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SPIRAL, a radioactive ion beam facility (R.I.B) is under construction at GANIL (Caen, France).
The heavy ion beams of GANIL will be used to produce radioactive atoms by the ISOL method. After ionisation by an ECR ion source (E.C.R.I.S.), the low energy radioactive beam is axially injected on the first orbit of a k = 265 compact cyclotron.
The final energy will range between 1.7 and 25 MeV/u (harmonics 5 to 2) and the accelerated ions will be sent to the existing GANIL experimental areas.
The green light for this facility was given in late 1993. The construction started in 1994. The first tests of the cyclotron with stable beams are foreseen in mid 1997 and the first beams of radioactive ions in late 1998.

1 Introduction

The interest for beams of radioactive ions is growing on many places in the world. These beams are asked for by nuclear physicists to study the exotic properties of nucleus far away from the stability, by nuclear astrophysicists to get a better understanding of the basic nuclear phenomena driving the life of the stars and also by the atomic physicists and many others.

First experiments with exotic nuclei started at GANIL as soon as 1983 using the projectile fragmentation. In 1989, it was proposed to build a dedicated apparatus named SISSI (1) (Source d'Ions Secondaires à Supraconducteurs Intenses) for the production of high energy exotic beams by projectile fragmentation through a thin target. This apparatus uses an intense axial magnetic field created by a superconducting solenoid to focus the strongly divergent beam emerging from the target. It takes advantage of the existing α spectrometer to select the beam of interest for physics (Fig.1).

SISSI which is operational since 1994 already allowed to perform a number of original experiments. The beams from SISSI have an energy ranging from 30 to 80 MeV/u. They are then not convenient for physics near the coulomb barrier which is of great interest for many users.

In parallel with the construction of SISSI, the SPIRAL project was designed, based on the production of radioactive atoms (both proton and neutron rich) by the ISOL method, but using a high charge state ion source instead of a single charge state source as it is done at CERN, and injecting these ions in a new compact cyclotron (CIME) designed to produce beams of low to medium energy per nucleon.

The project implies that the intensity of the stable beam delivered by GANIL is increased up to 2.10^{13} pps for ions up to Ar, thus increasing the beam power from the present 400 W up to 6 KW.

SPIRAL was accepted by the French agencies (C.E.A. and C.N.R.S.) in late 1993 ; the construction started in 1994 and the first radioactive beam for physics is expected in late 1998.

2 Overall description of the project

2.1 Present status of GANIL

GANIL, the well known heavy ions facility based at Caen (France) is operational since 1983. It consists in a cascade of three cyclotrons in series : $C0_{1,2}$, SSC1 and SSC2 (Fig.1).

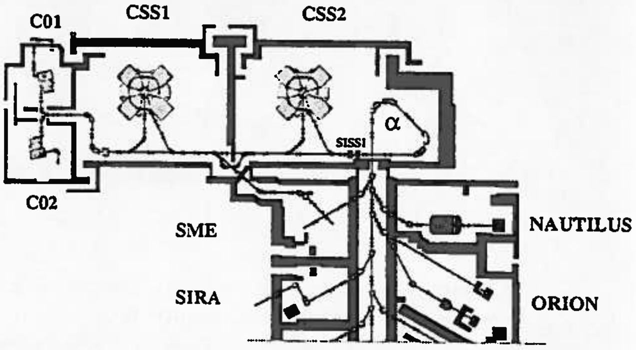


Fig.1 : GANIL general layout

2.2 Evolution of GANIL, the THI project

The production rate of radioactive nuclei being usually low, it is necessary to start with a primary beam as intense as possible. Some years ago, it was decided to increase the intensity of the GANIL beam up to 2.10^{13} pps for light ions up to Ar. The first part of this project : increase of the source production by adaptation of an ECR4 and improvement of the C0 transmission is realized and commissioned (2). The second part named T.H.I. (Transport des Hautes Intensités) is described elsewhere in this conference (3). Most of the modifications on equipments for T.H.I. will be completed in the forthcoming year. An other evolution foreseen at GANIL is the possible extension of the ions range to very light ones (^{2}H, ^{3}He) which will be very efficient in the production of exotic heavy elements by fission mechanism or spallation in an heavy target such as U or Ta. Nevertheless, such an evolution asks for further development as most of the beam diagnostics and beam stoppers are not suited for light ions.

