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Overview of the Fusion Program in China

B. N. Wan

Institute of Plasma Physics, Chinese Academy of Sciences

Fusion as an important part of the national strategic in clean energy

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国家中长期科学和技术发展规划纲要（2006-2020年） Outline of nation S&T development		国务院 State council
国务院关于印发国家重大科技基础设施建设中长期规划（2012-2030年） Plan for large scale science facilities	国发〔2013〕8号	国务院
国务院关于印发”十三五”国家科技创新规划 Plan of S&T innovation for 13th 5 year	国发〔2016〕43号	国务院
能源技术革命创新行动计划（2016-2030年） Acting plan for energy technology innovation	发改能源〔2016〕513号	国家发展改革委 /国家能源局

Fusion research is included in national science and technology developing plan and national innovation acting plan/program in clean energy

National Magnetic Confinement Fusion Science Program in 12th 5 year plan

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- **Supported R&D needed for ITER PA of China**
- **Supported research capability enhancement of EAST/HL-2A**
  - **Heating, diagnostics, in-vessel components, control…**
- **Supported domestic research program on EAST/HL-2A**
  - **ITER-physics including Modeling and simulation**
  - **International collaboration including ITPA→CTPA**
- **Supported conceptual design and some R&D of CFETR**
- **Supported education and training program for MF community**
  - **University program (JTEXT, KTX, SUNIST)**
- **Supported material and other key R&D**
  - **Material research, remote handling, W-mono-block…**

National Magnetic Confinement Fusion Science Program will be continuued in 13th 5 year plan

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It is emphasized to support ITER and CFETR related activities

- **ITER construction and operation**
  - **PA of China, ITER physics and preparation of operation…**
- **CFETR engineering design and key R&D**
  - **Engineering design**
  - **Key technologies and physics to support design**
- **Key physics and technologies on EAST/HL-2A/2M to support ITER operation and CFETR design (including model validation)**
- **Education and training program for MF community**

Route Map of China Magnetic Confinement Fusion Energy Development

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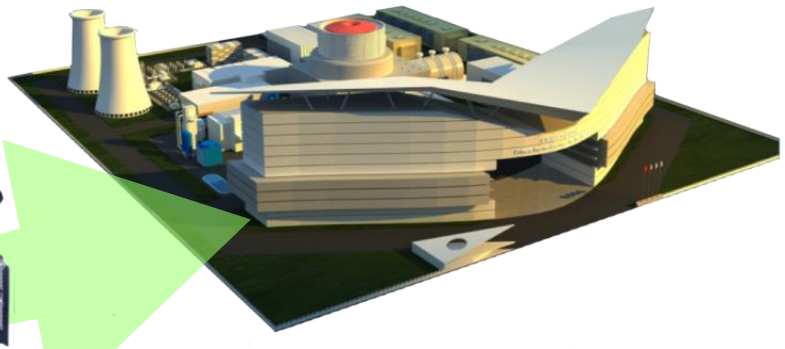
PFPP



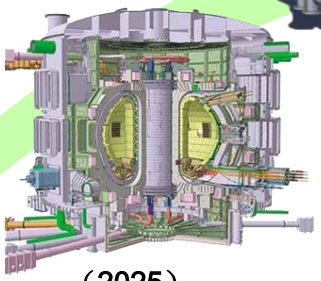
（2050）

First phase：engineering test，Q=1-5， steady state, 200MW，
Second phase：Demo，Q>10；steady state，1GW，50dpa

CFETR

（?20??）

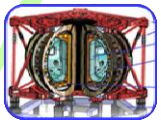
ITER



（2025）

First phase：Q=10；400s，500MW， D-T operation
Second phase：Q=5；3000s，350MW，steady state operation

EAST Advanced plasma configuration，long steady-state plasma operation

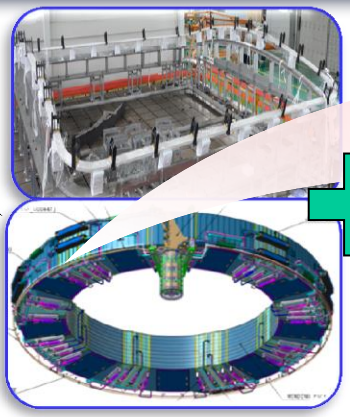


HL-2M Advanced divertor, AT physics

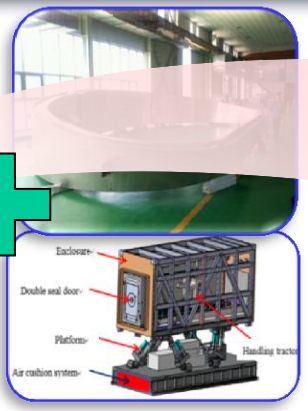
J-TEXT University Program

Strategy of magnetically confined fusion and advanced nuclear energy research in ASIPP

Fusion Reactor technology

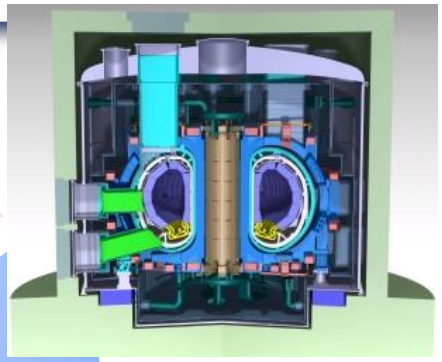


ITER package



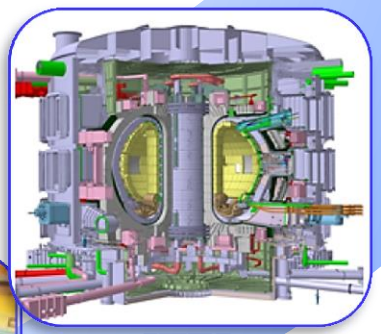
CFETR Design R&D

Engineering



Chinese Fusion Engineering Test Reactor

physics



ITER

High performance Steady state fusion plasma research

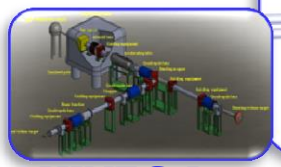
EAST

?

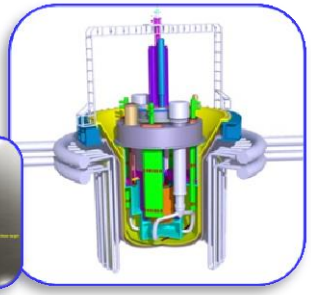
EAST-Upgrade

Burning plasma related physics and advanced divertor

Nuclear technology and material



HINEG-I



Lead-based Reactor

INEST

Power plant related issues

Under support of National Magnetic Confinement Fusion Science Program EAST/HL2A research capabilities have been significantly enhanced

EAST for high performance steady state operation

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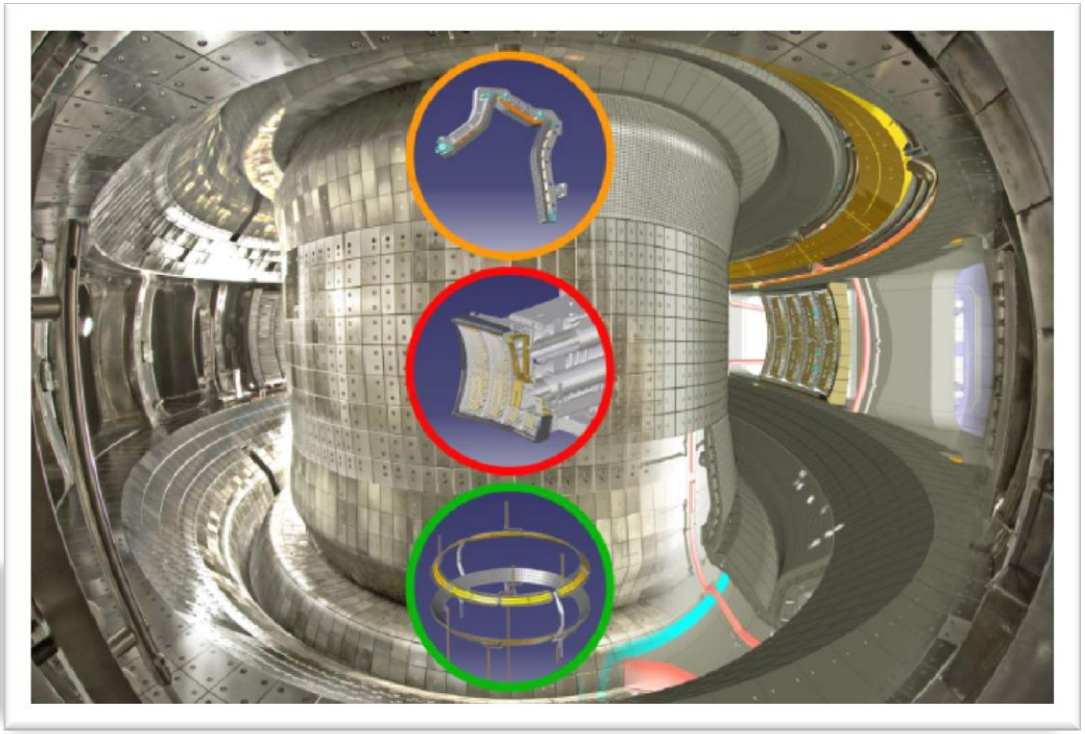
Significant engineering efforts have been made for high performance long pulse operation.

Provide supporting for ITER &CFETR



	Nominal	Upgrade
T_{coil} (K)	4.5	3.8
B_t (T)	3.5	4.0
I_p (MA)	1	1.5
R_0 (m)	1.8	1.8
a (m)	0.45	0.45
κ	1.2–1.8	1.2–2
δ	0.3–0.6	0.3–0.6
τ (s)	1000	1000

EAST is the fusion device in the world capable of **long pulse** high performance operation with **dominated electron heating** (as in ITER) to challenge **power and particle handling** at high normalized levels (10 MW/m^2) **comparable to ITER**.

Heating & CD

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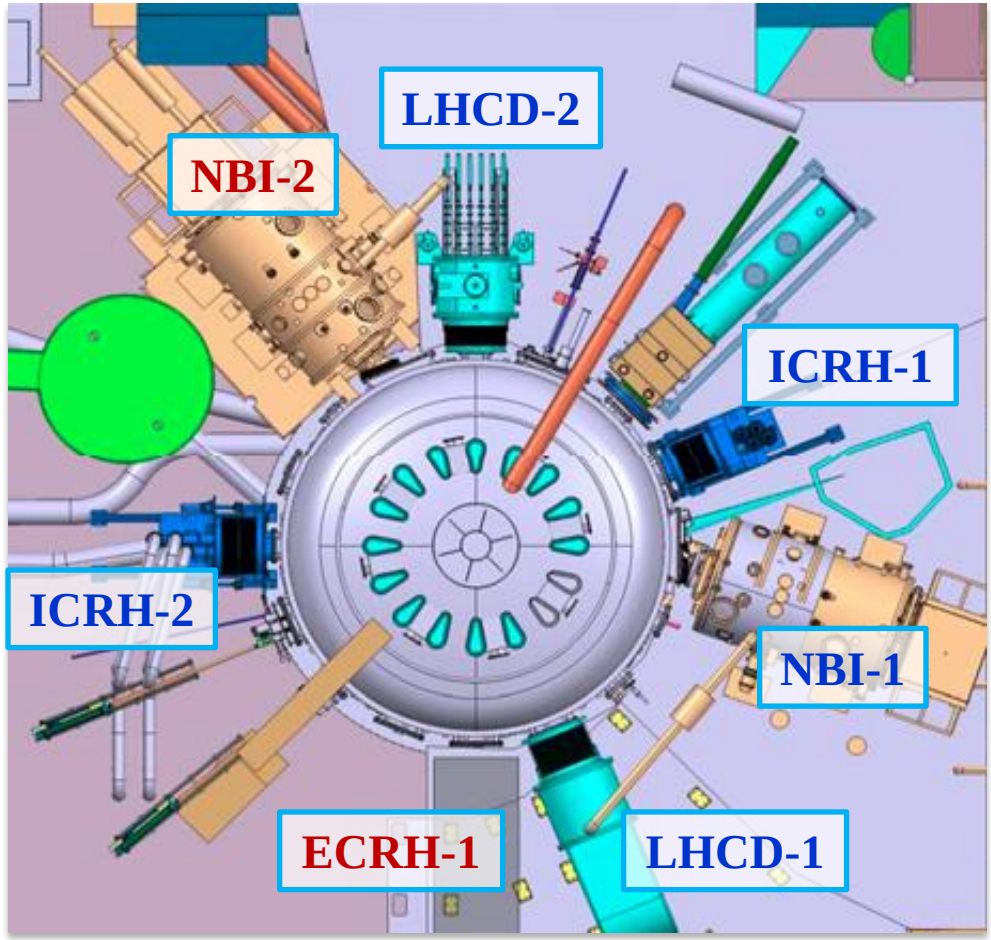

