIME) allowing to obtain a final energy ranging from 2.6 up to 25 MeV/u using harmonics 2, 3 and 4 (and in the future down to 1.7 MeV//u on harmonic 5).
These equipments are completed and under test with stable ions.
The first part of this paper concerns the results obtained on the equipments. more details on main items (cryogenic panels, R.F system, mass identification,etc...) can be found in specific communications.
The first internal beam was accelerated in dec.97 and the tuning of the machine was resumed after the three months winter shut down. Results and comparison with the calculations will be presented.

1. General description

SPIRAL [1], [2] the radioactive ion beam facility for GANIL is now in final completion and under test with a stable ion beam. Figure1 shows the general lay out:

- The production targets can be irradiated in casemate1 by a wide range of heavy ions of energies up to 95 Mev/u and of expected beam powers up to 6 kW. This beam from SSC2 may be directed toward the SPIRAL target located underground, by means of beam line (HE).
- The radioactive atoms produced by the target are ionized in an ECR source, in order to produce a low energy beam of multicharged radioactive ions.
- This beam is injected into the CIME cyclotron, via a low energy beam line (LE) including an analyzing magnet with a resolution of 200-250, an emittance limitation, a 6D matching to the injection conditions and an hyperboloid inflector.
- The K = 265 compact cyclotron CIME has been designed to accelerate the ions in the energy range of 2.6 to 25 MEV/u according to their Q/A factor. Harmonics 2, 3 and 4 can be used. Harmonic 5 necessitates a modification of the central region, and this possibility will be provided in the future. The average magnetic field has to vary between 0.75 and 1.56 T (see figure 2).

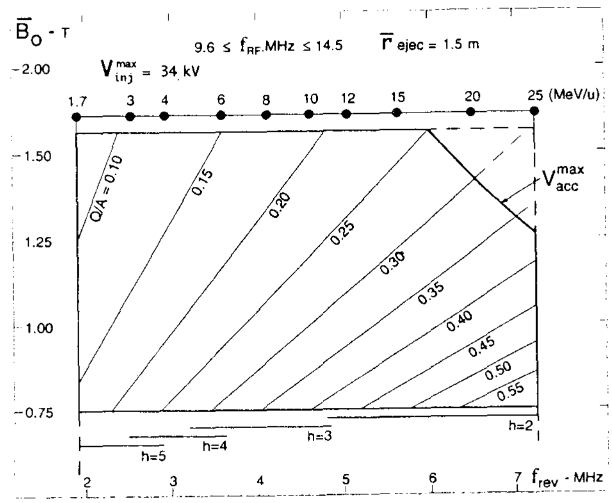

Figure 2 : Working chart

- The beam extracted from CIME is guided toward the experimental area via the medium energy line (ME) including a "S" shaped spectrometer.

