**P2B4**

# Progress of JA-DEMO Divertor Conceptual Design: Coolant Distribution and Thermal Stress Analysis

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# 1. JA-DEMO power handling and divertor concept

Divertor performance was simulated by SONIC code: $f^*{}_{rad}^{div}$ (=$P_{rad}^{div}/P_{sep}$)~0.8 is required.

- **JA-DEMO (steady-state):** high plasma performance of $HH_{98y2}$~1.3, $\beta_N$~3.4 is required in Ar seeding for $R_p/a_p$(8.5/2.4m), $B_t$(6T), $q_{eff}$ (4.1) ⇒ $f_{rad}^{main} = P_{rad}^{main}/P_{heat}$: 0.2-0.4 ⇒ $P_{sep}$ = 250-290MW

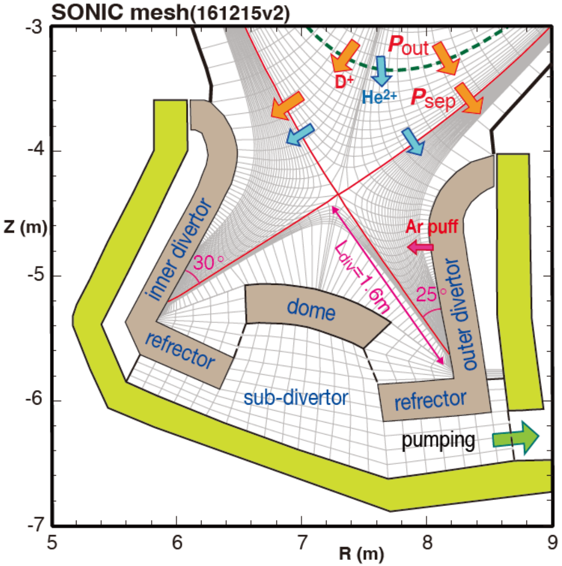
Conventional design concept based on ITER divertor is applied:

- Divertor encloses *all divertor plasma volume* for high $P_{sep}/R$ design (30-35 MWm$^{-1}$: ~2 times larger)
- Leg length is extended: $L_{div}$=1.6 m (1.6 times longer than ITER)⇒ reducing peak $q_{target}$=5-7MWm$^{-2}$

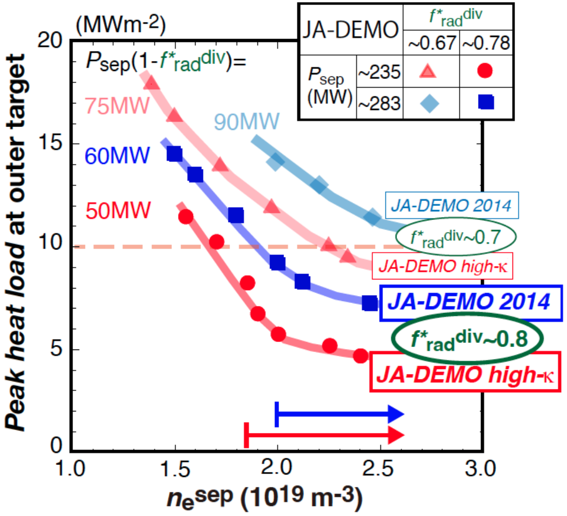
| **Parameters** | **DEMO 2014** | **higher-κ** |
|---|---|---|
| $\kappa_{95}$ | **1.65** | **1.75** |
| $I_p$ (MA) | 12.3 | 13.5 |
| $<n_e>(10^{19}m^{-3})$ | **6.6** | **7.2** |
| $P_{fusion}$ (MW) | 1462 | 1694 |
| $P_\alpha+P_{aux}(P_{heat}$, MW) | 376 | 435 |
| $n_{imp}/n_e$ (Ar, %) | 0.24 | 0.60 |
| $P_{rad}^{main}/P_{heat}$ | 0.22 | 0.41 |
| **$P_{sep}$ (MW)** | **294** | **258** |
| **$P_{sep}/R_p$ (MWm$^{-1}$)** | **35** | **30** |

[1] Asakura, et al. Nucl. Fusion 57 (2017) 126050.

Divertor geometry for SONIC simulation



$f^*{}_{rad}^{div}$~0.8 preferable to low $n_e^{mid}$

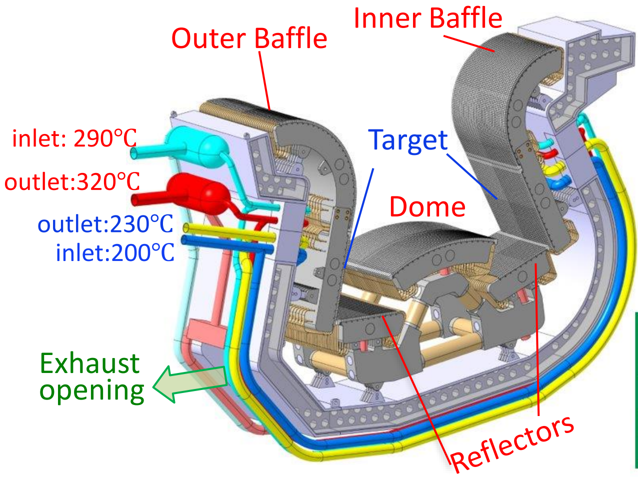


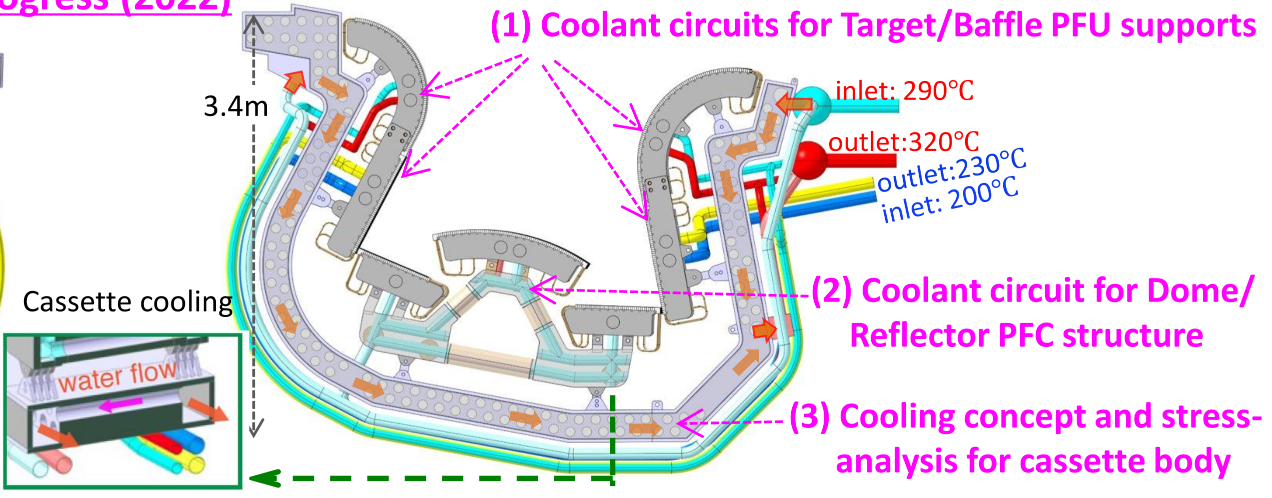
[2] Asakura, et al., Nucl. Mater. Energy 26 (2021) 100864

