Status and future Plan of Chinese ADS Project

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Outlines

- **Introduction**
  - **Motivation**
  - ADANES
  - Roadmap
- Progress
  - Accelerator
  - Target
  - Reactor
  - Fuel Recycle
  - Material
- Summary

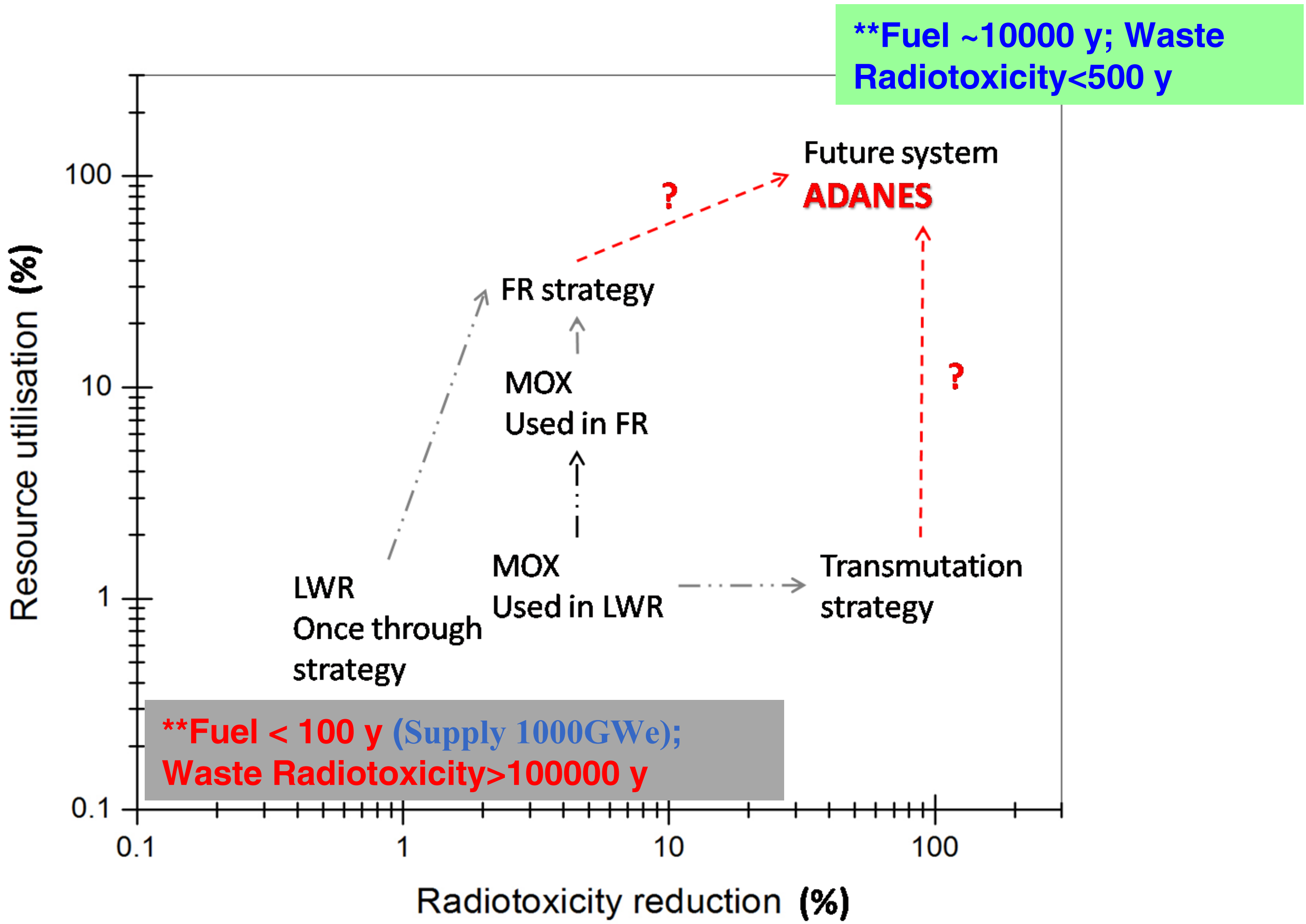
Nuclear Power Development in China

- **Nuclear energy is an inevitable strategic option to meet China energy demand in the future**
  - China is the largest energy consumer in the world and coal is the major resource for electricity production (79% in 2011)
  - China claim that the CO_2 emissions will reach a peak around 2030 while Paris Climate Agreement.
  - Nuclear power is a relatively clean energy without green-house gas emission
- **Current status of China nuclear power**
  - 22 nuclear power reactors in operation, 18.056GWe (6th in the world)
  - Produced electricity: 104.8TW.h, 2.1% share in 2013, (5th in the world)
  - 27 reactors under construction, 26.756GWe, (1st in the world)
- **The planned NP development in China (2011-2020)**
  - By 2015, the installed capacity reaches 40GWe and 18GWe under construction
  - By 2020, the installed nuclear capacity will be increased to 58GWe (~7%), and 30GWe are under construction

By 2050, 350~400GWe (~20%), comparable with the total NP capacity in the world (375GWe in 2014).

Sustainable Development of Nuclear Fission Energy

- High Resource Utilization → Breeding;

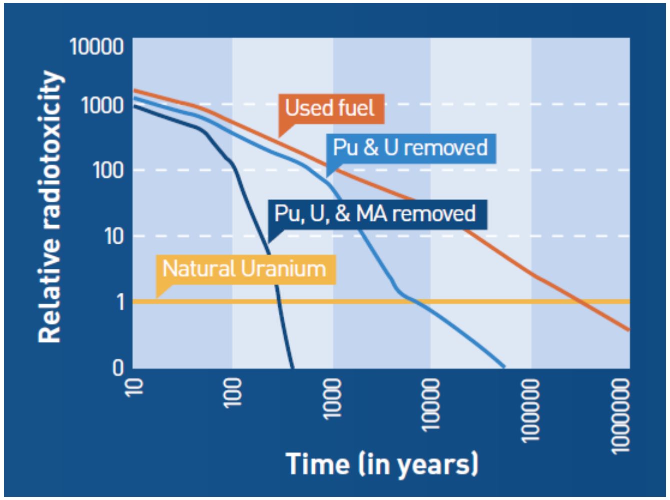


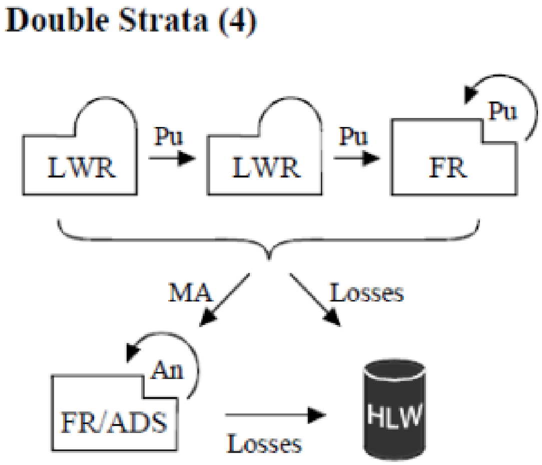
Fast Neutron

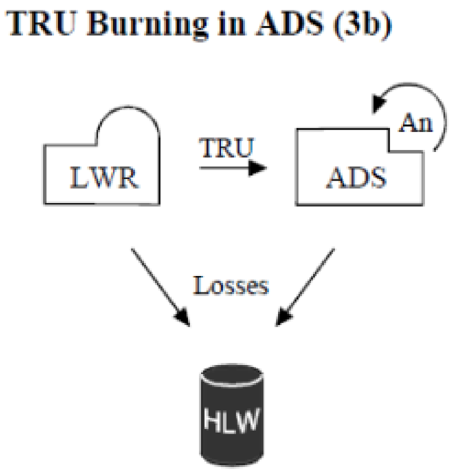
- Radiotoxicity Reduction → Transmutation

Status of Close Fuel Cycle P&T

- **Main difficulties of P&T:**
  - Extract high purity U， Pu & MA ≠ Residuals
    remain MA<0.3% (long lifetime in waste)
  - more Toxicity @ Complexes few generations later
  - High purity Pu, MA fuels is ：
    Unstable in burning & High risk of proliferation !!
  - Low feasibility (final solution?), low cost effective







Approach of ADANES

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

ADS Burner

- **New Approach: (optimizing SNF resources & radiotoxicity)**
  - **Remove part of FPs (>50%RE's) from SNF, Convert Residuals as recycle fuel (short lifetime in waste)**
  - **Transmuting, Breeding & Energy Amplify in Burning recycle fuel (higher cost effective)**

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ADANES (PWR SNF: 33GWd/Ton)

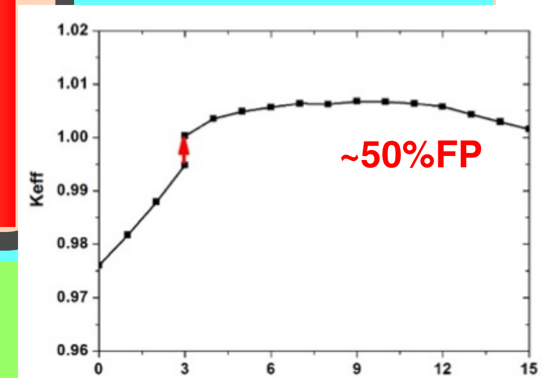
MA
TRU
NU
DU
Th
LEU…

>96%UNF

Energy

ADS Burner:
Transmutation(3~12) +**
Breeding > 1.1 +
Energy Amplifier ~ LWR
in Situ

**Burning :
SNF > 3
MA → 12



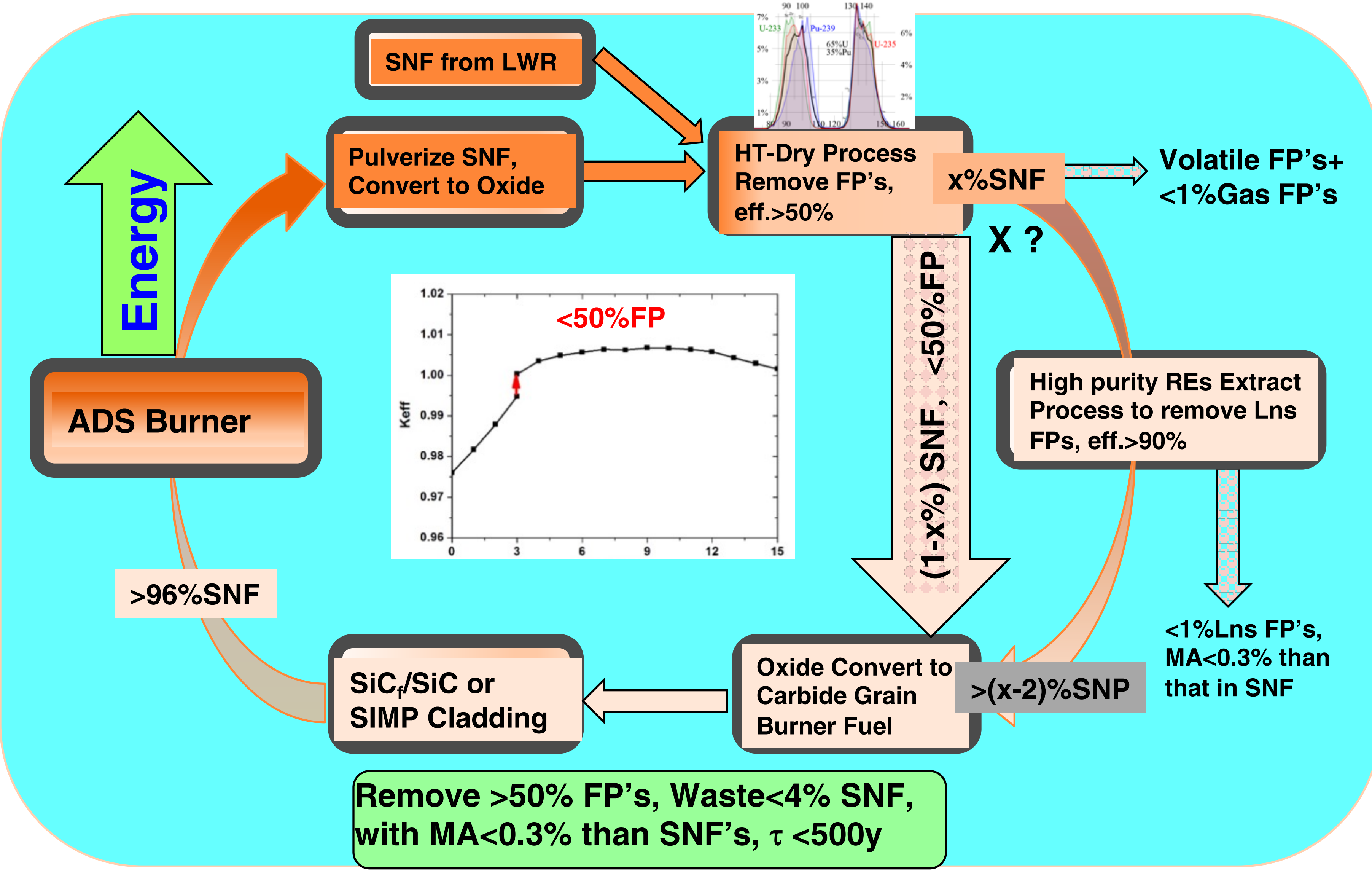
Convert SNF into Burner Fuel,
Waste <4% SNF @ MA<0.3%, τ<500Y,
Sustain NE for 1000's Y

SNF

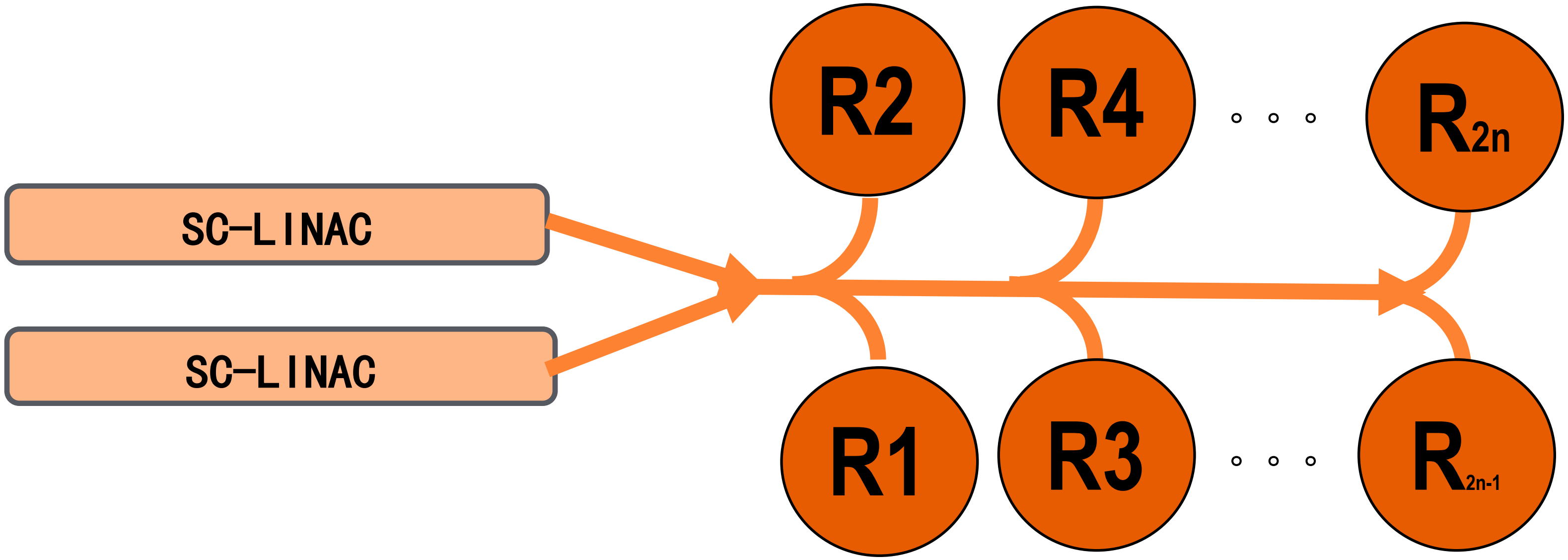
ADANES Fuel Recycles:
Remove >50% FP from SNF by HT Dry (Ext. AIROX), further Remove >90% Ln's by REs extract, MA<0.3% of Origin

