Fusion Engineering Aspects of LHD Deuterium Experiment

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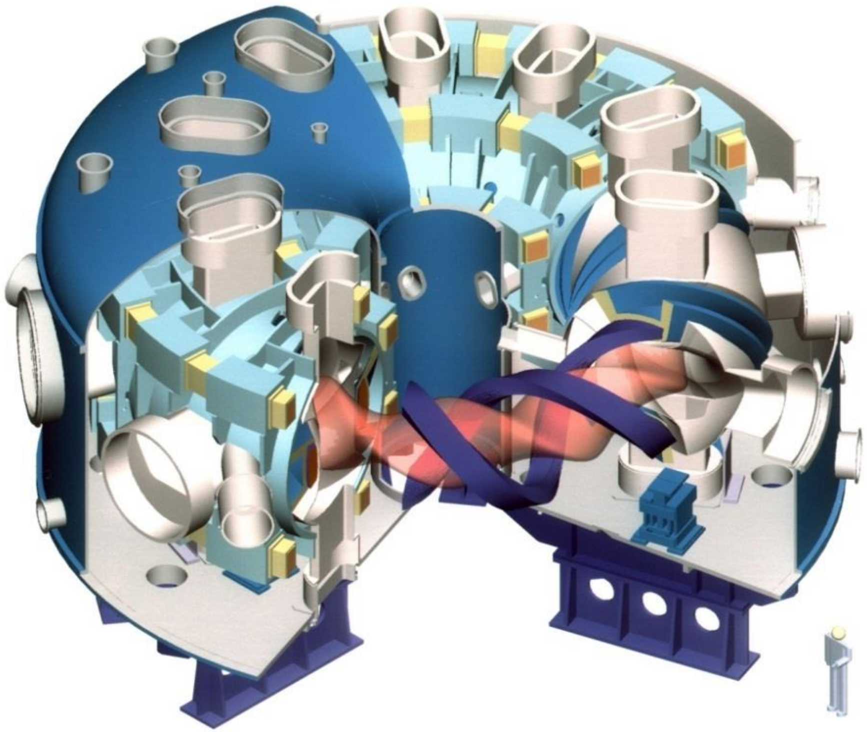
CONTENTS

LHD (Large Helical Device)



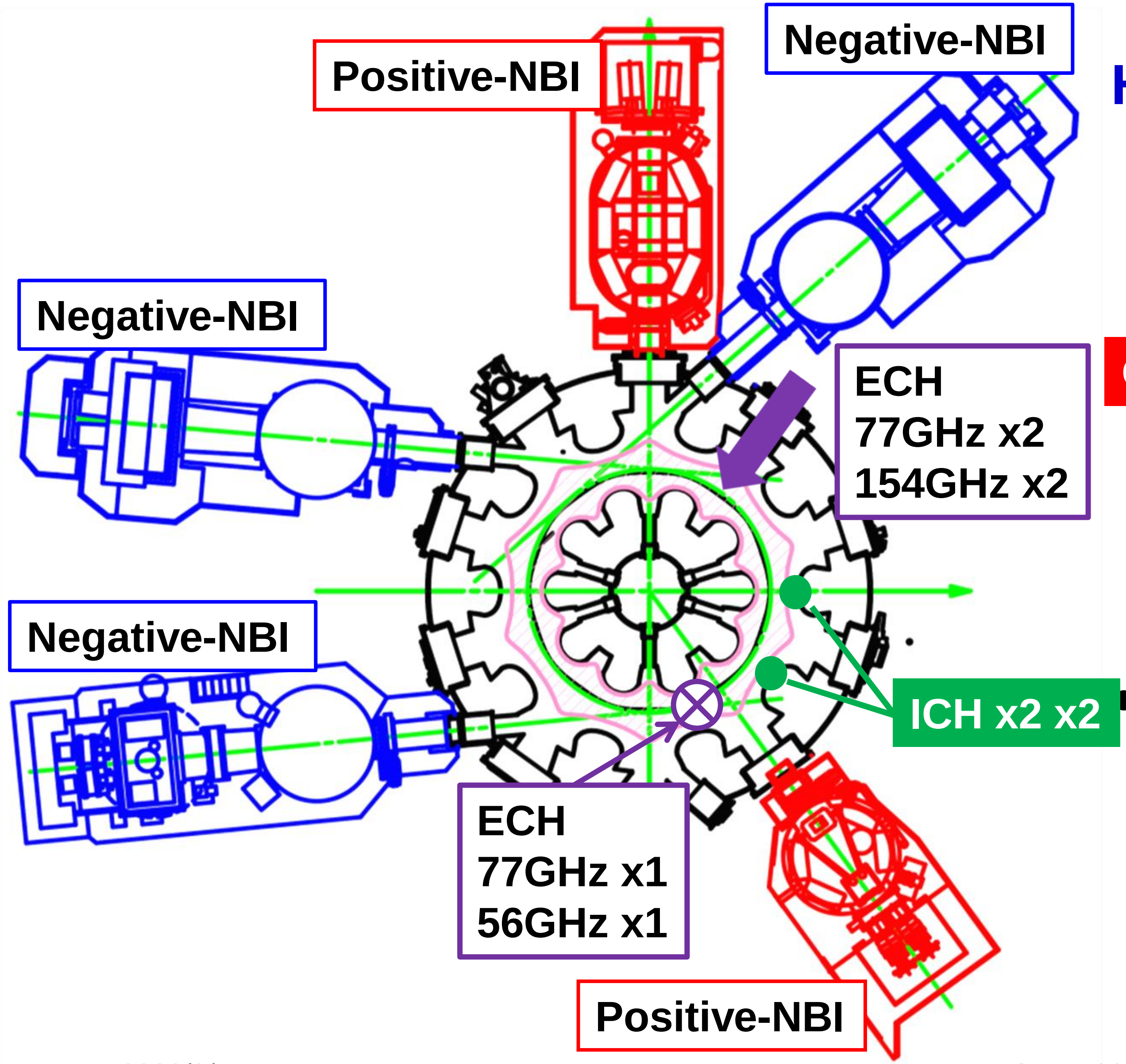
One of the largest superconducting machine in the world

Specifications

- Mode numbers : *l*/*M*=2/10
- All superconducting system
  helical coils, poloidal coils and bus lines
- Plasma major radius: 3.55-4.1 m
- Plasma minor radius: ~0.6 m
- Plasma volume: 30 m^3
- Toroidal field strength: ~3 T
- 10 pairs of RMP coils

March 31st, 1998	1st plasma
March 7th, 2017	Deuterium Experiment started
December 2nd,2022	Deuterium Experiment ended

Heating System on LHD



Heating Systems

- Negative-NBI (tangential)x 3 (180-190keV),
  H16MW, D8MW

Only machine using N-NBIs as main heating device

- Positive-NBI (radial) x 2 (40-80keV),
  H12MW, D18MW
- ECH (77GHz x 3, 154GHz x 2, 56GHz)
  5.5MW
- ICH (38.47MHz) x 4 2MW

Objectives of the Deuterium Experiment

1. Realization of high-performance plasmas by confinement improvement and by the improved heating devices and peripheral facilities

   ⇒ Extend the operational region of LHD to the reactor relevant plasmas and explore the new important physics related reactor

2. Exploration of the isotope effect study in plasma confinement

   ✓ Isotope effect is long underlying mystery in plasma physics

   ⇒ The information of isotope effect in helical system will lead to the comprehensive understanding on plasma physics

3. Demonstration of the confinement capability of energetic particles (EPs) in helical system and exploration of their confinement studies

   ⇒ Perspective understanding on EP physics for burning plasmas will be provided for toroidal plasmas

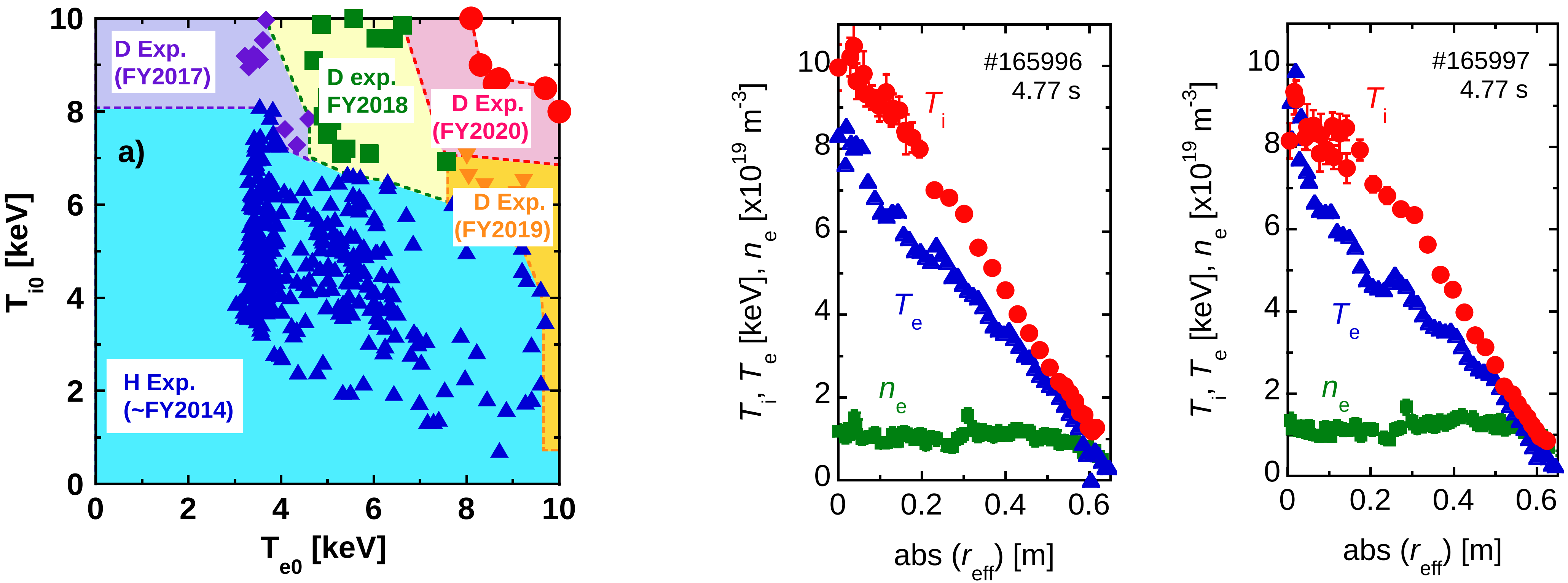
4. Extended studies on Plasma-Wall Interactions (PWI) and tritium retention studies

Achievements in Plasma Phyics of LHD during D-exp.

