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BEAM INSTRUMENTATION, CHALLENGING TOOLS FOR DEMANDING PROJECTS – A SNAPSHOT FROM THE FRENCH ASSIGNED NETWORK

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Abstract

Particle accelerators are thrusting the exploration of beam production towards several demanding territories that is beam high intensity, high energy, short time and geometry precision or small size. Accelerators have thus more and more stringent characteristics that need to be measured. Beam diagnostics accompany these trends with a diversity of capacities and technologies that can encompass compactness, radiation hardness, low beam perturbation, or fast response and have a crucial role in the validation of the various operation phases. Their developments also call for specialized knowledge, expertise and technical resources. A snapshot from the French CNRS/IN2P3 beam instrumentation network is proposed. It aims to promote exchanges between the experts and facilitate the realization of project within the field. The network and several beam diagnostic technologies will be exposed. It includes developments of system with low beam interaction characteristics such as PEPITES, fast response detector such as the diamond-based by DIAMMONI, highly dedicated BPM for GANIL-SPIRAL2, emittance-meters that deals with high intensity beams and development for MYRRHA, SPIRAL2-DESIR and NEWGAIN.

NETWORKS AT THE IN2P3

The scientific programs carried out at the French National Institute of Nuclear and Particle Physics (IN2P3) require specific instruments that can only be developed within the laboratories themselves. Indeed, the expected performance of the instruments are more and more constrained in terms of granularity, sensitivity, dynamics, resolution, speed, tolerance to radiations, integration and transparency.

Instrumentation therefore mobilises a large number of professions and skills and becomes, in itself, a strategic axis of Research & Technology (R&T). The hyper-specialisation of professions and the current context of resources have led to rationalising this R&T upstream, by promoting the emergence of networks of experts across laboratories around the main families of detectors and associated transverse techniques for examples mechanics, gas detectors, cryotechnics, semi-conductors, photo-detection, beam instrumentation.

These networks are intended to be privileged exchange tools allowing experts to best share the know-how acquired between projects and between laboratories. They are an important factor of cohesion and efficiency, just as they generate specific training.

This network organisation makes it possible to identify emerging technologies, local skills, and to support them. Exchanges between experts promote the sharing of best practices, the identification and management of common engineering tools, and the rationalisation of resources.

THE BEAM INSTRUMENTATION NETWORK (RIF)

The Beam Instrumentation Network (in French, RIF i.e. Réseau Instrumentation Faisceau) is one of the identified transverse structures in the IN2P3. The RIF was born at the end of 2018 with the aim of bringing together experts in the field of diagnostics and associated instrumentation for particle beams in accelerators.

Missions

The Network animates, coordinates, encourages, and promotes interdisciplinary initiatives carried out in the various fields of beam instrumentation. As part of these missions, the network undertakes structuring actions that aim to:

- Take an active part in scientific and technological monitoring and, in particular, on the subject of the evolution of research support.
- Identify and promote the skills and expertise of the Network by updating pools of experts, and by ensuring a prospective analysis of skills in conjunction with the IN2P3.
- Ease communication and skills and/or information exchange between its members (sharing of good business practices, know-how) in the form of seminars or feedback.
- Pool experiences, with a view to solve particular technical problems, and capitalise to eventually make available, and manage a set of common tools, operating methods or best practices.
- Develop proposals relating to its missions for CNRS bodies, institutes and, more broadly, higher education and research bodies.
- Identify and help promote one or more research themes relating to technological locks in the field in order to boost R&D.

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- Identify R&T projects in addition to IN2P3 Masters Projects to overcome certain technological obstacles in the field.
- Develop, if necessary, specific training offers relating to beam instrumentation in conjunction with the IN2P3 training Mission Manager. Promote learning and internships in the field of instrumentation within IN2P3 units.

In order to support its mission, the network is gathering almost 40 active members disseminated throughout several laboratories in France. It has lead more than 22 meetings since its creation. The subjects of the presentations have been on a wide spectrum of diagnostics ranging from beam position monitor and emittance-meters to diagnostics tools for complete beamlines in leptons and ions machines and has produced a report for the IN2P3 2020-30 prospects[1].

Within its years of existence, several Working Groups (WG) have been created: one WG had the task to perform a survey of the domain and the experts in the field. It showed the large range of specialty and tools necessary for the experts to perform their work, i.e. from physics and electric modelling tools, to mechanics and computing. The survey also pointed out the training, the need for exchanges, and some specifics as, for example, the implication of the experts in the development phases of the diagnostics (see diagnostics section). A second WG focused on establishing an overview on emittance-meter as discussed later on.

