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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Vilamoura, Portugal, 1 - 6, November, 2004

JAERI JT-60

National and International Collaboration on the JT-60 Project

JT-60U

The JT-60 Team

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- **National collaboration** (shown in red)

  4) Central Research Institute of Electric Power Industry, Japan, 9) Fukui University, 11) High Energy Accelerator Research Organization, 12) Hiroshima Insitute 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 fur Plasmaphysik, Germany, 31) Oak Ridge National Laboratory, USA, 33) Post-Doctoral Fellow, 34) Princeton Plasma Physics Laboratory, USA, 38) Southwestern Institute of Physics, Chin

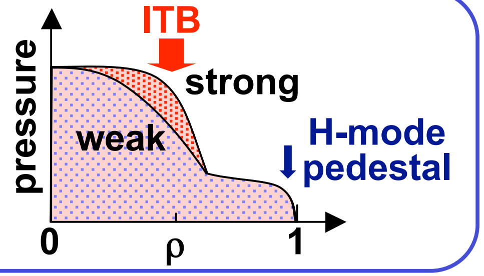
  - including IEA/ITPA collaboration

the JT-60U program

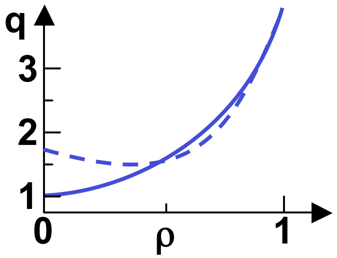
Objectives: •R&D for ITER physics basis
•Advanced Tokamak (AT) development towards ITER & DEMO

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

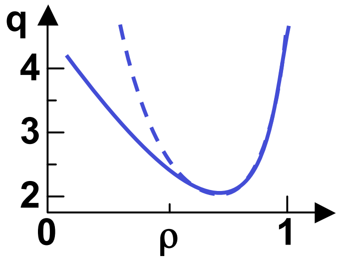
In JT-60U, the AT development has been pursued base on two types of internal transport barrier (ITB) plasmas mainly with pedestal.



- High β_p plasma (since 1994)
  - Monotonic/weak shear, $\beta_N \leq 5$, $f_{BS} \leq 70\%$, full CD



- Reversed shear (RS) plasma (since1996)
  - RS w or w/o current hole, $\beta_N \leq 2.5$, $f_{BS} \leq 80\%$, full CD



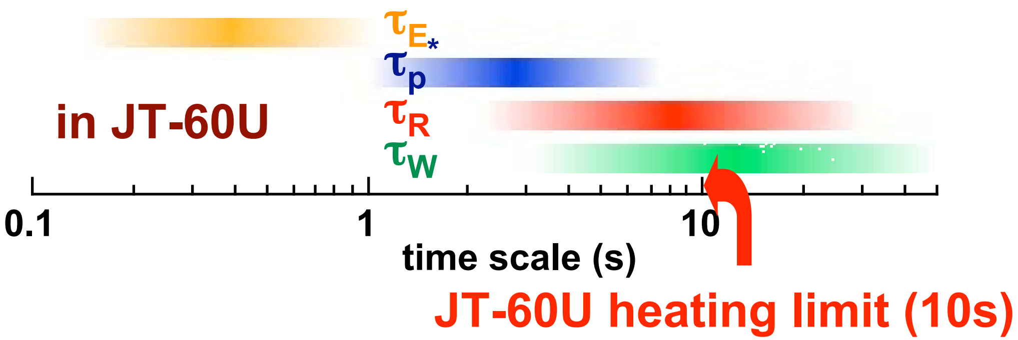
Integrated performance, proof of principle (full CD, control…)

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

why long pulse

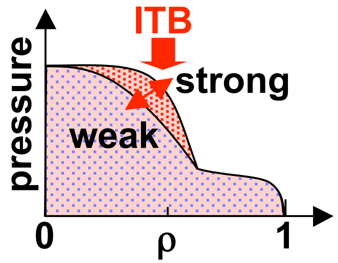
In AT research, control is increasingly an important issue.
Robustness of AT scenario against perturbations is also a key issue.

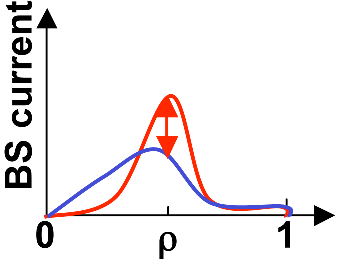
- The fight is against key characteristic time constants in various time scales;
  - energy confinement (τ_E)
  - effective particle confinement (τ_p^*)
  - **current profile relaxation (τ_R)**
  - **wall saturated with particles (τ_w)**

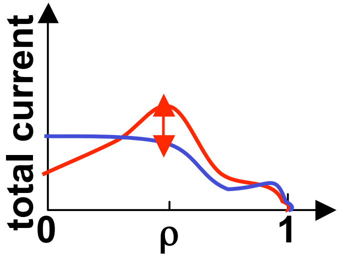


Genuine control must work over these time constants.

e.g.: When ITB (χ) changes=> 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

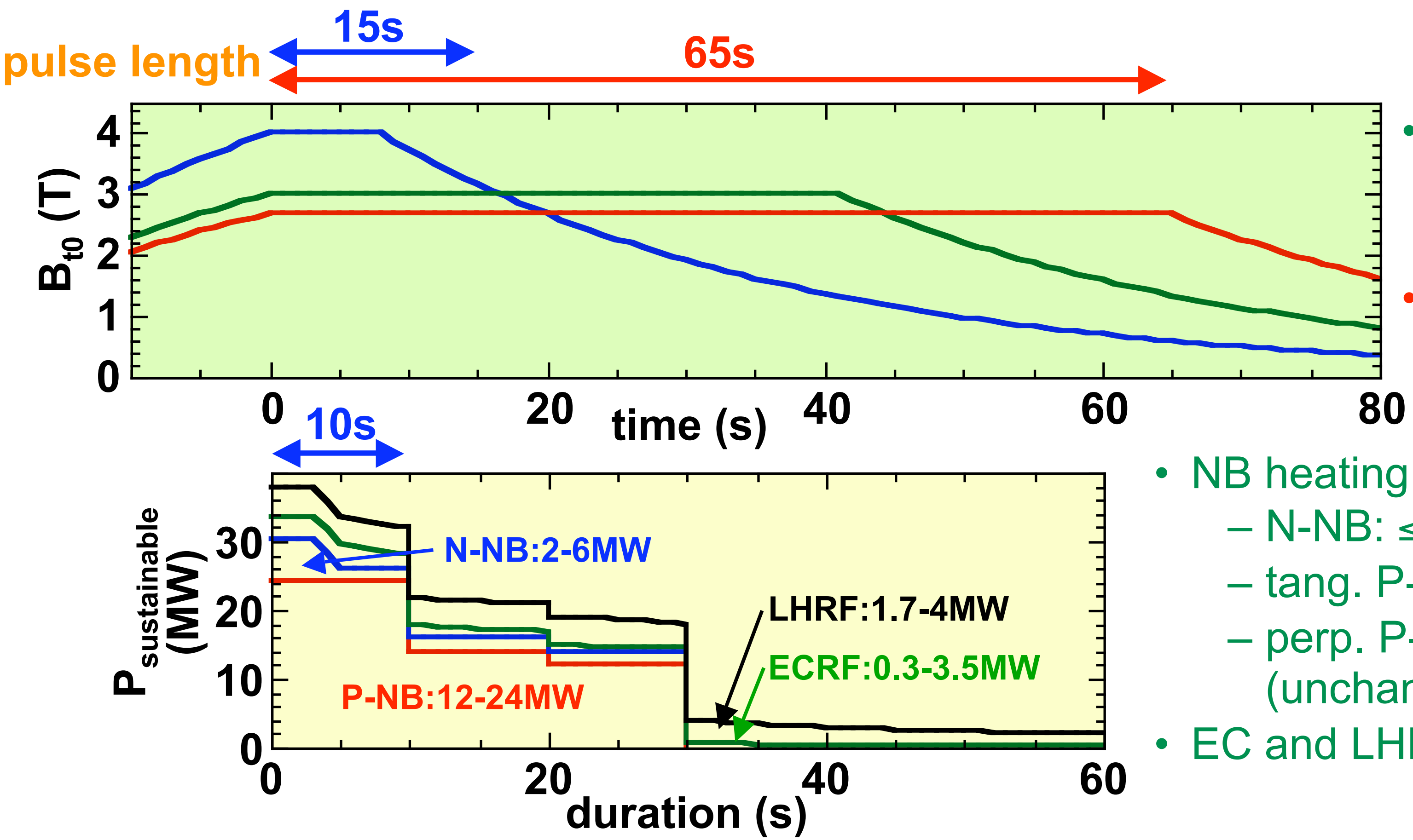
1. Machine Improvement

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

Extension of a discharge, heating/CD and diagnostics duration

The max. pulse length of a discharge is extended from 15s to 65s.