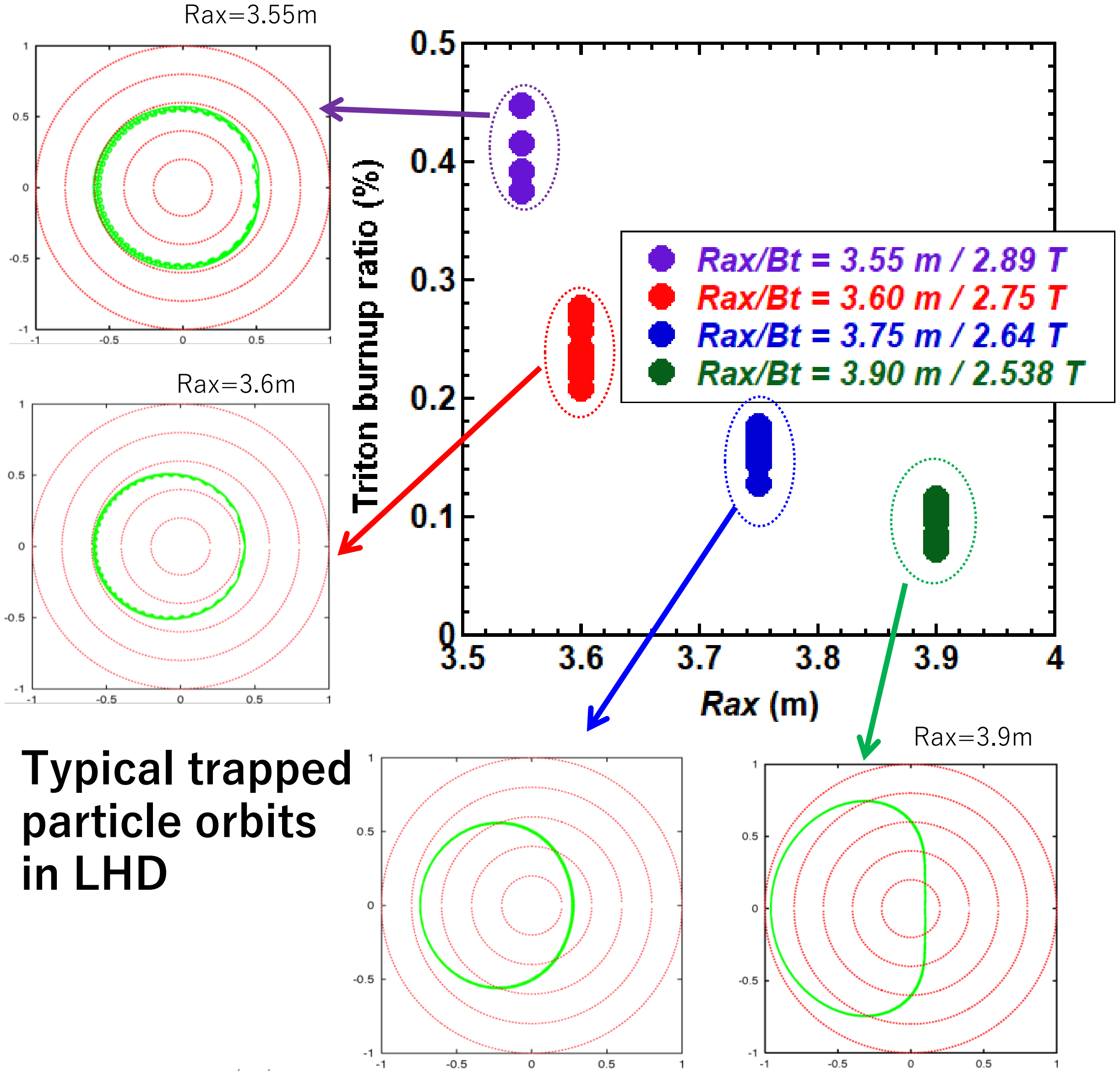
- Extension of High Temperature domain
- Demonstration of EP confinement by T burn-up exp.
- Observation of α-channeling like phenomena

The operational region of high T_i and T_e plasmas was successfully extended by D-exp.

High temperature plasmas of **(1) T_{i0} = 10 keV with T_{e0} = 8.1 keV, and (2) both T_{i0} and T_{e0} = 8.7 keV (100 million degree) are achieved.**



Triton burn-up experiments reveals good Energetic Particle (EP) confinement property of LHD at inwardly shifted magnetic-axis configuration



Typical trapped particle orbits in LHD

D + D => ^{3}He + **n**(2.5MeV)

D + D => p + **T**(1 MeV)

$S_T \approx S_n$

T + D => **n**(14MeV) + ^{4}He (3.5 MeV)

Reaction rate max. @ ~40keV(COM)

$$(\text{T burn-up ratio}) \equiv \frac{S_n{}^{14MeV}}{S_n{}^{2.5MeV}}$$

T burn-up ratio in similar size tokamaks :

- TFTR~1%*, KSTAR~0.45%**

T burn-up ratio comparable to similar size tokamaks is achieved

*C.Barnes, *et al.*, NF**38**(1998)597, ** J. Jo, *et al.* RSI**87**(2016)11D828

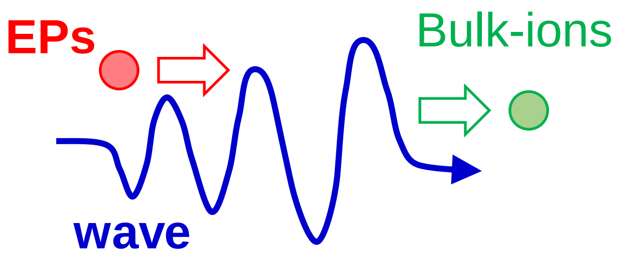
The α channeling like phenomena were observed clearly for the first time [1,2]

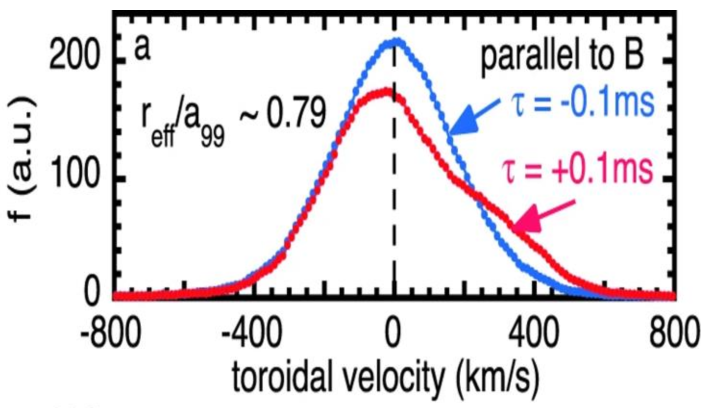
The α channeling

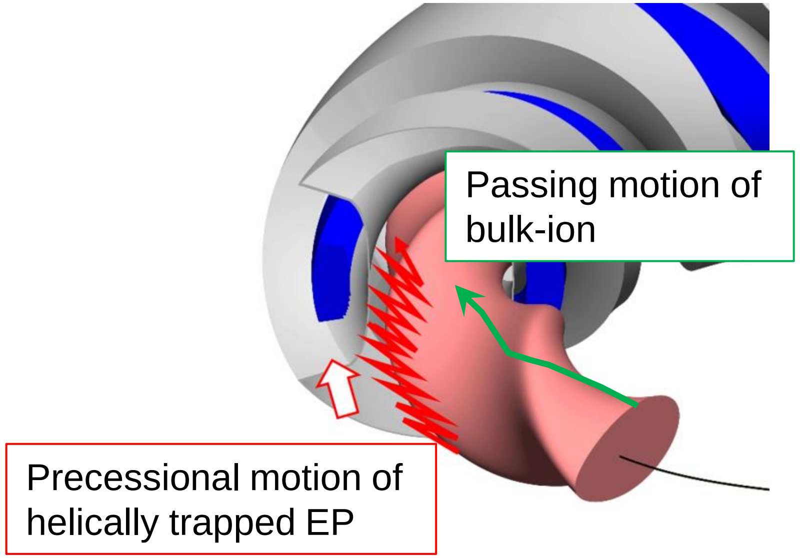
- ✓ **Energy transfer from** fusion born **energetic α-particles to bulk–ions via wave**
- ✓ Proposed by N.J.Fisch (PPPL) : PRL **69** (1992) 612, NF **34** (1994) 1541

- ➢ Excitation of an instability (wave) by helically trapped energetic particles (EPs) was already reported in [3].
- ➢ Acceleration of passing bulk-ions by the instability was newly observed [1,2].

Energy transfer to Bulk-ions from EPs via WAVE







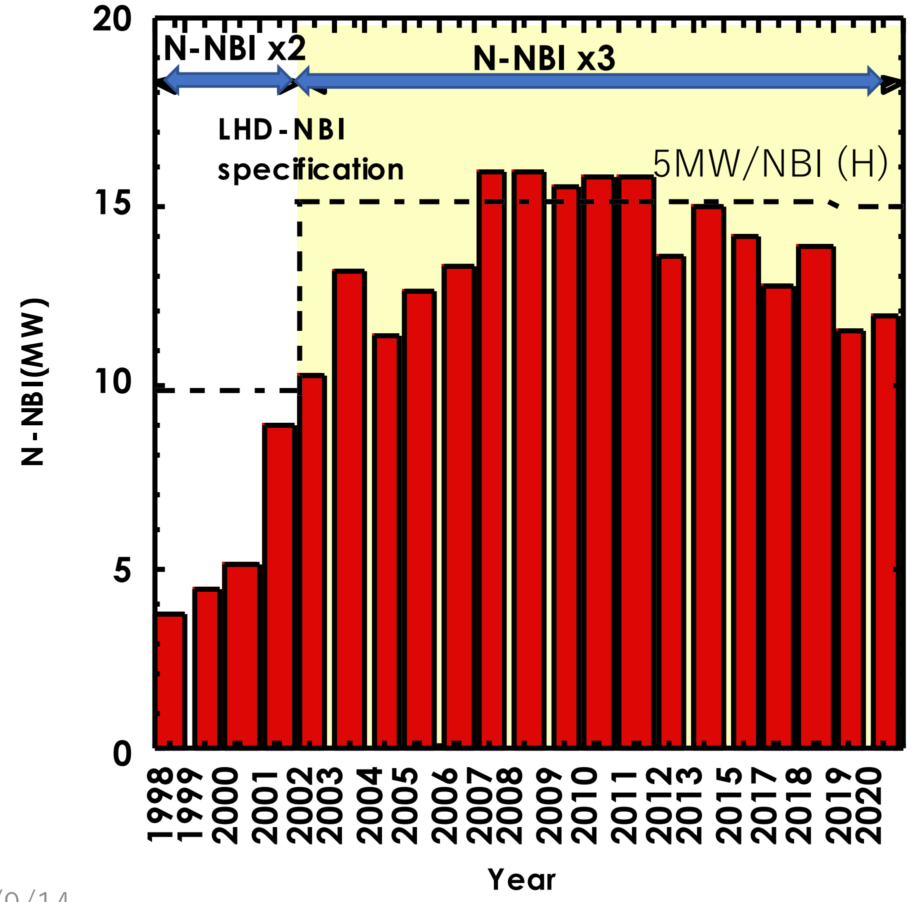
[1] K.Ida, *et al.*, Comm. Phys. **5** (2022)228, [2] K. Ida *et al.*, IAEA-FEC 2023 OV/3-2
[3] X. Du, *et al.*, PRL **114** (2015)155003

Engineering Achievements

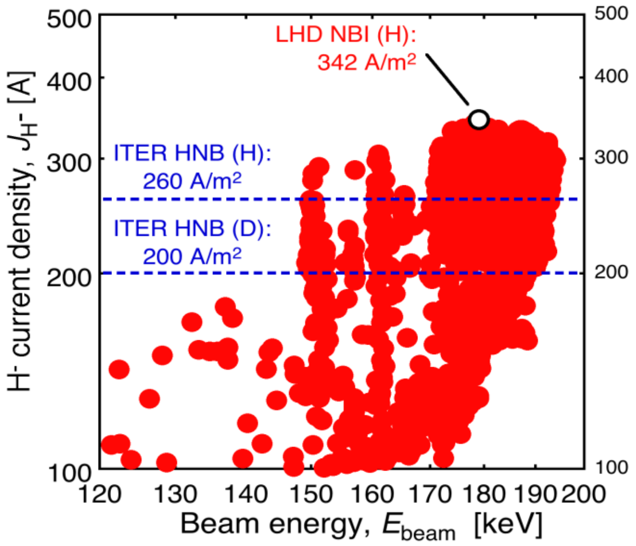
- Development of negative-ion based NBI
- Tritium retention studies
- In vessel cryo-sorption pump development
- Development of full metal divertor target plate

LHD has demonstrated the reliable operation of Negative-ion based NBI for toroidal plasma injection for more than 20 years.

