EuCARD^2

CERN

Feb. 07, 2017

Recent ADS/ADANES Activities in China

(Accelerator Driven Advanced Nuclear Energy System)

Wenlong Zhan IMP/CAS

OUTLINE

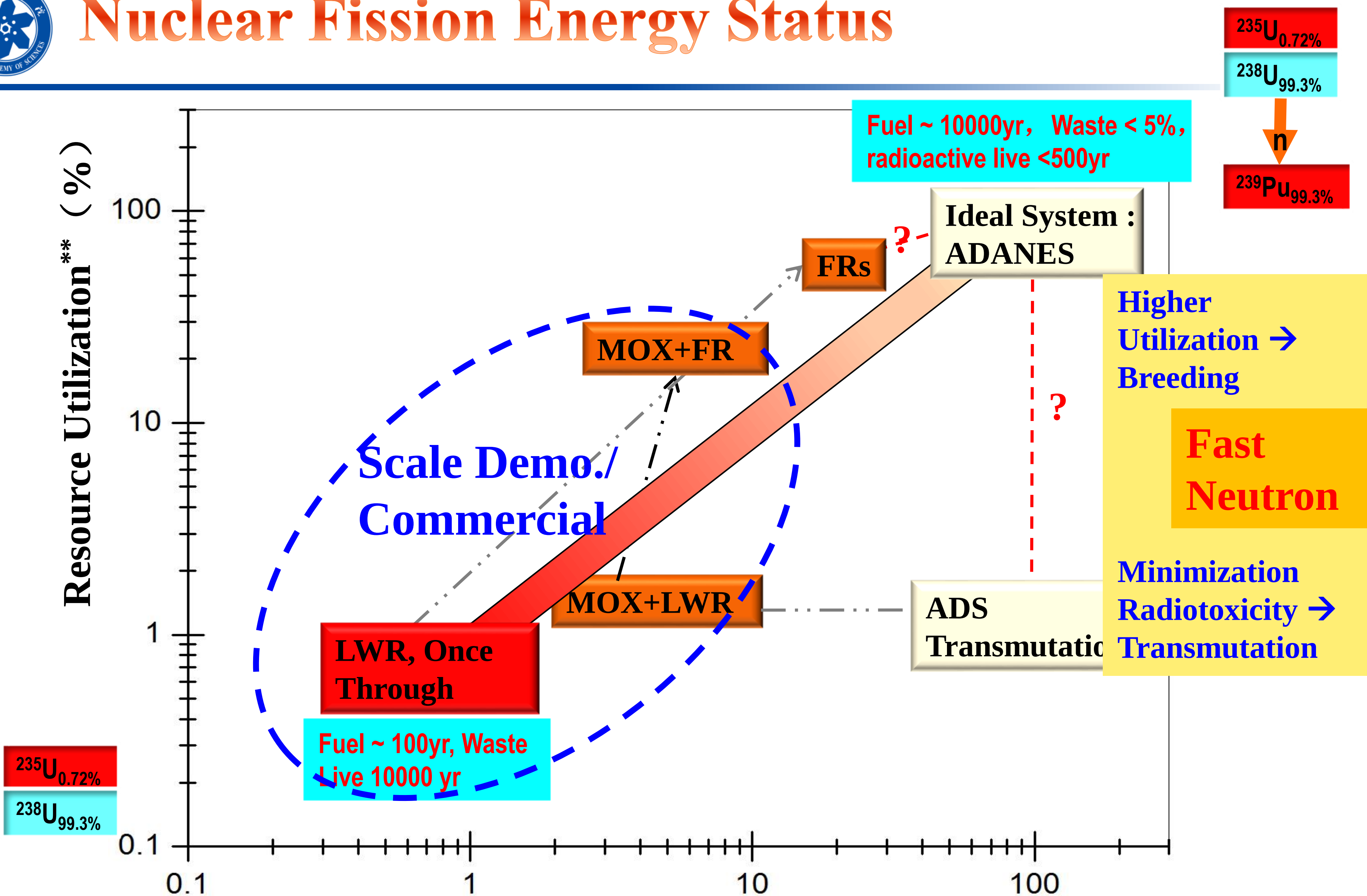
I. Introduction

- 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
- …

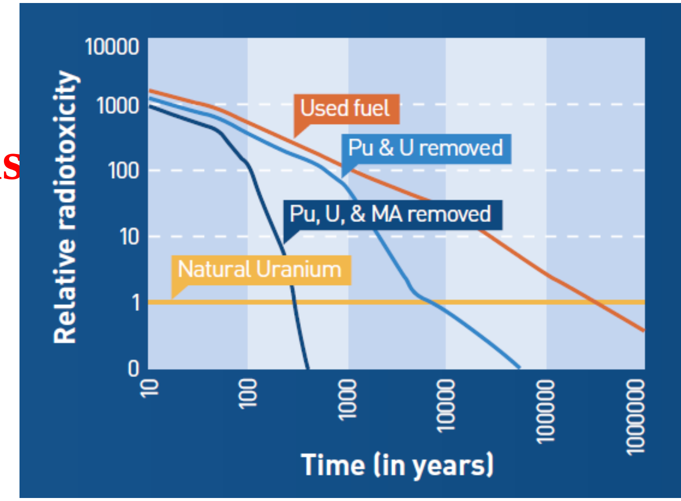
Nuclear Fission Energy Status



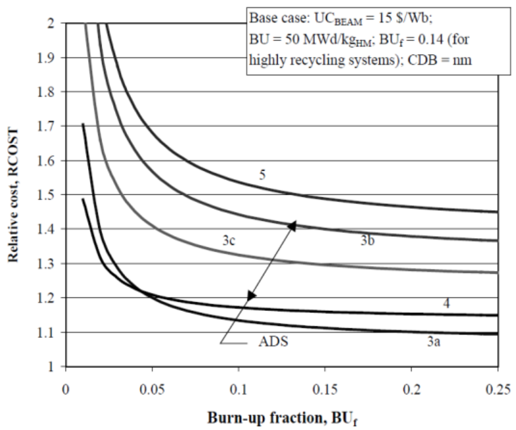
**Fuel Supply 1000GWe

Status of Close Fuel Cycle

- **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)**



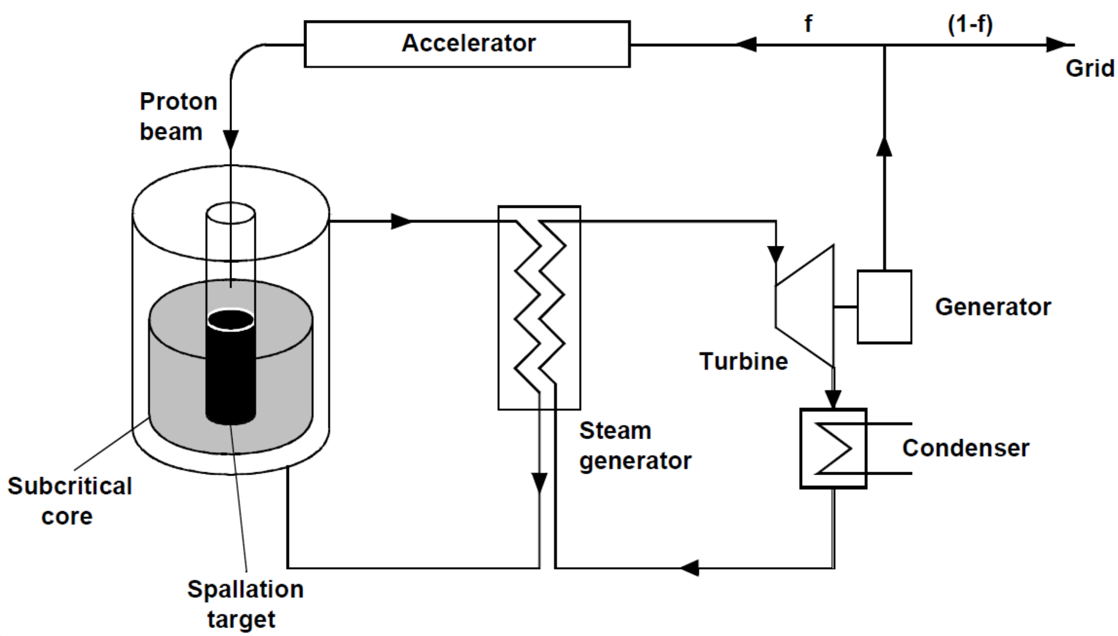
Evolution of ADS to ADANES Burner

(Accelerator Driven Advanced Nuclear System)

