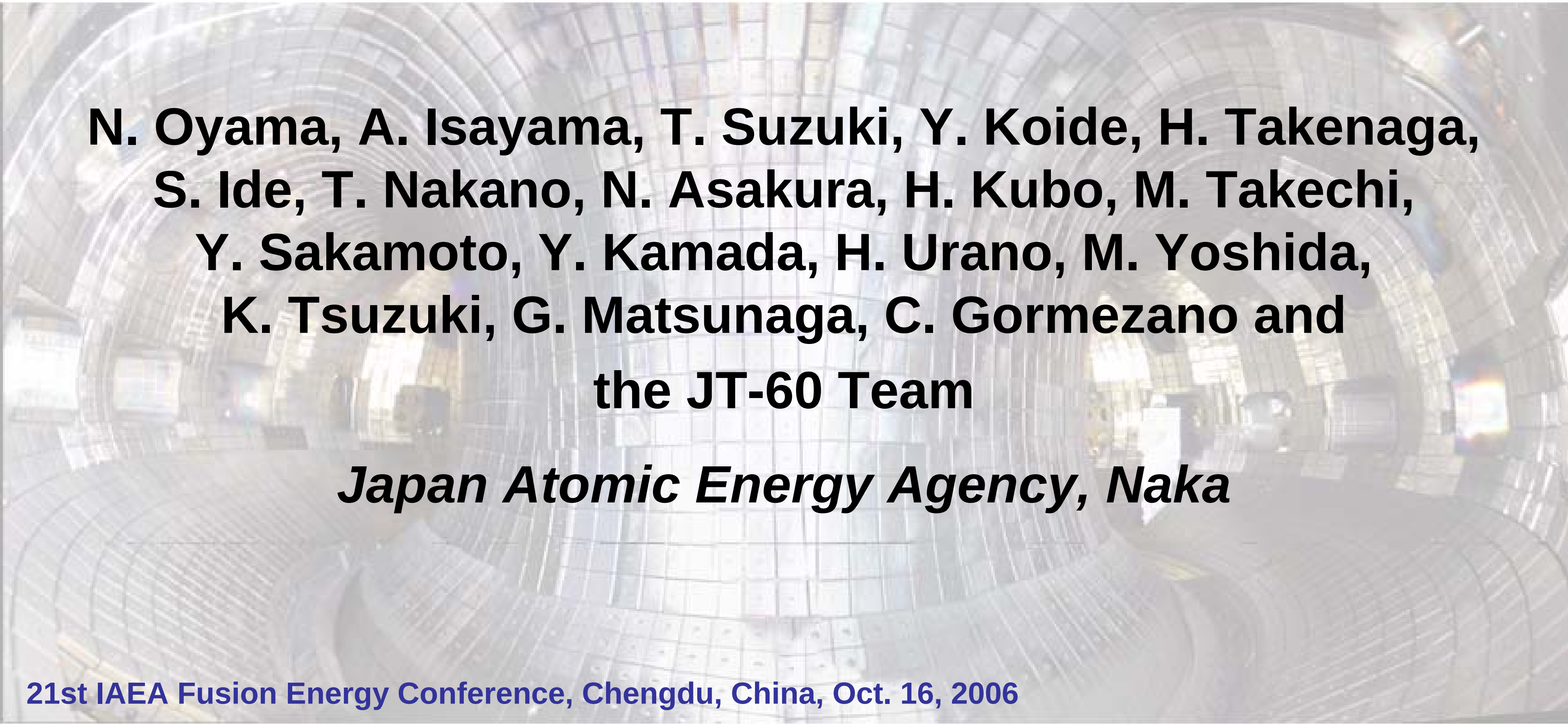
EX/1-3

Improved performance in long-pulse ELMy H-mode plasmas with internal transport barrier in JT-60U



