Development of Accelerator Driven Advanced Nuclear Energy (ADANES) and Nuclear Fuel Recycle

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Institute of Modern Physics, CAS

- **Supported by**
- **"Strategic Priority Research Program" of the Chinese Academy of Sciences, Future Advance Fission Energy-ADS**
- **Mega scientific project: China Initiative Accelerator Driven System**

Outlines

- Background and concept of ADANES
- Introduction of CiADS
- Progress of key technologies
    - Accelerator, Target and Reactor
    - Materials SIMP
    - New approach of Fuel recycle
- Conclusion

Strategy and Status of NP in China

- **Current status of China (including Taiwan, China) nuclear power (by the end of 2018)**
  - 46 nuclear power reactors in operation, 42.858 GWe (3th , total 452 and 399.354 TWe in the world)
  - Produced electricity: 286.5 TW.h, 4.22%
  - 11 reactors under construction, 10.982 GWe, (1st , total 54 in the world)
- **The development plan of NP in China (2014-2020)**
  - By 2020, the installed nuclear capacity will be 58 GWe, and 30 GWe are under construction
- **Nuclear energy is an inevitable strategic option to meet China energy demand in the future**
  - China is the largest energy consumer and Greenhouse Gas source.
  - She has claimed that the CO_2 emissions will reach the peak before 2030 on Paris Climate Agreement.

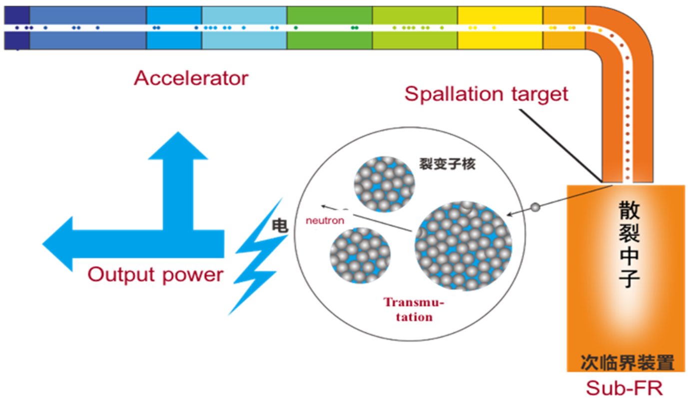
Data from IAEA/PRIS, update on 2019-05-18

Issues of Sustainable Development

- **Management and safe disposal of nuclear waste**
  - 1 GWe PWR ~25 ton/year;
  - ~2200 ton/year in 2030 in China; ~10000 ton/year now in the world
  - Total capacity of Yucca Mountain ~ 70000 ton;

"The ADS has the advantage that it can burn pure minor actinides while avoiding a deterioration of the core safety characteristics."

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

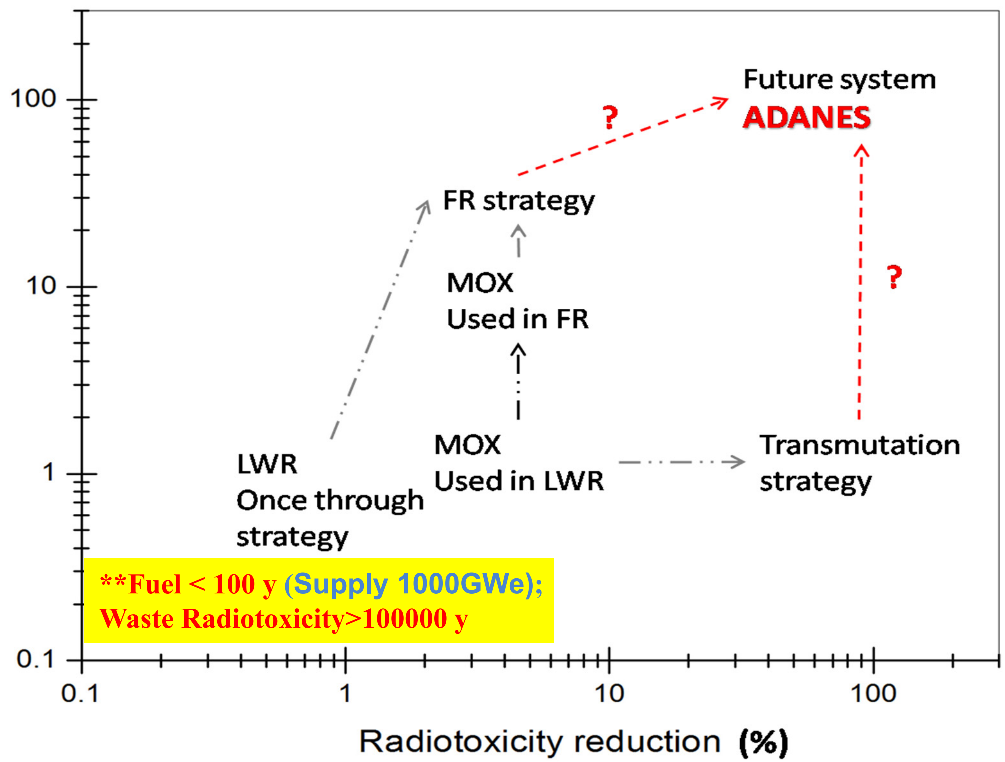


- **Estimated available energy sources in China**
  - Fossil fuels ~16000 EJ;
  - Uranium, 19.9 EJ;
  - Renewable, 14.92 EJ;

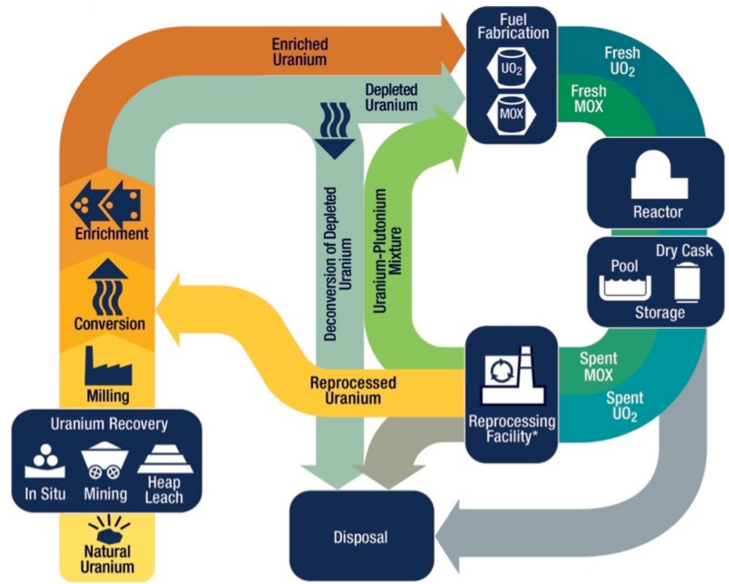
Nuclear waste is not only the issue of sustainable, but also the long-term supply.

Sustainable Perspective of NP

**Fuel ~10000 y; Waste Radiotoxicity<500 y



- High Resource Utilization → Breeding
- Radiotoxicity Reduction → Transmutation



Nuclear fuel cycle

https://en.wikipedia.org/wiki/Nuclear_fuel_cycle#Partitioning_and_transmutation

Accelerator Driven Advanced Nuclear Energy System

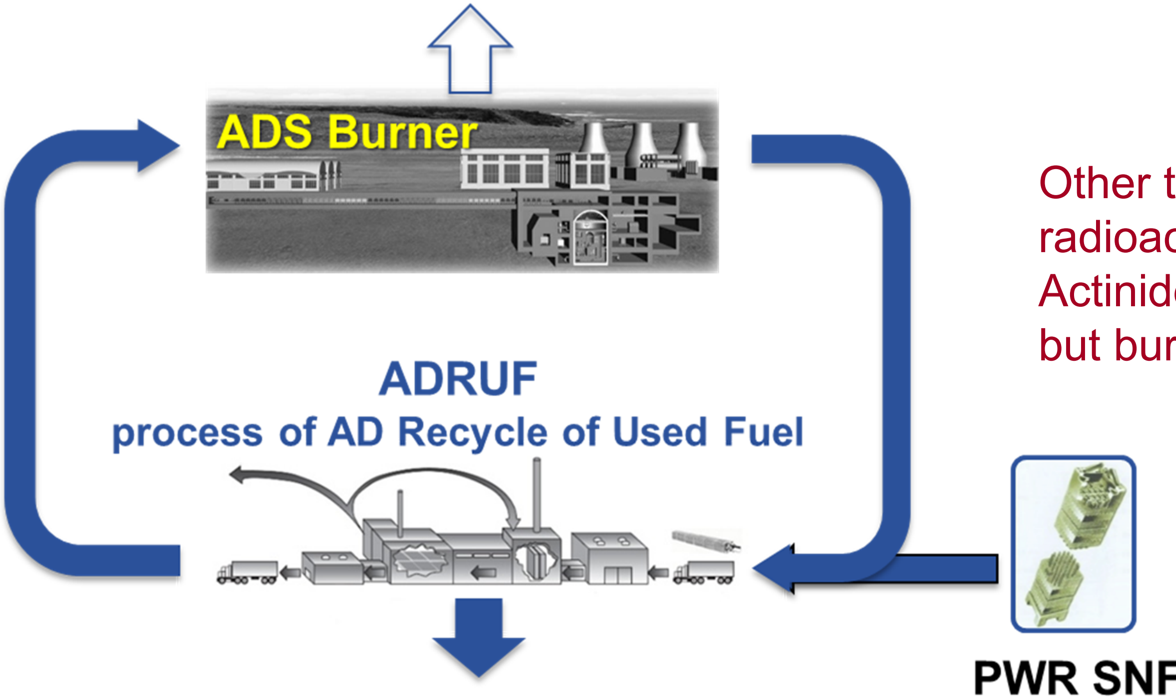
- **Accelerator Driven System was proposed for:**
  - **Nuclear waste transmutation (ADS)**
  - **Isotopes production (ex. Breed, ISOL, APT)**
  - **Energy Amplifier (ADTR)…**

AD Burner

- **AD Recycle of Used Fuel (ADRUF): (optimizing SNF resources & radiotoxicity)**
  - **Remove part of FPs (>50% of REs) from SNF, Convert Residuals as recycle fuel (short lifetime in waste)**
  - **Transmuting, Breeding & Energy Amplify in Burning recycle fuel (ADB)**

Approach of ADANES

Waste transmutation, breeding, power production

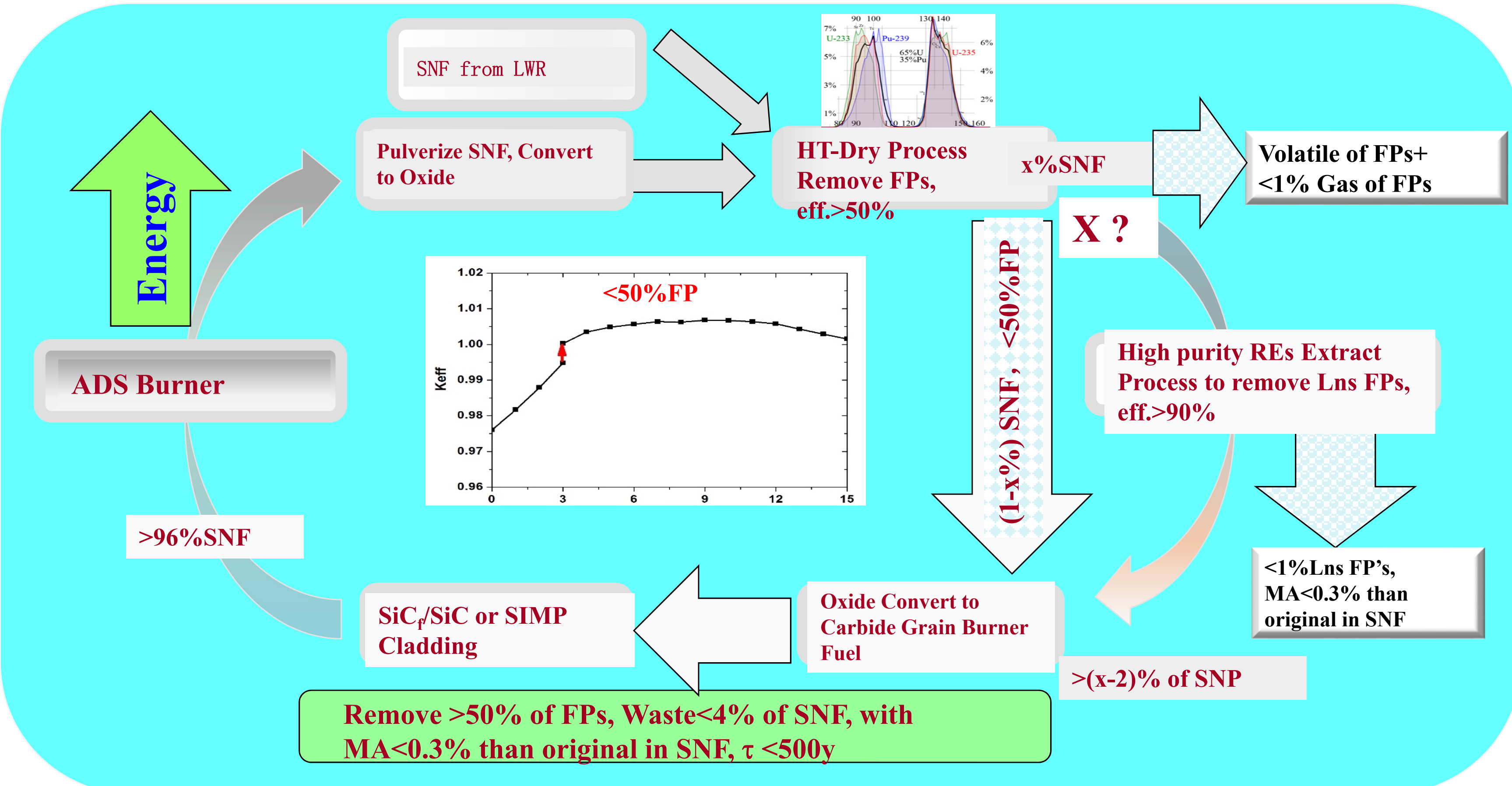


Other than P&T, high radioactive elements, like Minor Actinide, will not be Partitioned but burned in ADS Buner.

