Proposal for a Verification Facility of ADS in China*

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Abstract: The concept, the general layout and some specifications of a proposed verification facility of the accelerator driven radioactive clean nuclear power system (AD-RCNPS) in China has been described. It is composed of a 150 MeV/3 mA low energy accelerator, a swimming pool reactor and some basic research facility. The 150 MeV accelerator consists of an ECR proton source, LEBT, RFQ, CCDTL and SCC. As the sub-critical reactor, the swimming pool reactor is an existing research reactor in China Institute of Atomic Energy, its maximum output power is 3.5 MW. The effect of the instability of proton beam and possibility of simulation test on the verification facility have been analyzed.

Key words: verification facility, accelerator driven system, sub-critical facility

INTRODUCTION

In recent years, there has been a growing interest in the R&D of high power proton accelerator (HPPA) driven system (ADS) for the application of energy resources, nuclear fuel breeding and the high level radioactive waste transmutation [1]. In almost all known ADS projects, the high power proton accelerator, in general, is required as ADS driver, delivering an average beam of 30 mA to 100 mA at 1 GeV energy and operating at CW mode [2]. In the accelerator development, proton linear accelerator has been selected to meet the requirement with such a high beam power.

In China, the rapid increase of the national economy asks for a rapid increase of the energy supply. It is a more and more important issue at present to develop the energy resources science, especially the nuclear fission energy. At the advocacy of some nuclear scientists, the conceptual study on the

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accelerator driven radioactive clean nuclear power system (AD-RCNPS) has begun in China. A group of scientists in the field of nuclear physics, reactor physics and technology, accelerator physics and nuclear chemistry from China Institute of Atomic Energy (CIAE), Institute of High Energy Physics (IHEP) and Peking University has been formed since the middle of 1995.

As the first phase of long term plan, a proposal of verification facility has been made [3]. It consists of a 150 MeV/3 mA low energy accelerator and a sub-critical light water swimming pool reactor, which is a modified core structure of an existing research reactor at China Institute of Atomic Energy. The verification facility will also include some facilities to be built for nuclear data measurement, material testing, target assembly testing and manufacturing of super conducting cavity and high power klystron laboratory.

This facility will play a role in testing and verifying the most basic concept of the physics and the technology for ADS. It should give us a better understanding of the critical points for the HPPA at different operation modes, for example, the low duty factor or the high duty factor and even the CW operation possibility. It should also give us a better understanding of some problems for the target and for the sub-critical reactor. This verification facility will be also used for some basic research topics, such as material science, neutron physics and nuclear transmutation study.

The accelerator should operate at two different operation modes, it will be not only at a long pulse mode (1 ms) to drive a sub-critical reactor system but also at a short pulse mode (1 ns) to realize the time-of-flight (TOF) experiments for neutron physics. The conceptual layout of the verification facility [3] is shown in Fig.1.

1 THE FRONT END OF THE ACCELERATOR PART

The accelerator portion is composed of an ECR ion source, a low energy beam transportation (LEBT) section, a low energy radio-frequency quadrupole accelerator (RFQ), a normal conducting cavity coupled drift tube (CCDTL) linac and a super conducting cavity linac (SCC). The primary specifications of this accelerator are listed as follows:

