ACCELERATOR DRIVEN SUSTAINABLE FISSION ENERGY

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Abstract

It is the new approaches of sustainable fission energy that high power accelerator driven to produce intensive external neutron for close fuel cycle and utilize fission resources ≥90%, which is two higher efficiency than that in exist fission energy. New approaches include the fission fuel burner and the used nuclear fuel (UNF) recycle. The burner is designed as the nuclear waste transmutation, the fissile material breeding and the energy production in situ by accelerator driven in start. The UNF recycle designed is to remove ~50% fission products (FP), and other residual of UNF is made as recycle fuel, then， burn inside burner. Typically, LWR FP can be removed by extension "AIROX" for volatile FP and rare earth element extraction for lanthanide FP. Thus, new approaches could sustain the fission energy close to 10000yr and minimum nuclear waste <4% in quantity with live time <500yr. There are 4 phases in Chinese development roadmap and new research sites are introduced.

The burner, evolution from ADS, is consists of the high power superconductor linac (SCL), the spallation target and subcritical core. ~25 MeV SCL prototype will extract proton beam before end of 2016. Presently, 10 MeV SCL is under tuning in 10's kW CW beam. The 14~18GHz ECRIS R&D shows more stable as the RF power is 1/10 and feed in/ pumping out gas is 1/3. New concept of the intense granular fluid spallation neutron target prototype shows the simple and stable operation as sand clock, the heat removed off line. This kind target could extent the spallation neutron target power up 10~100 MW. The different material could be used as different purpose target.

INTRODUCTION

The nuclear fission energy, which provide low-carbon energy at stable, scale and cost effective, is one of important clean energy to mitigate global warning. To meet this requirement, 4 criteria: sustainability, safety and reliability, economic competitive and proliferation resistance and physical protection, become common understanding for further nuclear energy technical development[1]. The main items concerning the sustainability of nuclear energy are maximum resources utilization and radiotoxicity reduction. Figure 1 shows the nuclear energy status by taking these two item as parameter. The commercial nuclear power is thermal neutron reactor in the status of resource utilization <1% and radiotoxicity reduction <1%. By using this technology, the reactor can burn ^{235}U, which is 0.73% in nature uranium. Therefore, the fuel could only supply ~100 yr for <1000 GWe nuclear power plant and the most UNF with > 10,000 yr live time in fuel once throughout. The MOX fuel burned in LWR or sodium faster reactor (SFR) is the few percentage of resources utilization, the radiotoxicity reduction and less the economic competitive even operating in scale demonstration. The accelerator driven subcritical system (ADS) has been proposed mainly to transmuting the long live time nuclear waste for more than 20 years [2–5]. In principle, ADS's partition & transmutation (P&T) could close fuel cycle, however, it is lower resource utilization as at lower right in Fig. 1. Moreover, ADS's technical difficulty and lower cost effective [4–6] are not only for the high power accelerator, the high power spallation target, but also for partitioning UNF. Therefore, ADS progress is slow down in US and EU in last 10 year.

Obviously, the idea nuclear power system, locating in the top right in Fig. 1, should be higher resources utilization and radiotoxicity reduction. In this idea system, the fissile resources (^{238}U, 99.3% in nature uranium, ^{232}Th) could be burned by breeding ($^{238}U+n \rightarrow {}^{239}Pu$, $^{232}Th+n \rightarrow {}^{233}U$) in advance and the long live time radiotoxicity could be transmuted during burning. Therefore, the fissile resources could be utilized two more order higher in efficiency and the waste are two order small with short live time (<500yr). In the physical point of view, the fast neutron is favour for transmutation and breeding in burner.

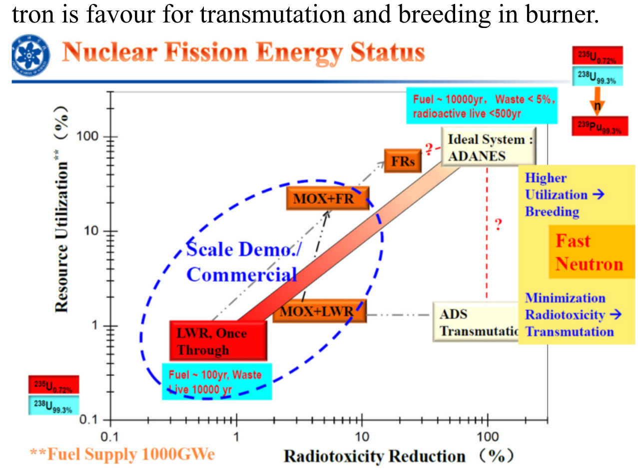

Figure 1: Nuclear fission energy status.

