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# CONTRIBUTION OF IN2P3 TO PIP-II PROJECT: PLANS AND PROGRESS*

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*Abstract*

IJCLab is one of the labs of IN2P3 (National institute of nuclear and particle physics), one of the ten research institutes composing the French National Center for Scientific Research (CNRS). Since 2018, IJCLab has been involved in the PIP-II project, assisting with the design, development, and qualification of accelerator components for the SSR2 (Single Spoke Resonator type 2) section of the superconducting linac. The first pre-production components (cavity, coupler, and tuner) have been fabricated, and some of the first qualification tests have been performed at IJCLab. This paper will summarize the complete scope of IJCLab contributions to PIP-II and give updates on the performances of the first pre-production components.

## INTRODUCTION

The Proton Improvement Plan-II (PIP-II) encompasses a set of upgrades and improvements to the Fermilab accelerator complex. In particular, PIP-II project is aiming at constructing a new superconducting linac for which Fermilab benefits from a strong commitment as in-kind contributions of international partners among which France is involved through CEA and CNRS/IN2P3 agencies. Since 2018, year of signature of a SoI (Statement of Interest), IJCLab [1, 2] is the only laboratory of CNRS/IN2P3 French research institute to be involved in this contribution. The scope of technical contribution and project schedule are captured in the Project Planning Document Part2 (Non legally binding document) that will be signed in a near future by IN2P3 institute and DOE.

A complete set of deliverables and associated milestones have been mutually built and agreed aiming at monitoring the progress during the project. Both International Milestones (linked to partner activities) and PIP-II project internal milestones (linked to PIP-II project activities) have been defined. These milestones are on both sides tracked and updated on a regular basis (monthly reporting) allowing each party to evaluate efficiently the impact of any delay on their own schedule and risk register. The definition of the complete list of milestones allowed the definition of early and late delivery dates for each deliverables. The early delivery dates are defined by partners whereas late delivery dates by PIP-II Project. This ensures partner schedule to be encapsulated in PIP-II Project schedule with defined margins. This proceeding aims at describing the In-Kind contribution of CNRS/IN2P3 to PIP-II project and share the progress up to date.

## TECHNICAL CONTRIBUTION

The technical contribution of CNRS/IN2P3 is limited to the second Spoke section (SSR2 cryomodules) of the superconducting linac [3] but covers from the preliminary design phase up to delivery phase of production components. The contribution focuses on the three main components composing the so-called SSR2 dressed cavity meaning the cavity, tuner and power coupler.

### *Preliminary Design Phase*

This phase is completed since 2019 when Final Design Reviews (FDR) of the pre-production cavity, tuner and power coupler have been closed.

CNRS/IN2P3 involvement in this phase was limited as most of design work was already well advanced in 2018 for most of components. Based on IJCLab experience on the design, fabrication and integration of Spoke cryomodules for ESS project [4], several inputs in term of lessons learned served to consolidate the initial design performed at Fermilab.

- For SSR2 cavity, RF design [5] was fully accomplished by Fermilab but mechanical design was jointly achieved [6] benefitting from lessons learned from both SSR1 and ESS experiences.
- For SSR2 tuner, the system was fully designed already by Fermilab for the first Spoke section (SSR1) [7]. SSR2 mechanical design was limited to interface adaptation so as to optimize the number of standardized parts.
- For SSR2 power coupler, support has been provided to Fermilab team to optimize SSR1 coupler design and make it compatible with SSR2 requirements. This support consisted in performing thermal simulations and providing inputs based on IJCLab experience for XFEL [8].

### *Final Design Phase and Pre-production*

This phase has started at the successful completion of the preliminary design phase and will end with the successful completion and close-out production SSR2 dressed cavities FDR. This phase is including the fabrication of pre-production components and the full experimental validation of one dressed cavity in horizontal cryostat at Fermilab.

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CNRS/IN2P3 contribution to this phase is summarized below:

- Support procurement (fabrication and surface processing follow-up) of 6 pre-production SSR2 cavities. Costs of Niobium and cavity fabrication are covered by Fermilab.
- Upgrade SRF infrastructure at IJCLab (SUPRATECH [9]) to perform surface processing of cavities (rotational BCP).
- Re-process surface of cavities when required.
- Perform reception and vertical testing of the 6 pre-production cavities and ship to Fermilab.
- Procure 4 pre-production SSR power coupler and ship to Fermilab for RF power test.
- Procure 5 tuners and proceed with qualification during vertical test at IJCLab.
- Perform a life cycle test of a fully integrated tuner cartridge in the dedicated nitrogen cooled cryostat in operation at IJCLab [10].

