The Summary of Researches on ADS in China

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Abstract

The conceptual study of Accelerator Driven System (ADS) had lasted for about five years and ended in 1999 in China. As one project of "the major state basic research program (973)" in energy domain, which is sponsored by the China Ministry of Science and Technology (MOST), a five years program of basic research for ADS physics and related technology has been launched since 2000 and passed national review last month. CIAE (China Institute of Atomic Energy), IHEP (Institute of High Energy Physics), PKU-IHIP (Institute of Heavy Ion Physics in Peking University) and other institutions are jointly carrying on the research.

The research activities are focused on HPPA physics and technology, reactor physics of external source driven sub-critical assembly, nuclear data base and material study. For HPPA, a high current injector consisting of an ECR ion source, LEBT and a RFQ accelerating structure of 3.5MeV has been built. In reactor physics study, a series of neutron multiplication experimental study has been carried out and is being carrying on. The VENUS facility has been constructed as the basic experimental platform for the neutronics study in ADS blanket. It's a zero power sub-critical neutron multiplying assembly driven by external neutron produced by a pulsed neutron generator. The theoretical, experimental and simulation study on nuclear data, material properties and nuclear fuel circulation related to ADS is carrying on to provide the database for ADS system analysis. The main results on ADS related researches will be reported.

Introduction

China, as a developing country with a great number of population and relatively less energy resources, reasonably emphasizes the nuclear energy utilization development. To develop nuclear power in large scale, two problems must be solved. First, as we understand the technically and economically exploitable natural uranium resources are limited domestically or overseas, so the uranium utilization rate has to be raised greatly. Second, long-lived radioactive nuclear wastes have to be in disposal to reduce its impact to environment and public fear to nuclear power.

Right now only small amount of spent fuels from NPPs has been accumulated in China. But the situation will be very serious in the future according to above prediction of nuclear energy development in China. The annual generation of waste is estimated to 2 275, 7 500 and 10 000 m3 respectively for the year 2004, 2010 and 2020.

Considering MA and LLFP transmutation with more efficiency and non-criticality risk for new nuclear application, the accelerator-driven sub-critical system (ADS) have been started to develop as a national research projects in China.

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In the last years the scientific and technical exchange and cooperation with foreign research Institutions in different aspects are of really a great help to our work.

Venus Ⅰ Experiment

—The measurement on subcritical assembly driven by pulsed external source

A composed structure of zero-power sub-critical assembly combined with a pulsed neutron source, Venus Ⅰ program is being carrying on. The pulsed-neutron was provided by a Cockroft-Walton machine, routinely operated since 2001. 14MeV and 2.5 MeV neutron was derived by d-T and d-D reaction. The neutron yield in DC mode can reach 10^{12}n/s, while in micropulse mode 10^{9}n/s~10^{10}n/s for d-T reaction.

There are source and buffer in the center of the composed core, a driven zone consisted of natural Uranium pin is very dense lattice with aluminum in between, an active zone with 20% and mainly 3% enriched ^{235}U fuel pin is polyethylene lattice and the polyethylene reflector. Different neutron spectra in different zone are expected. The buffer will shift the sharp 14 MeV and 2.5 MeV neutron to the fast neutron spectra to mock-up the evaporation bump in the spallation neutron spectrum and fission spectrum as possible as. In the driven zone not much neutron multiplication is to be expected, while the hard neutron spectra with average energy about 700 keV is expected. In the active zone the thermal neutron is expected. The assembly will be operated in deep sub-criticality $k_{eff} \approx 0.90 \sim 0.95$ range.

The neutron importanceφ^*, k_{eff}, spatial distribution of neutron flux, neutron spectra and fission rate is being measured for d-T and d-D source respectively.

Beside the SSNTD and small fission chamber will be used for thermal neutron measurement, the TOF technique will be used to measure the neutron spectra from buffer (while there are no core structure), the activation foils, fission rate for ^{235}U and ^{238}U, ^{3}He proportional counter and special designed NNSTD detector will be used for the neutron spectra measurements in eV, spectra index, 100~1000 keV and MeV energe region in different zones.

