

OV/1-1

Overview of JT-60U Progress towards Steady-state Advanced Tokamak

S. Ide and the JT-60 Team

**Naka Fusion Research Establishment
Japan Atomic Energy Research Institute**

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National and International Collaboration on the JT-60 Project

JT-60U

The JT-60 Team

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• National collaboration (shown in red)

9) Fukui University, 11) High Energy Accelerator Research Organization, 12) Hiroshima Institute of Technology, 13) Hiroshima University, 14) Hokkaido University, 17) Japan Society of the Promotion of Science Invitation Fellowship, 18) Kanazawa University, 19) Keio University, 21) Kyoto University, 22) Kyushu Tokai University, 23) Kyushu University, 26) Mie University, 27) Nagoya University, 28) National Institute for Fusion Science, 29) National Institute of Advanced Industrial Science and Technology, 30) Nippon Advanced Technology Co.Ltd., 32) Osaka University, 35) Research Organization for Information Science & Technology, 36) Shinshu University, 37) Shizuoka University, 40) The University of Tokyo, 41) Tohoku University, 42) Tokyo Institute of Technology, 43) University of Tsukuba

– JT-60U is functioning as the central tokamak in Japanese fusion research

• International collaboration (shown in blue)

2) AF Ioffe Physical-Technical Institute of the Russia, Russia, 3) Association Euratom-CEA, France, 5) Chinese Academy of Sciences, China, 6) EFDA Closed Support Unit, Germany, 7) Euratom/UKAEA Association, UK, 10) General Atomics, USA, 15) Idaho National Engineering and Environmental Laboratory, USA, 16) JAERI Fellow, 17) Japan Society of the Promotion of Science Invitation Fellowship, 20) Kurchatov Institute, Russia, 24) Lawrence Livermore National Laboratory, USA, 25) Max-Planck-Institut für Plasmaphysik, Germany, 31) Oak Ridge National Laboratory, USA, 33) Post-Doctoral Fellow, 34) Princeton Plasma Physics Laboratory, USA, 38) Southwestern Institute of Physics, Chin

– including IEA/ITPA collaboration

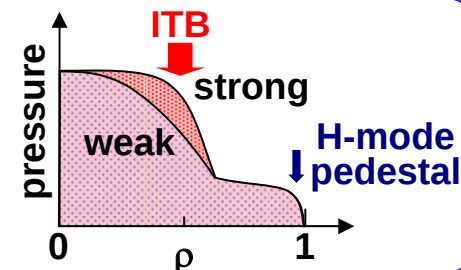
the JT-60U program

JT-60U

- Objectives:**
- R&D for ITER physics basis
 - Advanced Tokamak (AT) development towards ITER & DEMO

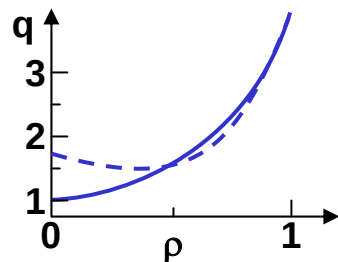
- high bootstrap current fraction (f_{BS}) for steady state
- high β_N for high fusion output

In JT-60U, the AT development has been pursued base on **two types of internal transport barrier (ITB) plasmas** mainly with pedestal.



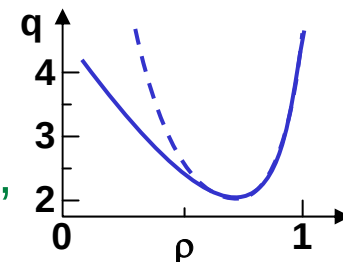
- High β_p plasma (since 1994)

- Monotonic/weak shear, $\beta_N \leq 5$, $f_{BS} \leq 70\%$, full CD



- Reversed shear (RS) plasma (since 1996)

- RS w or w/o current hole, $\beta_N \leq 2.5$, $f_{BS} \leq 80\%$, full CD



Integrated performance, proof of principle (full CD, control...)

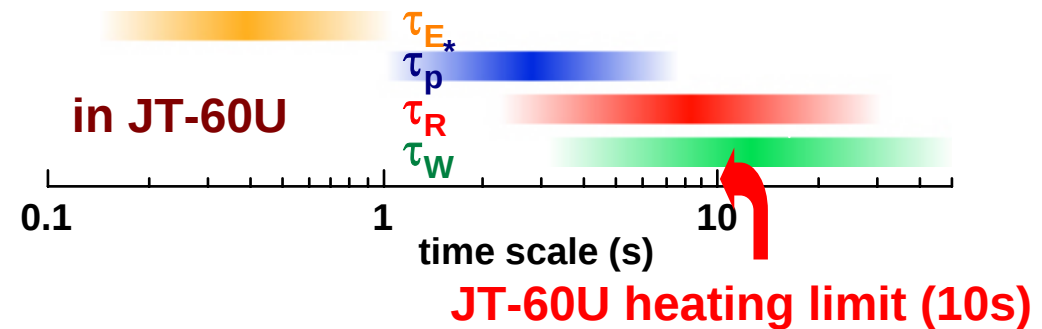
In the last two years, we have concentrated in longer pulse operation

why long pulse

JT-60U

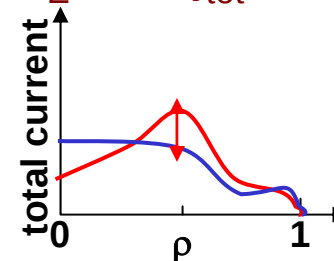
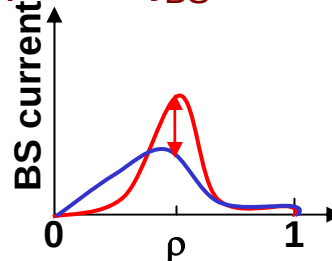
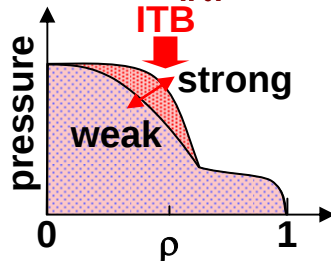
In AT research, control is increasingly an important issue.
Robustness of AT scenario against perturbations is also a key issue.

- The fight is against key characteristic time constants in various time scales;
 - energy confinement (τ_E)
 - effective particle confinement (τ_p^*)
 - **current profile relaxation (τ_R)**
 - wall saturated with particles (τ_w)



Genuine control must work over these time constants.

e.g.: When ITB (χ) changes $\Rightarrow$ p and j_{BS} changes in τ_E . But j_{tot} changes in τ_R .



We need real long pulse plasmas to investigate control and scenario robustness against inter-play of different times scale physics.

Contents

JT-60U

1. Machine Improvement
2. Long Pulse Operation
3. Extension of AT Relevant Plasmas
4. Progress in Physics Studies
5. ELMs, Pedestal, Divertor, SOL and Plasma Wall Interaction
6. Summary

1. Machine Improvement

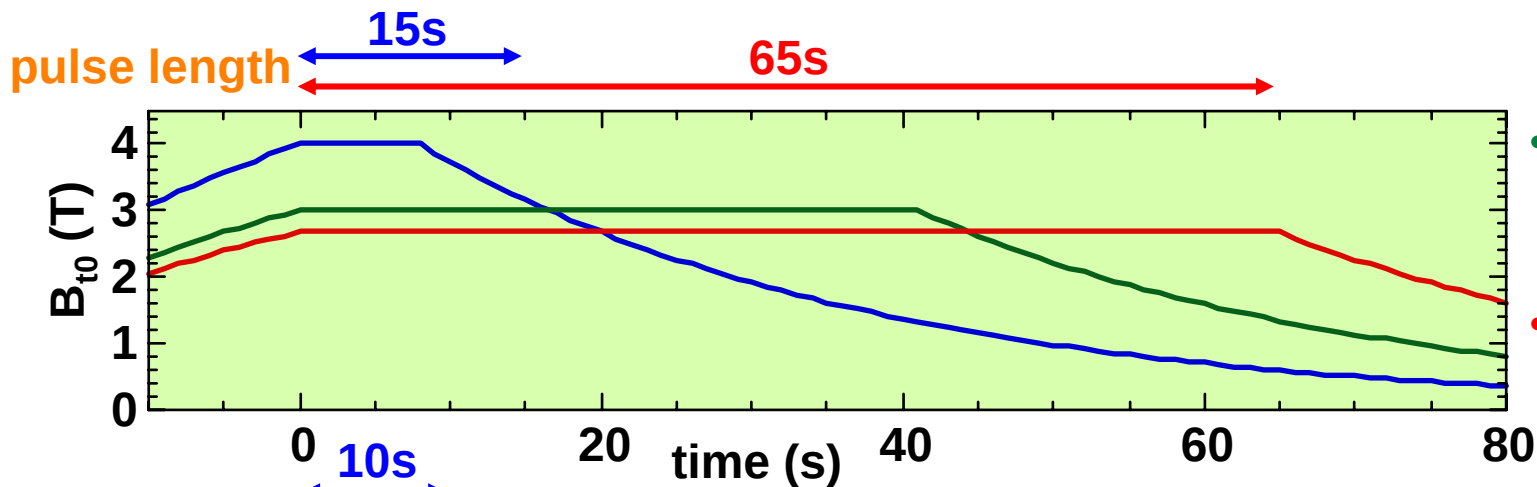
JT-60U

- Extension of a discharge, heating/CD and diagnostics duration
- A 65 seconds JT-60U discharge

