CHAPTER I - INTRODUCTION AND OVERVIEW

This chapter summarizes the main technical solutions chosen to achieve the performance required by the physics needs, and presents reference project.

1. THE PHYSICS OBJECTIVES AND SPECIFICATIONS

The SPIRAL 2 project aims at delivering high intensities of rare isotope beams by adopting the best production method for each respective radioactive beam. The unstable beams will be produced by the ISOL “Isotope Separation On-Line” method via a converter, or by direct irradiation and by in-flight techniques. The combination of all these techniques (i.e. via fission induced by fast neutrons in a uranium target or by direct bombardment of the fissile material, or via fusion-evaporation with unstable beams or heavy ion beams) will allow to cover broad areas of the nuclear chart. In addition to fundamental research in nuclear physics, the SPIRAL 2 facility could also offer a high performance multidisciplinary tool, especially in fields of science requiring high fluxes of neutron, such as material sciences, atomic, plasma and surface physics.

The list of specifications resulting from the physics needs are summarized below:

driver and primary beams

- the driver must deliver deuterons up to an energy of 40 MeV with a beam current up to 5 mA and heavy ions with beam currents up to 1 mA.
- it will be optimised in energy for ions of mass-to-charge ratio A/q=3, resulting in an output energy of about 14 MeV/u.
- it will also be able to accelerate ions of mass-to-charge ratio A/q=6
- the beam energy will be adjustable between the maximal energy and as low as the RFQ ouput energy. The layout of the facility takes account of the possible future increase in energy up to 100 MeV/u.
- a fast chopper is required for some physics experiments to select one bunch out of a few hundred to a few thousand.

production hall

- the production rate of the radioactive beams produced by neutron-induced fission of an uranium target from a deuteron beam bombarding a carbon converter, must be higher than 10^{13} fissions/s. The use of high-density targets could allow us to reach an upper limit of 2.10^{14} fissions/s. However, the fission rate is limited to a maximum of 10^{14} fissions/s and this value has been used for all safety and radiation-protection-related calculations.
- the converter has to withstand a maximum beam power of 200 kW.
- without the use of a converter, the primary beam will consist of deuterons or other species (such as ^{3,4}He, ^{12,13}C) and the maximum power is limited by the most restricting condition, namely that the induced activity must remain below the activity induced by 10^{14} fissions/s obtained with the converter method and the maximum power that the target can withstand (presently estimated to about 6 kW for a UC_x target).
- different thick targets will replace the uranium target for fusion evaporation reactions with stable ion beams.
- different types of ion sources will be studied in order to get the best efficiency for the selected ion specie.
- a mass separator must deliver simultaneously at least two independent beams, with a mass resolution of about 250.
- an identification station is essential for the control of the desired specie output.
- the isotopes will be bred to higher charge states by means of an ECR charge breeder prior to post-acceleration.

experimental area

- without post-acceleration, the secondary beams will be transported to the low-energy experimental hall (LIRAT).
- after post-acceleration in the existing CIME cyclotron, the secondary beams will be transported to the existing experimental area at GANIL.
- new direct beam transfer lines will allow the direct delivery of beams out of CIME to the existing caves G1/G2.
- for the study of fusion evaporation reactions with the in-flight method, the high-intensity stable ion beams from the linac will be transported to a new experimental hall.

use of neutrons for other applications

- the possibility of material irradiation studies, using the large neutron flux, especially for the study of the behaviour of materials considered for future fusion machines (ITER, DEMO), has to be investigated.
- room must be left for possible installation of a pulsed neutron beam facility, including an experimental hall and a ~10 m long neutron line to be used for neutron-TOF like experiments.

2. REFERENCE PROJECT

The schematic layout is shown in Figure 1. The facility can be divided into 4 main areas: accelerator driver, production station (including converter, target and ion source), secondary beam transfer lines and high energy RIB beam lines.

