The Strasbourg superconducting coil cyclotron project

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Abstract.- A project for a superconducting coil compact cyclotron which allows to accelerate ions to energies up to 80 MeV/A from a 16 MV MP Tandem is presented. Some specific points are emphasized : the injection, the magnetic field configuration, the bunching and the beam transfer from the Tandem.

The Strasbourg project[1,2] consists of a superconducting coil, K = 560, compact cyclotron. Ions from the 16 MV MP Tandem of the Centre de Recherches Nucléaires in Strasbourg will be stripped inside the cyclotron before being accelerated. Conclusions of prospective studies[1] have shown that energies of 10 to 80 MeV/A for light ions and 5 to 16 MeV/A for the heaviest are needed. A careful examination leads to the conclusion that a 3 sectors K = 560 compact cyclotron with superconducting coils corresponds the best to this choice. The following table and Fig. 1 give the main characteristics of the project. A working group

Effective bending limit	K = 510 to 700 (Q_f/A 0.1 to 0.24)	
Focusing limit	$K_{foc} \sim 170$	
RF low energy limit	E/A = 5 MeV/amu	
Injection	16 MV MP Tandem	
3 Sectors		
Iron	Pole diameter	180 cm
	Hill iron gap	8 cm
	Average spiral constant	~ 2 rad/m
	Total weight	200 t
	Extraction radius	83 cm
Field	Max central field	4.4 T
	Min central field	2.45 T
	Max average field at extraction radius	4.6 T
RF System	3 Dees	
	Frequency range	22 - 50 MHz
	Harmonic numbers	2,3,(4)
	Dee voltage	100 KV
	Max total RF power	230 KW
Superconducting coils	Pancake type Nb-Ti	
	2 Sections (inner 40 %, outer 60 %)	
	Max total Ampere-turns	$5.7\ 10^6$
	Effective stored energy	43 MJ
Field trimming	17 Pairs of trim coils	
	P ≤ 30 KW	
Extraction system	One turn extraction with $\nu_r = 1$ excitation	
	2 Electrostatic deflectors	
	Magnetic channels	
Beam characteristics	^{12}C 20 → 85 MeV/A	$10^{11} \to 10^{13}$ pps
	^{127}I 5 → 40 "	$5.10^{10} \to 5.10^{11}$ "
	^{238}U 5 → 12.4 "	$10^{9} \to 10^{10}$ "

has been constituted which made detailed studies on the following points : calculation of the magnet configuration leading to isochronism, injection and stripping, mechanical structure of the magnet and mounting of the machine, superconducting coils, cryostat and cryogenics, bunching and beam transfer from the MP. The study of the RF system and computer control have also been started*.

* Internal reports have been written on all this subjects and are available on request.

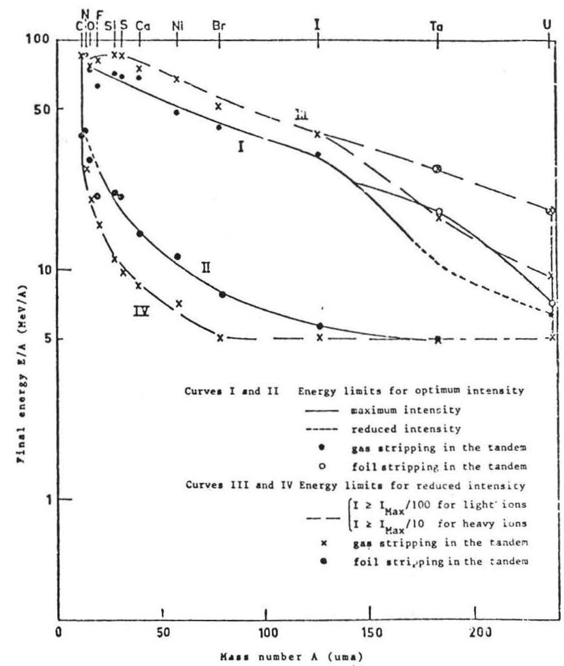

Fig. 1

In the following we give more details about the superconducting coil, the injection, the magnetic field configuration and the beam transfer.

