# Extension of Operational Regime of LHD towards Deuterium Experiment

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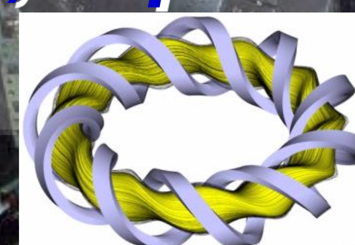
*SOKENDAI, Japan*



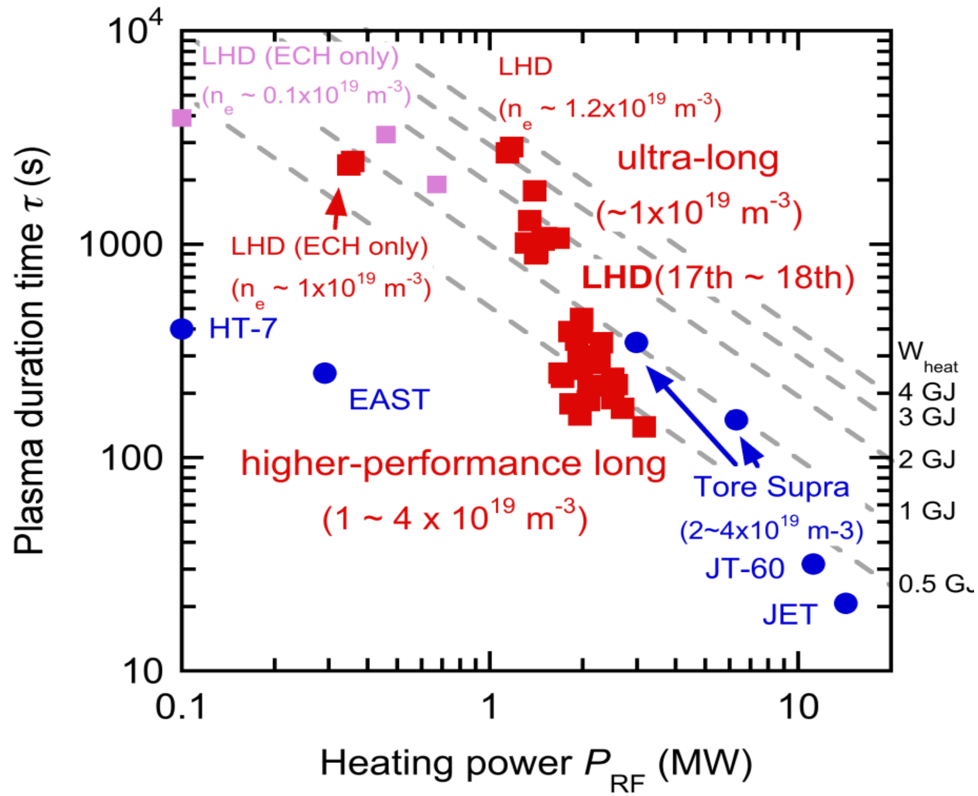
26th IAEA Fusion Energy Conference, Oct. 17-22, 2016, Kyoto, Japan

# Significance of LHD in the world fusion research

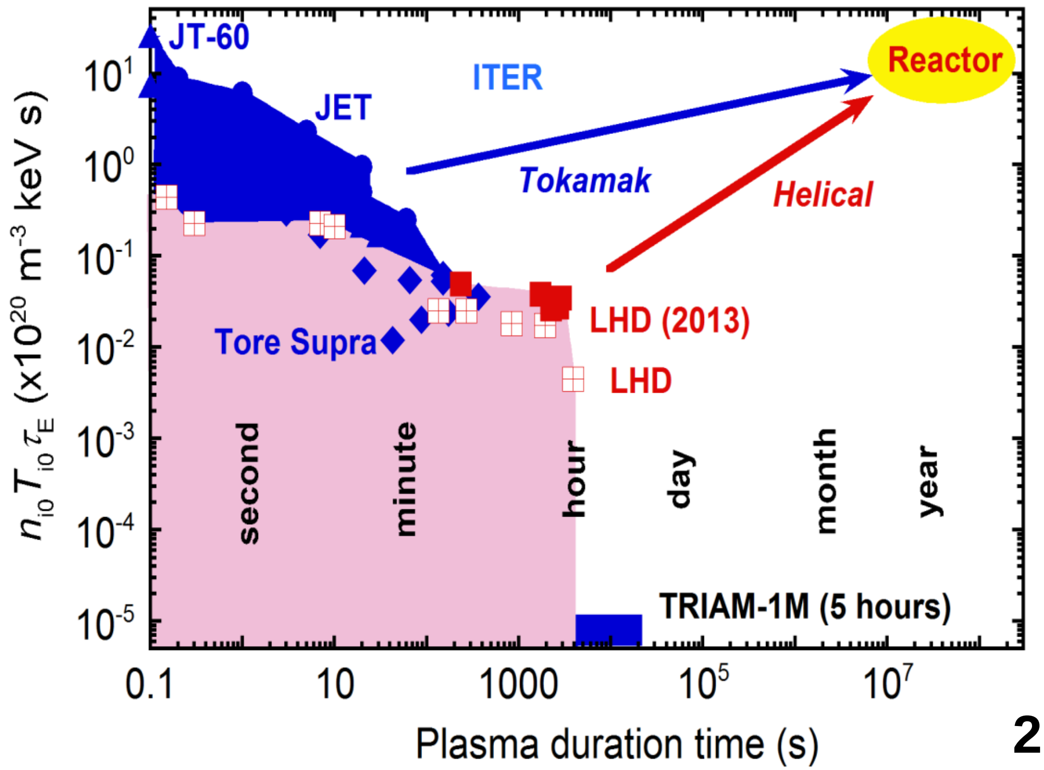
- High-performance steady-state plasmas is required to realize fusion reactor
- LHD is based on Japan-originated heliotron concept, and the world-largest class of superconducting fusion device
- LHD has demonstrated its inherent advantage for steady-state operation

*Duration: 47min.39sec*

*2keV, 1.2 ×$10^{19}$m$^{-3}$, 1.2MW,* ***3.36GJ***




*towards steady-state*
*high-performance regime*



# Progress towards high-performance plasmas

- Steady increase of plasma parameters in recent years
- Coming deuterium experiment should further extend the parameters towards reactor-relevant regime, in which advanced research can be performed for establishing firm basis for steady-state helical reactor

| Parameters | Achieved | Key physics | Target |
|---|---|---|---|
| $T_i$ | 8.1 keV ($n_e = 1\times10^{19}$ m$^{-3}$) | **Ion ITB**<br>**Impurity hole** | 10 keV<br>($n_e = 2\times10^{19}$m$^{-3}$) |
| $T_e$ | 20 keV (2×10$^{18}$ m$^{-3}$)<br>10 keV (1.6×10$^{19}$ m$^{-3}$) | **Electron ITB** | 10 keV<br>(2×10$^{19}$m$^{-3}$) |
| **Density** | 1.2×10$^{21}$m$^{-3}$ ($T_e$ = 0.25 keV) | **Super dense core** | 4×10$^{20}$ m$^{-3}$<br>($T_e$ = 1.3 keV) |
| $\beta$ | 5.1 % ($B_T$ = 0.425 T)<br>4.1 % (1 T) | **MHD in current-free plasmas** | 5 %<br>($B_T$ = 1 - 2 T) |
| **Steady-state operation** | 54min. 28sec<br>(0.5MW, 1keV, 4×10$^{18}$m$^{-3}$)<br>47min. 39sec.<br>(1.2MW, 2keV, 1×10$^{19}$m$^{-3}$) | **Dynamic wall retention** | 1 hour<br>(3 MW) |

# Contents

1. Introduction on LHD

2. Recent progress
   - Extension of operational regime
     - high $T_i$, $T_e$
     - high $\beta$,
   - Impurity transport
   - LHD as the advanced academic platform

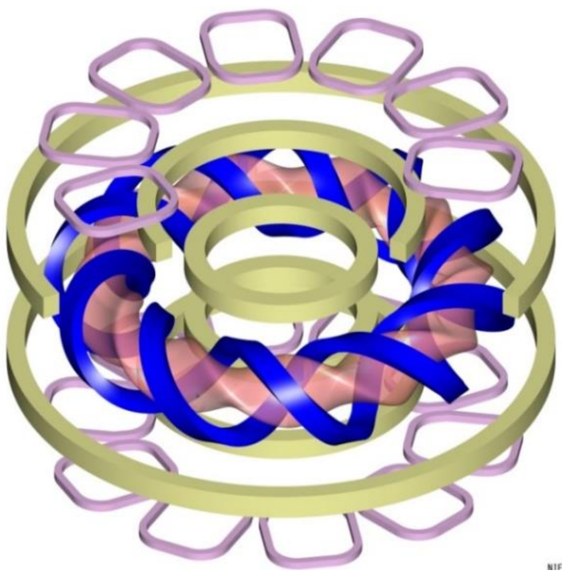
3. Deuterium experiment
   - Objects
   - Schedule
   - Hardware improvement (negative-ion based NBI)

4. Summary

# Introduction

***Large Helical Device (LHD), the largest helical device***

LHD is optimized heliotron with simply and continuously wound helical coils.