Waste:<4%SNF ;
FP's: Volatile FP's, <1%gas, <1% Ln's;
MA<0.3% than SNF

ADANES Close Fuel Recycle



ADANES —— Operation Mode



- **Safety, Abundant, "Raw Fuel", High cost effective**
- **Higher Resource Utilization, Minimization Radiotoxicity, (same power) :**
  >3 PWR SNF (33GWd/T) / ADANES
  ~60 yr／【PWR SNF（3set.yr）】
- **Accelerator Driven Subcritical Time:**
  7% ~ < 15%

Depend power density, temperature, cladding & core material performances, number of reactors and …

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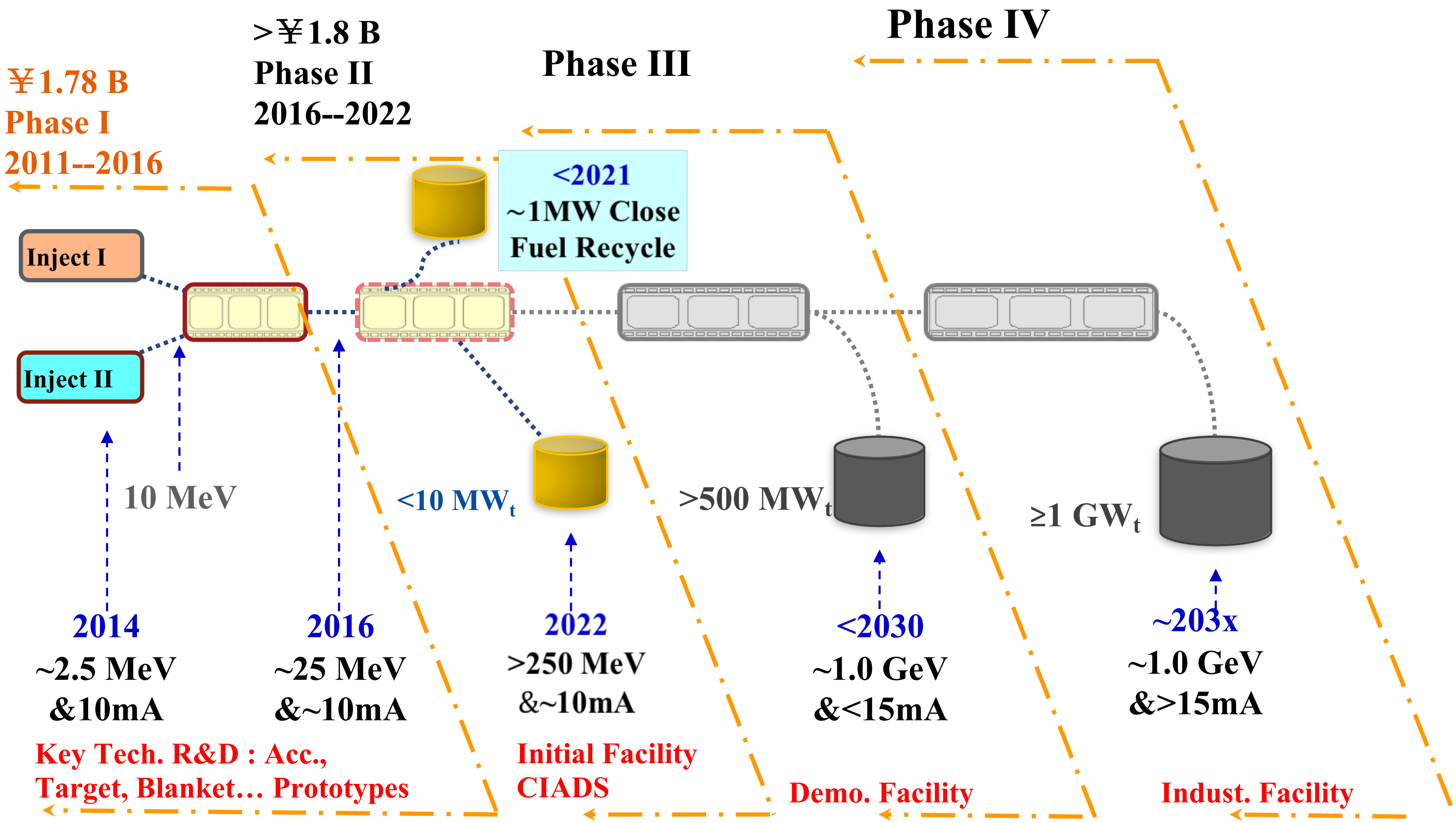
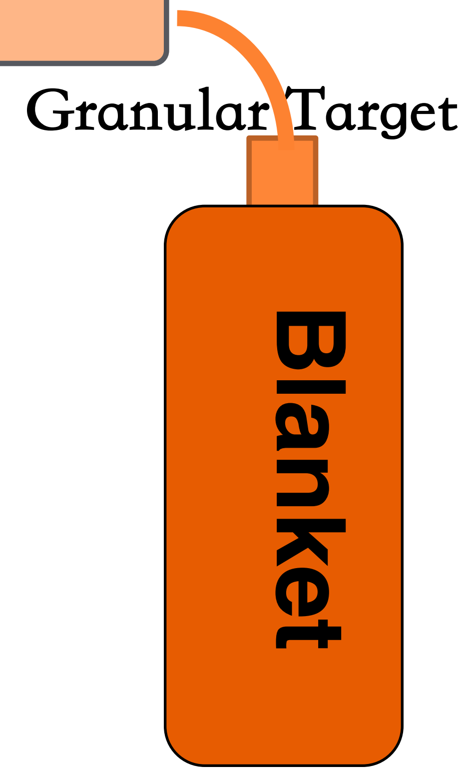
ADS/ADANES Roadmap in China



Accelerator Driven Used Fuel Recycling

SC_Linac (5~10mA@<150~250MeV D+Be)



- **Recycle Fuel**
- **Compact Neutron Source：**

■ **Verify Recycle Fuel**

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

■ **Irradiation of Materials**

- Cladding（SIMP、SiC_f/SiC…）
- Core (...same as above...)
- Window between Accelerator and Target
- …

New Research Center in Huizhou & Ningde

Researches Based on High Intensity Ion Beam:

I. Nuclear Physics
- Low energy Nuclear Structure & Nuclear Astrophysics
- Hadron Nuclear Physics

II. High Energy Density matter Physics(+electron)

III. Nuclear Energy
- ADS→ADANES Burner
- *Fusion?*

IV. Irradiative Material
- Compact, High Flux Neutron Source/electron

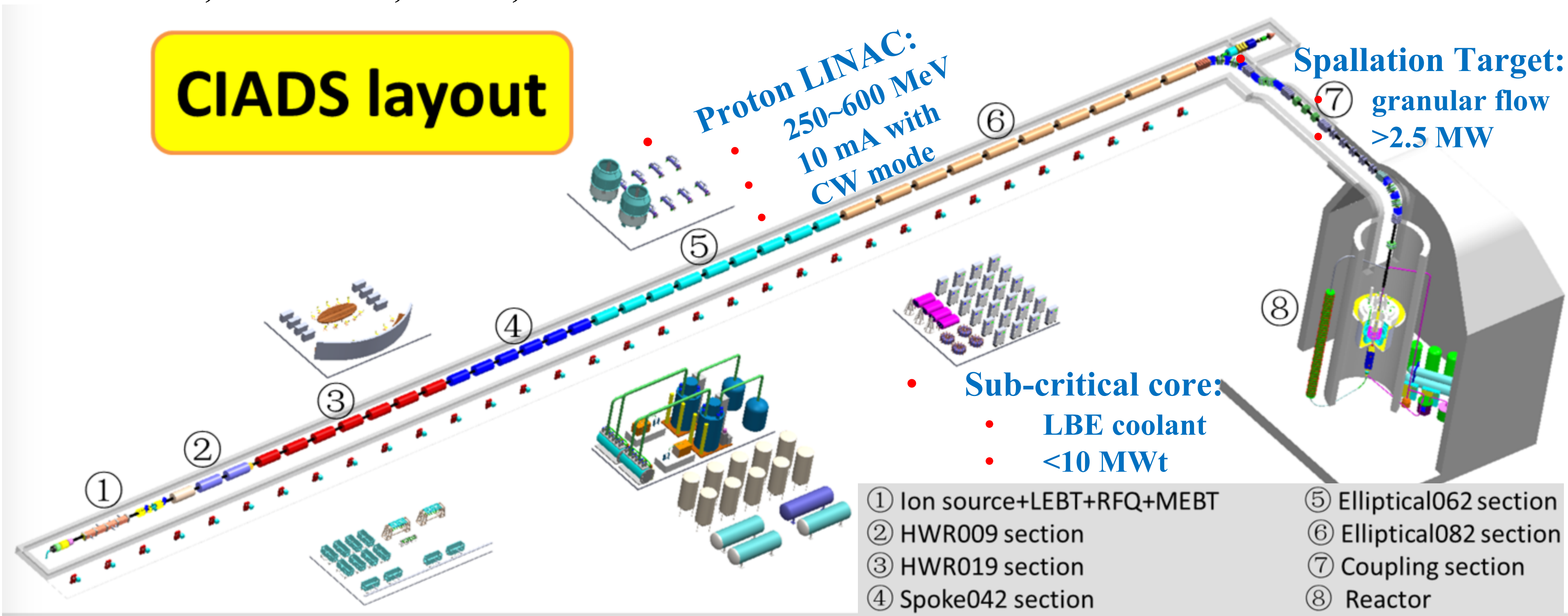
V. Integrate with Neutrino Experiment

VI. Convert SNF → Recycle Fuel

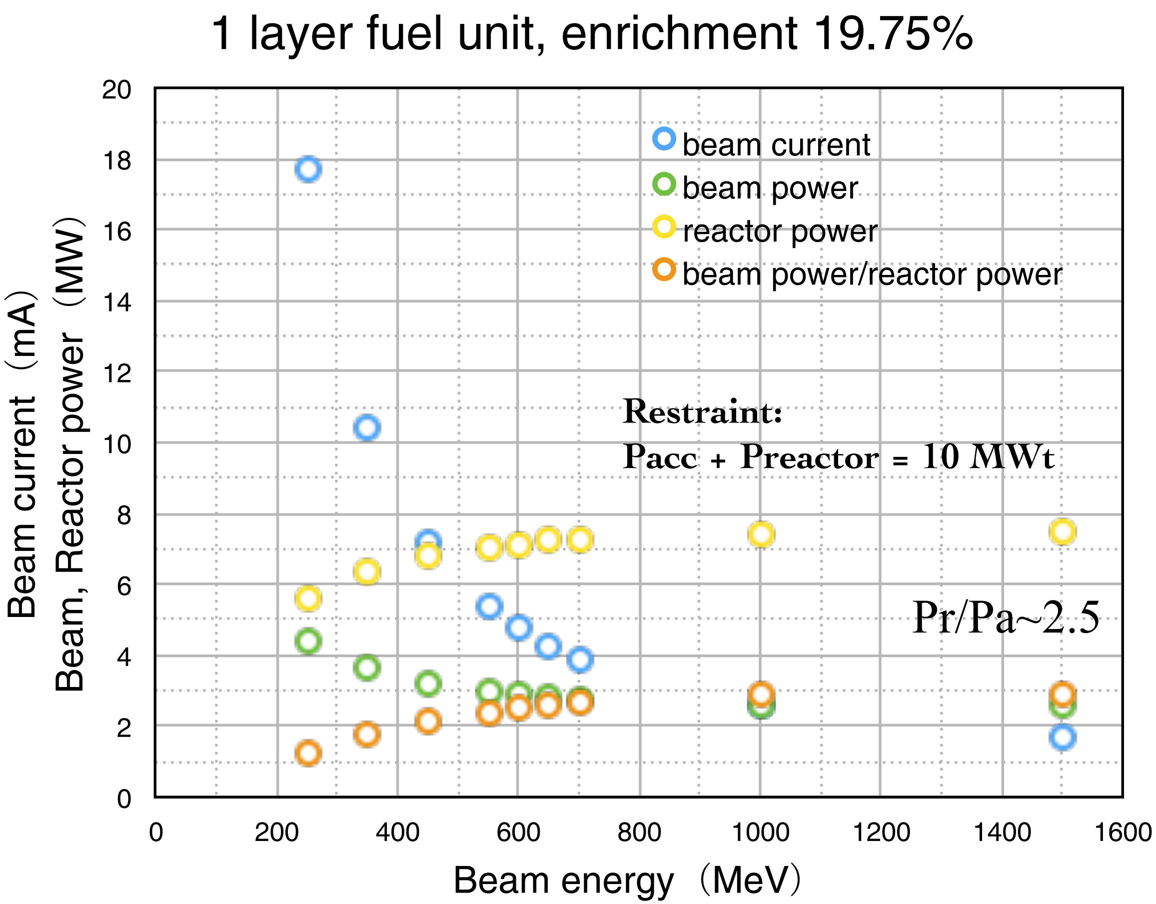
CIADS Project (2016-2022)

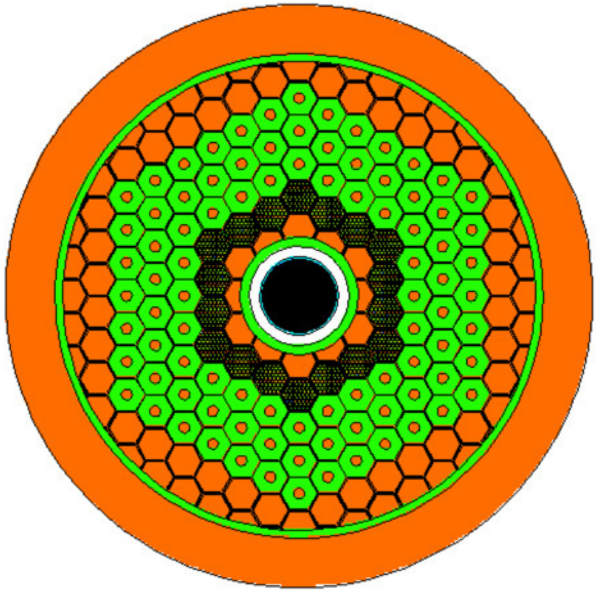
China Initiative Accelerator Driven System (CIADS)

