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Development of high intensity D–T fusion neutron generator HINEG

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SUMMARY

The high intensity D–T fusion neutron generator (HINEG) has been developed at Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences/FDS Team, which will be a significant neutronic experimental platform for research and development of nuclear technology and safety, including the validation of neutronic method and software, radiation protection, material activation, and irradiation damage as well as neutronic performance of components. Its application can also be extended to nuclear medicine, radiotherapy, neutron imaging, and other nuclear technology applications. HINEG consists of two phases: the first phase, named HINEG-I, aims to have the intensity of 10^{12} n/s in order of magnitude, and the second phase, HINEG-II, is designed to reach a neutron yield of 10^{14}–10^{15} n/s via high-power tritium target system and high-intensity ion source. HINEG-I has been completed and commissioning with the intensity produced of 1.1×10^{12} n/s, while the feasibility of HINEG-II has been preliminarily demonstrated. This paper will summarize all the latest progress and future plans for the research and development of HINEG. © 2016 The Authors. *International Journal of Energy Research* Published by John Wiley & Sons Ltd.

KEY WORDS

neutron generator; tritium target; ion accelerator; neutronic experiment; nuclear technology application

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1. INTRODUCTION

The high intensity D–T fusion neutron generator (HINEG), accelerating deuterium ions to hit tritium targets to produce 14.1 MeV mono-energetic neutrons, is an essential experimental platform for the research and development on nuclear energy and nuclear safety technology. It can be directly used to represent the neutron environment in future fusion reactors, on which fusion energy science and technology experiments can be performed regarding tritium breeding, energy generation, material activation/damage, radiation protection, and verification and validation (V&V) of the neutronics method and software, etc. [1,2]. Furthermore, the moderated D–T neutron can be used to simulate neutron environment of advanced fission reactors for nuclear safety experimental research. Meanwhile, the application of HINEG can also be extended to nuclear medicine, radiotherapy, neutron imaging, etc.

Currently, several D–T neutron generators have been built, such as RTNS-II in USA [3], SNEG-13 in Russia [4], FNS in Japan [5], and FNG in Italy [6], which generally have the neutron yield of 10^{11}–10^{13} n/s. China has also developed the neutron generators like CPNG-6 [7], ZF-300 [8], and PD-300, which generally have the neutron yield of 10^{10}–10^{12} n/s.

In order to satisfy the growing demand for experiments in fusion energy, fission safety, and nuclear technology applications, the HINEG has been developed at Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences/FDS Team. HINEG consists of two phases: the first phase, named HINEG-I, aims to have the intensity of 10^{12} n/s in order of magnitude, and the second phase, HINEG-II, is designed to reach a neutron yield of 10^{14}–10^{15} n/s via high-power tritium target system and high-intensity ion source. In this contribution, the latest progress and step forwards for the research and development of HINEG will be summarized.

2. OVERALL DESIGN

HINEG-I is designed to have both steady and pulse modes. The neutron yield of the steady mode can reach 10^{12} n/s, while the full width at half maximum of neutron pulse is less than 1.5 ns for the pulse mode. HINEG-I has been completed and commissioning with the D–T neutron yield up to 1.1×10^{12} n/s, and the further tuning experiments are still ongoing, with the goal of approaching 7×10^{12} n/s.

With these two modes, HINEG-I consists of steady beam line and pulse beam line. The devices mainly include high-voltage power supply, high-intensity ion source, low-energy beam transport, accelerating tube, high-energy beam transport, and high-power rotating tritium target, as shown in Figures 1 and 2. The deuteron beams are extracted from the ion source, accelerated by the accelerating tube, and will be switched by a deflection magnet for different working modes. In steady mode, the deuteron beam goes straight to hit the high-power rotating tritium target. In pulse mode, the deuteron beam is deflected 90° by the guiding device, goes through the pulse beam device, and finally hits another tritium target.

For HINEG-II, in order to reach a neutron yield of 10^{14}–10^{15} n/s, several key technologies have been developed, such as the spraying cooling technology for the target as well as a high-intensity ion source. The feasibility of technological route has been demonstrated by conducting corresponding experiments. Furthermore, the neutron yield of 10^{15}–10^{16} n/s is expected to be achieved by adopting accelerator-array and high-power target. The design and development of the key components of HINEG-II are still ongoing.

