EU – China collaboration on CFETR and EU-DEMO Reactor Design
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A Phased Roadmap for the Development of Fusion Reactor Materials in China

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Outline

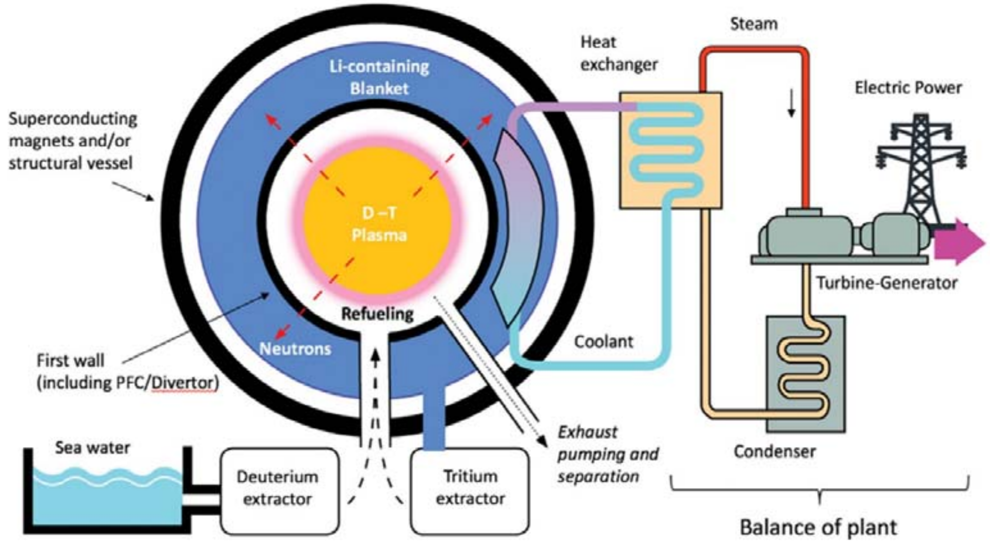
- ❖ Service environments and requirements of fusion reactor materials
- ❖ A phased roadmap for fusion reactor materials
- ❖ Recent R & D progress of fusion reactor materials in China

Service Environments and Challenges of FRMs

- Materials determine the economy and advancement of nuclear energy applications, and are also the design basis and safety guarantee of nuclear power plant.
- After D-T fusion, a large number of hydrogen isotopes and helium bombard the first wall, resulting in high heat and surface damage, and 14 MeV neutrons carry most of the energy, causing radiation damage to the materials, and producing tritium and heat transfer in the blanket.
- Materials with radiation and high-temperature resistance are one of the major bottlenecks in the application of fusion energy.
- However, there are different requirements for fusion reactor materials at different stages of fusion energy development.

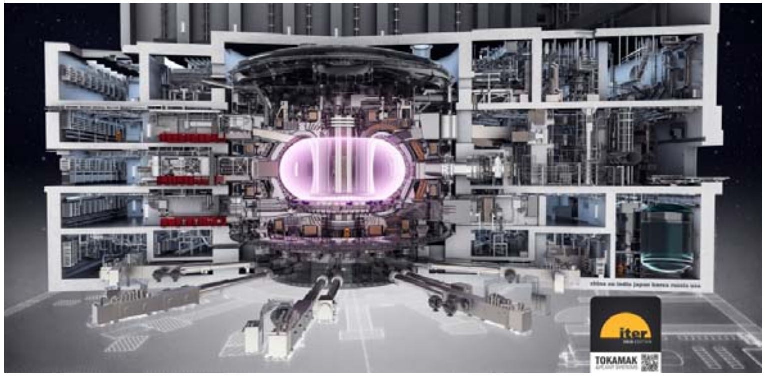
$$D + T \rightarrow {}^{4}\mathrm{He}(3.5\ \mathrm{MeV}) + n(14.1\ \mathrm{MeV})$$

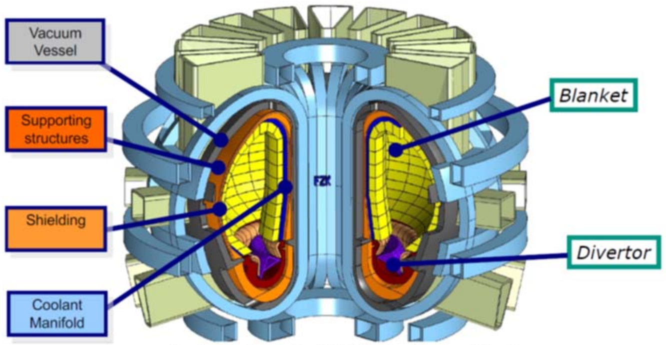
Tritium half-life: $T_{1/2}$=12.43 y



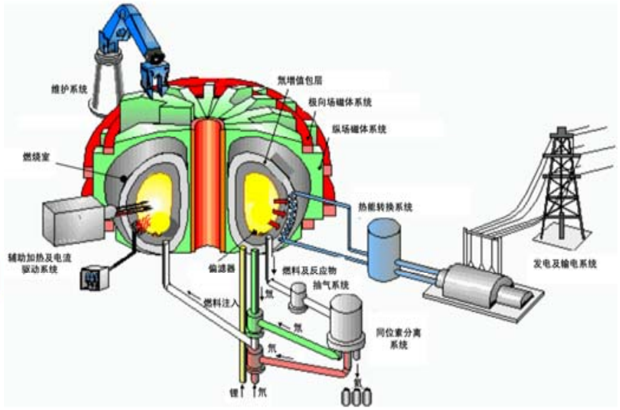
Steven J. Zinkle, MRS BULLETIN • VOLUME 47 • OCTOBER 2022

Materials from ITER to DEMO to FPP





Basic Design of a FPP (Fusion Power Plant)



	ITER	DEMO	FPP
Fusion Power [MW]	500	2000 (@500 Pel)	2500-5000 (@1500 P_{el})
Operation scenario	Pulsed (400s/1200s)	Pulsed (2h/10-20m)	Stationary or long pulses (~8h)
Plant lifetime [cal. y]	~20	20-25	~ 30 y
Duty factor [%]	Very low	30	75-80
NWL [MW/ m^2]	0.78 (max at TBM)	~1.0 (av)	2.0-2.4 (av)
Operation time [fpy]	< 0.38	7	25
Neutr. Load [MW/m^2·a / dpa(Fe)]	<0.3 / 3	7 / ~70	50-60 / ~500-600

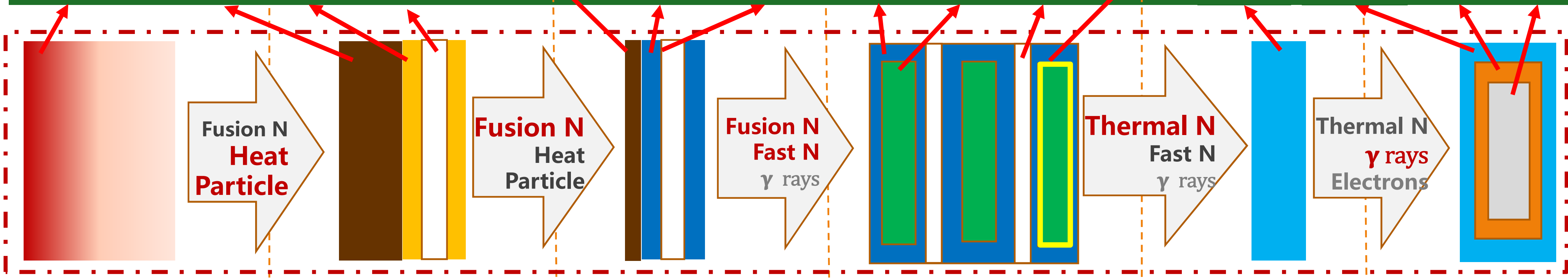
Boccaccini, 6th IAEA DEMO Workshop, 2019

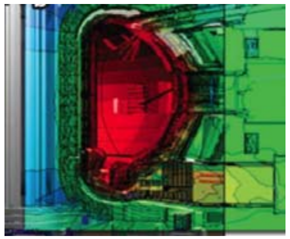
ITER uses mature materials, such as pure Tungsten, 316L SS;
Radiation damage is related to the service environment and operation mode

Different Components in Fusion Reactor

Plasma Core	Divertor	First Wall	T-Blanket	Vacuum V	SC Magnet
D-T fusion, production of fusion neutrons and helium particles and hydrogen isotopes	Removal of particles or helium ash; Resistant to high thermal loads	Shields other components from thermal heat and plasma bombardment	Tritium breed and recovery, shielding other components from neutron irradiation, and extracting heat energy	shielding outside components from neutron and γ irradiation	Provide strong magnetic fields; structural support and insulation at low temperatures

Plasma Core | PFM | Heat sink | Cooling Channel | PFM | Struc. M | Cooling Channel | Struc. M | Breed M | Cool Ch. | FCI | Struc. Steel | Low-T Steel | Low-T Resin | SC M