The superconducting LHD has been operated since 1998 **without any severe cryogenic troubles**.

*FIP/3-4Rc, Takahata*

**Specification**

- Helical mode numbers: *l*/*m*=2/10
- All superconducting coil system
- Plasma major radius: 3.42-4.1 m
- Plasma minor radius: 0.63 m
- Plasma volume: 30 $m^3$
- Toroidal field strength: 3 T
- 20 RMP coils

**Heating Systems**

- negative-NBI x 3
  H-inj. 180 keV, 16MW
- positive-NBI x 2
  H-inj. 40-50 keV, 12MW
- ECH (77 GHz x 3, 154 GHz x 2, 82.7 GHz, 84 GHz), 5.4MW (0.6 MW CW)
- ICH (20 –100 MHz) x 6 3 MW

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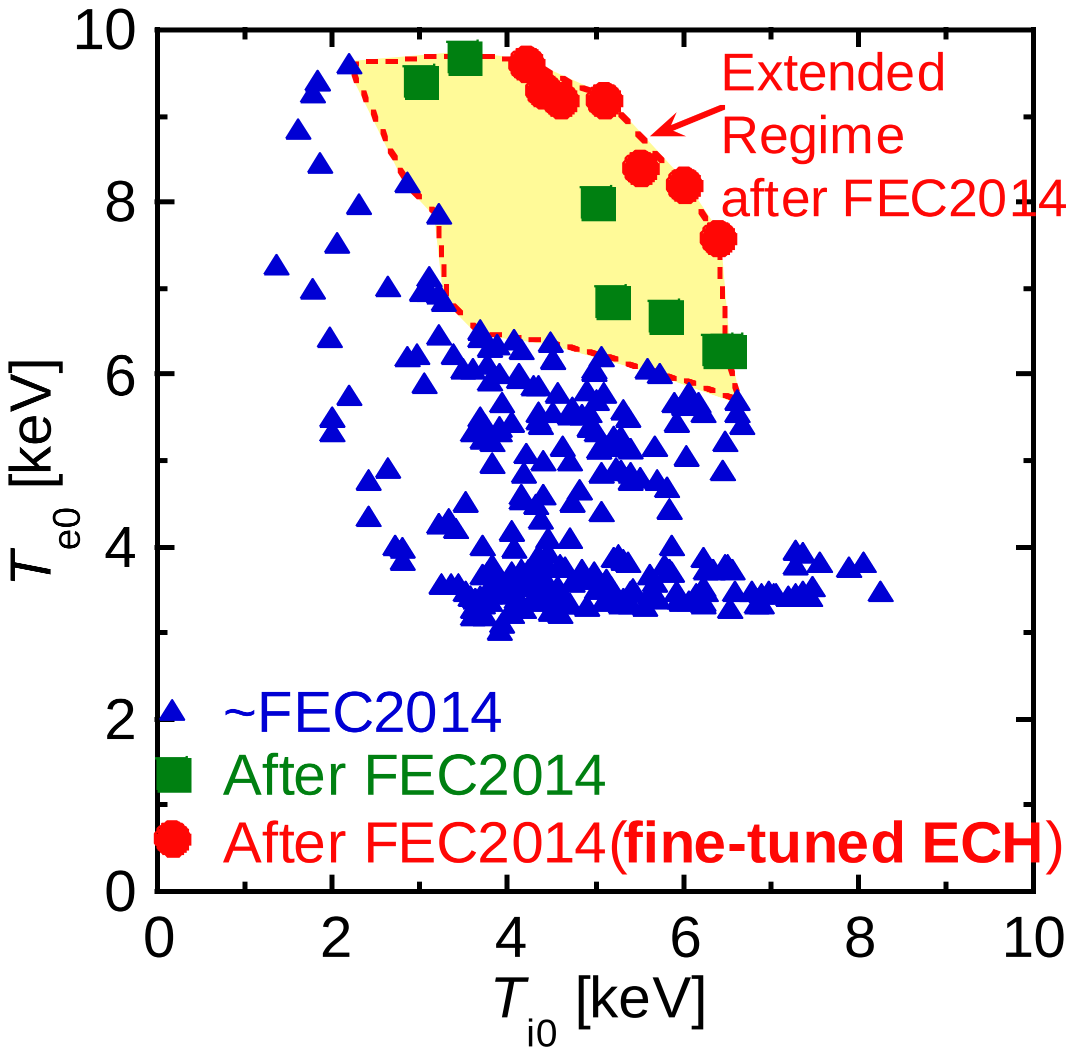
# Extension of temperature regime

***Plasma control and physics findings extended temperature regime***

*PPC/1-1, Takahashi (Wed)*




- *T*i had been extended to above 8 keV (ion ITB) (FEC2014, Nagaoka)
- ICH/ECH wall conditioning is effective to reduce recycling, leading to enhancement of NB penetration to the core region.

*EX/P8-2, Tsujimura*

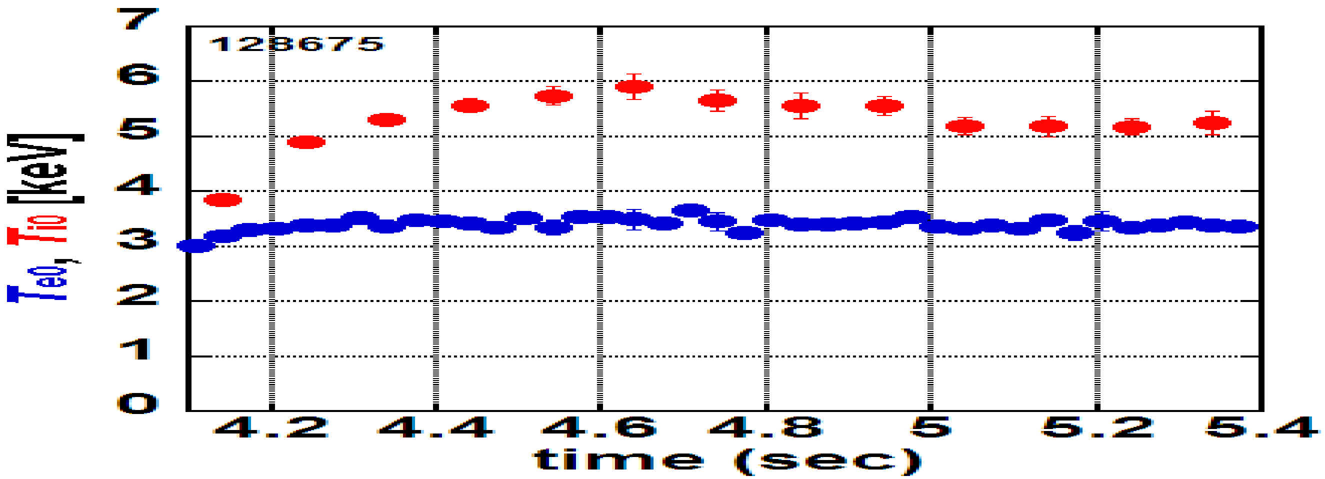
- Feedback ECH optimization for fine-tuned ECH is applied onto high-*T*i plasmas
  → Extended temperature regime to high *T*i and *T*e, simultaneously reaching around 6 and 8 keV, respectively.