3. KEY TECHNOLOGIES

3.1. High-power tritium target

In order to produce high-intensity neutrons, D–T fusion neutron generator needs to use high-current deuteron beam, which will bring high heat-flux on the target. For HINEG-I, the heat flux can reach around 10 kW/cm^2, with the deuteron beam of 35 mA/400 keV, which becomes a key issue for the reliable operation of HINEG. The key technologies of high-power tritium target mainly include three aspects: cooling and thermal conduction, mechanical driving and dynamic sealing, and high-efficiency tritium utilization.

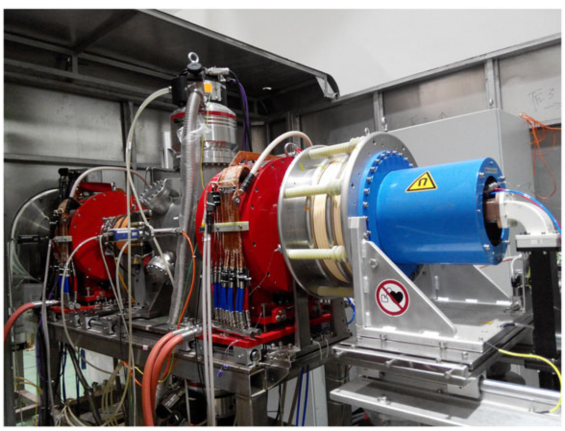

Figure 1. Ion source and low energy beam transport of HINEG-I.

Figure 2. High-power rotating tritium target of HINEG-I.

3.1.1. Cooling and thermal conduction

The impinging jet cooling concept is utilized in the HINEG-I target system, which the cooling water impinges at the center of the target and cools the system by forced convection. The experimental results demonstrate that the impinging jet cooling system with 1000 rpm rotating can tackle the intense cooling issue under the high-intensity beam bombardment, and the temperature in the target spot can be successfully suppressed to less than 200 °C.

For the HINEG-II target system, as the heat flux will reach at least 50 kW/cm^2, the spray array or jet array cooling technology as well as the nanofluid and more effective flow channel structures have been explored. Recently, an experimental platform was established for the cooling technology verification of full-scale high-power target, including spray, jet cooling, and nanofluid, as shown in Figure 3. Experimental and numerical results suggest that an equivalent convective heat transfer coefficient of approximately 57 kW/(m^2 K) can be achieved with a coolant flow rate of 30 L/min, while the target maximum temperature is kept below 180 °C.

The thermal conductivity of the substrate material of the target will affect the overall heat transfer performance. For HINEG-I, satisfactory performance can be achieved using chromium zirconium copper as the target substrate material. However, for HINEG-II, explosive work is still required for a composite substrate material with super high-thermal conductivity and good mechanical properties. Potential candidates are diamond composite materials, such as diamond composite aluminum, diamond composite

Figure 3. Platform for high-power target cooling experiment.

copper, and so on. Further work is in progress to verify the performance.

3.1.2. Mechanical driving and dynamic sealing

The design speed of the HINEG-I target system is 1000 rpm, with adoption of belt drive and magnetic fluid-sealing technologies, while a higher rotation speed (approximately 5000–10 000 rpm) is required for HINEG-II. New technologies, for example, pneumatic turbine drive, are now under consideration to satisfy this driving requirement of the target. Furthermore, the high-speed rotation will bring new challenges for the dynamic sealing. Here, the labyrinth structure is being considered to minimize the contact friction and then realize superior sealing performance for the coolants. The dynamic molecular sealing is expected to be used for the vacuum sealing.

3.1.3. High-efficiency tritium utilization

In order to improve the efficiency of tritium utilization, tritium online injection and recycle technology, such as using an ion source to inject tritium onto the target surface, are being explored to extend the life of tritium target and improve the economics of neutron generator. Additionally, gas target and liquid target systems are being designed, owing to them benefits of higher neutron yield and tritium utilization, and one of the key technologies is to use the differential vacuum in order to achieve leaping transition from the level of 10^{-5} mbar in accelerator to the level of 10^{2} mbar in gas target and meanwhile to avoid problematic gas injection.