N Flux: 3E22/cm^2
P Flux: 1E24/m^2.s
Heat: ~20 MW/m^2
PFM T: 1-2E3 ℃

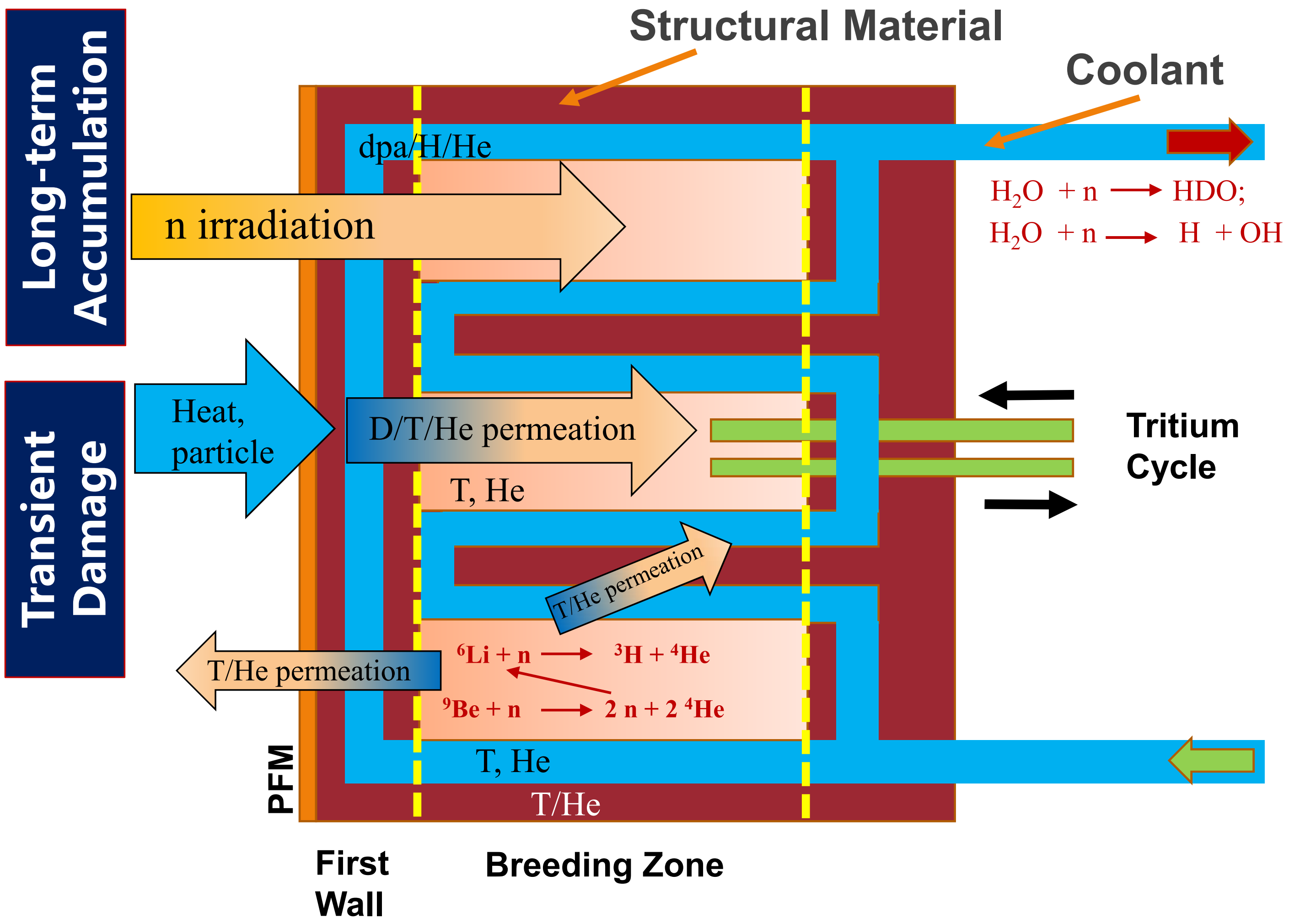
N Flux: 5E22/cm^2
P Flux: 1-10E20/m^2.s
Heat: ~1 MW/m^2
PFM T: 0.5-1E3 ℃

N Flux: ~1E22/cm^2
WC-Blk: 350-550 ℃
HeC-Blk: 350-650 ℃
LL-Blk: 350-850 ℃

N Flux: 1E20/cm^2
Working T: 100-400 ℃

N Flux: 5E15/cm^2
Working T: -268.7--266 ℃

Service Environments of FRMs in Blanket



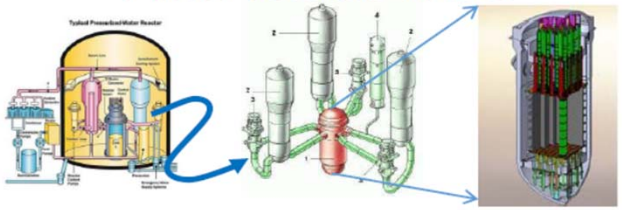
- PFMs could be tested mostly by ITER/BEST or other plasma devices;
- Materials in FW and blanket need to be tested by reactors or neutron sources;
- As a whole, lifetime of blanket and replacement frequency are determined by the weakest material within.

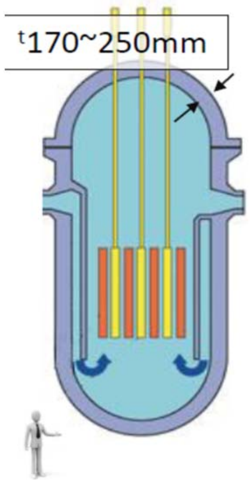
Materials in Main Components of FR

	Divertor	First Wall	Breeding Blanket	VV	SC Mag.
PFM	W-based alloy (ODS-W, etc.), W-coated SiC_f/ SiC; flowing liquid metal: Li, Ga, Sn, Sn–Li	W, W-based alloy, W-coated SiC, Be, W-coated ODS/RAFM steels, flowing liquid Li	as in the first wall		
Heat Sink	Copper alloys (PH and DS copper)				
Structural M	ODS steel, W-based alloy	RAFM steel, ODS steel, V-based alloy, SiC_f/SiC	RAFM steel, ODS steel, V-based alloy, SiC_f/SiC, SiC-FCI		
T-breed M			Liq.Li, Eutectic Pb–Li, Li-based ceramic pebbles		
N-multi. M			Be, $Be_{12}Ti$, $Be_{12}V$, Pb		
T Barrier			Oxides, Nitrides		
Coolant	Water, He	Water, He, Super-critical CO_2, Eutectic Pb-Li, Li	Water, He, Super-critical CO_2, Eutectic Pb-Li, Li		
SC Mat.					Ni-based SC、HT-SC
Struc. Steel				316L series	Low-T Steel
Insulation M					Insul. resin
Replaceability	**Replaceable**	**Difficult (as blanket)**	**More difficult**	**cannot**	**cannot**

Structural Materials in PWR and FR

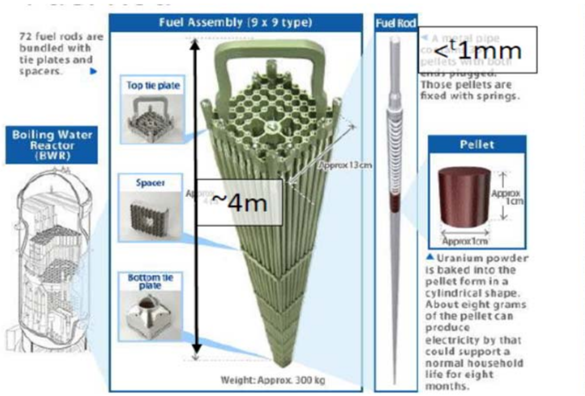
PWR Pressure Vessel





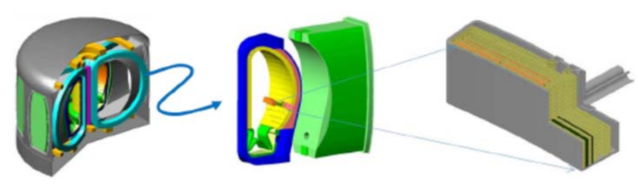
- **Thick-walled**-cylindrical/hemispherical structure, rarely welded
- **Non-replaceable**
- Uniform irradiation over the entire structure
- **Low-dose** low-energy neutron irradiation
- Thermal stress caused by start-stop or transient overpressure

PWR Fuel Assembly ⟷ FR Breeding Blanket



- The fuel cladding is a **thin tube** without welding
- **12-18 months replacement** Irradiation is uniform over the entire cladding
- **High-dose** fission neutron irradiation
- Thermal stress is caused by start-stop or transient overpressure

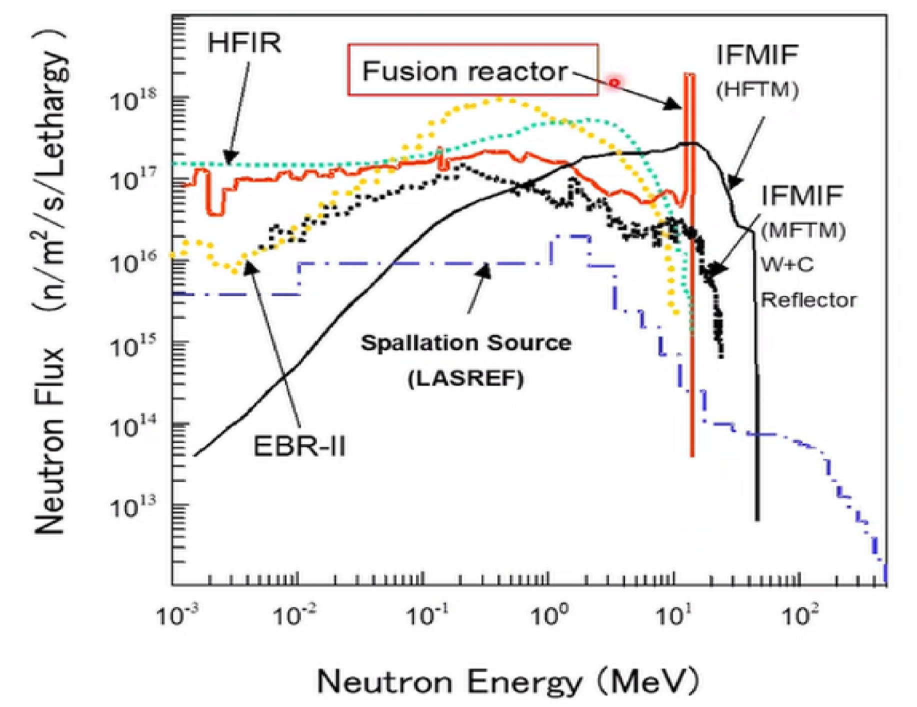
FR Breeding Blanket



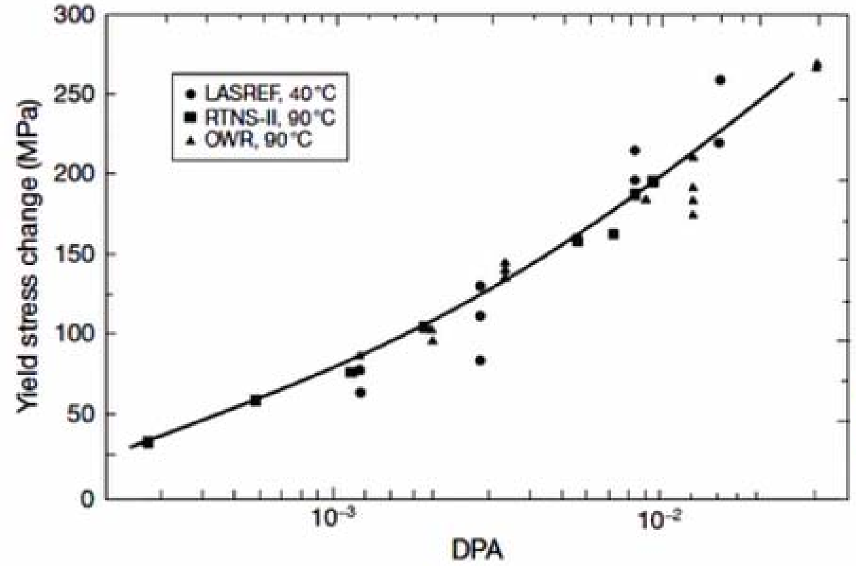
- **Thin-walled**-box-shaped structure, many welds
- **Somewhat replaceable** (depending on material)
- ***High-dose fusion neutron irradiation***
- There is a large irradiation dose gradient (about an order of magnitude decrease per 10 cm neutron flux) at a distance of several tens of centimeters, and the **neutron energy gradually decreases from 14 MeV to fast neutron energy**
- Stresses are due to electromagnetic forces , coolants, thermal stresses, and magnetic forces

FR blanket is similar to PWR fuel assembly in terms of replaceability and safety, and the structural material in blanket is similar to that of fuel cladding in PWR

Fusion and Fission Neutron Irradiation



Neutron spectrum determines cross-section of the nuclear reaction in the reactor and the pathway of radiation damage.

