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THREE YEARS OPERATION OF CYCIAE-100

Tao Ge#, Yinlong Lyu, Tianjue Zhang, Yaoqian Li, Shiqiang Li, Zhenwei Liu, Lei Wang, Lei Cao, Zhenhui Fu, Hao Jiang, Lipeng Wen, Bin Ji, Zhiguo Yin, Shigang Hou, Gaofeng Pan
China Institute of Atomic Energy, Beijing, PR China

Abstract

The 100 MeV high intensity proton cyclotron (hereinafter referred to as CYCIAE-100) developed by China Institute of Atomic Energy is a multi-purpose variable energy AVF cyclotron for nuclear fundamental research and nuclear technology application. Its design specifications are: energy from 75 to 100 MeV continuously adjustable, beam intensity 200 μA, beam current can be extracted in both directions. The first physics experiment was carried out in November 2016 right after the national acceptance. By June 2019, we completed the construction of multiple experimental terminals for CYCIAE-100, such as single-event effect experimental terminal, ISOL experimental terminal, and white-light neutron experimental terminal. Several typical physics experiments of CYCIAE-100 have been carried out. Such as: The physics experiment of CYCIA-100 driving ISOL device to generate radioactive nuclear beam, white light neutron experiment, SiC and SRAM proton irradiation experiments, calibration experiment of high-energy proton electron total dose detector probe, and proton irradiation damage effect experiment of photoelectric devices. At present, the beam time for beam development of CYCIAE-100 is about 5000 hours, providing effective beam time for more than 3000 hours for many users at home and abroad, and the other beam time for beam development. This paper introduces the operation of CYCIAE-100 in the past three years, as well as the construction of experimental beam lines and terminals and typical experiments carried out.

CONSTRUCTION OF BEAMLINES AND EXPERIMENTAL TERMINALS

At the beginning of the design, the CYCIAE-100 had multiple beam lines and experimental terminals. Further, due to lack of funds and other factors, construction of some beam lines and experimental terminals were not completed when the accelerator was first beamed out in 2014. Then, as the accelerator gradually putting into the operation and while carrying out physical experiments, the construction of some beam lines and experimental terminals were also gradually carried out [1]. By July 2019, we completed the construction of multiple experimental terminals for CYCIAE-100, such as single-event effect experimental terminal, ISOL experimental terminal, and white-light neutron experimental terminal.

18610094847@163.com

Single-event Effect Beam Line and Experimental Terminal

The single-event effect beam line and experimental terminal are located on the east side of the physical experiment hall. They are mainly used to carry out experiments on single-event effect and anti-radiation reinforcement of aerospace devices. Figure 1 shows the single-event effect beam line and the experimental terminal. The proton beams are transmitted along the south to the common beam line, after they are extracted from CYCIAE-100. Then, after the proton beams are deflected by the southward switching magnet, they enter the single-event effect beam line. At present, a large number of experiments about single-particle effects and radiation-resistant reinforcement have been carried out at the experimental terminal.

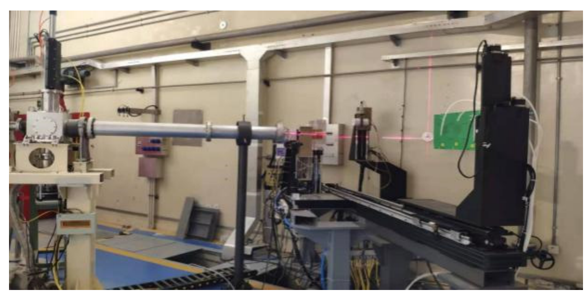

Figure 1: Beam line and experimental terminal of single-event effect.

Construction of ISOL Beam Line and Experimental Terminal

The ISOL beam line and experimental terminal are one of the important components in the HI-13 Tandem Accelerator Upgrade Project. The ISOL experimental terminal uses the proton beams generated by CYCIAE-100 to bombard the target material to produce medium- and short-lived radionuclides. Subsequently, the neutral radionuclide atoms generated in the target are converted into charged particles, and the required radioactive nuclear beams are sorted by a magnetic analyzer and accelerated up to 300 keV. A new set of superconducting post-accelerators and existing HI-13 tandem accelerators can further accelerate ions. The proton beams generated by CYCIAE-100 are transmitted through the north common beam line, pass through the northward switching magnet, enter the ISOL beam line, and are transmitted to the ISOL target chamber. The proton beams interact with the selected target material to generate the desired radioactive nucleus. The radionuclide atoms diffuse out from the target and enter the ion source ionization chamber to be ionized.

