Progress of divertor design concept for Japanese DEMO

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Summary:

Design concept for JA DEMO has been developed based on ITER divertor technology:

• W-MB & CuCrZr heat sink are applied at high heat-flux and low neutron-flux area ⇒ replacement is required every 1-2 year: degradation of mechanical property (softening) of CuCrZr. The design concept will be used in the early period of DEMO operation.

• Cassette design, considering nuclear heat removal, n-shield against VV, fuel/He exhaust opening and target replacement in hot cell, has been recently developed.

(1) Cassette design with PWR cooling water (290˚C, 15MPa) is proposed:

• Parallel cooling route to inner and outer targets to avoid fast flow speed at inboard.

• Inner and outer target units (W-MB & CuCrZn-pipe) together with baffle units (W-MB & F82H-pipe) and the cooling pipes are removed in the toroidal direction.

• Further optimization of two water routes (CuCrZr/F82H-pipes) is required.

(2) Heat removal by W-monoblock & CuCrZr-pipe cooling unit:

• *Heat trans. analysis in the target geometry* showed max. temperature of W(1200°C) by peak q_{target} = 9 MWm^{-2}-level and Cu-alloy (~350°C) ⇒ stead-state operation limit. The peak-$q_{\perp}^{tot}$ can be increased by reducing $T_{coolant}$ (200˚C) and/or the surface shape.

• Elasto-plastic stress analysis of stress and strain for repeating transient $q_{\perp}^{tot}$= 11MWm^{-2}-level (W surface:1400°C, highly recrystallization): the heat sink will be survive.

In progress:

• Electromagnetic analysis of the divertor structure against current quench disruption and improvement of the divertor cassette structure.

• Fuel/He exhaust and pumping design is planned.

1. Introduction: Divertor Design Concept for JA DEMO

Divertor power handling of P_{sep}~250 MW (P_{sep}/R ~30 MW/m) is reference concept

ITER-like geometry and larger-size (divertor leg is 1.6 m)[1] is a baseline design.

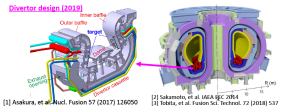
(1) Remote maintenance (RM): one cassette covers 7.5° toroidal area
⇒ 3 cassettes are replaced from 1 port (total 48 cassettes from 16 ports)

(2) Cassette design for RM, Replacement of cooling-unit, Vacuum-vessel protection against neutron-irradiation ⇒ *on going*

(3) Power exhaust design under n-irradiation ⇒ *on going*
• Design of W-monoblock & CuCrZr/F82H-heat sink
⇒ Arrangement of cooling-pipes in the cassette.
⇒ Heat transport and stress analysis of heat load: ≥10 MWm^{-2}.

(4) Fuel/He exhaust and pumping design ⇒ *tentatively*
• Opening in the cassette at outboard against n-flux to VV.
⇒ Exhaust port and (TMP) Pump design for 2Pa at sub-divertor.
⇒ He exhaust simulation in the detached divertor started.

Divertor design (2019)



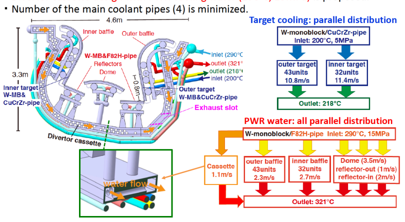
R_p/a_p	8.5/ 2.42	m
A	3.5	
κ_{95}	1.65	
q_{95}	4.1	
I_p	12.3	MA
B_T	5.94	T
P_{fus}	1.46	GW
n_e	0.66	10^{20} m^{-3}
HH_{98y2}	1.31	
β_N	3.4	
NWL	1.0	MW/m^2

[1] Asakura, et al. Nucl. Fusion 57 (2017) 126050
[2] Sakamoto, et al. IAEA FEC 2014
[3] Tobita, et al. Fusion Sci. Technol. 72 (2018) 537

2. Recent progress of water-cooling design (2018-19)

Optimization of two water routes (CuCrZr/F82H-pipes) is still required.

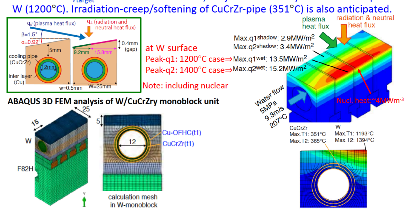
• Parallel cooling route to inner and outer targets to avoid fast flow speed at inboard.
• Higher $T_{coolant}$ = 200°C is used for CuCrZr-pipe, rather than increasing in the critical heat flux of the heat sink: $T_{coolant}$ (150-200°C) is a design issue.
• Divertor cassette design with PWR cooling water (290°C, 15MPa) is proposed.
• Number of the main coolant pipes (4) is minimized.