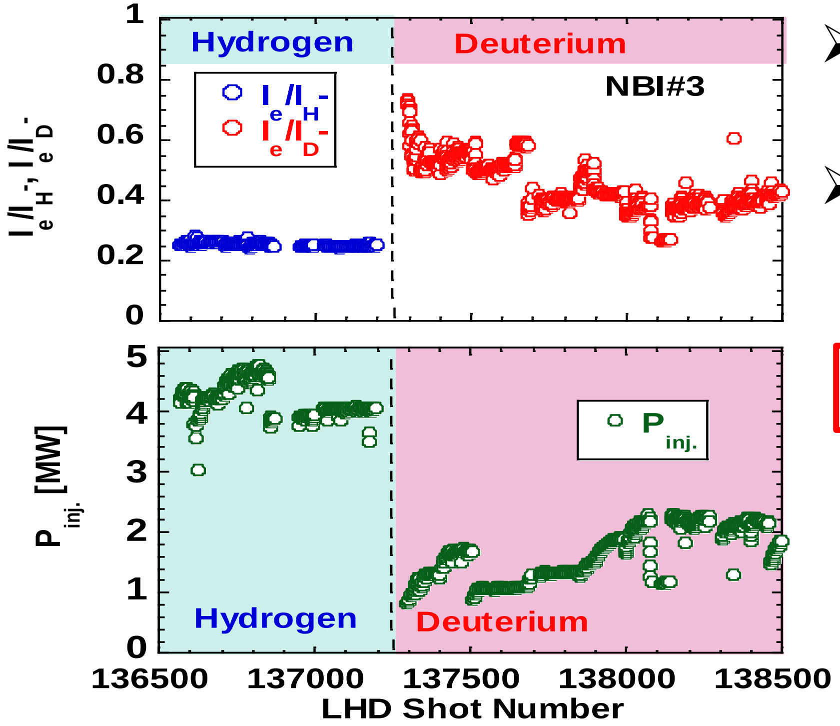
It was proved that the specification of ITER-NBI can be fulfilled simultaneously using negative-ion source at the real operation for plasma injection.



	ITER-NBI	LHD-NBI
J_{H^-}	> 260A/m^2	340 A/m^2
I_e/I_{H^-}	<1	0.25
$\theta_{div.}$	3-7mrad	5mrad

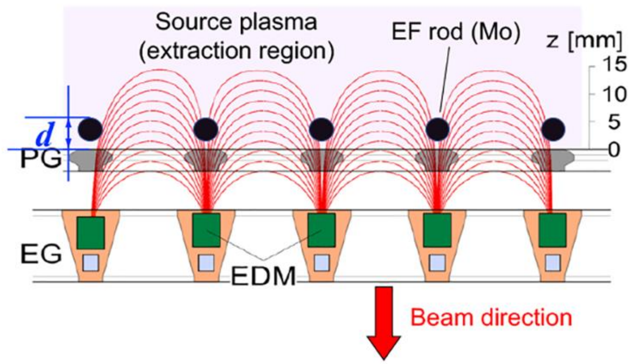


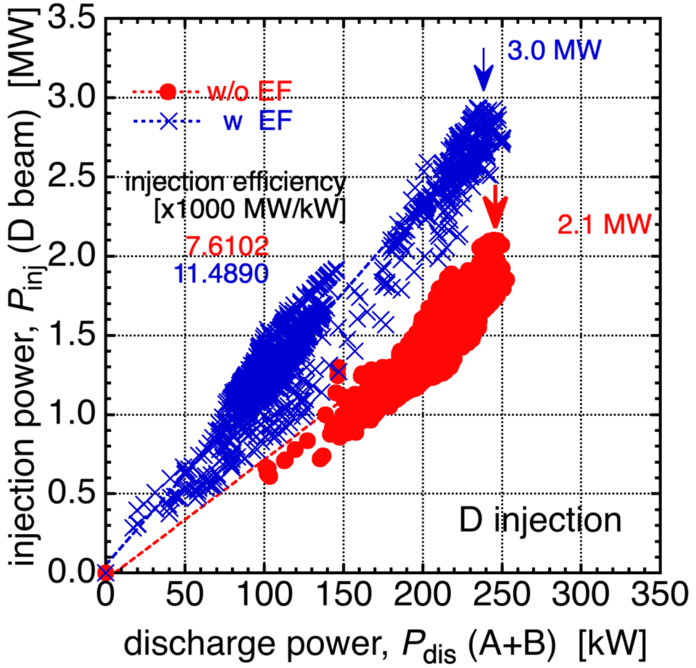
Isotope effects in negative-ion source, i.e., increase of co-extracted electron, prevents the high-power operation of N-NBI

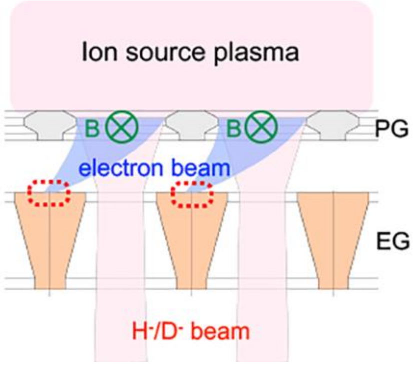


- Electron Fence (EF), which is an array of Molybdenum rods, was installed to shield plasma near the Plasma Grid (PG) surface.
- The EF successfully reduced the co-extraction fraction and also increased arc efficiency.

The injection power of N-NBI in D-operation becomes 1.5 times larger.



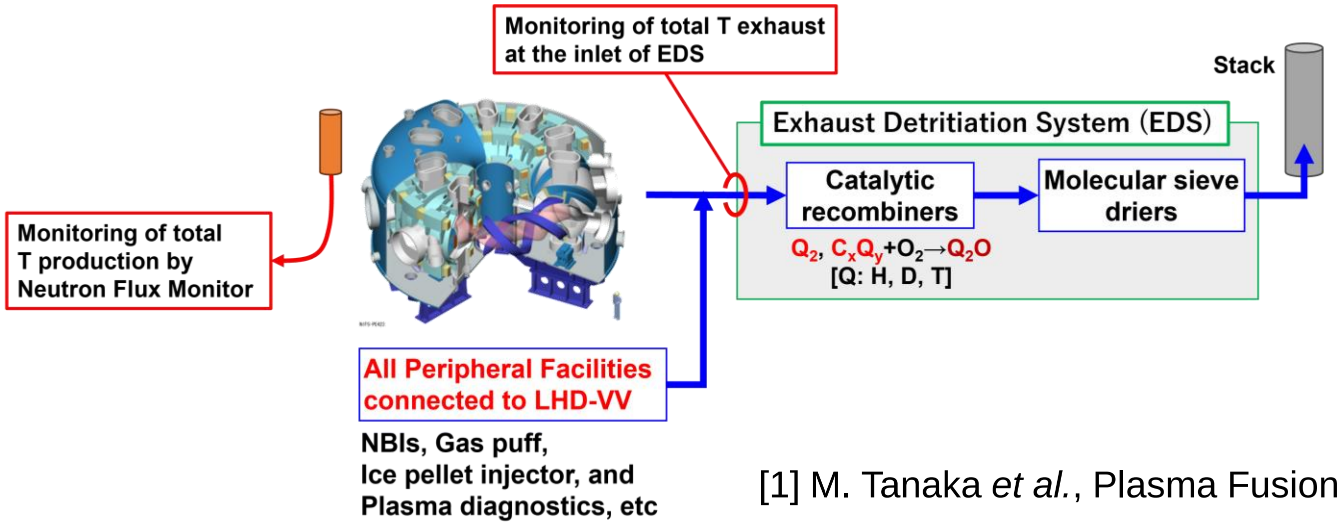


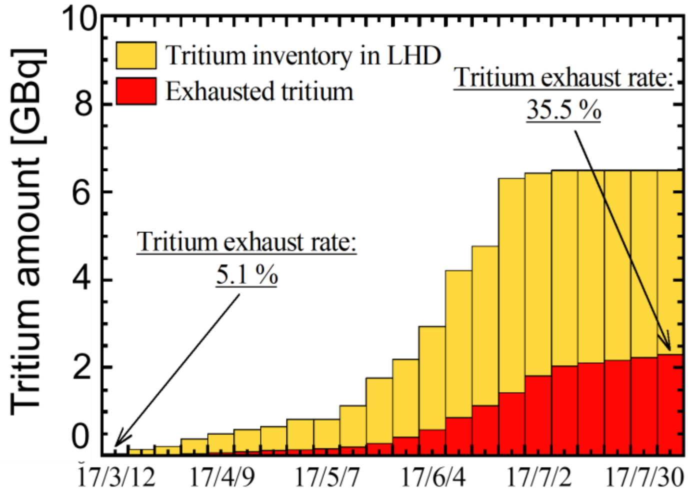


Co-extracted electron beam is a source of excess heat load onto the grids/electrodes of ion source

Comprehensive T mass balance study was performed

- All of the vacuum exhausts from LHD Vacuum Vessel (VV) and peripheral devices were transferred to the Exhaust Detritiation System (EDS) and the tritium contents in the gas are monitored at its inlet.
- The total tritium production rate (S_T) is evaluated from the absolutely calibrated neutron flux monitor with the assumption of $S_T = S_n$, i.e., the neutron emission rate.
- Total T-production : 6.4GBq in the 1st D-exp. [1]





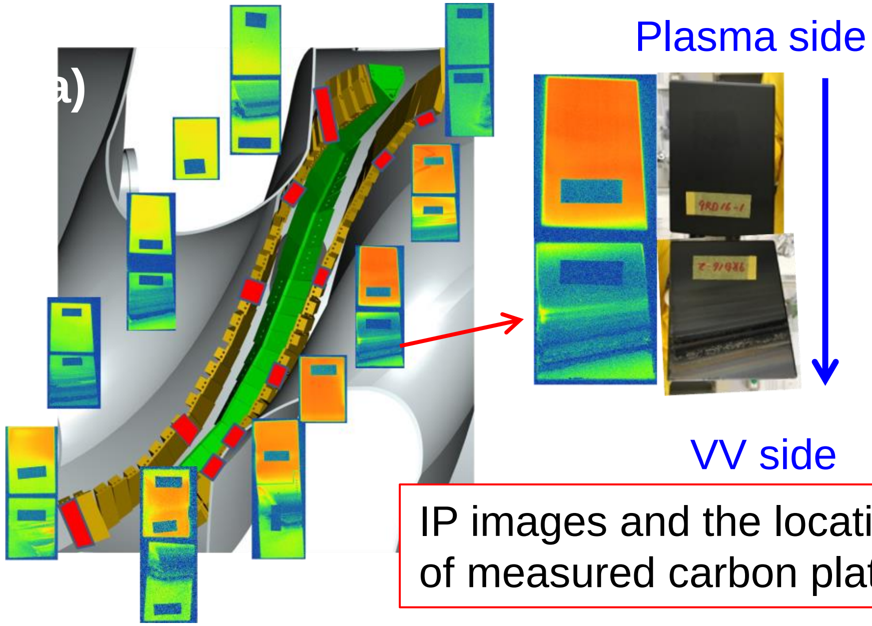
Tritium inventory in LHD for the 1st D-exp.

