28th IAEA Fusion Energy Conference 2021/May/10-15 TECH/P3-20, May/12

RECENT DEVELOPMENT OF ENGINEERING DESIGN FOR QUASI-AXISYMMETRIC STELLARATOR CFQS

Akihiro Shimizu[1,2], Shigeyoshi Kinoshita[1], Mitsutaka Isobe[1,2], Shoichi Okamura[1], Kunihiro Ogawa[1,2], Motoki Nakata[1,2], Yasuo Yoshimura[1], Chihiro Suzuki[1], Masaki Osakabe[1,2], Takanori Murase[1],Sho Nakagawa[1], Hiroyuki Tanoue[1], Yuhong Xu[3], Haifeng Liu[3], Hai Liu[3], Jie Huang[3], Xianqu Wang[3], Jun Cheng[3], Guozhen Xiong[3], Dapeng Yin[4], Yi Wan[4], Changjian Tang[3,5]

[1] National Institute for Fusion Science, National Institutes of Natural Sciences, Toki, Gifu, 509-5292, Japan
[2] The Graduate University for Advanced Studies, SOKENDAI, Toki, Gifu 509-5292, Japan
[3] Institute of Fusion Science, School of Physical Science and Technology, Southwest Jiaotong University, Chengdu 610031, China
[4] Hefei Keye Electro Physical Equipment Manufacturing Co., Ltd, Hefei 230000, China
[5] Physics Department, Sichuan University, Chengdu 610041, China

Abstract

The CFQS is a quasi-axisymmetric (QA) stellarator device, which is constructed on the joint project of National Institute of Fusion Science in Japan and Southwest Jiaotong University in China, and its design work has been performed.
Based on CHS-qa design, the magnetic field configuration for CFQS is determined. Typical parameters of magnetic field strength, major radius and aspect ratio are 1.0 T, 1.0 m, and 4.0, respectively.

Up to now, a mock-up modular coil having the most complicated shape was constructed to check feasibility and accuracy of modular coil production. Heat run test was performed to check temperature increase of conductors, and the capability of 1 T operation was confirmed. Construction of actual modular coils and vacuum vessel has begun since 2020.

In this paper, recent progress of the physics, the engineering design, and construction status of the CFQS are presented.

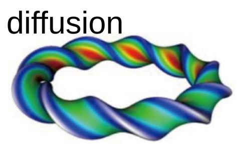
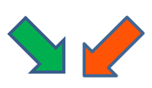
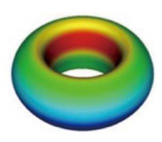
Advantage of quasi-axisymmetry

Helical

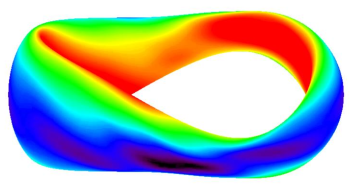
- **No inductive plasma current → Steady-state operation capability**
- Large neoclassical transport by ripple diffusion

Tokamak

- Requiring plasma current →Major disruption, pulse operation
- **Reduced neoclassical transport and good particle orbit by axisymmetry**

Quasi-axisymmetry



Both advantageous points are combined

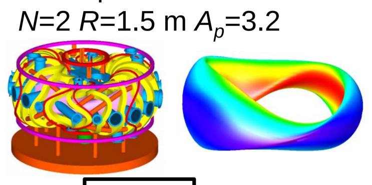
Quasi-axisymmetric stellarator has attractive features for future reactor.

Quasi-axisymmetric devices

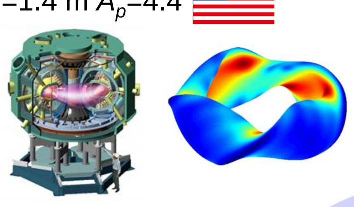
Concept of quasi-axisymmetry was proposed by J. Nührenberg (1994) and P. Garabedian (1996).

