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Design study of structural components and issues on maintenance scenario for helical reactor FFHR-d1A

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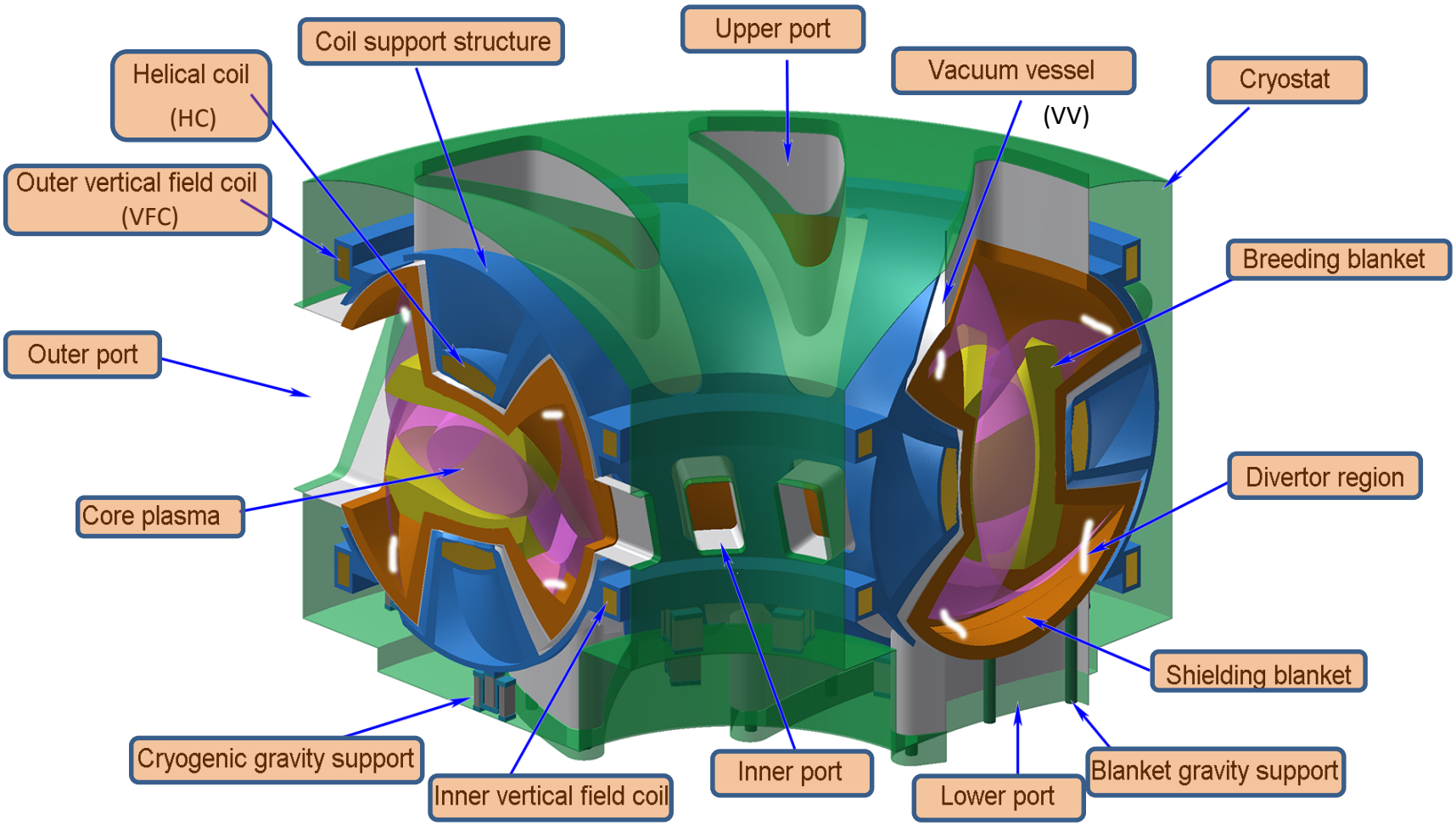
Structure of the FFHR-d1

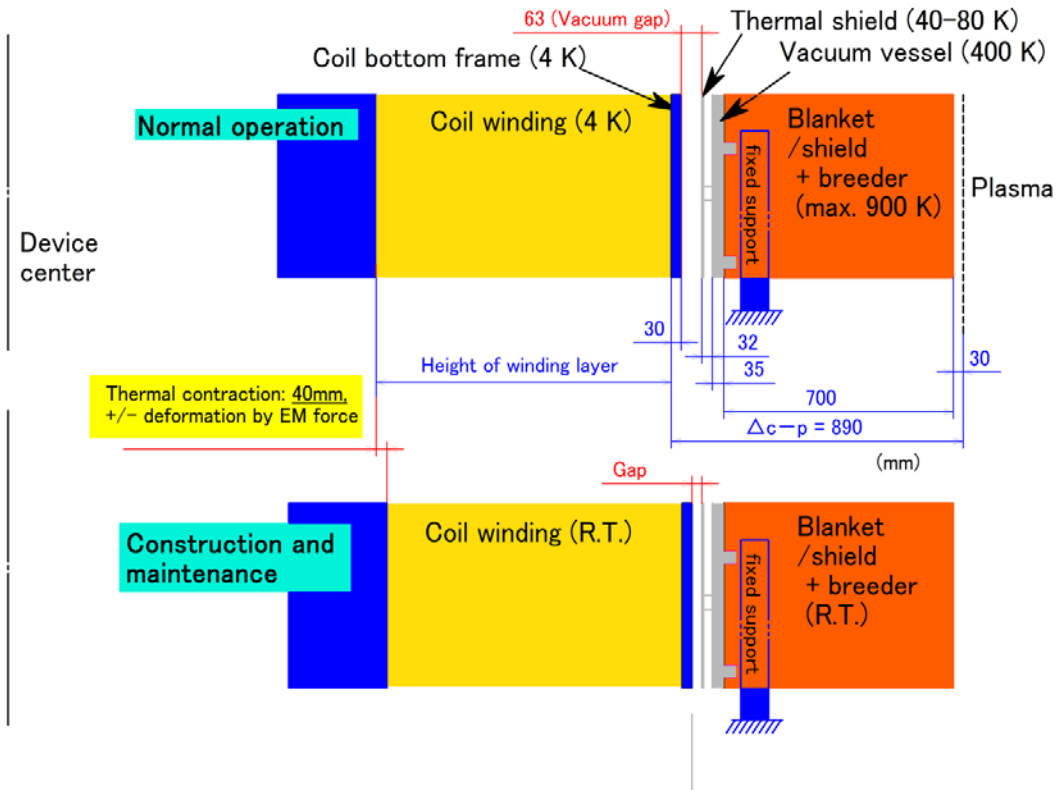


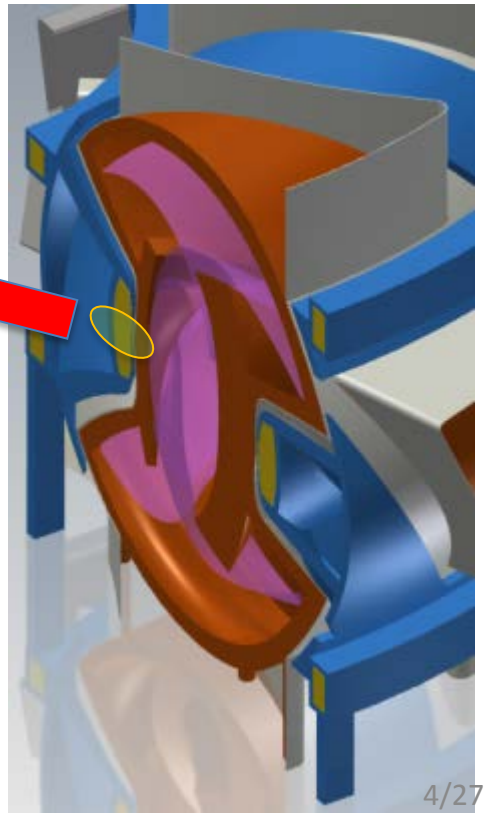
Key issues of structural components

Subject	Goal	Achievement	Next move
1. Radial build	Ensure a blanket space and an adiabatic gap	✓ Distribution of the space during an operation and a maintenance period	Expand into 3-D Construction and maintenance method
2. VV	Geometry definition to be consistent with the blanket and EM force support structure	✓ Basic geometry using numerical equations ✓ Access ports with large aperture	Optimization in accordance with maintenance scenario
3. Electromagnetic (EM) force support structure	Optimized design of robust and minimum-weight support structure	✓ Design with 3-D FEM calculation ✓ 660 MPa stress and further optimization	Further optimization in accordance with maintenance scenario
3. Gravity support	Support method of heavy weight both in mechanical and thermal viewpoints	✓ Multi-fold-type gravity support for cryogenic components ✓ Concept design of blanket system	Fabrication method
4. Maintenance	Draw up a maintenance scenario	✓ Research of maintenance condition and machinery ✓ Development of autonomous mobile robot	Visualization

Radial build design①

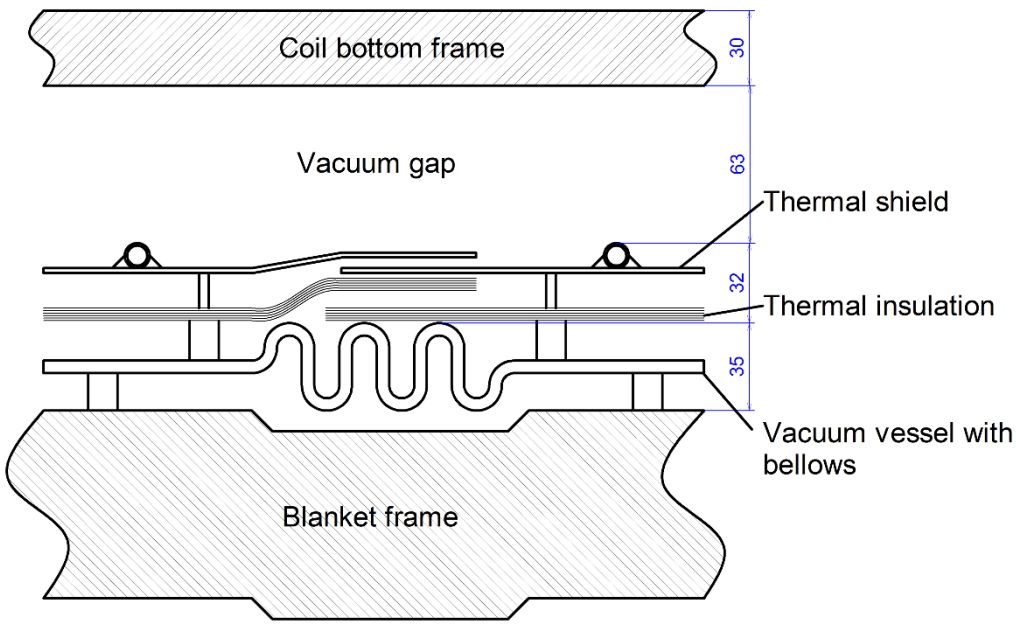
- An LHD-type configuration offers limited space between plasma and HC (Δc-p), especially at the inboard of the torus.
- Δc-p at the inboard of the torus was estimated to be 890 mm from a system code analysis and a blanket design investigation.
- A 700-mm blanket space can be achieved, and a clearance of 30 mm is assigned between the plasma surface and the first wall.
- Residual 190 mm is distributed to a VV (35 mm), thermal shield (32 mm), coil case (30 mm), and gap (63 mm).





