Recent ADS/ADANES Activities in China

(Accelerator Driven Advanced Nuclear Energy System)

Wenlong Zhan IMP/CAS
OUTLINE

I. Introduction
- Evolution of ADS to ADANES
- Roadmap of ADS/ADANES
- New Site, New Research Center

II. Progress of ADS/ADANES
- Configuration of C-ADS
- Accelerator System
- Spallation Target
- Key Issue of AD in ADANES Burner
- ...
Nuclear Fission Energy Status

MOX+LWR

Resource Utilization ** (%)

100
10
1
0.1

Radiotoxicity Reduction (%)

Scale Demo./ Commercial

LWR, Once Through

MOX+FR

FRs

MOX+LWR

Ideal System : ADANES

ADS Transmutation

Higher Utilization → Breeding

Fast Neutron

Minimization Radiotoxicity → Transmutation

235U_{0.72%}

238U_{99.3%}

Fuel ~ 1000yr, Waste < 5%, radioactive live < 500yr

238U_{99.3%}

239Pu_{99.3%}

Fuel Supply 1000GWe

**Fuel Supply 1000GWe
Main difficulties of P&T:

- Extract high purity U, Pu & MA ≠ Residuals remain MA<1% (long lifetime in waste)
- more Toxicity @ Complexes after few cycles
- High purity Pu, MA fuels is:
  Burning Unstable & High risk of proliferation !!
- Lower feasibility, lower cost effective

New Approach: (Optimizing resources & radiotoxicity)

- Simplify Fuel Recycle: Remove part of FPs (~50%) UNF, Convert Residuals as recycle fuel
- Power Burner: Transmuting, Breeding & Energy produce by fast neutron for burning recycle fuel (~50% FP)
Accelerator Driven System was proposed for:
- Nuclear waste \textit{transmutation} (ADS)
- Isotopes production (ex. \textit{Breed}, \textit{ISOL}, \textit{APT})
- Energy Amplifier (ADTR)...

ADS consists of \textit{high power proton accelerator, spallation target} & \textit{subcritical core} mainly

\textbf{ADANES Burner}

\textit{ADS and FR in Advanced Nuclear Fuel Cycles — A Comparative Study, NEA/OECD, 2002}
HT-Remove ~50% FP from UNF (Ext. AIROX)
ADANES (LWR UNF: 33GWd/Ton)

Energy

ADANES Burner:
- Transmutation (5~12) +
- Breeding > 1.1 +
- Generation ~ LWR in Situ

Convert UNF into Recycle Fuel
- Waste <4% UNF @ MA<1%, τ<500Y, Sustain NE > 10000yr

ADANES Fuel Recycles:
- Remove >50% FP from UNF by HT Dry (Ext. AIROX), further
- Remove >50% Ln’s by REs extract, MA<1% than Origin

Waste:<4%SNF;
FP’s: Volatile FP’s, <1%gas, <1% Ln’s;
MA<1% than UNF

Burning:
UNF → 5~6
MA → 10~12

~50% FP

ADS Roadmap in CHINA
Starting ADS $\rightarrow$ Long refueling cycle FR (Accelerator $\rightarrow$ Starter)

AD duration: 10% ~ < 15% depending on power density, fuel, ...

Safety, Flexibility $\rightarrow$ Close fuel Cycle, “Raw Fuel” $\rightarrow$ Simple UNF recycle

Max. Resource Utilization >95%, Min. Radiotoxicity <4% waste & <500 yr.

Transmutation MA capabilities: $\sim$6 LWR ($3GW_{th}$) /10MW$_b$ ($\sim$50% ADS)

Efficiency of Nuclear Electricity Generator: ($\sim$33% LWR)

ADANES: $>31\% \rightarrow >36\%$ (SHO2) $\rightarrow >40\%$ (SCO2) with AD
$>35\% \rightarrow >40\%$ (SHO2) $\rightarrow >44\%$ (SCO2) no AD $\rightarrow$ Water free
Safety & Proliferation

- **Reactivity Control**
  - Subcritical → AD
  - Critical → FR
  - $\Delta k > 5\%$ (B$_4$C)

- **Decay Heat Remove**
  - Smaller decay heat source ($<10\%$ PWR at discharge, $<1/3 \sim 10$ yr UNF)
  - Weaker neutron, gamma source $< 1/3$ of PWR at discharge
  - Fuel Cladding material ($>1500^\circ$C) for removing heat by air in accident

- **Confinement of radioactive material**
  - Multilayer confine fuel against radioactive material release during accident
  - ATF fuel cladding to limit radioactive containment **within control region**

