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SPIRAL FACILITY : BEAM DYNAMICS AND EXPERIMENTAL TESTS WITH STABLE IONS

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Abstract

SPIRAL, the R.I.B. facility using the ISOL method at GANIL, includes a high energy primary beam transfer line, a target ion source system, low and medium energy secondary beam transfer lines and a K265 compact cyclotron (CIME) giving a final energy adjustable from 1.7 up to 25 MeV/u using RF harmonics 2, 3, 4 and 5.

Until the administrative authorisation to produce radioactive ion beams is obtained, about 650 training hours have been allocated to reach the required beam quality with stable ions. Three directions have been carried out during these last three years in order to produce different ion beams and cover entirely the working diagram, simulate the tune shift of CIME and its injection beam line from a stable to a radioactive beam using magnetic ΔB/B or frequency ΔF/F correction with two close stable ions, improve more deeply injection and extraction settings of CIME.

This paper presents significant experimental results and encountered disagreements on beam 6D matching with the SPIRAL facility just before its official start-up.

1. INTRODUCTION

SPIRAL, the GANIL radioactive ion beam facility began its test period with stable beams in 1998 and was presented at the last International Cyclotron Conference[1]. Due to the delay to obtain administrative authorisations to produce radioactive beams[2], we carried out up to now all the tests with stable beams. The main goal was to accelerate typical beams to check our capability to cover the whole SPIRAL working range, taking into account parameters issued from our simulations to match these various beams[3], and prepare the facility to master more conveniently the acceleration of radioactive beams.

2. EXPERIMENTAL RESULTS

CIME cyclotron has the particularity to provide a large energy range using only two different central geometries. High energy beams (from 4.8 to 25 MeV/u) are injected with an hyperboloid Muller inflector (34 mm magnetic radius) through a 60° azimutal extension of dee tips for RF resonators, and accelerated using harmonics 2 and 3. To obtain low energy beams (from 1.7 to 6 MeV/u), we use an hyperboloid Pabot-Belmont inflector (45 mm magnetic radius) with 40° azimutal dee tip extensions and accelerate them using the harmonics 4 and 5. The main difference between these two states is the lower mass resolution CIME can achieve in the low energy mode. To partially compensate for this limitation, we have shown that it is possible to use the 4th harmonic with the small injection radius. *Figure 1* illustrates the stable beams we have accelerated, extracted from CIME and analysed.

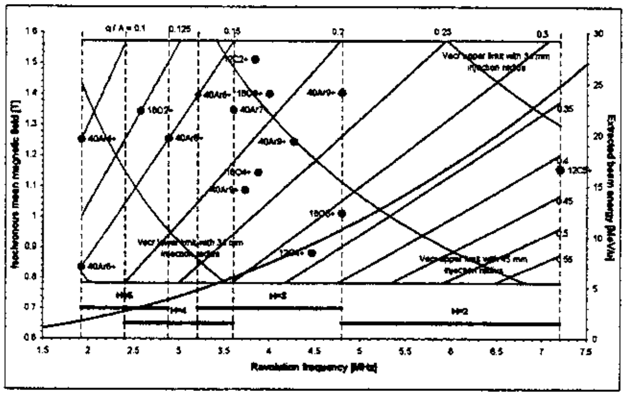

Figure 1 : Working diagram of CIME

2.1 Harmonic 2 results (34 mm injection radius)

A 25 MeV/u $^{12}C^{5+}$ was chosen to validate both the H=2 mode and the radiological shielding. Since computations of injection conditions are not satisfactory, we have injected this beam with extrapolated harmonic 3 conditions. However the resulting 12% global efficiency, between analysed source beam and CIME extracted beam has still to be improved (mainly through CIME extraction).

2.2 Harmonic 3 results (34 mm injection radius)

We have performed a great number of beam tests on harmonic 3 to validate the isochronism data fields and the injection matching conditions at different field levels and different frequencies. *Figure 2* illustrates the typical evolution of turns inside CIME on that harmonic.

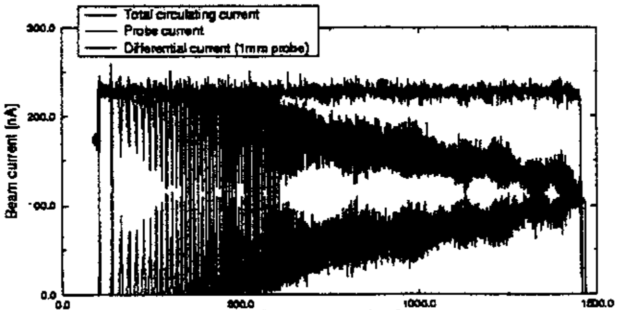

Figure 2 : $^{18}O^{4+}$ beam at 14.4 MHz on harmonic 3

Typical efficiencies obtained are in the order of 40 %, shared in 65 % at injection and 65% at ejection. If the injection efficiency reached the theoretical limit of our linear buncher, we should certainly increase the extraction one in the future with a better matching of injected beam. As it can be seen in *Figure 2*, a betatron oscillation is still existing in the cyclotron.