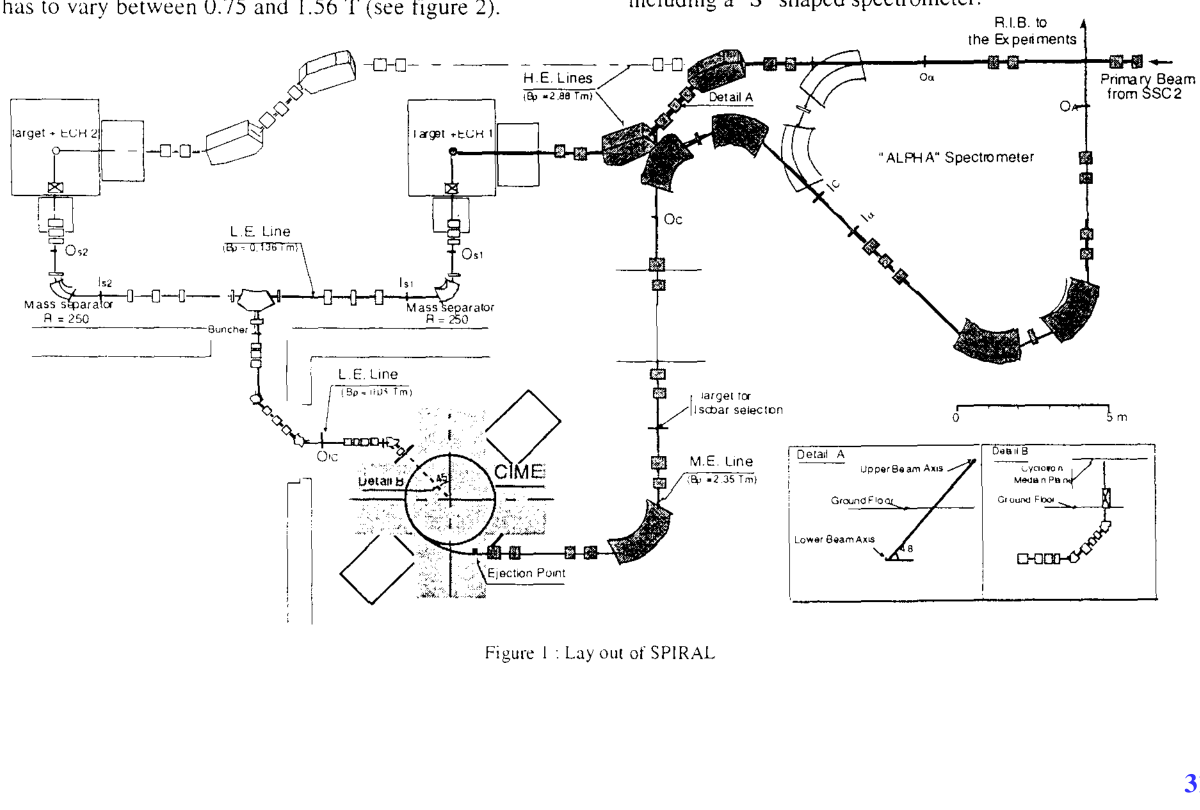

Figure 1 : Lay out of SPIRAL

2. Status of the installation

The installation of the facility was longer than expected due to the lack of people, to the delays on the power-supplies delivery, the compromise with the Ganil operation and so on as shown in table 1.

The LE line and CIME were partly ready in Dec.97 and a very preliminary internal beam was obtained 2 days before the winter shut down, with very poor conditions on the RF voltage. Five weeks have been provided for the tests with a $^{18}O^{4+}$ ion beam before the conference.

Table 1

CIME magnet circuit assembly	mid 96
basic field maps	nov - dec 96
isochronous field maps	apr - may 97
resonators delivery and assembly	may - dec 97
amplifiers delivery and tests	sept - dec 97
ejection elements, probes,	sept.97
cryopanels	nov 97
LE line delivery and assembly	april-nov 97
ECR source	oct.97
Tests with stable beams :	2days dec 97
	april - may 98
Physics with radioactive beams :	april 99

The HE and ME lines will be completed at the end of this year. At this point, the realization of Spiral will be complete for the phase 1. Unfortunately, for administrative reasons, we will not be allowed to deliver a radioactive beam before at least April 1999.

3. Results obtained on the Cime equipments

Figure 3 shows the plan view of CIME.

Most of the equipments are rather classical or already used at Ganil. But some are particular, as the magnet calculated with the Tosca code, the pumping provided by cryogenics panels, the special diagnostics for the measurements of the very low flux expected of the exotic beams, and the central region with its hyperboloid inflector working on 3 harmonics, and its associated dee tips.

3.1 The magnet structure

In order to obtain a compact machine adapted to the present building, and a low cost, an unconventional design was choosen [3].

The magnet (see table 2) is made of 4 individual return yokes and a common circular pole (3.5 m diameter) equiped with four 44° sectors. It was specially designed by us, and machined (by CLI and SFAR companies) to insure the field symmetry and to produce a first harmonic as low as possible (figure 4). Sectors were machined with a 0.02 mm precision in parallelism and 0.05mm on the side profile. The final gap precision obtained is lower than 0.05 mm on the whole useful area.

The magnetic fied calculations were performed with the three dimensionnal code TOSCA [4]. The figure 5 shows the curves of the polar average field B(R) from TOSCA, and the measured maps at 2 levels. The discrepancies do not exceed 0.003 T, except in the central region where the modelisation does not perfecly fit the reality.

