# Installation of the NEBULA-Plus neutron array

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The direct investigation, through high-energy reactions and invariant mass spectroscopy, of neutron unbound states and systems requires the detection of one or more neutrons. In the case of the RIBF, the principal permanently available fast neutron detector is the two-wall 120-element NEBULA array,[1] which has been in operation since the commissioning of the SAMURAI setup in 2012. In order to augment the detection efficiency, in particular for multineutron channels, an upgrade comprising two supplementary walls to be located just forward of NEBULA (Fig. 1) has been built within the context of the French ANR funded project EXPAND.[2]

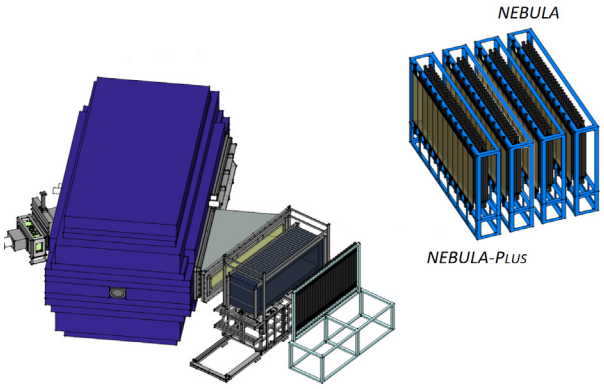


Fig. 1. Schematic view of the SAMURAI setup including the NEBULA-Plus and NEBULA arrays.

The NEBULA-Plus walls are composed of a total of 90 plastic scintillator bars (Eljen EJ200), with dimensions identical to those of NEBULA,[1] read out by Hamamatsu H11284 PMT assemblies. Each wall is composed of two layers - with each layer in the first wall comprising 22 bars and in the second wall 23 bars. As for NEBULA, each of the walls is preceded by a layer of thin (1 cm thick) large area charged-particle veto detectors. The read out of the PMT signals is performed using the FASTER digital electronics and acquisition system[3] developed at LPC-Caen. Whilst FASTER has been conceived as a triggerless system, it has been modified for use with NEBULA-Plus to generate a trigger (derived from the coincidence between the signals from the two PMTs of each bar) so as to allow for its integration into the SAMURAI data acquisition system (DAQ).

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After detailed acceptance testing of all the bars and PMTs at LPC-Caen and optimization of the operation of the FASTER electronics (in particular the timing and charge measurements) NEBULA-Plus was shipped to the RIBF in summer 2022, following the easing of covid travel restrictions. The mechanical installation and cabling were completed in early October (Fig. 2) and were followed by the installation of the high voltage system and electronics. Extensive testing was then performed during October and early November using cosmic rays and $\gamma$-ray sources with NEBULA-Plus running in a stand alone mode with FASTER. Subsequently the effort has been focused on the coupling of the FASTER electronics and DAQ with that of SAMURAI. At the time of writing (January 2023) this work and that required to merge the NEBULA-Plus data with that from the SAMURAI detectors has been completed and tested with cosmic ray data acquired with NEBULA and NEBULA-Plus operated in tandem. Initial in-beam commissioning is planned to be undertaken using the well-known $^{7}$Li$(p, n)$ reaction which will also enable the single-neutron detection efficiency of NEBULA-Plus to be determined.[4]

Fig. 2. View of the NEBULA-Plus array, including the veto detectors, prior to the installation of the electronics.

References

1) T. Nakamura *et al.*, Nucl. Instrum. Methods Phys. Res. B **376**, 156 (2016).
2) EXPAND: "Explorations Beyond the Neutron Dripline," ANR-14-CE33-0022-02.
3) `http://faster.in2p3.fr/`.
4) Y. Kondo *et al.*, Nucl. Instrum. Methods Phys. Res. B **463**, 178 (2020).