ISBN: 978-3-95450-204-2 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2019-MOPP036

SPIRAL2 DIAGNOSTIC QUALIFICATIONS WITH RFQ BEAMS

C. Jamet†, S. Leloir, T. Andre, V. Langlois, G. Ledu, P. Legallois, F. Lepoittevin, T. Le Ster, S. Loret, C. Potier de courcy, R.V. Revenko, GANIL, Caen, France

Abstract

The SPIRAL2 accelerator, built on the GANIL's facility, at CAEN in FRANCE is dedicated to accelerate light and heavy ion beams up to 5mA and 40 MeV. The continuous wave accelerator is based on two ECR ion sources, a RFQ and a superconducting LINAC. The beam commissioning of the RFQ finished at the end of 2018. This paper presents the Diagnostic-Plate installed behind the RFQ, with all associated accelerator diagnostics. Diagnostic monitors, measured beam parameters, results are described and analyzed. A brief presentation of the next steps is given.

INTRODUCTION

The SPIRAL2 facility is designed to produce deuteron and proton beams with the first ECR source and ion beams with the second source. The acceleration is given by a CW RFQ (A/Q ≤ 3) and a high power superconducting linac. Table 1 recalls the main beam characteristics.

Table 1: Beam Characteristics

Beam	P	D+	Ions (1/3)
Max. Intensity	5 mA	5 mA	1 mA
Max. Energy	33 MeV	20 MeV/A	14.5 MeV/A
Max. Power	165 kW	200 kW	43.5 kW

The linac is composed of 19 cryomodules, 12 with one cavity (ß=0.07) and 7 with 2 cavities (ß=0.12).

The HEBT lines distribute the linac beam to a beam Dump, to the NFS (Neutron For Science) or S3 (Super Separator Spectrometer) experimental rooms.

Major challenges are to handle the large variety of beam characteristics (particle types, beam currents from few 10µA to few mA, wide energy range), the high beam powers (up to 200 kW CW) and the safety issues [1].

The first commissioning phase consisted to qualify the RFQ beams with a Diagnostic Plate (D-Plate), this injector commissioning took place from the end of 2015 up to 2018. The D-Plate was removed to install the full MEBT at the beginning of 2019.

Three different beams were chosen, Proton, Helium and Oxygen, to qualify the injector performances. Argon beam was also measured.

The 5mA proton beam is easy to produce but more difficult to transport in the LEBT due to the space charge forces. 4He2+ was selected to mimic the future deuteron beam without neutron production due to the d-d reactions.

It also allowed to test the heavy ion ECR source and LEBT1 [2].

The same accelerator frequency, on all the RF devices, is 88.0525 MHz.

The RFQ beam power is to 3.5 kW with 5 mA of protons and 7 kW with Helium. In order to limit the beam losses in the D-Plate and on the various interceptive diagnostics, the duty cycle applied on the chopper was usually around of few ms per few 100 ms.

INJECTOR AND D-PLATE DESCRIPTION

The injector schematic is given in Fig. 1.

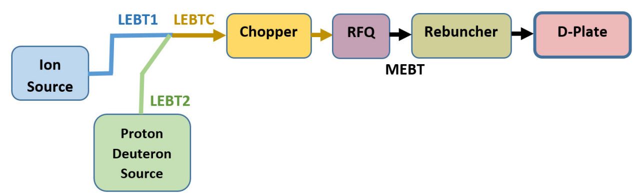

Figure 1: Injector Diagram.

The D-Plate (named BTI in French: Intermediate Test Bench) was defined to characterize the beams from the RFQ and also to qualify the SPIRAL2 diagnostic monitors.