# JA-DEMO divertor design has been developed to handle the larger heat load and larger neutron load (nuclear heating) & fluence (dose) than ITER

- W-MB & CuCrZr-pipe PFU and 200°C coolant are used to high heat load & low neutron flux (<2dpa/FPY) area (target) ⇒ replacement is required 1-2 year: degradation of CuCrZr mechanical property (softening).
- 290°C (15 MPa) coolant is used for baffles, reflectors, dome and cassette body (CB), where W-MB & F82H-pipe PFU is installed due to *higher neutron flux* and *lower heat load condition*.
- Coolant is distributed **parallel** to inner and outer targets (baffles) with **comparable flow velocity**.
- Remote maintenance (RM): one cassette covers 7.5° toroidal area and weight is ~22 ton.
  ⇒ 3 cassettes are replaced from 1 port (total 48 cassettes from 16 ports)
- Total nuclear heating (PFUs, coolant pipes, supports, cassette bodies): 113 MW (2.4 MW/cassette).

**Divertor design in progress (2022)**





(1) Coolant circuits for Target/Baffle PFU supports

(2) Coolant circuit for Dome/ Reflector PFC structure

(3) Cooling concept and stress-analysis for cassette body

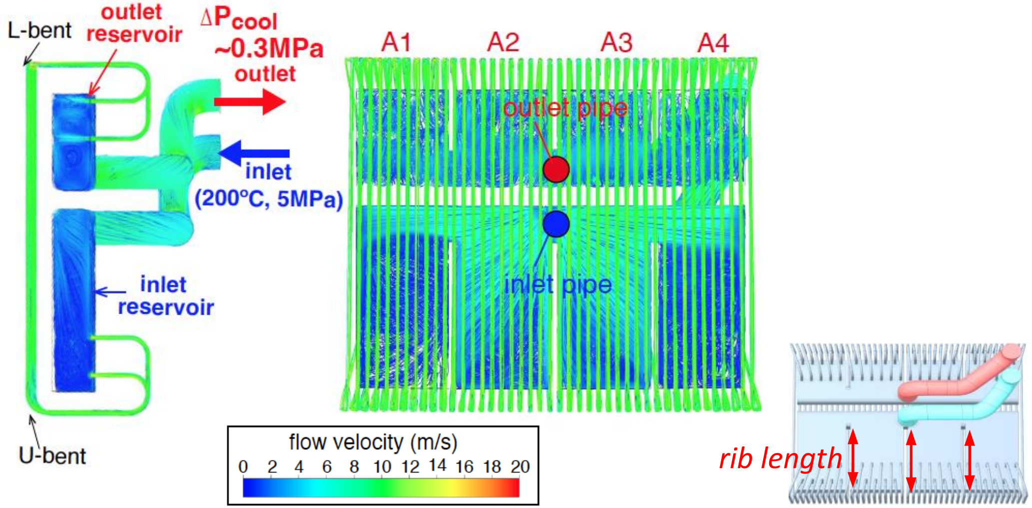
# 2. Coolant circuit design for PFUs in targets, baffles and dome

## Computational Fluid Dynamics (CFD) study for CAD-based design was carried out

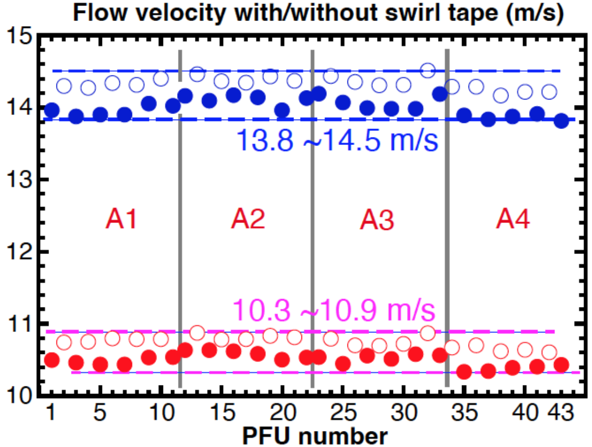
- Coolant (200˚C, 5MPa) is provided to inlet reservoir of outer target support (W-MB/CuCrZr-pipe PFU): divided into 4 rooms (A1-A4) by 3 support ribs, 43 PFU pipes are connected to the bottom.
- $V_{cool}$~10 m/s and inserting swirl tape are required to exhaust 10 MWm$^{-2}$-level heat load.
- Flow velocities ($V_{cool}$) in 43 pipes *without swirl tape* are adjusted by *inlet mass flow* and *rib lengths*: $V_{cool}$: 10.3-10.9 m/s, pressure drop($\Delta P_{cool}$): 0.3 MPa for total mass flow: 44 kg/s.

  *note:* $V_{cool}$ and $\Delta P_{cool}$ are increased *with inserting t1 swirl tape* to 13.8-14.5 m/s and 0.95 MPa, respectively.

