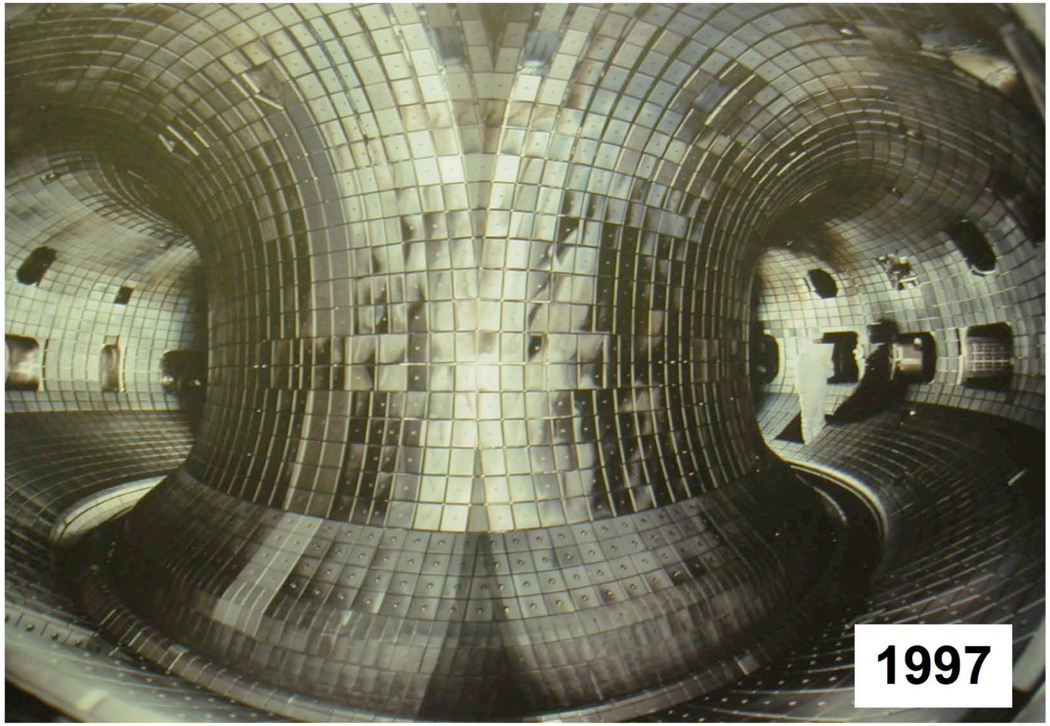
OV/1-2

Overview of JT-60U Results for Development of Steady-State Advanced Tokamak Scenario

H. Takenaga[1] and the JT-60 Team



[1] Japan Atomic Energy Agency

21st IAEA Fusion Energy Conference
16 - 21 October 2006
Chengdu, China

Enhanced national and international collaborations.

The JT-60 Team

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Japan Atomic Energy Agency, 1)Post-Doctoral Fellow, 2)Staff on loan, 3)Nippon Advanced Technology Co.Ltd., Japan

National collaborations : as the central tokamak in Japanese fusion research.

4)National Institute for Fusion Science, Japan, 5)Osaka University, Japan, 6)Japan Society of the Promotion of Science Invitation Fellowship, 7)University of Tsukuba, Japan, 9)Kyoto University, Japan, 10)The University of Tokyo, Japan, 13)Kyushu University, Japan, 14)Tohoku University, Japan, 15)Keio University, Japan, 16)Hokkaido University, Japan, 17)Nagoya University, Japan, 18)National Institute of Advanced Industrial Science and Technology, Japan, 20)Fukui University, Japan, 21)Tokyo Institute of Technology, Japan, 22)Hiroshima Insitute of Technology, Japan, 23)Shizuoka University, Japan, 26)Mie University, Japan, 27)Kyushu Tokai University, Japan, 28)Yamaguchi University, Japan, 29)Hiroshima University, Japan, 30)Central Research Institute of Electric Power Industry, Japan, 33)Shinshu University, Japan, 35)Kanazawa University, Japan

International collaborations : including IEA/ITPA collaboration.

8)Southwestern Institute of Physics, China, 11)General Atomics, USA, 12)Princeton Plasma Physics Laboratory, USA, 19)Max-Planck-Institut fur Plasmaphysik, Germany, 24)JAERI Fellow, 25)Euratom/UKAEA Association, UK, 31)Lawrence Livermore National Laboratory, USA, 32)EFDA Closed Support Unit, Germany, 34)Idaho National Engineering and Environmental Laboratory, USA

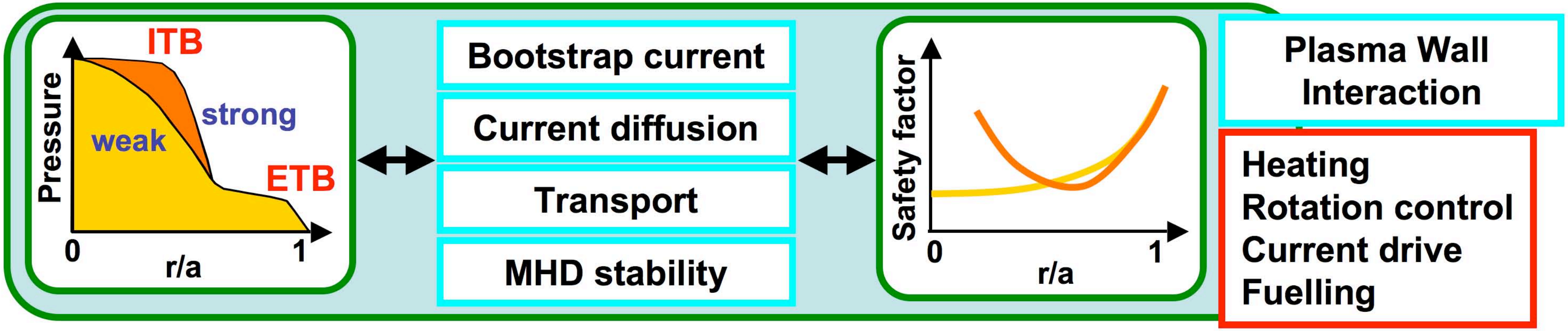
JT-60U objectives and strategy

- **ITER Physics R&D**
- **Advanced Tokamak (AT) Concepts for ITER & DEMO**

AT plasmas : high β_N & high bootstrap current fraction (f_{BS})

- **high β_p mode plasma**
- **reversed shear (RS) plasma**

Strong p(r) and q(r) linkage among physics with various time scales



Bootstrap current

Current diffusion

Transport

MHD stability

Plasma Wall Interaction

Heating
Rotation control
Current drive
Fuelling

Main topics

'03-'04 • Sustainment of high β_N below no wall ideal limit and high f_{BS} longer than the current diffusion time.

'05-'06
- **High β_N exceeding no wall ideal limit.**
- **Integrated performance in the long high β_N discharges.**
- **Development of real time control systems towards intelligent control for the high f_{BS} plasmas.**

Schematic view of research area in β_N-f_{BS} space

JT-60U

High β_N exceeding no wall limit

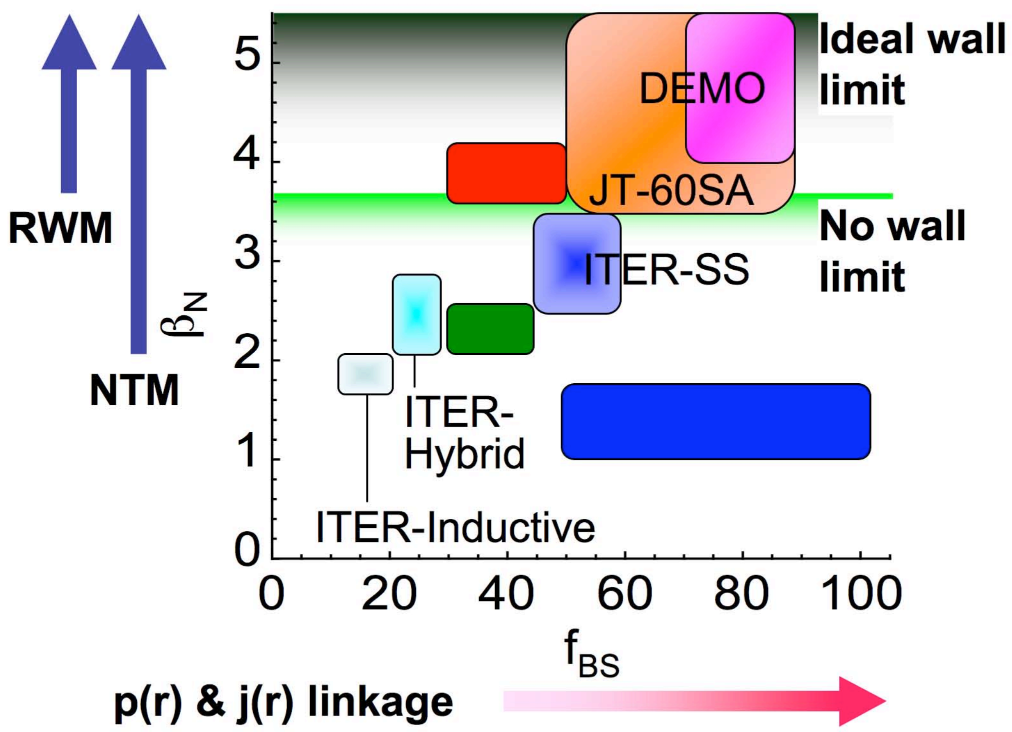
- Wall stabilization effect
- Suppression of resistive wall mode (RWM) by plasma rotation

Integrated performance

- Confinement improvement

Real-time control systems

- Pressure profile control
- Real-time current profile control



Ferritic Steel Tiles (FSTs) are installed inside the vacuum vessel to reduce toroidal field ripple.

➔ **Decrease in fast ion loss with the large volume configuration close to the wall, where wall stabilization effectively works.**

Contents

1. Installation of ferritic steel tiles and its effects in L- and H-mode plasmas
2. Extension of operation regime to high β_N exceeding no wall ideal limit and RWM study
3. Integration of plasma performance in the long high β_N discharges
4. Development of real time control with high bootstrap current fraction
5. Physics studies on issues implicated for ITER
6. Summary

1. Installation of ferritic steel tiles and its effects in L- and H-mode plasmas.

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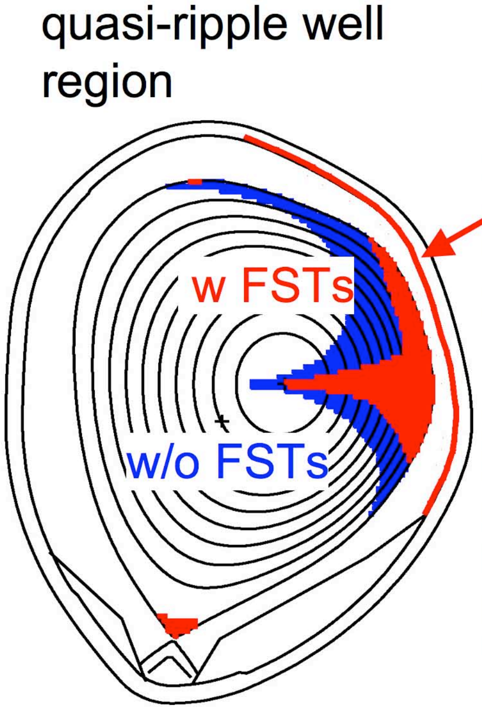
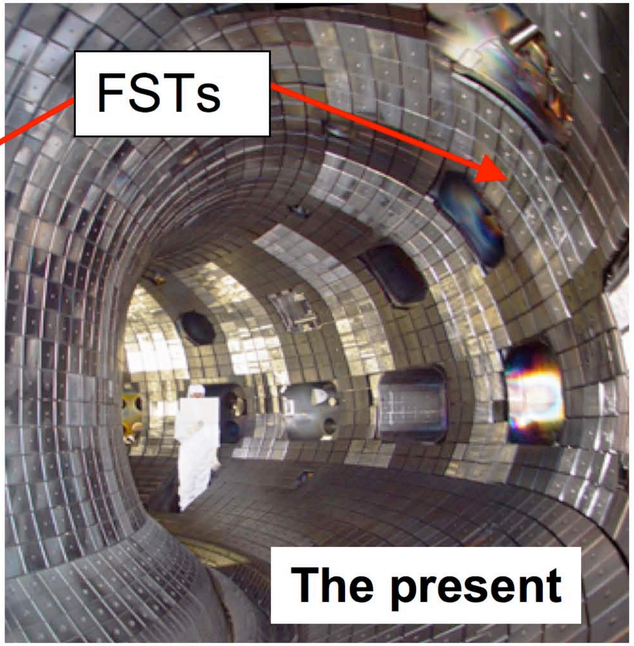
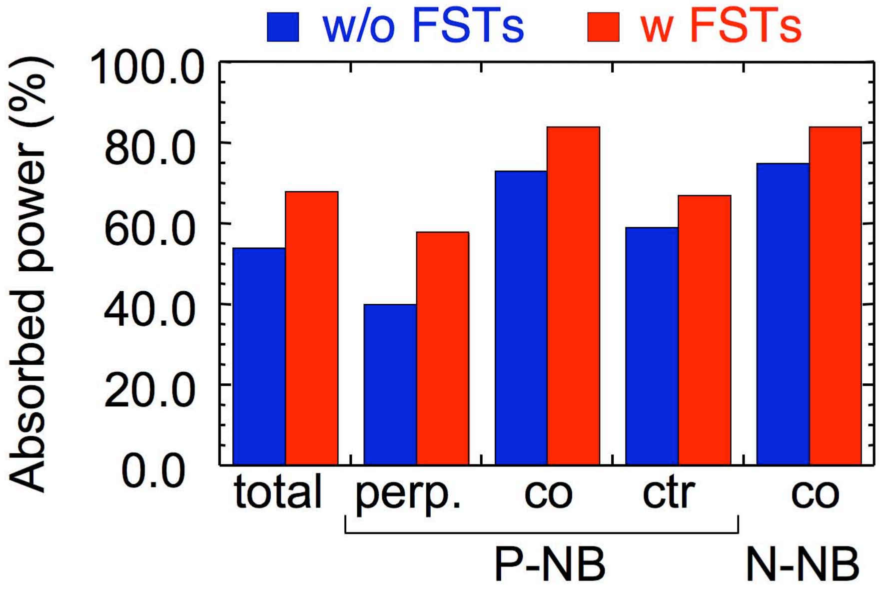
- **FSTs cover ~10% of the surface.**
- **Large effect is obtained at $B_T < \sim 2$ T.**
- **3-D Monte-Carlo simulations (F3D OFMC) for fast ion behavior indicated that total absorbed power is increased by 30% (by 50% for perpendicular NB) in the large volume configuration.**





I_p = 1.1 MA, B_T = 1.86 T, V_P = 79 m^3



K. Shinohara (FT/P5-32, Thu.)

Spin-up of toroidal rotation in co-direction due to reduction of fast ion loss.

