

# Recent Progress of HL-3 Experiment

**Xuru Duan, Min Xu, Wulyu Zhong**  
**on half of HL-3 Team and collaborators**

***Southwestern Institute of Physics (SWIP), Chengdu, China***

*29th IAEA Fusion Energy Conference (FEC 2023), 16-21 October 2023, London, United Kingdom*

- **Fusion research activities at SWIP**
- **HL-3 experiment progress**
  - ✓ **1 MA plasma**
  - ✓ **H-mode operation**
  - ✓ **Advanced divertor discharge**
- **Summary and outlook**

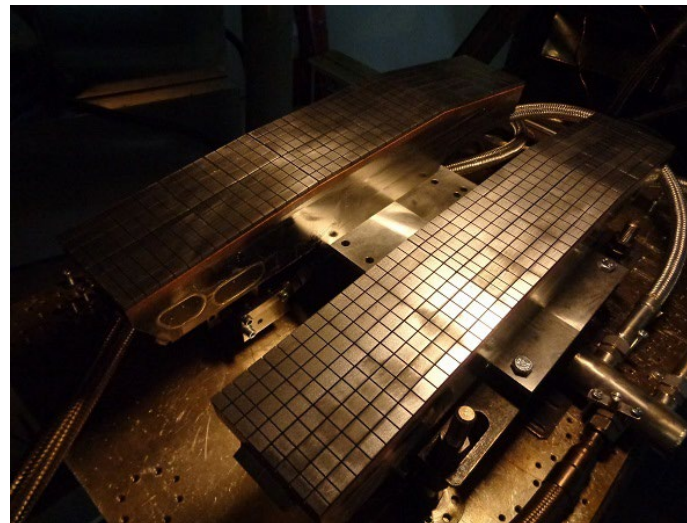
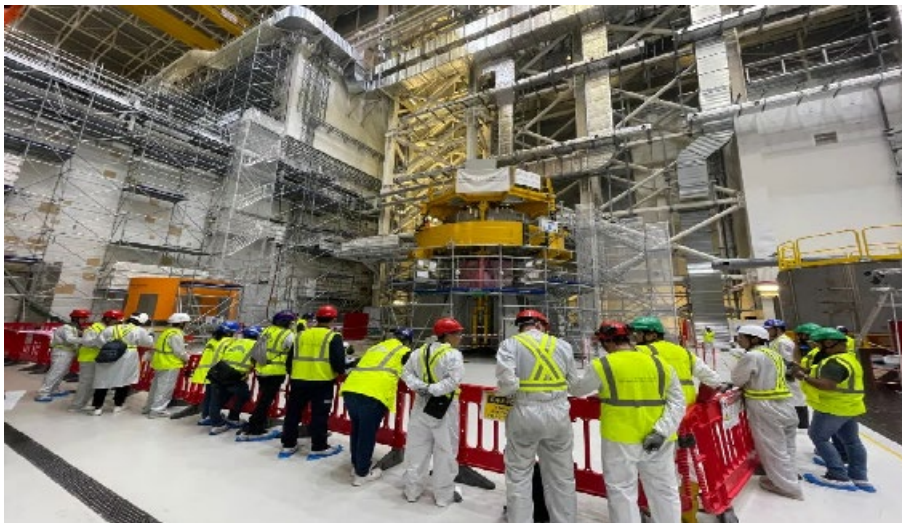
- **Tokamak program** (HL-3 & HL-2A)
  - ✓ *Engineering*
  - ✓ *Experiments*
  - ✓ *Theory & Modeling*
- **R&D of ITER Procurement Packages**  
*TBM, first wall & shielding blanket, GIS & GDC, magnet supports, neutron flux monitoring, langmiur probe*
- **Fusion reactor relevant activities**  
*Design, Materials , RF driven negative ion source...*

- Full Scale Prototype qualification (FSP) assembly completed.
- 2 Hot Helium Leak Test (HHLT) facilities delivered.
- Released **1<sup>st</sup> nuclear fusion ISO (HHLT) standard in the world, Hot Helium.**
- TAC1: installation of ITER cryostat and all systems between cryostat & vacuum vessel.
  - ✓ **Phase 0 complete: Installation of Cryostat Base**
  - ✓ **Phase 1 ongoing: Installation of PF5, PF6 and CS3L complete**

INTERNATIONAL  
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ISO  
4233

First edition  
2023-03



**Reactor technology — Nuclear fusion reactors — Hot helium leak testing method for high temperature pressure-bearing components in nuclear fusion reactors**

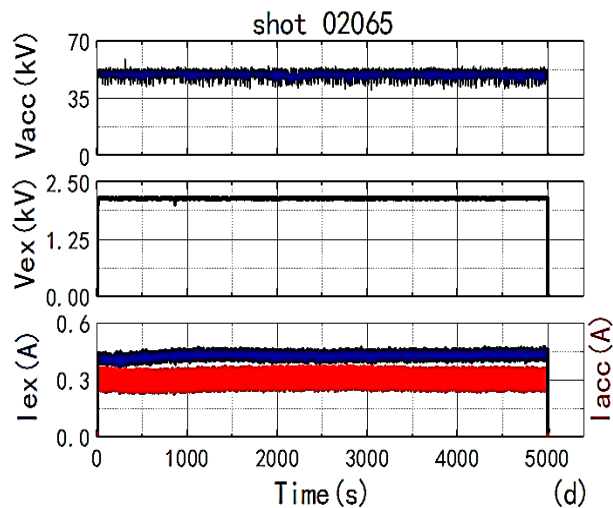
*Technologie du réacteur — Réacteurs à fusion nucléaire — Méthode de contrôle d'étanchéité par détection de fuite d'hélium à chaud pour les composants sous pression à haute température de réacteurs à fusion nucléaire*

# RF driven Negative Ion Source

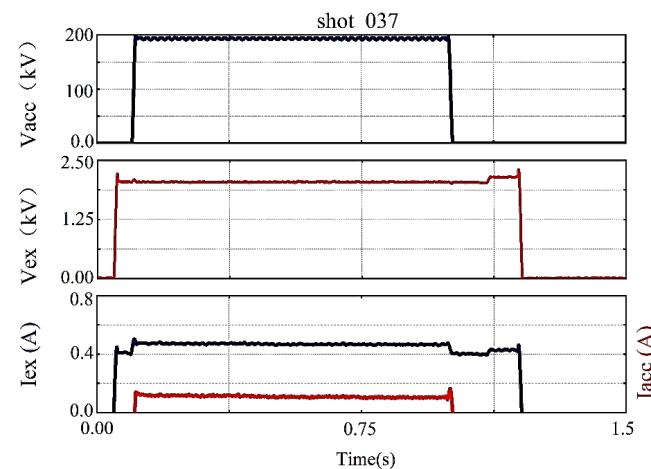
## RF driven negative ion source NBI heating system very important for ITER

- RF driven negative ion source developed : 2MHz frequency & 266 extraction apertures.
- Achieved Beam power  $13.0 \text{ A} \times 100 \text{ keV}$  .

5000s beam conditioning



200keV H- ions beam Waveform



One Driver( Developed)



Two Drivers( Assembling)

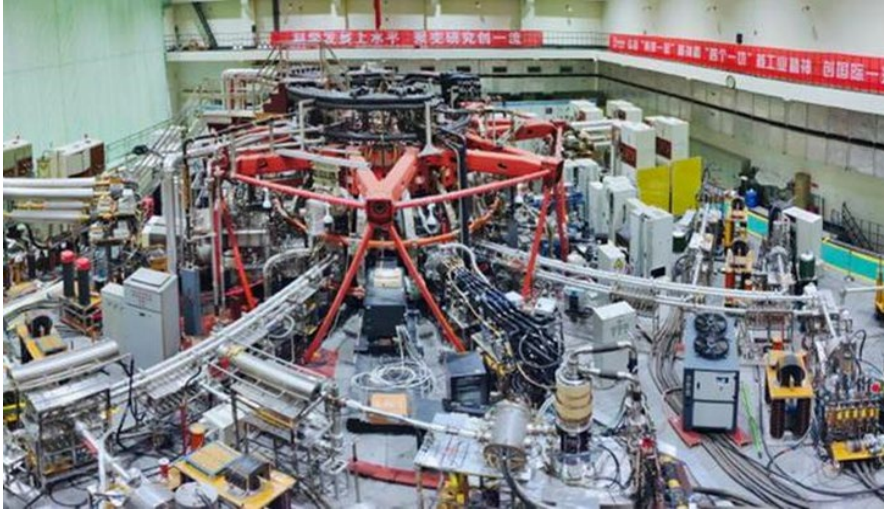


200keV beam teststand for one driver ion source



Beam Footprint

# Present Status of the HL-2A Tokamak



## Contributions of HL-2A team in FEC 2023

| Presenter  | Session, Time       |
|------------|---------------------|
| W.L. Zhong | EX/5-6 19/10, 15:25 |
| G.L. Xiao  | 2214 20/10, 10:00   |
| J. Zhang   | 2052, 20/10, 10:00  |
| N. Zhang   | 2246, 17/10, 10:00  |
| Y.R. Zhu   | 2191, 17/10, 10:00  |
| Y. Zhang   | 2056, 17/10, 10:00  |
| W. Chen    | 2080, 20/10, 10:00  |
| P.W. Shi   | 2050, 20/10, 10:00  |