1990's~2000's

CHS-qa NIFS
N=2 R=1.5 m A_p=3.2

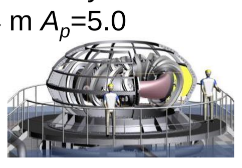


NCSX PPPL
N=3 R=1.4 m A_p=4.4

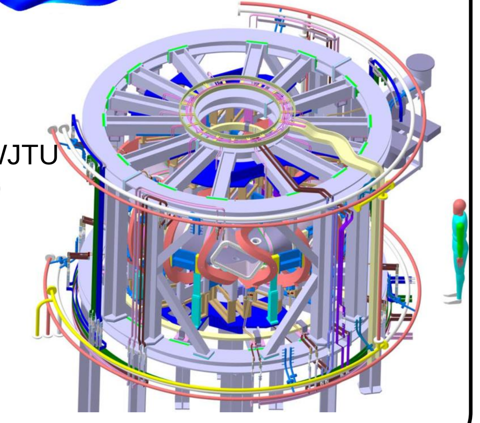


2010's

ESTELL University of Lorraine
N=2 R=1.4 m A_p=5.0



CFQS NIFS and SWJTU
N=2 R=1.0 m A_p=4.0



There is no operational quasi-axisymmetric stellarator in the world.

Research target of CFQS experiments

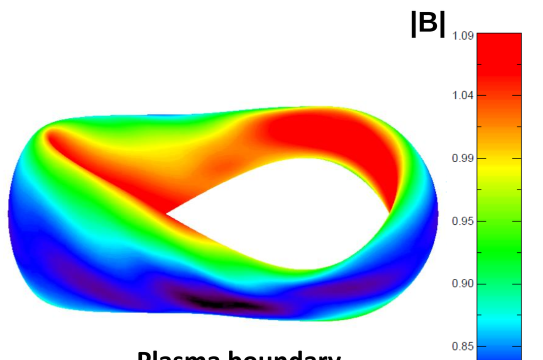
Main Parameters B_t = 1 T, R = 1 m, <a> = 0.25 m, A_p = 4, N_p = 2
ECH: 54.5 GHz 450 kW
NBI: 20~40 kV 30 A 1 MW

Topics

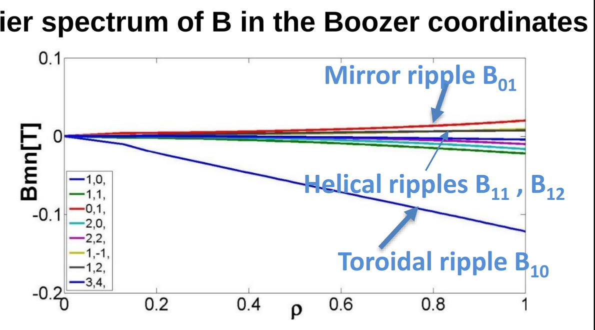
- Demonstration of good confinement with QA configuration.
- Achievement of improved confinement mode like H-mode to suppress turbulent driven anomalous transport.
- Experimental study of turbulence and transport barrier formation physics.
- Confirmation of stable MHD equilibrium by magnetic well property.
- Experimental study of bootstrap current, its effect on MHD stability and magnetic configuration.
- High energy particle physics in QA with NBI.
- Feasibility study of divertor configuration.

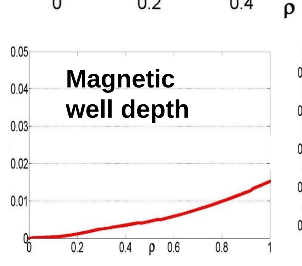
CFQS TEAM, "*NIFS-SWJTU JOINT PROJECT FOR CFQS - PHYSICS AND ENGINEERING DESIGN VER. 3.1.*" RESEARCH REPORT NIFS-PROC Series : NIFS-PROC-119 Jan. 25, 2021.

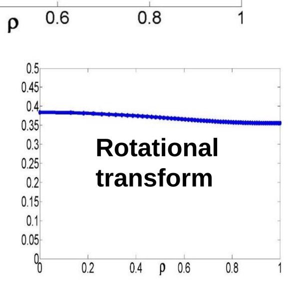
Quasi-axisymmetric configuration of CFQS



Fourier spectrum of B in the Boozer coordinates







Magnetic well structure in entire region — Weak shear profile

A. Shimizu *et al.*, Plasma and Fusion Research 13 (2018) 3403123.

Finite beta equilibrium with bootstrap current

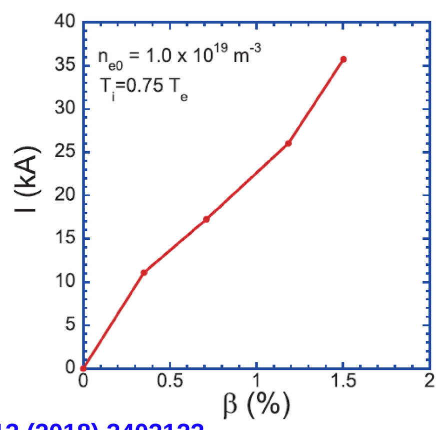
Bootstrap current in CFQS

In QA, large bootstrap current is expected, because its neoclassical character is similar to tokamak.