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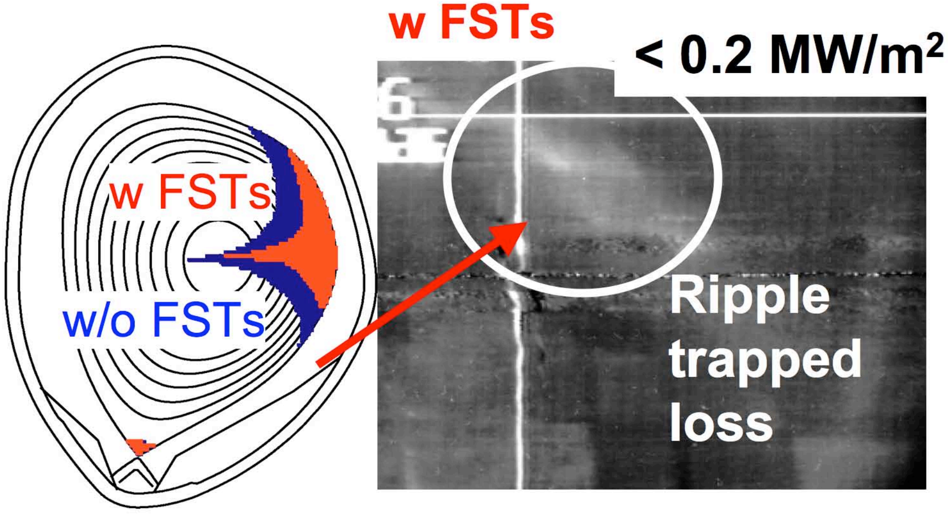
- **Heat flux in the ripple trapped loss region measured with IRTV is consistent with that calculated by F3D OFMC.**
- **Toroidal rotation shifts to co-direction due to the reduction of the fast ion loss.**

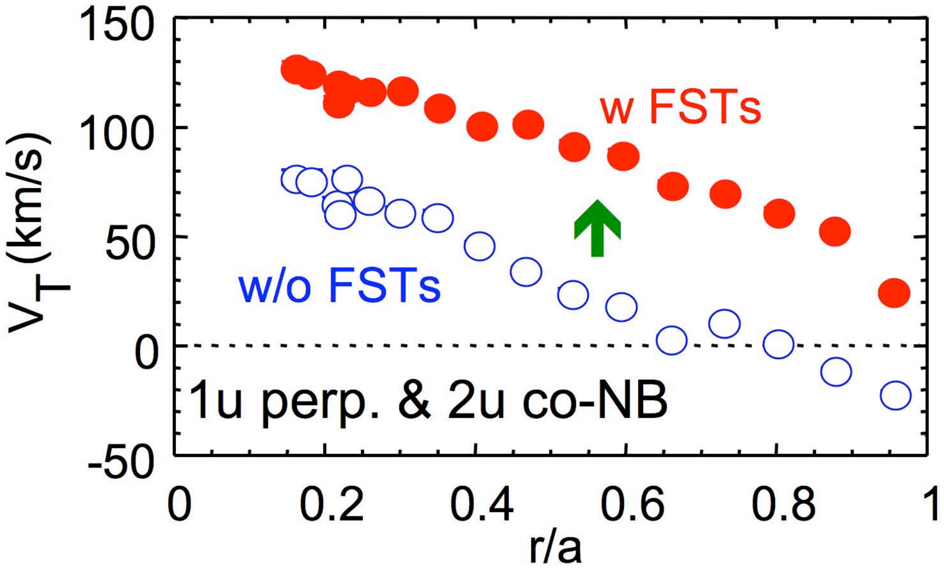


F3D OFMC calculation

< 0.3 MW/m² w FSTs

> 1 MW/m² w/o FSTs

I_p = 1.2 MA, B_T = 2.6 T,
q_{95} = 4.1, V_p = 75 m³, L-mode



K. Shinohara (FT/P5-32, Thu.)

M. Yoshida (EX/P3-22, Wed.)

Pedestal parameters and confinement are enhanced with co-rotation in H-mode.

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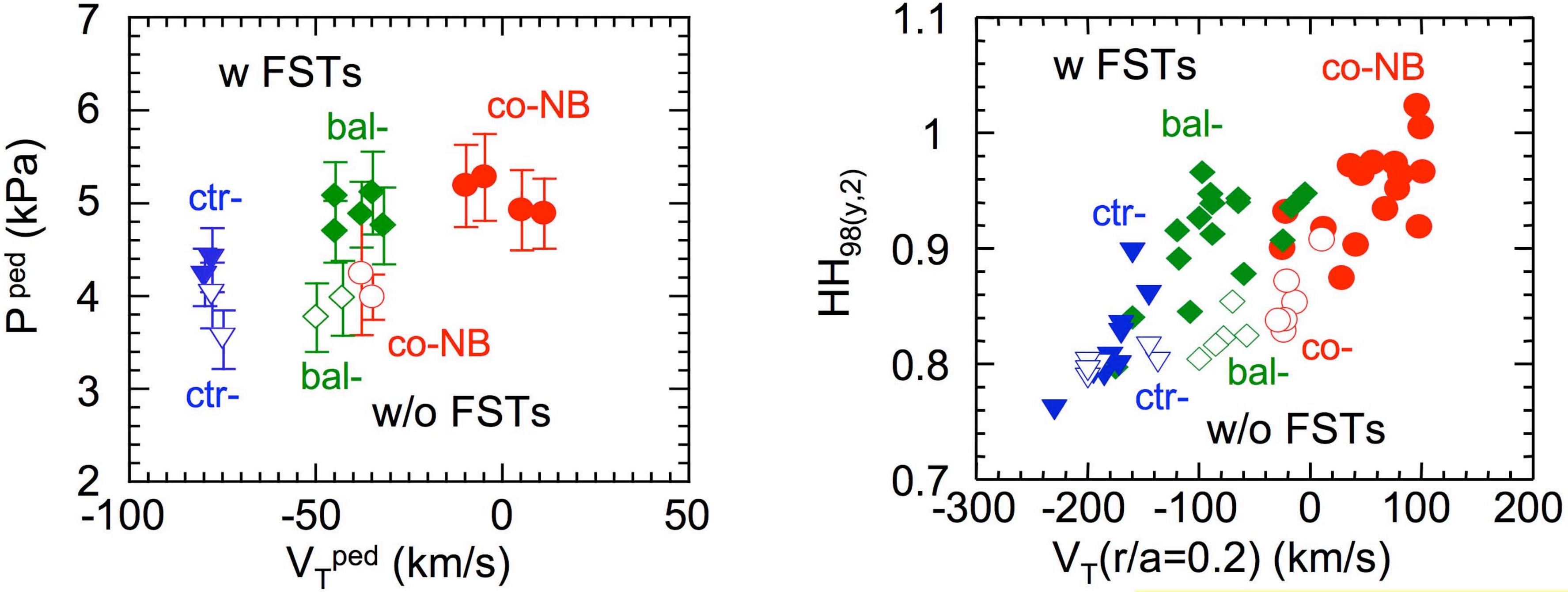
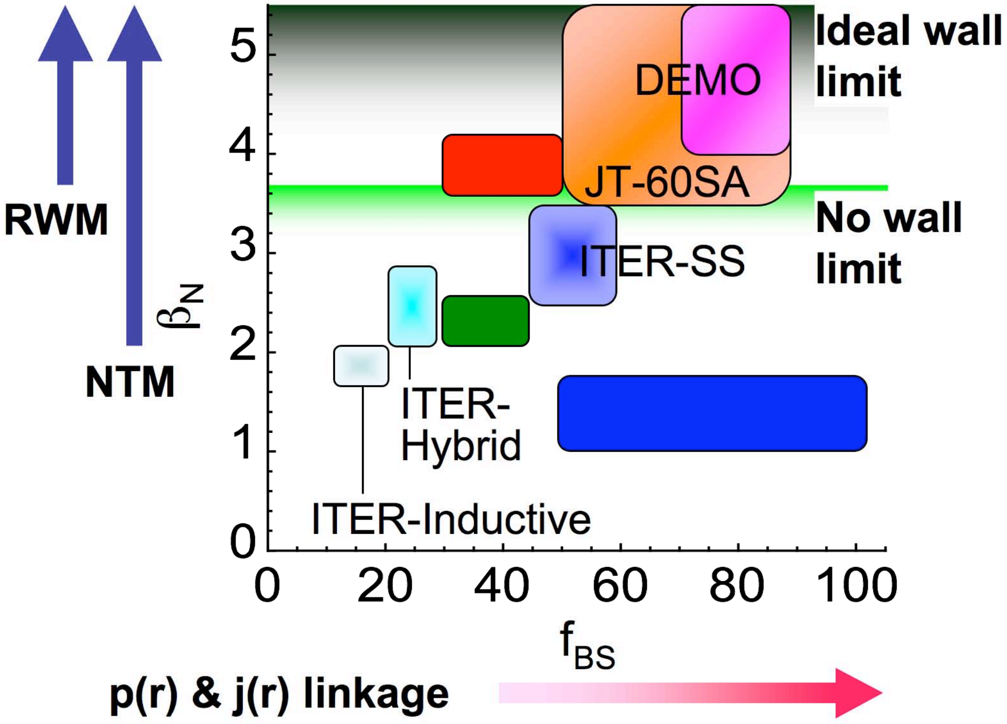
- I_p = 1.2 MA, B_T = 2.6 T, q_{95} = 4.1, V_p = 75 m^3
- **Pedestal pressure increases with the increase in toroidal rotation at the pedestal in co-direction.**
- **Energy confinement is improved by enhancing core toroidal rotation in co-direction.**
- **Pedestal pressure and confinement are raised with FSTs even at a given toroidal rotation.**



H. Urano (EX/5-1, Thu.)

2. Extension of operation regime to High β_N exceeding no wall ideal limit and RWM study

- **Suppression of RWM by plasma rotation is a key.**
- **Estimation of critical rotation velocity for suppressing RWM is important.**



β_N reaches ideal wall limit.

