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UPGRADE OF THE RCNP AVF CYCLOTRON*

M. Fukuda†, T. Yorita, H. Kanda, Y. Yasuda, K. Hatanaka, T. Saito, H. Tamura, S. Morinobu, K. Nagayama, H. Yoshida, S. Ano, D. Tomono, H. Kamano, T. Aoi, T. Shima, E. Ideguchi, S. Ota, N. Kobayashi, T. Furuno, S. Imajo, M. Murata, Y. Yamamoto, T. Suzuki, Y. Kon, Y. Morita, K. Takeda, T. Hara, T. H. Chong, H. Zhao, M. Kittaka, S. Matsui

RCNP, Osaka University, Ibaraki, Japan

M. Nakao, GHMC, Gunma University, Maebashi, Japan

Design and Manufacture Teams, Sumitomo Heavy Industries, Ltd., Niihama, Japan

Abstract

The upgrade program of the K140 AVF cyclotron at Research Center for Nuclear Physics (RCNP), Osaka University, was started in 2019 to provide not only intense light ion beams for production of short-lived radioisotopes (RIs), neutrons and muons but also high-quality intense beams for precision experiments in nuclear physics. Most of equipment besides the main coil, pole and yoke of the cyclotron magnet was replaced by new one. Especially the RF, injection and extraction systems were fully modified to increase a beam current. A new coaxial-type resonator was designed to cover a frequency range from 17 to 37 MHz for acceleration of staple particles using acceleration harmonic mode of 2 and 6. The acceleration voltage of ion sources was increased from 15 kV to 50 kV to enhance the beam intensity and to reduce the beam emittance for injecting a high-quality intense ion beam into the cyclotron. The central region of the cyclotron was fully redesigned to improve beam transmission from the LEBT system. Beam commissioning was started from May 2022, and a 28.5 MeV $^4He^{2+}$ beam was supplied to produce a short-lived RI of ^{211}At used for the targeted alpha-particle therapy. A 65 MeV proton beam was successfully injected into the K400 ring cyclotron to provide a 392 MeV proton beam for production of a white neutron flux and a muon beam. Several ion beams have been already used for academic research and industrial applications.

INTRODUCTION

RCNP was founded in 1971 as Domestic Joint Usage Center for nuclear physics research in Japan. Construction of the RCNP AVF cyclotron with K-number of 140 MeV was completed in 1973, and nuclear physics experiments started from 1976 [1]. The accelerator facility was fully opened to nuclear physics community globally. The cyclotron cascade project was started in 1987 and construction of the K400 ring cyclotron was completed in 1991 [2]. The AVF cyclotron was mainly used as an injector for the ring cyclotron. Partial upgrade of the two cyclotrons and beam lines was conducted in 2005 [3] and 2014. The bird-eye view of the cyclotron facility is shown in Fig. 1.

In recent years, the strong demand for increasing beam intensity was growing for production of short-lived RIs such as ^{211}At and secondarily produced particles such as neutrons and muons. In addition, intense halo-free high-quality light ion beams are required for very precise nuclear experiments with energy resolution less than 0.01 %. On the other hand, the number of troubles with the AVF cyclotron was increasing and the condition of the AVF cyclotron has deteriorated gradually. We decided the full-scale upgrading of the AVF cyclotron for improvement of beam performance and operation reliability.

Renovation and reinforcement of the RCNP accelerator facility was started in 2019. After completing the renewal of the building and facilities, the most of the AVF cyclotron components except for the main magnet were removed in 2020, and reinstallation of new components was completed in March 2021. Adjustment of the new components was conducted in 2021, and beam commissioning was started in March 2022. Trial beam utilization has been carried out occasionally in parallel with beam commissioning.

