SCL-Key Issue of ADANES in China

(Accelerator Driven Advanced Nuclear Energy System)

Wenlong Zhan CAS
I. ADANES
- Introduction
- ADANES Burner ← Evolution from ADS
- Roadmap of ADANES in China
- New Site, New Research Center

II. Progress of ADS/ADANES
- Configuration of C-ADS
- Accelerator System
- Spallation Target
- Other Key Issues
- …
Status of Fission Energy

Goals of Fission Energy (from GIF2014)
- Sustainability → Max. Resources & Min. Radiotoxicity
- Safety and Reliability
- Economic Competitiveness
- Proliferation Resistance and Physical Protection

Situation of Sustainability
Main difficulties of P&T:

- Extract high purity U, Pu & MA ≠ Residuals remain MA<1%, Serious 2nd Contamination
- more Toxicity @ Complexes after few cycles
- High purity Pu, MA fuels is:
  Burning Unstable & High risk of proliferation !!
- Low feasibility(final solution?), low cost effective

New Approach: (Optimizing UNF resources & radiotoxicity)

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

ADS consists of high power proton accelerator, spallation target & subcritical core mainly

HT-Remove ~50% FP from UNF (Ext. AIROX)
ADANES Configuration (LWR UNF: 33GWd/Ton)

ADANES Burner:
Transmutation + Breeding > 1.1 + Energy Amplifier ~ LWR in Situ

ADANES Fuel Recycles:
Remove >40% FP from UNF by HT Dry (Ext. AIROX), further Remove >50% Ln’s by REs extract, MA<1% than Origin

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

Energy

MA
TRU
NU
DU
Th
LEU...
>95%UNF

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ADANES Configuration (LWR UNF: 33GWd/Ton)

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- Transmutation +
- Breeding > 1.1 +
- Energy Amplifier ~ LWR in Situ

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

Waste:<4%UNF; FP’s: Volatile FP’s, <1%gas, <1%Ln’s; MA<1% than UNF
SNF
~50%FP
ADANES — Operation Mode

- ADS + Long Refueling Cycle FR → Accelerator as Starter
- AD Duration:
  - 10% ~ < 15% (depend on fuel, material…)
- Safety, Flexibility, Close Fuel Cycle, “Raw Fuel” → Simplify UNF Recycle
- Transmutation MA capabilities : 3~6 LWR (3GW$_{th}$/10MW$_{b}$) depend on Scale & Fuel
- Max. Resources Utilize ~95%, Min. Radiotoxicity <4%, Decay Life<500yr;
- Generation E-Efficiency: PWR~33%
  - ADANES (Higher Temperature):
    - >31% → >36%(SH$_2$O) → >40%(SCO$_2$) (AD)
    - >35% → >40%(SH$_2$O) → >44%(SCO$_2$)

**Double AD:**
- Enhance Reliability;
- Increase Cost about 25% as same power SCL

SC-LINAC1 ≤ (1GeV&20mA)
SC-LINAC2 ≤ (1GeV&20mA)
Safety & Proliferation

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

- **Decay Heat Remove**
  - Smaller decay heat source (<10% PWR at discharge, <1/3 ~ 10yr UNF)
  - Weaker neutron, gamma source < 1/3 of PWR at discharge
  - Fuel Cladding material (>1500°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$^3$</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>0.65</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>
</tbody>
</table>
Roadmap of ADANES in China

￥1.78 B
Phase I
2011–2016

Inject I
10 MeV

Inject II

￥1.8 B
Phase II
2016–2022

>10 MW
10 MeV
&10 mA

<2021
~1 MW Close
Fuel Recycle

Phase III

>600 MW
400–600 MeV
&5–10 mA

<2030
~1.0 GeV
&<15 mA

≥1 GW
<203x
<1.5 GeV
&<20 mA

Phase IV

Key Tech. R&D: Acc.,
Target, Blanket… Prototype

Initial Facility

Demo. Facility

Indust. Facility

10 MW
~2.5 MeV
&10 mA

2014

2016

2022

2030

SCL – Key issue of ADANES in CHINA
**CIADS Main Parameters:**

- High CW Power (>2.5MW, >500MeV) SC-LINAC
- High Power (>2.5MW) Spallation Target
- Sub-Core (<10MWth)
- Coupling all Components → Full System (~10MW)