- **LHCD 4+6 MW(2.45/4.6GHz)**
  - Fast Electron Source
  - Edge Current Drive /Profile
- **ICRH 6+6 MW (25-75MHz)**
  - Ion and Electron Heating
  - Central Current Drive
- **NBI 4+4 MW (co/counter, 80kV)**
  - Sufficient power to probe β limit
  - Variable rotation/ rot-shear
- **ECRH 2(4) MW (140GHz)**
  - Dominant electron heating
  - Steering mirror, j_ϕ tailoring

- **ITER-like RF-dominant H&CD, capable of high performance SS operations**
- **Each individual power is sufficient to access H-mode plasmas**

PFC Upgrade Facilitates for High Power Long-pulse Operations

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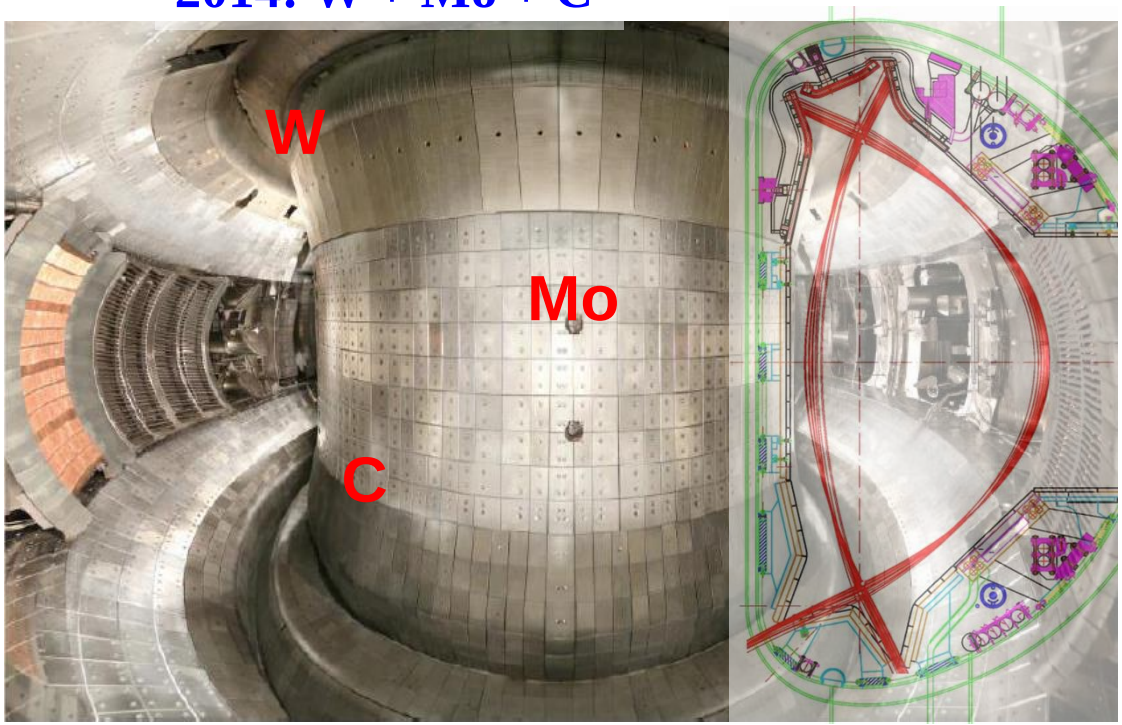
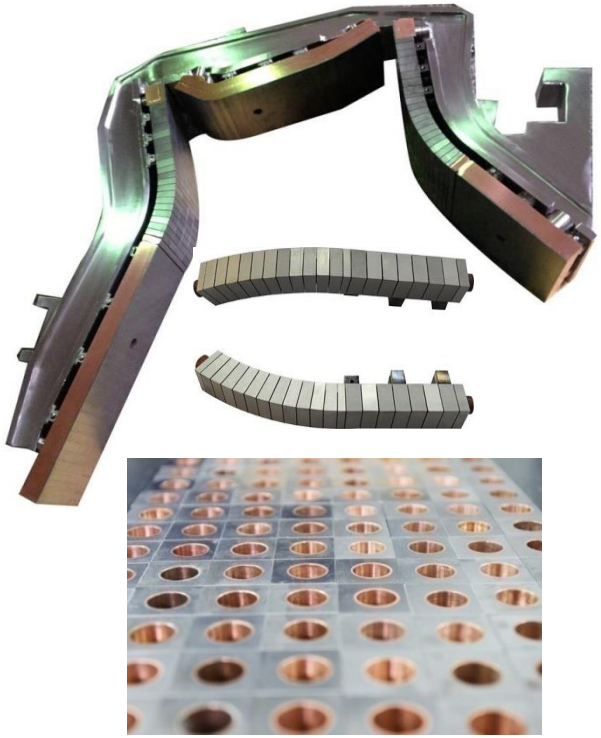
2014: W + Mo + C

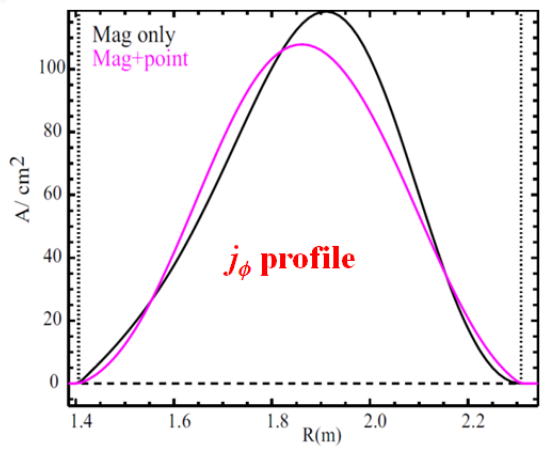


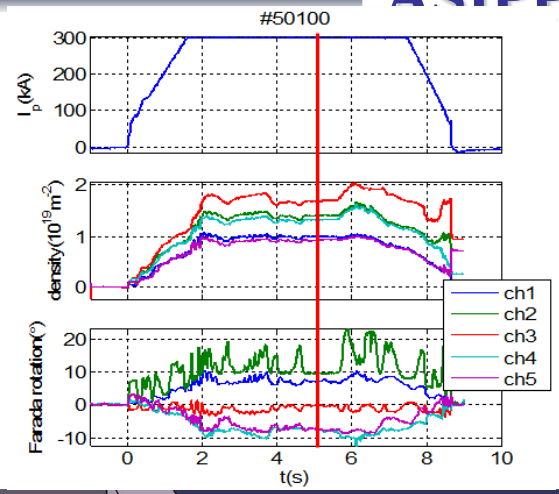


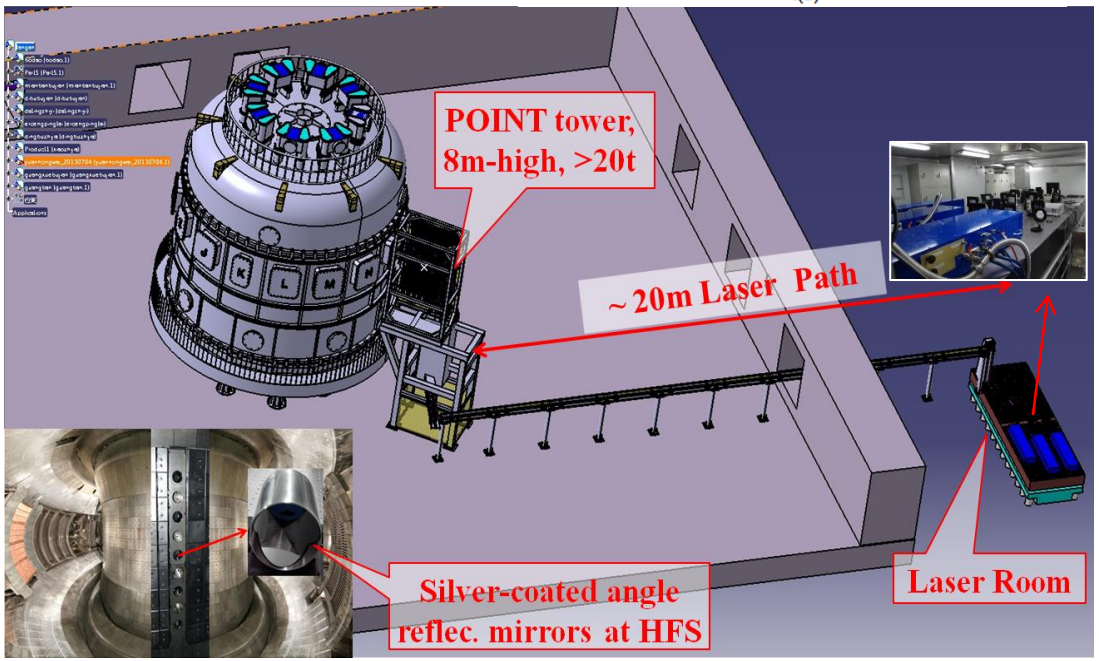
- **ITER-like cassette body structure with actively water cooling**
- **ITER-like W mono-blocks:**
- **Divertor targets (10 MW/m^2)**
- **Flat type W/Cu PFCs:**
- **Divertor dome and baffles (5 MW/m^2)**

Diagnostics for key profiles covering from core to edge

- **Polarimeter interferometer (POINT):** n_e, j_ϕ, q, B_p profiles
- **Core & edge TS:** T_e, n_e
- **AXUV & Bolometer:** radiation
- **CXRS & XCS:** T_i, rotation
- **SXPHA & ECE:** T_e
- **Reflectometry:** pedestal n_e
- **He-BES:** edge n_e, T_e
- **Recip.-LPs:** SOL n_e, T_e, flow
- **Filterscope:** D_α, impurity
- **Bremsstrahlung:** Z_{eff}
- **FIDA:** $V_{fast\text{-}particle}$
- **High speed CCD**
- **IR camera:** heat flux
- **Div-LPs:** div. particle/heat flux
- **……**
- **Total: 76 diagnostics**







