Progress of CFETR Design

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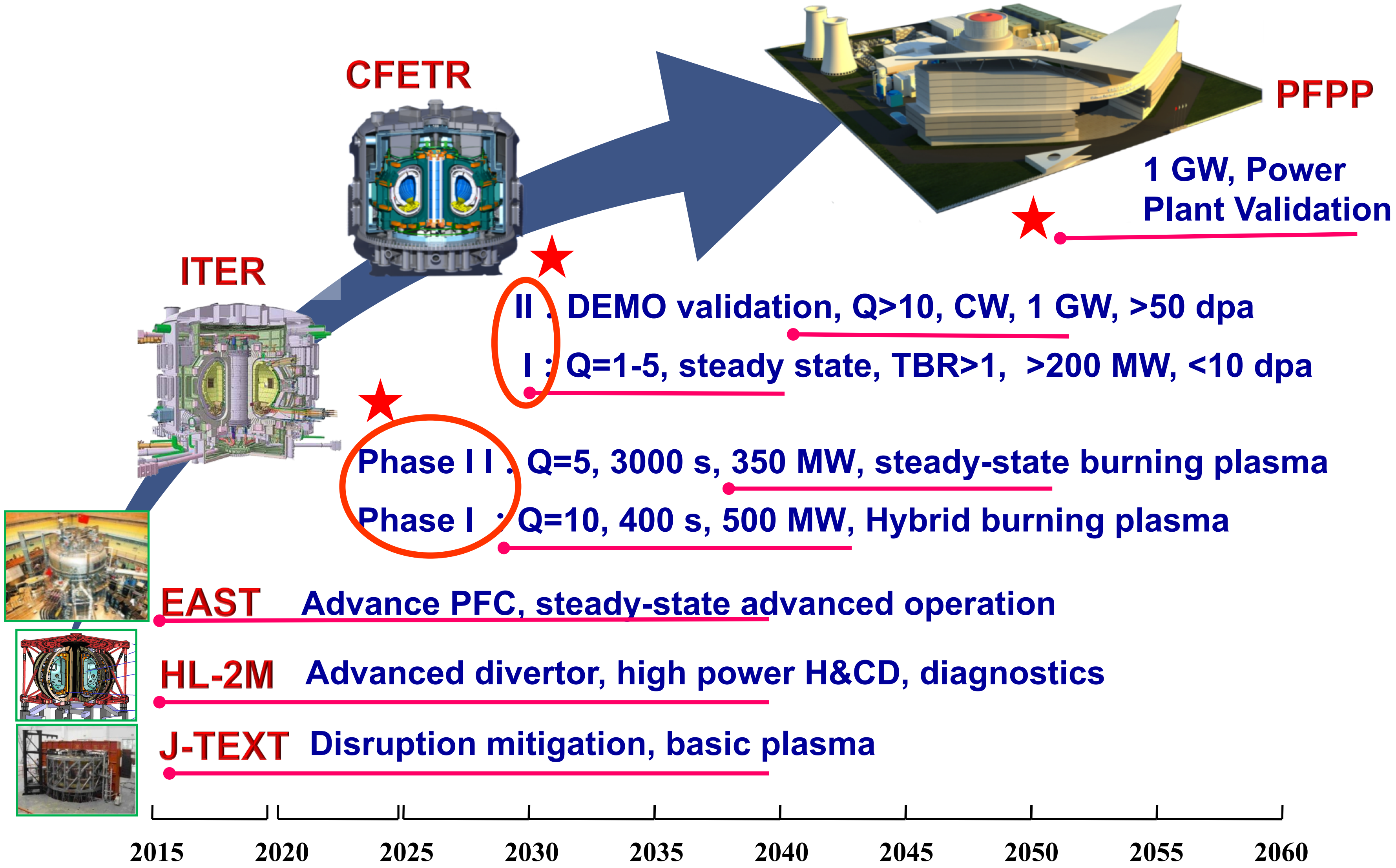
China MCF Roadmap



CFETR Mission

- Fusion power production of P_f = 200~1500 MW
- Generates steady-state burning plasmas (duty time ~ 50%)
- Tests the self-sustainable burning (Q ≧ 25~30, Hα ~ 83-86%)
- Realizes Tritium self-breading (TBR ≧ 1)
- R&D for structural and functional materials which have high neutron flux resistive

Buildup the science and technology base for PFPP

Key Issues of CFETR Mission

Obtained burning Plasma for fusion power

1. P = 200-1500 MW
2. Q = 1-10, SSO, hours
3. Q = 20-30 hours-SSO
4. High energetic α heating

Steady-state operation for fusion energy

5. SSO (Ext H&CD + Higher f_b)
6. Hybrid (OH+BS+CD)
7. PSI on the first wall
8. Heat & particle exhaust on Div.

Breeding tritium for T self-sustained

9. T-breeding by blanket
10. T-plant: extract & reprocessing
11. Materials & components
12. Reliable and quick RH
13. Licensing & safety

Course of CFETR Design Events

- **Concept design (2011-2017)**

  - First period (2011-2015)

    R = 5.7 m, a = 1.6 m, B_T = 4–5 T, P_f = 200 MW

  - Second period (2015-2017)

    R = 6.6 m, a = 1.8 m, B_T = 5–7 T, P_f = 1 GW

- **Integrated engineering design (2017-, 30 M$)**

  - New version

    R = 7.2 m, a = 2.2 m, BT = 6.5 T, P_f = 200 MW - 1 GW

- **Small scale R&D continues (70 M$)**

- **Large scale R&D will start soon (500 M$)**

Outline

- **Introduction**
  - New version of CFETR design
- **CFETR Physics Design**
  - Development of operation scenarios
  - Consideration of divertor conf. & impurity effects
  - Investigation of MHD stability
- **CFETR Engineering Design**
  - Magnet system
  - Vacuum system
  - Remote handling and maintenance system
  - Others…
- **Summary**

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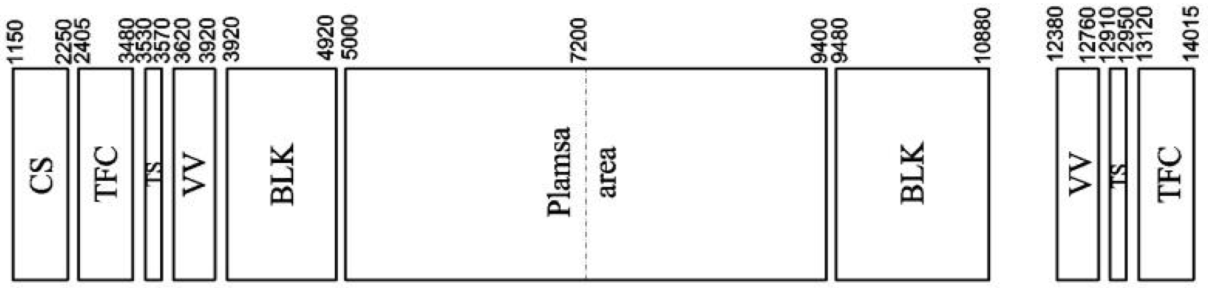
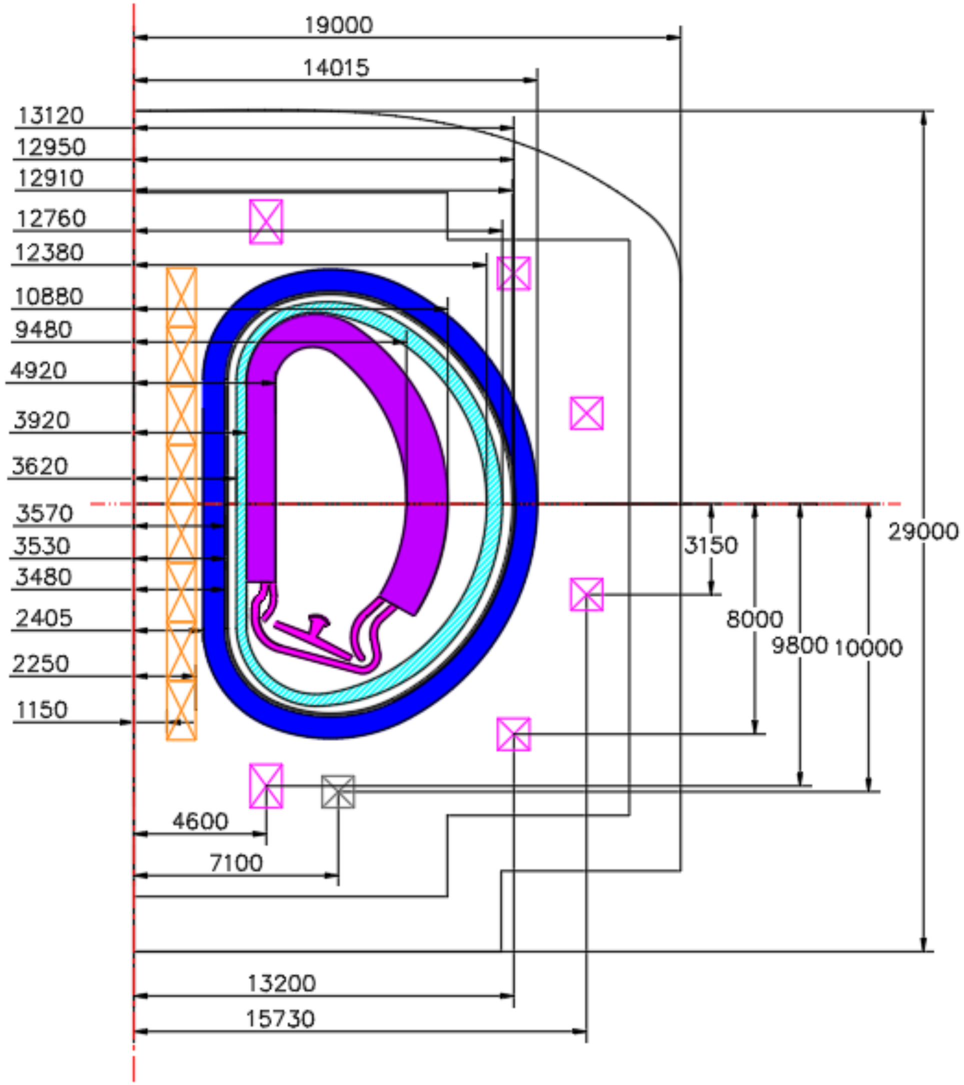
New version of CFETR design

Key parameters	
Major Radius R_0	**7.2 m**
Minor Radius a	**2.2 m**
Elongation	**2**
Toroidal B Field B_T	**6.5 T**
Plasma Current Ip	**14 MA**
Divertor Conf.	**Lower Single Null**





Proposed CFETR Research Plan

- **Some new features of CFETR design**

  - Higher B_T, Lower I_p, Advanced CS (≥ 480 VS), 16 TF coils for easy RH → More reliable plasma targets and higher confidence

- **CFETR operation plan (Staged approach)**

  - H/He: 1-2 years

  - DD: 1-2 years

  - DT: < 100 MW：1 years

  200 MW, SSO, T fuel cycle, 5 years

  500 MW, SSO, TBR > 1, 3 years

  - DT: DEMO validation, 1 GW, 5 years

  Advance Scenario, > 1.5 GW , Q~30, 2-3 years

  - Total: ~ 20 years

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Primary Tasks of CFETR Physics Design

- **CFETR physics design mainly focuses on development and optimization of the operating scenarios with respect to physics and engineering constraints**

- **Operating scenarios will**
  - Predict the fusion performance
  - Explore and determine a robust operation space possessing good confinement, MHD stability and acceptable transport level
  - Evaluate and limit the fraction of helium and other impurity particles while approaching the desirable fusion performance
  - Size up the power and particle exhaust compatibility with the chosen divertor configuration
  - Assess and manipulate the transit and steady heat load to the first wall and divertor to keep the machine safety
  - …