[1] M. Tanaka *et al.*, Plasma Fusion Res. **15** (2020)1405062

The **~65%** of tritium was estimated to remain in the VV for the 1st D-exp.

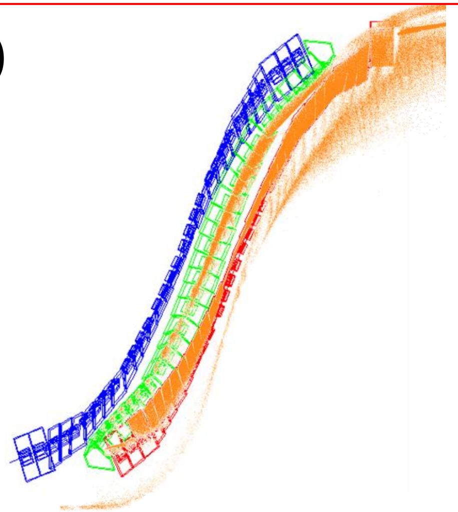
T distribution at in-vessel components for the 1st D-exp [1,2]

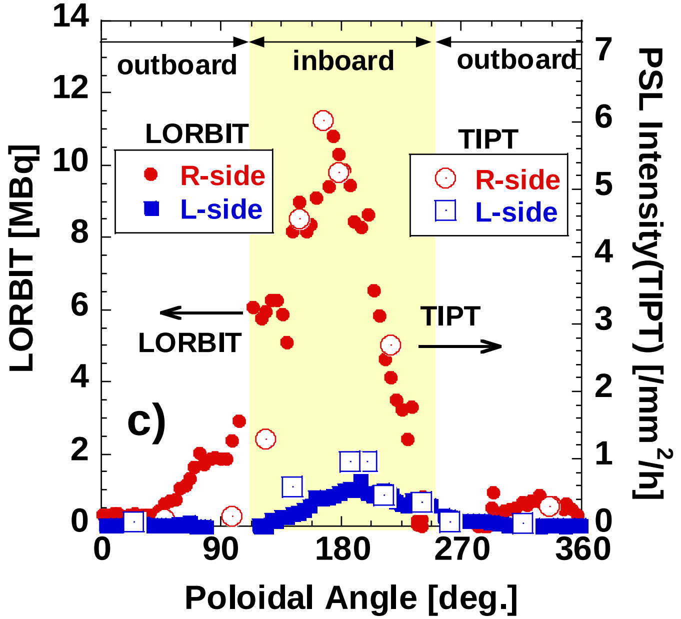
- Tritium distribution in in-vessel components was evaluated using **Tritium Imaging Plate Technique(TIPT) for selected divertor plates** **and** **the First Wall Panels (FWPs)**
- The evaluated distribution is compared with **the distribution of First Orbit Loss (FOL) points calculated by LORBIT-code**. It was estimated by the code that the 3.50GBq of T produced in the 1st D-exp was lost by FOL.



IP images and the location of measured carbon plates

First Orbit loss points of T-ions by LORBIT code

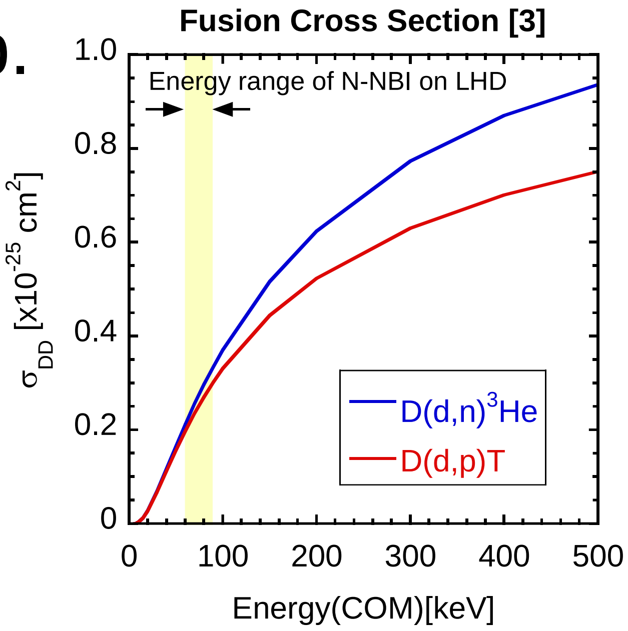




Good agreement in shape between the distributions evaluated by the experiment(TIPT) and the calculation was found.

[1] S. Masuzaki *et al.*, Phys. Scr. **T171** (2020) 014068, [2] M. Osakabe *et al.*, NF **62** (2022) 042019

Further analysis on T-inventory during the 1st D-exp.

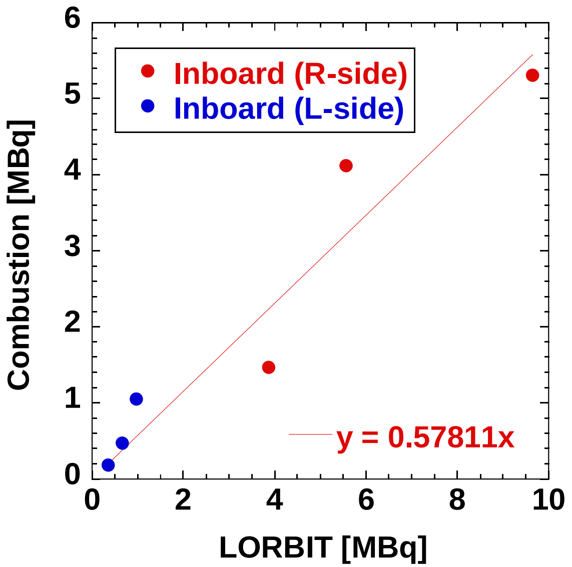


➢Correction on T production from neutron emission

- ✓ The cross section of DD-reaction for T-production is slightly smaller than n-production in the energy range of LHD N-NBI.
- ⇒ Total T-production is estimated to be 93.6% of n-production [1].
- ✓ 6.4GBq x 0.936 =5.99GBq =~6.0GBq
- ⇒ Considering the total exhausted T (2.1GBq), the remained T in the LHD-VV is:
  6.0-2.1 = 3.9GBq

➢T distribution in LHD-VV [2]

- ✓ Absolute measurements of T by Combustion Method showed 57.8% of T evaluated by LORBIT code remained at the surface of the carbon divertor plates.
- ⇒ 3.50 x 0.578 = ~2.0 GBq may remain in the divertor plates.
- ✓ The T contents on the surface of FWPs were also investigated using TIPT.
- ⇒ The remaining T density on FWPs is three order smaller than that in the divertor plates. The most of Ts remains in the divertor plates.



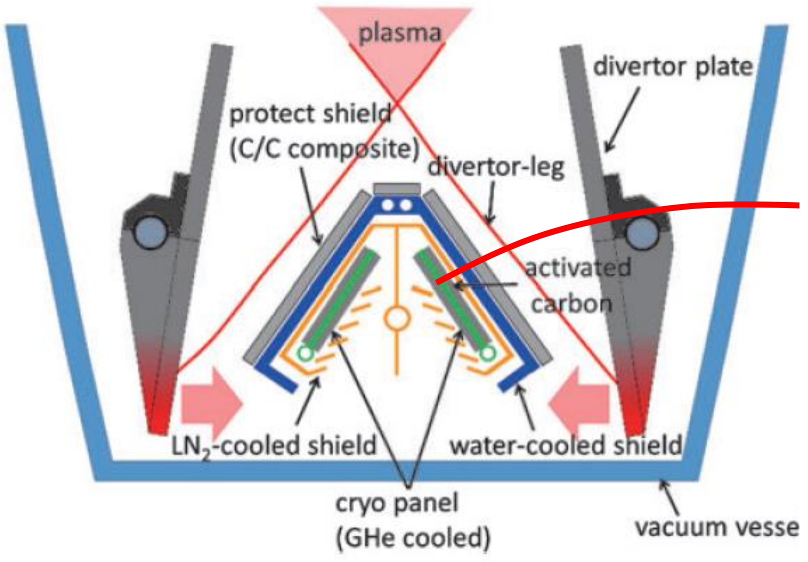
The location of 1.9GBq (=3.9 - 2.0 GBq) of remained T needs to be identified.

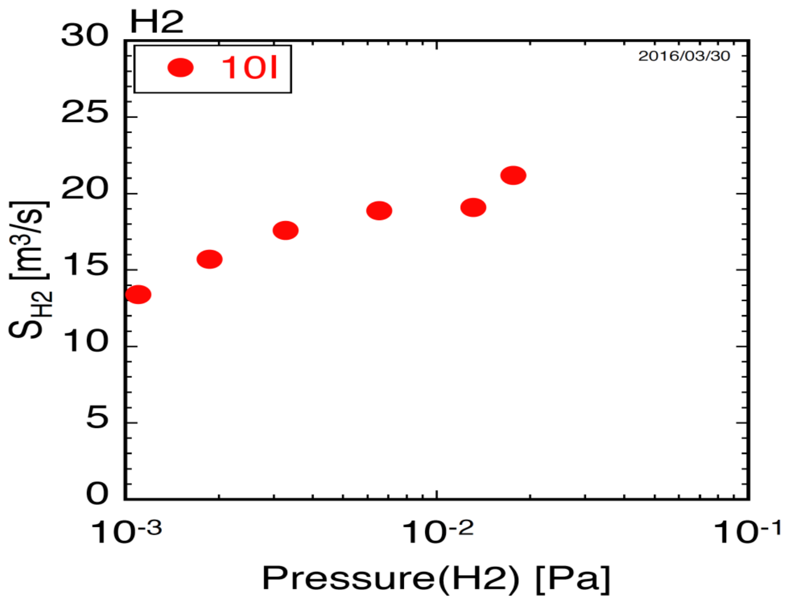
[1] H. Nuga *et al.*, PFR **17** (2022) 2402023, [2] M. Osakabe *et al.*, NF **62** (2022) 042019, [3] H. S. Bosch and G. M. Hale, NF **32** (1992) 611

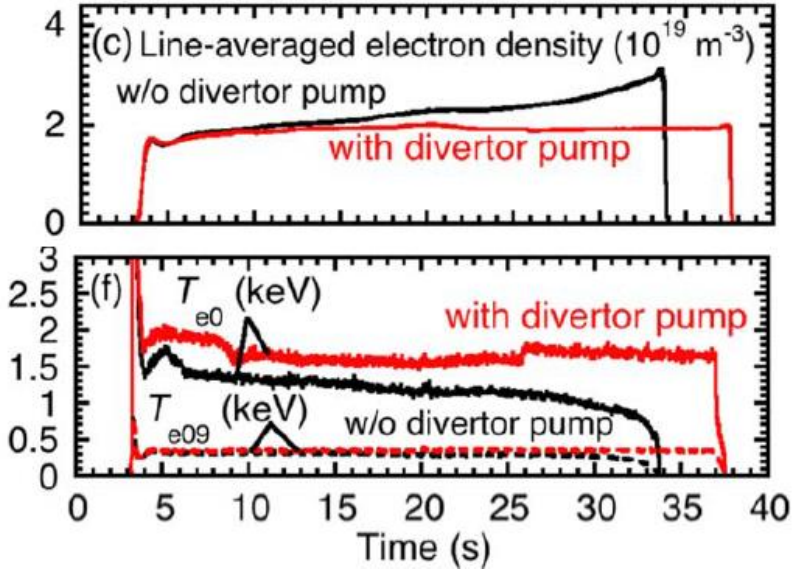
In-vessel cryo-sorption pump was newly developed

An organic adhesive free cryo-sorption was newly developed for the Closed Helical Divertor of LHD[1].