Three quadrupoles, one rebuncher (Fig. 2) were installed behind the RFQ to tune the beam transport in both transverse and longitudinal planes. The D-plate allowed to measure:

- Intensities with Faraday cups, ACCT and DCCT,
- Transverse profiles with classical multi-wire profilers and Residual Gas Monitor (RGM)
- H and V transverse emittances with Allison type scanners
- Energies with a Time of Flight (TOF) monitor,
- Phases with the TOF and 2 BPMs
- Longitudinal profiles with a Fast Faraday Cup (FFC), and a Beam Extension Monitor (BEM)
- Beam position and ellipticity ($\sigma_x^2 - \sigma_y^2$) with the BPMs

The D-Plate was a workpackage supported by the French Laboratory IPHC. This CNRS laboratory had in charge the mechanical design and the supply of the D-Plate.

† christophe.jamet@ganil.fr

ISBN: 978-3-95450-204-2 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2019-MOPP036

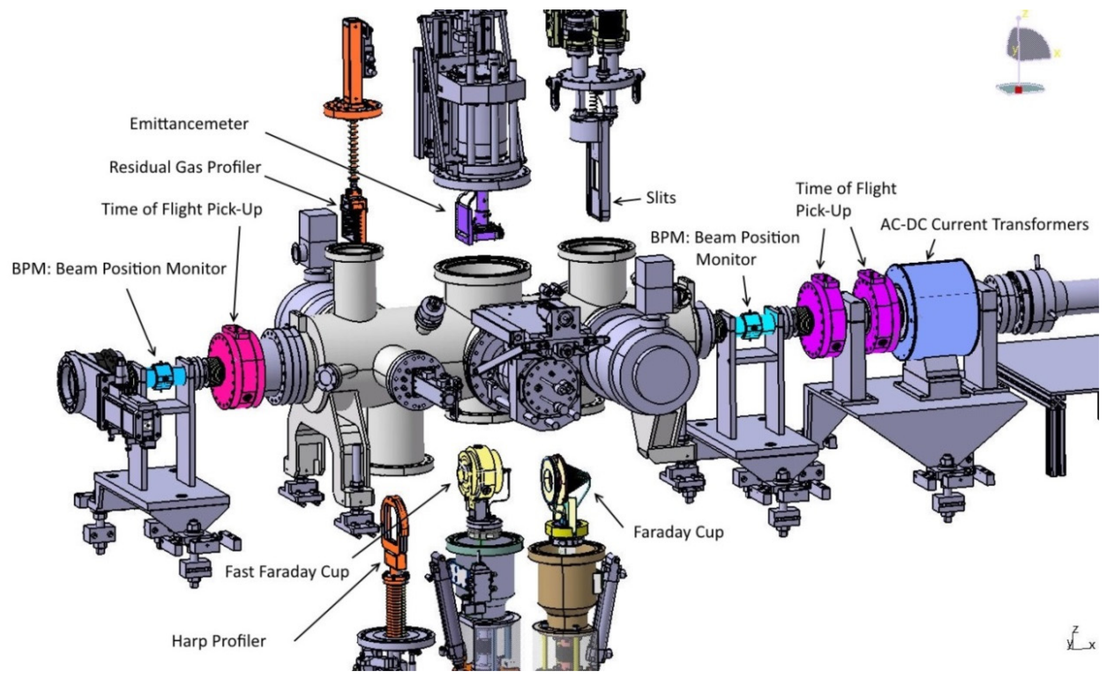

Figure 2: Extracted View of the D-Plate.

INTENSITY MONITORS

Two types of water cool Faraday cups are installed, a 100 mm aperture in the LEBT and 60 mm in the MEBT.

A DCCT bloc (New PCT from Bergoz Company) is located just at the entrance of the RFQ and an ACCT-DCCT bloc is installed at the end of the D-Plate. The ACCT transformer is a nanocrystalline torus with winding turns ratio of 300:1, built at GANIL.

Two complementary intensity measurements are available, the average and the peak intensity measurements. The average is measured, controlled with a special electronic that integrates the signal over 1s [3].

The intensities values are digitalized with a fast acquisition cards and displayed on screens like an oscilloscope. The peak value is the value measured in a time zone defined by users when the beam is on (chopper voltage off).

The tests of the intensity monitors consisted of validating and quantifying the accuracy of intensity and transmission measurements. The transmission measurements are important to verify the RFQ and linac efficiencies [4].