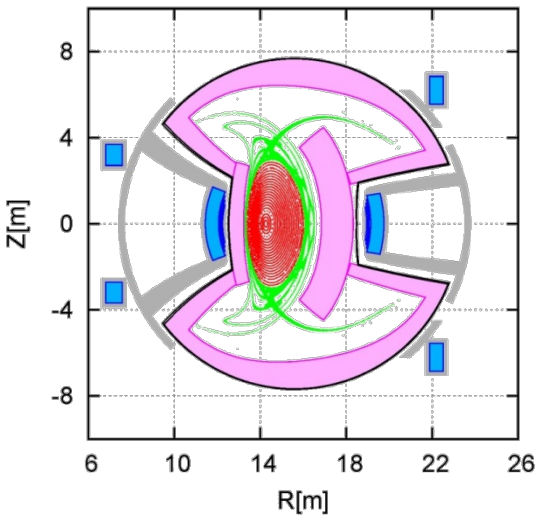
Radial build design②

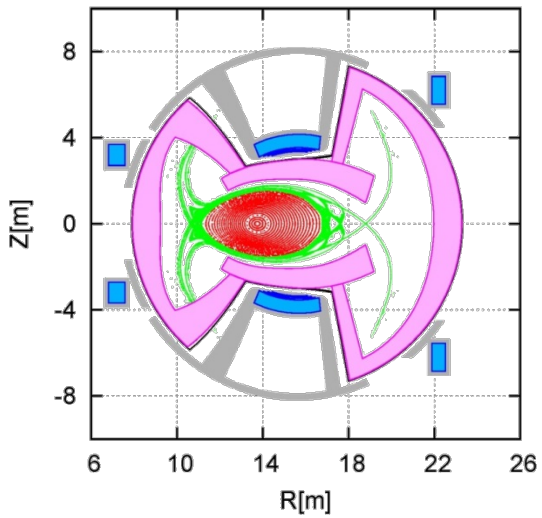
- To maintain the geometric position:
  - The blanket toroidal/poloidal cross section is divided into several sections.
  - The support for the blanket system is set near its coil side to restrict the inward displacement of the blanket.
  - The VV is composed of a thin steel plate and is attached to the surface of the blanket.
  - The thermal shield is connected to the outer surface of the VV.
- The positions of the HC and the support structure should be set, considering a deformation by the thermal contraction and EM force.

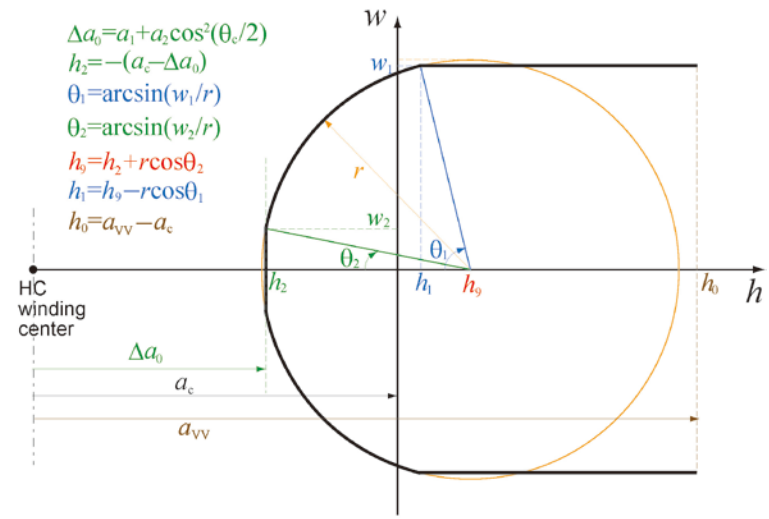


Schematic of structure at between the blanket and the coil.

Mathematical Expression of the Basic Shape of VV and Blanket

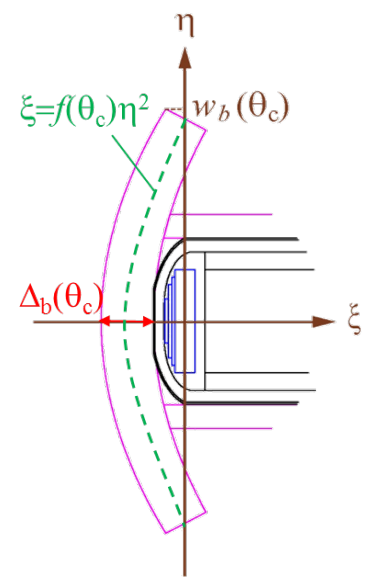






$\theta_c = -(5\phi + 0.1\sin(5\phi))$

- The basic shape of the VV and the blanket / shield were defined by using a mathematical expression as a function of toroidal angle ϕ.
- VV:
  Based on a torus shell structure.
  Dome-like shape around the HC.
- Blanket/shield:
  A thickness was set from 400 mm to 700 mm depending on a neutron irradiation and a tritium bleeding.
- Mathematical Expression was defined to make modification of the design and translation to CAD data easy.
  (by T. Goto)



EM force support structure -outline-

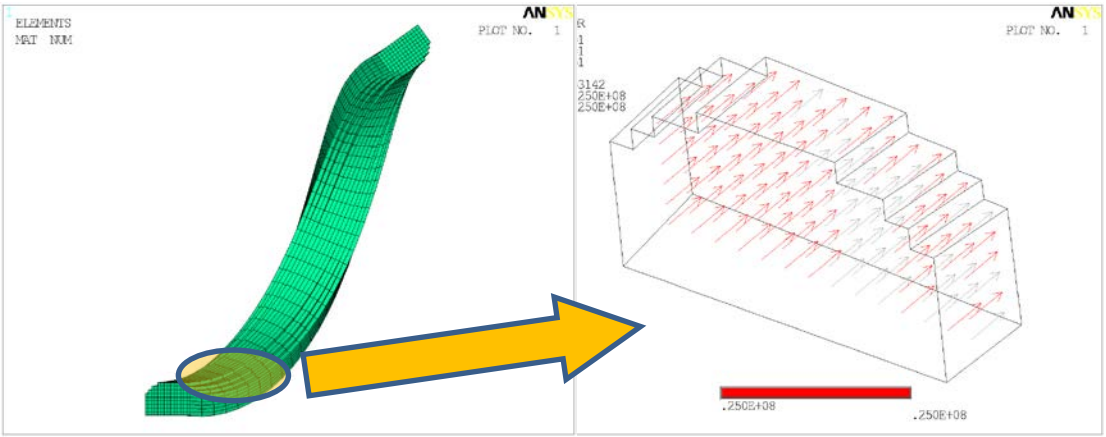
- Tough structure is needed to support superconducting coils whose total stored magnetic energy is 160 GJ.
- A blanket system and a divertor system require maintenance and part exchange.
- VV, coil support structure, and cryostat require large apertures to implement a maintenance of a blanket and divertor.

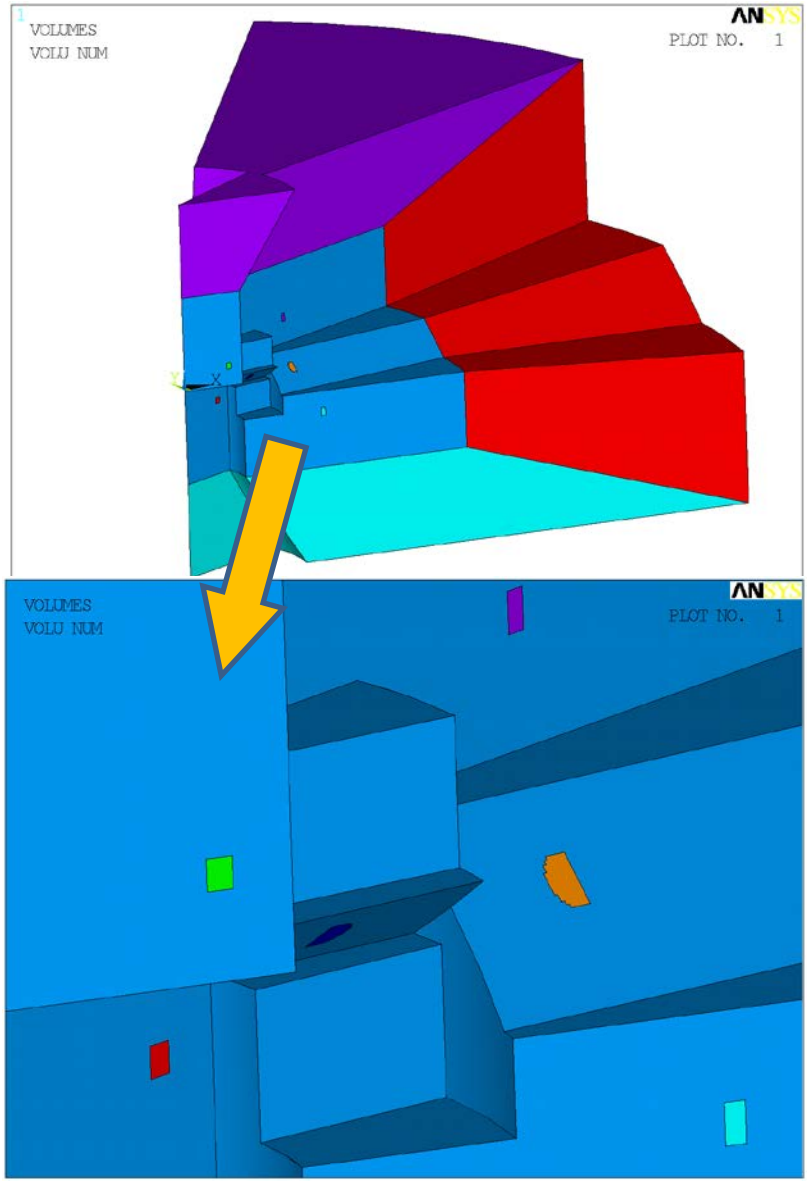
- In parallel with the design activities for the FFHR-d1, modifications for the fundamental design parameters have been investigated.
- FFHR-d1A is one of the optional design;
  changed the helical pitch parameter from 1.25 to 1.20 for improving high energy confinement,

- The structural design for FFHR-d1 and FFHR-d1A are introduced.