Collaborative efforts

Technology for ELM control

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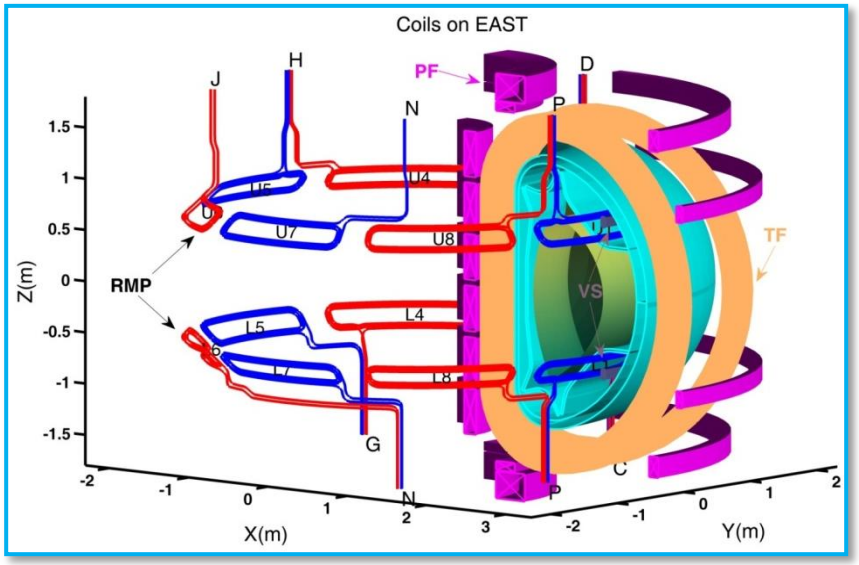
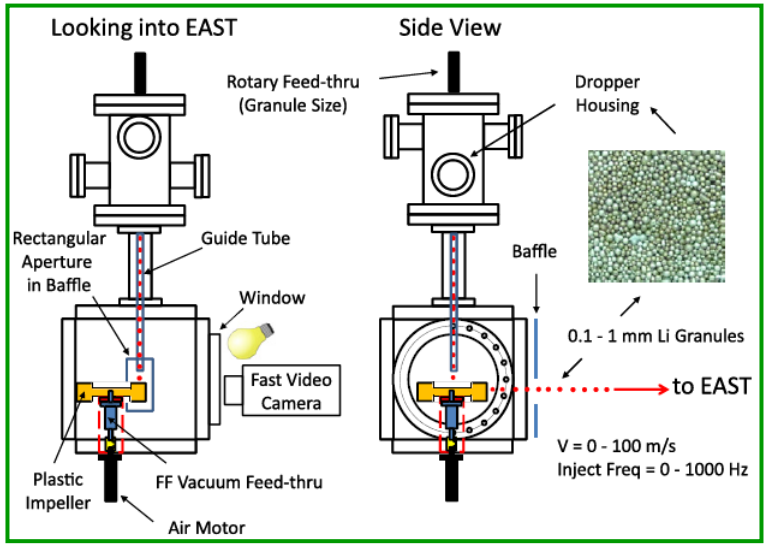
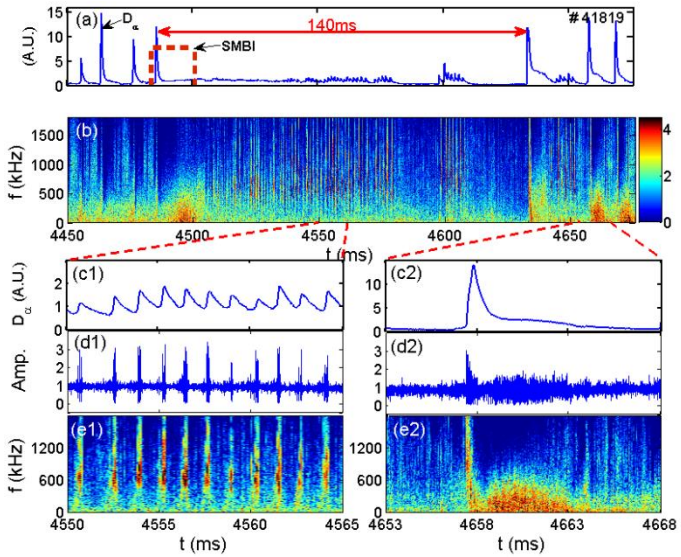




Li-aerosol

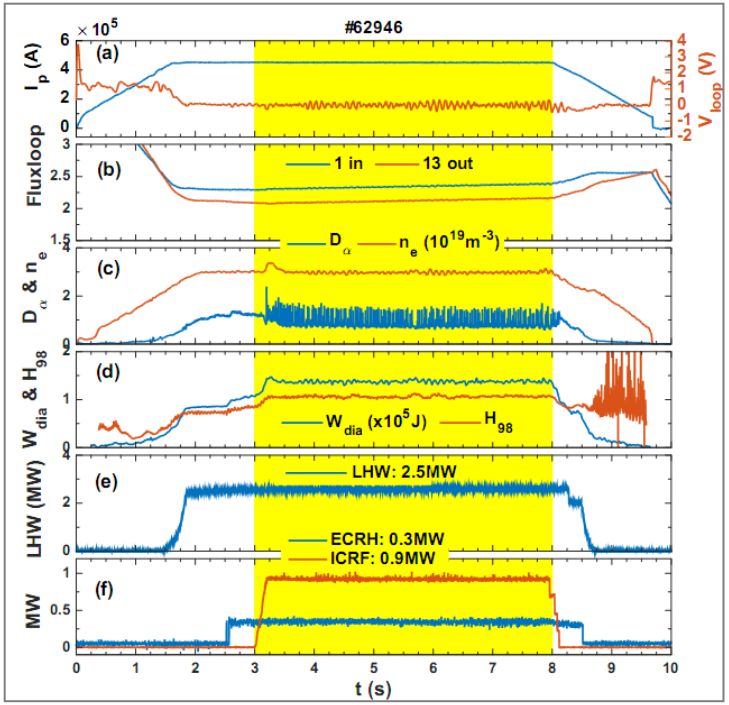
- **RMP coil set-up: 8 (U) + 8 (L)=16 coils; n = 1-3 rotating and n=1-4 non-rotating.**
- **Multi-Functions:**
  - **Error Field correction (EFC)**
  - **Resistive Wall Mode (RWM Control)**
  - **Edge Localized Mode (ELM Control)**
  - **3-D physics studies**

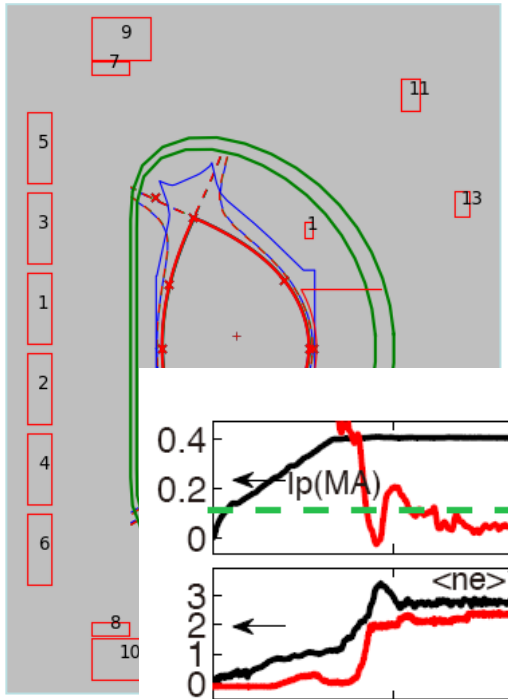


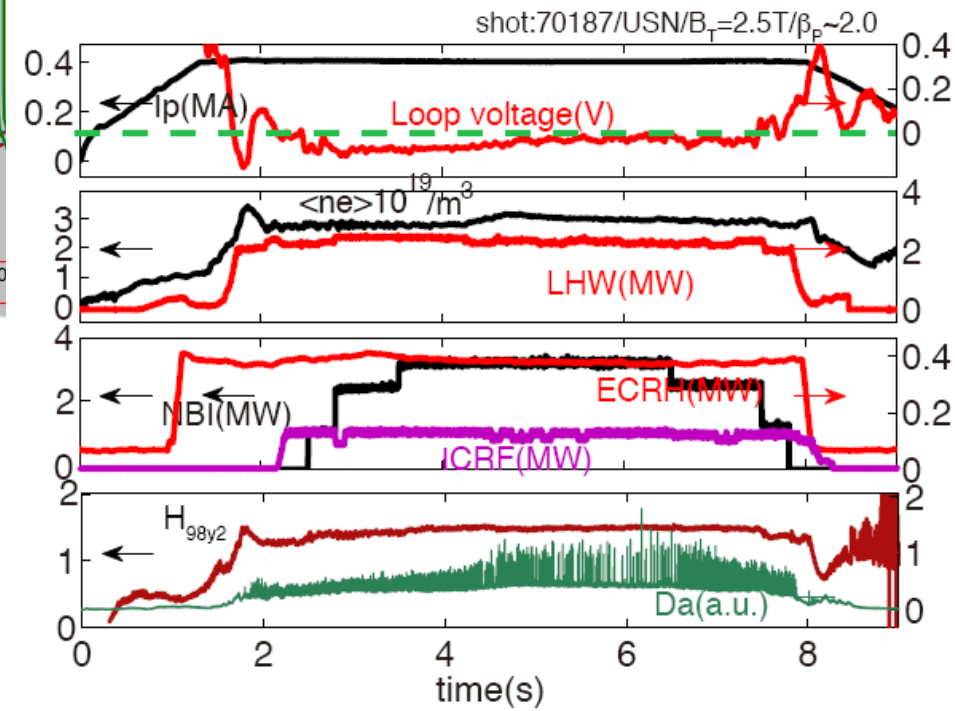
- **SMBI**
- **Pellet**
- **LHCD**

Operation Scenarios of Fully Non-Inductive H-mode has been developed

ASIPP







- ➢ USN with W-Divertor
- ➢ Fully Noninductive H-mode
- ➢ RF only (no torque input)
- √ Good confinement, H98≤1.2
- √ High heat-load resistant
- x Hot spot on RF guide-limiter prevent long-pulse operation

- ➢ RF +BNI for fully non-inductive H-mode
- √ Good confinement, with H98 up to 1.5