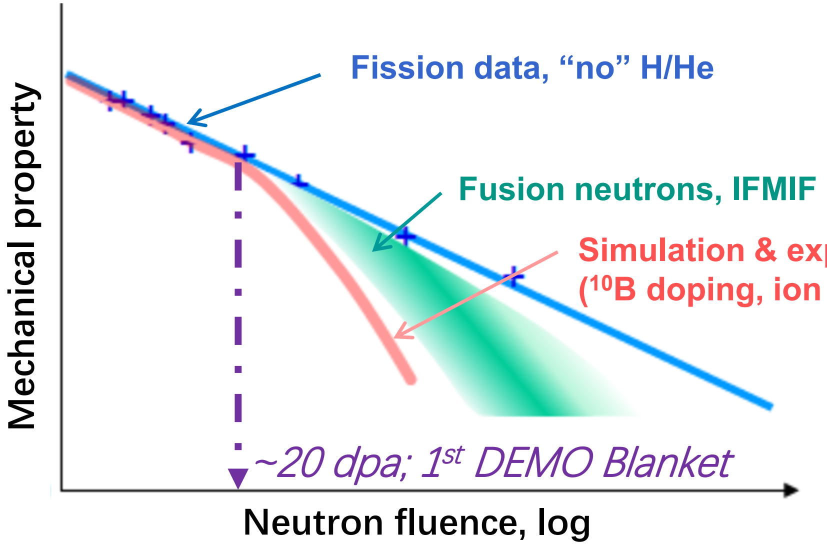


L.R. Greenwood, J. Nucl. Mater. 216 (1994)

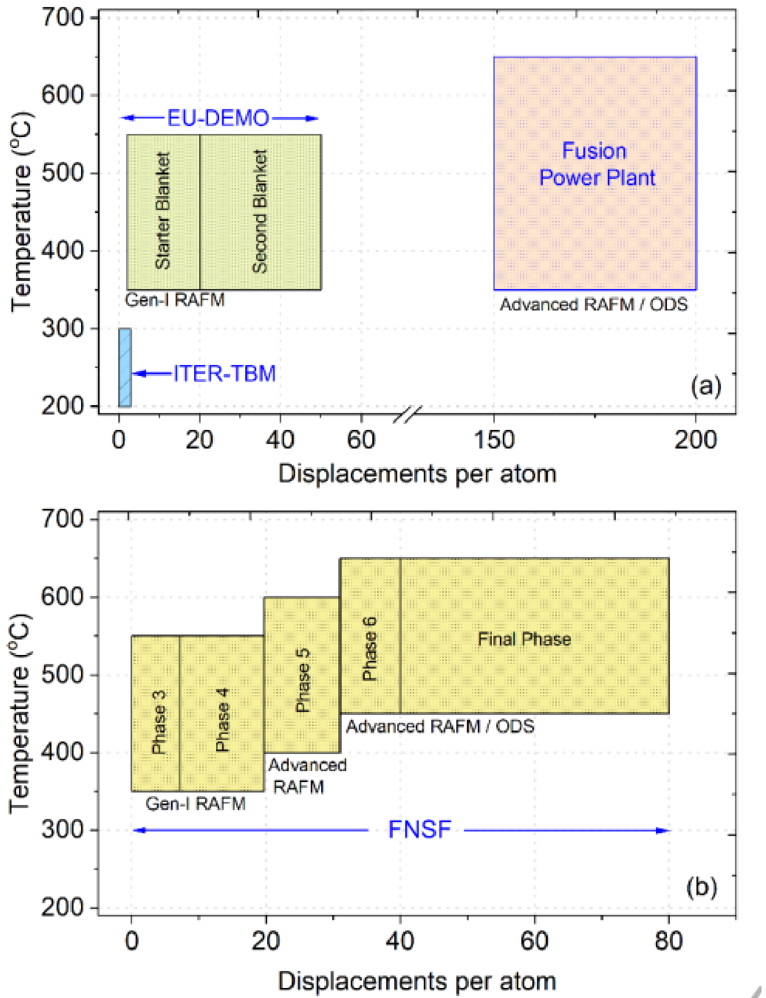
Transport in the blanket, part of fusion neutrons moderates to fast neutrons. Using fast neutrons from fission reactors for low-dose irradiation evaluation of fusion reactor materials has good similarity.

Strategy of FRM Application

- **Within 20 dpa, the irradiation effect of 14 MeV fusion neutrons is similar to that of fission neutrons.**



Since high-flux fusion neutron source is not available in 10 years, choosing of different materials in different phases has been proposed.

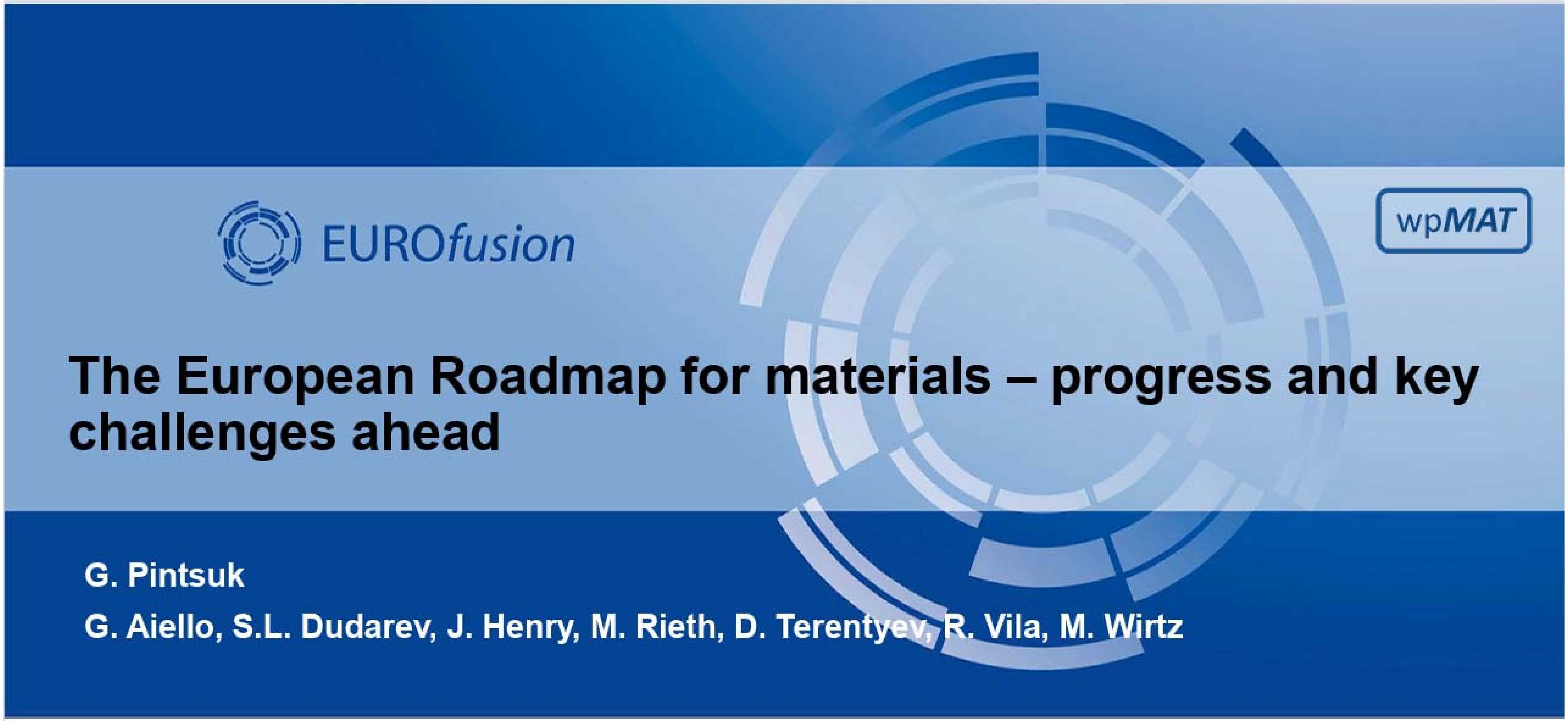


A. Bhattacharya, *J. Phys. Energy* 4 (2022) 034003

Outline

- ❖ **Service environments and requirements of fusion reactor materials**
- ❖ **A phased roadmap for fusion reactor materials**
- ❖ **Recent R & D progress of fusion reactor materials in China**

R&D Roadmap of FRM - Europe



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R&D Roadmap of FRM - UK

Key waypoints in fusion landscape	2020	2024	2028	2032	2036	2040
	• STEP concept design starts	• ITER first plasma • STEP concept design review	• DEMO Conceptual Design Consolidation	• STEP build starts	• ITER high power operation	• STEP first plasma • DEMO build starts