3. Heat analysis in W-monoblock and CuCrZr-pipe target:

$q_{\perp}^{plasma}$= 6.2, $q_{\perp}^{rad-n}$= 2.9MWm^{-2} (max. q^{tot}=13.5MWm^{-2}) is a critical case

• Base-temp. (200°C) of the pressurized water and Nuclear heat are larger than ITER.
• Heat load profile (plasma, radiation, neutral) is applied on *ITER-like shaped target*: two peak q_{target} cases (Case1: 9.1MWm^{-2}, Case2: 10.8MWm^{-2} to the flat target) is used for 3D FEM calculation of heat flux and thermal stress.
• Case1: Peak q_{target}=9.1 MWm^{-2} is a critical, i.e. just below recrystallization temp. of W (1200°C). Irradiation-creep/softening of CuCrZr-pipe (351°C) is also anticipated.



Design constrain of W & CuCrZr under neutron irradiation

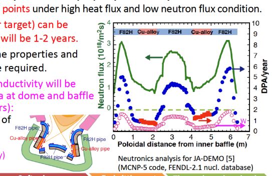
W-PFC with CuCrZr and F82H cooling-pipes is a baseline design

▪ **Firstly, design is determined by mechanical property of Cu-alloy:**
1~1.5 dpa/fpy near the strike points under high heat flux and low neutron flux condition.

ITER technology (W&CuCrZr target) can be applied, while replacement will be 1-2 years.
⇒ Systematic database of the properties and their improvement will be required.

▪ Reduction in W thermal conductivity will be acceptable up to several dpa at dome and baffle (replacement will be ~3 years): comparable to replacement of the Breeding Blanket.

Note: 1 dpa (W)=2.87 dpa (Cu-alloy)



Neutronics analysis for JA-DEMO [5] (MCNP-5 code, FENDL-2.1 nucl. database)

Heat sink/ Coolant pipe	Yield strength at RT (MPa)	T-threshold (˚C) (Softening)	Radiation-induced (dpa): hardening	Radiation-induced (dpa): softening	Embrittlement by transmuted He (dpa) (Embrittlement)	Reduction (20%) in Thermal cond. by transmuted product (dpa) (Thermal cond. reduction)
Pure-Cu	~60 MPa	---	~0.1	---	6 (at 350˚C)	10
CuCrZr	>400 MPa	280	~0.2	~1	40appm limit with 7appm/dpa	10
ODS-Cu(GlidCop®[5])	>400 MPa	300	~0.2	1~2		10

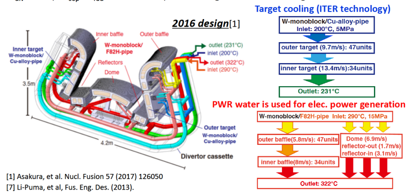
[4] S.J. Zinkle et al., Fusion Materials DOE/ER-0313/16 (1994). [5]B.N. Singh et. al, J. Nucl. Mater. (1993). [6] Tokitani, et al. ICFRM-19 (2019).

Divertor concept for JA DEMO divertor (2016)

W-PFC with CuCrZr and F82H cooling-pipes is a baseline design

• ITER target design (W-monoblock &CuCrZr-pipe) is applied near the strike point (≤10MWm^{-2}).
• Different pressurized waters are used: **200°C, 5 MPa for the CuCrZr-pipe to reduce the embrittlement** [7], and **290°C, 15MPa** (similar to pressurized water reactor: PWR), **for the F82H-pipe** to use for the electric generation (steam turbine).
• Heat removal concept was designed for $P_{div}^{thermal}$: 380MW + $P_{div}^{neutron}$: 118 MW: $P_{div}^{thermal}$ (= P_{sep}– P_{rad}^{SOL} = 220MW) has a margin of 1.7 times larger than simulation.

2016 design[1]



[1] Asakura, et al. Nucl. Fusion 57 (2017) 126050
[7] Li-Puma, et al, Fus. Eng. Des. (2013).