### *Production Phase*

This phase starts upon successful completion of previous phase and ends with the completion of all component fabrications and successful System Acceptance Review conformance with SSR2 technical requirements. For production, the CNRS/IN2P3 contribution is the following:

- Support the cavity fabrication follow-up of 33 SSR2 production cavities. Costs of Niobium and cavity fabrication are covered by Fermilab.
- Perform vertical testing of the 33 cavities and proceed with shipping by batch of 5 or 6 cavities to Fermilab if validated.
- Re-process at IJCLab a maximum of 25% of cavities if not validated during the first vertical testing.

## TECHNICAL PROGRESS

As an overall status of SSR2 at this date, a general overview and status can be found in [3]. More specifically for CNRS/IN2P3 contribution, at least 2 prototypes of each component (cavity, coupler and tuner) have been fabricated, delivered at IJCLab or Fermilab and tested. The end of deliveries of prototypes components is foreseen before the end of the year. IJCLab infrastructure have been successfully adapted and upgraded and is now fully operational to qualify prototype cavities and tuners.

### *Upgrades of Facilities at IJCLab*

CNRS/IN2P3 has invested in Supratech platform for the need of PIP-II project. This consisted in designing and building all the tooling required to check quality (QC at reception) and perform all surface processing steps as chemical etching (BCP), High Pressure Rinsing (HPR), heat treatment in vacuum furnace (hydrogen degassing), clean assembly (ISO4 cleanroom), 120 °C baking and finally vertical testing (See Fig. 1).

The main improvement was the study, development and fabrication of a rotational BCP cart [11, 12]. This tool provides optimized etching uniformity, allows to maintain acid and cavity at a lower temperature thanks to the agitation and last but not least, eases significantly the work of operators during the process as the cavity doesn't need to be drained, disassembled and flipped at half time (less manipulations, less risks, improved safety).

Figure 1: Photographs of a SSR2 cavity installed on HPR unit (left) and on rotational BCP cart (right) on Supratech platform at IJCLab.

### *Progress on SSR2 Cavities*

Three pre-production SSR2 cavities have been fabricated and delivered jacketed at IJCLab [13]. Two cavities were fully processed by the company and delivered under vacuum "ready for vertical testing" whereas one was first delivered bare at IJCLab to perform advanced tests on the newly developed rotational BCP tool. The goal was to qualify the etching uniformity by measuring the wall thickness at several positions thanks to an ultrasonic probe [12]. The cavity was then sent back to the company for hydrogen degassing and helium tank integration. Final surface processing was then performed at IJCLab consisting of a flash BCP, HPR and 120 °C during 12 h. This reduced duration of baking compared to the standard 48h aimed at mitigating multipacting and avoiding Qo drop [14].

The three first pre-production SSR2 cavities show very sound mechanical behaviour. All frequency shifts observed during surface processing, cooling down and frequency sensitivities are reproducible and in perfect agreement with simulations done during design phase (See Table 1). For ZA01, the tuner was found engaged after cooling down explaining why shifts and sensitivities are different from ZA02 and ZA03. No cold leaks have been reported.

As depicted in Fig. 2, the three cavities didn't meet the nominal gradient of 11.5 MV/m because of strong field emission with an onset below 5 MV/m. New HPR tooling (wand tip and nozzle) and new procedure are being upgraded [13]. The Qo at low field for the two cavities processed by the company is at 1.6E10 corresponding to a surface resistance of 7 nΩ (G=115) whereas for the cavity processed at IJCLab, Qo is at 2.7E10 and surface resistance at 4.2 nΩ. This is explained by the fact that the company performed a 120°C baking during 48 h whereas it was limited at about 12 h at IJCLab. As said previously, a long baking tends to increase the residual resistance.

From first observations, a 12 h baking is sufficient as leads to a similar multipacting conditioning time (~3 h) than after a 48 h baking. Several multipacting bands have been systematically measured between 0.5 MV/m and 3 MV/m.

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Table 1: Frequency Shifts and Sensitivities

| Cavity (processed at) | Criteria or simulated value | Cavity ZA01 (company) | Cavity ZA03 (Company) | Cavity ZA02 (IJCLab) |
|---|---|---|---|---|
| Freq. shift during cool-down (kHz) | 457 | 476 | 460 | 465 |
| Frequency at 2 K (MHz) | 325.075 ±65 kHz | 325.021 | 325.009 | 325.088 |
| Pressure sensitivity (Hz/mbar) | < 25 | 2.5 | -4.1 | -3.1 |
| Lorentz factor (Hz/(MV/m)$^2$) | -7.99 | -4.8 | -7.1 | -7.2 |
| Tuner status | | Engaged | Disengaged | Disengaged |
| Base Qo (Surface resistance in nΩ) | > 9E9 | 1.7E10 (7.2) | 1.9E10 (6.8) | 2.7e10 (4.3) |