Superconducting coil

Coil		Apparent maximum current density	3200 A/cm²
Inner diameter	2060 mm	Total ampere-turns	$5.7\ 10^6$ A.t
Outer diameter	2416 mm	Maximum stored energy	49 MJ
Distance between coils	120 mm	Maximum field at the conductor	4.6 T
Overall coil height	512 mm	Conductor	
Inner coil height	307 mm	size	15x4 mm²
Outer coil height	206 mm	total Cu-Nb 53 % Ti ratio	20:1
Double pancakes per coil	15	Cu resistivity at 4.5 K	3.10^{-8} Ω.cm
Turns per double pancake	80	critical current at 4.5 K and 5T	3045 A
Turns per coil	1200	design working point at 4.6 T	850 A/mm² (85 % of critical current at 4.5 K)
Insulation between turns	0.35 mm	individual lengths	570 m
Insulation between pancakes	2 mm	total length	34200 m
Nominal current	2380 A	conductor weight	9 t
Maximum rated current		Coil and cryostat weight	~ 15 t
{ inner section	1860 A		
{ outer section	2380 A		
{ inner section	2380 A		
{ outer section	- 820 A		

Injection parameters

Injection geometry has been chosen to enhance high energies-high intensities for light ions from ^{12}C, leading to the following figures :

- Common steering point 2.5 m from the center
- Stripping in a hill and injection "with the spiral" allowing to have most of the injection path near along the median line of a valley where the field is low and nearly does not vary
- Minimum entry angle into the field as small as possible.

From that the main parameters are :

- Steering distance 2.5 m
- Steering angle ± 1°
- Stripping position (15.5 to 20.3 cm ; $\Delta\theta_e$ = 37.5°)
- Entry angle 10 to 25°
- Charge state ratio 2.85 to 3.95
- Energy gain 17 to 32.5

Detailed calculations from an analytical description of the actual (calculated) field given by the magnet configuration described below give the injection limitations as shown on Fig. 2. These limitations are somewhat restrictive for high energy intermediate and heavy ions and mainly for low energy light and intermediate ions keeping the best for light-high energy ions.

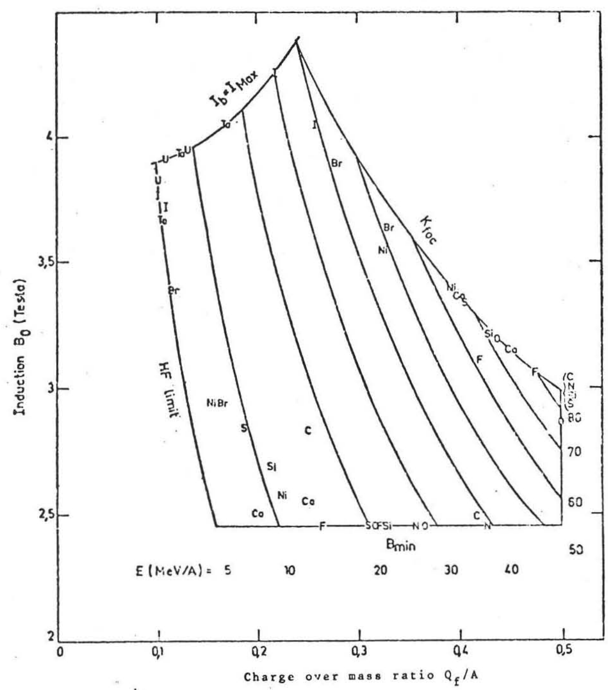

Fig. 2 Working area in the (B_o, Q_f/A) plane showing the position of representative ions.

Magnetic field configuration

Several possible configurations have been studied, ending with the final design described below (Fig. 3). The criteria are dictated essentially by the need to obtain good isochronous fields together with adequate focalization for the whole ion range with optimized excitation for main and trim coils. Spacing and mechanical requirements, particularly severe in such a compact cryogenic cyclotron in which the housing space for injection, extraction and acceleration components is so small, are to be carefully examined as well.