Integrated Modelling Strategy

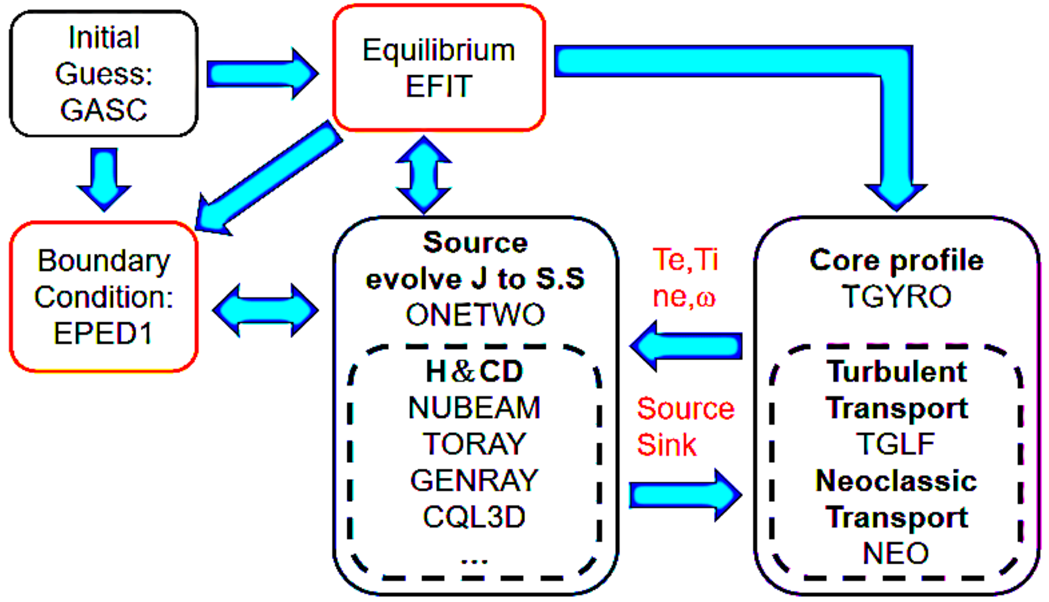
- **0D system code used to scope out parameter space**
  - Provides 0th order engineering parameters e.g. R, a, I_P, B_T
  - Consistent set of H_{98}, β_N, f_{BS}, etc. for target Q_{fus}, P_{fus}
  - Ballpark estimates of P_{aux}
  - Does not identify actual operating scenario
- **Integrated Modeling (IM) used for scenario development**
  - Physics-based models, beyond experimental scaling laws
  - Reproducing experimentally demonstrated scenarios
  - Ensuring consistency of core, pedestal and boundary
- **IM informs key engineering design requirements**
  - H&CD, Divertor heat and particle fluxes, fueling
  - Plasma control and disruption mitigation
- **IM critical to CFETR diagnostics design and operation**
  - Provides best-guess, hard to measure profile information

Code Suites for Multi-physics Modeling

- Core-pedestal coupling for scenario design
  - A workflow was developed under the framework **OMFIT**
- SOL and divertor **SOLPS, OEDGE/DIVIMP, …**

- MHD stability **NIMROD, MARS-F, AEGIS, GATO …**
- Energetic particle **NOVA-K, M3D, ORBIT …**
- Pedestal Ana. & Opt. **ELITE, BOUT++ …**

- Plasma shape design **TEQ, EFIT**
- Discharge simulation **TSC, TOKSYS**



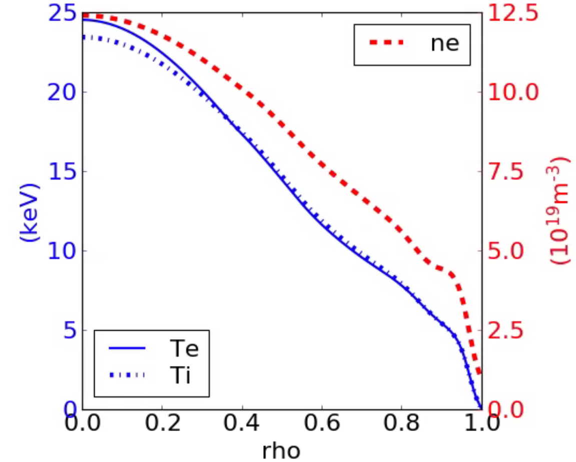
- **Evolving particle densities, T_e and T_i, and momentum**
  - ne/He/impurity profiles evolved and D&T obey quasi-neutrality
- **SOL solutions match core parameters at pivot point ~ top of pedestal**
  - Heat and particle fluxes, iterate boundary densities and temperatures

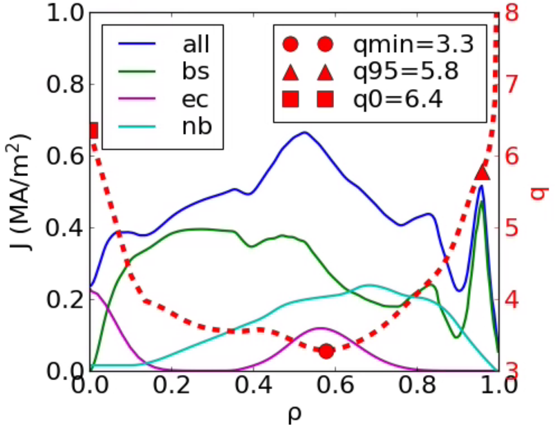
Fully Non-inductive Operation Scenario Designed with System Code (0D)

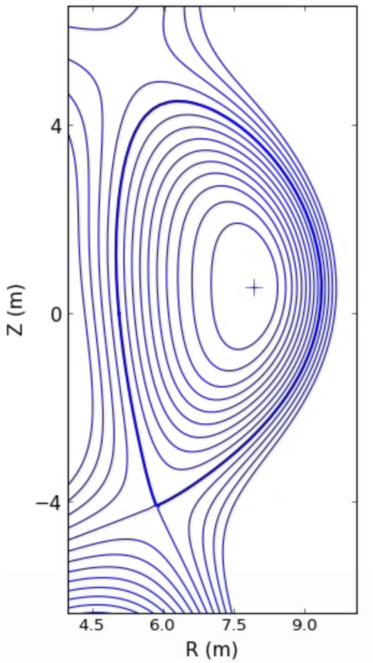
CFETR fully non-induct. R=7.2m, a=2.2m, κ =2	Parameters	A.1 100MW	A.2 200MW	A.2 500MW	A.3 1GW	A.4 DEMO-level
fusion power	P_f	120	229	482	974	2192
power to run plant	$P_{internal}$	199	196	223	238	265
Pfusion/Paux	Q_{plasma}	1.56	3.06	5.87	11.89	28.17
net electric power	$P_{netelec}$	-107	-58	30	232	738
Neutron Power at Blanket	P_n/A_{wall}	0.12	0.23	0.49	0.99	2.23
normalized beta	β_N	1.00	1.20	1.50	2.0	3.0
bootstrap fraction	f_{bs}	0.40	0.40	0.40	0.50	0.75
H factor over ELMY H_net	$H_{ITER98Y2}$	1.12	1.25	1.32	1.41	1.42
current drive power	P_{cd}	77	75	82	82	78
plasma current	I_p	8.61	10.34	12.92	13.78	13.78
field on axis	B_T	6.5	6.5	6.5	6.5	6.5
Ion/electron Temperature	$T_i(0)/T_e(0)$	18	24	32	36	32
Electron Density	n(0)	0.48	0.52	0.61	0.78	1.31
Ratio to Greenwald Limit	n_{bar}/n_{GR}	0.57	0.51	0.48	0.57	0.96
Zeff	Z_{eff}	2.45	2.45	2.45	2.45	2.45
Power per unit R	P/R	8.52	9.42	11.66	15.69	30.70
q95_Iter	q_{95_iter}	8.87	7.39	5.91	5.54	5.54

1GW Non-inductive Operation Scenario by Core-Pedestal Coupling Simulation

- **Preliminary results**
  - No self-consistent tritium fueling
  - Deviation (~30% for P_{aux}) VS system code







li ~ 0.64

$f_{GR,vol}$ ~ 0.89

- **NBI** → 500 keV (68 MW,CD) + 100 keV (10 MW, rotation drive)
- **EC** → maintain large radius RS and control q_{min} > 2 to avoid low n deleterious MHD modes
- **Large BS current** → RS and reduce CD power requirement
- **Moderate q_{95}**

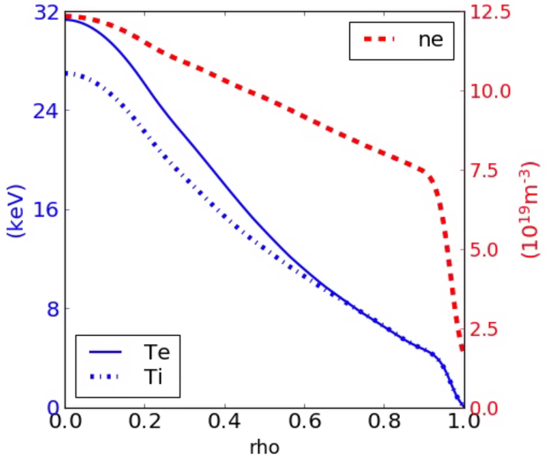
	Simulation	Sys. Code
P_f (GW)	1.0	0.97
Q	9.1	11.9
P_{EC}/P_{NB}	31/78	82(tot)
$\beta_{N,th}(\beta_{N,tot})$	2.05(2.36)	2.0(~)
$H_{ITER98Y2}$	1.11	1.41
f_{bs}(%)	59	50
Ip (MA)	12	14
I_{NB}/I_{EC} (MA)	4.0/0.9	~

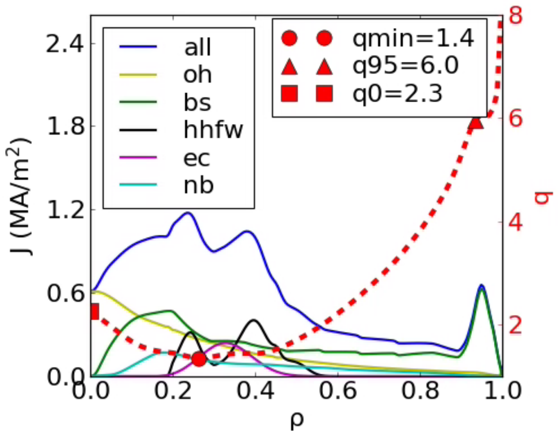
Hybrid Operation Scenario Designed with System Code (0D)

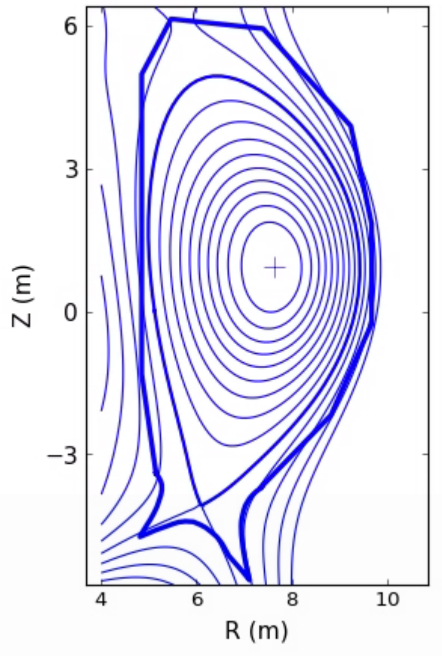
CFETR Hybrid Mode R=7.2m, a=2.2m, κ =2	Parameters	B.1 100MW	B.2 200MW	B.2 500MW	B.3 1GW	B.4 DEMO-level
fusion power	P_f	114	250	558	1128	2192
power to run plant	$P_{internal}$	190	196	202	222	75
Pfusion/Paux	Q_{plasma}	1.54	3.35	7.65	15.30	795.16
Neutron Power at Blanket	P_n/A_{wall}	0.12	0.25	0.57	1.15	2.23
normalized beta	β_N	1.00	1.20	1.50	2.00	3.0
bootstrap fraction	f_{bs}	0.40	0.40	0.40	0.50	0.75
H factor over ELMY H_net	$H_{ITER98Y2}$	1.01	1.09	1.18	1.19	1.54
Ohmic fraction	f_{ohm}	0.30	0.30	0.30	0.30	0.24
current drive power	P_{cd}	74	74	73	74	3
plasma current	I_p	8.61	10.34	12.92	13.78	13.78
field on axis	B_T	6.5	6.5	6.5	6.5	6.5
Ion/electron Temperature	$T_i(0)/T_e(0)$	13	17	24	24	34
Electron Density	n(0)	0.67	0.74	0.82	1.16	1.23
Ratio to Greenwald Limit	n_{bar}/n_{GR}	0.79	0.72	0.64	0.85	0.90
Zeff	Z_{eff}	2.45	2.45	2.45	2.45	2.45
Power per unit R	P/R	7.58	9.33	12.63	19.11	22.97
q95 Iter	q_{95_iter}	8.87	7.39	5.91	5.54	5.54

1GW Hybrid Operation Scenario by Core-Pedestal Coupling Simulation

- **Preliminary result**
  - No self-consistent tritium fueling
  - Deviation (~25% for P_{aux}) VS system







li ~ 0.93

$f_{GR,vol}$ ~ 1.0

- **NBI** → 1 MeV (32 MW,CD) + 600 keV (11 MW, CD & rotation drive)
- **EC** → maintain flat q profile and control q_{min} > 1
- **Moderate li** → plasma stability
- **~300 Volt-sec** (8-hours in flattop)