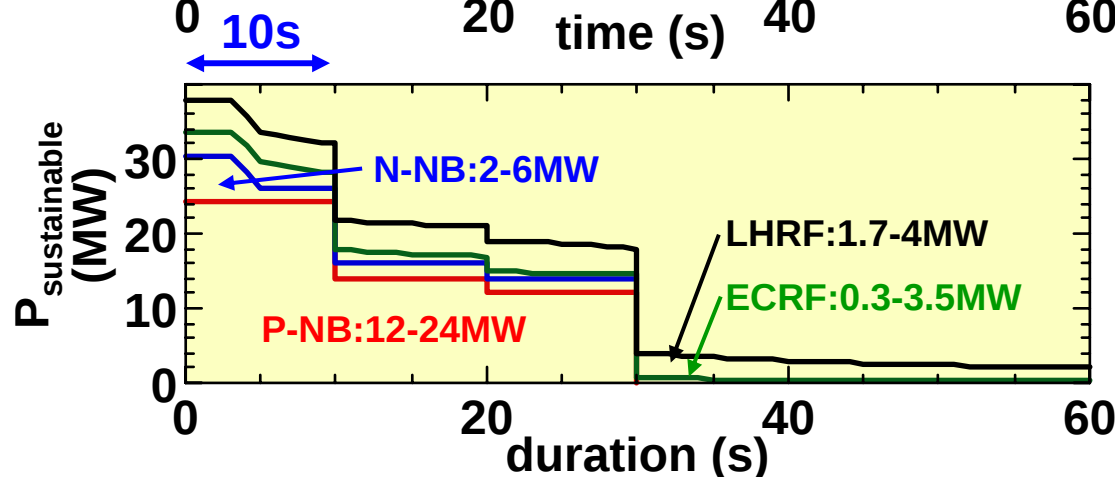
Extension of a discharge, heating/CD and diagnostics duration

JT-60U

The max. pulse length of a discharge is extended from 15s to 65s.
Modification on controls in operation, H/CD and diagnostics systems, but not on major hardware.



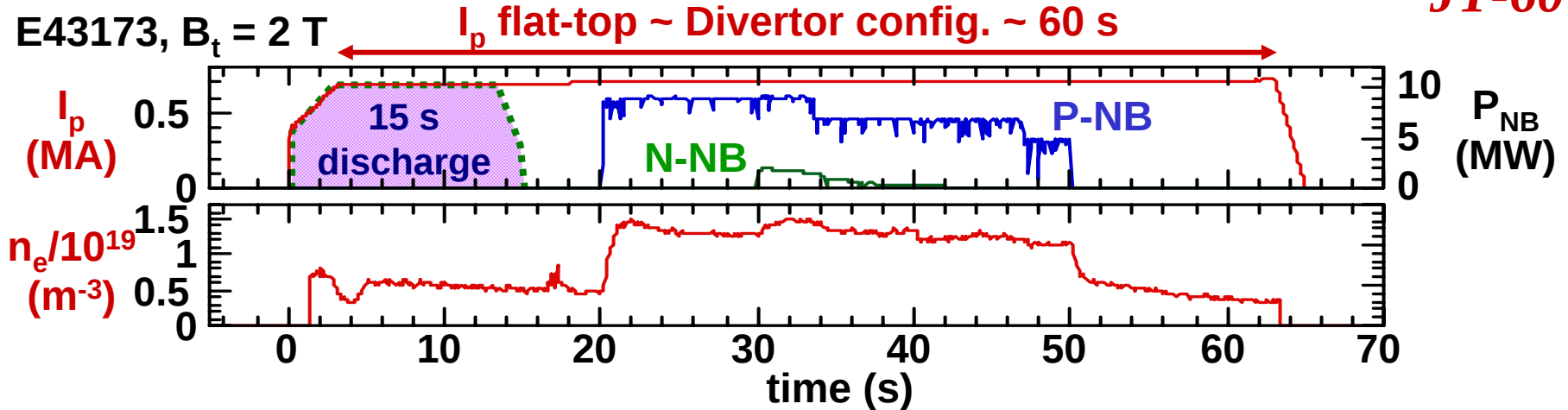
- B_{t0} flat top
4Tx8s =>
~2.7Tx65s.
- $f_{EC}=110\text{GHz} \Rightarrow 3.9\text{T}$
(cold plasma)



- NB heating (formally 10s)
 - N-NB: $\leq 30\text{s}$
 - tang. P-NB (4units): $\leq 30\text{s}$
 - perp. P-NB (7units): $\leq 10\text{s}$ (unchanged)
- EC and LHRF 10s => 60s

A 65s JT-60U discharge

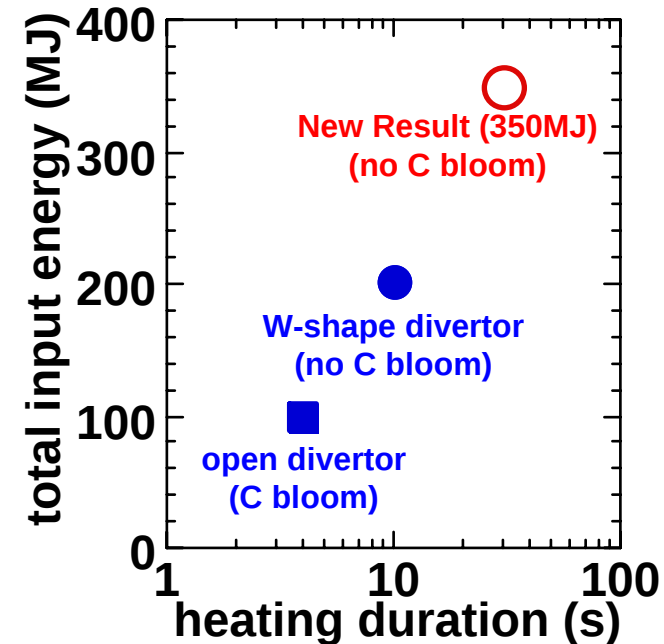
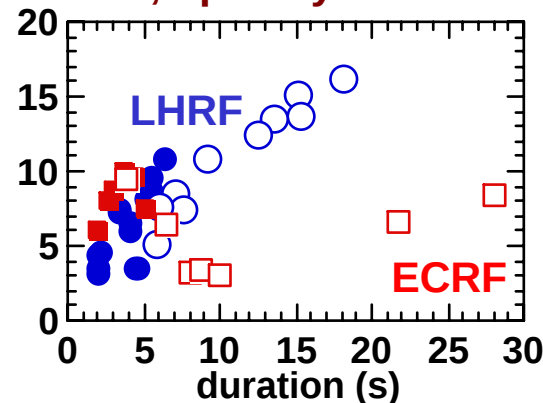
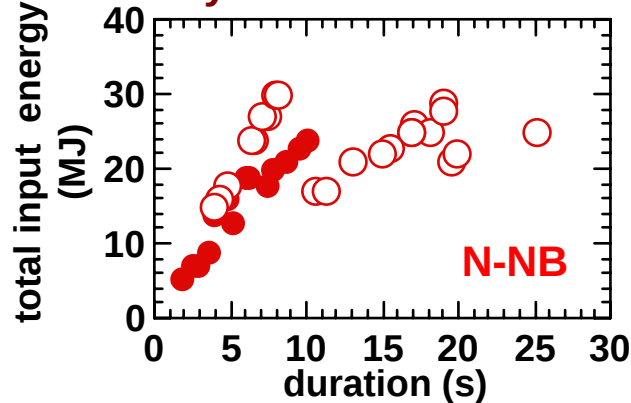
JT-60U



tangential P-NBs have reached full length (30s)