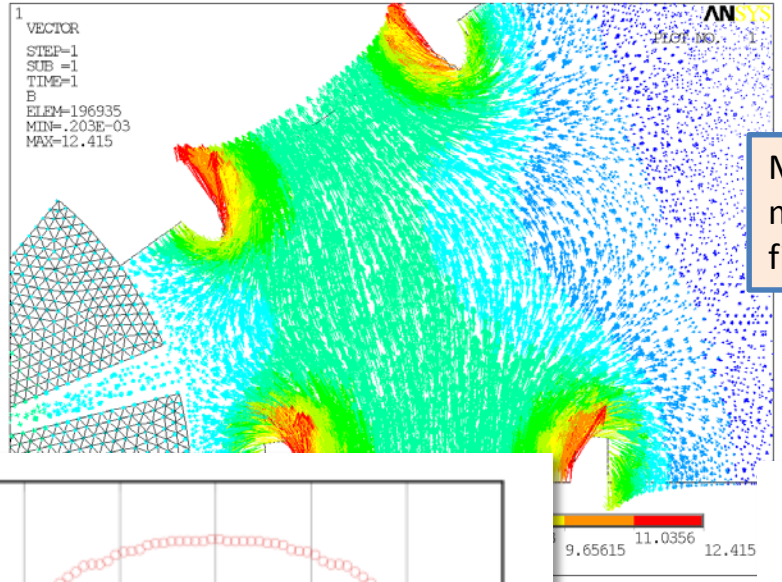
EM force of the magnet –analytic model-

- Winding section; current density 25 A/mm2, magnetomotive force 36.66 MAT.
- The coils and surrounding vacuum space were modeled as a vector potential element in an ANSYS program.
- HC is divided into sections in every toroidal angle of 1 degree.
- The direction of current flow corresponds to the axis of the element coordinate system.

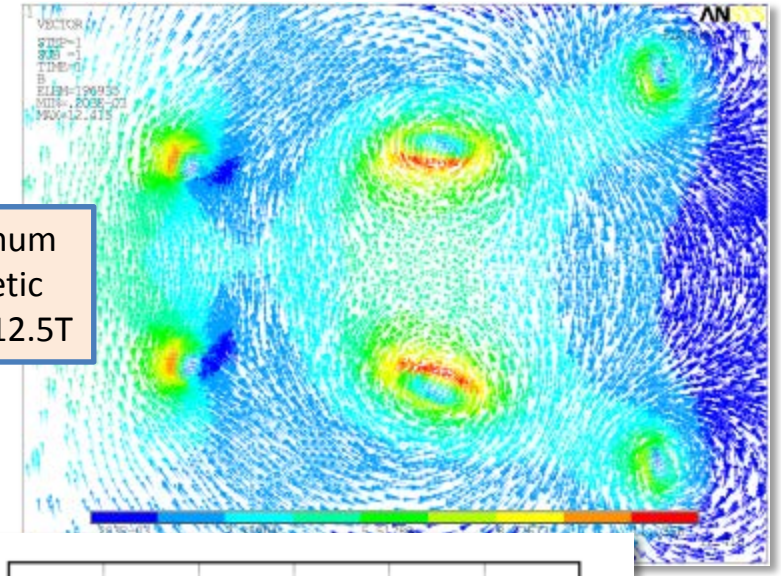


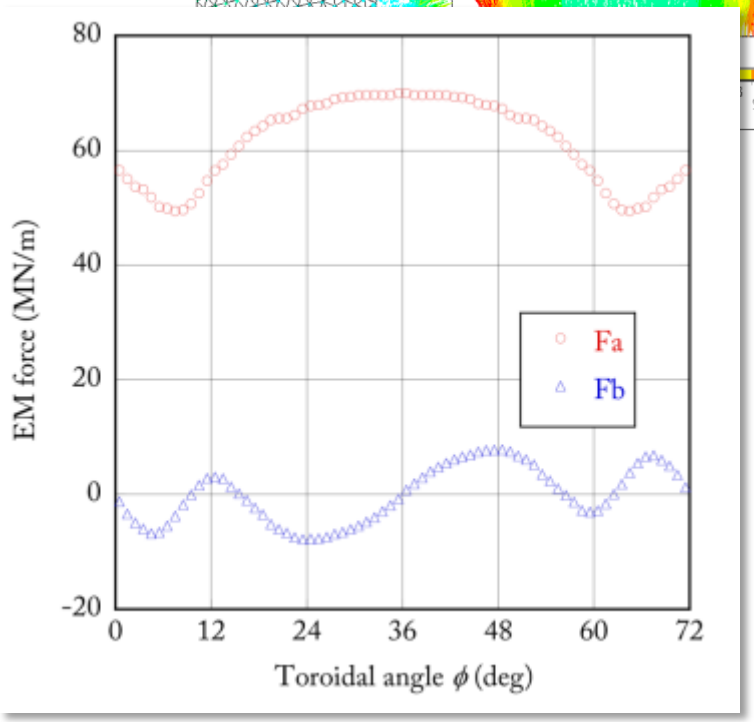


EM force on the magnet –result–

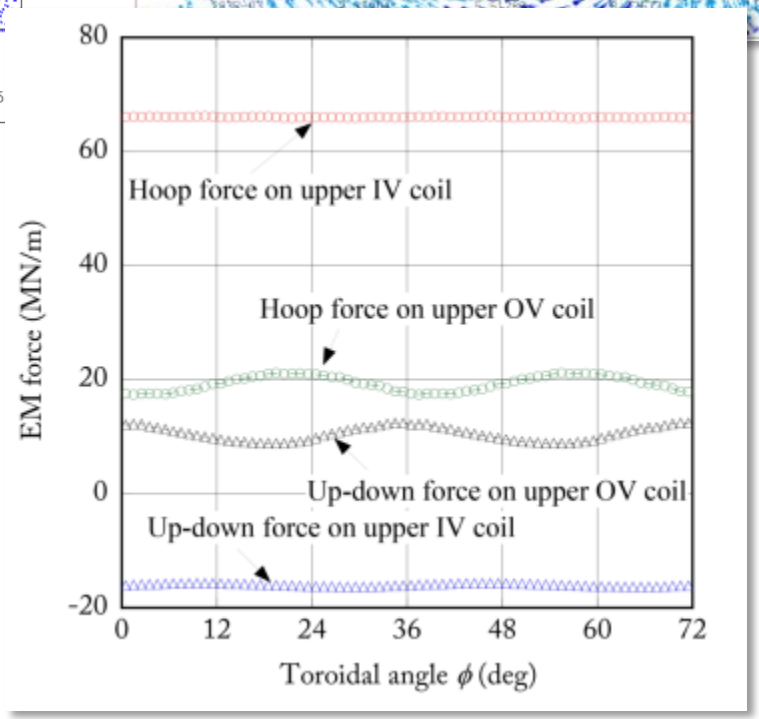


Maximum magnetic field: 12.5T





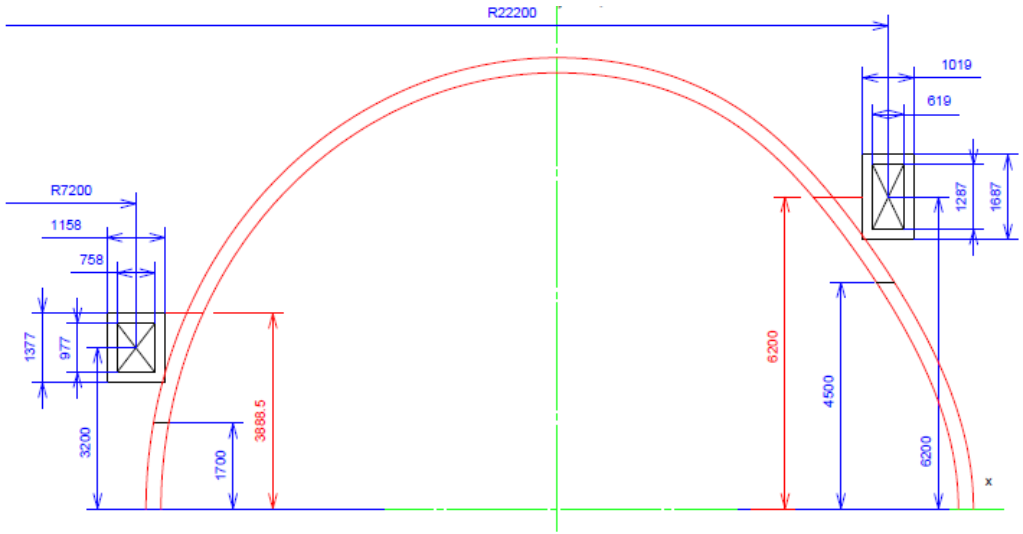
Overall EM forces on the HC at every cross section.
Fa: direction of the minor radius of the HC.
Fb: perpendicular to the coil winding and the minor radius direction.



EM forces on the IVC and the OVC.
Because of dyad rotational symmetry, only the upper portions are shown. The positive value indicates an expansion or a repulsion force.

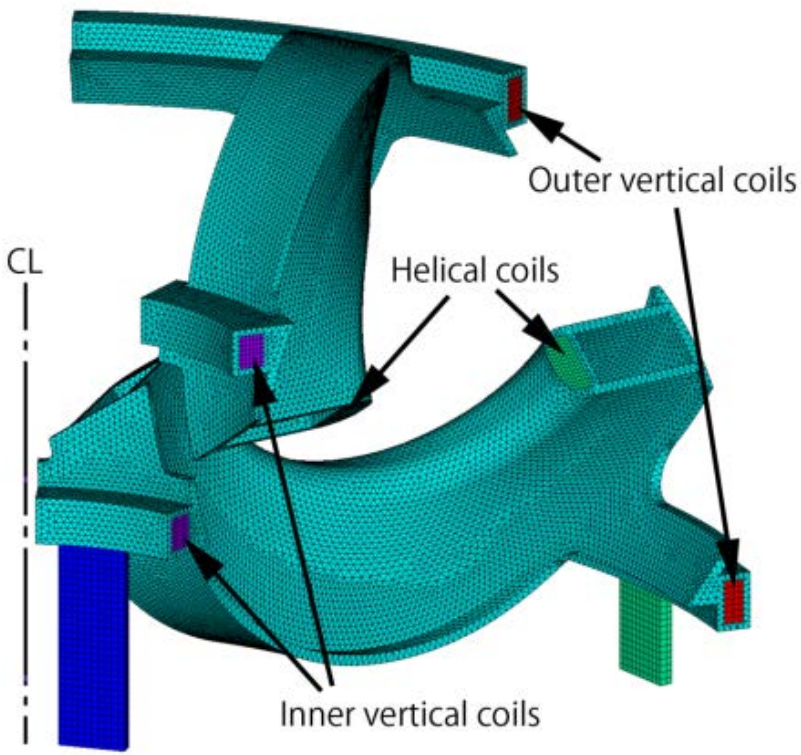
Stress analysis –model-

- An analytical model of the coil support structure;
- ✓ made of SS 316; 300 mm thick,
- ✓ a vacuum gap of 200 mm between the support and the outer surface of the VV,
- ✓ VFCs are surrounded by 200 mm–thick SS and were connected to the support.
- Modelling was repeated until the stress level becomes allowable.



