HEBT LINES FOR THE SPIRAL2 FACILITY

L. Perrot#, J.L. Biarrotte, IPNO-IN2P3-CNRS, Orsay, France
P. Bertrand, G. Normand, GANIL, Caen, France
D. Uriot, SACM/IRFU/DSM/CEA, Saclay, France

Abstract

The SPIRAL2 facility at GANIL-Caen is now in its construction phase, with a project group including the participation of many French laboratories (CNRS, CEA) and international partners. The SPIRAL2 facility will be able to produce various accelerated beams at high intensities: 40 MeV Deuterons, 33 MeV Protons with intensity until 5 mA and heavy ions with q/A=1/3 up to 14.5 MeV/u until 1 mA current. We will present the status of the beam dynamics studies recently performed for the high energy beam transport lines of the facility. Various studies were performed on beam-dump concerning beam dynamics, safety and thermo-mechanical aspects. New experimental areas using stable beams and the cave dedicated to radioactive ion production will be presented according the scientific program.

INTRODUCTION

The construction phase of SPIRAL2 is already launched within a consortium formed by CNRS, CEA and the region of Basse-Normandie in collaboration with French, European and international institutions [1, 2]. The facility will deliver high intensity rare isotope beams for fundamental research in nuclear physics, high intensity stable heavy ions beams, and high neutron flux for multidisciplinary applications. SPIRAL 2 will give access to a wide range of experiments on exotic nuclei, which have been impossible up to now. In particular, it will provide intense beams of neutron-rich exotic nuclei (10^6–10^{10} pps) created by the ISOL production method. The extracted ion beams will subsequently be accelerated to higher energies (up to 20 MeV/nucleon) by the existing CIME cyclotron, typically 6–7 MeV/nucleon for fission fragments. A low energy branch will be built to transport the beam to the DESIR hall. High intensity stable isotope beams and high power fast neutrons are other major goals of the facility. After two years of preliminary study, and following the decision to launch the construction phase, a complete design of the driver accelerator is presently under way [3]. This paper describes the studies performed on the high energy beam transport lines which deliver stable beams to experimental areas, radioactive production cave and beam dump.

GENERAL LAYOUT OF THE DRIVER ACCELERATOR

The driver accelerator delivers CW beams of deuterons (40 MeV, 5 mA) and heavy ions (q/A=1/3, 15 MeV/A, 1 mA). The injector is composed of two ion sources (deuterons and heavy ions) and a common RFQ cavity (88 MHz) [4]. The superconducting LINAC is composed of two sections of quarter-wave resonators (QWR), beta 0.07 and 0.12 at the frequency of 88 MHz, with room temperature focusing devices [5, 6]. After the LINAC, ions are transported using various high energy beam transport (HEBT) lines according to experimental programs. Beams can be transported to the beam-dump, to experimental areas like the Neutrons For Science (NFS) area, the Super Separator Spectrometer (S3) or to the converter of the radioactive ions production area.

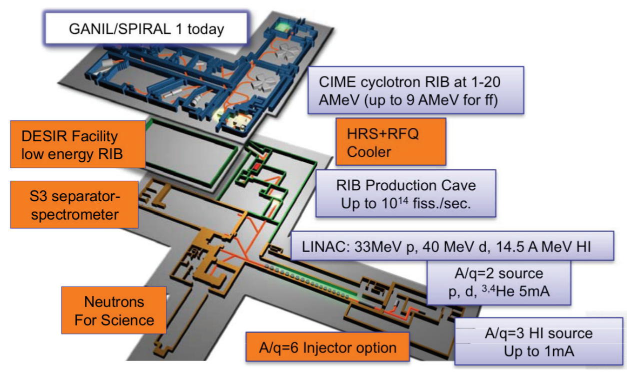

Figure 1: General scheme of the SPIRAL2 facility.

It must be noticed that in a second phase of SPIRAL2, a heavy ion source with q/A=1/6 will be built with its associated injector. The LINAC will accelerate these ions up to 8.5 MeV/u. This point must be taken into account for the design of the HEBT lines.

SPIRAL2 HEBT LINES

This paper will only focus on the beam transport description after the superconducting LINAC. In a first subsection we will give a compilation of the beam characteristics at the LINAC exit. In a second subsection, we will give the structure of the HEBT.