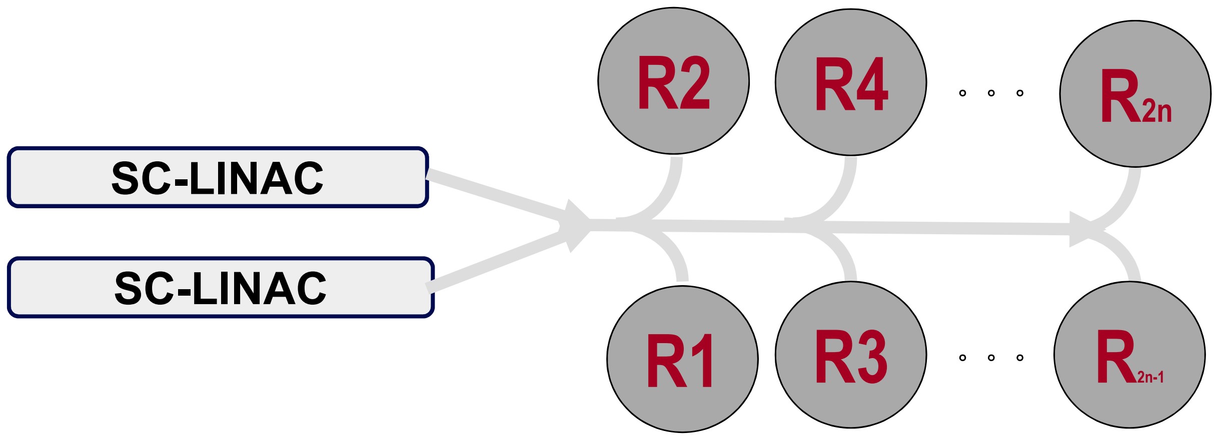
Simply the dry stacking disposal can be used.

A small amount of waste with low radio-toxicity (Lanthanides)

Closed Fuel Recycle of ADANES



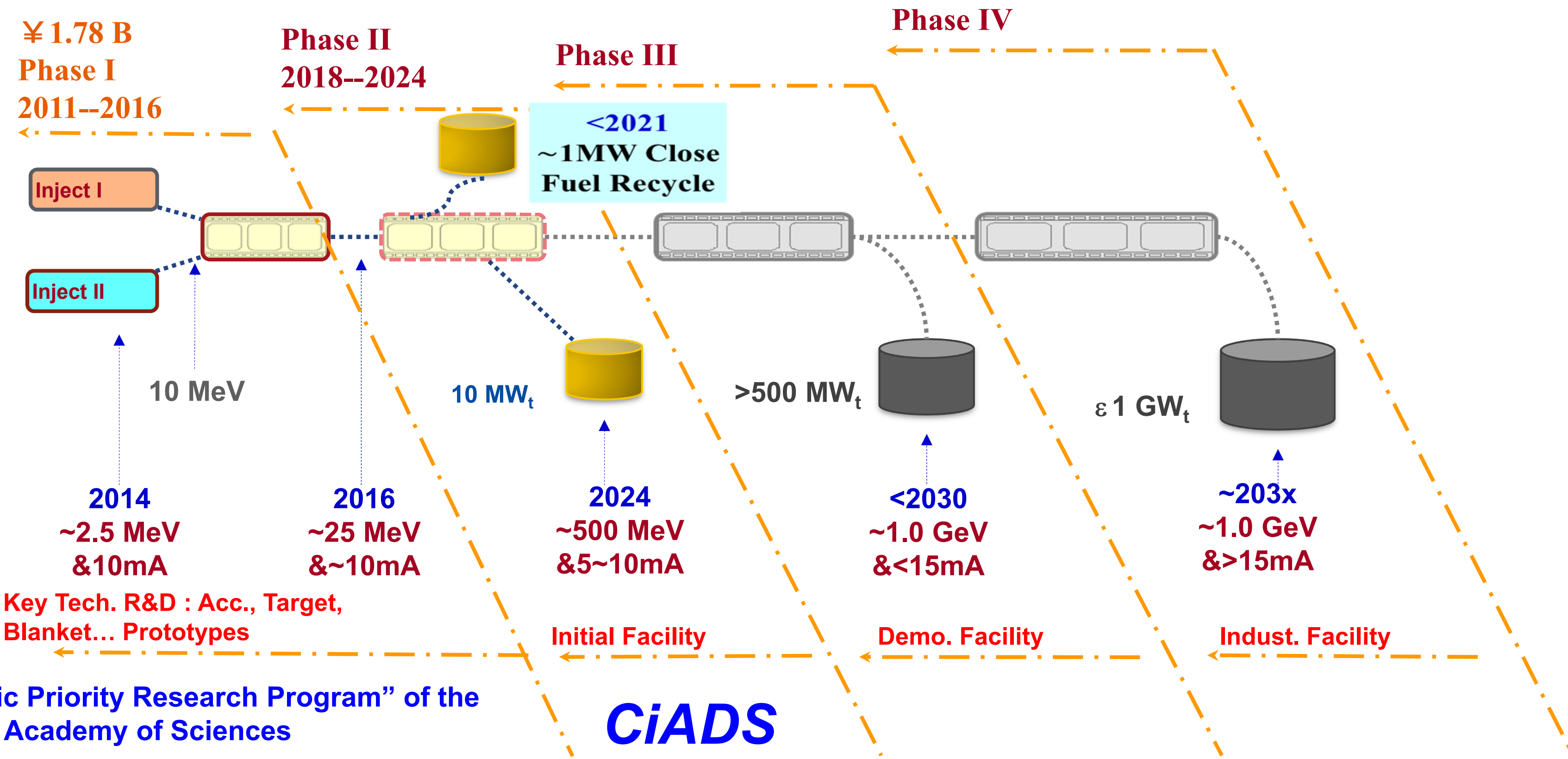
Concept of ADANES Power Plant



- **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%**

Challenge: 1) high power, high stability superconducting linac, target, and reactor
2) high property steel (materials)
3) new methods of fuel recycle other than P&T

ADS/ADANES Roadmap in China



"strategic Priority Research Program" of the Chinese Academy of Sciences

CiADS

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CiADS Project (2018-2024)

- Approved in Dec. 2015
- Leading institute: IMP
- Budget: ~4 B CNY (Gov. + Corp.)
- Location: Huizhou, Guangdong Prov.
- Partners: CIAE, CGN, IHEP, etc.
- Ground broke in August 2018

CiADS Project (2018-2024)

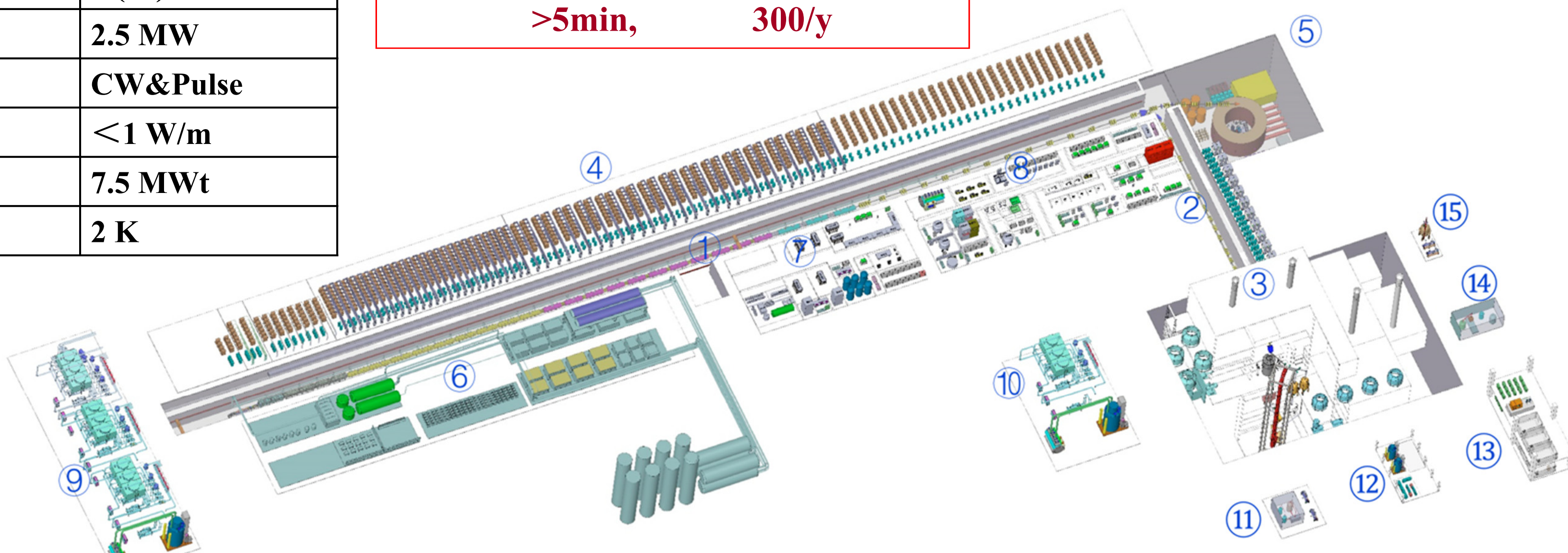
Design Particle	**proton**
Energy	**500 (250) MeV**
Beam current	**5 (10) mA**
Beam power	**2.5 MW**
Operation mode	**CW&Pulse**
Beam loss	**＜1 W/m**
Reactor power	**7.5 MWt**
Cryogenic	**2 K**

Beam trips goal:

<10s, -

10s～5min, 2500/y

>5min, 300/y



① SC linac

② Coupling transport

③ Target and reactor hall

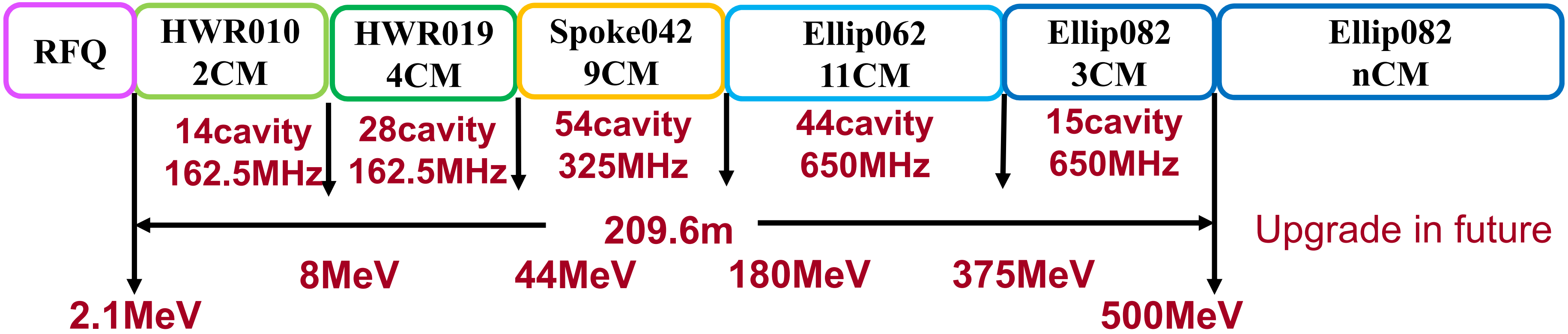
④ Accelerator equ. hall

⑤ Beam dump and granular target exp.