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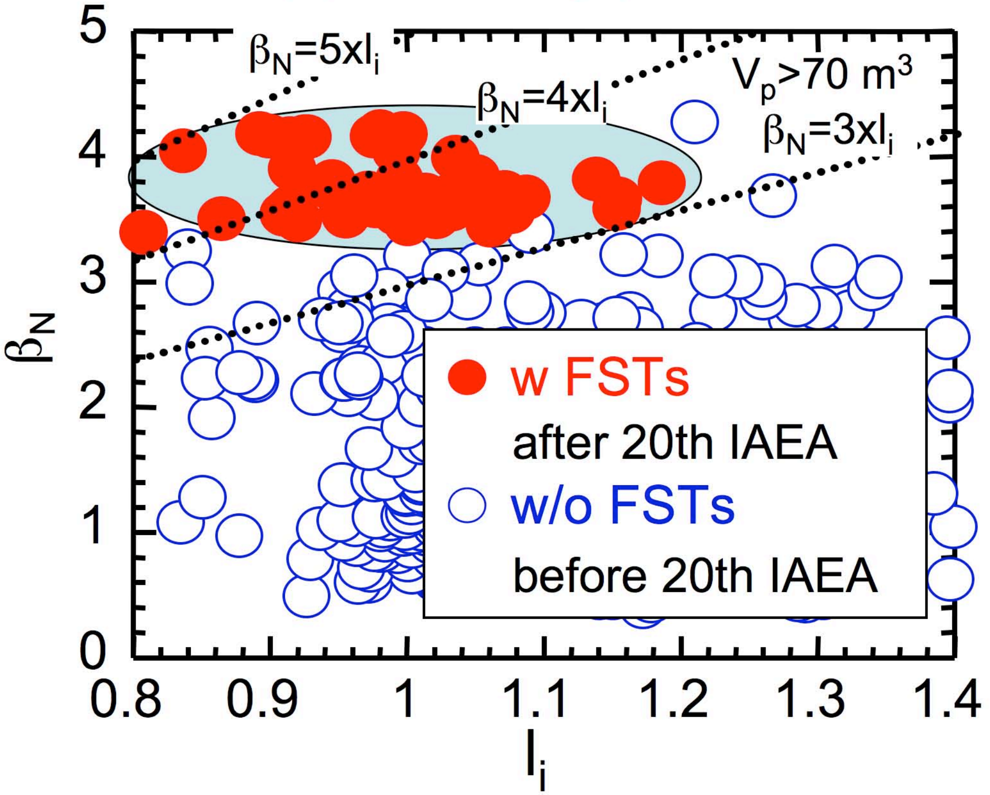
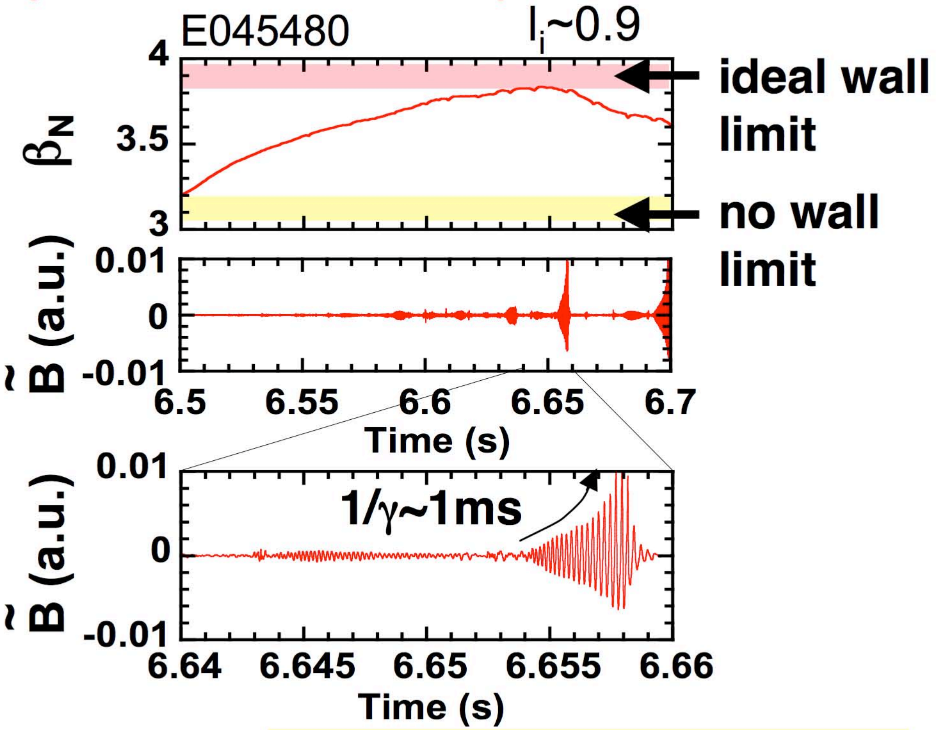
- **High β_p ELMy H-mode plasma :** B_T=1.58 T, I_p=0.9 MA, δ_0~20 cm **(d/a=1.2)**
- **Increase in net heating power due to the FSTs installation allows to access high β_N up to 4.2 with l_i=0.8-1.**
- **n=1 (m~3) mode at high beta region.**
- **Growth time of 1/γ~1 ms (< τ_w~10 ms) before collapse.**
- **RWM is suppressed by plasma rotation (100km/s at r/a=0.3).**



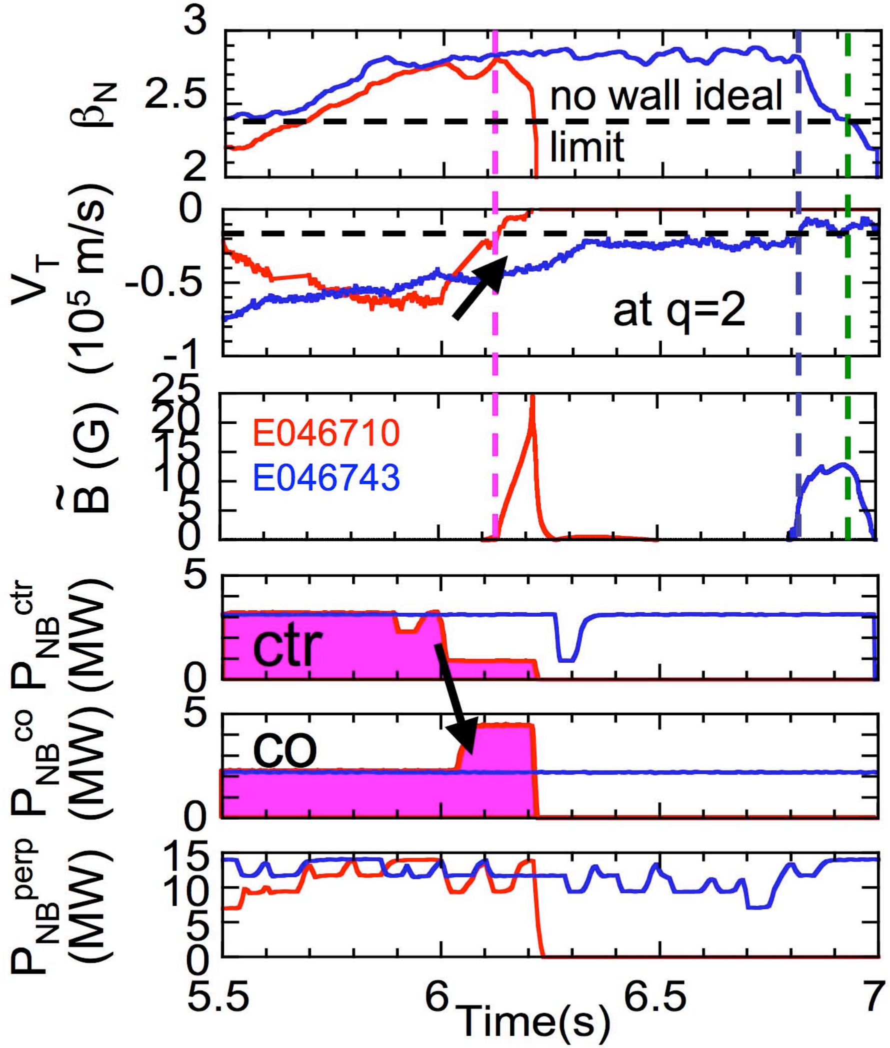


M. Takechi (EX/7-1Rb, Fri.)

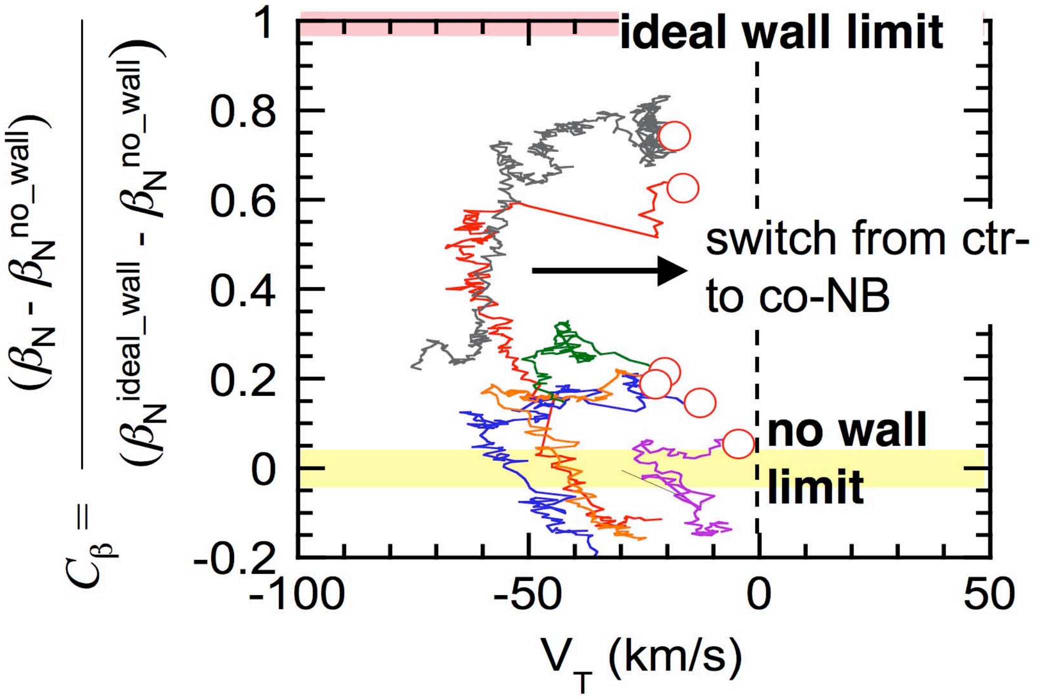
Small critical rotation velocity of V_C/V_A~0.3% is found at q_{95}=3.5 for suppressing RWM.

JT-60U

- **Less counter rotation** due to the FSTs installation enables to change the rotation in co-direction close to zero.



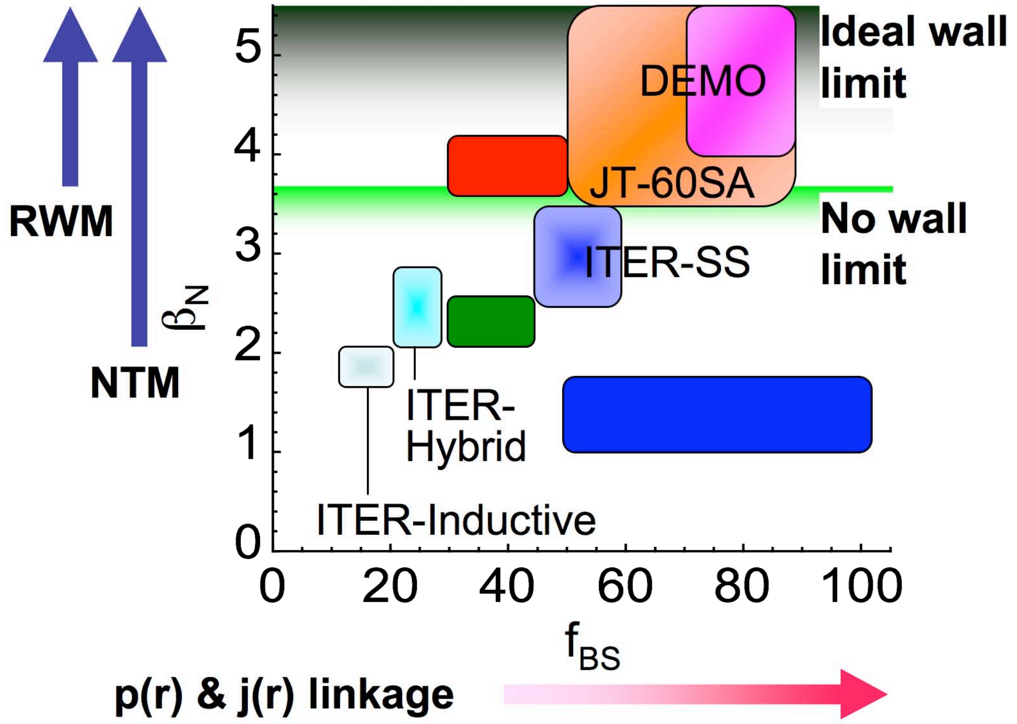
- **V_C~15 km/s**
- **Growth time of 1/γ~10 ms (~ τ_W)**
- **No increase in V_C for higher C_β .**
- **Large impact on ITER & DEMO.**



M. Takechi (EX/7-1Rb, Fri.)

3. Integration of plasma performance in the long high β_N discharges.

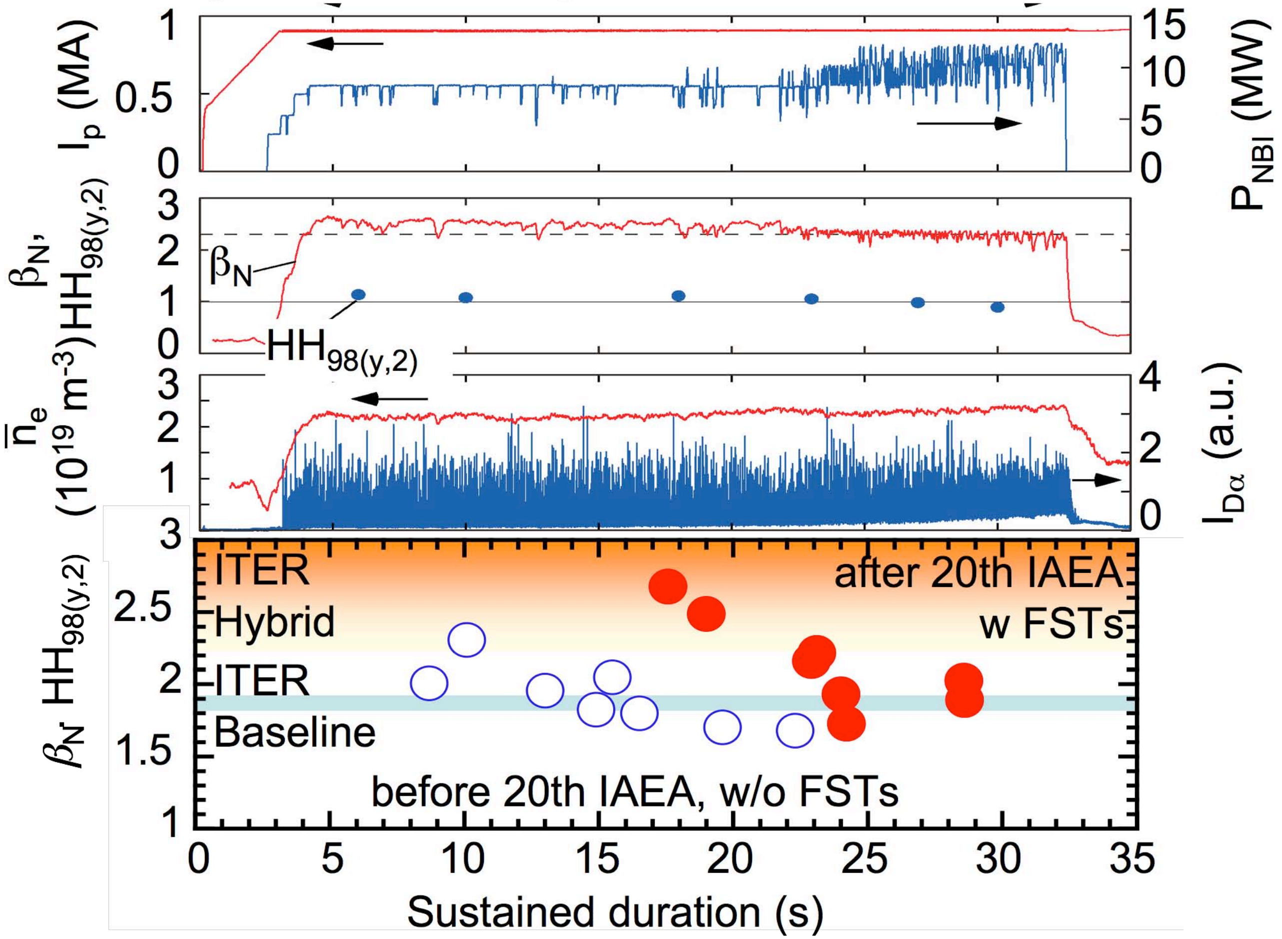
- Confinement improvement is a key.
- Robustness for current profile diffusion should be demonstrated.
- Change of wall pumping with a long time scale is important issue.