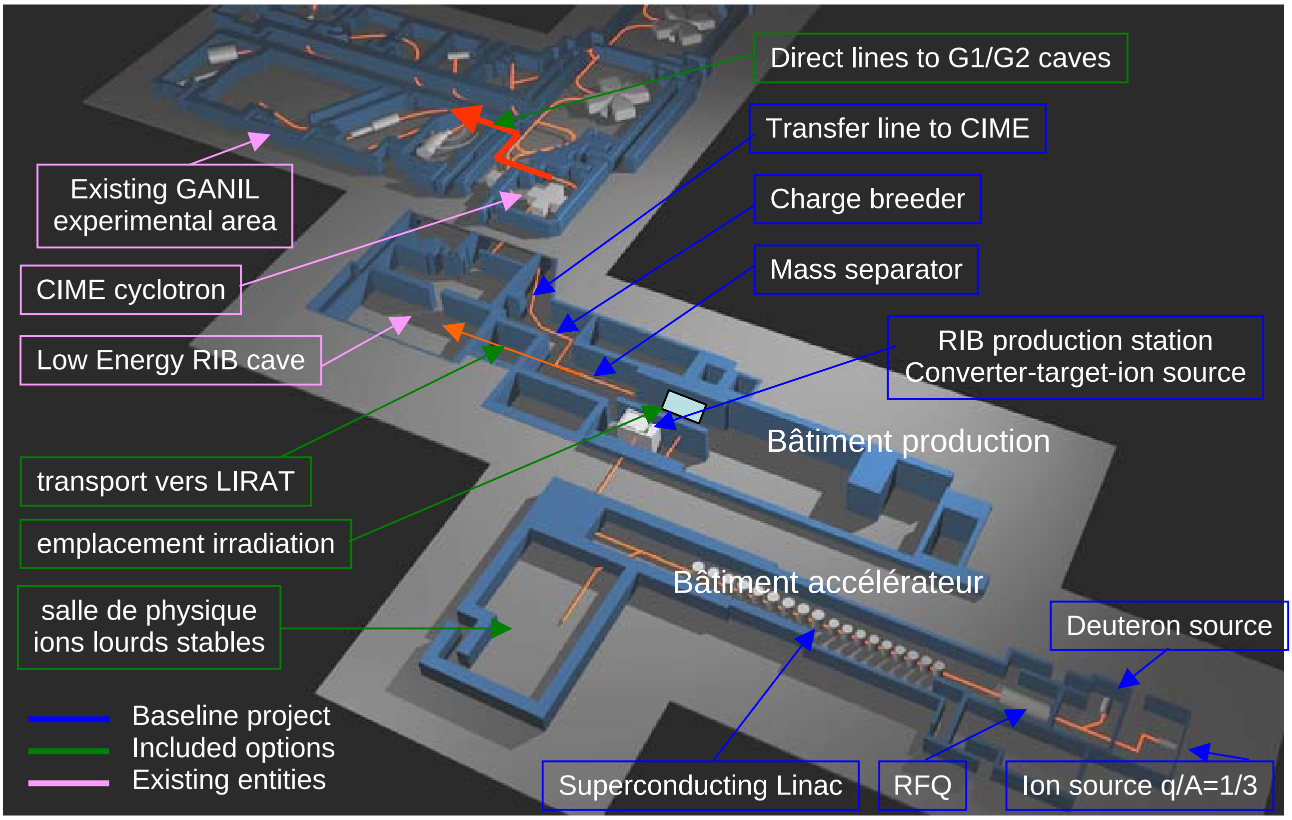


Figure 1: Schematic layout of the reference project : baseline (blue), included options (green) and existing entities (violet).

In addition to the baseline project, which provides the minimal equipment to deliver stable beams and exotic beams, some options can be included from the beginning of the project or postponed at a later stage. The choice of the included options wa made by the Steering Committee in February 2004.

The **reference project** is then the sum of the baseline project and of the included options and comprises :

Baseline

- the full driver able to deliver a deuteron beam at design power and a heavy ion beam (q/A=1/3) at intermediate intensity (state-of-the-art)
- one production station and two plugs for RIB production, equipped with converter, low density UCx target, and ECR source
- the secondary beam lines including the separator, the charge breeder and beam transport to the existing CIME cyclotron

Included options

- the new experimental hall for stable heavy ion beams
- the RIB transfer lines to the low energy experimental hall (LIRAT)
- the direct beam lines to the existing G1/G2 caves
- a site for a possible material irradiation station

The layout of the facility has been thought out in such a way that the possible extensions, which are not included in the reference project can be implemented later.

The **possible extensions** are listed hereafter :

Short-term extensions

- A High-performance heavy ion source (A/q=3) under development
- 2nd injector for heavy ions (A/q=6) requiring a new RFQ
- A fast chopper in the MEBT line
- A irradiation station for material testing using the 14 MeV neutrons

Long-term extensions

- A linac extension for energy upgrade (up to 100 MeV/u)
- An experimental area with pulsed neutron beams for n-TOF like experiments, including a low-power converter and a ~10 m long baseline

The costs of the reference project, as well as the time schedules for safety procedures and construction of the facility are presented in Chapter X.

3. ACCELERATOR DRIVER

The driver must accelerate beams of high power (200 kW deuteron beam power), different ion species and mass-to-charge ratios (deuterons as well as heavier ions with mass-to-charge ratio A/q=3 and up to A/q=6 at a later stage) with high output-energy flexibility (from 40 MeV deuteron energy down to energies, as low as that at the RFQ exit). The concept of “Independently Phased Superconducting Linac” has been chosen because it provides safe continuous wave (CW) operation and high flexibility in the acceleration of different ion species and charge-to-mass ratios. A schematic view of the accelerator is shown in Figure 2.

