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UPGRADE OF THE HEAVY IOC ACCELERATOR COMPLEX AT INFN-LNL

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Abstract

LNL heavy ion accelerator complex is based on three main accelerators: Tandem, ALPI and PIAVE. The Tandem XTU is a Van de Graaff accelerator normally operated at terminal voltages of up to about 14 MV. It can be operated in stand–alone mode or as an injector for the linac booster ALPI. The linear accelerator ALPI is built of superconducting resonant cavities and consists of a low–beta branch, particularly important for the acceleration of the heavier mass ions, a medium–beta branch, and a high–beta branch. ALPI can be operated also with the PIAVE injector that consists of a superconducting RFQ and an ECR source. In the last two years, accelerator complex underwent special maintenance to improve its availability and reliability in view of the operation with both Uranium and radioactive beams. In this framework, the main improvements that will be presented will concern Tandem injector and laddertron system, PIAVE ECR source, cryogenic control system and SRFQ tuning system, ALPI low and medium beta design, vacuum control system and new techniques for beam dynamic simulation and commissioning.

INTRODUCTION

Since 2017 LNL heavy ions accelerator complex experienced a strong reduction in beam on target (BoT) hours. The BoT average moved from more than 3000 hrs in 2012-2016 down to less than 1000 hrs in 2017-2021 with 528 hrs minimum in 2019. A deep maintenance/upgrade started in March 2021 and was completed in two steps: April 2022 for Tandem electrostatic accelerator and September 2022 for ALPI [1] and PIAVE [2,3] RF accelerators. Some details will be described in the next paragraphs. The three main results are:

- the deep analysis of Tandem laddertron chain weak points improving materials, tolerances and balancing: current laddertron lifetime reached 4660 working hours showing no performance degradation;
- the strong increase of PIAVE injector availability: annual beam time using PIAVE injector increased from 250 hours per year to 1556 hours per year;
- the improvement of heavy ions accelerating capability without adding any cavity but strengthening the current system: an example is 208Pb which maximum energy was increased by more than 16% reaching 7.58 MeV/u improving low beta section reliability.

Accelerator radio frequency control system is also undergoing several upgrades which will extends its lifetime and will provide enhanced performance. Details can be found in [4].

TANDEM

The major cause of reduction in beam availability since 2017 was Tandem accelerator. Many issues were discovered during the last years: SF6 water pollution, SF6 air pollution, Nylatron stiffening bars fragility and laddertron chain lifetime reduction. All issues were successfully fixed except the last one. Maximum voltage recovered 14.5 MV in 2020 after the 12.5 MV minimum reached in 2018, but laddertrons lifetime were limited to 4000 hours at maximum and in some cases, breakage could occur just after 1500 hours working time.

Base and terminal wheels design and assembly procedure were finally identified as the major cause of laddertron issue. Many actions were implemented to solve it:

- a new shaft was machined and assembled with new bearing with the right tolerance;
- new self-centering keyless locking device was implemented on the driving wheels;
- new aluminum rings were realized according to original drawings;
- conductive inserts for the base wheels were replaced with new ones harder than previous ones and similar to the original ones;
- all dimensions were rectified after assembly;
- both wheels experienced dynamic balancing.

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In February 2022, during first run after special maintenance, dimensional checks, executed two times per day, confirmed that lateral deviation, bars inclination and chain elongation effects were strongly suppressed. Since then, laddertron chain has never been replaced.

PIAVE

PIAVE injector includes an ECR ion source installed on a 400 kV high voltage platform, a transfer line and two Supeconducting Radio Frequency Quadrupoles (SRFQs).

ECR Ion Source

Source upgrades were mainly focused to improve safety and reliability as well as to improve beam characteristics. Optimization of plasma chamber dimensions allowed enhancement of production towards high charge state ions. Beam intensity of $^{136}Xe^{28+}$, that is one of the most frequently accelerated at LNL, was improved by a factor 2 with the new chamber. More details on the source upgrades and first tests to produce Uranium beam can be found in ref. [5].