- Approved in Dec. 2015, CD0
- Leading institute: IMP
- Budget: >1.8B CNY (Gov. and Corp.)
- Location: Huizhou, Guangdong Prov.
- Contribution Partners:
  IHEP, CASHIPS, CIAE, CGN



Top level specifications





sub-critical reactor core
(61 pins in each Assembly)

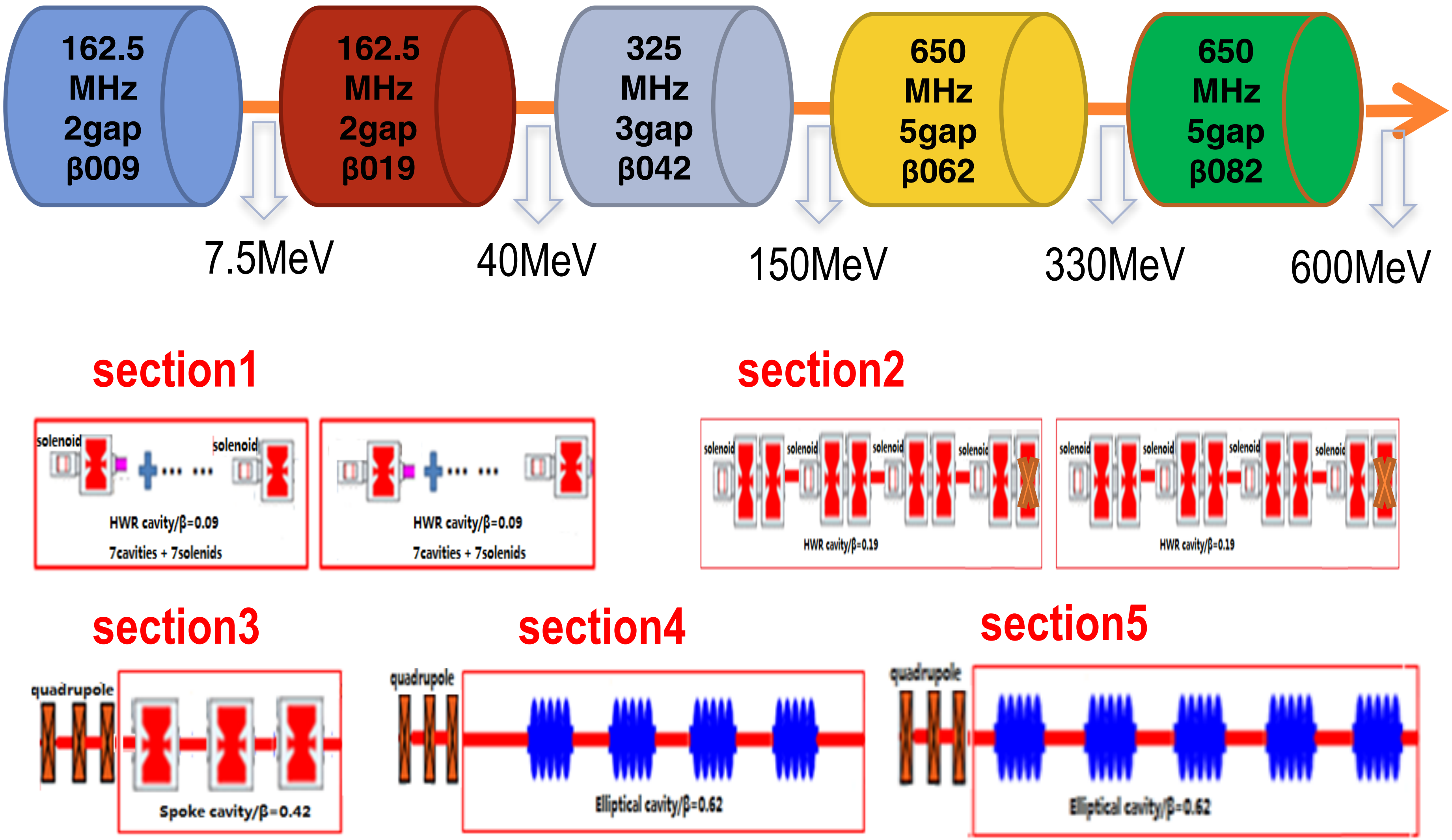
Top level specifications:

Sub Reactor: fuel enrichment 19.75%, one layer with 18 assemblys, power 7.14 MWt

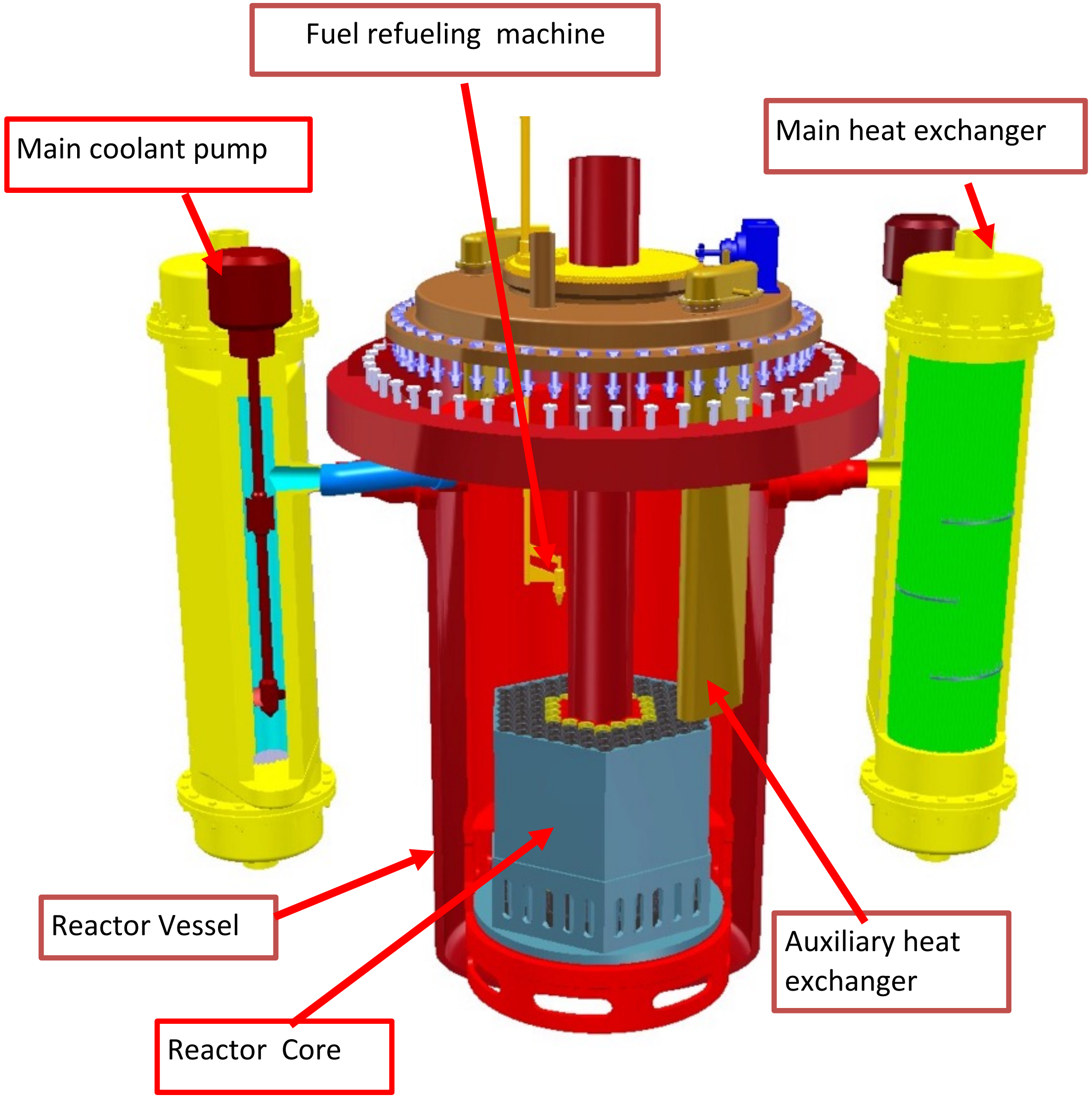
Driven Linac: beam energy 600 MeV, current 4.78 mA, power 2.86 MWt

Target: sustained power ~2.5 MWt

Configuration of Accelerator

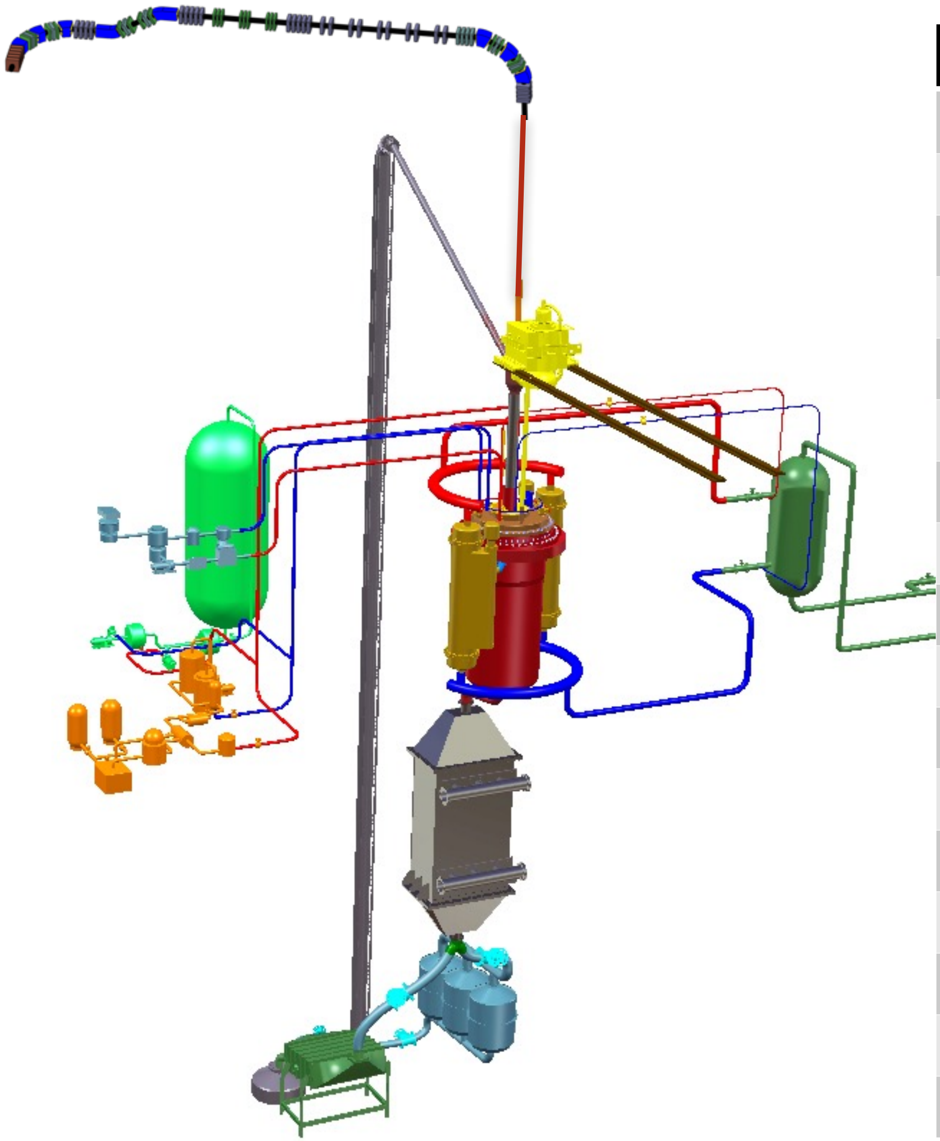


Configuration of Subcritical Reactor



Core	4.95%	19.75%
Type of fuel	UO2 (4.95%)	UO2 (19.75%)
Diameter of central tube	42.8cm	42.8cm
Thickness of central tube	3.6cm	3.6cm
Number of fuel assemblies	72	18
Number of dummy assemblies	90	36
Number of control rods	None	None
Height of activity region	60cm	60cm
Equivalent diameter of activity region	124.61cm	80.80cm
Material of cladding	15-15Ti	15-15Ti
Material of structure	316L	316L
Uranium loading	4.202t	1.05t

Configuration of Granular Target



	parameters
ion	proton
beam energy	250 ~ 600 MeV
beam current	<= 10 mA
beam spot on target	~18 cm
granular material	tungsten alloy
Granular size	~1 mm
average temp. at entrance	250℃
average temp. at exit	<500℃
average speed of fluid	<0.5 m/s
structure material of tube	alloy
loop material	316L/TZM/SIMP
energy of leak neutron	~2.5 MeV
neutron yield	> 2 n/p
pressure of He	<0.05 MPa
heat exchange	~2.5 MW
mass flux	<200 kg/s
leakage of He	$<10^{-5}$ Pa·m³/s