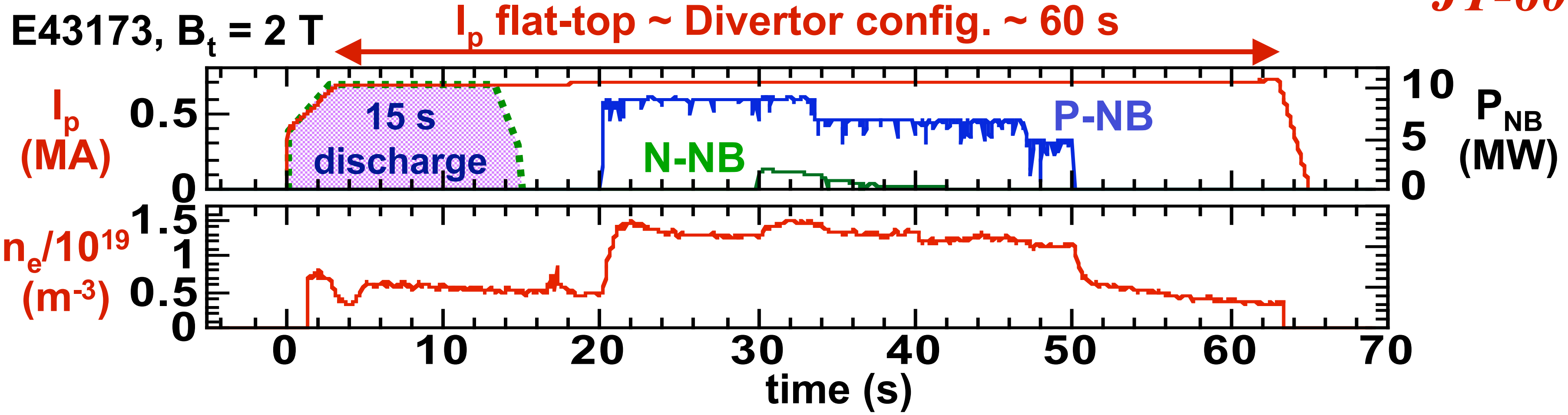
Modification on controls in operation, H/CD and diagnostics systems, but not on major hardware.



- B_{t0} flat top 4Tx8s => ~2.7Tx65s.
- f_{EC}=110GHz => 3.9T (cold plasma)
- NB heating (formally 10s)
  - N-NB: ≤30s
  - tang. P-NB (4units): ≤30s
  - perp. P-NB (7units): ≤10s (unchanged)
- EC and LHRF 10s => 60s

A 65s JT-60U discharge

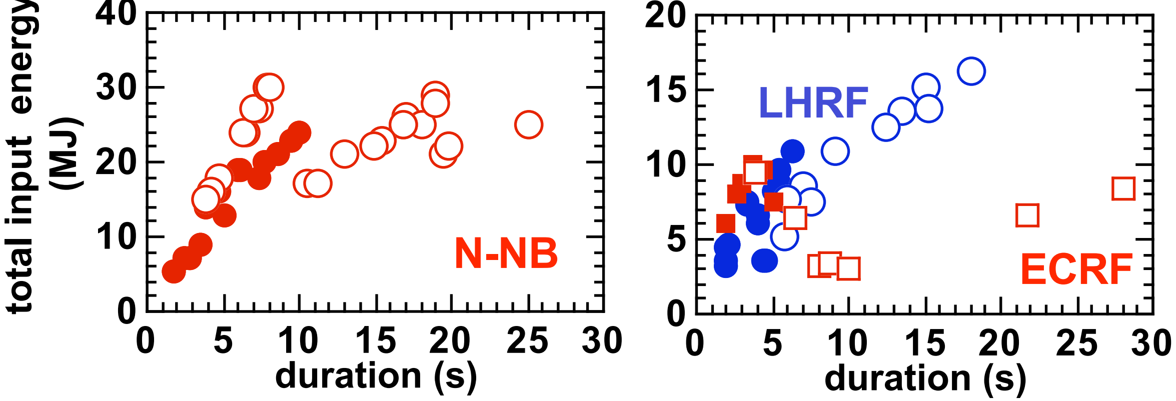
JT-60U

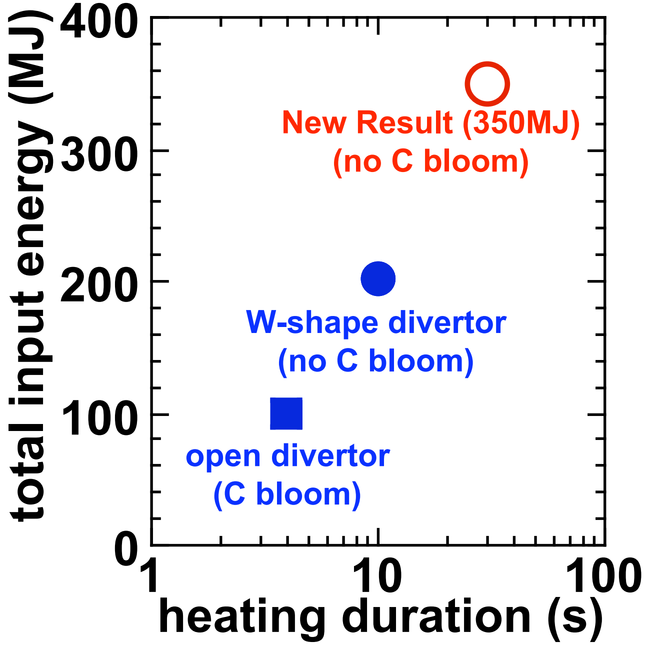


tangential P-NBs have reached full length (30s)

=> 30s ELMy H-mode ≤1.4MA at 2.7T

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





total injected energy into the torus => 350MJ

2. Long Pulse Operation

- Long sustainment of high β_N

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

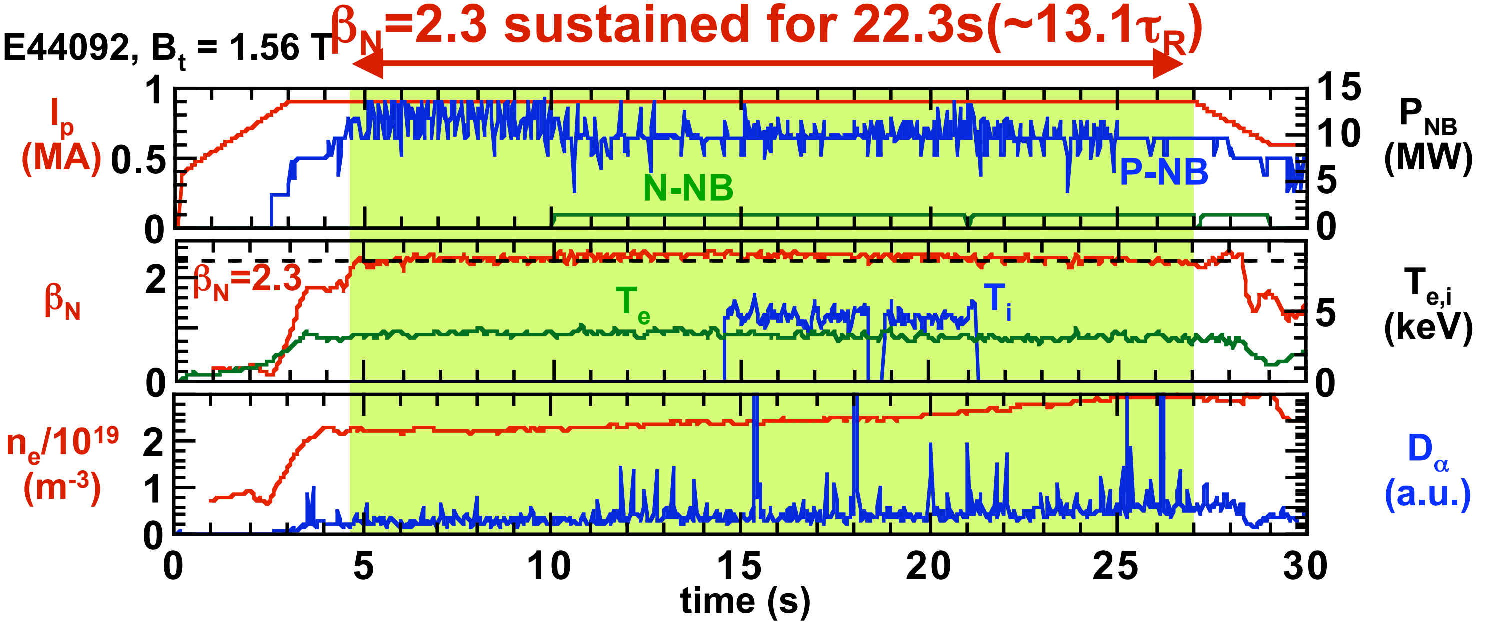
- High recycling H-mode and saturation in wall recycling