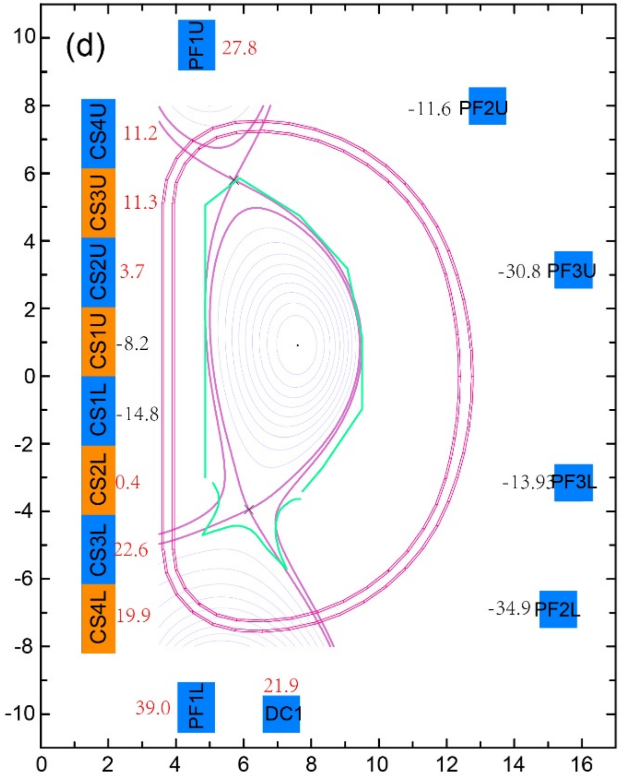
	Simulation	Sys. code
P_f (GW)	0.92	1.1
Q	10	15
$P_{EC}/P_{FW}/P_{NB}$	30/20/43	74(tot)
$\beta_{N,th}(\beta_{N,tot})$	2.09(2.3)	2.0(~)
$H_{ITER98Y2}$	1.16	1.19
f_{bs}(%)	49	50
Ip (MA)	13	14
$I_{NB}/I_{EC}/I_{FW}/I_{OH}$	1.4/0.8/1.6/3	~/~/~/4

H & CD Scheme Consideration

- **EC: necessary tool for current profile control**
  - Optional freq/power: 190 GHz ~ 250 GHz, 20 ~ 40 MW
  - HFS top launched with high freq. for efficient off-axis ECCD
  - LFS above midplane for flexible location of ECCD
  - Optional application in NTM control
- **LH: efficient far off-axis current drive**
  - Optional freq/power: 4.6 GHz or beyond, ~20 MW
  - HFS launched above midplane (adapting for toroidal field along counter-clockwise direction) for CD at r/a >= 0.7
- **HHFW: efficient off-axis or near-axis current drive**
  - Optional freq/power: 0.8 ~ 2 GHz, ~20 MW
  - Optional launched positions: HFS, LFS
  - High CD efficiency at r/a < 0.6
- **NB: broad current drive and possible significant rotation drive**
  - Option for CD: 600 keV ~ 1 MeV NNBI, 16 ~ 32 MW, (1 ~ 2 beam)
  - Option for rotation drive: 100 keV PNBI, 10 MW, (1 beam)

Considerations of Plasma Shape and Divertor

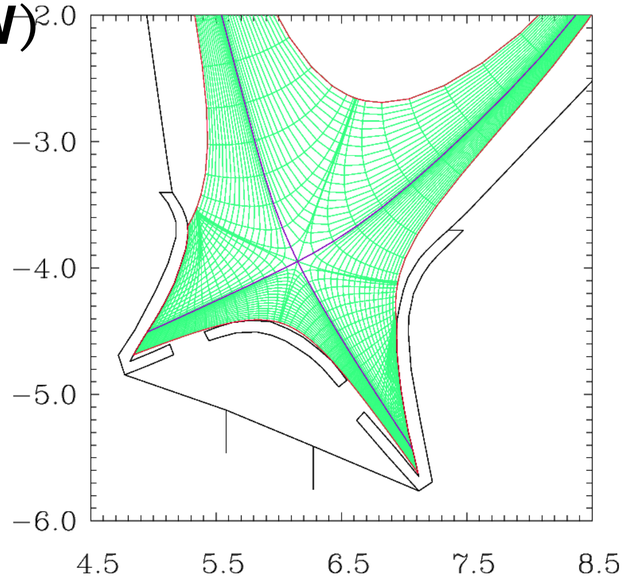
- **ITER-like plasma configuration**
  κ_{sep}=2.0, δ_u = 0.39, δ_l = 0.45
- **A divertor coil (DC1) is added for possible advanced divertor configuration (Snowflake+)**



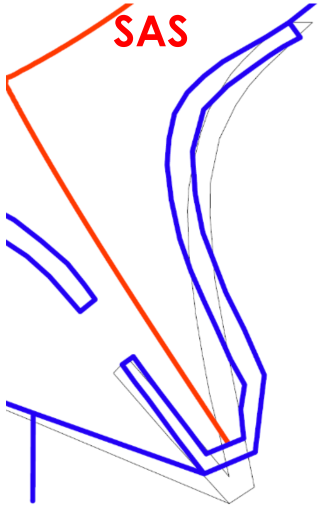
κ_{sep}=2.0
δ_u = 0.39
δ_l = 0.45
dR_{sep}= 6.0 cm

- **Plasma-facing Materials （W）**
- **Different Divertor configurations**
  - Conventional
  - Small Angle Slot（SAS）
  - Snowflake+
- **Optimization target**
  - $P_{peak} \leq 10\ MW/m^2$
  - $T_e \leq$ 5-10 eV
  - $n_{e\text{-}sep} \leq 5\times10^{19}\ m^{-3}$
  - $Z_{eff\text{-}ped} \leq 3$

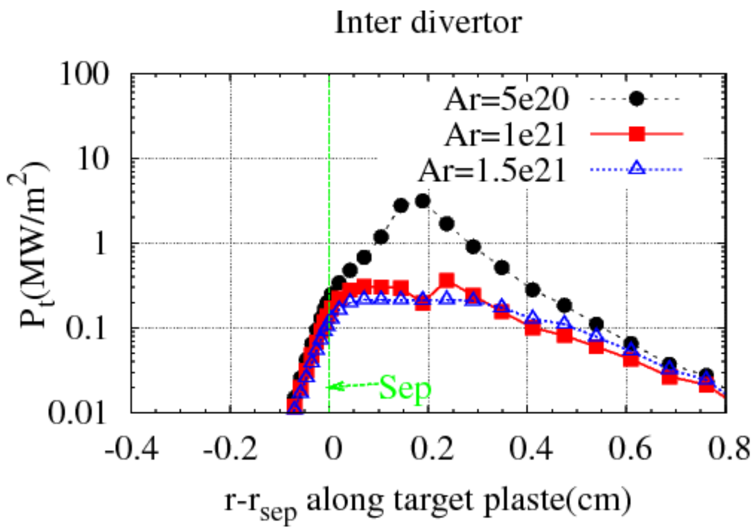
Conventional

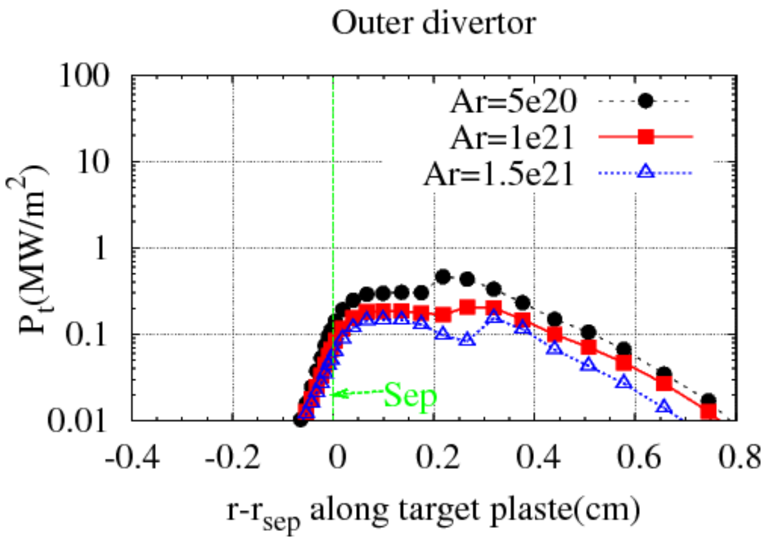


SAS

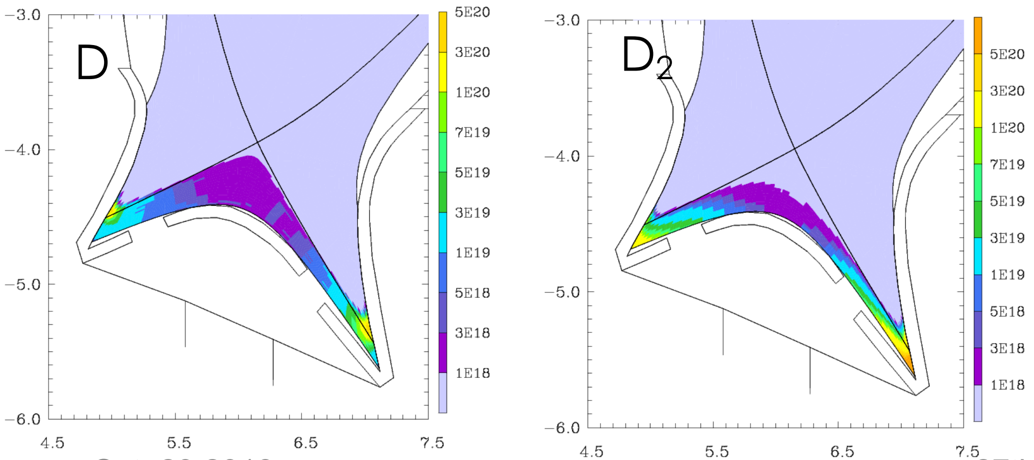


Ar Injection Can Effectively Reduce the Divertor Heat Load to below 10 MW/m²

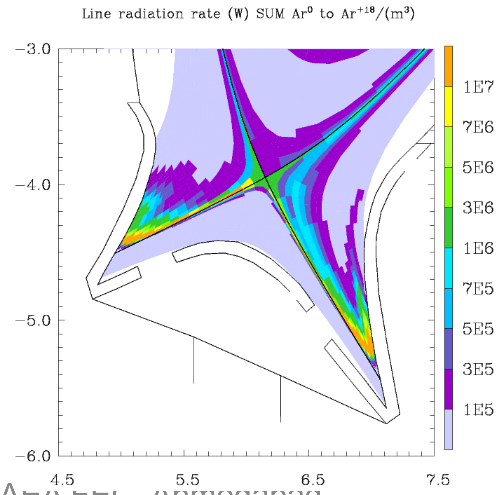




Neutral density (m^{-3})



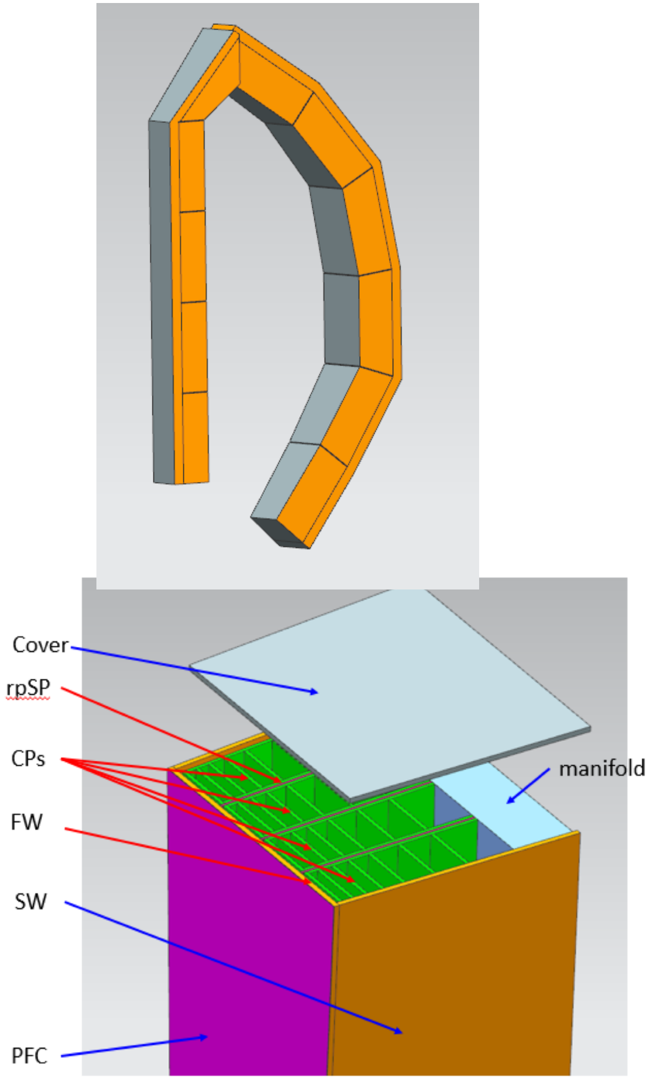
Ar radiation (W/m^{-3})