- ✓ A low melting point metal (In) was used as an adhesive in order to avoid the unfavorable outgassing during non-cooled phase of the pump and also to avoid the detachment of activated carbon by age.
- ✓ Pumping speeds (H) of 15~20 [m^3/s] were realized with the cryo-sorption pump of ~0.57m^2 pumping area [2].
- ✓ The developed new cryo-sorption pump contributes to the better density control in the long pulse discharge. An improvement in core transport was also observed with the use of the in-vessel pump [3,4]







[1] T. Murase *et al.*, PFR **11** (2016) 1205030, [2] T. Murase *et al.*, J. Plasma Fusion Res. **93** (2017) 213
[3] G. Motojima *et al.*, Phys. Scr. **97** (2022) 035601, [4] G. Motojima *et al.*, IAEA-FEC 2023

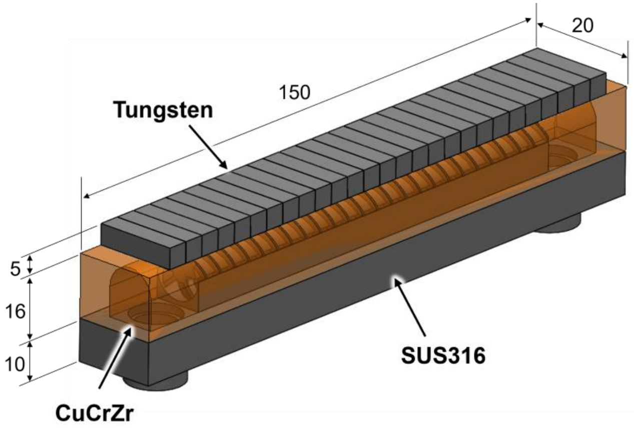
Development of full metal divertor target plate [1]

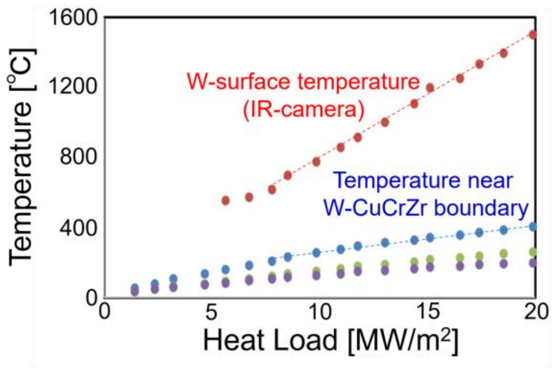
In order to explore the effect of high recycling plasma facing components on the plasma performance and the plasma-wall interaction, full metal divertor target plate was developed.

- ✓ Tungsten (W) plates were attached to a CuCrZr block with water cooling channel
- ✓ A new Spark Plasma Sintering (SPS) technique was developed for the bonding between W and CuCrZr layers.
- ✓ Heat load test up to 20MW/m^2 was performed for 10 min. with electron-beam irradiation at ACT2.

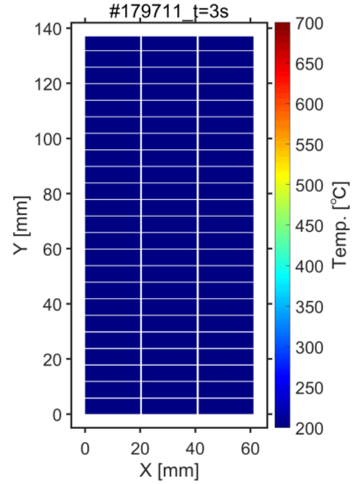
  ⇒No crack and peeling were observed at the W-CuCrZr boundary.
- ✓ The plate was also tested at the diverter region of LHD and the 830 times of heat loads exceeding 15MW/m^2 were applied.

  ⇒No significant damage was observed at the target surface.





Temperature rise with 10 min. heat load with electron-beam using ACT2 at NIFS



(Left) Surface temperature of the target during the test at LHD
(Right) Phots of the target surface after the exp. campaing

[1] T. Murase *et al.*. This conf. PS3-17

SUMMARY

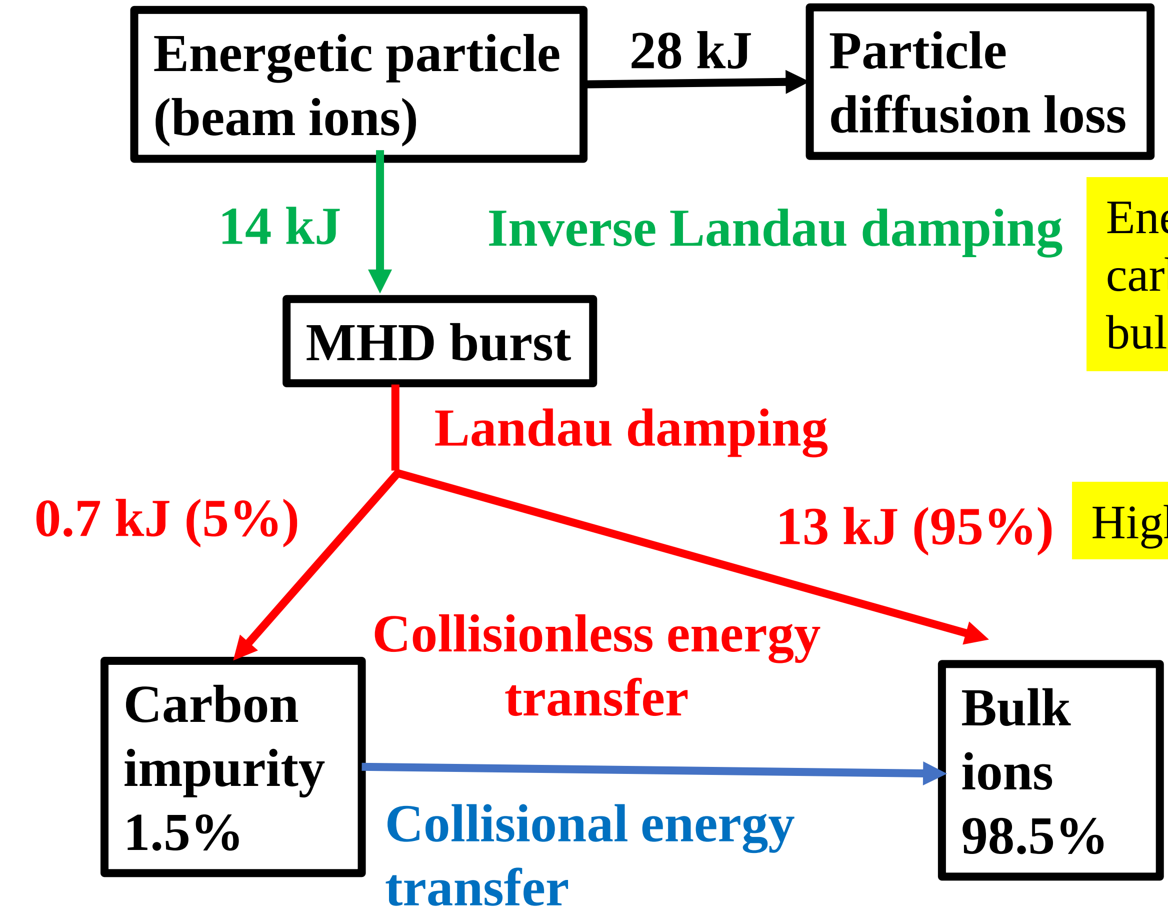
- Deuterium experiment was performed on LHD from March 2017 to December 2022.
- In plasma physics;
  1. Temperature domain of LHD was successfully extended to (T_{i0}, T_{e0})=(10, 8.1) or (8.7,8.7) [keV].
  2. Isotope effects were observed and examined for various conditions. [1]
  3. Good energetic particle confinement property, which is almost equivalent to similar size tokamak, were demonstrated by T burn-up exp. (T burn-up ratio of 0.45% achieved.)
  4. The alpha channeling like phenomena in toroidal plasmas was observed for the 1st time in the world.
- As engineering aspects;
  1. The isotope effect in negative-ion source for NBI, i.e., increase of co-extracted electron beam, was examined and showed the method, i.e. EF, to solve this problem.
  2. T-inventory was studied. Detailed analysis was performed for the 1st D-exp. campaign.
     - ✓ The 6.0GBq of T was produced by the DD reaction and 2.1GBq was exhausted through the pump.
     - ✓ The 2.0GBq of T is expected to remain on the surface of divertor target plates.
     - ✓ The rest is1.9GBq and the location of remaining T needs to be identified.
  3. A new in-vessel organic-adhesive-free cryo-sorption pump was developed
     - ✓ Pumping speeds (H) of 15~20 [m^3/s] were realized with the cryo-sorption pump of ~0.57m^2 pumping area.
  4. A new full metal divertor target plate using SPS techniques was also developed
     - ✓ Heat load test up to 20MW/m^2 was performed with 10 min. electron-beam irradiation at ACT2
     - ✓ The 830 times of heat loads exceeding 15MW/m^2 were applied at the divertor region of LHD

     ⇒ No significant damage observed at both of the tests.