Material properties for FEM

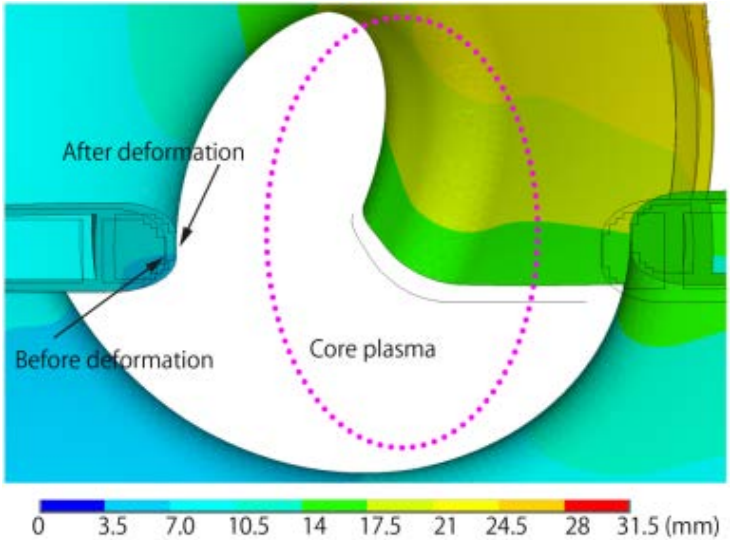
Component	Young's modulus	Poisson's ratio
HC	80 GPa	0.3
VFC	110 GPa	0.3
Support	200 GPa	0.3



Fundamental design of the coil support structure with FEM mesh.

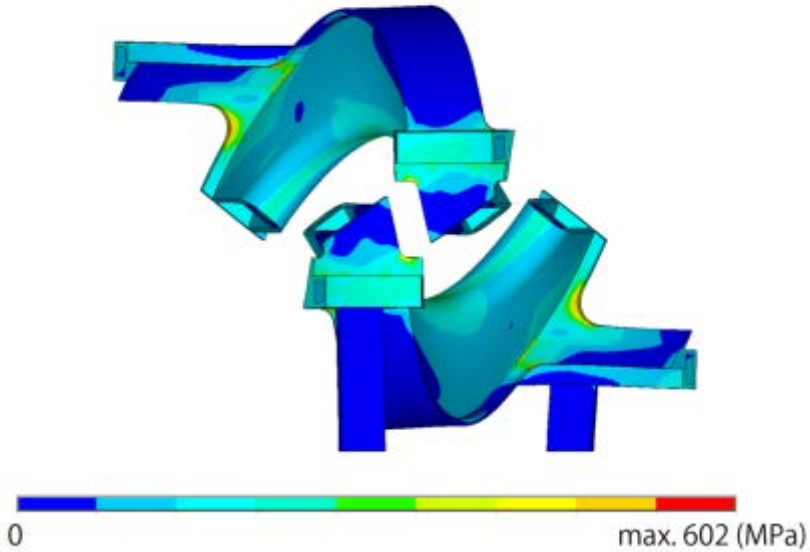
Stress analysis –result-

- The maximum von Mises stress of 600 MPa was at the corner area of the port region, which is the permissible limit for SS 316 at cryogenic temperature.
- As spatial stress distribution did not exceed 400 MPa, the soundness of the structure can be consequently guaranteed.
- A maximum deformation of 32 mm appeared near the OVC.
- The displacement near the bottom region of the HC toward the plasma side was 7 mm. With a thermal contraction of 40 mm, there would be a 30-mm gap between the surface of the thermal shield and the bottom of the coil case during the construction/maintenance phase.

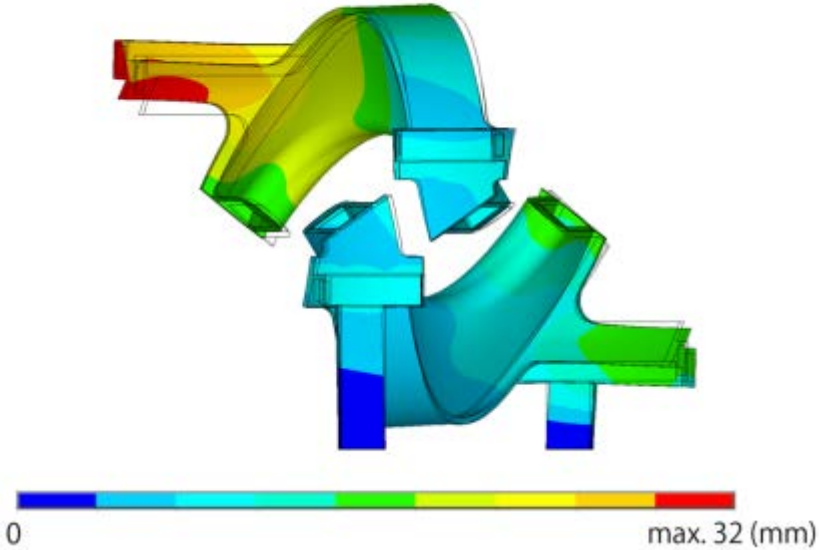


Deformation at the bottom of the coil

(a) Von Mises stress distribution



(b) Amount of deformation



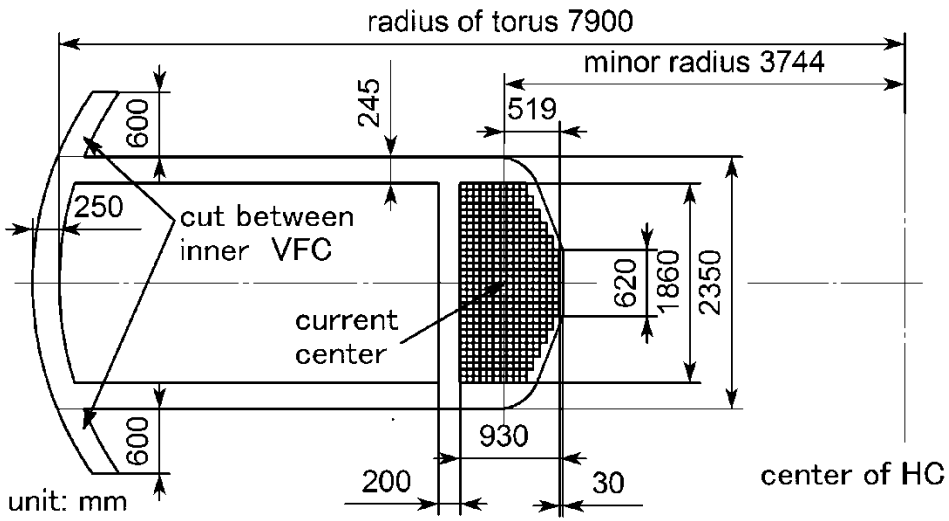
Shift to FFHR-d1A

- According to the physical analyses of core plasma, the HC pitch had been changed from 1.25 to 1.2. Defined as FFHR-d1A.
- The minor radius of the HC was changed from 3.9 m to 3.744 m.
- The major radius (15.6 m) and geometrical position of VFCs were the same.
- The EM force support structure was also modified;

✓ reconsideration of the cross sectional configuration of the HC,
✓ reduction of basic thickness to be lighter,
✓ revising the local shape to prevent stress concentration,
✓ enlarge inner ports for a divertor maintenance.

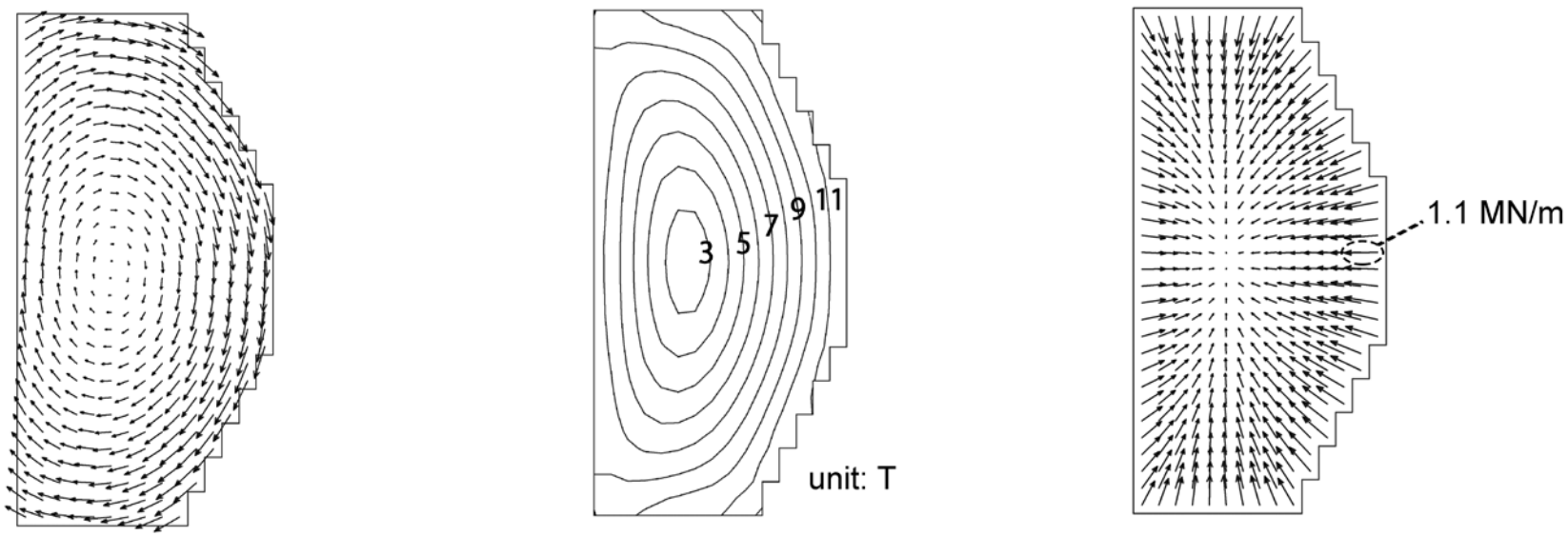
Cross section of HC

- The coil winding area consists of 390 turns.
- One superconductor has a square shape, with each side being 62 mm. (including an insulator and cooling path)
- The capacity of the superconductor is 94 kA of current flow.
- The bottom of the coil has a step-like feature to prevent interference in the VV.
- Basic thickness is 250 mm.