⑥ Cryogenic plant

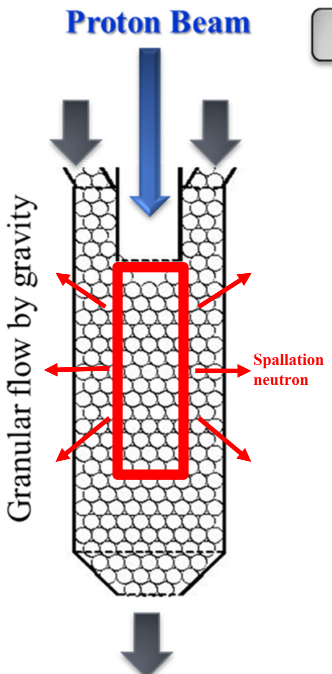
⑦ SRF hall

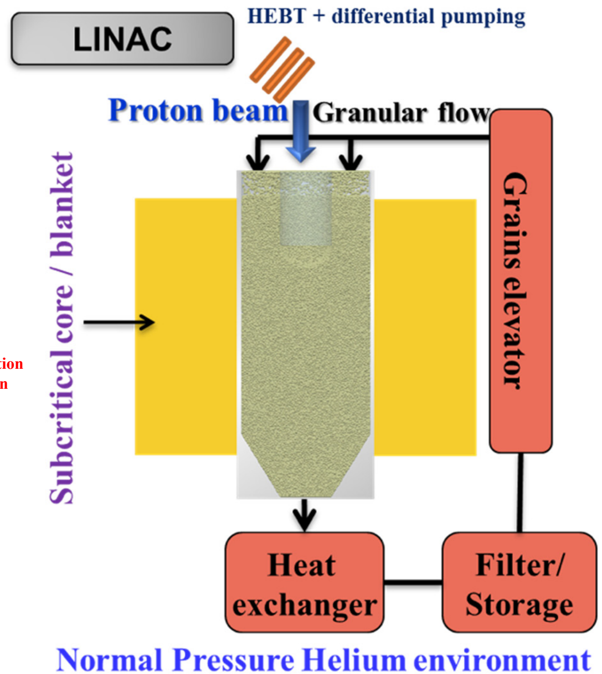
Superconducting LINAC

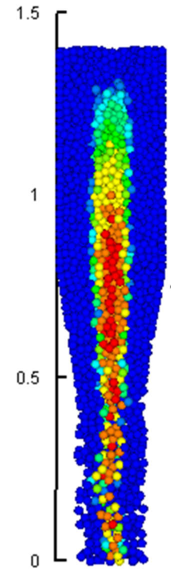


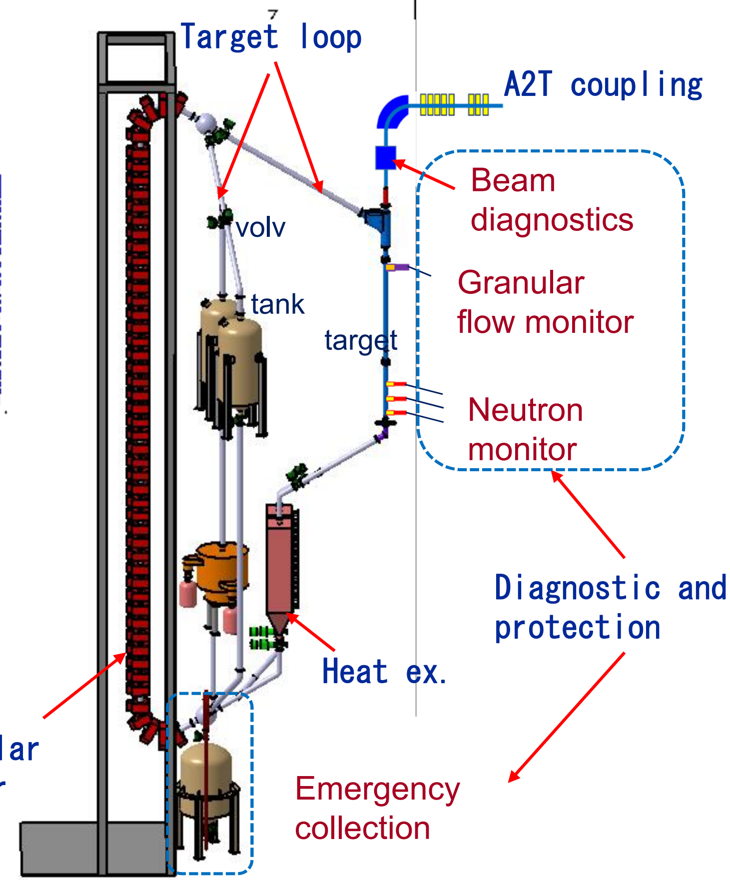
	Unit	HWR010	HWR019	SPOKE042	Ellip062	Ellip082
f	MHz	162.5	162.5	325	650	650
type		Sqreezed	Taper	Double	5 cells	5 cells
Vmax	MV	1.0	2.5	6.5	13	20
Ep	MV/m	28/20	32/25	35/28	35/28	35/28
Q0	E09	5.00	5.00	6.00	10.0	10.0
S or Q	per CM	7/7	4/7	2/6	1/4	1/5
CMs	m/Num.	5.5/2	7.3/4	8.2/9	6.5/11	8.1/3

High Power Target









Merits:

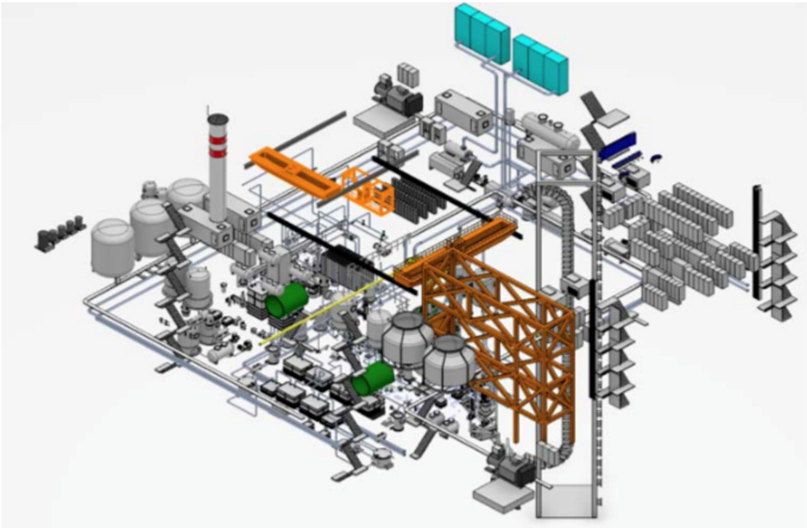
- Heat exchange outside
- No Stress due to beam trip
- No thermal shock due to beam pulse

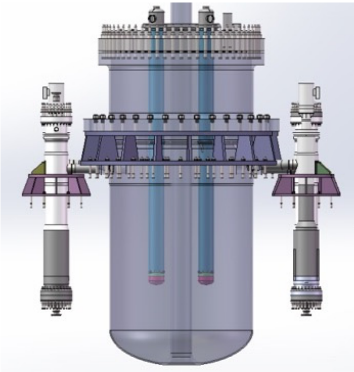
Drawbacks :

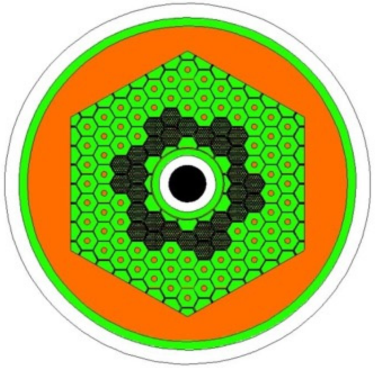
- Dusty due to abrasion
- Volume of target materials

Subcritical Fast Reactor

	Top level spec.
type	LBE sub- FR
Power	10MWt (incl. beam)
fuel	UO_2 (19.75%)
Keff	~0.75
Main coolant Configuration	Pool-loop
Main coolant driven mode	Forced circulation
Coolant	LBE
Main coolant pressure	Normal
Main coolant temp	280-380℃
main coolant exchanger	Main exchanger×2 Auxiliary exchanger×4
Main pump	Mechanical pump×2
Secondary Loop coolant	Pressure water
Secondary Loop pressure	1.4MPa
Secondary Loop Temp	225-260℃







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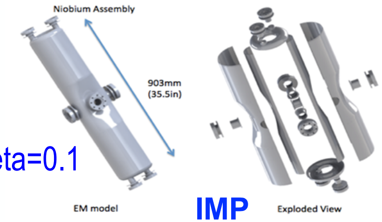
Chinese ADS Front-end Demo linac (CAFe)

- **IMP collaboration with IHEP 2011 ~ 2017**

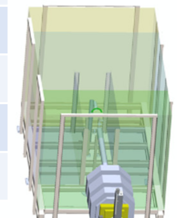
162.5 MHz Half-wave Cavity

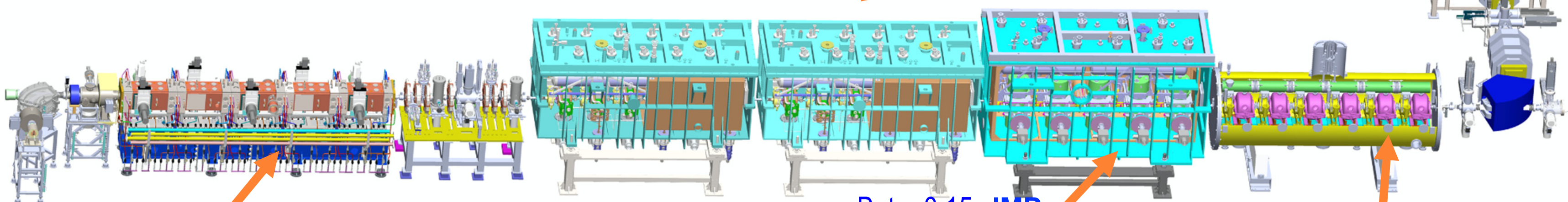


Beta=0.1

IMP

ions	P，H_2^+，α
frequency	162.5 MHz
current	10 mA
E in RFQ	40 keV
E out RFQ	3.1 MeV
Energy	25/30/40MeV
Temp.	4.5 K

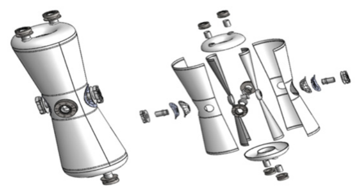




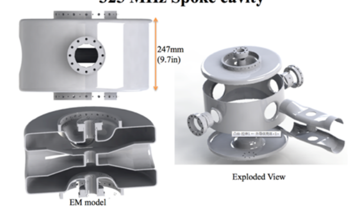
ADS RFQ：2014-2017
(cooperation with LBL)
CMIF RFQ：2018-

Beta=0.15 IMP

162.5 MHz Taper HWR



325 MHz Spoke cavity



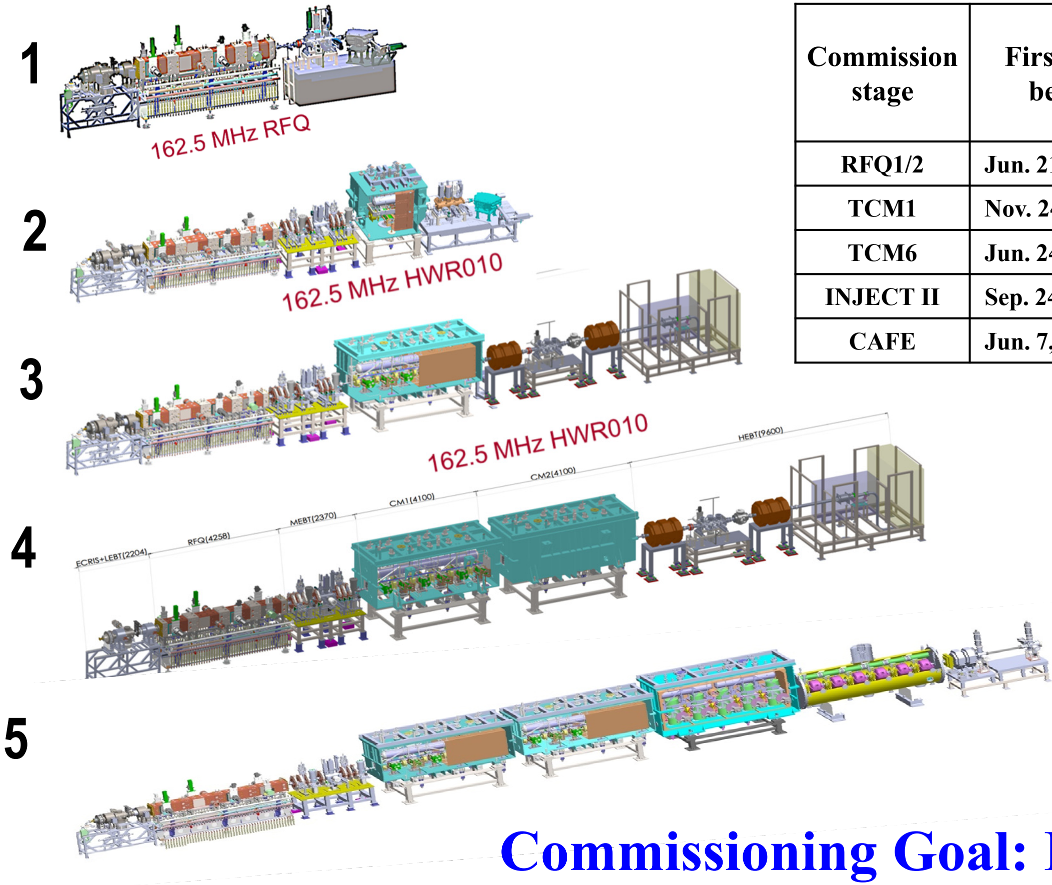
Beta=0.21

IHEP

- **Goal: to demonstrate 10 mA CW beam of superconducting front-end Linac for CiADS.**

