OV/1-1

Extension of Operational Regime of LHD towards Deuterium Experiment

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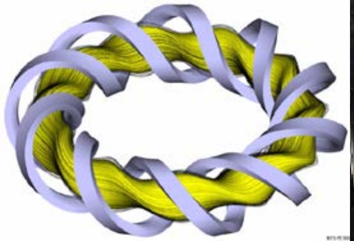
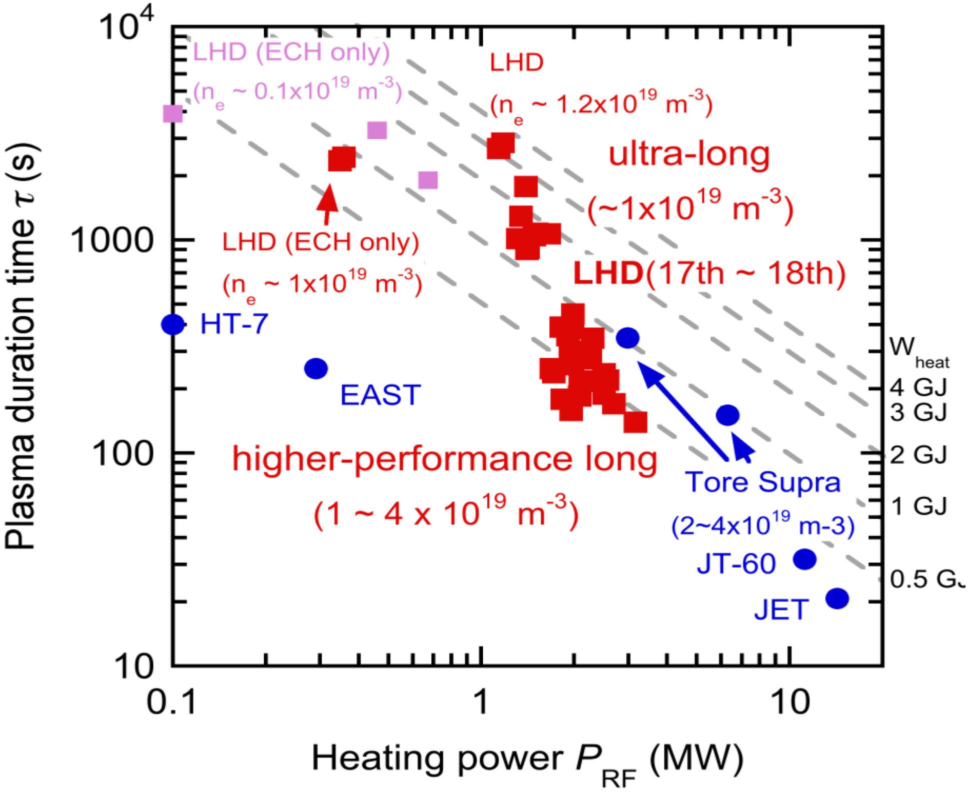


26th IAEA Fusion Energy Conference, Oct. 17-22, 2016, Kyoto, Japan

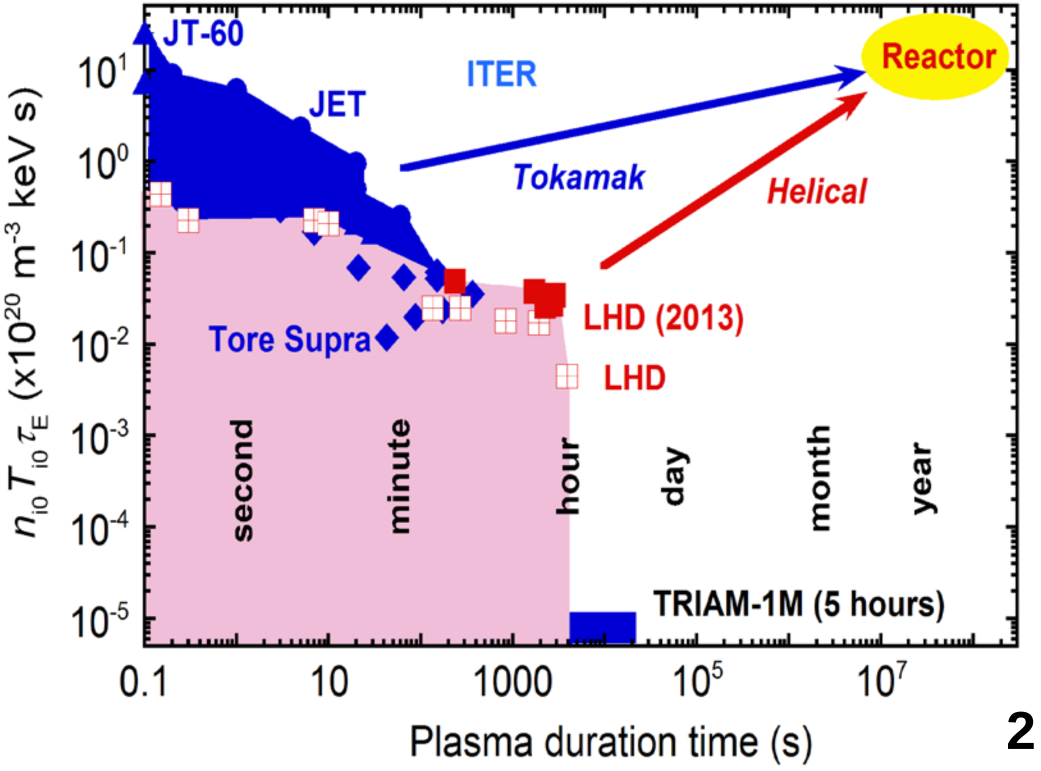
Significance of LHD in the world fusion research

- 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** **Impurity hole**	10 keV ($n_e = 2\times10^{19}$m^{-3})
T_e	20 keV (2×10^{18} m^{-3}) 10 keV (1.6×10^{19} m^{-3})	**Electron ITB**	10 keV (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} ($T_e = 1.3$ keV)
β	5.1 % ($B_T = 0.425$ T) 4.1 % (1 T)	**MHD in current-free plasmas**	5 % ($B_T = 1 - 2$ T)
Steady-state operation	54min. 28sec (0.5MW, 1keV, 4×10^{18}m^{-3}) 47min. 39sec. (1.2MW, 2keV, 1×10^{19}m^{-3})	**Dynamic wall retention**	1 hour (3 MW)

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1. Introduction on LHD

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

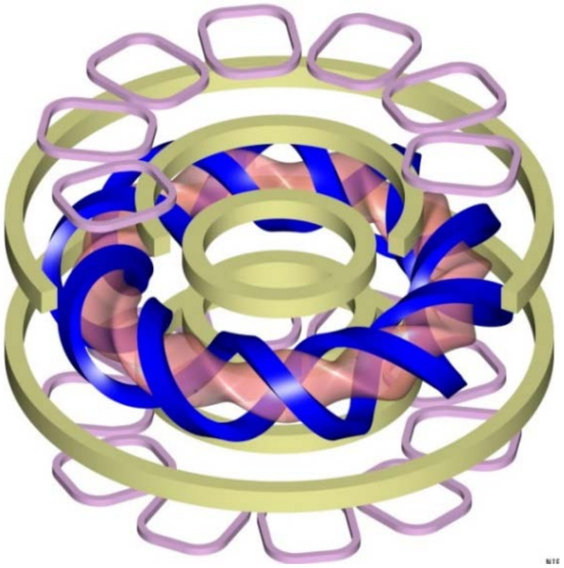
3. Deuterium experiment
   - Objects
   - Schedule
   - Hardware improvement (negative-ion based NBI)