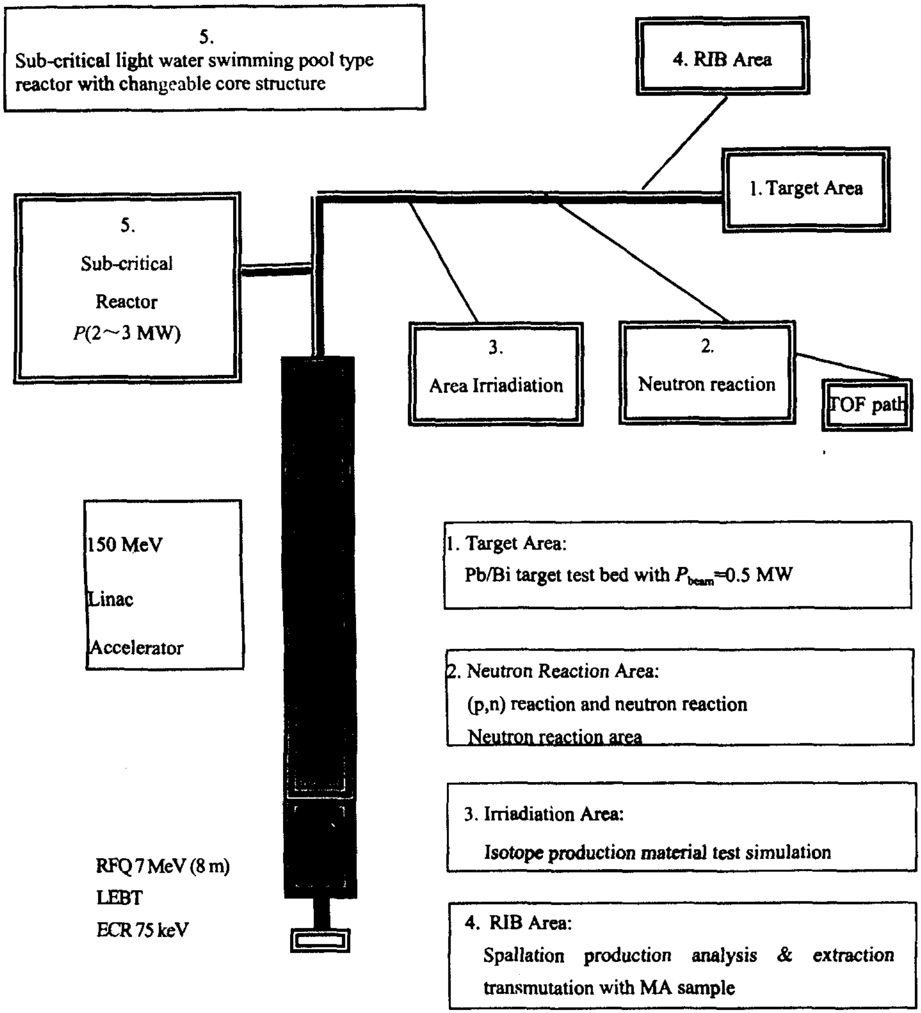

Fig. 1 Conceptual layout of verification facility for ADS in China

Accelerated particle	Proton
Particle energy	150 MeV
Average current	3 mA
Accelerating frequency	350 MHz

Pulse structure		
Long pulse mode	Macro pulse: Repetition rate	50 Hz
	Pulse duration	1 ms
	Duty factor	5%
	Micro pulse: Repetition rate	350 MHz
	Average current	3 mA
Short pulse mode	Macro pulse: Repetition rate	50 Hz
	Pulse duration	1 ms
	Micro pulse: Repetition rate	1.75 MHz
	Repetition period	571 ns
	Pulse duration	1 ns
	Pulse intensity	4×10^{8} ppp
	Average current	15 μA

In order to meet the requirements mentioned above, a proton electron cyclotron resonance (ECR) ion source is selected for the source of our verification facility system. This kind of ion source has some attracting advantages [4], for example, better reliability, high ionization efficiency, low emittance and high intensity and low gas load on the vacuum system. The structure of ECR source is similar to the one at Chalk River Laboratory in 1993 [5], which is shown in Fig.2.