- **Accelerator Driven System was proposed for:**
  - **Nuclear waste transmutation (ADS)**
  - **Isotopes production (ex. Breed, ISOL, APT)**
  - **Energy Amplifier (ADTR)…**

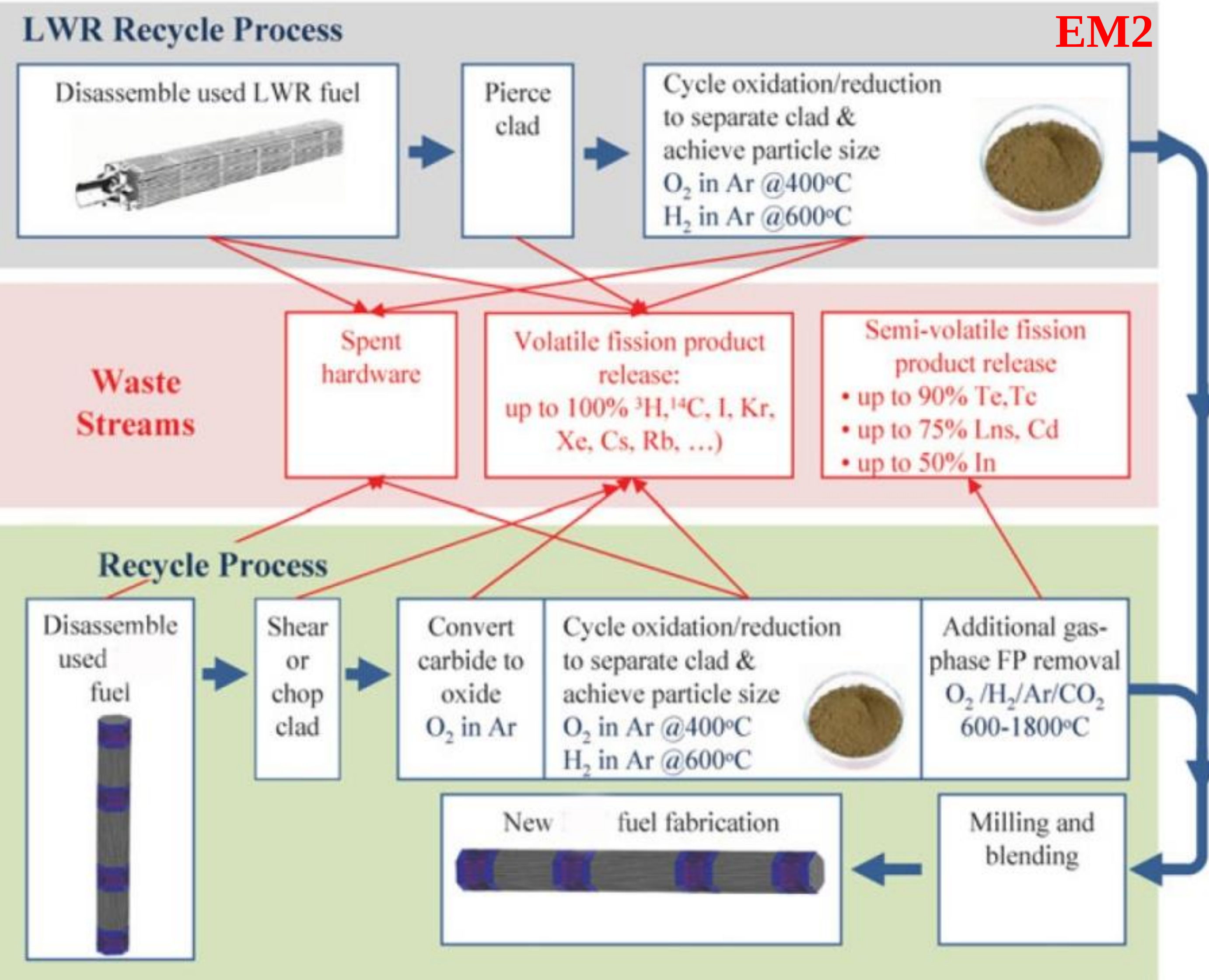
  } ADANES Burner

- **ADS consists of <u>high power proton accelerator, spallation target</u> & <u>subcritical core</u> mainly**

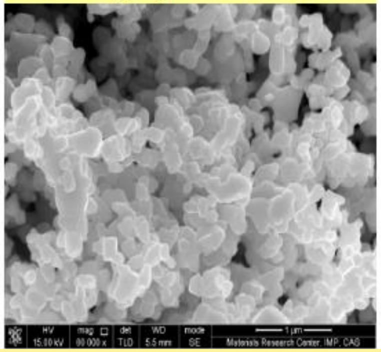


ADS and FR in Advanced Nuclear Fuel Cycles — A Comparative Study, NEA/OECD, 2002

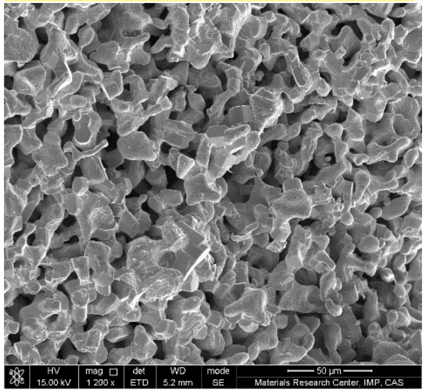
HT-Remove ~50% FP from UNF (Ext. AIROX)

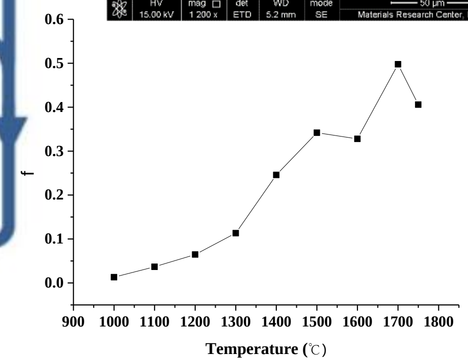


U_3O_8 900℃ 4h



U_3O_8 1700°C 6h





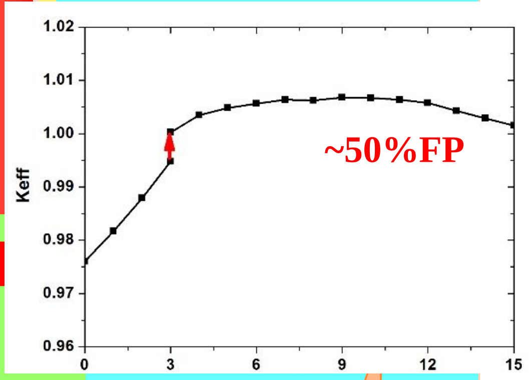
ADANES (LWR UNF: 33GWd/Ton)