T. Nakano (EX/10-3, Sat.)

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

Long Sustainment of High β_N

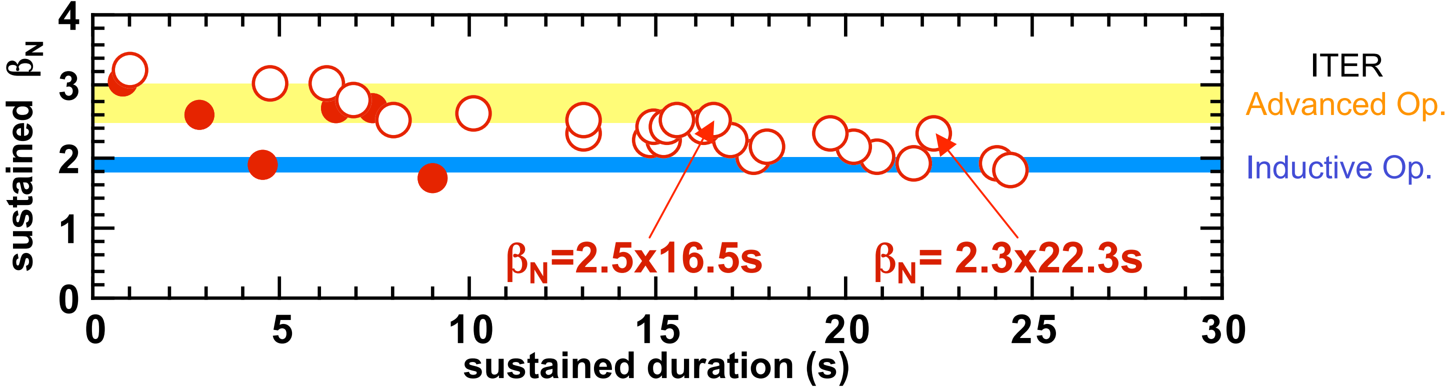
JT-60U



q_{95}~3.1-3.2

H_{89p}~1.9

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



$\beta_N H_{89p}/q_{95}^2$ > 0.4

β_N=2.5 and 2.3

f_{BS}~35-40%

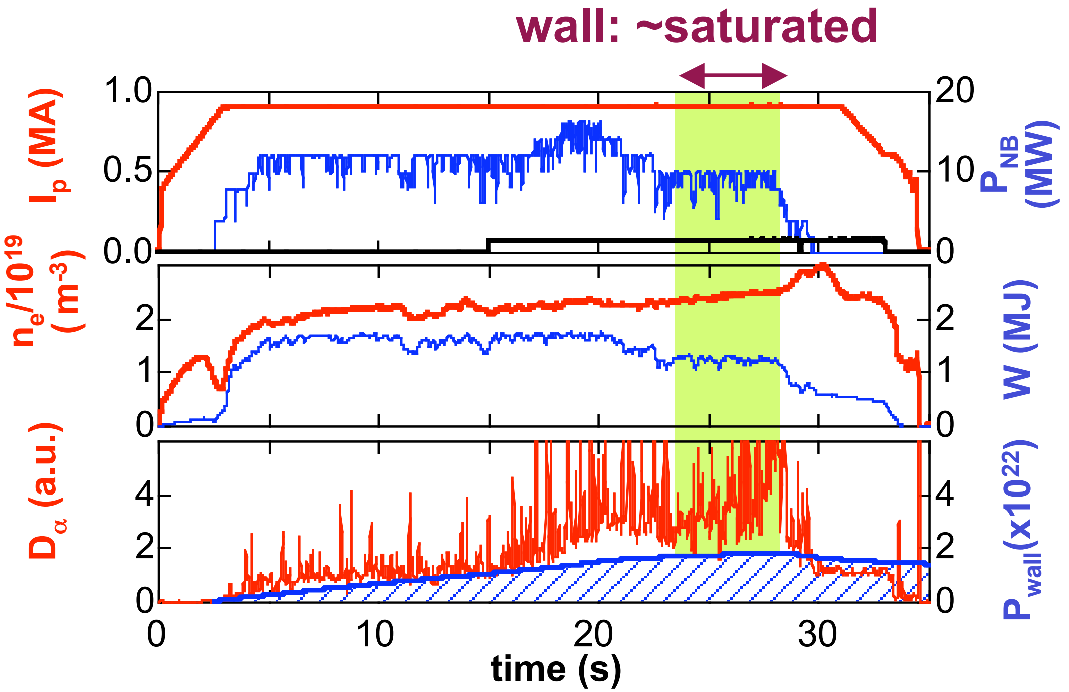
In ITER, $\beta_N H_{89p}/q_{95}^2$ = 0.4: standard (Q=10) and =0.3: steady state (Q=5)

=> ITER Hybrid operation

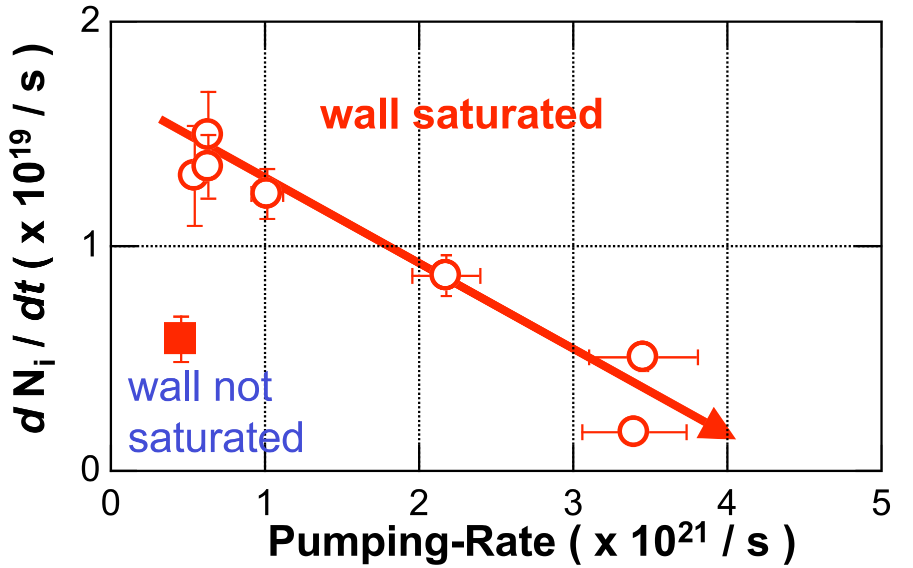
T. Nakano (EX/10-3, Sat.)

High recycling H-mode and saturation in wall recycling

JT-60U



- **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).**



- P_{wall} = particles retained in the wall, **Wall saturation unveils only in long pulse discharges.**
- When wall is saturated

⇒D_α and n_e increase uncontrollably

⇒cause degradation in confinement

3. Extension of AT Relevant Plasmas

- Sustainment of **high β_N normal shear** plasma

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

- Sustainment of **f_{BS}~45% weak shear** plasma

Y. Sakamoto (EX/4-3, Wed.)

- Sustainment of **f_{BS}~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.)

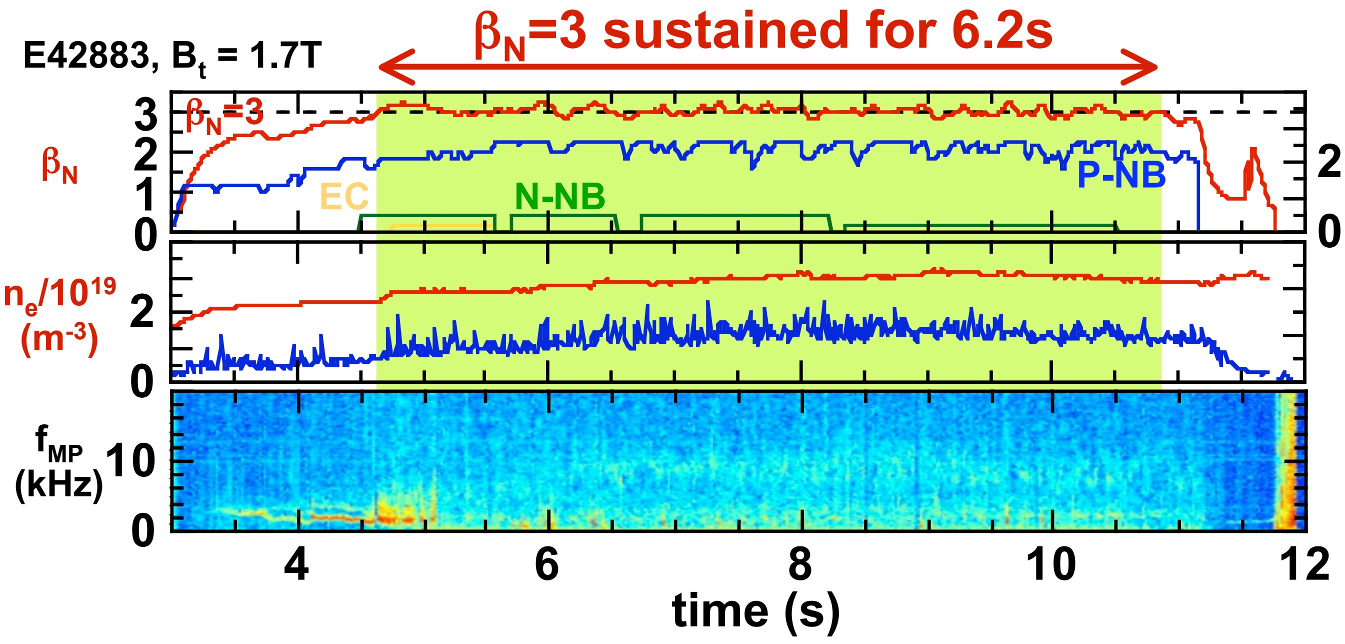
Development of CS-less tokamak

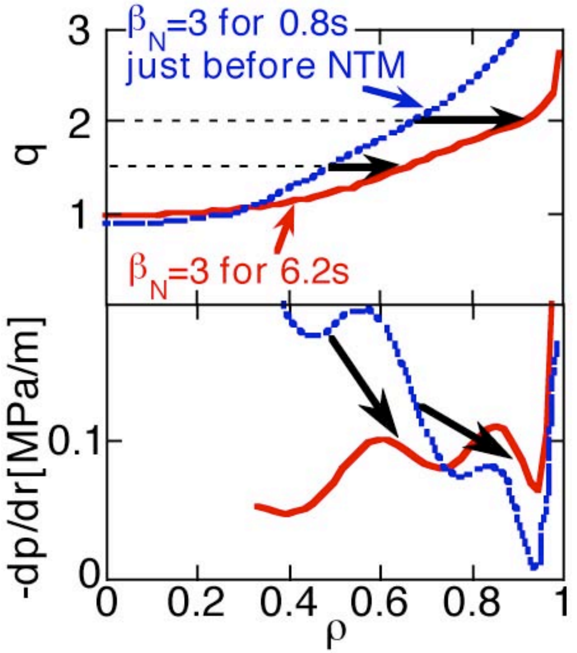
Y. Takase (EX/P4-34, Thu.)