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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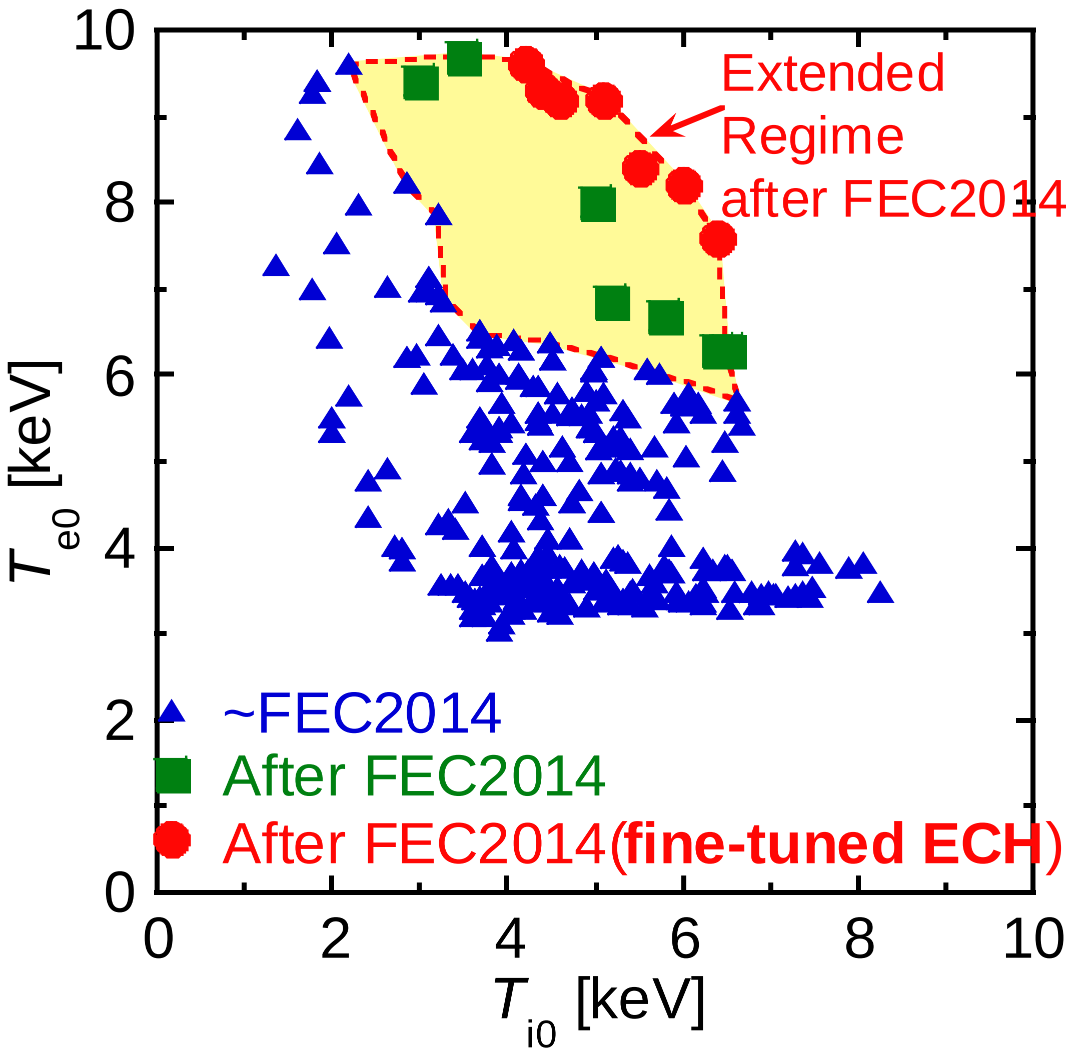
4. Summary

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

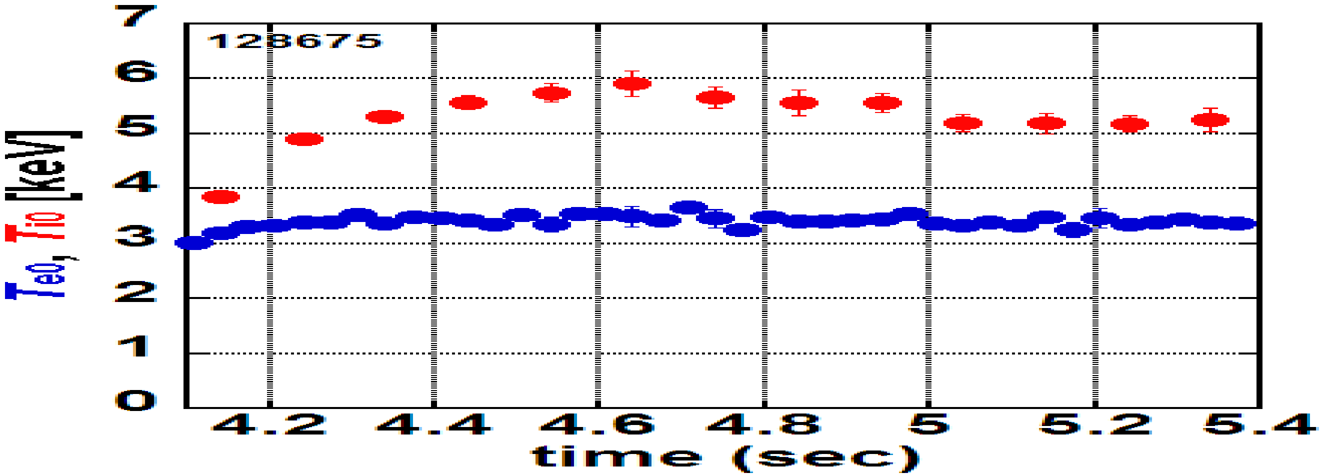
- Feedback ECH optimization for fine-tuned ECH is applied onto high-*T*i plasmas
  → Extended temperature regime to high *T*i and *T*e, simultaneously reaching around 6 and 8 keV, respectively.