**Coolant distribution and Flow stream w/o swirl tape**



**Flow velocity in CuCrZr pipe (w/wo swirl tape): Variation of $V_{cool}$ is smaller than 5%-6%**



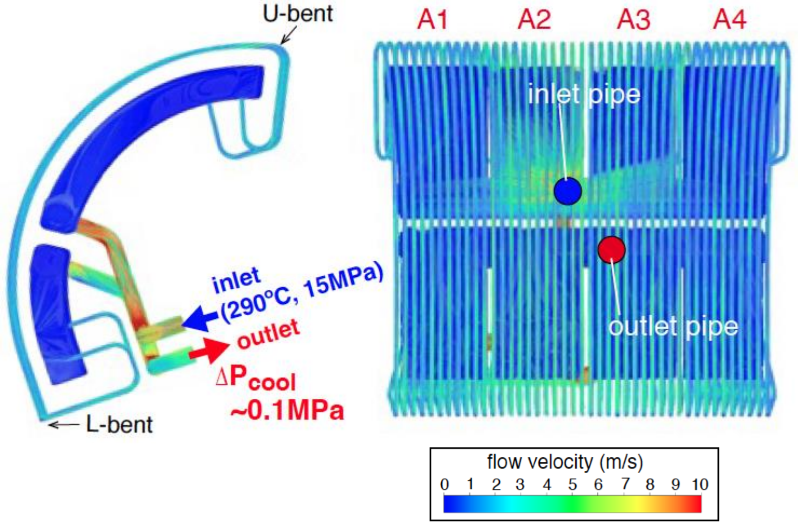
# Coolant distribution to W-MB/F82H-pipe PFUs for *outer Baffle*

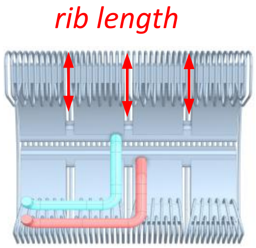
$V_{cool}$ of high-T coolant is adjusted to reach $T_{cool}$ from Breeding Blanket for elc.-generation

- Coolant (290˚C, 15MPa) is provided to inlet reservoir of outer baffle support: similarly divided into 4 rooms (A1-A4) by 3 support ribs.
- Nuclear heat on W is larger (5-9MWm$^{-3}$), but smaller plasma heat load: 1-2 MWm$^{-2}$(assuming $P_{rad}$).

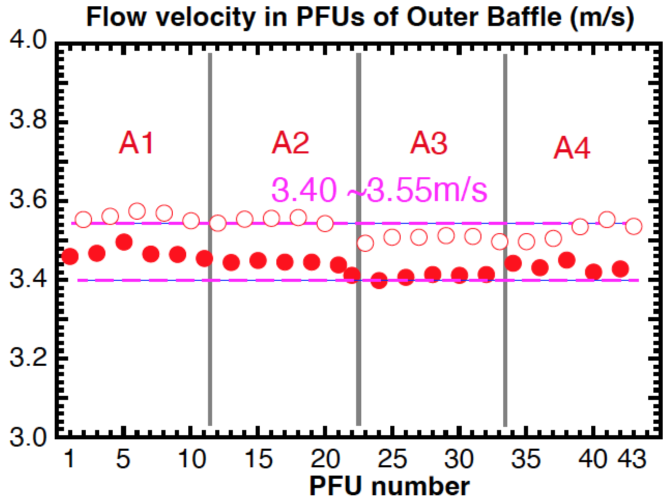
  Note: outlet coolant ($T_{cool}$~320°C) will be used for electricity-generation (steam-turbine) via heat exchanger.
- $V_{cool}$ values of 43 PFUs are adjusted between 3.4-3.55 m/s by *inlet mass flow* and *rib lengths*, and $\Delta P_{cool}$ is small (0.1MPa) for the total mass flow: 10.7 kg/s.

**Coolant distribution and Flow stream**





**Flow velocity in F82H pipe:**
**Variation of $V_{cool}$ is smaller than 4.3%**

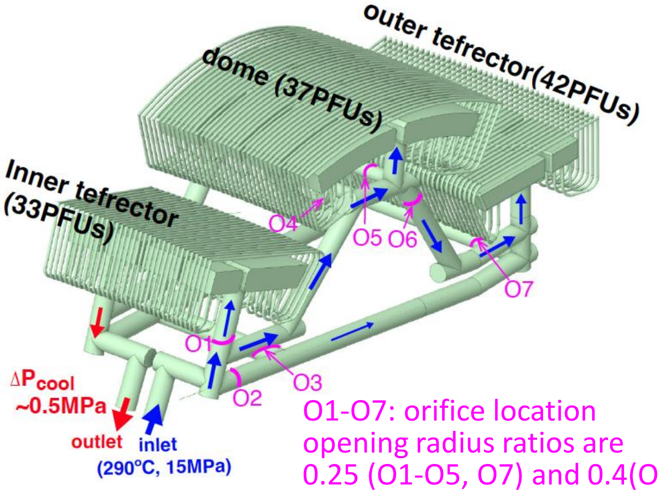


# Coolant circuit design for Dome and Reflector structure

## Parallel to inner ref. (33 PFUs), dome (37 PFUs), outer ref. (42 PFUs) and support structures

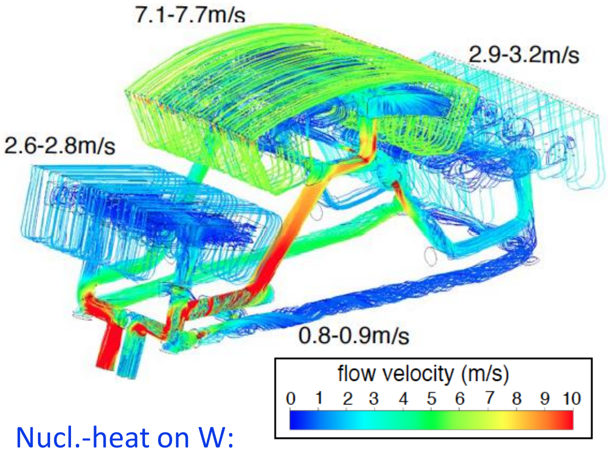
- Main coolant (290˚C, 15MPa) pipes are provided under inner reflector to avoid gas exhaust route.
- n-heat (W) is large at Dome (7-10MWm$^{-3}$), while plasma heat load is 1-2 MWm$^{-2}$ ($P_{plasma}$ & $P_{rad}$ from SONIC).
- *Mass flow in the main circuit* is adjusted by orifices (O1-O7): (IR) 5 kg/s, (D) 16 kg/s, (OR) 8 kg/s. $V_{cool}$ :(IR) 2.74 m/s, (D) 7.28 m/s, (OR) 3.07 m/s [$\Delta V$<6%]: Inlet/outlet pipes are located at other sides, and relatively low $\Delta P_{cool}$ ~0.5 MPa for the total mass flow: ~33 kg/s incl. dome support cooling.
  ⇒ $V_{cool}$, mass flow and $\Delta T_{cool}$ will be optimized after determining the dome support design.