NEW APPROCHES ADS → ADANES

Base on above comments, the idea nuclear power system has to be the close fuel cycle. It is clear that 100% radiotoxicity reduction do not mean higher resources utilization. In contrast, burn out the most of resource means there are no more long live time radiation heavy elements in waste. Therefore, the minimum radiotoxicity can be solved by maximum resources utilization. It is also clear that the burning capability and the partition efficiency are complementary, which means increasing burning capability could be simplifier the partitioning.

Status of Traditional P&T

The principle of traditional P&T is to partition the radiotoxicity isotopes from UNF, then, the long live time isotopes are transmuted to short live time or stable isotopes by

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fast neutron mainly. The existing procedure of partition is extracting U & Pu (>95% of UNF) elements from UNF firstly, by which the residual of UNF radiotoxicity live time reduce from >100000 year to >5000 year, further extracting minor actinide (MA) from residual of UNF, then, the residual radiotoxicity live time are <500 year. In this procedure, the most of UNF could be extracted if the efficiency would be in higher level.

In fact, besides the expensive in executing this kind partition, there are some weak points in technology and logical:

1, the residual of UNF remain amount of long live isotopes, since the extraction efficiency and contamination of solution. Therefore, the residual of UNF need post treatment still and the fuel is not close completely;

2, the UNF is more complexes and more radiotoxicity after several cycle;

3, the purity Pu, MA are unstable during burning in burner;

4, the higher proliferation risk for purity Pu, MA as these kind of isotopes are very useful.

Consequently, there is no final version of traditional P&T.

Principle of ADANES

As comments above section, there are two important hinds: I, the more of fission resource utilization, the more radiotoxicity reduction; II, the relative live time of fission products is <500 year comparing that of nature U ore. Following these hinds, it should be an idea system to remove part of FP from UNF, then, convert the residual of UNF as recycle fuel and burn it inside of power burner in recycle.

Fortunately, the gas state and low melt point FP could be remove from UNF in high temperature (ext. ARIOX) simply, which has been developed for more than 50 year, then, the concentrated Lanthanide elements, which is neutron toxicity during burning, could be extracted by using Rare Earth extraction. The system design to remove ~50% FP by this hybrid method without water.

In history, the motivations of ADS are proposed to transmute the nuclear waste for more than 20 years [2-6], to produce isotope for basic research, radio-medicine, APT for long time [7,8], to produce energy by the energy amplifier respectively at least for 20 year [9]. Since the subcritical system is driven by external high flux fast neutron, the system can be designed to burn in the large reactivity range fuel under safety state. Consequently, these motivation could be integration and optimization in the high power burner, in which the nuclear waste is transmutation, the fissile material is breeding and energy is producing in situ.

New approaches is proposed as Accelerator Driven Advanced Nuclear Energy System (ADANES) by adopting the removing part of FP from UNF and high power burner concepts as ADANES fuel recycle and ADANES burner. As the system flowchart in Fig. 2, ADANES burner is designed to transmute the long live time isotopes in UNF recycle fuel, breed the ^{238}U to ^{239}Pu as fuel for long burnup, and produce energy simultaneously in situ. Considering the beam trip does not avoid during high power accelerator operation and the cost effective, the accelerator is designed as the starter for burner, in which the burner start operation in subcritical state and driven by accelerator. Sometime later, burner turn to critical operation state without accelerator driven (AD) in right plot of Fig. 2. In this approaches, the most of UNF can be treated as recycle fuel, then, nuclear waste, <4% FP with live time <500yr, is removed (referencing UNF after 33GWd/T burnup in PWR) and stored by the dry storage. Summary this flowchart, the income is fuel with UNF, the output is < 4% FP and energy, the resources utilization is >100 time comparing <1% of that by LWR and the radiotoxicity reduction is similar improvement.