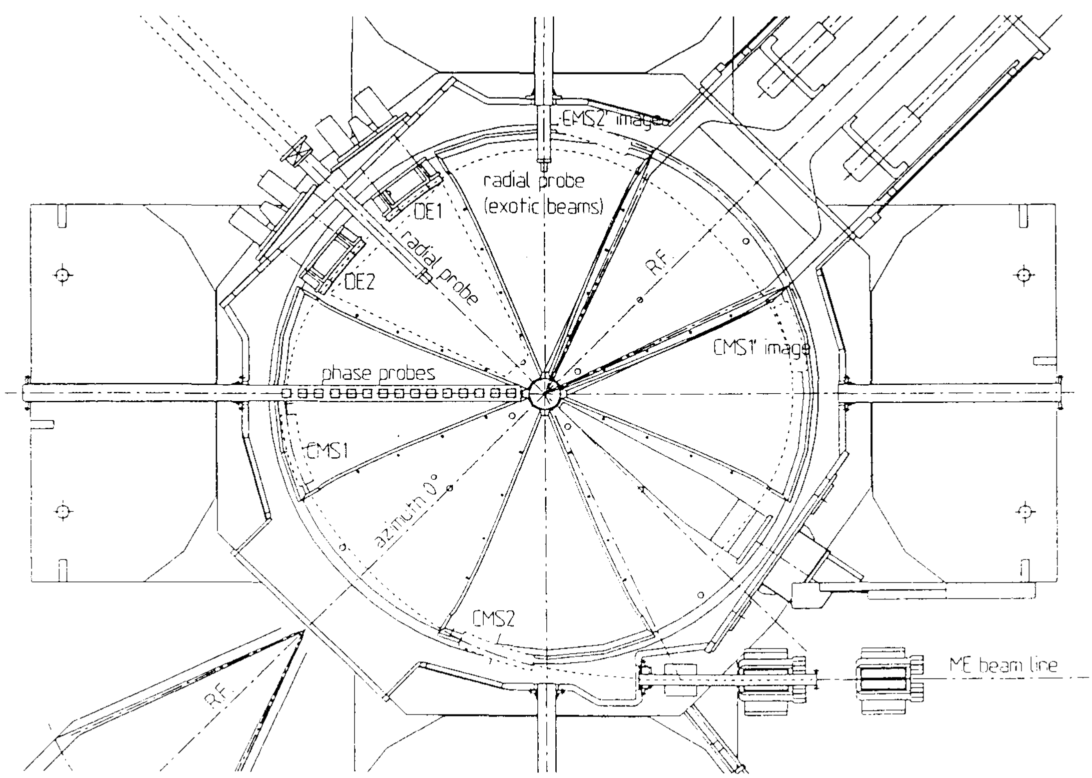

Figure 3 : Plan view of CIME

Table 2

MECHANICAL FEATURES	
Total magnet mass	550000 K
Dimensions : lenght x width	6.4 m x 6.4 m
height	3.2 m
MAGNETIC FEATURES	
Average magnetic field	0.75 - 1.56 T
Max.hill magnetic field	2.1 T
Pole diameter	3.5 m
Hill gap	0.12 m
Valley gap	0.30 m
Damping gap	0.015 m
MAINS COIL (each coil)	
7 double pancakes of 24 turns	
Nominal Amp-Turns	136000 A.T
Nominal current	810 A
Conductor	19 mm x 19 mm
Cooling channel diameter	12 mm
TRIM-COIL (one set)	
Circular coils number	11
Number of turns per coil	8 & 10
Max current	800 A (1 & 2)
	250 A (3 to 9)
	375 A (10 & 11)
Conductors	6.5 x 6.5 mm
Cooling hole diameter	4.5 mm

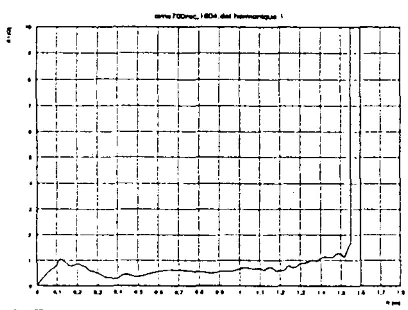

Figure 4 : Harmonic 1 (measured)

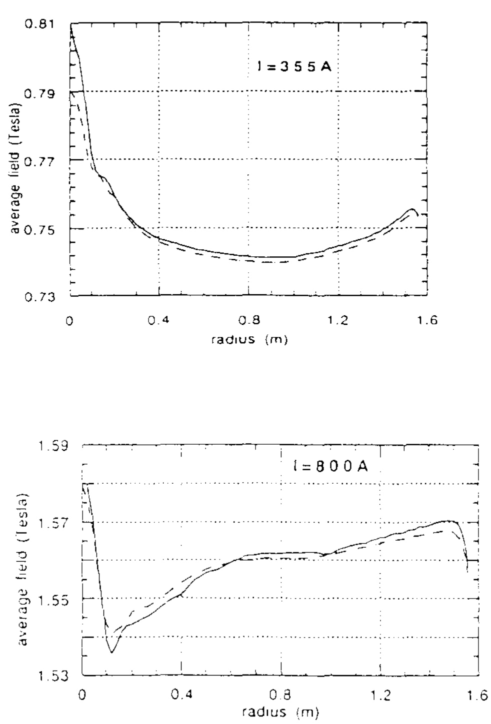

Figure 5 : Average magnetique field
Tosca (dotted line) and measurement

In order to obtain the best isochronism, a set of 10 basic field levels is measured, the trim-coil currents are calculated, then the 10 corrected fields are measured. The synoptic (figure 6) shows the process to obtain a set of currents corresponding to the particle energy and to have only small corrections on-line.

The phase measurements on the accelerated beam(par.5) show that the method is correct

An example of corrected field with the corresponding betatron curves nur-nuz is given (figures 7 and 8).