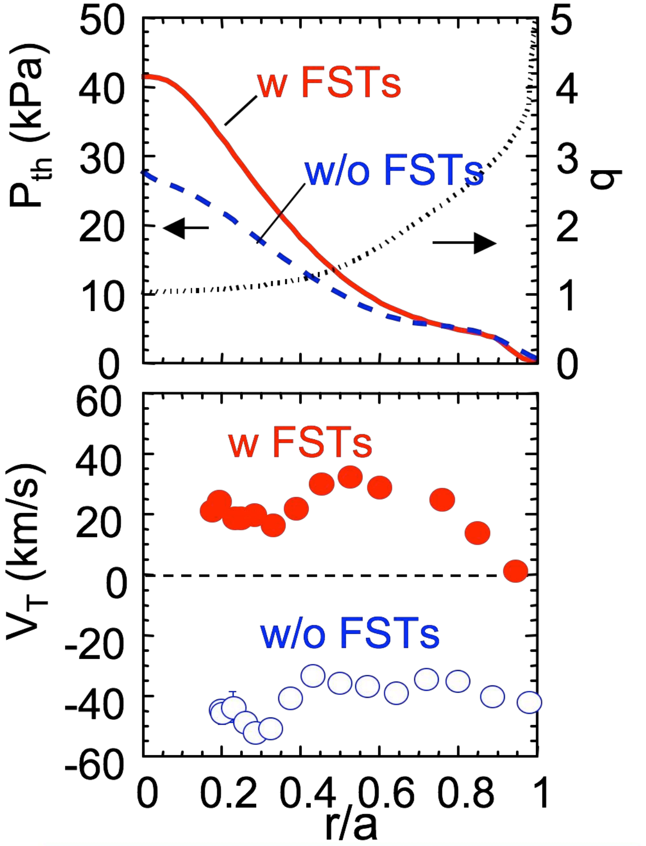


High $\beta_N HH_{98(y,2)}$=2.2 is sustained for 23.1 s (~12τ_R) with f_{BS}=36-45% at q_{95}~3.3.

JT-60U

- **High β_p ELMy H-mode plasmas** : I_p = 0.9 MA, B_T = 1.6 T, V_p = 67 m^3
- **Increase in net heating power due to the FSTs installation allows flexible combination of NB units. ➔ peaked heating profile.**
- **Density increase degrades confinement in the latter phase.**





N. Oyama (EX/1-3, Mon.)

High $\beta_N HH_{98(y,2)}$=2.2 is sustained for 23.1 s (~$12\tau_R$) with f_{BS}=36-45% at q_{95}~3.3.

JT-60U

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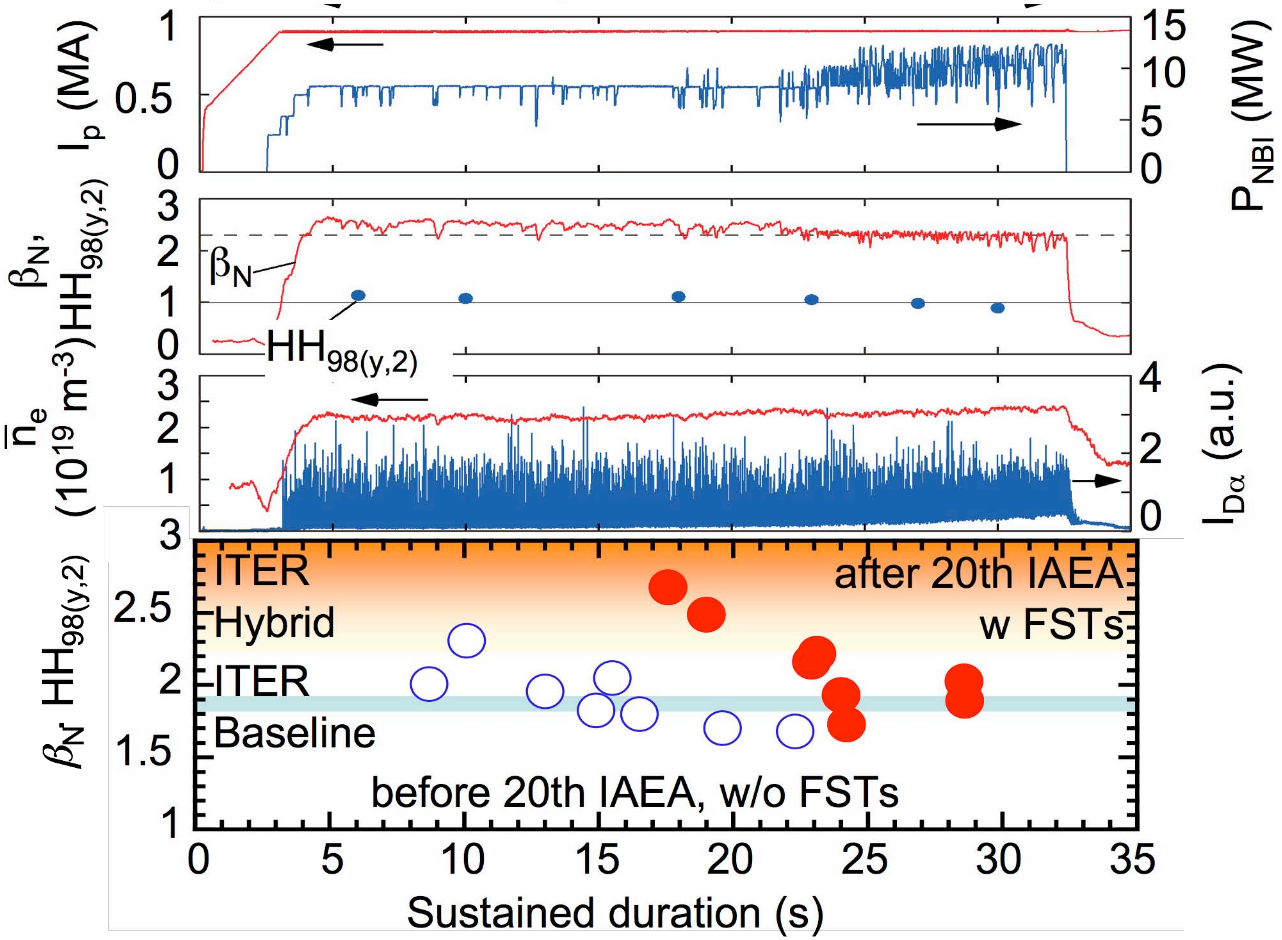

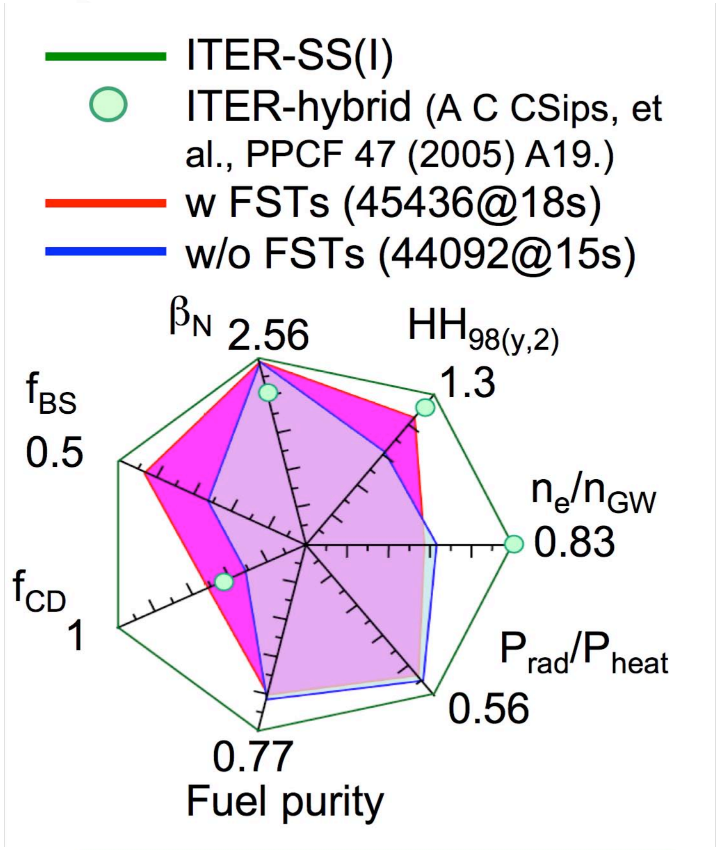

N. Oyama (EX/1-3, Mon.)

Density is successfully controlled by divertor pumping in enhanced recycling region.

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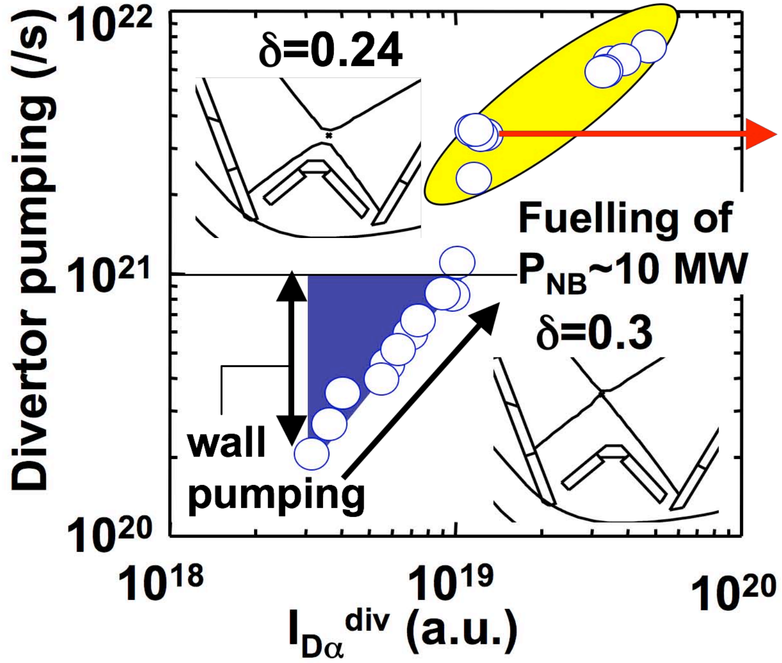
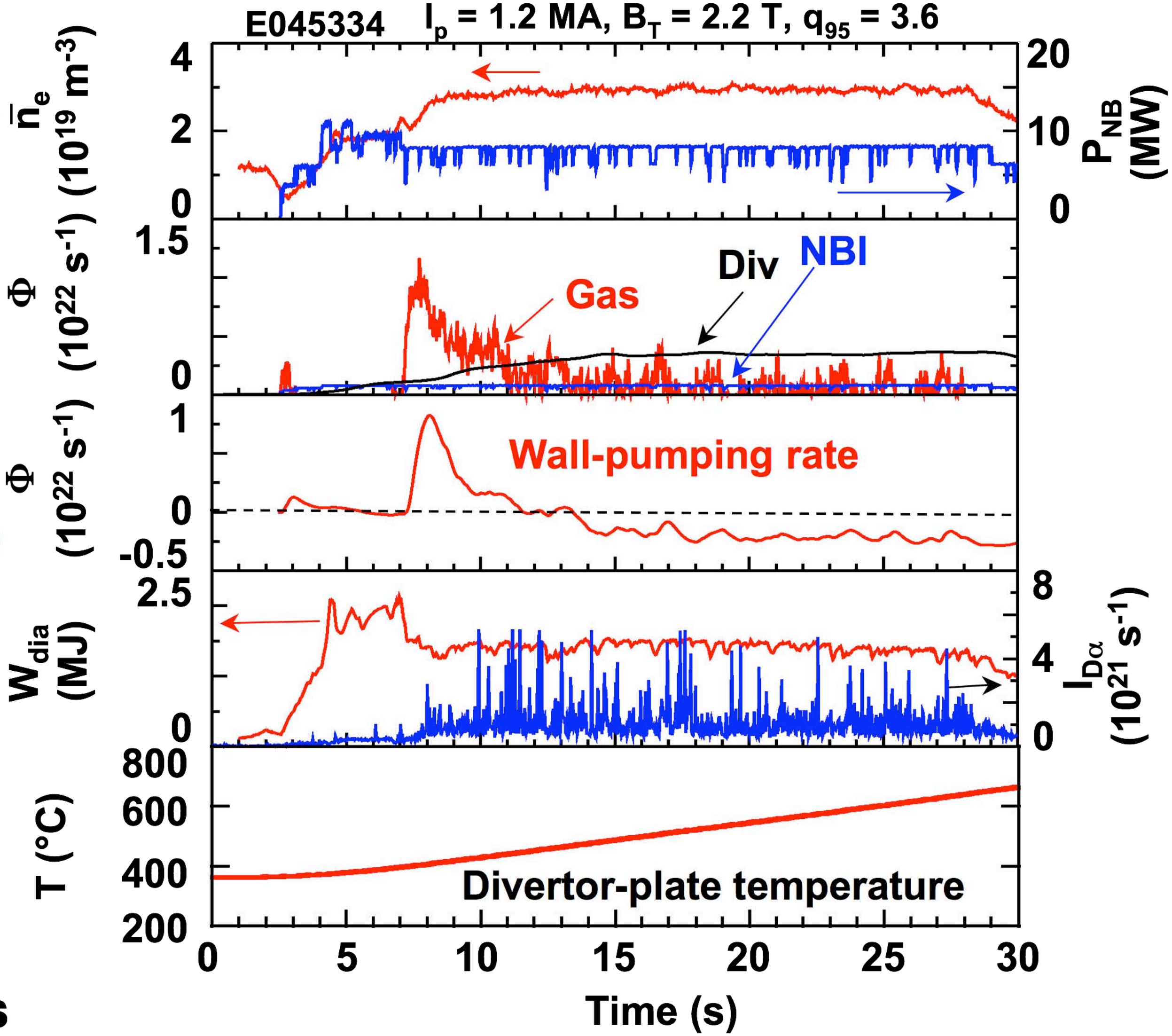


