

SPIRAL2 AT GANIL

M.-H. Moscatello for the Spiral2 Project Group, GANIL-CEA/CNRS, Caen, FRANCE

ABSTRACT

The SPIRAL2 project has been under detailed design study since beginning of 2003. The aim of this facility is to produce rare ion beams, using a Uranium carbide target fission process, based on a fission rate of 10^{13} to 10^{14} fissions/s.

The driver accelerator accelerates a 5 mA deuteron beam up to 20 MeV/u, impinging on a carbon converter to produce the neutrons necessary to the fission process. It has also to accelerate $q/A=1/3$ heavy ions, to energies between 0.75 and 14.5 MeV/A for different types of nuclear and non-nuclear physics experiments.

The accelerator is based on a RFQ followed by an independently phased superconducting cavity linac with warm focusing sections.

This paper presents the reference design chosen for the SPIRAL2 driver accelerator, and gives the design status of the different components: Sources, RFQ, Superconducting linac, RF Systems, Cryogenics, Mechanical layout.

INTRODUCTION

The Spiral2 project is originally based on the LINAG1 conceptual design [1], that proposed a facility aiming at delivering high intensity radioactive beams produced by different methods (fission of uranium target via a carbon converter, direct target irradiation), as well as high intensity stable ion beams.

Since the creation of the Spiral2 project group at the beginning of 2003, many detailed studies have been undertaken [2], and have led now to new solutions and technical choices for the accelerator design as well as for the target ion source system and radioactive beam transport lines.

SPIRAL2 GENERAL LAYOUT

The facility consists of a linac driver able to accelerate a 5mA deuteron beam up to 20A.MeV as well as light ion ($q/A=1/3$), 1mA beams up to 14.5 A.MeV. The deuteron beam impinges on a carbon converter to produce neutrons, used then in the fission process of a uranium carbide for the production of radioactive ion beams (RIB). These fission products, extracted from a source, are transported towards a charge breeder, and accelerated by the existing CIME cyclotron to maximum energies between 5 and 10 A.MeV, according to the ion q/A ratio. The stable ion beams can be used also for the production of RIBS on different target types, or sent directly towards an experimental cave, for nuclear physics experiments. Fig.1 shows a schematic layout of the planned facility.

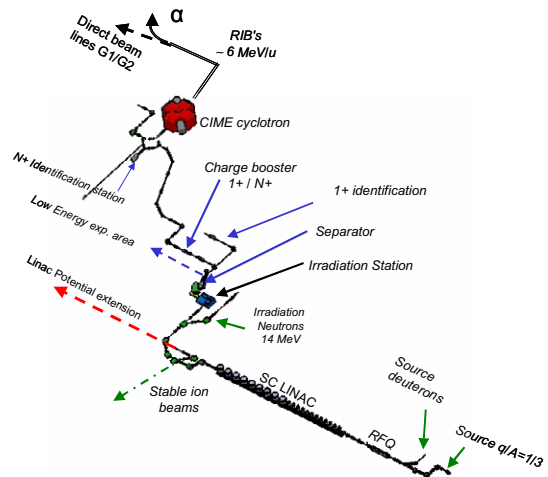


Figure 1: Spiral2 facility schematic layout

THE LINAC ACCELERATOR

Linac Main Specifications and Parameters

The accelerator has been designed with the following main specifications:

- CW accelerator.
- 0.15–5 mA of, 40-MeV deuterons.
- Up to 1 mA (Argon) for $q/A=1/3$ ions, 14.5 MeV/u.
- Two ion sources, one for the deuterons, the other one for the ions $q/A=1/3$.
- Normal conducting RFQ injector designed for both D^+ and $q/A=1/3$ ions.
- Optimisation of the accelerator for 1mA $q/A=1/3$ ion beams, with the capability of accelerating a 5 mA deuteron beam to the required energy.
- Possibility for the SC linac to accelerate ion beams of $q/A=1/6$ (up to 1 mA) in the future, and to be extended towards higher energies.
- Maximum energy gain for each kind of ion, which implies independently phased cavities.