[1] M. Osakabe *et al.*, NF **62** (2022) 042019

Thank you for your attention

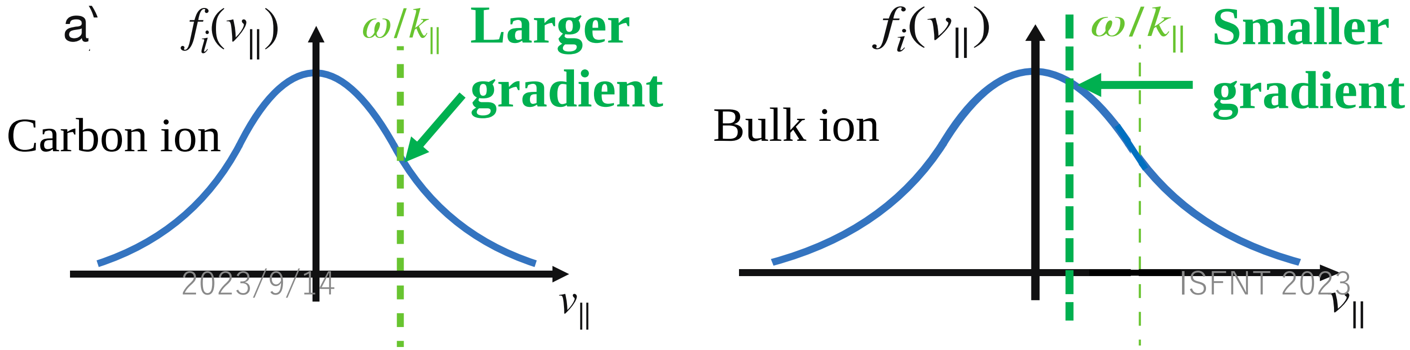
Collisionless energy transfer is observed

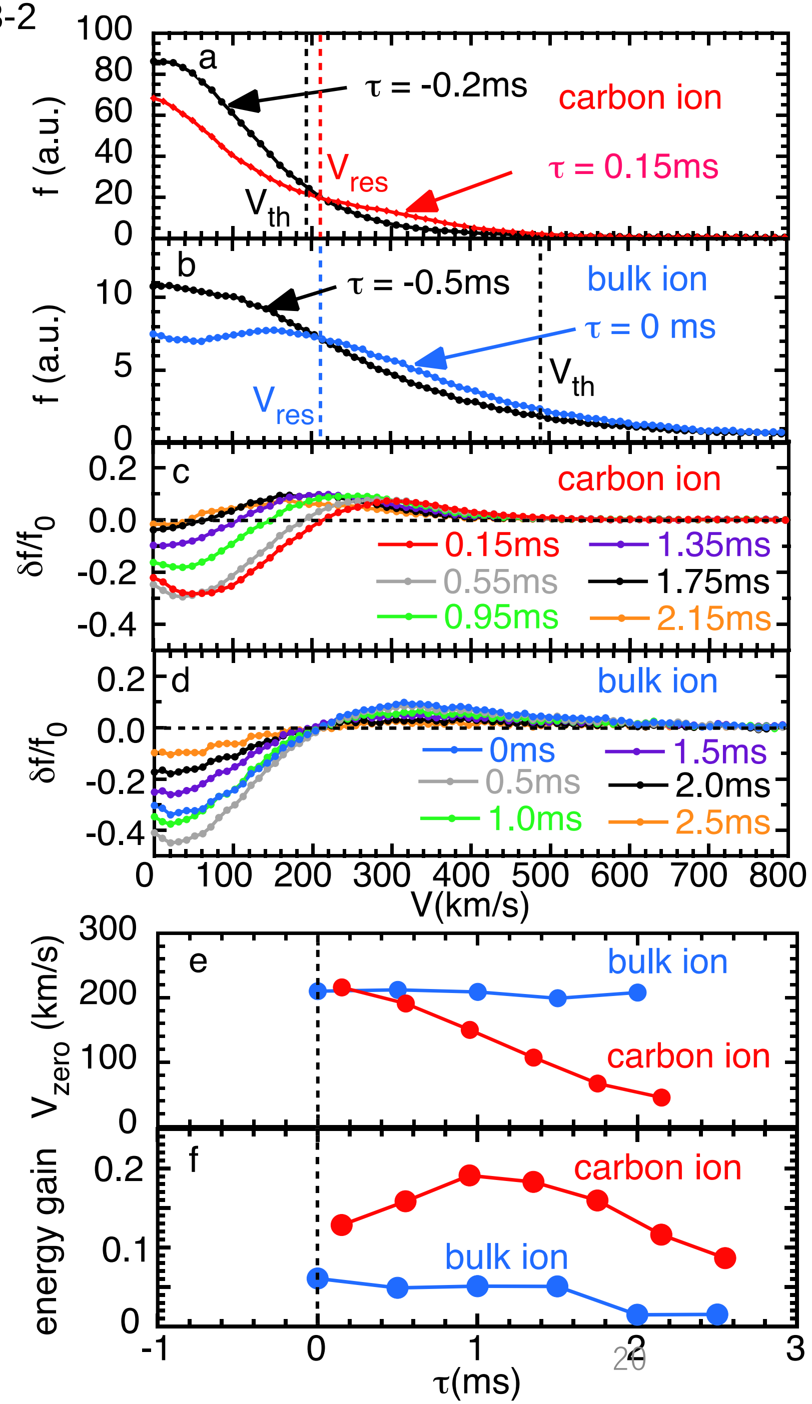


Energy transfer rate to carbon is high than that to bulk ion (deuterium)

Higher efficiency for heavier

Insight of isotope effect of collisionless energy transfer



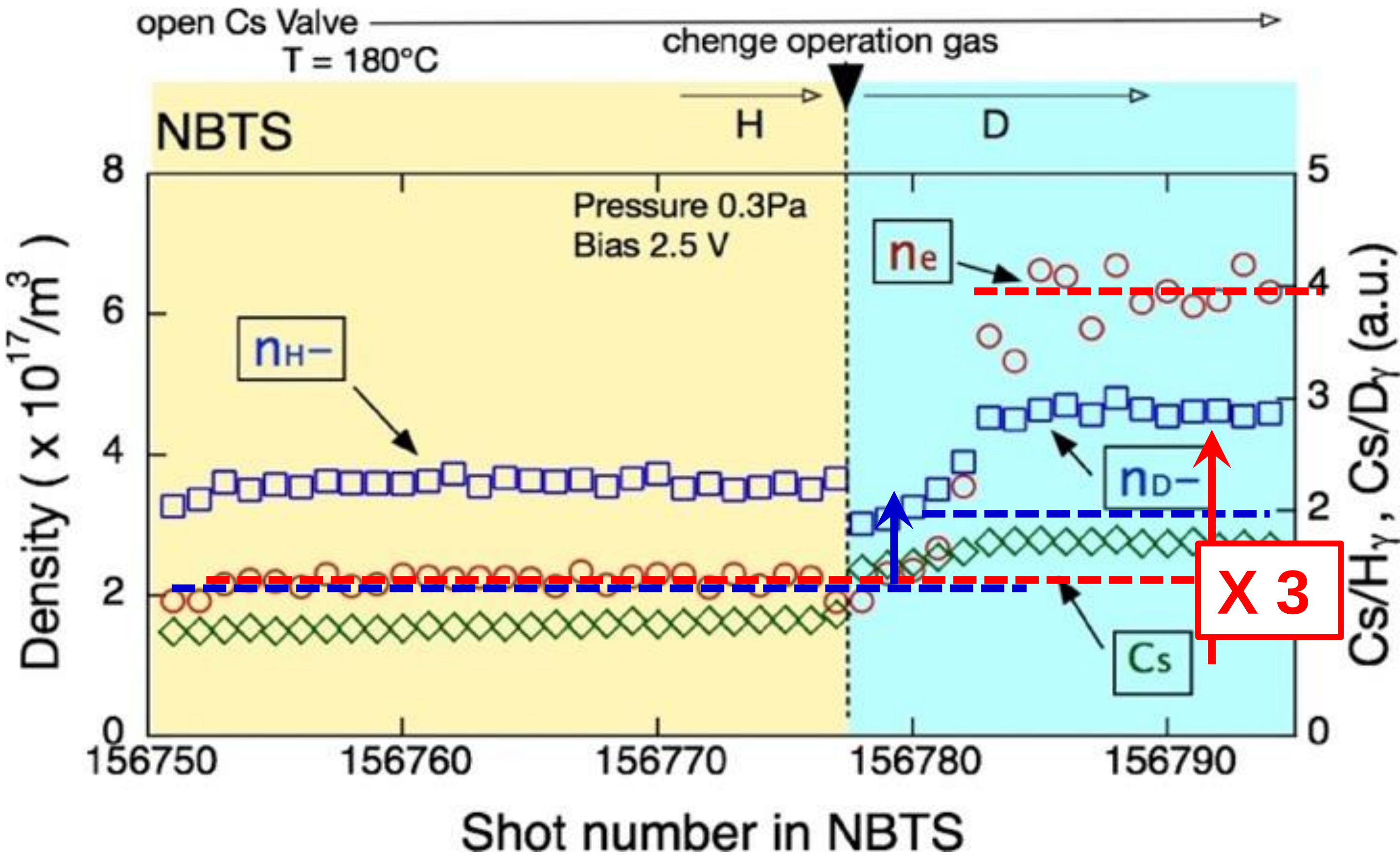


Effect of negative-ion production is evaluated using R&D ion-source at the NB test stand

Changing the ion-species of ion-source plasma fro H to D,

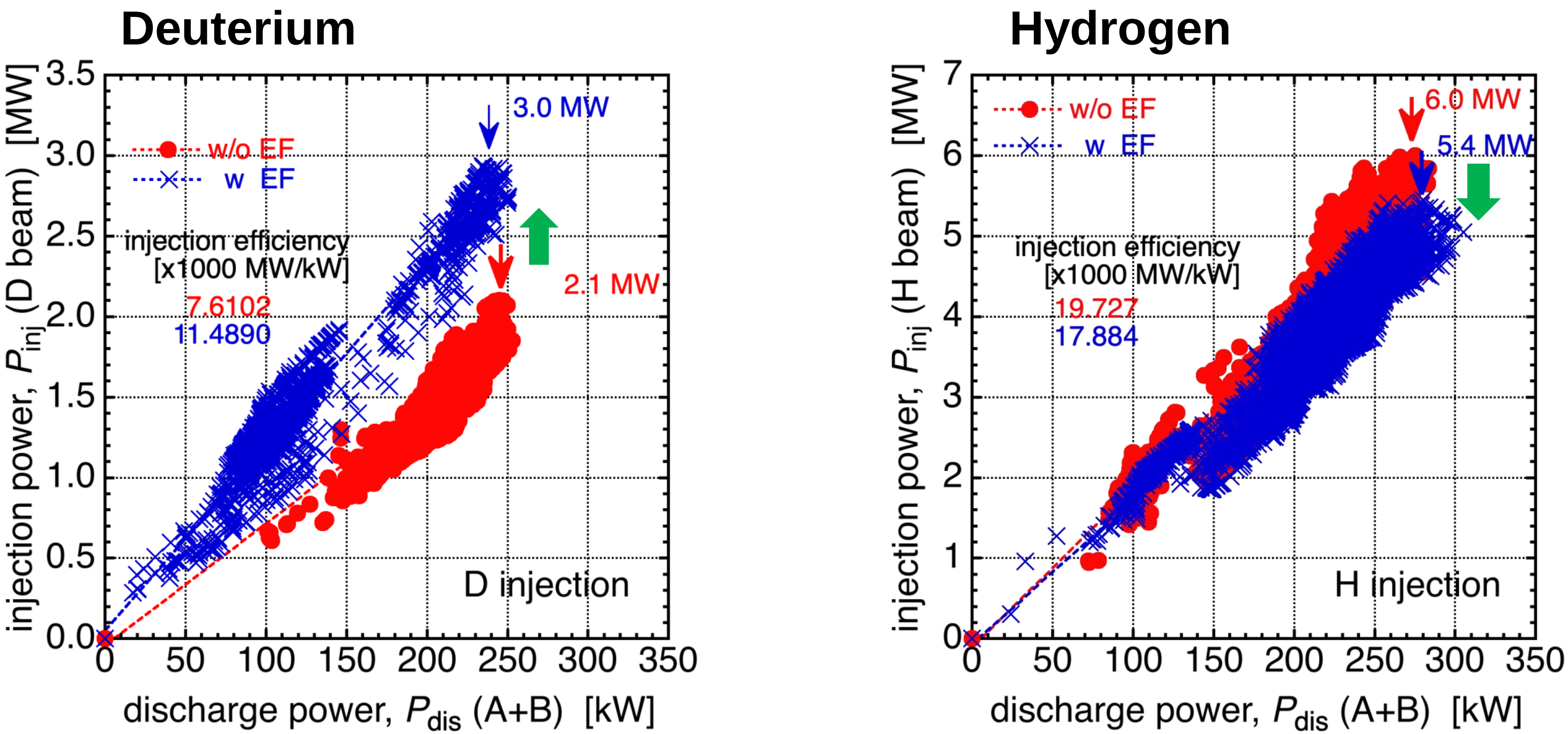
✓Negative-ion density becomes 1.3 times larger in D than in H