The well known TRACEWIN code is used for all beam dynamics calculations [7].

Beams Characteristics after the LINAC

From TRACEWIN, we extract transverse and longitudinal beam characteristics for all species after the LINAC. They are used as inputs for HEBT lines calculations. As an example, we give here a compilation for deuterons at minimum and maximum available energies (cf. Tab. 1).

#perrot@ipno.in2p3.fr

Table 1: Beam Specifications at the LINAC Exit for Deuteron Beams

Deuterons	E=40 MeV	E=4 MeV
X-X’	E_{norm}=0.1797 π.mm.mrad Beta=1.0691 mm/π.mrad Alpha=-0.0729	E_{norm}=0.1733 π.mm.mrad Beta=1.1194 mm/π.mrad Alpha=-0.105
Y-Y’	E_{norm}=0.2090 π.mm.mrad Beta=2.5362 mm/π.mrad Alpha=-1.1941	E_{norm}=0.1783 π.mm.mrad Beta=3.6565 mm/π.mrad Alpha=-1.5975
Z-Z’	E_{norm}=0.3301 π.mm.mrad Beta=7.0461 mm/π.mrad Alpha=-0.1228 rms Phase=-1.74 ° rms E=0.04 MeV	E_{norm}=0.4415 π.mm.mrad Beta=30.3660 mm/π.mrad Alpha=-0.5693 rms Phase=-22.6 ° rms E=0.005 MeV

HEBT Structure

Since the preliminary design study phase, various designs have been studied, according to the evolution of physics requirements. In addition, a lot of parameters have to be taken into account: beam dynamics of various ion species at various energies, measurements (beam profiles, position, energy, phase, emittance, current, power loss) using different techniques, quadrupoles, dipoles, and steerers sizes and locations, valves, vacuum pumps. Transport lines cost and building implantation are also some crucial aspects. Finally, a major pressure on the HEBT design is the safety and radioprotection.

Present design takes into account most of these previous listed parameters (cf. Fig. 2).

HEBT lines are designed with a limited number of repeated structures. The basic idea for this type of structure is taken from the existing “arête de poisson” at GANIL:

- matching sections composed of 4 quadrupoles are used at the LINAC exit, for the beam dump, and at the entrance of each experimental room;
- triplet or sextuplet sections are used for transport, with repetitive transverse waists and periodic envelopes;
- achromatic double deviations are used for beam distribution and protection of targets against energy fluctuations.

The HEBT beam dynamics scheme is such that we have always the same radial envelopes, up to an homothetic, according to the type of beam and the final energy.

For the beam transport in the transverse plane, the most important is to properly match the beam with the first section at 4 quadrupoles (cf. Fig. 3). Quadrupoles adjustment is obtained with 3 diagnostics at equal distances. Same beam size for the two extreme diagnostics (D1 and D3) is required; a central diagnostics (D2) will tune a beam waist with RMS size in both planes verifying relation:

$$Size_{x,y} = \sqrt{\frac{L\varepsilon_n}{\sqrt{3}\beta\gamma}} \,. \qquad (1)$$

where L is the distance between 2 consecutives diagnostics (L=1863 mm), ε_n is the normalized transverse emittance in x and y and β, γ the particle speed and the Lorentz factor. RMS beam size values at the waist diagnostic are from 1.0 mm up to 2.1 mm.