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The ISOL experimental terminal is shown in Fig. 2. At present, the ISOL beam line and experimental terminal have been completed, and we have carried out the radioactive nuclides experiments such as ^{38}K and ^{20}Na.

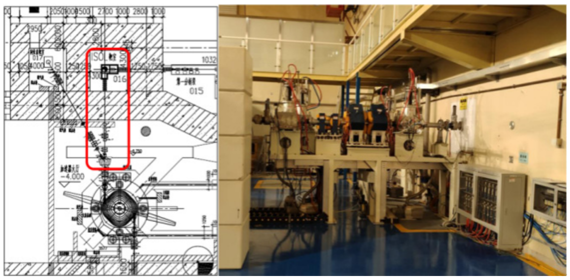

Figure 2: ISOL Beam line and experimental terminal.

Construction of Quasi-Single Neutron Beam line and Experimental Terminal

The study of neutron reference radiation field and calibration method in the energy region above 20 MeV is the hotspot of neutron metrology international research. The operation of CYCIAE-100 has laid a research foundation for the study of high-energy neutron reference radiation field in China. After the construction of the quasi-single-neutron beam line and the experimental terminal are completed, we will carry out research on high-energy neutron reference radiation field and calibration technology.

The quasi-single-energy neutron beam line and experimental terminal are located on the west side of the physical experiment hall. The proton beams generated by CYCIAE-100 pass through the south common beam line and are deflected by the south switching magnet to inject the quasi-single-energy neutron beam line. Figure 3 shows the quasi-single-energy neutron beam line and experimental terminal. At present, the beam line and experimental terminal have been completed, and relevant experimental work will be carried out soon.

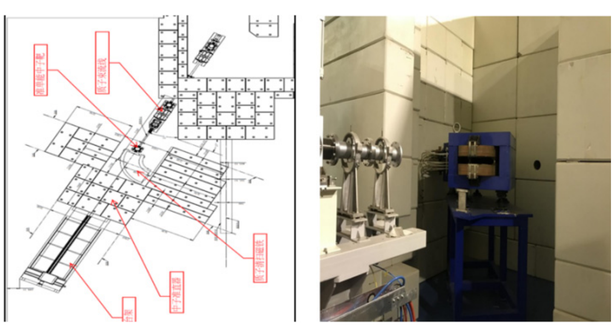

Figure 3: Quasi-single-energy neutron beam line and experimental terminal.

Construction of White Neutron Beam Line and Experimental Terminal

The operation of CYCIAE-100 laid the foundation for the research of white neutrons in China. After the construction of the white neutron beam line and the experimental terminal are completed, we will obtain the best pulse beams in China (pulse width/2.6 ns, 1 MeV-20 MeV neutron energy resolution is better than 1%). White light fast neutrons have a relatively broad energy spectrum, relatively high pulse frequency (1M/500 kHz), and the white light fast neutron yield and irradiation fluence rate are the highest in China. The best time-resolved white light neutron source in China is suitable for time-of-flight measurement methods.

The white neutron beam line and the experimental terminal are located in the middle of the physical experiment hall and are divided into two beam lines of 0° and 15°. The proton beams generated by CYCIAE-100 passes through the south common beam line and the south switching magnet. Then, they enter the white-light neutron beam stream, and finally hit the white-light neutron target. At present, the beam line and the experimental terminal have been constructed. Upon completion, the first test was carried out and a white neutron beam was obtained. Figure 4 shows the installed white light neutron target and pipe.

Figure 4: White light neutron target and beamline.

TYPICAL EXPERIMENT

Since the CYCIAE-100 was put into operation, dozens of users at home and abroad have used the accelerator to carry out various types of experiments. For example, the CYCIAE-100 design index debugging experiment was carried out, and the maximum extracted beam on the target reached 520 μA with a power of 52 kW. Achieve a supply beam range from 1 pA to 520 μA, and the beam intensity stability is 1%/8 hours. An experimental study on the sub-second half-life (445 ms) $^{20}Na^{+}$ radioactive nuclear beam, several β–γ–α singular decay sequences of ^{20}Na discovered for the first time in the world [2].