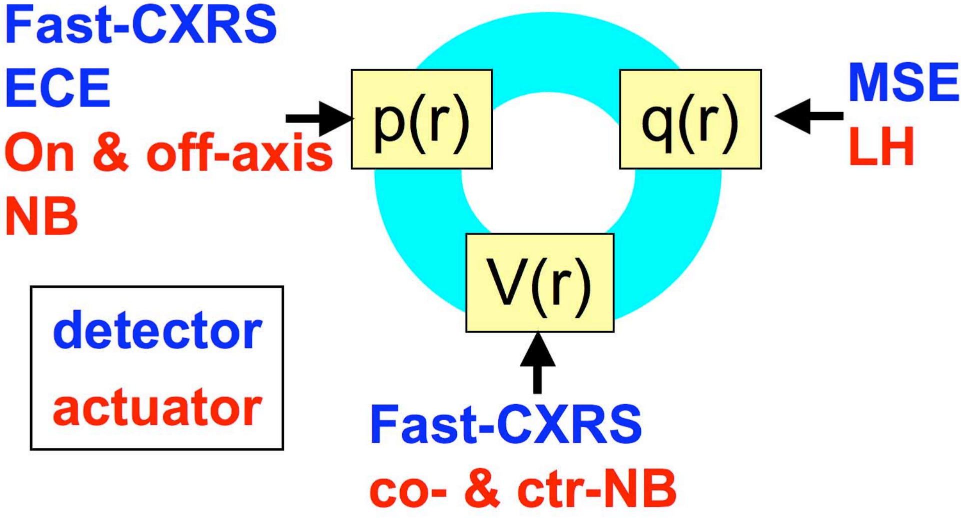


- Divertor pumping depends on recycling.
- $HH_{98(y,2)}$ ~ 0.71 at $0.64n_{GW}$.
- The outgas could be attributed to increase in divertor plate temperature.
- Integration for high density is remaining issue.

H. Kubo (EX/P4-11, Thu.)

4. Development of real time control with high bootstrap current fraction

- Understanding of p(r) and j(r) linkage.
- Current profile control is important for AT plasmas.



Fast-CXRS
ECE
On & off-axis
NB

p(r)

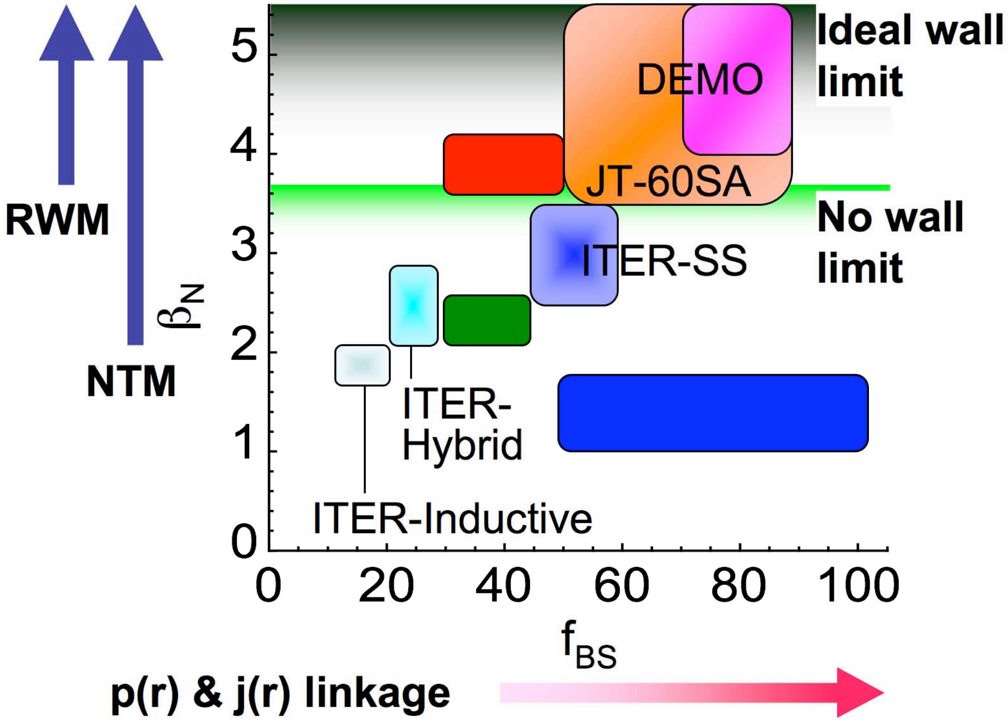
q(r)

MSE
LH

V(r)

Fast-CXRS
co- & ctr-NB

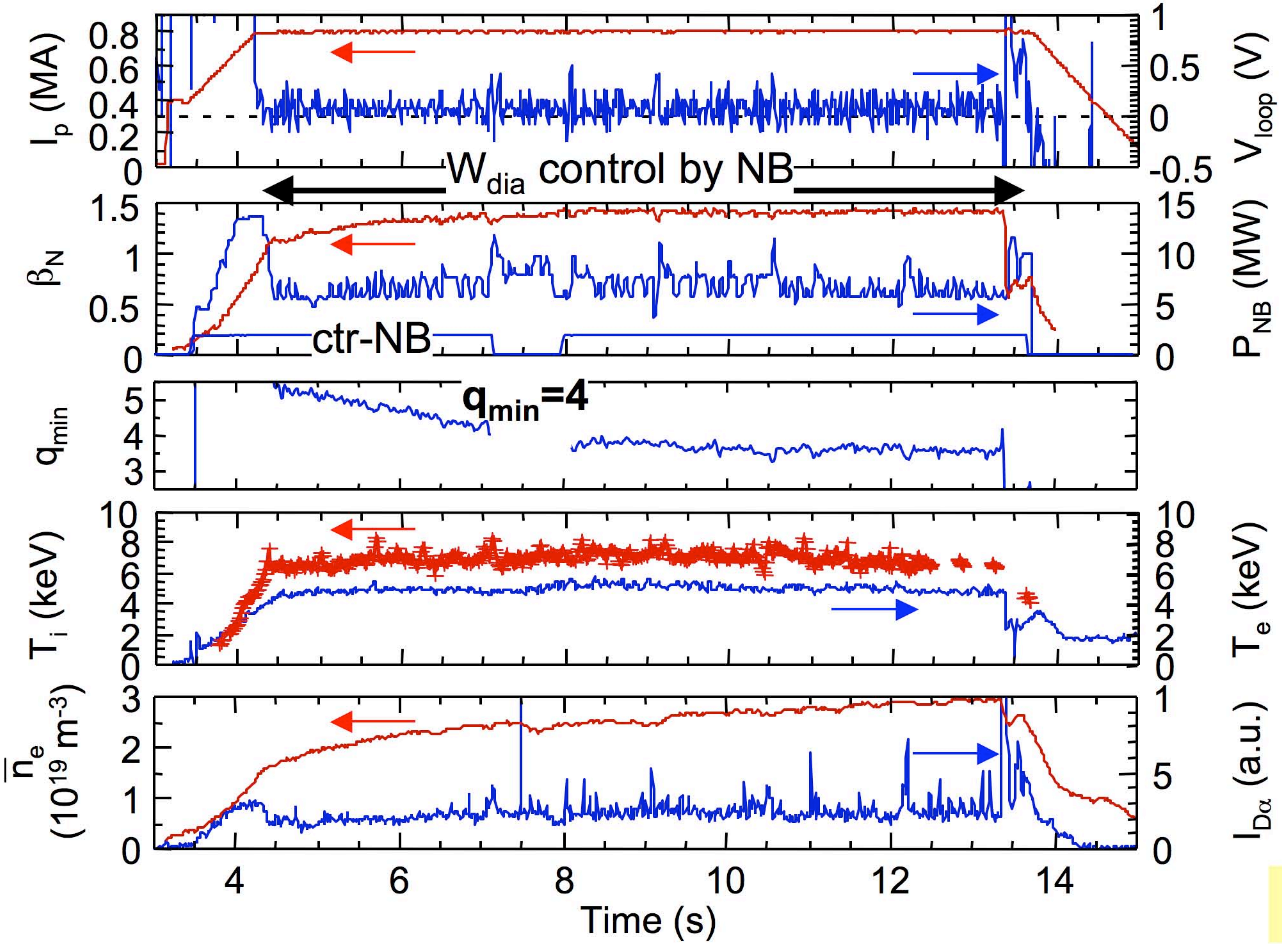
detector
actuator

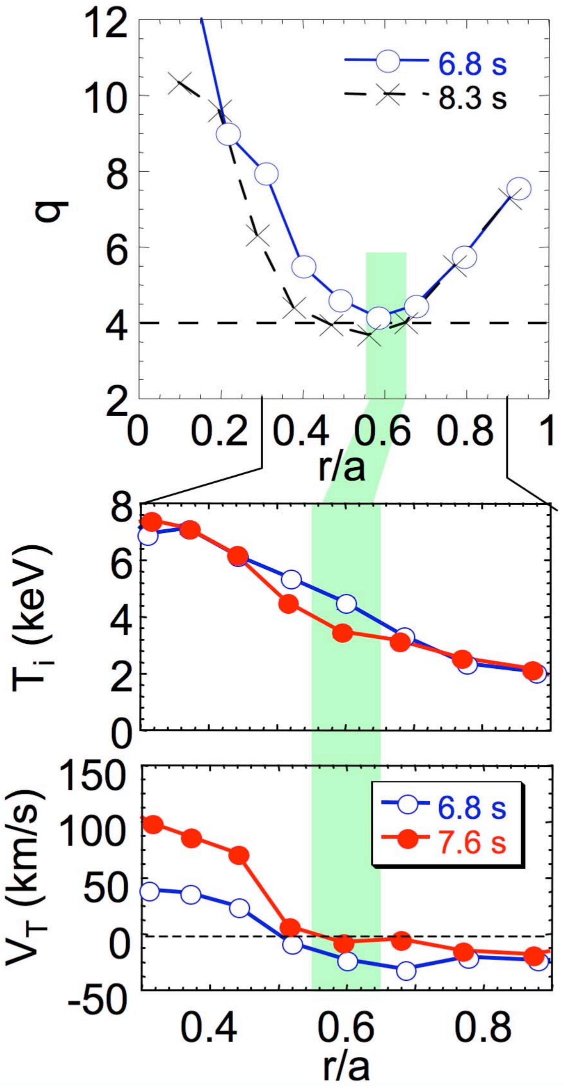


High f_{BS} of 70% is sustained for 8 s by p(r) control at q_{min}= 4 with real time q_{min} estimation.

JT-60U

- **RS plasma : q_{95}~8.5, $HH_{98(y,2)}$~1.8, β_N~1.4.**
- **Ctr-NB off for p(r) control at q_{min}=4 for 1.0s.**





Y. Sakamoto (EX/P1-10, Tue.)

High f_{BS} of 70% is sustained for 8 s by p(r) control at q_{min}= 4 with real time q_{min} estimation.