- **Proliferation resistance and physical protection**
  - No enrichment, no attractive for weapon and against the acts of terrorism

**Table 4.4. Comparison of UNF Decay Heat at Discharge**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PWR-50</th>
<th>PWR-100</th>
<th>CANDLE</th>
<th>SSFR</th>
<th>FMSR</th>
<th>ULFR</th>
<th>EM$^2$</th>
<th>TWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific power density, MW/t</td>
<td>33.70</td>
<td>33.70</td>
<td>3.66</td>
<td>16.89</td>
<td>15.67</td>
<td>9.39</td>
<td>11.76</td>
<td>7.51</td>
</tr>
<tr>
<td>Decay heat per unit UNF mass, MW/t</td>
<td>1.99</td>
<td>2.00</td>
<td>0.24</td>
<td>0.76</td>
<td>0.74</td>
<td>0.63</td>
<td>0.68</td>
<td>0.43</td>
</tr>
<tr>
<td>Normalized decay heat per unit electricity generation, MW/GWe-yr</td>
<td>39.14</td>
<td>19.74</td>
<td>0.83</td>
<td>2.20</td>
<td>2.30</td>
<td>3.11</td>
<td>3.32</td>
<td>4.02</td>
</tr>
<tr>
<td></td>
<td>Traditional ADS</td>
<td>ADANES</td>
<td></td>
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</tr>
<tr>
<td>UNF Partition</td>
<td>Complex, 2\textsuperscript{nd} contamination PUROX(water)/pyro-process</td>
<td>Simple, Extend AIROX + RE extracted (&lt;1/3, no water)</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Fuel</td>
<td>Precise, MA + LEU</td>
<td>Raw, recycle Fuel (containing ~50%FPs) + LEU in 1st cycle</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Burner Function:</td>
<td>$10\sim12/\text{MW}_b$</td>
<td>5 \sim 6/10\text{MW}_b</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Transmute rate$_{\text{max}}$</td>
<td>$&lt;&lt;1.0$ ?</td>
<td>&gt;1.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Breeding</td>
<td>Low quality @ efficiency</td>
<td>Higher quality @ efficiency</td>
<td></td>
<td></td>
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<tr>
<td>Produce electricity</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Operation Mode</td>
<td>Subcritical core driven by accelerator in all cycle</td>
<td>Accelerator as starter ($\sim10%$), + Long refueling Fast Reactor</td>
<td></td>
<td></td>
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<tr>
<td>Proliferation &amp;</td>
<td>Enrich Actinide, high risk</td>
<td>No enrichment, lower risk</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>physical protection</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Close Fuel Cycle</td>
<td>Yes, Minimum radiotoxicity</td>
<td>Yes, Minimum radiotoxicity, Maximum resource utilization</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Cost Performance</td>
<td>Low</td>
<td>Higher</td>
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</tbody>
</table>
ADS/ADANES Roadmap in China

Phase I
- 2011--2016
- ¥1.78 B
- Inject I
- Inject II

Phase II
- 2016--2022
- >¥1.8 B
- 10 MeV
- ~2.5 MeV &~10mA
- 2014
- ~25 MeV &~10mA
- 2016
- 400~600 MeV &5~10mA
- 2022
- >1 MW
- >10 MW
- <2021
- ~1 MW Close Fuel Recycle
- Key Tech. R&D: Acc., Target, Blanket… Prototype

Phase III
- <2021
- ~1 MW Close Fuel Recycle

Phase IV
- ≥1 GW
- ~203x
- ~1.0 GeV &~20mA
- <2030
- ~1.0 GeV &<20mA
- >2021
- <2030
- ~1.0 GeV &<20mA
- >2021

Initial Facility
- Demo. Facility
- Indust. Facility
- Phase I
- Phase II
- Phase III
- Phase IV

ADS Roadmap in CHINA
Accelerator Driven Recycling Used Fuel

SC_LINAC (~5mA@~200MeV d+Be)

- Fuel Recycle
- Compact Neutron Source (>50dpa)

1. Verify Recycle Fuel
   - UC Fuel Properties
   - $^{238}\text{U} \rightarrow ^{239}\text{Pu}$ Breeding rate
   - Optimization of Fuel Assembling

2. Irradiation of Materials
   - Cladding (SiC$_f$/SiC…)
   - Core Structure (Oxide + Carbide Ceramics…)
   - Window between Accelerator and Target
   - …
New site, New open research center

CAS: IMP, IHEP, HIPS, USTC, UCAS, ...
GNC, CNNC, Universities, Other Inst....
I. Introduction
- Evolution of ADS to ADANES
- Roadmap
- New Site, New Research Center

