NEW DESIGN FOR THE OLD CYCLOTRON OF SARA

S. Albrand, J.L. Belmont, M. Fruneau, A. Khallouf
Institut des Sciences Nucléaires
I.N2.P3
53 Avenue des Martyrs
38026 Grenoble Cédex - FRANCE

The first cyclotron of SARA is compact and had dee angles of 80°. The beam had a poor stability in RF harmonic h = 3. Recently, the machine was stopped for 5 months to improve its performances. We modified the dee angle by translating the present dees by 80 mm along the axis and by adding new tips with an angle of 60°.

We use exclusively the external E.C.R. source. The matching of the central region is obtained by injection in the first dee for h = 2 and in the 2nd dee for h = 3 : the 2 particular gaps associated with each harmonic allow centred orbits to ± 25° RF phase.

We have also improved the magnetic shimming of the poles and the extraction. ν_r is very close to 1 for the heaviest ions and even with a first harmonic of magnetic field as low as 0.5 gauss, radial oscillations appear at large radii.

Nevertheless the machine has now an improved reproductibility and we obtain an efficiency of 15 % between external beam of the source and the extracted beam even in harmonic 3.

Introduction

SARA (Système Accélérateur Rhône-Alpes) was presented at the last Conferences on Cyclotrons at CAEN and East-Lansing[1].

It is a two cyclotron accelerator.

The second accelerator (K = 160) has four separated sectors. Its first beam was accelerated in March 1982 at the nominal energy of 30 MeV/amu. The beam, which comes from the first cyclotron, is stripped before injection. The first cyclotron, compact, with an azimuthal varying field, is 20 years old.

Originally designed for light particles (with K ⩽ 60 MeV), the operating range of this cyclotron has been extended to heavy ions by a PIG internal ion source, (1974) and now with K = 88 MeV, it has been routinely operated (since September 1983) with the ECR MICROMAFIOS source designed by R. GELLER.

This has made available heavier ions and it was interesting to improve the performance of the first machine in RF harmonic 3 in order to accelerate them more efficiently : the operation of a compact cyclotron in harmonic h = 3 is well-known to be delicate if the dee angles are close to 90° and they have 80°[2]. Instabilities appear when there is an off-centring of the beam in the direction of the axis of dees. This off-centring leads to a large phase difference which in turn augments the off centring.

Unfortunately an improvement in the acceleration of heavy ions with h = 3 can only be obtained at the expense of operation in h = 1, used particularly for protons above 18 MeV. It was decided that SARA should become principally a heavy ion accelerator. Thus the machine would be required to function best with h = 2 and h = 3 and it was necessary to redesign the centre.

Computer simulation predicted that the instabilities, disappear if the dee angles are changed by translating the 80° dees by 80 mm along their axes and by adding new tips with angles of 60°. Moreover this solution does not affect operation in h = 2. The gain in energy per turn for protons above 18 MeV with h = 1 is diminished by about 25 % however.

I) The new configuration at the centre

I-1) Methods of calculation

Instead of deriving the measured equi-potentials to integrate the equations of motion the method uses measurements directly.

The programs AGORA and AGOVER use this principle[3]. The programme "Centre" written at Grenoble also uses this method.

We can suppose that the gap between dee and dummy-dee is decomposed into n micro-gaps, and that each of these micro gaps has constant electric field $\vec{E}_i$ and magnetic field B_i inside this micro-gap. The motion is obtained analytically. The equi-potentials in the region of the passage of the beam are given analytically in parabolic form.

For the determination of the electric field one searches for the points P_i and P_{i+1} where the trajectory leaving the micro-gap (i-1), inside the electric field E_{i-1}, would cut the parabolas i and (i+1) if E_i was null (or was E_{i-1}). The tangents at these points give a mean value for E_i and one can then recalculate the path with this value. The error in E_i is small and little is to be gained from an iteration.

Evidently, the overall precision of the calculation and the time needed depend on the value of n. An optimum value was found to be 11 equipotentials. With the exception of the first and last they are regularly distributed in value. We determined the positions of equipotentials in an electrolytic tank.

The directions of the axes of the first gaps are extremely important as they permit the fine adjustement of the centring of orbits at the inflector. The computer codes for calculation of the centre permit the local modification of the topography of E (translation, rotation, change of scale of the gap, etc...).