# Study on Impurity hole has progressed

***Density profile: Carbon and helium ions are hollow, while bulk ion is peaked***

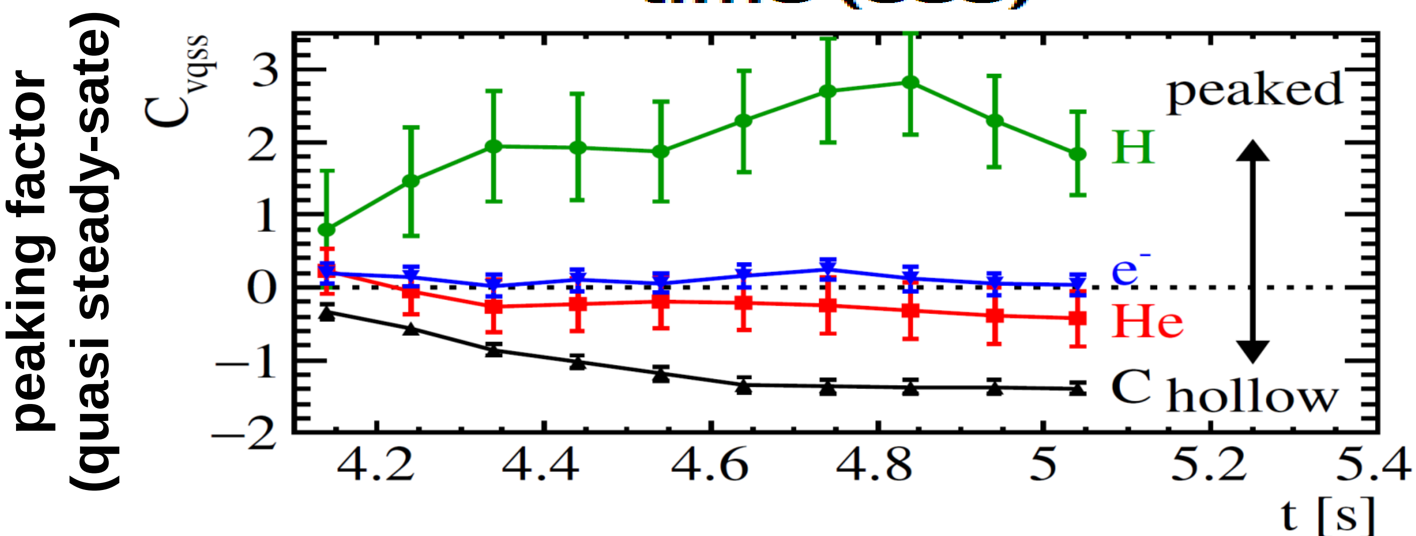
Radial density profiles of bulk and impurity ions are simultaneously measured by CXS

A. Perek, K. Ida et al., to be submitted to NF (2016).




Ti ~ 5-6 keV

Te~ 3-4 keV




H: peaked

C, He: hollow

# Strategy of high-beta plasma production

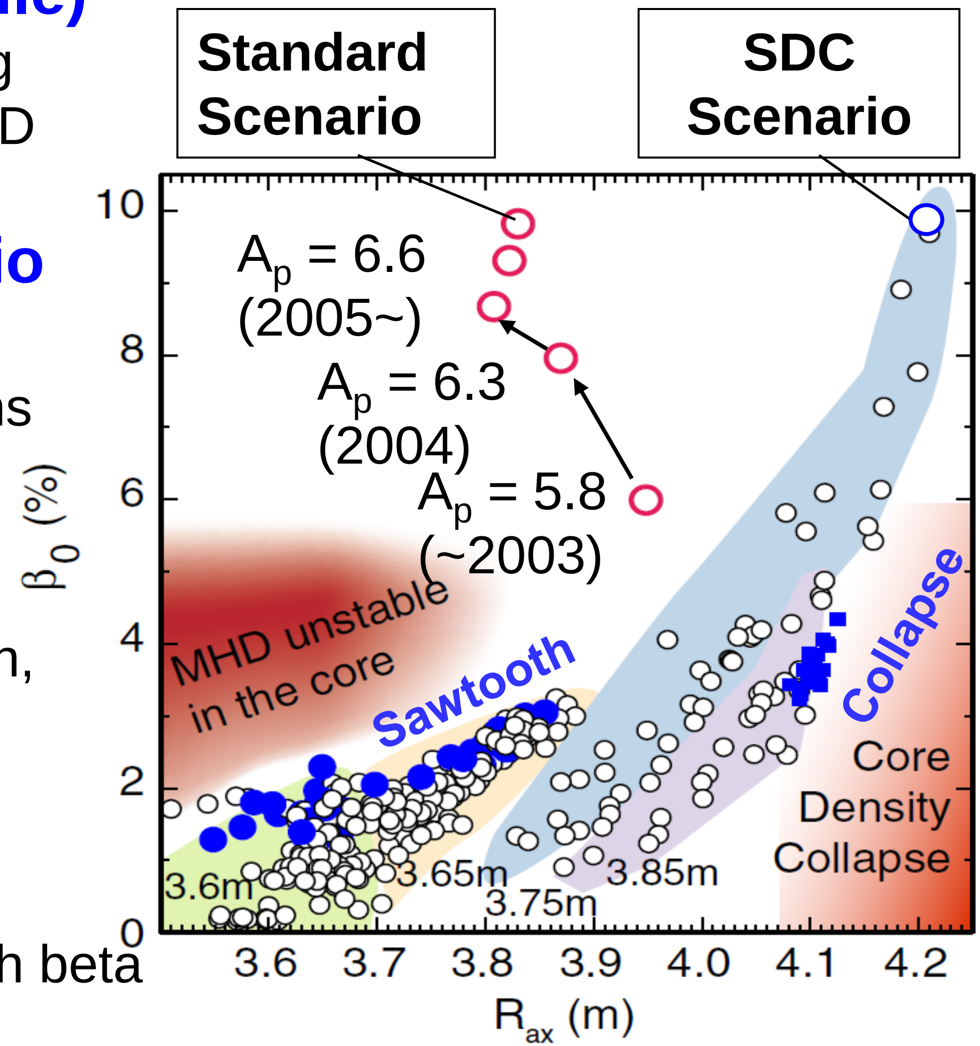
**High beta has been realized with two scenarios in previous experiments**

## Standard scenario (broad *P*-profile)

- Low $A_p$ configuration to increase heating efficiency, and to optimize transport, MHD
- **$\langle\beta\rangle$ of 5.1 %** was obtained at **low-$B_t$**

## SDC (Super Dense Core) scenario (peaked *P*-profile)

- Peaked P profile by multi-pellet injections
- High density (> $10^{20}$ $m^{-3}$)




Towards more reactor-relevant research, high beta plasmas in low-collisional regime are necessary

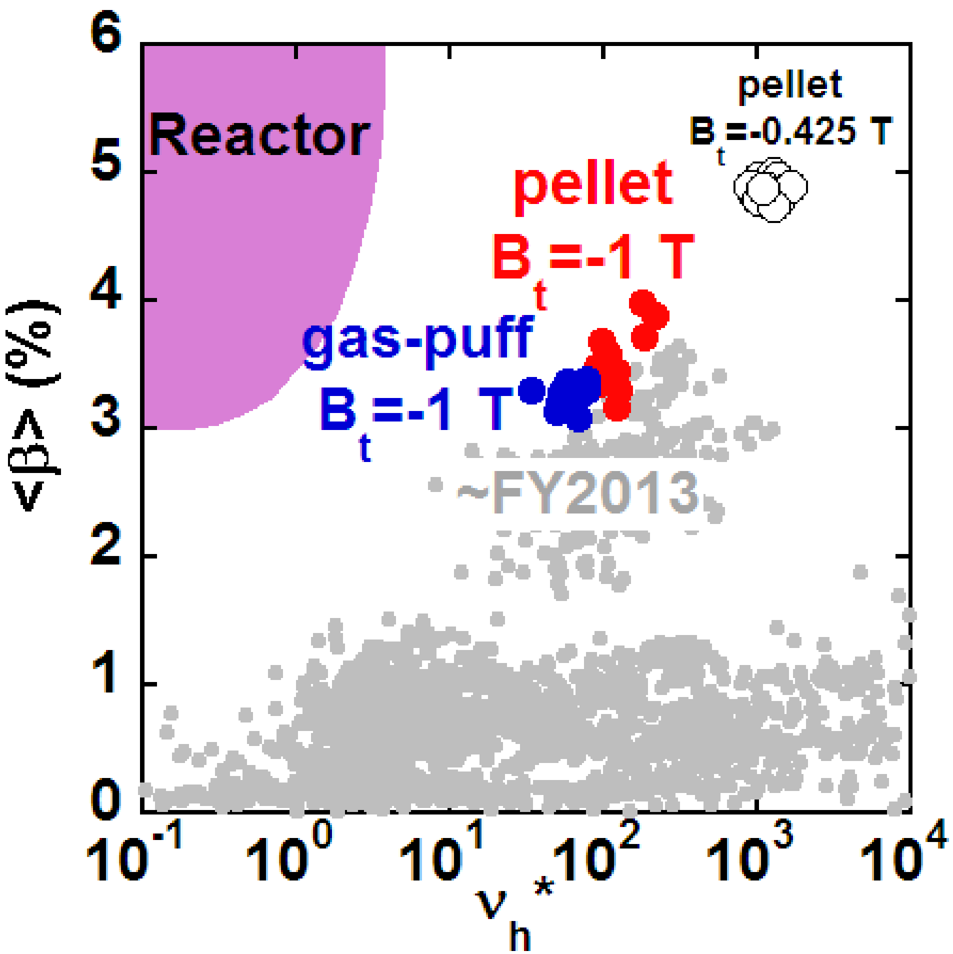
Realization of high temperature and high beta plasma in inward shifted configuration