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

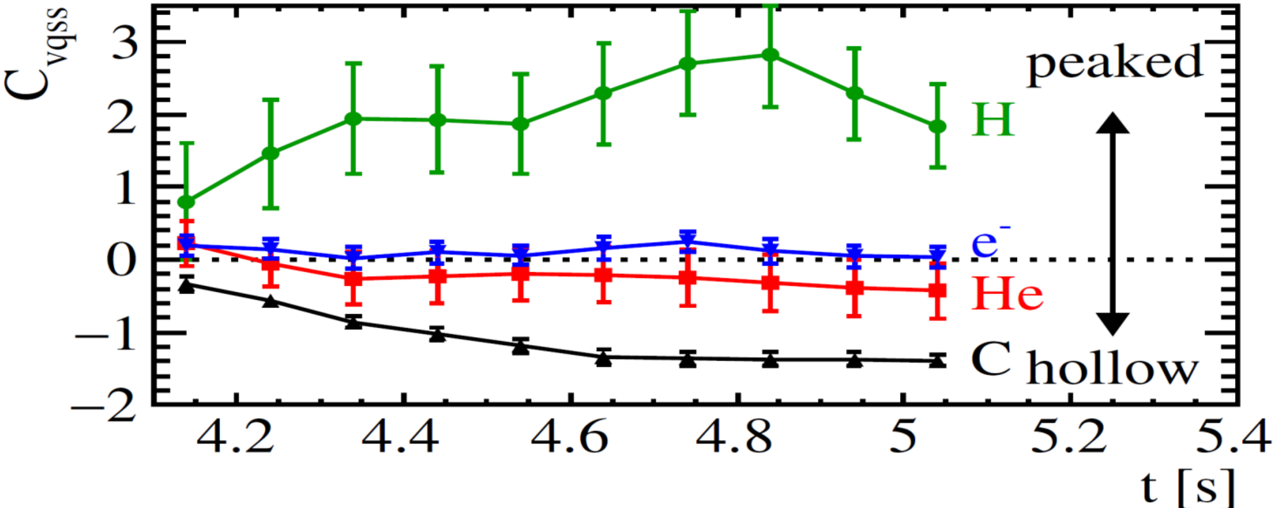
A. Perek, K. Ida et al., to be submitted to NF (2016).



Ti ~ 5-6 keV

Te~ 3-4 keV

peaking factor
(quasi steady-sate)



H: peaked

C, He: hollow

Strategy of high-beta plasma production

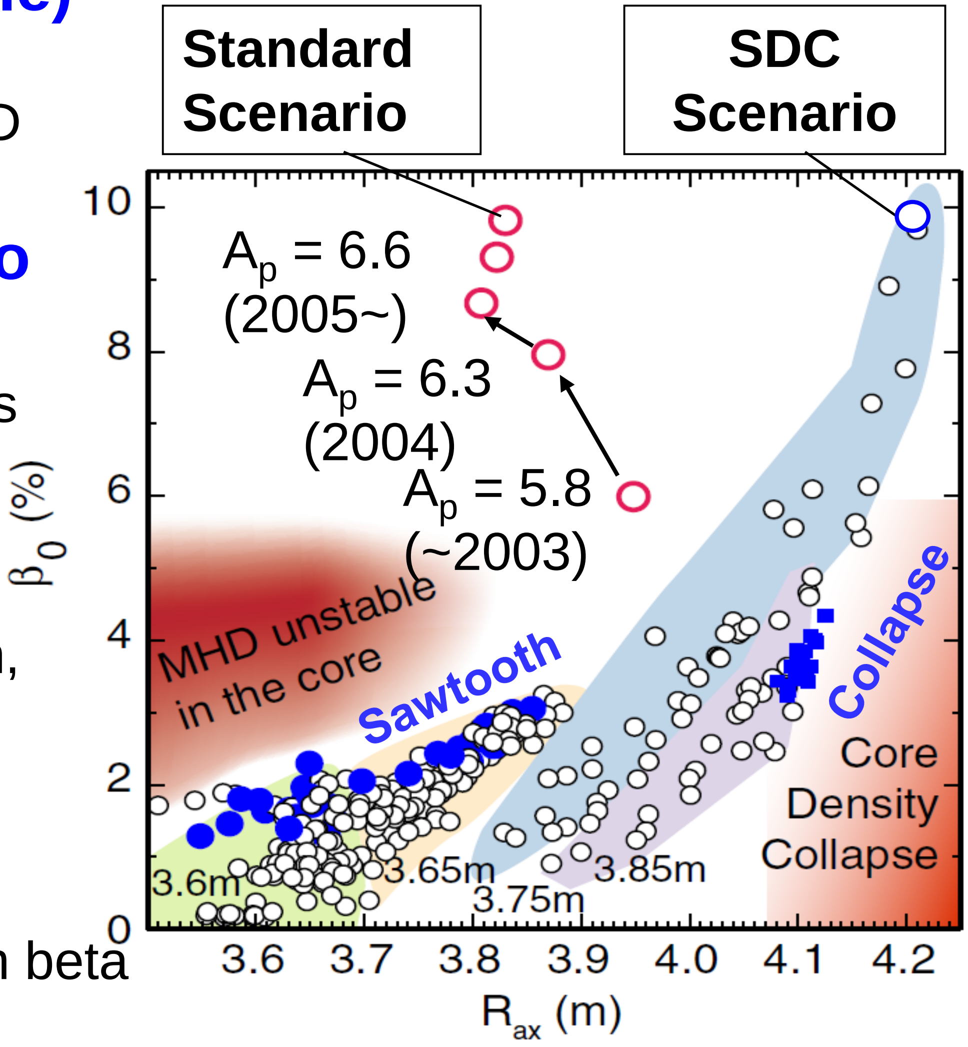
High beta has been realized with two scenarios in previous experiments

Standard scenario (broad *P*-profile)

- Low A_p configuration to increase heating efficiency, and to optimize transport, MHD
- **<*β*> 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

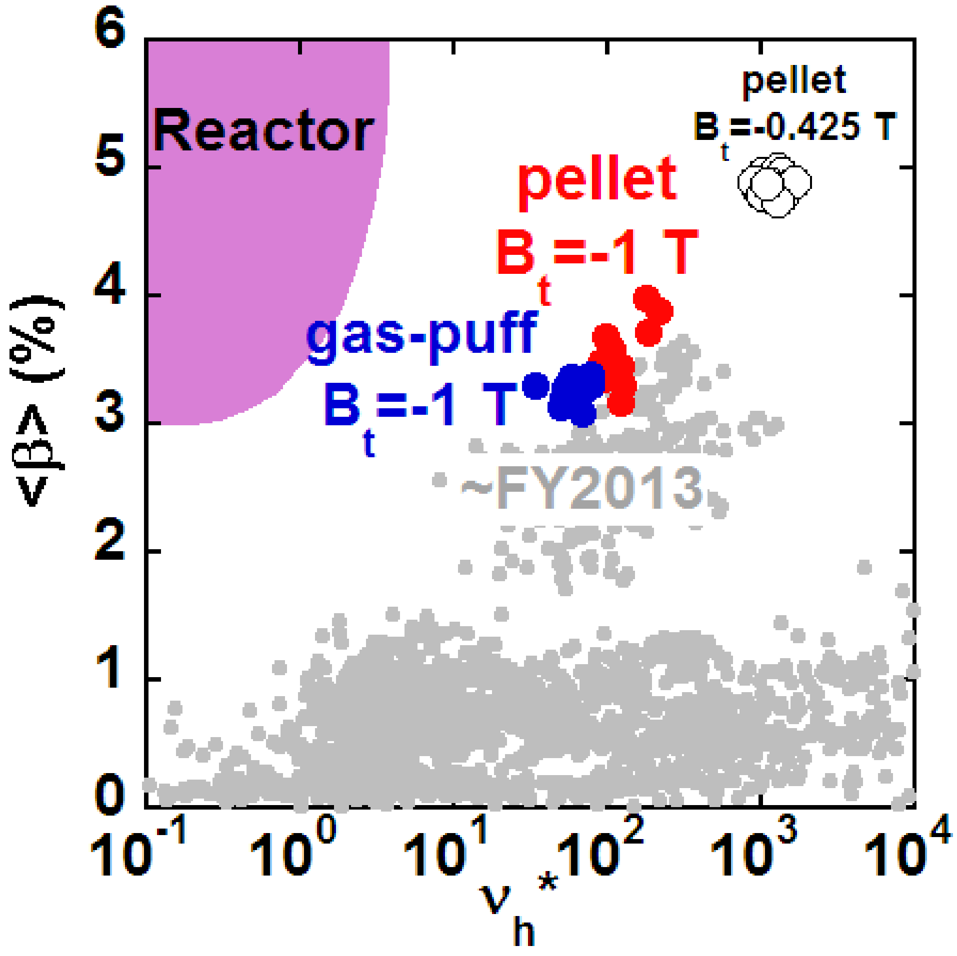
Realization of high temperature and high beta plasma in inward shifted configuration