2.3 The SPIRAL project

The SPIRAL project was first described in the foundation report (4) and later on presented at the London, 1994 EPAC conference (5). The Fig.2 shows schematically the updated layout of the installation. The GANIL beam line is extended down to a cave built at the underground level. This vault which is heavily shielded will contain the target/source assembly and the front-end. The source itself is operated to a rather high voltage (up to 34 kV DC with the presently planned axial injection system).

2.4 Building

The whole project is housed in the north end of the GANIL machine hall (Fig.1 and 2). Nevertheless, it was necessary to build a complete underground level including :

- Two 10 m^2 source caves, shielded with up to 4 m of heavy concrete (hematite charged concrete, d = 3.4) in the forward direction.
- A zone for the storage of the irradiated sources before they can be disassembled.

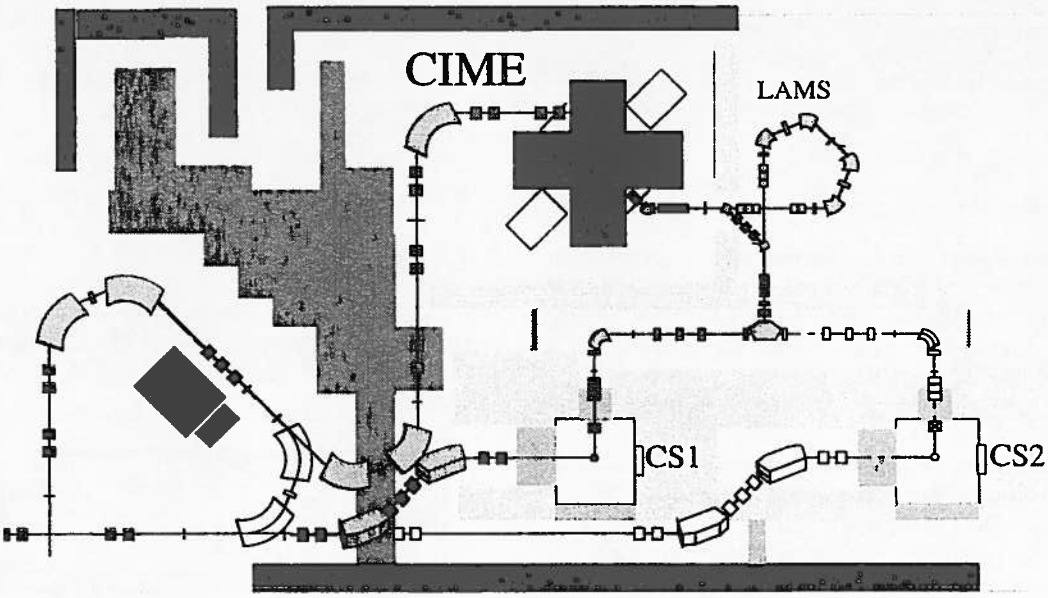


Fig. 2 : Layout of SPIRAL

The postaccelerator is a medium energy, 3.5 m pole diameter compact cyclotron specially designed to have a good beam transmission and a large energy range: from 4.8 MeV/u up to 25 MeV/u (depending on the q/A delivered by the source) on harmonics 3 and 2.

The expected transmission (including the injection) is larger than 30% for a 80 π mm.mrad beam on harmonic 3.

The energy can be down to 2.6 MeV/u by using the harmonic 4 and even possibly down to 1.7 MeV/u with harmonic 5 (but with some modifications of the injection region). The Fig.3 shows the working diagram.