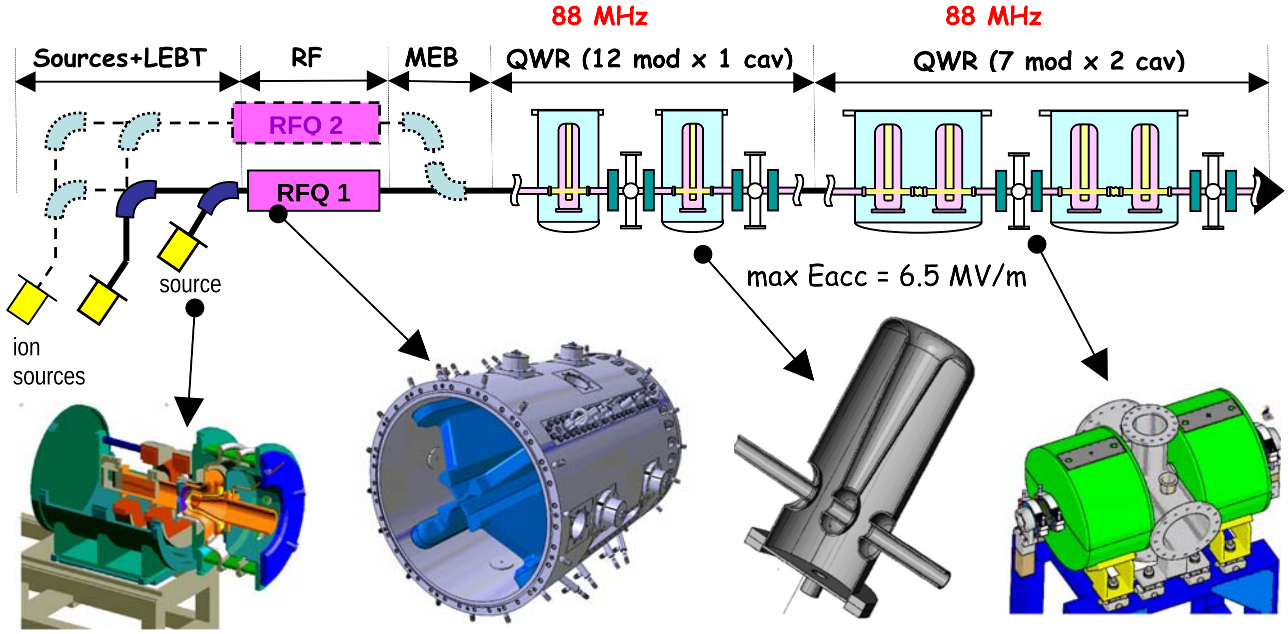


Figure 2: Schematic view of the accelerator.

3.1. Injector

One injector will deliver both kinds of ion beams at the required energy of 0.75 MeV/u.

Two types of deuteron source have been developed during the APD phase : the SILHI-type source (DAPNIA/Saclay) and the Micro-Phoenix source (LPSC/Grenoble). The SILHI-type source will be tested again in 2005 for final optimisation. The final choice between these two sources can be made by a technical committee.

For the A/q=3 ions, the present state-of-the-art of ECR sources produces 1 mA for O^{6+} and 0.3 mA for Ar^{12+}. The reference project starts with such a source at intermediate intensity, as the “GTS” source - which has been shipped to GANIL – or the “Phoenix V1” (60 kV, 18 GHz).

High confinement fields (Br ~ 2-3 T) and high frequency (f > 28 GHz) are required to increase the ion beam currents. The A-Phoenix source (60 kV, 28 GHz), based on the combination of permanent and high temperature superconducting magnets, will permit to reach the highest intensities for noble gases. This source is under development at LPSC and should reach the expected performance before 2008. For the production of metallic ions (Ni, Cr, etc), the required R&D will go on after the start of the facility and can be carried out at GANIL or at LPSC.

The RFQ cavity must bunch and accelerate the beam to the required energy with a high transmission to allow for hands-on maintenance. Different technologies at 88 MHz were studied and the four-vane structure was finally chosen because the RF power consumption is the lowest and of the team has much experience on this type of structure. The power tests on a 1 m long prototype were successful.

The second injector for heavier ions (A/q=6) planned to feed ions into the MEBT system (Medium Energy Beam Transport) is not part of the reference project but can be developed and installed later. The beam coming from both ion sources can then be independently transfered either to the 1st RFQ or to the 2nd RFQ (dashed lines of the source area in Figure 3).

In order to satisfy the physics request, a fast chopper has been asked in the MEBT line to select one bunch from $N = 10^3$ to 10^5 bunches (for physics of solids and atomic physics) or from $N = 10^2$ bunches (for nuclear physics). This device, which needs significant R&D effort owing to the small rise time required (less than 8 ns), is not part of the reference project but can be developed and installed later.

3.2. Superconducting linac

The choice of short superconducting cavities, exhibiting very wide velocity acceptance in comparison with long multi-cell structures, allows the optimisation of the output energy for each ion specie by re-adjusting the individual RF phases. Two types of superconducting cavities were considered, Quarter-Wave Resonators (QWR) and Half-Wave Resonators (HWR), and several different frequency scenarios have been studied. The use of 2 families of QWR resonators at 88 MHz (β=0.07 and β=0.12) was finally adopted for the following reasons:

- lower total number of cavities
- no frequency jump which would require longitudinal matching
- larger cavity aperture
- identical frequency for all RF power sources
- moderate cost

In addition, the focusing by means of room-temperature quadrupoles, instead of superconducting solenoids, resulting in one cryostat per focusing lattice, has been chosen. Despite a slight cost increase, this arrangement offers many advantages: residual magnetic field of solenoids close to superconducting resonators too high, much simpler cryostats, much easier cavity and magnet alignment, larger space available for diagnostics, simpler linac tuning.

Intensive beam dynamics studies and simulations have been carried out to ensure a very low beam loss along the linac. Systematic start-to-end simulations including all combined effects, such as field and alignment errors, confirmed the robustness of the linac design.

A realistic accelerating field of 6-7 MV/m was chosen because the resulting maximum peak fields ($E_{pk} < 40$ MV/m, $B_{pk} < 80$ mT) can be achieved without too much effort by using well-tried methods developed in the last ten years, such as high-pressure rinsing, high-purity niobium and clean conditions. Tests of cavity prototypes in cryostat have confirmed the choice of the design gradient (nearly 10 MV/m have been reached in the low-beta cavity prototype). Furthermore, free room has been left at the end of the linac to allow for the insertion of two additional high-β cryomodules should the field gradient in operation be lower than expected.

Detailed drawings of both cryostats have been worked out and the construction of the two types of cryomodules can now be launched.

The power coupler has been designed at LPSC and tests of prototypes including two types of window (disk and cylinder) are planned in 2005.

The design of the cryogenic plant has been worked out from the cryogenics loads and from operation requirements. An industrial solution has also been explored.

3.3. High energy beam transport

From the linac exit, the beam will be transported either straight to a beam dump (10-20% of full beam power) or to a new experimental hall for stable ions, or down to the RIB production station. The layout also allows for a possible future linac extension by removing the beam dump.