# High $\beta$ trial in low collisional regime

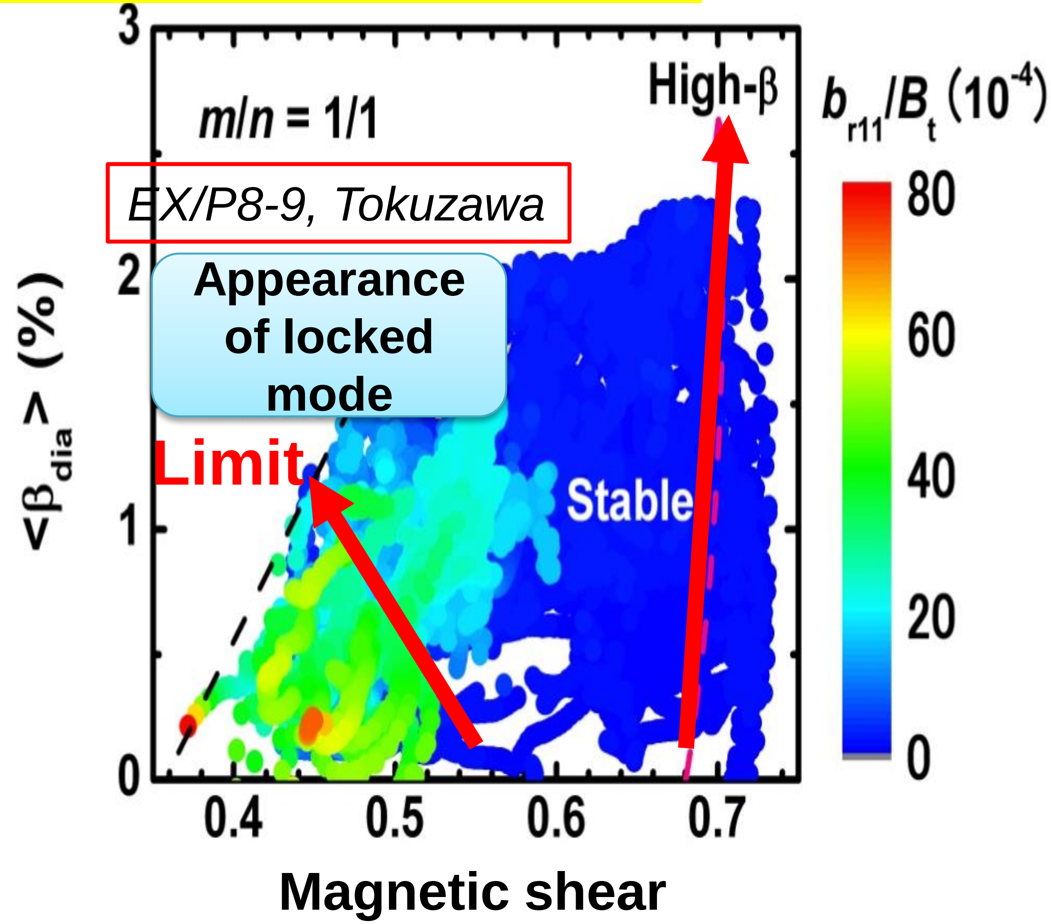
***High beta operation has been extended to low collisional regime***

*EX/4-4, Sakakibara (Wed)*

$R_{ax}^{v}$ = 3.56 m, ***B*$_t$ = -1T**, $A_p$ = 5.8




*EX/P8-9, Tokuzawa*




**Multi-pellet injections (Maximum beta)**

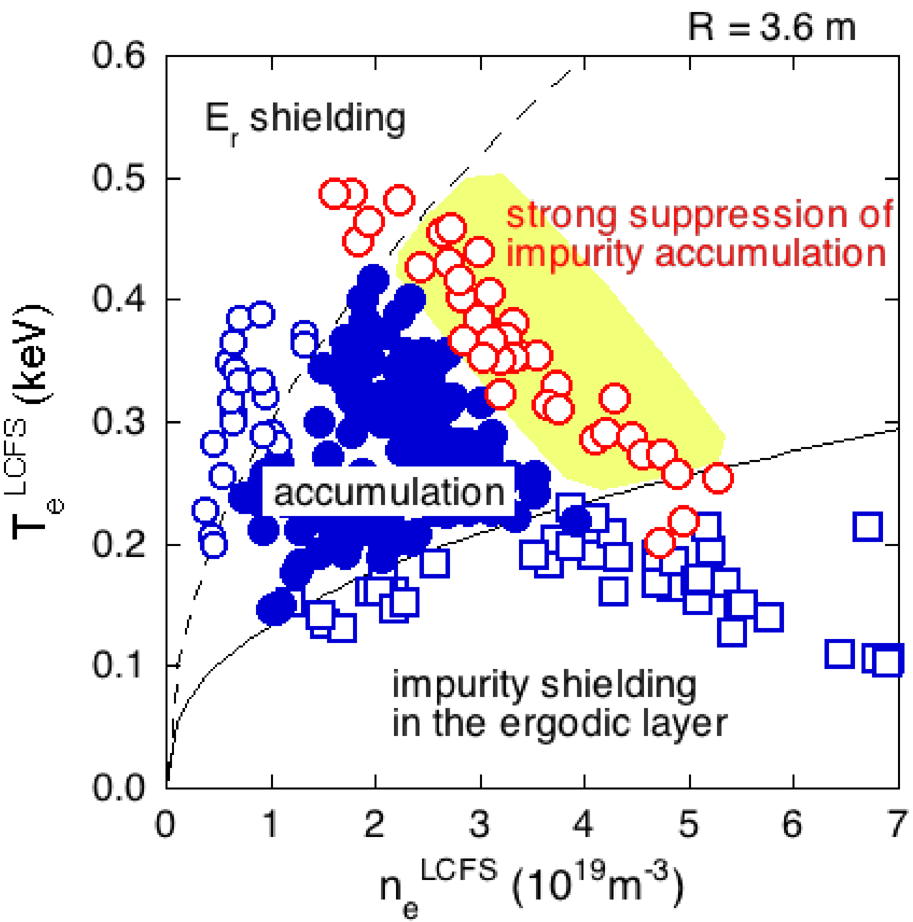
⇒**4.1** %（$T_{e0}$ = 0.9 keV, $n_{e0}$ = 6 × $10^{19}$ $m^{-3}$)

**Gas puffing (Quasi-steady state)**

⇒**3.4** %（$T_{e0}$ = 1.2 keV, $n_{e0}$ = 3 × $10^{19}$ $m^{-3}$)