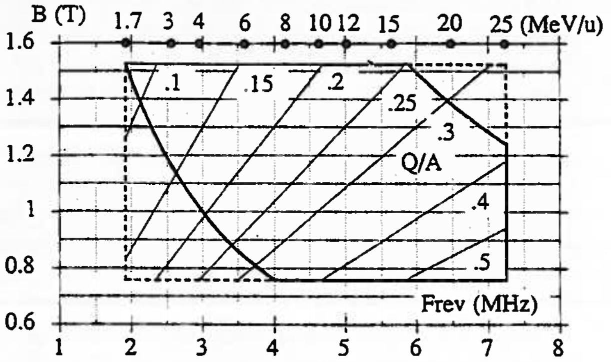


Fig. 3 : Working diagram

- A very low radiation level zone where will pass part of the low energy injection line. This room will receive the ion identification station and possibly a high resolution mass spectrometer once this later will be approved.
  This room could also receive later on some experimental set up for energy physics in the KeV domain.
- The cyclotron basement and support and all the necessary piping, cabling, primary pumping and so on.
- A room mainly devoted to the source power supplies.

The beam lines and cyclotron power supplies will be installed in an extension of the power supply hall which is parallel to the machine hall ; underground tunnels provide an easy and short path for cabling.

2.5 Cost, organisation and planning

The total cost of SPIRAL was estimated at 105.5 MFF in 1993. At the end of 1994, the main parts of the project being frozen, a new and careful estimate was made which gave a total cost of 107 MFF.

A part of this money was already spent in 1993 to equip a GANIL beam line with an experimental setup (SIRa) for R§D work on targets and sources.

One third of this money is afforded by the French Nuclear Agency (C.E.A.), one third by the National Research Center (C.N.R.S.) and the last third by the Region de Basse Normandie. The table 1 gives the breakdown of this cost.

Table 1 : Breakdown of the SPIRAL cost (MFF, VAT excluded)

SIRa experiment set-up	5.7
Building and infrastructure	22.8
CIME cyclotron	40.1
Targets and sources	8.5
Source handling	4.0
Beam lines	19.8
Radioprotection	3.4
Control/command	2.7
Total	107.0

A scientific committee defines the main orientations of the project and organizes workshops where specialists in the domains of interest for SPIRAL present their projects of experiments. A technical committee meets three times a year and helps the project leader and the engineers to define their choices.

An important aspect is the participation of others French laboratories who are in charge of parts of the project. A list of these participants is given in annex.

According to the original planning, the first R.I.B. should be available for experiments by late 1998.

The first orders concerning the building civil work and the cyclotron magnet were passed in the first half of 1994. The building is now ready to receive the equipment and for cabling and piping. The magnetic circuit of the cyclotron should be assembled mid 1996, field measurements completed at the end of 1996 and the cyclotron assembly should be complete by mid 1997.

The second half of 1997 will be mainly devoted to first tests with stable beams while commissioning of the target and source assembly will start in the first months of 1998.

3 Targets and sources

The originality of the project and the element which will finally decide of its success is the target and source assembly. A fundamental point is the wide range of primary ion beams which are currently available at GANIL. This gives the opportunity to select the projectile best suited for the production of the radioactive beam required.

On the other hand, the cyclotron needs multicharged ions. This means that the source must be rather sophisticated. The challenge is that we must develop a source very efficient for multicharged ions, sufficiently resistant to the radiation environment to have a long life-time, sufficiently simple to be remotely installed, controlled and removed and finally ... cheap.

Taking advantage of the GANIL experience on ECR sources, permanent magnet ones are presently designed and tested for the project.

Experiments with targets and sources have started as soon as 1991 (6). The test bench named SIRa (Source d'Ions Radioactifs) was installed in the GANIL experimental room D2 and several tests were already performed with the GANIL beam (presently limited to 400 W beam power).

3.1 Targets

The primary beam is fully stopped in the target. Depending on the nature of the target and of the beam, different nuclear reactions (projectile fragmentation, target fragmentation, fusion, fission) produce in the target exotic nuclei which are trapped in the lattice. The process is accompanied by a large flux of neutrons and light charged particles, emitted with a wide energy range, mainly in the forward direction.

The radioactive nuclei must be firstly extracted from the target lattice. This process named "diffusion" is temperature dependant. It's efficiency increases rapidly with the target temperature.