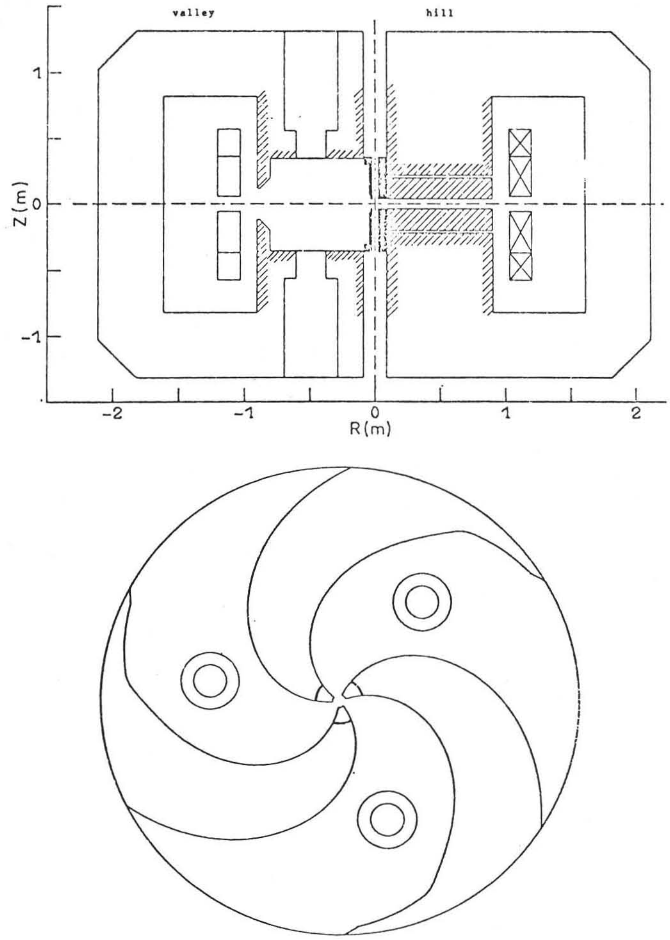

Fig. 3

For each configuration the resulting magnetic field has been determined as already done elsewhere[3,4] by the combination of two separate contributions, the one from the components with cylindrical symmetry, the other from the iron pole tips. For several values of the intensities I_a and I_b in each pair of superconducting coils the relaxation method (code POISSON) has been used to calculate two different field maps. The first one corresponds to the field produced by the coils together with the main part of the iron which is cylindrically symmetric : the yoke, the two end rings and the cylindrical poles generated by the valley profile. The second calculation is also for cylindrical symmetry and for the same iron part with addition of pole pieces with the same axial profile as the pole tip in a hill stretched out over to 2π. The actual average field value is between those two results and is obtained by a combination of the two field maps with a weighting factor depending on the hill width. The azimuthally variable field component given by the spiral pole tip has been calculated with a specially written code, using the uniform magnetization approximation.

Isochronism and betatron oscillations frequencies have been studied for twelve different ions from ^{12}C up to ^{238}U and for final energies near the maxi-

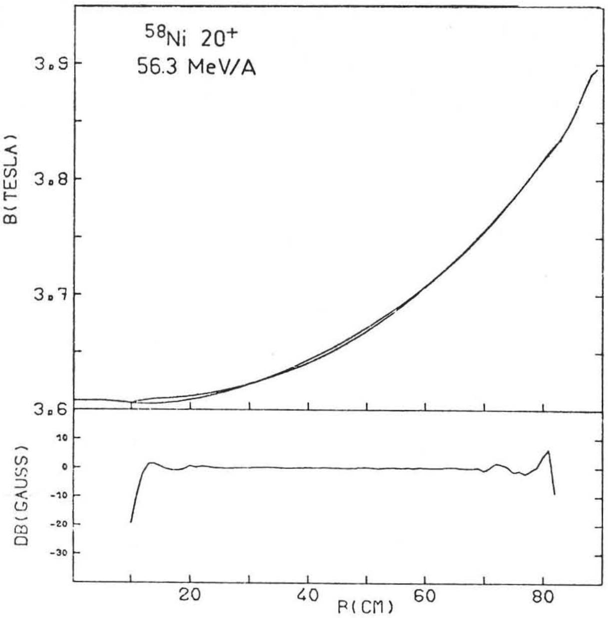

Fig. 4 *Upper part : Calculated field compared with theoretical isochronous field.*
Lower part : Residual field defect with trim coil corrections.