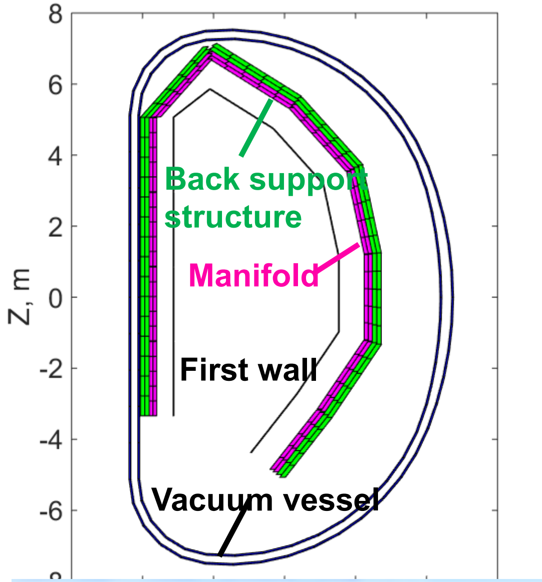
- **Simulation performed with SOLPS code**
- **The peak heat fluxes on both inner and outer divertor are below 10 MW/m²**
- **Total radiation is higher than 80%, mainly by Ar impurities**
- **Detachment occurs at the strike points, but still too high T_e in far SOL region**
- **Fueling dilution and fusion performance degradation in core region should be carefully concerned for high radiation scenarios**

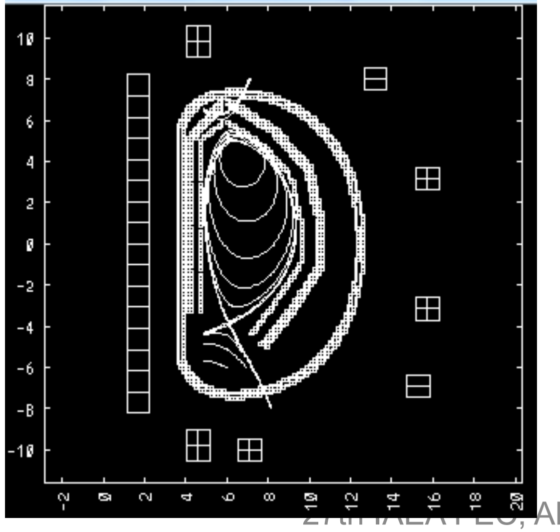
Blanket has strong stabilization effect on vertical instability

Real blanket structure



Modeled blanket structure



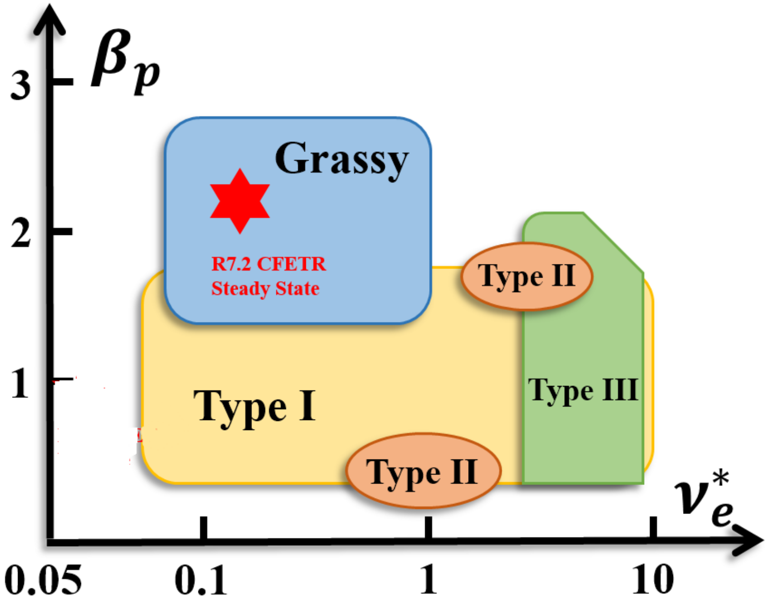


- **Simulations are performed with TSC and TOKSYS codes**
- **Blanket modules (BM) are modeled with three-layer structures. Resistivity is evaluated and scanned**
- **Calculations show BM could significantly reduce the growth rate**

Passive stru included	VV	VV + BM (7.6×10^{-7} ohm*m)	VV + BM (7.6×10^{-6} ohm*m)
Growth rate of VD (/s)	Out of control	2.2	18.1

- **Internal coils are still necessary to control the vertical instability. It is under assessment**

Operation in Grassy ELM regime?

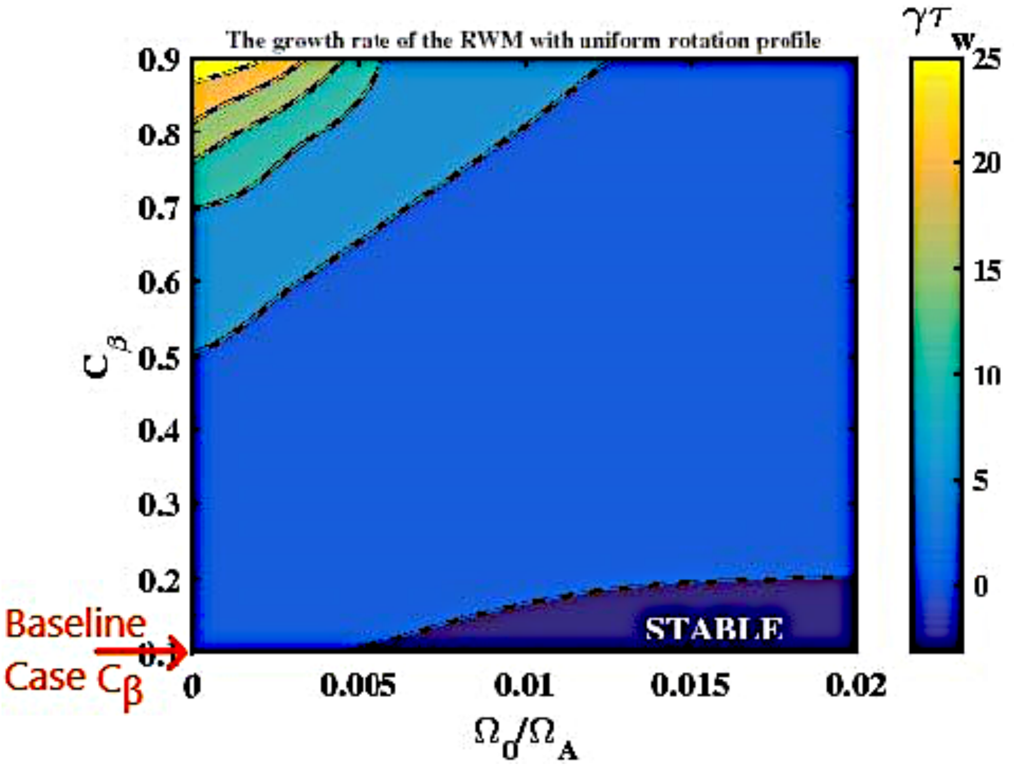


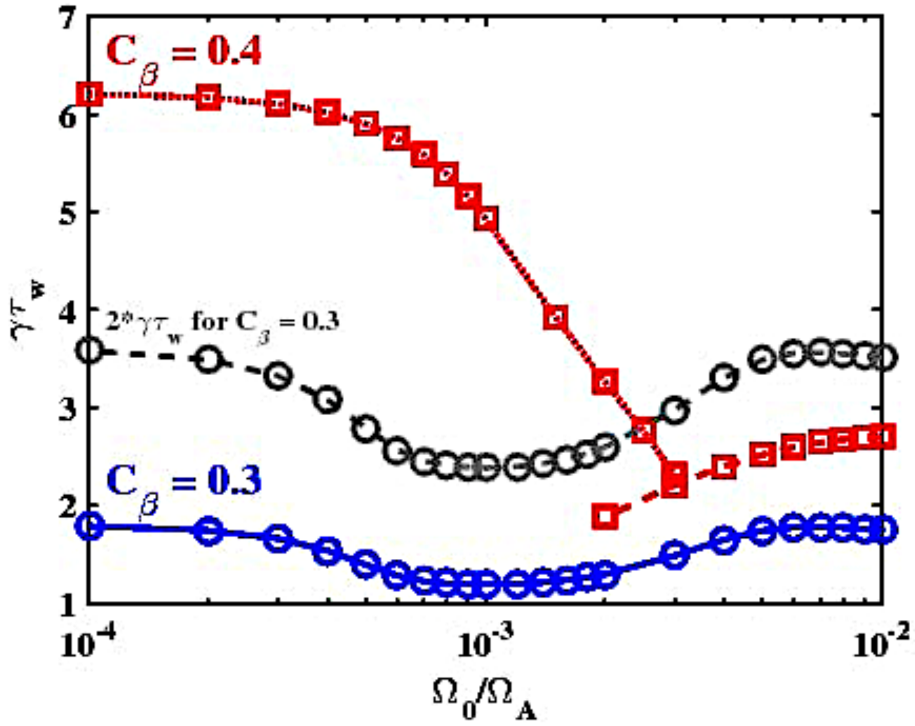
Oyama N. 2008 J. Phys.: Conf. Ser.

- **Type-I ELM must be avoided**
- **Mostly likely, RMP coils will not be installed**
- **According to experimental data classification, β_p and ν^* from EPED1 for the reference scenario put it in the grassy ELM regime**
- **BOUT++ and other codes are being used to verify the ELM prediction**

Resistive Wall Mode Should be Stable for the Steady-state Scenario

- **MARS-K has been used to calculate the stability of RMWs, with uniform rotation**
- **The steady-state scenario is marginally unstable**
- **A small rotation of $\Omega_0/\ \Omega_A<0.01$ could make the RMW stable**