The first experiments were realized using a graphite target which presents many advantages :

- As a refractory material, graphite is able to sustain temperatures as high as 2300 °C without damage.
- As a light material, the carbon nucleus does not produce too many long-life time radioactive nuclei, thus limiting activity and contamination.
- The structure of the material ease the diffusion process.
- The range of the primary beam is higher in a light material.

On the other hand, the use of a graphite target produces mainly proton rich isotopes by projectile fragmentation.

The use of an heavy material target for the production of heavy, neutron rich nuclei will be considered for future development.

First tests with a lamelled graphite target have demonstrated an efficient production of radioactive elements but with a rapid destruction of the target itself by evaporation or sublimation.

The cause of this destruction is that, with heavy projectiles, the peak of energy loss (Bragg peak) is very narrow, thus producing locally excessive temperature.

A conical, lamelled graphite target (Fig.4) was designed in view of the distribution of the energy deposition over a larger volume. A code was written (7) to simulate the target heating by the beam.

An experiment done using the 30 MeV proton beam of Louvain-La-Neuve (whose Bragg peak distribution is very similar to the heavy ion one) has shown a very good agreement between simulation and experiment (Fig.5) and the ability of this target to sustain the 6 kW power of the primary beam.

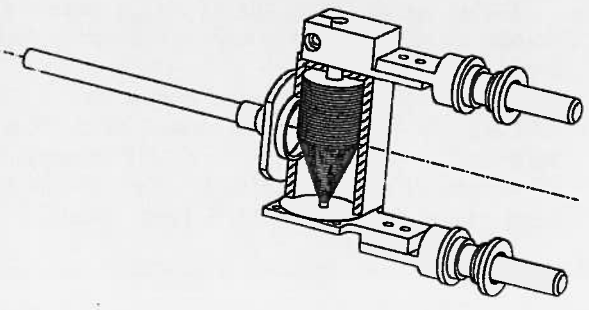


Fig. 4 : Structure of the conical target

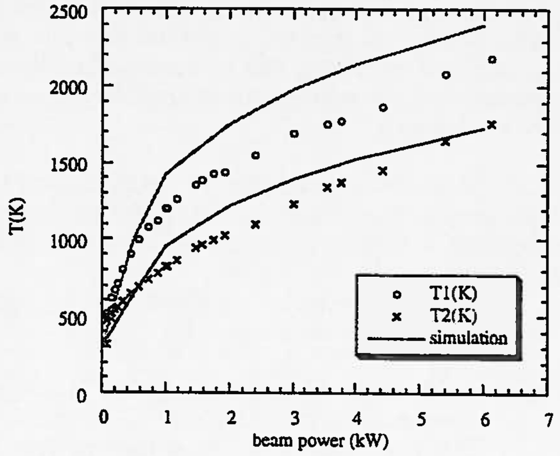


Fig. 5 : Simulation and test of the target temperature increase

3.2 The sources

As already said, the cyclotron requests multicharged ions which can be best produced by an ECR source. The source must also be as simple and cheap as possible. These principles have led us to design a small-permanent magnet-ECR source named NANOGAN 2 (8,9) (Fig.6). This source, extensively table-tested with stable ions has demonstrated a good efficiency for multicharged ions

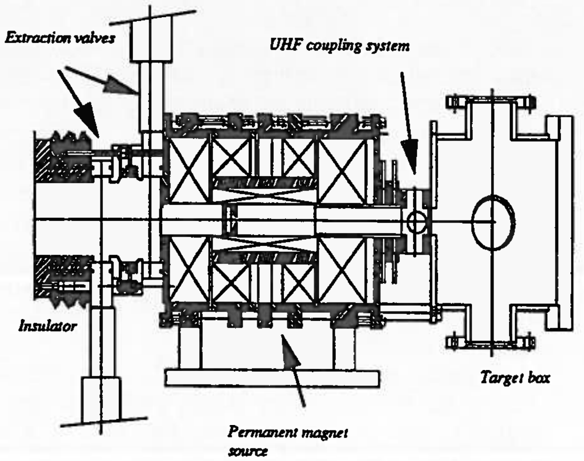


Fig. 6 : Source Nanogan 2

Tests were performed on SIRa with the target 65 cm away from the source, the radioactive atoms diffuse from the target to the source plasma along the 65 cm cold tube.