IONS ACCELERATORS WITHIN THE RIF

The accelerators presented in the next section pertain to machines in operation, through machines in commissioning and towards projects.

The ARRONAX Cyclotron

ARRONAX uses a 4-sectors isochronous cyclotron 70XP that produces protons from 34 MeV up to 70 MeV, deuterons from 15 MeV up to 35 MeV, and alpha particles at a fixed extracted energy of around 67.4 MeV [2]. Its operational average intensity usage ranges from a few pA to 350 µA with bunches separated by 32.84 ns (Freq=30.45MHz) with a continuous beam. As the machine can use several beamlines at the same time it can operates up to 52 kW beams. In 2021 the RF equivalent running time was 4700h. In the last few years, the injection has been adapted to perform trains of bunches with a chopper system. The trains of bunches can thus be shortened to a few µs (with non-dominating transit time, otherwise it is a few 100s of ns) with a repetition up to ~50KHz. The application of the beams is from short time ultra-high dose rates for flash-like experiments, and, long period of irradiations for radio-isotope production, to very low intensity irradiation for physics and detector studies. For the machine, beam instrumentation has been developed as a first purpose for machine protection i.e. with external beam loss monitor and intensity monitors [3]. Low intensity diagnostics are also being extensively investigated as detailed below and with this respect, the ARRONAX cyclotron provides a test-beam for future medical and application instrumentation. The compact injection (~5 m long line) has also seen as well dedicated studies with, for example, the use of a newly built emittance-meter (see later), and is at the present time the focus of a study for a compact instrumented multi-layer collimators system.

The SPIRAL2 Linac

The SPIRAL2 accelerator is a facility characterised by a wide range of operations, both for the different types of accelerated ions, for the energy and intensity ranges, and a wide duty cycle range. The accelerator consists of a 5 mA p-d ion source, a 1 mA heavy ions source ($A/Q \leq 3$), a CW RFQ and a superconducting linac. The linac is composed of 26 cavities divided into two sections: a first low energy section (β=0.07) with 12 cryomodules, each containing one cavity, and a second high energy section (β=0.12) with seven cryomodules, each containing two cavities. This high power CW superconducting linac accelerates beams up to 200 kW (D+) and produces beams with a wide range of intensity (from few 10 µA to 5 mA), as well as energies from 0.75 MeV/u to 33 MeV/u. The duty cycle range applied on the chopper is included between 100 µs per second to a continuous wave mode [4].

Beam diagnostic monitors were designed to best meet these requirements and those of the machine protection system. Protections to control the operation field, the limitation of equipment activation, the beam power and losses have also been considered. To obtain the commissioning authorisation of the French Safety Authority, AC and DC current transformers (intensity and transmission control), Time of Flight (ToF) and beam loss monitors (energy control) were built to the standards of quality assurance rules, including Failure Modes and Effect Analysis (FMEA).

Modifications of measurement systems are still in progress to improve their sensitivity and increase their measurement range at low intensities.

The DESIR Facility at SPIRAL2

The DESIR facility [5, 6] will be, in a few years, the SPIRAL2 experimental hall at GANIL dedicated to the study of nuclear structure, astrophysics, and weak interaction at low energy. New 10–60 keV exotic ion beams from (i) the upgraded SPIRAL1 facility [7] and (ii) the super separator spectrometer S3 [8] under commissioning will be transferred to high precision experiments in the DESIR building. SPIRAL1 will continuously produce ions at a maximum rate of about 10^8 ions/s, meaning a 20 pA CW single charged ion beam to be transferred to the DESIR Hall. The beams from S3 will be similar, except the time structure (Bunched beams). To guarantee high purity beams to perform high precision measurements on specific nuclei, three main devices are currently being developed at LP2i Bordeaux: a High Resolution Separator (HRS) [9], a General Purpose Ion Buncher (GPIB), and a double Penning Trap named “PIPERADE” [10]. On one hand, the final resolution of the HRS will mainly depend on the correction of optical aberrations. These aberrations can be studied

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through the beam emittance figure. The use of a commercial pepperpot-type emittance-meter to correct the HRS aberrations is described in [9]. On the other hand, specific instrumentation developments described in [11] have been developed and are still being improved to characterise the low energy (3 keV) bunches produced by the GPIB. This RFQ-Cooler-Buncher is designed to handle large samples (10^6 ions in a 1µs bunch) with the best transverse and longitudinal emittances [12].