### High beta plasmas & underlying physics

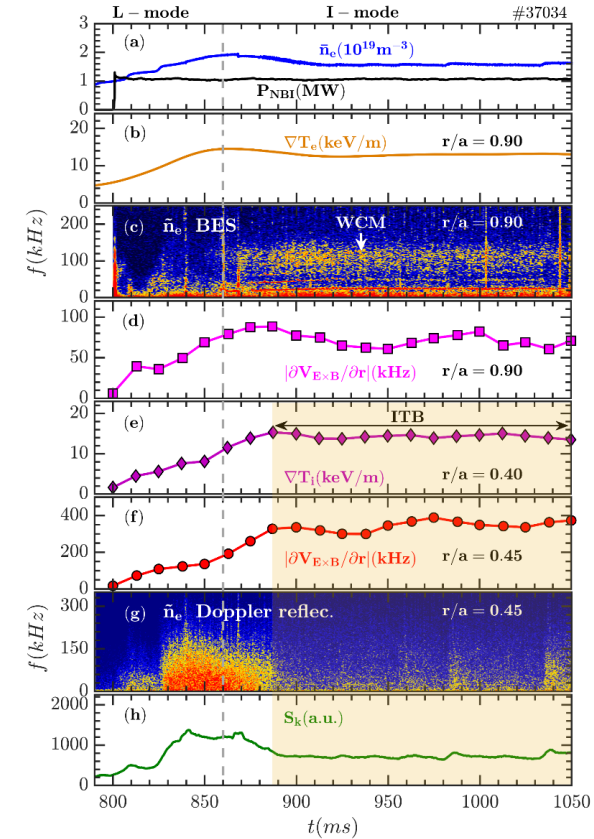
- ✓ Advanced scenarios
- ✓ Pedestal dynamics
- ✓ Type-I ELM control with SMBI, RMP, impurity seeding, LHW, PI...
- ✓ ITB physics
- ✓ NTM, EP, disruption mitigation

### Divertor physics

- ✓ Closed divertor, PWI
- ✓ Detached H-mode & heat flux control

### Physics with high power RF heating

- ✓ MHD modes (AEs, EPM) induced by energetic electrons during ECRH
- ✓ Heat, particle & momentum transport



Oral talk (EX/5-6) by W. L. Zhong

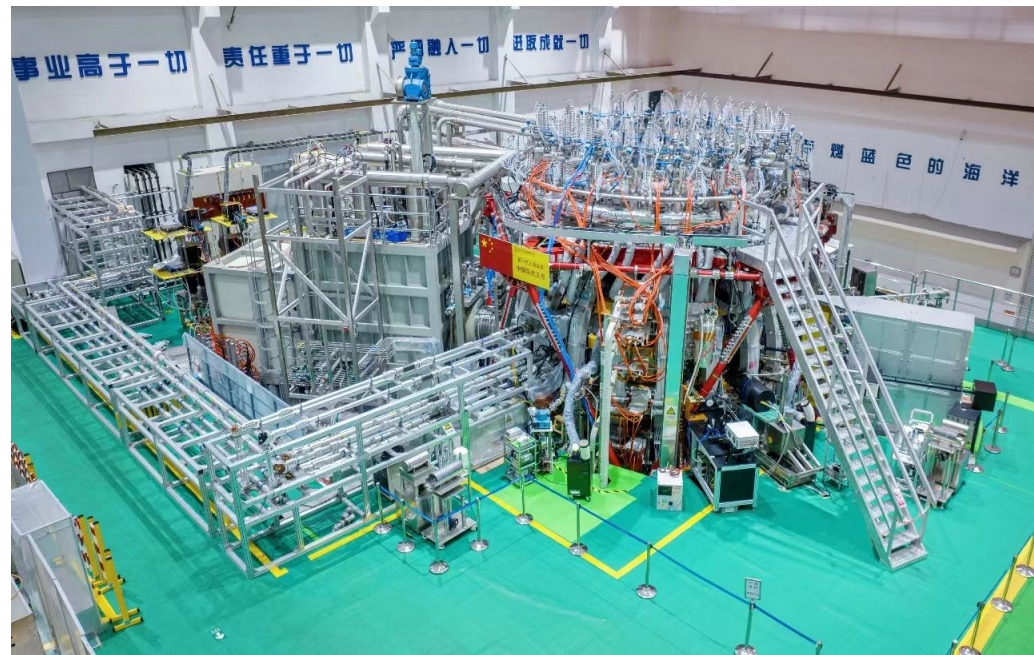
- Fusion research activities at SWIP
- **HL-3 experiment progress**
  - ✓ 1 MA plasma
  - ✓ H-mode operation
  - ✓ Advanced divertor discharge
- Summary and outlook

## Addressing critical physics and technology issues for ITER & fusion reactors

- ITER-related scenarios, such as baseline H-mode, hybrid & steady state. Explore **high-performance operation regimes toward fusion reactors**, such as  $\beta_N > 3$ , high density with Greenwald fraction  $> 1$ , etc.
- **Advanced divertor configuration concept** and physics. Test and validate **high heat flux PFCs**.
- Key plasma physics and technologies concerned by ITER, including **EP / VDE / NTM / ELM control, disruption alerting & mitigation**, etc.
- D-T fusion experiments to explore **burning plasma physics and technologies**.

### HL-3 Parameters

|                |                               |
|----------------|-------------------------------|
| Major radius   | $R = 1.78 \text{ m}$          |
| Minor radius   | $a = 0.65 \text{ m}$          |
| Plasma current | $I_p = 2.5 \sim 3 \text{ MA}$ |
| Toroidal field | $B_T = 2.2 \sim 3 \text{ T}$  |
| Elongation     | $\kappa = 1.8$                |
| Triangularity  | $\delta > 0.5$                |
| Heating power  | $> 30 \text{ MW}$             |