=> 30s ELMy H-mode $\leq 1.4\text{MA}$ at 2.7T

closed symbols: before the last IAEA, open symbol: after



total injected energy into the torus => 350MJ

2. Long Pulse Operation

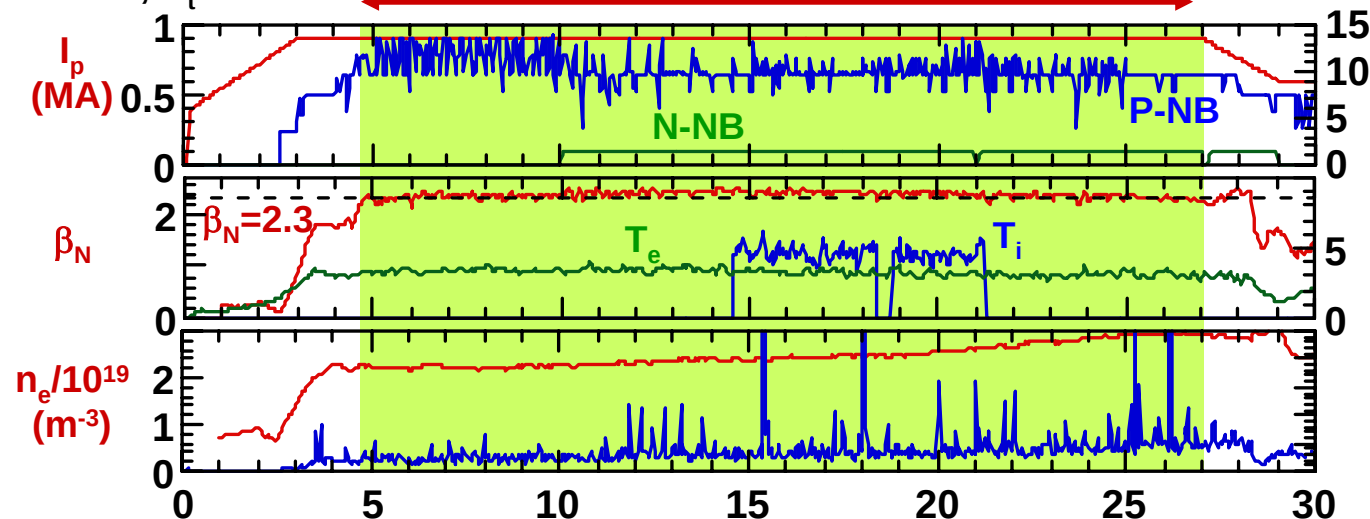
JT-60U

- Long sustainment of high β_N
T. Suzuki (EX/1-3, Tue.)
- High recycling H-mode and saturation in wall recycling
T. Nakano (EX/10-3, Sat.)

Long Sustainment of High β_N

JT-60U

E44092, $B_t = 1.56$ T $\beta_N = 2.3$ sustained for 22.3s ($\sim 13.1\tau_R$)



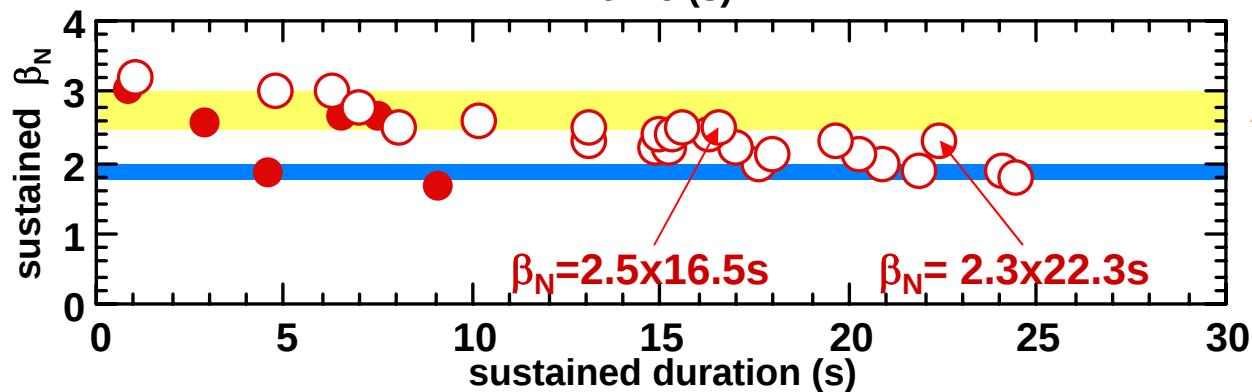
P_{NB}
(MW)

$q_{95} \sim 3.1-3.2$
 $H_{89p} \sim 1.9$

$T_{e,i}$
(keV)

D_α
(a.u.)

τ_R : Dr. D. R. Mikkelsen
Phys. Fluids B 1 (1989) 333.



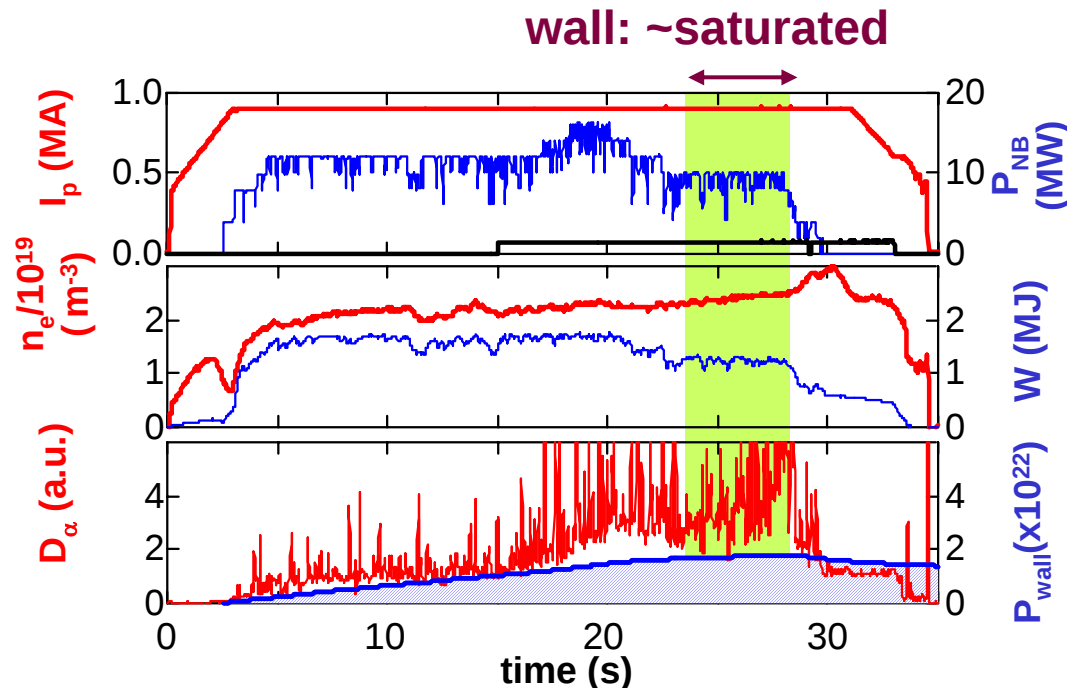
ITER
Advanced Op.
Inductive Op.

$\beta_N H_{89p} / q_{95}^2 > 0.4$
 $\beta_N = 2.5$ and 2.3
 $f_{BS} \sim 35-40\%$

In ITER, $\beta_N H_{89p} / q_{95}^2 = 0.4$: standard ($Q=10$) and $=0.3$: steady state ($Q=5$)
 $\Rightarrow$ ITER Hybrid operation

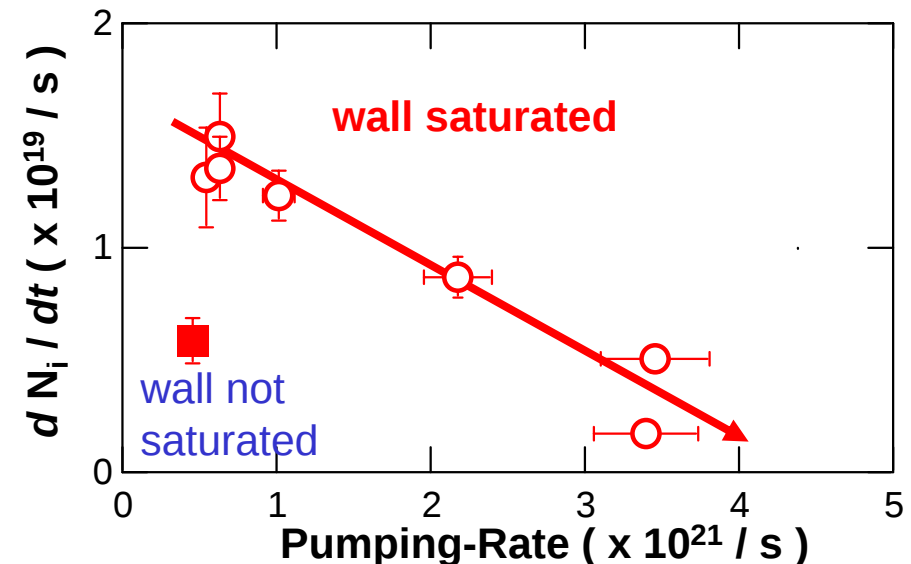
High recycling H-mode and saturation in wall recycling