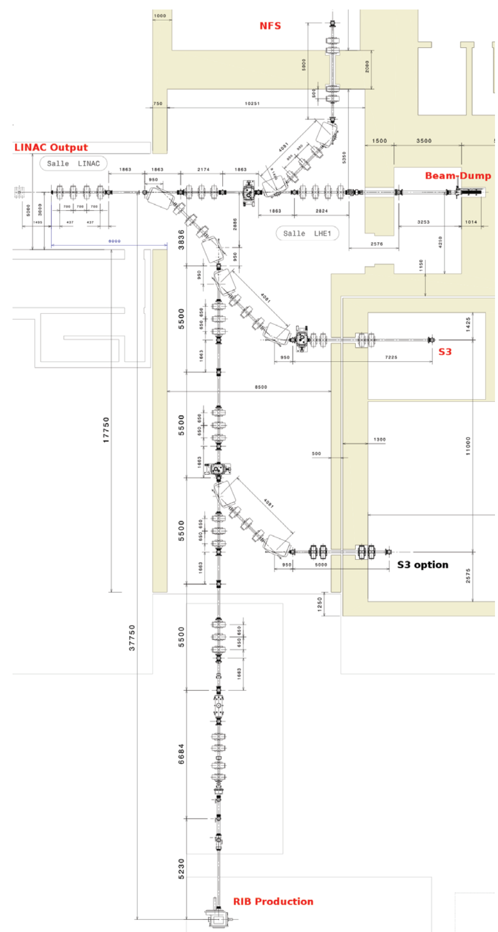

Figure 2: Detailed HEBT lines of SPIRAL2.

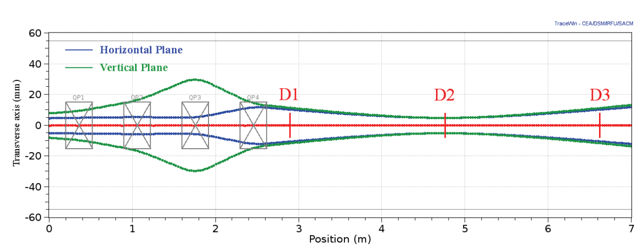

Figure 3: Transverse beam envelopes at 5 RMS for deuterons at 40 MeV in the matching section following the LINAC.

An important feature will be the measurement precision and reproducibility provided by secondary emission profilers at low intensity. The impact of this type of errors on HEBT lines is presently under study.

Other repeated sections (triplet, sextuplet and deviation sections) are tuned using a magnetic rigidity scale.

Components in connection with the beam dynamics can be summarized:

- 44 quadrupoles with internal diameter 120 mm, L_m=120 mm;
- 2 rectangular dipoles at 45° with ρ=1.4 m, gap=100 mm;
- 4 rectangular dipoles at 45° with ρ=1.5 m, gap=100 mm;
- 2 SC cavities (β=0.07) used to provide very short bunch time lengths required by NFS and S3;
- 14 steerers (both transverse planes), one per section;
- 27 EMS profilers;
- energy measurement (using diamond detector and/or time of flight method) ;
- phase measurement;
- few beam position monitors, beam loss monitors;
- intensity measurements using ACCT, DCCT.

We can now present beam characteristics requirements for the heavy ions experimental areas, beam dump and radioactive ions production area.

RIB PRODUCTION

As we have already seen, the SPIRAL 2 facility will deliver a high intensity, 40 MeV deuteron beam as well as a variety of heavy-ion beams with mass over charge ratio equal to 3 and energy up to 14.5 MeV/n. Using a carbon converter, fast neutrons from the breakup of the 5 mA of deuterons impinging on a uranium carbide target will induce a rate of up to 10^{14} fissions/s. The RIB intensities in the mass range from A=60 to A=140 will be of the order of 10^6 to 10^{11} part./s surpassing by one or two orders of magnitude any existing facilities in the world [8]. A direct irradiation of the UC2 target with beams of deuterons, ^{3,4}He, ^{6,7}Li, or ^{12}C may also be used if higher excitation energy leads to a higher production rate for a nucleus of interest.

SPIRAL 2 would allow to perform experiments on a wide range of neutron- and proton-rich nuclei far from the line of stability (cf. Fig 4) using different production mechanisms and techniques to create the beams.

According to the technical risk for the project to start with a 200 kW deuterons beam on the converter, it has been decided to increase the beam current progressively. That is why, in a first step of operation, beam power will be limited at 50 kW. Objectives are in particular the validation of the carbon converter, target system, safety.

In addition, for thermo-mechanical constraints, the converter at 50 kW must be representative to the conditions at 200 kW. It is only in a second step that the beam power will increase until the 200 kW nominal value.

In this context, considering a Gaussian beam in X and Y directions, the maximum beam power for 50 kW at the center must be identical to 200 kW. For the full beam power, size at ±3 RMS will be 40 mm. Therefore, the beam size for 50 kW will be 10 mm at ±3 RMS.