# Magnets System and Vacuum Vessel

## Demountable TF coils

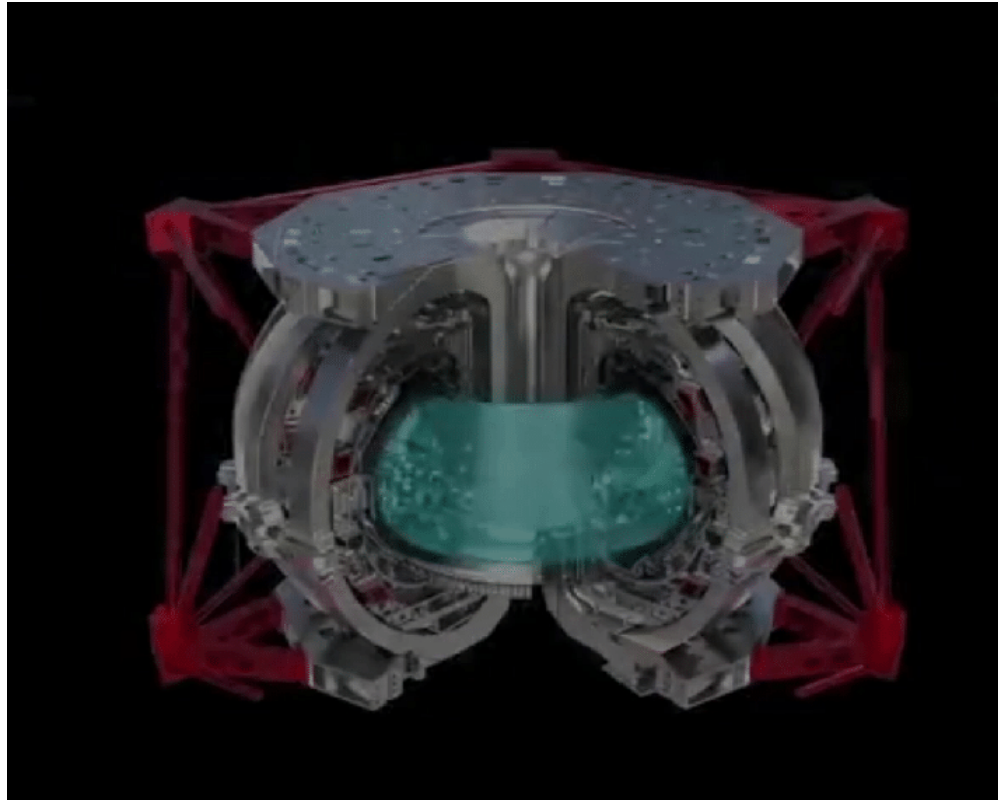
- 20 TF coils
- Maximum 3T at 190 kA

## CS and PF coils

- 1CS+16 PF coils
- Between VV and TFC

## Vacuum Vessel

- Double-shell structure
- 42 m<sup>3</sup>, baking at 300 °C



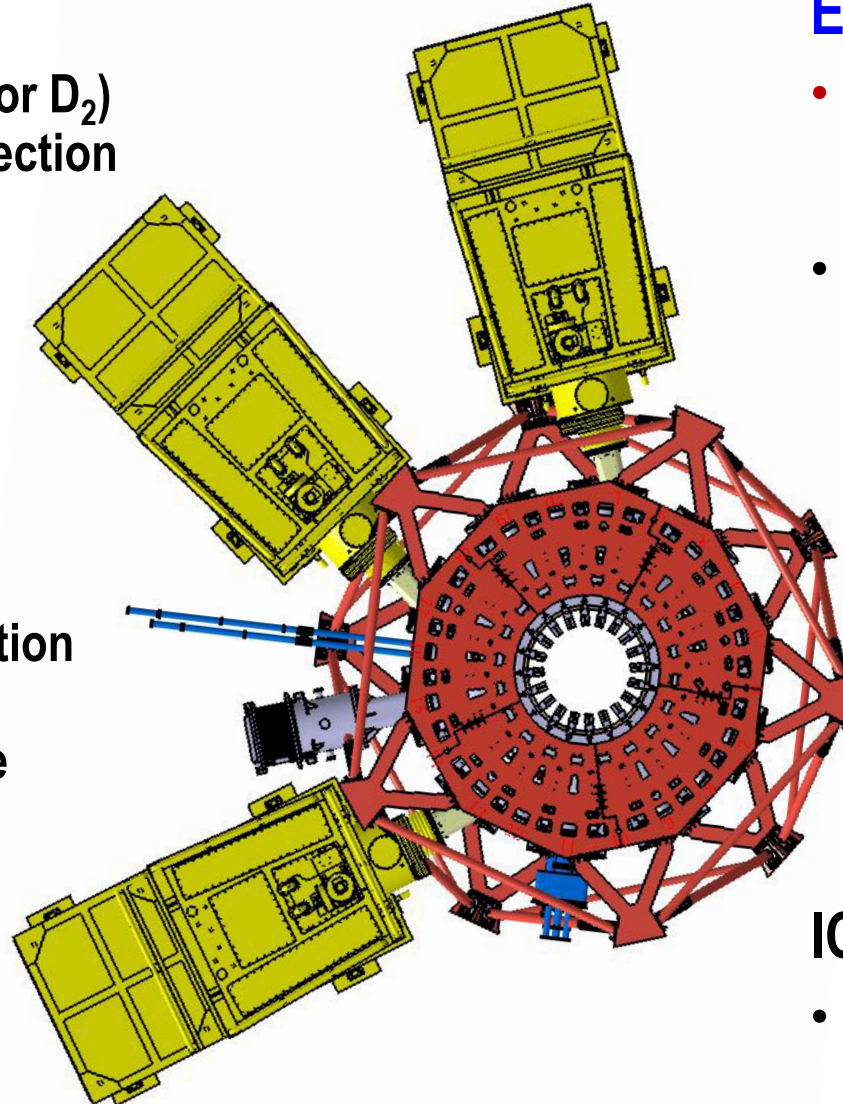
# Heating & Current Drive System Planed

## NBI

- **>15 MW** (80—120keV for D<sub>2</sub>)
- Co (2) & counter(1) injection

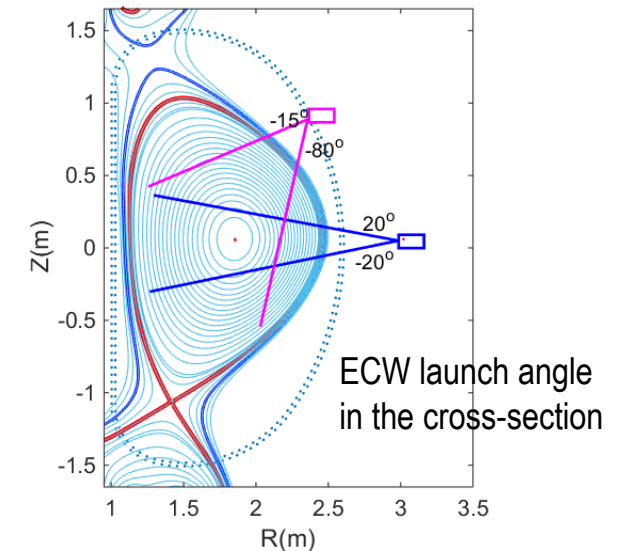
## LHCD

- **4 MW** (3.7GHz)
- Fully Active Multi-junction launcher
- Peak parallel refractive index  $N_{||}(0) = 2.25$



## ECRH&CD

- **14 MW**
  - 6 MW equatorial launcher(105 GHz, X2)
  - 8 MW upper launcher(140/150 GHz, X3)**
- Fast steering mirror for controlling MHD



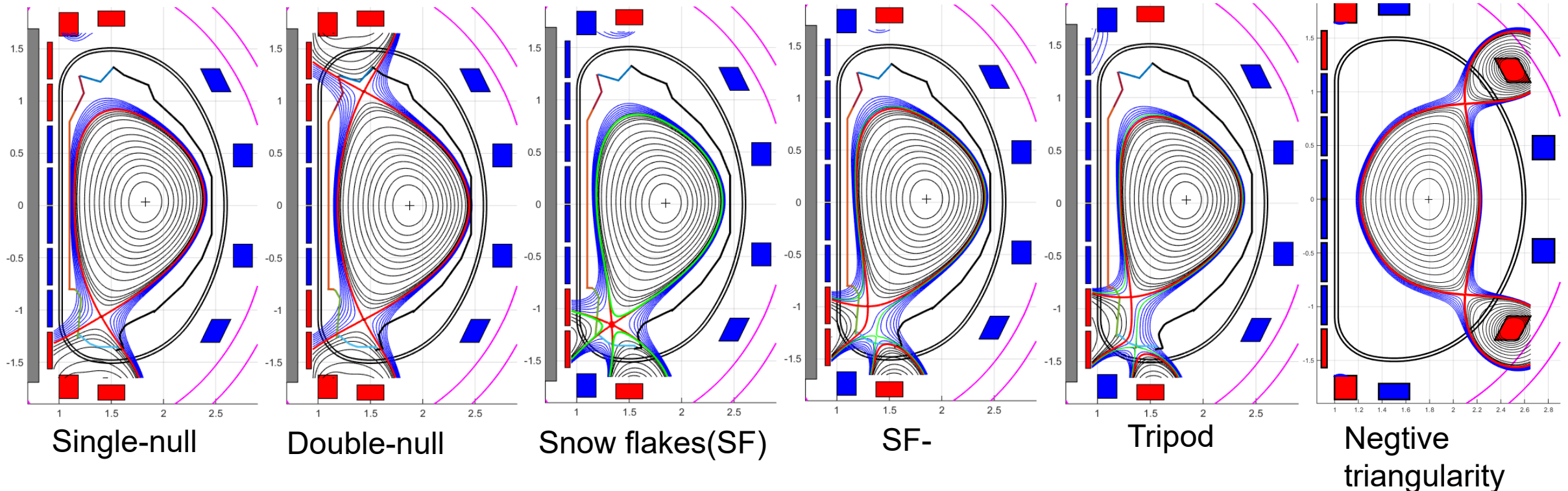
## ICRH

- **6MW** ( being designed )