JT-60U



- P_{wall} = particles retained in the wall, **Wall saturation unveils only in long pulse discharges.**
- When wall is saturated
 $\Rightarrow D_\alpha$ and n_e increase uncontrollably
 $\Rightarrow$ cause degradation in confinement

- **Particle control under wall saturation** is an important issue in a long pulse discharge.
- **Divertor pumping is effective to suppress increase in particle (dN_i/dt).**



3. Extension of AT Relevant Plasmas

JT-60U

- Sustainment of **high β_N normal shear plasma**
T. Suzuki (EX/1-3, Tue.)
- Sustainment of **$f_{BS} \sim 45\%$ weak shear plasma**
Y. Sakamoto (EX/4-3, Wed.)
- Sustainment of **$f_{BS} \sim 75\%$ RS plasma**
Y. Sakamoto (EX/4-3, Wed.)
- **Compatibility with divertor**
H. Takenaga (EX/6-1, Thu.)

Real time current profile control

T. Suzuki (EX/1-3, Tue.)

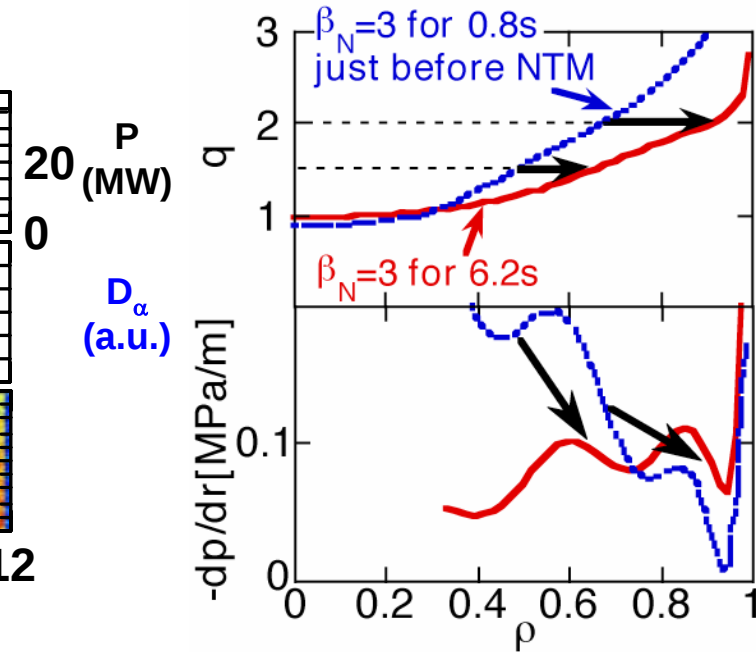
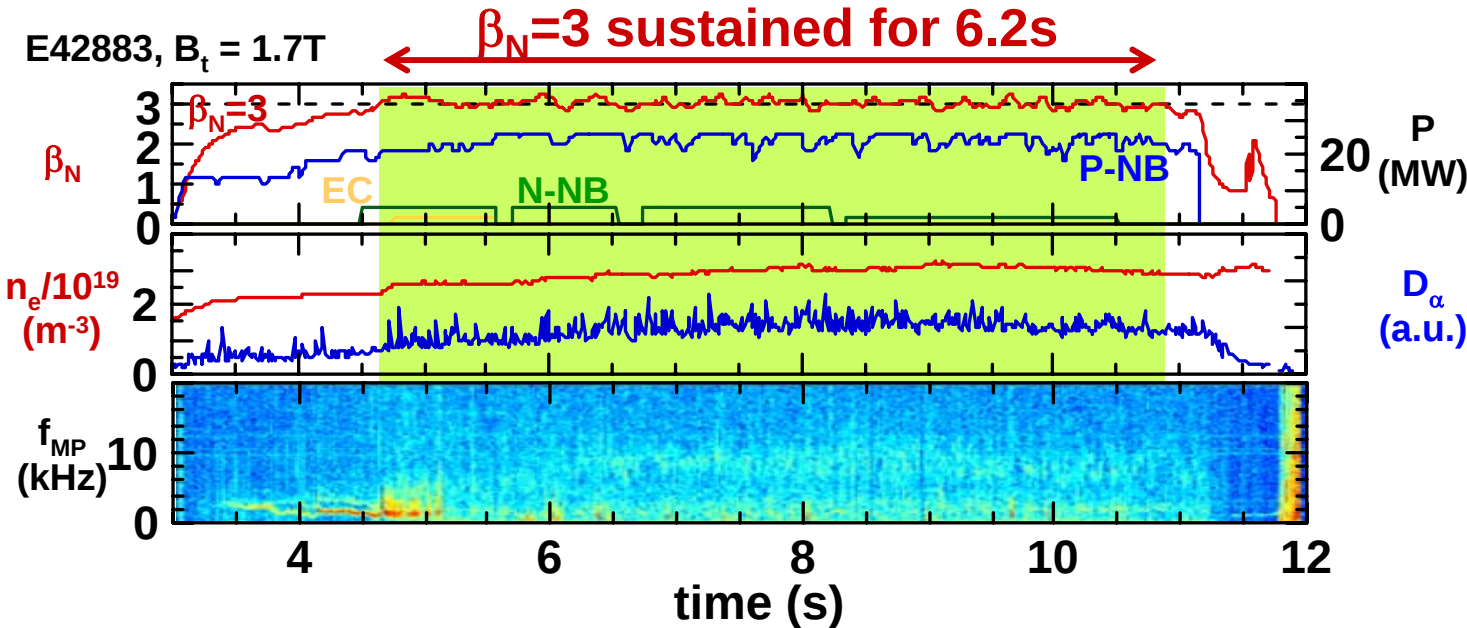
Development of CS-less tokamak

Y. Takase (EX/P4-34, Thu.)

$\beta_N=3$ sustained for 6.2s ($\sim 4.1\tau_R$) without NTMs in normal shear ($q_0\sim 1$)