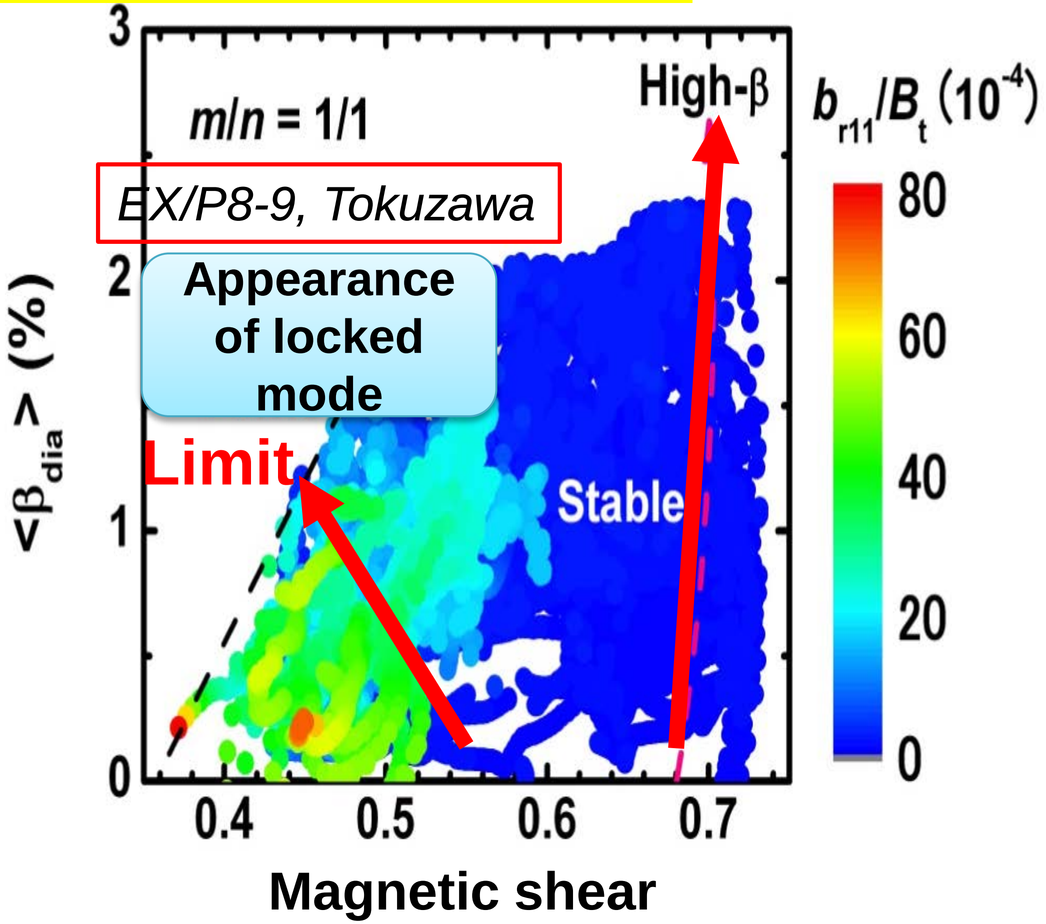
High β trial in low collisional regime

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

Appearance of locked mode

Multi-pellet injections (Maximum beta)

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

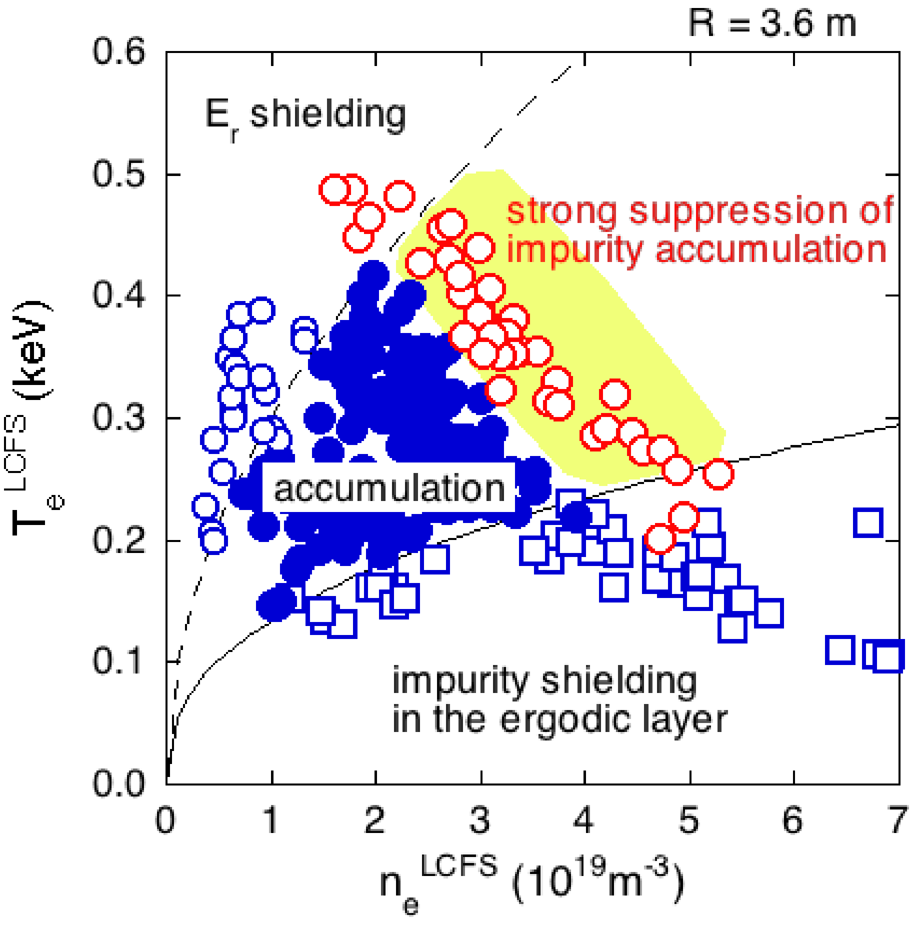
Gas puffing (Quasi-steady state)