Proton irradiance effect test for single-event effect of large-capacity SRAM memory and DSP, etc. Total dose effect and displacement damage effect based on 100 MeV energy region wide beam intensity range proton beam were first carried out in China.

For the first time in China, the single crystal diamond wafer proton irradiation experiment for LHC/ATLAS applications was carried out. Table 1 shows some typical experiments.

Index Debugging Experiment of CYCIAE-100

The CYCIAE-100 has two radial insertion stripping targets, each with twelve carbon films, which can be replaced online. By adjusting the radial insertion position of

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the stripping target, the stripping extraction of H-ion in the energy range from 75 MeV to 100 MeV can be realized. After the H-ion is accelerated to a certain energy, it passes through the stripped membrane, loses two electrons and becomes a proton. By fine-tuning the angle of the stripped membrane, it changes the direction of motion under the effect of magnetic field, and is drawn out of the main vacuum and injected into the corresponding beam line.

Table 1: Some Typical Experiments

No	Experiment name	User Name	Beam Intensity	Experimental Time
1	^{20}Na decay study	CIAE	5 μA	150 h
2	Proton irradiation experiment of Single Crystal Diamond Module	Nanjing University	300 nA	50 h
3	Reinforcement test from check main nucleus in 28nm SOC asymmetric mode	Xi'an Jiaotong University	2 nA	3 h
4	The relationship between luminescence efficiency of scintillating fiber and proton irradiation dose was studied	Tsinghua University	2.5 nA	2.5 h
5	High-energy proton electron and total dose detector probe calibration experiment	Aerospace Fifth Research	1.6 pA	4 h

The accelerator debuted its first beam extraction in 2014 and first physics experiment in 2016. On this basis, 2018 has carried on the accelerator design index debugging experiment. By means of further increasing the main vacuum of the accelerator (the highest vacuum is 4.8×10^{-8} mbar), improving the stability of the high-frequency system under high power conditions, and improving the efficiency of the buncher, etc. The maximum stripping beam intensity of 520 μA was obtained on Beamdump target. Figure 5 shows the beam measurement curve for the Beamdump target.

Proton Irradiation Test of Single Crystal Diamond Module

The next-generation upgrade plan for the Large Hadron Collider (LHC) is to increase the transient brightness by a factor of ten. When the upgrade is complete, the original material will not be able to withstand such high colliding brightness. So they hope to place a diamond mini-FCal module in front of ATLAS's Liquid-Argon front-end energy meter, using the diamond module as a buffer to resist such high-brightness particle beams. Therefore, the high-energy Proton beam produced by the CYCIAE-100 was used to study whether the single crystal diamond module can maintain more than 5% signal output after being exposed to a beam dose equivalent to that of the LHC for 10 years. Single crystal diamond chips are widely used, not only as energy meter modules, but also as dose detection windows, track detectors, Pixel detectors, etc. Therefore, this experiment has important reference significance for the development of detector modules in large-scale Collider such as CEPC.

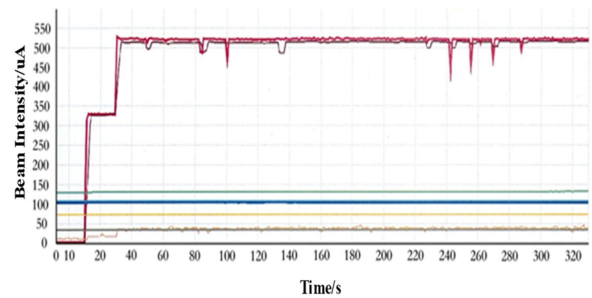

Figure 5: The beam curve of the beamdump target.

The data of one of the two samples in the experiment were processed. The sample was exposed to about 1.5×10^{17} p/cm^2 of Proton radiation, and the final output signal was about 5.6% of the initial signal. Figure 6 shows a photo of the experiment.

Figure 6: Proton irradiation experiment of single crystal diamond.

CONCLUSION

The steady operation of the CYCIAE-100 for nearly three years and a large number of experiments show that the design of the accelerator is reasonable and the index is advanced. The results demonstrate the China Institute of Atomic Energy's extensive experience in building and debugging cyclotron. The China Institute of Atomic Energy has the ability to develop high energy, high power, high current proton cyclotron.

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