Fusion Roadmap driver	Materials Roadmap	Near Term	Stretch Targets / Disruptors
New regulatory framework for fusion without high level waste	**Enable low activation waste predominance in fusion**	▪ Weldable, cost-effective Reduced Activation Ferritic Martensitic (RAFM) structural materials ▪ High purity raws for armour, structure, divertor baseline materials ▪ Full tritium inventory model across plant material interfaces (first wall, cooling circuit, detritiation plant)	▪ 'Dust'-free armour materials for safe recycling
Breeding ratio >1; fuel self sustainability	**Boost breeding ratio, block tritium losses**	▪ New breeder materials beyond orthosilicates and titanates, developed via UK compact neutron source facility ▪ Mitigate segregation of non-multiplying zones in $BeTi_{12}$ amplifier ▪ Tritium permeation barriers for balance of plant	▪ Additive manufactured Li ceramic as continuous blanket ▪ Feasible alternative multipliers ($LaPb_3$, Zr_5Pb_4, YPb_2) ▪ Optimised tritium extraction microstructures
High fusion energy through effective confinement at high magnetic fields (>8T)	**Define the possible in irradiation resilient magnets, insulation at cryogenic temperatures**	▪ Irradiation tests on REBCO to E>0.1MeV / ~0.001 dpa (current limit) at operating T, spectrum, B ▪ Improved insulation e.g. novel amorphous ceramics or imides ▪ Understanding of annealing path in irradiated cryogenically-cooled resistive aluminium	▪ Cryogenic irradiation tests on REBCO beyond ~0.001 dpa (aiming for overtest to 0.1dpa)
Plant efficiency (100 MWe)	**Develop higher temperature structural materials (>550°C)**	▪ Fabrication-scale microstructural tuning of castable complex nanostructured alloys (carbide / nitride / more inert precipitates) to reach >600°C ▪ Optimised SiC-SiC composites (nanostructured SiC fibre for enhanced irradiation resilience; pyrolysis free interphases; transmutation gas routine architecture)	▪ Weldable and lower cost ODS / HiP'd powermetallurgy variants to reach 700°C ▪ Additive manufactured divertor materials with integrated cooling structures ▪ Thermo electric first wall /divertor material for direct plant output contribution
Plant availability (50%) and cost (£10bn)	**Deliver engineering assurance for materials under powerplant conditions**	▪ Synergistic dual ion beam irradiation campaigns (proton + load; proton + corrosion; proton + cryo) on baseline materials for low dpa mechanical property degradation ▪ First Finite Element based failure prediction models *across* microstructures ▪ Simulated in situ (dose-temperature conditions) material response via 'whole problem approach' utilising physics-derived atomistic response laws	▪ Synergistic irradiation campaigns (neutron + load; neutron + corrosion; neutron + cryo) on baseline and novel materials with emphasis on high dpa impact quantification on mechanical properties (especially creep-fatigue) ▪ Stitched length- and time-scale failure prediction models ▪ Modelled transmutation gas impact on mechanical degradation

UK Fusion Roadmap 2021-2040 United Kingdom Atomic Energy Authority

General Strategy of FRMs Roadmap in China

- The development of FRMs in China should match with the requirements of Chinese Fusion Roadmap at different stages and in different service environments.
- The roadmap of FRMs needs to have a time schedule
- There are three major missions:

1. Developing of new fabrication techniques for ODS-steel, Copper Alloy and etc.; improving of material properties of Chinese RAFM-steel, pure tungsten and etc.
2. Using CRAFT/BEST to test PFMs and some functional materials; using fission reactors, spallation source to obtain irradiation data of FRMs and triple-beam ion-irradiation to benchmark multiscale simulation; standardizing of small specimen test technology.
3. Constructing of facilities to test irradiation effects of fusion neutrons.

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Neutron Irradiation at Different Fusion Power

Duty Factor: 0.5

Fusion Power	Components	Materials	DPA/ FPY	He (appm/ FPY)	H (appm/ FPY)
200 MW	PFC	W 100%	0.79	1.05	2.57
	First Wall	**RAFM/ODS**	**1.97**	**17.69**	**84.17**
	First Breeder	Mixed Pebble	1.25	1144.60	509.83
	Cu	CuCrZr	0.27	1.51	1.75
500 MW	PFC	W 100%	1.99	2.62	6.42
	First Wall	**RAFM/ODS**	**4.93**	**44.22**	**210.43**
	First Breeder	Mixed Pebble	3.13	2861.50	1274.58
	Heat Sink	CuCrZr	0.67	3.77	4.37
1000 MW	PFC	W 100%	3.97	5.24	12.84
	First Wall	**RAFM/ODS**	**9.87**	**88.43**	**420.87**
	First Breeder	Mixed Pebble	6.25	5723.00	2549.15
	Heat Sink	CuCrZr	1.33	7.54	8.74
1500 MW	PFC	W 100%	5.96	7.86	19.26
	First Wall	**RAFM/ODS**	**14.80**	**132.65**	**631.30**
	First Breeder	Mixed Pebble	9.38	8584.50	3823.73
	Heat Sink	CuCrZr	2.00	11.31	13.11
3000 MW	PFC	W 100%	11.92	15.72	38.52
	First Wall	**RAFM/ODS**	**29.60**	**265.30**	**1262.60**
	First Breeder	Mixed Pebble	18.75	17169.00	7647.45
	Heat Sink	CuCrZr	4.00	22.62	26.22

Platforms for Materials/components Testing

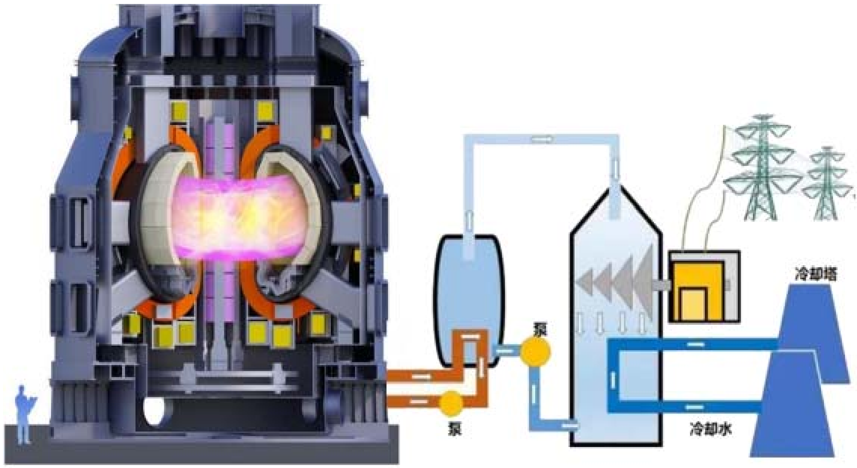
CRAFT

(> 1×10^{24} $m^{-2}s^{-1}$、3T)

High-heat Loading

(860kW)

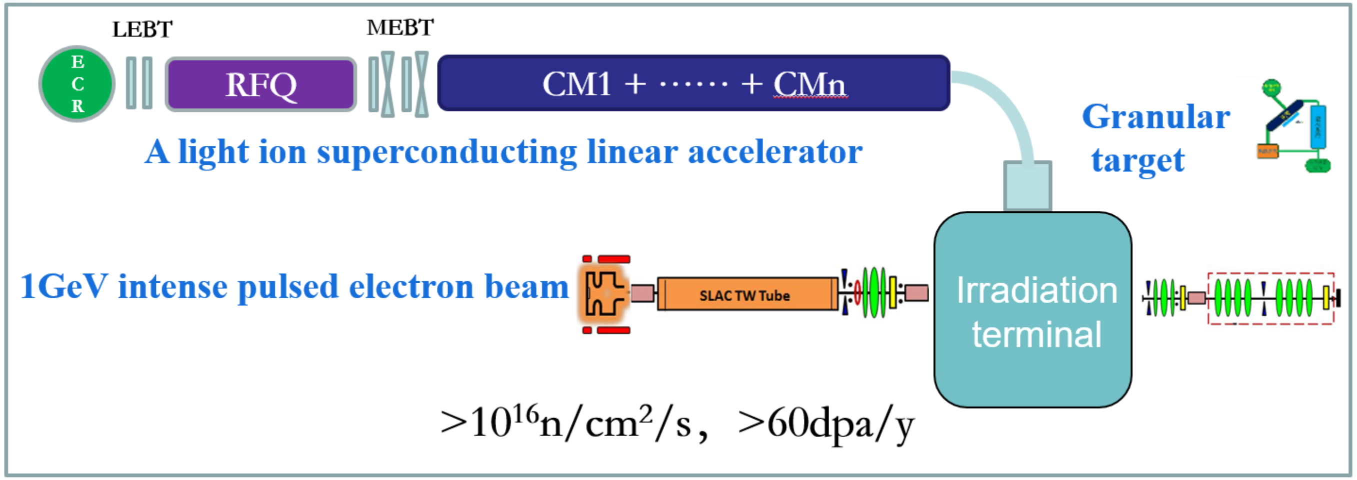
Fission reactors, Spallation neutron source

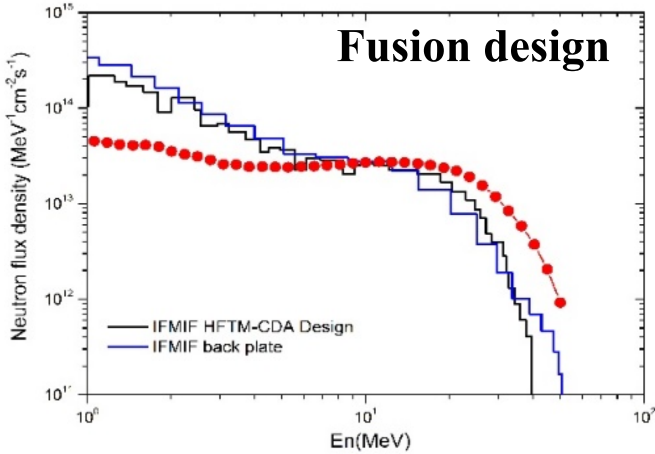


BEST/BEST-TBM

Triple-beams

Dense Energy Experimental Facility (DEEF)





Construction content	Typical indicators
Light ion continuous wave superconducting linear accelerator	Continuous wave beam, average beam power greater than 4MW
Fission fuel research platform	Generate fast/thermal neutron spectra The maximum Neutron flux is greater than 10^{16}n/cm²/s
Fusion Fuel Research platform	Generate neutron spectra close to DEMO The maximum Neutron flux is greater than 10^{16}n/cm²/s
Universal research platform	Withstand>50MeV/ A@5mA Light ion beam (60 DPA/y) The design energy spectrum of IFMIF covered by high energy neutron spectrum of samples
Strong pulse electronic quasi online detection system	Energy approximately 1GeV Bundle charge in tens of nanometers Spatial resolution at submicron scale
Hot cells group and related detection and analysis platform	Conduct post irradiation research on fuels and materials