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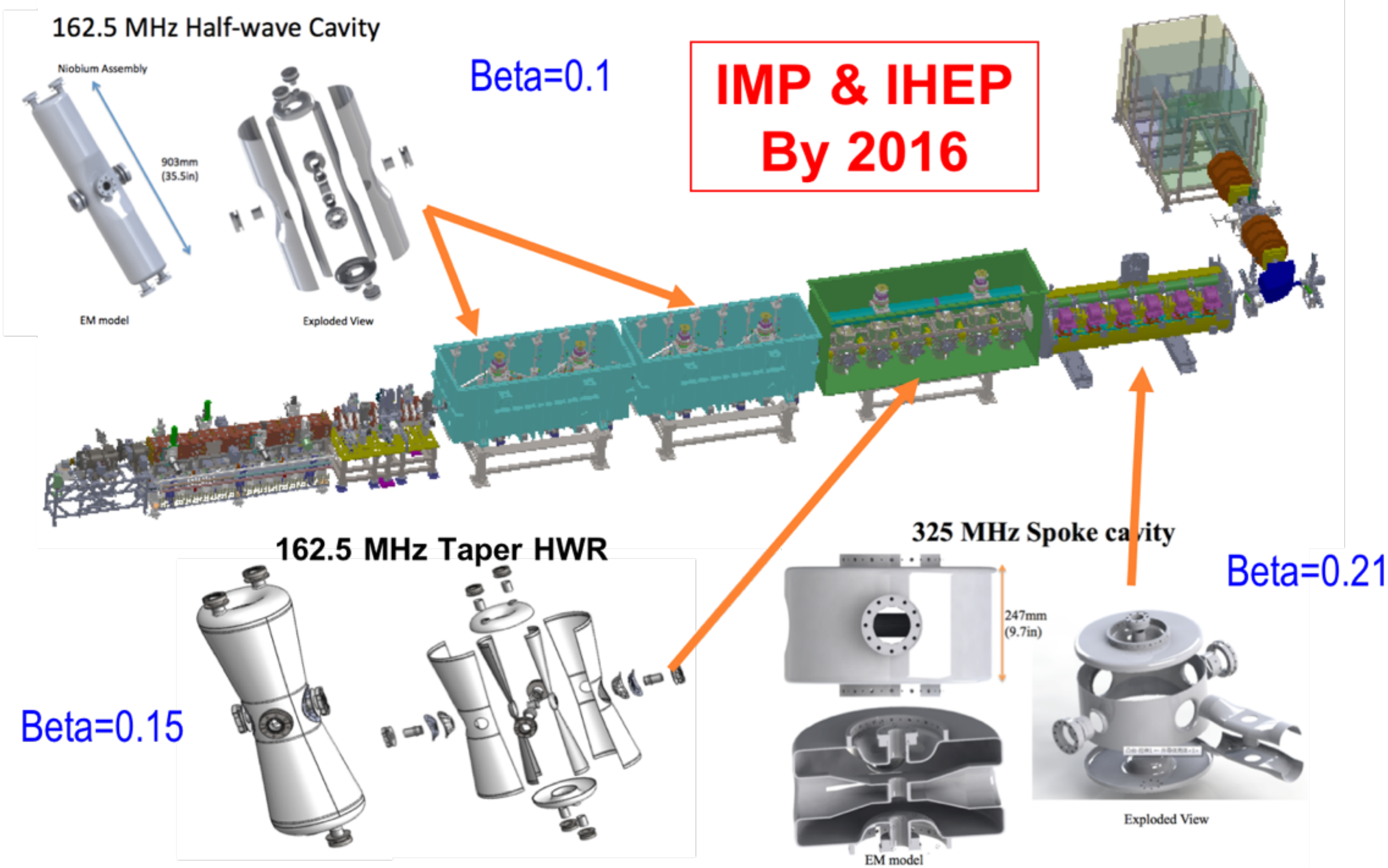
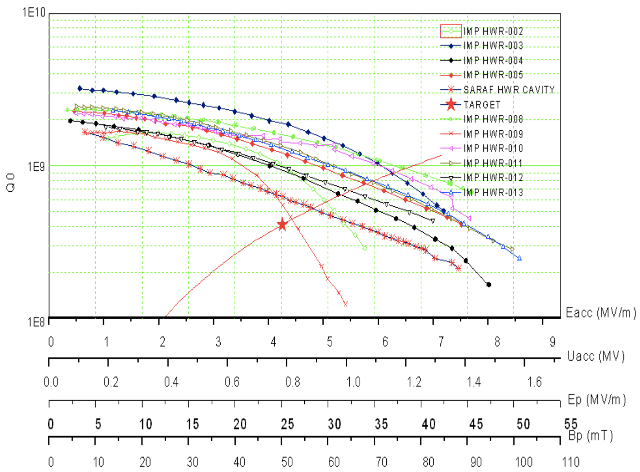
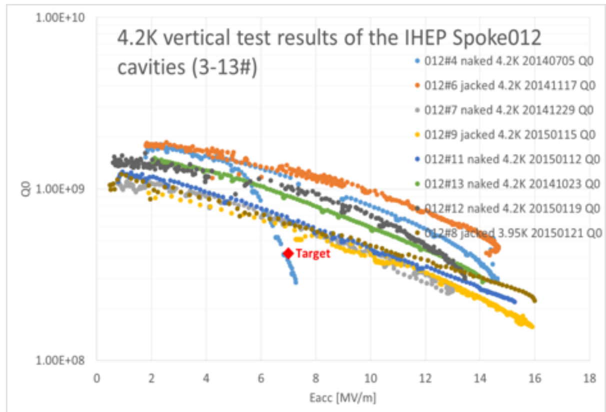
Demo facility of SC-Linac at Lanzhou

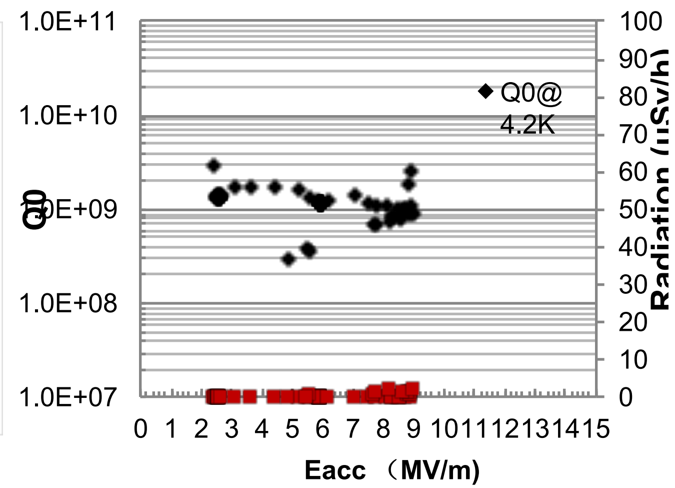


Beam: 25 MeV, 10 mA, CW, 250 kW
Target: tungsten granular, windowless, vacuum differential
Lifter: mechanical

Prototypes of Superconducting Resonator

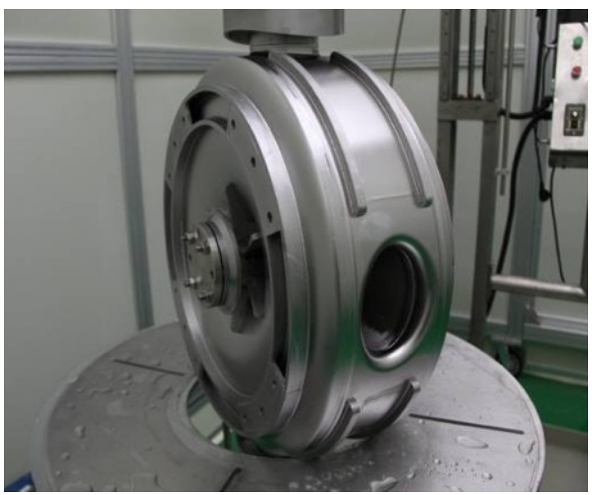




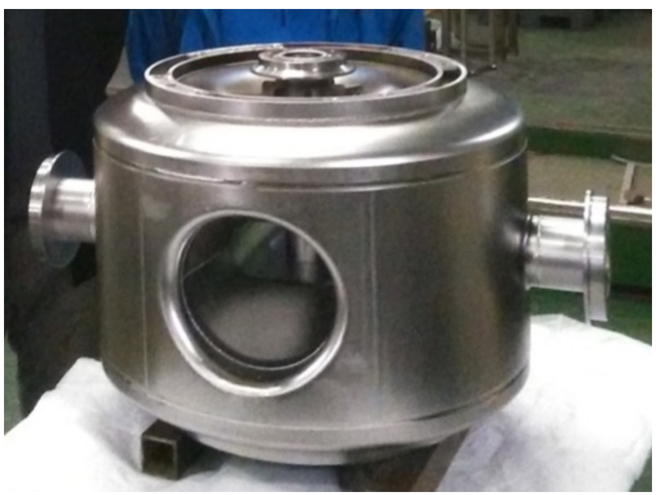


HWR010

spoke012

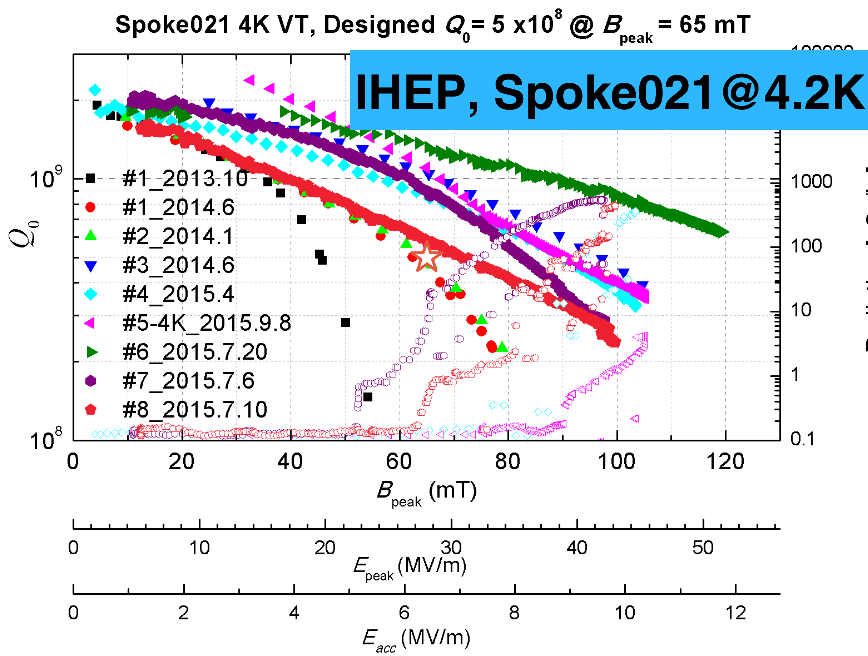


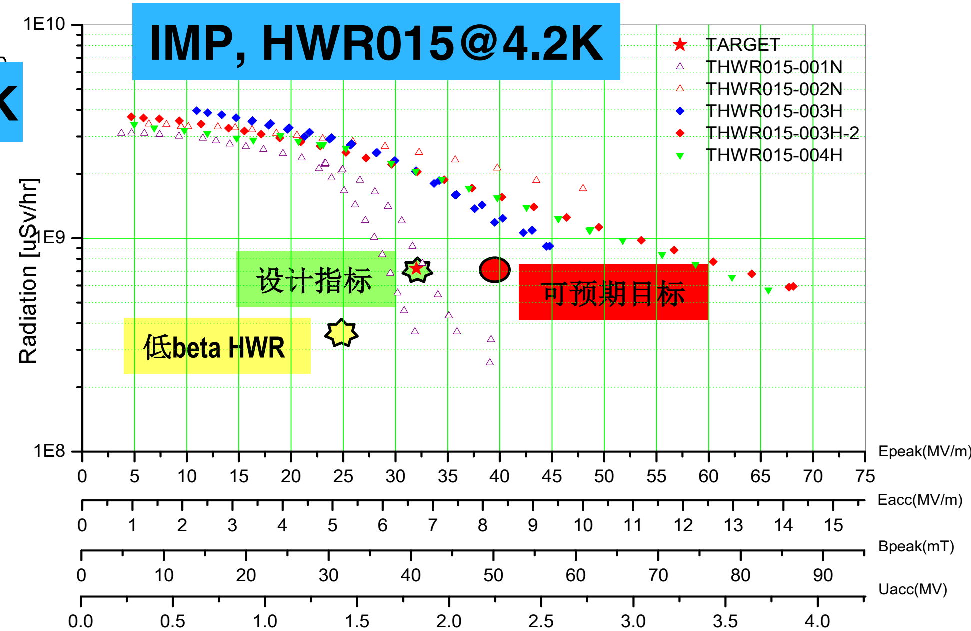
spoke040



Ellip063

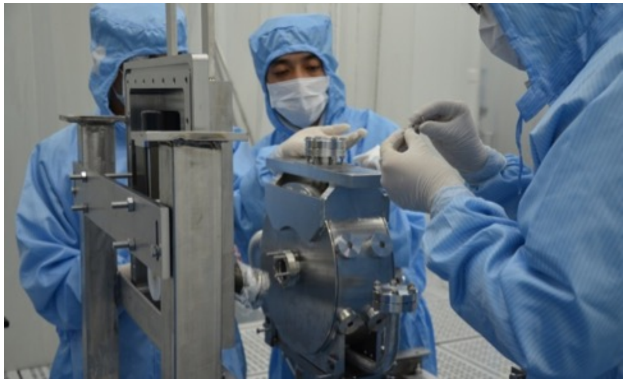
Prototypes of Superconducting Resonator

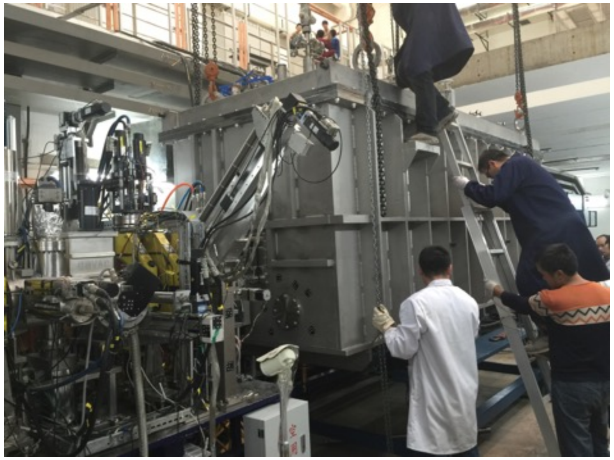




- ✓8 Spokes were tested
- ✓Hp=98 mT @ Q0=5e8
- ✓4 T-HWR were tested
- ✓Hp=85 mT @ Q0=5e8

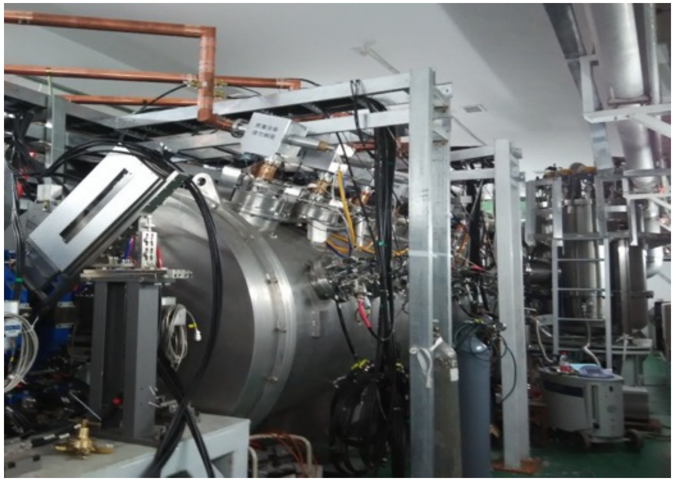
Assembly of HWR module





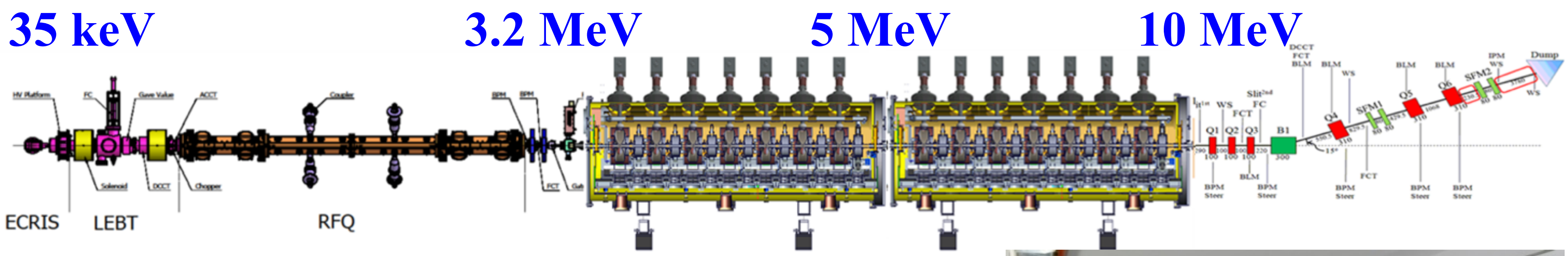
Assembly of a 5 MeV HWR Cryomodule in IMP Lanzhou (China)