4. RIB PRODUCTION STATION

In order to provide against radiation and contamination, the “plug” technology, developed at TRIUMF (Canada) was chosen and adapted to the RIB production system of SPIRAL 2.

The production plug (Figure 3) comprises essentially:

- containment tanks for the converter, the target and the ion source
- shielding for biological protection against radiation
- a service cap for the ancillary equipment (e.g. pumping system, motors for converter, valves, etc)

After target irradiation and enough cooling time, the plug will be isolated by valves and disconnected from all external supplies. It can be then transported to a shielded bunker. After a few months of storage, the plug will be transported into a hot cell for maintenance (disassembly and replacement of components) by means of remote hand-operated manipulators. A minimum of two production plugs, one in place and one in preparation, will be needed to ensure an acceptable RIB production time. The purchase of two production plugs is included in the reference project and additional plugs will be purchased in the course of the operation of the facility.

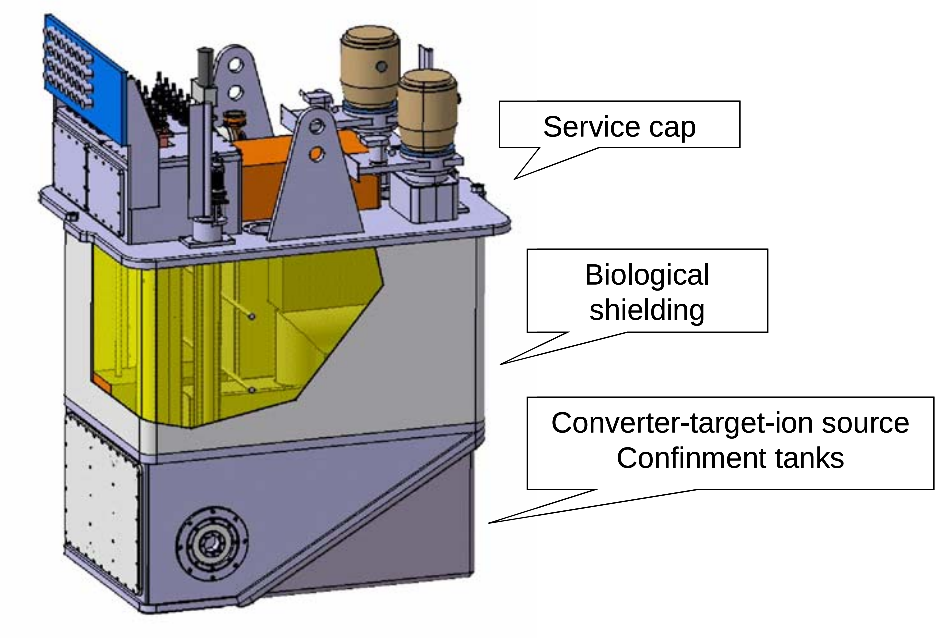


Figure 3: Schematic view of the production plug.

The expected times are about one to two weeks for in-situ cooling of the plug after irradiation and two weeks for disconnection, remote handling and re-connection. The dead time between two consecutive irradiations is thus about one month.

Different technical solutions were studied: i) one single plug containing both converter and target-ion source or ii) two separate plugs, one for the target-ion source and one for the converter. The former was chosen because a minimum distance is required between converter and target and configurations without converter have to be considered. The entire plug will be insulated and raised to high potential (up to 60 kV) and will be mounted within a vacuum-tight tank The other solution, which consists of raising only the essential equipment to high voltage, has been ruled out because the free space between converter and target either would be too small to sustain the high voltage, or would require an electrical contact on the rotating carbon wheel.

On-line measurements (wheel temperature and rotation, neutron monitor) will be implemented to monitor the converter behaviour. In order to make it impossible for the target to reach the melting temperature, a protection system (a thin fuse-wire and a few mm thick carbon piece) will increase the maximum time allowed for activating the interlock system up to a safe delay time (a few tens of ms).

4.1. Converter

The converter, which has to withstand a maximum incident beam power of 200 kW, is a carbon wheel, rotating at a sufficiently high speed (a few hundreds rpm) so as to distribute the temperature uniformly along the circumference. The beam impinges horizontally onto the rim of the wheel, composed of individual graphite tiles (Figure 4). Based on the experience of such carbon wheels developed at PSI, the maximum temperature has been fixed at 1750°C in order to limit the evaporation, resulting in a wheel diameter of 1 m.

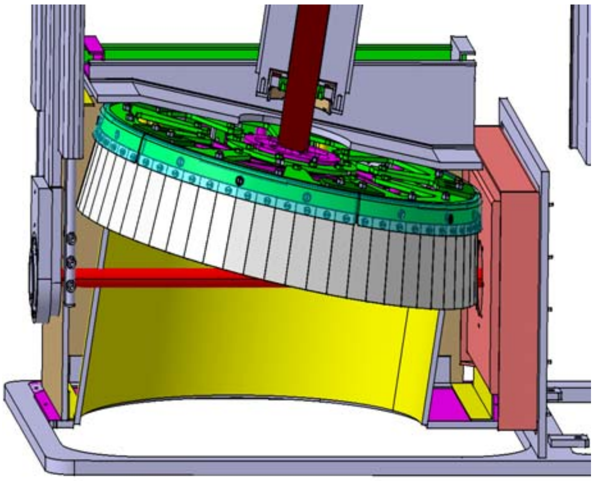


Figure 4: Carbon wheel.