AIM OF THE UPGRADE

When the AVF cyclotron is operated in the standalone mode, lower energy proton and helium ion beams are mainly provided for RI production. We have two experiment rooms exclusively used for RI production in the AVF cyclotron building. In one of the experiment rooms, ^{211}At is frequently produced and provided for non-clinical research on targeted alpha-particle therapy. In November 2021, investigator-initiated clinical trial for practical treatment was started at Osaka University Hospital. We will need to supply ^{211}At of the order of more than several hundred MBq for the clinical trials in 2023. In addition, we have another beam line for production of short-lived RIs. In recent years, there is a growing need for supplying short-lived RIs for academic use, especially for the research on diagnosis and therapy in nuclear medicine. In Japan, the short-lived RI supply platform was organized in 2016 in cooperation among RCNP, Osaka University, RIKEN RIBF, CYRIC and ELPH, Tohoku University, QST NIRS and TIARA to support basic and applied research using RIs in a variety of academic fields. The ^{211}At with a half-life of 7.2 hours, is one of the major short-lived RIs which are provided from the short-lived RI supply platform. One of the main purposes of the AVF cyclotron upgrade was increase of the light ion beam intensity to more than 100 μA.

A 392 MeV proton beam is used to produce secondary particles such as neutrons and muons. Especially the neutrons, obtained at an emitted angle of 30 degrees from a tungsten target, have almost the same energy distribution as terrestrial neutrons. The so-called white neutrons are very useful for accelerated-simulation experiments of soft-errors occurred in semi-conductor devices resulting from

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the terrestrial neutrons. Muons, produced by irradiating a graphite target with the 392 MeV proton beam, are provided especially for non-destructive element analysis and μ–SR analysis. The maximum proton beam current was limited to 1.1 μA due to the regulation of radiation shielding performance of the RCNP accelerator facility so far. Objective of the upgrade program was to increase the beam intensity of the 392 MeV proton up to more than 10 μA.

A high-quality light ion beam with the energy spread of $\Delta E/E = 10^{-4}$ is available for very precise nuclear physics experiments using an ultra-high-resolution spectrograph called Grand-RAIDEN. Increase of the high-quality beam will give advantage to high efficiency of data acquisition in the precise nuclear physics experiments. In addition, intense heavy ion beams accelerated by the AVF cyclotron is required for increase of secondarily produced unstable nuclei beam intensity used for high-spin-state nuclear physics experiments.

Figure 1: The bird-eye view of the cyclotron facility.

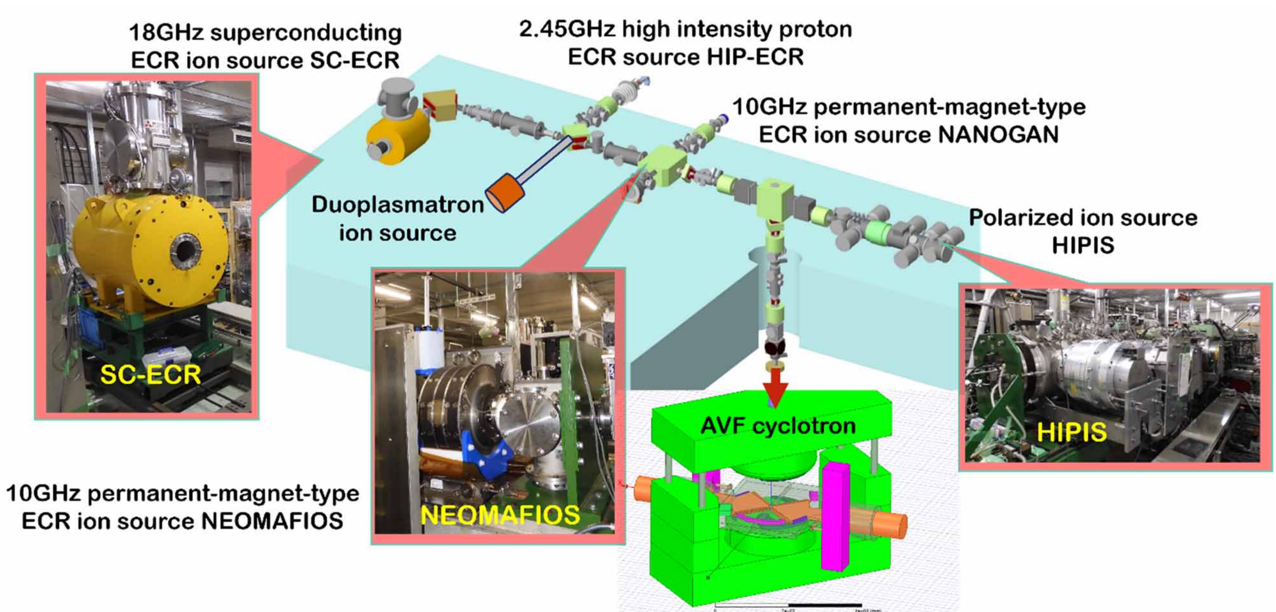

Figure 2: Layout of six ion sources and the LEBT system.