**N. Oyama, A. Isayama, T. Suzuki, Y. Koide, H. Takenaga,
S. Ide, T. Nakano, N. Asakura, H. Kubo, M. Takechi,
Y. Sakamoto, Y. Kamada, H. Urano, M. Yoshida,
K. Tsuzuki, G. Matsunaga, C. Gormezano and
the JT-60 Team**

Japan Atomic Energy Agency, Naka

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Introduction

AT plasmas (high f_{BS} & β_N) based on ITB plasmas

contribution to “hybrid scenario” in ITER

Larger neutron fluence per ITER pulse

Extension of burning plasma longer than 1000s

- substantial fraction of I_p is sustained by BSC and NBCD

Q~5 for >1000s: H_H=1, β_N~1.9-2.3 with f_{NI}~42-52%

(B.J. Green PPCF 45 (2003) 687)

Q=11 for 1550s: H_H=1.2, β_N~2.1 with f_{NI}~44%

(A.C.C. Sips PPCF 47 (2005) A19)

High confinement and high β plasmas with large non-inductive current should be sustained longer than τ_R.

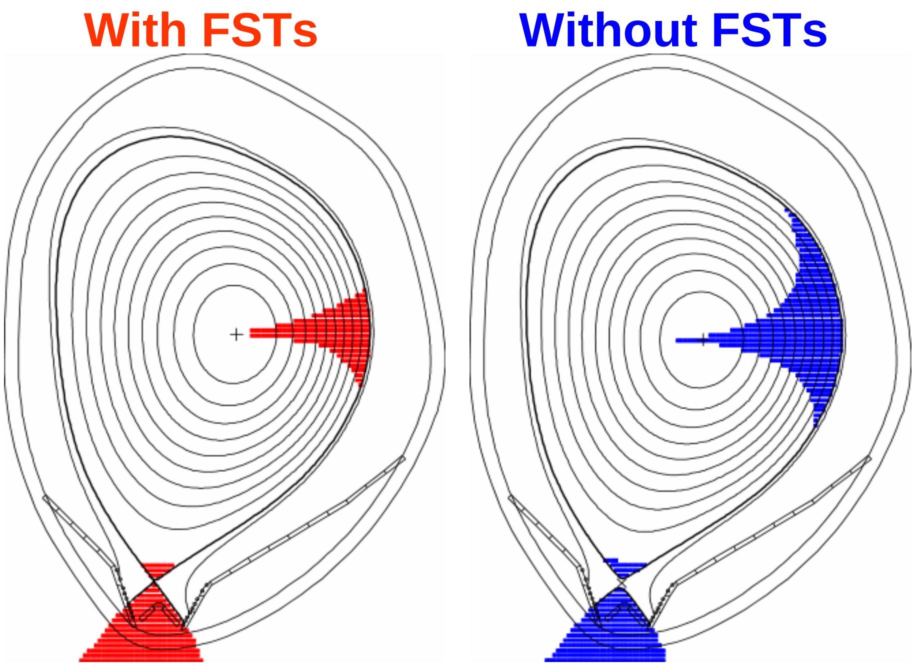
Sustainability of ITB, which drives significant BS current, should be understood in actual long-pulse plasmas (~τ_w).