A principle layout of the accelerator is presented in fig.2.

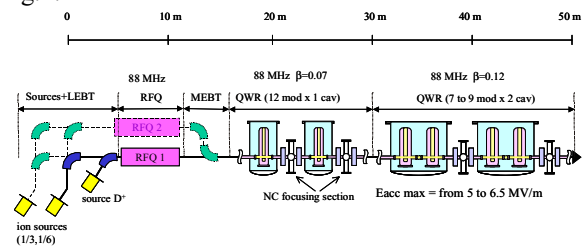


Figure 2: Principle layout of the accelerator

Detailed beam dynamics studies have led to the final frequency choice of 88.05 MHz for the whole

accelerator, and 2 beta QWR families for the superconducting linac: $\beta=0.07$ and $\beta=0.12$, for the following reasons:

- The RFQ and QWR beam apertures are larger, and lead thus to a higher acceptance.
- In the superconducting linac, the cavity number is highly reduced in the high beta family, compared to a 176 MHz solution, thanks to an approximately twice longer accelerating gap.
- concerning the RFQ, even if the cavity is bigger, the thermal problems and power consumption are minimized.

Beam Dynamics

Beam dynamics calculation have been performed with several different multi-particle codes, including beam space charge [3], and have led to an almost frozen design:

- A Low Energy Beam Transport (LEBT) line which allows to inject D^+ and $q/A=1/3$ ions from 2 different sources inside the RFQ.
- A RFQ that bunches and accelerates beams up to 0.75 A.MeV.
- A Medium Energy Beam Transport (MEBT) line that allows the insertion of a $q/A=1/6$ injector for a possible upgrade, as well as a possible high frequency chopper (for physics needs).
- A superconducting linac with minimum technical risks (warm conducting sections, short cryostats, numerous diagnostics).
- A High Energy Beam Transport (HEBT) line that distributes beams towards the production caves (with a uniformisation of the beam density), as well as towards stable ion experimental areas.

Emittances considered for all the calculations are:

- $\epsilon_{rms, norm}=0.4 \pi.mm.mrad$ for $q/A=1/3$
- $\epsilon_{rms, norm}=0.2 \pi.mm.mrad$ for D^+ beams

These values should ensure a rather large acceptance compared to beam emittance that have been measured with D^+ and ion beams up to now.

Start-to-end simulations of the whole linac have been performed [4], considering a Gaussian distribution truncated at 4σ at the source extraction (fig.3).

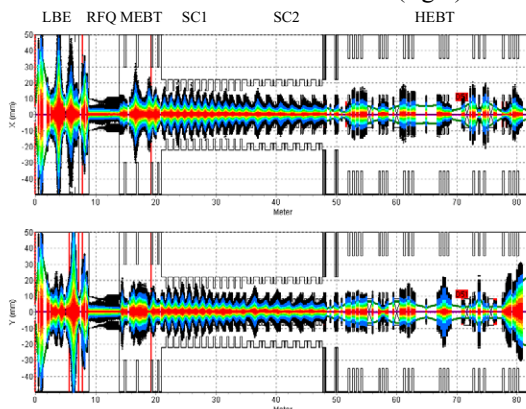


Figure 3. Start-to-end simulation with a 5mA, 0.2 $\pi.mm.mrad$, D^+ beam, without errors

Statistic error have then been introduced in the start-to-end simulations. The following static error values have been considered for the various accelerator components:

- RFQ: $\pm 0.05mm$ for machining defects, and ± 0.1 mm for segment positioning in various directions.
- Magnets: $\pm 0.1mm$ for positioning and around 0.05° for rotations, $\pm 1\%$ for gradients.
- Superconducting cavities: $\pm 1mm$ for positioning and $\pm 0.3^\circ$ for rotations, $\pm 1^\circ$ for field phase and $\pm 1\%$ for field amplitude.