# Provide Divertor High Heat Flux Solution

**Extreme divertor heat flux handling capability, compatible with heating >30 MW.**

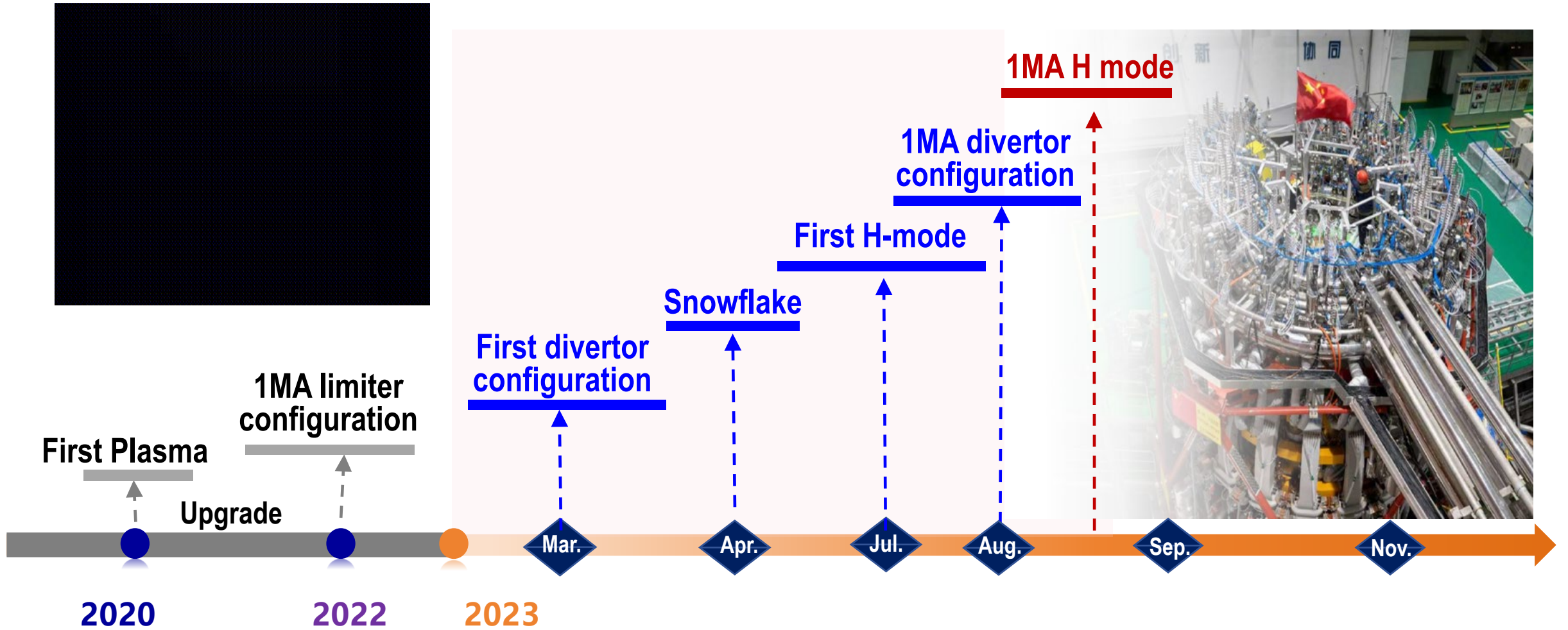
- Advanced divertor configuration (snowflake, tripod, fishtail, etc.)
- Detached divertor operation during ELMy H-mode



|                                                                    | Baseline    | Hybrid      | Full non-inductive |               |
|--------------------------------------------------------------------|-------------|-------------|--------------------|---------------|
| $I_p(\text{MA}) / B_T(\text{T})$                                   | 2.5/2.2     | 1.2/2.2     | 1.2/1.7            | 1.0/1.85      |
| $a / R \text{ (m)}$                                                | 0.65/1.78   | 0.65/1.78   | 0.65/1.78          | 0.65/1.78     |
| $f_G$                                                              | 0.74        | 0.6         | 0.5                | 0.5           |
| $P_{\text{NBI}} / P_{\text{EC1}} / P_{\text{LH}} (P_{\text{EC2}})$ | 12 / 0 / 0  | 8 / 6 / (2) | 10 / 5.5 / -       | 1.5 / 3.5 / 4 |
| $q_{95}$                                                           | 3.0         | 4.7         | 5.1                | 4.8           |
| $\beta_p$                                                          | 0.95        | 1.6         | 1.8                | 1.9           |
| $\beta_N / 4I_i$                                                   | 2.4 / 3.5   | 3.0 / 3.4   | 3.4 / 4.0          | 2.3 / 3.2     |
| $f_{\text{BS}} / f_{\text{NI}}$                                    | 0.18 / 0.21 | 0.4 / 0.7   | 0.55 / 1.00        | 0.63 / 1.00   |
| $T_{e0} / T_{i0} \text{ (keV)}$                                    | 6.8 / 8.3   | 6.2 / 6.5   | 7.5/12.0           | 4.0 / 4.0     |
| $W_{\text{th}} \text{ (MJ)}$                                       | 2.8         | 1.2         | 1.3                | 0.95          |
| $H_{98(y,2)}$                                                      | 1.0         | 1.1         | 1.3                | 1.3           |

- Hybrid:  $I_p=1.0\sim1.4 \text{ MA}$ ,  $f_{\text{BS}} \sim 40\%$ ,  $f_{\text{ni}} \sim 70\%$ ,  $\beta_N > 2.5$ .
- Steady state: hybrid steady state & reversed magnetic shear,  $I_p \sim 1 \text{ MA}$ ,  $f_{\text{BS}} > 60\%$ ,  $\beta_N > 3.0$ .

# Timeline



# Main Upgraded Systems of HL-3 since last FEC

- ✓ **New:** Toroidal cryogenic system; RMP coils; 18 power supply of magnetics ; **Graphite first wall; Lower divertor;** PCS commissioning.....
- ✓ **Upgrades:** coil cooling, baking and glow discharge systems



11/2021

Start installation



7/2022

Installation of graphite  
first wall finished



9/2022

Divertor installation  
finished



9/2022

Restart experiment

- Total 28 diagnostic systems installed, i.e. **plasma density, electron temperature, radiation, magnetic field & plasma current.**

| Measurement   | Diagnostics                            | Technical parameters                                     |
|---------------|----------------------------------------|----------------------------------------------------------|
| $n_e$         | FIR interferometer                     | Temporal resolution: 0.1 ms / Spatial resolution: 10 cm  |
|               | Microwave reflectometer (FMCW)         | Temporal resolution: 10 us                               |
|               | Langmuir probe (LP)                    | Temporal resolution: 1 us / Spatial resolution: 2 mm     |
| $T_e$         | ECE radiometer                         | Temporal resolution: 0.1 ms / Spatial resolution: 1.5 cm |
|               | Core Thomson Scattering (CTS)          | Temporal resolution < 100 ms                             |
|               | Langmuir probe (LP)                    | Temporal resolution: 1 us / Spatial resolution: 2 mm     |
| $\tilde{n}_e$ | Doppler reflectometry (DR)             | Temporal resolution: 1 ms / 8-channels                   |
| $\tilde{B}$   | Mirnov probe                           | Temporal resolution: 10 us                               |
| Impurity      | Vacuum ultraviolet spectroscopy (VUV)  | Temporal resolution: 2 ms / Wavelength: 500-2000 Å       |
|               | Extreme ultraviolet spectroscopy (EUV) | Temporal resolution: 6 ms / Wavelength: 10-130 Å         |
| Radiation     | Bolometer                              | Temporal resolution: 50 us / Spatial resolution: 2 cm    |