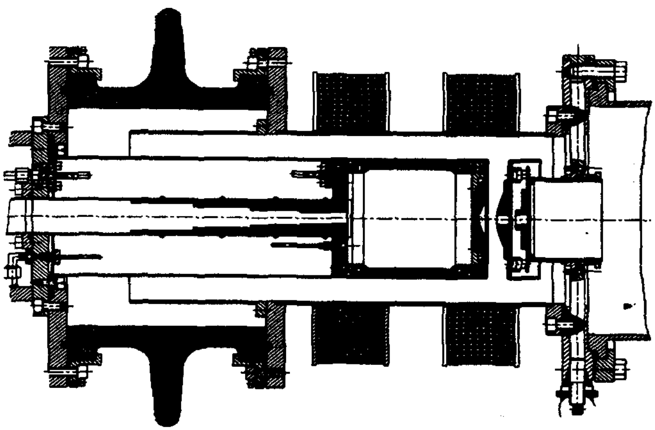

Fig.2 ECR ion source

The 2.45 GHz microwave power is adopted, 1 kW microwave power is coupled to the plasma chamber by a rectangular-to-ridged wave-guide through a microwave window. The plasma chamber is a cylinder 100 mm long and 100 mm in diameter. An accelerating and decelerating three electrodes extraction structure is adopted. A normalized rms emittance as low as 0.2 π mm mrad is required. The discharging chamber is designed to withstand up to 75 kV potential voltage. At CIAE and Peking University, the DC proton beam current can be produced up to 45 mA with a slit extraction structure. A new source is under construction now in CIAE.

The low energy beam transport (LEBT) is used to match the beam transport between the ion source and the RFQ accelerator. The LEBT should consider two operating modes. The long (1 ms) and short (1 ns duration pulse, 1.75 MHz modulating) pulse operating modes should be incorporated in one optical arrangement. In the long pulse mode, the pulse duration of 1 ms is a result of modulation of microwave support of ion source with 50 Hz repetition rate. It gives us a duty factor of 5%. At the peak current of 60 mA, the average current can reach 3 mA. For space-charge neutralizing by the electron ionization, two solenoid magnets are used to match lenses in LEBT. The beam optics layout of LEBT section is illustrated in Fig.3.

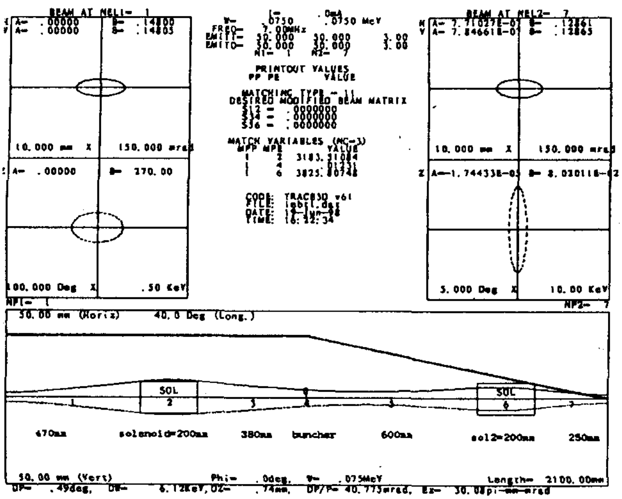

Fig. 3 Beam optics of LEBT section

The proton beam from the ion source is focused by two solenoid magnet lenses. A beam diagnostic box is put in between. The solenoid magnet used in the LEBT is 200 mm in length and 80 mm in diameter, the maximum magnetic field strength at beam axis is about 0.7 T.

In order to realize the short pulse mode, a pair of chopper plates at repetition rate of 1.75 MHz and a bunched gap at repetition rate of 7 MHz have to be inserted between two solenoids. The time period of pulse structure is 571 ns and the pulse width is around 1 ns at the entrance of RFQ. The total length of the LEBT section is around 2.1 m.

2 THE RFQ ACCELERATOR AND CCDTL LINAC

The rationalization of the parameters for the verification facility of 150 MeV is dependent on the estimation and empirical fitting, the neutron yield is estimated to be roughly one to one proton at 150 MeV [6]. We can take this value as the threshold of the spallation reaction. The proton range in lead is roughly 3.5 cm at 150 MeV, this makes the possibility to realize the target heat-extraction and to meet its hydraulic properties.