Assembly of Spoke Module

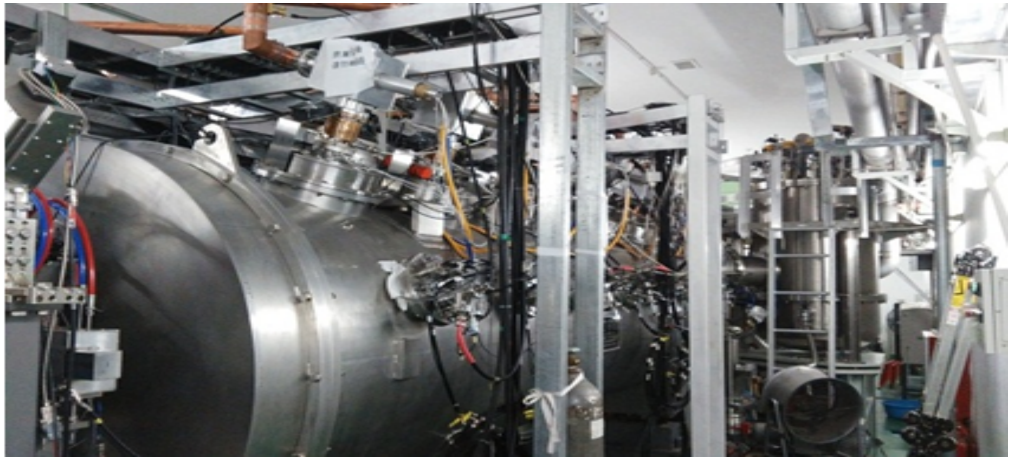


Assembly of a 5 MeV Spoke Cryomodule in IHEP Beijing (China)

Commissioning of Spoke linac at IHEP

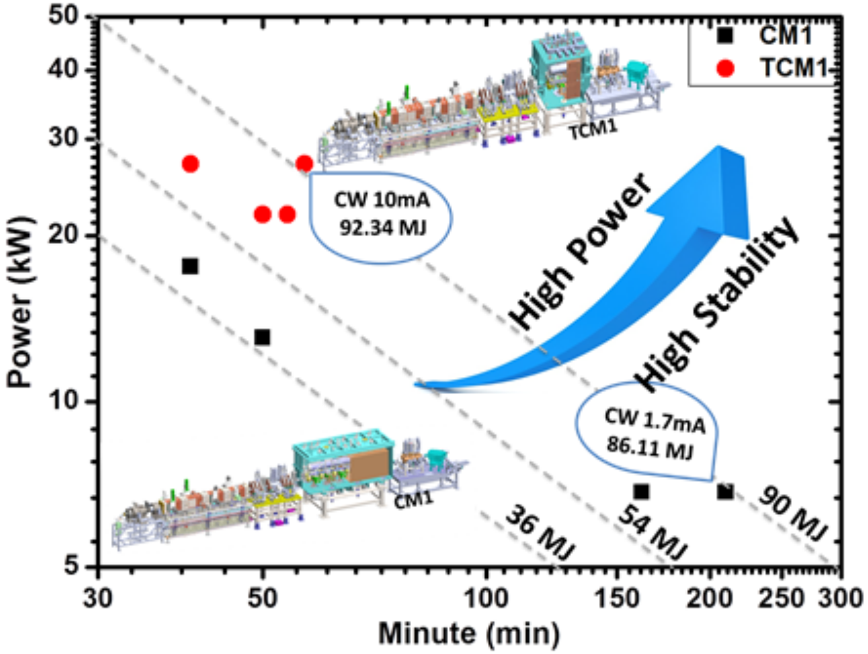


- Pules: 11 mA, 50 Hz, duty factor>90%
- Efficiency > 97% （duty factor 70%）
- Energy 3.2 MeV, average power > 31 kW



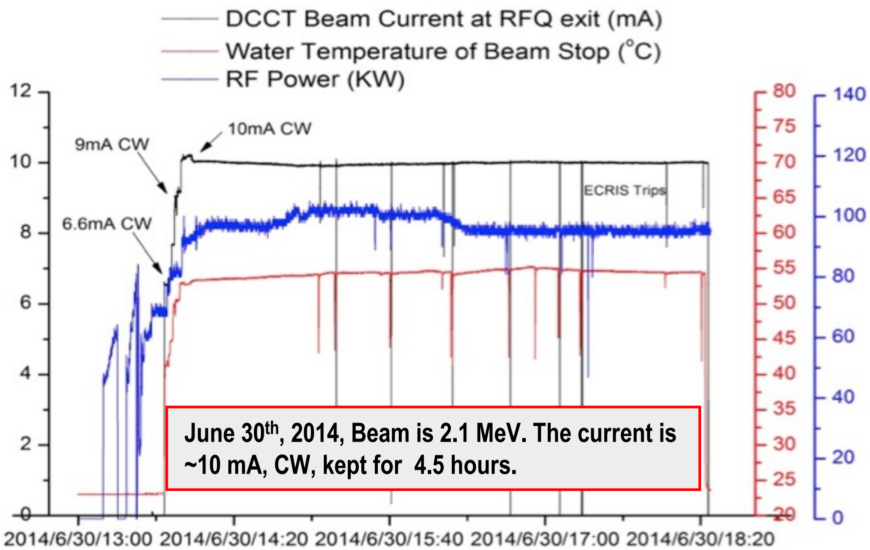
- Beam duty factor: 2‰ (2Hz/1ms)
- CM 1 output energy with 7 cavities : Eout=6MeV
- CM1 transmission ：100%
- RFQ+CM1 transmission ：88.4%
- Output current: 10.6mA

Summary of High Power Beam at IMP

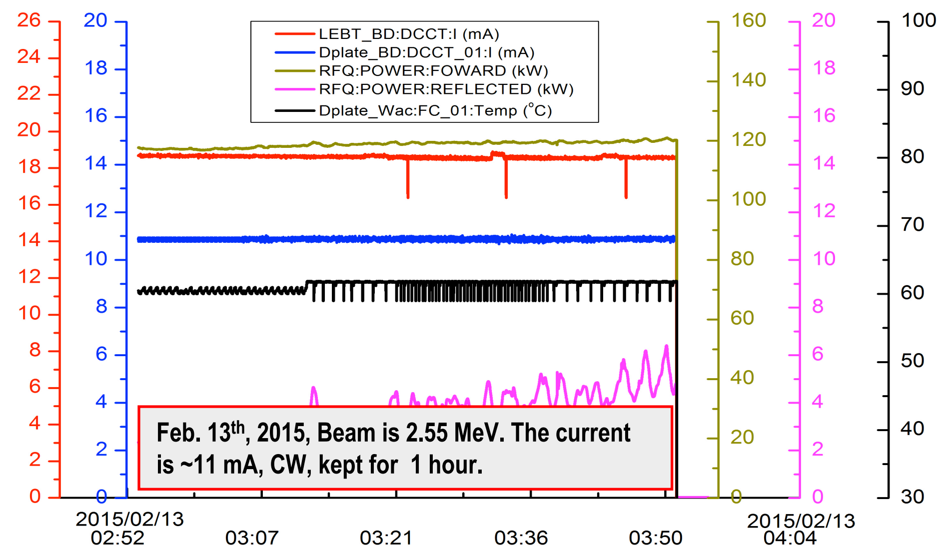


Accelerator	*Time of first beam*	*Beam energy*	*Beam time*	*CW*	*CW @ 10 mA*
RFQ	*Jun. 6th, 2014*	*2.1 MeV*	*1390 h*	*59 h*	*10 h*
TCM1 (1 HWR)	*Oct. 1st, 2014*	*2.5 MeV*	*208 h*	*22.5 h*	*2.5 h*
CM1 (6 HWRs)	*Jun. 6th, 2015*	*5 MeV*	*400 h*	*20 h*	*Imax = 4mA*
CM1+CM2 (12 HWRs)	*Sept. 2016*	*10MeV*	*Conditioning*		

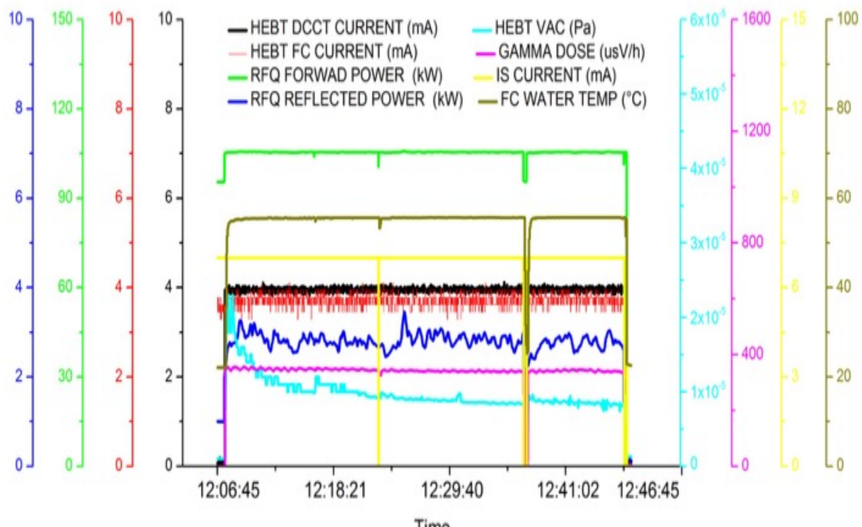
CW Beam Commissioning at IMP



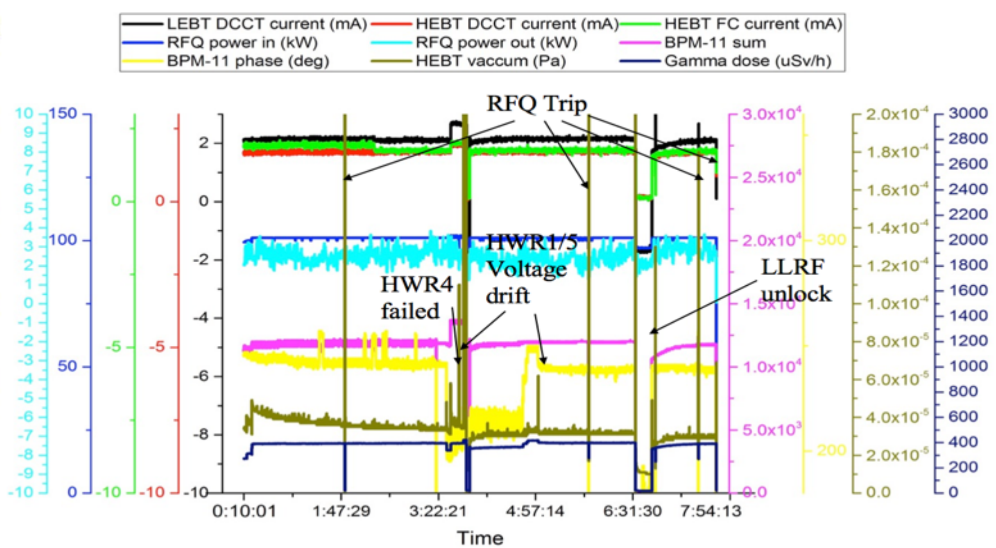
June 30th, 2014, Beam is 2.1 MeV. The current is ~10 mA, CW, kept for 4.5 hours.



Feb. 13th, 2015, Beam is 2.55 MeV. The current is ~11 mA, CW, kept for 1 hour.



Nov. 28th, 2015, Beam is 4.6 MeV. The current is ~4 mA, CW, kept for 40 minutes.



Jan. 2nd, 2016, Beam is CW. The current is ~2 mA, kept for 7.5 hour.

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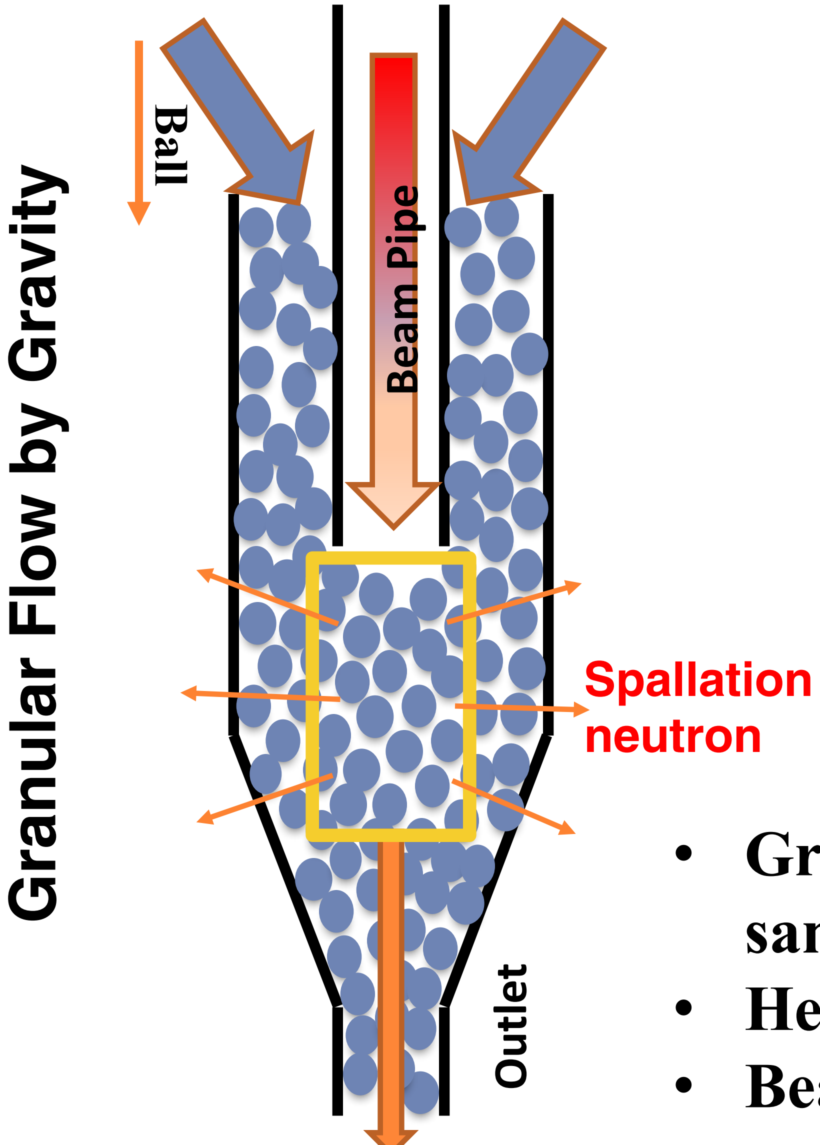
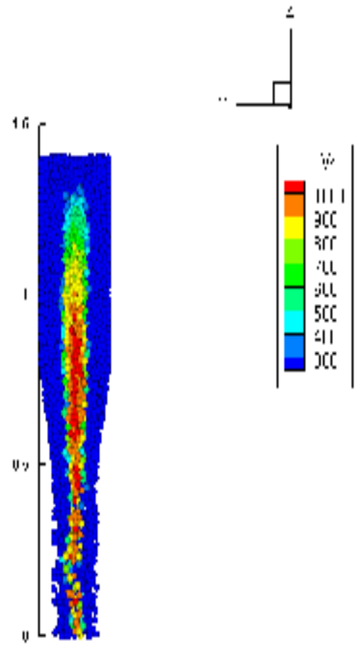
Principle of Granular Flow Spallation Target