4.2. Targets

The neutron-rich isotopes are produced by fission of a depleted uranium carbide target. A low-density target, based on the technology used at PARRNE and ISOLDE, has been designed to reach at least 10^{13} fissions/s. A high-density target permitting us to reach 10^{14} fissions/s is under study, in collaboration with the Gatchina and Legnaro laboratories.

The geometry of the low-density target has been optimised by taking into account the distribution of the incoming neutron flux and the effusion process. A tantalum oven has been designed to stabilize the target temperature around 2200°C to allow efficient diffusion (Figure 5).

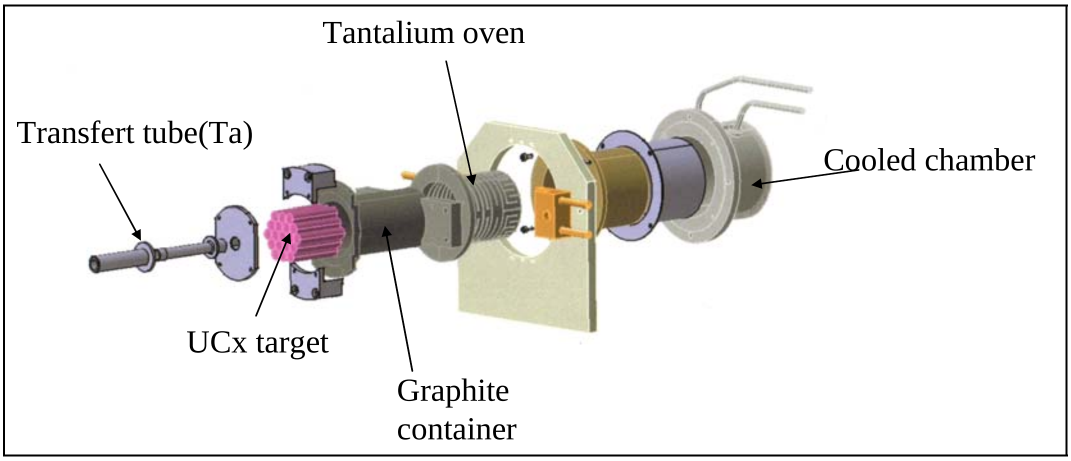


Figure 5: Uranium carbide target inside the oven

4.3. Ion sources

Different types of ion sources have to be coupled to the target to cover the largest range of radioactive isotope beams. Four types of ion sources are then considered:

- ECR ion sources for the production of gaseous elements such as noble gases
- FEBIAD (Forced Electron Beam for Ionization by Arc Discharge) ion sources for less volatile elements
- thermo-ionisation sources for alkalis, alkali-earth and some rare earth elements
- laser ion sources for a large variety of non-volatile elements such as metallic ones

R&D focused on ECR (at GANIL) and FEBIAD (at IPN-Orsay) ion sources during the APD phase. First tests of the ECR prototype have been performed, as the measurement of $^{40}Ar^+$ versus the magnetic field, beam emittance and ionisation efficiencies. New tests on a second improved version (new magnetic structure and plasma chamber) are planned in 2005. A FEBIAD source, very close to an existing model (Nitschke’s Electron Beam Generated Plasma) was also developed, and first tests are planned in 2005.

The reference project includes these two source types, in addition to the thermo-ionisation source which will be an adaptation of the source, presently used at TRIUMF.

The development of the resonant ionisation laser ion source, which requires larger efforts in terms of manpower and budget, has been postponed and will benefit from the experience gained at IPN-Orsay and ISOLDE at CERN.

4.4. Hot cell

The purposes of the hot cell are the disassembling and the replacement of irradiated components contained in the plugs after cooling. The hot cell is also the upstream component of the waste management system: sorting, characterisation and conditioning (packaging) of waste. A preliminary design has been studied (LPC-Caen) and the final design will be provided by the nuclear engineering company (see Chapter 6.1).

5. SECONDARY BEAM TRANSPORT LINES

The radioactive isotopes extracted from the ion source are collected and mass selected through a separator. The beams of different ion species are split up, some to the charge breeder prior to post-acceleration in the existing CIME cyclotron, and some to the low-energy experimental hall. Direct beam lines to G1/G2 caves from CIME will extend the capability of GANIL to deliver simultaneous beams, from both the existing GANIL cyclotrons and from SPIRAL 2.

In order to transport only the ion specie of interest in the experimental area, every effort is presently being made to purify the beams upstream. In particular, the ion source showing the best efficiency for the required ion specie will be used. In addition, the resolution (down to a few 10^{-4}) of the cyclotron CIME will be enhanced (down to a few 10^{-4})

As all these components are working in a high radiation environment, they are located in the so-called “production hall”. Specific studies have to be carried out by nuclear engineering companies in order to find appropriate solutions which allow their maintenance without personnel exposure to radiation and without dissemination of nuclear matter (see Chapter 6).

5.1. Separator

Two solutions (Figure 6) are considered for the two-channel separator, which has to be able to switch the required mass to the required channel.:

- the BRAMA (“Broad-Range Acceptance Mass Analyser”) solution, based on a magnet with sliding slits at the focal plane and electrostatic deflectors to steer the beams to the right channels. A pre-selection dipole has been added upstream in order to get rid of the high current low mass beams and then to eliminate the space charge effects.

- the “Wien filter” solution, based on a short section of electric and magnetic cross-fields, located in a plug close to the ion source exit. The final mass purification in each channel is achieved by means of two independent magnetic spectrometers.

The final choice between both solutions will be determined by the optical performances but also by the capability to allow an easy maintenance in high radiation environment of the active parts and the resulting cost and will take place after the nuclear engineering studies.

In addition, a simplified one-channel solution involving a simple mass selection dipole has been studied in case the more complex two-channel system is not ready in due time.