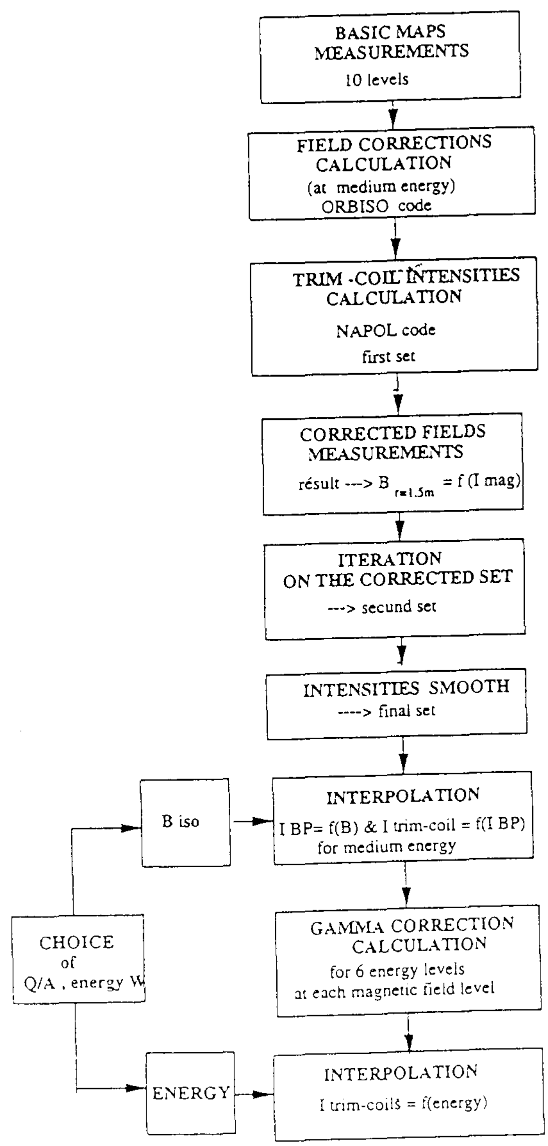

Figure 6 : Synoptic

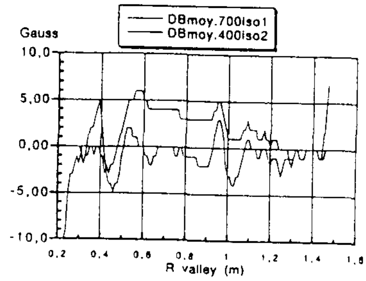

Figure 7 : Difference between B(r) and Biso(r)

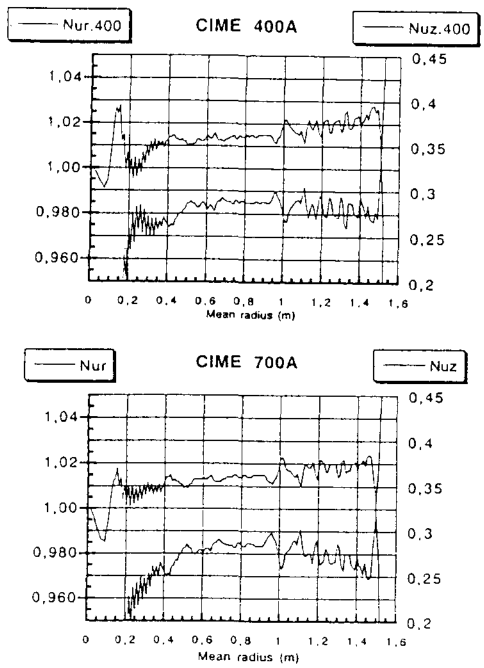

Figure 8 : curves nur-nuz

3.2 The cryopumping

In the CIME design, it was proposed to use a set of 2 cryopanels with a pumping speed of 25000 l/s. They are installed inside the ejection valley in order to obtain a pressure lower than $5*10^{-6}$ Pa. The heat transfer between each cryogenerator and its associated panel is provided by a heat pipe, taking into account the original concept [5] proposed in 89 by S.Bulher and A.Horbowa.

The design and the realization (6) were given to them at IPN/ORSAY while the panels themselves were made at GANIL.

It was an imperious necessity to succeed and this was done.

Typically the pressures obtained in the vacuum-chamber are the following :

10**-5mBar	after 2-3 h (with turbo-mol-pumps)
10**-6 "	2h later
10**-7 "	7h "
4*10**-8	12h "

that means one can use only one panel when there is no charge exchange problem.

It has to be noticed that this vacuum pressure is obtained although many elastomere seals are installed in the machine.

3.3 The exotic diagnostics

For exotic beam measurements [7], the main radial probe is equiped with a plastic scintillator in order to be able to tune the cyclotron with the radioactive beam. Another radial probe, in the hill, is equiped with a Si detector. They were tested with reduced intensity stable beams and provide useful checking of the beam phase (see par 5).

3.4 The R.F resonators

The frequency range (from 9.6 to 14.5 MHz) is limited in order to keep a short coaxial line (1.3m) and to avoid the problems due to a lower frequency. On the other hand, we had to accept the complexity of the injection with harmonics 4 and 5.

The construction and the assembly of the inner line, of the short circuit and of the 40° dees, was subject to tight tolerances [8]. The realization has been made by SDMS company.

An other particularity concerns the dee tips which are removable so that the central geometry can be changed for the very low energy mode in harmonics 4 and 5.