⇒**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

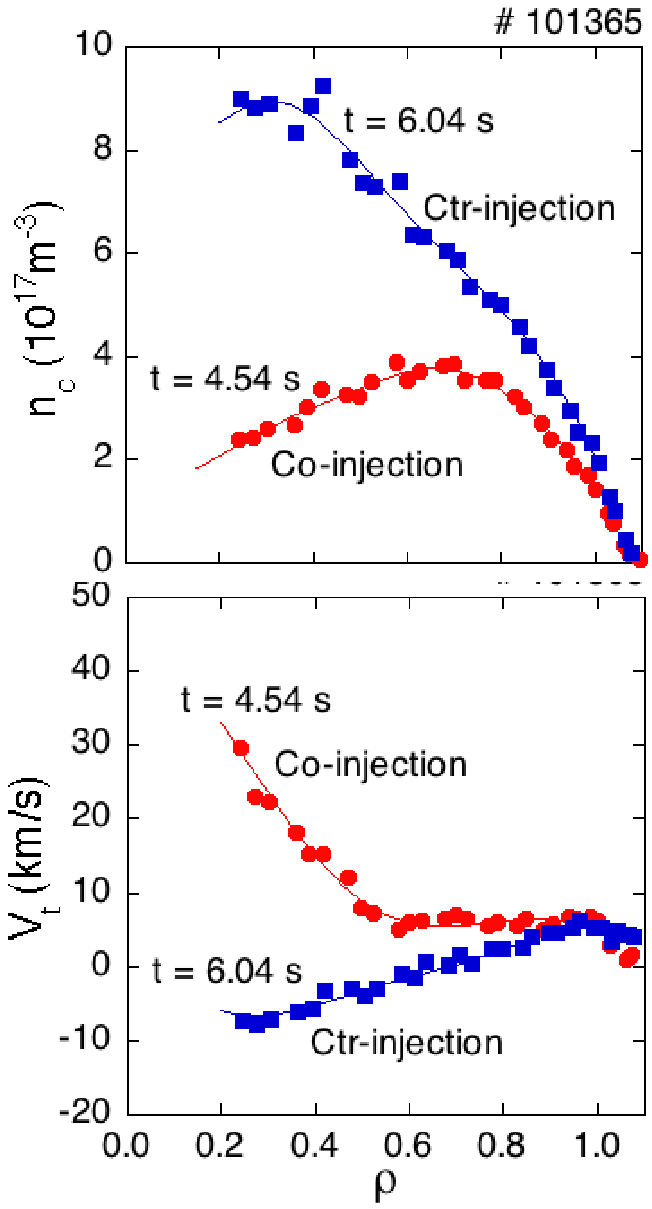
1) E_r
2) edge stochastic layer
3) NBI (power, torque), etc.

- *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

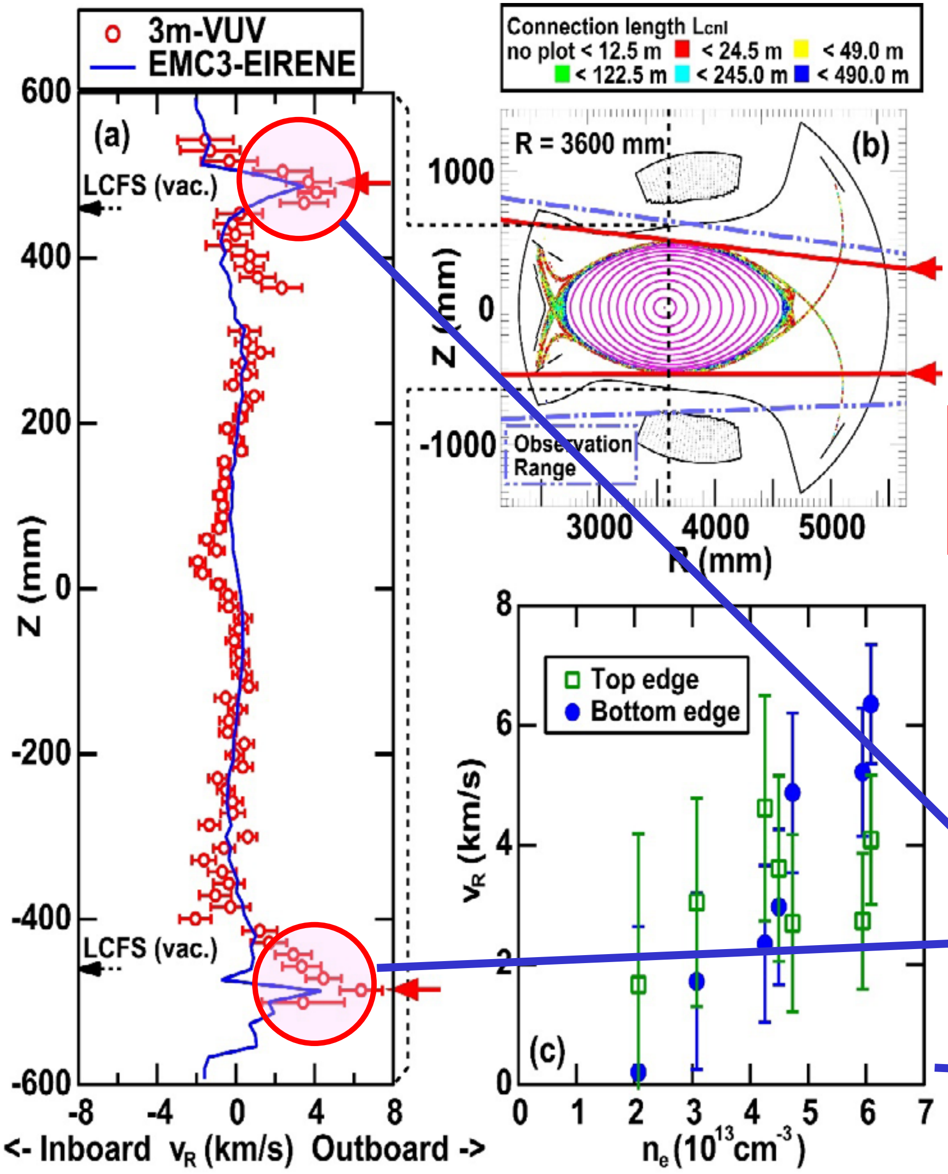
When NBI torque input direction is switched from co- to ctr-injection,

- 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.

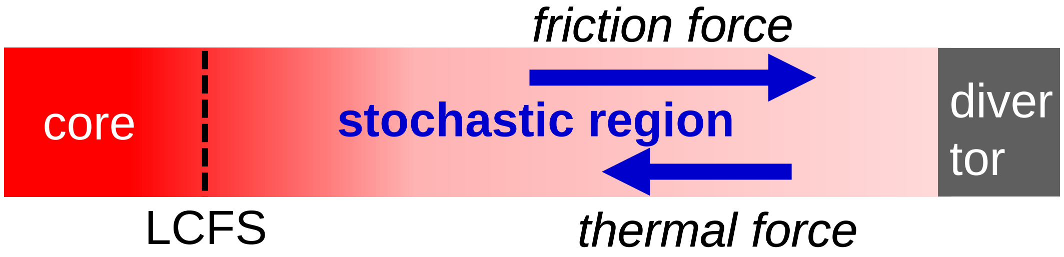
EX/P8-4, Nakamura

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.