Intense Proton Ion Source

An electron cyclotron resonance (ECR) ion source is selected for the source of our verification facility system which is shown in fig.1. The microwave power generated by a 2.45GHz-1kW magnetron is coupled into the copper chamber (54×72 mm in cross section and 36 mm long) through a three stubs tuning unit and a ridged wave guide. Inside the chamber, a ϕ54 mm in diameter quartz tube which is tightly fixed by a BN disk and a plasma electrode is placed to confine the plasma. A BN plate is placed between the ridged waveguide and plasma chamber to separate the plasma and vacuum. Three holes are made on the waveguide to evacuate the wave guide after the microwave window; with this configuration the gas in the waveguide can be evacuated quickly to avoid interfering the discharge. The microwave window for vacuum sealing is placed behind a bend section in order to avoid any damage due to the back streaming electrons. The microwave system including its power supply is placed on the 75kV high voltage platform.

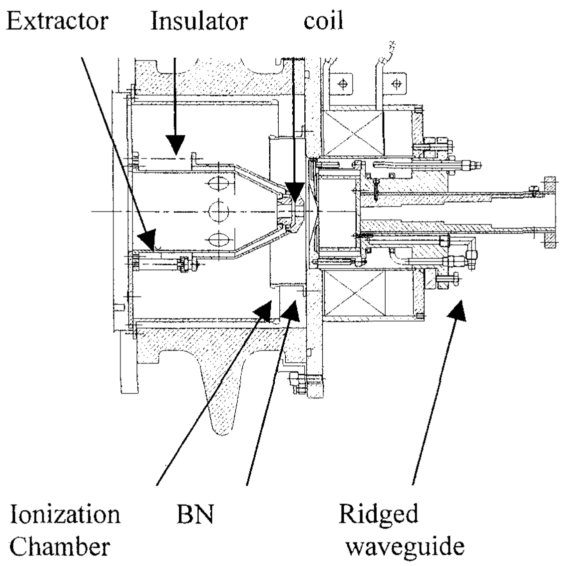

Fig. 1 The cross section view of the microwave ion source

A 65 mA hydrogen beam can be routinely extracted from a ϕ6.5 aperture of the source. The emittance of the extracted beam is measured by a multi-slits and single thread emittance-measuring unit. The measured emittance of the total beam at 60 mA, 60 kV, 50 cm downstream of the ion source is 0.129πmm.mrad. At a specific extraction distance, an adequate extraction voltage always can be found for various beam currents to obtain minimum emittance. The proton ratio is measured by analyzing a portion of the beam with a mini-deflection magnet. The result shows that proton fraction is more than 80% which satisfied the requirement of the system. The proton fraction slightly varies with the changes of microwave power but no significant effect is found.

The more stringent request concerning the reliability test have been investigated. There are three breakdowns in the 121 hours test, first 2 breakdowns occur at first 5 hours and the last one occurs 2 hours to the end of the test. All three breakdowns caused by self-protection of the power supply of magnetic coils. The beam is restored in one minute by simply restarting the power supply each time. The longest uninterrupted beam time is 110 hours. A solenoid has been installed 0.6 m downstream of the extraction aperture. The primary result shows that the solenoid works as expected, a through investigation of the solenoid is being conducted.

RFQ Accelerator study

The structure of RFQ is a four-vane type and designed to accelerate 50mA peak current of proton beam with input energy of 80kV. In preliminary research phase, the 352.2 MHz RF system will be operated in pulse mode. CERN kindly provided IHEP with some RF equipment. Because the given RF system was used for CW operation at CERN before, to apply them to our pulse mode operation, some modifications and improvements are necessary. We have made some indispensable assemblies, and also did some tests and commissioning of every sub-system. At present, we have already finished the 100 kV power supply test and long pulse floating desk hard tube modulator test. Furthermore, the initial high power conditioning of the klystron is carried out, and output power can reach up to 800 kW.

The fabrication of the RFQ copper model was performed in a company in Shanghai, China. At first, some tests for development the mechanical technology have be done, for example, the brazing technology for assembling four vanes together with required mechanical tolerance, the characteristics of melting filler, the structure surface and the vacuum leak; the drilling of the coolant hole through the 1.2meter RFQ cavity with 12mm in diameter; the precision machining of the vane electrodes on the numerical controlled mill. The fabrication of the RFQ was finished last Month.