II. Progress of ADS/ADANES
- Configuration of C-ADS
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- Key Issues of AD for ADANES Burner
- ...
Requirement of Accelerator for ADS/ADANES

- **Scale**
  - Transmutation Demo
  - Industrial transmutation
  - Industrial Power Generation (IPG)

- **Mean Beam Power (IPG): 10~20MW**
  - Energy: ~1GeV
  - Mean current: 10~20mA

- **Beam Strips & Availability (IPG)**

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Availability</th>
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</thead>
<tbody>
<tr>
<td>t &lt; 1 sec.</td>
<td>&lt; 25000/yr.</td>
</tr>
<tr>
<td>1 &lt; t &lt; 10 sec.</td>
<td>&lt; 2500 / yr.</td>
</tr>
<tr>
<td>10s &lt; t &lt; 5 min.</td>
<td>&lt; 250 / yr.</td>
</tr>
<tr>
<td>t &gt; 5min.</td>
<td>&lt; 3 / yr.</td>
</tr>
<tr>
<td></td>
<td>&gt; 85%</td>
</tr>
</tbody>
</table>
**Configuration of C-ADS**

**Phase I:** Low Energy SCL  
Energy: ~25 MeV  
Current: 1~10 mA (depending on permission of environment)

**Main Linac**

- **Tasks of IMP**
- **Tasks of IHEP**

**Injector I**
- RFQ 325.0 MHz
- Spoke 325 MHz
- 35 keV

**MEBT1**
- 162.5 MHz
- SC-HWR
- SC-CH 162.5 MHz
- 35 keV

**MEBT2**
- 162.5 MHz
- 2.1 MeV

**Spoke021**
- 325 MHz
- 28 cavities

**Spoke046**
- 325 MHz
- 72 cavities

**Elliptical 063**
- 650 MHz
- 28 cavities

**Elliptical 082**
- 650 MHz
- 85 cavities

**Target**
- 1500 MeV

**HEBT**

**Diagram Details**
- Injector I
- Injector II
- Main Linac
- Spoke021, 046
- Elliptical 063, 082
- Target
- ECR
- LEBT
- MEBT1
- MEBT2

**Tasks of IMP**

**Tasks of IHEP**
ECR+RFQ+2CM: 10.5mA @ 10.1MeV
Pulse ~0.04%, 2016;
~2.1mA @ 10MeV, CW Jan. 2017

Commission:
ECR+RFQ: 11mA @ 3.2MeV,
Pulse >99%, 2014
Low $\beta$ 350MHz Spoke & 650MHz Ellipse SC

Spoke012 4.2K VT, Designed $Q_0 = 5 \times 10^4$ @ $E_{\text{peak}} = 31.5$ MV/m

2K much better!
Spoke012 <4K VT results

650MHz SC (082) Vertical test 9MV/m

<table>
<thead>
<tr>
<th>CM</th>
<th>$G_{\text{max}}$ [MV/m]</th>
<th>$Q_0@7$ [MV/m]</th>
<th>CM 2</th>
<th>$G_{\text{max}}$ [MV/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1#</td>
<td>13.4</td>
<td>6.4e8</td>
<td>1#</td>
<td>17.4</td>
</tr>
<tr>
<td>2#</td>
<td>15.4</td>
<td>5.5e8</td>
<td>2#</td>
<td>15.2</td>
</tr>
<tr>
<td>3#</td>
<td>16.6</td>
<td>5.9e8</td>
<td>3#</td>
<td>13.7</td>
</tr>
<tr>
<td>4#</td>
<td>15.3</td>
<td>6.5e8</td>
<td>4#</td>
<td>15.7</td>
</tr>
<tr>
<td>5#</td>
<td>13.4</td>
<td>1.0e9</td>
<td>5#</td>
<td>14.6</td>
</tr>
<tr>
<td>6#</td>
<td>14.1</td>
<td>9.0e8</td>
<td>6#</td>
<td>11.3</td>
</tr>
<tr>
<td>7#</td>
<td>14.3</td>
<td>1.1e9</td>
<td>7#</td>
<td>13.6</td>
</tr>
</tbody>
</table>
ECRIS+RFQ (>3000 hrs): >10mA @ 2.15MeV, CW, Eff.= 95~97%, δE/E ~1.9%, June, 2014

ECR+RFQ+CM1: CW, >2.7/3.9mA @ 5.3/4.6MeV, June 2015

ECR+RFQ+CM1+CM2: CW, 1.1/2.7mA @ 10.3/9.55MeV, Nov. ~ Dec. 2016, He Plasma clean, Coupler improve→