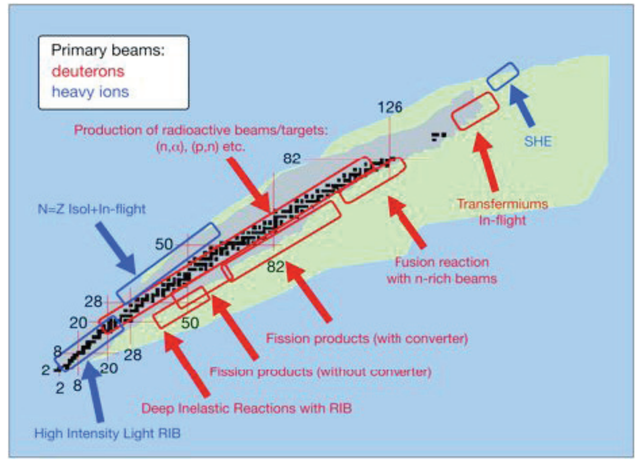

Figure 4: Regions of the chart of nuclei accessible for research on nuclei far from stability at SPIRAL2.

From the HEBT lines point of view, the major constraint comes from the Deuterons beam at 40 MeV and 5 mA current (cf. Fig. 5).

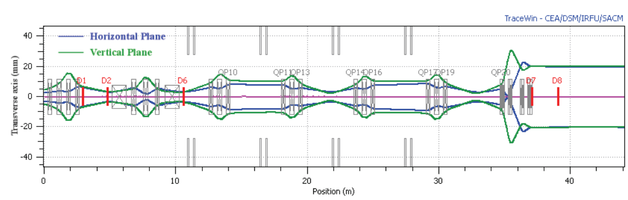

Figure 5: Transverse beam envelops at ±3 RMS for deuterons beam at 40 MeV, 5 mA from LINAC exit up to RIB production target.

Careful studies are in progress to choose the most appropriate method to match the beam on the converter. It must also demonstrate the absolute reproducibility of the quadrupoles matching for safety reasons.

BEAM-DUMP

The LINAC Beam dump (BD) is dedicated to the commissioning of the facility. It will be used during the beam tuning, for beam control and qualifications. Beam dump must be able to accept 200 kW beam power (40 MeV, 5 mA Deuterons) on the thermo-mechanical point of view. To restrict BD activation, beam power actual limit is 10 kW during 1 hour per day in normal operation.

The SPIRAL2 beam dump is located at 21 m in the straight line of the LINAC (cf. Fig 2). BD entrance is located 6 m from the last quadrupole which is imposed by a dedicated room. An optimized beam-dump geometry profile has been defined: 20 copper blocs of 50 mm long and 130 mm external diameter. Each bloc is drilling with internal cone shape to accept 10 kW beam power in normal operation (cf. Fig. 6). From this basic structure, some improvements have been done.

Transverse beam characteristics at BD entrance must be independent of the species and their energy. Using last 4^{th} quadrupoles, we match the beam to obtain transverse beam distributions at the BD entrance around 14 mm and 2.5 mrad RMS. For this condition, no deposited beam power is observed before the beam-dump.

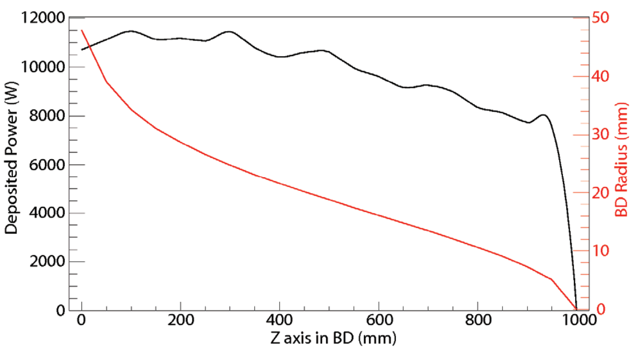

Figure 6: Beam-dump profile and deposited power for initial 200 kW beam power.