All the intensity monitors can be tested separately with the same test signal. A current generator and a distributor are controlled remotely to inject the current of test.

With Faraday cups, the average transmission deviations are under 0.2%, and with peak measurements around 1%. The main transmission deviation of DCCT is due to the offset variation, around 10µA in few minutes with a temperature regulation.

A lot of actions were done to minimize the perturbations and the noises on the ACCT chains, displacement of the preamplifiers near the transformers, cable shielding, and specific cable paths. We obtain a level of noise with a factor of 2 in comparison with the laboratory level.

ACCT : Noise 20nA / Clamp 5µA / Offset 100nA

DCCT : Noise 4µA / Offset variation 30µA

The difference between ACCT and DCCT is around 0.2% with a beam intensity of 4.5 mA. Transmission measurements give an RFQ efficiency close to 100%. The management of thresholds and alarms with the Machine Protection System (MPS) were also tested.

TRANSVERSE PROFIL MONITORS

Two different kinds of profile monitor were installed on the D-Plate. A “classical”, multi-wire profilers and a residual gas profiler [5]. On the D-Plate, the multi-wire profiler is composed of 47 wires with a constant spacing of 1mm. The wire diameter is 150µm. It analyze the X and Y planes, providing the centroid position, sigma σ, and various values on each planes. Behind the RFQ, the wires support a DC up to 1ms/s for the 5mA proton beam.

The Residual Gas Monitor (RGM) developed at GANIL were tested with pulsed and CW proton beams at currents up to 5 mA [6]. The devices are based on ionization of the residual gas in the beam transport lines under the impact of the high-energy ion beams. The charged ions or the electrons produced in the residual gas drift by means of electrical or magnetic fields onto a position sensitive detector, such as a micro-channel plate (MCP), which amplifies the collected charge. Two RGM were installed on the D-plate. Profile comparison with SEM profiler have been made with protons and Helium beams at intensities from 0.1 mA to 5 mA.

A size increase of 30% was observed on the RGM profiler compared to the SEM profile and an increase of 12% with a beam intensity of 1mA in comparison of 0.28 mA (Fig. 3).

ISBN: 978-3-95450-204-2 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2019-MOPP036

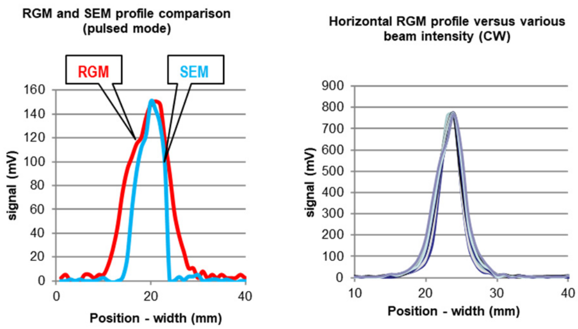

Figure 3: Beam profiles obtained with RGM.

EMITTANCEMETERS

Water cooled scanner emittancemeters also named Allison Scanner are installed in the LEBT and in the D-Plates (Fig. 4). The supply of two LEBT and one MEBT emittancemeters was taken care of by the French laboratory IPHC.

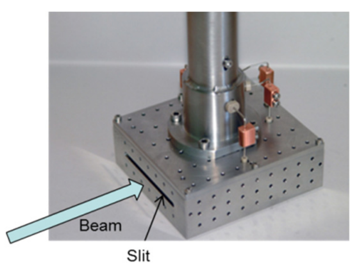

Figure 4: Emittancemeter Head.

Table 2 gives the main characteristics of the MEBT emittancemeter installed on the D-Plate.

Table 2: MEBT Emittancemeter Characteristics

Slit gap	0.12 mm
Max. Deviation Voltage	8 kV
Max. Beam Power Density	1 kW/cm^2
Max. Emittance	1 π.mm.mrad
Min. Emittance	0.01 π.mm.mrad
Position accuracy	< 0.1 mm
Angle accuracy	< 0.1 mrad

The emittances measured in LEBT1, LEBTc and behind the RFQ (MEBT) were compared with the simulations, like for the 5 mA H+ beam (Fig.5).