The maximum output power of the original swimming pool reactor is 3.5 MW. It is the reason why we take the maximum beam current up to 3 mA, because of the requirement of running the sub-critical reactor with the *k* value varying from 0.90 to 0.97. The proposal accelerator facility contains nearly all of the accelerating structures, such as ECR source, RFQ and CCDTL, which are essential components for the construction of the full-scale accelerator.

The RFQ is a four-vane type and designed to accelerate 60 mA peak current of proton beam with the energy of 75 kV. The structure of this proposed RFQ is similar to the one of Los Almos Laboratory (APT). The CW APTF RFQ at Los is described in detail in reference[7]. In our verification facility, the RFQ machine is composed of four segments joining together with three coupling plates which separating the segments and reducing the magnetic coupling. The overall length of the RFQ linac is 8 m. Each segment is 2 m long. The dipole stabilizers will be designed to be amounted on the coupling plates and on the end plate too. The structure of the coupling plates and the dipole stabilizers is shown in Fig.4 [8]. The specifications of the proposed RFQ are listed in Table 1:

Table 1

Type	Four-vane type	Work frequency	350 MHz
Injecting energy	75 keV	Cavity length	8 m
Output energy	7 MeV	Average accelerating gradient	1.4 MV/m
Peak current	60 mA	Cavity average power losses	7.2 kW
Duty factor	5%	Peak RF power consumption	1.6 MW
Output average current	3 mA	Average RF consumption	96 kW
Normalized rms emittance	0.2 π·mm·mrad		

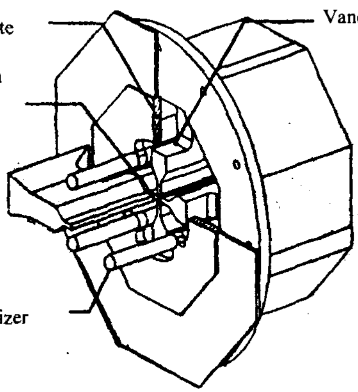

Fig. 4 Structure of the coupling plates and the dipole stabilizers

At Peking University, an integral splitting RFQ has been built and beam test has been conducted, which is especially for the purpose of ion implantation with adjustable output energy [9, 10]. At the Institute of High Energy Physics, a four-rod type RFQ is under conduction as the injector of their existing proton linac of 35 MeV [11, 12]. The new model of proposed RFQ machine will be built based on these experiences.

The Coupling Cavity Drift Tube Linac (CCDTL)[13] system will be subsequently the RFQ and MEBT bringing the beam energy from 7 MeV to 100 MeV. And then a Super Conducting Cavity Linac (SCC) is proposed to accelerate the beam up to 150 MeV. The work frequency of the CCDTL and the SCC is 700 MHz. The specifications of the proposed CCDTL are listed in Table 2:

Table 2

Injecting energy	7 MeV
Output energy	100 MeV
Peak current	50 mA
Length	100 m
Bore radius	1～1.7 cm
Structure accelerating gradient	1～1.8 MV/m
Synchro phase	-30°
Cavity power losses	5.0 MW
Beam power	2.8 MW

The construction of the verification facility is expected to be in two phases until 2007. In phase one, the technical development will be carried out individually, while in phase two the integral will be undertaken. In the first five years, the front end of the verification facility should be completed, including ECR ion source, LEBT and a 2.5 MeV RFQ. At the same time, it is excepted to develop the CCDTL model tests, to build a super conducting accelerator cavity laboratory and a high power CW klystron laboratory.

On the base of this verification facility, we expect that a full-scale demonstration experimental facility may be realized in the middle of 2010's.