MA
TRU
NU
DU
Th
LEU…
>95%UNF

Energy

Burning:
UNF → 5~6
MA → 10~12

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



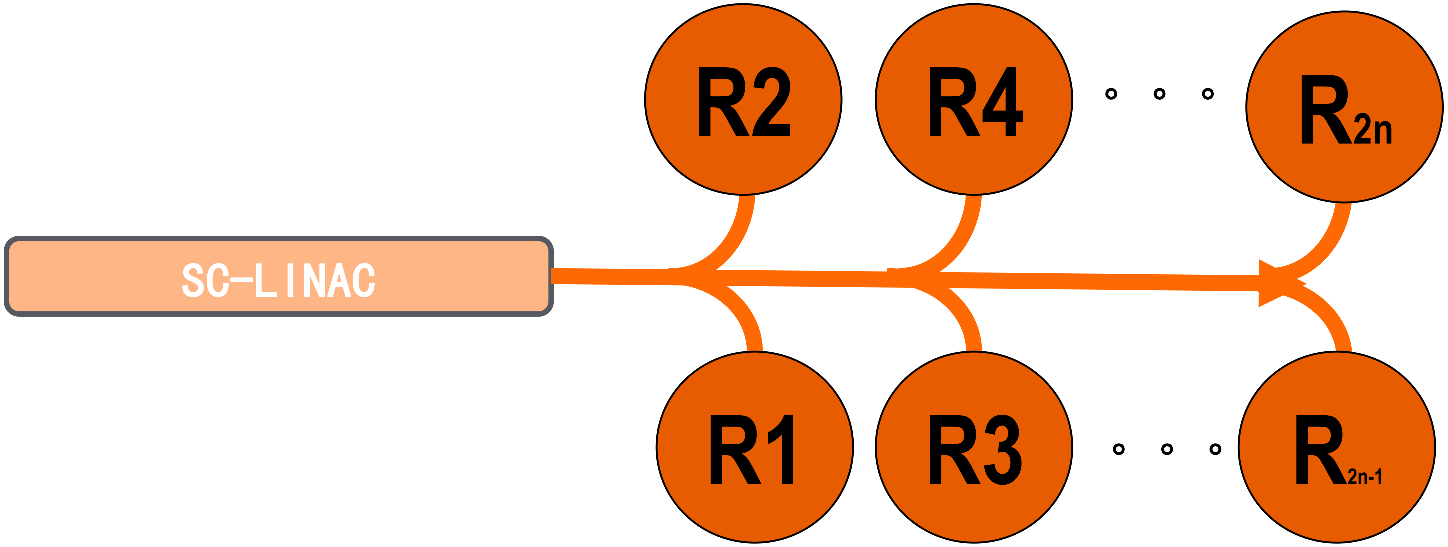
Convert UNF into Recycle Fuel
Waste <4% UNF @ MA<1%,
τ<500Y, Sustain NE > 10000yr

SNF

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

ADANES —— Operation Mode



- Starting ADS → Long refueling cycle FR（Accelerator → Starter)
- AD duration: 10% ~ < 15% depending power density, fuel, …
- Safety, Flexibility→ Close fuel Cycle, "Raw Fuel"→ Simple UNF recycle
- Max. Resource Utilization >95%, Min. Radiotoxicity <4% waste & <500 yr.
- Transmutation MA capabilities : ~6 LWR (3GW$_{th}$) /10MW$_{b}$ （~50% ADS）
- Efficiency of Nuclear Electricity Generator: (~33% LWR)

  ADANES: >31% → >36% (SHO2) → >40% (SCO2) with AD

  >35% → >40% (SHO2) → >44% (SCO2) no AD → Water free

Safety & Proliferation

- **Reactivity Control**
  - **Subcritical → AD**
  - **Critical → FR**

  Δk>5% （B_4C）

Table 4.4. Comparison of UNF Decay Heat at Discharge

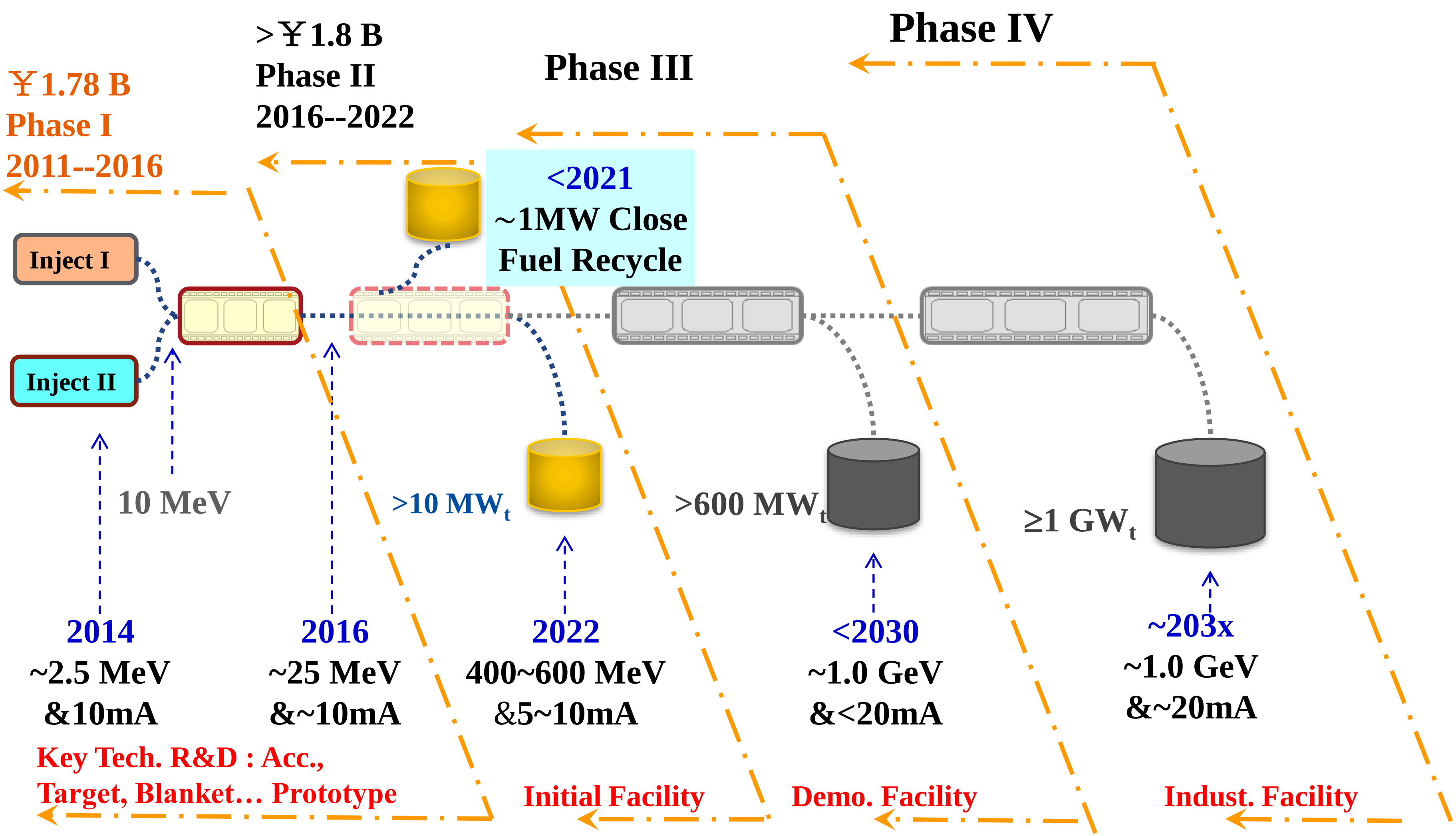
Parameter	PWR-50	PWR-100	CANDLE	SSFR	FMSR	ULFR	EM^2	TWR
Specific power density, MW/t	33.70	33.70	3.66	16.89	15.67	9.39	11.76	7.51
UNF production rate, t/GWe-yr	19.71	9.86	3.42	2.90	3.13	4.93	4.87	9.26
Decay heat per unit UNF mass, MW/t	1.99	2.00	0.24	0.76	0.74	0.63	0.68	0.43
Normalized decay heat per unit electricity generation, MW/GWe-yr	39.14	19.74	0.83	2.20	2.30	3.11	3.32	4.02

- **Decay Heat Remove** **(Ref. Fuel Recycle Analysis of Once Through… ANL-FCRD-308, 2010)**
  - **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