The NEWGAIN Project

The NEWGAIN project (NEW GAnil INjector) aims to construct a second injector A/q=7 [13], so as to produce very intense Super Heavy Elements, well beyond the performance of the existing injector. With the addition of this new injector, the SPIRAL2 LINAC will deliver, within its energy interval of operation, the most intense beams in the world over a large variety of ions (up to uranium). This second injector will be designed to be fully compatible with the existing facility; it will be composed of a high-performance superconducting ion source, a first low energy beam transport line connecting the superconducting ion source to the RFQ, a second LEBT connecting the existing ion source PHOENIX V3 (A/q=3) to the RFQ, an RFQ that will accelerate heavy ions up to the injection energy for the superconducting LINAC, and a medium energy beam line connecting the RFQ to the LINAC.

The MYRRHA Project

The MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) project [14] requires a proton beam of 4mA at 600 MeV operated in continuous mode. It aims at demonstrating the feasibility and operability of an efficient transmutation of nuclear waste products. MYRRHA will use external neutron produced by protons coming from Accelerator Driven Systems (ADS). The beam will be delivered to the reactor vertically from above through an achromatic beam line and window. Currently under design, MYRRHA is foreseen to release first beams at 100 MeV in few years now.

DIAGNOSTICS IN THE RIF

The design of beam diagnostic monitors involves the consideration of many parameters and requirements (i.e. mechanics, vacuum, beam parameters, safety and human-machine interfaces). These domains are important and continue iteratively throughout the design phase of the diagnostics and accelerator advancements.

As illustrated in Fig. 1, the development of diagnostics can go through several phases, here, separated as a pre-project, a prototype, and an operation phase. The pre-project phase starts up with the definition of the physics phenomena to be measured and might include pre-testing on a beam test. A prototype phase, for a specific accelerator, is usually necessary, except in the case where existing measurement systems can make it possible to carry out laboratory validation tests. Prototyping makes it possible to validate technical solutions that meet measurement and operating requirements. This can also involve the design and use of a laboratory measurement bench. In the case of safety requirements, it is necessary to quantify the measurement uncertainties by listing all the influencing parameters and evaluating their effect on the measurements. The reception tests of the final equipment, coming from the suppliers, are carried out first in the laboratory and then on the accelerator before the beam commissioning.

Interfaces with the command-control are essential but not so easy to specify. Definitions of the exchange data include both the various commands for setting the measurements, the measured data, and the operating and default status, for experts and for operation.

The last steps concern the beam commissioning, operation verifications of the beam diagnostic monitors, the measured values between diagnostics, and the level of disturbances in the electromagnetic environment. Modifications, optimisations, and evolutions are often necessary.

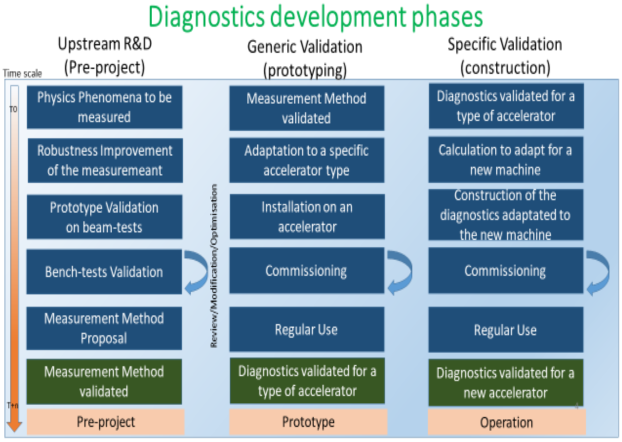

Figure 1: Diagnostics development phases: the pre-project, generic validation, and specific validation.

In the case of SPIRAL 2 injector commissioning, a test bench (Diagnostic plate) with all diagnostic monitors was installed at the exit of the RFQ [15,16]. This test bench had two main objectives: qualify the beam at the RFQ exit and qualify and validate the diagnostic monitors of SPIRAL2. The D-plate allowed to measure:

- Intensities with Faraday cups, ACCT, and DCCT,
- Transverse profiles with classical multi-wire profilers and ionisation gas monitor (MIGR),
- 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 test bench allowed optimising and developing diagnostics, such as ToF energy measurements and the fast Faraday cup. Difficulties arose with the BPM qualification tests due to the lack of beam profilers installed in the test bed. A detailed analysis of the measurement needs must be carried out before the design of the test bench.

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A New Emittance-meter for the Community

A new emittance-meter has been constructed and commissioned at IPHC in 2020 [17]. This device is based on the Allison principle and follows other similar achievements done in the framework of SPIRAL2 and MYRRHA projects and soon NEWGAIN [18]. The newly developed instrument was installed in the injection channel of the ARRONAX cyclotron in Nantes at the beginning of 2021. The aim of the experiment was to investigate beam properties and improve current intensity [19].