### Coolant circuit in Dome and Reflectors



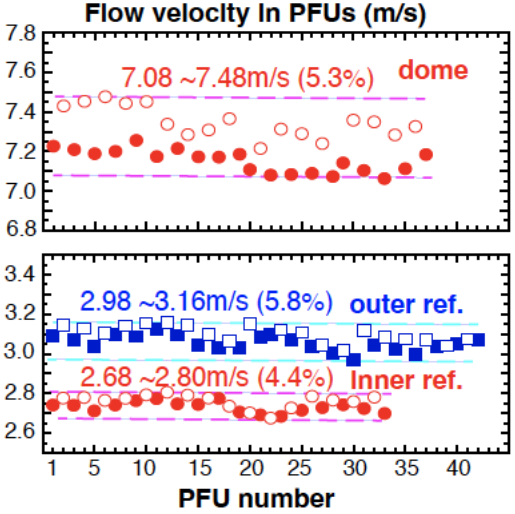
O1-O7: orifice location opening radius ratios are 0.25 (O1-O5, O7) and 0.4(O6)

### Velocity streamlines



Nucl.-heat on W:
Dome (7-10MWm$^{-3}$), Ref.(5-6MWm$^{-3}$)

### Flow velocities in FPUs



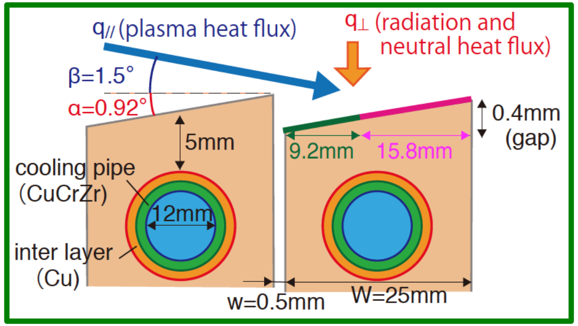
# 3. Heat & stress analysis of W-MB and CuCrZr-pipe target

## Temperature is increased at wet-area on fish-scale target: reducing margin to W-recrystallization

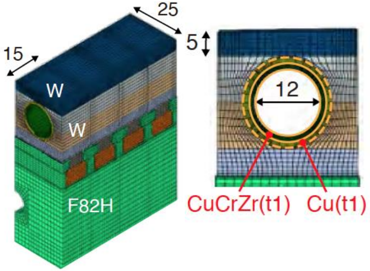
- Relatively high-$T_{cool}$ (200°C) is provided to W&CuCrZr PFU for minimizing rad.-ind. hardening on Cu-alloy under high n-dose ⇔ Rad.-ind. softening is also anticipated at high-$T_{CuCrZr}$ (>300°C).
- Heat load profile (plasma+radiation/neutrals) is applied on *ITER-like (fish-scale) target*: increasing *heat load on wet area* ($q^{wet}=q_{//}+q_{\perp}$). *Nuclear heat* ~4MWm$^{-3}$ *is also added* ~4MWm$^{-3}$.
  ⇒ 3D FEM calculation of heat transport and thermal stress.
- *Steady-state heat load* is restricted below $q_{target}$= 9.4 MWm$^{-2}$ on flat target ($q^{wet}$=13.5MWm$^{-2}$) by W-recrystallization (>1200°C) ⇒ Irradiation-creep/softening of CuCrZr is also anticipated at 351°C.

Note: SONIC simulation[2] expects peak-$q_{target}$ =5-7 MWm$^{-3}$ on flat target ⇒ $q^{wet}$ <10 MWm$^{-2}$

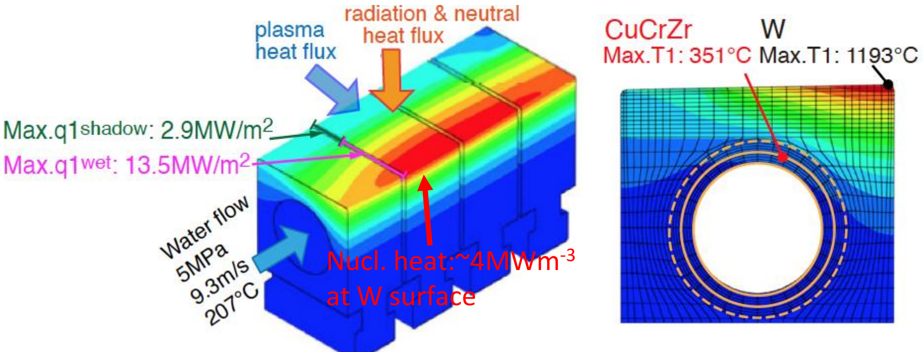
**ITER-like W-monoblock /CuCrZr-pipe:**
smaller thickness (5mm) and width (25mm)



**4-MB model & mesh for 3D FEM analysis**



**Temperature on MB-surface and cross-section**



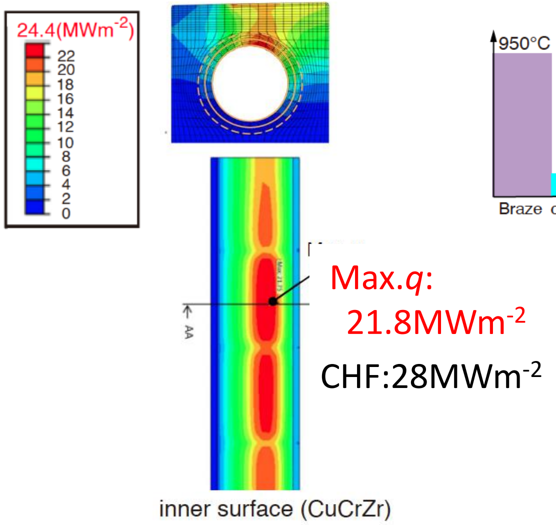
Note: heat transfer coefficient with swirl tape was used.