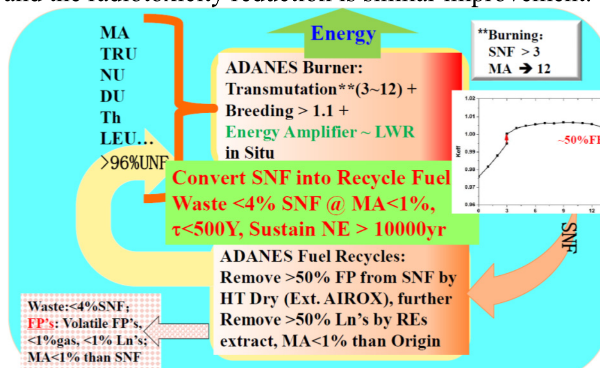

Figure 2: ADANES flowchart (LWR UNF 33GWd/T).

It is clearly that UNF's reactivity is poor comparing the fissile material, therefore, if the ADANES could burn >90% UNF recycle fuel that means the ADANES burner could burn all fissile material for sustainable nuclear fission energy ~10000 year. Final, ADANES is not only close fuel cycle, but also produce clean, economical competitive and anti-proliferation nuclear energy.

The operation mode of ADANES burner indicates in Fig. 3. ADANES nuclear power plant is configured as some burners driven by an accelerator alternatively. The duration of AD for a burner is about 10% to 15% percent of the burner operation period, which could reduce the RAMI requirements of accelerator, and, share the cost of the accelerator. Taking the advantages of the more safety, more flexibility of AD, ADANES burner is designed to burn the "raw" UNF recycle fuel for transiting the fuel from "raw" to the controllable during AD phase.

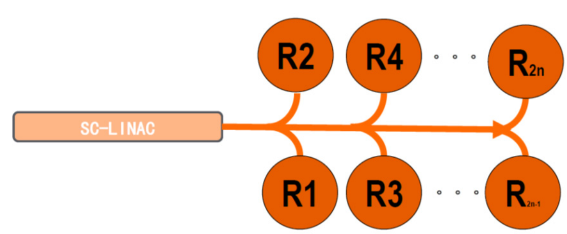

Figure 3: ADANES operation mode in power plant.

Further Development of ADANES

Comparing ADANES's UNF recycle and the burner sub-system, UNF recycle is more difficult in the environment friendly and the economic competitiveness. In fact, both sub-system are complementary, that means UNF recycle would be simpler by reducing removing FP, if the burner could burn more burden of UNF. There are more potential of ADANES burner to develop, such as, high power SCL, new core structure and fuel cladding material for long live operation or in case of accident, new coolant to improve the reactivity control, higher temperature operation for high quality heat, modular faster reactor design and fabrication in factory.

ROADMAP OF ADS/ADANES

The roadmap of ADS/ADANES is in Fig. 4, which include 4 phases: the key technique and prototype R&D, the initial phase to construct experimental setup for R&D, the demo phase to construct full size setup for system demonstration, industry phase to commercialize.

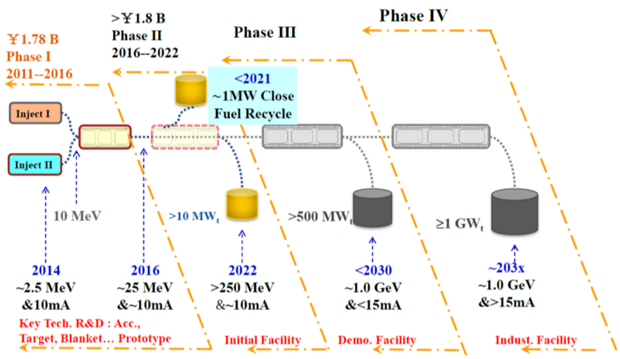

Figure 4: Roadmap of Chinese ADS/ADANES.

In 1st phase (2011~2016), the intensive ADS project (¥1.78B) has started from 5 year ago and followed the traditional ADS approaches in beginning. So far, besides to propose ADANES approaches, the main R&D progresses are ongoing smoothly. (See in next section). All activities are distributed at the institutes of CAS.