EM force analysis for FFHR-d1A

- The calculated maximum overall EM hoop force and the overturning force among each cross section of the HC was 64 MN/m, while the maximum EM overturning force was ±8 MN/m.
- These results were slightly lower than those of the original FFHR-d1.
  →The force depends on the shape of the HC cross section and the distance between the HC and VFC.

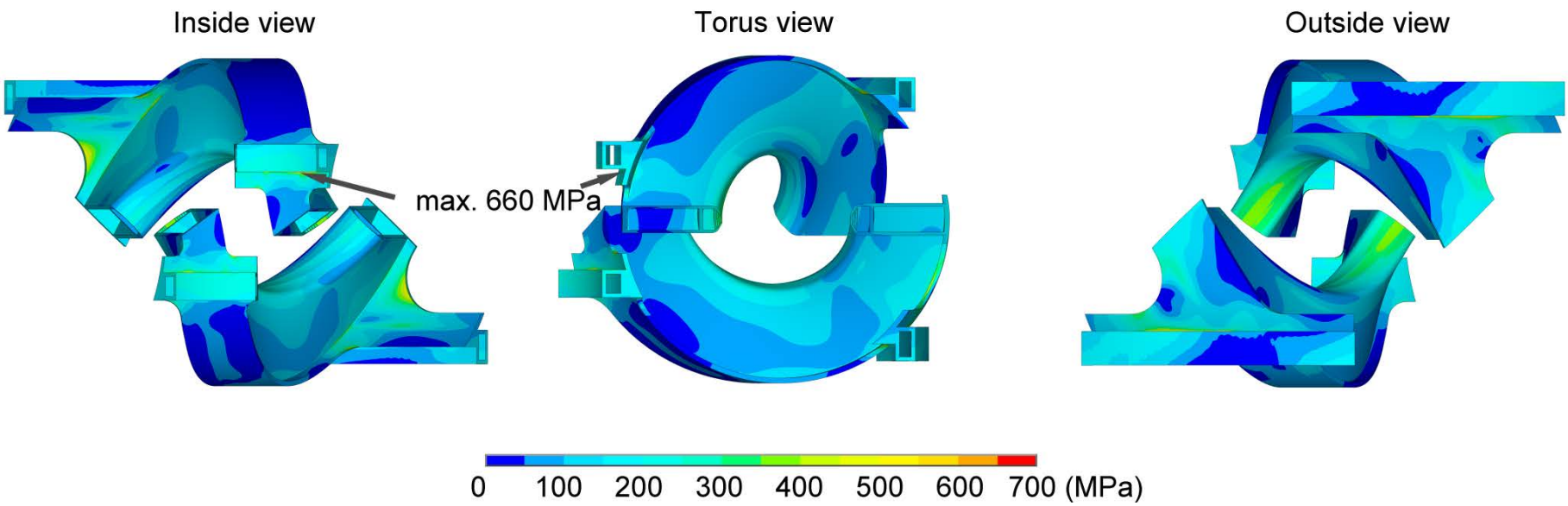


(a) Magectic field vector map (b) Magnetic field contour map (c) Electromagnetic force vector

Magnetic field distribution in HC at inboard of the torus.

Stress analysis for FFHR-d1A ①

- The maximum stress of 660 MPa appeared in the inner VFC support region. (600 MPa in FFHR-d1)
- Stress near the bottom of the HC was relatively high. ~400 MPa.

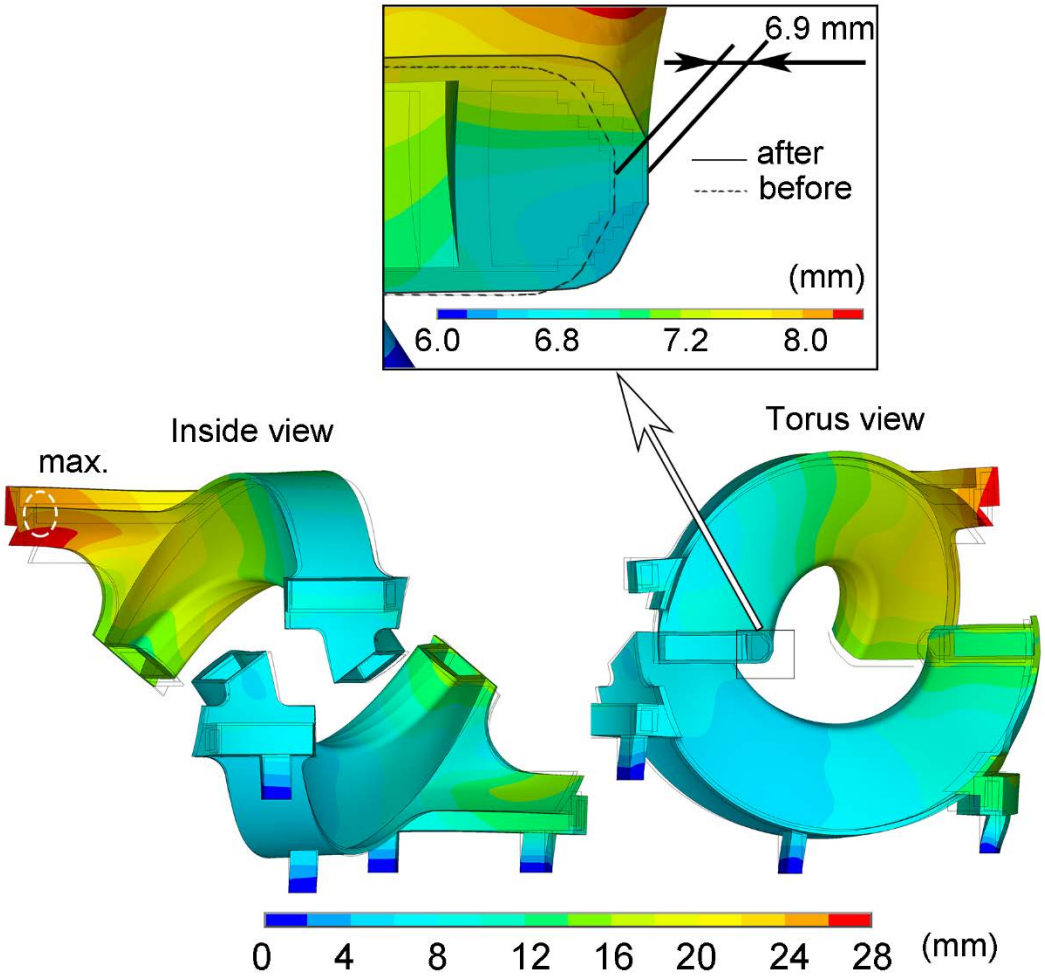


Results of structural analysis: Von Mises stress distribution in the EM force support structure.

Stress analysis for FFHR-d1A ②

- The maximum amount of deformation of 28 mm appeared in the outer VFC region.
- The deformation at the bottom of the HC where the radial build is critical was 6.9 mm.

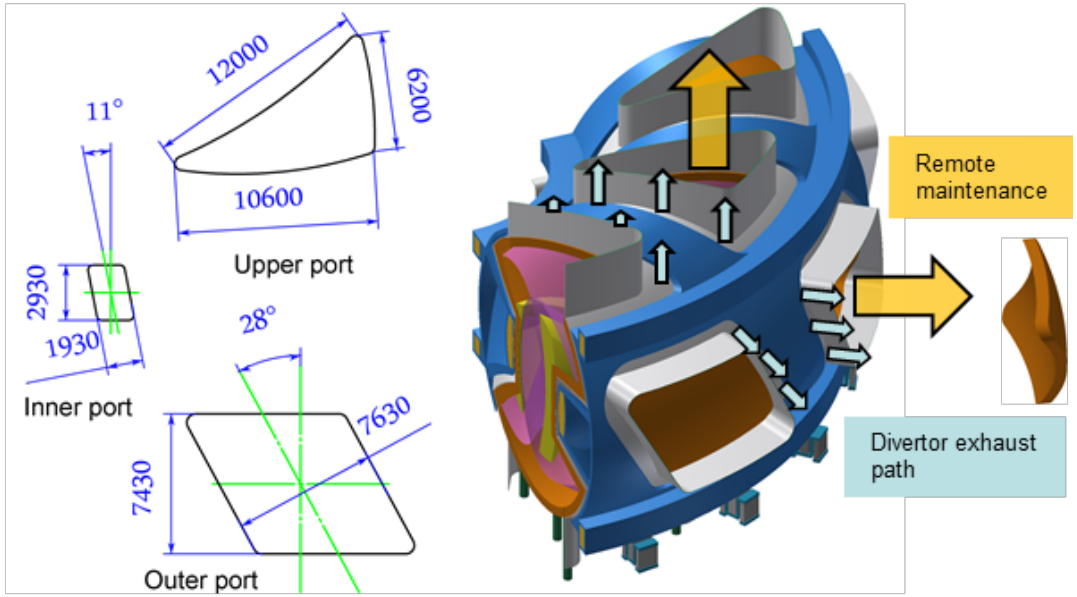
- The stress level and the deformation were within the permissible design limit.



Results of structural analysis: amount of deformation.

VV and ports

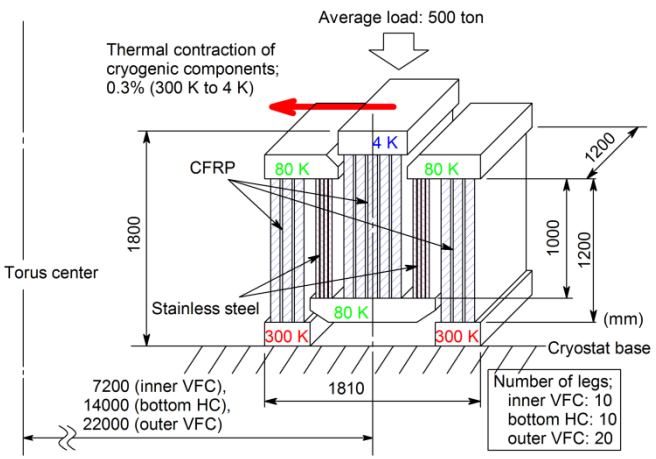
- VV was determined considering the radial build, core plasma, and the blanket system.
- ✓ 35 mm thick (implies a spatial occupancy with a flexible connection),
- ✓ does not act as a base wall that supports the in-vessel components,
- ✓ attached to the surface of the blanket,
- ✓ the distance between the VV and the CSS was set as 200 mm (for the thermal shield and the gap),
- ✓ the distance at the port section was set from 750 to 850 mm. Of this distance, 500 mm was prepared for the divertor exhaust around the ports (except for the inner port section).