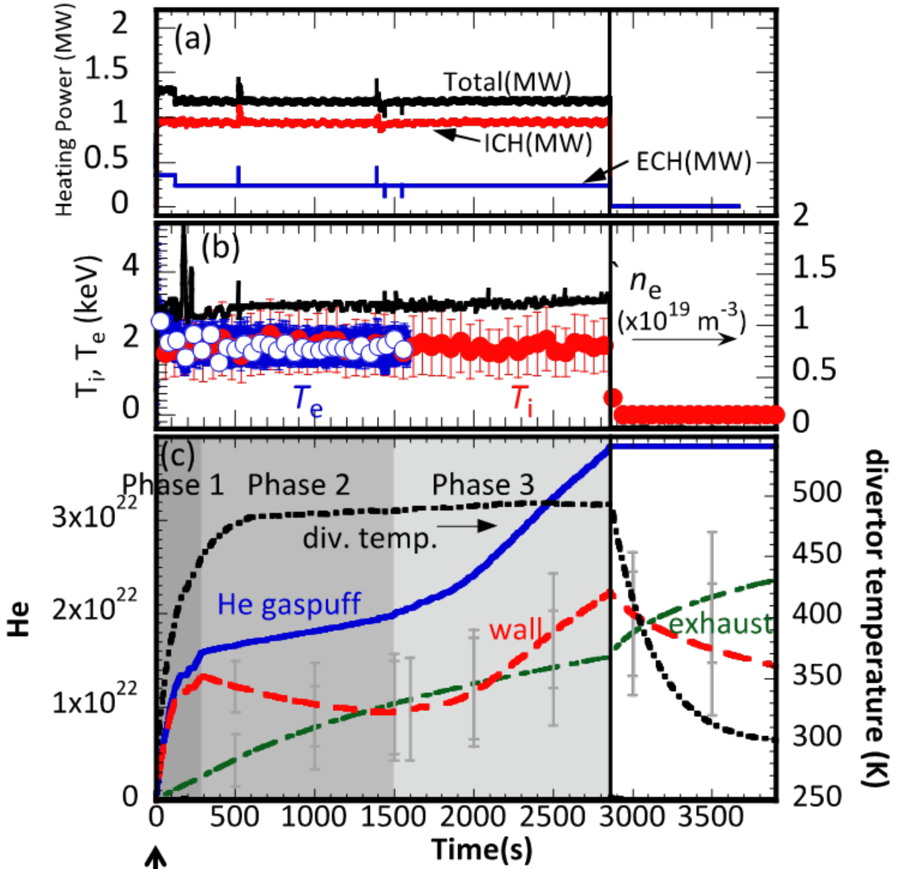
⬆ **EMC3-EIRENE model (expectation)**

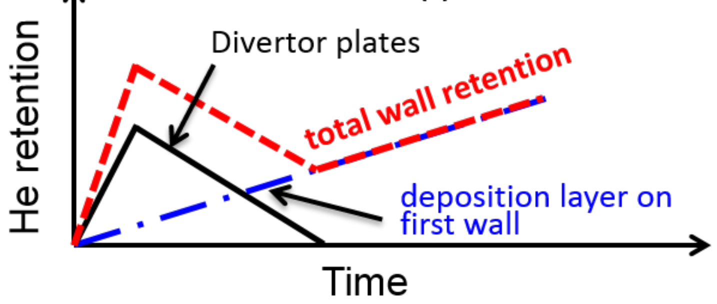
⬅ **C-flow observed by VUV spectroscopy**

- 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.

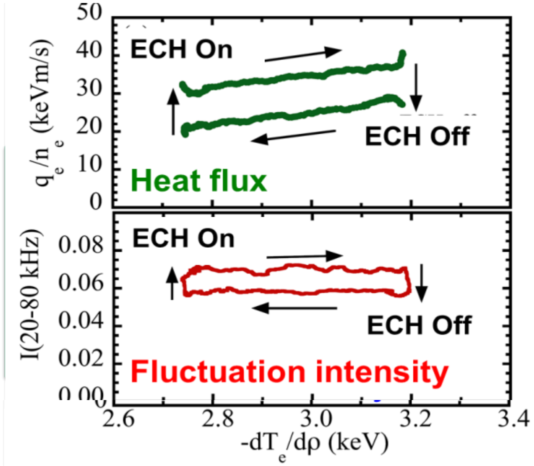
Deposition layers continuously grows during the long-pulse discharge.

EX/P8-3, Motojima

LHD as the advanced academic platform

Hysteresis in transport relation

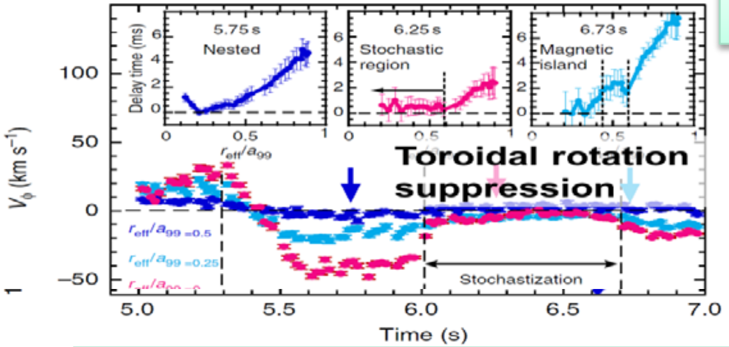
OV/P1-8: K.Itoh



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

Impact of stochastization on momentum transport

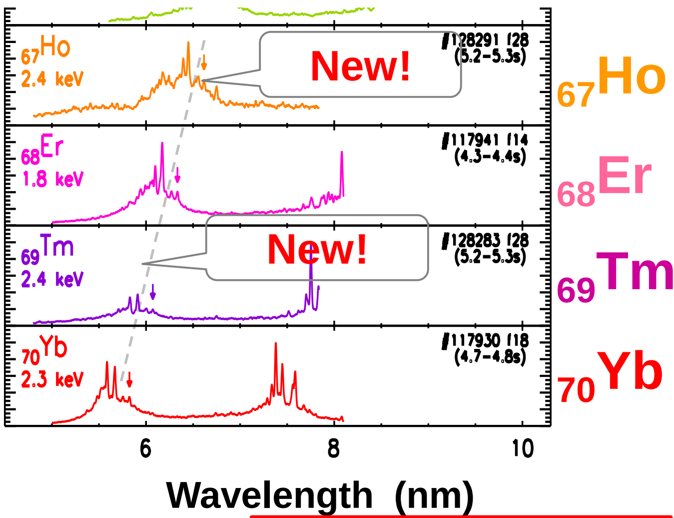
EXC/P8-7, Ida



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

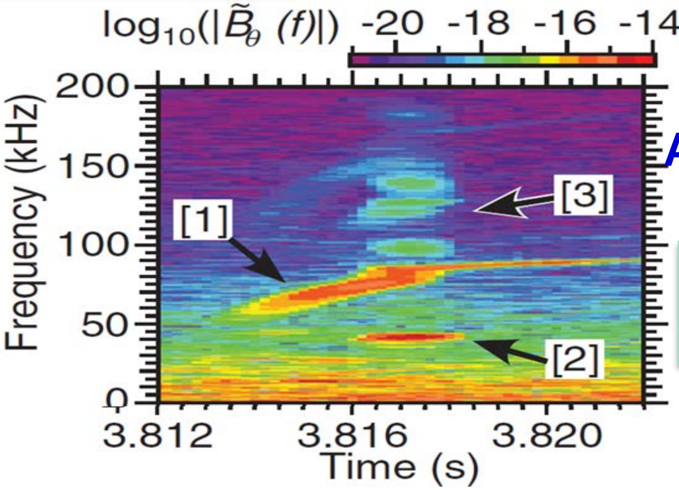
Impact of high-T_e laboratory plasma on fundamental physics, industry