Since then, the device has been used to characterise beams at the exit of DESIR/SPIRAL 2 High Resolution Spectrometer at LP2I Bordeaux, and on the ARIBE beam line of the CIMAP/GANIL facility in Caen. The system is now fully operational and is shared by the community at IN2P3, the beam instrumentation network. It is currently installed on a secondary beam line of the ALTO facility at IJCLab, Orsay, in order to characterise beams of new ion sources before the summer 2022.

The goal of the collaborative work is not only to share equipment, but also to discuss, analyse measurements, and improve collective knowledge of emittance-meter, ion-beam behaviour and data analysis.

Perspective of Ion Beam Emittance Measurements

Performance limitations of Allison-based systems are well known and IPHC's system ones have been investigated in order to propose improved phase-space distribution measurements, see summary in Table 1.

Table 1: IPHC's Emittance-meter Performance Limits

Front-end electronics	1 nA total beam, EMI issues (as shielding)
Data acquisition	BW limitation at ~10 MHz, limited dynamic capabilities
Power dissipation	300 W (5 mA at 60 keV)
Resolution	0.1 mm, 1 mrad, not sufficient for small beams and halo definition
Accuracy	10-20%, integration of different subsystems errors and internal beam-optics defects
Packaging	Weight and dimensions are penalising

Apart from the technical limitations, there are several issues raised by the shared use of the instrument: its versatility in respect to the different applications at IN2P3 (with time and resources required for adaptation), its availability over the year (an experiment takes several months), and radioprotection and transport between laboratories (preliminary dose and radiation exposure evaluation, activation inventory, decay time estimation, safety procedures, and regulations are mandatory) [20]. A commercial solution is expensive and shows little flexibility. IPHC, as, a unique external lab involved in installation, commissioning, support and feedback on the different facilities, does not have sufficient resources for long-term sustainability. The future will favour open source solutions with sharing of drawings, knowledge and community experiences, which are not only unique to this instrument.

DIAMMONI Monitor

Compared to other semiconductors, diamond exhibits a high resistivity (>10^{13} Ω.m) associated to a large electronic gap (5.48 eV) that results in an almost negligible leakage current, and thus a low noise level. The high charge carrier mobility leads to a very fast response allowing tens of picoseconds time resolution and high count-rate capabilities [21]. Diamond detectors are also highly resistant to radiation [22]. For beam monitoring purposes, CVD-diamonds (Chemical Vapor Deposition) are used as solid-state ionisation chambers. Diamonds are metallised (~100 nm Al layer) to permit charge collection. In addition, the very original lift-off process allows a large number of user-defined electrode designs to satisfy beam profile requirements.

The DIAMMONI pulsed proton beam tagging monitor is foreseen to be equipped with the largest possible sensors (> 1 cm^2, CVD single crystals or polycrystals). In order to ensure short charge carrier drift time and limit the detector current (compulsory for very intense beam pulses), their thickness needs to be optimised. Furthermore, to provide spatial resolution and low detector capacitance values, the diamond detectors are to be segmented with double-sided metallic strip readouts (X and Y directions). Indeed, DIAMMONI objectives are a spatial resolution of the order of a millimetre linked to the transverse dimension of the diamond strip metallisation. Finally, a high dynamic range for particle counting can be reached: from a single particle up to bunches of thousands of protons (or He ions) while beam intensity is monitored with a current integration mode that relies on a QDC design. As a result, a first prototype of DIAMMONI, made of a 150 µm thick CVD single crystal read-out by a QDC developed at LPSC, demonstrated, in May 2022 at ARRONAX, its capability to perform particle counting in 100 µs trains of nano-pulses. The beam intensity was raised up to 5 µA (measured on the diamond surface), which corresponds to an average of 10^6 protons per nano-pulse every 30 ns, with an energy deposit of 500 GeV/bunch over a 7 mm^2 detector area.

PEPITES Profiler

PEPITES [23] is a brand new operational prototype of an ultra-thin (<10µm water-equivalent thickness), radiation-resistant, SEE-based beam profiler capable of continuous operation on mid-energy (O(100 MeV)) charged particle accelerators. Characterised at ARRONAX with 68 MeV proton beams and at medical energies at CPO-Orsay, the system has been exposedto doses of up to 10^9 Gy without showing significant degradation. A demonstrator with a new ASIC 32-channel electronics is installed at ARRONAX in a dedicated chamber.

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SPIRAL2 Beam Position Monitor

SPIRAL2 BPM [24] instrumentations are used to measure positions and phases of ion beams, and also transverse shapes, called ellipticity, as well as beam energy. Specifications involve knowing and calculating the sensitivities in position and in ellipticity as a function of the beam velocities. The ß values in the linac are from 0.04 up to 0.26 for the 33 MeV proton beam.