β_N=3 sustained for 6.2s (~4.1τ_R) without NTMs in normal shear (q_0~1)

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

JT-60U

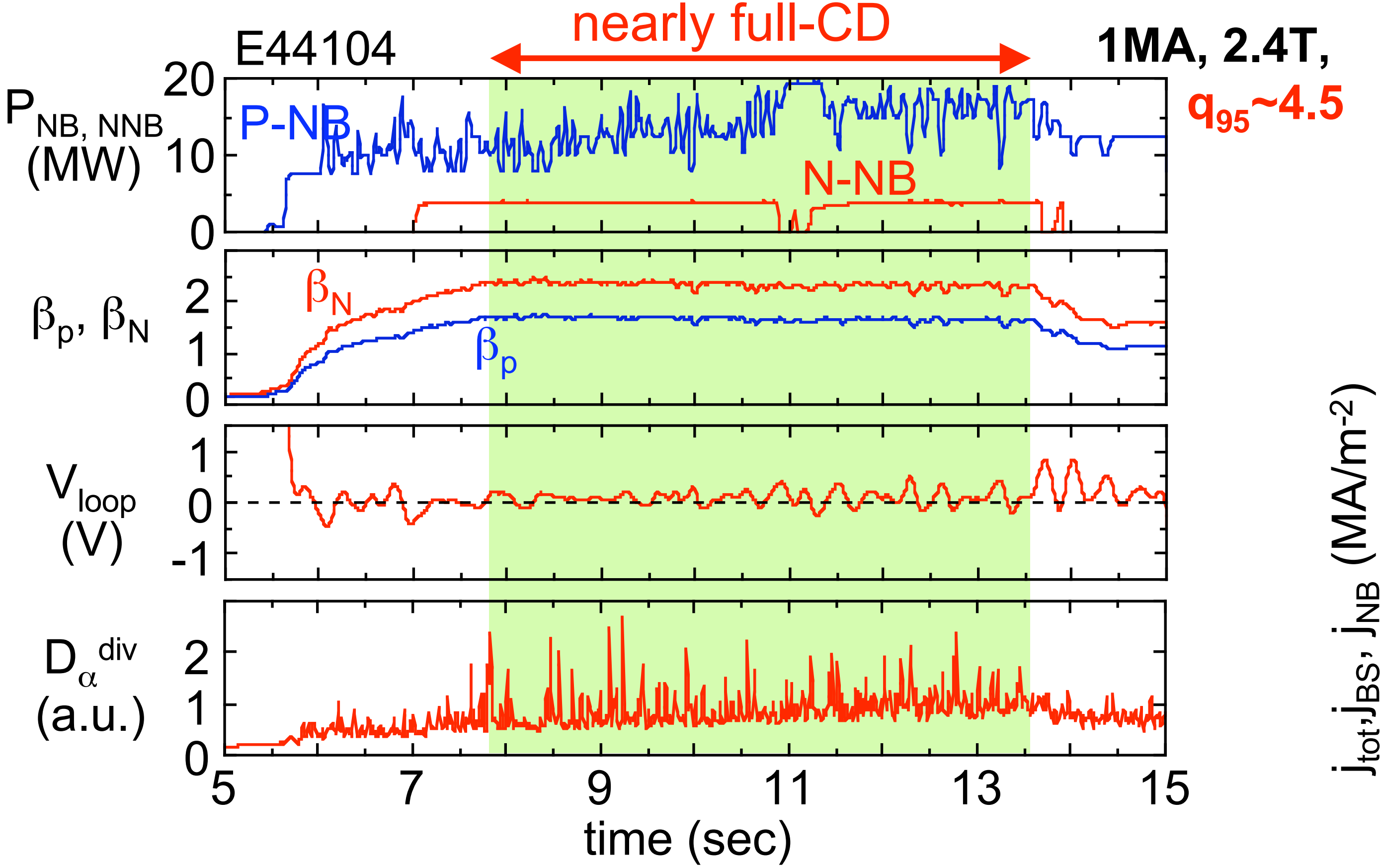


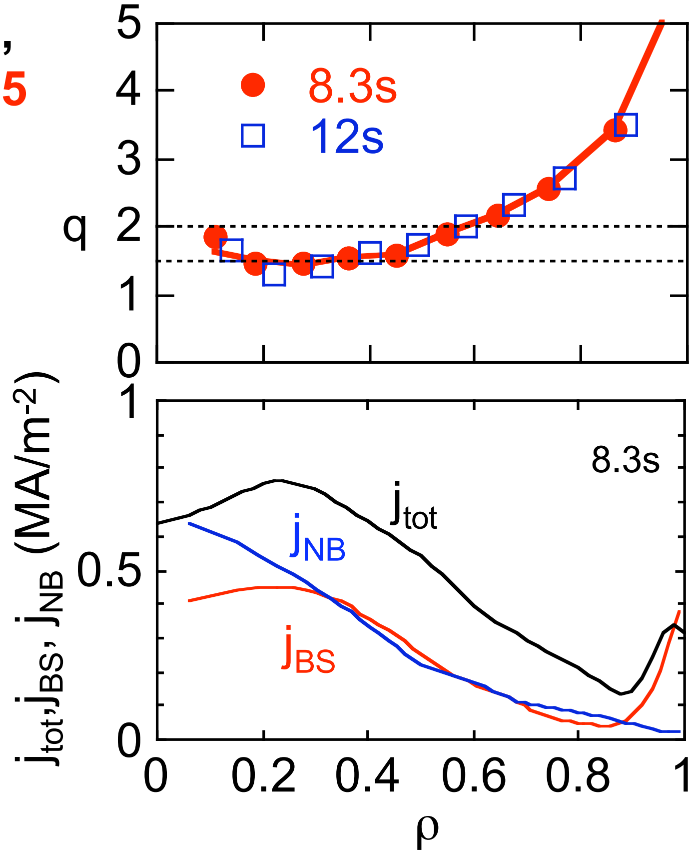


- I_p=1.0MA, B_t=1.7T, q_{95}=2.8-2.2, $H_{H98(y,2)}$=0.7, n_e/n_{GW}~0.6, $\beta_N H_{89P}/q_{95}^2$~0.75
- **No clear NTM observed.<= can be attributed to low q_{95} operation.**
  q=3/2 and 2/1 surfaces misalign to steep pressure gradient.
- **NTM avoidance by profile control.**

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

JT-60U



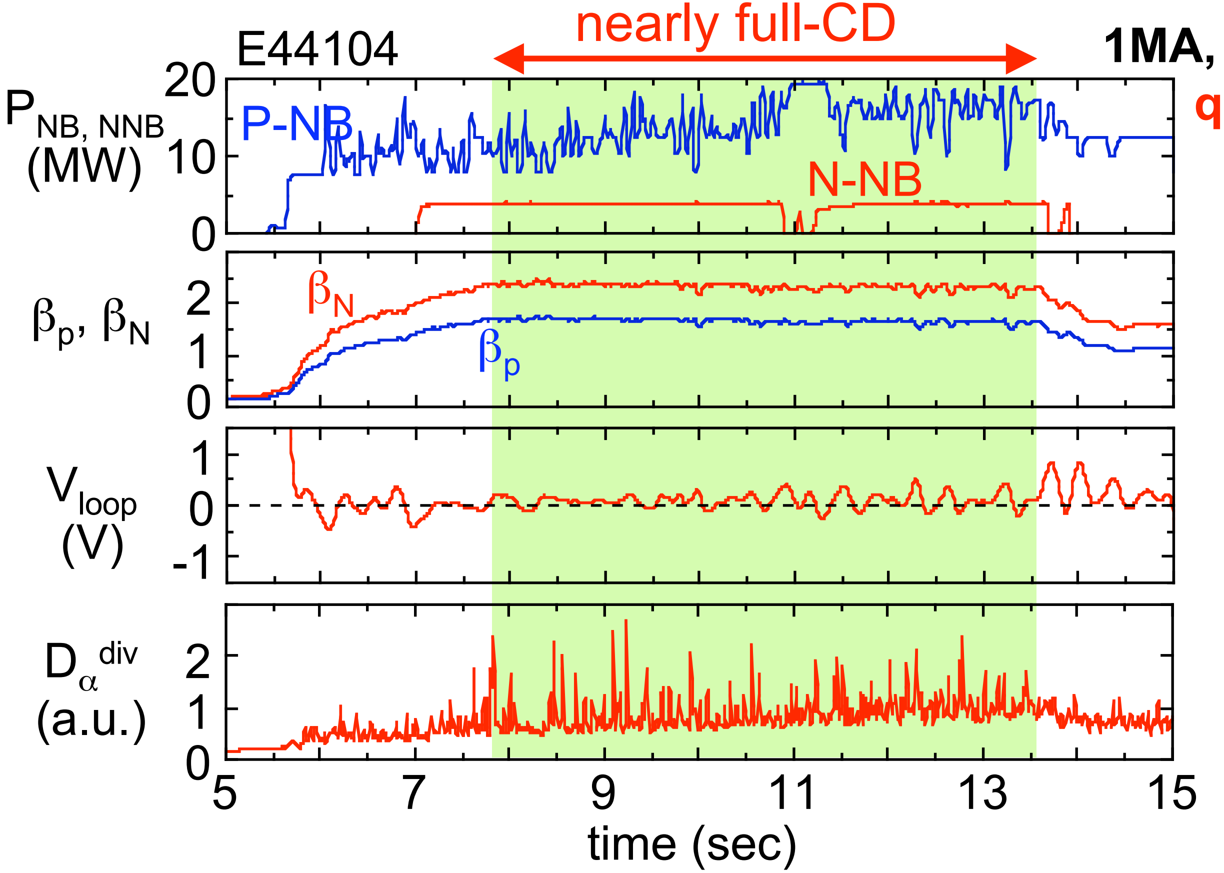


- Weak shear with q_{min}>~1.5 => no NTM.
- β_N~2.4 (β_p~1.75), f_{CD}>90%(f_{BS}~50-43%, f_{BD}>52-47%) , $H_{H98(y,2)}$~1.0