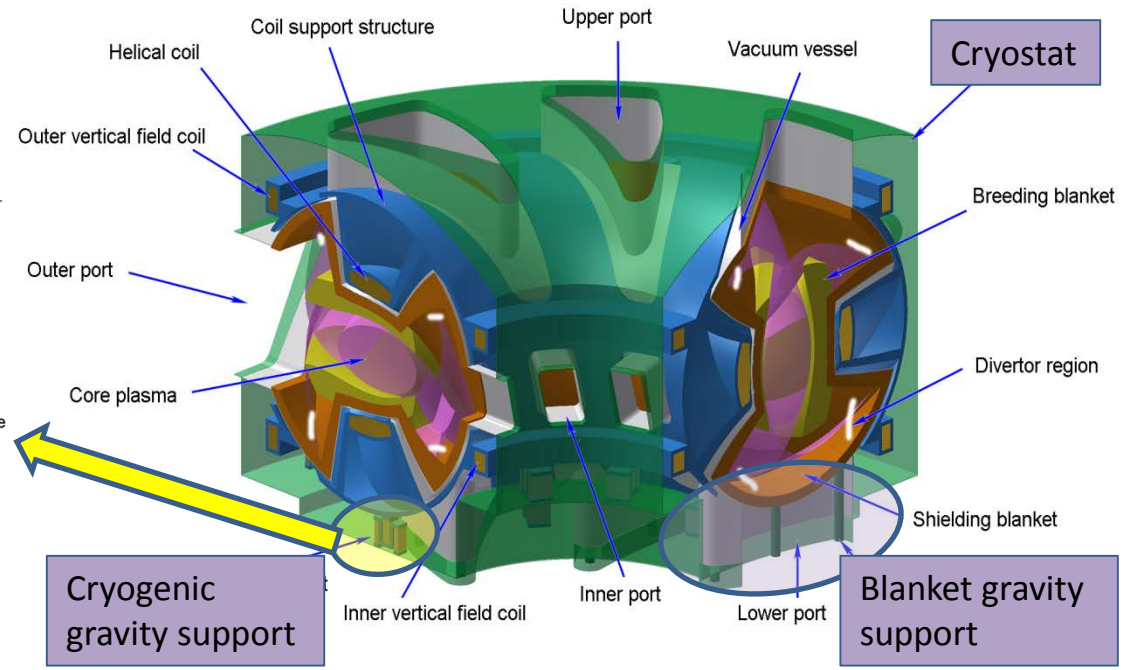
Schematic of the VV and a concept of maintenance and divertor exhaust.

Gravity support and cryostat

- The total weights of the blanket system and the magnet system are estimated to be 35,000 tons and 20,000 tons, respectively.
- The LHD-type gravity support with a “folded multi-plate” design is suitable from both mechanical and thermal viewpoints.
- The blanket can be supported using a rigid support through the lower port.
- The adiabatic condition is realized by the cryostat vessel. The base plate section is designed to meet the height of gravity support, and the outline was set by considering the geometry of the inner component.



LHD-type cryogenic gravity support for FFHR-d1A.



General assembly of FFHR-d1A

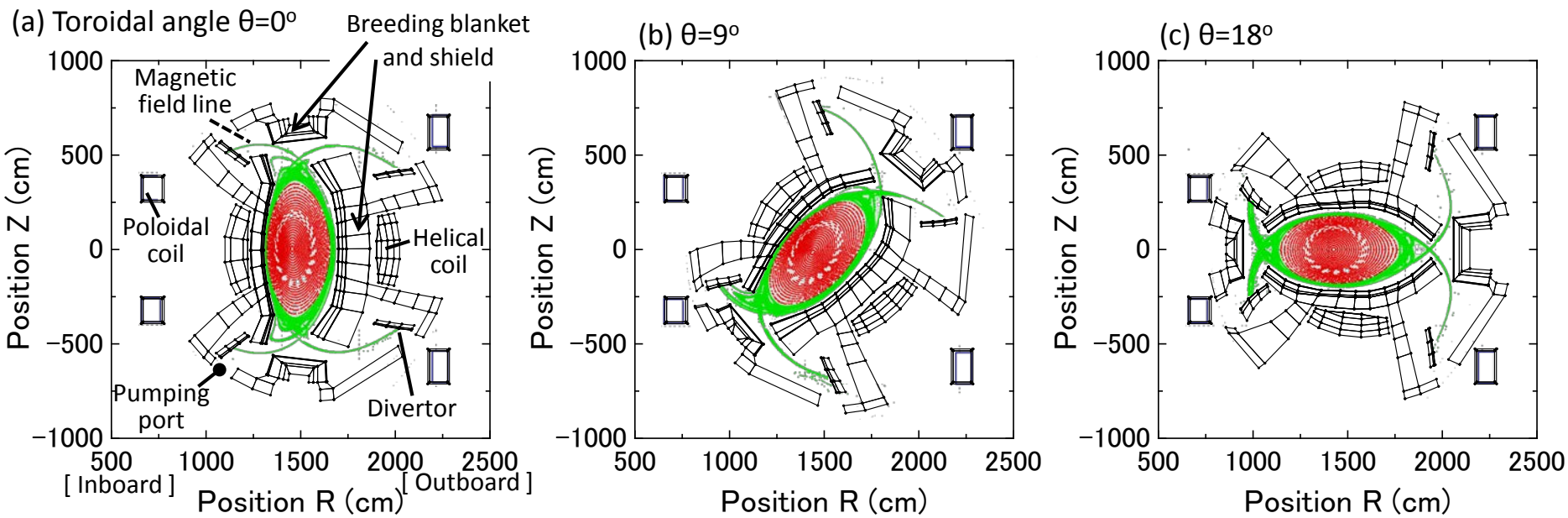
Design of the blanket outline

T. Tanaka, presented at ISFNT-11

- Divertor can be placed behind blanket and shielding layers in helical reactors.
  - Reduction of irradiation damages and radioactivity of divertors.
  - Impact on selection of divertor materials.
    (Use of Cu materials instead of ferritic steel for cooling pipes.)

In the present study:

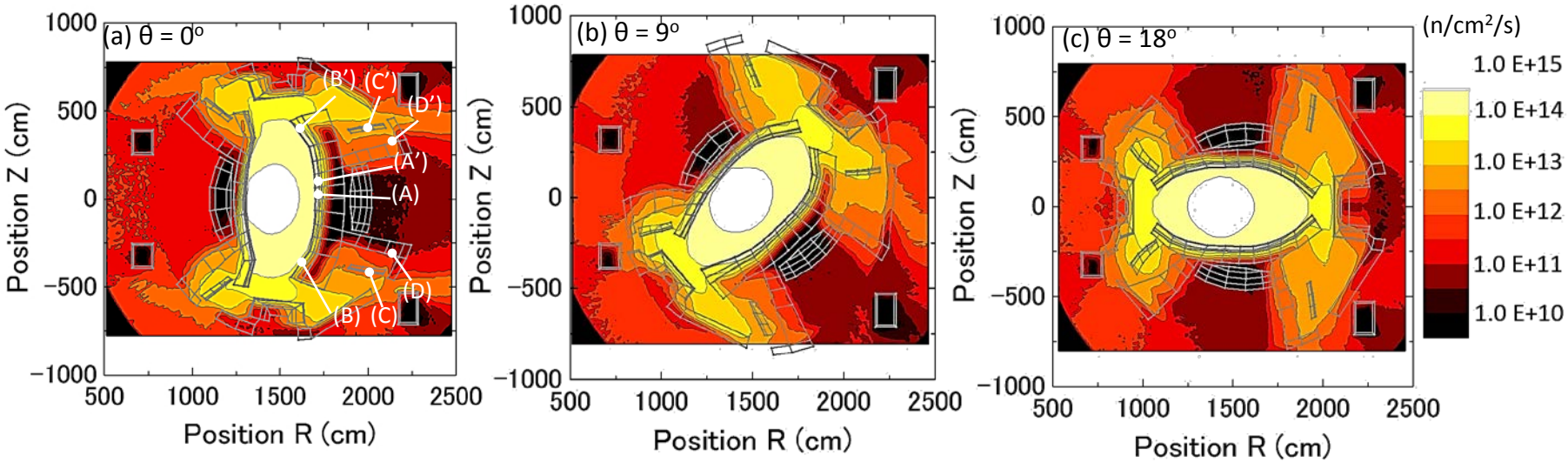
- Quantitative evaluation of neutronics environment around divertors in helical reactor FFHR-d1.

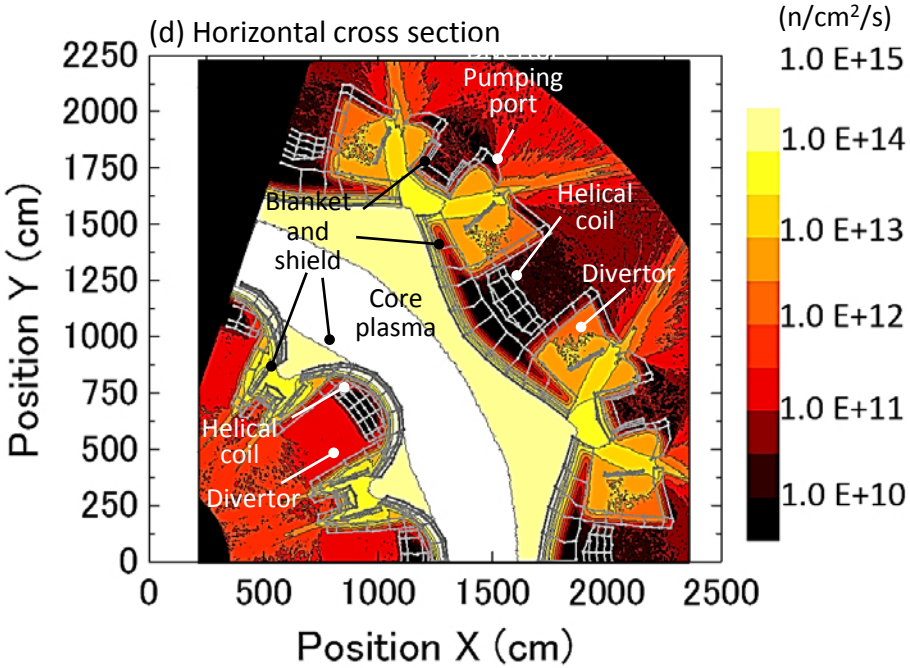


Poloidal cross sections of FFHR-d1 and magnetic field lines.