They are corrected with various steerers, and using various beam profile and beam position monitors. Some dynamics errors, that cannot be corrected, have also been considered. The QWR steering effect is not compensated, neither with the cavity shape, nor with a cavity vertical displacement, but is just corrected by magnetic steerers.

The losses can be concentrated in localised points inside the LEBT and MEBT, with the use of scrappers that cut a few percent of beam, as presented on fig.4.

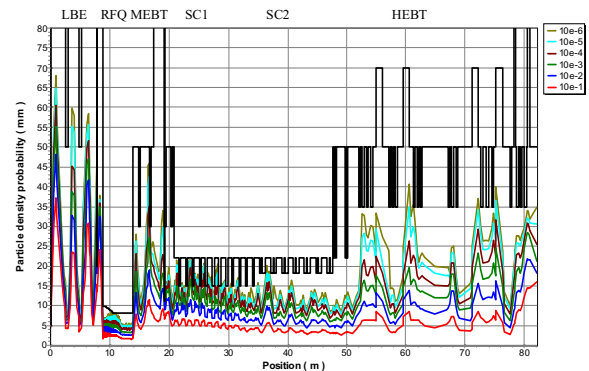


Figure 4: Loss distribution along the accelerator with a 100% error combination for D^+ beam

The next step will consist in performing these calculations with measured beam distributions and emittances, for both D^+ and $q/A=1/3$.

Calculations have also been performed with a faulty cavity, and show that beams can be accelerated with good characteristics, wherever it is situated.

Deuteron and Ion Sources

The deuteron source under study is of SILHI type, running at 2.45GHz and including a modified magnetic structure, with permanent magnets [5]. The 5mA beam is extracted at a 40kV voltage, and must fit an rms normalized emittance lower than $0.2 \pi.mm.mrad$. Some preliminary emittance measurements have been performed, showing that the source should be well inside the emittance requirements (fig.4).

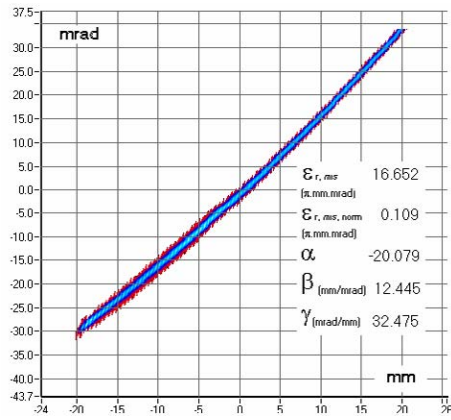


Figure 4: 4.2mA deuteron beam measured emittance with SILHI like source

The $q/A=1/3$ ion source under study is a A-Phoenix type, running at 28 GHz and using high remanence magnet as well as high temperature superconducting (HTC) coils for the magnetic structure [6].

Preliminary emittance measurements have been performed on the existing 28GHz PHOENIX source, with a 1mA $^{16}\text{O}^{6+}$ beam, extracted at 60kV (fig.5).

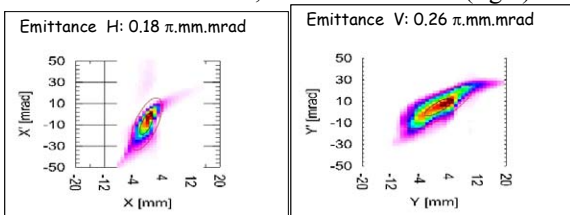


Figure 5: Emittance measurements on the LPSC PHOENIX source 1mA $^{16}\text{O}^{6+}$ beam

The next step will be to perform emittance measurements with a 1mA $^{36}\text{Ar}^{12+}$ beam, with a preliminary version of the A-PHOENIX source, in the next weeks.

RFQ

Preliminary studies were performed for different types of cavities (4-vanes, 4-rods, skirt-RFQ,...), and the final choice has been made in favour of a 4-vane structure, without any brazing and based on a mechanical assembly [7]. The main parameters of this RFQ are presented in Table 1.

