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DEVELOPMENT AND FUTURE APPLICATIONS OF THE NARI 70 MeV CYCLOTRON

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Abstract

The National Atomic Research Institute (NARI) is developing a 70 MeV proton cyclotron, with construction set from 2023 to 2026. The cyclotron is designed to operate at proton energies from 28 to 70 MeV and a maximum current of 1000 micro-amperes. It will serve three main purposes: (1) medical isotope productions, (2) proton irradiation testing, and (3) cyclotron-based neutron source development. NARI aims to ensure a stable supply of radioisotopes for nuclear medicine, such as Tl-201, I-123, and Ga-67, while advancing the development of isotopes like Cu-67 and Mo-99. In addition to medical uses, the cyclotron will simulate space radiation environments for aerospace materials testing and radiation measurement standards. The cyclotron will also support neutron-based technologies, benefiting nuclear physics, new materials, and industrial applications. Expected to be fully operational by 2028, the facility will include six beam lines, two solid target stations, one gas target station, and specialized laboratories for proton, fast neutron, and thermal neutron research.

DEVELOPMENT OF NARI 70 MeV CYCLOTRON

The NARI 70 MeV cyclotron is designed by Best Cyclotron Systems Inc. and built by Best Theratronics Ltd. in Canada.[1] Cyclotron has been designed to accelerate high intensity negative ion beams generated by using an external ion source with minimum beam losses during acceleration and extraction. The NARI 70 MeV cyclotron is a four-sector cyclotron capable of accelerating a total of 1000 μA of H^-. Two RF cavities (4 accelerating gaps) can accelerate a beam up to 70 MeV. Two extraction probes located at 180 degrees from each other can extract simultaneously two beams of proton by intercepting the H^- beam with carbon stripper foils. The extracted beams are sent down two beam lines (BL1 and BL2) to the selected production targets, as shown in Fig. 1. Table 1 shows the Specifications of the NARI 70 MeV cyclotron.

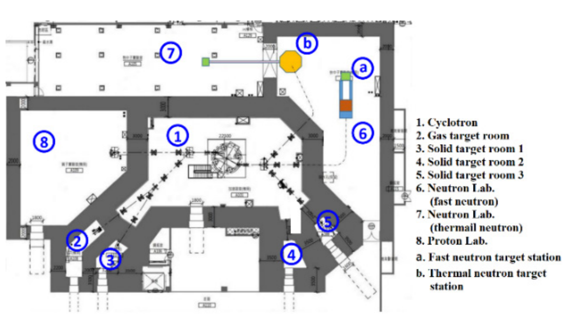

Figure 1: The layout of the Facility within the 70 MeV Cyclotron building.

Table 1: Specifications of the NARI 70 MeV Cyclotron

Parameter	Specification
Extracted Beam Energy	Variable: 28 to 70 MeV
Proton Currents	1000 μA (max.)
Magnet	Four hill, isochronous, Bavg=1T
Vacuum cyclotron (4 cryo-pumps)	No beam: 5×10^{-8} Torr With beam: 1×10^{-7} Torr
RF System	Separated λ/2 resonators, 56 MHz, 4th harmonic
Ion source, H^-	Multi-Cusp, 12 mA
Extraction	Double beam extraction
Beam line design	CM, SM (3-Way), Quad Triplets, Wobbler, Vacuum stations
Beam monitoring	BCM, BPM, Collimator (4 slits)

MEDICAL ISOTOPE PRODUCTION

For the production of medical isotopes, this project will utilize a 70 MeV cyclotron to produce established radioactive isotopes such as Tl-201, Ga-67, and I-123, supplementing the output of the existing NARI 30 MeV cyclotron. In addition, the 70 MeV cyclotron will be used to develop therapeutic isotopes like Cu-67 and diagnostic isotopes including Tc-99m. The characteristics of these nuclides—such as half-life and decay modes—are presented in Table 2, along with their irradiation conditions, including incident proton energy and associated nuclear reactions.