mum and minimum working values (Fig. 2). In every case, for a given magnet configuration, optimum intensities I_a and I_b in the main coils for which the average field is the nearest to isochronism have to be determined. Such a calculation is done from the following grid : The average field value has been computed with POISSON code for a set of equally spaced current densities covering the overall range : I_a = 1100, 1800, 2500 and 3200 A/cm^2 for the coil nearest to the median plan (inner coil) ; I_b = -1000, -300, 400, 1100, 1800, 2500 and 3200 A/cm^2 for the farthest one (outer coil). From this grid the average field value for a given ion has been derived by interpolation using a least squares fit method to minimize isochronism defects. From that result corrections have been made setting trim coil currents to compensate these defects. As an example the average field for ^{58}Ni is shown on Fig. 4 while Fig. 5 shows ν_r and ν_z for ^{12}C at two different energies.

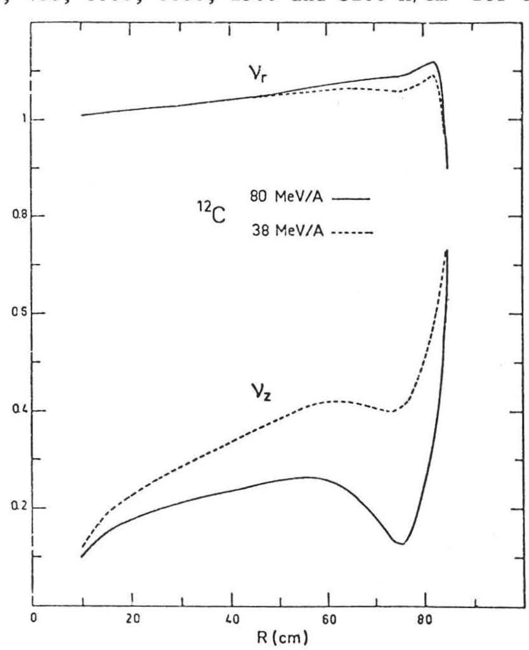

Fig. 5

Such a method has been used optimizing main coil dimensions and iron geometry : pole tip azimuthal profile (angular width and spiral constant), valley axial profile near the extraction radius and central region configuration. The trim coil array has been chosen taking into account the residual field differences from the isochronous field.

Resulting main characteristics for the coils and the iron geometry are listed in the following table.

Inner coil cross section	532 cm^2
Outer coil cross section	358 cm^2
Median plane distance	6 cm
Valley gap	70 cm
(progressively shrinked to 24 cm for R > 80 cm)	
<u>Hills</u>	
Iron gap	8 cm
Center angular aperture	45.6°
Angular aperture at extraction radius	56 °
Average spiral constant	2 rad/m
<u>Trim coils</u>	
Number	17
Maximum total power	30 kW
Return path gap z = 20 to	22 cm
<u>RF holes</u>	
Diameter: 22.6 cm up to z =	56 cm
41 cm further	
Radial position	49 cm

Beam matching and injection system

Using most of the present experimental facilities has been our aim but we could not avoid the usual apparent complexity of the transfer line and of the bunching system shown in Fig. 6.