A Phased Roadmap for the Development of Fusion Reactor Materials in China

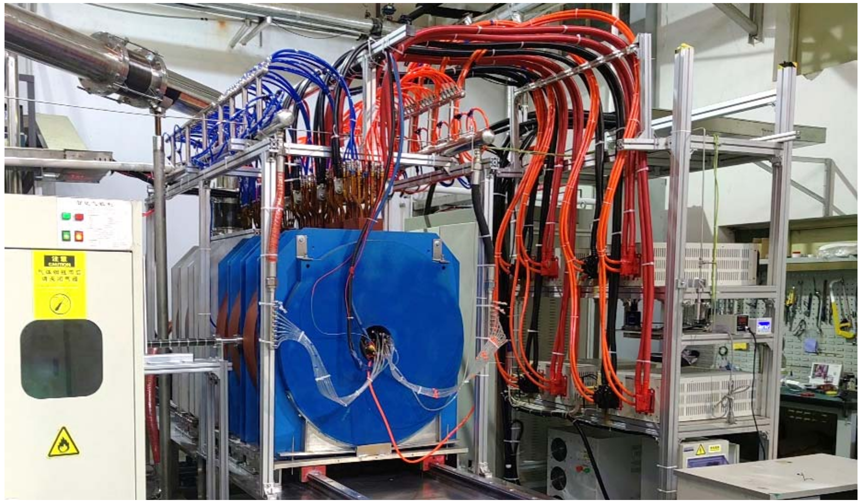
			2023-2030（to BEST/ITER-TBM）	2031-2040（to DEMO）	2041-2050（to PFPP）	Comprehensive Database of FRM
PFM/PFC	Pure Tungsten	FW & Divertor	1. Pure W performance and mass production stability are improved; 2. Complete > 10^{24} $m^{-2}s^{-1}$ plasma irradiation, 20 MW m^{-2} heat load test and >2dpa fission neutron irradiation; 3. Obtain comprehensive key data on mechanical, thermal, irradiation, and H-isotope compatibility. 4.. Master the connecting process of W with heat sink, establish the production standard of pure W PFC, 5. Use CRAFT and BEST to evaluate the pure W divertor.	1. ~5 dpa fission neutron irradiation, > 1 dpa fusion neutron irradiation; 2. CRAFT, BEST, DEMO test; 3. Optimize the design and manufacturing process and improve the production standard.	1. Determine the PFC manufacturing process in PFPP; 2. Develop PFC on-line detection and *in-situ* repair technology.	
PFM/PFC	Adv. W-based Materials	FW & Divertor	1. Large-scale fabrication process is determined, and cold state performance is completely tested; 2. High-flux plasma irradiation; 3. Complete >2 dpa fission neutron irradiation.	1. The output meets the needs of the demonstration reactor, and the production capacity of components is established; 2. ~5 dpa fission neutron irradiation, > 1 dpa fusion neutron irradiation; 3. Test of BEST and DEMO.	1. Determine a W-based material for PFPP; 2. R&D of advanced W-based materials for DEMO applications.	
PFM/PFC	Liq. Metal PFM	FW & Divertor	1. Determine the material, structure and process of the first wall of flowing liquid metal; 2. Complete the test and analysis of the basic data of the first wall of flowing liquid metal; 3. High-flux plasma irradiation, substrate material > 2 dpa fission neutron irradiation.	1. Establish manufacturing standards for advanced liquid metal parts; 2. Study the synergistic effect of strong electromagnetism, high heat load and high particle flow; 3. The substrate material > 5 dpa fission neutron irradiation, BEST and DEMO test.	1. Fabrication of advanced liquid metal modules to meet PFPP requirements; 2. R&D of new flowing liquid metal wall structures for commercial applications.	
PFM/PFC	Heat Sink	Divertor	1. Complete R&D of Cu-based heat sinks, determine the large-scale fabrication process, and complete the cold performance test 2. The connection process of new heat sinks with W was established; 3. >2 dpa neutron irradiation.	1. Determine the process of large-scale fabrication of plates and pipes; 2. >5 dpa fission neutron irradiation, BEST and DEMO test.	1. Identification of a Cu-based heat sink for PFPP; 2. R&D of new heat sinks for commercial applications.	
PFM/PFC	C, other PFM	FW & Divertor	Continue to pay attention to R&D progress and explore breakthrough technology applications			
Structural M	RAFM Steel	FW & Blanket	1. Establish database of cold state (including welding); 2. Complete the certification of materials in nuclear industry and material manuals; 3. Complete 20 dpa fission nd ~5 dpa fusion neutron irradia. 1. BEST/ITER-TBM application evaluation; 2. Component manufacturing and standard certification.	1. Complete 30 dpa fission neutron and 10 dpa fusion neutron irradiation; 2. DEMO test to evaluate its application prospects.	Complete the application verification on DEMO	
Structural M	Adv. RAFM	FW & Blanket	1. Fabrication of 100 kg and cold state database; 2. Complete 5 dpa fission neutron irradiation. 1. R&D ton-scale fabrication technology; 2. BEST/ITER-TBM application evaluation; 3. Certification of materials for the nuclear industry.	1. Complete 20 dpa fission neutron and 10 dpa fusion neutron irradiation; 2. Establish industrial production processes, material manuals and component manufacturing standards; 3. DEMO test to evaluate its application prospects.	Complete the application verification on DEMO	
Structural M	ODS Steel	FW & Blanket	1. Ton-scale fabrication, complete cold state database; 2. 5 dpa fission neutron irradiation and preliminary database; 3. Establish an additive manufacturing blanket process. 1. Ton-scale industrial production, standardization system and quality certification; 2. Establish standard connection technology.	1. Complete the certification of materials in the nuclear industry and the establishment of material handbook, and component manufacturing standards; 2. 20 dpa fission neutron and 10 dpa fusion neutron irradiation; 3. DEMO is tested to evaluate its application prospects.	1. Irradiation of small specimen of >50 dpa with fusion neutron; 2. Complete the application verification on DEMO. Establish a comprehensive database of FRM irradiation and evaluate its commercial application	
Structural M	V Alloy	Liq. Li Blanket		1. According to the requirements of T-breeding Blanket, R&D in a timely manner; 2. Development of 100-kilogram fabrication technology and establishment of cold state database.		
Structural M	SiC	LLDC Blanket	Fabrication process R&D of FCI and performance tests of SiCf/SiC with low thermal and electrical conductivity, strong T resistance, appropriate toughness and radiation resistance of about 100 kg were completed. 1. Industrial production process and specification; 2. BEST-TBM application evaluation; 3.~5 dpa fission neutron irradiation.	1. Complete 10 dpa fission and 5 dpa fusion neutron irradiation; 2. Compatibility of liquid multiplier materials; 3. DEMO is tested to evaluate its application prospects. Fabrication process of SiC_f/SiC composites with about 100 kg of nuclear-grade pure silicon carbide, near-stoichiometric ratio, high thermal conductivity, high strength and toughness, radiation resistance and gas-tightness.	1. Irradiation of small specimen of >50 dpa with fusion neutron; 2. Complete the application verification on DEMO. Establish a comprehensive database of FRM irradiation and evaluate its commercial application	
Functional M	Be Be Alloy	Solid Blanket Solid Blanket	1. Master the fabrication process, mass production capacity, and reduce costs; 2. BEST/ITER-TBM application evaluation; 3. Complete 5 dpa fission neutron irradiation.	1. Complete the certification of materials in the nuclear industry and the establishment of material handbook,; 2. 10 dpa fission and 5 dpa fusion neutron irradiation; 3. DEMO is tested to evaluate its application prospects.	1. DEMO engineering test under actual working conditions; 2. > 30 dpa fission neutron irradiation performance assessment.	
Functional M	Li Ceramics	Solid Blanket	1. Ton-scale mass production capacity, and reduce costs; 2. BEST/ITER-TBM application evaluation; 3. Complete 5 dpa fission neutron irradiation.	1. Complete the certification of materials in the nuclear industry and the establishment of material handbook; 2. 10 dpa fission and 5 dpa fusion neutron irradiation; 3. DEMO is tested to evaluate its application prospects.	1. DEMO engineering test under actual working conditions, TBR>1; 2. > 30 dpa fission neutron irradiation performance assessment.	
Functional M	Pb-Li Liq FLiBe Molten	Liquid Blanket Liquid Blanket	1. Corrosion of structural materials and retardation technology; 2. Effect of 5 dpa fission neutron irradiation on material compatibility and hydrogen isotope behavior of structural materials; 3. Liquid metal flow and MHD effects.	1. Certification of materials in the nuclear industry, material handbook, and establish industrial production processes; 2. 10 dpa fission and 5 dpa fusion neutron irradiation; 3. DEMO is tested to evaluate its application prospects.	1. DEMO engineering test under actual working conditions, TBR>1; 2. > 30 dpa fission neutron irradiation performance assessment.	
Functional M	T Barrier	FW & Blanket	1. Master the fabrication process, PRF at 500°C > 1000; 2. >5 dpa fission neutron irradiation and evaluation of performance.	1. Certification of materials in the nuclear industry, material handbook, and establish industrial production processes; 2. DEMO is tested to evaluate its application prospects.	1. DEMO engineering test under actual working conditions; 2. > 20 dpa fusion neutron irradiation performance assessment.	
Functional M	Shielding M	VV	1. Master the engineering fabrication process of radiation shielding materials and components for BEST; 2. R&D of new high-performance radiation shielding materials.	1. BEST/DEMO test under actual working conditions; 2. R&D on industrial fabrication process and performance of new shielding materials.	DEMO engineering test under actual working conditions	
Functional M	Diagnosis M	First Mirror, etc	1. Neutron/gamma irradiation, plasma sputtering or high heat load assessment; 2. Determine the diagnostic materials for the fusion experimental reactor.	BEST/DEMO engineering test and in-situ cleaning or repair technology research under actual working conditions		
Irradiation Platform		Fusion N Source	1. Build a small fusion neutron source and 5-10 dpa fusion neutron irradiation for small specimen; 2. Completed the engineering design of fusion neutron source and started construction.	1. Complete 5-10 dpa fusion neutron irradiation of small specimen, and verify them with computational simulation; 2. Using the DEMO and fusion neutron source, 5-10 dpa irradiation for important components; 3. Upgrade the fusion neutron source, and start the construction of a medium-sized fusion neutron source.	1. Irradiation and evaluation of small specimen of 20-50 dpa; 2. 10-20 dpa Irradiation and evaluation of small components such as blanket with low-power DEMO reactor; 3. Irradiation of small specimen of 60-80 dpa.	
Irradiation Platform		Fission N & Triple-Ions	1. 10-20 dpa fast neutron irradiation; 2. Establish equivalent experimental methods for fusion, fission neutron and ion irradiation; 3. Establish a national standard for small specimen testing.	1. 20-30 dpa fission neutron irradiations; 2. Establish evaluation criteria for FRMs based on fission neutron and triple ion irradiation.	Systematical fission neutron irradiation (30 dpa) for different new materials to improve the irradiation performance data of various FRMs.	
Irradiation Platform		High Heat Load	1. Build the highest power electron gun and high heat load test platform; 2. Complete the high thermal load test of the full-size test piece of divertor and blanket components.	1. Design and build a high heat load test platform in the hot cell; 2. Evaluate the performance and life of the divertor and blanket components.		
Irradiation Platform		Plasma Bombard	1. Build a linear plasma device with the highest parameter level in the world; 2. Complete the plasma irradiation + steady-state heat flux synergy test of materials and modules; 3. Establish a screening standard for the plasma irradiation resistance of the FW material.	1. Design and build high-flux plasma irradiation conditions that can accept neutron irradiation activated samples; 2. Build a high-flux plasma irradiation facility that can use gram-scale tritium.	1. Plasma irradiation of high-dose fusion neutron irradiation material/component module: 2. Build advanced PFC full-scale module large-beam area plasma irradiation conditions; 3. Verify PFC in-situ repair technology.	
Simulation Platform		Fusion *vis* Fission	1. Establish the relationship between fission and fusion neutron irradiation; 2. Simulation and prediction of micro-macro effects of 10-20 dpa fusion neutron irradiation.	1. Establish a material evaluation system that includes organizational structure and mechanical and thermal properties; 2. Fusion neutron irradiation simulations of FRMs in 20-50 dpa.	1. Simulations of materials with fusion neutron irradiation at 50-100 dpa; 2. Establish a service performance evaluation and failure analysis system for blanket structural materials and PFMs.	
Simulation Platform		PMI	1. Simulation of surface morphology evolution under H-isotope/helium plasma synergistic irradiation; 2. To investigate the sputtering etching of the wall surface under H-He synergistic irradiation.	1. Coupling the PSI simulation with the neutron irradiation; 2. Prediction synergistic effects of FRMs under hydrogen-helium and neutron irradiation.		