Compare Approaches between ADS & ADANES

	Traditional ADS	ADANES
UNF Partition	Complex, 2nd contamination PUROX(water)/pyro-process	Simple, Extend AIROX + RE extracted (<1/3, no water)
Fuel	Precise, MA + LEU	Raw, recycle Fuel (containing ~50%FPs) + LEU in 1st cycle
Burner Function : Transmute rate$_{max}$ Breeding Produce electricity	 10~12/MW$_b$ <<1.0 ? Low quality @ efficiency	 5 ~ 6 /10MW$_b$ >1.1 Higher quality @ efficiency
Operation Mode	Subcritical core driven by accelerator in all cycle	Accelerator as starter (~10%), + Long refueling Fast Reactor
Proliferation & physical protection	Enrich Actinide, high risk	No enrichment, lower risk
Close Fuel Cycle	Yes, Minimum radiotoxicity	Yes, Minimum radiotoxicity, Maximum resource utilization
Cost Performance	Low	Higher

ADS/ADANES Roadmap in China



Accelerator Driven Recycling Used Fuel

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

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

1, Verify Recycle Fuel

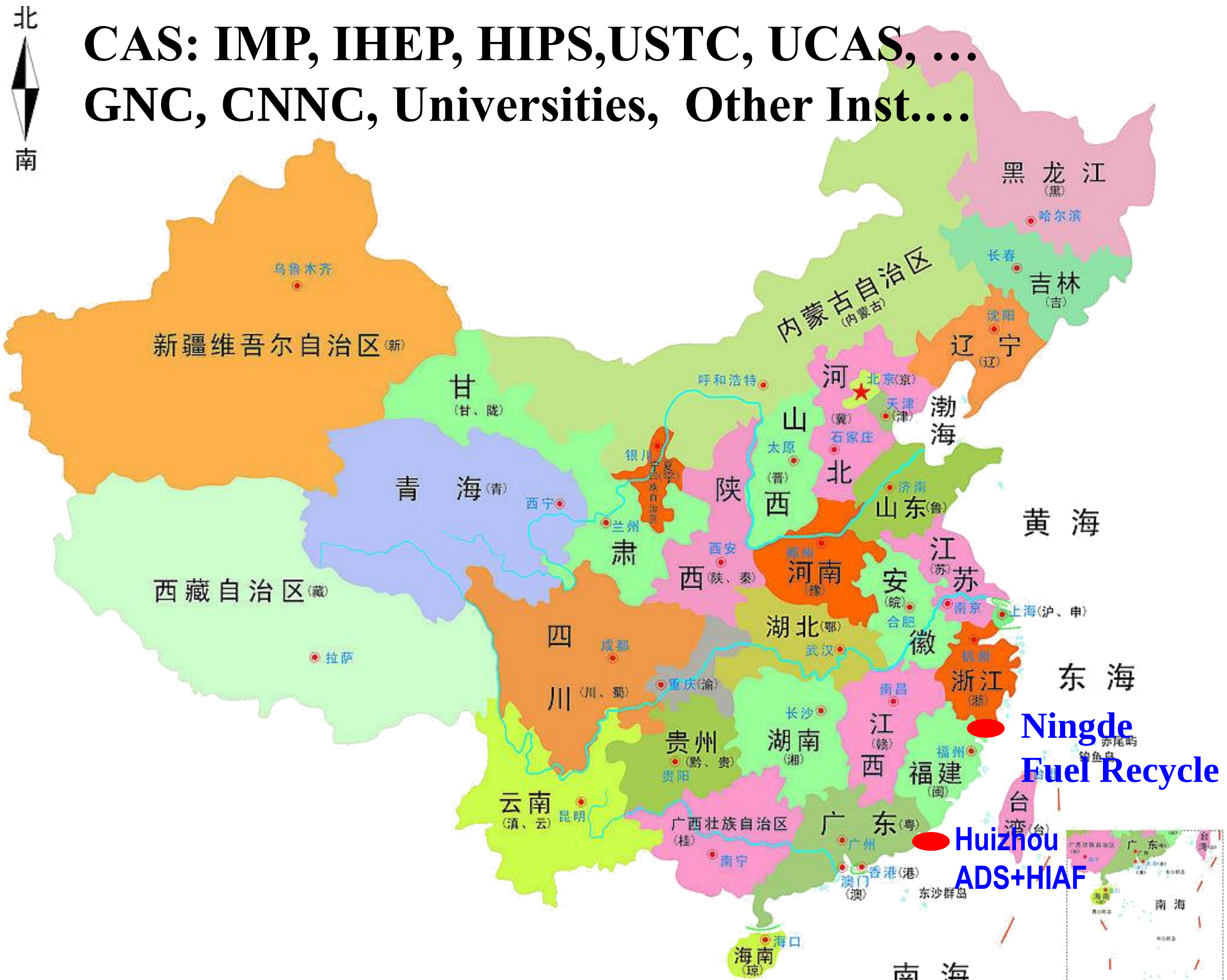
- **UC Fuel Properties**
- **$^{238}U \rightarrow ^{239}Pu$ Breeding rate**
- **Optimization of Fuel Assembling**

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.…



OUTLINE

I. Introduction

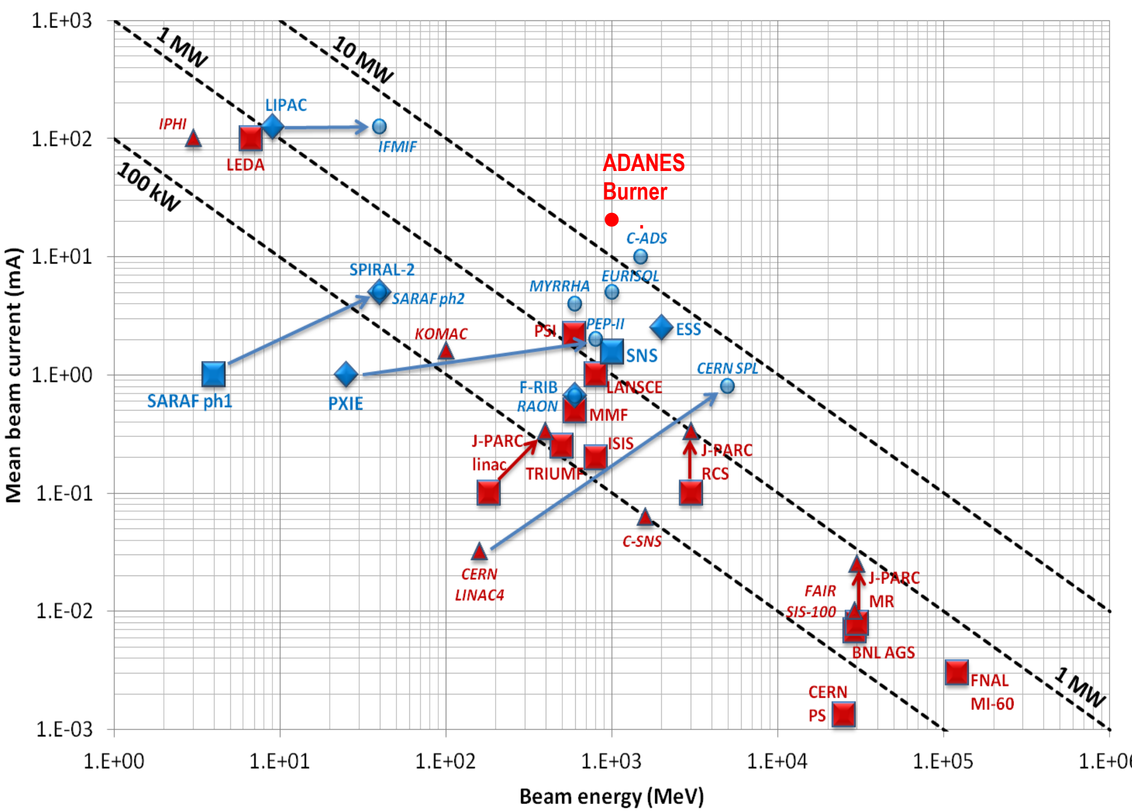
- Evolution of ADS to ADANES
- Roadmap
- New Site, New Research Center