# Impurity transport in core region

***Strong suppression of accumulation behavior is observed in impurity accumulation window, during high power heating***




*EX/P8-4, Nakamura*

Impurity accumulation window exists with boundaries determined by

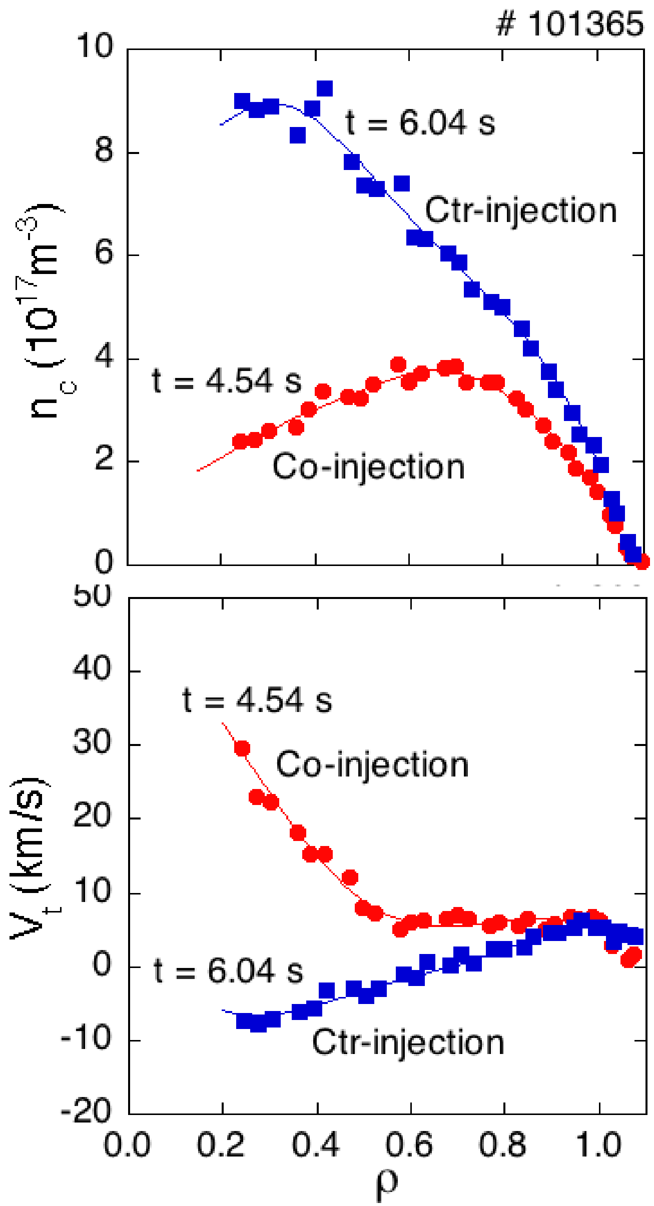
1) $E_r$
2) edge stochastic layer
3) NBI (power, torque), etc.

- *experimentally confirmed*

- *newly found*
- *including impurity hole in high T regime*

*TH/P2-3, Nunami*

# Impact of NBI torque input on impurity transport




***It is suggested that NBI torque plays an important role in exhausting C impurity***

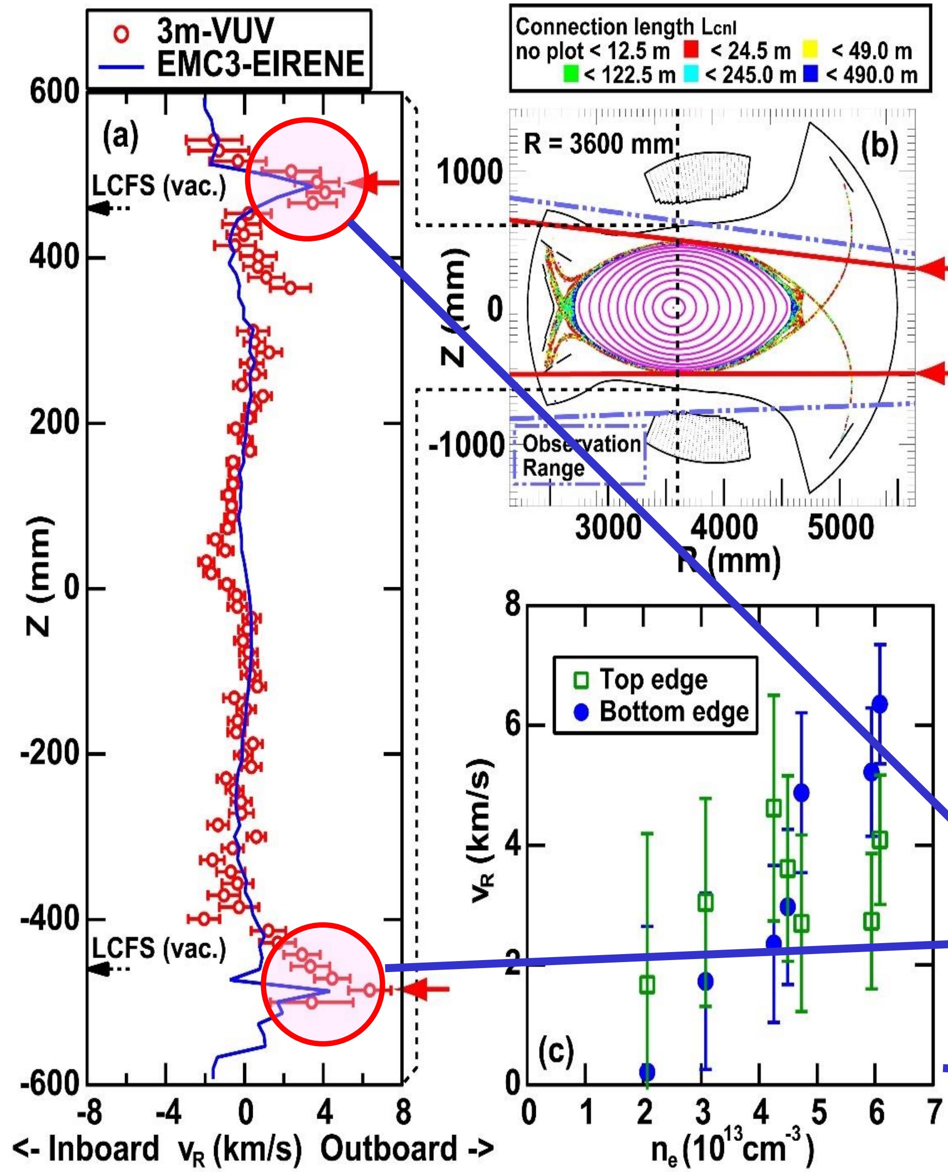
When NBI torque input direction is switched from co- to ctr-injection,

- little change in $T_e$ and $T_i$ is observed
- drastic change of $n_C$ profile is observed in response to the rotation parameters ($V_t$ and $u_c'$)
- $n_C$ profile is hollow in the co-injection
- $n_C$ profile is observed to be peaked in the ctr-injection

On the other hand, it is also observed that the carbon density profile becomes hollow with increasing in the *T*i-gradient.