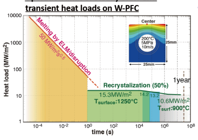
Power handling issues of W-PFC target for year-long operation:

Reduction in recrystallization temp.* and *net-erosion in partial attached plasma

▪ **W-recrystallization will progress even at lower temperature (~900˚C)** [8,9]:
Peak q_{target} should be reduced to <10MWm^{-2} for the coolant temperature of 200˚C.

▪ **Net erosion will be increased to *a few mm level* (if T_e^{div}~20eV at attached area):**
Reduction in T_e & T_i of attached plasma is necessary such as "pronounced detachment: AUG"[10]
Experiment data and Modeling of erosion & transport (finite-Larmor effect [11]) must be improved.

Operation limit of steady-state and transient heat loads on W-PFC



Simple estimation of net erosion: 90% re-deposition

・Net erosion (Δd) becomes a half of W-width (d:5mm)

Net erosion/year(mm)	T_e=5eV	10eV	20eV
DEMO (steady state)	0.15	1	2.5
ITER(400s, 2000 shots)	0.004	0.026	0.064

attach plasma area Γ_i~10^{23} m^{-2}s^{-1}, ~20eV <Z>=4, n_{Ar}/n_i =0.2%, assuming net erosion: R_{net}=0.1

Erosion yield with Ar imp. Y_iC_i ~4x10^{-4} (at 20eV)[12]

Δd (mm)= 4.95x10^{-19}R_{net}*Y_iC_i*Γ_i*t(year)

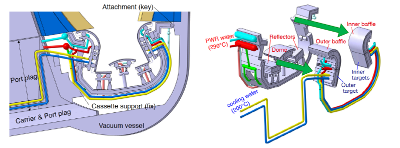
[8] Alfonso et al., J. Nucl. Mat. (2014).
[9] Alfonso et al., Fus. Eng. Des. (2015).
[10] AUG: Kallenbach, et al., Nucl. Fusion (2015).
[11] Homma, et al., Nucl. Mater. Energy. (2017).
[12] Kallenbach, et al., J. Nucl. Mat. (2011).

Concept of divertor remote maintenance

RM of the cassette and replacement of cooling units (CuCrZn-heat sink)

Remote handling in the vacuum vessel:
• *Key-attachment* is located at the inboard. It is fixed to the port plug at the outboard.
• Cassette is transported with the port plug through the maintenance port after cutting the main coolant pipes.
• Total weight of a cassette including cooling units is ~23t: 3 times larger than ITER (8t).

Replacement of target units (Cu-ally heat sink) in the hot cell:
• Inner and outer target units (W-MB & CuCrZn-pipe) together with baffle units (W-MB & F82H-pipe) and the cooling pipes are removed in the toroidal direction in order to avoid the cutting or welding process. Then, the target units are replaced.
⇒ Instruments for the remote maintenance in hot cell will be designed in future.

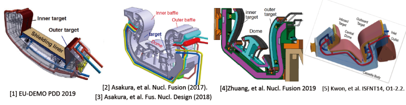


Design concepts for water-cooling DEMO divertor:

W-PFC & CuCrZr-pipe is a common baseline design. Divertor weight is increased.

		EU DEMO1 [1]	JA DEMO[2, 3]	CFETR (2nd step) [4]	K-DEMO (1st ph.) [5]
Number at units in a cassette		48	48	80	Upper: 32/Lower: 32
Weight of one cassette (ton)		11	23	11	TBD
Target	PFC & Heat sink	W&CuCrZr*1	W&CuCrZr	W&(CuCrZr/ODS-Cu/RAFM)*2	W&(CuCrZr or RAFM)
Target	Water T(°C)/P(Mpa)	130/ 3.5	200/5	140/5	290/ 15
Target	Dose on pipe/fpy (dpa)	<10	<1.5	TBD	<1.2
Dome/Baffle	PFC & Heat sink	W&CuCrZr (liner)	W&F82H	W&(CuCrZr/ODS-Cu/RAFM)	W&RAFM
Dome/Baffle	Water T(°C)/P(Mpa)	180/ 3.5	290/ 15	140/5	290/ 15
Dome/Baffle	Dose on pipe/fpy (dpa)	<10	<8.5	TBD	< 10.9
Cassette	Material	EUROFER97	F82H	RAFM	RAFM
Cassette	Water T(°C)/P(Mpa)	180/ 3.5	290/ 15	140-180/ 5	290/ 15
Cassette	Dose on struct. material/fpy (dpa)	<6	<3	TBD	TBD

*1: Alternative target concepts: liquid metal and He-cooling. *2: He-cooling is an option.