3 THE CORE STRUCTURE OF MODIFIED SWIMMING POOL SUB-CRITICAL REACTOR

The modified core structure of the swimming pool reactor is shown in Fig.5. The fuel elements and assembly will be the same as original one, while 3×4 assemblies of the fuel in the central of the core is substituted by beam pipe and target with some space for different materials, in order to meet the purpose to verify various conceptions of blanket structure, including the fast-thermal coupling, transmutation and so on. The *k* value is 1.035 when all cells are filled by the fuel assembly besides the central part is filled by lead moderator. This gives us a quite large range to vary the k value by changing the fuel assemblies used and/or the fuel management in meeting the requirement of k value from 0.90 to 0.97.

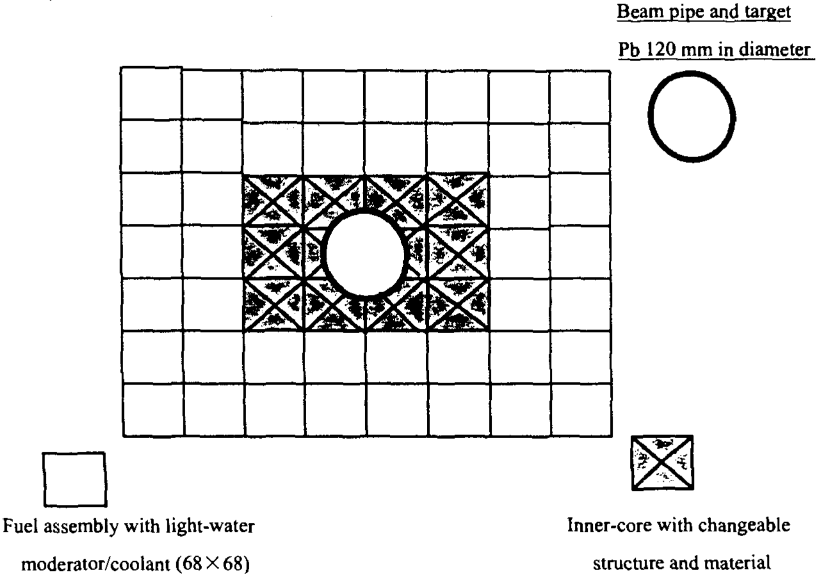

Fig. 5 Core Lattice Structure of Verification Facility Blanket

Some specifications of the core structure are listed in Table 3:

Table 3

Target and Moderator	Pb
Length of core	500mm
Fuel	^{235}U (10%)
k	1.035
Anticipated k_{eff}	0.94~0.98, power ≤ 3MW

4 ACCELERATOR RELIABILITY REQUIRED BY SUB-CRITICAL REACTOR IN ADS AND SIMULATION STUDY OF REACTOR'S RESISTANCE TO THERMAL SHOCK

In this section a conceptual analysis about the effect of the instability of proton beam and beam trip, and possibility of simulation test on the verification facility is presented. In sub-critical reactor of ADS operating at high power level, the thermal power density due to fission is about the same magnitude as that in reactor core of similar nuclear power plant, thus the design criteria relevant to reactor safety are similar to those for the existing reactor core. As the power level of sub-critical reactor core in ADS is sustained by the neutron source generating from bombarding the spallation target by high current protons, both the instability of proton beam and beam trip in any form will influence the power level of sub-critical reactor.

The reliability of high power proton accelerator (HPPA) in ADS comprises beam stability and beam trip. In connection with sub-critical reactor, the beam trip refers to proton beam interruption in HPPA or its loss from beam tube due to some causes. Such beam trip will result a fission power of sub-critical reactor to be drop and force the reactor shut-down.

In power reactor design, various measures are taken to avoid thermal stress concentration due to repeated thermal shock, which will bring about fissure occurrence and result in harmful effects on nuclear safety. First, for large scale thermal neutron tractor, restrain xenon oscillation induced by neutron flux oscillation in space and time domains is taken into consideration. Second, emergency shutdown of power reactor will undoubtedly bring about intense thermal shock to system's corresponding parts, thus in the operation phase, unplanned reactor shutdown is strictly prevented and times of emergency shutdown is limited. Besides economic consideration, it is for the purpose of reducing thermal shocks to guarantee the good condition and reliability of the equipment.