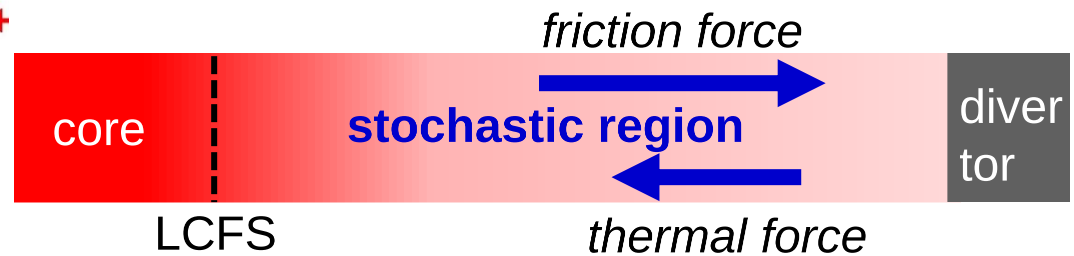
*EX/P8-4, Nakamura*

# Impurity transport in stochastic region




***Impurity flow direction in stochastic region is determined by the balance between friction and thermal forces***

***Agreement between experimental and numerical (EMC3-EIRENE) results was confirmed.***



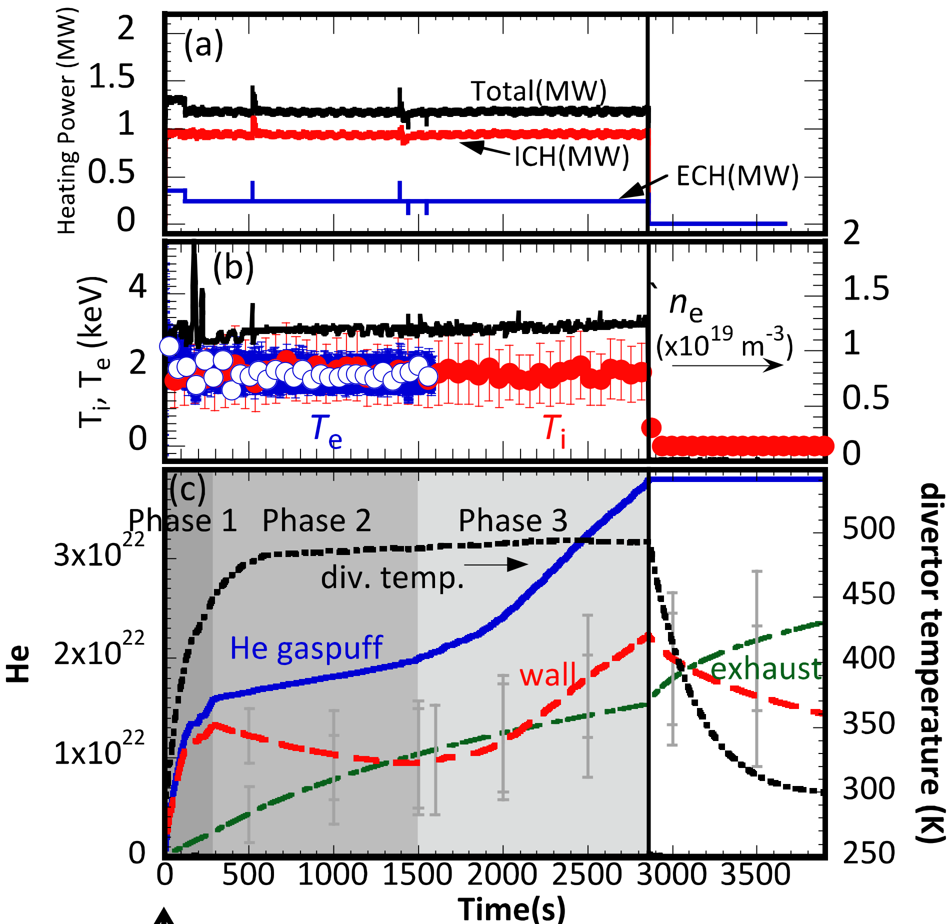

**EMC3-EIRENE model (expectation)**

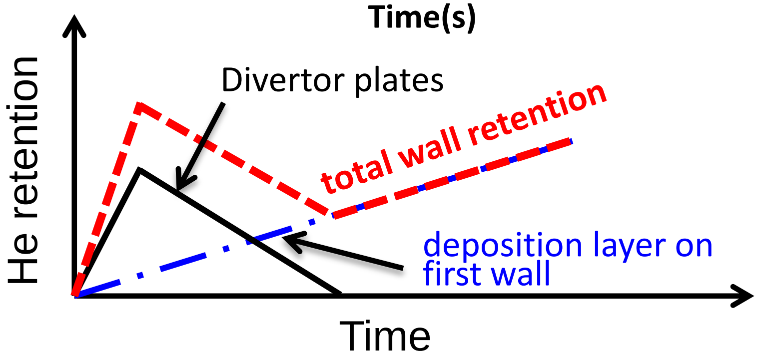
**C-flow observed by VUV spectroscopy**

- Downstream flow towards the divertor plate was experimentally observed.
- Impurity outboard flow is enhanced as $n_e$ increases.

*EX/7-2, Oishi (Fri)*

# Particle balance in steady-state plasma




***Wall does not saturate during 48 min. discharge due to deposition layers***

## Dynamic change of He retention

Three different retention phases:

1. **quite high wall pumping**
   *by implantation in divertor plates*
2. **inventory declination**
   *by out gassing due to increased surface temperature of divertor tiles*
3. **continuous wall pumping**
   *by deposition layer on the first wall*

can be explained by the global particle balance and plasma-exposed sample analyses.

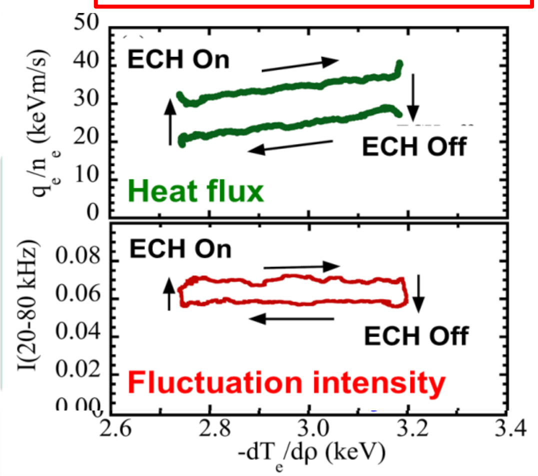
Deposition layers continuously grows during the long-pulse discharge.

*EX/P8-3, Motojima*

# LHD as the advanced academic platform

## Hysteresis in transport relation

*OV/P1-8: K.Itoh*

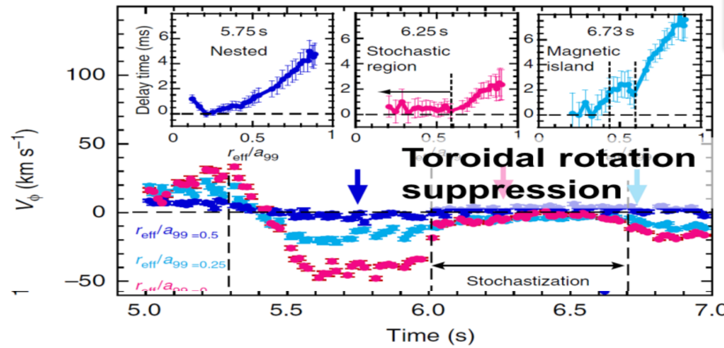



K.Ida et al., NF 55 (2015) 013022.

*EXC/P8-607: T.Kobayashi*

## Impact of stochastization on momentum transport

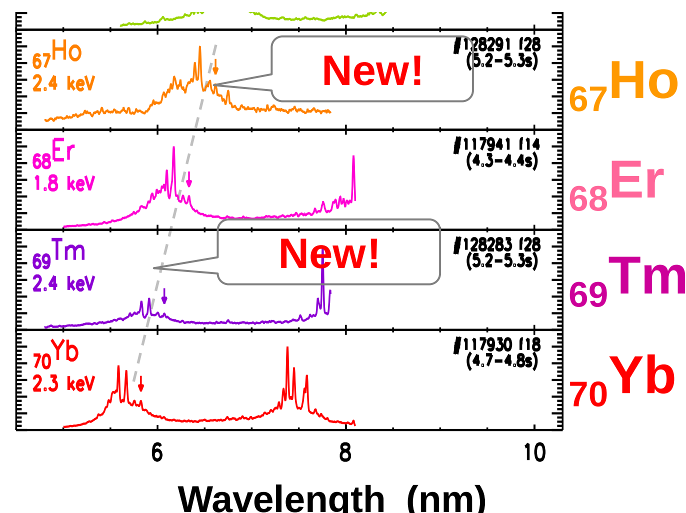
*EXC/P8-7, Ida*



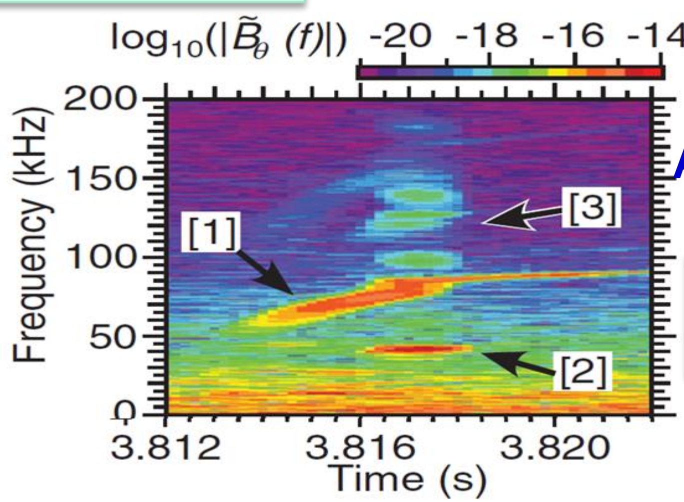

K.Ida et al., Nature Communications 6 (2015) 5816.