II. Progress of ADS/ADANES

- Configuration of C-ADS
- Accelerator System
- Spallation Target
- Key Issues of AD for ADANES Burner
- …

Requirement of Accelerator for ADS/ADANES

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

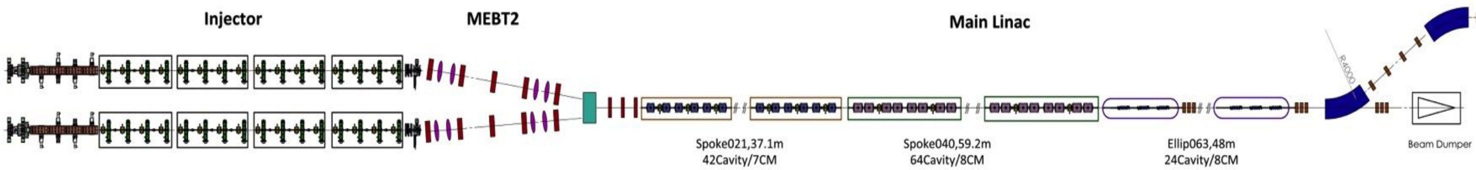


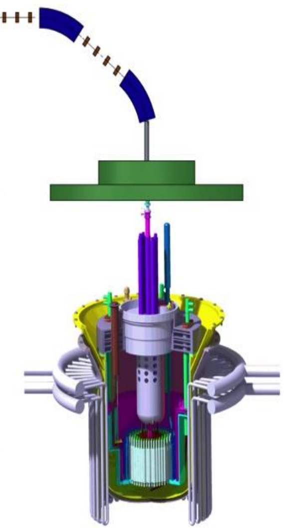
- **Mean Beam Power (IPG) : 10~20MW**
  - Energy : ~1GeV
  - Mean current : 10~20mA

- **Beam Strips & Availability（IPG）**

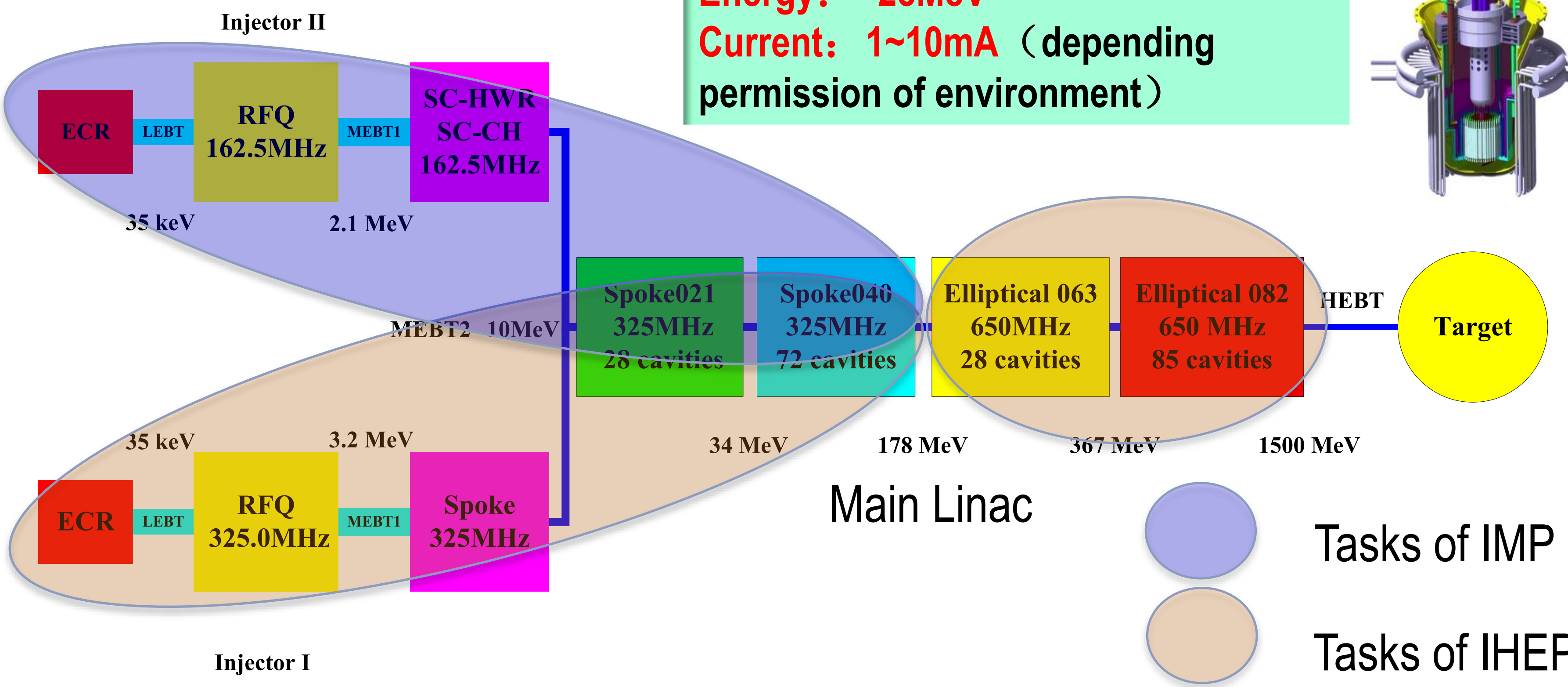
t < 1 sec.	1 < t < 10 sec.	10s < t <5 min.	t > 5min.	Availability
< 25000/yr.	< 2500 / yr.	< 250 / yr.	< 3 / yr.	> 85%