Bootstrap current is calculated by BOOTSJ code based on Shaing's analytic formula (K.C. Shaing, Physics of fluids B 1 (1989) 1663).
Relatively flat density profile, n=n_0(1-0.8 s+1.3 s^2-1.5 s^3) are assumed.

At the volume averaged beta of 1.2 %, current of about 25 kA is expected which makes a significant effect on equilibrium.

Dependence of bootstrap current on volume averaged beta

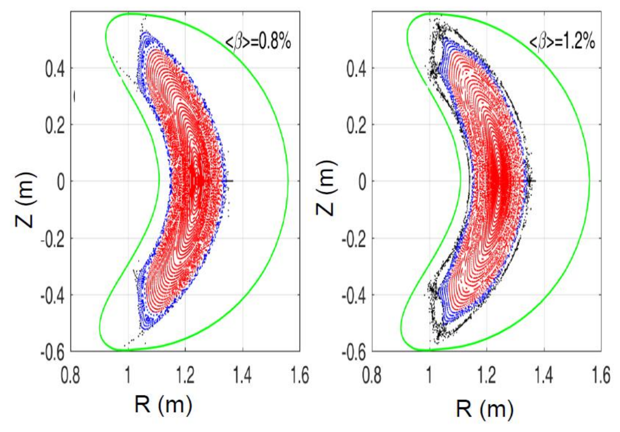


A. Shimizu *et al.*, Plasma and Fusion Research 13 (2018) 3403123.
X. Wang *et al.*, Nuclear fusion 61 (2021) 036021.

Finite beta equilibrium

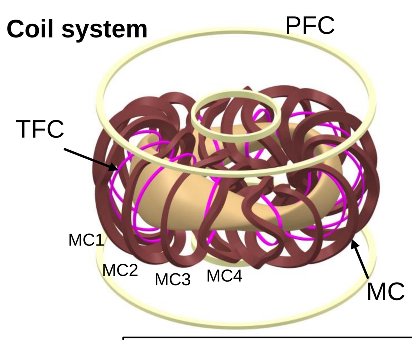
MHD equilibrium with finite beta considering bootstrap current is calculated by HINT2.

Good magnetic surface is sustained, at least up to the volume averaged beta of 1.2 %, which is attainable by NBI.



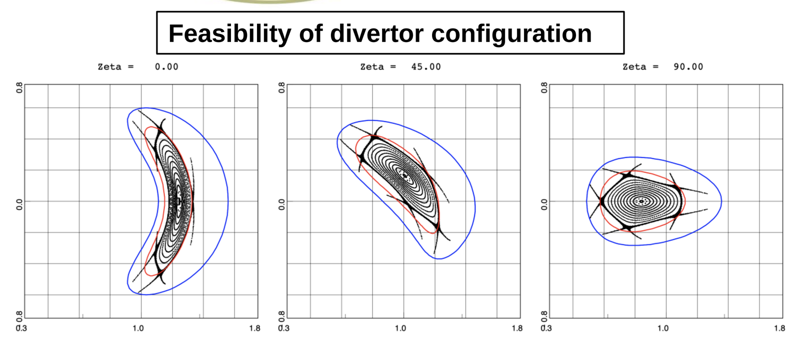
X. Wang *et al.*, Nuclear fusion 61 (2021) 036021.

Progress of engineering design



4 type, 16 modular coils (MC): producing main configuration. Current ratio can be controlled.
2 pairs of PFCs: producing vertical field to suppress Shafranov shift
12 TFCs: controlling rotational transform