Demonstration of >60s H-mode discharges

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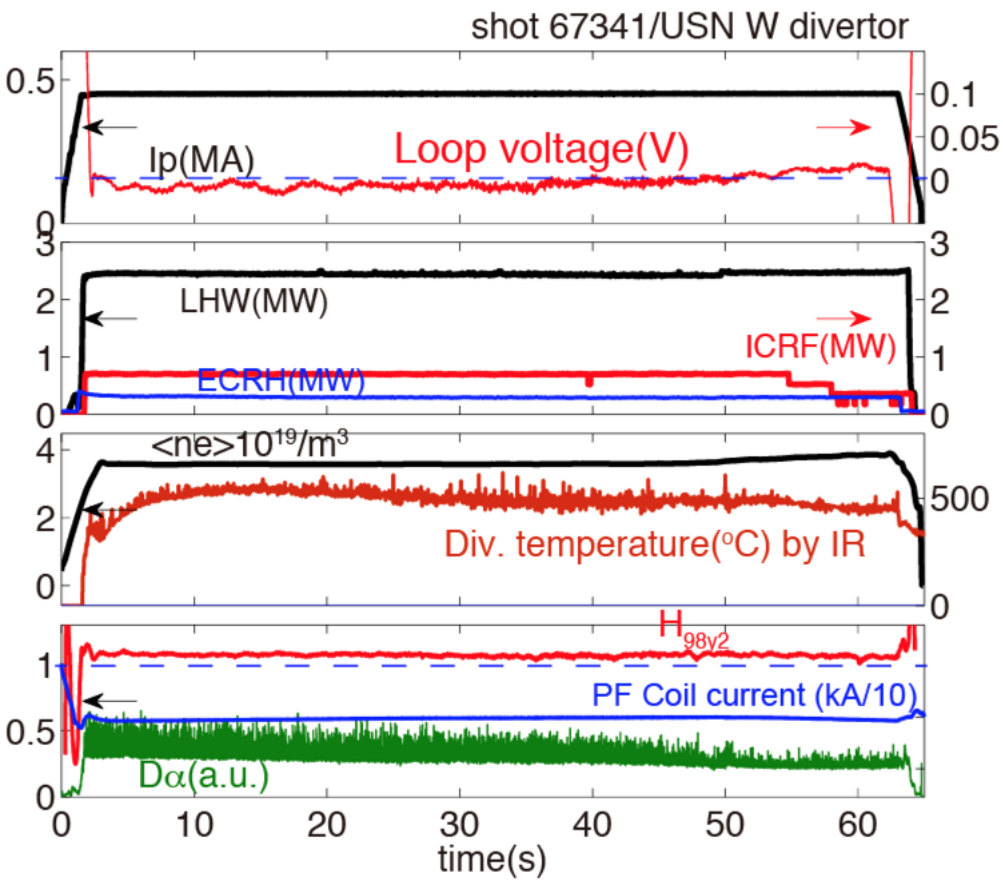
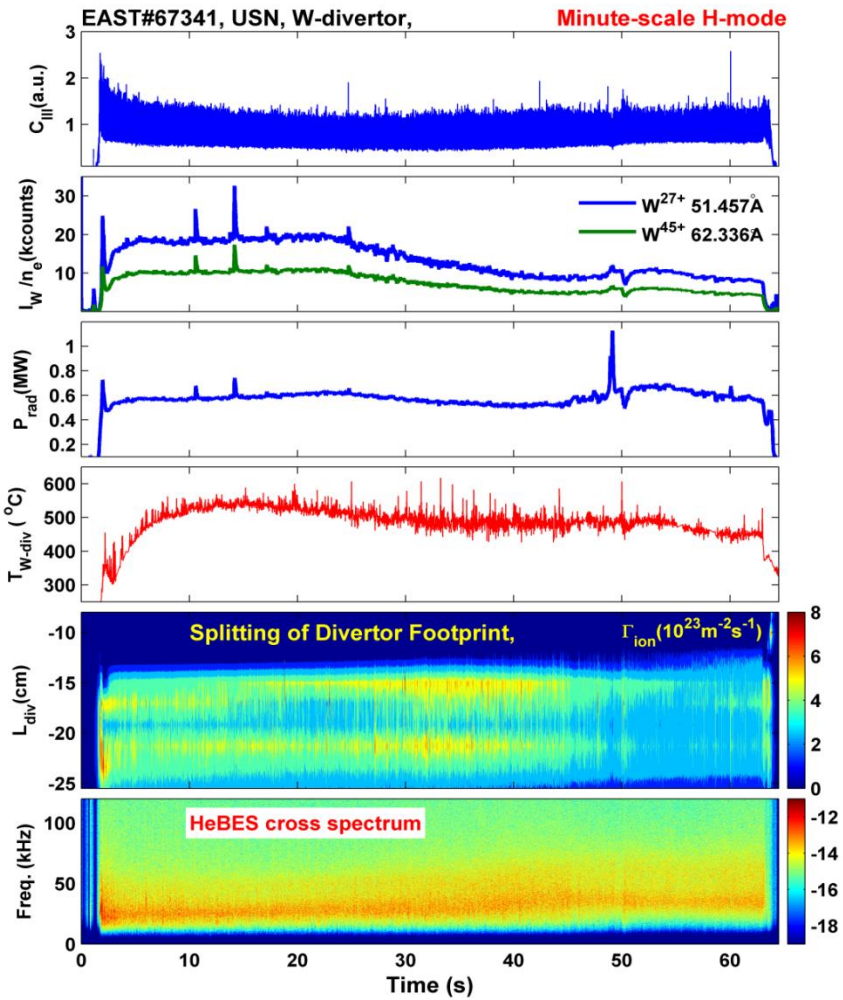
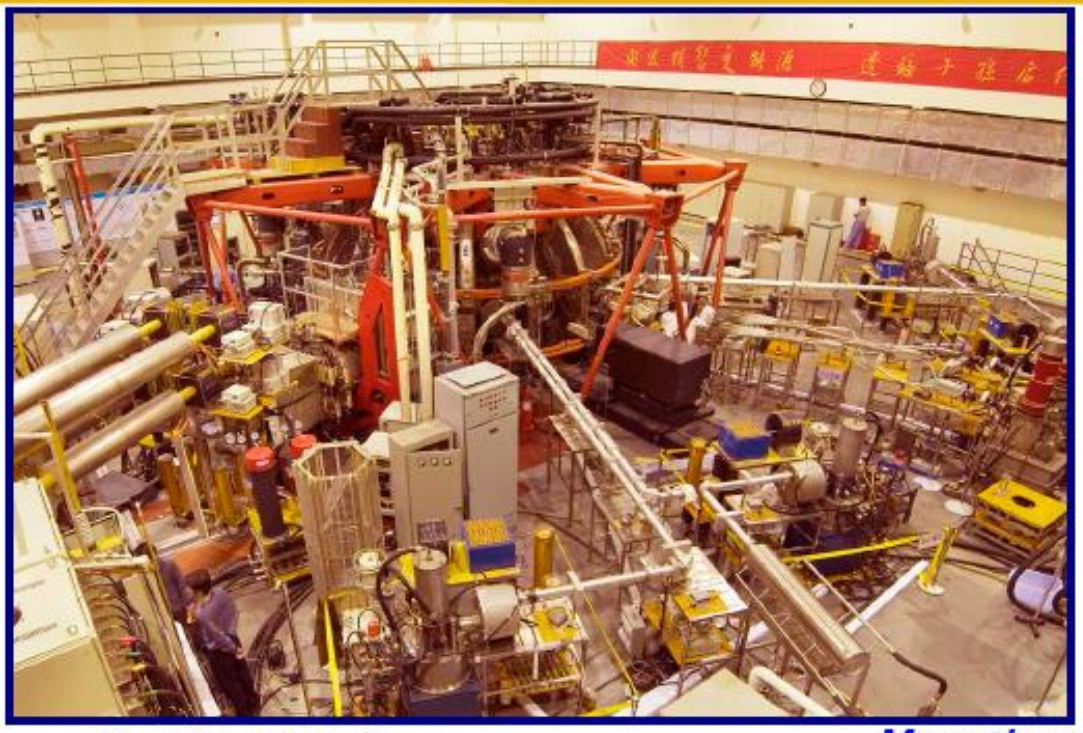




- **RF heating, fully non-inductive**
- **Good confinement $H_{98(y2)}$~1.1;**
- **Good control of impurity level**

Divertor heat flux was mostly controlled below 2.0 MW/m^2

HL-2A tokamak-*present status*



- *R:* 1.65 m
- *a:* 0.40 m
- *Bt:* 1.2~2.7 T
- *Configuration:*
  Limiter, LSN divertor
- *Ip:* 150 ~ 480 kA
- *ne:* 1.0 ~ 6.0 x 10^{19} m^{-3}

Auxiliary heating:

ECRH/ECCD: 5 MW
(6 X 68 GHz/500 kW/1 s,
2 X 140 GHz/1000 kW/1 s)

NBI (tangential): 3 MW

LHCD: 2 MW (4/3.7 GHz/500 kW/2 s)

More than 30 kinds of diagnostic systems with good spatial-temporal resolution

Fueling system (H_2/D_2):

Gas puffing (LFS, HFS, divertor)
Pellet injection (LFS, HFS)
SMBI (LFS, HFS)
LFS: f =1~80 Hz, pulse duration > 0.5 ms
gas pressure < 3 MPa

Highlights on HL-2A in recent years

H-mode Physics

ELM mitigation by SMBI:
Two types of LCOs during L-I-H
Role of MHD mode in triggering I-H transition
Quasi-coherent modes before and between ELMs

Zonal flow & turbulence

Nonlinear energy transfer from turbulence to ZFs
3D GAM/LFZF
Blobs & filaments

Transport & confinement

Spontaneous particle transport barrier
Core turbulent transport
Non-local transport triggered by SMBI
Fueling by cluster jet injection

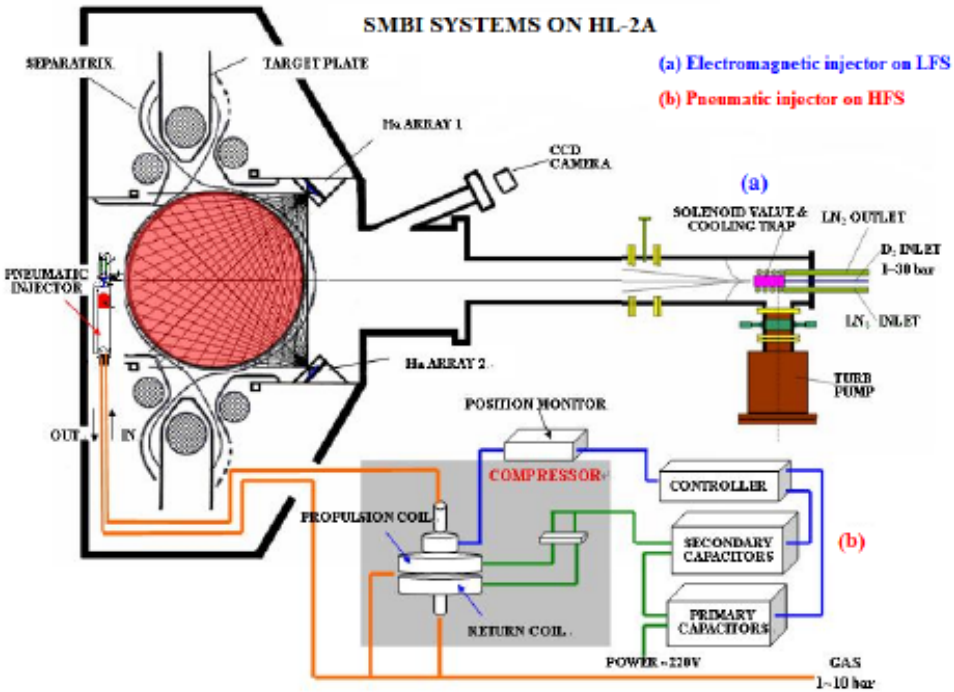
MHD activities

BAE excited by energetic electrons
Interaction between AEs and magnetic island
EGAM during magnetic island
Frequency jump of e-fishbone mode
Interaction between NTMs and non-local transport

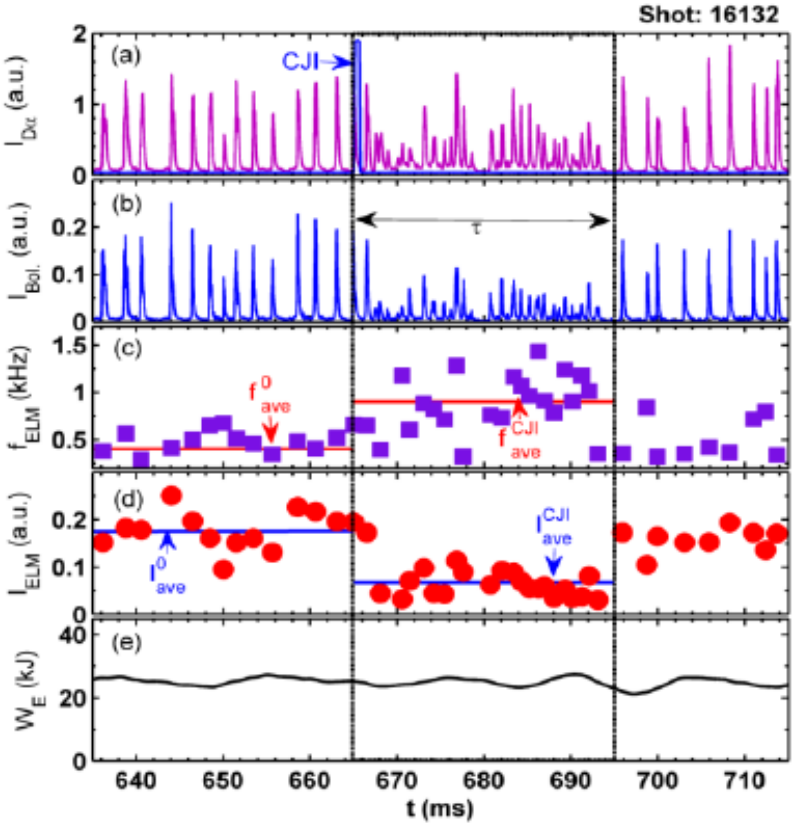
SMBI/CJI Fuelling Technique

Supersonic Molecular Beam Injection (SMBI) & Clusters Jet Injection (CJI)

Proposed by Prof. L H Yao at SWIP and applied on HL-1 in 1992
applied on HL-1M, W7-AS, Tore-Supra, KSTAR, EAST etc.