The BPM specifications to tune the SC linac cavities are given in (Table 2).

Table 2: BPM Specifications

Parameter	Resolution	Range
Position	+/- 150 µm	+/-20 mm
Phase	+/-0.5 deg.	+/-180 deg.
Ellipticity	+/-20 % or +/- 1.2 mm2	

These also impose small amplitude differences between channels, which require precise calibration of electronics. At low velocities, sensitivities in position and ellipticity are a function of the beam beta and the frequency harmonic. One of the objectives was to find a formula to calculate the ellipticity sensitivity correction.

BPM systems process signals either at the 88.0525 MHz fundamental frequency or at the second harmonic for both amplitude and phase measurements. Horizontal and vertical positions, ellipticity, amplitude and phase of the vectorsum are calculated from both h1 and h2 measurements. The design of the BPM system is based on the scheme of autogain equalisation using offset tone. In this scheme, the gain of the different channels is equalised with respect to the injected offset tone.

In order to obtain the required resolutions, two solutions were implemented in the electronic process: a very precise calibration, and stabilisation of the four gains and phases.

After numerous modifications and optimisations, position and ellipticity values calculated from the level measurements at harmonic 1 (88 MHz) and at harmonic 2 (176 MHz) are very close, and confirm the correctness of the formulas of the sensitivity coefficients.

In early 2021, an improved cavity tuning procedure using beam energy measurements from the BPMs was tested. A new calibration procedure, taking into account the phase drift from BPM outputs, was applied to correct these phase shifts and to have the same phase reference for the 20 BPM monitors.

In July 2021, with a helium beam at 40 MeV, beam energies were measured using the Time of Flight monitor (ToF) located at the linac exit to check the BPM measurements. The energy differences were relatively small and validated the BPM phase accuracies and the phase accuracy from BPMs.

The current actions concern an automation of the calibrations and an increase of the sensitivity towards the very low levels.

DESIR Diagnostics

The DESIR transfer beamline will use Faraday Cups (FC) coupled with a low-bandwidth transimpedance linear amplifier called PicoLIN [24] to cover a very wide range of CW beam intensity measurements, from 50 fA to 100 µA. These diagnostics, developed at GANIL, are crucial to optimise the beam transport efficiency. The other main diagnostics used are Beam Profile Monitors (BPM) based on secondary electron emission of 47 tungsten wire harps (0.5 mm step) for both horizontal and vertical planes [25]. Equipped with high-sensitivity charge preamplifiers, these semi-interceptive BPM, also developed at GANIL, are used to monitor down to a few tens of pA ion beams with a transparency higher than 90% to obtain the beam position, size, and shape on focal plane of each optical section.

Ion bunches generated by the GPIB can be detected by the FC, coupled to a fast commercial I/V converter (FEMTO DHPCA-100). This detection system can be used only for high-intensity bunches (>10^4 particles in a 1 µs bunch), the lower ion number limit strongly depending on the time distribution of the bunch. A commercial RedPitaya board is used to readout the bunch intensity signal close to the diagnostics and serve it as an EPICS [26] Process variable on the Ethernet network. Micro-Channel-Plates (MCP) are also used to measure low-intensity beams in counting mode and to perform Time-Of-Flight (TOF) measurements, using a LP2i-Bordeaux FPGA development called “RedPiTOF” [11] implemented into a dedicated Red Pitaya board. The TOF spectra has been constructed in the RedPiTOF and is used daily to commission the GPIB RFQ-Cooler-Buncher but also to test and perform in-trap techniques in a similar manner as with the PIPERADE Penning traps at Bordeaux.

Additive Manufacturing

Studies are also ongoing in France to see how additive manufacturing can benefit to accelerators. As an example, a beam position monitor was developed and thanks to additive manufacturing, a thin electrodes were built and tailored to be closer to the optimal impedance [27].

CONCLUSION

The present network keeps working efficiently on its activities, organises meetings and technical exchange, to align its work-in-progress with the demands of the experts in the field. This means also taking into account the past two years’ events, experienced by the world from a health and military point of view, that have affected projects and collaborations. Though, the development of the network is consistent with the recommendations on the IN2P3 2020-30 prospects that occurred in 2021, as its report outlined “prime importance to guarantee a suited scientific and technical support for accelerators development” and “to strengthen the connection between accelerators and detectors community” “particularly R&D activities on beam instrumentation”. A potential future would be the integration of the network within a larger structure that would allow sharing information within fields that are not usually nor specifically close to beam instrumentation.

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