The centring and the vertical motion have to be studied together.

With measurements made in the median plane alone one can use equations for the vertical focusing similar to those of R. Cohen[4] (see annex).

The knowledge of the analytic expression of the equipotentials which are parabolas in the median plane leads to a simple numerical integration.

I-2) Chosen design

The tips of the 2 dees were changed and adapted to the inflector of axial injection. We suppressed the internal ion source.

Only one inflector of spiral type is used but ions are injected into dees 1 or 2 for harmonics 3 or 2 respectively. It is vertically introduced.

For each harmonic we have 2 particular gaps.

The first gap focuses the beam at the exit of the inflector.

The 2nd gap, a vertical slit, has a strong radial focusing effect and provides a large phase width to be accelerated.

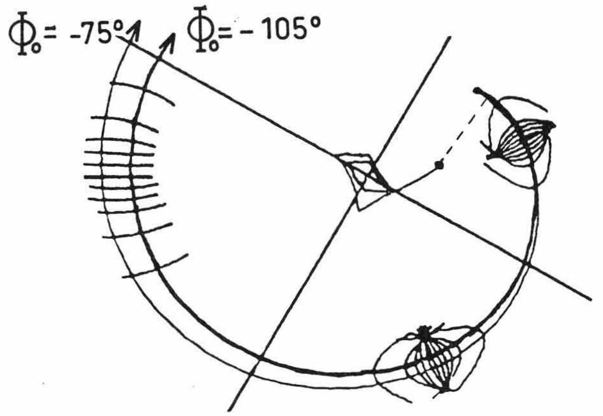

Fig. 1 : Display of the first half orbit through the 2 first gaps, movement of the orbit center (h = 2).

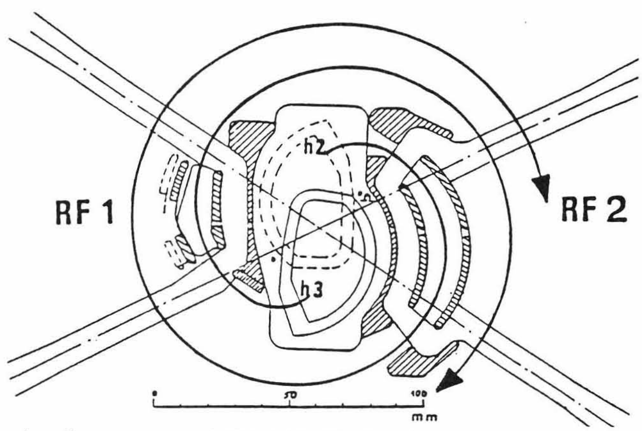

Fig. 2 : Lay-out of the central region.

We found a well centred beam (± 1 mm) for a range of RF phase close to 60°.

For h = 1 we use the h = 2 position and the beam passes through slits reserved for h = 3 ! (in this case K < 25 MeV).

I-3) The experimental results

The improvement is spectacular with the RF harmonic h = 3. The variation of the beam current on a differential probe in function of radius shows that there are no oscillations at the centre, for the turns are now well separated (fig. 3). Before the modification we were never able to obtain this fine structure.

The yield at the injection between the external and internal beams exceeds 25 %.

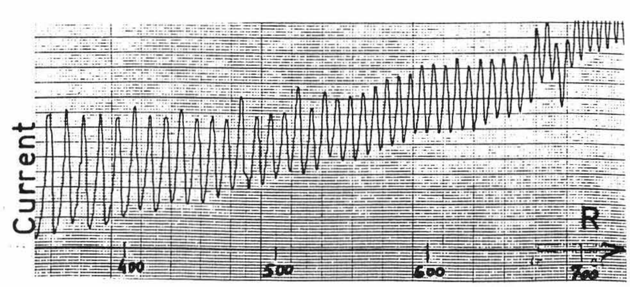

Fig. 3 : Differential probe plot showing centring.

II) The effects of harmonic 1 on the internal beam

II-1) It is well-known that the acceleration of heavy ions in a compact cyclotron is not to be recommended, since ν_r is always in the neighbourhood of 1 ! Having obtained a well-centred beam,we hope to be able to continue by a serene acceleration. It turns out that one of the biggest factors to be avoided is a first harmonic in the magnetic field. An example follows.