# Elasto-plastic stress analysis on W-MB and CuCrZr-pipe

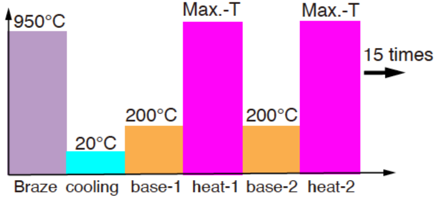
Repeating larger heat load cycles of $q_{target}$= 11.2MWm$^{-2}$ on flat target ($q^{wet}$=15.2MWm$^{-2}$)

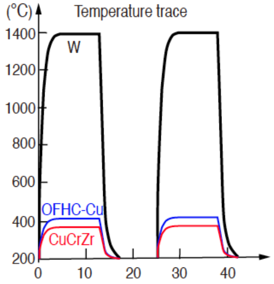
- Max. Temp. increased to W:1400°C (recrystallization) and to CuCrZr:365°C (creep/softening). Heat flux to coolant is increased from 18MWm$^{-2}$ (CHF ratio: 64%) to 22MWm$^{-2}$(79%).
- Stress-strain was evaluated, considering residual stress-strain after braze process (950°C).
- Large stress of W-MB and CuCrZr-pipe appears at *inner surface under W-MBs*, and at *upper (inner surface) under W-MBs* and *side (outer surface) between W-MBs*.

**High heat flux in MB and at inner CuCrZr pipe**

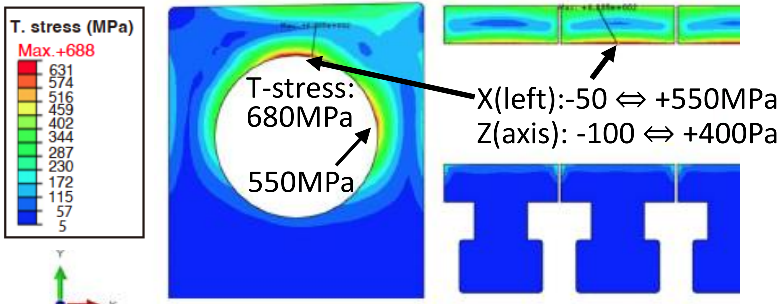


**Temperature and heat load history for stress-analysis**

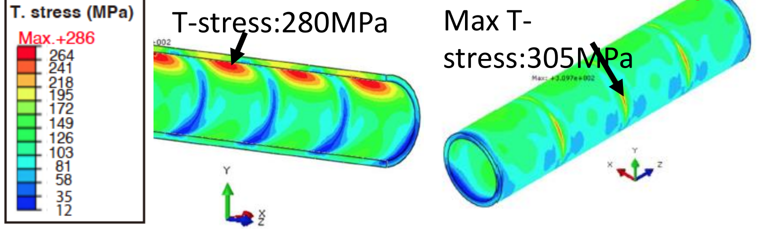




**During heat loading:** max. Tresca stress on W:680MPa



**Inner and outer surfaces of CuCrZr-pipe**



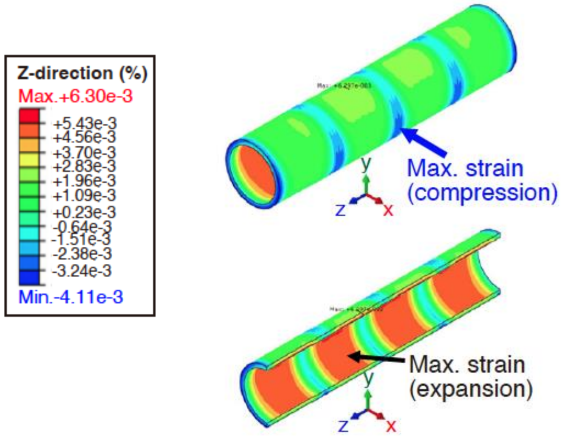
# Stress-Strain cycle of heat sink for *small* transient heat load

- Mechanical strain is increased at inner (expansion) and outer (compression) of CuCrZr pipe: at maximum Tresca-stress, Stress ($\sigma_Z$) -Strain ($\varepsilon_Z$) trace in Z-direction repeats similar trajectory

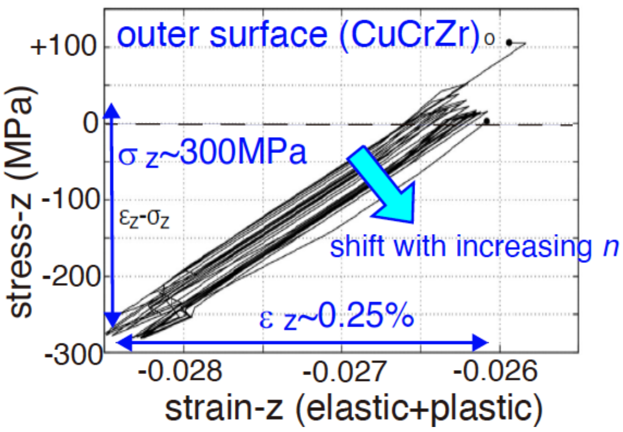
⇒ Stress-Strain cycle ($\Delta\sigma_Z$ ~300MPa, $\Delta\varepsilon_Z$ ~0.25%) by $q_{target}$ >10MWm$^{-2}$ on flat target ($q^{wet}$= 15.2 MWm$^{-2}$) may not be a critical lifetime issue in early DEMO stage, while W-recystalization is progressing.

⇒ Reduction in $T_{cool}$ is necessary to handle slow transients such as 20MWm$^{-2}$ (~10 s).

**Strains (z-direct.) in CuCrZr pipe**



Stress-Strain trace (z-direction)



# 4. Cooling concept and stress analysis for divertor cassette

## Design proposal of PWR coolant (290°C,15MPa) from side routes to toroidal peddles

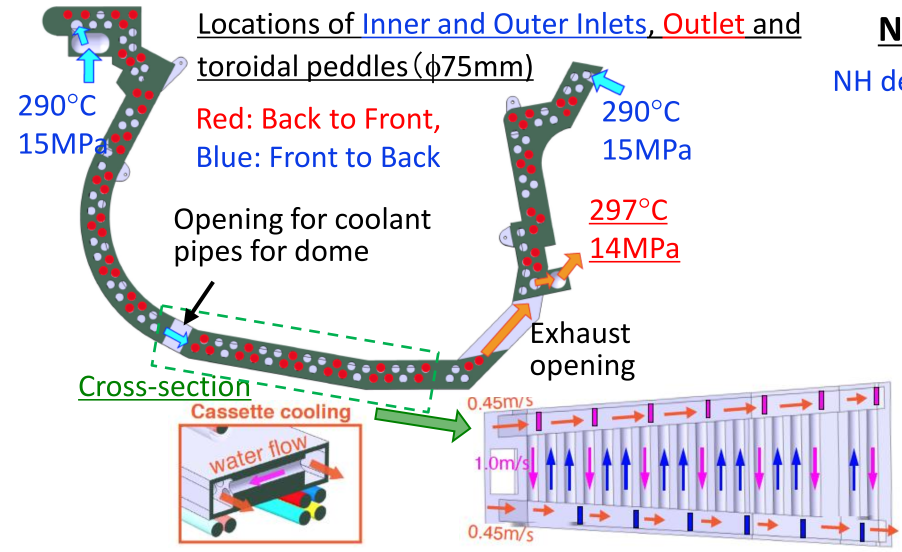
- RAFM steel (F82H) is used for cassette body (CB). PWR condition water (15 MPa, 290 ˚C) is supplied.