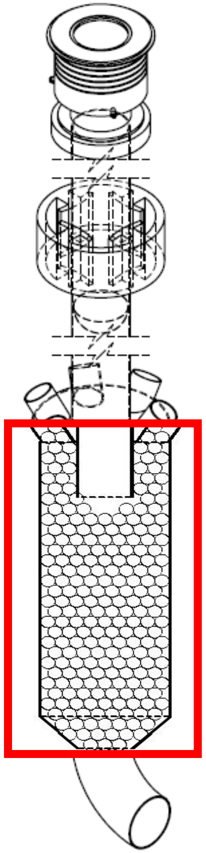


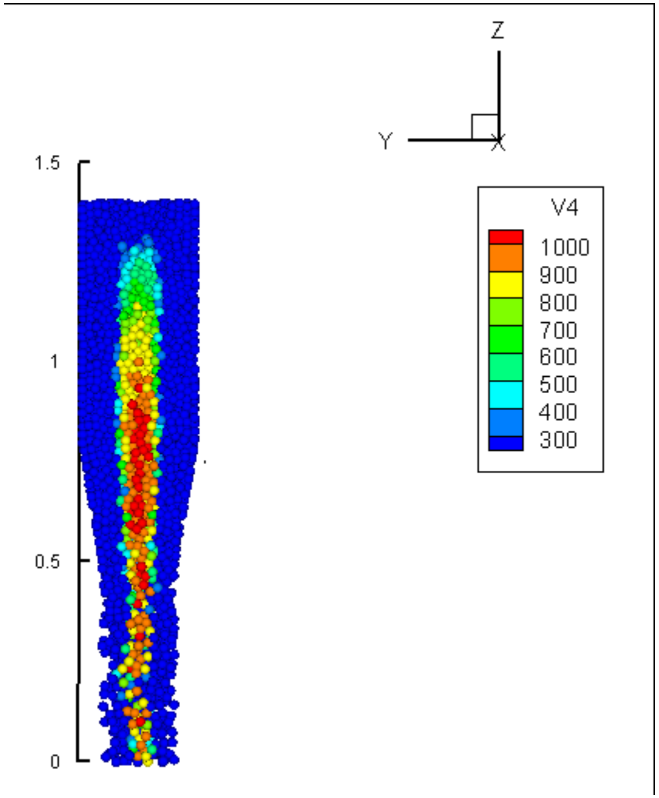


- **Granular flow operates similar as sand clock**
- **Heat is treated off line**
- **Beam intensity ：>100 μA/cm²**

Design Granular Flow Spallation Target

Parameters	
Granular material	Tungsten / **Tungsten alloy** /…
Structure material	TZM/SiC
Granular size	10±5mm
Inlet temperature of granular	250 C
Proton beam	1GeV@10mA=10MW
Intensity of beam	>100 μA/cm²
Diameter of beam spot	10cm
Average temperature increase	**Average velocity**
400	~0.8m/s
500	~0.5m/s
600	~0.35m/s
800	~0.25m/s

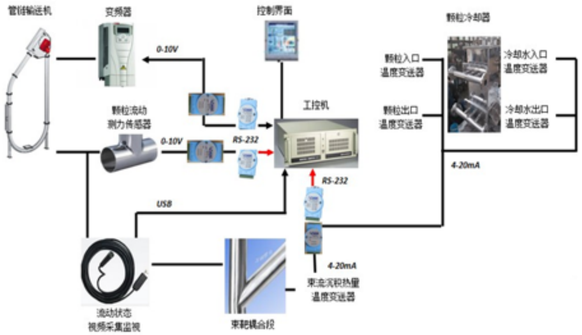


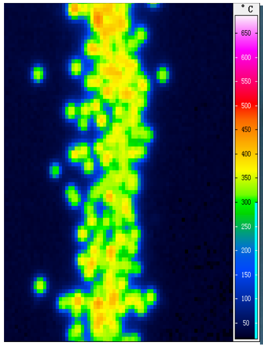


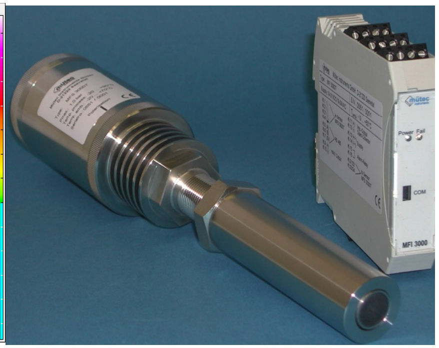
Mass parallel Simulation:
Contact mechanism + MD + MC transport
K20GPU 2500ALU * 32
Number of Ball: 0.5 M

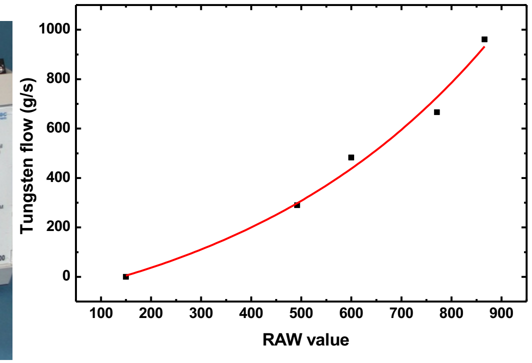
Prototype of Granular Target

Measurements and control

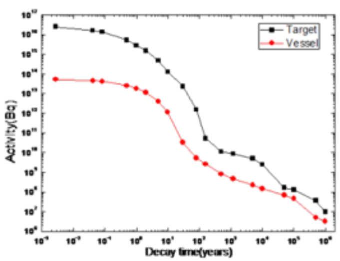


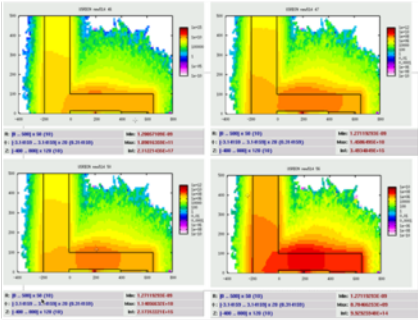


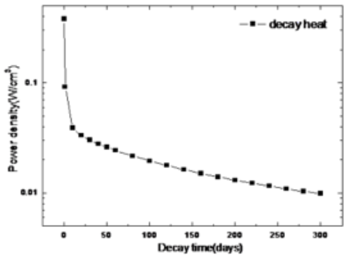


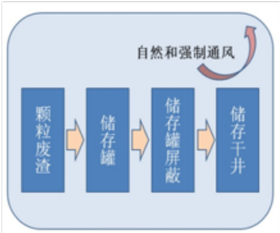


Storage



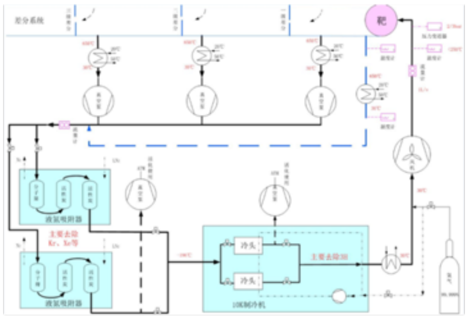


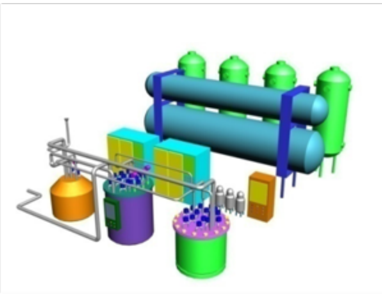




颗粒回收储存系统

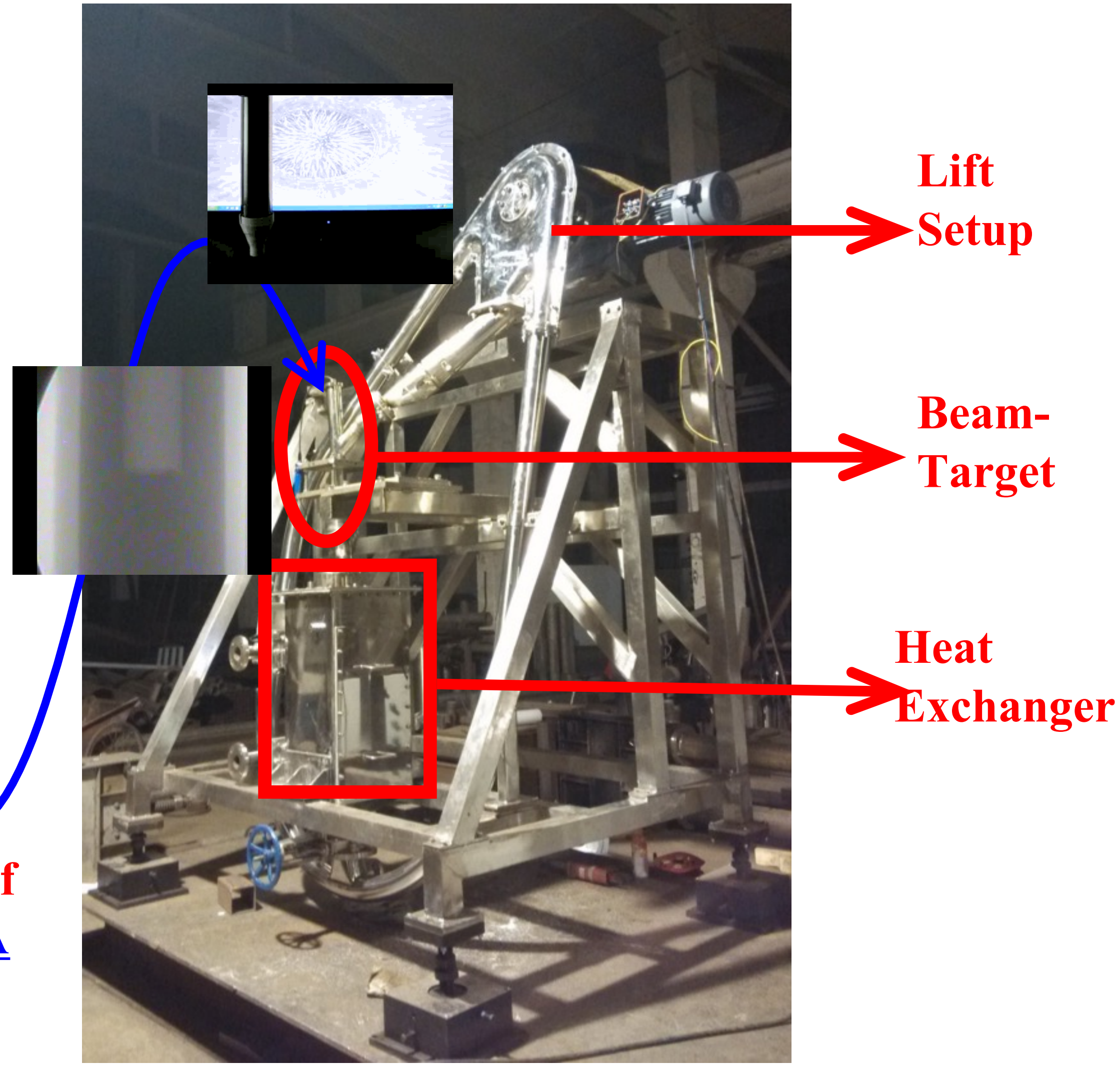
Cover gas





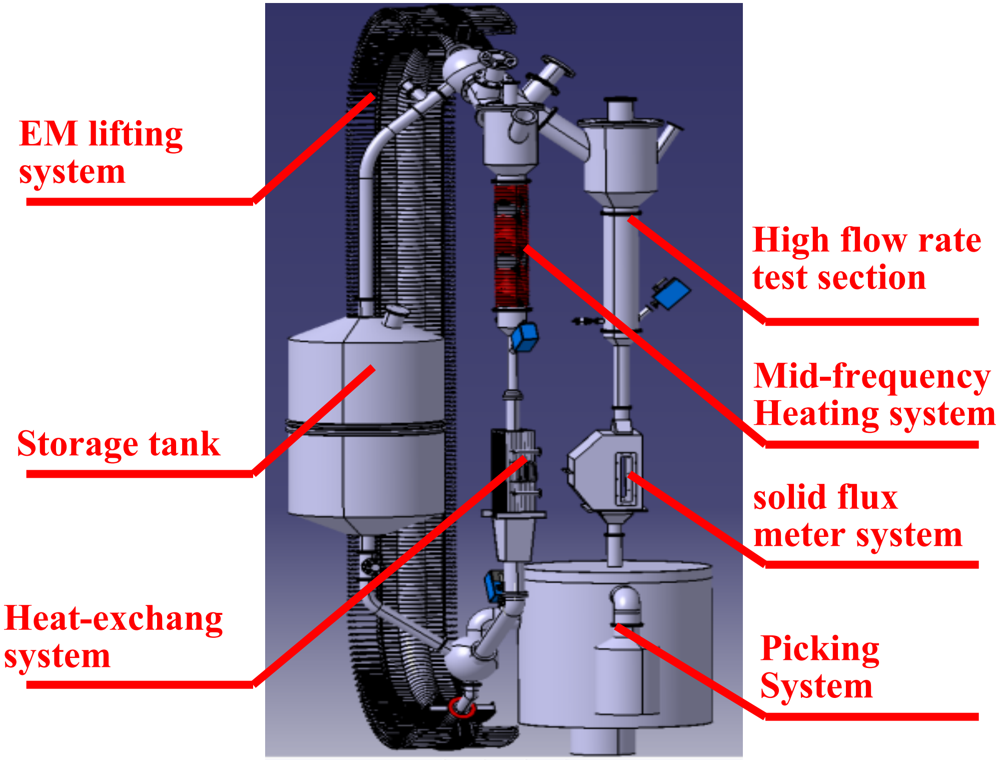
Exp. of E-Beam on W Granular Target

<20mA@2.5MeV e



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

Test Platform of Granular Target



Challenge of granular target:

- corrosion and erosion
- lifting
- heat exchange with water
- reduce the highest temp.
- clean dust
- radiation damage
- fluid detection

Outlines

- Introduction
  - Motivation
  - ADANES
  - Roadmap
- **Progress**
  - Accelerator
  - Target
  - **Reactor**
  - Fuel Recycle
  - Material
- Summary

LBE Coolant R&D

1. LBE Loop Test Bench:

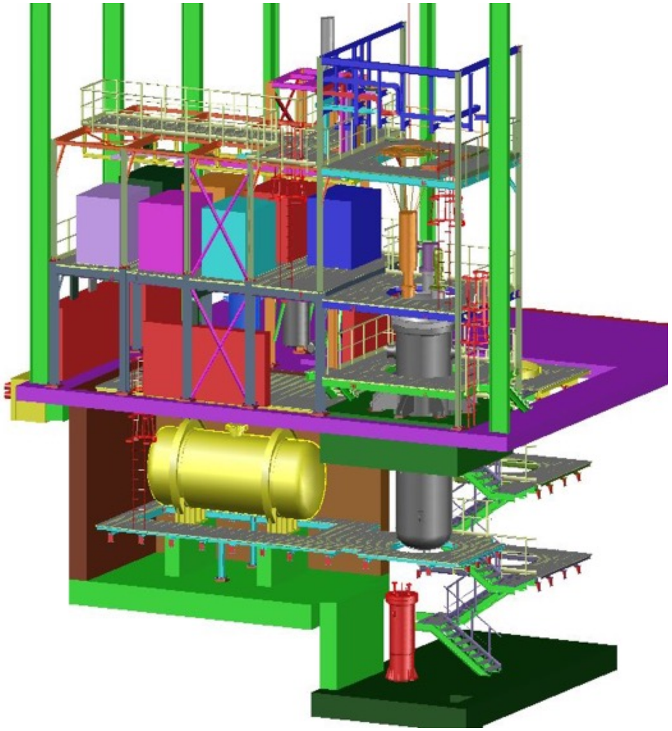
- T：~500℃, (Tmax:~1000℃/Min)
- V: 2~3m/s; V_{max}<10m/s in small pipe
- Size：20m x 20m x 13m；
- $Power_{max}$：<2000 kW
- O_2：10^{-9}~10^{-6}wt%