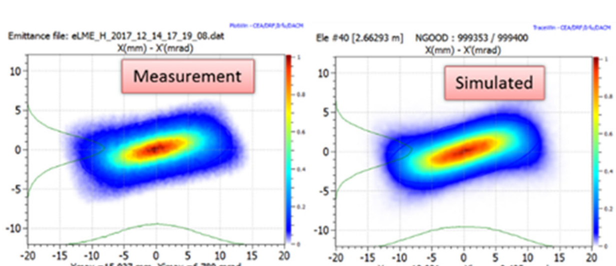

Figure 5: Phase space distribution in the MEBT.

The MEBT transverse emittances are in agreement for all the tested particles, while for the LEBT beam the discrepancy can be explain by the unknown exact sources extraction beam and their associated transport simulation.

LONGITUDINAL PROFIL MONITORS

Two different diagnostics were developed to measure longitudinal profiles, a Fast Faraday Cup (FFC) [7] and a Bunch Extension Monitor (BEM).

The FFC is a coaxial Faraday with the outer conductor, cooled by water, and the inner conductor cooled by conduction via tree ceramic rods. The return loss measured with a VNA Analyzer gives an attenuation of 10 dB at 2 GHz. The FCT limited bandwidth causes a standard deviation of the pulse enlargement between 120 and 160 ps.

In 2016, first FFC measurements with the beam show oscillations at 266 MHz due to the metal shield in front of the cup. A resonance was caused by the shield capacitance and the inductance of a little cable which connected this shield to the ground. The solution, taken quickly, was to connect the shield with pieces of copper foil to the ground and decrease the inductance.

After disassembly of the cup in 2018, several modifications have been tested to improve the shield connection and optimize the return loss.

The front part which supports the grid and the shield is now made of copper instead of insulating (Fig.6).

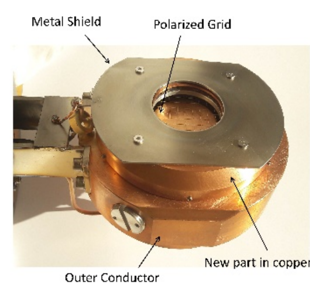

Figure 6: FFC picture.

The new return loss, with an attenuation of 4 dB at 3 GHz, is much better than before. Its installation in the MEBT is planned in September 2019, we expect good improvements in accuracy.

Bunch Extension Monitor (BEM) [8] is based on the registration of X-rays emitted by the interaction of the beam ions with a thin tungsten wire (Fig.7). The time difference between detected X-rays and accelerating RF gives information about distribution of beam particles along the time axis. These monitors are installed inside diagnostic boxes on the first five warm sections of the LINAC. The monitor consists of two parts: X-ray detector and mechanical system for positioning the tungsten wire into the beam. Emitted X-rays are registered by microchannel plates with fast readout. Signal processing is performed with constant fraction discriminators and TACs coupled with MCA.

The estimated temporal resolution σ = 47 ps corresponds to1.5° of phase resolution at 88 MHz.

ISBN: 978-3-95450-204-2 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2019-MOPP036

Figure 7: X-ray detector (left) and mechanical system for wire insertion (right) of BEM.

Series of tests for BEM with different beams have been performed during the commissioning phase. These measurements have shown good agreement with simulation data. The longitudinal emittance could be measured by using BEM [9].

An option of current measurements in the wire was realized and tested. These option permits to measure beam distribution on the axis of wire insertion and make positioning of tungsten wire in the beam center.

PHASE & ENERGY MONITORS

Time Of Flight (TOF) monitor is dedicated to calculate the beam energy by measuring beam Phases [7]. Three phase probes are installed on the D-Plates.

Phase measurements and energy calculations were also done with the 2 BPM probes. The main test consisted to scan the rebuncher phase and to compare beam energy measurements between the probes (TOF1/TOF2), (TOF1/TOF3), (BPM1/BPM2).