2nd phase (2016~2022), the project of Chinese Initial ADS (CIADS ~¥1.8B) conception design has been approved by central government. The main setup include 400~500MeV &10mA SCL, <5MW spallation target, total 10 MW subcritical blanket. New site was chosen in seaside of Huizhou, Guangdong.

3rd phase (<2030), the main setup of the demonstration will include ~1GeV & 10mA SCL, ~10MW spallation target, total ~1GW_{th} subcritical/critical core.

4th phase (>2030), the industry setup will be upgraded beyond the demonstration setup.

The UNF fuel recycle R&D is planned in 2016~2021, which was introduced after ADANES proposed. Its main activities are cover the UNF fuel recycle within 100kg scale, a compact neutron source (50~250MeV & 5mA D+Be) with the flux ~ 10^{14}n/sec. for fuel cladding and core structure material R&D, a <1MW subcritical blanket and a corresponding hot cell. This activities will be performed in the seaside of Ningde, Fujian province.

PROGRESS OF ADS/ADANES BURNER

The intensive ADS R&D had started in 2011. Besides the coordinate unit (Institute of Modern Physics, IMP, CAS in Lanzhou), its main activities distribute at the different institute of CAS and collaborate with universities, other institutes and some companies. Following the configuration as Fig. 5, two branch of low energy SCL (Injector I/II) R&D is in charge by Institute of High Energy Physics (IHEP) in Beijing and IMP, the spallation target is in charge by IMP.

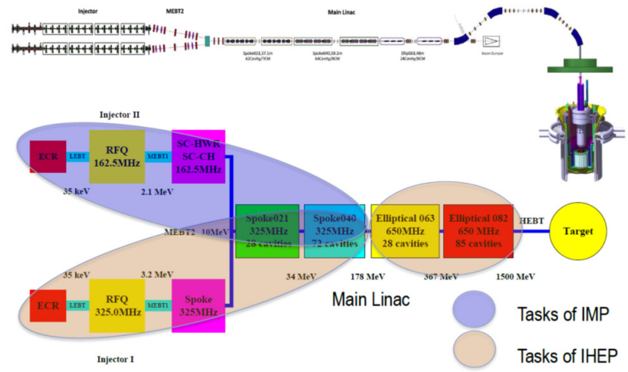

Figure 5: The configuration of ADS/ADANES burner.

SuperConductor_LINAC

By using of two branch of 10MeV & 10mA injector design, the different RF frequency and corresponding type of SCL are in R&D. Injector I is working in 350MHz, which design as ECRIS + RFQ (3MeV) + SC spoke cavity; Injector II is working in 162.5MHz, which design as ECRIS + RFQ (2.1MeV) + SC_HWR. Before end of 2015, Injector I has extracted pulse proton beam > 6MeV & 10mA in low average beam power; Injector II has extracted pulse and CW proton beam ~ 5.5 MeV &10mA, ~5MeV & 1.7~4mA respectively. It will assemble a ~25MeV & 10 mA SCL (ECRIS+3HWR+SP) and tuning pulse beam at IMP before end of 2016. So far, the all hardware are ready, both 10MeV SCL are under tuning individually.

Ion Source 2.45GHz ECRIS had been used as proton ion source for more than 3000 hr, which is higher RAMI performance. ~ 8 short time (<1sec.) beam trips and recover automatically were observed during more than 100 hr test.

As the higher plasma density is driven by higher frequency in general, 14GHz~18GHz ECRIS is under R&D. The preliminary test results confirm the above assumption as in Table 1. The preliminary results indicate that higher frequency ECRIS is more stable in operation, and it will be more favour for deuteron beam as higher vacuum will mitigate the degradation of accelerator gradient due to the cupper of RFQ is permeated by light gas for long operation period.

Table 1: Pre-Test-Results of ECRIS

	14~18 GHz	2.45 GHz
Beam	10 (mA)	10 (mA)
RF Power	30 (W)	300 (W)
Vacuum	0.6~1.2×10^{-3}(pa)	2~5×10^{-3}(Pa)
Feed Gas	Smaller	2~5 (sccm)
Bump speed	700 (l/sec.)	2000 (l/sec.)