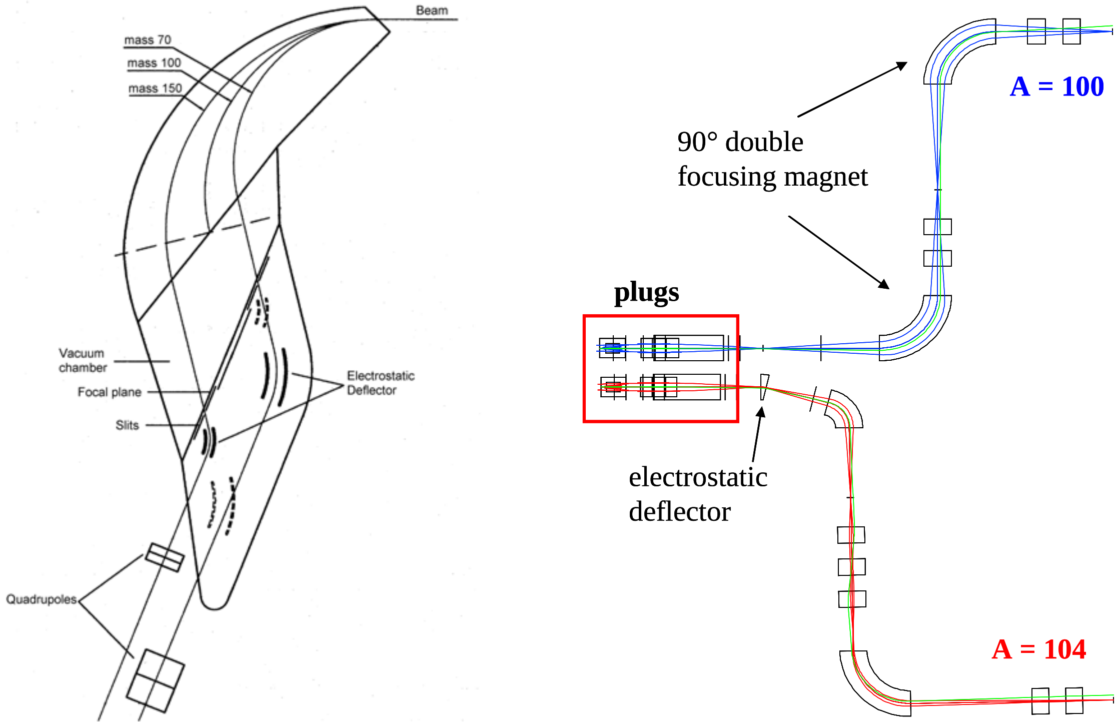


Figure 6: Two-channel separators BRAMA (left) and Wien Filter (right)

An identification station is also implemented for the control of the required specie, similar to that of SPIRAL 1.

5.2. Charge breeder

The charge breeder is the “Phoenix booster”, developed at LPSC-Grenoble. The system includes a double Einzel lens for injection matching and up- and downstream bending magnets for beam cleaning. The specific needs of SPIRAL 2 called for a modified design, including a higher operation voltage (60 kV) in addition to reliability and dismantling capability in view of the maintenance study by the nuclear engineering company.

6. INFRASTRUCTURE AND CONVENTIONAL FACILITIES

The infrastructure and conventional facilities were designed around the reference project in such a way that future extensions, such as the 100 MeV/u linac and an experimental hall for pulsed neutrons could be later on implemented. The site layout is shown in Figure 7.

As the SPIRAL 2 site extends beyond the present GANIL “INB” (Installation Nucléaire de Base) a request for INB modification must be made to the safety authorities.

The concrete shielding needed for biological protection is included in the planned production hall, mainly around the production station and downstream components, as the separator and charge breeder. In the same way, the driver accelerator is surrounded by concrete shielding for radiation protection, with a thickness dependent on the location along the linac (from 30 cm around the deuteron source to 1.5 m at the high-energy end).