NEUTRONS FOR SCIENCE

The deuteron and proton beams delivered by the SPIRAL2 LINAC are particularly well suited to produce high energy neutrons in the 1 MeV – 40 MeV energy range. The NFS area will be composed of mainly two rooms: a converter room where neutrons are produced by the interaction of deuteron or proton beams with thick or thin converters, and an experimental hall with a well collimated pulsed neutron beam. A white neutron source from 1 up to 40 MeV energy range and quasi mono-energetic neutron beam will be available. This facility is of first importance for academic research and applied physics. Several research areas will be covered by NFS, such as the study of the fission process, the transmutation of nuclear waste, the design of future fission and fusion reactors, the nuclear medicine or the test and development of new detectors, etc. In addition, cross-section measurements of neutron- and deuteron- induced reactions could be realized by activation technique in a dedicated irradiation station [9]. This experimental area will be also used to study materials under irradiation (dpa, neutron damage) in atomics physics fields.

As we can see only light particles beam will concern NFS area: deuterons, protons, helium. For safety reason, maximum current will be limited to 50 μA for D-beam at 40 MeV. Neutrons ToF experiments impose a fast chopper able to select 1/100 beam pulse. The fast chopper is under study, and will take place in the Medium Energy Beam Transport (MEBT) line of SPIRAL2. Beam sizes on targets or converters are 4 mm RMS in X and Y with a variable focal point. Neutrons ToF experiments require a short time pulse length ($\Delta T \sim 1$ ns at ±3 RMS) which is almost realized using a β=0.07 cavity place before the achromatic deviation along the HEBT line (cf. Fig. 7).

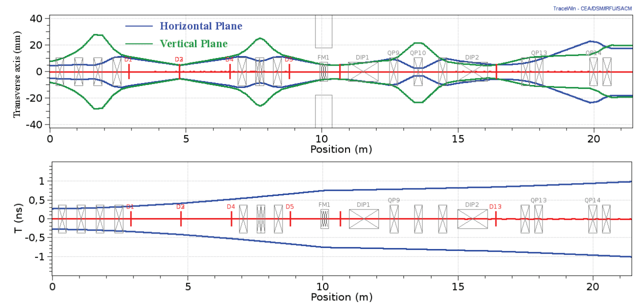

Figure 7: Transverses and longitudinal beam envelopes at ±5 RMS for Deuterons beam at 40 MeV, 5 mA from LINAC exit up to NFS area.

Additional studies have been done on the dynamic of the primary beam (slow down in the converter, deviation using a dipole and stop with a dedicated system). Complementary calculations will be done to take into account all the processes in the NFS target area.

SUPER SEPARATOR SPECTROMETER

S3 is a device designed for experiments using the very high intensity stable beams of LINAC. These beams, which will be provided in a first phase of SPIRAL2 ions with A/q=3 (and in a 2^{nd} step A/Q=6), can reach intensities exceeding 100 pμA for light ions (A<40-50). These unprecedented intensities open new opportunities in several physics domains, e.g. super-heavy and very-heavy nuclei, spectroscopy at and beyond the dripline, isomers and ground state properties, multi-nucleon transfer and deep-inelastic reactions. All of the experiments have the common feature of requiring the separation of very rare events from intense backgrounds. S3 will have a large acceptance and clearly must have excellent primary beam suppression.

Primary beam requirements on target are:

- 0.2 ns time pulse length at ±3 RMS (in a second phase of operation). This feature imposes to use a b=0.07 cavity placed after the deviation (cf. Fig. 2);
- $\Delta E/E<0.5\%$ at ±3 RMS. This feature will be almost fixed by the LINAC characteristics;
- transverse flat beam, ±1 mm in X , ±10 mm in Y.

Transverse beam requirements have been carefully studied. First of all, it is theoretically possible to use some sextupoles [11, 12]. But beam sizes are too small to obtain a stable solution. Otherwise, the variety of beams and energies would impose to have a large set of values for the sextupole tuning. In complement, real transverse distributions present large peak power densities at the extreme positions, and distributions are largely sensitive to the beam position in the line. This solution was eliminated. According to Shafer remarks [13], we proposed to use also a beam raster magnet only in the vertical plane placed after the last quadrupole of the matching line and at a distance of 2.7 m before the S3 target. Beam spot with 2 mm at 3 RMS in X and Y direction can be provided. In this configuration, the field gradient in the raster magnet with a magnetic length of

0.2 m will be less than 500 G, fixed by the heavy ions with A/q=6 at 8.5 MeV/u. It can be noticed that the beam will have an oscillation angle on the target of less than ±4 mrad.