## Impact of high-$T_e$ laboratory plasma on fundamental physics, industry

C. Suzuki, EPS2016 Invited Talk




*EX/P8-14, D. Kato*




## Abrupt excitation of a linearly stable mode: subcritical instability

T. Ido, et al., PRL116 (2016) 015002 .
M. Lesur, et al., PRL 116 (2016) 015003.

*TH/P4-11, Wang*

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4. Summary

# Objectives of LHD deuterium experiment

1. High-performance plasmas through confinement improvement
   - ✓ Scientific research in more reactor-relevant conditions
   - ✓ Full of research opportunities
2. Clarification of the isotope effect on confinement
   - ✓ Long-standing mystery in world fusion research
   - ✓ Needs to be understood towards burning plasma
3. Demonstration of the confinement capability of energetic ions in helical systems
   - ✓ Perspectives towards helical reactor
4. Isotope effect on PWI
   - ✓ Global particle balance for hydrogen isotopes

# Schedule for LHD deuterium experiment

- *Concluded the agreements for LHD deuterium experiment with local governments in 2013*
- *Deuterium experiment will start in March 2017 and will last 9 years*

**2013 — 2016**

**Preparation for D-experiment**

Hydrogen Experiments

Agreements for D-exp.

**Legal License**

Upgrade for Heating System (NBI, ECH, ICRF)

Upgrade for Diagnostics System (Neutron diagnostics, etc.)

Installation of Safety Equipments (Tritium removal system, etc.)

Remodeling of Building and Facilities

Calibration Experiments for Neutron Diagnostics

**2017 — 2025**

**Deuterium Experiments (9 years)**

**Preliminary Experiments for Commissioning**

Deuterium Experiments

Closed Helical Divertor with Pumping System

NBI: 18MW (60-80keV, 2sec)
14MW (180keV, 2sec)
ECH: 6MW-3sec, 1MW-CW
(77GHz & 154GHz)
ICRF: 6MW-5sec, 2-3MW-CW

Neutron Diagnostics
High-energy Particle Measurement
3-Dimensional Measurement
High-Accuracy Measurement
Divertor Diagnostics
Steady-State Data Acquisition

PWI Laboratory

**Target in D-Exp.**

**$T_i$ = 10keV at $2\times10^{19}$ $m^{-3}$**

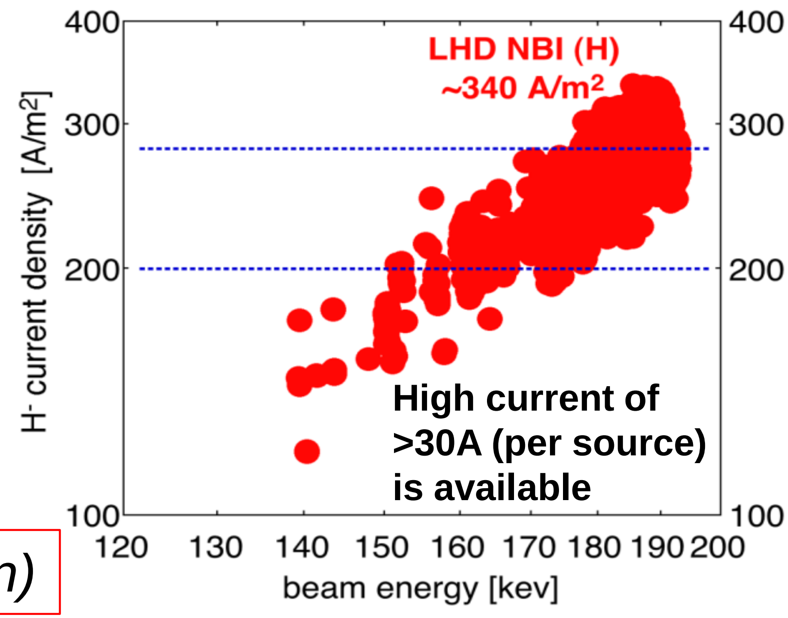
**$\langle\beta\rangle \sim 5\%$ at $B_t$=1T**

**$nT\tau > 1\times10^{20}$ $m^{-3}$ keV s**

**3MW Heating for 1 hour**

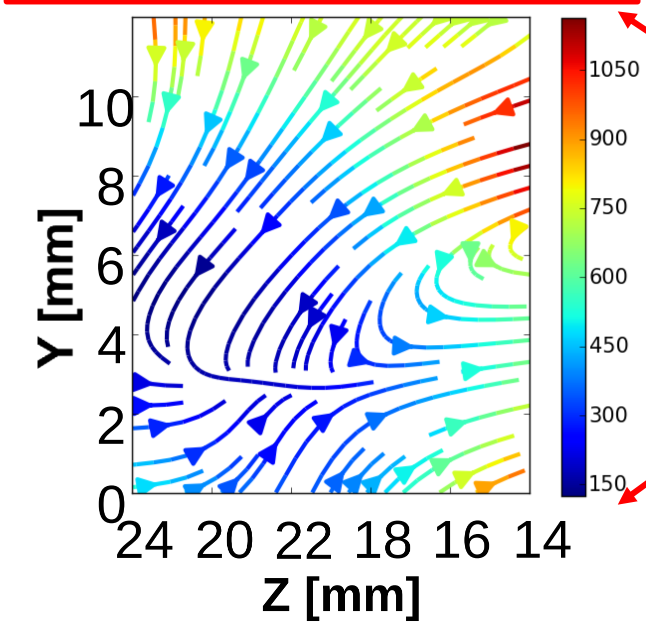
# World-leading negative-ion-based NBIs

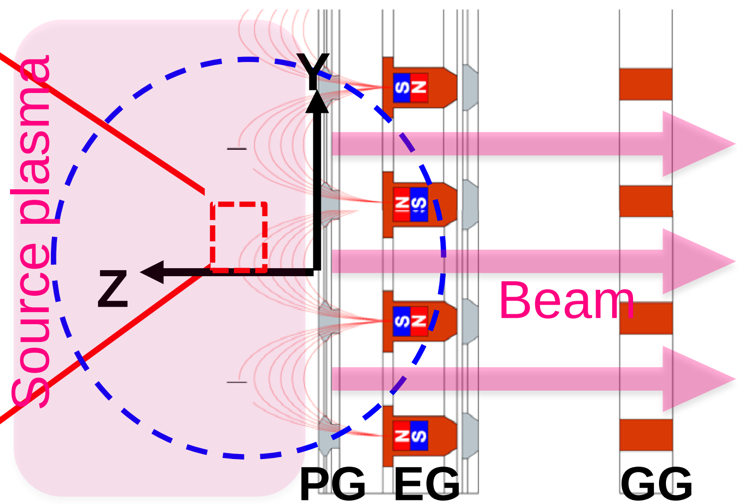
- Negative-NBIs reliably inject 15MW of 180keV-H-beams into LHD plasma.
- For D-beam injection, upgrade of the negative ion source performance with understanding of the source physics is being carried out.
- Such engineering and physics research should contribute to ITER-NBI development.