Configuration of C-ADS





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

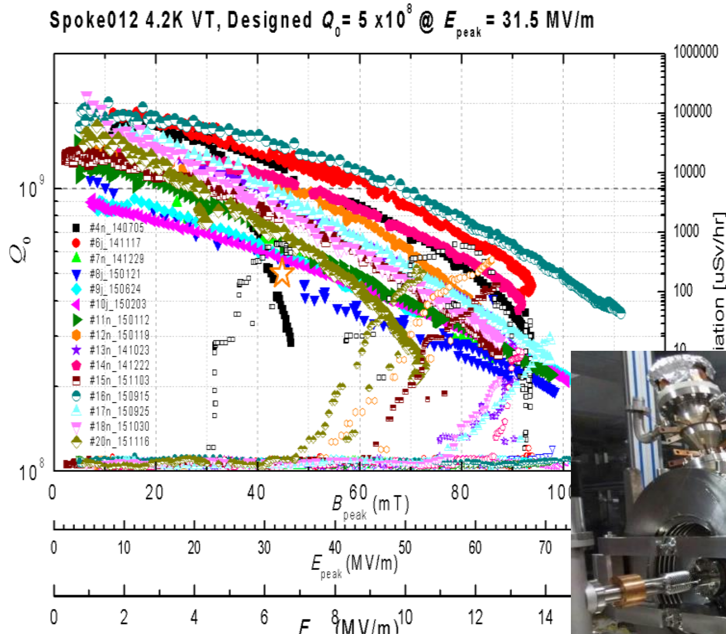


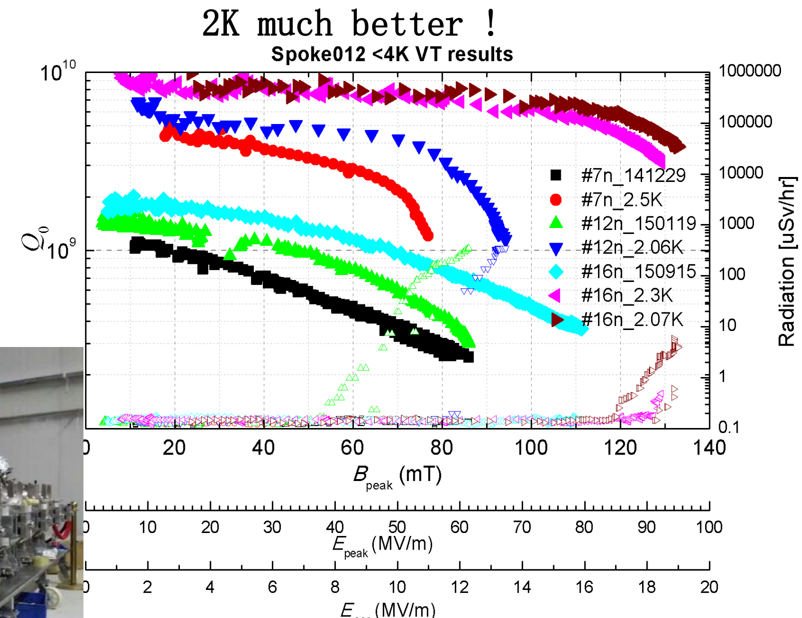
Injector I：325 MHz RFQ+2CM（2*7*Spoke）

Commission:
ECR+RFQ：11mA@3.2MeV，
Pulse >99%, 2014

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

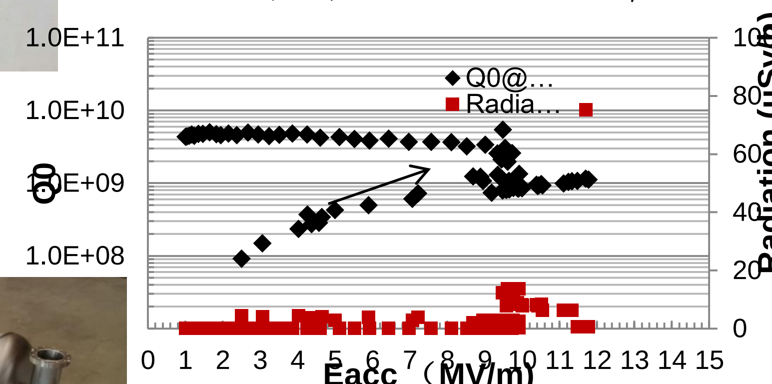
Low β 350MHz Spoke & 650MHz Ellipse SC



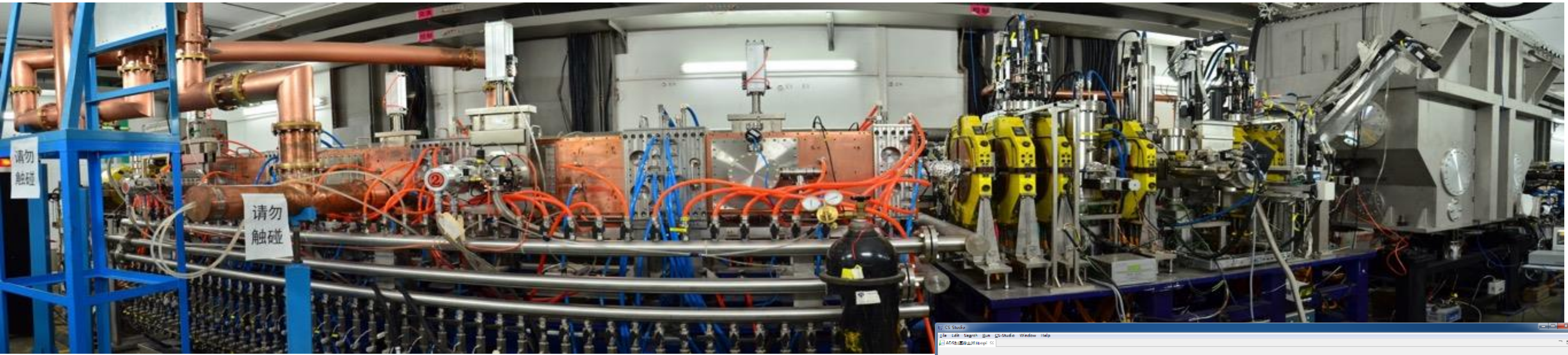


CM 1	G_{max} [MV/m]	Q_0@7MV/m	CM 2	G_{max} [MV/m]	
1#	13.4	6.4e8	1#	17.4	1.4e9
2#	**15.4**	5.5e8	2#	15.2	9.4e8
3#	16.6	5.9e8	3#	13.7	8.2e8
4#	15.3	6.5e8	4#	15.7	5.7e8
5#	13.4	1.0e9	5#	14.6	1.2e9
6#	14.1	9.0e8	6#	11.3	7.0e8
7#	14.3	1.1e9	7#	13.6	8.0e8

650MHz SC（082）Vertical test 9MV/m



Injector II: 162.5MHz RFQ+CM2 (2*6*HWR)

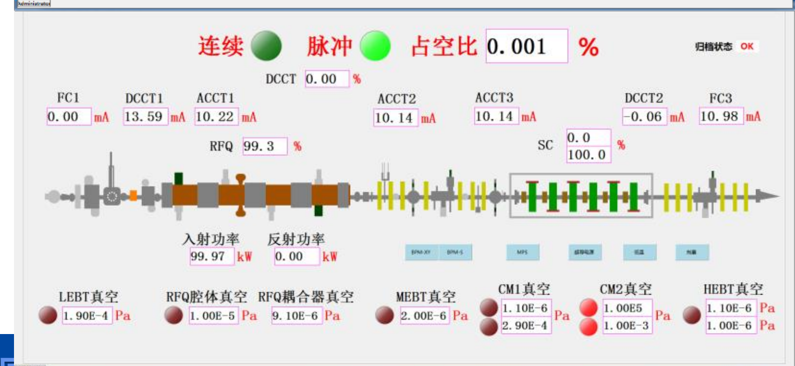


ECRIS+RFQ (>3000 hrs)：>10mA@2.15MeV, CW，Eff.= 95~97%，δE/E ~1.9%, June, 2014

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→

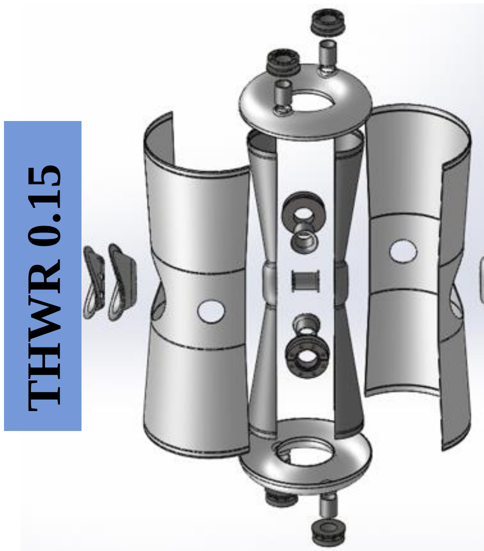
Epeak$_{mean}$: 23.8 MV/m，Epeak$_{max}$：36.2 MV/m

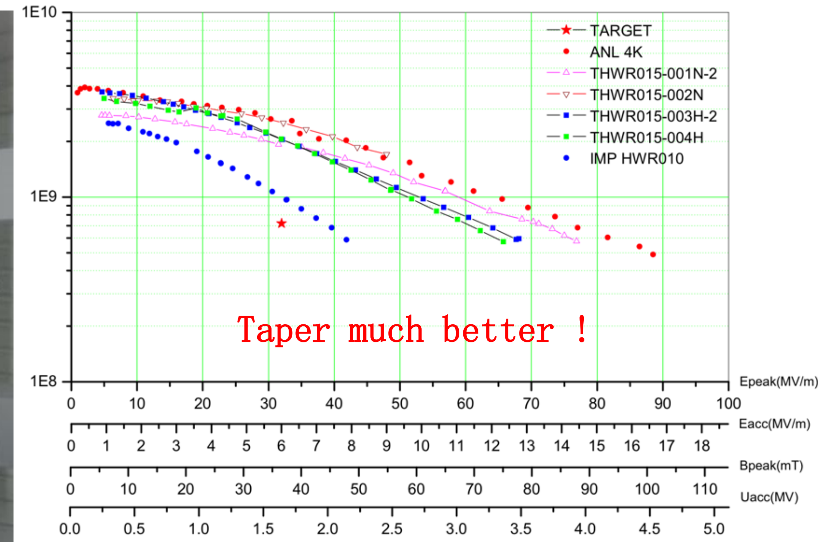


Low β 165MHz HWR & Taper HWR (4.2K)