We have investigated the effect of a first harmonic on the acceleration of a well-centred particle, using the simulation program ANJO[6]. From our magnetic field maps our program reconstitutes the magnetic field of the cyclotron over 360°,including the effect of the trim coils and the harmonic coils[7].

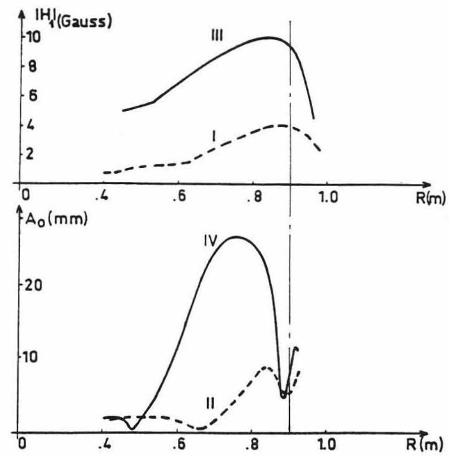

Fig. 4 : Oscillations induced by 1st harmonics of field.

Figure (4) shows some results for the ion $^{20}Ne^{6+}$ (K = 61 MeV). Curve (I) shows the amplitude of the first harmonic of the field and (II) the amplitude of the oscillation about an ideal trajectory (a monotonic increase in radius with respect to the number of turns), when the harmonic coils are off. The origin of the first harmonic is the imperfection of the principle magnet (Fig 7). Curves (III) and (IV) are the equivalent curves when one of the harmonic coils has a large arbitrary negative value. The catastrophic effect is clear : in the latter case many turns will become mixed.

The simulation program has also shown that if the odd harmonics are removed from the field,then the particles do not oscillate. To achieve this we used only half the measured field and set $B(r, 180 + \theta) = B(r, \theta)$: $0 < \theta < 180°$.

Thus it is useless to centre the beam if we have no knowledge of the first harmonic of the field in the operating conditions for heavy ions. The translation of the dees implied the modification of the passive magnetic channels at the extraction. The installation of dummy-channels in symmetric positions has been shown to be almost essential.

II-2) Magnetic field measurements

Five months shut down of SARA were necessary for modifying the machine. That enable us to undertake a programme of magnetic field mapping. We used an apparatus consisting of a bar on which 27 Hall probes are fixed with a spacing of 0.02 m. The bar is manually positionned to a fixed azimuth by means of a dowel in precisely drilled holes (every 2°) in a plate fixed on the pole face.

The whole data acquisition was controlled by a single board computer with a 68000 microprocessor . Each probe was calibrated in situ at 27 field levels against a NMR probe. A polynomial law (6th order) is deduced by means of a min-max algorithm.

For speed, we used an azimuthal step of 4° and afterwards an interpolation by a "spline" function to provide other points. This procedure, although satisfactory, is far from ideal, and it would have been preferable to use a smaller azimuthal step, but it was imperative to complete the measurements on time. Four different excitation levels of the main magnet were used. For each one we measured the complete field over 360°, the effect of the trim coils and the effect of the harmonic coils.

Our preliminary measurements revealed that one of the four sectors of the magnets contained a large field "hollow" in a region not covered by correcting coils, and these defects depend on the level of magnetic field. Thus it became essential to calculate a shim to remove the faults.

We estimate that for K = 70 MeV, an iron shim 0.35 mm thick over an angle θ° on the sector would correct the first harmonic. We measured that the average correction $<\Delta B_{90}>$ of the average magnetic field $<B_{90}>$ on 90° by the shim on θ° is :

$$<\Delta B_{90}> \cdot (90^\circ) = (\Delta B_\theta) \cdot (\theta^\circ)$$

and

$$\theta = 7.4\ 10^4\ (<\Delta B_{90}>) \ / <B_{90}>$$

These simple formulae permit the calculation of the first shim. With this shim in position we obtain a second field map, we then perform a Fourier analysis on the two measured fields. We obtain, for each radius, $\vec{V}_0$ and $\vec{V}_1$, vectors representing the first harmonic in the field, without and with the shim, respectively.