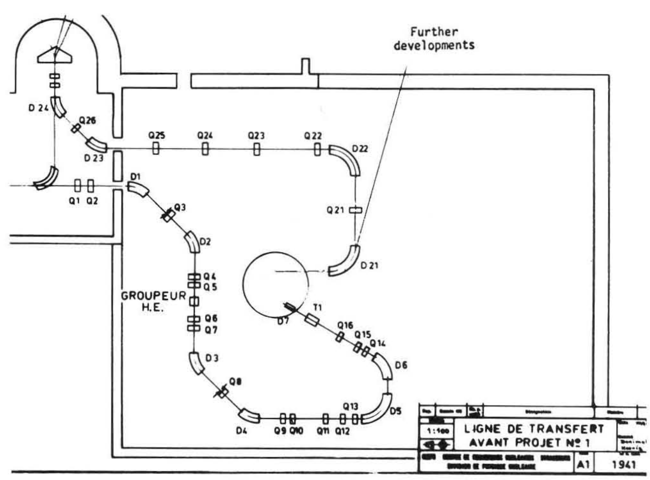

Fig. 6 *Lay out of the facility (MP on the left and experimental areas above are out of scope).*

The time structure is obtained by a double drift buncher[5,6] positioned on the low energy platform placed upstream of the MP Tandem and operating on the RF frequency. The efficiency of such a buncher is about 65 %. The dimensions of this system have been determined according to Hinderer's formulation[7] (Fig. 7). A high energy buncher placed roughly in the

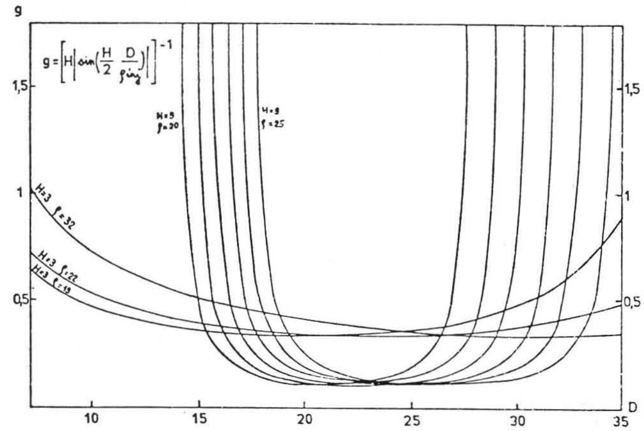

Fig. 7 *Determination of the 1st klystron dimension according to Hinderer's formula.*

middle of the transfer line provides an upright emittance ellipse at the cyclotron injection stripper and a pulse width of ± 3°.

The platform voltage is varied so as to compensate partially the variations of the effective lengths between the terminal of the MP and the cyclotron. Fig. 8 shows how the mean position of the H.E. buncher was determined.

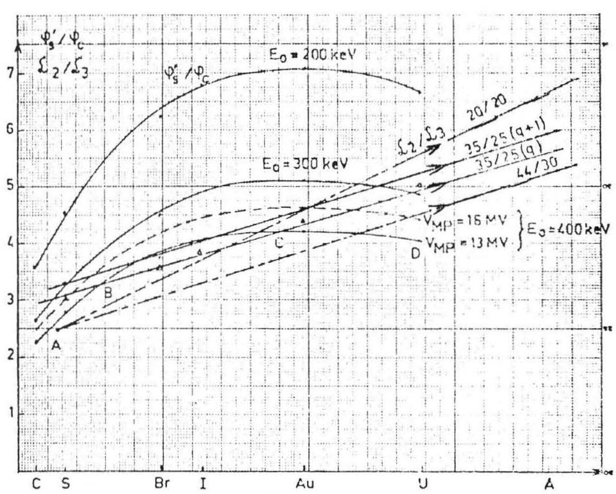

Fig. 8 *Variation of the ratio of the pulse width (φ'_s/φ_c) at the MP terminal and at the cyclotron stripper as a function of the mass number for different injector voltages (E_o) and different effective lengths of the transfer line ($\pounds_2/\pounds_3$).*

The transfer line is achromatic to first order so as to decouple the phase spaces. In the three dimensions, the beam is focused at the two strippers to minimize the effects of angular and energy straggling.

Classically it is divided into three parts, the two first being connected to the L.E. buncher and the M.P. corona system to regulate the fast and slow fluctuations of the injected ion energy.

The third section is similar to the Chalk River[8] line and is destined to the emittance and dispersion matching. Another but more expensive solution has been proposed based on the use of variable lengths as suggested by F. Hinterberger[9].

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