3.2. High-intensity ion accelerator

The current of deuteron beam on target of HINEG-I is designed as 35 mA, while HINEG-II is in the order of 100–1000 mA. However, the current of ion beam is restricted by several key issues, such as the extraction of high-current ion beam with low emittance and the transmission and acceleration of ion beam under the strong space charge effect.

3.2.1. The extraction of high-current ion beam with low emittance

It is known that the electron cyclotron resonance ion source has the advantages of high-intensity beam, low emittance, high D^+ fraction, long life, etc. This kind of ion source is introduced for HINEG. For HINEG-I, the emittance of the ion beam is less than 0.2 pi · mm · mrad when the 50 mA ion beam is extracted with the five-electrode extraction system. For HINEG-II, the ion source will be improved to realize the extraction of higher current ion beam.

3.2.2. The transmission and acceleration of ion beam under the strong space charge effect

The space charge effect is very significant in the transmission and acceleration of the low-energy high-current ion beam, which will induce the divergence of the beam. For non-electrostatic components like low-energy beam transport, the space charge compensation mechanism is used to reduce the space charge effect. For high-voltage electrostatic accelerating tube, the following strategy is employed: The double solenoid lens is adopted before the accelerating tube to focus the D^+ beams and then achieve the fraction of D^+ to more than 97%; the accelerating tube with the high-gradient uniform-field design is utilized to increase the focusing ability and shorten the acceleration distance, which controls the divergence and loss of the beam; a space charge lens is installed at the exit of the accelerating tube in order to neutralize the space charge.

4. EXPERIMENTAL PLANS

The HINEG could be used to simulate the neutron environment in fusion reactor, and the moderated neutrons produced by HINEG could also be used to simulate the neutron environment for advanced fission reactors.

The first phase of HINEG will focus on the basic research of neutronics, and the recent experimental plan is focused on neutron physics, including nuclear data measurement, as well as V&V of the neutronic method and software. Small-scale macro verification experiments can be carried out to validate the method, program, and nuclear data required for the neutronic design and safety analysis of advanced nuclear energy systems, such as fusion reactor, lead cooled fast reactor and accelerator-driven sub-critical systems, etc. For example, HINEG-I can be used to validate the SuperMC program developed by Institute of Nuclear Energy Safety Technology Chinese Academy of Sciences/FDS team [9]. Meanwhile, the nuclear reaction cross-sectional data can be measured, such as (n, p), (n, t), (n, ^{3}He), (n, a), and other cross section because of the interaction of high-energy neutrons with Cu, Fe, W, Ni, etc. Note that these reactions, producing hydrogen, helium, and other gases, are strongly related to the properties and lifetime of the materials in fusion reactor [10]. However, these cross-sectional data are micro barn in order of magnitude, and it is extremely difficult to verify the data. Furthermore, there is still lack of the angular distribution and energy spectrum measurement data [11]. The measurement data of the photon-induced microscopic cross section, as a result of the interaction of neutron with Fe, Li, Pb, and other nuclides, can be used in the shielding design of fusion reactor superconducting coil [12].

The second phase of HINEG will focus on basic research in nuclear technology such as the mechanism of material irradiation damage, neutronic performance of key components, and so on. A series of material irradiation experiments will be performed, such as the test of the China low-activation ferritic/martensitic steel, the primary candidate structural material for CN ITER test blanket module (TBM), in the real fusion neutron environment [13]. Moreover, experiments for different kinds of TBM (such as the dual-function lithium lead liquid TBM [14,15] and helium-cooled ceramic breeder TBM [16]) will be performed to confirm whether the neutronic performance is consistent with the design, including tritium breeding ratio, nuclear heating deposition, material activation behavior, etc.

Moreover, HINEG is also an important platform for radiation protection, such as radiation protection design optimization, property verification of shielding material, fundamental research for radiation biology, including DNA damage and repair, and experimental data for the environmental impact assessment. HINEG could also be used to support the research on nuclear technology applications, such as nuclear medicine, radiotherapy, neutron imaging, radioactive isotope production, etc.