ADS Related Nuclear Data

The new nuclear reaction theoretical models code MEND, which can give all kinds of reaction cross sections and energy spectra for six outgoing light particles (neutron, proton, alpha, deuteron, triton, and helium), gamma and recoil nuclei in the energy range up to 250 MeV, is being developed. The incident particle can be neutron, proton, alpha, deuteron, triton and helium. A program[4] for automatically searching optimal optical potential parameters in $E<300$ MeV energy region has been developed. By this code the best optical potential parameters can be searched automatically to fit with the relevant experimental data of total cross sections, nonelastic scattering cross sections, elastic scattering cross sections and elastic scattering angular distributions. Nuclear data evaluation method has been developed for ADS. According to the experimental data of neutron-induced reactions, and theoretical model calculation codes UNF[5], ECIS and DWUCK, all cross sections of neutron induced reaction, angular distributions, double differential cross sections for neutron, proton, deuteron, triton, helium and alpha emission, γ-ray production cross sections and γ-ray production energy spectrum are calculated and evaluated at incident neutron energies from 10^{-5} eV to 20 MeV. Since the recoil effect is taken into account, the energy for whole reaction processes is balance. Nuclei have been evaluated as follow: ^{50,52,53,54,nat}Cr, ^{54,56,57,58,nat}Fe, ^{90,91,92,94,96,nat}Zr, ^{112,114,115,116,117,118,119,120,122,124,nat}Sn[6], ^{180,182,183,184,186,nat}W, ^{204,206,207,208,nat}Pb, ^{209}Bi[7],

^{232}Th[8], ^{233,234,235,238}U. By using advanced nuclear models that account for details of nuclear structure and the quantum nature of the nuclear scattering, nuclear data are calculated and evaluated for both incident neutrons and incident protons at incident neutron energy from 20 to 250 MeV as follow: ^{50,52,53,54}Cr, ^{54,56,57,58}Fe, ^{90,91,92,94,96}Zr, ^{180,182,183,184,186}W, ^{204,206,207,208}Pb, and at incident proton energy from threshold energy to 250 MeV as follow : ^{54,56,57,58}Fe, ^{180,182,183,184,186}W, ^{204,206,207,208}Pb, ^{209}Bi[9].

ADS Related Target Physics

The calculations for the standard thick target were made by using different codes. The simulation of the thick Pb target with length of 60cm, diameter of 20cm bombarded with 800,1000,1500,and 2000MeV energetic proton beam was carried out. The yields and the spectra of emitted neutron were studied. The spallation target was simulated by SNSP, SHIELD, DCM\CEM (Dubna Cascade Model \Cascade Evaporation Mode), and LAHET codes. The neutron yields calculated by SHIELD and DCM\CEM were in agreement within ±10%.

Material Development for ADS Beam Window

Three heats of 9Cr2WVTa steel have been smelted. The mechanical properties of the smelted 9Cr2WVTa steel have been investigated. It is indicated that the C and Mn content as well as the heat treatment technologies affect the mechanical properties, therefore, the optimum of the elements content and the heat treatment technologies will be the key issues for the improvement of the 9Cr2WVTa steel. This research is being performed at moment. In order to get the martensitic structure and increasing its mechanical properties, the quenching treatment was performed. It can be seen that the black dots in the matrix become more and more with the increasing of the tempering temperature, this may results from the carbides become more and more with increasing of the temperature. There are little carbides in the matrix without tempering. The measurement results of the micro-hardness indicated that the hardness decreases with the increasing of the tempering temperature, it may results from the dissolution of the martensitic under the increasing of the temperature.

ADS Related Material Radiation Effects Study

The spallation neutron source system is one of the three key parts of ADS, which provides source neutrons of ~10^{18} n/sec for the burning-up of fuels. It is mainly composed of the target and beam window. Stainless steels and tungsten are important candidate materials of the beam window and the spallation neutron source target. They are irradiated by high-energy and intense protons and neutrons during operation. The accumulated dose could reach a couple of hundred dpa per year, and radiation damage is very severe in them. The radiation damage study of the spallation target and beam window materials is of great importance for the understanding of the their lifetimes and the safe operation of the ADS.