A special care was taken to minimize the vertical component of the electric field on the dee tips : a three dimensionnal code [9] using BEZIER's surfaces allows to compute the total electric field. For reliability reason the initial dee voltage of 90 -100 kV was reduced to 75-80 kV. The 90 kV dee voltage obtained during the tests demonstrated that the prudence was excessive.

4. Simulation of the beam behaviour

The particularity of CIME is to provide the nominal energy range from to 2.7 to 25 Mev/u with only one hyperboloid inflector, MULLER type (having a magnetic radius of 3.4 cm and a maximum injection voltage of 34 kV) on harmonics 2, 3 and 4.

An other hyperboloid inflector, SPIRAL type (with magnetic radius of 4.5 cm) is provided for the harmonics 4 and 5 in order to get the low energy from 4.8 down to 1.7 Mev/u, with the same maximum injection voltage.

The injection conditions are very different for each harmonic, but the 6D beam matching and the quality of the buncher in the LE line make them possible.

4.1 Central Region

The question is : is it possible to obtain a well-centered and matched beam in the cyclotron, on harmonics 2, 3 and possibly 4, with the same geometry, having in mind that :

1) The low energy beam line allows to match the beam in 6 dimensions.

2) But, for an emittance of 80 π.mm.mrad at injection, the radial beam divergence cannot exceed 100 mrad to avoid non linearity phenomenas in the last section of the beam transport.

3) The bunching cannot be too tight.

4) The vertical beam amplitude at the injection has to be limited to 6 mm due to the inflector aperture.

A central geometry (figure 9) was designed in 3D, after a 2D calculation, using the CHA2D and CHA3D codes, to find (by forward and backward iterations), with the LIONS code [9], the 3 central rays corresponding to the same injection point, with a simple rotation of the inflector (figure 10).

- A 60° azimutal extension of the dee tips optimizes the phase in harmonic 3.
- The first trim coil allows to shift this phase for harmonics 2 and 4.
- Posts on the first turn allow to be rather free with regard to the phase focusing for the vertical motion, and also to reduce the transit time on harmonic 4.
- The turn number is different on each mode.

4.2 Beam matching process

Around this central particle (obtained by forward run), at the radius of about 50 cm, a 6D matched beam (10000 ions) is associated (figure 11). The backward run of these particles gives in principle the correlations (r, r'), (r',ϕ), (r, ϕ), (z, z'), (z, ϕ) to realize at the inflector output and allows to define the ellipses at the inflector output.
An other method, used in the phase of the central region design, is to define the ellipses (r, r'), (r',ϕ) with 12 particles at the inflector output and to observe, for each particle, the barycentre of its orbit after a few turns. The beam is nearly matched when the barycentres are located on a circumference which the radius is equal to the amplitude of the matched beam, i.e 1.65 mm for an emittance of 80π.mm.mrad at the injection.

On harmonic 3, the matching conditions can be perfecly realized by the LE line. We find :

- a maximum radial divergence r' max of 57 mrad
- a maximum radial envelope r max of 1.7 mm
- a phase extension ϕ_0 of 4°
- a maximum vertical envelope z max of 5 mm.

In these conditions, as the turn separation is about 2.8 mm at the ejection, the simulated beam, can be ejected in 3 turns as follows :

- 89 % of the particles in the second turn
- $\pm$ 0.5x10^{-3} for the energy spread.
- $\pm$ 3° for the phase extension.

On harmonic 2, the matching conditions are different : the beam radial divergence increases up to 130 mrad, that exceeds the possibilities of the LE last section. The limitation to 100 mrad obliges to accept a not perfectly matched beam. Nevertheless, the simulated beam shows that the ejection in 3 turns remains possible and not too bad since the total energy spread does not exceed $\pm$ 3x10^{-3} with about $\pm$ 1.2x10^{-3} for the second turn.

With the harmonic 4, the transit times in the first gaps give some non-linearity effects.

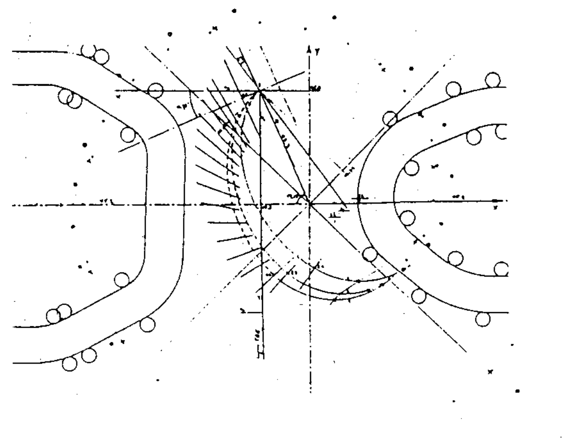

Figure 9 : Central region with the 3 rays (H = 2, 3, 4)