✓Electron density becomes 3 times larger in D than in H

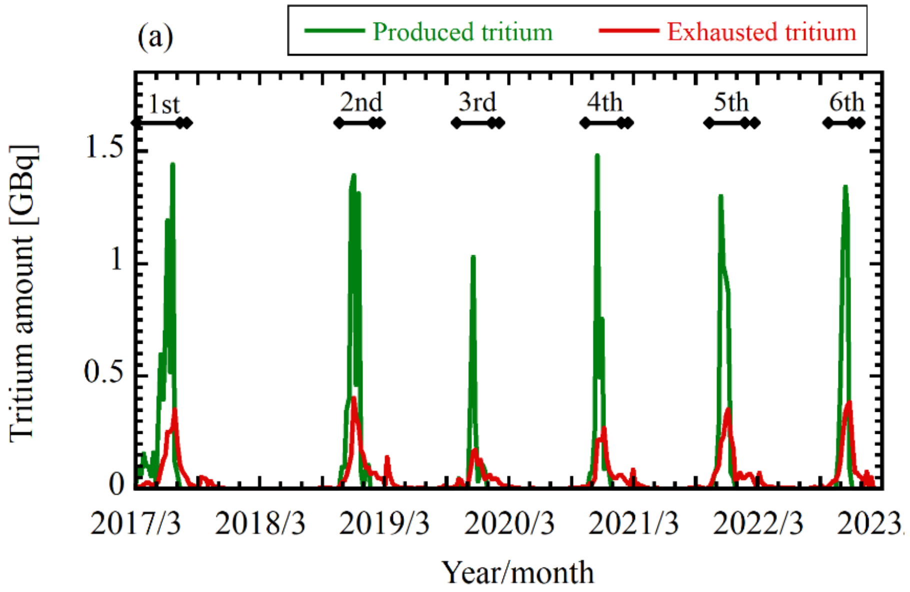


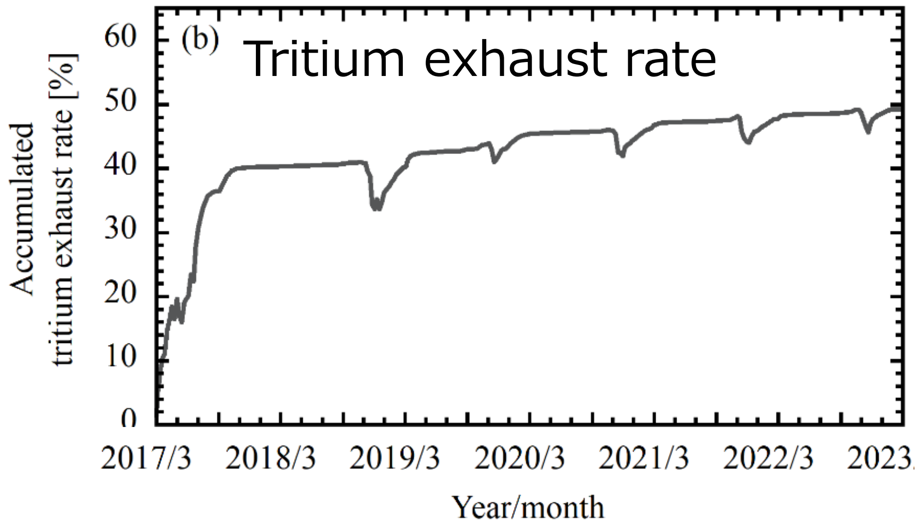
H. Nakano *et al.*, (2016) *J. Instrum.* **11** C03018

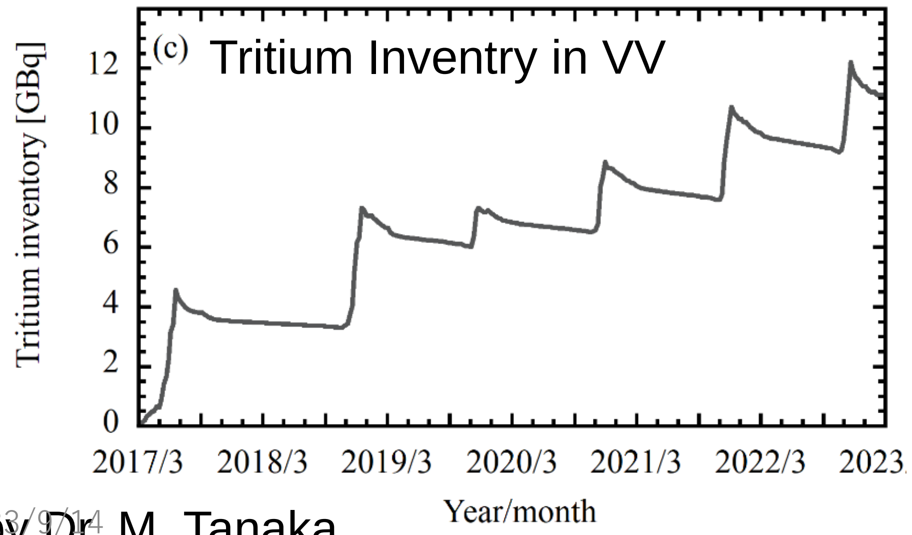
EF contributes injection power of N-NBI in D, while it reduces the power in H



Tritium Mass balance during the whole D-exp. campaigns







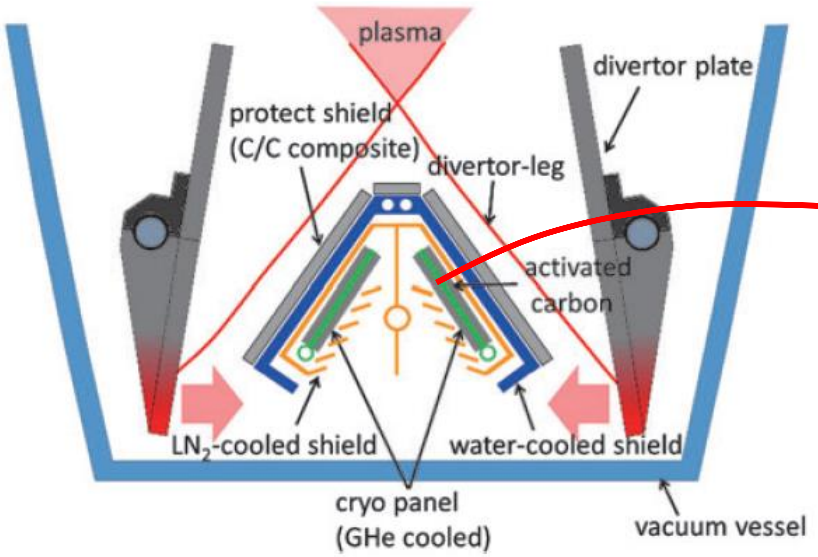
- Tritium inventry for the whole D-exp. Campaigns is estimated to be ~11GBq
- The accumulated tritium exhaust rate is also estimated to be ~50%

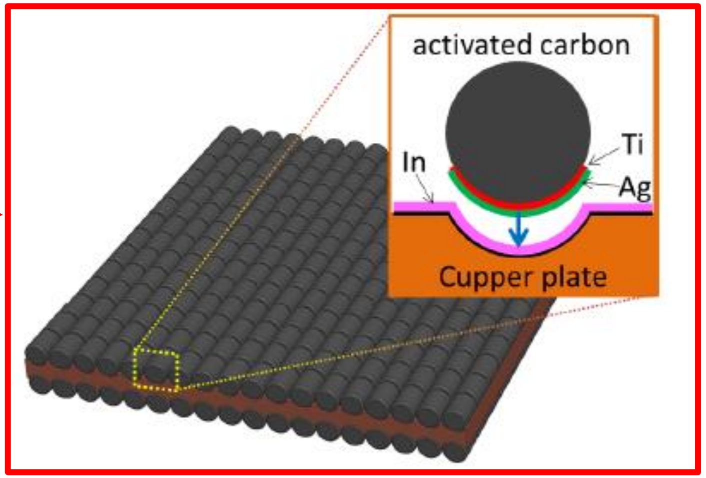
Courtesy by Dr. M. Tanaka

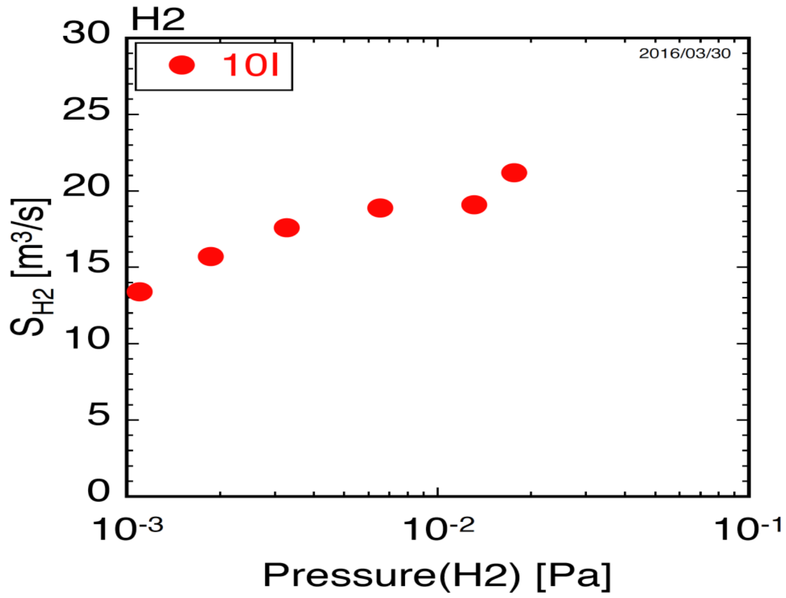
In-vessel cryo-sorption pump was newly developed

An organic adhesive free cryo-sorption was newly developed for the Closed Helical Divertor of LHD[1].