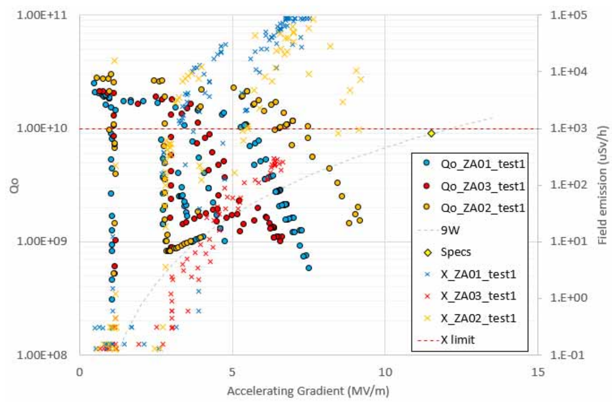


Figure 2: Graph representing the intrinsic quality factor Qo versus accelerating gradient of the three first SSR2 pre-production cavities during their first vertical test.

## *Progress on SSR2 Tuners*

Five tuners have been procured and delivered at IJCLab (beside stepper motors). Four of them have been already assembled and tested on cavities during vertical test. So as to ensure an efficient cool-down of the tuner to reach a stable temperature within 24 h, eight copper thermal straps have been installed between the two massive arms and the cavity lifting lugs (See Fig. 3).

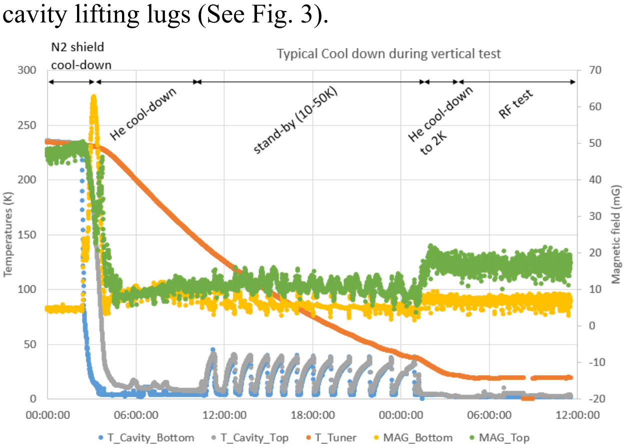


Figure 3: Evolution of temperatures of cavity and tuner during the helium cool-down. Residual magnetic field is as well monitored.

Qualification tests consisted in tuning the cavity down to the frequency target of 325 MHz and assessing the frequency sensitivity, the mechanical hysteresis (in Hz/step) as well as the maximal detuning achieved by the piezo actuators when polarized at 100 V [10].

## *Progress on SSR Power Couplers*

Four couplers have been procured by IJCLab based on Fermilab design. The couplers are cleaned and delivered "ready for RF test". Two couplers out of the four have the ceramic window coated with TiN. Some design change during production have been performed based on feedback from companies [15]. Up to date, two vacuum side assemblies, including the ceramic assembly, antenna assembly and outer conductor, have been shipped to Fermilab, power tested and qualified up to 12 kW CW [16]. Remaining parts (two vacuum sides and four air sides) are finalized and are undergoing final tests as complete assembly (See Fig. 4) prior shipping.

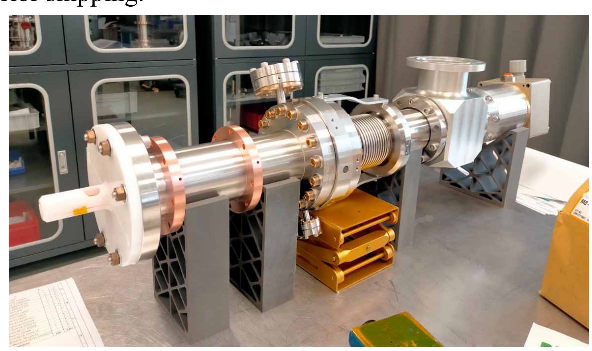

Figure 4: Photograph of a fully assembled SSR power coupler.

The final shipping of all components is foreseen before end of summer.

# CONCLUSION

CNRS/IN2P3 French research institute is contributing to PIP-II project since 2018 with all activities located at IJCLab. The In-Kind Contribution is covering both the pre-production and production phases. First pre-production components (cavities, tuners and couplers) have been fabricated and tested. SSR2 cavities and tuners show very sound mechanical behaviour at cryogenic temperature. The quality factor of the three cavities at low field is in the expected range qualifying the quality of Niobium material and cavity fabrication procedure. The only remaining problem preventing from reaching nominal gradient is field emission. Extensive analysis showed that current HPR configuration doesn't allow a complete coverage of relatively high electric field regions. HPR procedure is being improved and new cryogenic tests are foreseen this summer.

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