T. Suzuki (EX/1-3, Tue.)

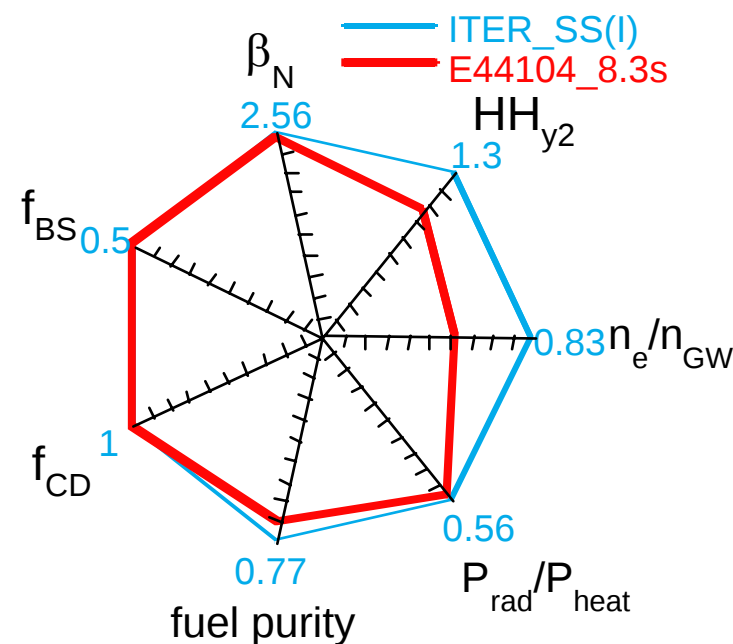
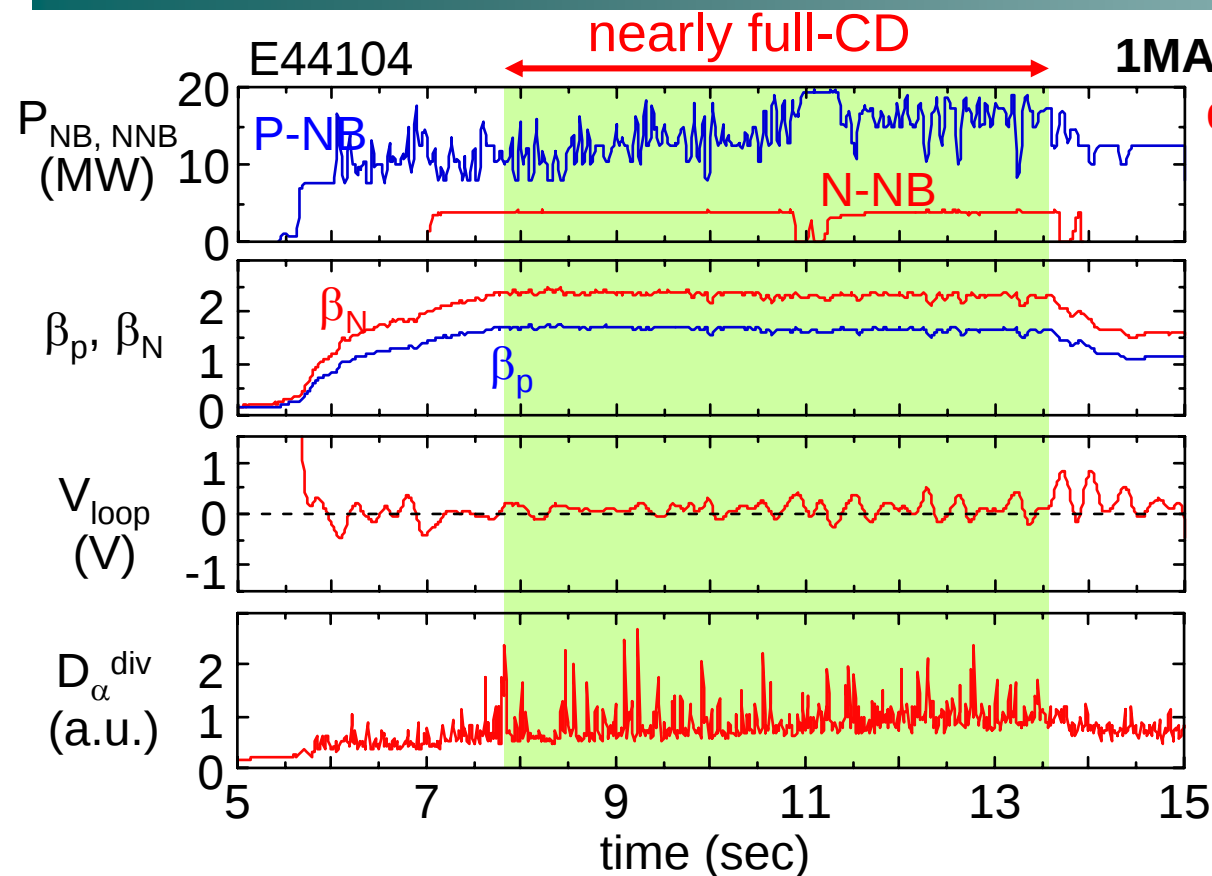
JT-60U



- $I_p=1.0MA$, $B_t=1.7T$, $q_{95}=2.8-2.2$, $H_{H98(y,2)}=0.7$, $n_e/n_{GW}\sim 0.6$, $\beta_N H_{89P}/q_{95}^2\sim 0.75$
- No clear NTM observed.** $\leq$ can be attributed to low q_{95} operation.
 $q=3/2$ and $2/1$ surfaces misalign to steep pressure gradient.
- NTM avoidance by profile control.**

$f_{BS} \sim 45\%$ sustained for 5.8s ($\sim 2.8\tau_R$) under nearly full CD in weak shear ($q_{min} \sim 1.5$) plasma

JT-60U

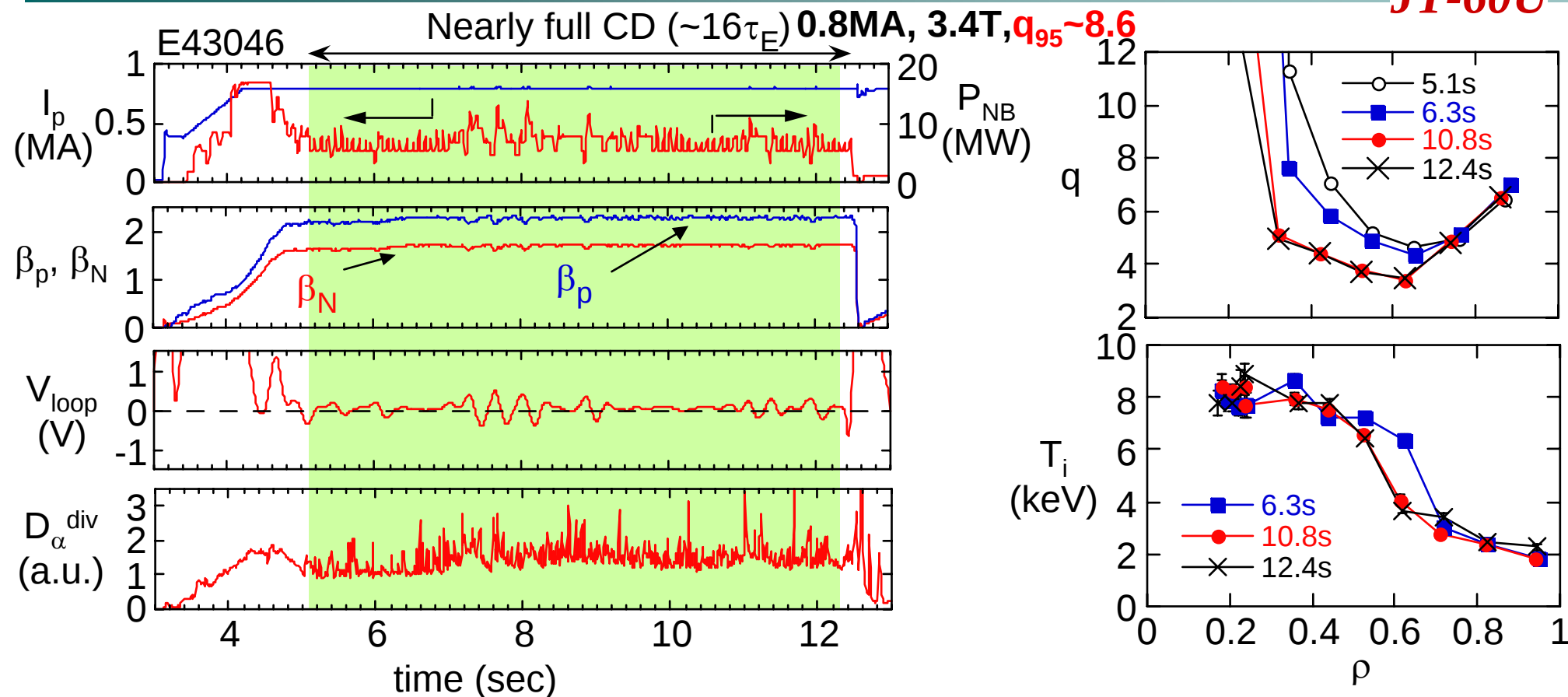


- Weak shear with $q_{min} > \sim 1.5 \Rightarrow$ no NTM.
- $\beta_N \sim 2.4$ ($\beta_p \sim 1.75$), $f_{CD} > 90\%$ ($f_{BS} \sim 50-43\%$, $f_{BD} > 52-47\%$), $H_{H98(y,2)} \sim 1.0$

Integrated performance $\Leftrightarrow$ the ITER steady state domain

$f_{BS} \sim 75\%$ sustained for 7.4s ($2.8\tau_R$) under nearly full CD in reversed shear plasma

JT-60U



- Very high confinement characteristics:

$H_{H98(y,2)} \sim 1.7$ ($H_{89p} \sim 3.0$), $f_{BS} \sim 75\%$, $f_{BD} \sim 20\%$, $\beta_p = 2.2-2.3$, $\beta_N \sim 1.7$, $n_e/n_{GW} \sim 0.55$