C. Suzuki, EPS2016 Invited Talk



EX/P8-14, D. Kato

EXC/P8-607: T.Kobayashi



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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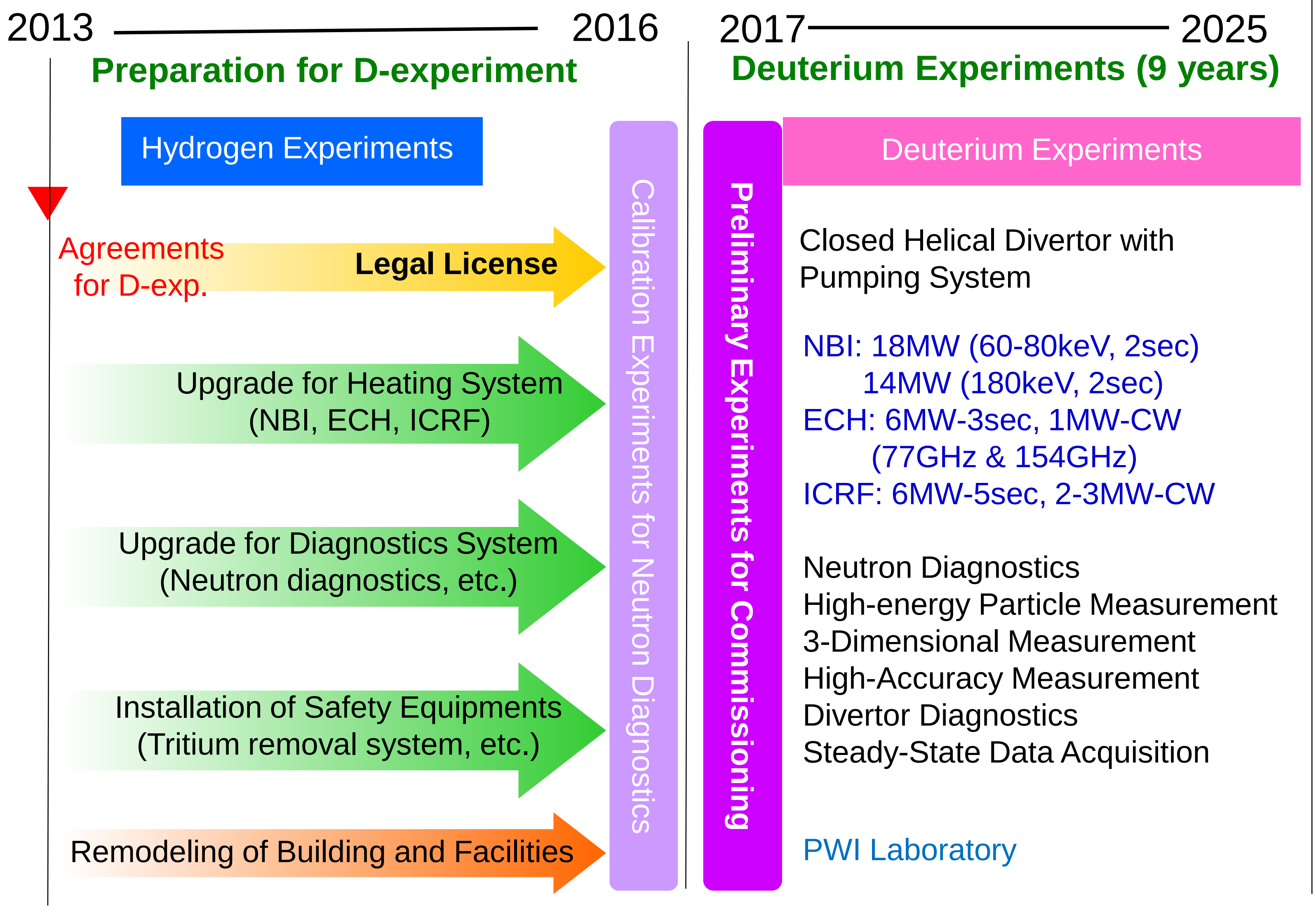
4. Summary

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 2×10^{19} m^{-3}

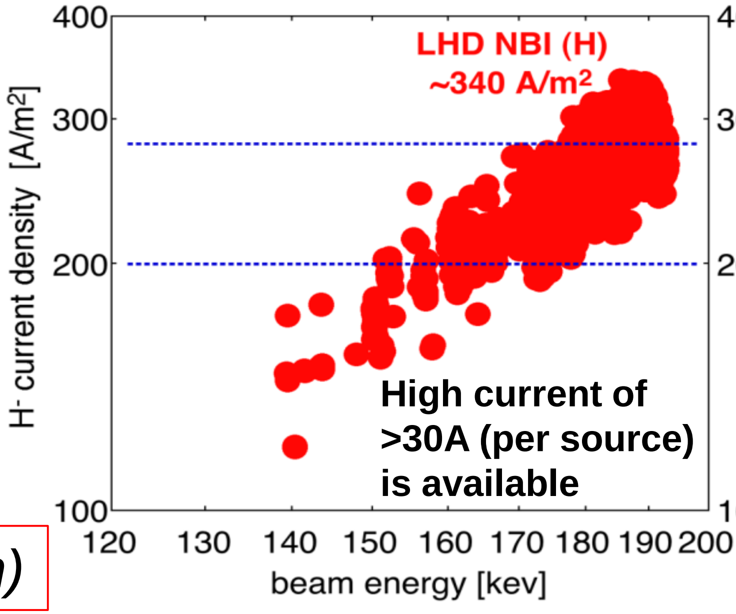
$\langle\beta\rangle$ ~ 5% at B_t=1T

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

3MW Heating for 1 hour

World-leading negative-ion-based NBIs

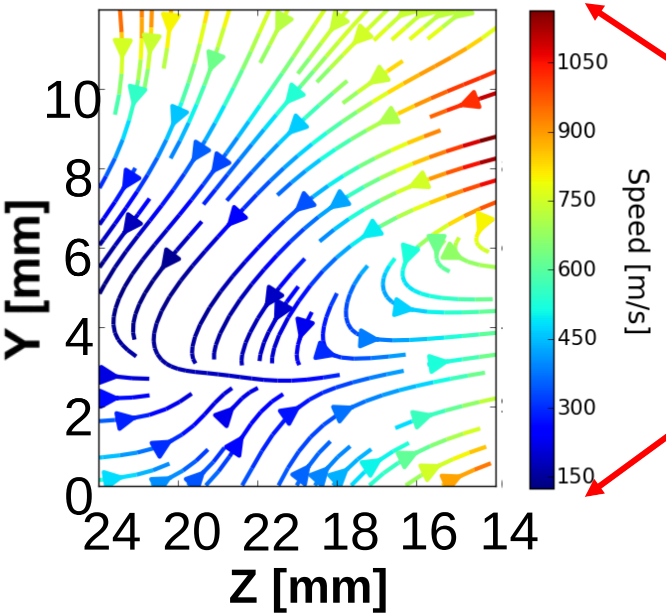
- Negative-NBIs reliably inject 15MW of 180keV-H-beams into LHD plasma.
- For D-beam injection, upgrade of the negative ion source performance with understanding of the source physics is being carried out.
- Such engineering and physics research should contribute to ITER-NBI development.