The table 2 gives the atom species and the intensities (normalised to 1 kW of beam power on the target) which were produced. The next development of this target/source assembly will be the heating of the transfer tube in order to ionize also some condensable atoms.

Table 2 : Nanogan 2 ion production

Ion	Source intensity (1 charge state) (normalized incident power : 1kW)
^{6}He	1.10^{8}
^{8}He	4.10^{5}
^{17}Ne	6.10^{4}
^{18}Ne	6.10^{6}
^{19}Ne	1.10^{8}
32Ar	2.10^{2}
^{33}Ar	4.10^{4}
^{34}Ar	3.10^{6}
^{35}Ar	1.10^{8}
^{72}Kr	6.10^{2}
^{73}Kr	5.10^{3}
^{74}Kr	1.10^{5}
^{75}Kr	4.10^{5}
^{76}Kr	8.10^{6}
^{77}Kr	1.10^{7}

The life-time of the source is expected to be two weeks. We have still to demonstrate that it is a realistic figure and that the magnets will not be demagnetized by the severe radiation environment.

A test was also made at SIRa with a different source arrangement named NANOMAFIRA (Fig.7). This source is like NANOGAN except that the target is inside the source, very near the plasma. This means that the primary beam passes through the source in a path between the permanent magnets. The idea was to demonstrate that an ECR source can work with the hot target very near the plasma surface and thus produce condensable radioactive ions.

The test was successful as significant intensities of ^{34,32}Cl, ^{28}Al, ^{26}Na, ^{7}Be were observed. Unfortunately, a very rapid demagnetization of the permanent magnets along the forward direction of the incident beam occured. A new configuration design will be soon tested to get a longer life-time source.

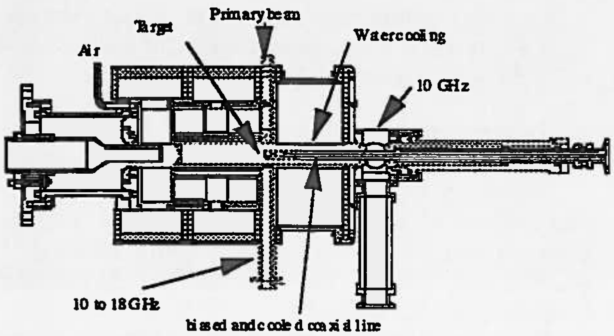


Fig. 7 : Source Nanomafira

4 The cyclotron

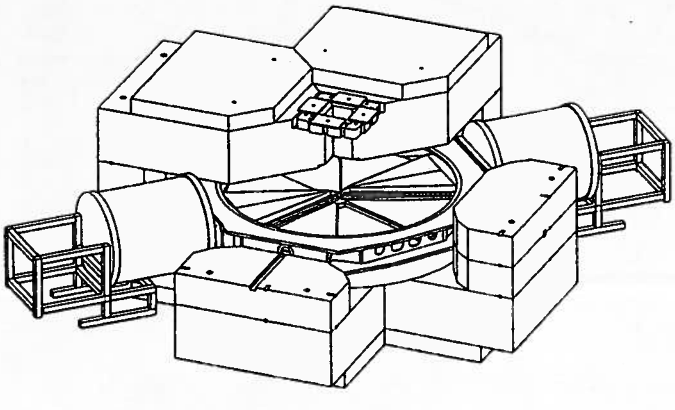
CIME (Cyclotron pour Ions de Moyenne Energie) is a room temperature, compact cyclotron. The table 3 summarises its main characteristics.