The radioisotope production system comprises irradiation target stations and shielded lead chambers for isotope separation and purification. The facility will feature three solid target rooms and one gas target room. Solid target rooms will support the production of isotopes such as Tl-201, Ga-67, Cu-67, and Mo-99, while the gas target room will focus on I-123 production.

Table 2: Characteristics of Radioisotopes Produced by NARI 70 MeV Cyclotron

	Half life	Decay mode	Incident energy (MeV)	Nuclear reaction
Tl-201	72.9 h	EC	28.5	Tl-203(p, 3n)Pb-201 → Tl-201
I-123	13.2 h	EC	30 or 35	Xe-124(p, x) Xe-123 → I-123 Xe-124(p, 2n) Cs-123 → Xe-123 → I-123
Ga-67	3.3 d	EC	24	Zn-68 (p,2n)Ga-67
Cu-67	61.8 h	β^-	55	Zn-68(p, 2p) Cu-67
Mo-99 → Tc-99m	65.9 h (Mo-99) 6 h (Tc-99m)	β^- IT	65	Mo-100(p,x) Mo-99 Mo-99 → Tc-99m

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PROTON LABORATORY

The Proton Irradiation Verification and Analysis Laboratory provides proton beam irradiation with an output current range of 1 nA to 1 μA at energies between 28 and 70 MeV. Currently, the laboratory operates one proton beamline in the Single-Point Irradiation Section. The beam system includes key measurement components such as a beam profile monitor, Faraday cup, irradiation samples, and beam collector, which enable characterization of the proton beam profile, energy, and flux. Additionally, a 4-way switching is installed to facilitate the extension of proton beam applications across the functional sections, as illustrated in Fig. 2.

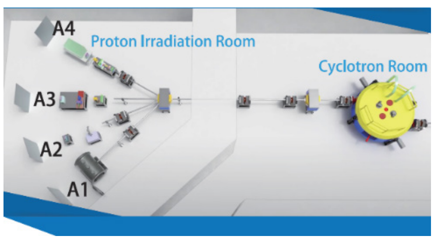

Figure 2: 28~70 MeV Proton Irradiation Verification Analysis Laboratory.

NEUTRON LABORATORY

Figure 3 presents the preliminary architectural layout of the first-floor neutron instrumentation area within the 70 MeV cyclotron facility. There are a total of six proton beamlines, with two dedicated to neutron applications. One beamline is used for neutron scattering and imaging, while the other is utilized for fast neutron irradiation.

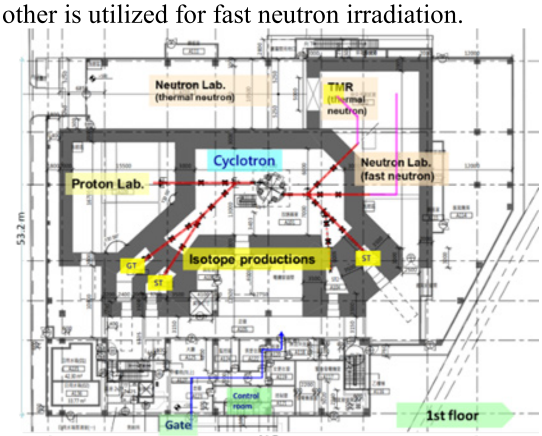

Figure 3: Preliminary Architectural Layout of the First-Floor Neutron Facility within the 70 MeV Cyclotron Hall.

Fast Neutron

NARI is developing fast neutron sources primarily for the soft error rate (SER) testing of semiconductor chips, with particular importance for the future of AI technologies.

Fast neutrons, with energies above 1 MeV, are critical for simulating atmospheric and space radiation environments to evaluate SER and single-event effects (SEE) in advanced electronics. NARI has successfully constructed a quasi-monoenergetic neutron (QMN) source based on a 30 MeV cyclotron in 2023 and has been providing service ever since to the world-leading semiconductor manufacturing company [2]. Current, NARI is developing a new 70 MeV-cyclotron-driven QMN source featuring a purer energy spectrum and significantly higher neutron flux.