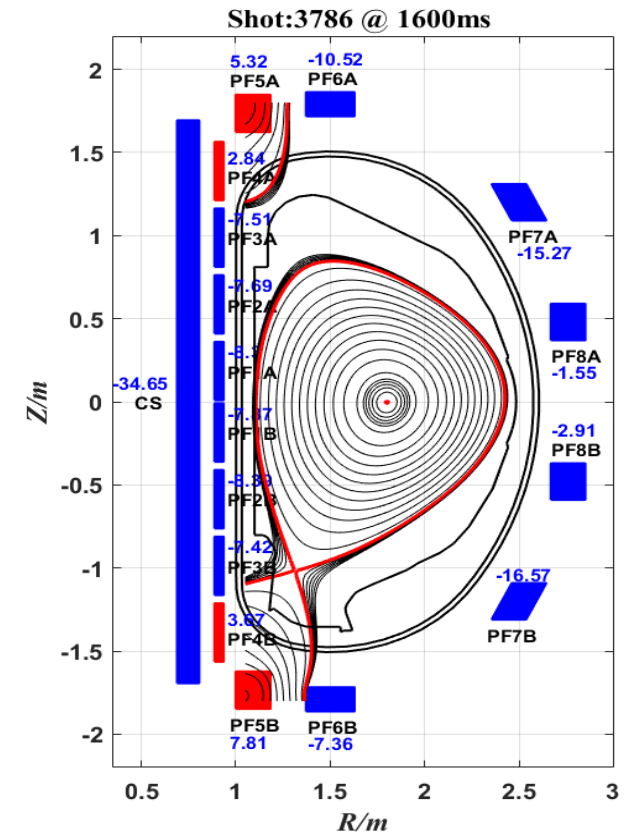
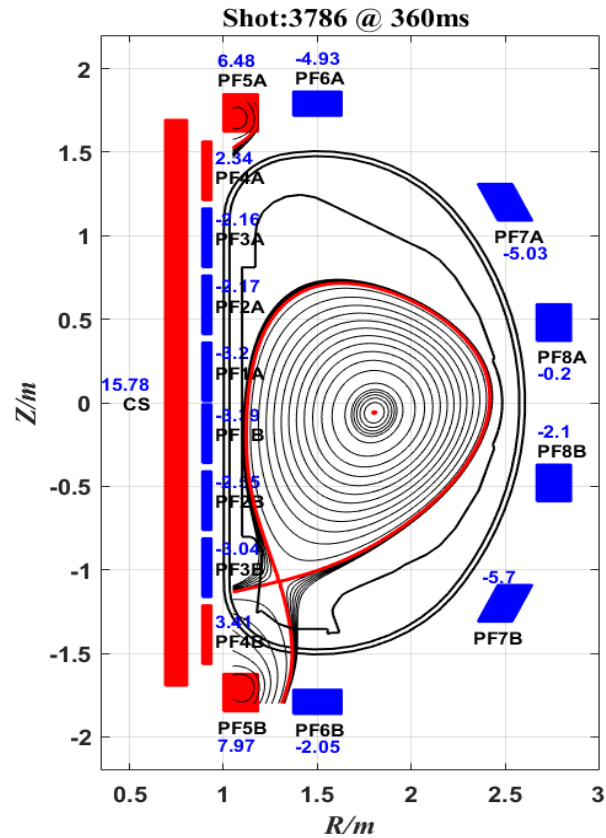
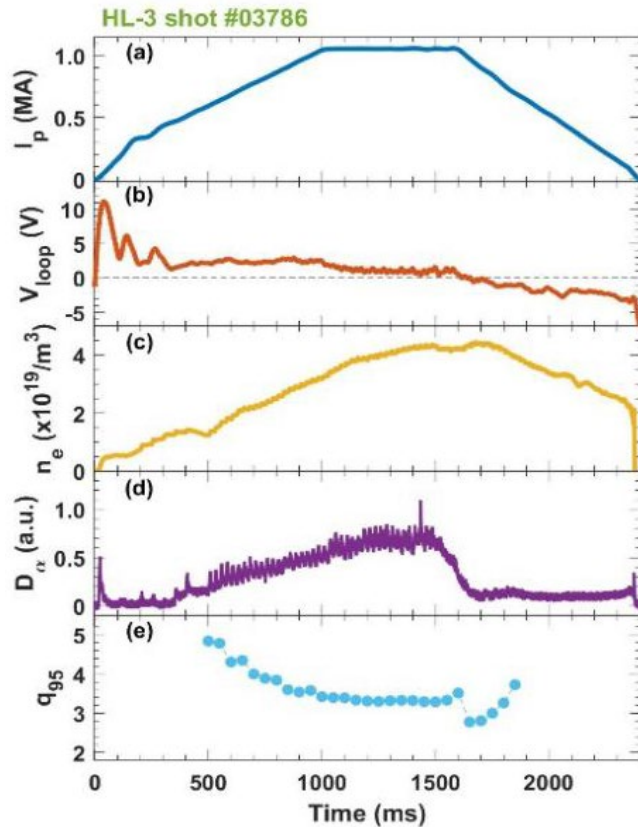
- **Auxiliary H&CD system of 11 MW equipped.**

✓ NBI 5 MW (80keV for D<sub>2</sub>, 55keV for H<sub>2</sub>)

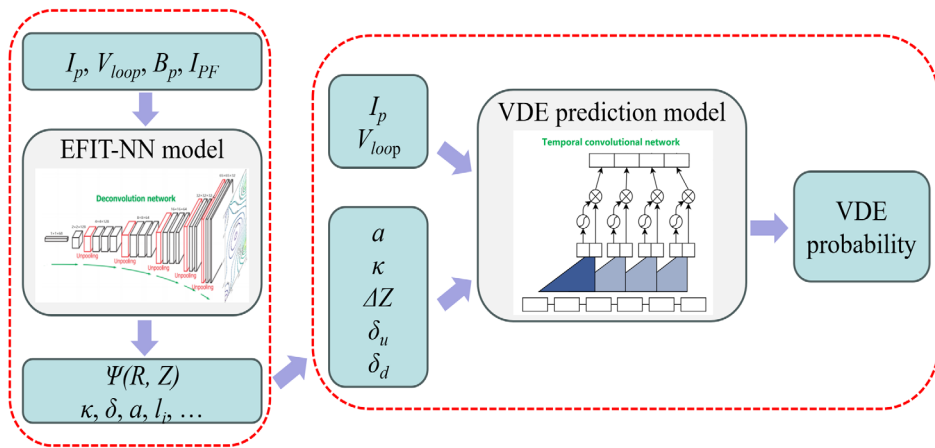
✓ ECRH&CD 4MW (105GHz, equatorial launcher)

✓ LHCD 2MW (3.7GHz, N<sub>||</sub>=2.25)

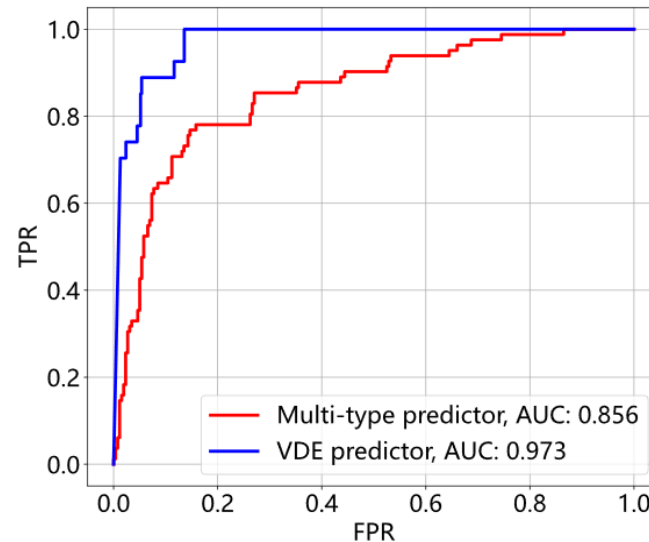
- Flat-top  $q_{95} = 2.6 - 3.4$ .



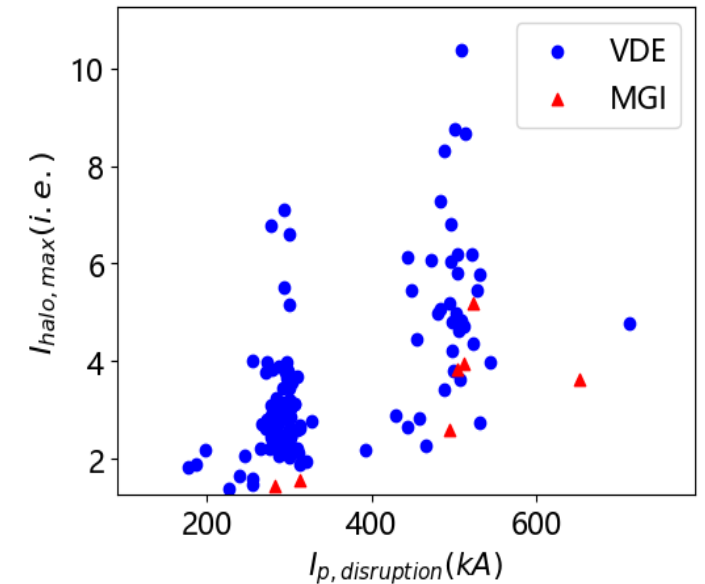
- Developed AI algorithm : VDE predictor (AUC~0.97) and multi-type predictor.
  - ✓ Training set extremely limited: ~600 shots
- Implemented **closed loop** : real-time disruption prediction and mitigation in PCS
  - ✓ Time consumption of a calculation cycle: ~0.6ms