Y. Sakamoto (EX/4-3, Wed.)

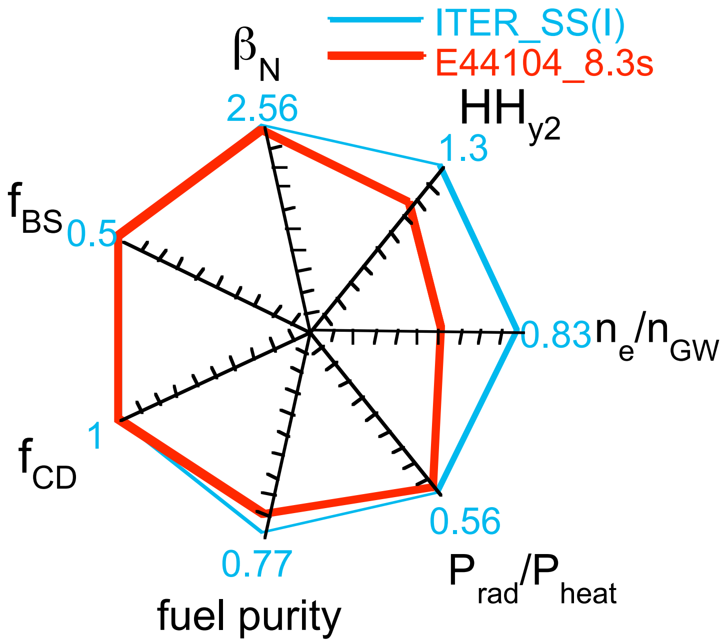
f_{BS}~45% sustained for 5.8s (~2.8τ_R) under nearly full CD in weak shear (q_{min}~1.5) plasma

JT-60U



1MA, 2.4T,

q_{95}~4.5



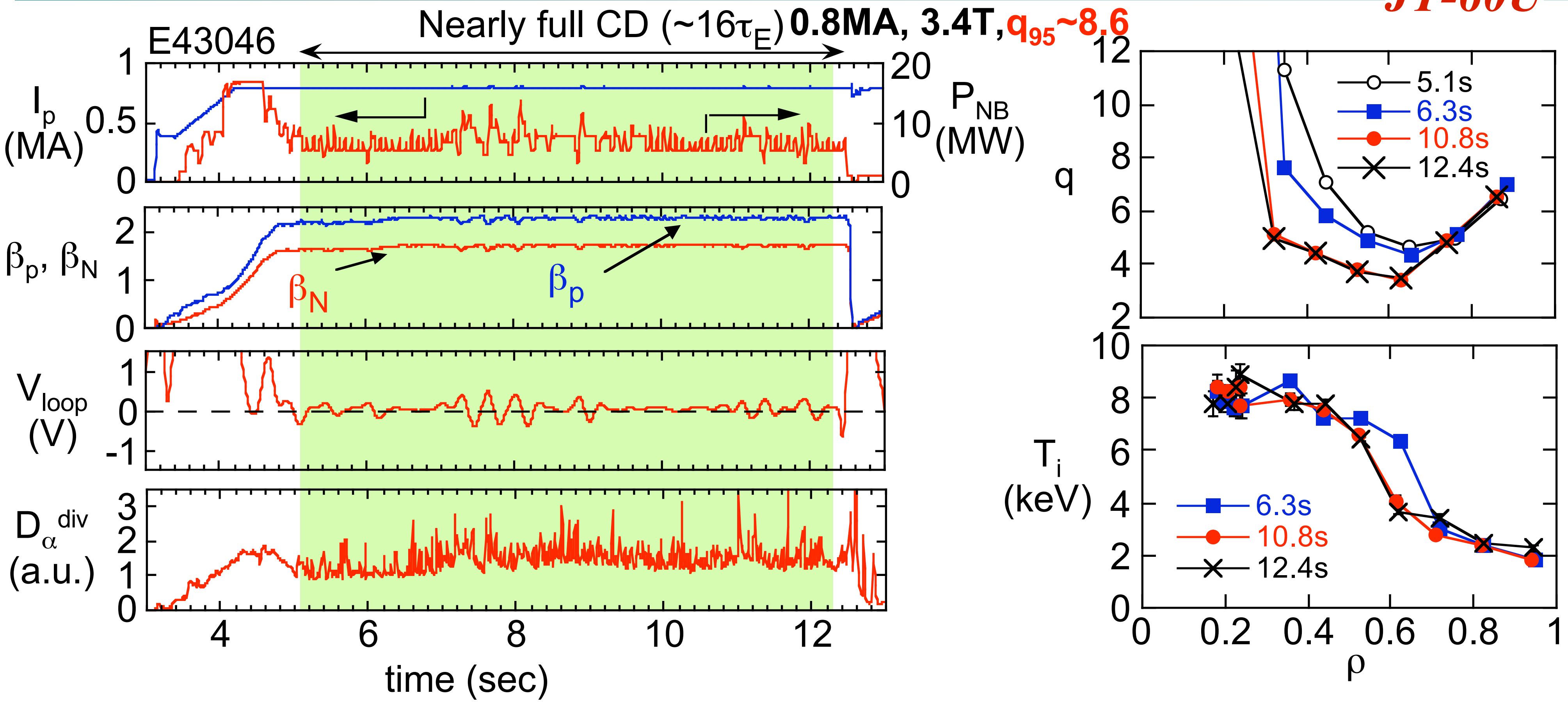
- **Weak shear with q_{min}>~1.5 => no NTM.**
- **β_N~2.4 (β_p~1.75), f_{CD}>90%(f_{BS}~50-43%, f_{BD}>52-47%) , $H_{H98(y,2)}$~1.0**

Integrated performance <=> the ITER steady state domain

Y. Sakamoto (EX/4-3, Wed.)

f_{BS}~75% sustained for 7.4s (2.7τ_R) under nearly full CD in reversed shear plasma

JT-60U



- Very high confinement characteristics:
  $H_{H98(y,2)}$~1.7 (H_{89p}~3.0), f_{BS}~75%, f_{BD}~20%, β_p=2.2-2.3, β_N~1.7, n_e/n_{GW}~0.55
- Although q_{95} is yet high, **demonstrates steady state with high f_{BS}**

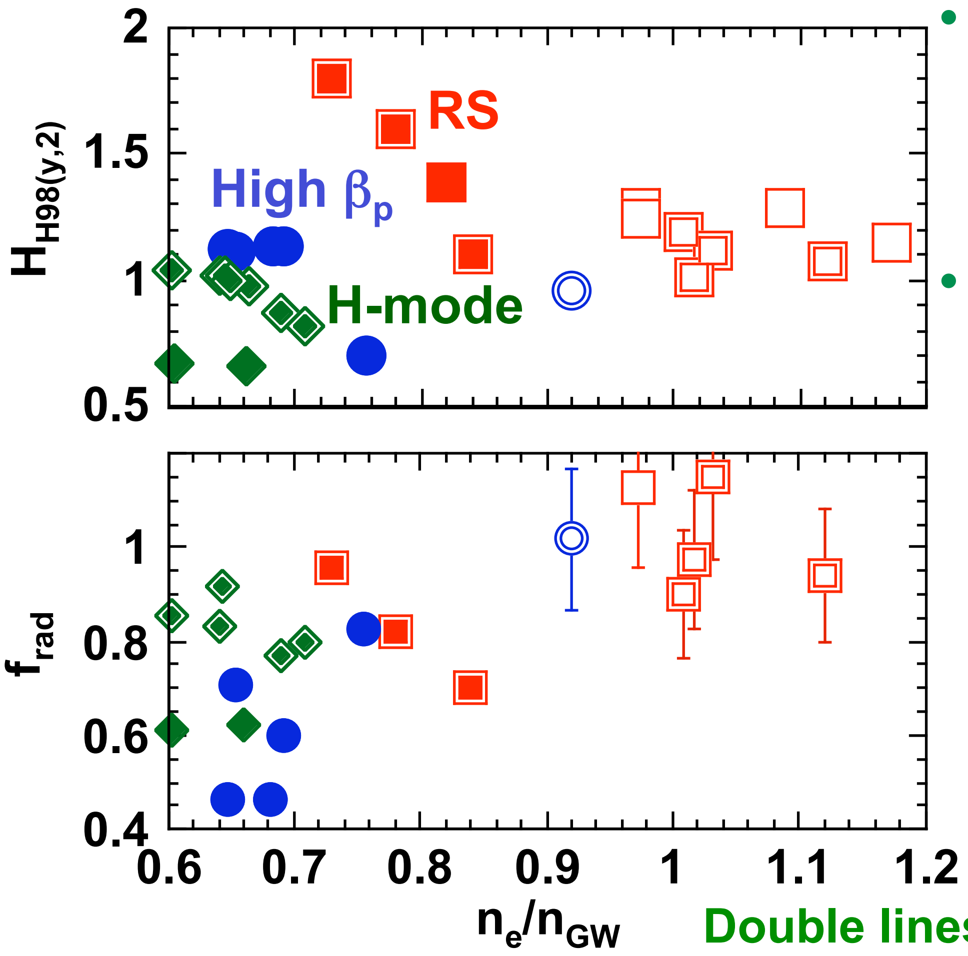
Y. Sakamoto (EX/4-3, Wed.)