Figure 4 presents the neutron spectra of 30 MeV and 70 MeV cyclotron-driven QMN sources. The spectra were calculated using PHITS v3.4 [3].

For the newly developing 70 MeV QMN source, both beryllium (Be) and lithium (Li) targets are under development. The incident proton energy can be set to 30, 40, 50, 60, or 70 MeV. The maximum proton current will be set at 100 μA. The designed neutron flux is targeted to exceed 1.0E+8 n/cm²/s, which is one to two orders of magnitude higher than that of world-leading neutron facilities. The neutron spectra calculated by PHITS are shown in Fig. 4(b).

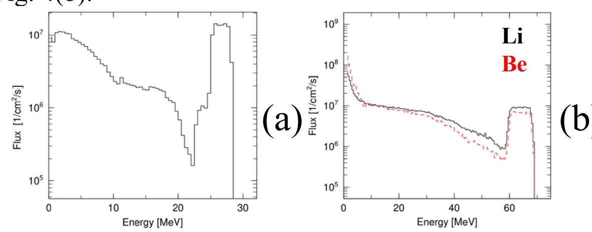

Figure 4: Fast neutron spectra of 30 MeV (a) and 70 MeV (b) cyclotron-driven quasi-monoenergetic neutron (QMN) sources. For the 30 MeV case, only a beryllium (Be) target is used. For the 70 MeV case, both beryllium (Be) and lithium (Li) targets are under development. The spectra were calculated using PHITS v3.4.

Thermal Neutron

NARI is developing a world-leading 70 MeV cyclotron-driven compact neutron source, with an incident proton energy of 28.5 MeV and a proton current of 400-500 μA. It will operate as a continuous-mode neutron source. The selected neutron target material will be either Be, BeCu alloy, or Cu. Water will be used as the moderator.

To overcome extremely high heat load (~14.25 kW) in neutron target, NARI is employing microchannel cooling technology to tackle this challenge. Microchannel cooling can typically handle heat fluxes up to 1–2 kW/cm^2, significantly outperforming traditional single-phase water-cooling systems, which are usually limited to about 0.05–0.1 kW/cm^2. Microchannels have also been successfully applied in the design of the German HBS neutron source. Two kinds of microchannels have been successfully constructed, i.e., a fishbone microchannel and an oblique fin-patterned microchannel. The opening width of microchannels is 0.4 mm. According to numerical simulations, the maximum temperature of the neutron target can be maintained below 143°C under a cooling velocity of 10 m/s and an inlet pressure of 8 bar, as illustrated in Fig. 5. Figure 6 illustrates the engineering design of the thermal neutron target station. The target station adopts a modular design that allows for on-site assembly, features an interleaved shielding configuration, and includes one proton beamline

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entrance, three neutron beamline exits, and one utility passage.

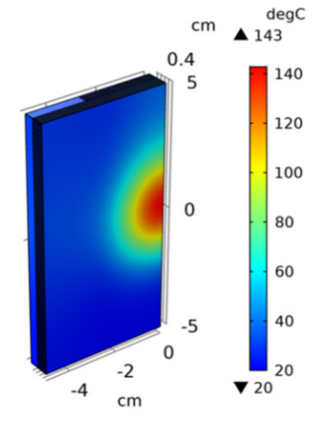
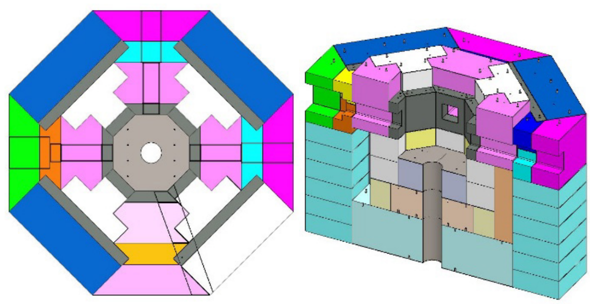


Figure 5: The temperature distribution of a thermal neutron target. The simulation was performed using COMSOL Mcultphysics® v5.5 [4] under conditions of Be target, incident protons at 28.5 MeV/500 µA, and an inlet cooling water velocity of 10 m/s.