In addition, HINEG can also be coupled with the China lead-based zero-power reactor (CLEAR-0) for the verification of neutronic physics and control technology of China lead-based reactor (CLEAR) series [17] as well as fusion–fission hybrid reactors.

5. CONCLUSION

In this paper, the latest progress and future plans of HINEG, including the experimental plan, have been presented. HINEG-I has been completed and commissioning with the D–T fusion neutron yield of 1.1×10^{12} n/s. Several key technologies are being developed for HINEG-II to achieve the design neutron yield of 10^{14}–10^{15} n/s. The design and development of the key components of HINEG-II are also ongoing. HINEG will become a very important platform for nuclear energy and nuclear safety research, such as the nuclear data measurement, V&V of the methods and code, material activation and irradiation damage, neutronic performance of key components, radiation protection, etc. It can also be used for the research and development of nuclear technology application.

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REFERENCES

1. Serikov A, Fischer U, Pitcher CS, *et al*. Computational challenges of fusion neutronics for ITER ports. SNA +MC 2013, Paris, France, 01502 June 2014.
2. Tanigawa H, Shiba K, Moeslang A, *et al.* Status and key issues of reduced activation ferritic/martensitic steels as the structural material for a DEMO blanket. *Journal of Nuclear Materials* 2011; **417**:9–15.
3. Logan CM, Heikkinen DW. RTNS-II — a fusion materials research tool. *Nuclear Instruments and Methods* 1982; **200**:105–111.
4. Kovalchuk VD, Mostovoy VV, Tereshkin VI, Markovskij DV. Activation study at SNEG-13 facility of the candidate ferritic steel 10X9VFA. *Fusion Engineering and Design* 1998; **42**:343–348.
5. Sumita K. Tritium solid targets for intense D–T neutron production and the related problems. *Nuclear Instruments and Methods in Physics Research Section A* 1989; **282**:345–353.
6. Martone M, Angelone M, Pillon M. The 14 MeV Frascati neutron generator. *Journal of Nuclear Materials* 1994; **212**:1661–1664.
7. Shen GR, Guan XL, Chen HT. CPNG ns pulsed system for high current beam. *Nuclear Techniques* 2002; **25**:730–736.
8. Su TL. Intense neutron generators and their applications. *Nuclear Techniques* 1989; **12**:553–556.
9. Wu YC, Song J, Zheng HQ, *et al.* CAD-based Monte Carlo program for integrated simulation of nuclear system SuperMC. *Annals of Nuclear Energy* 2015; **82**:161–168.
10. Marian J, Hoang T, Fluss M, Hsiung LL. A review of helium–hydrogen synergistic effects in radiation damage observed in fusion energy steels and an interaction model to guide future understanding. *Journal of Nuclear Materials* 2015; **462**:409–421.
11. Nuclear data services. Available at: http://www.nds.iaea.org 2011.
12. Unholzer S, Freiesleben H, Klein H, Seidel K. The measurement of neutron and neutron induced photon spectra in fusion related assemblies. *Nuclear Instrument and Methods in Physics Research Section A* 2002; **476**:160–164.

13. Huang QY, Team FDS. Development status of CLAM steel for fusion application. *Journal of Nuclear Materials* 2014; **455**:649–654.
14. Wu YC, Team FDS. Design status and development strategy of China liquid lithium–lead blankets and related material technology. *Journal of Nuclear Materials* 2007; **367**:1410–1415.
15. Wu YC, Team FDS. Design analysis of the China dual-functional lithium lead (DFLL) test blanket module in ITER. *Fusion Engineering and Design* 2007; **82**:1893–1903.
16. Feng K, Pan C, Zhang G, *et al.* Progress on design and R&D for helium cooled ceramic breeder TBM in China. *Fusion Engineering and Design* 2012; **87**:1138–1145.
17. Wu YC, Bai YQ, Song Y, *et al.* Development strategy and conceptual design of China lead-based research reactor. *Annals Nuclear Energy* 2016; **87**:511–516."