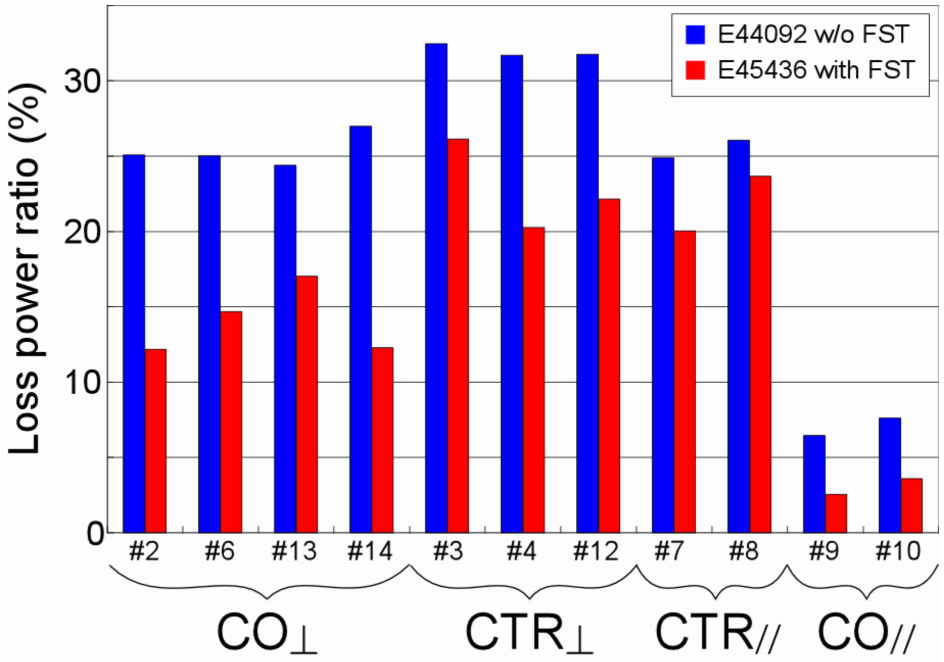
Outline

- Introduction
- Advantages of ripple reduction by FSTs especially for long-pulse plasmas with ITB
  - Reduction of toroidal field ripple and fast ion losses
- Improvement of ELMy H-mode performance
  - Extension of sustained time duration of high β_N
  - Improvement of thermal confinement property
  - Importance of particle control for ITB performance
- Summary

Advantages of ripple reduction by FSTs

Installation of FSTs => **Reduction of fast ion losses by 1/2~1/3 at 1.6T**





- Larger P_{abs} at given P_{in}

  => smaller required NB units for given β_N

  => better flexibility in NBI combination

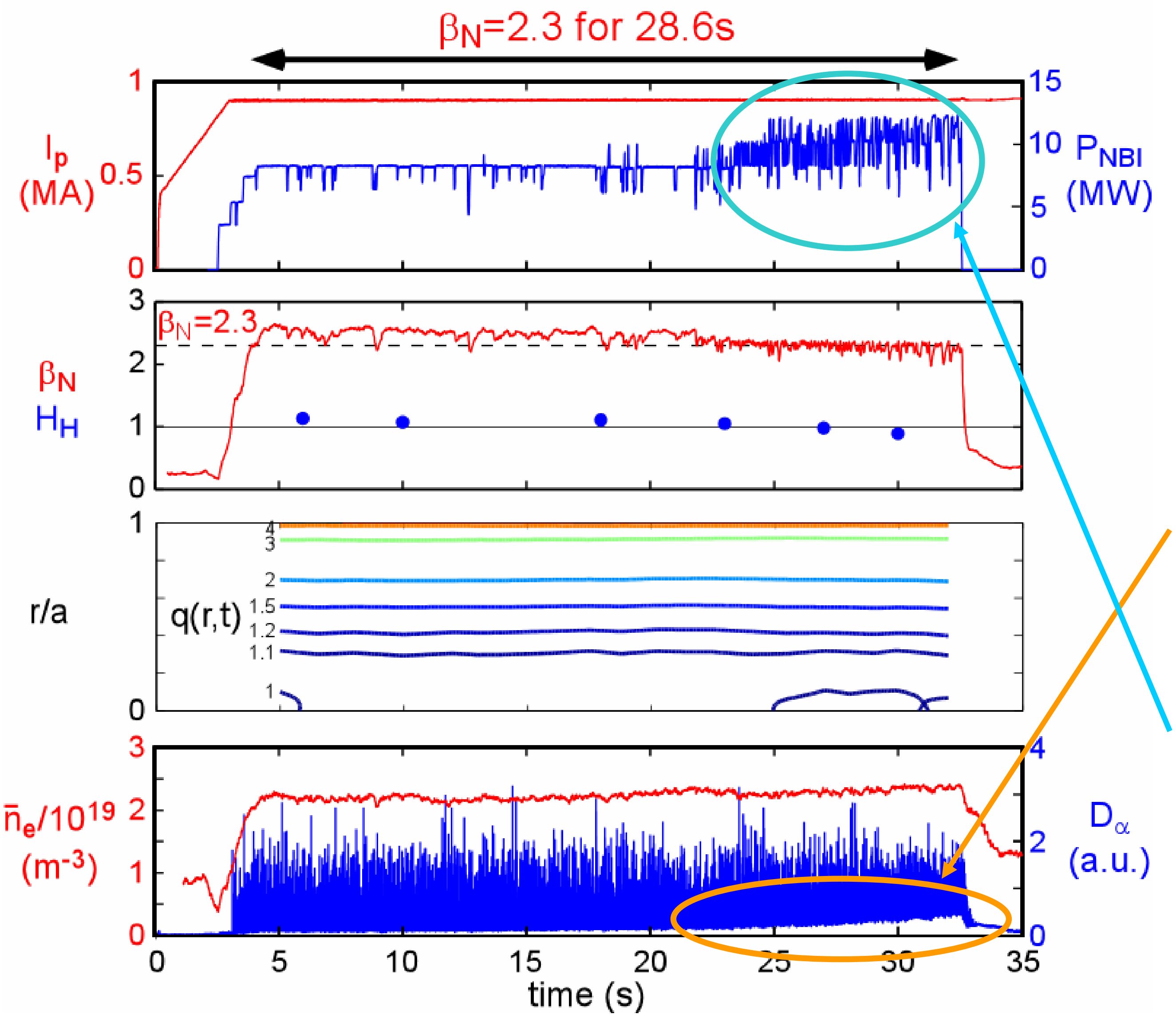
  => better flexibility of torque profile