Table 1: RFQ main parameters

Parameter	Value
Length	5.077m
Mean aperture R_0	8.1 – 10.0 mm
Vane voltage	100 – 113 kV
Modulation	1 – 1.99
Input rms emittance (π .mm.mrad)	0.2 (D^+) / 0.4 (1/3)
Transverse emittance growth	0
Peak electric field	1.65 kp
Transmission w/o errors	>99.9%
Transmission with errors	99.87%
Input energy	20 keV/u
Output energy	0.75 MeV/u

A 1meter prototype module has been built (fig.6), and will be tested at full power in INFN-LNS (Catania) at the beginning of September, before the final design of the complete RFQ.



Figure 6: RFQ prototype 1 meter module

Superconducting Linac

Several designs have been initially studied, with beam dynamics and RF considerations, assuming a 1 frequency (88 MHz) or 2 frequency linac (88 and 176 MHz), QWR and HWR for the different cavity families, superconducting solenoids or normal conducting quadrupoles for beam focusing, long or short cryostats. The final design has been frozen with the following parameters:

- 1 frequency machine: 88.05 MHz
- 2 β QWR families: 0.07 and 0.12, with a transition β of 0.11.
- normal conducting Qpoles for focusing
- short cryostats: 1 per cavity in the low beta part, and 1 for 2 cavities in the high beta part.

It appears to be safer from a technological point of view (simpler cryostats and alignments) and from the beam tuning point of view (one diagnostic box every cryostat), the acceptance, even if lower, being increased in the high beta family by a larger aperture of the cavity beam drift tubes. The beam dynamics calculations showed it was not necessary to tilt the accelerating gap walls in order to compensate the steering effect of the QWRs: it is corrected by the steerers placed inside the quadrupoles.

The QWRs have been designed in order to reach accelerating fields of 6.5MV/m in operation [8,9]. In the low beta family, among the 12 necessary cavities, only the 3 last cavities are tuned at the maximum accelerating field (for longitudinal phase advance reasons), and in the high beta part of the linac, beyond the 7 cryomodules, each of them containing 2 cavities, 2 spare cryomodules are planned to be installed if necessary (which would allow a maximum accelerating field of 5MV/m in that case).

The main parameters of the 2 β cavities are summarized in table 2.

Table 2: main parameters of the 2 QWRs

Optimal β	0.070	0.12
$E_{\text{peak}}/E_{\text{acc}}$	5.00	5.54
$B_{\text{peak}}/E_{\text{acc}}$ (mT/MV/m)	8.75	10.1
R_s/Q (Ω)	632	520
Quality factor Q_0	$2.2 \cdot 10^9$	$1.7 \cdot 10^9$
Cavity losses (@ $E_{\text{acc}}=6,5$ MV/m) (W)	1.75	8.2
Gasket losses (@ $E_{\text{acc}}=6,5$ MV/m) (mW)	26	-

The expected accelerating field in operation (6.5 MV/m) relies on: the choice of a high quality Niobium RRR250, a high quality electron beam welding, a high quality chemical etching and high pressure rinsing with high purity water. Two prototypes are under construction, one for each type of cavity, and the tests should be performed in November 2004 (fig.7).