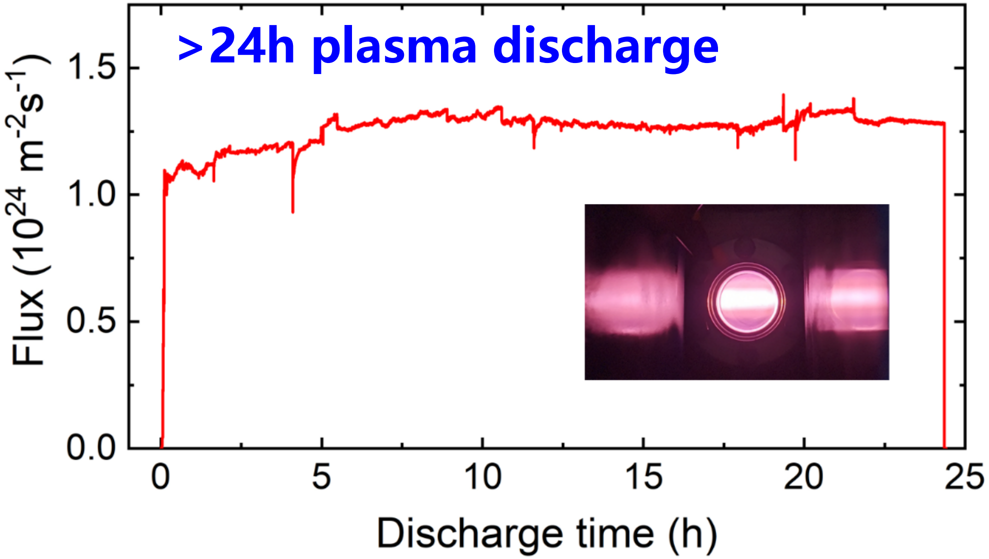
Outline

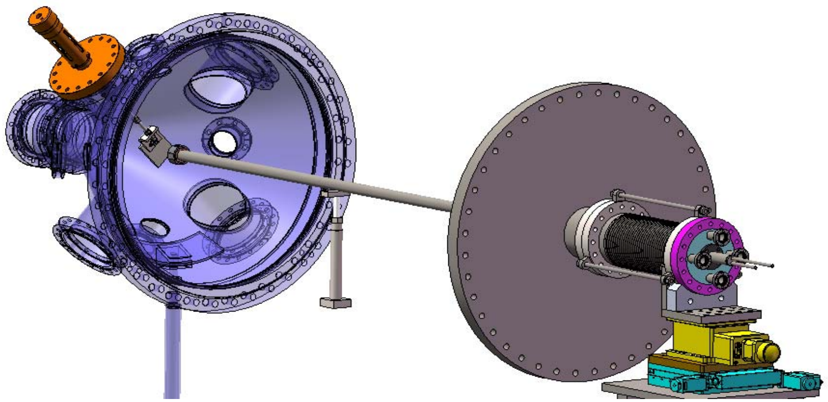
- ❖ Service environments and requirements of fusion reactor materials
- ❖ A phased roadmap for fusion reactor materials
- ❖ Recent R & D progress of fusion reactor materials in China

High Flux Linear Plasma Device

A compact linear device for plasma source testing







Machine parameter

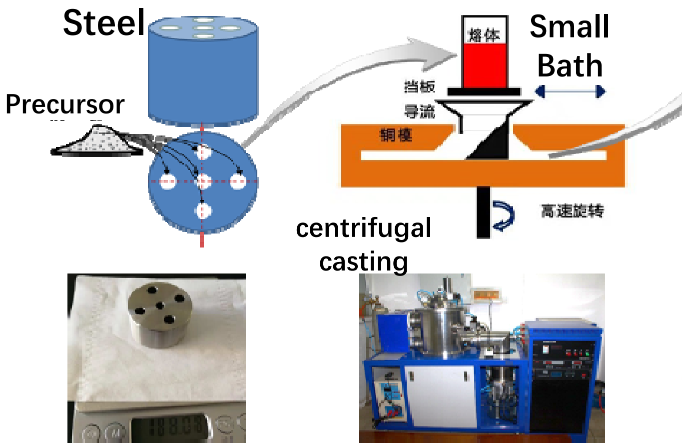
Particle flux	**10^{23} - 10^{24} m^{-2}s^{-1}**
Magnetic field	**- 0.9 T**

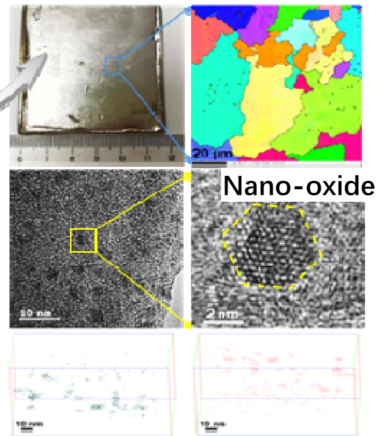
Precursor Assisted Casting ODS Steel

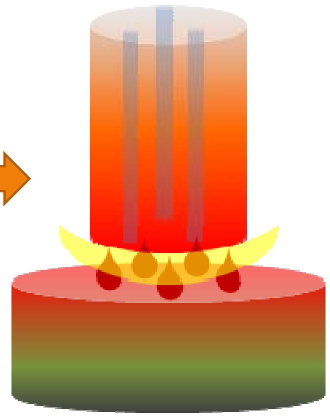
Precursor+rapid solidification in small bath

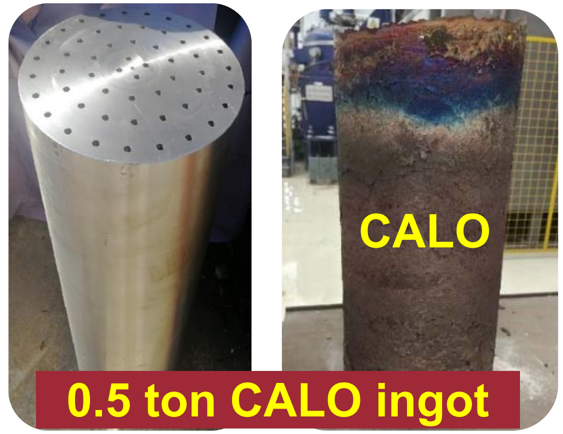
CALO：Cast Advanced Low-activation ODS steel