- **Supported by "Strategic Priority Research Program" of the Chinese Academy of Sciences.**

Commissioning of Superconducting Linac



Commission stage	First CW beam	Max Energy (MeV)	Beam time (hours)	CW beam time Total (hours)	CW Current Max(A)	CW Power Max(kW)
RFQ1/2	Jun. 21, 2014	2.15/3	2036/~200	90/~120	11	23
TCM1	Nov. 24, 2014	2.55	208	22.5	11	28
TCM6	Jun. 24, 2015	5.3	400	20	4	21
INJECT II	Sep. 24, 2016	10.2	327	11	2.7	26
CAFE	Jun. 7, 2017	26.1	~500	~140	2.55	45

1. 2014.06.06——2014.07.24, RFQ
2. 2014.09.14——2015.02.13, TCM1
3. 2015.03.26——2015.06.29, TCM6, beam accident, RFQ AMP and coupler broken
   2015.10.28——2016.01.21, TCM6 commissioning
4. 2016.05.01——2016.06.20, injector II, coupler broken
   2016.09.01——2016.12.17, injector II high power
5. 2017.04.28——2017.06.18, CAFe, current leads broken
   2017.10.03——2018.01.23, CAFe, operation stability
   2019.01.04 ——2 mA CW beam, operation stability

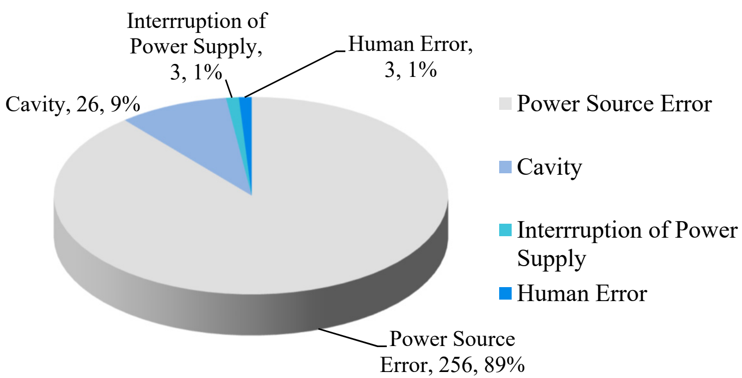
Commissioning Goal: Higher power, Higher stability

Operation Status of ADS RFQ

3264 hours

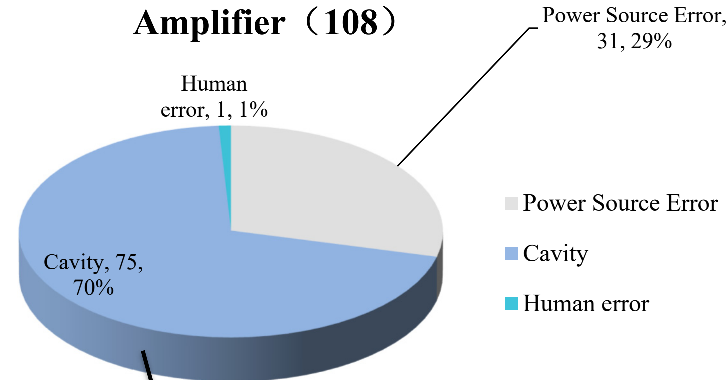
2638 hours

Trips @ Useage of Tetrode Amplifier（288）

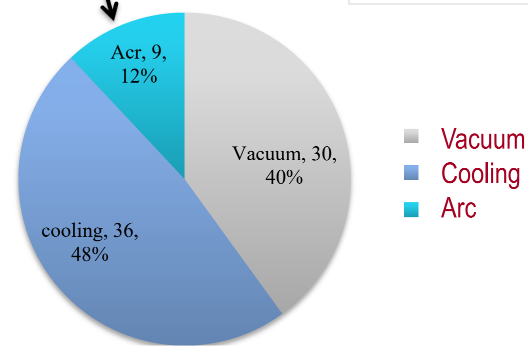


AMP change

Trips @ Usage of Solid-State Amplifier（108）



MTBF:24.4 hours

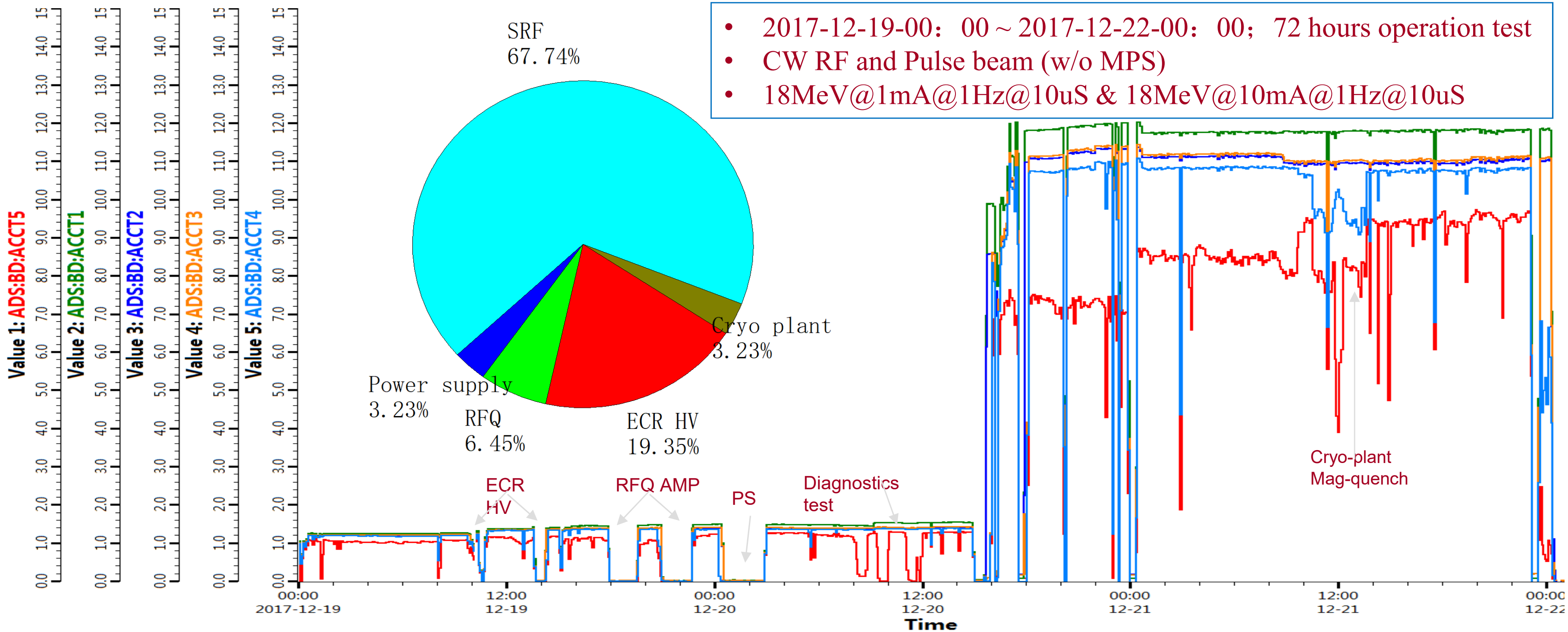


MTBF:11.3 hours

- Alarm of flux meters
- EMC of vacuum gauge
- chiller

Operation Reliability Test low power beam in 2017

- 2017-12-19-00：00 ~ 2017-12-22-00：00；72 hours operation test
- CW RF and Pulse beam (w/o MPS)
- 18MeV@1mA@1Hz@10uS & 18MeV@10mA@1Hz@10uS



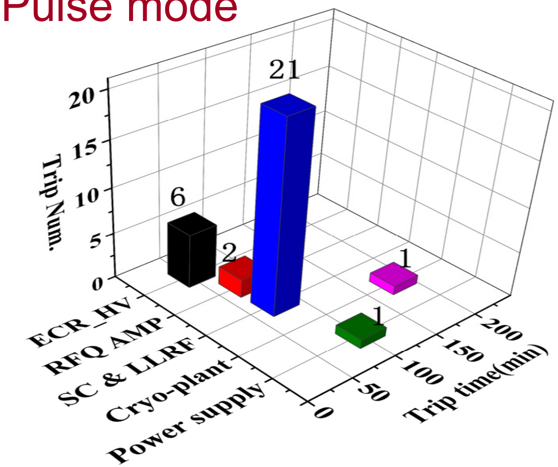
Preliminary RAMI analysis w/o active protection

Operation time	Beam time	Down time	Availability
4050 min	3566 min	484 min	0.88

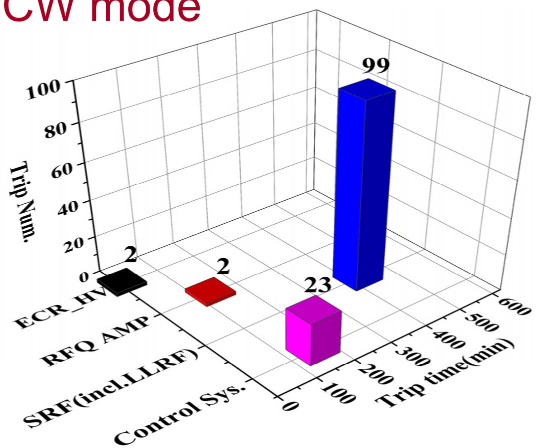
MTBF (min)	MTTR (min)	Beam trips (10s-5min)	Beam trips (>5min)
111.4	16.1	20	10

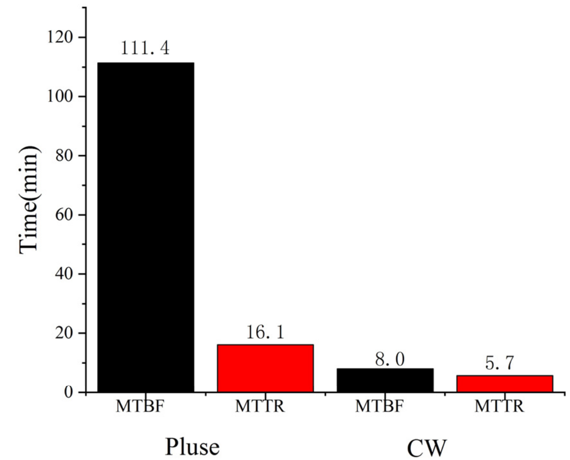
	ECR HV	RFQ AMP	SRF (incl. LLRF)	Cryo-plant	Power supply
Beam trips	6	2	21	1	1
Down time	53 min	77 min	78 min	183 min	100 min