**CIADS Time Schedule:**

- 2018—2023
Accelerator Driven Recycling Used Fuel

- Fuel Recycle
- Compact Neutron Source (10~50dpa)

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 ($\text{SiC}/\text{SiC}$…)
   - Core Structure (Oxide + Carbide Ceramics…)
   - Window between Accelerator and Target

>100MeV&5mA d +Be >10dpa/yr

~300MeV >30nC e/pp quasi-on line measure
Researches on Intense Beam at CIADS+HIAF

I. Nuclear Physics
   - Nuclear Structure & Nuclear Astrophysics
   - Nuclear Matter & Hadron Nuclear Physics

II. Foundation Physics
   - Ultra-high E_Field QED
   - Researches by Polarized nucleon, DAR neutrino, μ, π...

III. Nuclear Energy
   - ADS → ADANES Burner

IV. Irradiative Material, Biology
   - Compact, High Flux Neutron Source (10~50dpa)
   - Ion Therapy

V. Convert UNF → Recycle Fuel
**Configuration of HIAF**

**BRing:** Booster ring  
**Circumference:** 530 m  
**BT ~ 34 Tm → 1GeV/a U^{40+}**  
Beam accumulation  
Beam cooling  
Beam acceleration

**SRing:** Spectrometer ring  
**Circumference:** 265 m  
**BT ~ 15 Tm → 1GeV/a U^{92+}**  
Electron/Stochastic cooling  
Two TOF detectors  
Four operation modes

**MRing:** Figure “8” ring  
**Circumference:** 268 m  
**Rigidity:** 15 Tm  
Ion-ion merging

**iLinac:** Superconducting linac  
**Length:** >100 m  
**Energy:** 20 MeV/u(U^{40+})
New site, New open research center

CAS: IMP, IHEP, HIPS, USTC, UCAS, ...
GNC, CNNC, Universities, Other Inst....
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Configuration of C-ADS

Tasks of IMP

Tasks of IHEP
Challenge of SCL 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 Interval</th>
<th>Availability</th>
</tr>
</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>
25 MeV LINAC Commissioning

162.5 MHz Half-wave Cavity

Beta=0.1

IMP & IHEP

162.5 MHz Taper HWR

Beta=0.15

325 MHz Spoke cavity

Beta=0.21
25 MeV SCL (CW)

25MeV SCL:

- Ion Source: ECR
- RFQ, 162.5 MHz
- 1st CM, 2nd CM:
  - 6*HWR, 162.5 MHz
- 3rd CM:
  - 5*THWR, 162.5 MHz
- 4th CM:
  - 7*Spoke, 325 MHz

12mA/pulse, 0.2mA/CW
Principle of Granular Fluid Spallation Target

Granular Fluid by Gravity

Science China Tech. Sci. 58(10) July 2015
Principle of Granular Fluid Spallation Target

- Granular fluid operate stable as sand clock
- Target heat removing off line
- Grain update 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 require
- High cost effective
Dense Granular Target Test Bench

Test-Bench Checked 2017.6
Granular Target for Compact Neutron Source

- Granular of Be Alloy/Be$_2$C driven by gravity;
- The high power dense of deposited energy by D beam;
- Offline heat exchanger;
- Low Evaporation pressure;
- Small size of the irradiative target keep high neutron flux.
45MeV E-Beam measurement quasi- on line

\[
\sigma (\mu m) \approx 3 \text{ pixel} \times \frac{90\mu m}{(1185 - 1115) \text{pixel}} = 3.9\mu m
\]
Summary of CIADS/ADANES

- ADANES Conception Proposed, Approaches under optimizing

- Accelerator System (prototype in world)
  - Injector $>2.55\text{MeV}\&11\text{mA} \rightarrow 5.2\text{MeV}\&4.7\text{mA} \text{ CW}, \rightarrow >10\text{MeV}\&1\sim2\text{mA/CW}$, 
  $\rightarrow 25\text{MeV}\&12\text{mA/pulse} 0.2\text{mA/CW}$

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

- Subcritical Fast Core (new, simplify)
  - (Gas + Grain) / (Water + Steam) two phase coolant core R&D to optimizing one

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

- ADANES Material R&D (SIMP Steel, SiC$_f$/SiC, Ceramic, …)
  - SIMP Steel, SiC$_f$/SiC, & Oxide, Carbide Ceramic for cladding & core, R&D

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

Welcome to Collaboration!