*Kisaki, FIP/1-4 (Mon)*

*Negative-ion **flow** near PG*

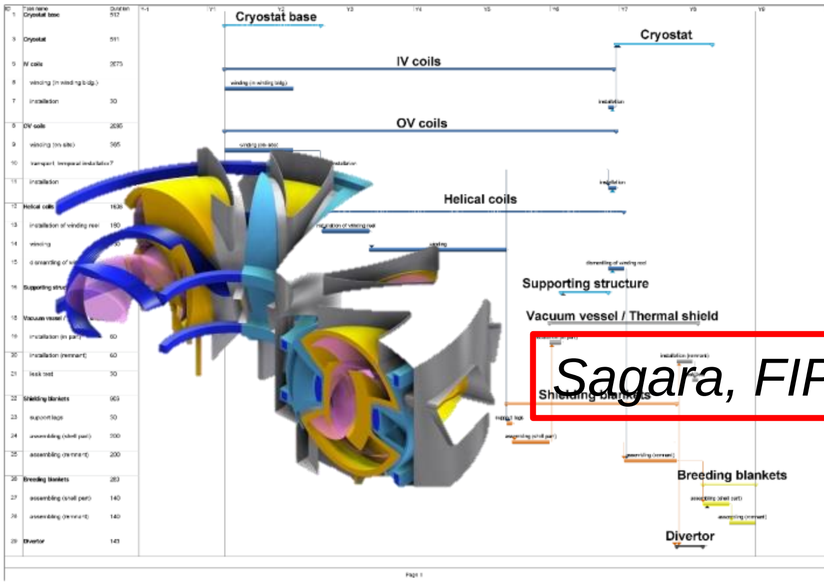



- Negative-ion rich plasma ($n_{H^-} >> n_e$) is produced near PG.
- Negative-ion flow in the source plasma is evaluated for the first time.

# Helical reactor (FFHR-d1) design and R&D

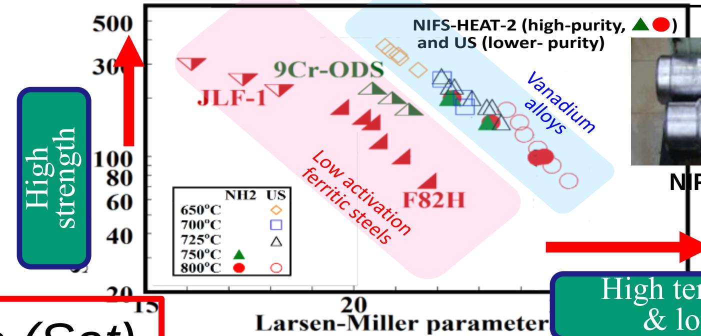
## 1. Construction/maintenance scenario




Sagara, FIP/3-4Ra (Sat)

## 2. Development of new materials

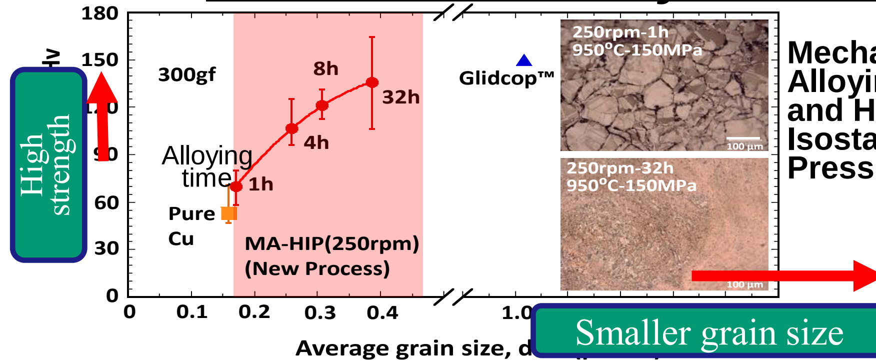
### Low activation vanadium alloys





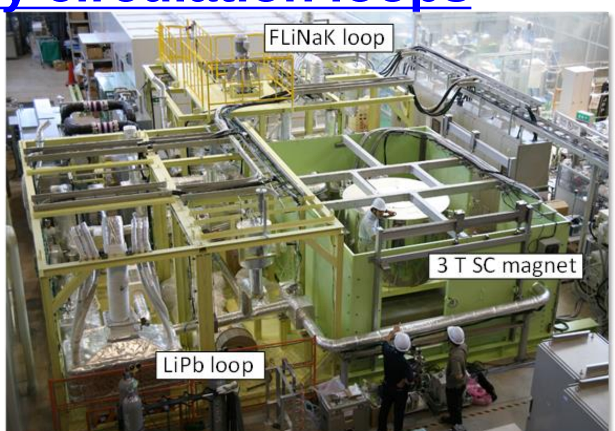
NIFS-HEAT-2 ingot (166 kg)

### Advanced Cu alloy for divertor



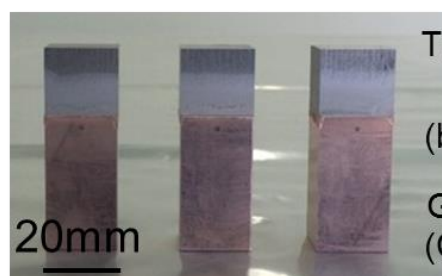

Mechanical Alloying and Hot Isostatic Press

## 3. Integrated blanket system study by circulation loops




**Oroshhi-2:** Operational Recovery Of Separated Hydrogen and Heat Inquiry-2

## 4. Divertor mock-up and heat load tests




Tungsten
BNi-6 (brazing)
GlidCop® (Cu alloy)

High heat flux test facility

# List of Presentations on NIFS activities

Overview

| | | |
|---|---|---|
| OV/1-1 | Y. Takeiri | Extension of Operational Regime of LHD towards Deuterium Experiment |
| OV/P-8 | K. Itoh | Hysteresis and Fast Timescale in Transport Relation of Toroidal Plasmas |

Oral

| | | |
|---|---|---|
| EX/1-4 | **O. Schmitz** | Enhancement of **helium exhaust** by **resonant magnetic perturbation fields** |
| EX/4-4 | S. Sakakibara | Extension of High-beta Plasma Operation to low collisional Regime |
| EX/7-2 | T. Oishi | Observation of carbon impurity flow in the edge stochastic magnetic field layer of Large Helical Device and its impact on the edge impurity control |
| FIP/3-4Ra | A. Sagara | Two Conceptual Designs of Helical Fusion Reactor FFHR-d1A Based on ITER Technologies and Challenging Ideas |
| PPC/1-1 | H. Takahashi | Extension of Operational Regime in High-Temperature Plasmas and Effect of ECRH on Ion Thermal Transport in the LHD |
| TH/6-2 | A. Ishizawa | Multi-Machine Analysis of Turbulent Transport in Helical Systems via Gyrokinetic Simulation |

# List of Presentations on NIFS activities

Poster

| | |
|---|---|
| **EX/P5-1** | **A. Dinklage** |
| EX/P6-19 | N. Ashikawa |
| EX/P8-1 | Y. Yoshimura |
| EX/P8-10 | S. Ohdachi |
| EX/P8-11 | K. Tanaka |
| EX/P8-12 | X. Du |
| EX/P8-13 | T. Ido |
| EX/P8-14 | D. Kato |
| EX/P8-15 | T. Kobayashi |
| EX/P8-2 | T. Tsujimura |
| EX/P8-3 | G. Motojima |
| EX/P8-39 | T. Goto |
| EX/P8-4 | Y. Nakamura |

| | |
|---|---|
| EX/P8-5 | H. Xianli |
| EX/P8-6 | B. Peterson |
| EX/P8-7 | K. Ida |
| EX/P8-8 | Y. Narushima |
| EX/P8-9 | T. Tokuzawa |
| FIP/3-4Rb | H. Hashizume |
| FIP/3-4Rc | K. Takahata |
| FIP/P4-37 | M. Tokitani |
| FIP/P4-41 | Y. Hatano |
| FIP/P4-7 | H. Nakanishi |
| FIP/P7-11 | N. Yanagi |
| FIP/P7-2 | J. Miyazawa |
| FIP/P7-35 | M. Yokoyama |

| | |
|---|---|
| FNS/P5-8 | K. Ogawa |
| MPT/P5-19 | Y. Nobuta |
| MPT/P5-21 | T. Nagasaka |
| MPT/P5-23 | A. Itoh |
| TH/P1-4 | K. Ichiguchi |
| TH/P1-5 | H. Miura |
| TH/P2-2 | M. Nakata |
| TH/P2-21 | S. Murakami |
| TH/P2-3 | M. Nunami |
| TH/P4-11 | H. Wang |
| TH/P6-17 | H. Hasegawa |

# Summary

- LHD has progressed as a large-scale superconducting device since 1998, without any severe cryogenic troubles
- Demonstration of steady-state operation as inherent advantage of helical systems
- Improvement of plasma performance based on extended experimental capabilities and physics findings
- Further plasma performance improvement is envisaged in the coming deuterium experiment, to provide firm basis for helical reactor design
- LHD as the academic platform, to provide opportunities for challenging and cutting-edge research

***Join us for the coming deuterium experiment !***