JT-60U

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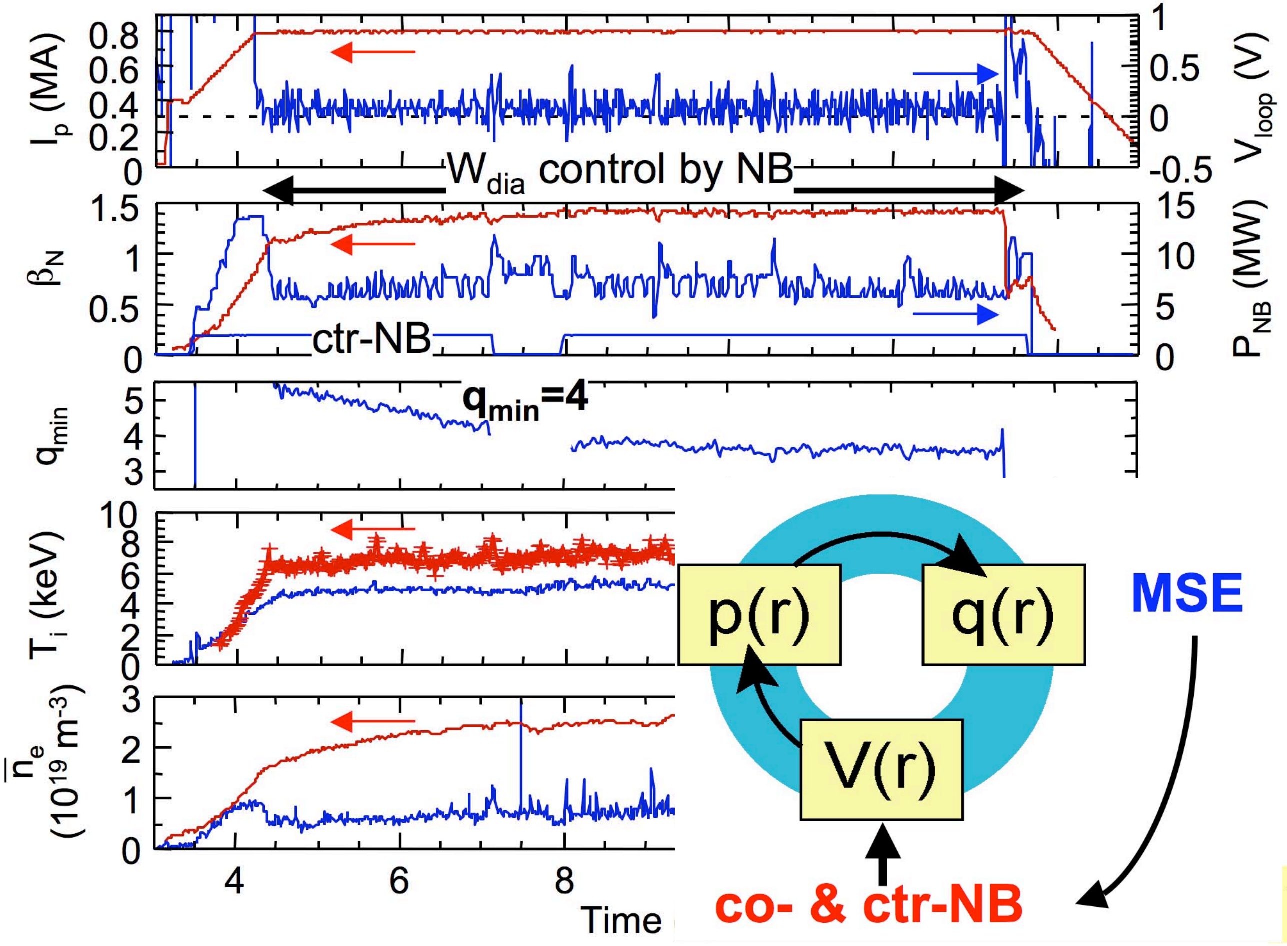
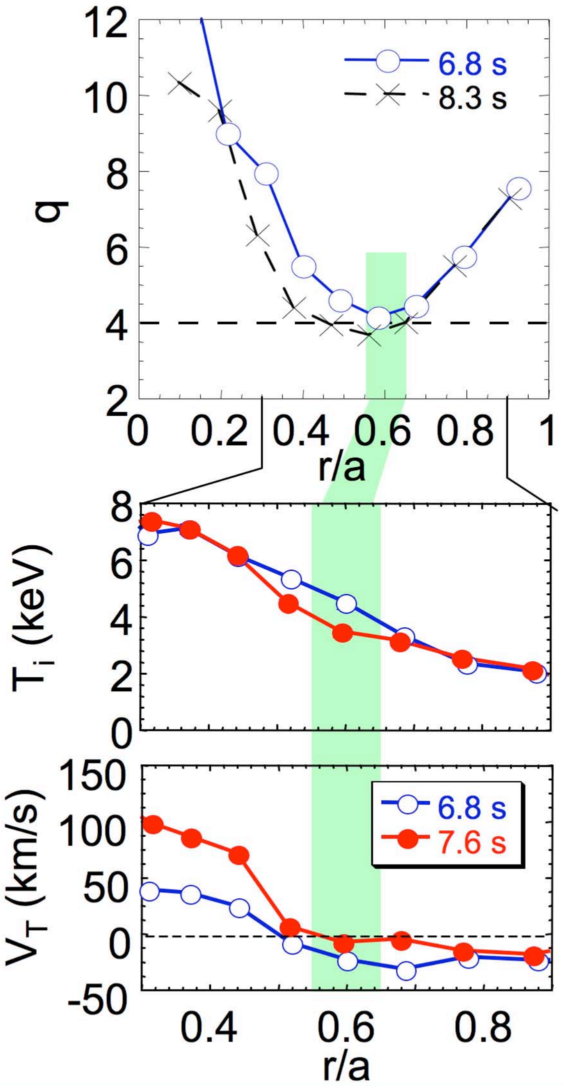


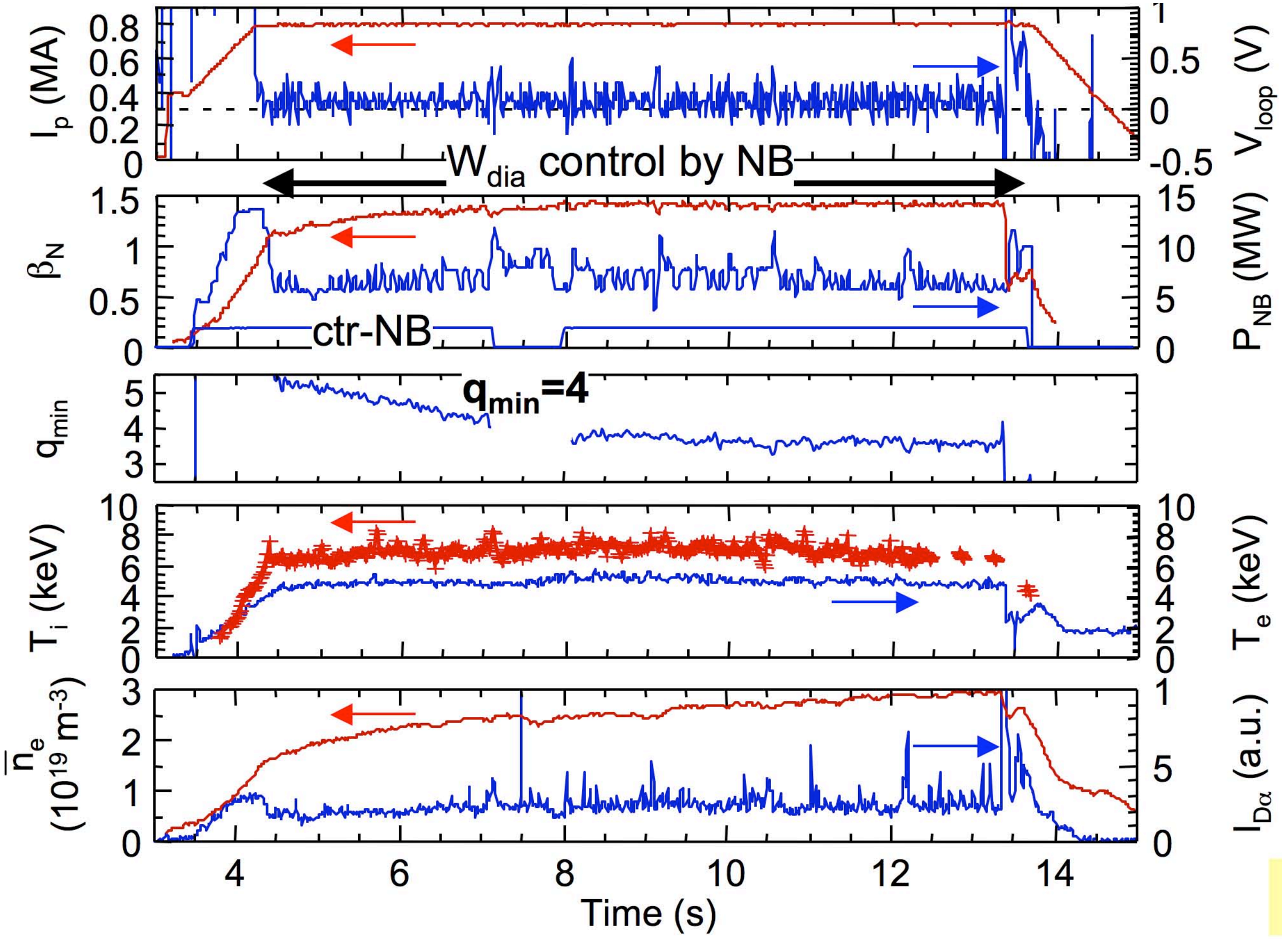


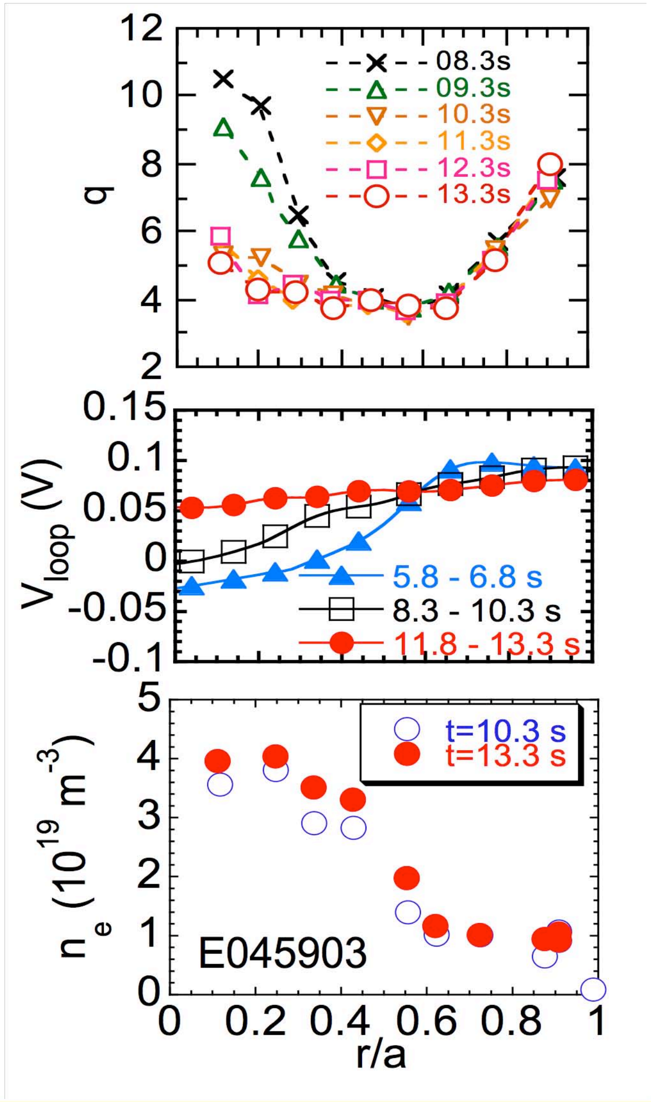
Y. Sakamoto (EX/P1-10, Tue.)

High f_{BS} of 70% is sustained for 8 s by p(r) control at q_{min}= 4 with real time q_{min} estimation.

JT-60U

- j(r) approaches SS, while, n_e(r) still evolves for $\tau > \tau_p^*$(~2s) and plasma collapses.
  ➔ p(r) control is important even with nearly SS j(r) and q_{min} being not integer.