Compatibility of AT plasmas with high density and divertor

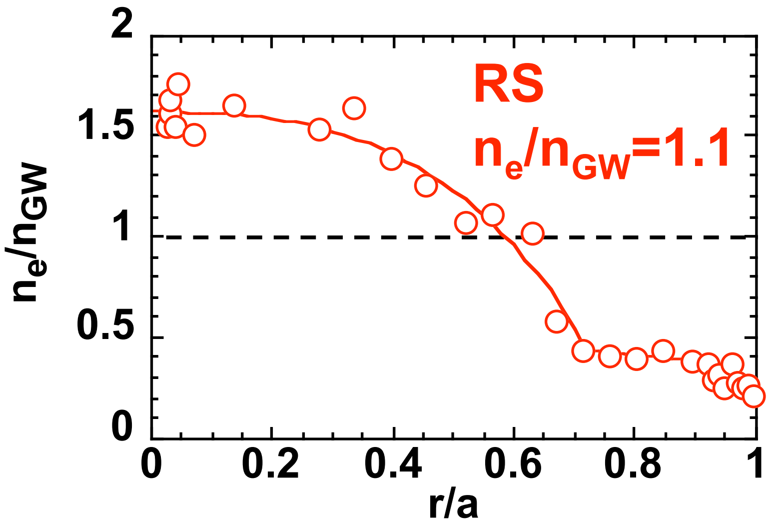
H. Takenaga
(EX/6-1, Thu.)

JT-60U

- ITB plasmas can raise n_e/n_{GW} due to peaked $n_e(r)$ =>edge n_e can be lower => 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

- NTM suppression by ECCD

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

- Confinement of high energy ions

M. 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

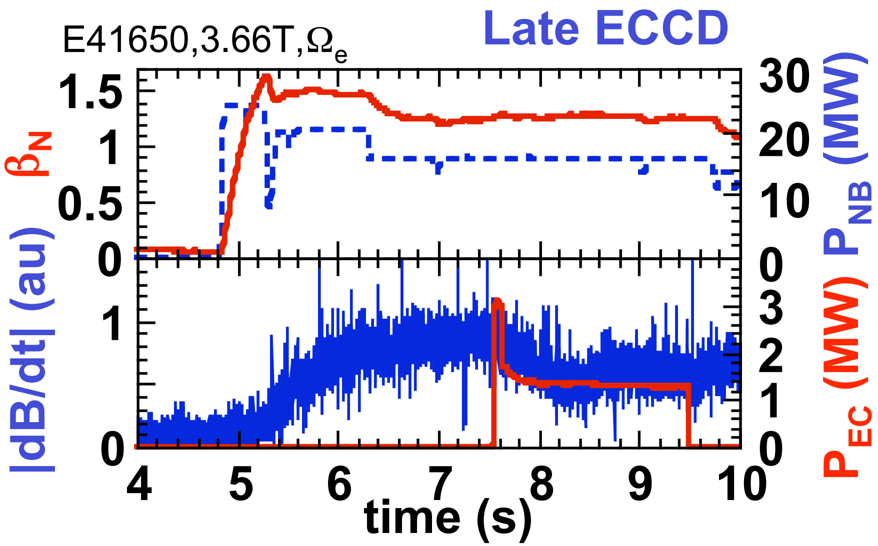
M. Takechi (EX/P2-32, Tue.)

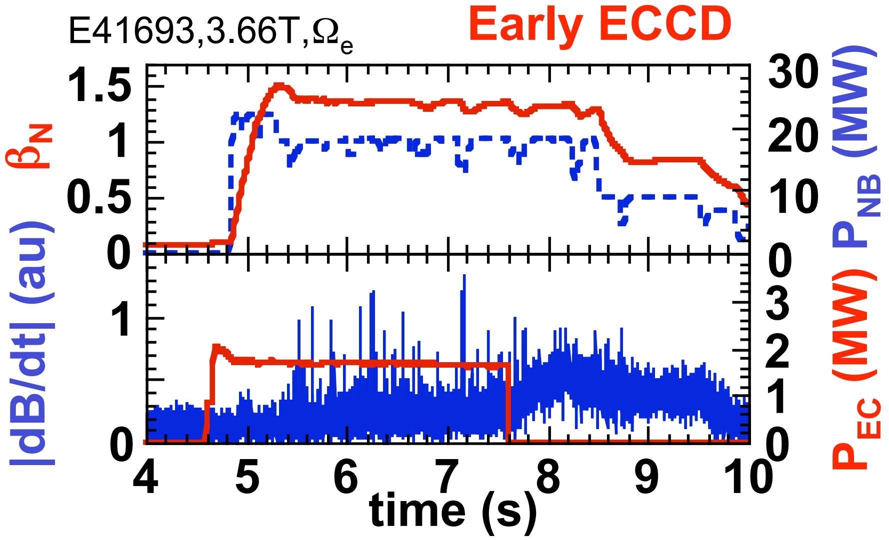
Disruption mitigation

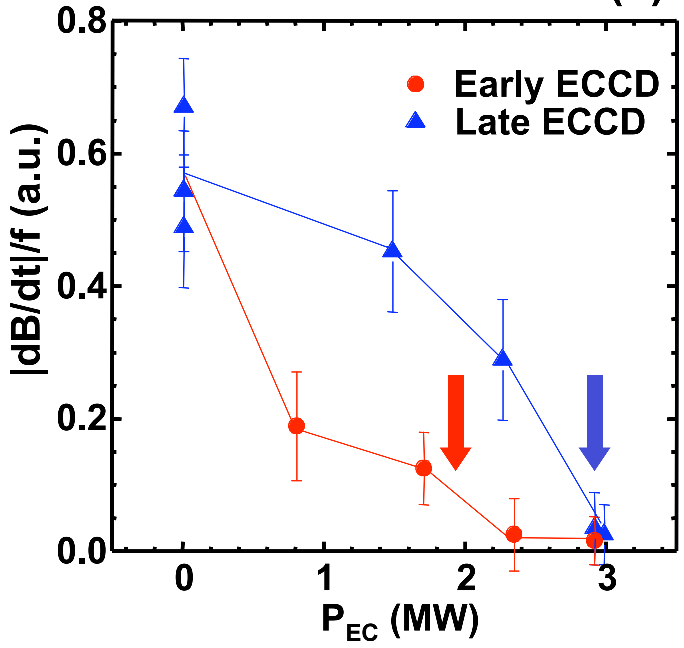
M. Bakthiari (EX/10-6Rb, Sat., poster Fri.)

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

JT-60U





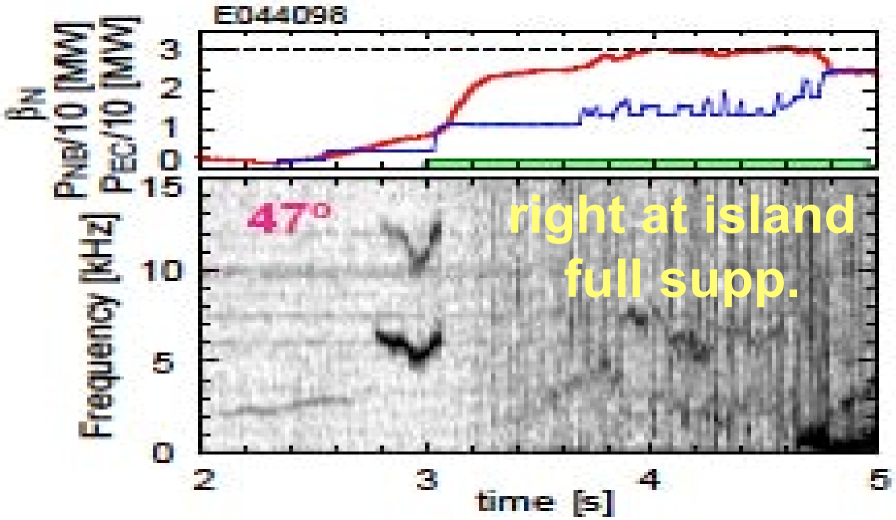


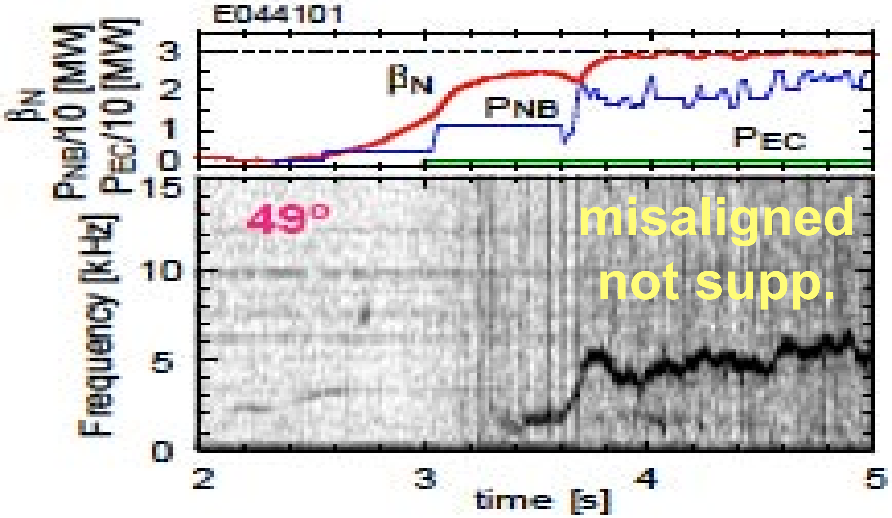
- **Early ECCD is more effective to suppress NTM:**
  - –island size (~|dB/dt|/f) quickly suppressed
  - –less power for full stabilization
  - –calculated necessary power for full suppression based on mod. Rutherford eq. agrees well with the experiments (arrows).