AI-based VDE prediction algorithm



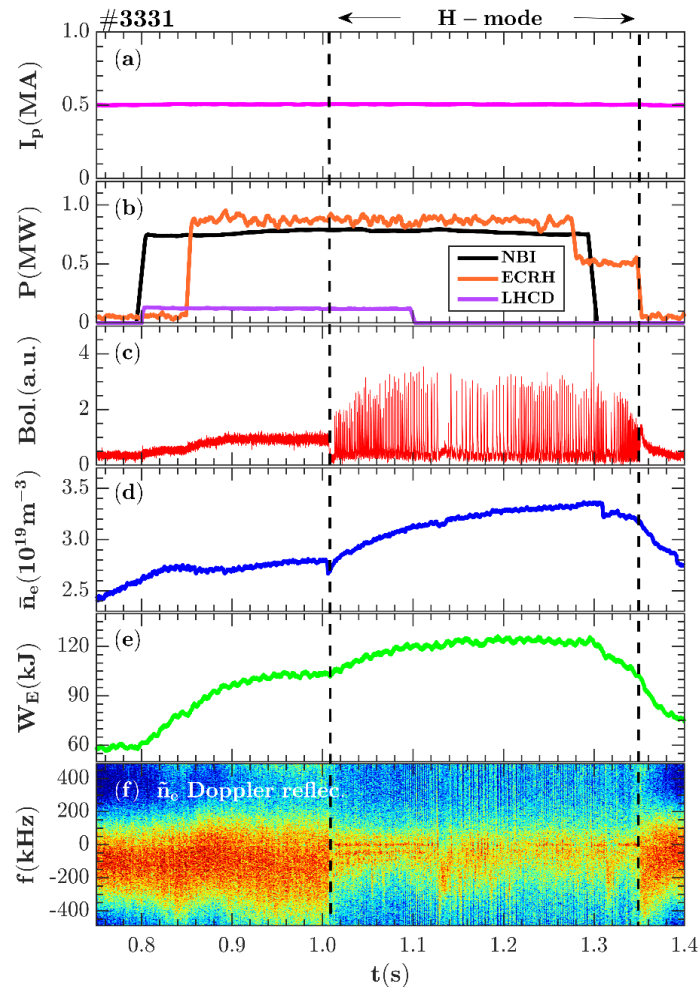
Receiver operator characteristic curves of the VDE predictor and the multi-type disruption predictor



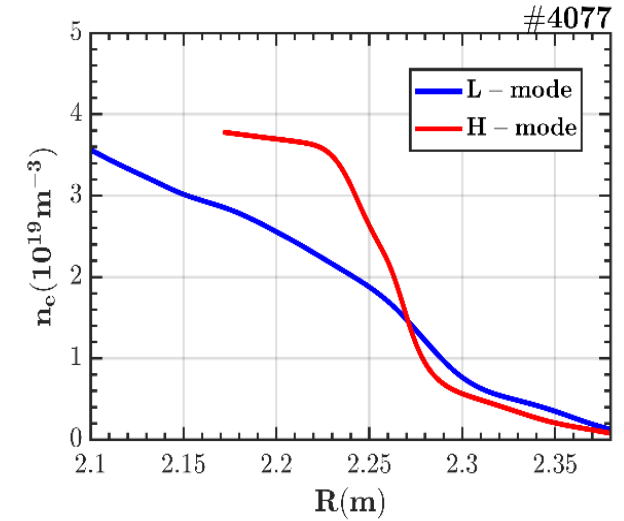
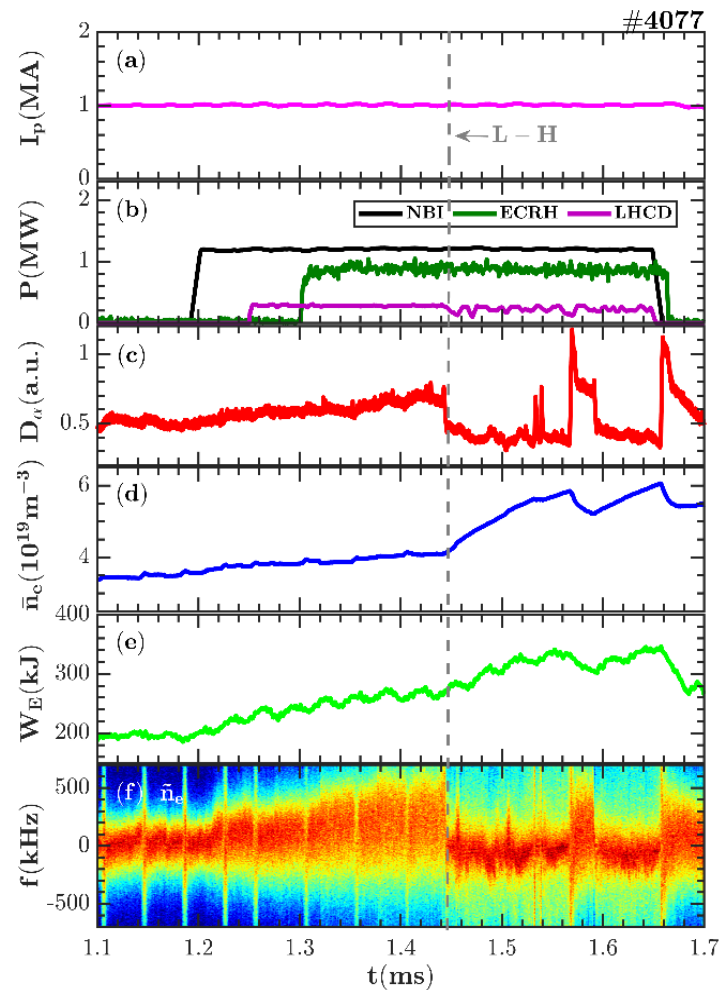
Comparison of halo currents during VDE and MGI induced disruptions