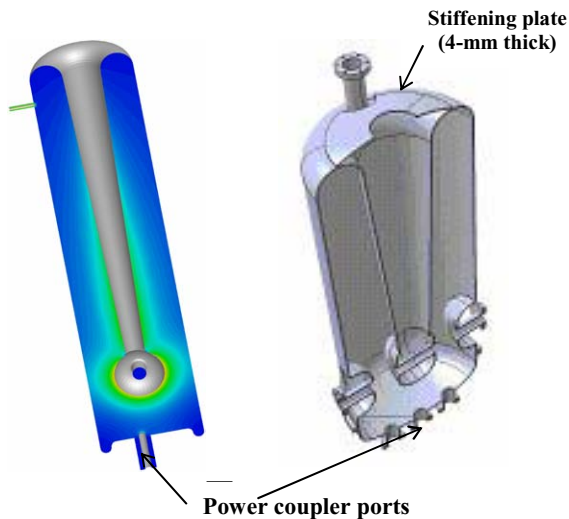


Figure 7: views of low beta (0.07) and high beta (0.12) SC linac QWR

The power coupler is under design [9], and is planned to be the same for both cavities, except the antenna penetration length. The beam load ranges from 1 kW to 13 kW, depending on the cavity position and beam intensity. Two types of ceramic windows are under design, disc and cylinder, and both prototypes are about to be constructed and will be tested at the beginning of 2005. The model with a ceramic disc window is presented in fig. 8.

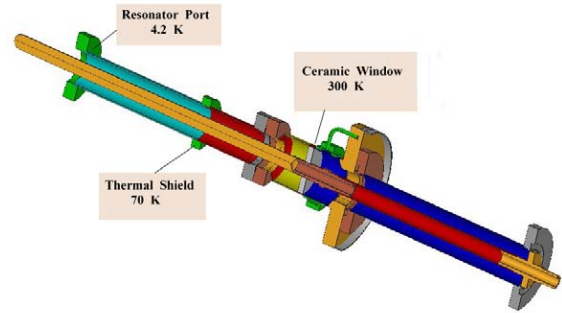


Figure 8: power coupler with ceramic disk window

For the cryostats, the choice was made to have small and simple cryostats (1 or 2 cavities), for technological and maintenance reasons. Besides, the use of tricky superconducting solenoids is avoided. The low beta family cryostat contains 1 cavity, and is box-shaped, with one door on each side for easy access, while the high beta family cryostat contains 2 cavities. For both types, the tube extremities are as short as possible, as well as the 70-4 K transitions and corresponding bellows, for beam dynamics reasons.

The warm sections, including 2 quadrupoles and 1 diagnostic box, are mechanically optimized to have very short longitudinal dimensions, as presented in fig. 9.

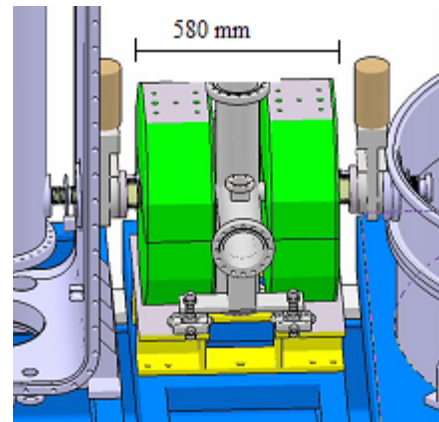


Figure 9: View of the SC linac warm section, including 2 quadrupoles and 1 diagnostic box

RF System

For the superconducting cavities, the choice of solid state technology has been made, for high reliability and ease of maintenance reasons [10]. The power required by the different cavities is mainly dominated by the beam loading, it will range from 1 to 13 kW. In the 88 MHz range (FM band), amplifiers around 30kW are now commercially available, the only difference between the FM broadcast applications and accelerator concerns the high voltage standing-wave ratio that is needed for superconducting cavity operation, and that requires the use of circulators.

For the RFQ cavity, a total power of 180 to 200kW has to be available at the amplifier exit: 150kW are required for the ion operation voltages (beam loading of a few kW), and 70kW are required for the deuteron operation voltage (beam loading around 7,5kW). The presently chosen solution is a set of 4 amplifiers, 50kW each, with circulators to eliminate coupling and oscillation risks; moreover, the cost of solid state amplifiers decreasing with time, it might be considered to use the solid state technology for the RFQ amplifier.

The Low Level RF system will be based on a digital solution, in order to fit the requirements of all the cavity types, RFQ, SC linac and normal conducting bunchers in the MEBT. Preliminary calculations show that a slow chopper can be used to tune the whole accelerator with a low mean intensity and the nominal peak intensity.