Pulse mode

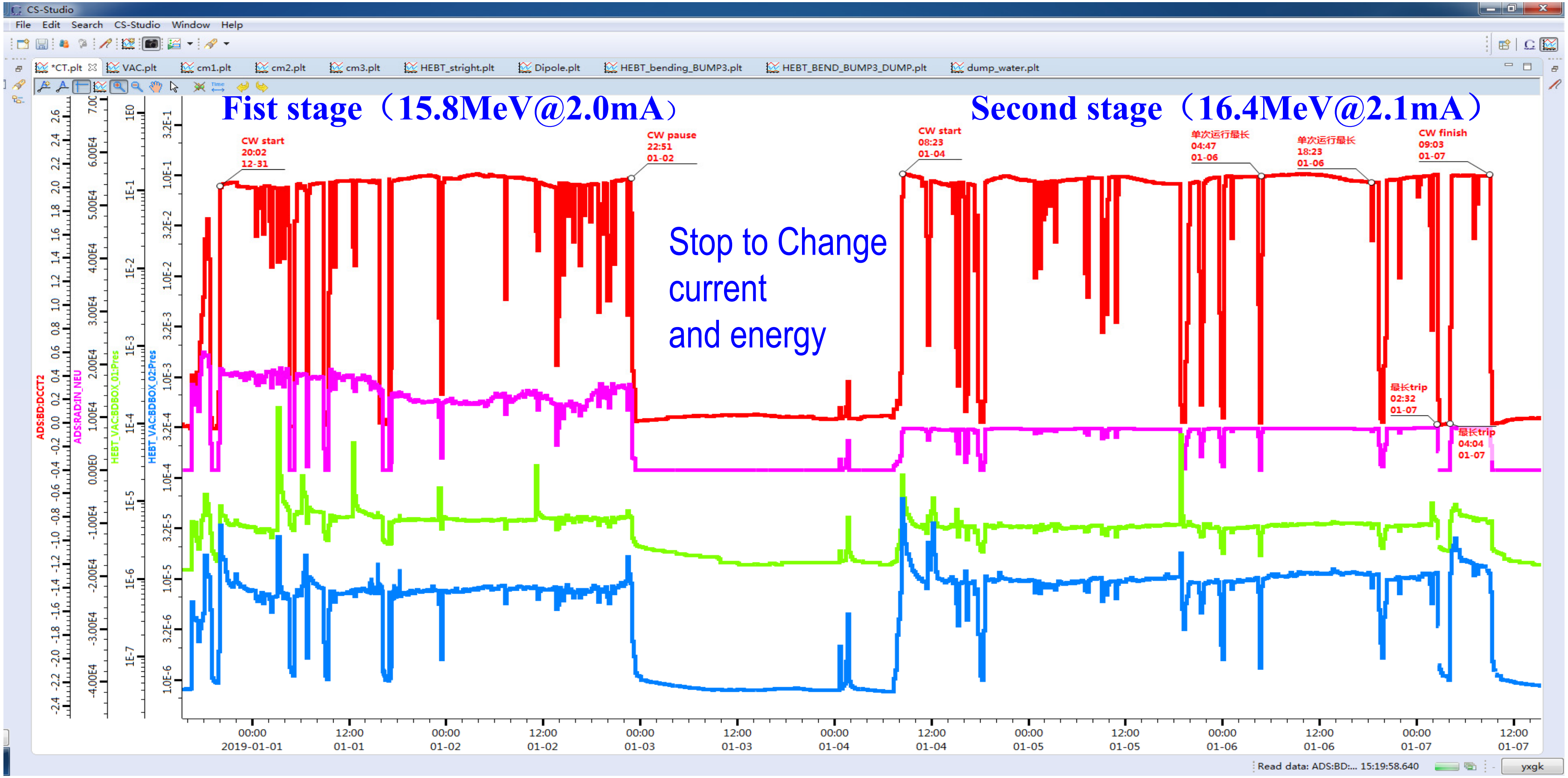


CW mode

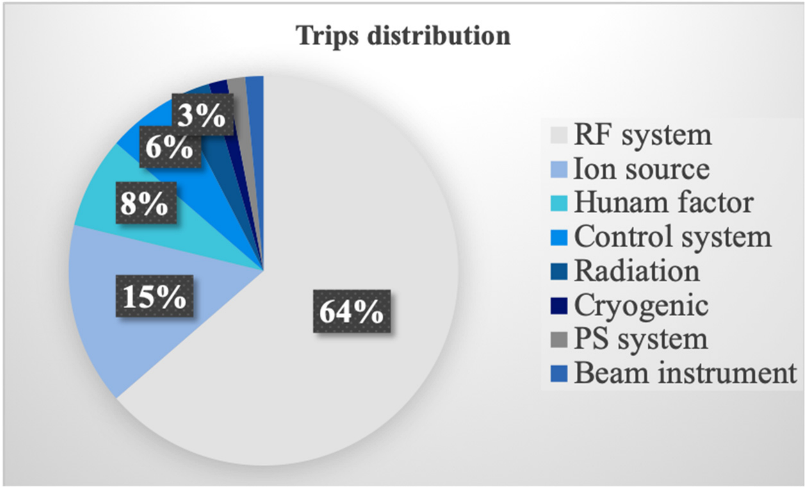


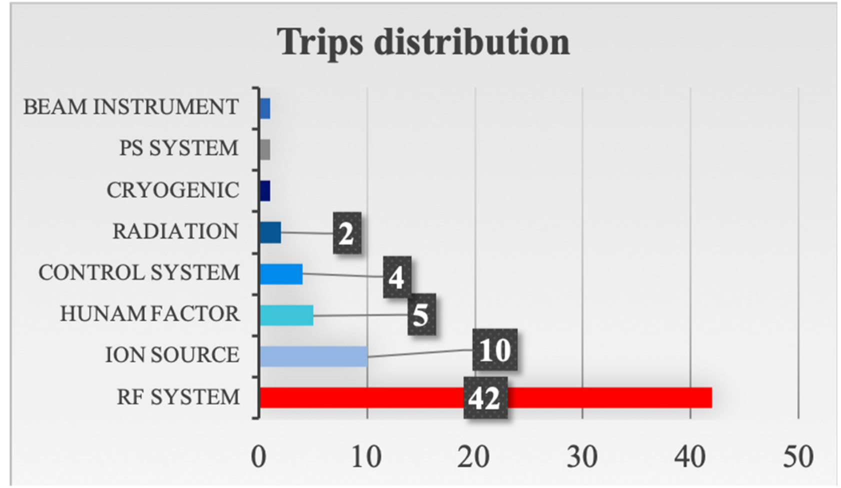


Operation Reliability Test with high power beam in 2019

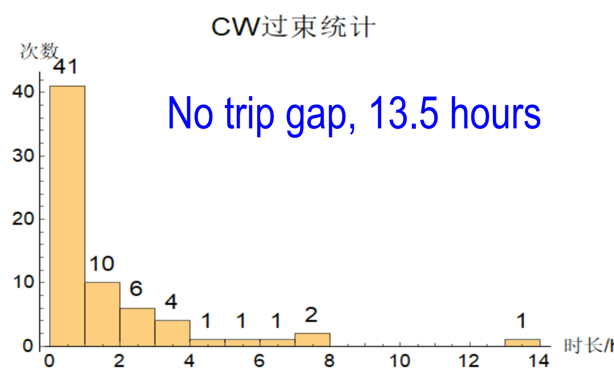


RAMI of CW beam with active MPS





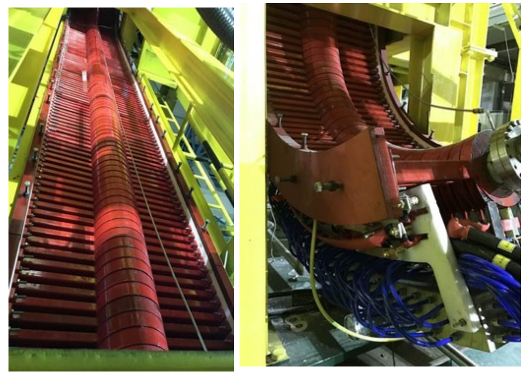
- Operation time 7553 min, downtime 737 min, availability 89%
- Max power is 45 kW with 2.55 mA @17.5 MeV



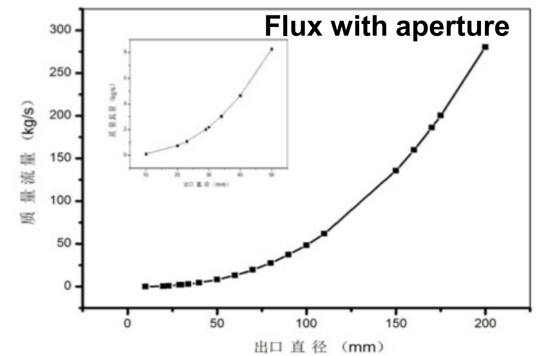
- 1st stage: 2018/12/31 18:44 - 2019/01/02 23:42
- 2nd stage: 2019/01/04 08:08 - 01/07 09:03

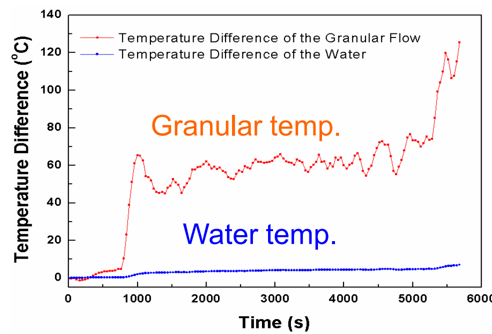
Availability	MTBF	MTTR	Availability	MTBF	MTTR
0.89	90.7 min	11.1 min	0.89	113.7 min	14.6 min

Prototype of granular target

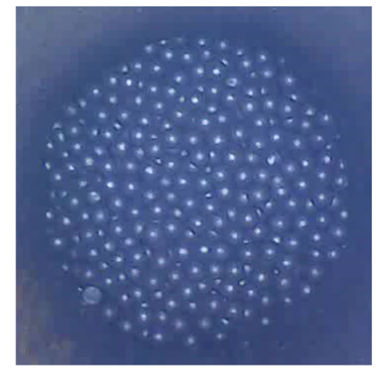


Electro-magnetic lifter





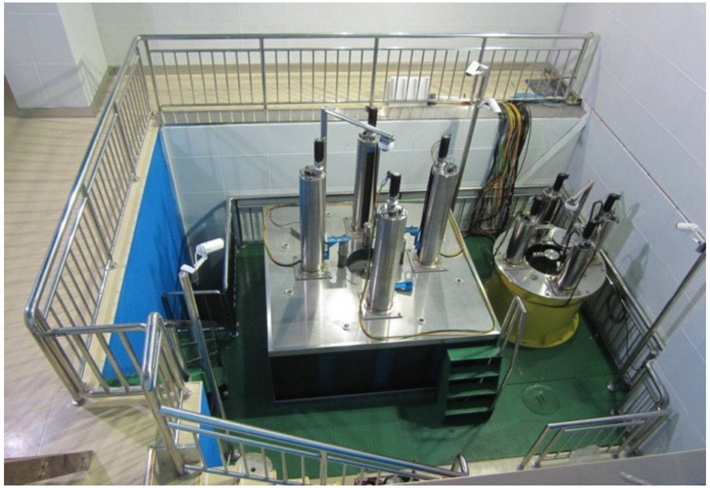
Heat exchange exp.

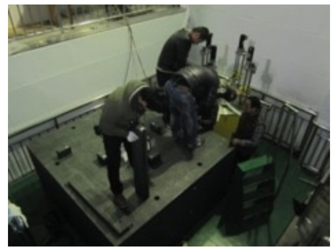


Granular flow

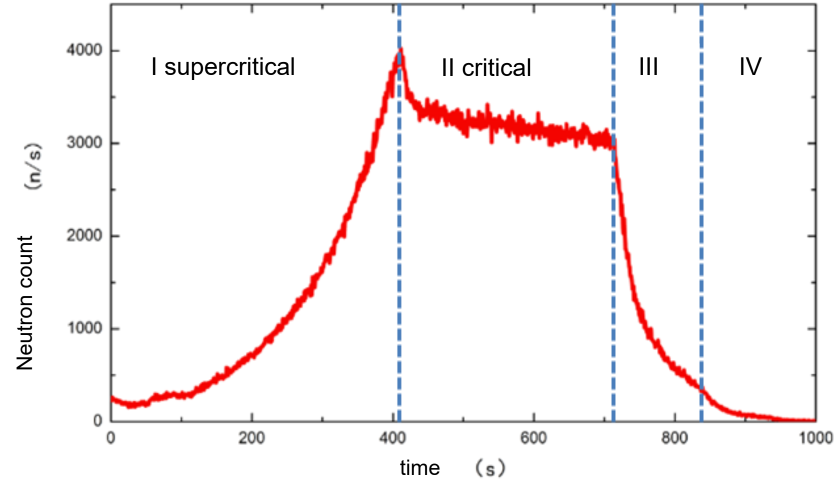
Integral target setup, verify granular flow, heat exchanger, electro-magnetic lifter, purifier, and so on

Zero-Power Lead Reactor





Experiments verified The accuracy of target-reactor coupling calculation and core design



operation monitoring system

Target material	Period method/mk	MCNPX/mk	Relative error/mk
Tungsten particles	-0.932	-0.99	-0.058
Tungsten	-1.144	-1.162	-0.018
Lead	1.322	1.562	0.24