For a helium beam, a RFQ voltage of 80kV and a rebuncher voltage of 90 kV, the energy was measured at 727 keV/A. The 360° scan in phase gives a beam energy variation ranging from 686 keV/A to 784 keV/A. The maximum difference measured between TOF probes is 0.05%, below the accuracy requirement of 0.1%. Between TOF and BPM probes, the maximum difference is 0.2% which is also acceptable.

Energy measurements were also used to validate the TOF electronic for the linac. The beam energy measurement at the linac exit will verify that the energy does not exceed the operating range of the accelerator. The manufacturing and the commissioning of this energy surveillance have to comply with quality assurance rules. FMEA (Failure Mode and Effects Analysis), measurement uncertainties, threshold management were realized to respect these requirements. The main verifications, with the RFQ beams, concerned the studies of noise levels, energy differences between probes, the management of the phase jump in case of bunch number changes, thresholds and alarm managements. The control system was validated after corrections and optimizations.

The BPM and TOF were used to validate the cavity tuning procedure using the signature matching method we intend to use for the LINAC cavity tuning [10].

POSITION & ELLIPTICITY MONITORS

The French Laboratory IPNO is in charge of the SPIRAL2 BPM furniture, this concerns the installation of 20 BPM monitors on the linac [11]. The Accelerator Control Division of Bhabha Atomic Research Centre (BARC *) realized the BPM Electronics modules as part of a collaboration with the SPIRAL2 project. The electronic modules, composed by an analog and digital cards, were designed to measure position, ellipticity and phase parameters either at the fundamental (h1=88.0525 MHz) or at the second harmonic frequency (h2=176.105 MHz). The transverse ellipticity corresponds to ($\sigma_x^2 - \sigma_y^2$), where σ_x and σ_y are the standard deviations of the beam transverse size. Position and ellipticity sensitivities are function of the energy, calculations and simulations are in progress to taking account this parameter [12].

The operation principle of the analog card is based on the gain equalization of the 4 inputs with an offset tone, a RF signal added to the main RF signal [13].

Electronic chains were tested in 2018 with the 2 BPM installed on the D-Plate. Before beam measurements, BPM electronics were calibrated precisely with the participation of the BARC team. Slits were scan to change the beam positions and beam ellipticities. Rotations of the four BPM signals were applied on the electronic inputs. Main tests consisted to compare BPM measurements at different rotations and at the two frequencies. The BPM position comparison gives differences within the requirements of ±150 µm. The global ellipticity differences were higher than ±1.2 mm^2 asked. This requirement imposes a gain difference between de 4 channels of ±0.03dB or ±0.3%. The analyzes showed that this was due to the difference of the four input return losses. Cross-couplings in the modules were also identified with small signals (under -60 dBm). BPM tests resulted in a list of corrections on the electronics and the necessity to test a BPM in the MEBT. Hardware and software corrections were applied in the first semester of 2019 with the help of the BARC Team to be ready to the BPM tests in the MEBT in September.

CONCLUSION

All SPIRAL2 diagnostic monitors were tested and qualified on the D-Plate. Beam characteristics were measured, studied to qualify the injector. Transmissions, transverse and longitudinal emittances were compared to the Tracewin [14] simulations with success. Measurements are very close to simulations with the tested reference beams. The tests made it possible to check and improve the operation of the measurement and monitoring chains, especially the diagnostic chains used by the Machine Protection System (ACCT-DCCT and TOF) [15]. Improvements were also applied after the D-Plate dismantling on the FFC and BPM. The MEBT line was installed in the first half of 2019.

On July 7, the French Nuclear Safety Authority gives the authorization to start the RF conditioning of cryomodules and begin the beam commissioning. The MEBT commissioning started on July in parallel with the start of the linac cavities. The beam is expected before the

*BARC: Bhabha Atomic Research Centre www.barc.gov.in

ISBN: 978-3-95450-204-2 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2019-MOPP036

end of 2019 in the linac, new steps for the diagnostic commissioning.