ITER: lower temperature water（70-100°C, 4MPa）is supplied to reservoir separated by ribs (SS316L(N)-IG).

⇒ reinforcing rib & wall thickness and neutron shield as well as exhausting larger nuclear heat

- Requirement of heat exhaust: 0.58 MW/cassette (totally 28 MW for 48 cassettes)
- Assuming $V_{cool}$: 0.45m/s (in two side routes) and 1.0m/s (in peddles) ⇒ expecting $\Delta T_{cool}$~9°C

⇒ Sufficient heat exhaust from high nucl. heat area: inner surface below dome (305-330°C), and opening edge regions for coolant pipes and gas exhaust ($\Delta T$ is lower than 110°C).

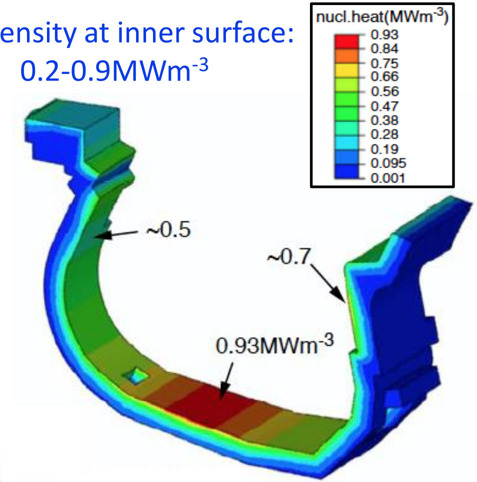


Locations of Inner and Outer Inlets, Outlet and toroidal peddles（ϕ75mm)

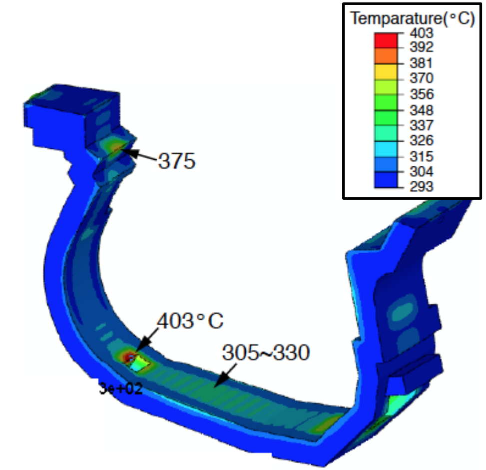
Red: Back to Front,
Blue: Front to Back

**Nuclear heat distribution**

NH density at inner surface: 0.2-0.9MWm$^{-3}$



**Surface temperature distribution**



# Analysis of heat transport (steady-state) and thermal stress

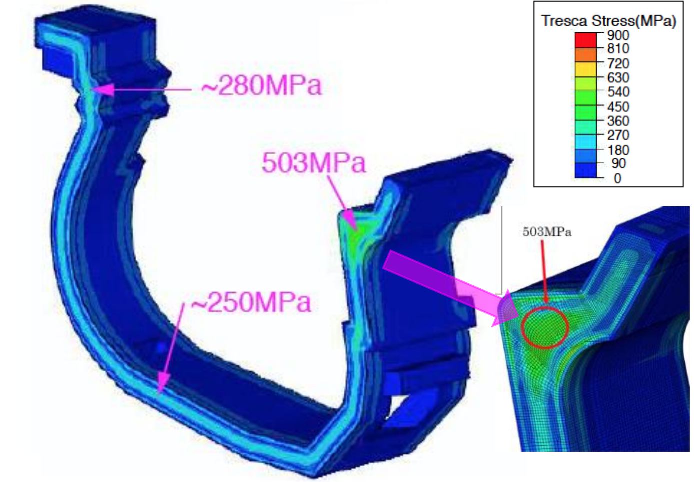
Total stress is below the critical value, while enforcing side-walls are required.

- Static stress on the side wall（t30mm) by 15 MPa coolant is widely increased to 250-280 MPa. Max. ~500MPa appears *locally at wide and bend region* ⇒ require to increase the thickness.
- Thermal stress analysis with 290°C (15MPa）coolant and n-heat (~0.9MW/cassette) showed: Thermal stress is increased *at the inner surface* (60-155 MPa), and *at support foot locations of PFUs and exhaust opening* (190-230 MPa).

⇒ Total stress: “gravity”+“pressurized water”+“thermal stress” less than 3Sm（423MPa）

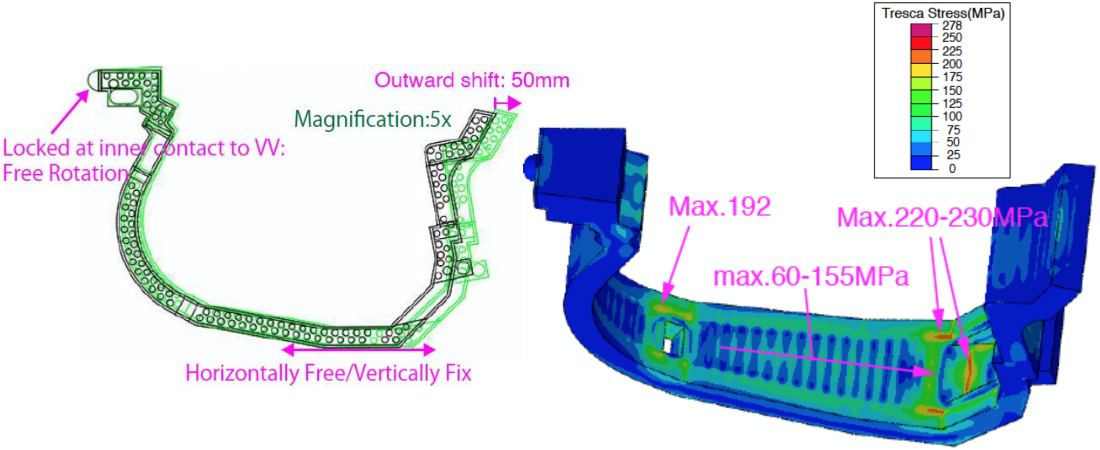
**Static stress by 15MPa pressurized water (25°C)**

Stress at side wall: 200-280MPa (except for wide region）



**Thermal expansion and stress under NH and PWR water**

Note: weight of PFCs on the support structures is considered.