ELM Mitigation by SMBI / CJI



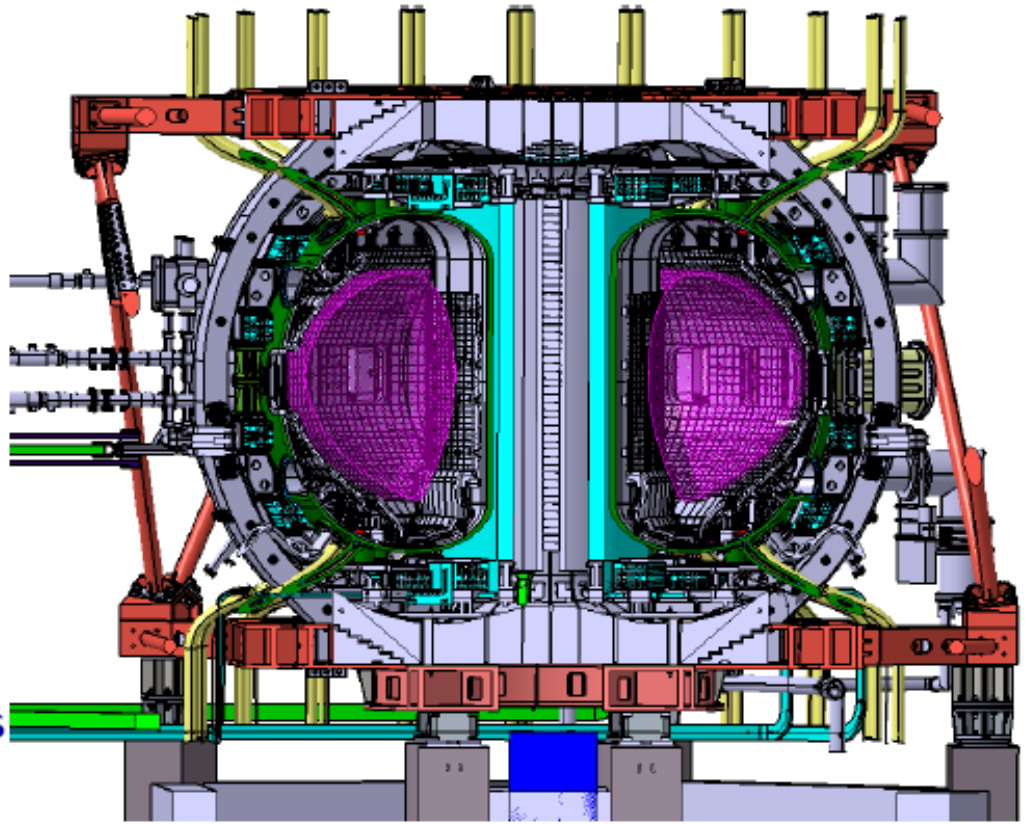
High fuelling efficiency are due to the directional particle motion and the post-SMBI inward convection.

HL-2M tokamak under construction

Mission: high performance, high beta, and high bootstrap current plasma; advanced divertor configuration (snowflake, tripod), PWI at high heat flux.

Main parameters

Plasma current	I_p = 2.5 (3) MA
Major radius	R = 1.78 m
Minor radius	a = 0.65 m
Aspect ratio	R/a = 2.8
Elongation	K = 1.8-2
Triangularity	$\delta > 0.5$
Toroidal field	B_T = 2.2 (3) T
Flux swing	$\Delta\Phi$= 14Vs
Heating power	25 MW



HL-2M tokamak

Auxiliary Heating Systems & Diagnostics

Total power ~ **25 MW**

developed 2MW LHCD + 2 MW ECRH

under developing 5MW NBI + 2MW ECRH + 2MW LHCD

A new reversed field pinch KTX device in China

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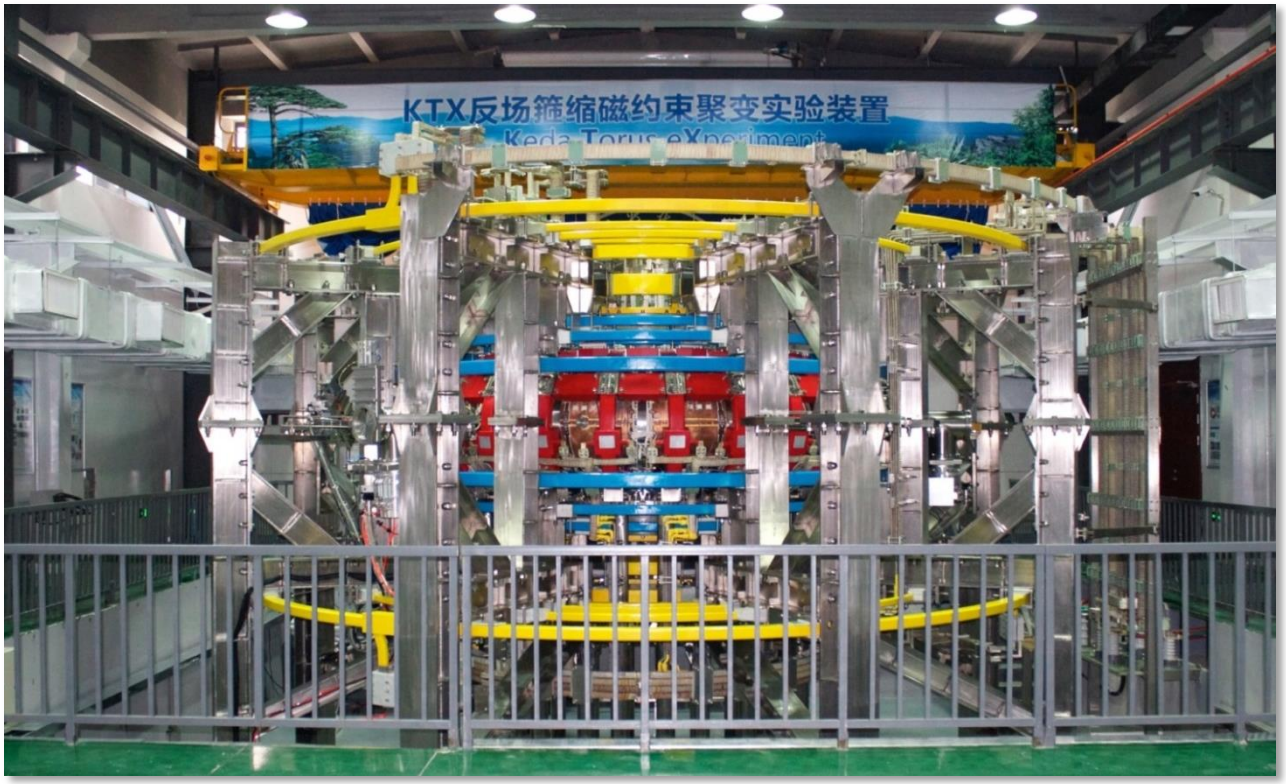

Major radius	1.4 m
Minor radius	0.4 m
Current	0.5-1.0 MA
Pulse length	30-100 ms
Loop voltage	20-100 V
Magnetic flux	3-5 V·S
Temperature	600-800 eV
Plasma density	~ 10^{19} m^{-3}
Toroidal field	0.7 T

- ☆Supported by National Magnetic Confinement Fusion Science Program (2011-2015)
- ☆Construction completed in Aug. 1, 2015; First plasma achieved in Aug. 15, 2015
- ☆In conditioning: Max 200kA, Max pulse length 22ms, typical RFP discharge

ITER related activities

ITER PA of China

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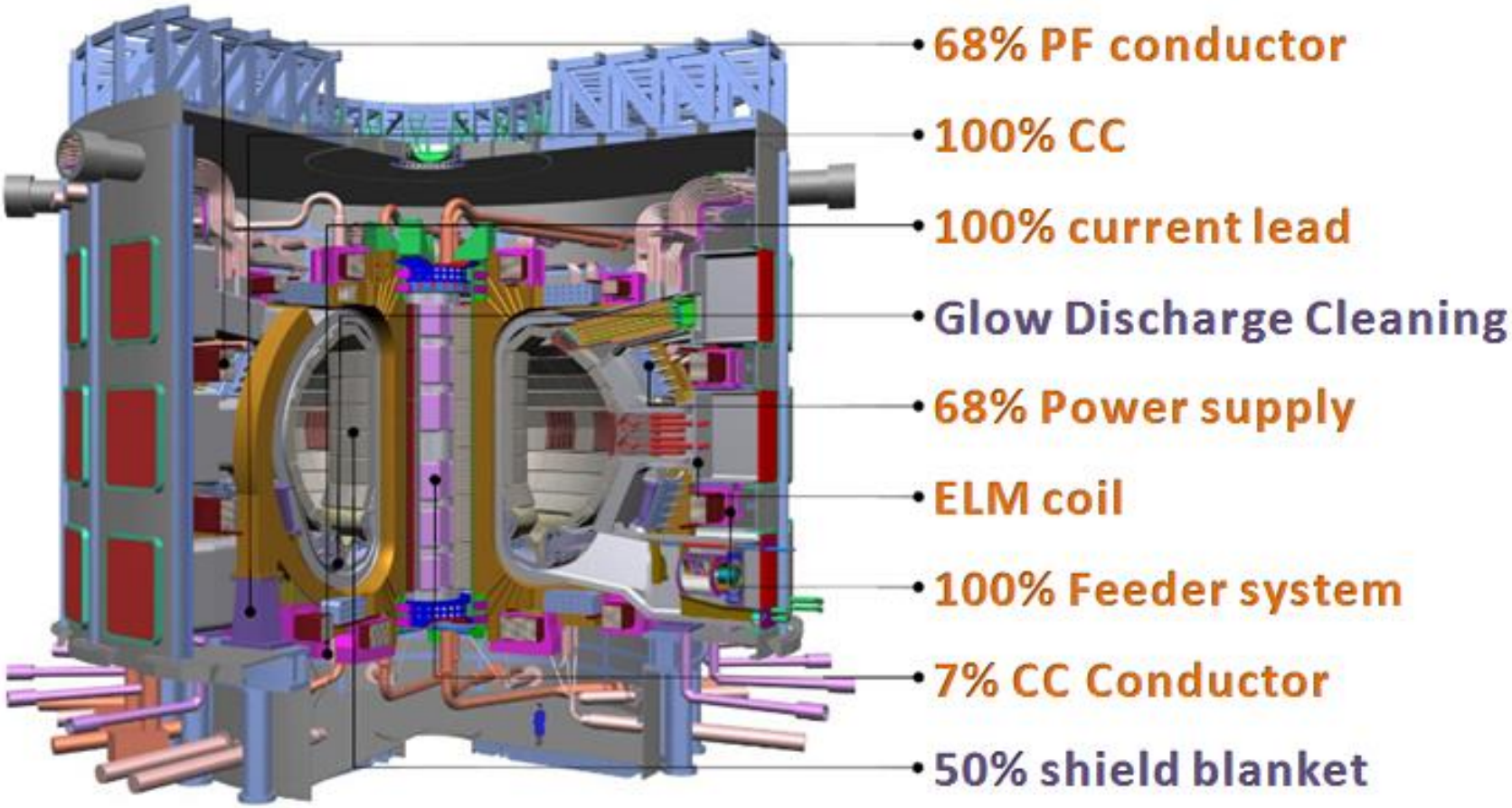

ITER packages in ASIPP

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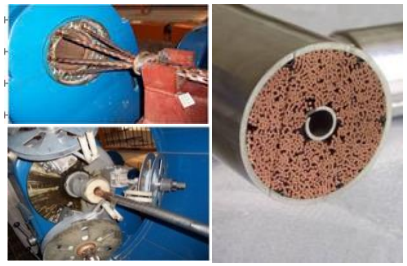
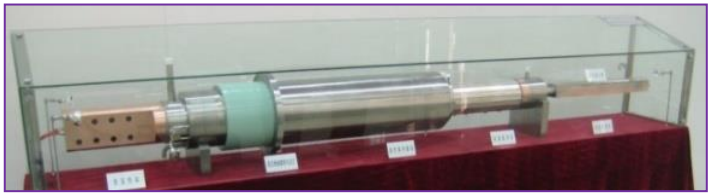
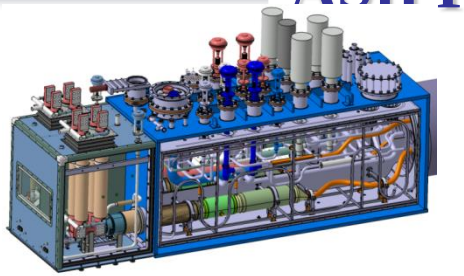