HWR 0.10

THWR 0.15



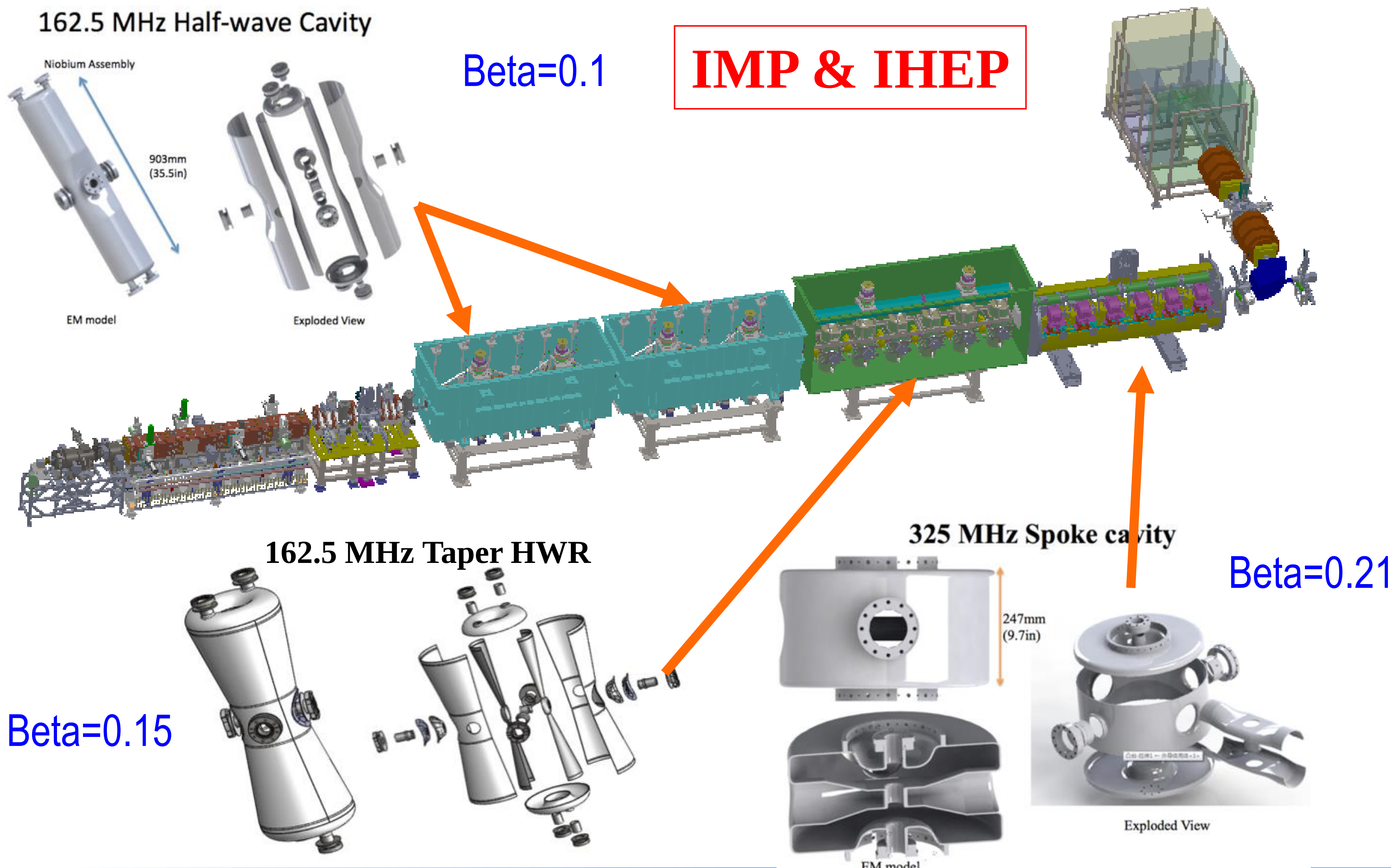


Optimizing:

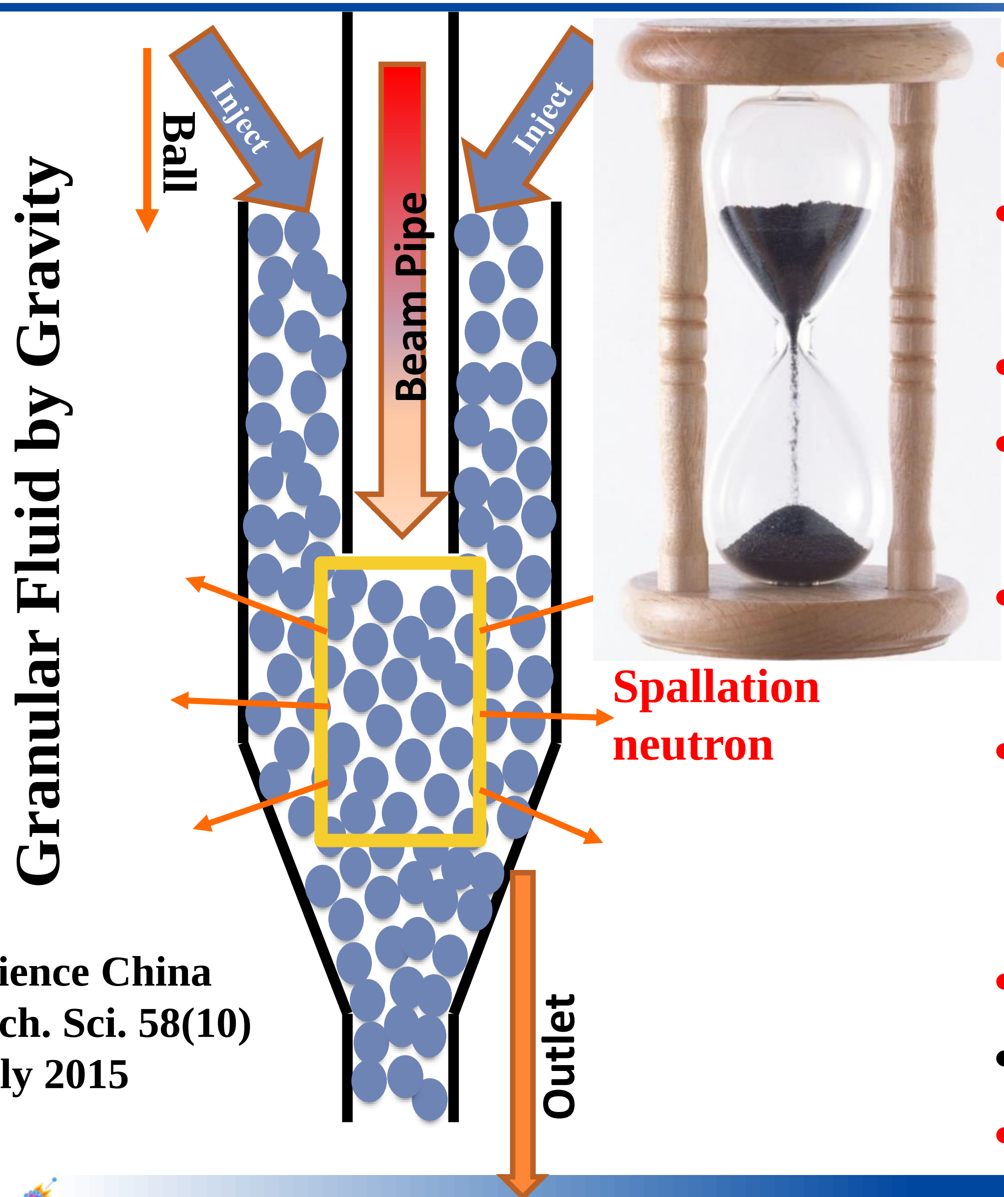
Startup
CM assemble
DC control
…

	THWR015	SHWR010
Vacc(MV)	1.8	0.78
Bpeak(mT)	40	50
Epeak(MV/m)	32	25
R/Q(Ω)	286	148
G (Ω)	52	28.5
Eacc(MV/m)	6.6	4.7
P(W)(Rs=70nΩ)	16	10
βopt	0.15	0.10
Q0	7.2E08	4.0E08