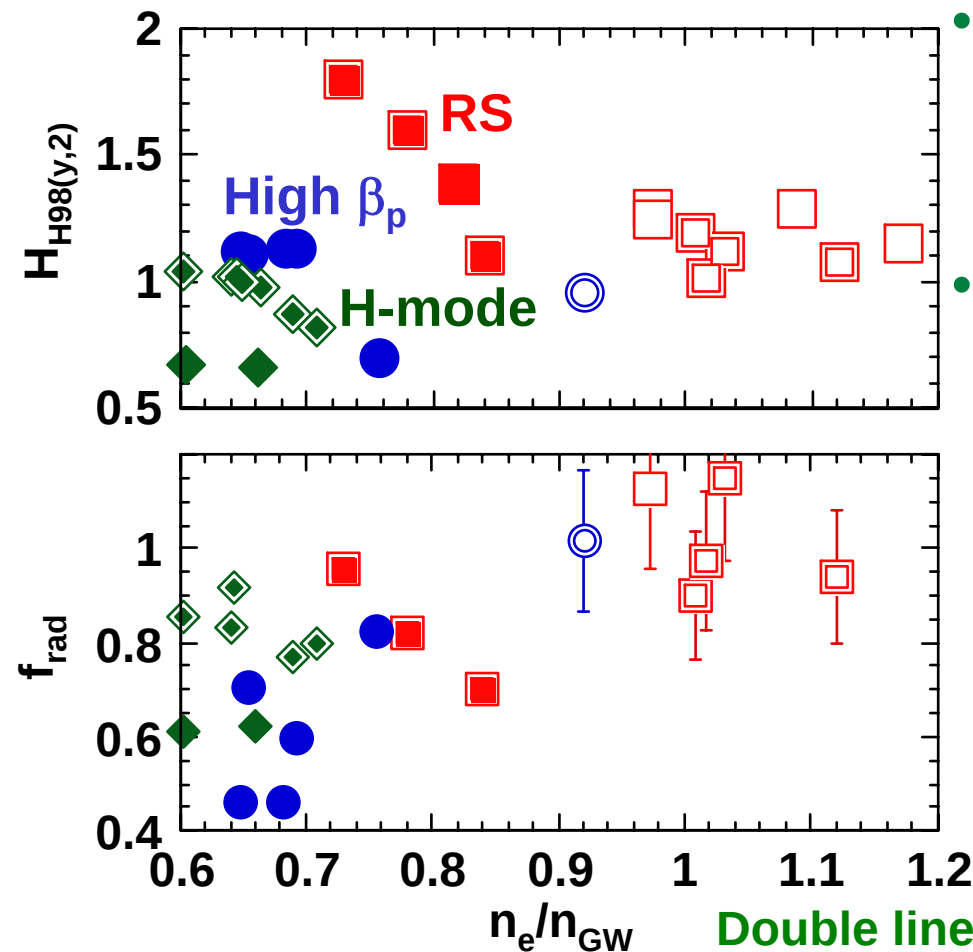
- Although q_{95} is yet high, demonstrates steady state with high f_{BS}

Compatibility of AT plasmas with high density and divertor

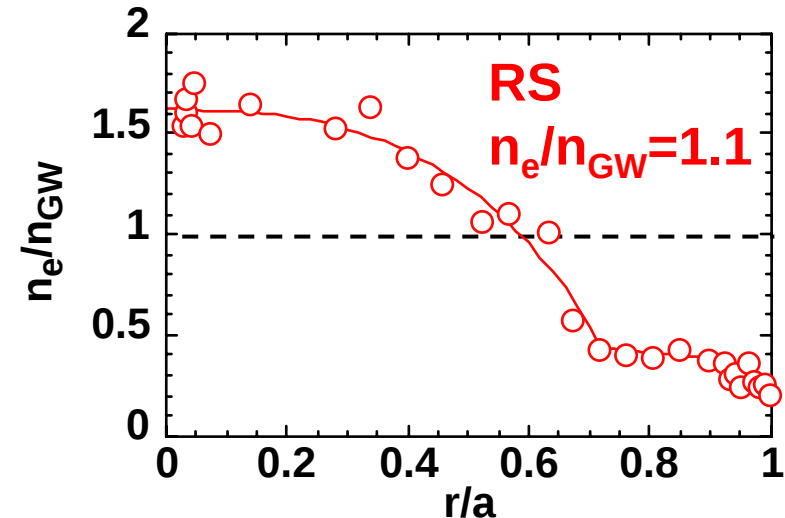
H. Takenaga
(EX/6-1, Thu.)

JT-60U

- ITB plasmas can raise n_e/n_{GW} due to peaked $n_e(r) \Rightarrow$ edge n_e can be lower $\Rightarrow$ necessary to increase radiation for divertor compatibility.



- n_e/n_{GW} is increased by tailoring n&T ITBs using various fueling (NB, HFS pellet, gas-puffing and impurity seeding) and configuration.
- Confinement is kept, f_{rad} increased.



Double lines : impurity seeding

4. Progress in physics studies

JT-60U

- NTM suppression by ECCD

K. Nagasaki (EX/7-4, Thu.)

- Confinement of high energy ions

K. Ishikawa (EX/5-2Rb, Thu., poster Fri.)

- Current hole

T. Fujita (EX/P4-3, Thu.)

Measurement of mode island

T. Oikawa (EX/P5-15, Fri.)

Transient electron heat transport

S. Inagaki (EX/P2-12, Wed.)

low β_N disruption in RS plasmas

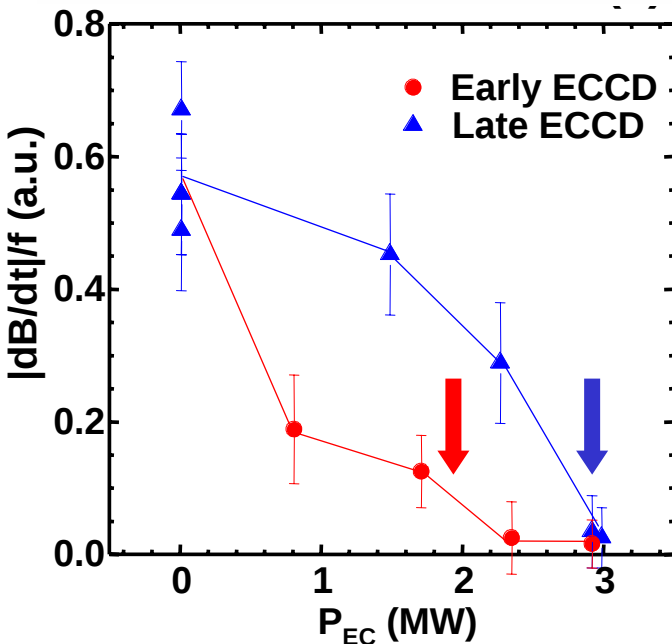
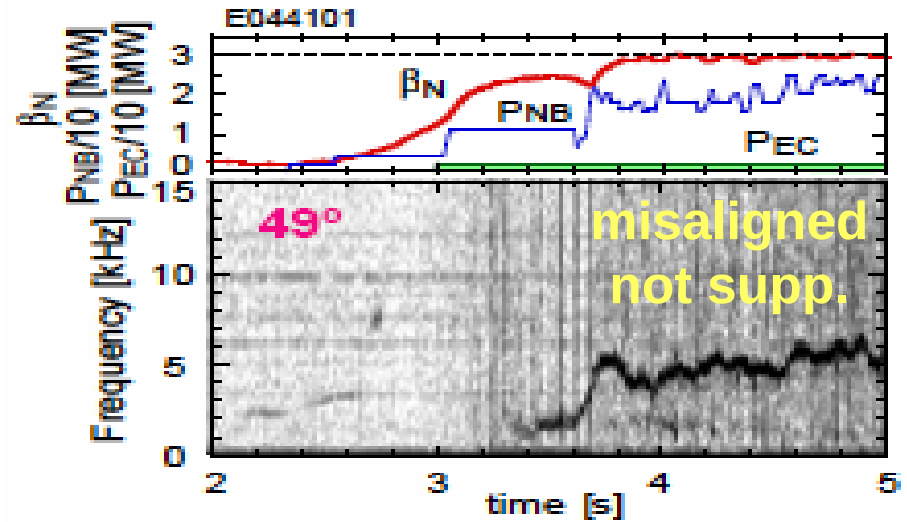
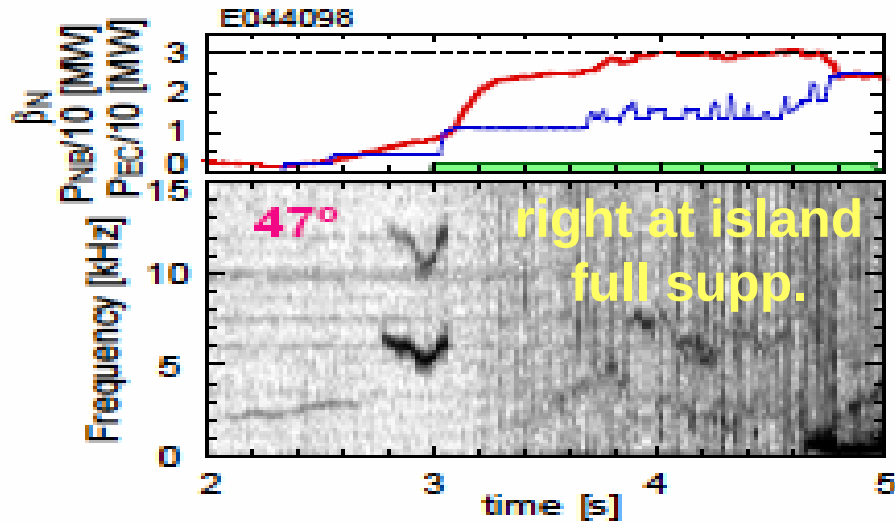
M. Takechi (EX/P2-32, Tue.)