# CFD study of peddle and fin concept for cassette body

*Peddle concept* is investigated with adjusting Fin size and location (grouping)

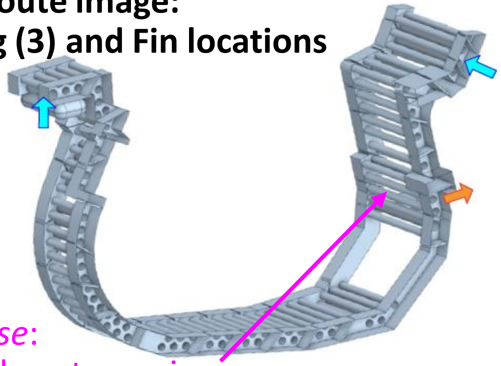
- Toroidal peddle concept was investigated by CFD analysis:

1) Peddle grouping (3) and Slit locations (~20 for each side) were determined:
$V_{cool}$ variation is decreased, but $\Delta P_{cool}$ is increased with decreasing grouping number such as 2.

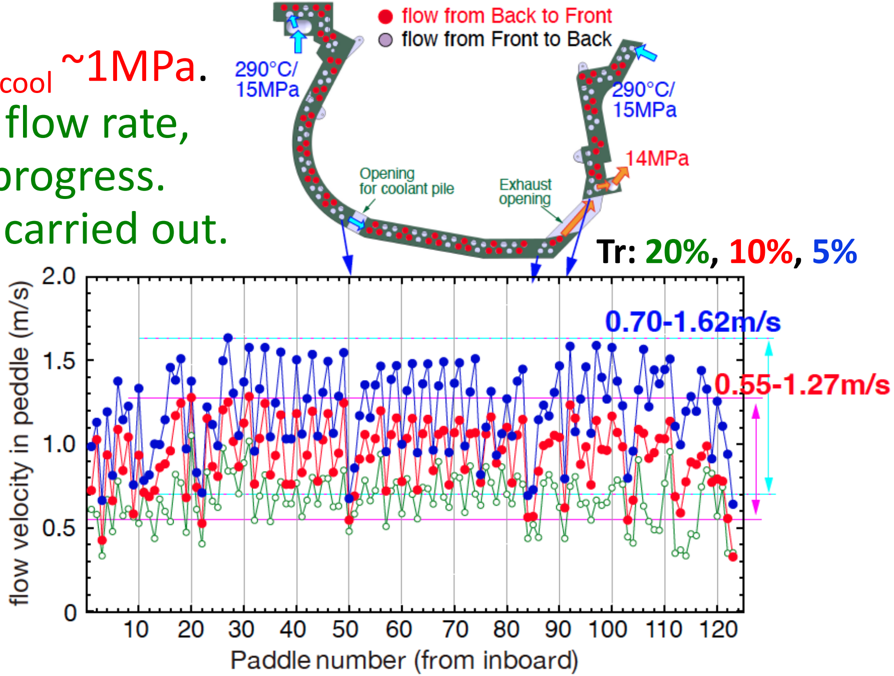
2) Fin transparency (Tr: 0-50%) was determined to ~10% for a given mass flow rate: 17kg/s (inboard route) and 13kg/s (outboard route):
Ave. $V_{cool}$ ~0.9m/s, $\Delta V/V_{cool}$ ~66%, total outlet $\Delta p_{cool}$ ~1MPa.

- Optimizations such as reducing $\Delta V_{cool}$ , total mass flow rate, and series circuit (from 1-inlet to 1-outlet) are in progress.
- Heat transport and thermal stress analysis will be carried out.

**Coolant route image:**
**Peddle grouping (3) and Fin locations**



*2-inlets and 1-outlet case*:
$V_{cool}$ adjustment is easer near Exhaust opening.



# Summary of recent progress on JA-DEMO Divertor design (1)

- Design concept of JA-DEMO divertor has been developed for Total plasma power ($P_{sep}$-$P_{rad}^{sol}$ = 270MW, 5.6MW/cassette) and Total nuclear heating of 113 MW (2.4 MW/cassette).
- Circuit design of 200°C coolant (5MPa) for high heat load targets (W-MB & CuCrZr-pipe) and 290°C coolant (15MPa) for high neutron-load PFUs (W-MB & F82H-pipe) and Cassette Body started.
- Parallel distributions for inner and outer targets/baffles, and Parallel circuit to dome, reflectors and support structure were investigated to avoid faster flow speed in the inboard PFUs.
- Peddle and fin cooling concept for CB was investigated to exhaust large n-heating and to reinforce rib&wall thickness and n-shield ⇒ improvement is in progress

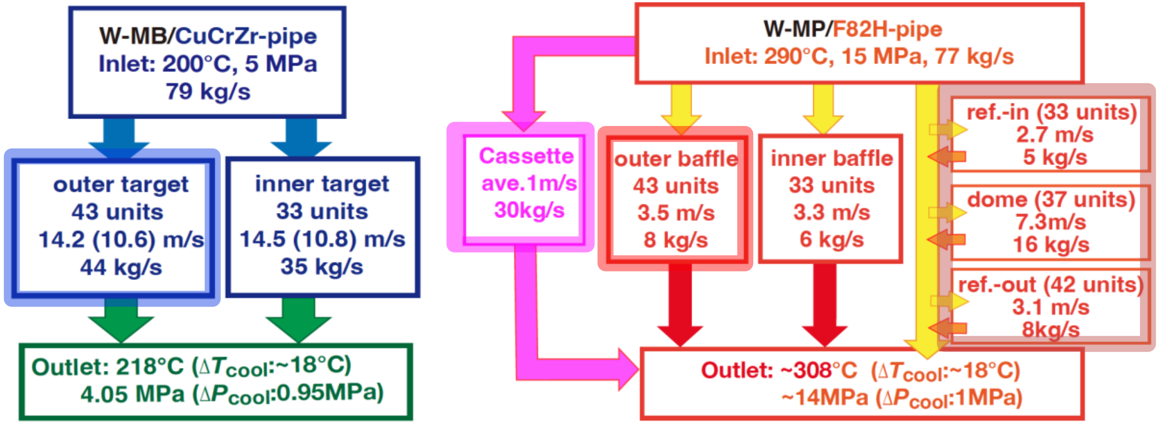
  ⇒ thermal and stress analysis on 3D modeling.