2.3 Harmonic 4 results (45 mm injection radius)

Working on harmonic 4 with a 45 mm injection radius appears really easy for CIME. Higher injection energy, lower number of turns and the help of an electrostatic quadrupole at the exit of the inflector make the matching of the beam easier. *Figure 3* illustrates a typical profile of acceleration on that harmonic.

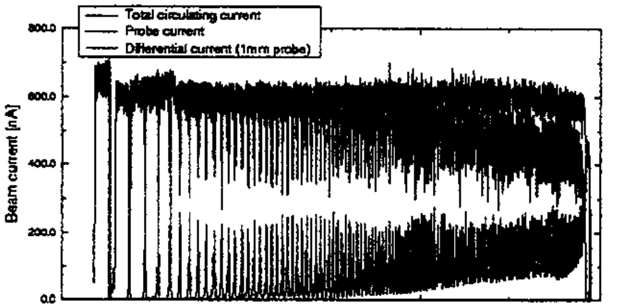

Figure 3 : $^{40}Ar^{6+}$ beam at 11.52 MHz on harmonic 4

Typical transmission from the analysed source beam to the extracted one is about 50% (65% at injection and 85% at ejection). The turn separation at extraction is sufficient to have an almost single-turn extraction.

We also tested CIME behaviour on harmonic 4 with the 34 mm injection radius to increase the mass resolution in this domain of the diagram. Results are encouraging but we still have to improve the injection parameters.

2.4 Harmonic 5 results (45 mm injection radius)

We accelerated only two different beams at the lowest energy of the CIME working diagram. As predicted by computations, the global efficiency of SPIRAL facility in that domain is low (about 15%). Theoretical injection conditions are impossible to be perfectly performed so that we obtain experimentally only a 50% efficiency. We will certainly increase this transmission but the major work on that harmonic 5 will be to improve drastically ejection matching, so as to reach the predicted global efficiency of 25%.

3. ENCOUNTERED PROBLEMS

3.1. Source extraction

The first section of the SPIRAL low energy beam line must at the same time guide the ion species extracted from the Nanogan ECR source and perform the transverse betatron matching. We use two electrostatic Einzel lenses positively polarised close to the extraction electrode and three quadrupoles located beyond the wall of the shielded cave (more than 1 meter). Experimentally, we never have obtained an appropriate alignment of the beam in this section. We estimate a resultant defect of approximately 10 mrad at the extraction electrode level (probably due to a magnetic asymmetry of the source fringing field). As we have to work at very low energy (10kV < Vecr < 34kV) and with a long lever arm, any misalignment of the beam at the source level is dangerous because it is easily amplified by electrostatics lenses. The direct consequence is that the first order elements (lenses and quadrupoles) are mainly fixed by the zero order conveniences (alignment) and the betatron matching is not well fulfilled. So we observe that a beam cut at 80 π.mm.mrad by emittance slits appears with only 60 π.mm.mrad at the object point of CIME, but it is not critical for injection as this beam is still contained into the 80 π line acceptance. A second disagreement arises from the too low divergence of the beam extracted from the source. Positively polarised Einzel lenses must work with a high divergence at the entrance in order to be efficient. In consequence, the first electrode has no action, so we lose one optical matching parameter.

The present solution to overcome these two problems is to polarise negatively the first Einzel lens, leaving the second one positive. This polarisation increases the beam divergence at the entrance of the second lens, which permits a better focusing efficiency, and limits the misalignment due to the fringing field of the source. We obtain a good compromise but we need a better understanding of the source extraction to improve the low energy beam line matching.

3.2. Fringing magnetic field at CIME injection

The last section of the low energy beam line is devolved to the 6D matching at CIME injection using separated functions. It is ended with the hyperboloid inflector whose entrance is just located at the edge limit of the fringing field of CIME cyclotron along the vertical axis. These separated matching functions give us a 70% possible injection efficiency which is only reachable in practice if a precise computed solution is given. However, to allow us a beam injection on the whole CIME range with a so low source energy (small injection radius), an off-centred injection point has been chosen. It results in a non axially symmetric fringing field along the injection axis and, at the entrance of the inflector, transverse magnetic components are of the same order as axial ones. Therefore the beam crosses over transverse steering forces in a region where no control is possible, so non-linear effects are present in the transfer through the inflector that we can't take into account in the calculations of the 6D first order injection matching.

During experimental tests, we have observed that it was necessary to misalign greatly the beam in the injection line to inject ions correctly (following in that way the optic axis of the fringing field of CIME). As a result, the inflector does not deliver the beam in the cyclotron with appropriate conditions in position. As a consequence, we have shown that a part of a permanent precession of dynamics inside CIME was due to that injection default.