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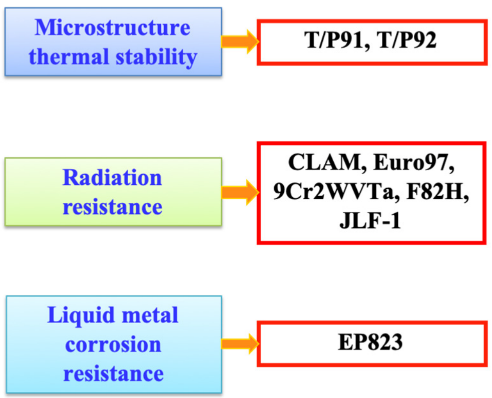
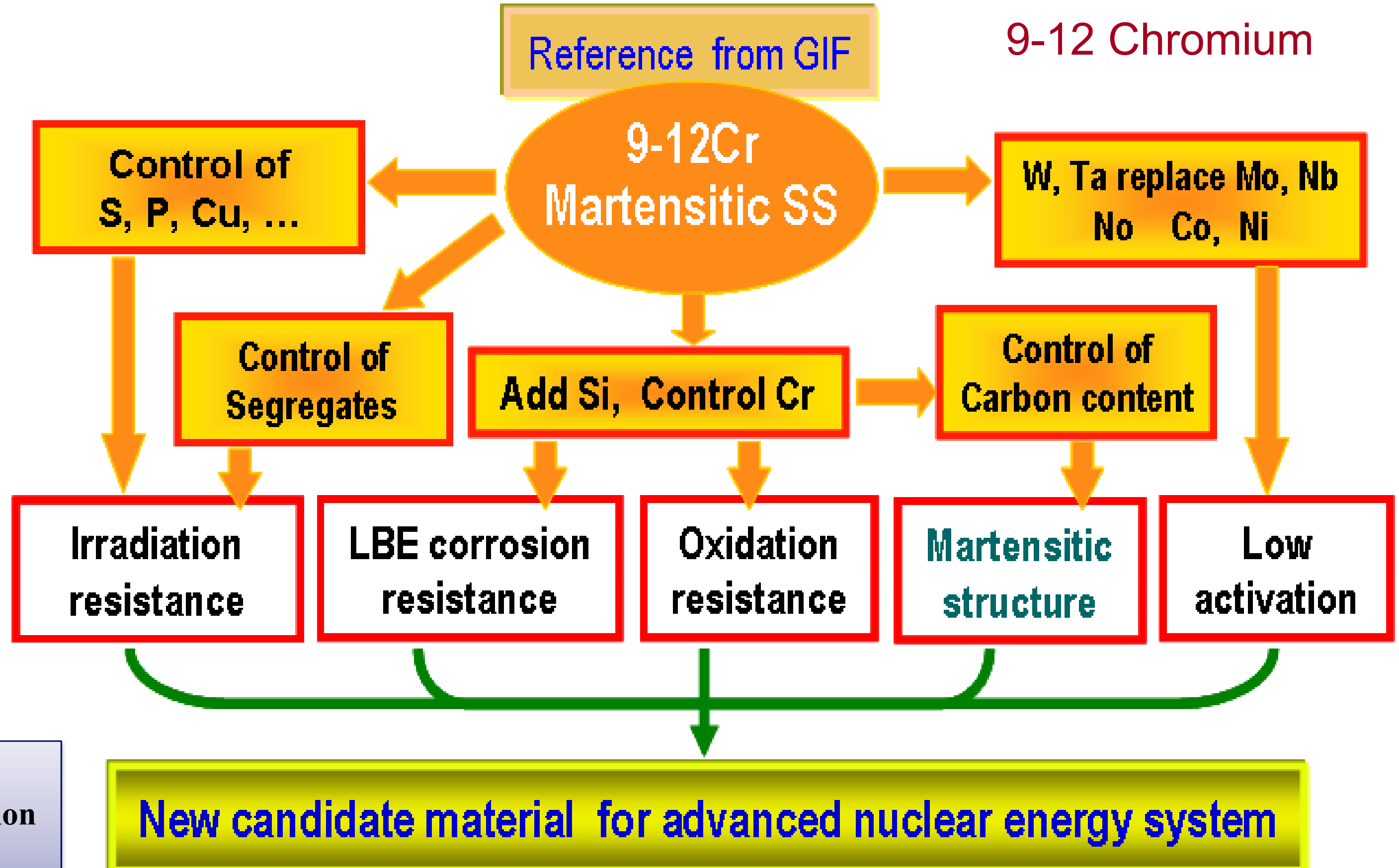
Chemical Composition Design

1%-2% Si containing ferritic/martensitic steels exhibit lower oxidation rate

9-12Cr martensitic steels: have good creep property

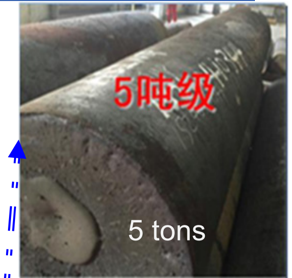


Tempered martensite: Excellent thermal stability and good irradiation and corrosion resistance



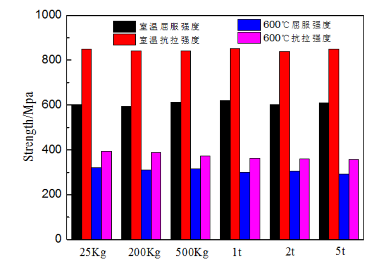
Smelting and Casting of SIMP

- 5 ton
- Industrial grade !

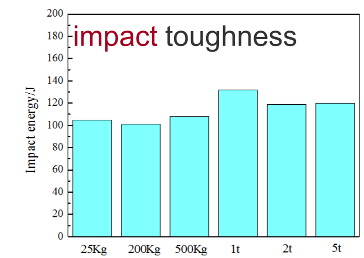


5ton SIMP ingot

stable mechanical properties

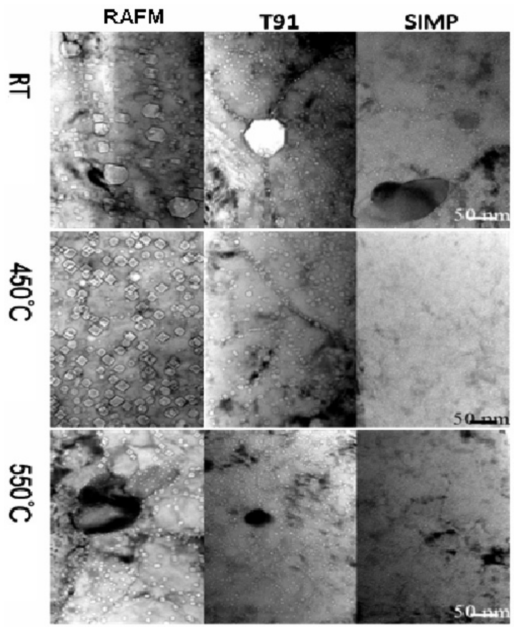


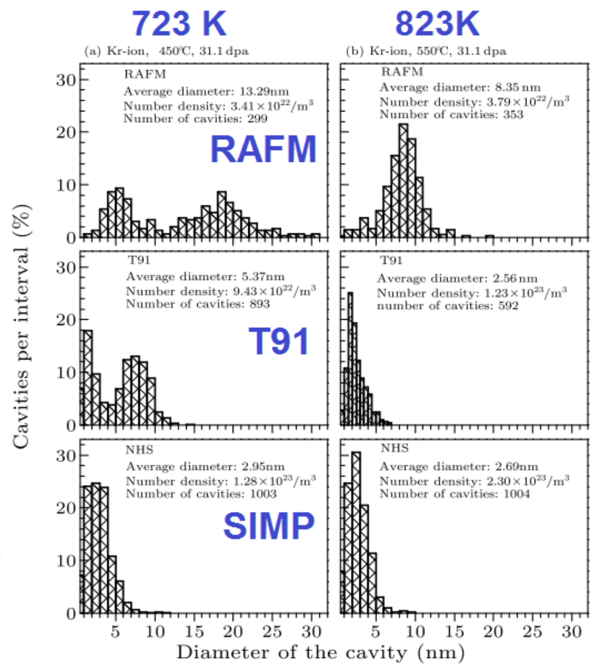
Tensile properties

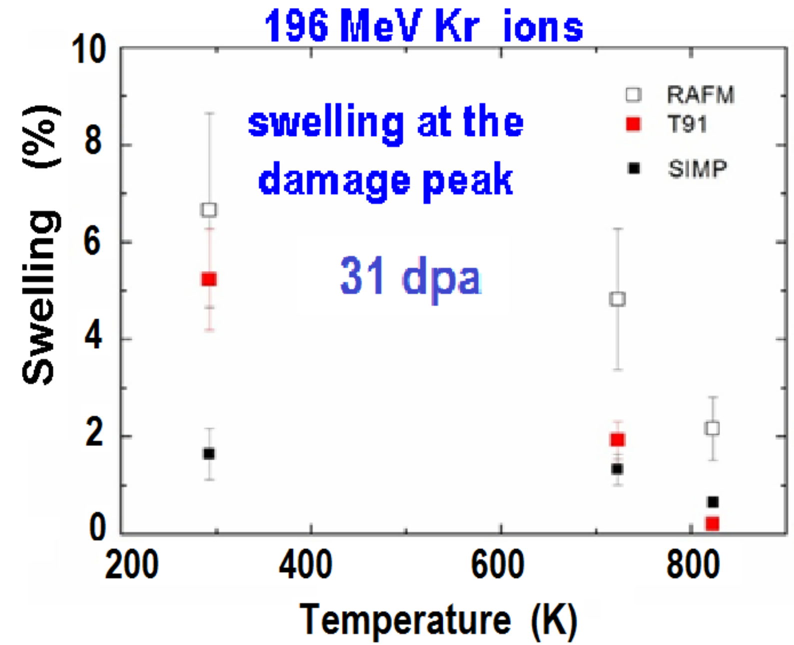


Control: purity, homogeneity

Ion Irradiation Resistance



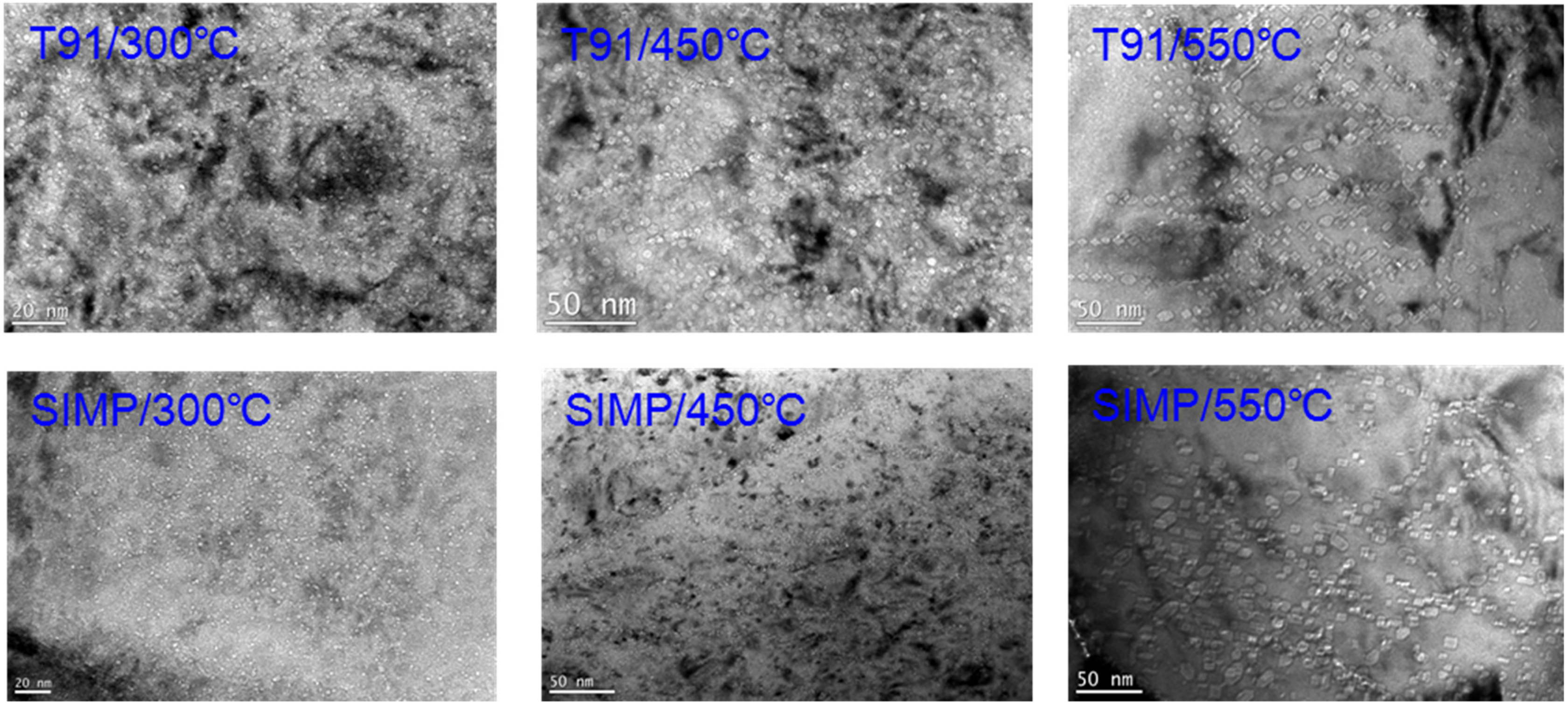




Irradiation at 196 MeV Krypton, 31 dpa; Swelling at the damage peak

Irradiation swelling resistance: SIMP > T91 > RAFM steels

Helium Effect

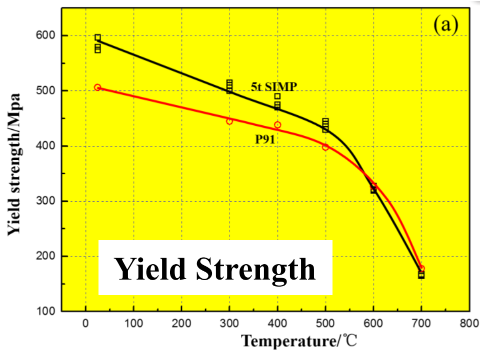


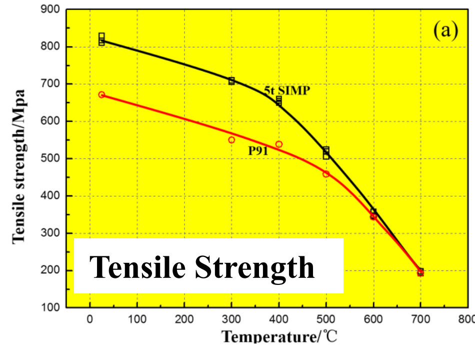
200 keV He ions
Mean size of helium bubbles, 5×10^{16}ions/cm^2