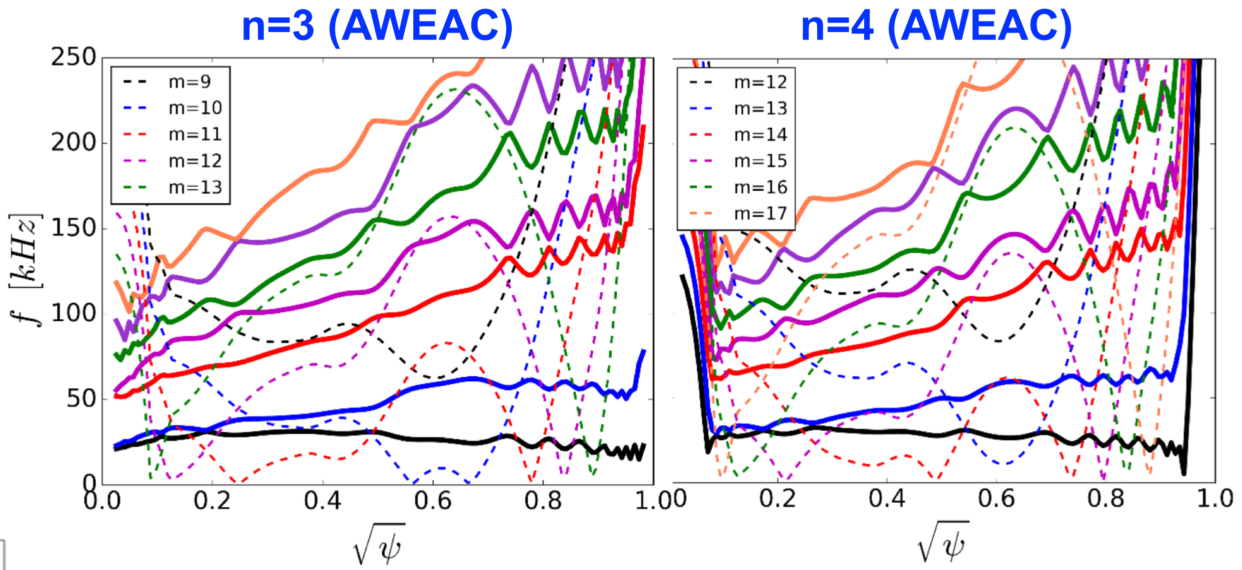


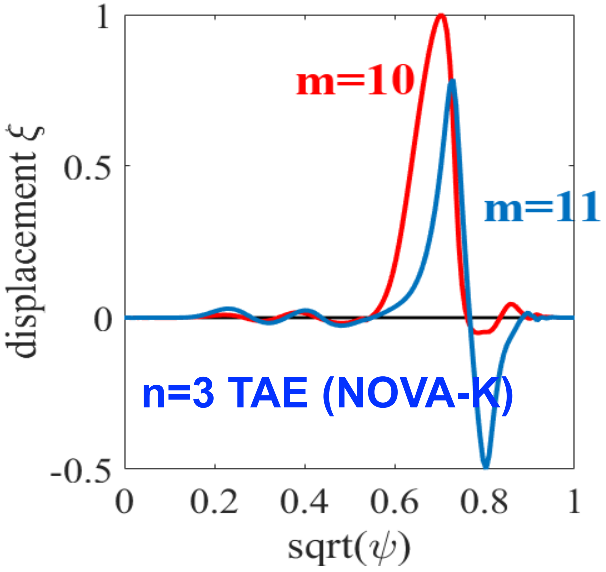


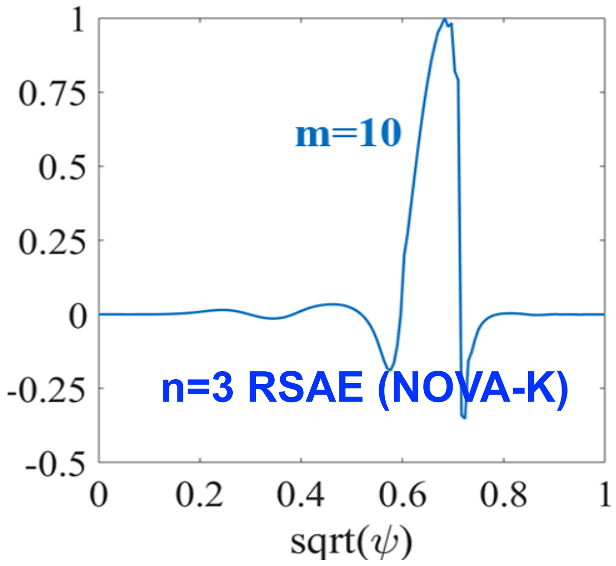
Growth rate of n = 1 RWM

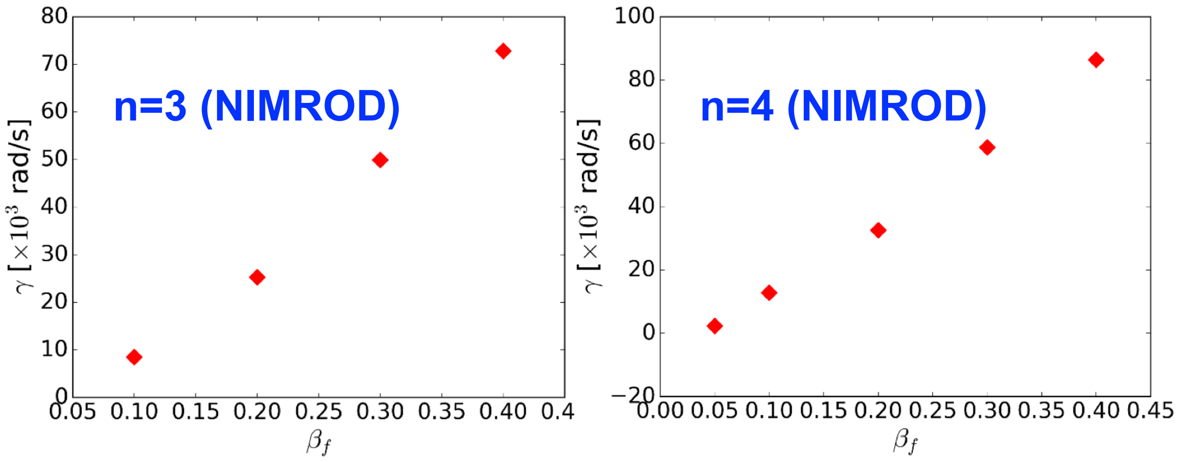
α particle drive is weakly destabilizing for TAE and RSAE in steady state scenario

- Linear calculations show the α particle drive weakly destabilizing
- NOVA-K shows the damp effects could make TAEs and RSAEs marginally stable
- Effects of nonlinear AEs and EPMs are under investigation









See Y. Hou TH/P2-7

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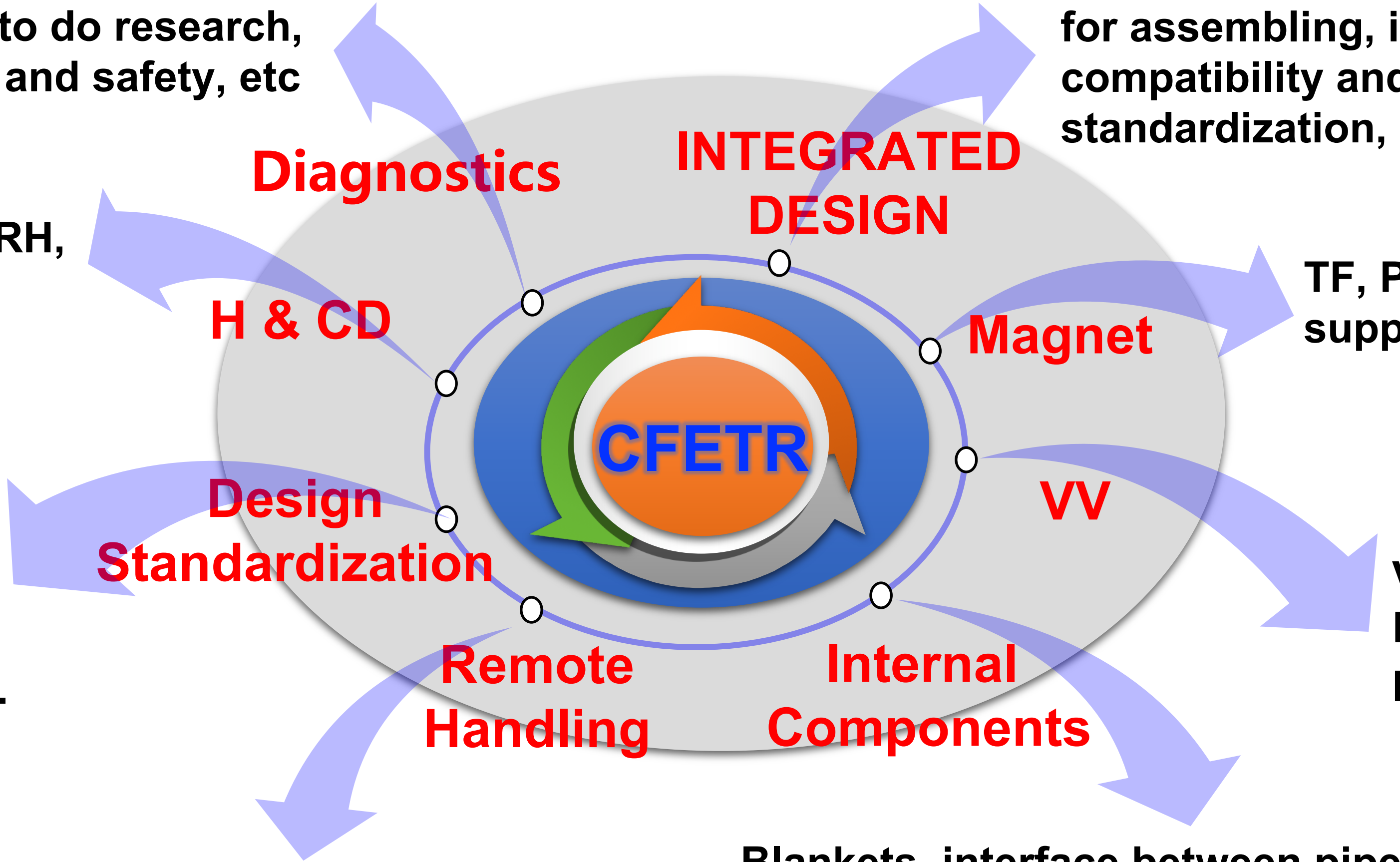
CFETR Engineering Design

Measurement capability aiming to do research, control and safety, etc

Strategy and procedure for assembling, interface compatibility and standardization, etc.

NBI, ICRF, ECRH, LHCD, etc

TF, PF, CS, and their supports, feeders



Establish design standardization, manual, quality management, etc.

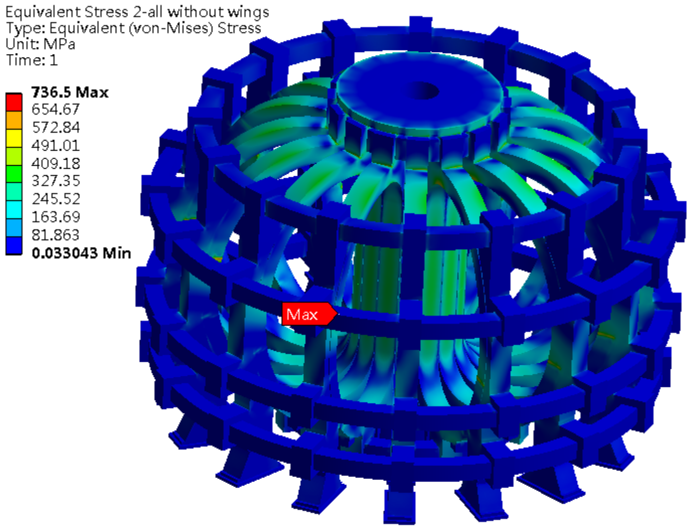
Vacuum Vessel, Neutron shielding, port, etc.

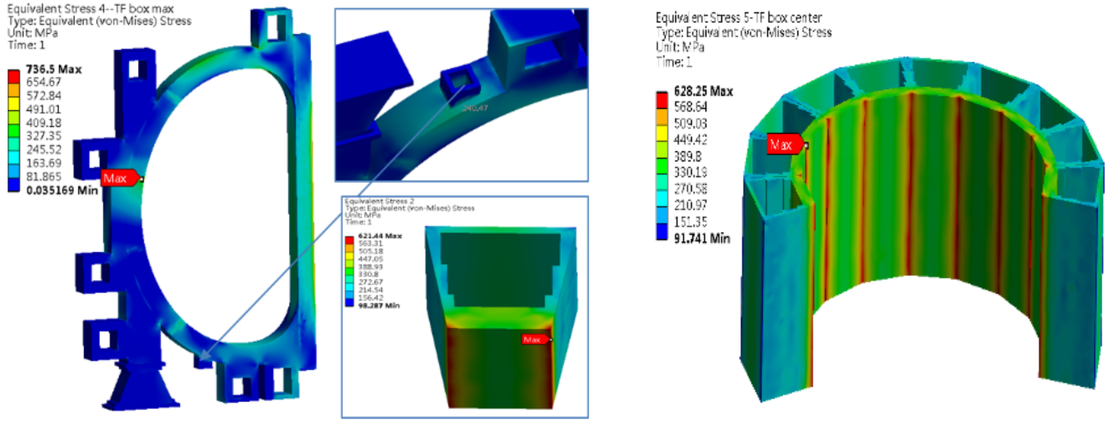
Maintenance and replacement for internal components, NBI, RF antennas, diagnostics, etc.