Table 3 : CIME characteristics

Energy constant K	265
Average magnetic field (T)	0.75 - 1.56
Ejection radius (m)	1.5
Frequency range (MHz)	9.6 - 14.5
Nominal energy range (MeV/u) (h = 2 - 3)	4.5 - 25
Low energy extension (MeV/u (h = 4 - 5)	1.7 - 4.5
Beam emittance at injection (mm mrad)	80 π
Beam emittance at extraction (mm mrad)	< 10 π

4.1. CIME magnet

The Fig.8 shows the magnet structure (10). The magnetic circuit is somewhat original as it has 4 return yokes made of stacked thick slabs. This structure was chosen for its compactness but also for the field homogeneity as well as for its low machining cost.



·Fig. 8 : Magnet structure

The poles are circular, flat steel sheets, 350 mm thick, on which are screwed 4 magnetic sectors for focusing. The magnetic field range is rather large (0.75 - 1.56 T on average), and the isochronism is obtained using 11 circular coils located between the poles and the sectors.

All the field calculations were done using a 3D code (TOSCA) while the mechanical behaviour under magnetic field, gravity and vacuum was analysed independently by two codes : CASTEM and SYSTUS. The results are comparable and show that the mechanical deformations will produce field variations which are well within the correction domain.

It is thought that the computer modelisation is reliable enough to avoid the realisation of a small scale model.

The manufacture is underway by CREUSOT-LOIRE and the delivery at Caen is foreseen in June 1996.

4.2 RF system

The main characteristics of the RF (11) are summarised on table 4. One resonator is shown Fig.9. The structure of these resonators is rather classical with a cantilever dee and a sliding short circuit using spring contacts around the stems. One difficulty is to build a structure sufficiently rigid to avoid unacceptable sag of the dee as well as temperature dependant deformations.

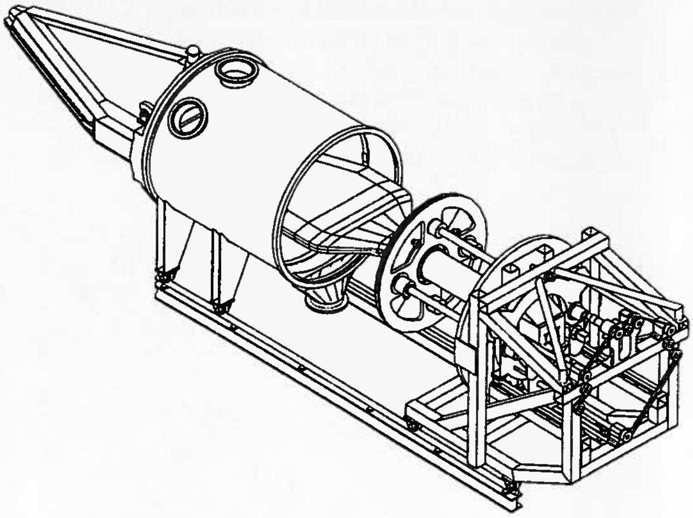


Fig. 9 : RF resonators

The resonators were ordered to SDMS (ST. Romans, France) in August 1995. The delivery is foreseen in May 97.

Table 4 : RF characteristics

Frequency range (MHz)	9.6 - 14.5
Dee number	2
Dee angle (°)	40
Accelerating gap (mm)	15 to 30
Free dee aperture (mm)	30
Total dee height (mm)	100
Max. peak voltage (kV)	100
Max RF power (kW)	50
Max surtension coefficient Q	913,2
Short-circuit range (mm)	700
Coupling system	variable loop
Total lenght (m)	4.95

4.3. The injection

The beam is axially injected on the first orbit. As the radioactive beams will usually be very weak, it is mandatory to obtain the best possible transmission. This imply that, not only the emittance is transmitted through the inflector without losses, but also that it is fully adapted to the cyclotron admittance.

A first order design allows to define a central geometry which seems correct at least for the central orbit. A 3D representation of this geometry is modelised and the electric field is computed (code CHA3D). The multiparticle code LIONS (12) is then used to calculate the behaviour of the particle bunches using the electric field map delivered by CHA3D and the magnetic field map given by TOSCA. A bunch of particles perfectly adapted and centered at a radius of 50 cm is computed backward down to the inflector exit. After some adjustment and a few iterations, this provides the beam characteristics at the inflector output which would give a perfectly matched beam at 50 cm. (This is confirmed by a forward calculation). The next step consists to say if it is possible or not to obtain these beam characteristics at the inflector output and to realize the best compromise between the matching conditions and a possible central region.