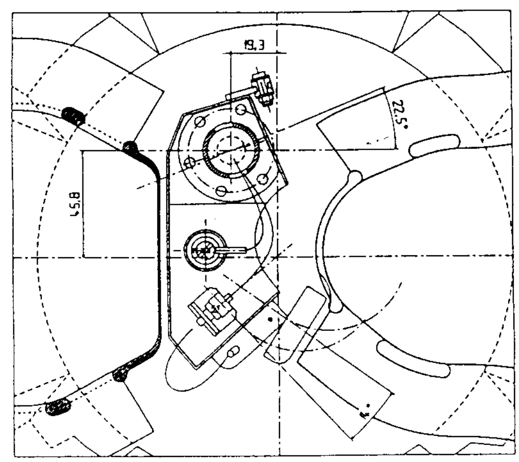

Figure 10 : Plan view of the central region

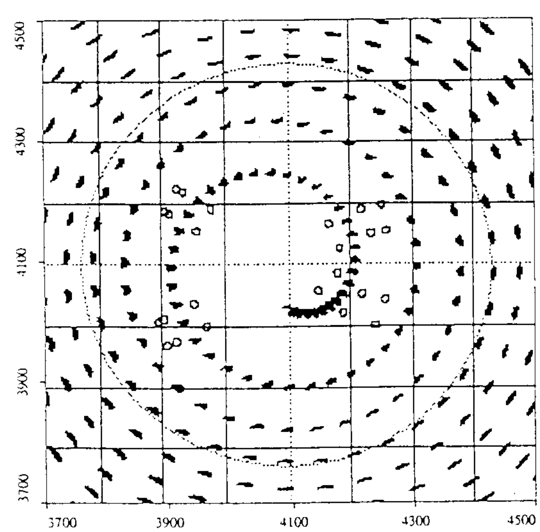

Figure 11 : Backward run of the matched beam H3

5. Experimental results

The first beam tests were done on the harmonic 3 at 2 different field levels (1.4 and 1.0 T), at a same frequency of 14.4 Mhz corresponding to an energy of 10.8 Mev/u, with respectively a $^{18}O^{4+}$ and a $^{16}O^{5+}$ ion beam.

5.1 Transmision in the LE line

The following values are routinely obtained :

- a transmission of 80% in the first analyzing section with the emittance limitation to 80*80Pi.mm.mrad in both planes.
- a transmission of 92% in the matching section up to the cyclotron.

These values are obtained with the calculated gradients providing the focusing as shown figure 12,

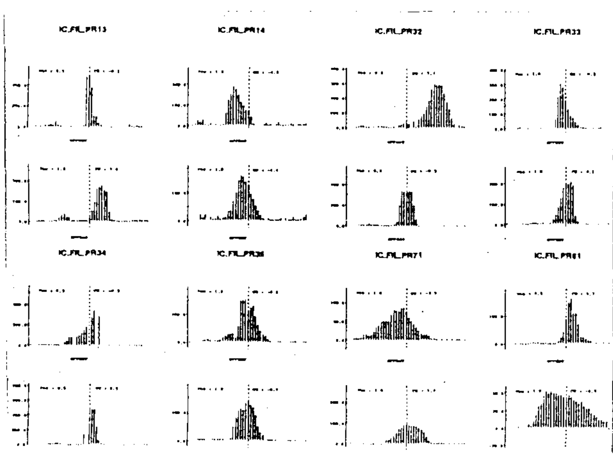

Figure 12 : Horizontal and vertical focusing on the wire probes (LE line)

excepted for the first section which must be matched to the particular source conditions. The shift on the first probe in the vertical plane comes from the source extraction and cannot be fully cancelled with the steerer magnet of the line. That means the first section transmission value can be improved.

Typically, the injected currents are limited from 500 to 900 nAe according the limitation of 10**11p.p.s when the cyclotron energy is >1Mev/u, given by the Nuclear Safety Authorities.

5.2 Tests at high magnetic field level

The first beam tests were done at 1.4 T (687 A in the main coils) with a $^{18}O^{4+}$ beam.
The figure 13 shows the currents measured on the valley radial probe after tuning.
It calls for the following remarks :
The first one is that the beam does not reach the ejection radius of 1483 mm and stops at the radius of 1420 mm and this is presently our main problem.
The other comments are rather sastifying :

- The isochronism is obtained by changing only by 0.13% the main coil current with the trim-coil calculated values. Figure 14 shows the phase measurements on the 15 phase probes (the last one does not receive the beam).

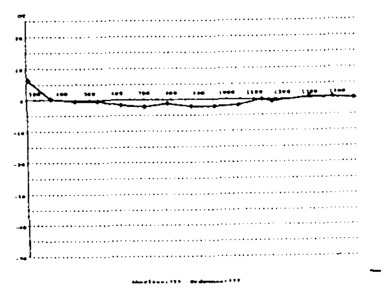

Figure 14 : Phase measurements (B = 1.4 T)

- The thirty first turns of the central region are found at the calculated positions after a tuning of the dee voltage (52 kV) and the inflector position does not require to be moved from its theoretical value.
- The turn separation as a function of the turn number is linear on the range up to a radius of 900mm where it is possible to count the turns.
- The precession is mainly induced by the dee voltage dissymetry (about 10%). It is reduced by applying a difference of 7% between the 2 dee voltages, but does not disappear. Many attempts show that the precession is not due to the axial injection parameters.
- A small betatron dismatching is superposed to the precession.