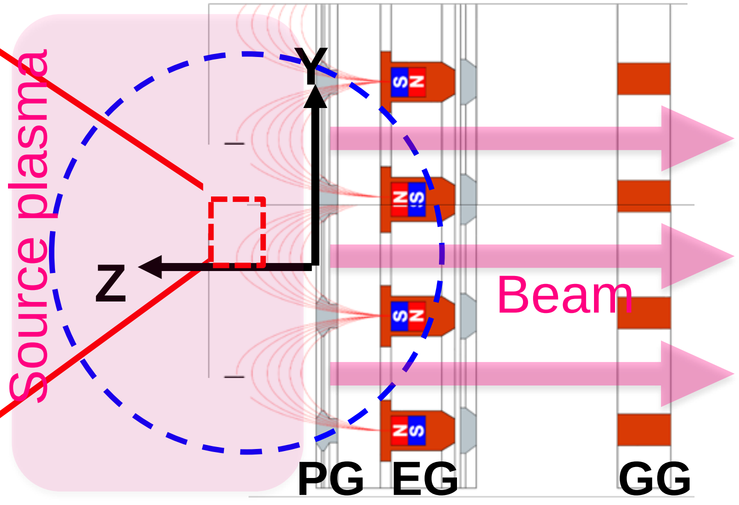


High current of >30A (per source) is available

Kisaki, FIP/1-4 (Mon)

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

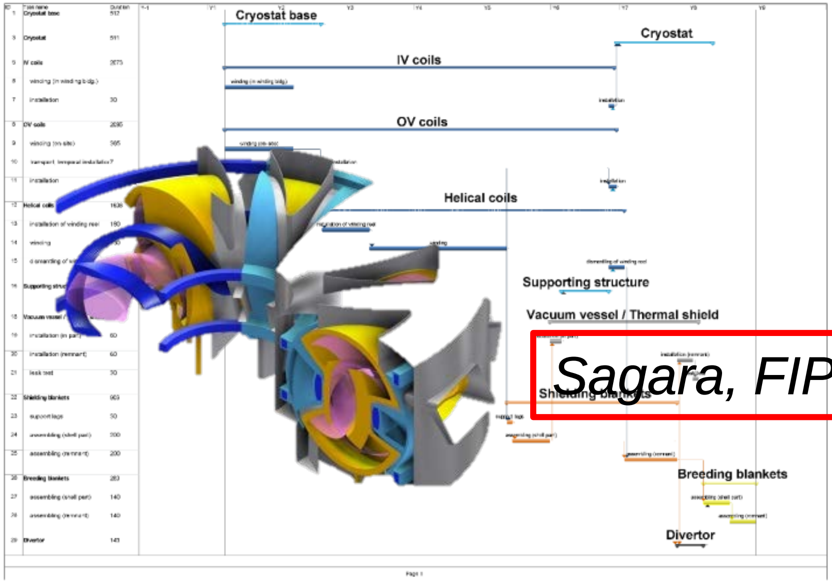




- Negative-ion rich plasma ($n_{H^-} >> n_e$) is produced near PG.
- Negative-ion flow in the source plasma is evaluated for the first time.

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

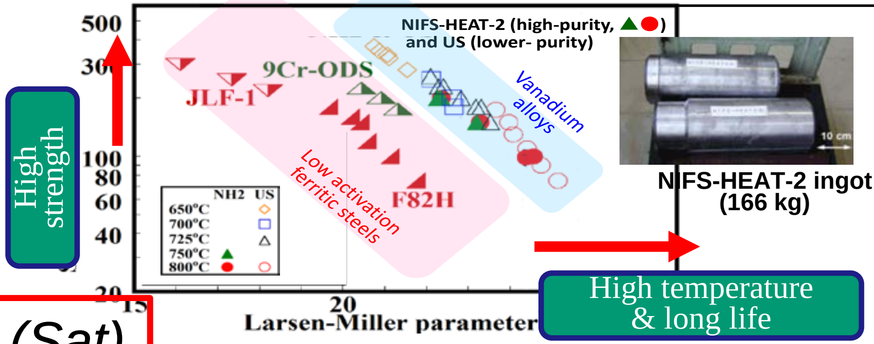
1. Construction/maintenance scenario



Sagara, FIP/3-4Ra (Sat)

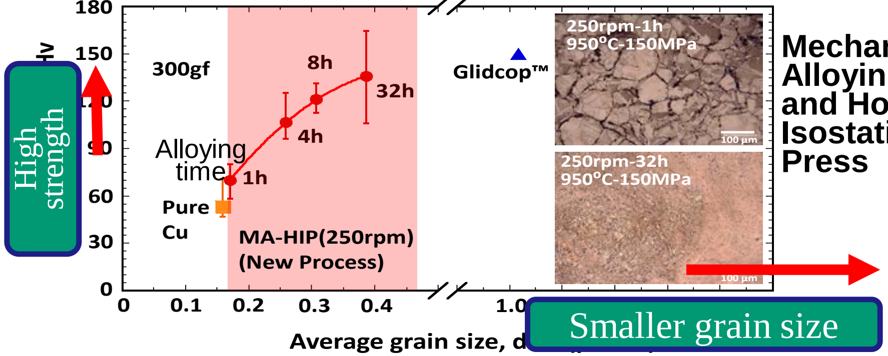
2. Development of new materials

Low activation vanadium alloys



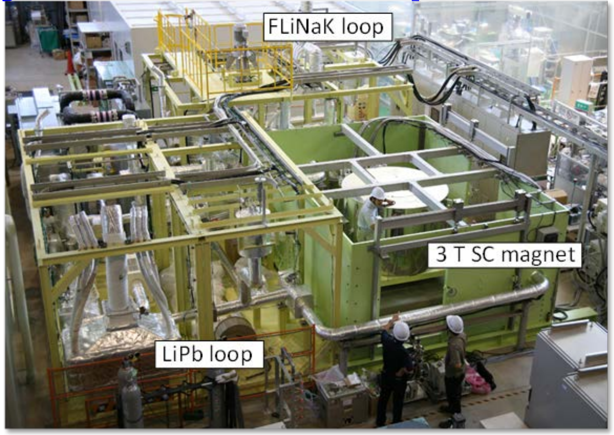
NIFS-HEAT-2 ingot (166 kg)

Advanced Cu alloy for divertor



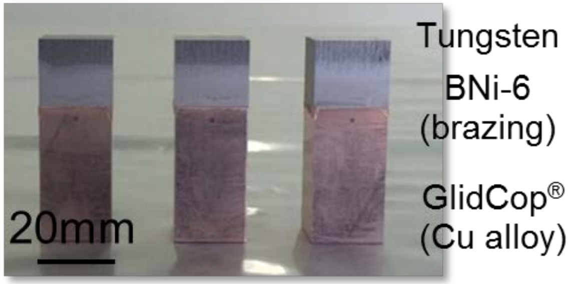
Mechanical Alloying and Hot Isostatic Press

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



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

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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 !