Blankets, interface between pipe and Blanket, Water cooled breeder blankets, Helium cooled breeder blanket, divertor, etc

Magnet System (Toroidal Field Coils)

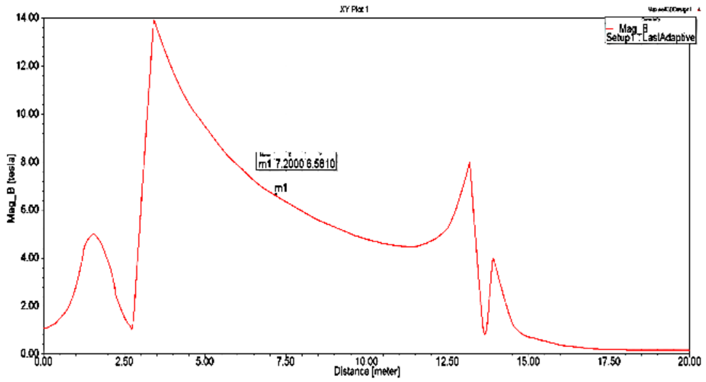
- **Design completed**
- **EM & Stress analysis done**





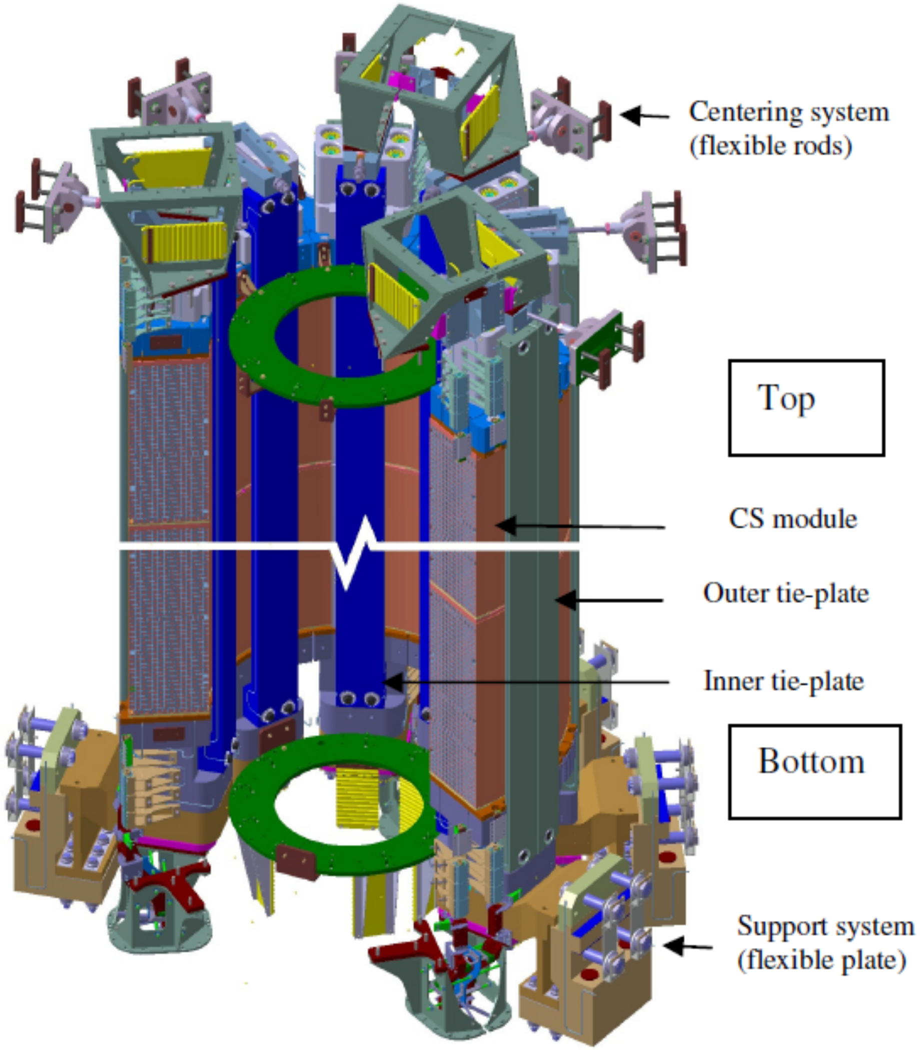
Max Force @TF coil ~736 Mpa; Max. Deformation ~ 16.5 mm

6.5 T @ R = 7.2 m; 174 Turns; 84.6 kA/Turn



	ITER TF	EU-DEMO[2015]	CFETR TF
No. of Coil	18	18	16
Current per Turn	68 kA	81.7 kA	84.6 kA
Total inductance	17.34 H	32.68 H	32.5 H
Total Storage Energy	40.1 GJ	109.08 GJ	116.34 GJ
Storage Energy per Coil	2.227 GJ	6.06 GJ	7.27 GJ

Magnet System (Central Solenoid)

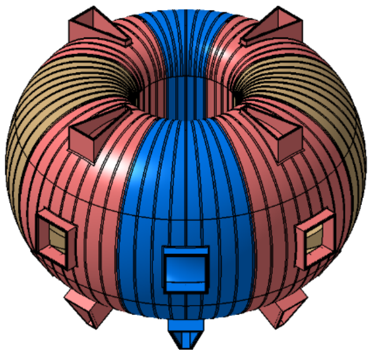


Perspective view of the CFETR CS

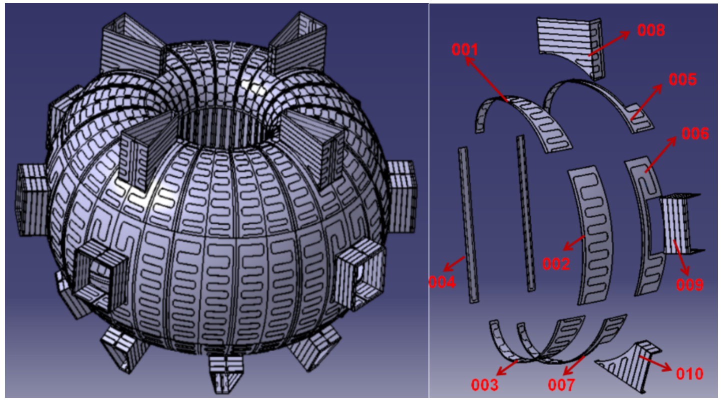
- **High temperature superconductor (Bi2212) + low temperature superconductor (Nb_3Sn) → a maximum 19.9 T@ 51.25 kA/turn.**
- **Each module has 720 turns, powered independently**
- **Maximum 400 VS flux with a maximum rate of field swing of ~1.2 Ts.**

Vacuum system

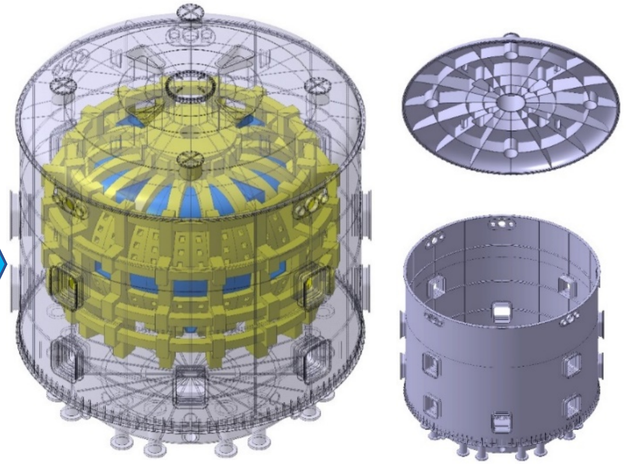
Vacuum Vessel+Thermal Shield+Dewar



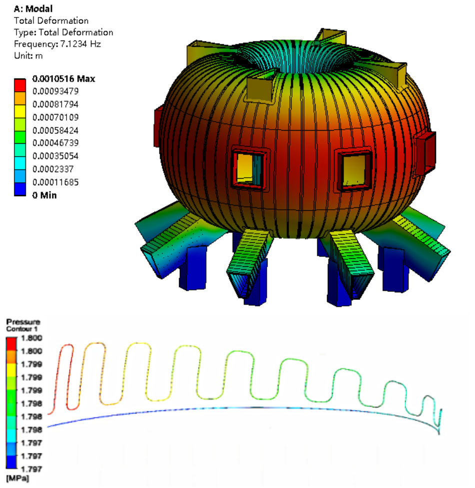
H ~15 m ，W ~ 9.1 m，Thickness ~50 mm，8 Sectors, 4/6/8 ports



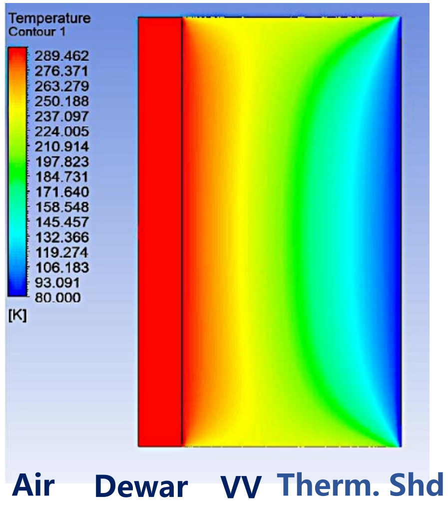
H ~ 15 m, W ~ 9.4 m, Thermal Shield~40mm



H ~ 29 m, D ~ 38 m，Background Pressure ~ 1x10^{-4} Pa



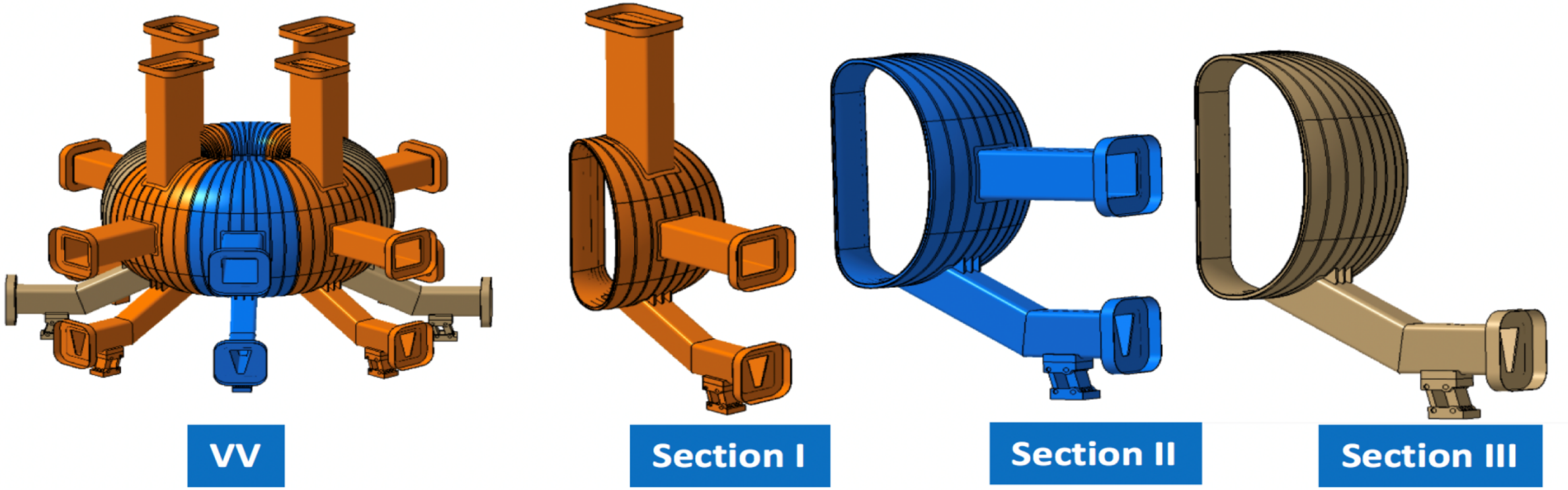
pressure drop @ cooling pipe



- **Design completed**
- **Analysis on gravity load**
- **Analysis on freq. and mode of Vibration**
- **Analysis on Seismic load**

Vacuum system

- **Torus with D-shaped cross-section, 4 upper vertical ports, 8 lower ports and 6 equatorial ports**
  - **- 4 upper ports → maintenance and disassembly of blanket.**
  - **- 6 lower ports → divertor maintenance and the cryo-pumps.**
  - **- 8 equatorial ports → NBI, diagnostic and some RH tools.**
- **Inner, outer shells and stiffening ribs joined by welding.**
- **Material of the VV is 316L(N)-IG.**