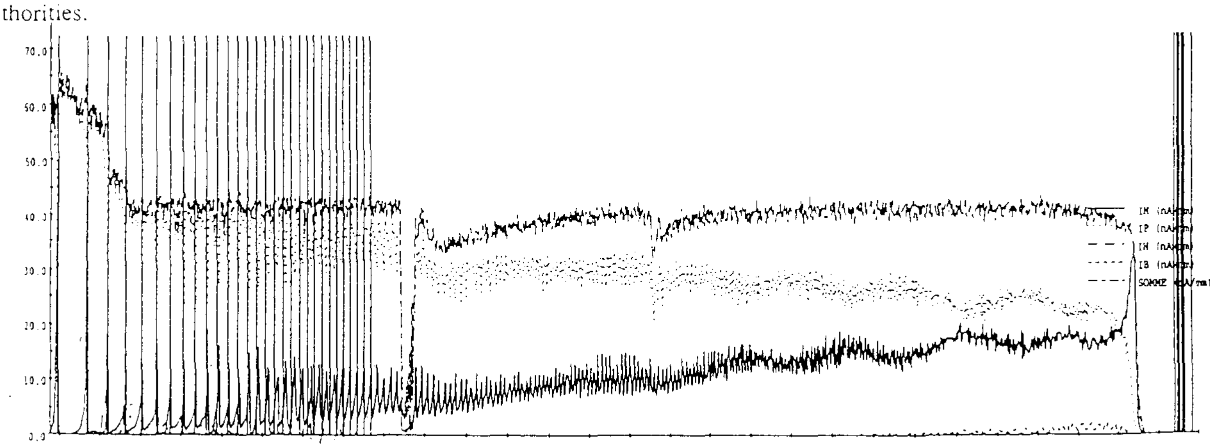

Figure 13 : Turn distribution on the differential fingers and the total beam (B = 1.4T)

- Concerning the vertical motion, not any significant current appears on the upper and lower fingers during the acceleration, except on the first turns. This is due to a small vertical misalignement.

- The optimization of the cyclotron transmission is obtained in modifying the matching section (about 10% on the solenoid through the axial fringe field which has not been measured).

This modifcation does not affect the initial LE line transmission, but means that the matching, in particular in the vertical plane, ask for improvement.

Finally, the measurements of the cyclotron transmission give :

- without buncher :	7 to 8%
- with buncher :	38%

5.3 Test at low magnetic fied level

At the low field level (1.0 T with a $^{16}O^{+5}$ beam at Vdee = 38 kV), the results are very similar as showed figure 15, with the corresponding phase shift (figure 16).

The matching being improved, the efficiency of the cyclotron is better than the previous value at 1.4T :

- without buncher :	10%
- with buncher :	53%

5.4 Beam loss

These results are rather good and in agreement with the computed values. All our efforts were carried on the problem of the sudden beam loss which has been observed before the ejection radius.

Several hypotheses for the beam loss have been examined : magnetic perturbation, resonance, isochronism, median plane. It should be noted that the magnetic measurements previously made, show an almost perfect regularity of the field. Therefore we have in mind that a strong magnetic perturbation has been somehow introduced. And in the present time, we are not in position to control any harmonic 1, because the power supplies of the harmonic coils are not already installed.

The magnetostatic channels CMS1, CMS2 and their symetric images were removed and of course the isochronism corrected. As this action was without effect on the beam loss, the isochronism was checked using a plastic scintillator dedicated to the radioactive beam. This measurement (5) had the additional advantage to give the bunch phase width value of 18° at $\pm 2\,\sigma$ (figure 17).

At last, with the hill radial probe and the main probe, we used the good old "shadow method".