- Smaller inward E_r

  => less ctr-rotation (M. Yoshida EX/P3-22)

β_N>2.3 has been sustained for 28.6s

- Steady current profile (q profile) much longer than τ_R was sustained



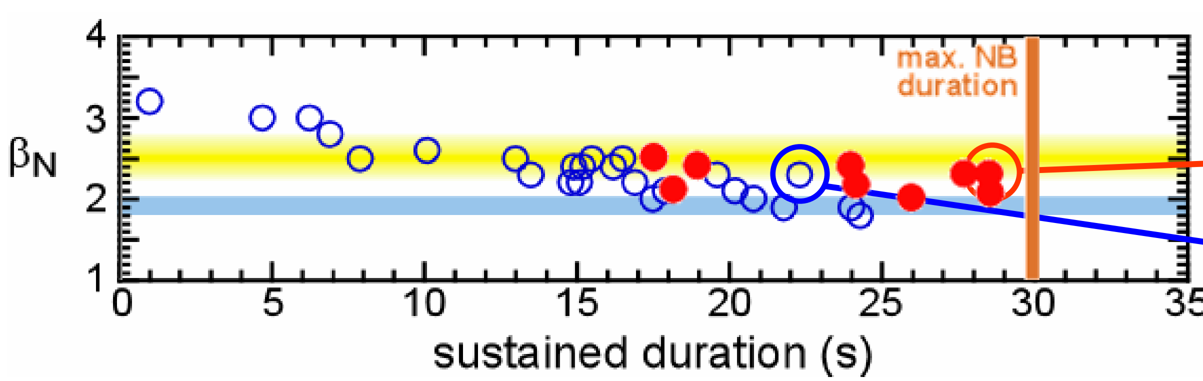
0.9MA/1.6T (t=18s)
P_{loss}/P_{NBI}=13.7%
H_H~1.1, β_N~2.5
P_{NBI}~8MW, β_p~1.4
n_e/n_{GW}~0.48, τ_R~2s
δ~0.32, κ~1.4
q_{95}~3.3, f_{BS}~43%