We have tried to compensate this zero order effect with modified inflector electrodes but it appears not to be the best solution. To palliate more efficiently this problem, we computed a different using of the inflector : we accept the misalignment inside the inflector but we minimise it by adjusting the injection energy and the magnetic field in the central region (the first isochronism coil affects only the central region). Of course, we don't inject at the required radius but we limit the zero order default inside CIME. We succeed in obtaining a beam with a really small precession using this solution and the 6D matching of the injected beam appears to be sufficient for the required injection efficiency.

3.3. Harmonic 1 component of CIME main field

At the time of the first tests with CIME, the accelerated beam was abruptly lost few centimeters before the ejection radius. It was impossible to explain that without adding an important harmonic 1 component in the magnetic field maps used for numerical simulation. But no control of the field pattern of CIME showed that failure. Nevertheless we succeeded in extracting the beam by applying experimentally a magnetic compensation using return yoke coils which balance the East/West sector field. We finally found the origin of this CIME magnetic field error after performing coupled mechanical and magnetic measurements under vacuum. The magnetic forces, under atmospheric pressure, ensure a quasi perfect forth order field symmetry. But under vacuum, the added constraints induce an abnormal deformation of the pole, due to the asymmetric design of the vacuum chamber, especially near the extraction flange (West sector) and create an harmonic 1 component. *Figure 4* illustrates that effect showing the imbalance of the magnetic field measured on these two opposite sectors when we add vacuum constraints to the magnetic ones.

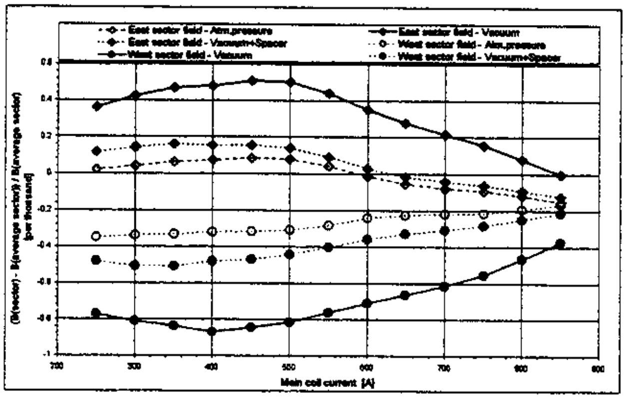

Figure 4 : Vacuum effect on CIME magnetic field and compensation due to the spacer compared to reference atmospheric pressure measurement

This figure shows also the effect of the mechanical compensation of the asymmetry of the vacuum chamber. To limit the current to be applied on the compensative coils, we have installed a stainless steel spacer at the opposite side (East sector) of the extraction exit. Its effect is to force an equivalent deformation of the pole in the East region to transform the harmonic 1 component into an harmonic 2 under vacuum constraints. To match the centring of the beam in the cyclotron, we have just now to perform a small dynamic compensation by exciting return yoke coils.

As illustrated by *Figure 5*, the barycentre of each turn, with these compensations, is well centred in comparison with the initial ones.

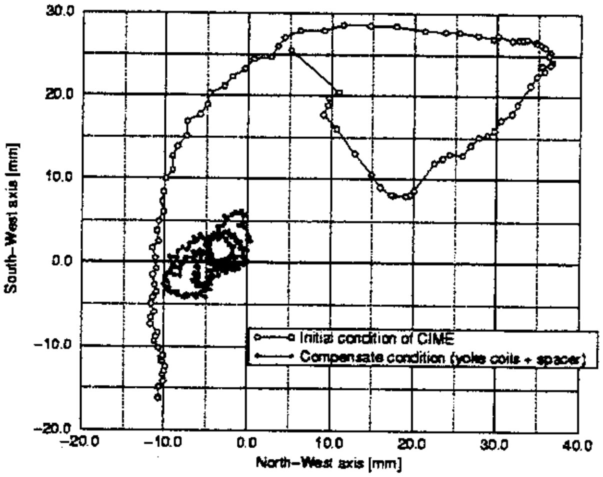

Figure 5 : Evolution of turn barycentres inside CIME

4. CONCLUSION

During the last three years, we have met and overcome several theoretical and technical problems and now the SPIRAL facility is able to produce the majority of the expected beams with the required quality.

We have now to go deeper into injection and ejection parameters by improving computations taking into account the experience acquired to extend the best reachable efficiency to the whole working diagram. As passing from stable to radioactive beams does not seem to be too difficult with the CIME compact cyclotron, we wait with confidence for the administrative authorisations to start up although the high energy beam line (transporting the GANIL beam to SPIRAL target) still has to be tested.

5. REFERENCES

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