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MODIFICATIONS OF ION SOURCE AND LEBT SYSTEMS

Ion Sources

Before the AVF cyclotron upgrade, light ions such as protons, deuterons, $^3He^{2+}$, $^4He^{2+}$ were produced mainly by a 10 GHz permanent-magnet type ECR ion source called NEOMAFIOS. Polarized proton and deuteron beams were provided by a polarized ion source with 2.45 GHz ionizer called HIPIS. Heavy ions were mainly produced by an 18 GHz superconducting ECR ion source called SC-ECR. For increase of the light ion beam intensity, a 2.45 GHz ECR proton source called HIP-ECR was developed, and another 10 GHz permanent-magnet type ECR ion source called NANOGAN and a duoplasmatron ion source were introduced in the LEBT system. A layout of the ion sources and the LEBT system is shown in Fig. 2.The extraction voltage of the ion sources was set at 10 or 15 kV to inject the ions efficiently into the former AVF cyclotron. The ion acceleration system of the six ion sources has been modified to increase the maximum voltage to 50 kV to improve the beam current and emittance.

Configuration of LEBT magnets and beam diagnostics stations was maintained since the space for LEBT components was limited. All of power supplies of magnets were replaced by new ones to increase the magnetic field of the LEBT magnets for the maximum acceleration voltage of 50 kV. The LEBT optics for each ion source was redesigned to optimize the beam injection into the central region of the upgraded AVF cyclotron for the ion energy higher than before.

Beam Buncher

Two types of bunchers with single-gap electrodes were installed in the axial injection beam line. A beam buncher of harmonic-voltage superimposing type is located just at the entrance of the upper yoke of the AVF cyclotron magnet. A saw-tooth-like voltage waveform is generated by mixing the second and third harmonic voltages with the fundamental one. The other beam buncher of charge-and-discharge type is located at the exit of the vertical bending magnet. Both beam bunchers are operated in sub-harmonic bunching mode using a half frequency of the fundamental one for the RF system of the AVF cyclotron. Originally the fundamental frequency range of both beam bunchers was from 5.5 to 20 MHz, covering the original fundamental frequency range of the former AVF cyclotron. The sub-harmonic bunching is needed to keep a period of beam bunches unchanged, because the ring cyclotron can be operated using the same parameters as before.

SPECIFICATIONS OF THE UPGRADED AVF CYCLOTRON

Design Principle

The upgraded AVF cyclotron is shown in Fig. 3. Main parameters of the upgraded AVF cyclotron are listed in Table 1. The maximum acceleration energy is the same as the original one since the yoke, pole, spiral sector, and main coil of the cyclotron magnet were reused. Sixteen pairs of trim coils and two sets of valley coils in the central and extraction regions were renewed due to deterioration of hollow conductors. Two Dee electrodes with an opening angle of 87 degrees were installed to increase the energy gain per turn to enlarge the turn separation before extraction. The fundamental RF frequencies are doubled, ranging from 17 to 37 MHz to accelerate most of light ions in the second harmonic mode to improve extraction efficiency.

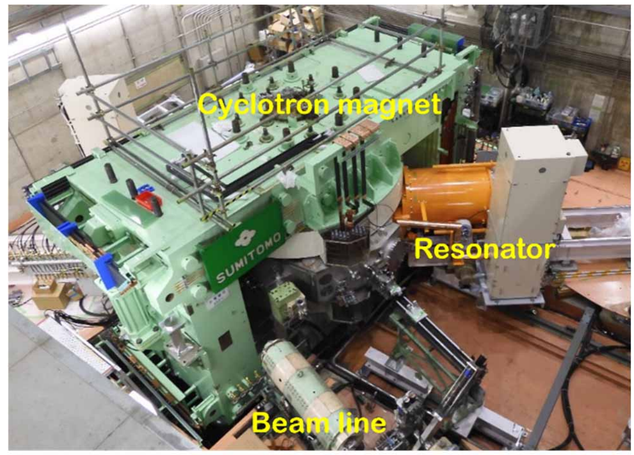

Figure 3: Photo of the RCNP AVF cyclotron.