2. Simulator of LBE reactor

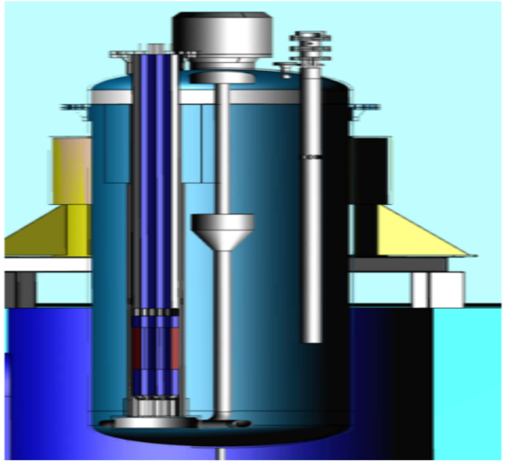
- Heat transfer prototype in full size
- 1：1 control bar

Integrated Test Bench of LBE Reactor

- Key equipment 1:1 integrated test
  - Bump, heat exchanger, coupling between target and reactor, DHR, etc.
- Heat transfer and fluid test
  - Coolant loop, measurement and control, software V&V, etc.
- Support of license for CIADS



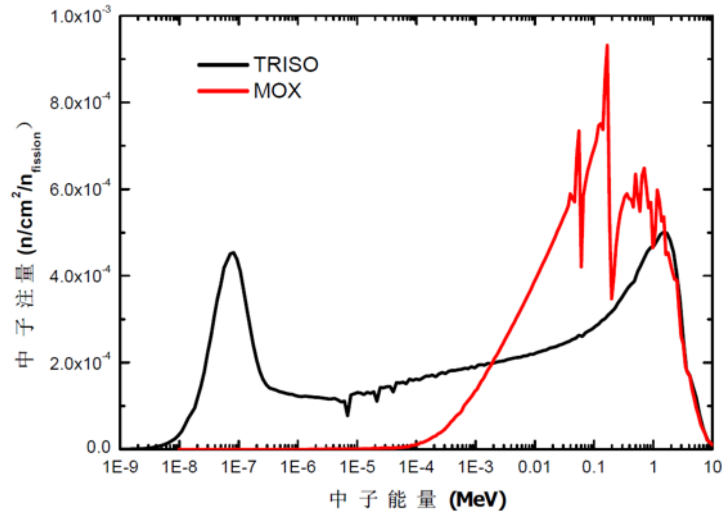
configuration		
Coolant	coolant	LBE
	Temperature/ ℃	250~500
	Quantity/ ton	~200
Heat echange	Power/ MW	2.5
	Flux/ m^3/h	100
Container	Diameter/ m	2
	Height/ m	6.5



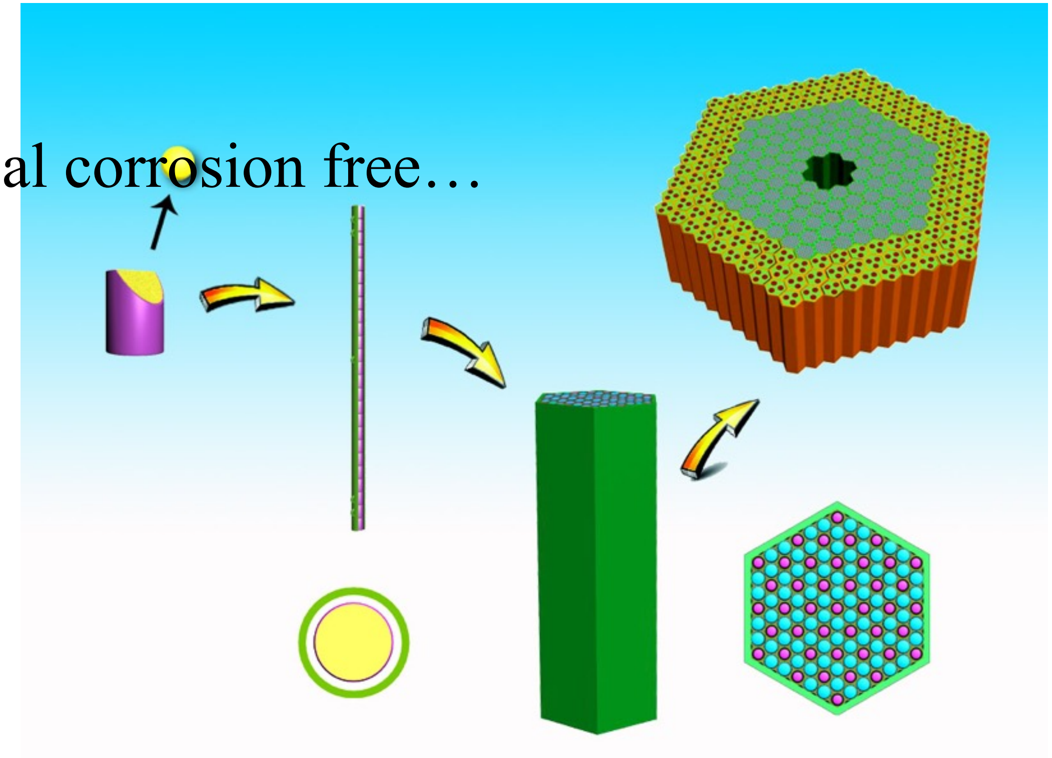
Granular coolant option

(G2FR: Granular Gas coolant Fast Reactor)

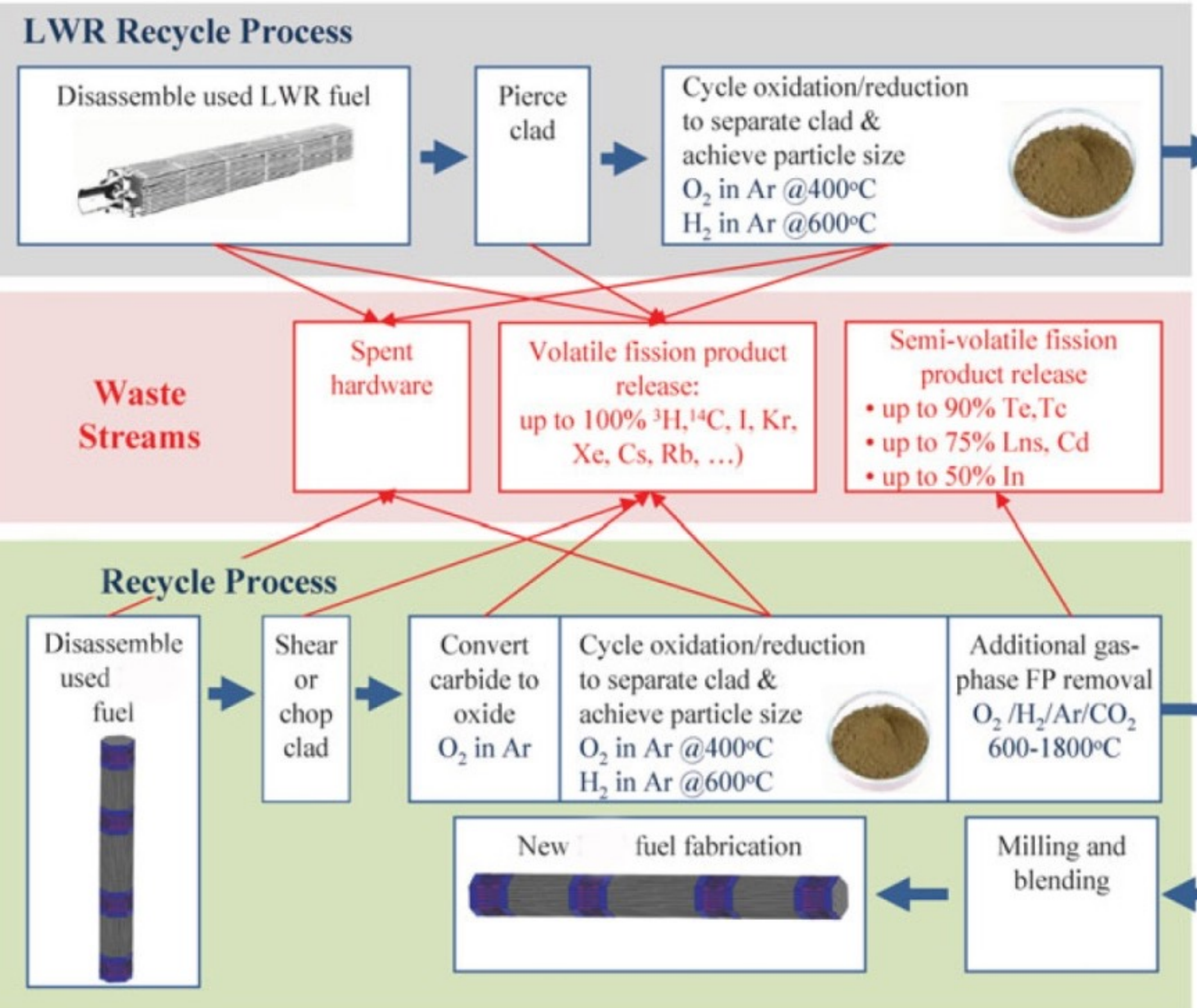
- Low pressure inter-fluid (He)
- High thermal inertia (Zr/SiC/C)
- The grains can be optimized for
  - Fast spectrum, High Melting Pt.
  - Low radio-toxicity
  - Small erosion and chemical corrosion free…



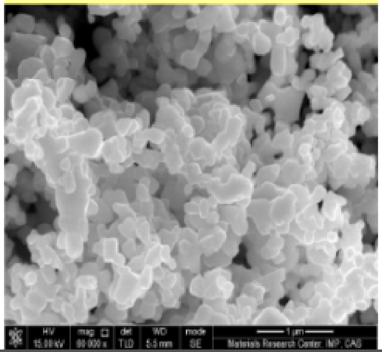
Design: Zr_3Si_2/ SiC/C… grains and Assembly SiC_f/SiC, /C Hexagonal prism for fast/thermal Reactor



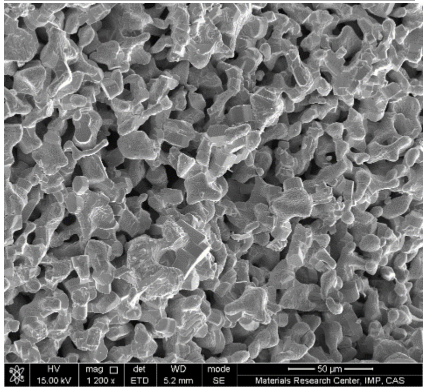
HT Dry Processing to Remove FP (Ext. AIROX)

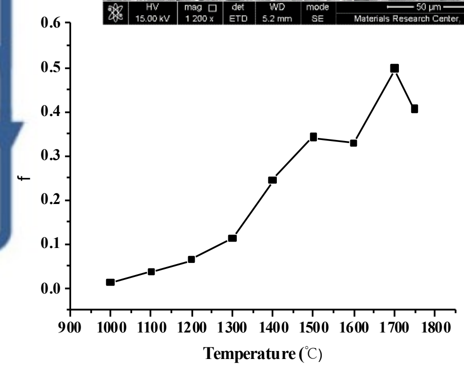


U_3O_8 900℃ 4h



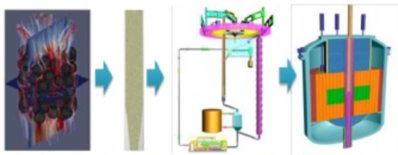
U_3O_8 1700°C 6h





Super-Computing, Simulation & Design System

Mass parallel simulation method (GPU)



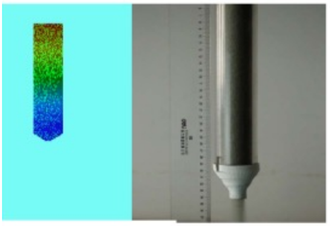
- Radiation transport computation in stochastic granular and neutronic analysis, etc.
- Granular flow and fluid flow simulations and thermal-hydraulic analysis.

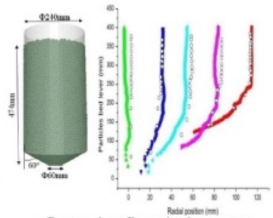
250 S1070 GPUs
~300 Tflops(S)

128 K20 GPUs
~150 Tflops(D)

Software Copyrights

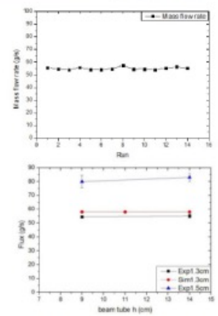
GPU method for Granular Flow (G2F)



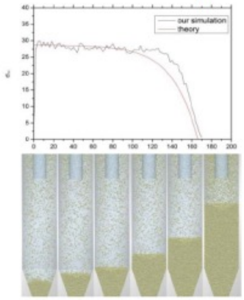


Granular flow in hopper

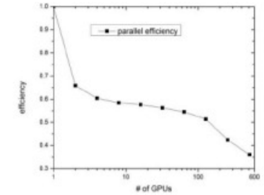
- Grains：~250 M；MD + Contact mechanic.
- 512GPU，512*448=229376 ALU；parallel efficiency：~38%.