- A low melting point metal (In) was used as an adhesive in order to avoid the unfavorable outgassing during non-cooled phase of the pump and also to avoid the detachment of activated carbon by age.
- **Pumping speeds (H) of 15~20 [m^3/s] were realized with the cryo-sorption pump of ~0.57m^2 pumping area [2].**



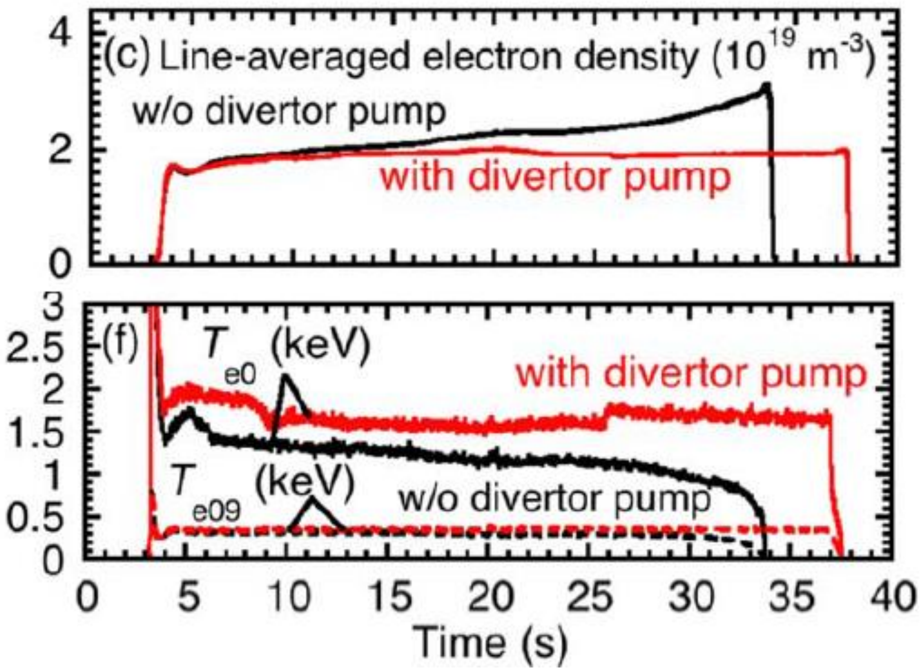




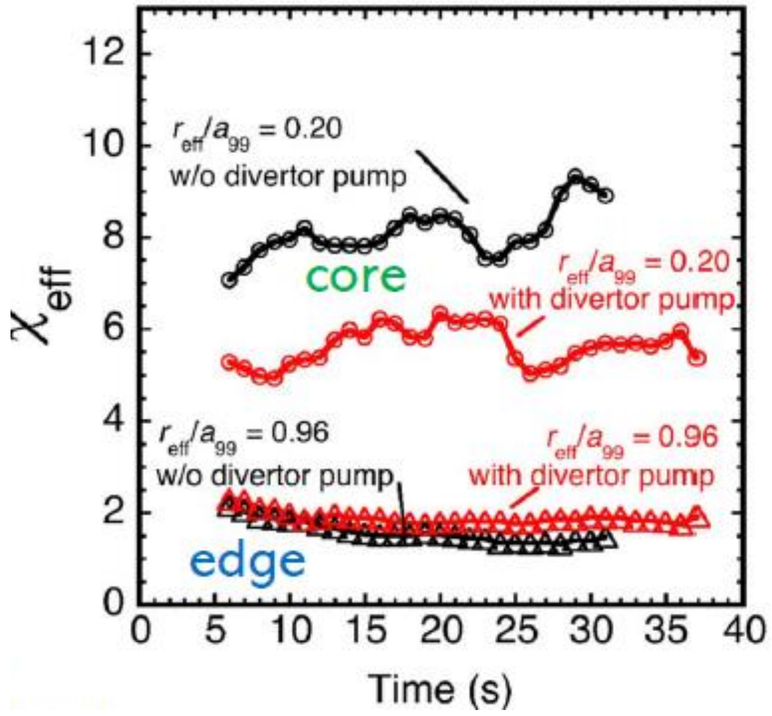
[1] T. Murase *et al*., PFR **11** (2016) 1205030, [2] T. Murase *et al*., J. Plasma Fusion Res. **93** (2017) 213

The developed new cryo-sorption pump contributes to the better density control in the long pulse discharge[1,2]

- ✓ Without the cryo-sorption pump, plasma collapse at 34s.
- ✓ With the cryo-sorption pump, no-collapse occurred until the end of the discharge.



- ✓ Improvement in core transport was observed with the cryo-sorption pump, although the edge transport remained same.



[1] G. Motojima *et al*., Phys. Scr. **97** (2022) 035601, [2] G. Motojima *et al*., IAEA-FEC 2023

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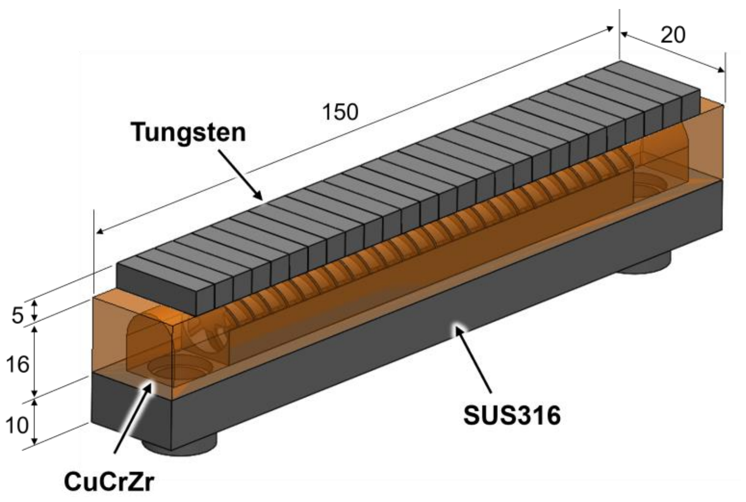
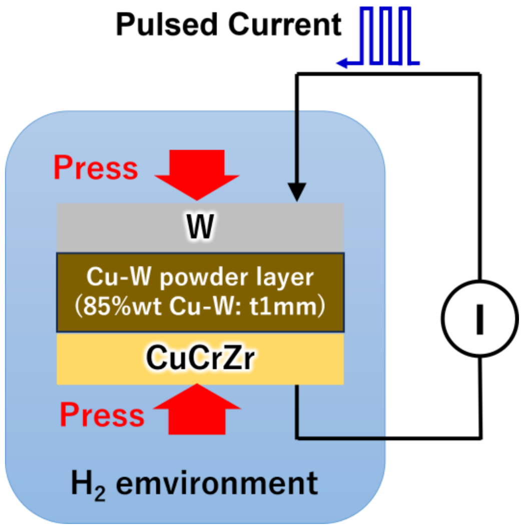
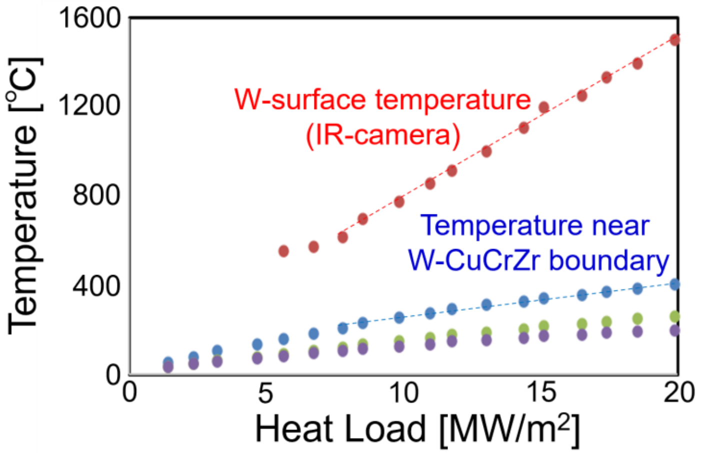
- ✓ A new Spark Plasma Sintering (SPS) technique was developed for the bonding between W and CuCrZr layers.
- ✓ Heat load test up to 20MW/m^2 was performed with 10 min. electron-beam irradiation at ACT2. No crack and peeling were observed at the W-CuCrZr boundary.





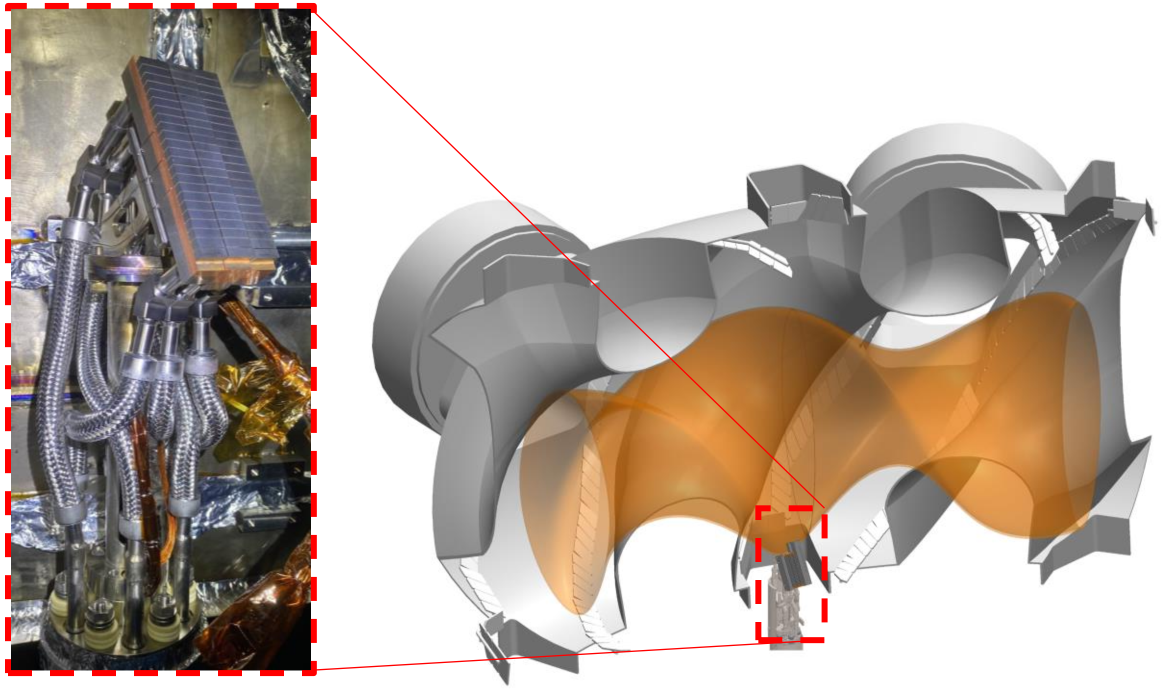


Temperature rise with 10 min. heat load with electron-beam using ACT2 at NIFS

Exposure test of W-target plates at the LHD plasmas

The developed W-target plates were tested with LHD-plasmas.

- The 830 times of the heat loads exceeding 15MW/m^2 were applied to the target plates at the divertor region of LHD plasmas
- No significant damages were observed with these exposures.



Courtesy by Mr. T. Murase Please visit his presentation at this conf.(PS3-17).