Beam dynamics studies have been done (cf. Fig 8). Impacts on the S3 rotating target and beam dynamic in S3 are not yet available. Technical design for the beam raster magnet is also under study.

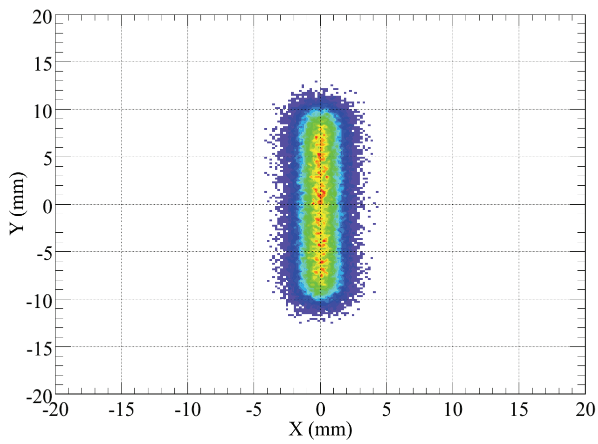

Figure 8: Integrated beam spot at the S3 target position for heavy ions with A/q=3 to all energies.

CONCLUSION

In this paper, we introduced the status of the High Energy Beam Transport Lines of the SPIRAL2 facility in connection with target location of the experimental areas NFS and S3. The beam dump has been also presented. RIB production line beam optics has been described. In each case, careful attention is taken to provide the beam characteristics required by each line end.

Various beam dynamics studies have been done in connection with safety aspects. The project objective in this field is to have less than 1 W/m beam power loss.

Up to now, new precise error calculations of the whole machine must be done [14].

Precise mechanical design of the HEBT lines will be available until the end of 2009 which will coincide with the permission for construction grant. First beams will be produced at the beginning of 2012 for stable beams and experimental areas (NFS or S3). RIB production will start for physics experiments at the end of 2013.

REFERENCES

[1] T. Junquera et al., "Superconducting Driver Linac for the New Spiral 2 Radioactive Ion Beam Facility GANIL".

[2] The SPIRAL2 Project Reports 2005-2006 http://www.ganil.fr/research/developments/spiral2.

[3] T. Junquera, “Status of the Construction of the SPIRAL2 Accelerator at GANIL”, TU102, LINAC 2008, Vancouver, Canada.

[4] R. Ferdinand, “SPIRAL2 RFQ Prototype – First Results”, MOPCH103, EPAC06, Edinburgh, Scotland.

[5] G. Devanz et al., “Status of the Low Beta Cryomodules For The SPIRAL2 LINAC”, THP007, LINAC 2008, Vancouver, Canada.

[6] Saugnac et al., “RF and Crygenic Tests fo the First Beta 0.12 SPIRAL2 Cryomodule”, THP009, LINAC 2008, Vancouver, Canada.

[7] http://irfu.cea.fr/Sacm/logiciels/

[8] M-G Saint-Laurent on behalf of the Spiral2 project group, “Future opportunities with Spiral2 at GANIL”, AccApp07, Pocatello, Idaho, July 30-August 2nd, 2007.

[9] X. Ledoux on behalf of the NFS Collaboration, “Status Report of the NFS collaboration”, 2008, December.

[10] H. Savajols on behalf of the S3 Collaboration, “Technical Proposal for the Spiral2 Instrumentation: S3 Spectrometer ”, 2008, December.

[11] N. Tsoupas et al., “Uniform Particle Beam Distributions Produced by Octupole Focusing”, Nuclear Science and Engineering, 126, 71-79 (1997)

[12] A. J. Jason et al., “Uniform Ribbon-Beam Generation for Accelerator Production of Tritium”, M02-58, LINAC88, Cebaf, USA

[13] R. E. Shafer, “Comment on Uniformization of the transverse beam profile by means of nonlinear focusing method”, Phys. Rev. Spe. Topics – Acc. & Beams, 11, 039001, 2008.

[14] R. Duperrier, D. Uriot, “Application of the extreme value theory to beam loss estimates in the SPIRAL2 linac based on large scale Monte Carlo computations”, Phys. Rev. ST Accel. Beams 9, 044202 (2006).