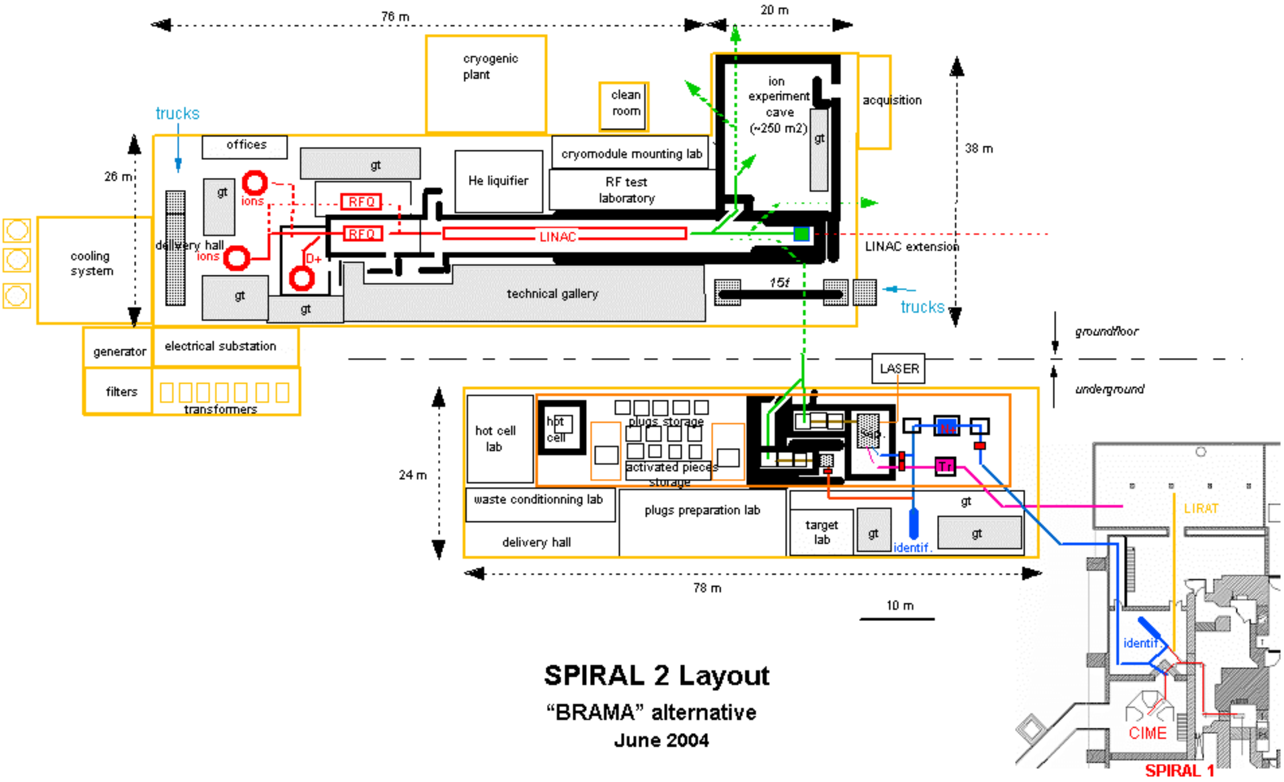


Figure 7: Site layout.

In order to fullfil the safety requirements in terms of personnel protection against radiation and radioactivity confinement, it was decided to resort to a **nuclear engineering company** for the study of the production building. The specifications have been complete in May 2004 and the studies will start at the the beginning of 2005 for a 10 months period. These studies will cover

- The maintenance system in hard environment of the componants of the secondary beam lines
- The design of the productionbulding, including the nuclear ventilation system, the hot cell and the nuclear waste management system
- The cost estimate of the production building and process
- The delivery of a preliminary safety analysis of the production building

The industrial-type buildings comprise the accelerator building and ancillary buildings which include:

- the technical galleries for electronics and power supplies
- the service galleries for cables and pipework
- the cryogenic plant for helium production
- the electrical sub-station
- the cooling system
- the laboratories for the superconducting cavities (test lab, assembling and clean rooms)

As the construction of the industrial buildings cannot start before the delivery of the building licence, it is highly recommended to study the possibility of the construction of a “SRF Lab” (including test lab, assembling and clean rooms) outside the “INB” fence as soon as possible, in order to assemble and test the series of cryomodules and to be ready to install them in the accelerator tunnel in due time.

7. SAFETY OPTIONS

The most crucial safety functions identified on the SPIRAL 2 facility are:

- the containment of radioactive matter
- the personnel protection against ionising radiation

The production hall - which encloses the production plug, the secondary beam lines for the transport of the fission products, the separator and the charge breeder - is the most critical area in terms of safety. In addition to specific studies connected with the maintenance and both safety functions, the nuclear engineering company was asked to provide a preliminary safety report (RPrS) for the production building.

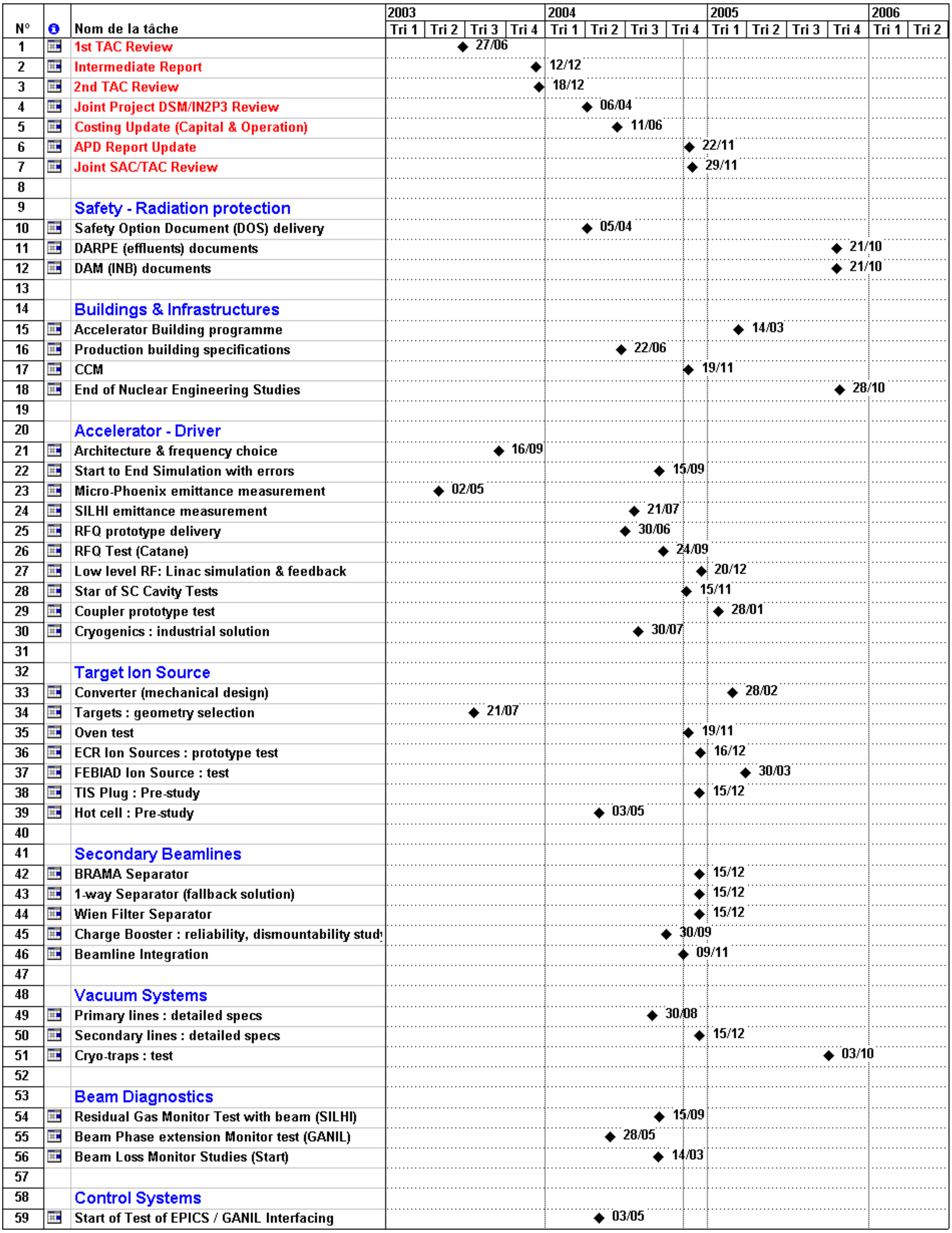
The SPIRAL 2 facility falls under the regulations applicable to the Nuclear Installations (INB), due to the quantity of radioactive materials located inside the facility, and it must thus cope with all safety rules and regulations. The Safety Option Document (DOS), which contains the full list of regulations and guides, was sent to the Safety Authorities in May 2004.