As this is a long process, all the details of the central region are not yet frozen.

The present work concerns the optimization of the central geometry for the harmonics 2 and 3 (which cover the nominal SPIRAL energy range).

As a very preliminary conclusion, it looks impossible to keep a very good beam transmission for harmonics 4 and 5 using the same geometry.

4.4 The extraction

The beam extraction is obtained by the way of two electrostatic channels (Fig. 10) and two magnetostatic channels which position can be slightly adjusted (13). An electromagnetic bump can be added to help the single turn extraction (not yet studied).

The main characteristics of these elements are given on table 5.

Table 5 : Extraction elements

DE1-DE2 azimutal extension/channel	17	°
DE1 septum input radius	1513 ± 5	mm
DE2 septum input radius	1488 ± 5	mm
Maximum electric field	70	kV/cm
Channel width	14	mm
CMS azimutal extension/channel	16	°
CMS1 input radius	1616 ± 10	mm
Nominal gradient	5.5	T/m
CMS2 input radius	1662 ± 10	mm
Nominal gradient	13.3	T/m
Channel free aperture	32	mm

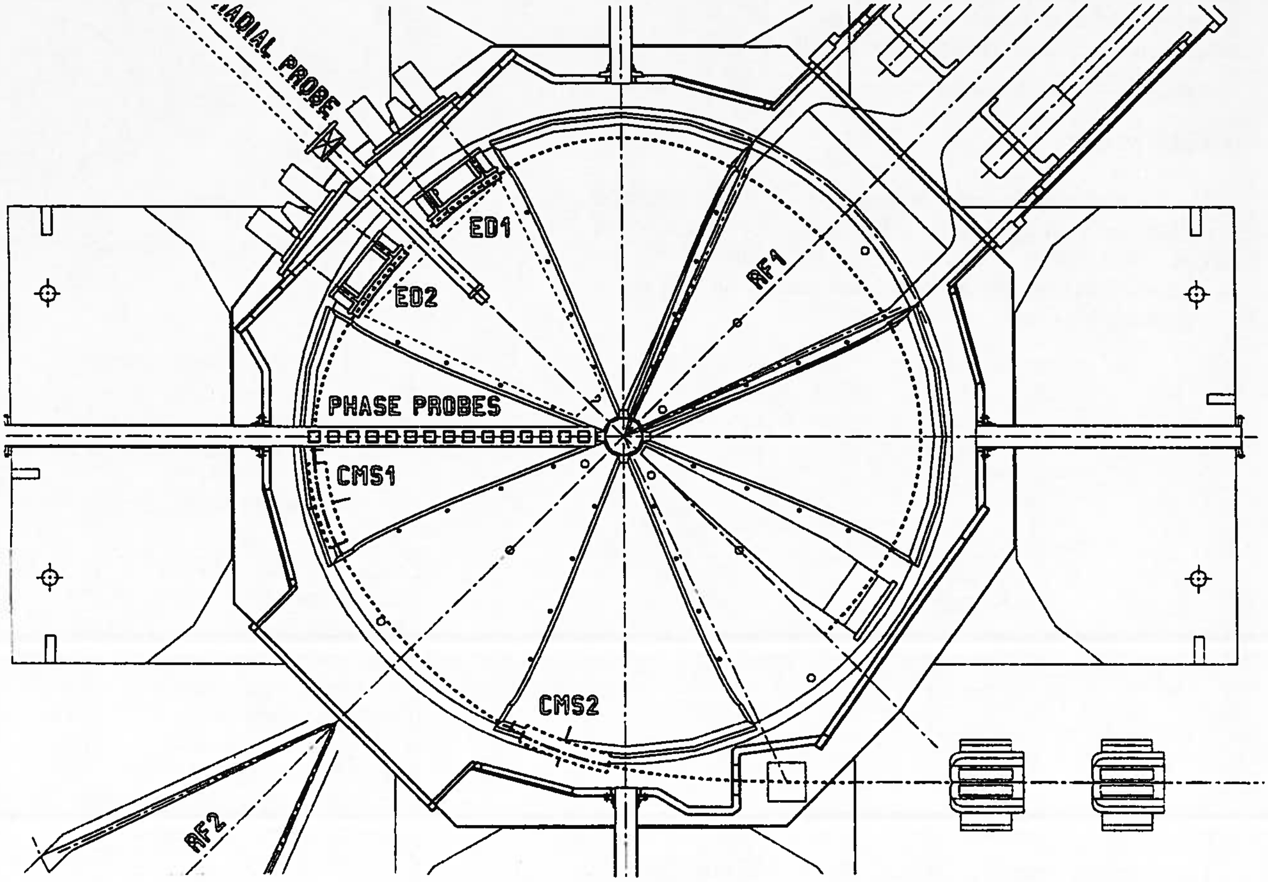


Fig. 10 : Extraction elements

4.5 Diagnostics

There must be two types of diagnostics in CIME :

- The classical ones which allow to adjust sufficiently intense beams. They include a full range radial probe, phase probes and extraction elements probes.
- The "nuclear"diagnostics which will be able to visualise ions individually.

These two types of diagnostics must be used alternatively, depending upon the intensity of the beam in the machine. These elements are more completely described in an other communication of this conference (14).

4.6. Vacuum

A residual pressure of 5.10^{-8} mbar is required inside the cyclotron vacuum chamber. An original solution, using a large 25000l/s cryopanel, positioned in one of the valleys, and its caloduc was designed. A prototype is under assembly at GANIL and will be tested in the forthcoming months. The system is completed by two 2200 l/s turbomolecular pumps mounted in the RF resonators (15,16).

5 Beam lines

5.1 The primary beam line

The primary beam line is designed (17) to transport the high energy GANIL beam down to the target. The beam transport is achromatic and the magnification is adjustable in order to vary the beam diameter on the target from a few mm up to 60 mm.