Dependence of radiation damage in the modified 316L stainless steel has been investigated on irradiation temperature from room temperature to 802 ^{o}C at 21 and 33 dpa and on irradiation dose up to 100 dpa at room temperature by the heavy ion irradiation simulation and positron annihilation lifetime techniques. A radiation swelling peak was observed at ~580 ^{o}C where the vacancy cluster contains 14 and 19 vacancies and has an average diameter of 0.68 nm and 0.82 nm, respectively for the 21 and 33 dpa irradiations. Fig. 2 shows the temperature dependence of positron lifetime $_{2}$ in MSS irradiated to 21 and 33 dpa. It can be seen that before the peak temperature the variation of positron lifetime $_{2}$ with irradiation dose increases with the increasing of irradiation temperature. The higher the irradiation temperature, the larger the increase of lifetime $_{2}$ with irradiation dose. This indicates that the radiation damage depends on irradiation temperature more sensitively than on irradiation dose.

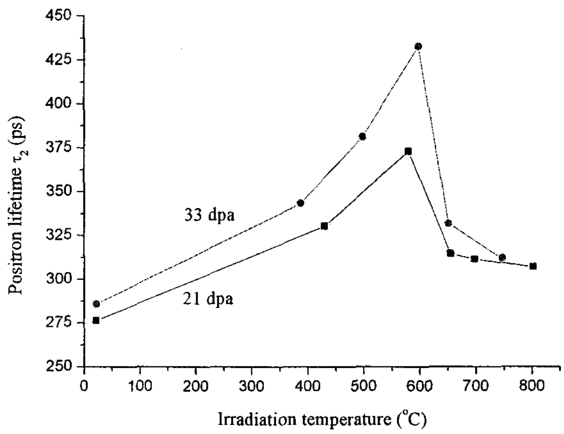

Fig. 2 Temperature dependence of positron lifetime $_2$ in MSS irradiated to 21 dpa and 33 dpa

Before this experiment, radiation damage and its detailed thermal annealing behavior in -Al_2O_3 irradiated at the equivalent dose, respectively, by 5.28×10^{16} cm^{-2} 85 MeV ^{19}F ions and by $3x10^{20}$ cm^{-2} $E_n \geq 1$ MeV neutrons have been investigated by the positron annihilation lifetime technique. The experimental results show that all the positron annihilation parameters of lifetime and intensity in the heavy ion irradiated -Al_2O_3 are in good agreement with the ones in the neutron irradiated -Al_2O_3, and verify that heavy ion irradiation can well simulate neutron (proton) irradiation.

Conclusion

For long term and sustainable nuclear energy development, ADS is an option in fuel circulation and energy generation. The ADS has been started to develop with a rather moderate project in China and it is still in the early stage. The goal for our ADS research is to establish the scientific and technological foundation for the future development of the ADS research step by step.

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Reference

[1] Ding Dazhao, The conceptual Study of Accelerator Driven Radiological Clean Nuclear Power System (AD-RCNPS) IN China,
3rd Workshop on Neutron Science Project,March 17-18,1998 pp.132-140 JAERI-conf.99-003.

[2] Xia Haihong, The Progress of Basic Research for ADS in China
Proceeding of the 35th IAEA TWG-FR annual meeting, April 22-27,2002

[3] Guan Xialing Fang Shouxian R/D Activities of ADS in China
Proceedings of 5th Accelerator and Transmutation Technology Workshop 2001 p-159

[4] SHEN QINGBIAO. Nucl. Sci. Eng., 141, 78 (2002).

[5] JINGSHANG ZHANG. Nucl. Sci. Eng., 142, 207 (2002).

[6] YINLU HAN. Nucl. Sci. Eng., 146, 106(2004).

[7] YINLU HAN, ZHANG ZHENGJUN. Nucl. Sci. Eng., 141, 154(2002).

[8] YINLU HAN, et al. Nucl. Sci. Eng., 143,202(2003).

[9] ZHENGJUN ZHANG, et al. Nucl. Sci. Eng., 143, 90(2003).