Note: Total mass flow of 290°C coolant will be reduced, providing enough margin to $T_{structure}$ (F82H) limit.

But, increasing to $T_{cool}$~320°C (Bleeding Blanket-level) is a critical

⇒ Divertor coolant will be used for pre-heat of the PWR coolant

**Coolant circuits for JA-DEMO and tentative parameters**



W-MB/CuCrZr-pipe
Inlet: 200°C, 5 MPa
79 kg/s

outer target
43 units
14.2 (10.6) m/s
44 kg/s

inner target
33 units
14.5 (10.8) m/s
35 kg/s

Outlet: 218°C ($\Delta T_{cool}$:~18°C)
4.05 MPa ($\Delta P_{cool}$:0.95MPa)

W-MP/F82H-pipe
Inlet: 290°C, 15 MPa, 77 kg/s

Cassette
ave.1m/s
30kg/s

outer baffle
43 units
3.5 m/s
8 kg/s

inner baffle
33 units
3.3 m/s
6 kg/s

ref.-in (33 units)
2.7 m/s
5 kg/s

dome (37 units)
7.3m/s
16 kg/s

ref.-out (42 units)
3.1 m/s
8kg/s

Outlet: ~308°C ($\Delta T_{cool}$:~18°C)
~14MPa ($\Delta P_{cool}$:1MPa)

# Summary and Future work for JA-DEMO divertor design (2)

- Heat removal of W-MB & CuCrZr-pipe PFU by 200˚C coolant with adding nuclear heating:
  Heat transport analysis *for fish-scale geometry* showed that *steady-state heat load* is restricted (by W-recrystallization) below 9.4 $MWm^{-2}$ on flat target ($q^{wet}$ =13.5 $MWm^{-2}$ on fish-scale).
  In addition, irradiation-creep/softening of CuCrZr-pipe is also anticipated at 351°C.
- Elasto-plastic stress analysis showed that Stress-Strain cycle by $q_{target}$ >10 $MWm^{-2}$ on flat target (*small transient heat load*), $\Delta\varepsilon$~0.25% may not be a critical lifetime issue, but reduction in $T_{cool}$ is necessary to handle ITER-like slow transients such as 20$MWm^{-2}$ (~10 s).

**Future work on baseline design and options:**

- Thermal stress analysis of this baseline concept is established for further design improvement.
- Divertor cooling for F82H-base design (baffle, dome, cassette) by lower $T_{cool}$ and $P_{cool}$ coolant (such as 200˚C, 5MPa) will simplify pressure boundary, temp. margin and cooling pipe number.
- Reduction in $T_{cool}$ (lower than 200˚C) and improvement for W-MB&CuCrZr-pipe design will be necessary to handle ITER-like slow transients such as 20 $MWm^{-2}$ (~10 s).

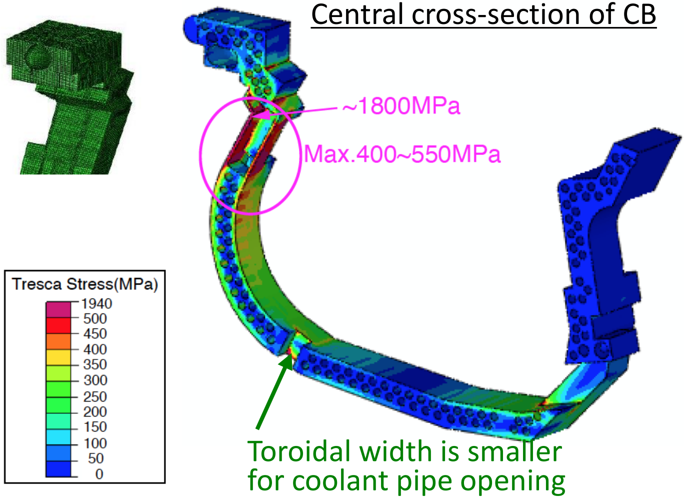
# Stress analysis induced by hallo currents during a VDE disruption

Induced EM force by hallo current may cause large stress on cutting structure of CB

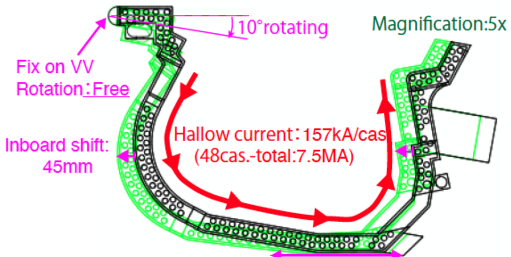
Assuming total hallow current (7.5MA) is driven from inboard to outboard in CB by VDE disruption, induced *jxB* electro-magnetic force and transient stress is evaluated:

- “Spherical shape” design of inboard attachment: it is easy for precise adjustment in RM.
  Large inboard shift (max. 45mm) due to rotating motion by the jxB force ⇒ Local Trasca stress is increased to 400-550MPa, due to narrow cassette (toroidal) width at coolant pipe slits
- “Key shape” (no rotation) will be preferable ⇒ Max. T-stress is reduced to 200-300MPa.

**Spherical attachment: displacement and Stress**

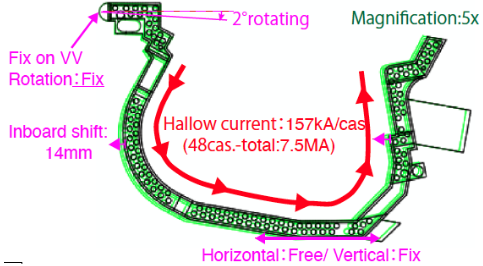


Toroidal width is smaller for coolant pipe opening



**No rotation case**

Horizontal：Free/ Vertical：Fix



**Assuming Key attachment (no rotation):**

Stress is increased near attachment location