Superconducting RF Quadrupoles (SRFQs)

Regarding SRFQs, the two cavities resonate at 80 MHz and are installed in the same cryostat, each of them is inside a liquid helium bath surrounding the cavity and working also as helium tank/buffer. Large cavity surface area is directly exposed to liquid helium bath and this makes cavity quite sensitive to He pressure variations. Estimated sensitivity is in the order of 50Hz/mbar and for this reason, cavity tuning is quite challenging. The original design includes two tuning systems both operating at the same time:

- Voltage Controlled Reactance (VCX)
- mechanical tuning system acting on both end plates for each cavity.

The former is designed to correct up to 2kHz bandwidth errors. Reactance is pulse-width modulated (PWM) by a 25kHz carrier and it allows a frequency correction that can reach up to ±20Hz for SRFQ1 and up to ±150Hz for SRFQ2. Tuning corrections above the previous limits are implemented using mechanical tuner. A software loop is monitoring the limits of the PWM modulation acting on the mechanical tuners when needed.

An attempt to upgrade the mechanical tuner was made between 2015 and 2017 [6]. Idea was to redesign the mechanical actuator within the cavity to have a double action:

- a slow and large effect through external stepper motors, as the original design;
- a fast and small action through a piezo-actuators installed in the same mechanism close to the tuning plate (@ 4K).

This in principle could have replaced the fast action of the original VCX, which were not removed to have a backup tuning system. The machine operation went quite smoothly using the old VCX system while piezo tuning development was scheduled, with low priority. At the beginning of 2020 a mechanical fault highlighted a design flaw on the new actuator. This required a new special maintenance on the SRFQ cryostat to solve the problem. Thermomechanical behaviour of the new solution was compared with original one and considering pros and cons it was decided to restore the original tuning mechanism. This required to add two steps to the common maintenance procedure. In particular:

- a complete High Pressure Water Rinsing cycle in clean room of both cavities, by an external company (tuning plates were cleaned at LNL);
- assembly of the old refurbished tuning mechanisms.

The complete procedure was completed in late September 2022 and lead to the successful test with beam last December. Tuners required a full characterization to measure the tuning windows of the VCX devices (Fig.1)

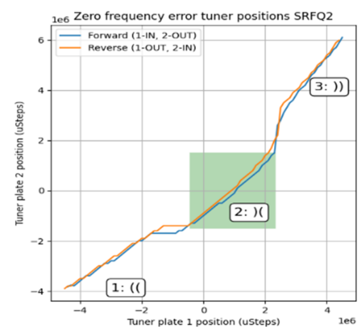

Figure 1: Tuner plate positions that tune the cavity @ 80MHz, the green areas show the chosen tuning range for the operation to avoid mechanical backlashes (vertical and horizontal regions).

Cryogenic Control System

To improve SRFQ cryogenic system safety and stability, PIAVE cryogenic plant, currently consisting of a Linde TCF50 refrigerator, a SRFQ cryostat, valve-boxes and transfer lines, was completely renewed according to the UNICOS standard. Migration included revamping of all electrical, pneumatics and control panels. Complete system was commissioned in 2022 and it is fully operational since last October.

ALPI

Low β Cryostats

In the framework of the ALPI LINAC upgrade, a huge work was done on the cryostat tuning systems. ALPI low-β sections include six cryostats (CR01-CR06), each containing four bulk niobium Quarter Wave Resonators (QWR). RF tuning is performed applying force normal to the lower plate of each cavity, through a complex kinematic chain connecting the stepper motor to the lower plate centre. Plate displacement has a strong impact on tuning quality and can be affected by backlash. This arises from the gap between kinematic chain components in the forward and backward motion, which is related to stepper motor rotation. Enough time was spent determining the stiffness of the spring installed on each tuner to avoid

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uncontrollable backlash. Ad-hoc test bench, composed of a special frame, a load cell connected to the plate and a position transducer, was designed and installed on cavities of CR01, CR03 and CR06 cryostats. An extensive campaign of measures was done to describe elastic response of the coupled plate and tuner system. After post-analysis it was possible to calculate the minimum stiffness required by the spring to avoid backlash phenomena. Analytic and experimental comparison of the tuner behaviour was finally performed (Fig.2).