Disruption mitigation

M. Bakthiari (EX/10-6Rb, Sat., poster Fri.)

Early ECCD is more effective for an NTM suppression, even at high β_N

JT-60U



- **Early ECCD is more effective to suppress NTM:**
 - island size ($\sim |dB/dt|/f$) quickly suppressed
 - less power for full stabilization
 - calculated necessary power for full suppression based on mod. Rutherford eq. agrees well with the experiments (arrows).

Early ECCD is also effective at higher $\beta_N=3$.

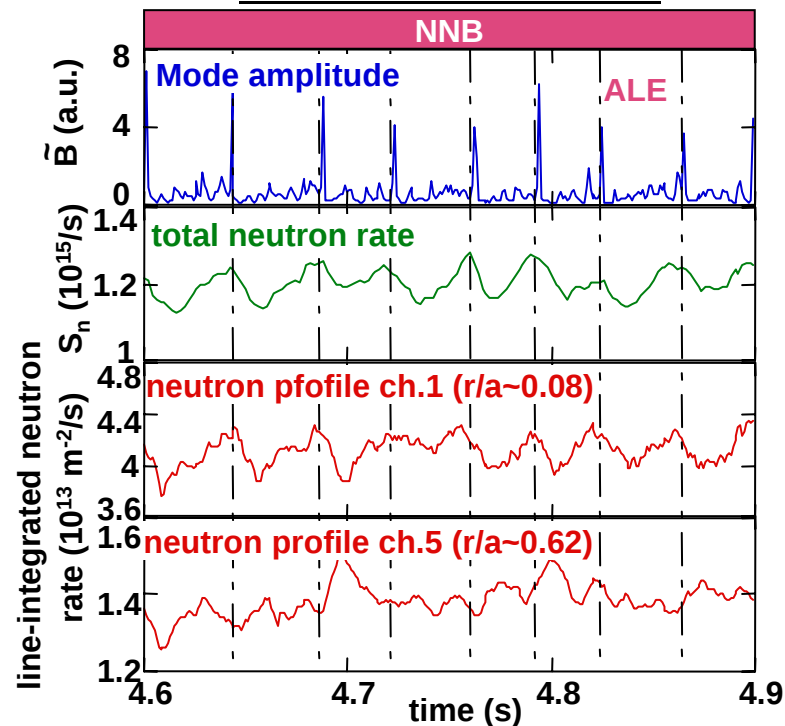
Confinement of energetic ions at ALE

K. Ishikawa (EX/5-2Rb, Thu., poster Fri.)

JT-60U

E43014, $I_p=0.6\text{MA}$ $B_t=1.2\text{T}$
 $P_{\text{NNB}} \sim 4.8\text{MW}$, $E_{\text{NNB}} \sim 387\text{keV}$

<neutron emission>

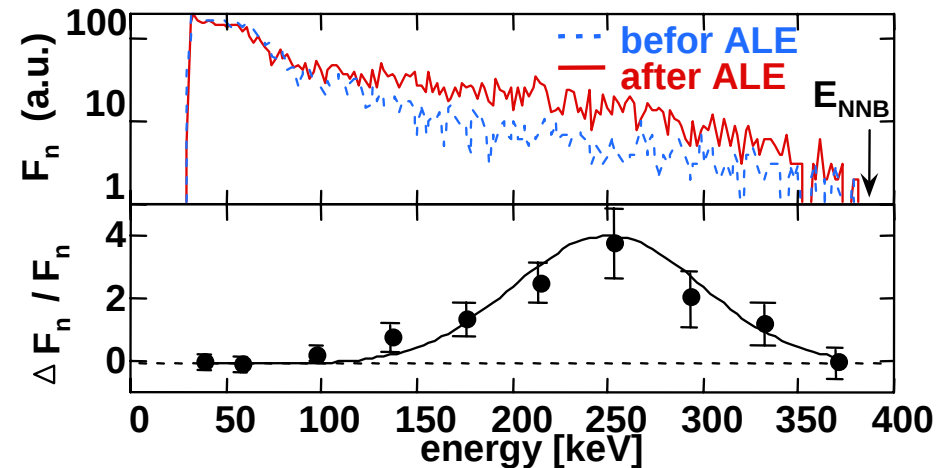


- In a JT-60U weak shear plasma, N-NB drives bursting mode in the TAE freq. range.

=> Abrupt Large Event (ALE)

- How are energetic ions affected?

<energy distribution of neutral particle>



- Only ions in limited energy are affected.

=>Agrees with AE resonant condition

=>Contribution to theory/modeling towards burning experiments.

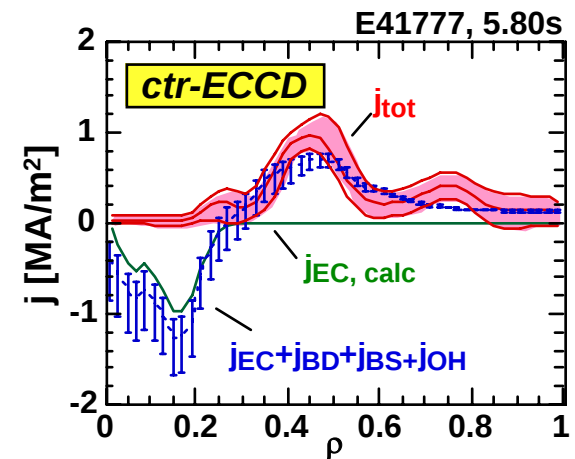
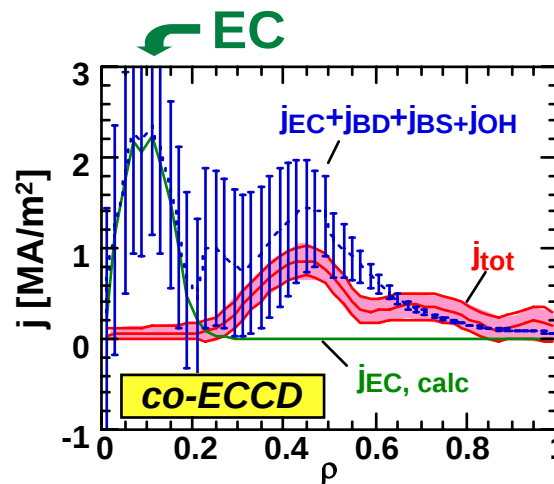
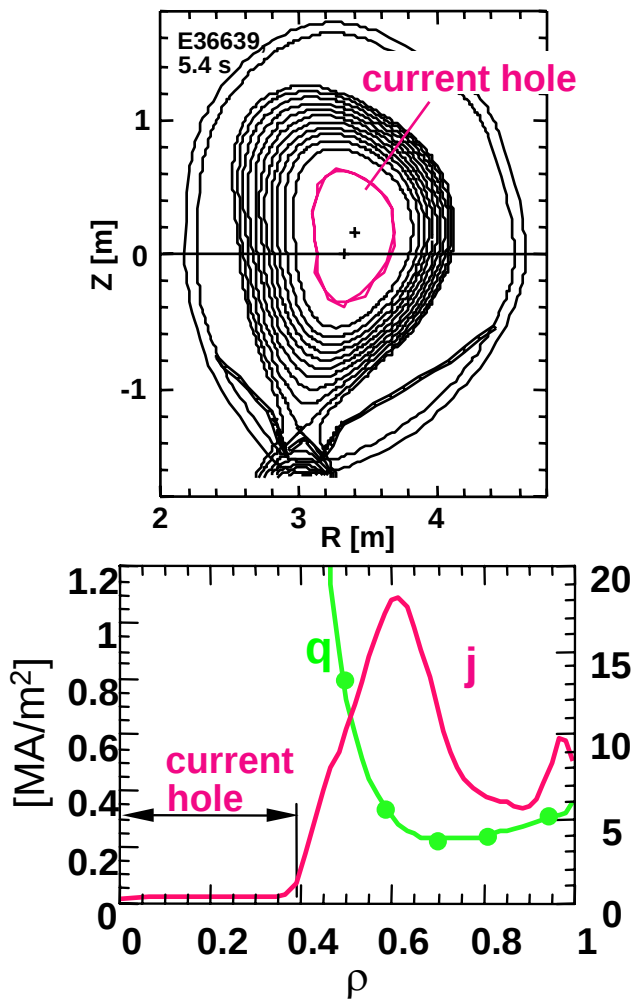
Stiffness of current profile in the current hole (CH) region

T. Fujita (EX/P4-3, Thu.)

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A CH can be formed in an RS plasma.