For a given radius, the effect of the first shim is :

$$\vec{S} = \vec{V}_1 - \vec{V}_0 \quad (1)$$

We wish to calculate a better shimming to remove the initial harmonic $\vec{V}_0$.

One part ($\vec{S}'$) of the second shim will be in the same direction, as the first, so that :

$$\vec{S}' = f\ \vec{S} \quad (2)$$

The second part ($\vec{P}$) for an adjacent sector will be perpendicular, with :

$$\vec{P} \cdot \vec{S} = 0 \quad (3)$$

and

$$\vec{S}' + \vec{P} = - \vec{V}_0 \quad (4)$$

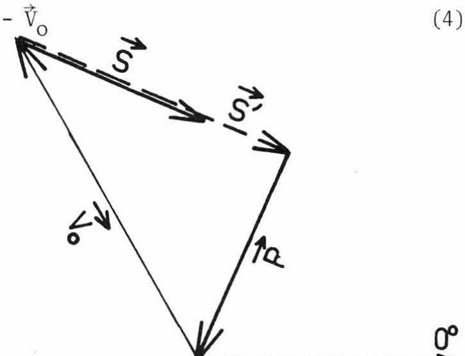

Fig. 5 : Vectorial analysis of the effects of shims on the 1st harmonic.

If we assume that the effect of a shim is proportional to its length, the second shims can be easily calculated. In fact we found it was necessary to add a shim to each of the four sectors of the magnet (fig. 6)

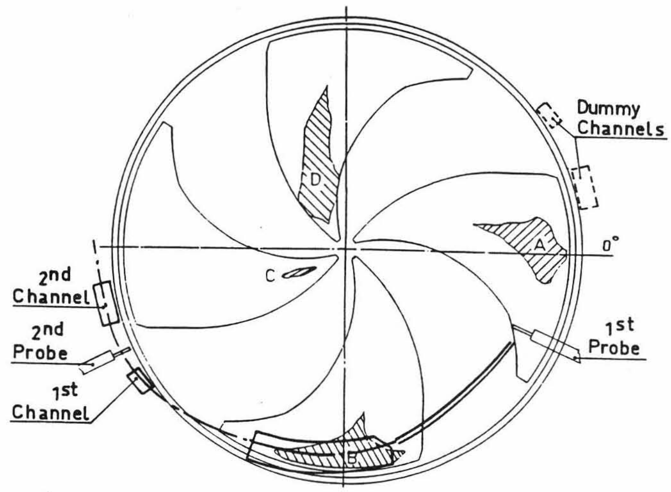

Fig. 6 : Lay-out of the magnetic elements on the pole of the cyclotron. (A, B, C, D are the added shims).

Evidently this method is iterative if necessary. However in our case we found that after the second shims were positioned the first harmonic became acceptably small (fig. 7).

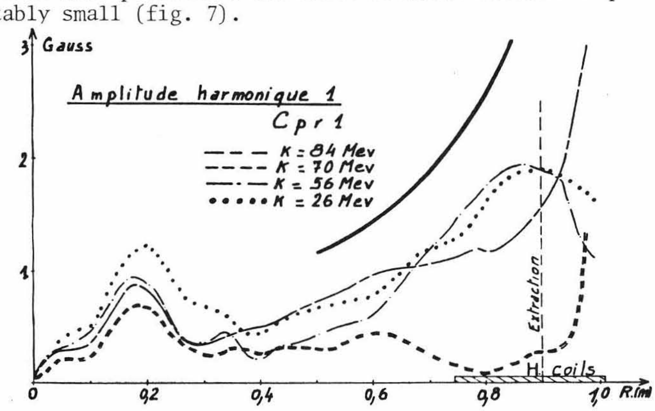

Fig. 7 : Amplitude of the field 1st harmonic, before (K = 70 MeV) after shimming (dotted line, 26 ≤ K ≤ 84 MeV).

Extra harmonic correcting coils are needed to complete the coverage. Only a few "ampere-turns" should be sufficient.

III) Improvements to the elements of extraction

The construction of a new electrostatic deflector and a new active magnetic channel is not yet completed We are still using the old guides, but the passive channels which follow these elements have already been adapted to the new position of the extracted beam.