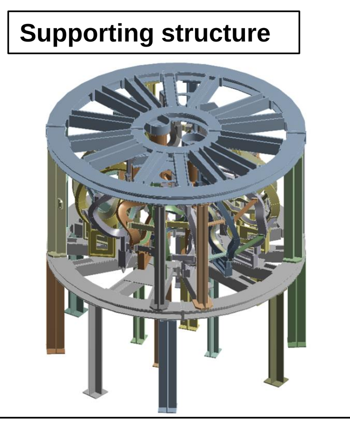
Feasibility of divertor configuration



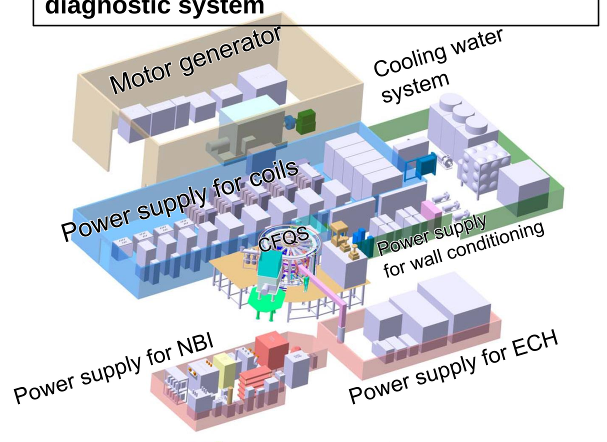
By the control of rotational transform with TFC, divertor configuration can be produced. 2/5 magnetic islands in peripheral region can be used.

S. Okamura *et al.*, Journal of Plasma Physics 86 (2020) 815860402.

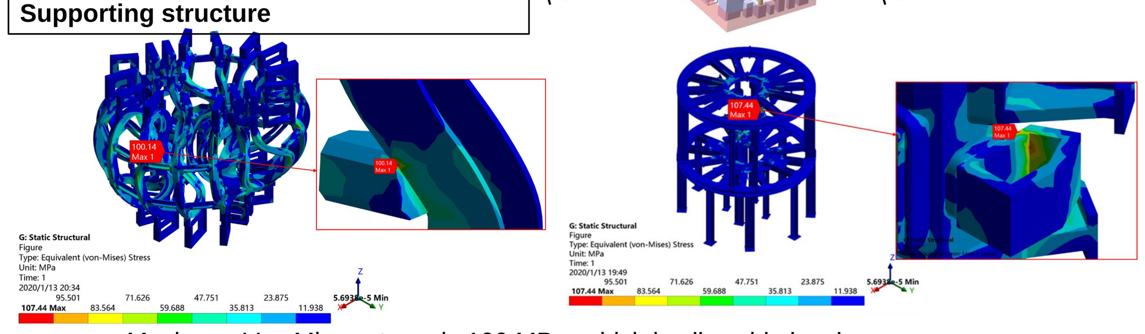
Supporting structure



Arrangement of CFQS, main heating, and diagnostic system

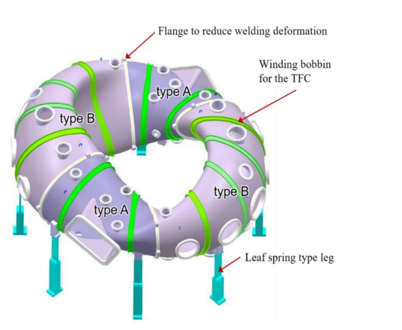


Finite elements method (FEM) analysis of Supporting structure

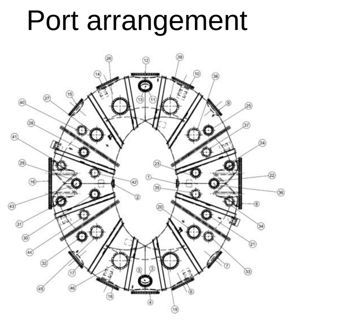


Maximum Von Mises stress is 100 MPa, which is allowable level.
G. Xiong *et al.*, Fusion Engineering and Design 160 (2020) 112021.