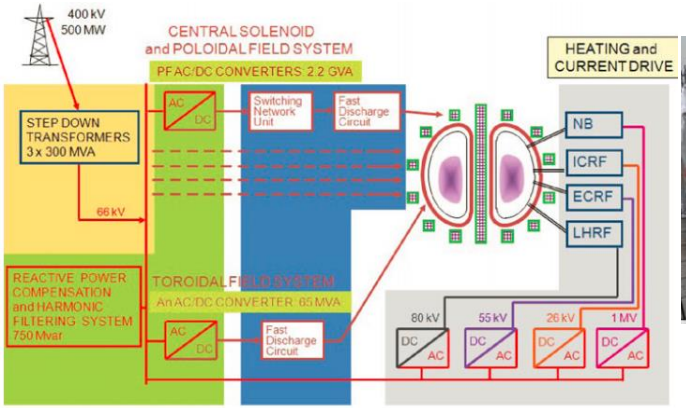
Superconducting Conductors



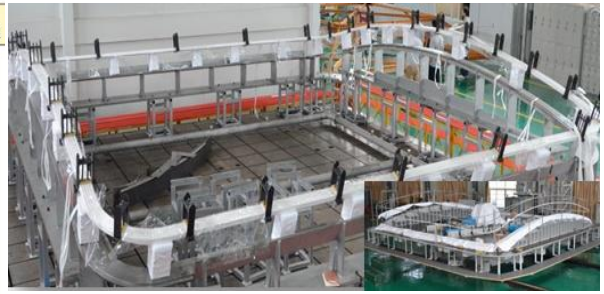
ITER Feeder 68 kA HTS current lead



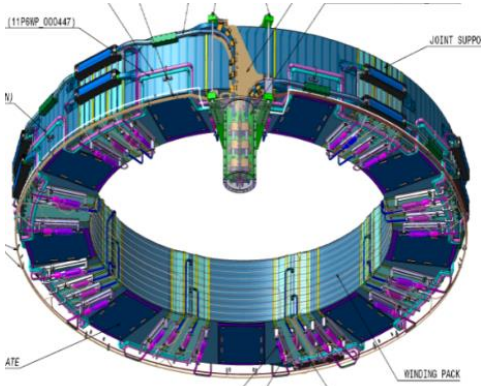
ITER feeder system



ITER Power supply



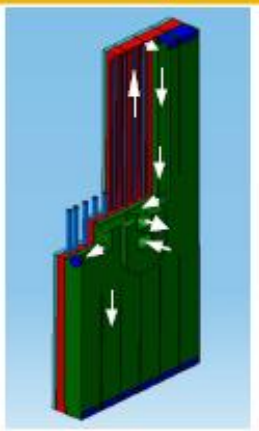
Correction Coils

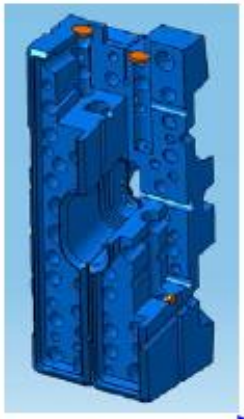


PF6 coil(EU)

All in mass-production phase and on schedule.
Part of components and equipment on ITER site

ITER Procurement -R & D at SWIP

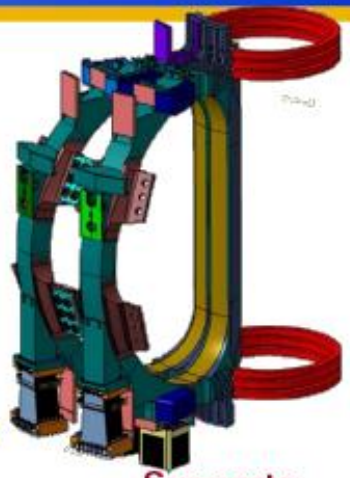




FW & SB

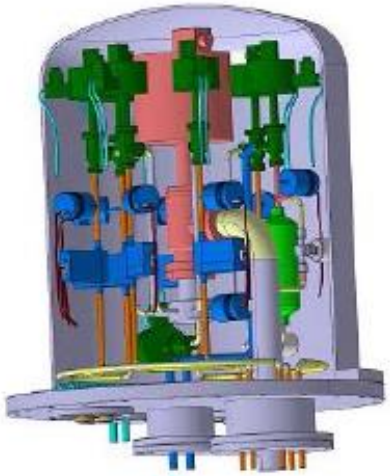
Developed HIPing joining technology

FW mock-up for qualification



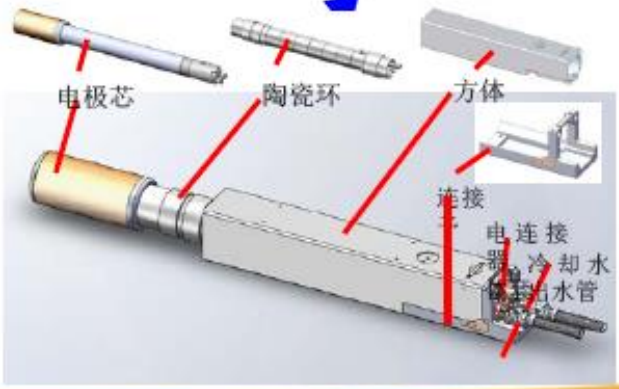
Supports

R&D for ITER related technologies

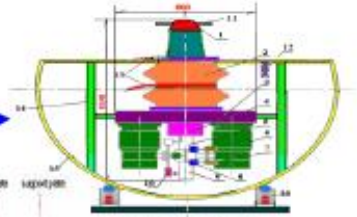


GIS

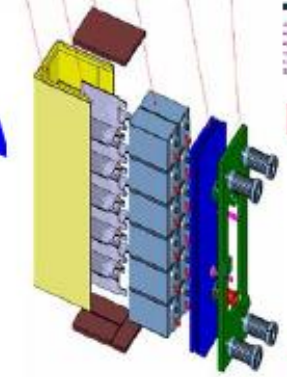
Upper port valve box



GDC



Diagnostic

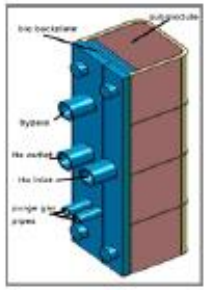


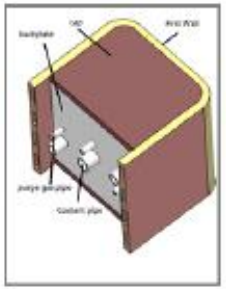
TBM

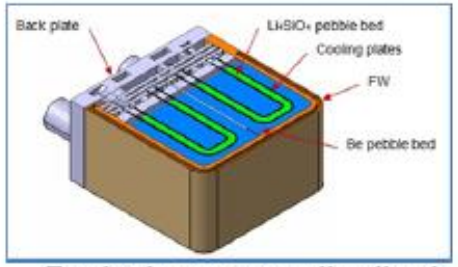
CN-ITER-TBM

Conceptual design of HCCB

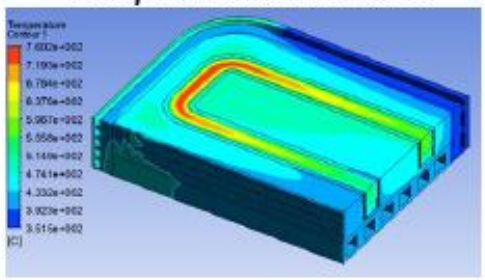
Neutron wall loading	0.78MW/m^2
Surface heat flux	0.3MW/m^2
Total heat deposition	0.75MW
Tritium breeder	Li4SiO4 pebble 80% 6Li enrichment 62% packing factor
Neutron multiplier	Be pebble 80% packing factor
Structural material:	RAFM steel
Coolant Temp. (inlet) /(outlet)	He gas, 8.0MPa, 300°C/500°C
Tritium purge gas	He gas ~0.1MPa
Total weight: Structural material Functional material	~1.32 tons ~0.20 ton



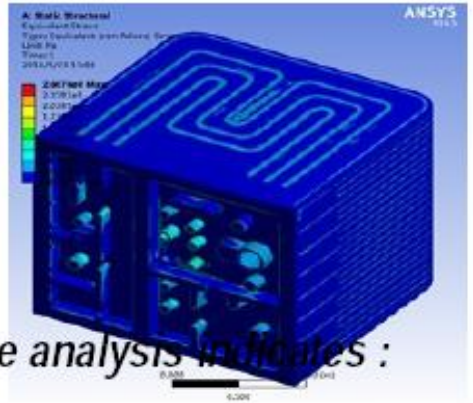




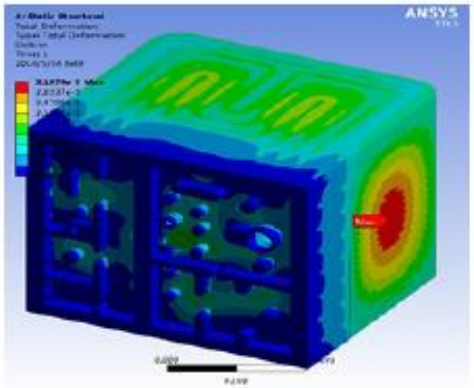
Temperature distribution



Equivalent stress distribution



Deformation distribution



Performance analysis indicates :

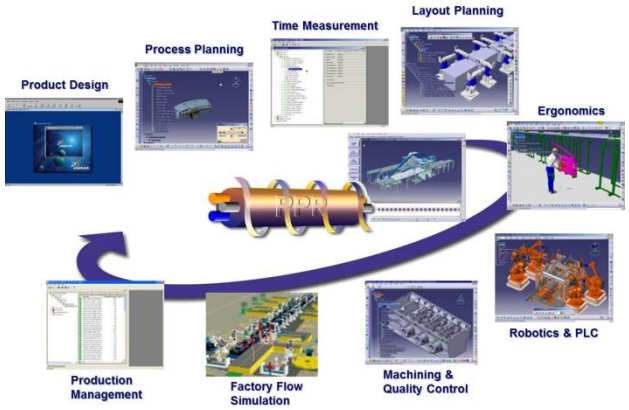
CN-HCCB-TBM satisfies the design requirements of ITER and passed the conceptual design review.

CFETR Activities

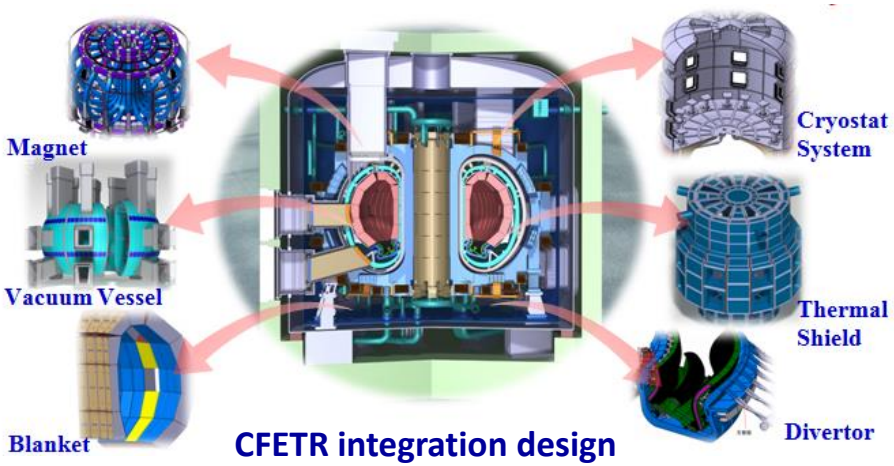
Conceptual design and R&D of CFETR

ASIPP

Chinese Fusion Engineering Testing Reactor address two fusion reactor issues: Tritium self-sufficiency and steady-state operation.