The analysis of the safety and radiation protection of the SPIRAL 2 extension is presented in Chapter IX. Additional studies will be likely required for the existing GANIL facility (from the cyclotron CIME up to the experimental halls) in order to minimize the total radioactivity and the risk of contamination.

8. MAIN MILESTONES

The main stages and milestones of the “APD” phase are summarized in Table 1.

Table 1 : Main milestones during the APD phase



N°	ℹ	Nom de la tâche	2003				2004				2005				2006	
			Tri 1	Tri 2	Tri 3	Tri 4	Tri 1	Tri 2	Tri 3	Tri 4	Tri 1	Tri 2	Tri 3	Tri 4	Tri 1	Tri 2
1	▦	1st TAC Review		◆ 27/06												
2	▦	Intermediate Report				◆ 12/12										
3	▦	2nd TAC Review				◆ 18/12										
4	▦	Joint Project DSM/IN2P3 Review						◆ 06/04								
5	▦	Costing Update (Capital & Operation)						◆ 11/06								
6	▦	APD Report Update								◆ 22/11						
7	▦	Joint SAC/TAC Review								◆ 29/11						
8																
9		Safety - Radiation protection														
10	▦	Safety Option Document (DOS) delivery						◆ 05/04								
11	▦	DARPE (effluents) documents												◆ 21/10		
12	▦	DAM (INB) documents												◆ 21/10		
13																
14		Buildings & Infrastructures														
15	▦	Accelerator Building programme									◆ 14/03					
16	▦	Production building specifications						◆ 22/06								
17	▦	CCM								◆ 19/11						
18	▦	End of Nuclear Engineering Studies												◆ 28/10		
19																
20		Accelerator - Driver														
21	▦	Architecture & frequency choice			◆ 16/09											
22	▦	Start to End Simulation with errors							◆ 15/09							
23	▦	Micro-Phoenix emittance measurement		◆ 02/05												
24	▦	SILHI emittance measurement							◆ 21/07							
25	▦	RFQ prototype delivery						◆ 30/06								
26	▦	RFQ Test (Catane)							◆ 24/09							
27	▦	Low level RF: Linac simulation & feedback								◆ 20/12						
28	▦	Star of SC Cavity Tests								◆ 15/11						
29	▦	Coupler prototype test									◆ 28/01					
30	▦	Cryogenics : industrial solution							◆ 30/07							
31																
32		Target Ion Source														
33	▦	Converter (mechanical design)									◆ 28/02					
34	▦	Targets : geometry selection			◆ 21/07											
35	▦	Oven test								◆ 19/11						
36	▦	ECR Ion Sources : prototype test								◆ 16/12						
37	▦	FEBIAD Ion Source : test									◆ 30/03					
38	▦	TIS Plug : Pre-study								◆ 15/12						
39	▦	Hot cell : Pre-study						◆ 03/05								
40																
41		Secondary Beamlines														
42	▦	BRAMA Separator								◆ 15/12						
43	▦	1-way Separator (fallback solution)								◆ 15/12						
44	▦	Wien Filter Separator								◆ 15/12						
45	▦	Charge Booster : reliability, dismountability stud							◆ 30/09							
46	▦	Beamline Integration								◆ 09/11						
47																
48		Vacuum Systems														
49	▦	Primary lines : detailed specs							◆ 30/08							
50	▦	Secondary lines : detailed specs								◆ 15/12						
51	▦	Cryo-traps : test												◆ 03/10		
52																
53		Beam Diagnostics														
54	▦	Residual Gas Monitor Test with beam (SILHI)							◆ 15/09							
55	▦	Beam Phase extension Monitor test (GANIL)						◆ 28/05								
56	▦	Beam Loss Monitor Studies (Start)							◆ 14/03							
57																
58		Control Systems														
59	▦	Start of Test of EPICS / GANIL Interfacing						◆ 03/05								