- Current drive in the current hole was attempted with **ECCD**, **NBCD** and **inductive $E_{||}$** , but in any case no current was generated **both for co and counter** directions.
- => **Current clamp**



5. ELMs, pedestal, divertor, SOL and plasma wall interaction

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- Energy loss at ELMs, Type I and grassy domains

N. Oyama (EX/2-1, Tue.)

H-mode pedestal (JT-60U/JET comparison)

G. Saibene (IT/1-2, Wed.)

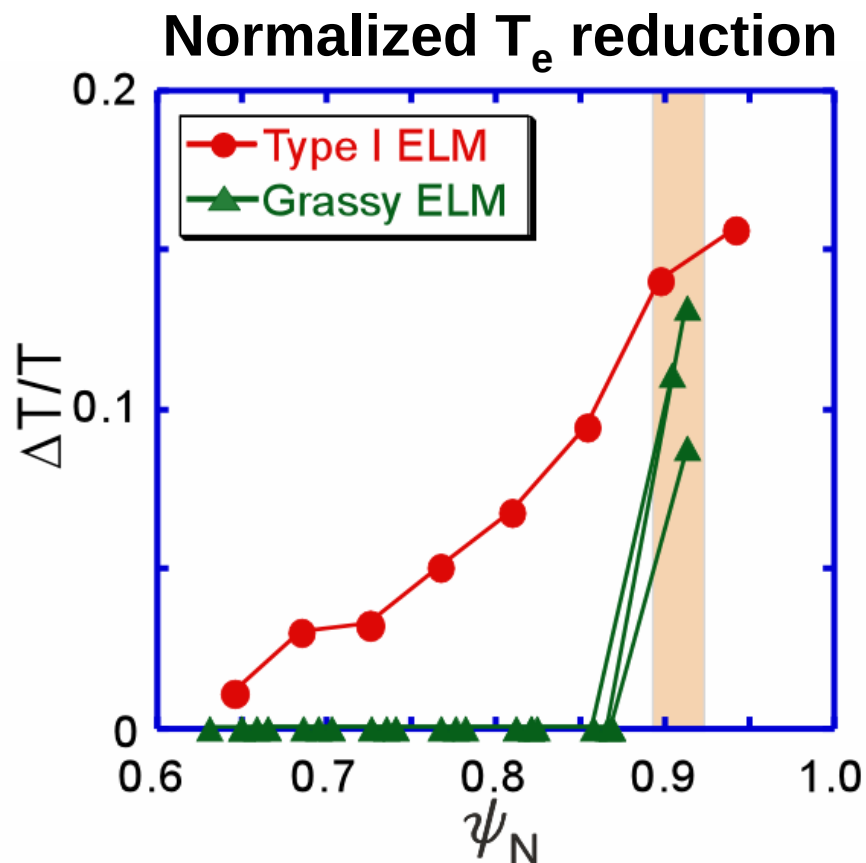
Plasma wall interaction (PWI)

T. Tanabe (EX/P5-32, Fri.)

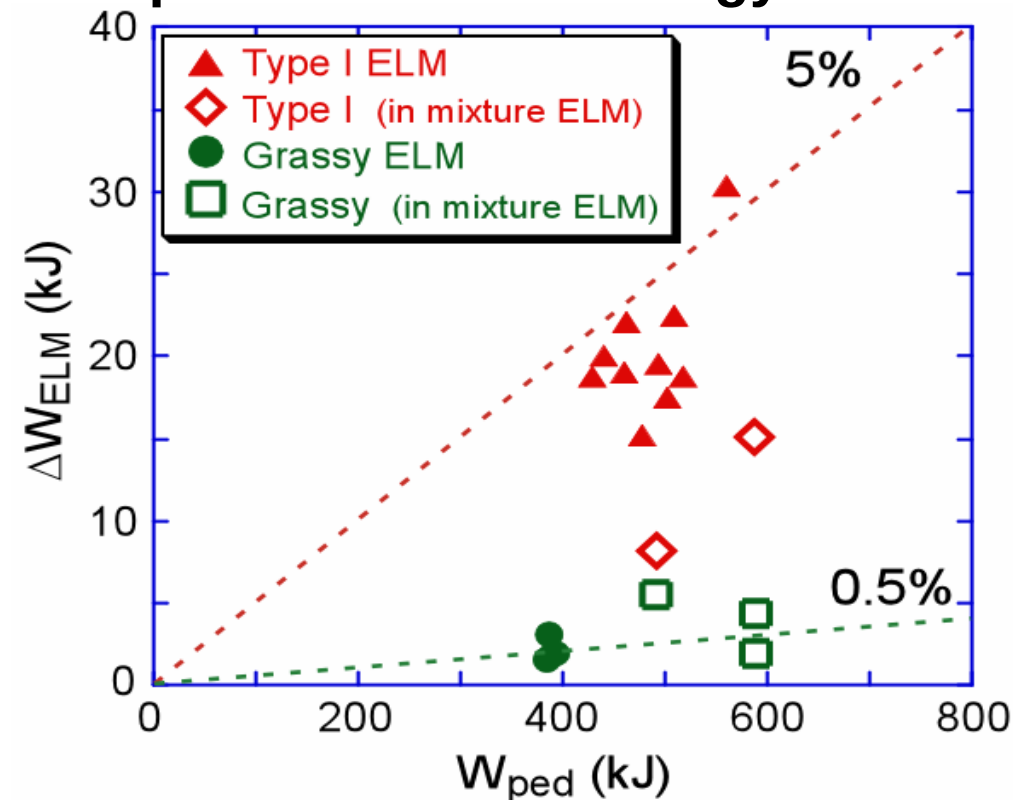
ΔW_{ELM} in grassy ELMs is 0.4%-1.0% of W_{ped}

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- Grassy ELM can be an attractive alternative to Type I ELM.
- It is confirmed that grassy ELMs affect only limited region. $\Leftrightarrow$ simulation.
- From the profile measurement, ΔW_{ELM} is estimated as 0.4-1.0% of W_{ped} in grassy regime.



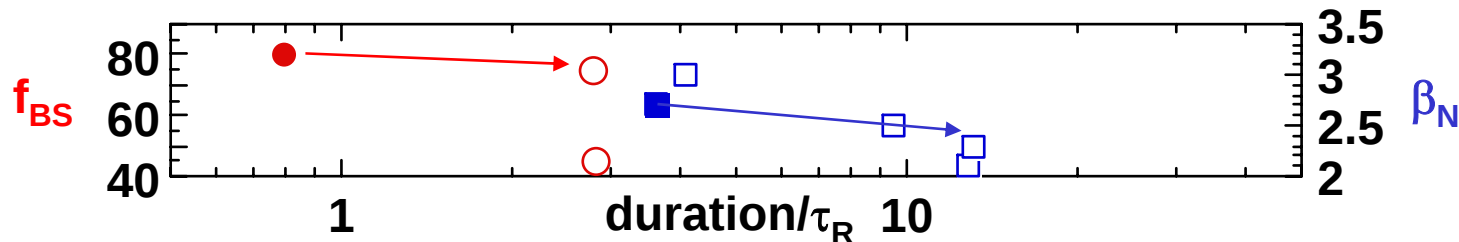
Comparison of ELM energy loss



Summary

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- Extension of pulse length of JT-60U plasmas.



Entering new domain in time scale

–in view of current relaxation, no significant phenomenon observed.

=> ITER hybrid scenario

future issues: $j(r)$ control, scenario robustness in $>\tau_R$ scale.

–wall saturation unveils in 15-20s

· effect on confinement, but **active pumping works effectively.**

- Progress in development of AT relevant plasmas
- Progress in physics studies
- Design study of machine upgrade is underway. (H. Tamai (FT/P7-8))

JT-60U presentations

Shown in Red(8): presented in this overview, in Green(7); not presented

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Tue.	Wed.	Thu.	Fri.	Sat.
T. Suzuki (EX/1-3)	G. Saibene (IT/1-2)	K. Ishikawa (EX/5-2Rb)	T. Oikawa (EX/P5-15)	T. Nakano (EX/10-3)
N. Oyama (EX/2-1)	Y. Sakamoto (EX/4-3)	H. Takenaga (EX/6-1)	T. Tanabe (EX/P5-32)	M. Bakthiari (EX/10-6Rb)
	S. Inagaki (EX/P2-12)	K. Nagasaki (EX/7-4)	<i>K. Ishikawa</i> (EX/5-2Rb,P)	
		M. Takechi (EX/P2-32)	<i>M. Bakthiari</i> (EX/10-6Rb,P)	
		T. Fujita (EX/P4-3)		
		Y. Takase (EX/P4-34)		