In ADS, the spallation target, located in a certain reactor zone, is equivalent to a localized neutron source. Its instability will produce a disturbance to the neutron flux density nearby. The disturbance and its probably induced xenon oscillation result in the fission power fluctuation. On the other aspect, the proton beam trip causes emergency shutdown whose speed depends on the reactor's sub-criticality and swiftness of the scram mechanism. For ordinary nuclear power plant, by mechanic and electronic means and relying on gravity drop to insert the control rods, the action time is on the order of second. For ADS during operation with existing sub-criticality, the action time is on the order of millisecond for the fission power cut-off by interrupting the proton beam. Thus in regard to the same sub-criticality, the shutdown speed for ADS is faster. It is of advantage to prevent unexpected power increase when accident occurs[14], but however unfavorable as view from reducing thermal shock, for faster the shutdown speed and more the shutdown times, greater the thermal shock to the equipment and more concentrated the thermal stress. Therefore, in order to reduce thermal shock, besides improving the reliability of HPPA and lowering the unexpected beam trip probability, it is not good if the sub-criticality of the sub-critical reactor in ADS is too low.

On verification facility problems relevant to the accelerator reliability will also be explored. We know that a reactor, as a power system, in linear condition, has properties of a inertia system. Its response characteristic to external disturbance can be described by proper time constant. Hence, by creating artificial beam disturbance on the verification facility, combining theory with experiment, the study on dynamic behavior of sub-critical reactor, for determining the time constant will be helpful to the understanding of problems concerned.

In ADS, HPPA beam disturbance brings about the disturbance of super-high energy neutron source, with average neutron energy 10 MeV or so. But average neutron energy in sub-critical fission reactor is very low. For fast breeding system it is less than 1 keV, for thermal neutron system below 1 eV. Therefore the disturbance magnitude and average energy of the spallation neutron source strength will have complicated problem in space-dependent neutron dynamics.

In fission reactor, the thermal power disturbance produced with the disturbance of neutron flux density is the direct cause to form thermal shock. Hence, to study the sub-critical reactor's resistance to thermal shock, it is possible and practical to begin with space-dependent neutron dynamics of HPPA beam instability acting on sub-critical reactor. As neutron dynamics and thermodynamics work together in reactor, two kinds of time constant are needed to describe high power sub-critical reactor, one is neutron dynamic, the another is thermodynamic.

As reactor thermodynamics time constant is related to thermal transfer process, it is much larger than that of neutron dynamics. This means, as viewed from coupling of neutron-thermodynamics, if the sub-critical reactor is not sensitive to the neutron disturbance of this transition frequency, it then must not be sensitive to various thermodynamic disturbance. Hence, using verification facility to simulate proton beam disturbance and to find ways of preventing beam loss, through studying time-space behavior of neutron flux density in sub-critical reactor to study the reliability requirement of HPPA, and developing early research on thermal shock resistance of sub-critical reactor, all these are feasible.

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关于建设加速器驱动次临界系统原理验证装置的建议

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摘　要　描述了一套我国加速器驱动次临界系统的原理验证装置的概貌和主要性能。它是由一个 150 MeV 平均流强 3 mA 的质子直线加速器、一个游泳池式反应堆和一些基础研究设备组成的。150 MeV 直线加速器系统由一个电子回旋共振(ECR)离子源、低能束流传输段(LEBT)、射频四极加速器(RFQ)、腔耦合漂移管式加速器(CCDTL)和超导腔加速器(SCC)组成。作为次临界系统的游泳池堆是中国原子能科学研究院(CIAE)现有的一个 3.5 MW 反应堆。分析了利用这套原理验证装置开展质子束的不稳定性给次临界反应堆带来的不良影响及性能检验工作的可能性。

关键词　原理验证装置　加速器驱动系统　次临界反应堆