E_{peak}^{mean}: 23.8 MV/m, E_{peak}^{max}: 36.2 MV/m
Low $\beta$ 165MHz HWR & Taper HWR (4.2K)

Optimizing:
- Startup
- CM assemble
- DC control

<table>
<thead>
<tr>
<th></th>
<th>THWR015</th>
<th>SHWR010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacc(MV)</td>
<td>1.8</td>
<td>0.78</td>
</tr>
<tr>
<td>Bpeak(mT)</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Epeak(MV/m)</td>
<td>32</td>
<td>25</td>
</tr>
<tr>
<td>R/Q(\Omega)</td>
<td>286</td>
<td>148</td>
</tr>
<tr>
<td>G (\Omega)</td>
<td>52</td>
<td>28.5</td>
</tr>
<tr>
<td>Eacc(MV/m)</td>
<td>6.6</td>
<td>4.7</td>
</tr>
<tr>
<td>$P(W)(Rs=70n\Omega)$</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>$\beta_{opt}$</td>
<td>0.15</td>
<td>0.10</td>
</tr>
<tr>
<td>Q0</td>
<td>7.2E08</td>
<td>4.0E08</td>
</tr>
</tbody>
</table>
25 MeV LINAC Commissioning

162.5 MHz Half-wave Cavity

162.5 MHz Taper HWR

325 MHz Spoke cavity

Beta=0.1

IMP & IHEP

Beta=0.15

Beta=0.21

Niobium Assembly

903mm (35.5in)

Exploded View

EM model

EM model

Exploded View

247mm (9.7in)
Principle of Granular Fluid Spallation Target

- Granular fluid operate stable as sand clock
- Target heat removing off line
- Grain maintaining on line
- Higher target power capacity: 10~100 MW
- Dissipation the shock wave induced by beam trip
- Relieve short beam trip (<10s) requirement as discrete medium in target
- Target material selectable
- Dust handling requirement
- Higher cost effective
Granular Loop Test

Large scale loop & HT test  Granular target test bench

ADS Roadmap in CHINA
Exp. of E-Beam on W Granular Target

<20mA @ 2.5MeV e

Identify Target Power
Density of proton beam
1.0GeV @ 10~20mA on W

Lift Setup
Beam-Target
Heat Exchanger
Key Issue of AD for ADANES Burner

- **System Optimizing (new approaches, operation mode)**
  - Starter of Burner → no AD requirement during critical as fast reactor
  - Longer refueling core → 10~15% of Duration Burner Operation
  - Faster neutron spectrum → burning UNF
  - Higher efficiency → ~10MW\textsubscript{b}/GW\textsubscript{th} → reducing scale of SCL (cost effective)

- **Stability (key tech., system optimizing)**
  - ECRIS: Lower RF Power, Flow H\textsubscript{2} (favor for D\textsubscript{2}), >90% H\textsuperscript{+} and stable
  - RFQ: 162.5MHz → Lower power density
  - SC-Cavity → Nb (or Nb\textsubscript{3}Sn) coating on copper cavity → SC-cavity!
  - Beam trip → Optimizing System: ECRIS, Target (<10Sec.), Burner operation mode…

- **Reliability, Maintainable (key tech., new design)**
  - RF : many lower power coupler, PS plug in / out
  - Beam lose : beam dynamics, collimator to mitigate halo beam ?
  - SCL : rapid fault recovery, He, Ar plasma cleaning on line…
  - Target : Granular fluid, heat remove off line, grain replace on line, target material optimizing
Summary of ADS/ADANES in CAS

- **ADANES Conception Proposed** Approaches under optimizing

- **Accelerator System** *(prototype in world)*
  - Injector 2.15~3.2MeV & 11mA (RFQ) $\rightarrow$ ~10MeV & 1.1~2.7mA (SCL) CW beam

- **Spallation Target** *(new, simplify)*
  - Granular fluid target is designed and prototype testing with e-beam

- **Subcritical Fast Core** *(Gas+Grain $\rightarrow$ new, simplify)*
  - LBE, Steam, Gas + Grain coolant cores R&D, Gas+Grain is more optimizing

- **Fuel Recycle** *(partial new, simplify)*
  - HT-Dry + REs Extracting Processes R&D intensively

- **ADANES Material R&D** *(Be/Alloy, SIMP, SiCf/SiC, Ceramic…)*
  - SIMP Steel (similar HT9) R&D and Improving in 5 Tone Scale
  - SiCf/SiC, oxide and carbide ceramic used in core and cladding, R&D intensively

- **GPU based S-Computing used for optimization of System Design**
THANKS FOR ATTENTION

Welcome to Collaboration!