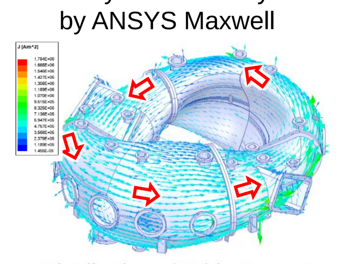
Vacuum vessel design



Port arrangement

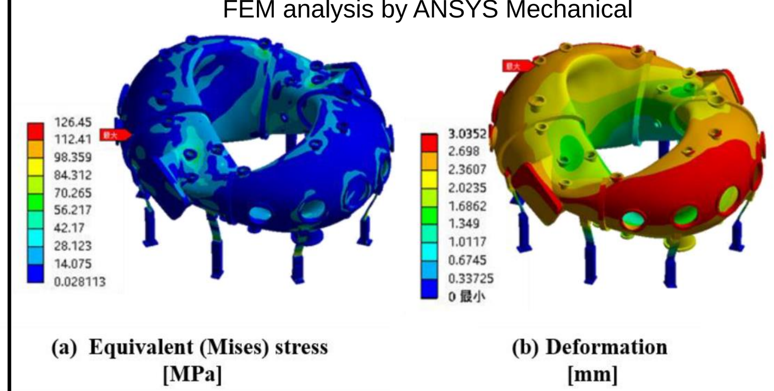


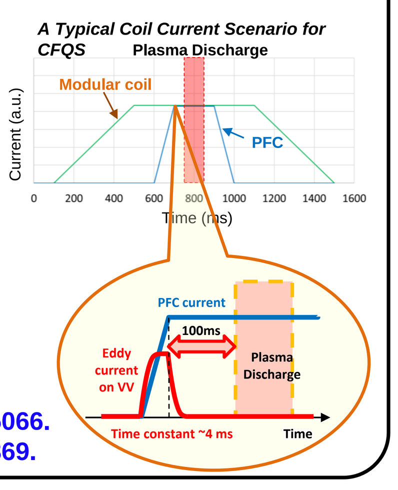
Eddy current analysis by ANSYS Maxwell



Distribution of Eddy Current on VV when PFC is used. Time constant of eddy current is 4 ms. This effect on magnetic configuration is not significant.

FEM analysis by ANSYS Mechanical





Maximum Von Mises stress is 126 MPa, which is acceptable level.

S. Nakagawa *et al.*, Plasma and Fusion Research 15 (2020) 2405066.
T. Murase *et al.*, Fusion Engineering and Design 161 (2020) 111869.

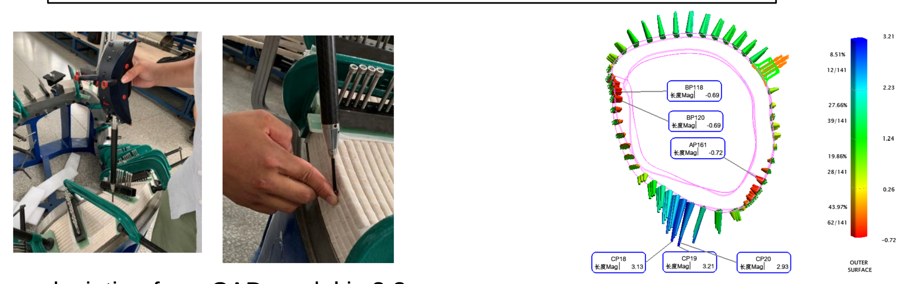
Mock-up modular coil

Mock-up coil was manufactured to check feasibility of construction, and achieved accuracy.

Fabrication of winding mould — Conductor winding process — Completion of conductor winding

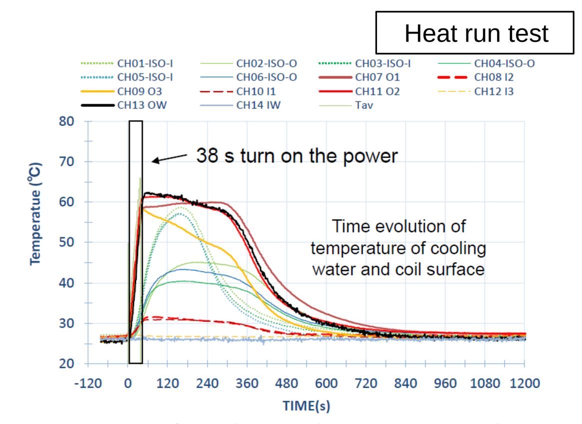
Accuracy check by laser tracker — Mould for vacuum pressure impregnation — Completion of mock-up modular coil construction

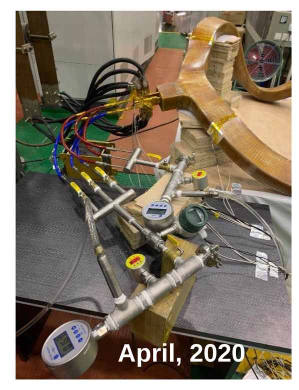
Dimension measurement of coil conductor by laser tracker



Maximum deviation from CAD model is 3.3 mm.
Model calculation suggests that the effect of this level deviation on the magnetic surface is not significant.
A. Shimizu *et al.*, Plasma and Fusion Research 14 (2019) 3403151.