Table 1: AVF Cyclotron Main Parameters

Parameter	New	Previous
K-value	140 MeV	140 MeV
Extraction radius	1 m	1 m
Max. $B_{extraction}$	1.65 T	1.65 T
Resonator and Dee electrodes	Double	Single
Opening angle of Dee	87 degrees	180 degrees
RF frequency	17 to 37 MHz	6 to 18 MHz
Harmonics	1, 2, 3, 6	1, 3
Max. V_{Dee}	60 kV	60 kV

A layout of the AVF cyclotron components is shown in Fig. 4. There was a severe geometrical condition that the position of the main magnet and the beam line were previously fixed and the space in the cyclotron vault was limited. That's why this layout was a unique solution to satisfy the difficult condition. First, we determined the resonator position considering the maintenance space of the cavities. Second, the deflector and field gradient corrector positions were fixed concerning the beam trajectory matching with the existing beam line. There were no room for putting other devices such as beam probes and phase slits, vacuum pumps.

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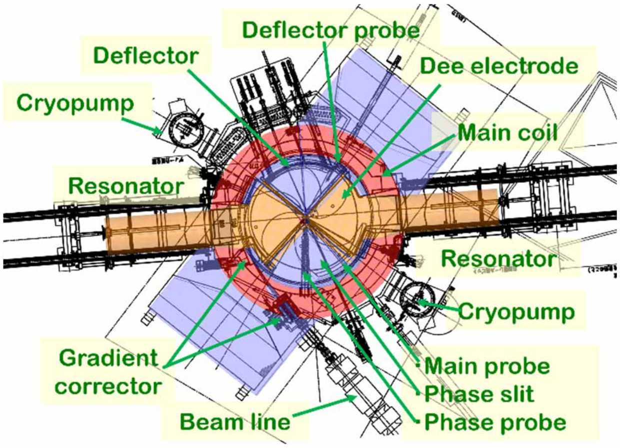

Figure 4: Layout of the cyclotron components.

Operation diagrams of the upgraded AVF cyclotron is shown in Figs. 5 and 6 as a function of a particle frequency and energy per nucleon, respectively. Most of high energy particles are accelerated in the harmonic mode of 2. Lower energy ion beams are provided by accelerating in the harmonic mode of 3 or 6. Especially, a 28.5 MeV $^{4}He^{2+}$ ion beam for ^{211}At production is accelerated using the harmonic mode of 6 to enlarge the energy gain per turn and to improve the beam extraction efficiency.

RF System

There was a severe restriction on the design of the new resonant cavity due to a vertical space between upper and lower main coils. When the resonant frequency is increasing, the short-plate position should be changed toward the center of the cyclotron. However, the effective vertical gap between the upper and lower main coils was 730 mm, which was obviously smaller than the reasonable diameter of the short plate and the outer tube. This meant that the short plate could not be placed at a position where a distance from the center of the cyclotron was less than 1800 mm. On the other hand, the fundamental frequency range of 17 to 37 MHz was required to accelerate most of light ions in the harmonic mode of 2. Thus, we optimized the size of inner and outer tubes, the gap between a Dee electrode and an earth plate, the neck width of the Dee electrode to fulfil the requirement. Finally, the diameter of the inner and outer tubes was determined to be 700 mm and 1000 mm, respectively.

A tetrode, EIMAC 4CW100,000E, was used for the final amplifier of the RF system. The output RF power from the final amplifier was transferred through a 50 W coaxial tube and fed into the cavity by a capacitive coupler. The resonator and the final amplifier are shown in Fig. 7. Main components in the vacuum chamber of the AVF cyclotron are shown in Fig. 8. An electrostatic deflector is placed in between the Dee electrodes. We have two gradient correctors for focusing a beam before extraction.