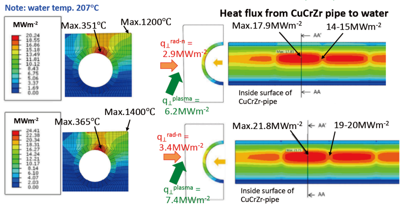
[1] EU-DEMO PDD 2019
[2] Asakura, et al. Nucl. Fusion (2017).
[3] Asakura, et al. Fus. Nucl. Design (2018)
[4]Zhuang, et al. Nucl. Fusion 2019
[5] Kwon, et al. ISFNT14, O1-2.2.

Heat transport in W and CuCrZr pipe, and maximum heat flux

$q_{\perp}^{tot}$ = 9 MWm^{-2} appropriate for both surface and heat sink temperatures

Peak $q_{\perp}^{tot}$= 9MWm^{-2}(13.5MWm^{-2}) case (W surface:1200°C, a critical for recrystalization):
Max. heat flux *to coolant*: 18MWm^{-2} is 51% of the Critical heat flux (35MWm^{-2}).
⇒ The peak-$q_{\perp}^{tot}$ can be increased by reducing $T_{coolant}$ (200˚C) and/or the surface shape.
Peak $q_{\perp}^{tot}$= 10.8MWm^{-2}(15.2MWm^{-2}) case (W surface:1400°C, highly recrystalization):
Max. heat flux *to coolant*: 22MWm^{-2} is 63% of CHF. ⇒ transiently acceptable.

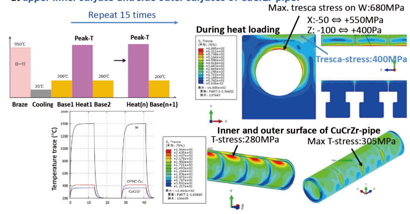
Note: water temp. 207°C



Elasto-plastic stress analysis of the cooling unit started for the high heat load (max. q: 15.2MWm^{-2}, W surface: 1400°C)

Maximum stress-strain is evaluated with elasto-plastic stress analysis, considering residual stress-strain after the braze process from 950°C.
⇒ repeating high heat loading (max. 15.2MWm^{-2}): base-temp. 200°C ⇔ max. 1400°C.

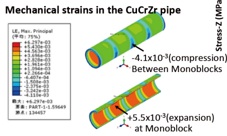
• **Thermal stress is increased at *upper and side inner surfaces* of W-monoblock, and at *upper inner surface* and *side outer surfaces* of CuCrZr-pipe.**

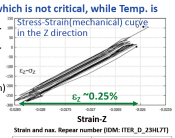


Heat sink (CuCrZr) will be survive for the repeat of the transient high heat flux, while W-surface becomes highly recrystallized.

• **Large strains are seen at inner (expansion) and outer (compression) of CuCrZr pipe.**
• **Stress-Strain curve at the max. T-stress traces similar trajectory ⇒ below the yield condition.**
• **Mechanical strain ε_T corresponds to ~0.25%, which is not critical, while Temp. is increased to 365℃ and n-irradiation.**

Mechanical strains in the CuCrZr pipe





Strain and nax. Repear number (IDM: ITER_D_23HL7T)

Max number of cycles	Total strain range, %
10	2.29
20	1.78
40	1.395
10^2	1.026
$2x10^2$	0.824
$4x10^2$	0.672
10^3	0.526
$2x10^3$	0.447
$4x10^3$	0.376
10^4	0.308
$2x10^4$	0.2631
$4x10^4$	0.2233
10^5	0.1852
$2x10^5$	0.1644
$4x10^5$	0.1487
10^6	0.1336

ε_M:= {(2/9)[($\varepsilon_1-\varepsilon_2$)^2+($\varepsilon_2-\varepsilon_3$)^2+($\varepsilon_3-\varepsilon_1$)^2]}$^{1/2}$ （ミーゼスの降伏条件ベース）
ε_T:=max(|ε_1|, |ε_2|, |ε_3|) （トレスカの降伏条件ベース）
ε_O:= [(2/3)($\varepsilon_1^2+\varepsilon_2^2+\varepsilon_3^2$)]$^{1/2}$ （その他の定義）、
$\varepsilon_1, \varepsilon_2, \varepsilon_3$は主ひずみ

Third Technical Meeting on Divertor Concepts, IAEA Headquarters, Vienna, Austria 4–7 November 2019