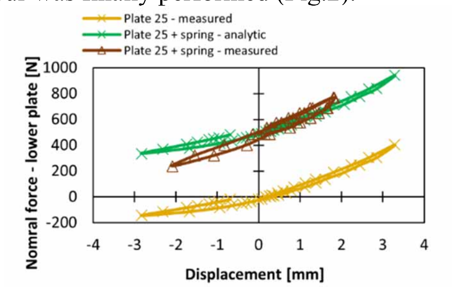

Figure 2: Experimental data of the elastic response of the plate (yellow), theoretical behavior of the plate-tuner system by using a spring of given stiffness (green), experimental data of the elastic response of the plate-tuner system by using a spring of a given stiffness.

First beam tests after maintenance of the three cryostats confirmed the strong improvement in the tuning system and therefore in the stability of the low β cryostats.

Medium β Cryostats

A few innovative technical solutions were also implemented on medium β cryostats. One of the main innovations was a new procedure for the alignment of the cryostats. It was developed since it was found an important misalignment on cavities connected to vacuum effect on cryostat upper flange. Cavities displacement could not be detected with the old alignment references. Therefore, cavities' movements related to both vacuum and low temperature were deeply analysed. Consequently, cavities support system inside cryostats were modified and new fiducials were identified on cryostats bodies.

Figure 3: New cavities support system inside cryostat improved alignment and cooling performances.

Alignment system modification involved the replacement of the copper bars supporting cavities, that were used for cavity pre-cooling. It was therefore necessary to design a new cavity pre-cooling circuit that could be integrated with the new alignment system. The new pre-cooling system also reduced cool-down time by more than 20% (Fig.3).

Vacuum System

The vacuum plant of ALPI accelerator includes about 40 pumping groups based on turbomolecular pumps (TMP) and controlled by 14 Racks. The control and supervision systems are composed of custom solutions for the hardware (HW) and software (SW) parts developed by an external company. The instrumentation is mainly the original one installed in the 90s. Obsolescence, deficit of spare parts and rigidity of the system required a complete renovation of the vacuum system and relative controls [7]. The upgrade activity started at the end of 2021 [8,9]. It included:

- high-level control system replacement, (HW and SW);
- modification of the new Vacuum Control System (VCS) rack already realized for the SPES project;
- replacement of all vacuum pumping groups and related control racks.

Renovation of the vacuum system concerned mainly the substitution of the TMPs, the reduction of one third of the primary pump number introducing new fore vacuum manifolds, the primary pumps replacement with oil free multi root models. In case all resources will be available, renewal plan will be concluded in 2025.

NEW TRANSPORT TECHNIQUE

During the last years of operation, a new effort to study the beam dynamics was set up. The goal was to explain mismatch between the 35% value as maximum transmission obtainable with ALPI Linac with 54% value obtained with beam dynamics simulations. Part of this discrepancy can be related to cavities and magnets residual misalignments. Analysis of last year runs, let to find a calibration factor on the cavity's fields using beam dynamics studies. Mismatch between the number of cavities used in real acceleration and the one foreseen by simulations was reduced from eight to one. Calibration studies now moved to better understand bunchers and SRFQ. Beside this effort, integration between BD calculations and experimental results improved even further: full accelerator scaling, from injector to experiments, strongly reduces beam setting time. Further initiatives are ongoing: one of that is the introduction of an automated setting routine that will help to optimize and set the transverse lens and the optimum synchronous phases of the machine [10].

CONCLUSIONS

Work done in the last years was very fruitful for LNL heavy ion accelerator complex. Accelerator is near to reach its maximum capabilities in terms of maximum energy, but it needs to be further improved in terms of transmission and setting time. It will be fundamental to achieved both results before starting to use ALPI as a radioactive ion beam post-accelerator.

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