Enhanced recycling in latter phase (t>23s) => ITB degraded

Increased P_{NBI} by stored energy FB sustained β_N>2.3 => H_H decreased

Thermal confinement is much improved

JT-60U



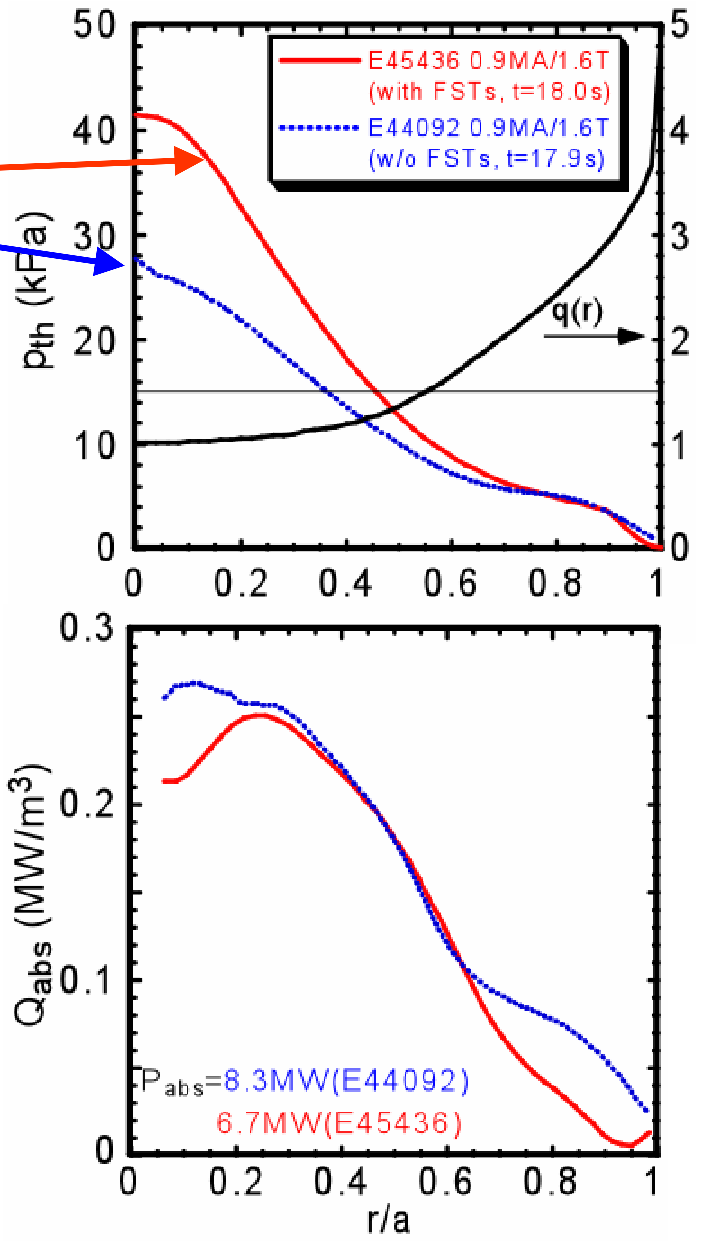
Sustained time duration of β_N=2.3 has been extended from 22.3s to 28.6s