# H-mode Experiment

## H-mode Operation ( $I_p=0.5$ MA)



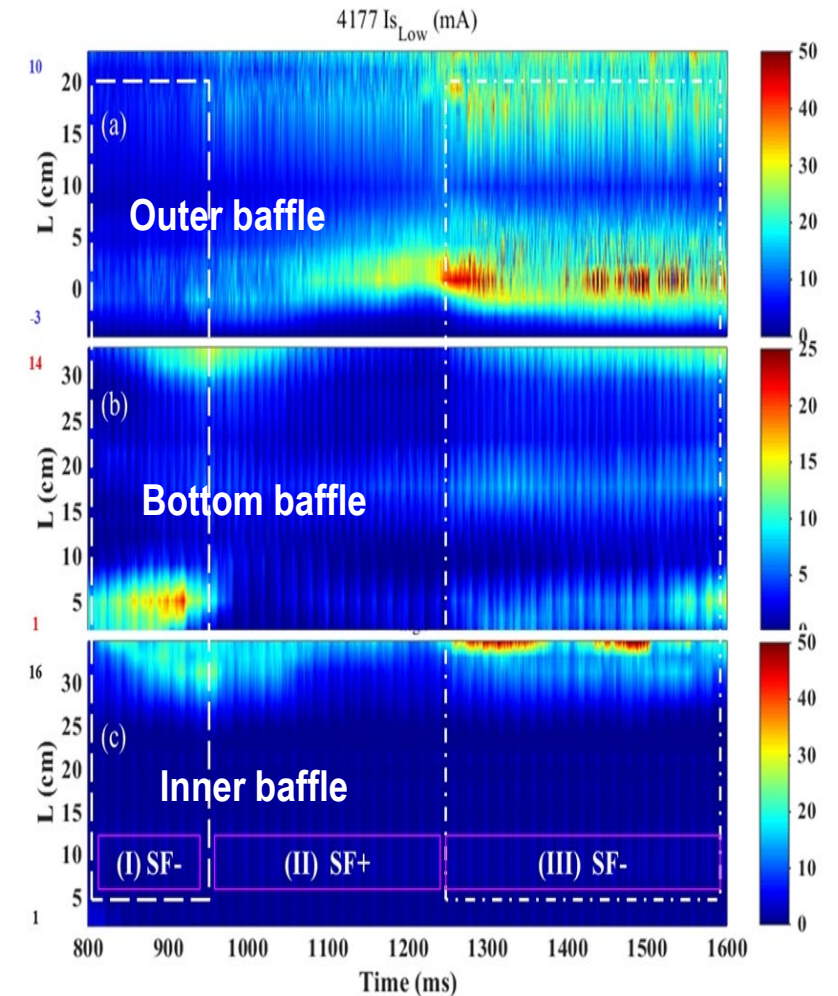
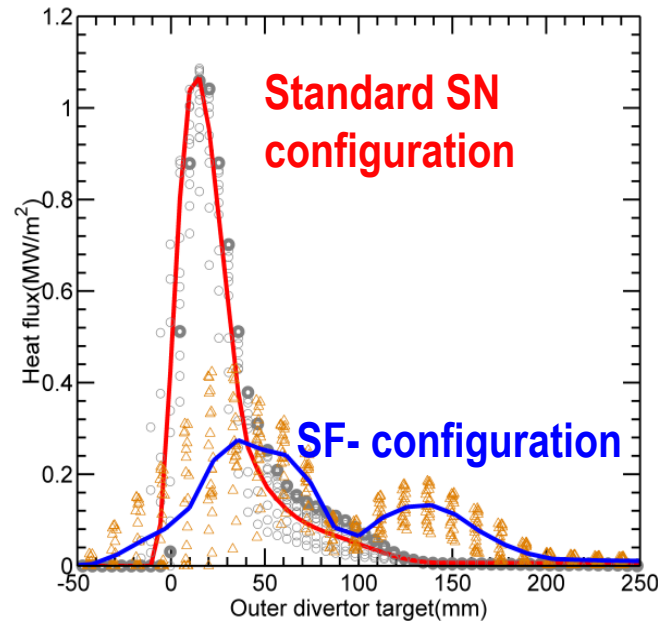
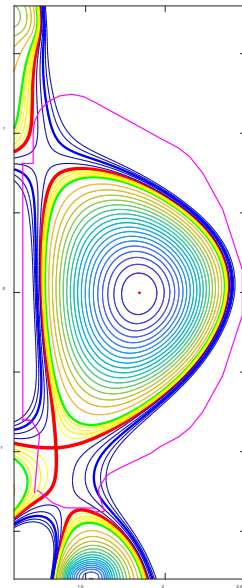
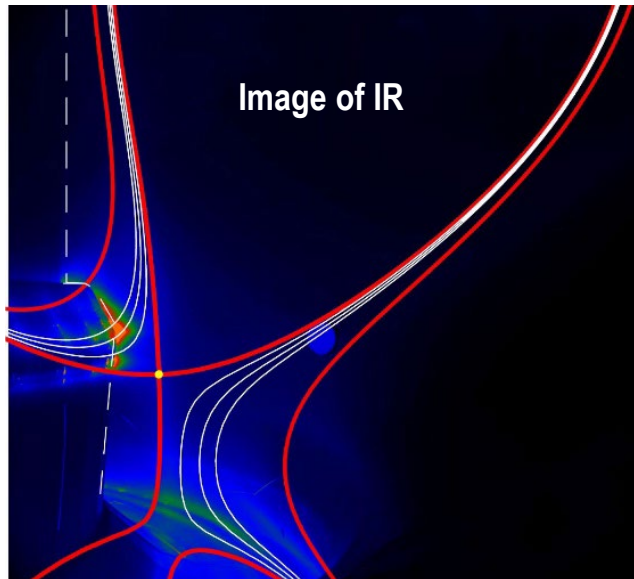
## H-mode Operation ( $I_p=1.0$ MA)



| Parameters                        | Shot 3331 | Shot 4077 |
|-----------------------------------|-----------|-----------|
| $I_p$ (MA)                        | 0.5       | 1.0       |
| $B_T$ (T)                         | 1.7       | 1.6       |
| $R$ (m)                           | 1.75      | 1.79      |
| $a$ (m)                           | 0.54      | 0.62      |
| $n_e$ ( $10^{19} \text{m}^{-3}$ ) | 2.9       | 4.53      |
| $P_{oh}$ (MW)                     | 0.22      | 0.45      |
| $P_{aux}$ (MW)                    | 1.64      | 2.32      |
| $q_{95}$                          | 4.6       | 2.8       |

# Snowflake Divertor Discharge

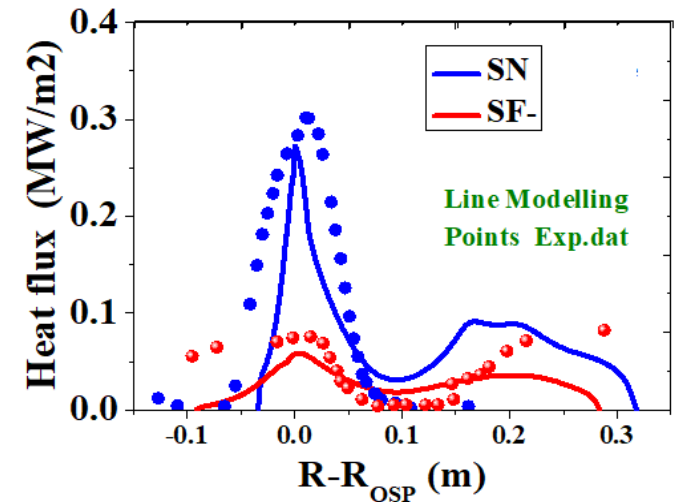
- **Snowflake configuration ( $I_p=0.5$  MA).** Strike point and broadened wet area observed clearly by CCD & infrared camera.
- Distribution of ion saturation current and heat flux on dome gets wide due to magnetic surface broadening.
- **SF- effectively reduce heat load, vs. SN.**



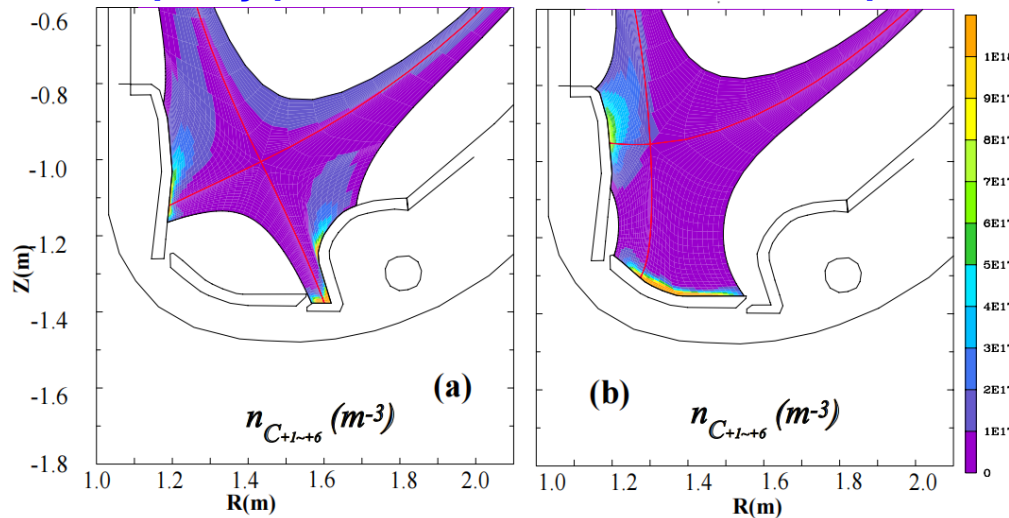
Time-space distribution of the ion saturation current

# Divertor Physics Study by Simulation

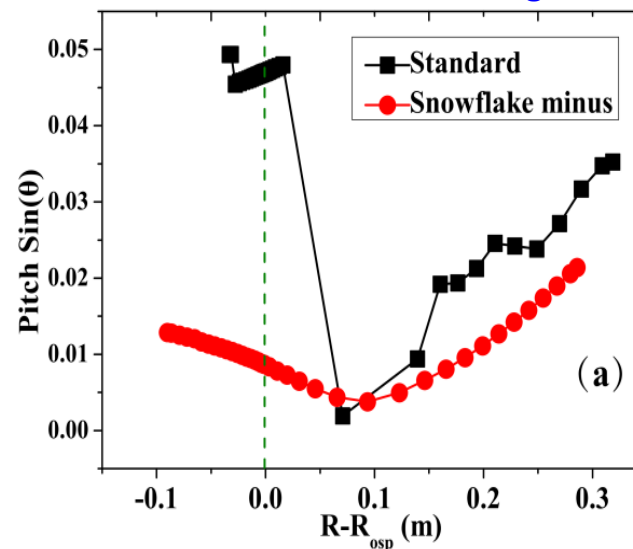
- SOLPS-ITER simulation matched experiment expained mechnism of SF- on divetor impurity screen and heat flux control.