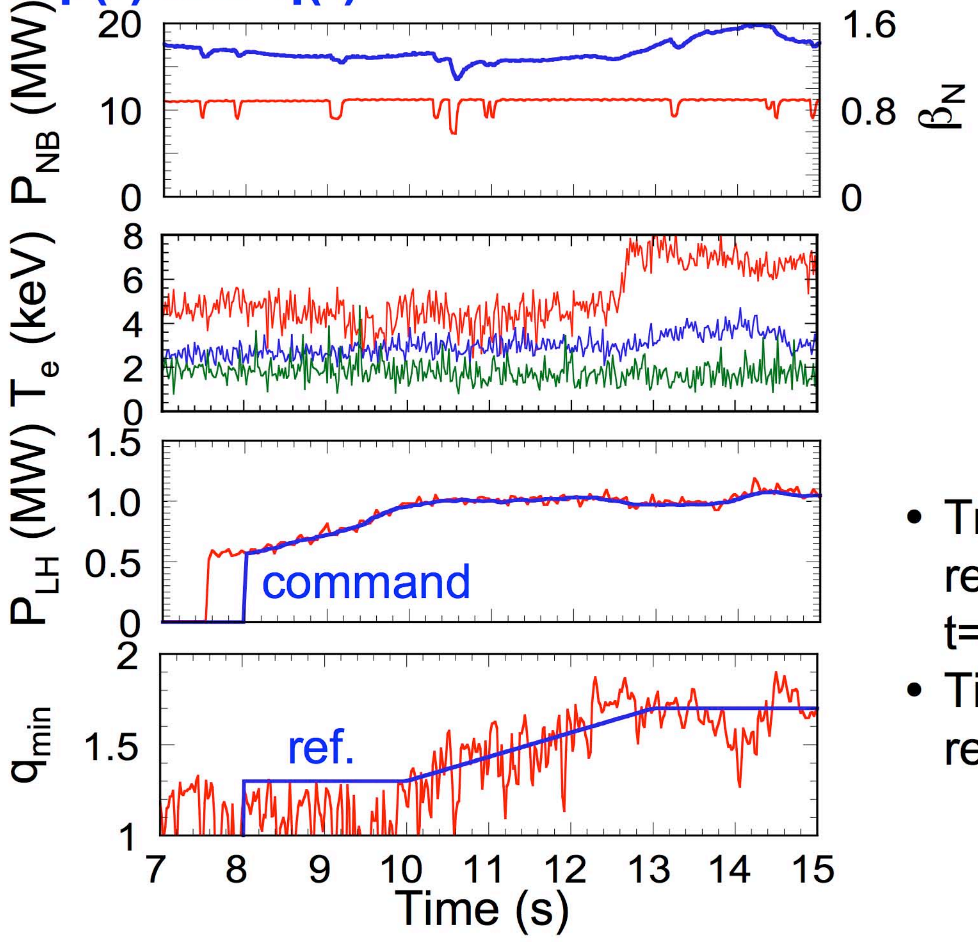


Y. Sakamoto (EX/P1-10, Tue.)

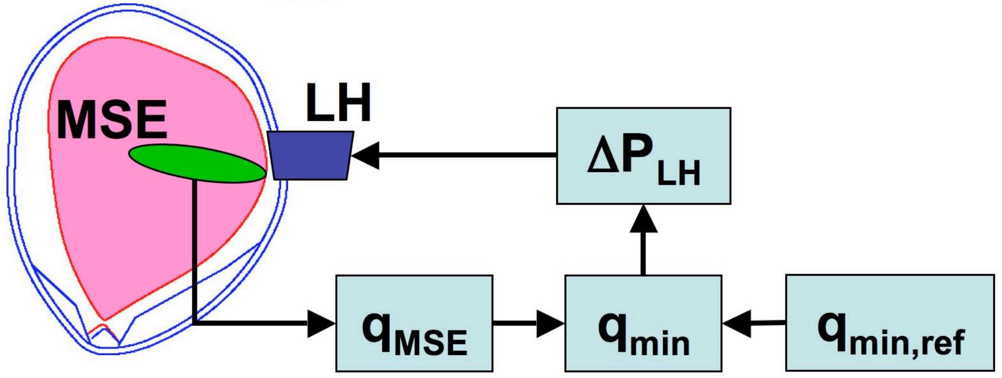
Real time q_{min} control demonstrated with MSE diagnostics and LHCD at f_{BS}=0.46.

JT-60U

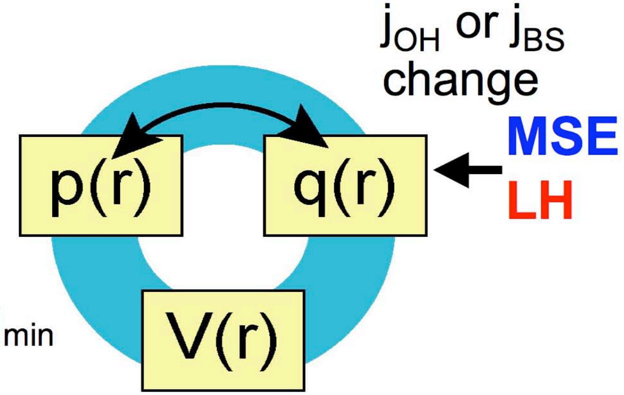
- **Reduction of fast ion loss due to the FSTs installation increases compatibility of LHCD with high power heating.**
- **q_{min} control is affected by dynamic behavior related to the strong linkage of p(r) and q(r).**



Real time q_{min} control scheme



- Transport reduction at t=12.4 s
- Time delay in response of q_{min}

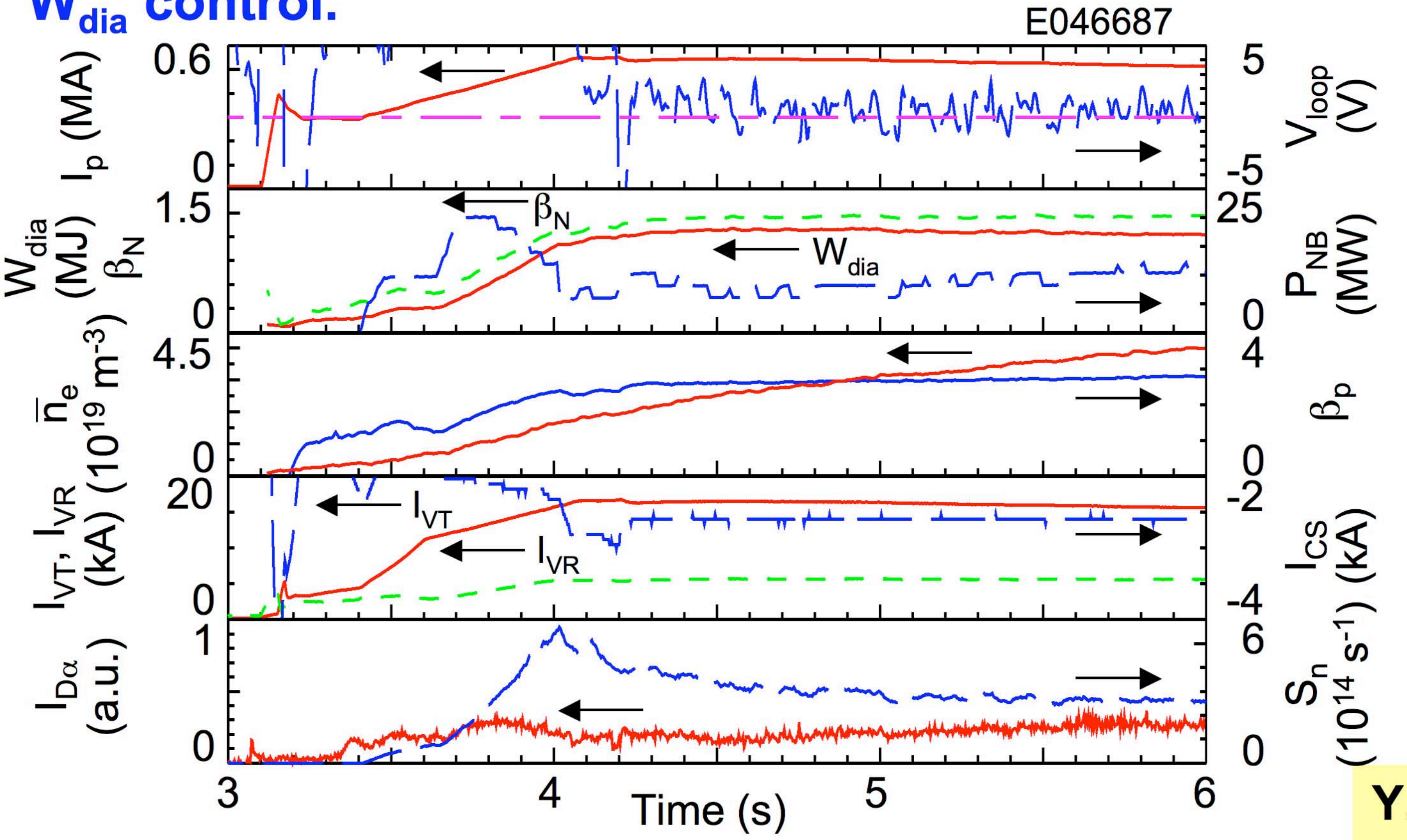


T. Suzuki (EX/6-4, Thu.)

Control for bootstrap sustained plasma (f_{BS}~100%) is challenging.

JT-60U

- **Bootstrap sustained plasma can reduce center solenoid (CS) coil capability, which has a large impact on the economic aspect.**
- **Nearly constant current (~0.54 MA) is maintained by BS current with constant I_{CS} and negative NBCD current for ~1 second.**
- **Both W_{dia} and I_p gradually decrease in the strong linkage even with constant W_{dia} control.**



B_T = 4 T, β_N=1.15
I_{CS} constant
W_{dia} constant FB

Y. Takase (EX/1-4, Mon.)

5. Physics studies on issues implicated for ITER.

- **NTM suppression by ECCD**
  - J_{EC}/J_{BS}
  - Dependence of EC deposition position
  - Modeling
- **Behavior of energetic ions with Alfvén eigenmodes**
  - Neutron emission profile measurements
  - Comparison with classical calculation
- **ELM propagation in SOL plasma**
  - Measurements with multi reciprocating probes (LFS and HFS)

2/1 NTM is suppressed at $J_{EC}=0.5J_{BS}$ with well aligned ECCD to q=2 surface.

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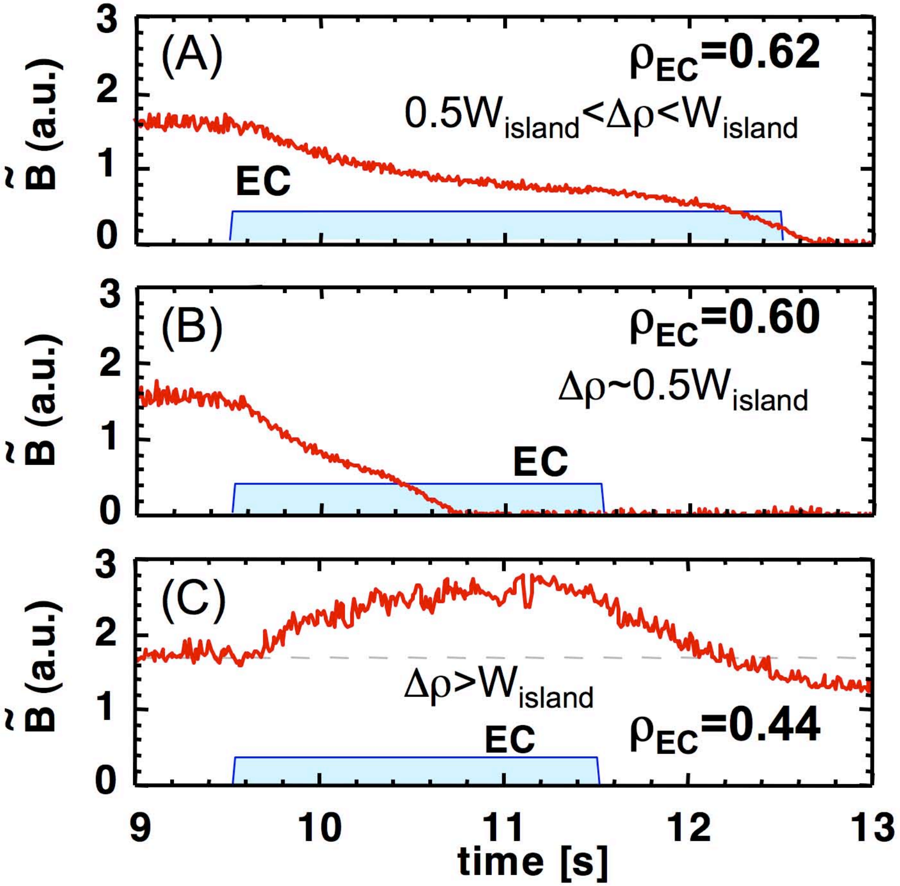
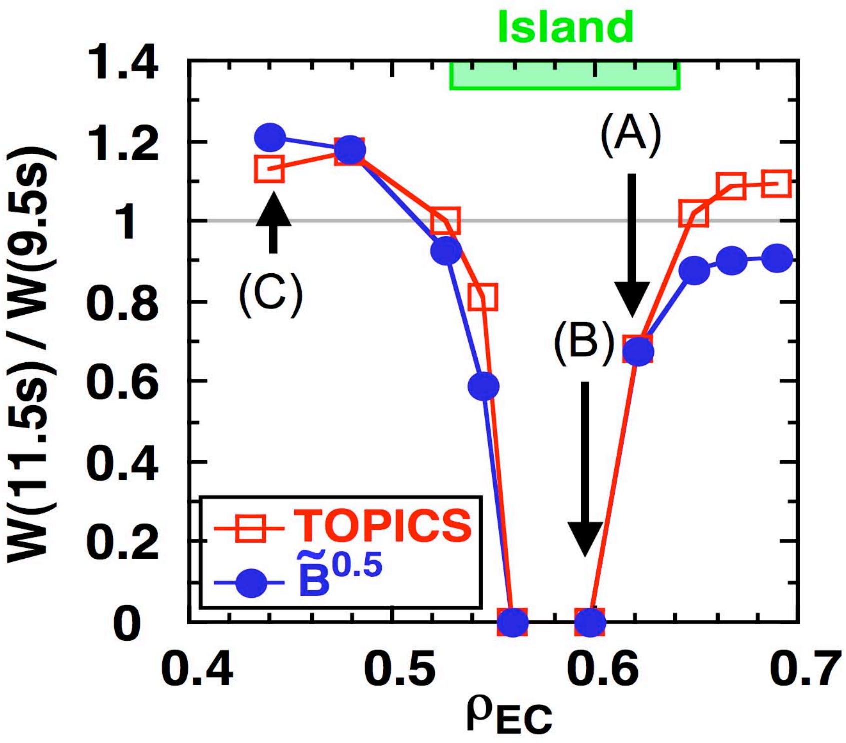
- **2/1 NTM is destabilized with the misalignment comparable to the island width.**
- **TOPICS simulation is well reproduced with the same set of coefficients of the modified Rutherford equation.**





A. Isayama (EX/4-1Ra, Thu.)

Energetic ions transported from core region due to AEs with moderate amplitude.