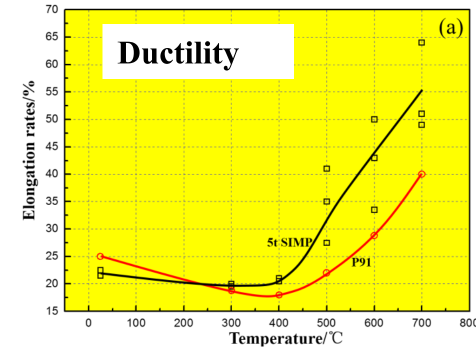
He-bubble size: SIMP < T91 @ 573K ~823 K

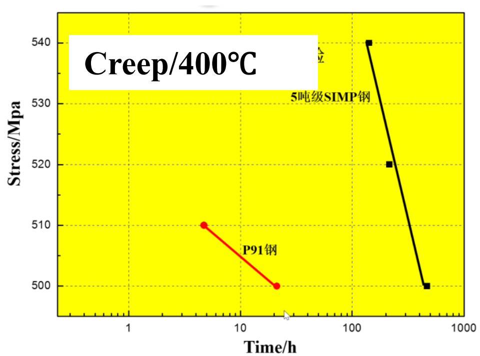
Mechanical Properties

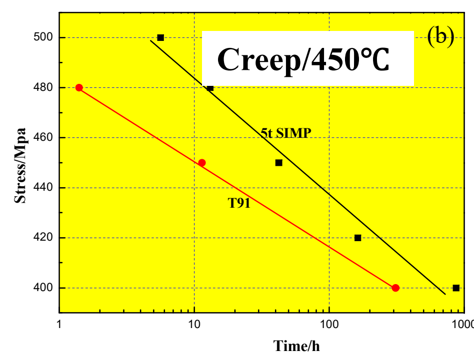
◆ (SIMP steel: normalized at 1050℃, tempered at 760 ℃)

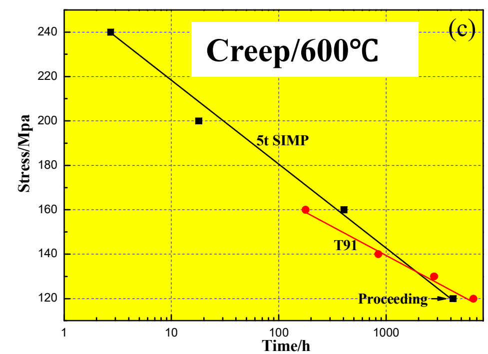








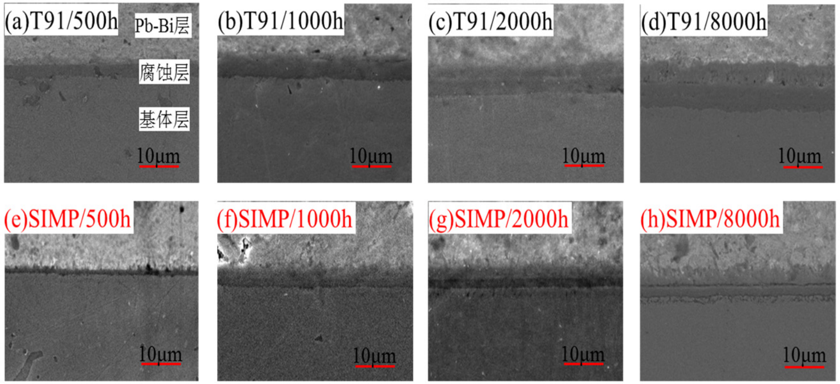




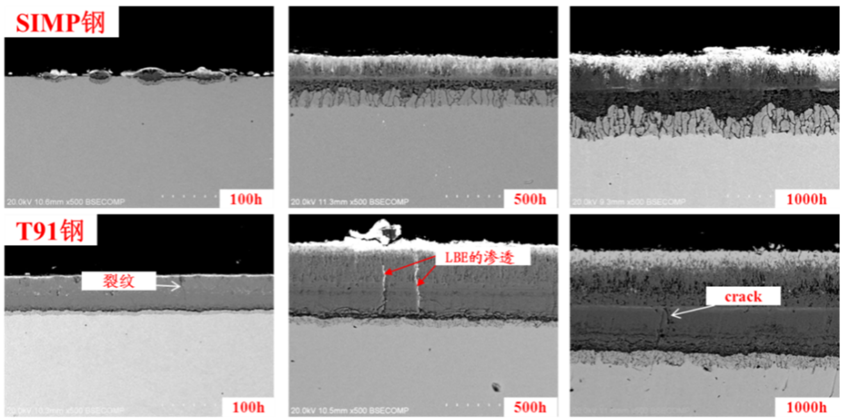
Better than T/P91 in a temperature range from RT to 550 °C

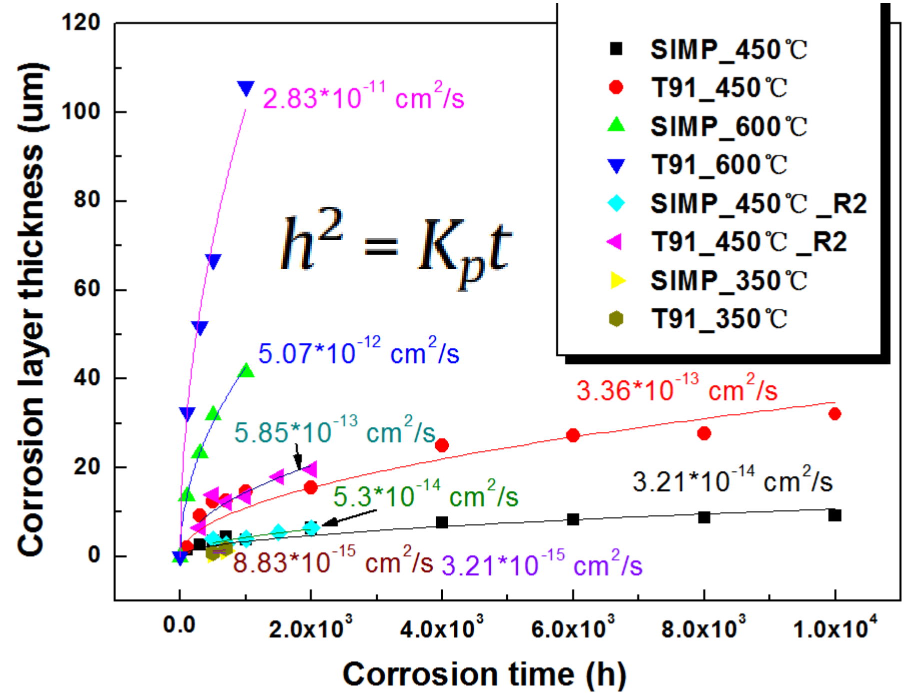
Liquid LBE Corrosion Resistance

600°C



450°C





Liquid LBE corrosion

450°C/600 °C, static, saturation oxygen

SIMP > T91

General Evaluation

Tests	Result
TS/YS/elongation rate at RT-600℃	SIMP ＞ (EP823, T91, RAFM)
Oxidation resistance at RT-800℃	SIMP ＞ (EP823, T91)
LBE corrosion resistance (600℃, static saturation oxygen）	SIMP ＞EP823 ＞ T91
LBE corrosion resistance (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
SC water corrosion resistance (600℃, 25Mpa, 1000h)	SIMP＞TP347, 304 SIMP＞ T/P91, T/P91

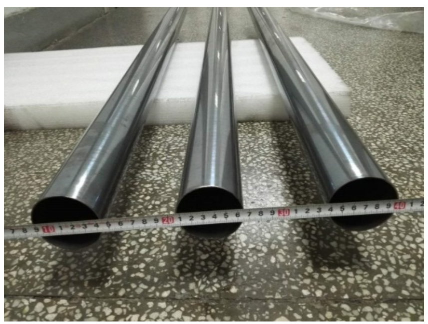
SIMP steels irradiated at SINQ-PSI, (n/p, ～20dpa, 2012-2014)
Post Irradiation Examination (PIE) is under way, more results is coming.