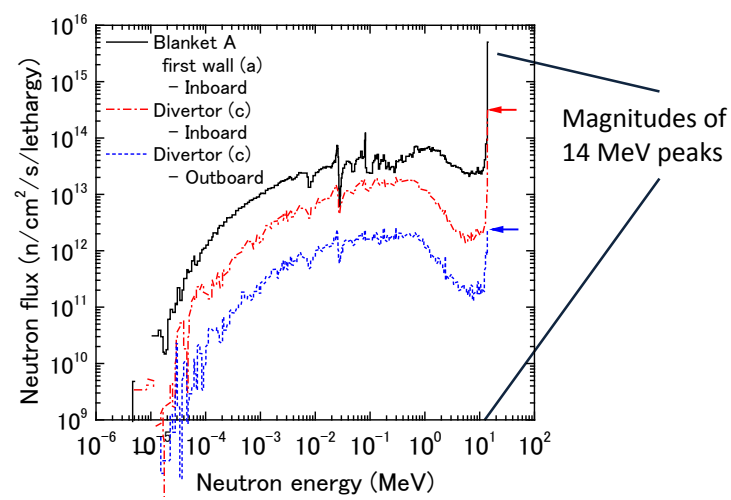
Fast neutron flux distribution

T. Tanaka, presented at ISFNT-11





Calculated fast neutron flux (>0.1 MeV) distribution in FFHR-d1



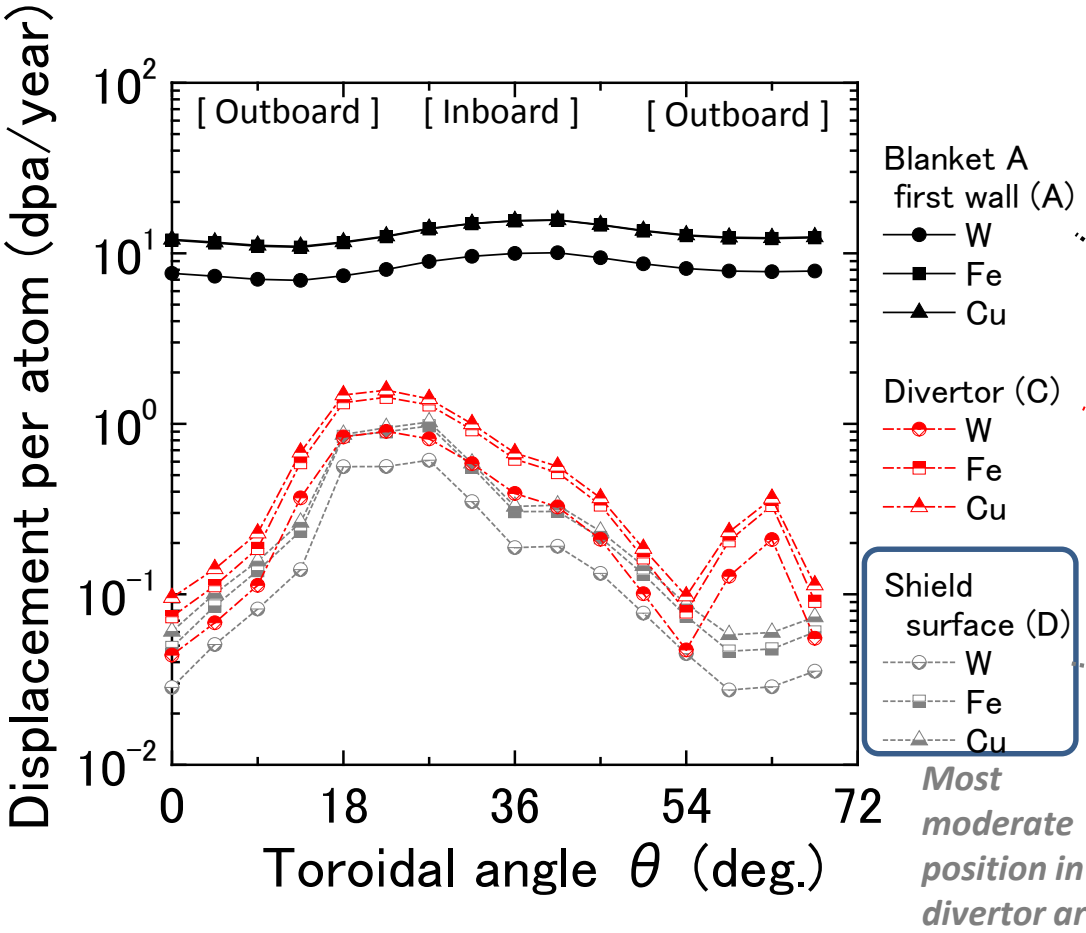
Neutron spectra at first wall and divertors

- Fast neutrons of >0.1 MeV are dominant in the present damage calculations.

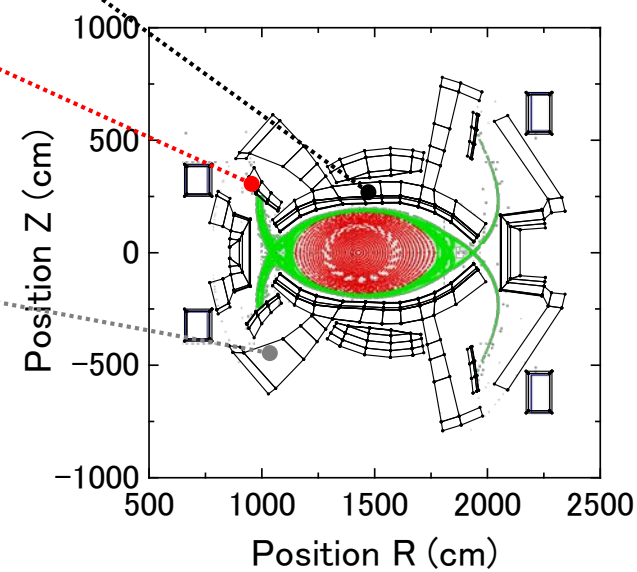
Irradiation damages in divertor materials

T. Tanaka, presented at ISFNT-11

- Damage calculation: Neutron spectrum x 42 group dpa cross section (based on JENDL-3 library*) *K. Maki et al., JAERI-Data/Code 97-002.



Most moderate position in divertor area

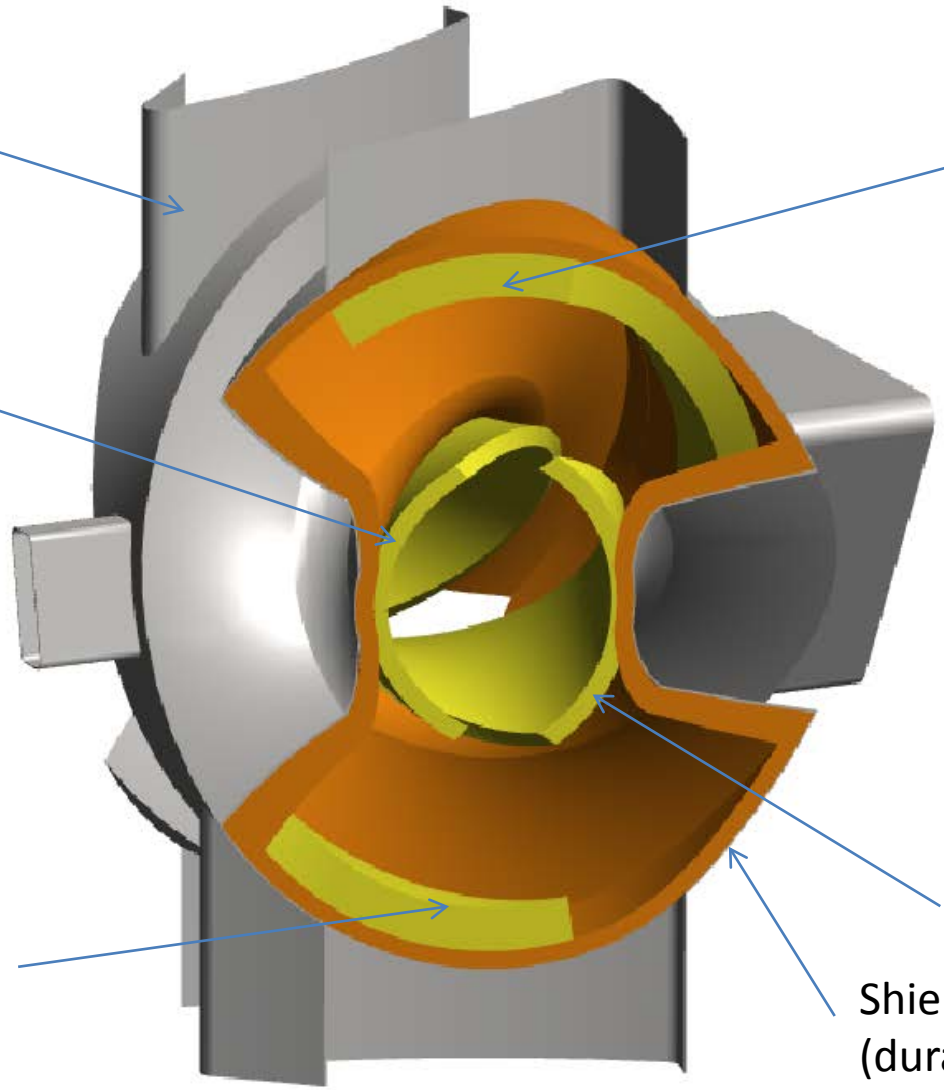


Irradiation damages at blanket and divertor areas.