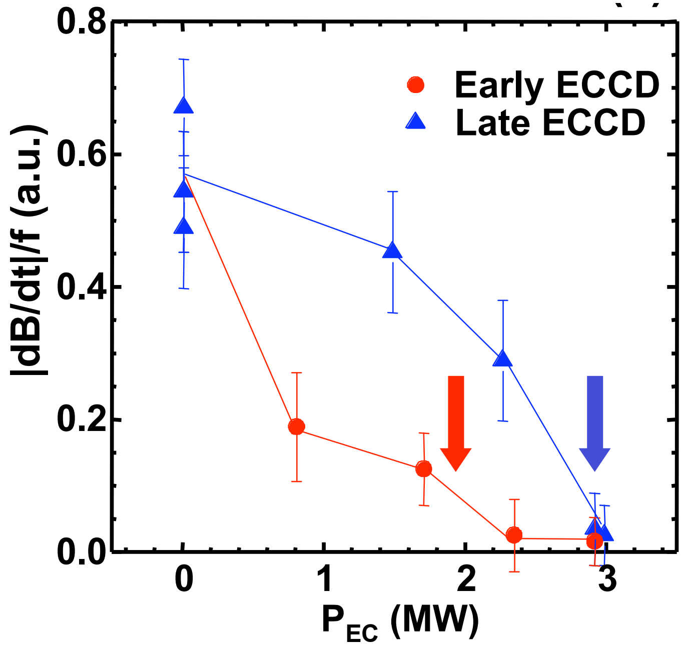
K. Nagasaki (EX/10-3, Thu.)

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 (~|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 β_N=3.

K. Nagasaki (EX/10-3, Thu.)

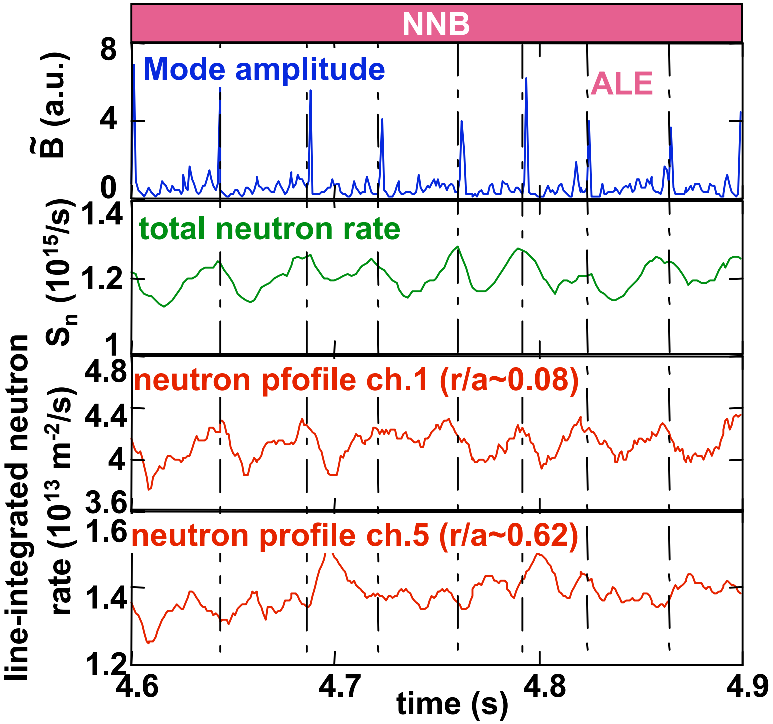
Confinement of energetic ions at ALE

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

JT-60U

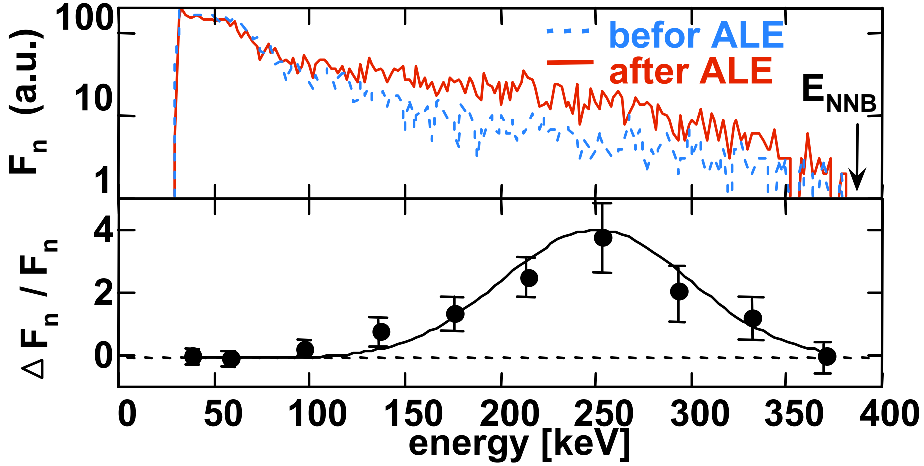
E43014, Ip=0.6MA Bt=1.2T
P_{NNB}~ 4.8MW, ENNB~387keV

<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

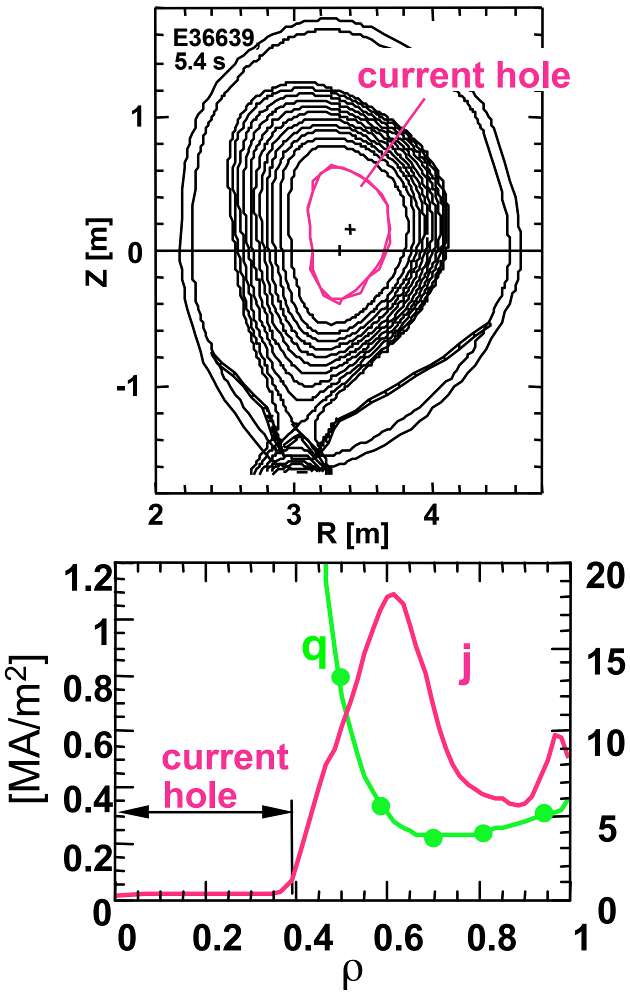
=>Contribution to theory/modeling towards burning experiments.

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

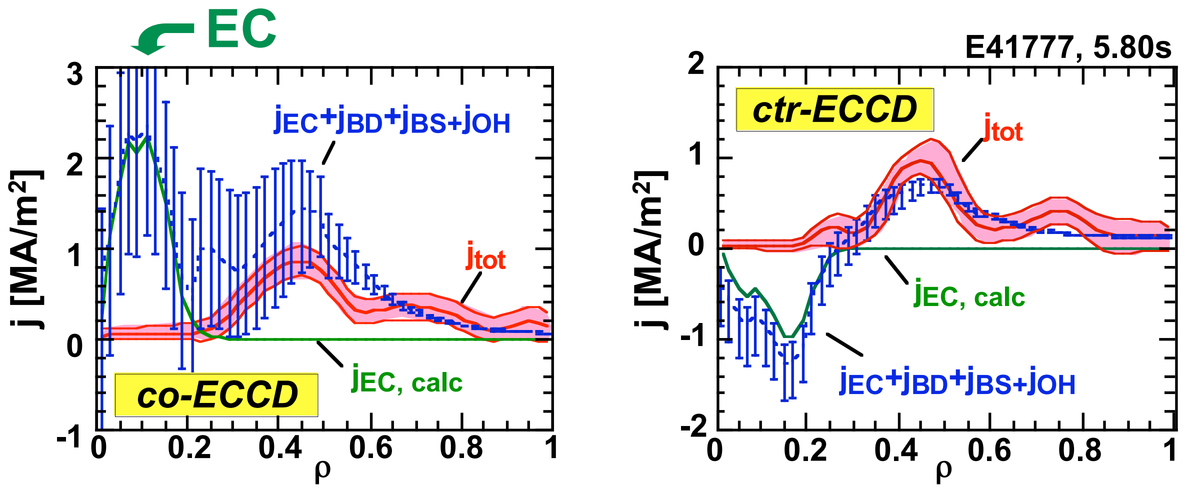
Stiffness of current profile in the current hole (CH) region

JT-60U

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

- 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.)

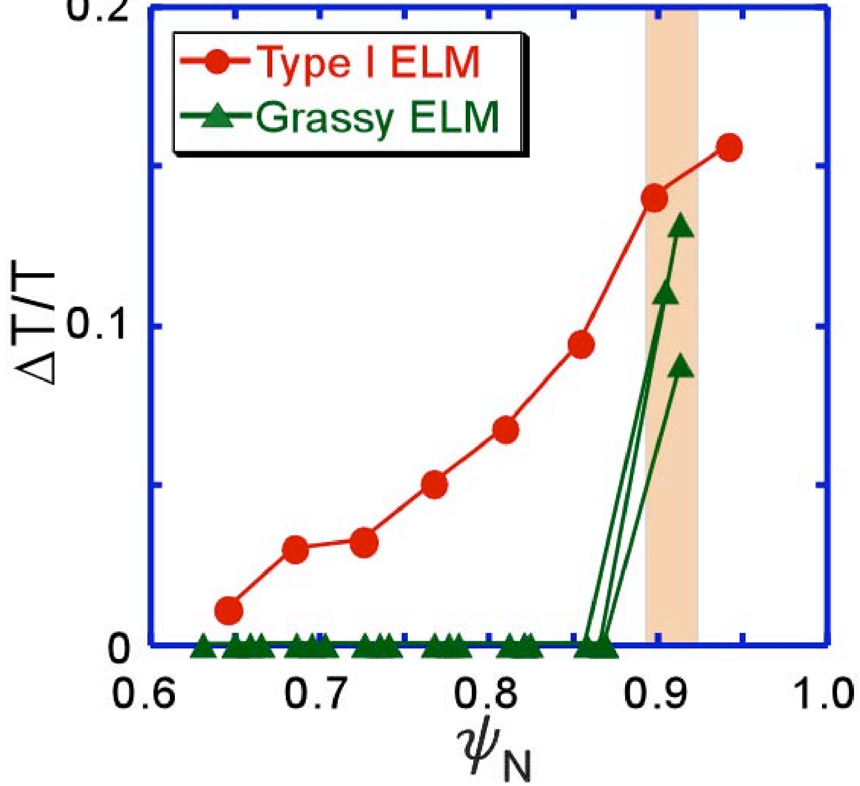
N. Oyama (EX/2-1, Tue.)