During the commissioning of the RF system, we had serious troubles with a final amplifier system. We observed large parasite components at a plate pick up, which were generated by the magnetic flux surrounding the amplifier tube. We placed many ferrite plates around the amplifier to absorb the parasite magnetic flux components. The variable capacitor located between the final amplifier and the coaxial power feeder, was damaged by sparking due to harmonic components with high amplitude, which might be generated by the RF power reflected from the capacitive coupler. We installed a corona ring outside of the capacitor to avoid the sparking damage on the capacitor. In addition, the length of the coaxial power feeder tube was configured to be changeable in accordance with the resonant frequency to decrease amplitude of the harmonic voltages. After making the improvements, the output power of the final amplifier became stable.

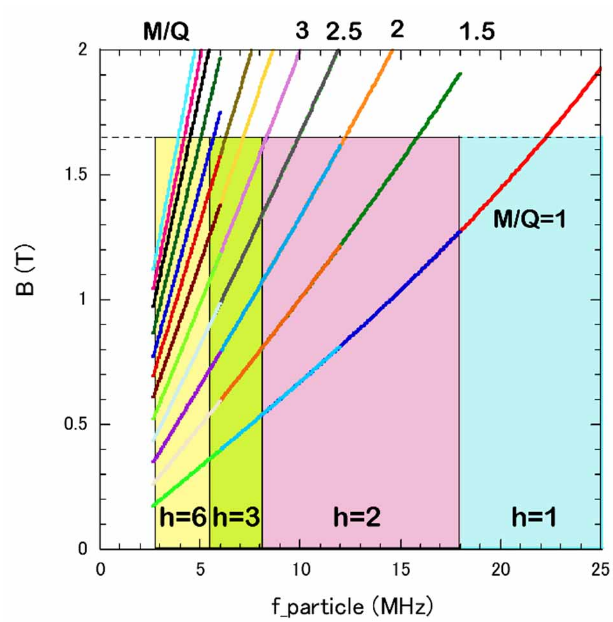

Figure 5: Operation diagram of the upgraded AVF cyclotron as a function of the particle frequency.

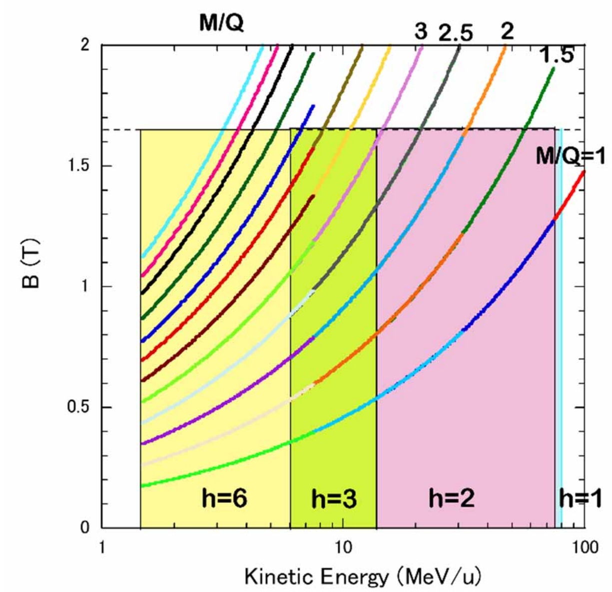

Figure 6: Operation diagram of the upgraded AVF cyclotron as a function of the particle energy.

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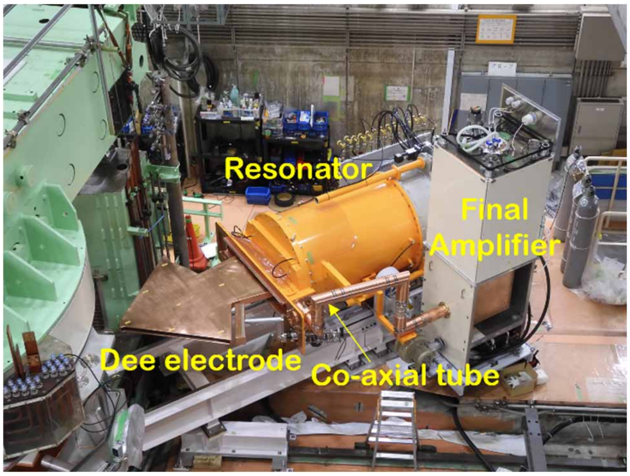

Figure 7: Dee electrode, resonator, power feeder and final amplifier.