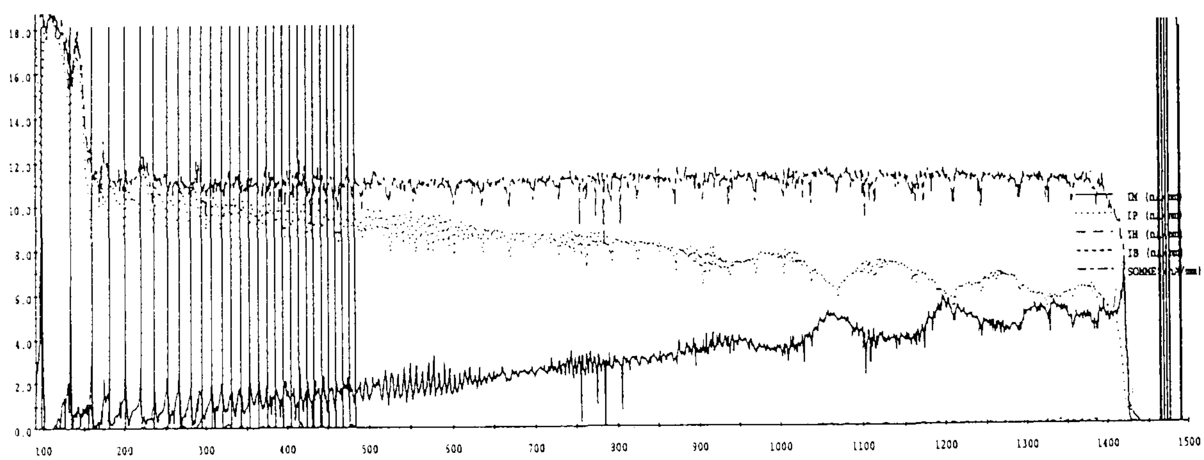

Figure 15 : Turn distribution and total beam (B = 1.0 T)

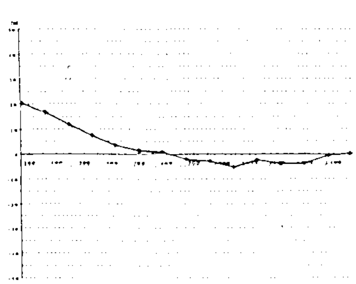

Figure 16 : Phase meassurements (B = 1.0 T)

The figure 18 shows the shift between the theoretical value of $R_{Hill} - R_{valley}$ and the measured one. The precession observed remains very smooth up to the hill radius of 1200 mm with an amplitude of 5 to 6 mm.

A third probe, at the entrance of the magnetic channel CSS2 showed large otbit shifts at higher radius.

Simulations show that this effect can be produced by a harmonic 1 of about 10 Gauss.

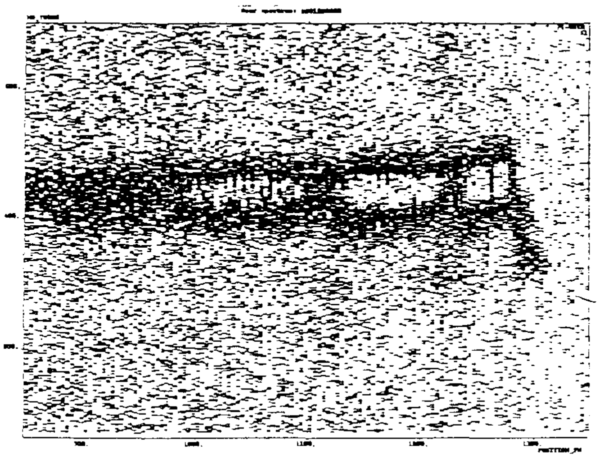

Figure 17 : Measurement of the isochronism with the plastic scintillator

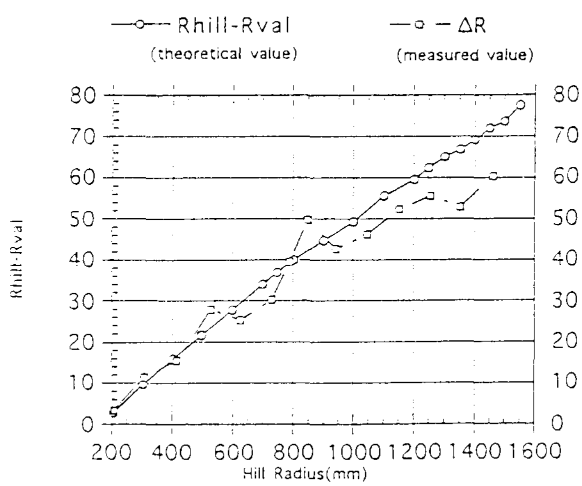

Figure 18 : »Shadow » method

Tests showed a good reproductibility of the beam and a fine stability of the machine. When the problem of the beam loss will be solved, we will test on the machine the shift from a stable ion beam to an exotic beam by a frequency or magnetic field variation. For doing so, we will first operate the machine using two beams of stable ions produced simultaneously by the source. The fact to have obtained the beam without tuning the trim-coils allows to be rather optimistic.

6. Conclusion

CIME was designed in using the splendid possibilities of the modern codes and in having in mind that the cyclotron qualities are those defined by its magnet, its central region, and its vacuum pressure.
Without TOSCA, it is not sure that we would have undertaken this type of magnet. The magnetic measurements are still necessary to control the quality of the realization of the magnet and its coils.
On the same way, a set of codes allows to optimize the central region and its complex axial injection, but this requires to have a man with the "feeling"as Charles Ricaud has, in order to be sure that, after many simulations, the tuning will be easy. The 6D matching is utterly difficult to achieve in operation without a proper simulation.
At least, something that does not owe to the computers, but all at the experiment, the cryogenic panels bring a new and an ideal solution for getting a good and clean vacuum in the accelerating chamber of the cyclotrons.
Finally, if the extraction of the beam is successfully achieved, CIME will be a good machine.

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