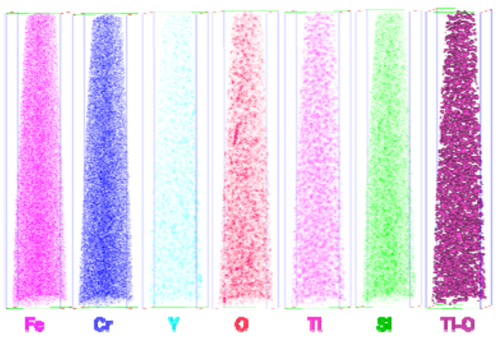
Fe-9Cr-0.09C-1.5W-0.2V-0.3Ti-0.2Y-0.3Si

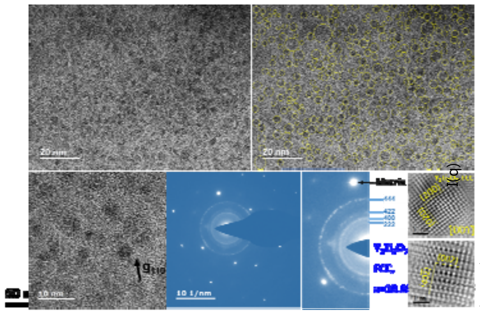




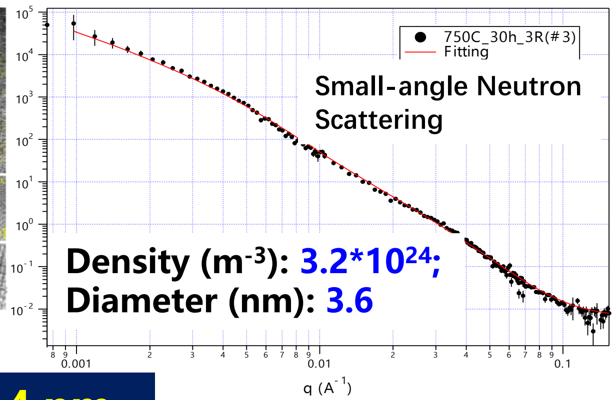




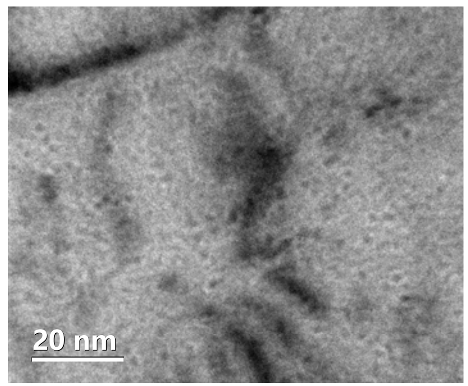




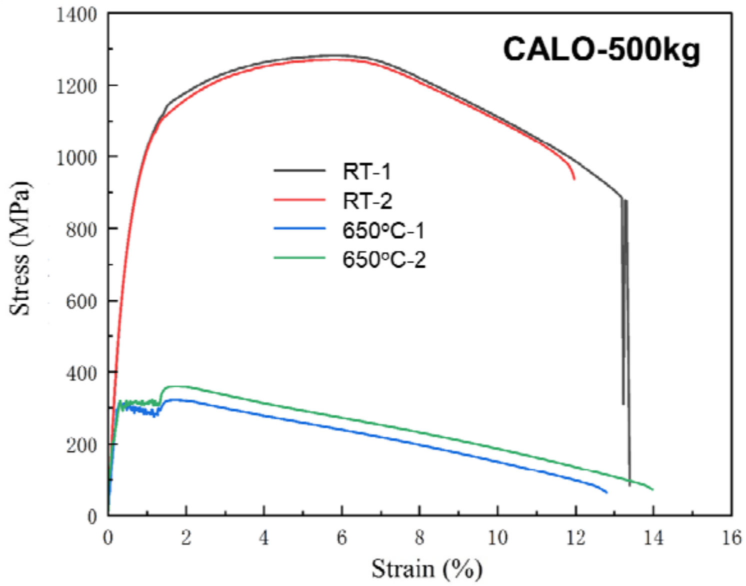
Y-oxide density: 1.8*10^{24} m^{-3}; Diameter: ~2.4 nm



No void-swelling after 200 dpa

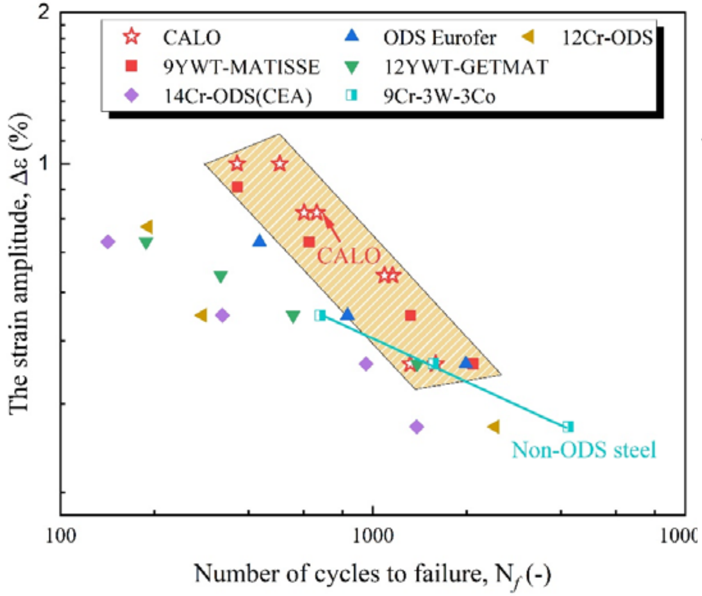


Precursor Assisted Casting ODS Steel



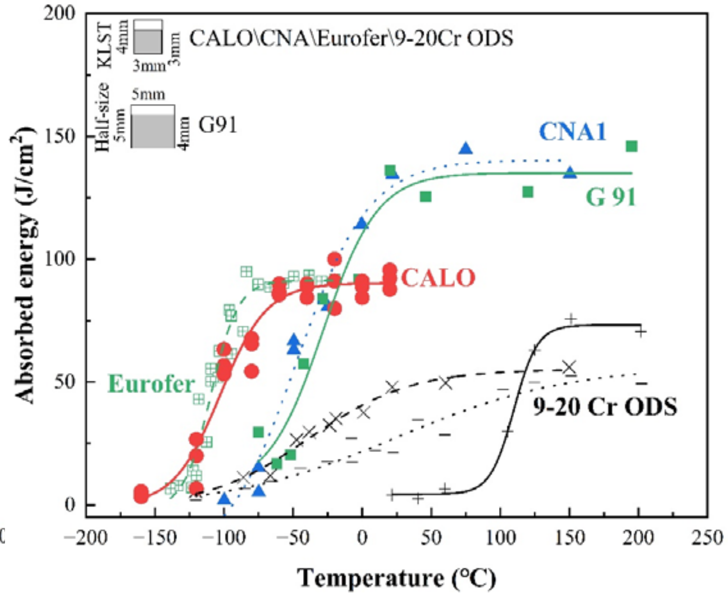
Tensile property at RT and 650°C

Tensile strength up to 1280 MPa at RT
similar to MA ODS steel



Fatigue property at 650°C

Good fatigue performance,
similar to MA ODS steel



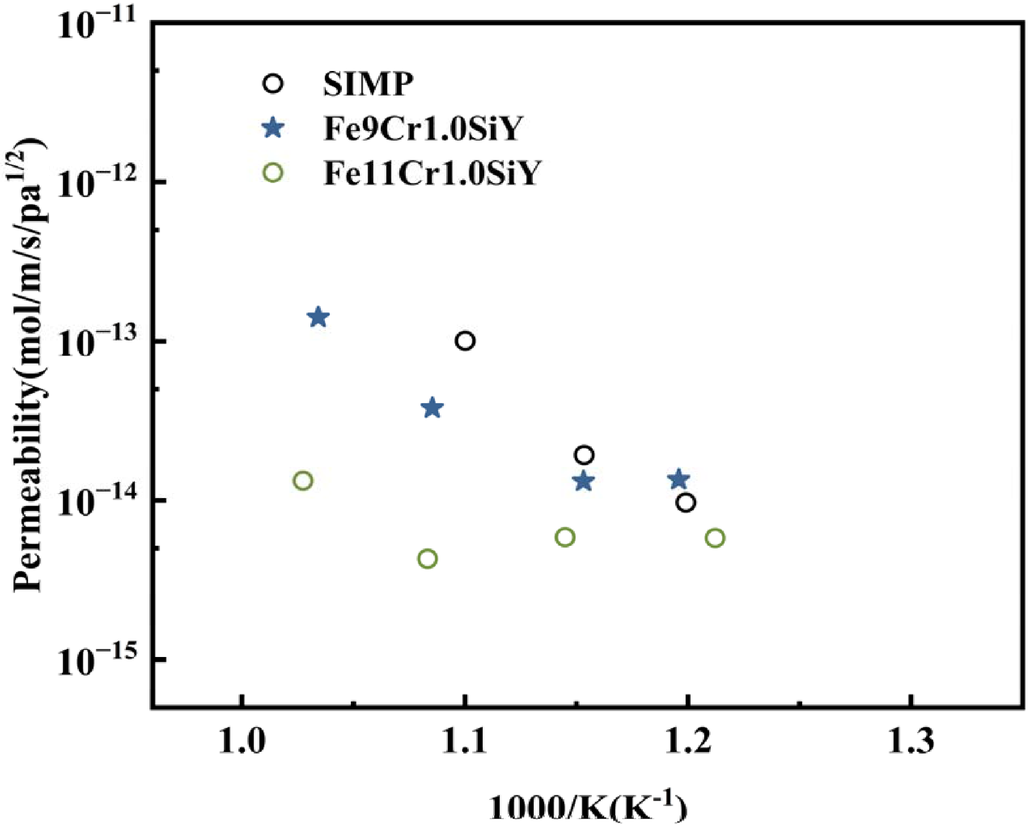
Impact property

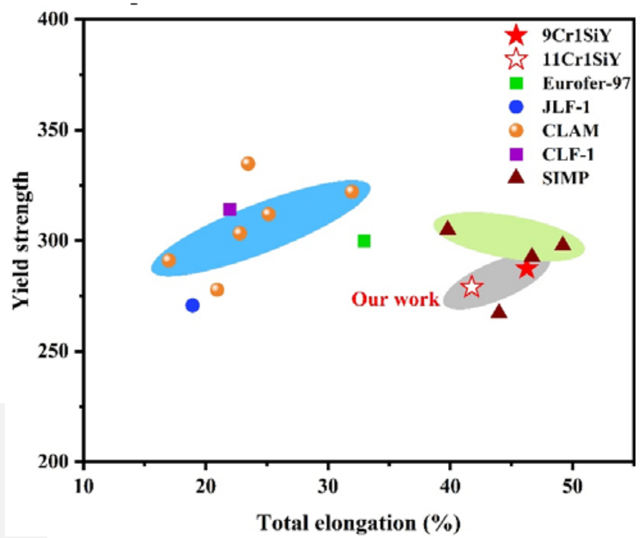
DBTT down to -103°C,
similar to RAFM

Creep: >6000 hr at 650 °C/120MPa; N irradiation in underway

Mechanical properties of CALO are similar to MA ODS with lower DBTT.
Mass production and low-cost of ODS-RAFM steel is possible!