Synergistic design platform



CFETR integration design

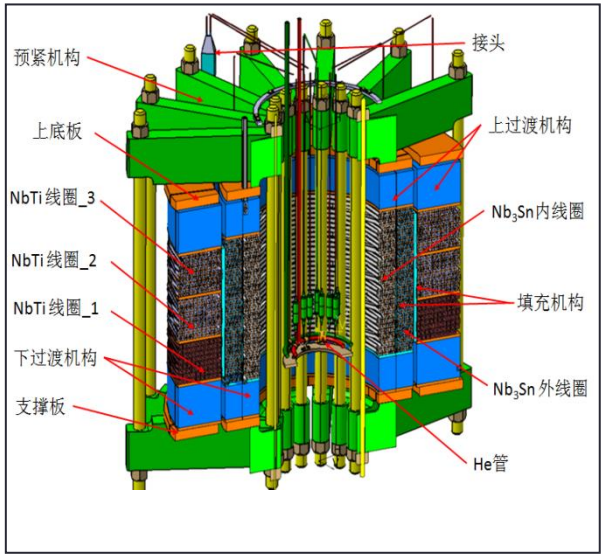
Magnet winding platform

Vacuum vessel R&D

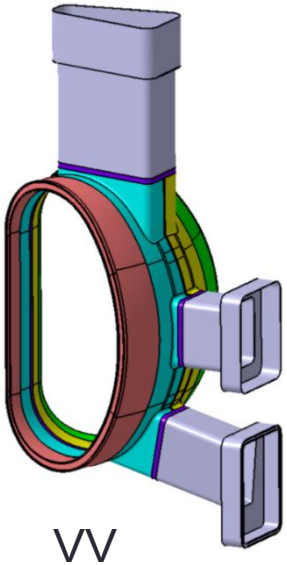
RH system design

R&D is progressed

ASIPP



CS Model Coil –Nb_3Sn

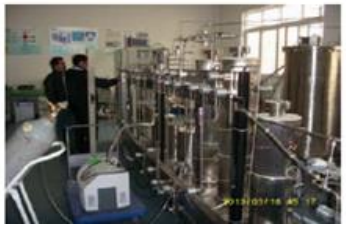


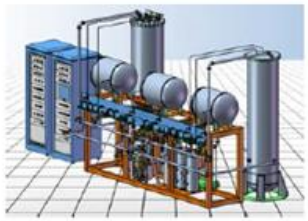
VV

4.6 GHz, 0.3MW

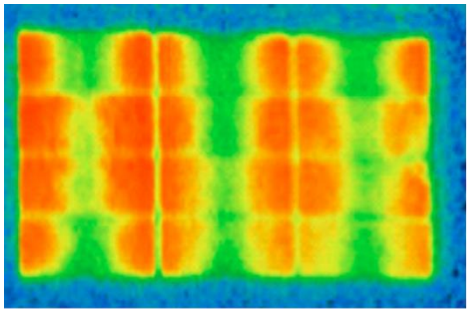
140GHz, 1MW, CW

ITER TBM tritium systems
- ✓Tritium Extraction System （TES）
- ✓Coolant purification system（CPS）
- ✓Tritium measurement system（TMS）



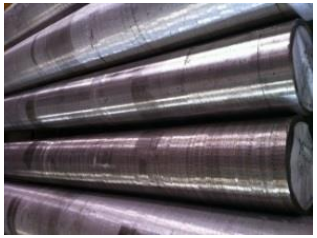


Monoblock W/Cu
5000 cycles at 10MW/m^2
300 cycles at 20MW/m^2.

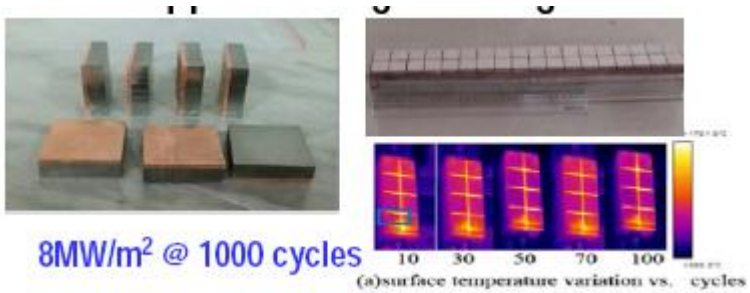


Materials

ASIPP



CLAM for TBM



·W/CuCrZr flat type, CFC/CuCrZr modules

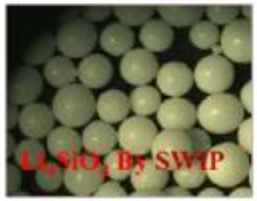
Functional materials

Li_4SiO_4 pebbles for tritium breeder

Be pebbles for neutron multiplier

Beryllium electrode

Li4SiO4 pebbles via melt-spray



University groups also deeply involved in material research

CFETR 5 years Plan

ASIPP

- Refine self-consistent, reliable physical design
- Detailed engineering design (main machine and auxiliary systems)
- R & D for some key technologies and systems

  (I): Blanket related to nuclear, thermal hydraulic processes

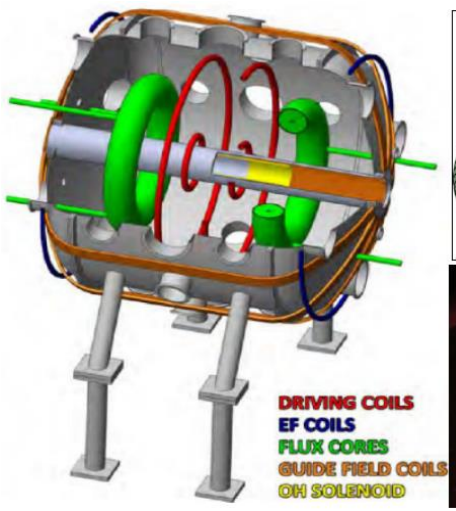
  (II): magnets、T- factories、NBI, ICRF, ECRH、RH

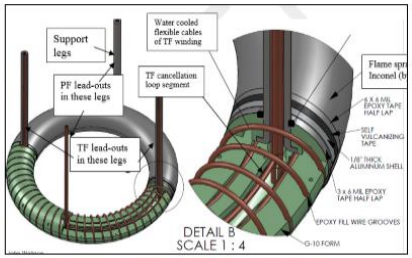
  (III): Experimental verification, diagnosis, control, divertor, cryogenic, radiation protection and so on.

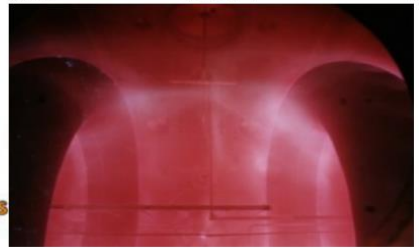
International collaboration

Engineering contribution to world fusion community

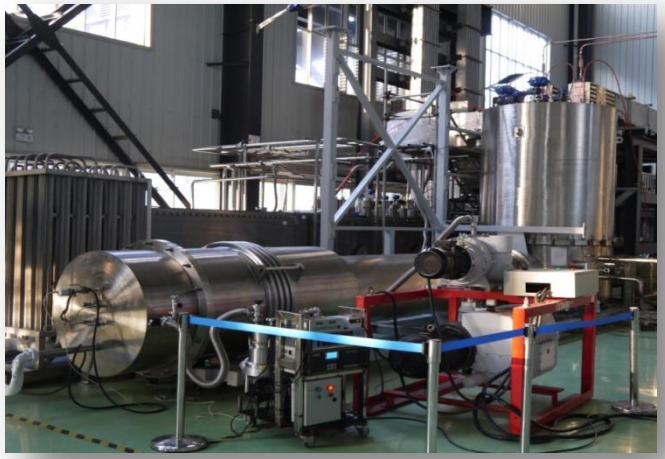
ASIPP



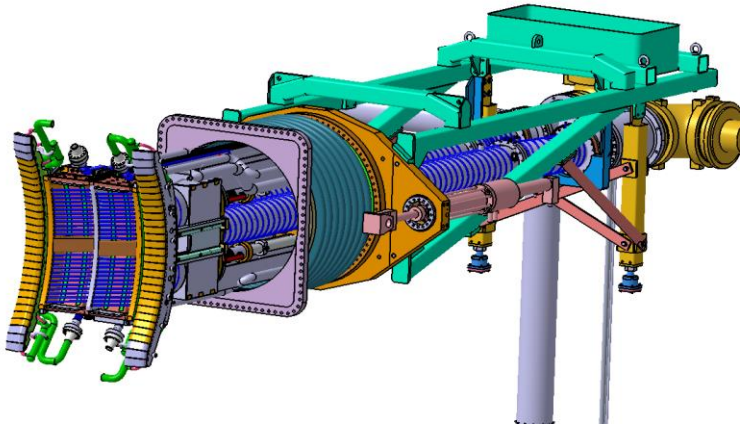




PPPL FLARE PROJECT



GA CSM FEEDER



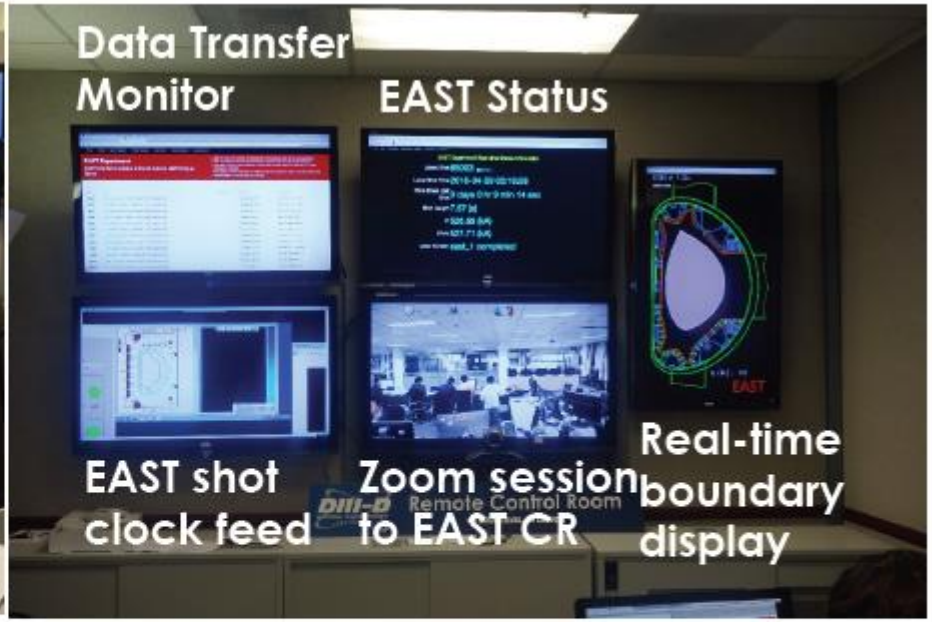
WEST&ASDEX-U ICRF antenna systems

DIII-D 3D Coils Power Supply

Remote third shift operation on EAST

ASIPP

First US-led 3rd Shift Experiment without U.S. Staff at ASIPP



- **Experiment on Thursday, April 28, 2016, was very successful**
  - Six-hour session, 26 tokamak pulses, highest-priority experiments completed
  - Good GA-ASIPP staff communications and EAST data transfer to US
  - No significant impact to GA staff or added cost from EAST schedule changes
  - Experiment focused on empirical scalings of error field thresholds for ITER

DIII-D NATIONAL FUSION FACILITY

Also Collaborative center with WEST

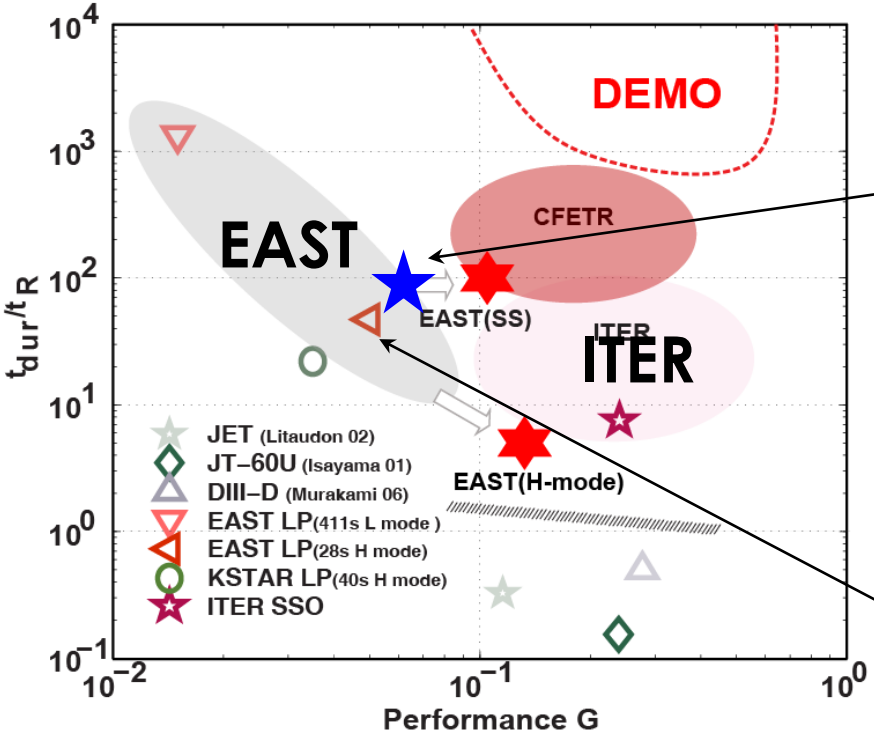
Broad participation from US, EU and A3 program on EAST