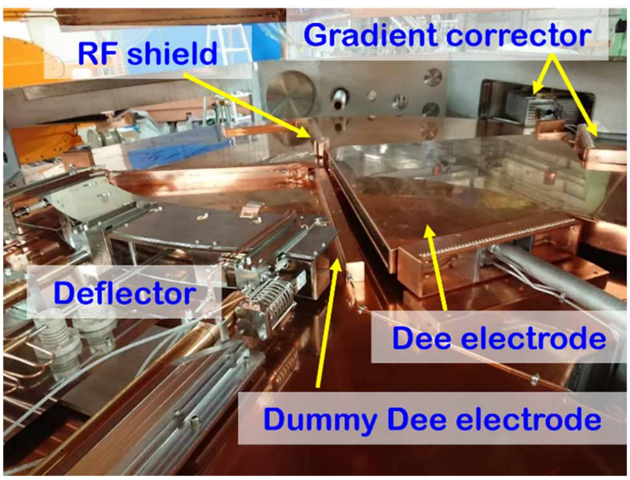

Figure 8: Main components in the vacuum chamber of the AVF cyclotron.

We had other RF troubles with inside of the vacuum chamber. A part of RF power was transmitted to the space between the dummy Dee electrodes, because the radial length of the dummy dee electrodes was not enough long to suppress the RF leakage. Beam probes and phase slits suffered from the large RF leakage noise. Therefore, we decided to install additional RF shield copper walls at the outside of the dummy Dee electrodes in the larger radius region. After this improvement, the RF leakage seemed to be reduced so much.

Central Region

Single particle trajectories for each acceleration harmonics of 1, 2, 3, 6 are shown in Fig. 9. First, we tried to design an inflector electrode for each harmonic mode to inject particles to the same Dee electrode. However, the performance of the phase defining by a phase slit was insufficient for the harmonic number of 3 and 6. Thus we decided that the inflector electrode for h = 3 and 6 was rotated by 180 degrees and inject the beam to another Dee electrode. Two configurations of the inflector electrode placed inside of an RF shield cover are shown in Fig. 9.

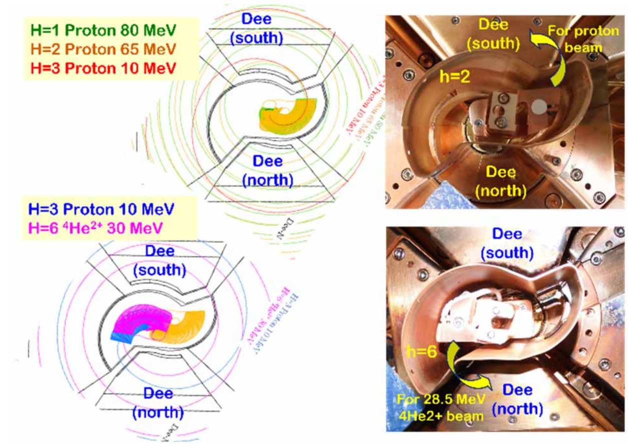

Figure 9: Single particle trajectories designed for each acceleration harmonic mode are shown in the left figure. Actual inflector electrodes for h = 2 and 6 are shown on upper right and lower right parts, respectively.

Extraction System

The maximum deflector voltage is 60 kV. The position and gap of the entrance and exit of the deflector electrode can be changed to optimize the extracted beam trajectories. The first gradient corrector placed downstream of the north Dee electrode is a half quadrupole type with active coils. The second gradient corrector of a quadrupole type with active coils is located at the exit of the vacuum chamber.

BEAM COMMISSIONING

We obtained permission for acceleration from Government on March 16th, 2022. We started beam commissioning from the end of March and the injected beam was successfully observed in the central region of the AVF cyclotron soon. In the beginning of April, the beam reached the entrance of the deflector, and the first extracted beam was observed on April 21st, 2022. In the beginning of May, we passed at the radiation facility inspection using a 65 MeV proton beam. After that, we started regular beam commissioning [4]. Occasionally, we provided a 28.5 MeV $^4He^{2+}$ beam for ^{211}At production, and 65 and 392 MeV proton beams for commissioning of the nuclear physics experiment equipment and for semiconductor soft-error analysis using secondarily produced neutrons.

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