(a) (b)

Figure 6: Engineering design of the thermal neutron target station. (a) Top view. (b) Oblique sectional view.

In response to the demands of residual stress analysis, structural characterization through powder diffraction, and neutron computed tomography, a conceptual layout of the planned instrument suite is illustrated in Figure 7.

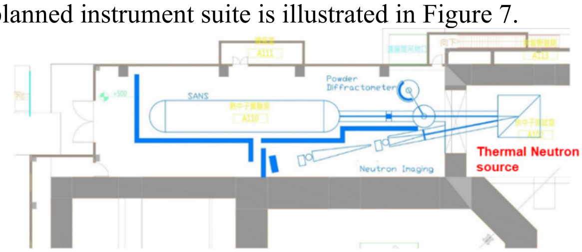


Figure 7: Conceptual Design and Layout of Proposed Neutron Instrumentation.

The preliminary scientific design of the thermal neutron powder diffractometer has been completed. A schematic diagram of the system is shown in Fig. 8. The instrument consists of a main beam shutter, a flight tube, a monochromator, a sample stage, and a position-sensitive detector (PSD).

To evaluate performance in terms of resolution and neutron flux, simulations were conducted using McStas software, considering two types of single crystals and three monochromator take-off angle configurations. Simulation results indicate that the maximum neutron flux at the sample position can reach 1.52×10^5 neutrons/cm²/s, with a best achievable lattice resolution of 8.1×10^{-3}.

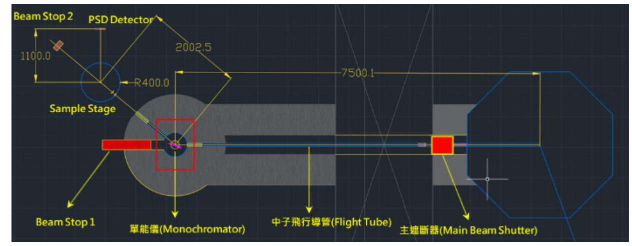


Figure 8: Schematic diagram of the setup for the thermal neutron diffractometer.

CONCLUSION

The NARI 70 MeV proton cyclotron represents a significant advancement in Taiwan's capabilities for radioisotope production, radiation effect research, and neutron science. Designed to deliver high-intensity beams with flexible energy outputs, the cyclotron will enable both routine medical isotope production and cutting-edge research in proton and neutron applications. With six beamlines and multiple target stations, the facility will support the development of therapeutic isotopes such as Cu-67, as well as diagnostic isotopes including Tl-201, Ga-67, I-123 and Mo99/Tc-99m.

Simultaneously, the cyclotron will power advanced irradiation laboratories tailored for aerospace radiation simulation, semiconductor single-event effect testing, and proton beam metrology. In the field of neutron science, the development of a quasi-monoenergetic neutron (QMN) source and a thermal neutron diffractometer illustrates the commitment to supporting both industrial needs and fundamental research. The integration of microchannel cooling technology further exemplifies NARI's engineering innovation in managing high thermal loads within compact target stations. Upon completion, the NARI 70 MeV cyclotron will serve as a national lab for nuclear science and applications, strengthening Taiwan's global competitiveness in medical, semiconductor, aerospace, and material research domains.

REFERENCES

[1] Best Theratronics Ltd., `http://www.bestcyclotron.com/#`

[2] Y. Chiang, H.M. Lee, K.Y. Chu, Y.H. Teng, "Using Quasi-Monoenergetic Neutrons from a 30-MeV proton beam for single event effects studies," presented at 2024 IEEE Nuclear & Space Radiation Effects Conference (NSREC 2024), Canada, July 2024.

[3] Y. Iwamoto *et al.*, "Benchmark study of particle and heavy-ion transport code system using shielding integral benchmark archive and database for accelerator-shielding experiments", *J. Nucl. Sci. Technol.* vol. 59, pp. 665-675, 2022. `doi:10.1080/00223131.2021.1993372`

[4] COMSOL Multiphysics®, COMSOL AB, Stockholm, Sweden