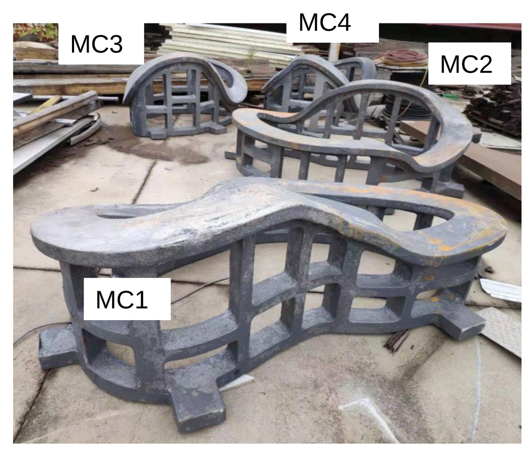
Heat run test





- Heat run test of mock-up coil was performed. Current of 1 kA for 38 s was applied. Time evolution of temperature of cooling water and coil surface were measured.
- Expected cooling performance was achieved, therefore, 4.34 kA current for 2 s can be conducted for 1 T operation.

Modular coil construction has begun



Casting for winding moulds are shown. Total of 16 coils will be made by 4 winding moulds.

MC4 winding mould manufactured by CNC

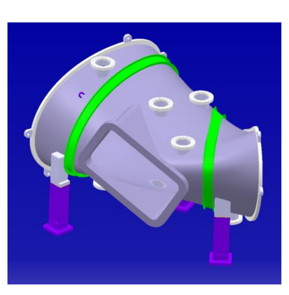
Completion of MC4 winding mould construction

Winding conductor

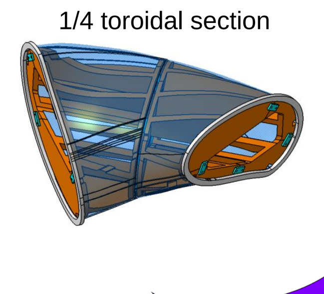
VPI mould

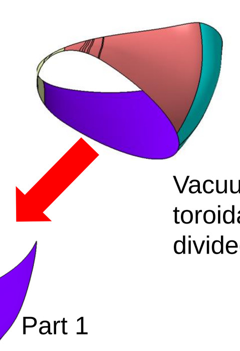
Current status of vacuum vessel manufacturing

Construction of vacuum vessel (VV) of 1/4 toroidal section is being constructed with modular coils in parallel.

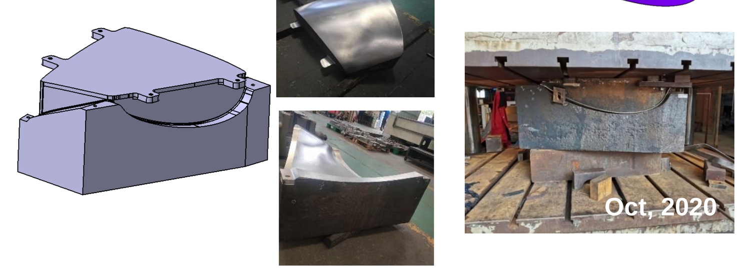


1/4 toroidal section





Vacuum vessel of 1/8 toroidal section is divided into 4 parts.



Part 1 plate was manufactured by pressing.

Moulds for other parts of vacuum vessel

Summary

- The CFQS device is being constructed in SWJTU as a joint project of NIFS and SWJTU.
- Major parameters of CFQS are R = 1 m, B_t = 1 T, and A_p = 4.
- CFQS has both advantage points of tokamak and helical devices.
- Finite beta equilibrium considering bootstrap current is estimated by HINT 2 code. Clear magnetic surfaces are maintained up to the volume averaged beta of 1.2 %, which is attainable by NBI in experiments.
- Coil system of CFQS consists of MC, PFC, and TFC. By the control of rotational transform with TFC, divertor configuration can be produced.
- Supporting structure to withstand large electromagnetic force was designed. FEM analysis shows that the maximum stress is acceptable range.
- VV having large rectangular ports was designed. For atmosphere pressure, FEM analysis was done, and the maximum stress is 126 MPa, which is allowable level.
- Mock-up modular coil has been constructed successfully. Heat run test was already performed, and temperature rise is 40 degree, which is expected range. Capability of 2 s discharge for 1 T operation was confirmed.
- Construction of modular coil and vacuum vessel has begun.
- We will continue steadily our work to achieve first plasma.