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RFQ 350 MHz RFQ is adopted in the injector I. It is higher accelerate gradient and compact, but is more complex with ~400 cooling tubes due to higher power density. The >10 mA pulse proton beam were accelerated from 35keV to 3.0MeV in duty factor close to 99%.

162.5 MHz RFQ is adopted in the injector II. In contrast to 350 MHz RFQ, the lower accelerator gradient lead to simple cooling with ~40 tubes as the lower power density. The >10mA proton beam has been accelerated from 35keV to 2.11Mev in pulse and CW operation mode.

Comparing two RFQ prototypes, the 162.5MHz version operation is more stable in smooth CW working condition. Therefore, 162.5 MHz RFQ has been chosen as final RFQ in CIADS.

Low energy SC-Cavity So far, 350 MHz SC-spoke cavity has been designed as the injector I. ~ 10 mA pulse proton beam were accelerated from 3 MeV to 6 MeV with 7 set of $\beta = 0.1$ SC-spoke cavities in a cryogenic modular. <1% duty factor lead to lower average beam power.

162.5 MHz half wave resonator (HWR) has been designed as the injector II from 2 MeV to 20 MeV. ~10mA pulse proton beam has been extracted from 2 to 5.3 MeV and 1.7~4.3 mA CW proton beam has been accelerated from 2.11 MeV to 5 MeV with 6 set of $\beta = 0.1$ SC-HWR cavities in a cryogenic modular. The main problem during tuning is high average beam power drilled hole in the vacuum chamber or beam stop which will be improved by thin beam window in higher energy beam.

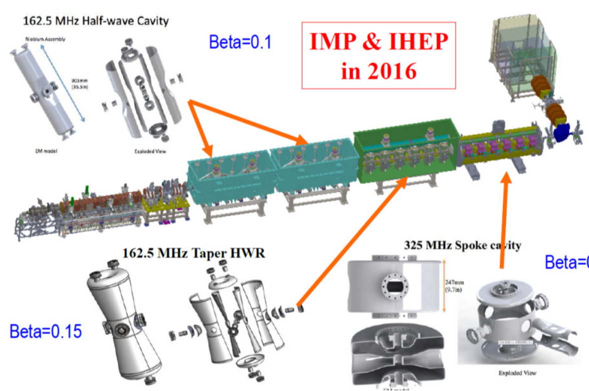

Figure 6: 25 MeV SCL prototype in CAS.

Comparing two kind of low energy injectors, the 162.5MHz SC-HWR is better to CW operation in low energy. Therefore, 162.5 MHz SC-HWR has been chosen as final low energy SCL in CIADS. However, a cryogenic with 7 set of 350MHz SC-spoke will be assemble as last section in 25MeV SC-LINAC to test its CW operation performance (see Fig. 6).

High Power Spallation Target

The 10's MW spallation target has been proposed in traditional ADS. Since the high power density, high temperature, high radiation flux in spallation target, it is one of most challenge technique in ADS. Up to now, the heavy liquid metal is considered as one of best candidates and used at MW's spallation target, ex. Megapie [10], SNS[11], J-PARC [12]. However, the live time of these target are less than design, and no one no leakage, which problems are influence to use as ADS target. The solution may come from new material or new concept.

New Concept of ADANES Spallation Target After introducing the heavy liquid metal as target material, the high power density of heat is transfer with flowing of liquid metal, the radiation influence of target material is free and the high temperature decreases more or less depending design in high power spallation target successfully. However, the phenomena of corrosion, erosion in surface of the container, the radiation influence are remained and turn into the main problems in further improvement. Moreover, the stronger shock wave, induced by high power fast beam trip, become one of key problems the heavy liquid spallation target in recent R&D.

