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# CALCULATIONS FOR THE DESIGN AND MODIFICATION OF THE 2 CYCLOTRONS OF S.A.R.A.

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## INTRODUCTION

S.A.R.A. (1,2) is a heavy ion accelerator constituted by 2 cyclotrons. The second cyclotron (post-accelerator) was entirely calculated at the I.S.N. The pole tips of the first cyclotron which is much older, have recently been modified.

An almost identical procedure was used for the calculation of each element of the post-accelerator of S.A.R.A. and also for the modifications to the first cyclotron.

1) - The basic design is predetermined by analytic means.

2) - The fundamental choice of parameters is made after calculation of beam dynamics with the programme (TRANSPORT). The matrices which result from this programme can also be used in certain analytic calculations. With a few precautions we obtain within a few per cent the definitives valves, for example the angles of the magnets, and of their faces, $\nu_r$, $\nu_z$, admittances etc.

3) - The measurement of field maps permits the simulation of the movements of ions subjected to these fields with a precision better than one millimetre. The superposition of electric fields or of additional magnetic fields is performed analytically by the programmes (TRAJ 3D, ANJO etc...). The quality of the acceleration depends on the quality of the field measurements.

CALCULATION OF THE MAGNET SHAPE

The shape of the elements with an axis of revolution is predicted with the aid of the programmes MAGNET and POISSON. We made evaluations of the complementary field flux which cannot be calculated by the above programmes and thus completed the magnetic circuits.

In the case of the principle magnets these elementary calculations had to be verified and completed by measurements on a model (1/7). Althoutgh the use of a model is fruitful, The fine adjustment of the shape of the pole is done by successive shimmings.

THE FIELD MAPS

After acquisition and pretreatment (programmes CARP and NEWETAL) we obtain a field map B(azimuth, radius) in Tesla for regular steps of the azimuth and radius. Qualitative analysis and hence judgement of the analytical studies is however difficult with an ensemble of around 7000 pts (for 1/4 of the accelerator). We often worked with a (hard-edge) equivalent of the magnets, obtained from the calculation of mean fields.

The use of mean fields <B> also permitted the calculation of the magnet shims, and the correcting coils. The biggest difficulty lies in the definition of the mean field. The best would be to average along an isochronous orbit, but these are known only after the calculation, thus we used trajectoiries of simplified geometry ("hard-edge") or simply along the arcs of circles.

For four different levels of the magnetic field we nedd

- The field maps of the magnet without any correcting coils
- The field maps of the effect of each correcting coil (11 and 15 coils).

The accuracy of the field measurements must be such that no smoothing is necessary, for each treatment of the data reduces the credibility of the results.

The aim of the calculations of the magnets of the second cyclotron is to obtain a synchronous field for a particular ion, without correcting coils. We chose the ion $O^{8+}$ at 32 MeV/A.

Starting with the measured field map one calculates the "isochronous" maps (by homothetic variation of the field $B(\theta)$ using the programmes TRAJ22 or ORBISO. By comparison of these 2 maps, or rather, the mean fields obtained under the same conditions, we calculate the shims and the currents required in the correcting coils.

## TAILORING OF THE SHIMS OF THE PRINCIPLE MAGNETS OF THE POST-ACCELERATOR

From the difference between the <B> obtained along the same path in an uncorrected field and that obtained in an "isochronous" field we obtain the average variations <ΔB> (R) which should then be redistributed along the trajectory to obtain the desired synchronous field. However this variation <ΔB> (R) is aplied only locally at the position of the shim. The trajectory obtained with this local modification is different from that previously calculated. Moreover the local modification of a gap where the trajectory passes influences the neighbouring trajectory a little. The continuity of trajectory and fields (the absence of an abrupt perturbation) leads to a convergence of an iterative process of modification of the shims and calculation.
A second problem encountered is that the local effect of the shim is not very precisely known. We precalculated this effect using MAGNET then mesured it with a model. One must take into account the apparent length of the shim under the considered trajectory.
An error of several per cent on <ΔB> is unavoidable in the calculation of a perturbation of <ΔB> /<B> of one per cent.
The process converges quickly and after 5 iterations the precision of the calculation was better than that possible for the machining of the steel.

## CALCULATION OF INTENSITIES OF CORRECTING COILS

A similar procedure to that described above is followed, to calculate the corrections which must be applied for a particular ion.
From the field measurements we obtain the effect $dB(I_j, r)$ of a current $I_j$ in the $j^{th}$ correcting coil at a particular point r.
The sum of the effect at radius R, of all the correcting coils is given by :

$$\Delta B(R) = \sum_{j=1}^{n} dB(I_j, R)$$

Where n = 12 for the first cyclotron
Where n = 16 for the second cyclotron
The $n^{th}$ coil represents the adjustement of the principle field

In matrix form for radius R.

$$\Delta B(R) = \sum_{j=1}^{n} T(R, I_j) \times I_j$$

The effect was measured for 58 and 54 values of N for the two cyclotrons respectively

Let

$B_{1i}$ = the mean field calculated along a path which follows the coil shape, in the measured field.

$B_{2i}$ = the mean field calculated under the same conditions but in the isochronous field.

$I_j$ = the current in the $j^{th}$ coil.

$T_{ij}$ = the matrix of the effects of unit current in the $j^{th}$ coil at the point $R_i$.

We seek to minimise

$$S = \frac{1}{N} \sum_{i=1}^{N} \varepsilon_i^2$$

where

$$\varepsilon_i = B_{2i} - \left( B_{1i} + \sum_{j=1}^{n} T_{ij} \times I_j \right)$$

The solutions found for $I_j$ (by the programme REPEND) can in general be directly applied to the correcting coils.

## CALCULATION OF THE INJECTION AND EXTRACTION

As already indicated, the calculations using TRANSPORT were completed by the exact calculations of trajectories in magnetic and electric fields.
In order to determine the limiting conditions of injected or extracted beams we seek equilibrium orbits with the programmes ANJO or TRAJ30. These orbits are calculated either in the synchronous field (results of ORBISO or TRAJ22) or in the reconstituted corrected field (result of REPEND).
The shape of the septa and the diaphragms was determined by the observation of the shadow of these elements in phase space (programme OMBRE).

## TABULATION OF OPERATING CONDITIONS

- The tabulation of correcting coil currents is the result of a systematic use of the programmes described above, starting from the 4 measured incorrected fields and the measured effects of the correcting.

- The geometry of the trajectories transferred between the machines is constant, so currents in optical elements obey a linear relation.

## PROGRAMMES USED

- TRAJ22, TRAJ30

  J. Fermé - Ganil, Caen.

- ORBISO

  J. Sautet, A. Chabert - Ganil, Caen.

- ANJO

  Groupe Théorie - Ganil, Caen.

- POISSON, MAGNET, TRANSPORT

  C.E.R.N.

- REPEND OMBRE CARP NEWETAL

  I.S.N., Grenoble.

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