Cryogenics

The cryogenics system has been designed with a liquefier of 900W power at 4K (calculated required power at 4K: 570W), 2000W power at 60-80K (calculated: 1600W), and that must supply 10l/h for other uses (RF tests, various experiments).

The liquid helium will be produced from 1 (or 2) cold box(es) and stored in a 3000 litre tank. The helium gas will be stored in three 15 bar tanks (fig.10).

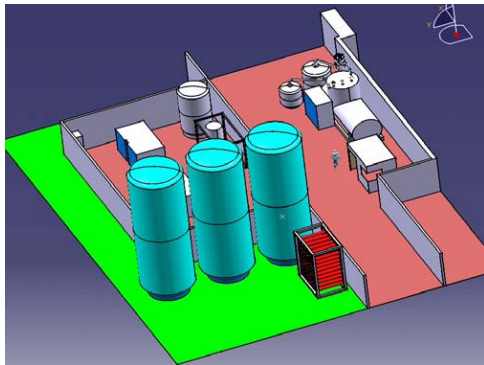


Figure 10: View of SPIRAL2 cryogenic plant

Mechanical Layout

The mechanical layout of the whole accelerator is under detailed design, and must take into account the strong longitudinal dimension constraints in the LEBT, MEBT and superconducting linac. Once the cryomodules, that contain only one or two resonators, are aligned onto the mechanical frame, their positions can be further adjusted in order to precisely re-align the

resonators according to beam trajectory measurements (fig.11).

CONCLUSION

The detailed study of the Spiral2 driver accelerator is almost completed. After the different prototype test results, that should occur around the end of 2004, the various designs will be frozen, in order to launch the calls for tender of the various components as soon as the decision on the project construction is taken.

REFERENCES

- [1] W.Mittig et al, "LINAG Phase1", Ganil internal report, June 2002, <http://www.ganil.fr/research/sp/reports>
- [2] A.Mosnier for the Spiral2 project team, "SPIRAL2: a high intensity deuteron and ion linear accelerator for exotic beam production", PAC 2003, Portland, USA, May 2003, p.595
- [3] R.Duperrier et al, "Beam dynamic development for the SPIRAL2 project- Intermediate report", SPIRAL2 internal report, January 2004, <http://www.edms.in2p3.f>.
- [4] R.Duperrier et al, "Status report on the beam dynamics developments for the SPIRAL2 project", EPAC 2004, Luzern, Switzerland, July 2004.
- [5] R.Gobin et al, "Development of a permanent magnet ECR source to produce a 5mA deuteron beam at CEA/Saclay", LINAC2004, Lübeck, Germany, August 2004.
- [6] T.Thuillier et al, "Advanced magnetic calculations for high magnetic field compact ion source", Rev. Sci. Instrum., Vol. 75, 5 (2004) .
- [7] R.Ferdinand et al, "SPIRAL2 RFQ design", EPAC 2004, Luzern, Switzerland, July 2004
- [8] P.-E. Bernaudin et al, "Design of a low-beta, quarter-wave resonator and its cryomodule for the SPIRAL2 project", EPAC 2004, Luzern Switzerland, July 2004.
- [9] T.Junquera et al, "High intensity linac driver for the SPIRAL2 project: design of superconducting 88 MHz quarter-wave resonators, power couplers and cryomodules", EPAC 2004, Luzern, Switzerland, July 2004.
- [10] M.Di Giacomo et al, "Preliminary design of the RF systems for the SPIRAL2 linac", EPAC 2004, Luzern, Switzerland, July 2004.

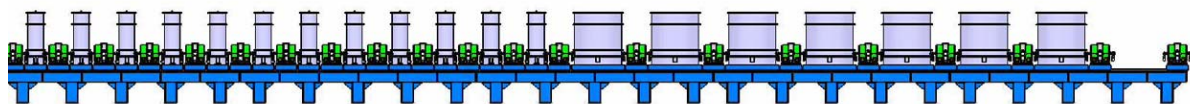


Figure 11: Superconducting linac layout