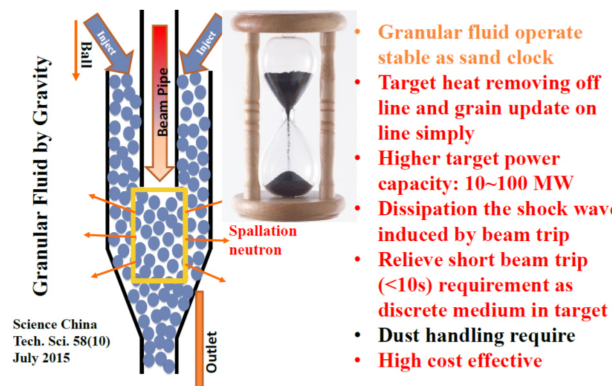

Figure 7: Principle of dense granular flow target.

The new concept of spallation target should be succeed the merits and avoid the burdens in heavy liquid metal target. Therefore, gravity driven dense granular flow target [13] has been introduced as the extra-high power density spallation target as Fig. 7. The solid granular flow from top to bottom as sand clock smoothly, the high power beam is delivery in same direction and bombarding the granular to produce spallation neutron in the centre of target simultaneously. As the massive granular movement is similar as that of liquid, the 10's MW heat can be treated offline easily. The main stronger points are: higher power density, higher temperature, corrosion free, dissipation the shock wave by beam trip, granular maintain on/off line. Obviously, these stronger points are cover those of heavy liquid metal target, and solve those main burdens. However, the erosion may cause the dusk problem which need further R&D. Consequently, the dense granular flow by gravity target is the higher quality to meet the requirements of ADANES.

Progress of ADANES Spallation Target The different scale of dense granular flow by gravity have been test by the experiments and supercomputing simulation from 2012. The experimental data are reproduced in supercomputing simulation from small to large scale in temperature range about 700 ºC.

The 10 MW spallation neutron target has been designed by using the tungsten alloy as target material, setting the intensity of beam ~100μA/cm^2, diameter of the beam spot ~10cm the inlet temperature as 250 ºC. The granular outlet temperature and average velocity are not the critical, for example, the outlet temperature is ~600ºC corresponding average velocity ~0.35m/sec. Obviously, this kind target should be able to design in 10's to 100MW spallation target by enlarge the beam spot, high heat capacity material, higher outlet temperature, faster flow speed…

Taking main parameters of 10MW spallation target, the prototype has been test by electron beam in identical power density. <5 MW beam power spallation target is design in CIADS project and the half scale test bench is constructing to test in hydrodynamic, material erosion, cooling component, electromagnetic granular lift, dusk handling, and operation stability (except radiation).

Beam Trip requirement in ADANES Target Concerning the beam trip, the dense granular fluid target is almost free to the stronger shock wave as the granular is the discrete medium and dissipate stronger shock wave is its inherent property. Moreover, the higher spallation neutron yield with higher heat capacity material can be chosen as granular material easily. Therefore, the requirements of < 10 sec. beam trip could be relieved for this kind of high power spallation neutron target.

FURTHER KEY ISSUES AD FOR ADANES BURNER

Except the reactor or blanket, the further key issues of accelerator driven for the ADANES Burner are considered as following:

➢ Coupling between AD and Subcritical core (system) Being the starter of ADANES burner, the optimized coupling will gain the benefits on the safety, AD duration, "raw" fuel, and cost effective;

➢ Beam Power (system)
- $10MW_b/GW_{th}$ can be reached by optimizing the neutron spectrum, k_{eff} value of subcritical state and material inside of core.
- Deuteron as projectile should be higher neutron yields more than 10s%, if deuteron could be ready.

➢ Stability (key tech., system)
- Higher frequency ECRIS is more stable of operation and plasma sparking due to reduce feeding in RF power. This feature will be favor for D_2;
- Lower frequency RFQ (162.5 MHz) is more stable as lower power density;
- Coating Nb or Nb_3Sn on cupper as SC-cavity is quenching "free". The lower accelerate gradient and no experience on high intensity beam need to improve.
- Beam trip requirement will relieve by adopting the fluid granular target (<10 sec.), duration of AD and the burner operation mode.

➢ Reliability (key tech., new design)
- RF power supplier can be design as plug in / out by using solid devices.
- Beam lose could be improved by the beam dynamics, collimator to mitigate halo beam?
- SC-LINAC fault recovery could be improved by introducing He, plasma cleaning.
- Target: Granular fluid, heat remove off line, grain replace on line;
- The beam window should need more R&D.

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