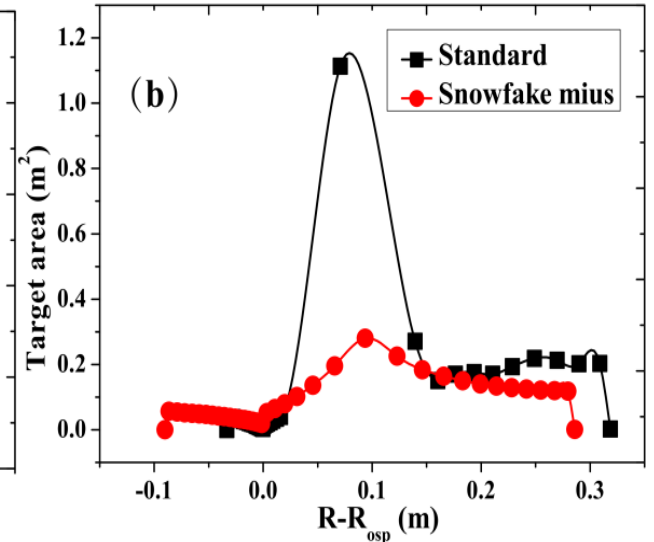
✓ SF- effectively screen the radiation carbon impurity particles,enhance the radiation power.



✓ SF- smaller magnetic line incidence angle



✓ SF- increase contact area.



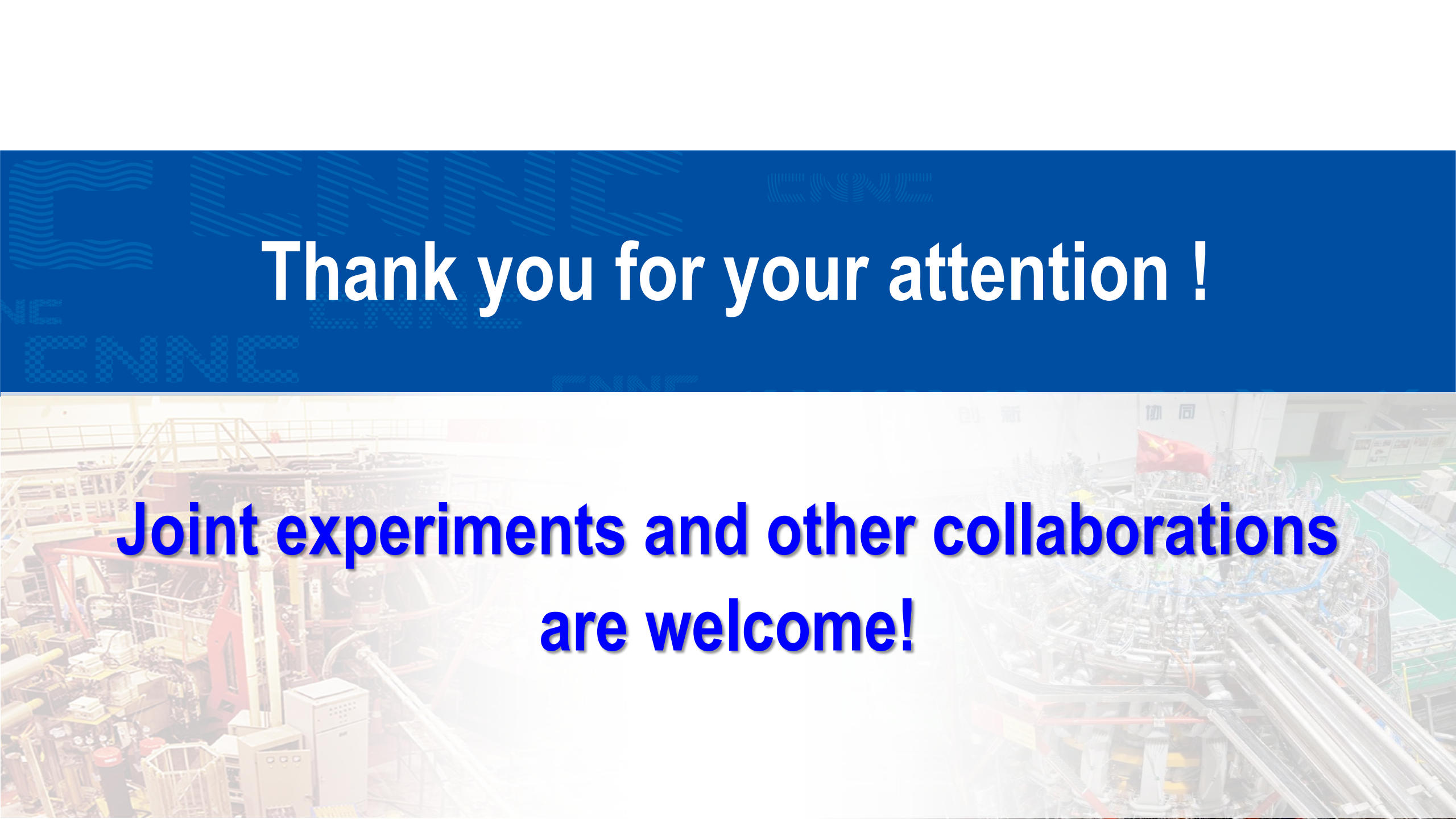
- Fusion research activities at SWIP
- HL-3 experiment progress
  - ✓ 1 MA plasma
  - ✓ H-mode operation
  - ✓ Advanced divertor discharge
- **Summary and outlook**

- In 2<sup>nd</sup> HL-3 experimental campaign (2022–2023), significant progress achieved.
  - ✓ The divertor configuration of 1.2 MA
  - ✓ H-mode plasma of 1 MA realized
  - ✓ Snowflake divertor configuration.
- In the near future, plasma current will be increased to 2 MA.
  - ✓  $n\tau T_i \sim 10^{20} \text{ m}^{-3}\text{skeV}$
  - ✓ High-performance operation
  - ✓ Advanced divertor physics
  - ✓ MHD / disruption mitigation
  - ✓ Energetic physics
- D-T experiment planned on HL-3 to support key physics and technologies towards ITER.
- Parallel to HL-3 experiments, HL-2A made progress in exploring plasma physics

Advanced operation scenarios, energetic particle physics, turbulence, the divertor detachment, etc.

**For further details relevant to SWIP research activities, please refer to contributions:**

| <b>Presenter</b> | <b>Session, Time</b>  | <b>Presenter</b> | <b>Session, Time</b> | <b>Presenter</b> | <b>Session, Time</b> |
|------------------|-----------------------|------------------|----------------------|------------------|----------------------|
| W.L. Zhong       | EX/5-6 19/10, 15:25   | W. Chen          | 2080, 20/10, 10:00   | T. Long          | 2235, 20/10, 14:40   |
| G.L. Dong        | TH/8-2 20/10, 14:17   | W.L. Zhong       | 2542, 20/10, 10:00   | R.R. Ma          | 2135, 20/10, 16:10   |
| J.M. Chen        | TECH/2-4 18/10, 13:08 | W.H. Lin         | 2118, 20/10, 10:00   | N. Wu            | 2141, 20/10, 16:10   |
| X.R. Duan        | 2485, 16/10, 16:14    | J.Q. Xu          | 2081, 20/10, 10:00   | T.F. Sun         | 2185, 20/10, 16:10   |
| N. Zhang         | 2246, 17/10, 10:00    | Y.P. Zhang       | 2120, 20/10, 10:00   | P.Y. Li          | 2209, 20/10, 16:10   |
| Y.R. Zhu         | 2191, 17/10, 10:00    | M.K. Han         | 2129, 20/10, 10:00   | G.L. Xiao        | 2214, 20/10, 16:10   |
| Y. Zhang         | 2056, 17/10, 10:00    | L.M. Yu          | 2180, 20/10, 10:00   | D.A. Kang        | 2218, 20/10, 16:10   |
| G.Z. Hao         | 2114, 17/10, 10:00    | L. Xue           | 2138, 20/10, 10:00   | S. Qu            | 2225, 20/10, 16:10   |
| B.P. Gong        | 2216, 19/10, 10:00    | C.Z. Chao        | 2219, 20/10, 10:00   | J. Du            | 2337, 20/10, 16:10   |
| D.M. Fan         | 2376, 19/10, 10:00    | T. Wu            | 2222, 20/10, 10:00   | X.J. Zhang       | 2370, 20/10, 16:10   |
| J.M. Chen        | 2562, 19/10, 10:00    | H.T. Chen        | 2336, 20/10, 10:00   | L. Zhang         | 2402, 20/10, 16:10   |
| P.W. Shi         | 2050, 20/10, 10:00    | J.Q. Li          | 2131, 20/10, 13.20   | B. Li            | 2134, 21/10., 07:50  |
| J. Zhang         | 2052, 20/10, 10:00    | A.S. Liang       | 2210, 20/10, 14:20   | G.Q. Dong        | 2521, 21/10, 10:23   |



**Thank you for your attention !**

**Joint experiments and other collaborations  
are welcome!**