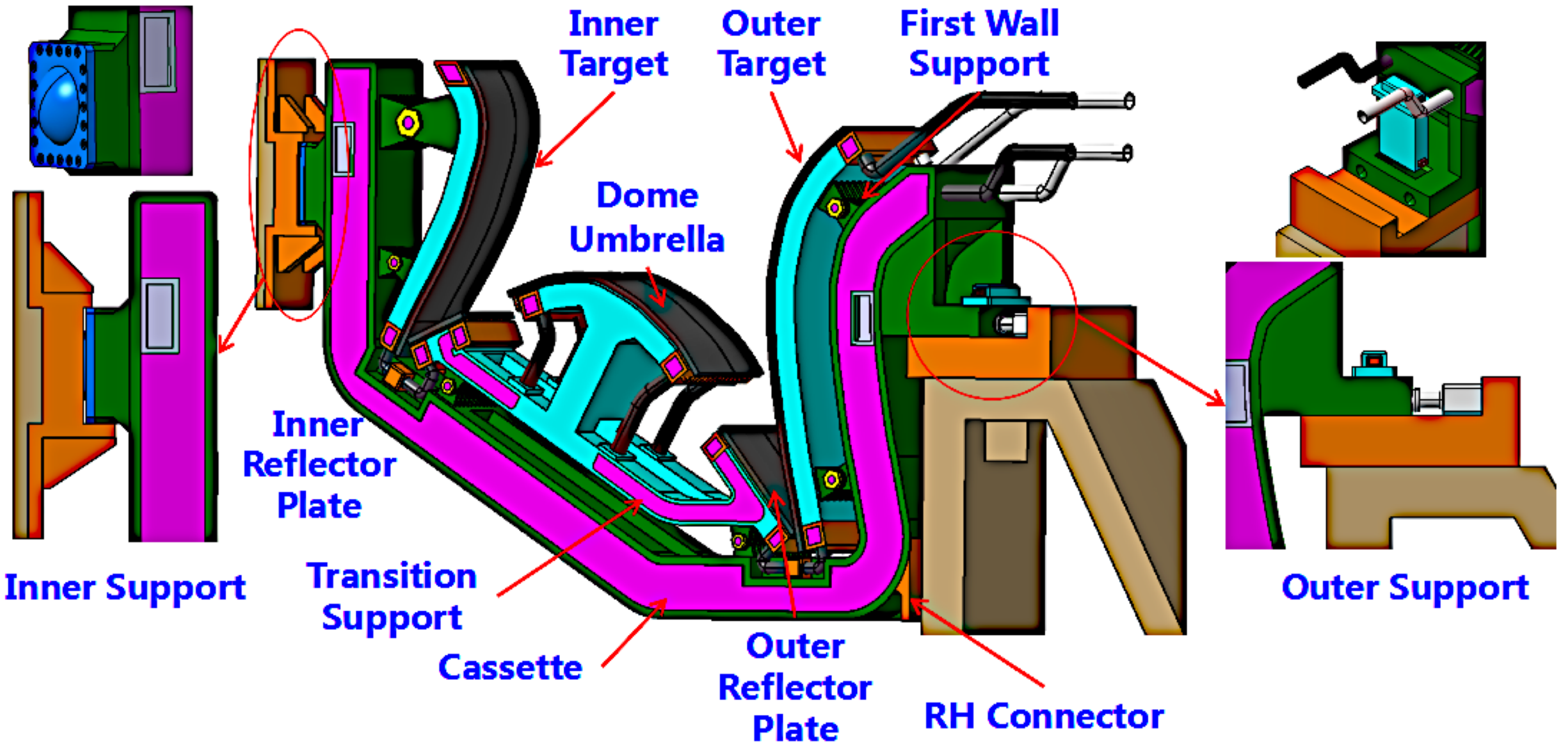


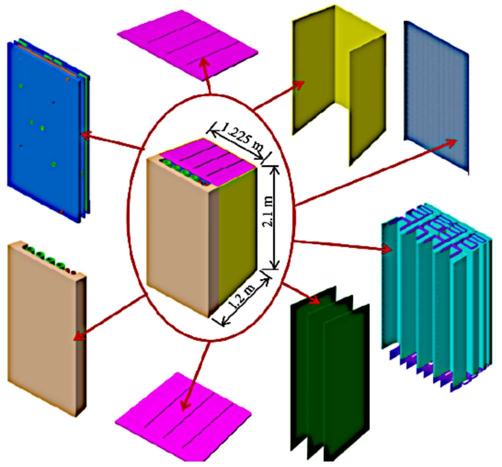
3D model Vacuum Vessel for CFETR

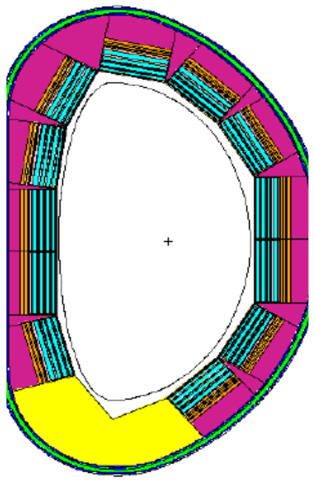
Divertor Structure

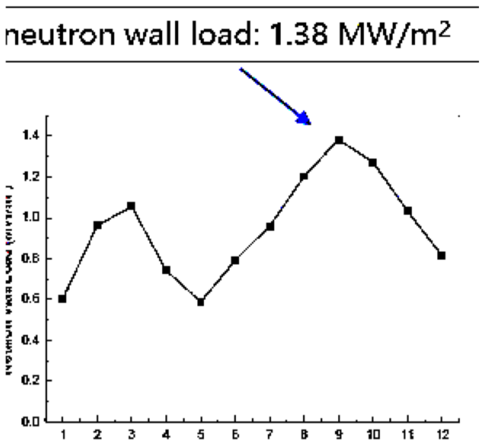
- Divertor targets divided into two halves on each module, totally 72 divertor modules, each one ~11 tons. RH from lower port
- Cooling water → outer target → inner target → baffles
- Cassette cooled separately → targets/baffles RH separately from Upper ports by Multi-Purpose Deployer

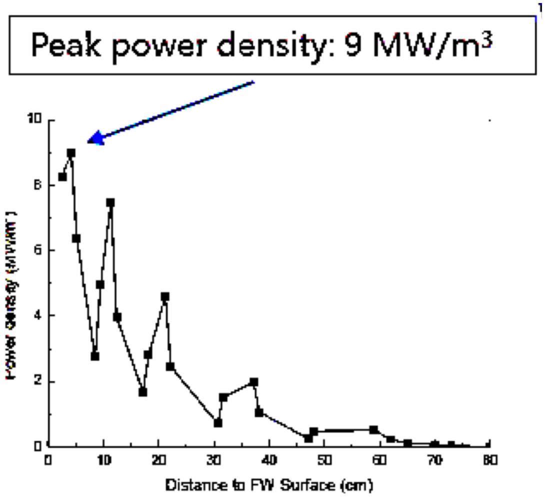
Conceptual engineering design of the CFETR divertor structure.



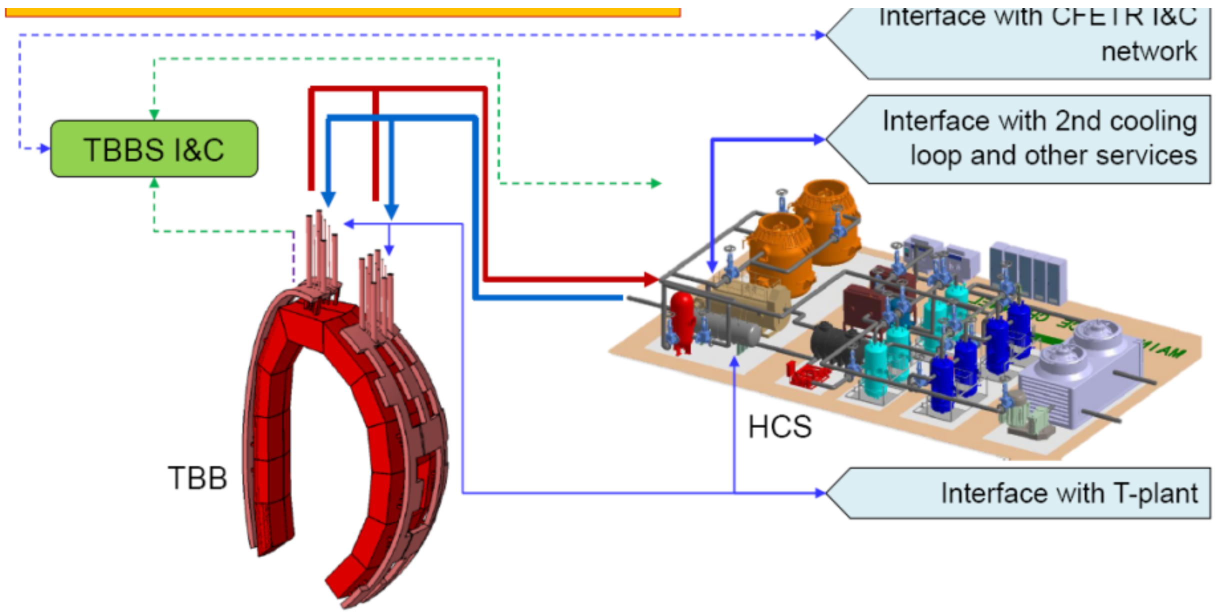






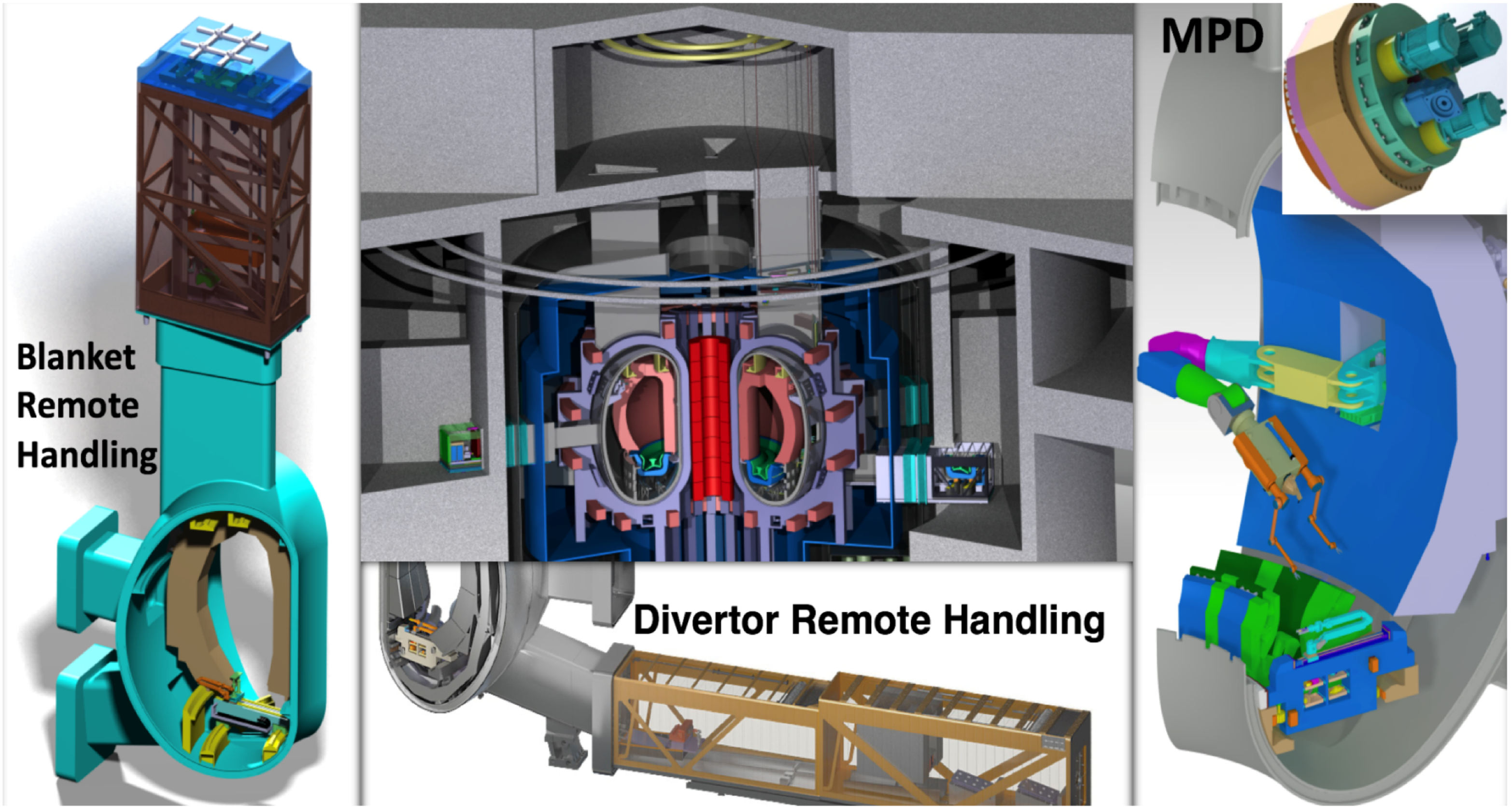


- **Helium cooled ceramic breeder blanket (HCCB) design completed**
- **Evaluate neutron energy deposition and wall load @ Fusion power = 1 GW, 2 GW**
- **Start the water cooled ceramic breeder (WCCB) design**



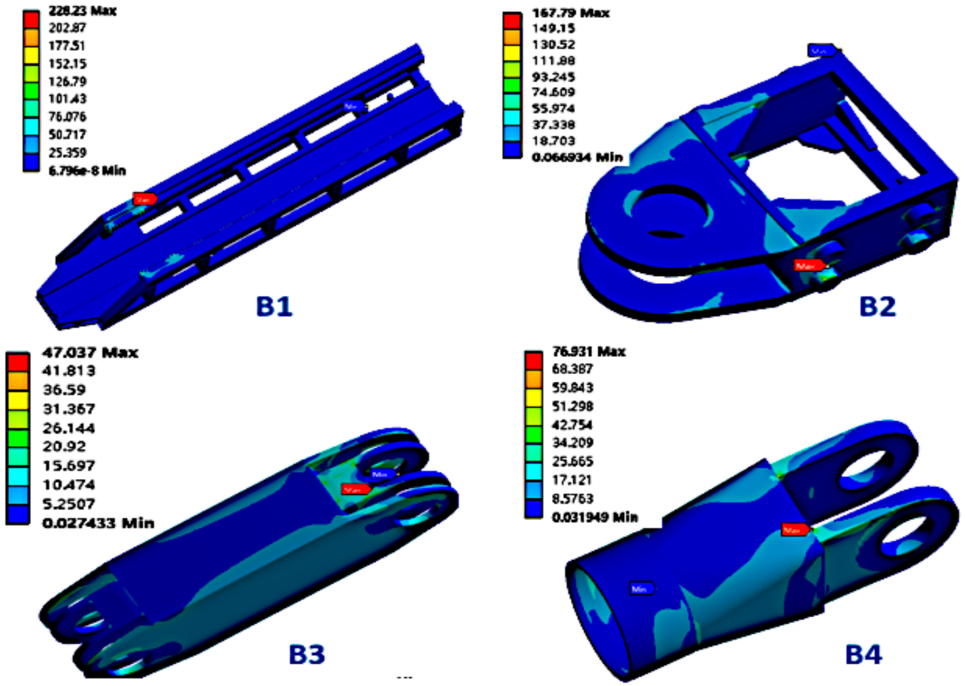
Remote Handling & Maintenance

- **Blanket RHM**: Inboard & outboard blankets → from upper ports by a corridor with a crane → hot cell.
- **Divertor RHM**: circular movement → lower horizontal port →cask → hot cell.
- **MPD** : equatorial port → maintenance of small pieces, inspection, diagnosis.