Experiments of verification

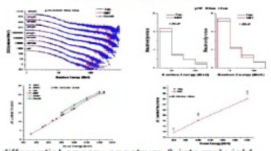


Micro simulation for Macro size

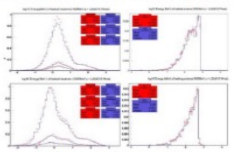


GPU MC Transport program (GMT)

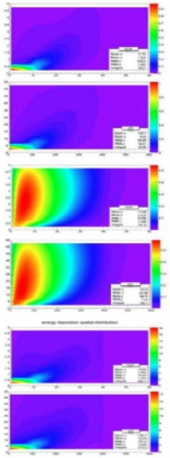
Procedure of GMT



differential energy spectrum & integral yield



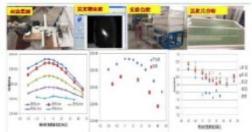
Leakage neutron spectrum



Spatial distribution of flux

Proton Beam in IMPCAS: 10MeV~1GeV

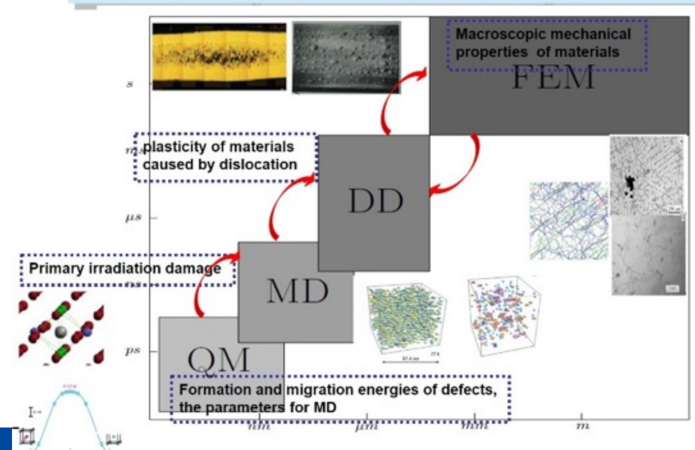
TOF device & Activation Measurement device



The calibration and verification for the measurements device

GPU irradiation effects (GIR)

GPU Time and length scales of multi-scale modeling for irradiation effects



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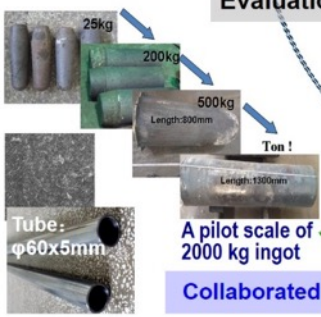
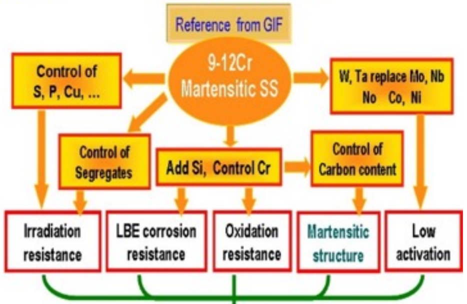
Material R&D : SIMP Steel (Martensite)

◆ R&D of new material —— SIMP steel

Analysis
Design
Fabrication
Processing
Evaluation



A pilot scale of 2000 kg ingot

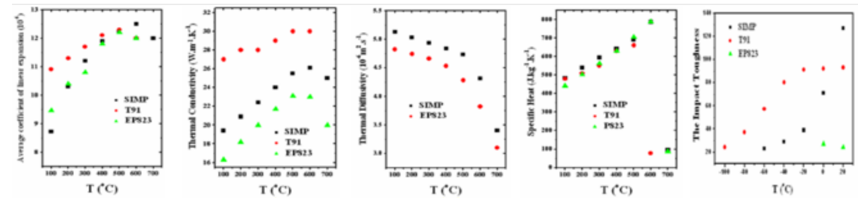


Significant tolerance to high-T, dpa, LBE

SIMP steel

Collaborated with IMR on the fabrication and processing

◆ R&D of SIMP steel —— Physical properties



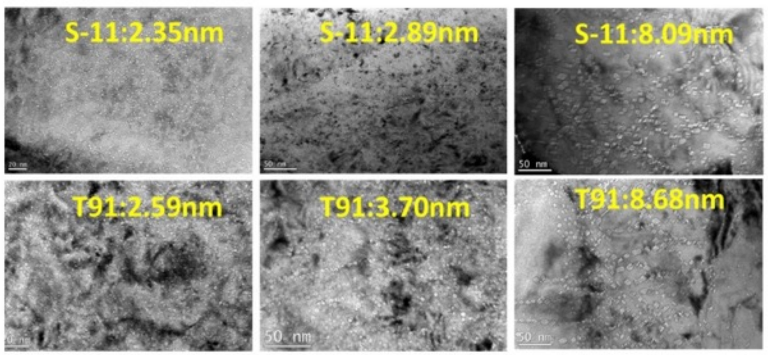
Linear expansion, heat conductivity, thermal diffusivity, specific heat, impact toughness

	SIMP								T91	EP823
Temperature(℃)	RT	100	200	300	400	500	600	700	RT	RT
Young modulus (GPa)	211	206	199	192	184	175	165	153	217	217
Shear modulus(GPa)	82.6	80.6	77.8	74.6	71.2	67.5	63.4	59.1	85.7	87.9
Poisson ratio	0.28	0.28	0.28	0.28	0.29	0.30	0.30	0.30	0.26	0.23

	SIMP			T91	EP823
Temperature (℃)	RT	600	650	RT	RT
Yield strength (MPa)	582	268	182	415	651
Tensile Strength (MPa)	825	355	269	585	855
Percentage of elongation (%)	23.5	44	34.2	20	25

◆ R&D of SIMP steel

—— Evaluation of He-effect



300℃ 450℃ 550℃

Mean size of helium bubbles, 5x10^{16}ions/cm^2, 200 keV He ions

He-bubble size: SIMP < T91

◆ Develop SIMP steel—— Primary Evaluation

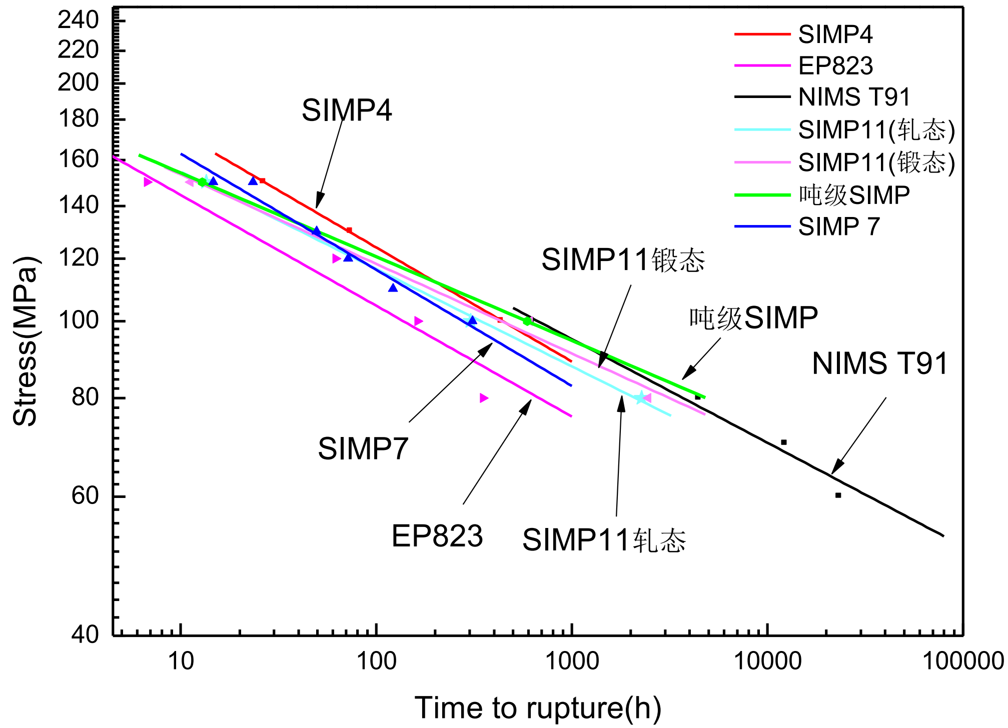
Compared to T91 (Jpn), EP823, RAFM

Tests	Result
TS/YS/elongation rate at RT-600℃	SIMP > (EP823, T91, RAFM)
Oxidation resistance at RT-800℃	SIMP > (EP823, T91)
LBE corrosion resistance at 600℃ (static saturation oxygen)	SIMP ~ EP823 > T91
LBE corrosion resistance at 450℃ (static saturation oxygen)	SIMP > T91
Short durability at 600℃ (150 MPa)	SIMP > (EP823, T91)
Durability at 650℃ (100 MPa)	SIMP ~T91 > EP823
Ion irradiation resistance at RT- 450℃	SIMP > (T91, RAFM)
Ion irradiation resistance at 550℃	SIMP ~T91 > RAFM

SIMP steels irradiated at SINQ-PSI, (n/p, ~20dpa, 2012-2014)

SIMP Main Properties

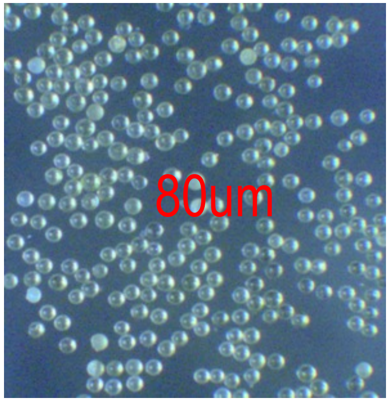
	C	Si	Cr	Mn	W	Ta	V	Nb	S	P
SIMP/Tons	*0.22*	*1.22*	*10.24*	*0.52*	*1.45*	*0.12*	*0.18*	*0.01*	*0.0043*	*0.0040*

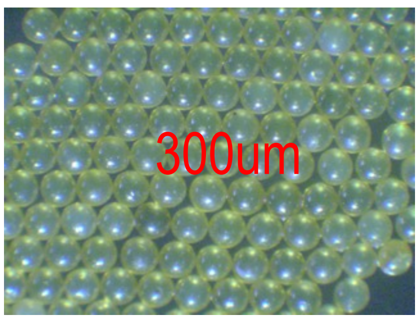


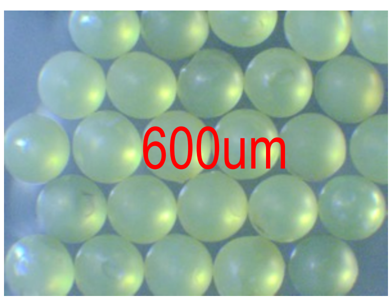
	550℃	600℃	650℃
SIMP11 Forged	-	-	44.1
SIMP11 Rolled	154.0	91.7	27.9
SIMP/2T Rolled	Testing	Testing	**58**
NIMS T91	175.2	99.9	56.1

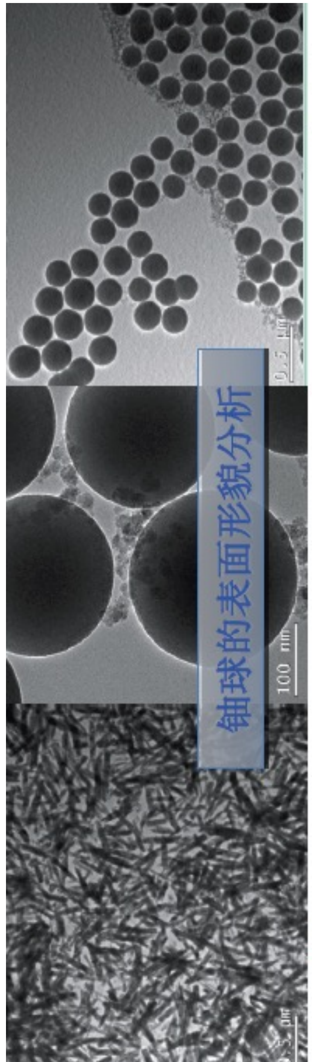
- **Stress vs Rupture of SIMP11 Rolled close to NIMS T91 in 600℃, 550℃;**
- **Stress vs Rupture of SIMP Rolled sample (2Ton) is similar as NIM T91 in 650℃, and expect better performance in 10^5h measurement;**
- **Stress vs Rupture of SIMP Rolled sample (2Ton) could be similar as NIM T91 in 600℃、550℃ pre-testing.**
- **5 Ton Sample will be ready soon**

Pellet Fuel and Cladding R&D

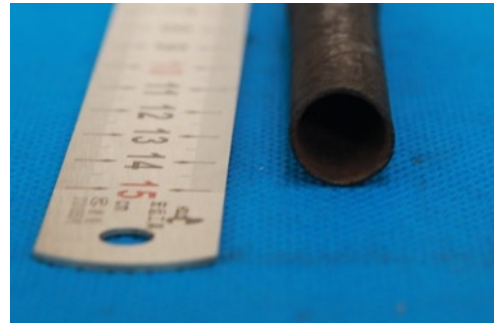


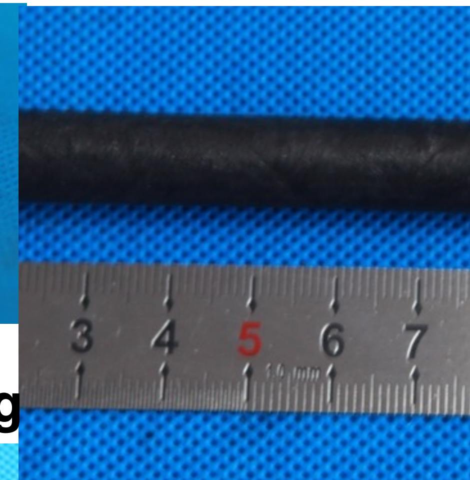






U Fuel Pellet





δ=0.5mm, PIP coating

SiC_f/SiC Cladding

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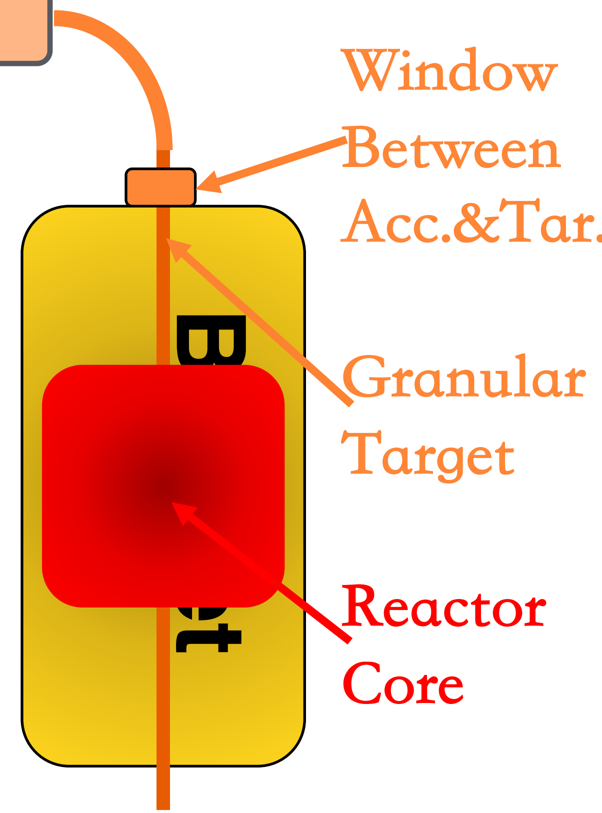
Optimizing in ADANES Coupling

Superconductor Linac (1GW$_t$: ~15mA@1GeV p+W…)



Item	*Present Design*	*Future Developing*
Beam Trip	*Demo Require*	*Industry Require*
Window Lifetime	*2~3 Month*	*>6Month*
Target Power	*≤15MW*	*≤10MW*
Cladding Material	*>5 year*	*>10 year*
Core Temperature	*≤550 °C / SIMP*	*~1500 °C // Si_fC/SiC*
Inlet/Outlet T	*250°C/<540 °C*	*300°C/>600 °C*
$G_{EM}[P_e/(P_b/\eta_{acc})]$	*>6.5*	*>13*

- **Efficiency of Nuclear Electricity Generator:**
  PWR: ~33%
  ADANES: >31%→>37% with AD
  >40% without AD

Summary of ADANES in CAS

- ADANES Conception Proposed, Approaches Optimizing
- Accelerator System (two options comparison in low energy part)
  - **ECRIS+RFQ+S-HWR & 162.5MHz Injector >2.55MeV&11mA CW proton beam**
- Spallation Target (new, simplify)
  - **Granular flow target is Proposed and testing with e-beam**
- Fuel Recycle (partial new, simplify)
  - **HT-Dry+REs Removing Processes R&D intensively**
- ADANES Material R&D (SIMP, W, Be_2C, Zr_3Si_2, SiC_f/SiC, …):
  - **SIMP Steel (similar H91 performances) produced and Improving in 5 Tone Scale**
  - **SiC_f/SiC is used in core and cladding, R&D intensively**
- GPU based S-Computing used for optimization of System Design

Thanks for your attention!

Welcome collaboration!