25 MeV LINAC Commissioning



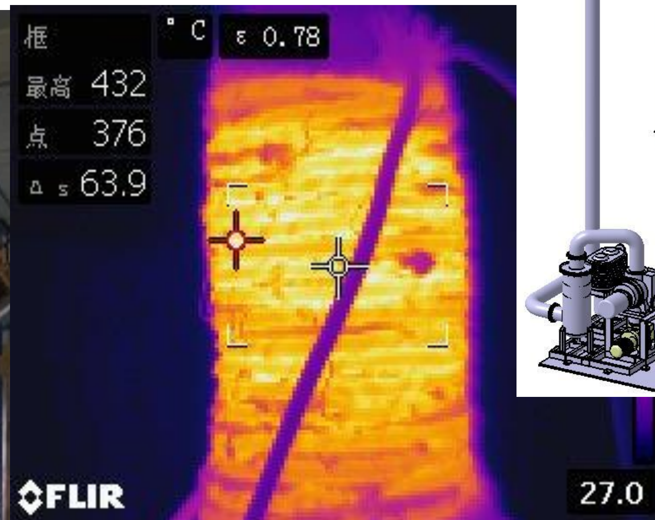
Principle of Granular Fluid Spallation Target

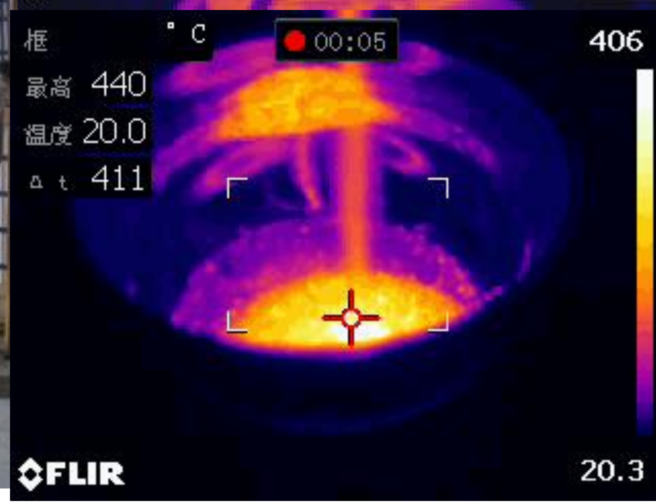


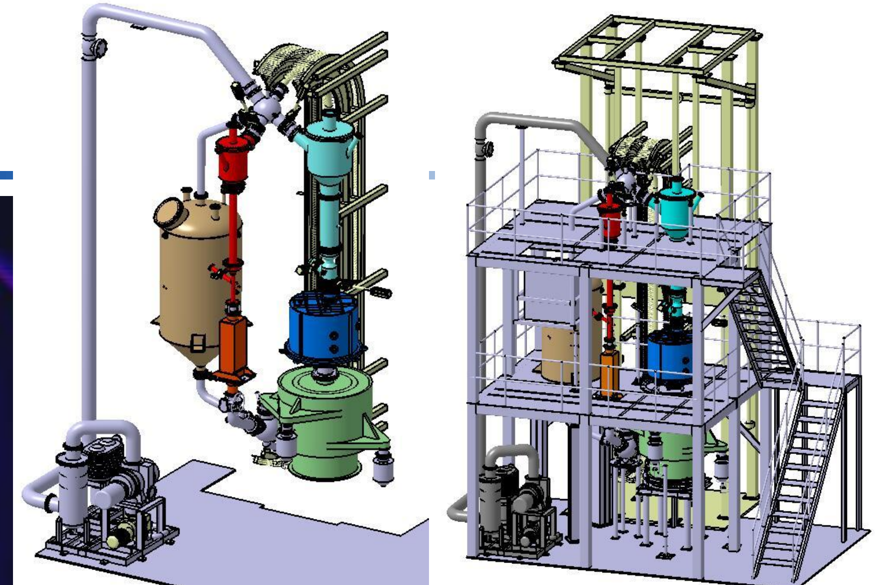
Science China
Tech. Sci. 58(10)
July 2015

- 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





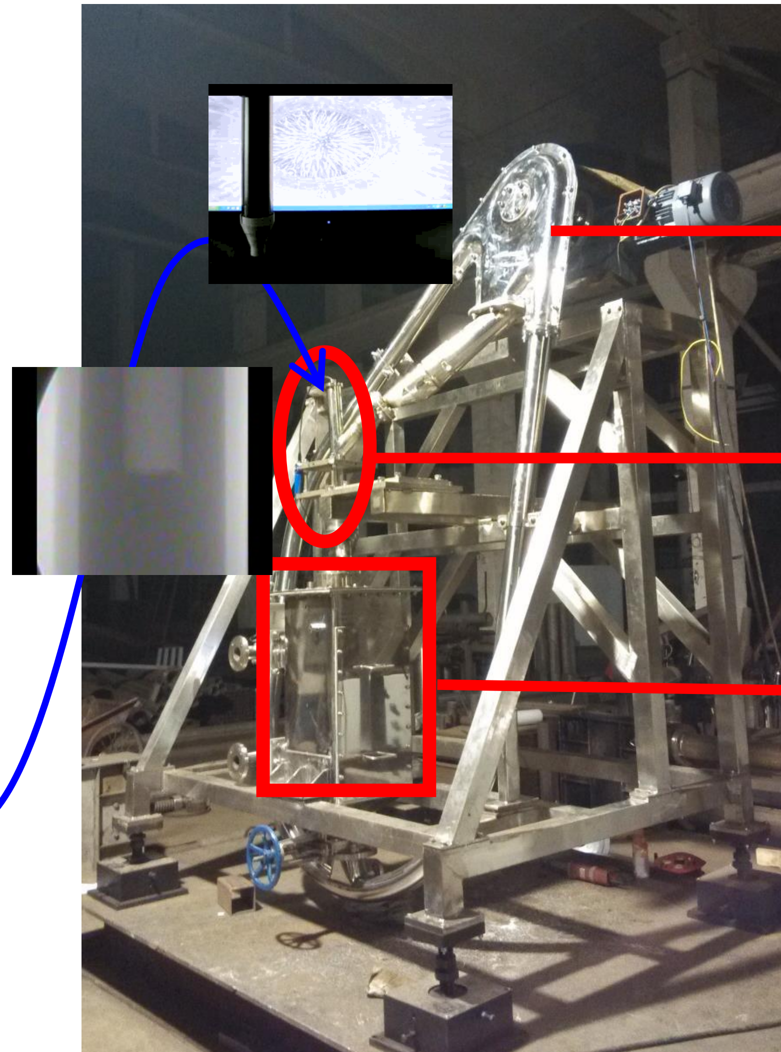


Large scale loop & HT test

Granular target test bench

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

Key Issue of AD for ADANES Burner

- System Optimizing (new approches, 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 →~$10MW_b/GW_{th}$→ reducing scale of SCL (cost effective)
- Stability (key tech., system optimizing)
  - ECRIS: Lower RF Power, Flow H_2 (favor for D_2), >90% H^+ and stable
  - RFQ: 162.5MHz→ Lower power density
  - SC-Cavity → Nb (or Nb_3Sn) coating on cupper 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) →~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 → 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, SiC_f/SiC, Ceramic…)**
  - **SIMP Steel (similar HT9) R&D and Improving in 5 Tone Scale**
  - **SiC_f/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 !