For the first passive channel we modified a design used at the N.A.C. by P.J. Celliers[8] in order to increase the radial admittance and diminish the focusing. Rheographic studies followed by tests in situ led us to adopt the structure shown in fig. 8.

The second channel is formed by a parallel steel sheets of 15 x 8 cm, 1.6 apart. This channel slightly increases the dipole effect of the field at the pole edges, but the radially divergent quadrupolar effect is cancelled locally in a region where it is large and (above all) does not have a linear variation with the magnetic induction because of saturation.

These 2 channels adapt the beam to the transport line with perfect transparence, but the overall yield does not exceed 70 % in spite of the various improvements.

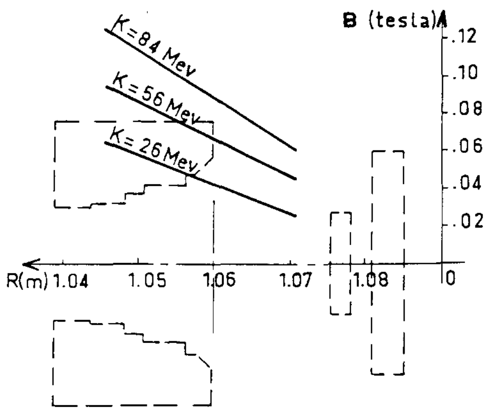

Fig. 8 : Outline of the 1st iron channel and its internal magnetic field.

The old active channel still in place would seem to be the cause of this poor performance. It creates a large first harmonic in the magnetic field -and the field maps were necessarily obtained without the channel in place. We have studied the defect with the limited diagnostic elements available : 2 radial probes in the extraction region (fig. 6). We observe the "shadow" in the beam made by one probe on the other.

This method, although somewhat qualitative, highlights two typical situations :

1) The shadow is not sharp but spreads radially (see figure 9 (a)). There is a first harmonic over a large area and the orbits are subject to precessional mixing (this was invariably the case before the recent improvements)

2) The shadow is sharp (figure 9(b)) but a limited radial movement of the probe causing the shadow, is not followed by an equivalent displacement of the shadow (after taking into account the shape of a closed orbit). This shows that the beam is well injected and well accelerated, but encounters a defect near the extraction.

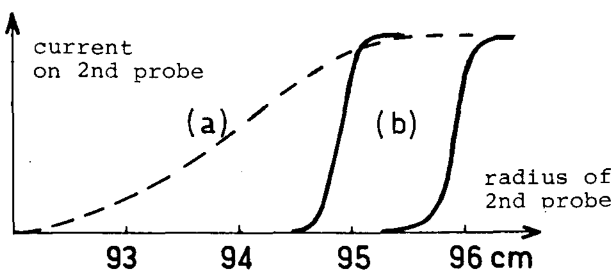

Fig. 9 : Shadows made by one probe one the other.

We will attempt to eliminate this first harmonic by the design of new channel, if necessary at the expense of the second harmonic.

Annex

With a symmetry axis, we have :

$$4 z'' w + 2 z'V_o' \cos \emptyset + zV_o'' \cos \emptyset = 0$$

where V_o is the static potential on the gap axis ($dV_o/dS = - E_o$)

$$- 1/2 mv^2 = qW = q \{U + V(S) \cos \{\emptyset (S)\}\}$$

If there is no symmetry (apart from the median plane) then we establish the equation[5] :

$$2Z'' (U + V \cos \emptyset) + z'(V'\cos \emptyset - V\emptyset' \sin\emptyset) + z ((\delta^2V/\delta x^2 + \delta^2V/\delta z^2) \cos\emptyset = 0$$

The knowledge of the analytic expression of the equipotentials which are parabolas in the median and the determination of a central trajectory as the optical axis permit a fit to the equation :

$$V = 1/2 V_o (1 + \tanh (as^2 + bs + c))$$

where s is the coordinate tangential to the beam direction. One can then obtain numerical approximations of $((\delta^2V/\delta x^2 + \delta^2V/\delta y^2)$. If one chooses for Z a set of solutions with the form of a third degree polynomiat in s, the differential equation can be directly integrated by identity.

Acknowledgments

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