5.2 The very low energy beam line

This beam line, which drives the beam from the source up to the cyclotron has several functions :

- A first part includes the source front end and an achromatic mass spectrometer (resolution 200 for a 80 π mm.mrad transverse emittance beam).
- The second part of the line includes the bunching system and perform the beam matching at the inflector exit.

This line must also accommodate an identification station which, using nuclear detectors, must allow to detect and measure the radioactive isotopes extracted from the source. It is also designed to add later on a high resolution spectrometer ($1300<R<2000$) which is proposed (18) but not yet accepted.

5.3. The medium energy beam line

This line drives the extracted beam up to the second dipole of the α spectrometer and then to the experimental areas.

It is composed of two main parts :

The first part, taking into account the beam characteristics at the CIME ejection will deliver an achromatic beam and will perform the betatron adaptation to the object point of the spectrometer. The emittance of the beam will be limited at this point. In addition, it will be possible to place a thin stripping target for separation of the ions of the same q/A or a thicker target allowing to separate the isobars by the stopping power method.

The beam will be analyzed in the second part of the line which uses the compensation section of the α spectrometer and adapt the beam to the object point of the experimental areas.

Annex : list of the French laboratories contributing to the project

I.P.N. (Institut de Physique Nucléaire - Orsay) :
Internal components of the cyclotron, realisation of the source targets, radioprotection

C.E.A./L.N.S. (Laboratoire National Saturne - Saclay)
Design of the high and medium energy beam lines

C.E.A/DAM/D.ING (Direction des Applications Militaires - Bruyères-Le-Chatel.
Design of the building and of the source handling system

L.P.C. (Laboratoire de Physique Chimie - Caen)
Mechanical design of parts of the cyclotron

C.E.N/BG (Bordeaux)
Participation to SIRa experiments

C.S.N.S.M (Orsay)
Participation to SIRa experiments

SUBATECH (Nantes)
Magnetic measuring bench for the CIME magnet

Service des Prototypes du CNRS (Meudon Bellevue),
Mechanical design of the extraction elements

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