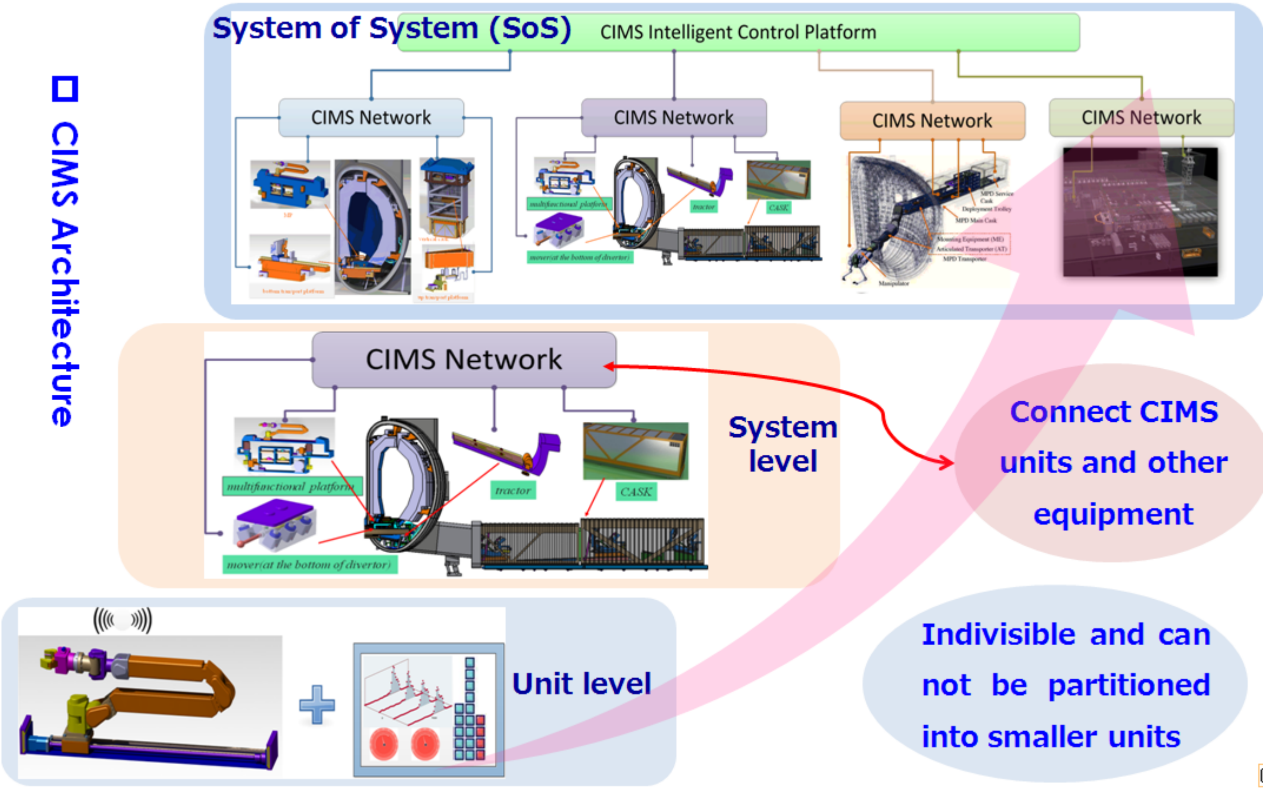


Remote Handling & Maintenance

Mechanical load on Manipulator joints



- CIMS Architecture

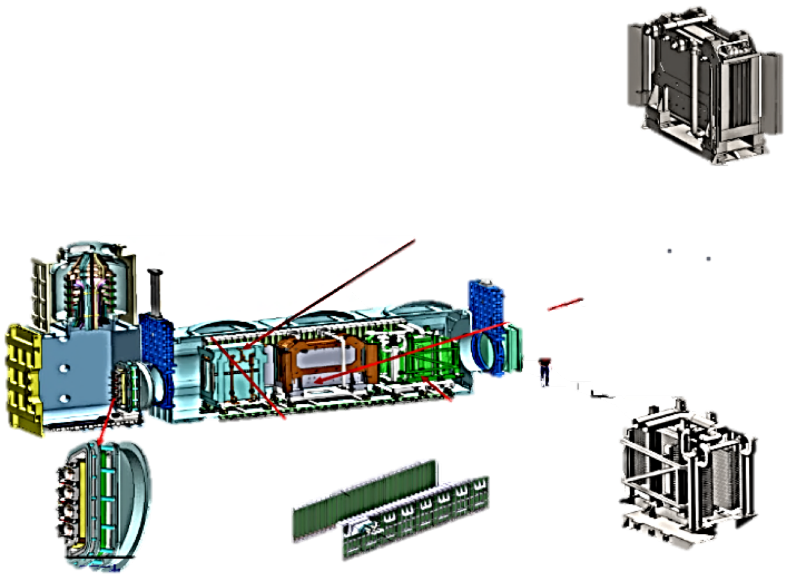


- Mechanical analysis on RHM of internal components;
- Establish overall control architecture, hardware and software control integration architecture @ Heterogeneous control architecture theory.

Design and R&D for H&CD Systems

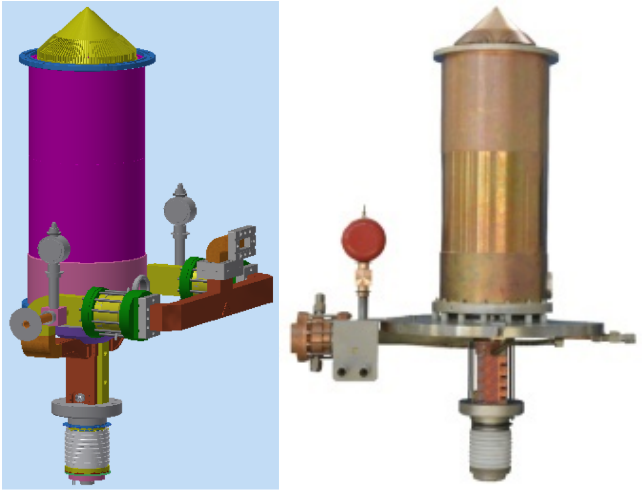
NBI

- Based on ITER NBI design, complete preliminary design of N-NBI System, R&D of key technologies of CFETR N-NBI
- Promote research of RF source, high RF power, long pulse ion source
- Achieve substantive results on isolation transformer for RF power transmission



LHW

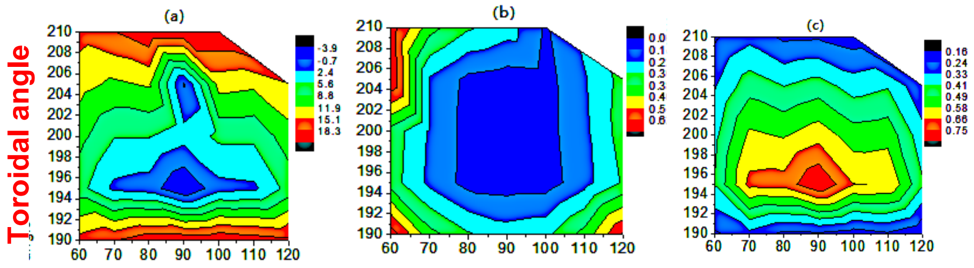
- Complete preliminary design of low power microwave power source driving circuit, control scheme of power and phase, and Investigate high-power klystron, and auxiliary power equipment
- Carry out high-field coupling and high-field antenna simulation study, R & D of key components of the transmission line



4.6GHz 500kW/CW Klystron model and structure

ECW

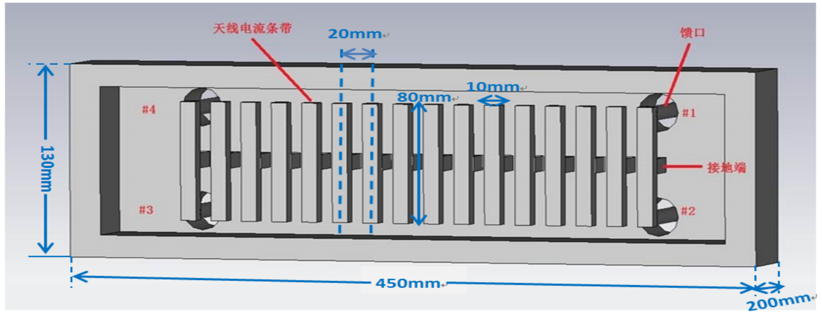
- Complete the ECRH system design, R&D of key technologies for Gyrotron
- Start the effectiveness analysis and performance evaluation of ECCD under various conditions (beam injection position, antennas incident parameter, different gyrotron freqs 170GHz, 230GHz)



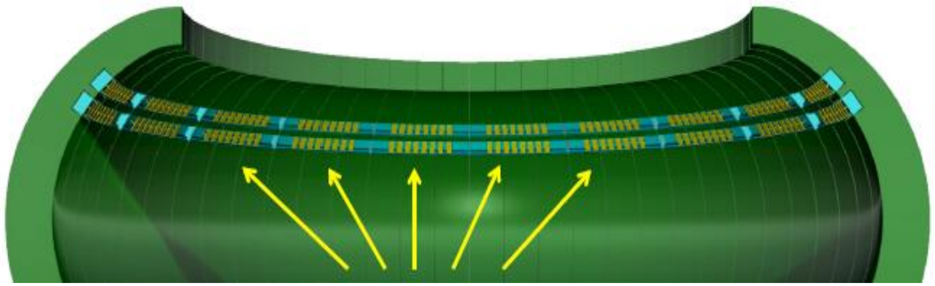
Performance of 230GHz ECCD (Za = 0 m)
(a) ECCD (kA/MW) ; (b) Peak location of J_{CD}; (c) 2^{nd} Harmonic absorp. ratio (%)

Helicon Wave

- Start design and analysis antenna of travelling wave



Helicon waves traveling wave antenna module



Traveling wave antenna modules arranged in the blankets, satisfying high power requirements

Outline

- Introduction
  - New version of CFETR design
- CFETR Physics Design
  - Development of operation scenarios
  - Consideration of divertor conf. & impurity effects
  - Investigation of MHD stability
- CFETR Engineering Design
  - Magnet system
  - Vacuum system
  - Remote handling and maintenance system
  - Others…
- Summary

Summary

- **New design with R = 7.2 m / a = 2.2 m & high B_T.**
- **Detailed designs of physics and engineering are under the way.**
  - **Progress of physics design**

    - Fully non-inductive and hybrid mode scenarios with performance that meets the CFETR mission have been developed

    - Broad operation range in β_N and $\beta_{p,}$ stable with wall at r/a = 1.2

    - Helium dilution f_{He} cannot exceeds 0.2 to meet P_{fus} target

    - Radiation in the core acceptable up to Z_{eff} ~ 3

    - Tungsten fraction at the edge can't exceed 4e-5 to stay in H-mode
  - **Progress of engineering design**

    - Concept design of key systems completed, detailed engineering design of the systems ongoing.
- **CFETR will be fully open to our cooperators, your input in very valuable for the success of the project.**

Acknowledgements

We are grateful to General Atomics, PPPL, LLNL, Wisconsin, U. York, MPG-IPP and U. Toronto for the use of their physics code suites and data, and their helps

Thank you for your attention !