LBE Bump Prototype using SIMP

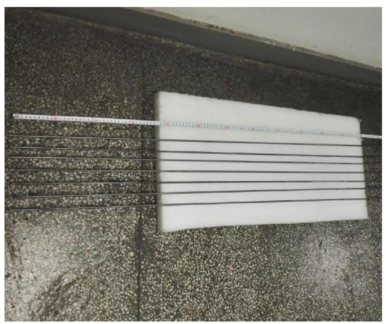
➢ Tubes/pipes

Φ60mm×10mm

Φ60mm×5mm



Φ60mm×1mm



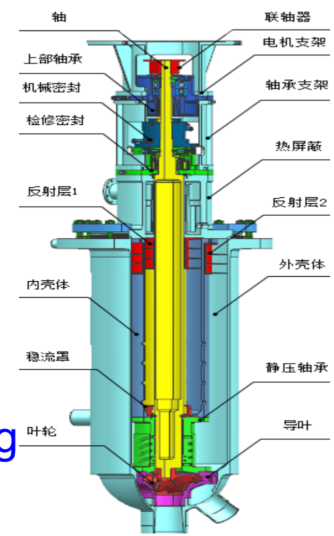
Φ5mm×1mm

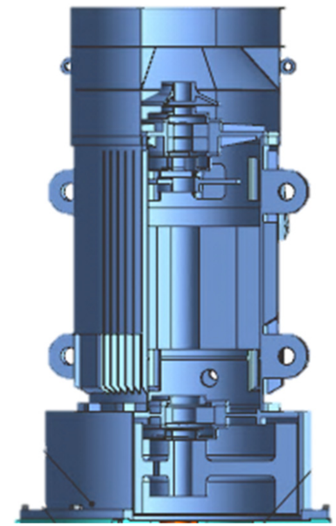
➢ Panel / plate

➢ Liquid LBE centrifugal pump

30kW
2950r/min

The pump is currently being manufactured

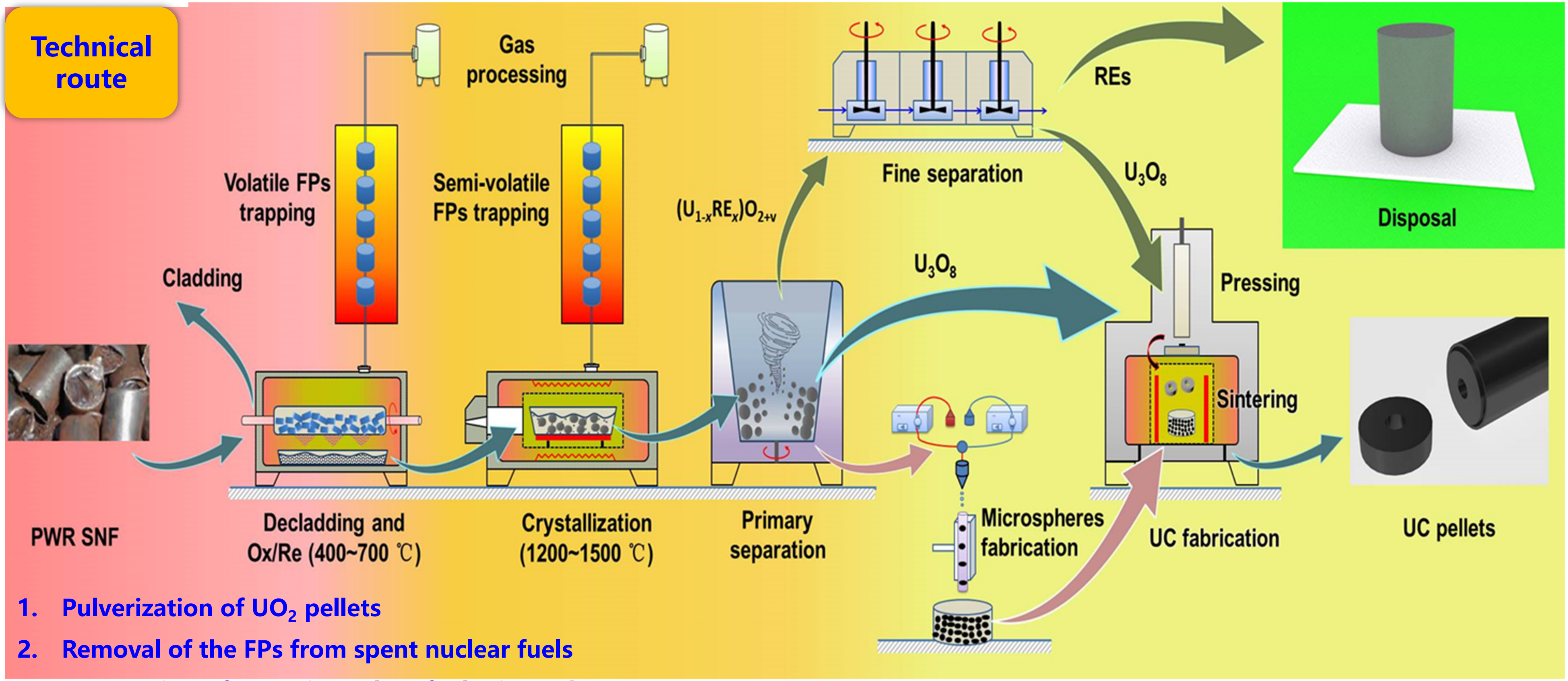




Outlines

- **Background and concept of ADANES**
- **Introduction of CiADS**
- **Progress of key technologies**
  - **Accelerator, Target and Reactor**
  - **Materials SIMP**
  - **New Approach of Fuel recycle**
- **Conclusion**

Technical Route of Reprocessing & Fabrication

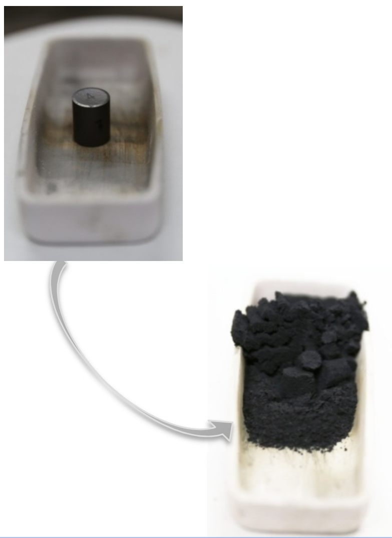


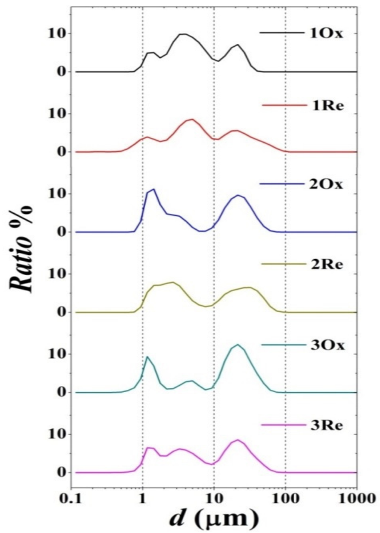
1. Pulverization of UO_2 pellets
2. Removal of the FPs from spent nuclear fuels
3. Preparation of ceramic nuclear fuel microspheres

Pulverization of Pellets & Removal of Volatile FPs

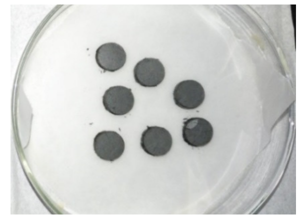
Pulverization & Ox/Re of real UO_2 pellets

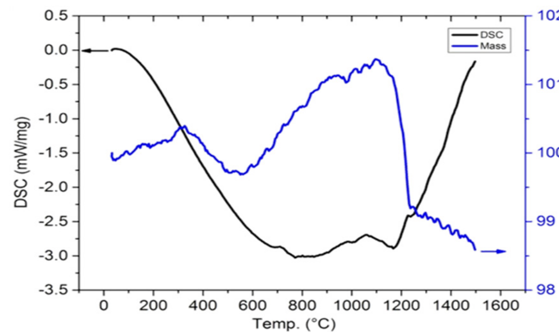
- **Oxidation：air, 450 ℃, 4 h**
- **Reduction：4% H_2-Ar, 700 ℃, 4 h**





Removal of the volatile fission products from spent fuel by the Voloxidation Process

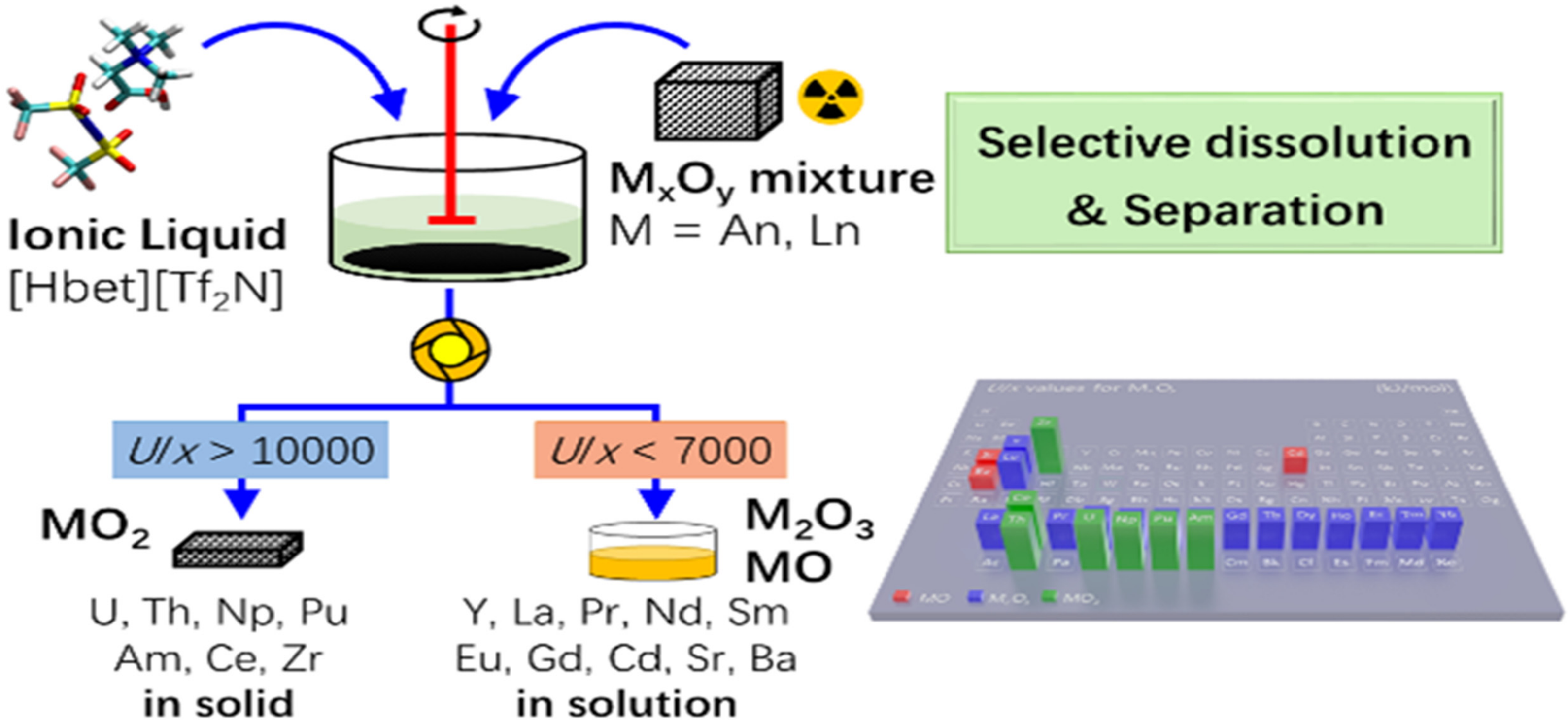




Element	Mo	Cs	Ru	Te	Rh	Se
Removal% (1200 ℃)	95	90	~50	82	＜5	100

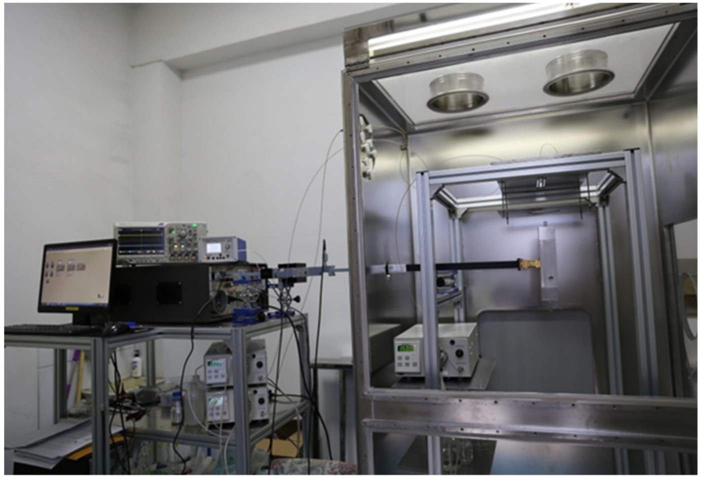
New Approach to Spent Nuclear Fuel Recycle

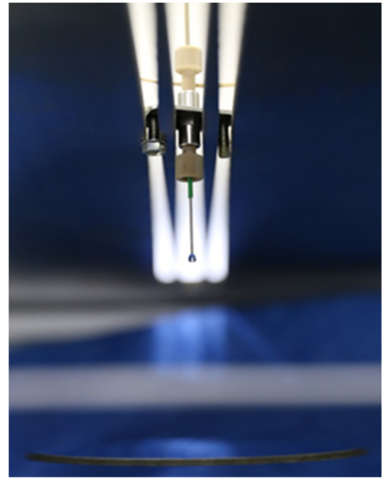
Highly Efficient and Selective Dissolution Separation of Fission Products from Spent Nuclear Fuels by an Ionic Liquid, [Hbet][Tf2N]



Fang-Li Fan et al., Inorg. Chem. 2019 58(1) 603-609

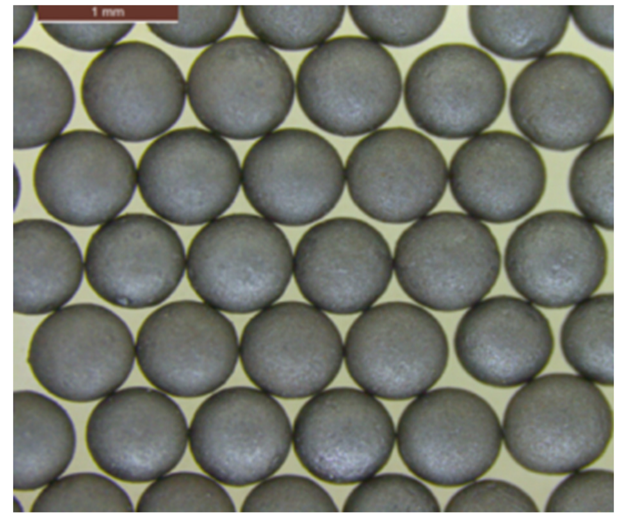
Preparation of ceramic nuclear fuel microspheres





In-situ mixing internal gelation-microwave heating device

Optical image of UC ceramic microspheres



Preparation of UC ceramic microspheres by an improved microwave-assisted rapid internal gelation process combined with carbothermic reduction

UC ceramic microspheres

size: Ø 675 μm

density : 12.53 g/cm^3 (92% TD)

Wei Tian et al., Ceramics International 44 (2018) 17945–17952

Outlines

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- Conclusion

Conclusion

- The ADANES was proposed as a new closed fuel cycle system, aiming sustainable nuclear energy.
- The CiADS (prototype of ADB) started earthwork in last August. It is planned to commission in 2024.
- The front-end demo CAFe (25 MeV superconducting linac) started commissioning in 2017. It has achieved max beam power of 45 kW with 2.55 mA @ 17.5 MeV. It operated at 2 mA more than 100 hours. 100 kW beam power, rapid recovery and long-term operation is the next goal.
- The granular flow spallation target was proposed to be a candidate for 10 MWs application. A prototype was built and tested.
- The SIMP steel was developed for the use to LBE related nuclear energy systems. The experimental results show that its property could be better than other candidates.
- The new recycle procedures of Spent Nuclear Fuel for ADB was proposed, and it is proved with SIMFUEL in IMP laboratory.

Thanks our team and worldwide collaboration in the past!

Thank you!
Welcome collaboration!