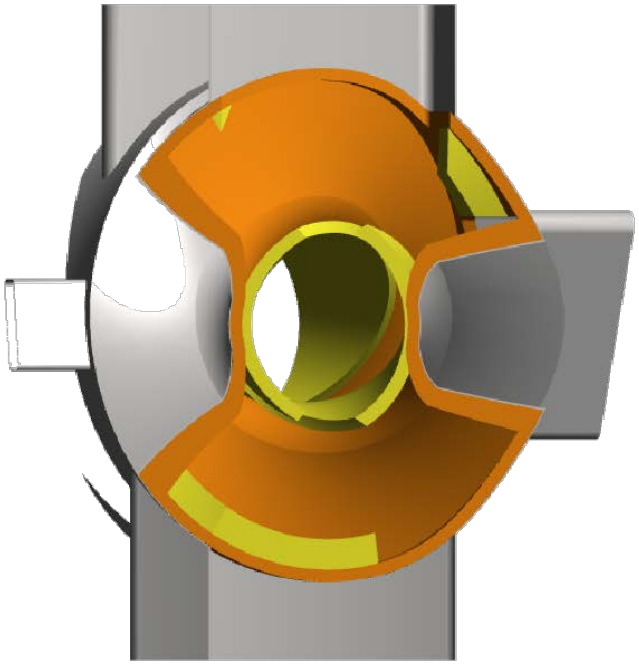
Poloidal cross section at θ=18°

Maintenance of blanket system

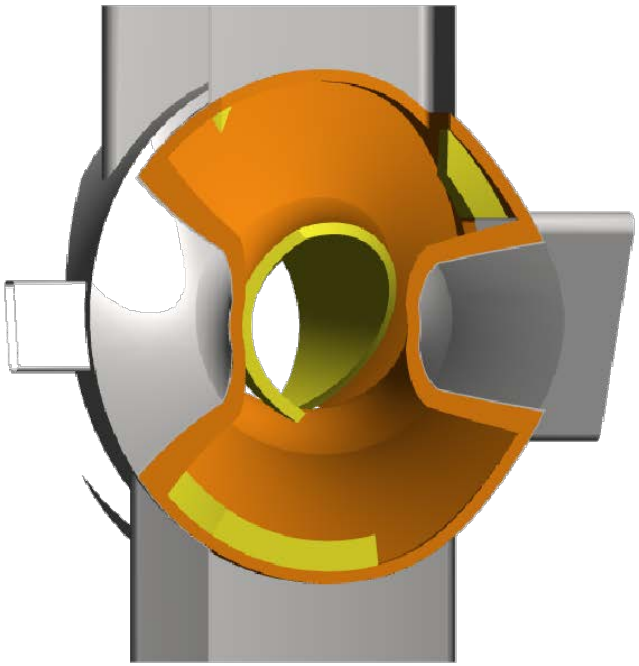
- Classify the blanket system into a durable part and a periodically needed exchange part.
- Maintenance scenario and a remote handling scheme are being considered under this condition.

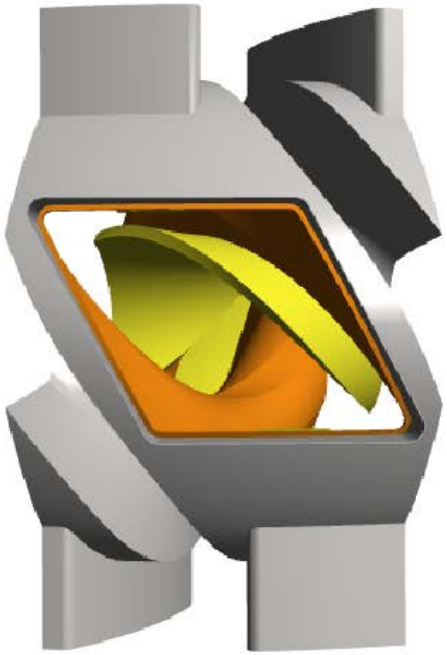


① Unplug the blanket at the outer and upper ports

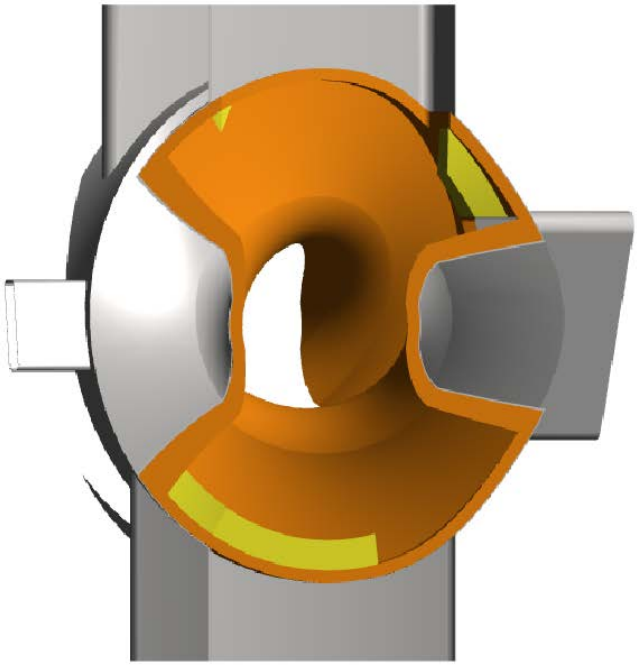


② remove the bleeding blanket at the helical coil #1

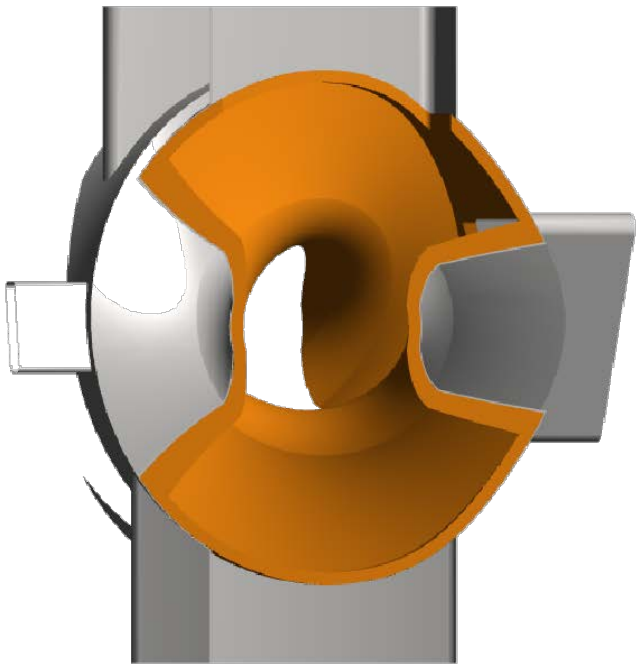


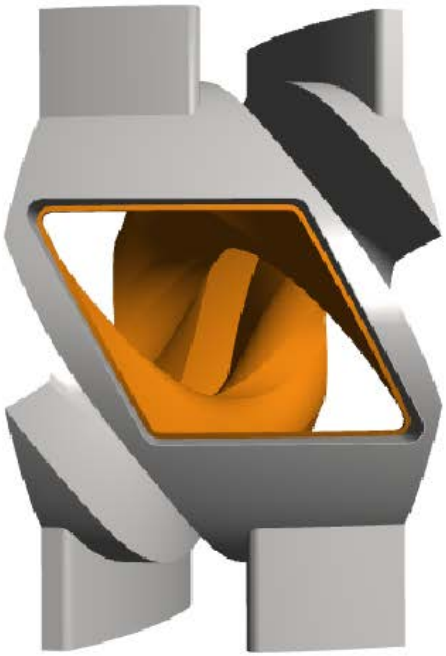


③ remove the bleeding blanket at the helical coil #2



④ remove other bleeding blanket

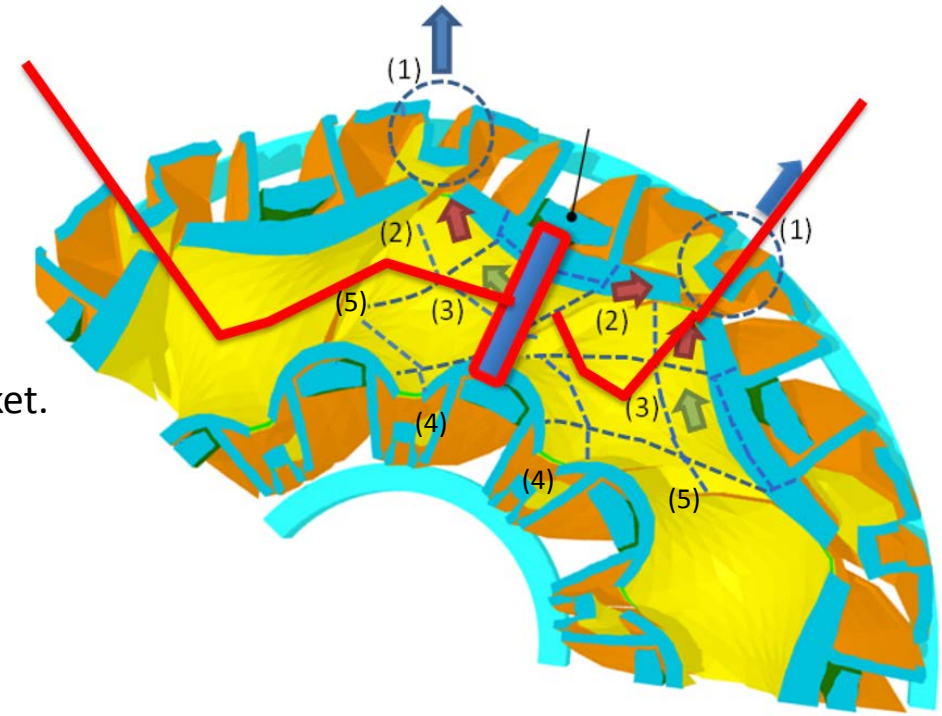




- Assuming that the average density of the bleeding blanket is 5g/cm^3, weight of exchange parts are;
  HC part: 3,500 ton (700m^3), O-port: 2,300 ton (460m^3), U-port: 1,800 ton (360m^3), L-port + I-port: 2,800 ton (560m^3), total: 10,400 ton (2,080m^3).
- If the coolant in the blanket is drained, the weight may decreases to 30% (3,120 ton).
- Shielding blanket: 13,000 ton (260 m^3).
- Total weight of blanket system: 23,400 ton (468m^3).

Issues on a maintenance of a fusion reactor

- ✓ Heavy weight; more than 10 ton per module.
  - cf. ITER remote handling: 4 ton.
- ✓ Complicated in-vessel geometry, especially for helical type.
  - Apertures should be as large as possible.
- ✓ Various exchange / maintenance frequency and period.
  - Proper use of ports, parallel operation.
- ✓ Accurate control.
  - Position sensing under irradiation environment.
- ✓ Safety boundary.
  - Cask? Reactor room? Whole building?



Example of divided pattern of the blanket.
(1) Outer port
(2) Side of HC
(3) Center of HC
(4) Inner port
(5) Lower port / upper port
Divided into ～30 modules / 36°

Summary

- The radial-build design, which ensures sufficient gaps among components during the operation / construction / maintenance phase, was introduced.
- To ensure the large apertures and the access ports for the maintenance of the in-vessel components, a structural design and analysis were performed.
- The results show that a sufficiently rigid coil support structure was provided.
- The fundamental design of the VV with a port section, cryogenic gravity support, and cryostat were developed.
- Maintenance and divertor exhaustion schemes are being investigated based on the fundamental design.
- A development of a maintenance scenario for the helical reactor is in progress.