New RAFM steel with H Permeation Resistance

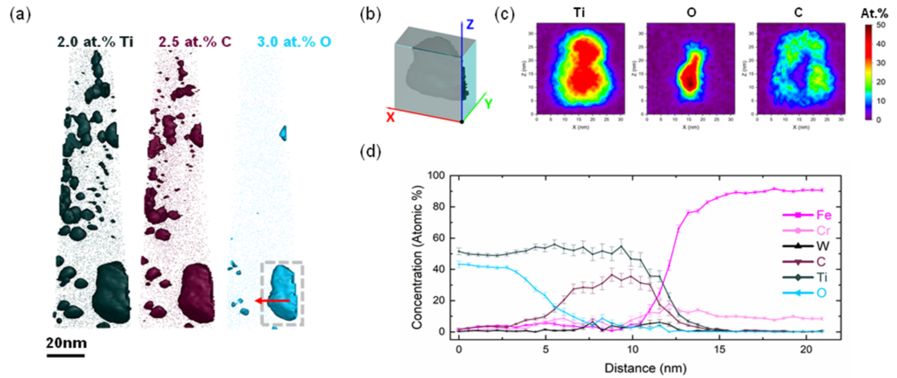


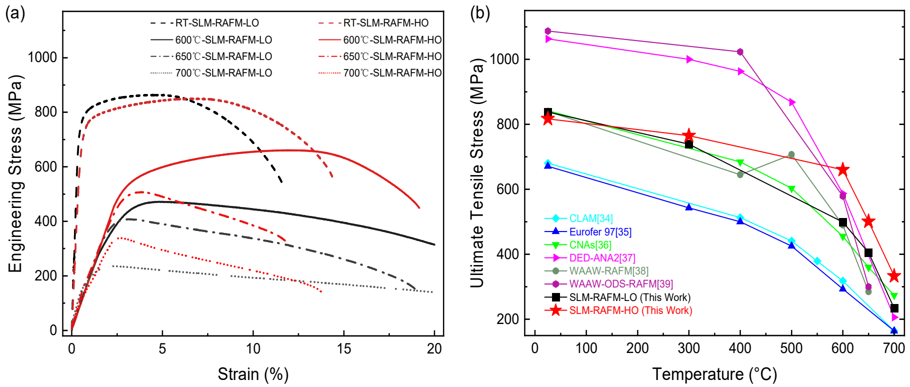


9Cr1Si is a good choice considering hydrogen resistance and irraidiation resistance

Additive Manufacturing of Components

Additive manufactured oxide strengthened low activation steels



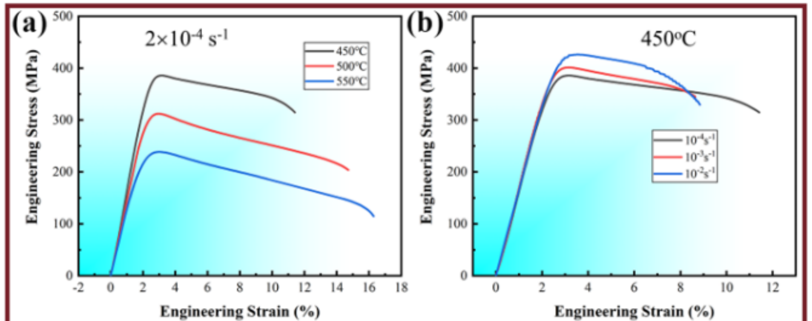


Additive manufactured downsized water-cooled blanket components

Size: 220 mm ×230 mm ×240 mm, Density≥99%

Ton-scale Fabrication of CuCrZr-Si Alloy

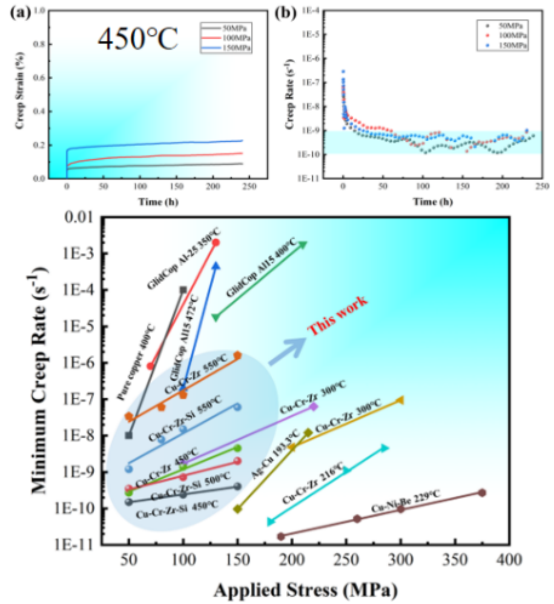
- Submicron Cr_3Si phase and nano-sized Cr phase strengthening were realized
- Thermal Conductivity is larger than 310 W/m•K (RT), similar to CuCrZr
- Good mechanical properties at high temperature and ton-scale fabrication



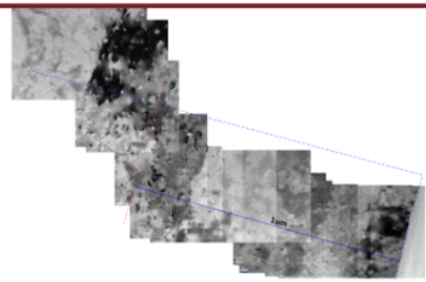
High temperature tensile data of Cu-Cr-Zr-Si alloy under different conditions

Alloy	ε/s⁻¹	T/°C	UTS/MPa	YS/MPa	EL/%
0.05Si	2×10^{-4}	450	385	336	11.4
	2×10^{-3}	450	401	369	8.7
	2×10^{-2}	450	426	394	8.8
	2×10^{-4}	500	312	269	14.7
	2×10^{-4}	550	264	228	16.3

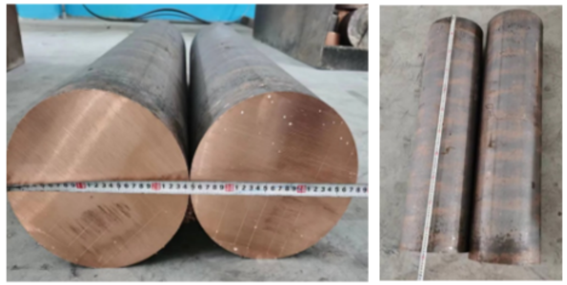
Excellent high temperature tensile properties



The high temperature creep rate of the alloy at 550°C is about one order of magnitude lower than that of the existing CuCrZr alloy.

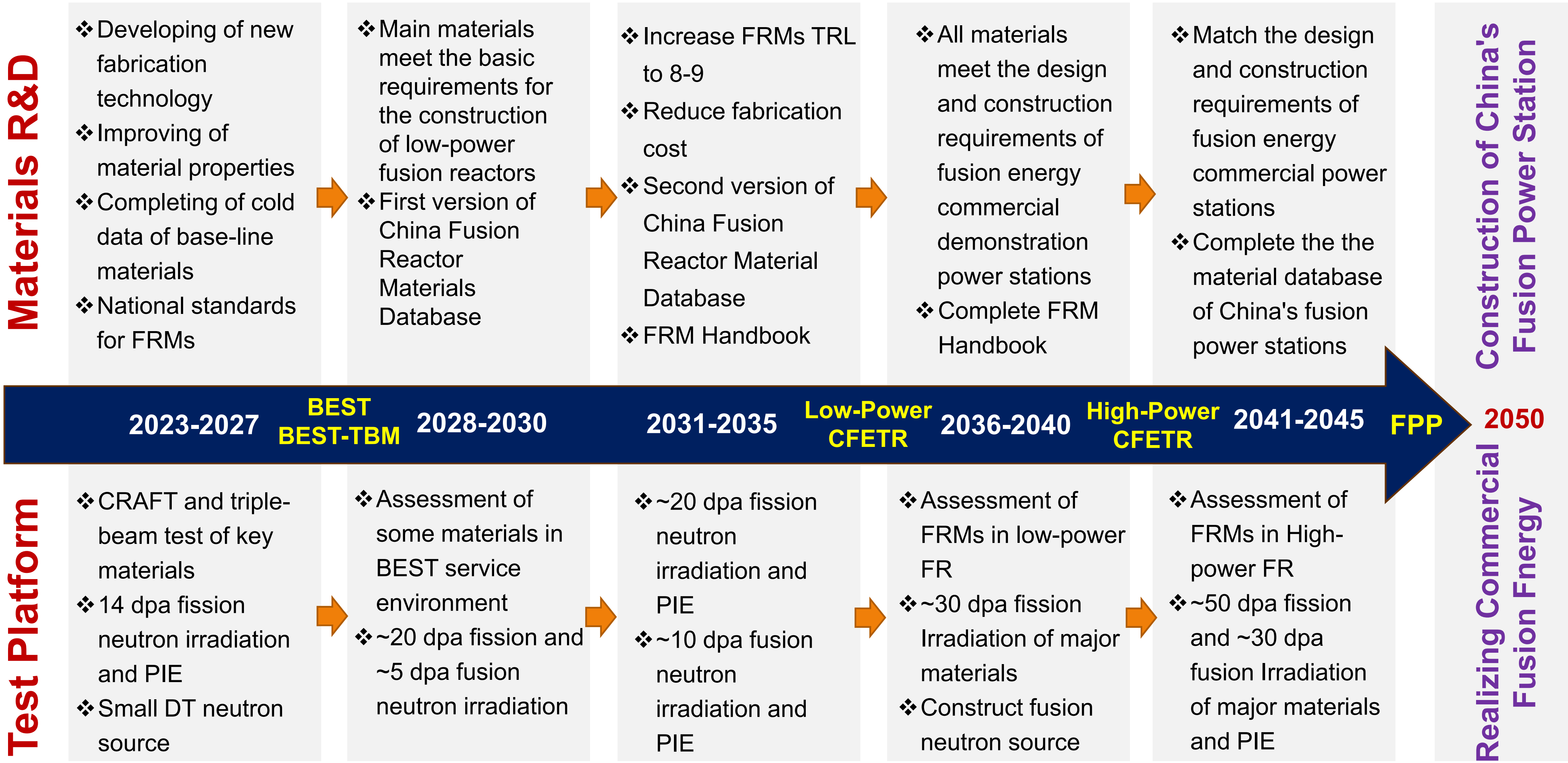


3.5 MeV Fe Ion Irradiation up to 50 dpa, no swelling observed



Industrial fabrication of ton-scale

Phased Roadmap for Development of FRMs in China



Hope we could have deeper collaboration with EU colleagues in the field of FRMs

Thank You for Your Attention!