Near Future Research Plan

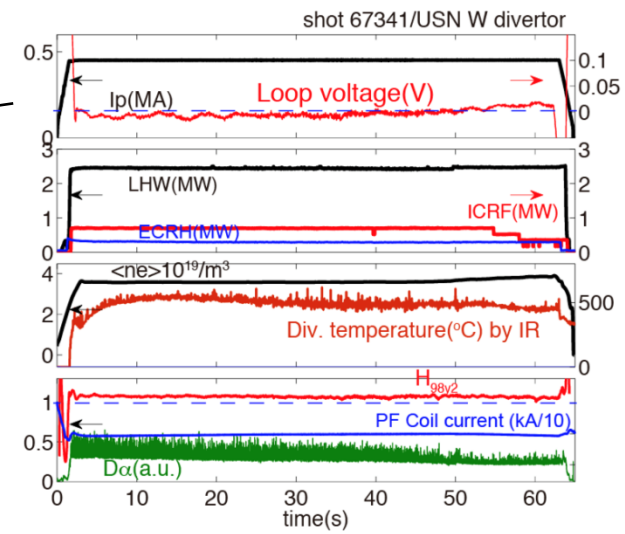
EAST steady-state scenarios supporting ITER and CFETR

ASIPP

Long pulse



2016: Long-pulse H-mode up to 62 s with H_{98}~1.2



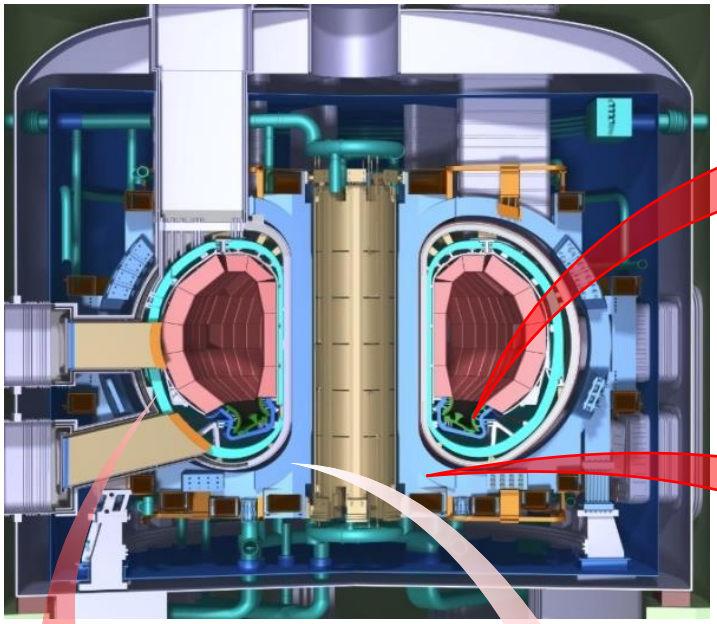
2012: Long-pulse H-mode up to 28 s

- Long pulse H-mode plasmas(≥100s) with integrated control of heat/particle flux and ELM mitigation
- Scenarios of steady-state high performance plasmas (H_{98}>1.2)
- Long pulse for > T_{wall} to address critical issues of recycling and heat exhaust
- Lower divertor solution

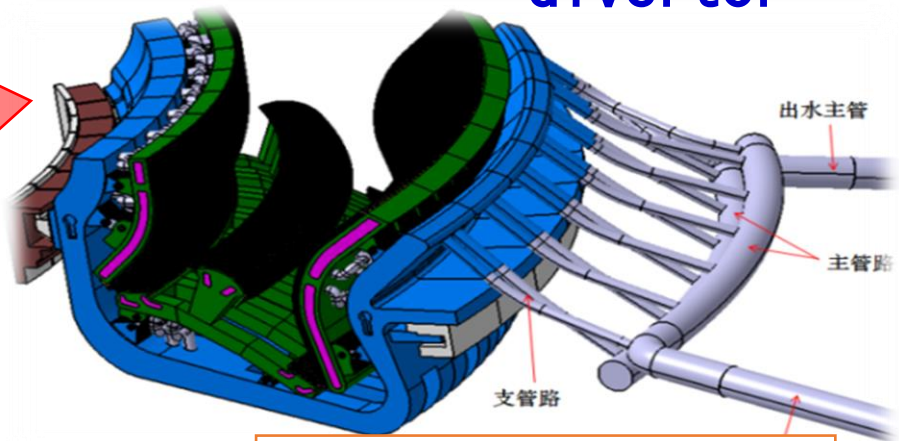
What are need to support fusion reactor construction

ASIPP

Reactor core is an highly integrated complex system

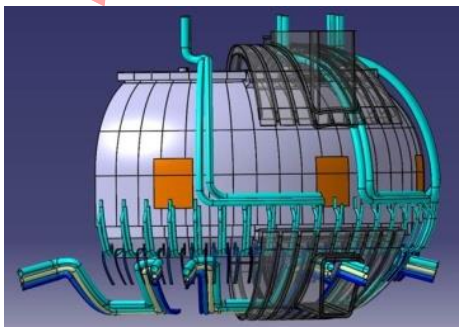


divertor

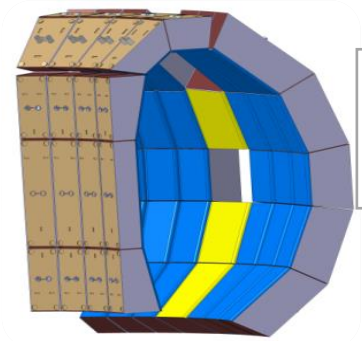


Heat: tens MW/m^2,
particle: 10^24/s.m^2

vacuum vessel

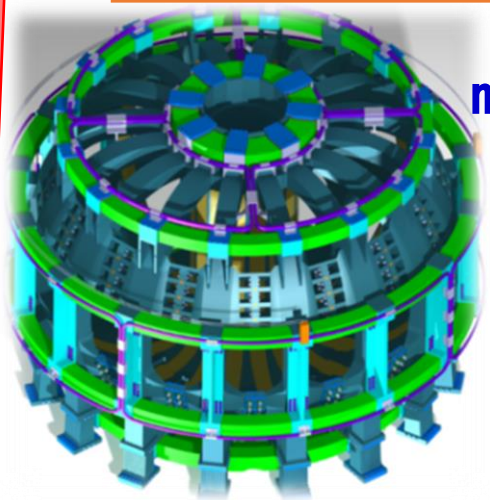


blanket



TBM on ITER

magnet



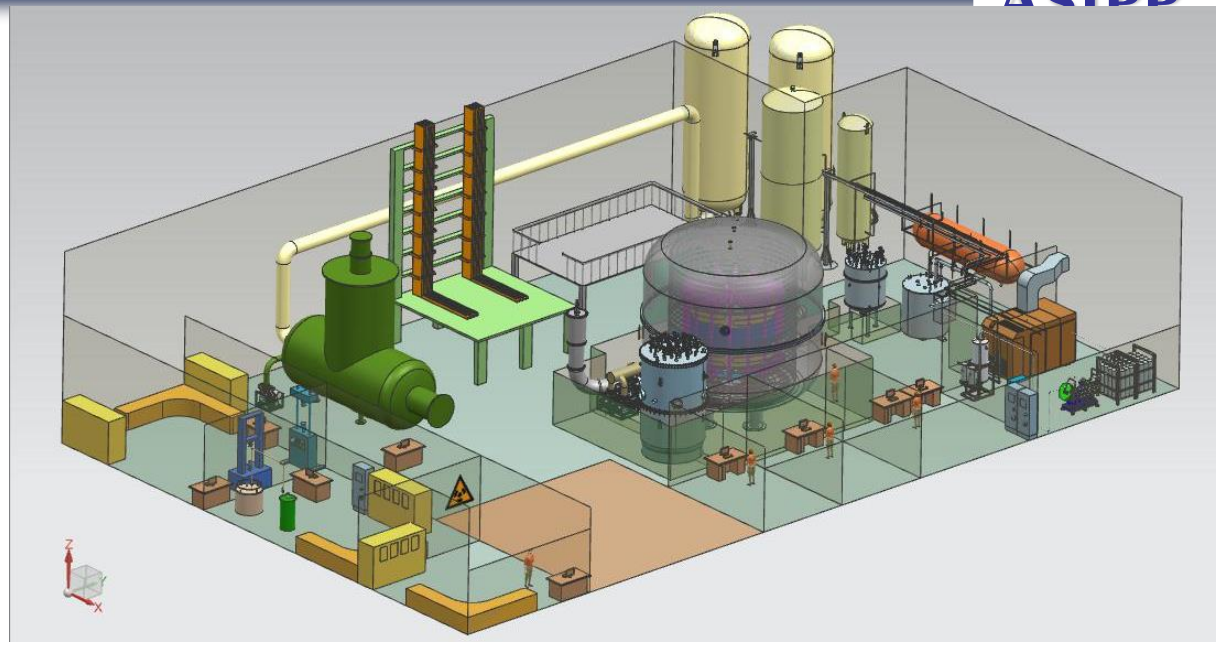
Energy:
Tens GJ,
GW in PF

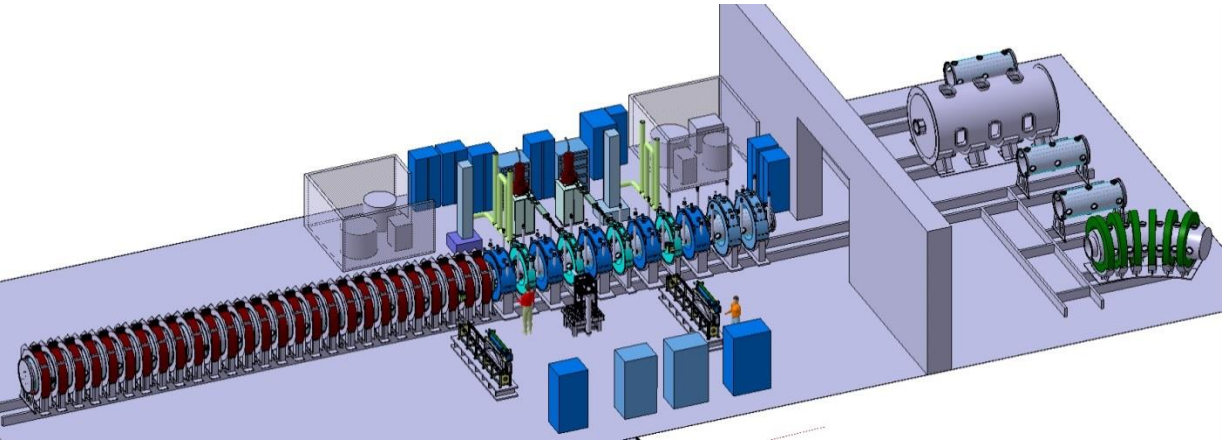
We proposed… and agreed by…

ASIPP

Superconductor and magnet testing facility

- R&D for CFETR
- For other large scale application
- New technology





High heat and particle flux testing facility

- Divertor material
- Module testing
- Basic plasma

Future Activities

ASIPP

1. Efforts on EAST/HL-2M to deliver key physics for ITER and CFETR steady-state operation and beyond

- Plasma control
- Development of steady-state operation scenarios
- Heat and particle exhaust: PWI issues with tungsten divertor (ITER-like)
- Heating and current drive, and diagnostics
- Theory and simulation, model validation via experiment

2. Fusion nuclear science and engineering for CFETR

- Conceptual design and optimization (System study and optimization)
- Engineering design and key R&D
- Nuclear science and technology (tritium breeding blanket)
- Materials

3. Education and young scientist training

- BPF for universities
- International collaboration

Thank You