REFERENCES

[1] P. Dolegieviez, R. Ferdinand, X. Ledoux, H. Savajols, and F. Varenne, "Status of the SPIRAL2 Project", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 844-847. doi:10.18429/JACoW-IPAC2019-MOPTS005

[2] R. Ferdinand *et al.*, "Final Results of the SPIRAL2 Injector Commissioning", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 848-851. doi:10.18429/JACoW-IPAC2019-MOPTS006

[3] C. Jamet *et al.*, "Failure Mode and Effects Analysis of the Beam Intensity Control for the SPIRAL2 Accelerator", in *Proc. 3rd Int. Beam Instrumentation Conf. (IBIC'14)*, Monterey, CA, USA, Sep. 2014, paper WEPF28, pp. 613-616.

[4] S. Leloir *et al.*, "Measurement Uncertainty Assessments of the SPIRAL2 ACCT/DCCT", in *Proc. IBIC'16*, Barcelona, Spain, Sept. 2016, paper WEPG39, pp. 712-714.

[5] J. L. Vignet *et al.*, "The Beam Profile Monitor for SPIRAL2", in *Proc. 9th European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators (DIPAC'09)*, Basel, Switzerland, May 2009, paper TUPB07, pp. 176-178.

[6] E. Gueroult, J.-L. Vignet, L. Weissman and A. Kreisel "Testing residual gas profiler at SARAF" 2013 JINST 8 T08005(http://iopscience.iop.org/17480221/8/08/T08005) doi:10.1088/1748-0221/8/08/T08005

[7] C. Jamet, W. Le Coz, G. Ledu, S. Loret, and C. Potier de Courcy, "Energy and Longitudinal Bunch Measurements at the SPIRAL2 RFQ Exit", in *Proc. 5th Int. Beam Instrumentation Conf. (IBIC'16)*, Barcelona, Spain, Sep. 2016, pp. 723-727. doi:10.18429/JACoW-IBIC2016-WEPG42

[8] R. V. Revenko and J. L. Vignet, "Bunch Extension Monitor for LINAC of SPIRAL2 Project", in *Proc. 5th Int. Beam Instrumentation Conf. (IBIC'16)*, Barcelona, Spain, Sep. 2016, pp. 486-490. doi:10.18429/JACoW-IBIC2016-TUPG59

[9] G. Normand *et al.*, "SPIRAL2 RFQ Bunch Length and Longitudinal Emittance Measurements.", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 1944-1947. doi:10.18429/JACoW-IPAC2019-TUPTS007

[10] T. L. Owens, K. L. Junck, T. Kroc, E. S. McCrory, and M. Popovicacute, "Phase Scan Signature Matching for Linac Tuning", in *Proc. 1994 Linear Accelerator Conf. (LINAC'94)*, Tsukuba, Japan, Aug. 1994, paper TH-80, pp. 893-895.

[11] P. Ausset *et al.*, "Operation of the Beam Position Monitor for the Spiral 2 Linac on the Test Bench of the RFQ", in *Proc. 5th Int. Beam Instrumentation Conf. (IBIC'16)*, Barcelona, Spain, Sep. 2016, pp. 642-645. doi:10.18429/JACoW-IBIC2016-WEPG11

[12] V. Langlois *et al.*, "Study and characterization of SPIRAL2 BPMs", presented at the 8th Int. Beam Instrumentation Conf. (IBIC'19), Malmö, Sweden, Sep. 2019, paper WEPP001, this conference.

[13] G. Joshi *et al.,* "An offset tone based gain stabilization technique for mixed-signal RF measurement systems", *Nucl. Instr. Meth.*, vol. A 795, 2015, pp. 399-408.doi:10.1016/j.nima.2015.06.015

[14] http://irfu.cea.fr/dacm/logiciels/

[15] P. Anger *et al.*, "Safety classified system using beam intensity monitoring for the respect of nuclear requirements of SPIRAL2 facility", presented at the 8th Int. Beam Instrumentation Conf. (IBIC'19), Malmö, Sweden, Sep. 2019, paper MOPP001, this conference.