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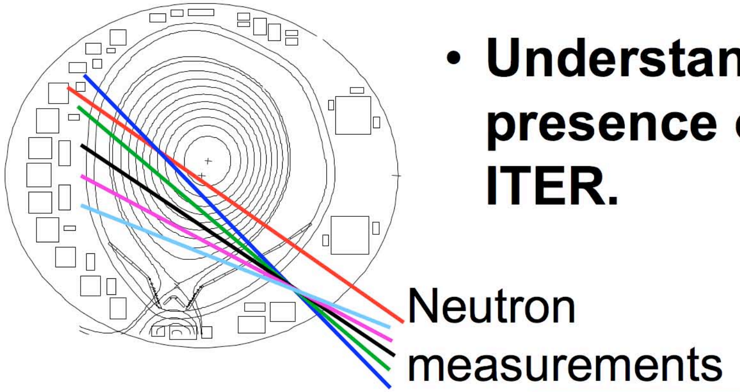
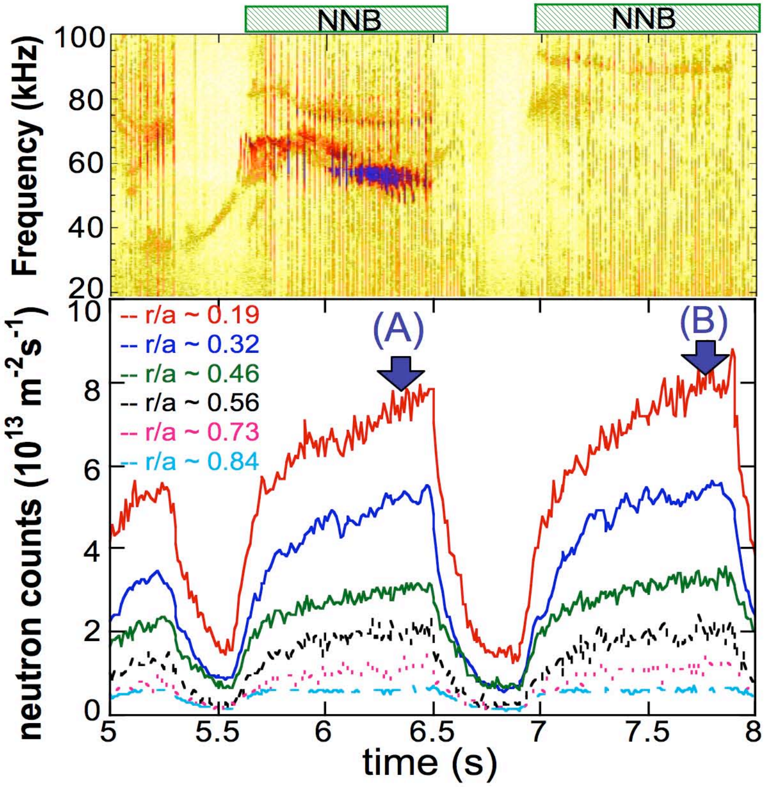
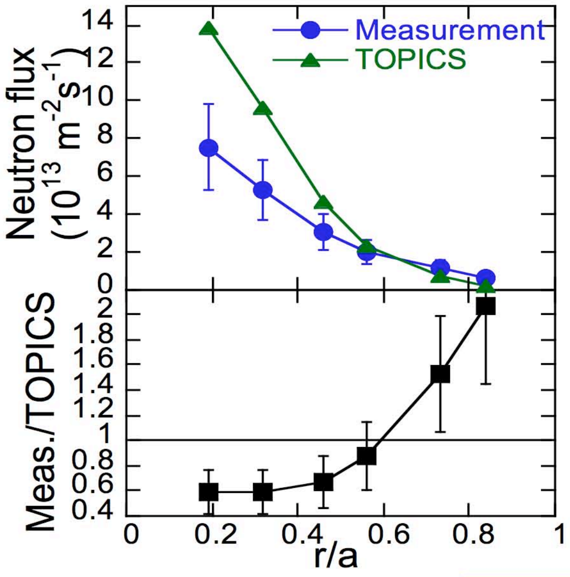
- **Understanding of the alpha particle transport in the presence of AEs is one of the urgent research issues for ITER.**



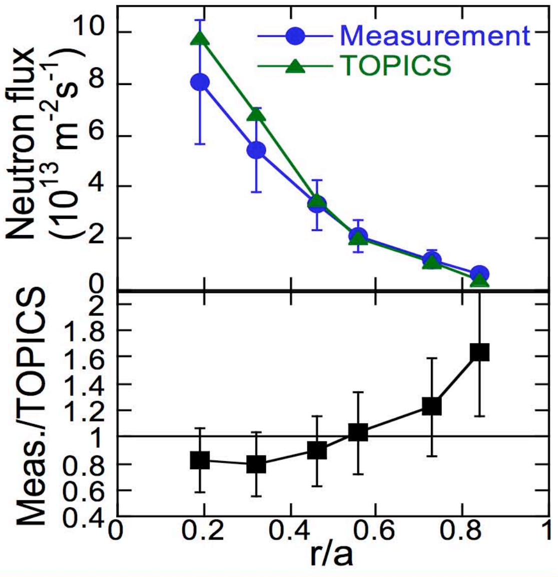
- **The measured neutron yield is significantly smaller than the classical calculation during AEs with moderate amplitude in the central region.**



(A) with AEs (t=6.4s)



(B) with weak AEs (t=7.8s)



M. Ishikawa (EX/6-2, Thu.)

Non-diffusive ELM propagation is observed in LFS SOL, but not in HFS SOL.

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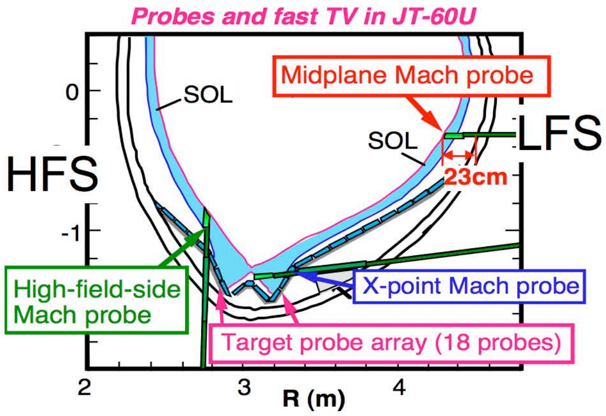
- **Transient heat and particle load to the plasma facing components (PFC) is a crucial issue.**
- **V_{perp}^{mid}(peak)=0.4-1.2 km/s (Δr^{mid}<5 cm), 1.5-3 km/s (Δr^{mid}>6 cm)**

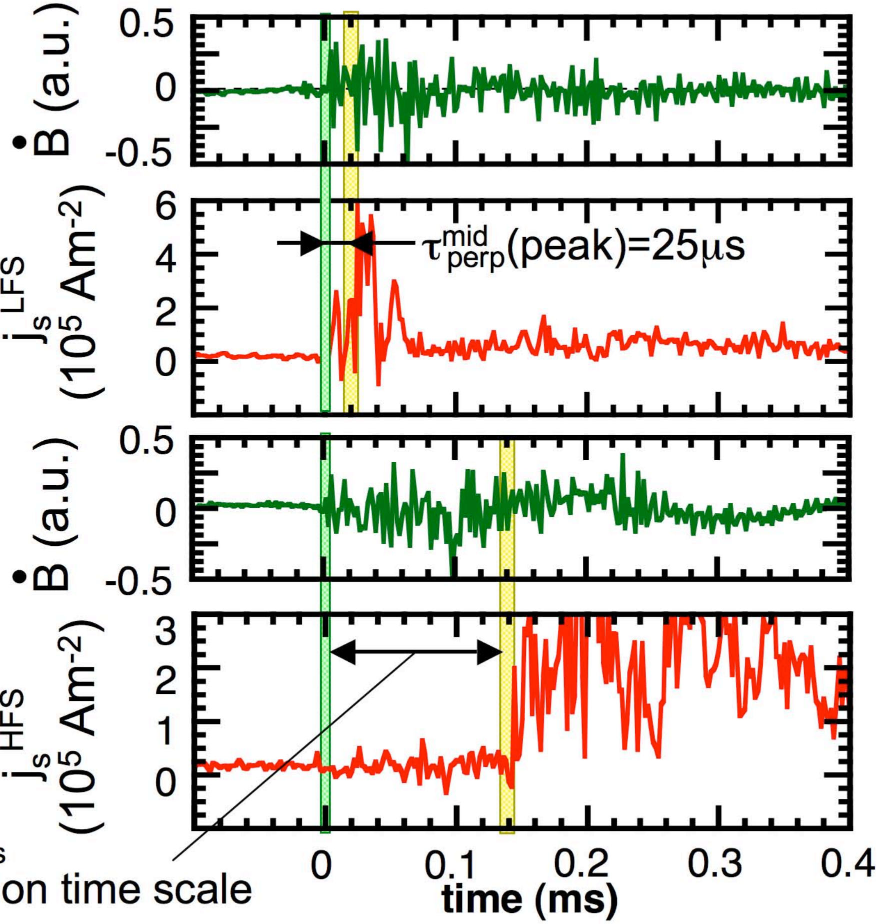


LFS

Δr^{mid}=1.0cm

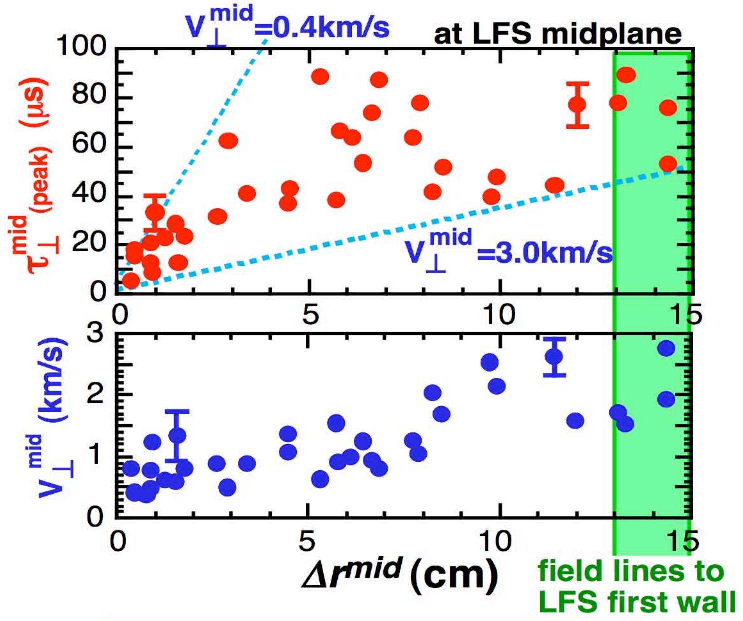
HFS

Δr^{mid}=0.8cm



~L_C^{HFS}/C_s
~convection time scale

LFS



N. Asakura (EX/9-2, Fri.)

6. Summary

The installation of FSTs enables to access new regimes.

- High β_N exceeding no wall ideal limit
  β_N~4.2 (=ideal wall limit)
  Small critical rotation of V_C/V_A=0.3% and no increase of critical rotation velocity in high C_β regime for suppressing RWM
  ➔ High β_N in ITER and DEMO

- Long sustainment of integrated performance
  $\beta_N H H_{98(y,2)}$=2.2 for 23.1 s (~12τ_R) with f_{BS}=36-45%
  ➔ ITER hybrid scenario

- Development of real time control methods for pressure profile control and current profile control.
  ➔ intelligent control for the high f_{BS} plasmas in DEMO

- Progress in physics studies implicated for ITER.
  NTM suppression, Energetic ions with AEs and ELM.

- JT-60SA (super advanced) design is optimized to support and supplement ITER toward DEMO. (M. Kikuchi, FT2-5, Fri.)

Presentations from JT-60U

Mon.	Long high β_N discharges	N. Oyama (EX/1-3)
	Bootstrap sustained discharges	Y. Takase (EX/1-4)
Tue.	ITB study in high β_p mode plasmas	S. Ide (EX/P1-5)
	High bootstrap discharges	Y. Sakamoto (EX/P1-10)
Wed.	FSTs effects on rotation & momentum transport	M. Yoshida (EX/P3-22)
Thu.	NTM suppression by ECCD	A. Isayama (EX/4-1Ra)
	FSTs effects on pedestal and confinement	H. Urano (EX/5-1)
	Energetic ions with AEs	M. Ishikawa (EX/6-2)
	Current profile control & off-axis current drive	T. Suzuki (EX/6-4)
	Particle control under wall saturation	H. Kubo (EX/P4-11)
	Hydrogen retention and carbon deposition	K. Masaki (EX/P4-14)
	Radiation processes of impurities and hydrogen	T. Nakano (EX/P4-19)
	ITB study in RS plasmas	K. Ida (EX/P4-39)
	Installation of FSTs	K. Shinohara (FT/P5-32)
Fri.	High β_N and RWM study	M. Takechi (EX/7-1Rb)
	ELM propagation and fluctuation in SOL	N. Asakura (EX/9-2)
	Spontaneously excited waves near ICRF	M. Ichimura (EX/P6-7)
Sat.	High density limit with high li	H. Yamada (EX/P8-8)
	NTM suppression by ECCD	A. Isayama (EX/4-1Ra, P)
	High β_N and RWM study	M. Takechi (EX/7-1Rb, P)