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

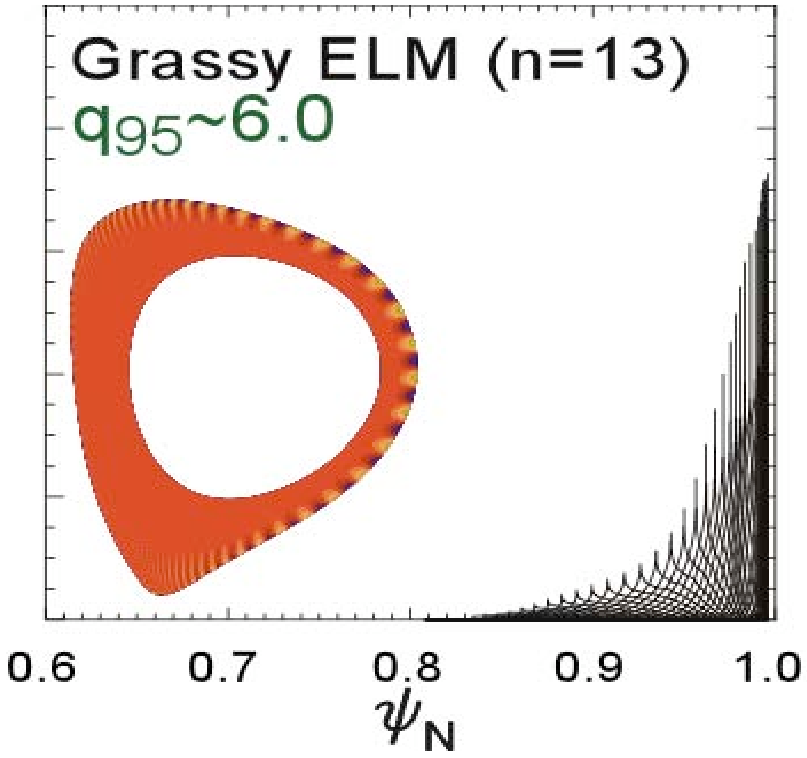
JT-60U

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

Normalized T_e reduction



Example of stability analysis using ELITE, P. Snyder et. al



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

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JT-60U

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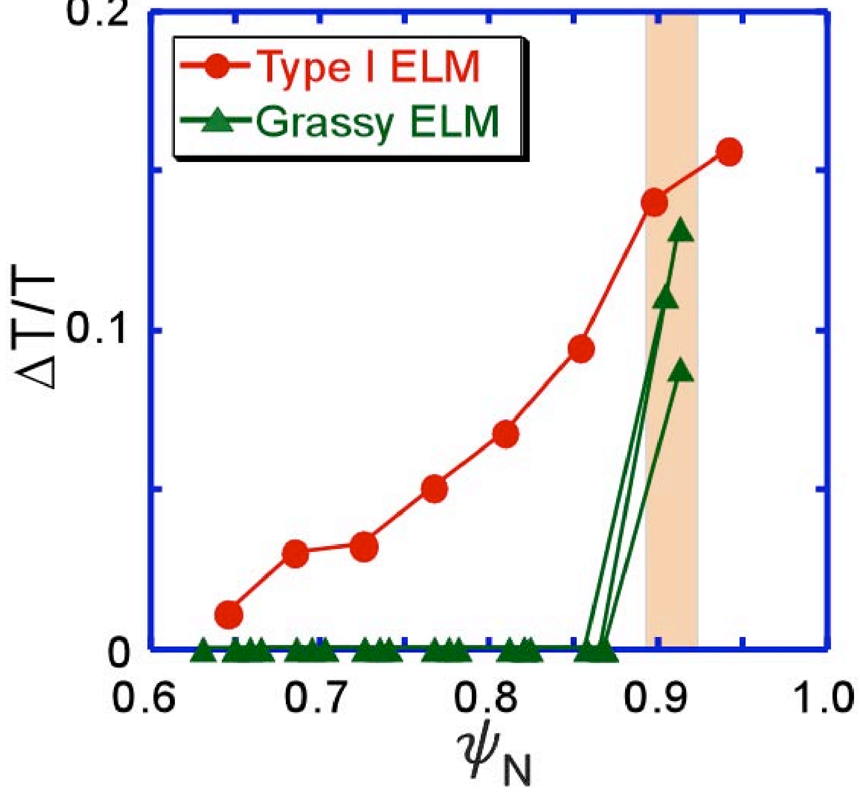
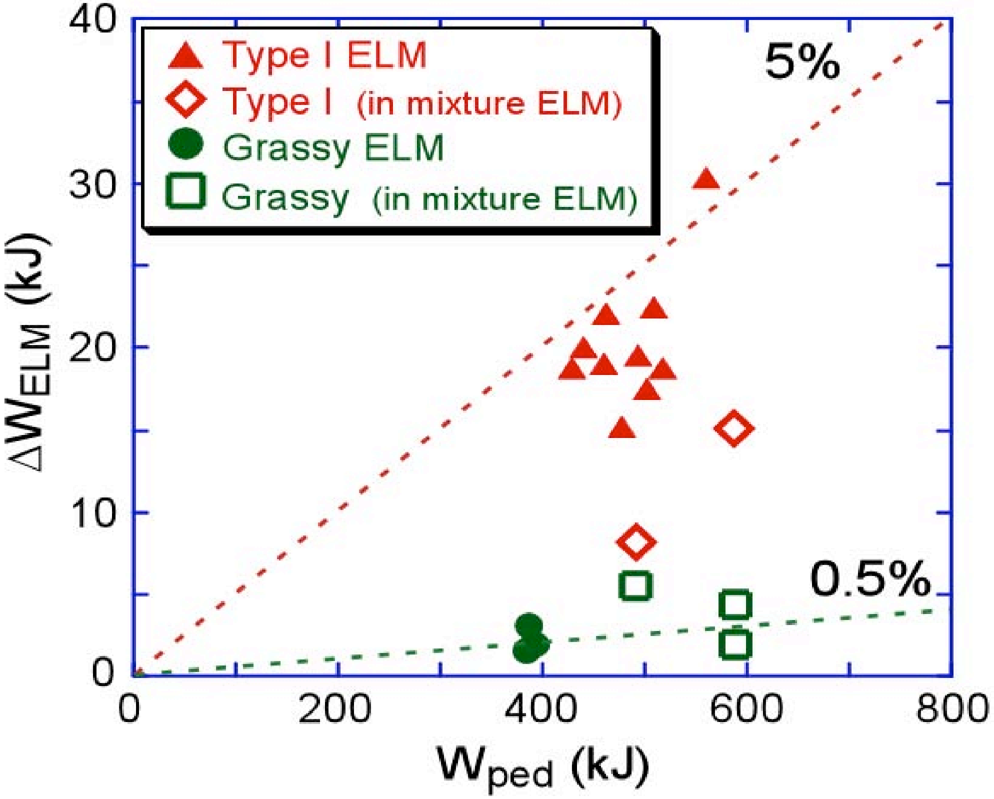
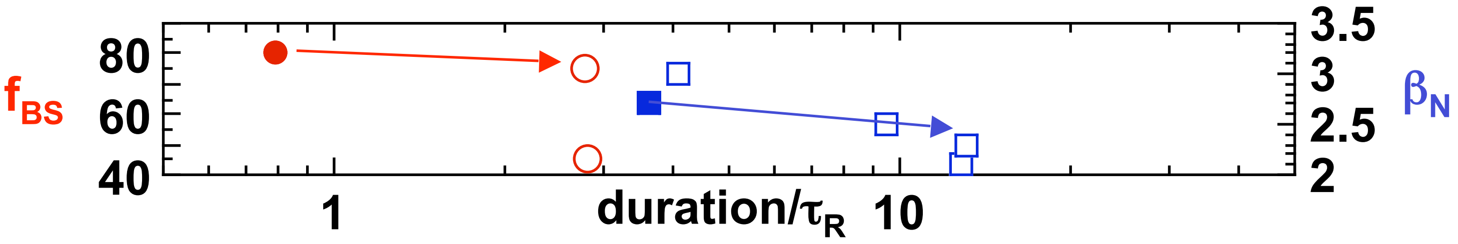


Comparison of ELM energy loss



Summary

- **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 >τ_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

Tue.	Wed.	Thu.	Fri.	Sat.
T. Suzuki (EX/1-3)	**G. Saibene** (IT/1-2)	**M. 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)	*M. Ishikawa* *(EX/5-2Rb,P)*	
		M. Takechi (EX/P2-32)	*M. Bakthiari* *(EX/10-6Rb,P)*	
		T. Fujita (EX/P4-3)		
		Y. Takase (EX/P4-34)		