Peaked pressure profile can be sustained without large sawtooth and NTMs

by smaller heating power

8.3MW in E44092 (5u+NNB+EC) => H_H=0.82

6.7MW in E45436 (4.5u) => H_H=1.1



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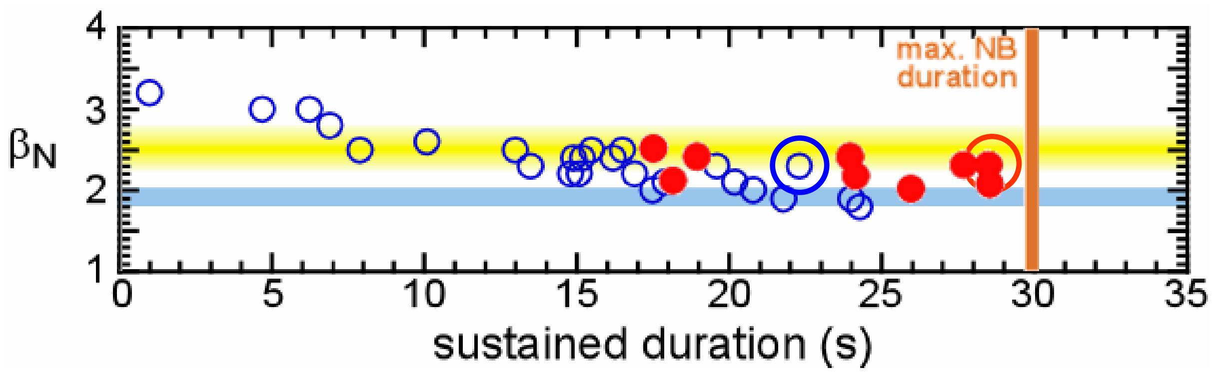
JT-60U



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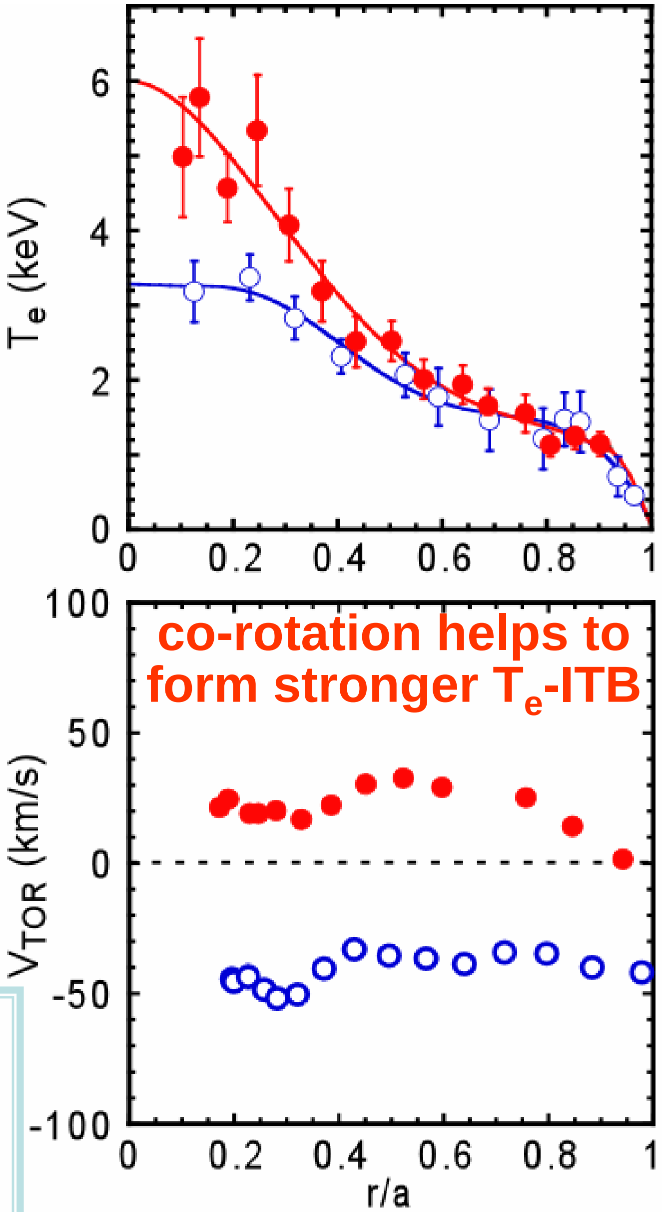
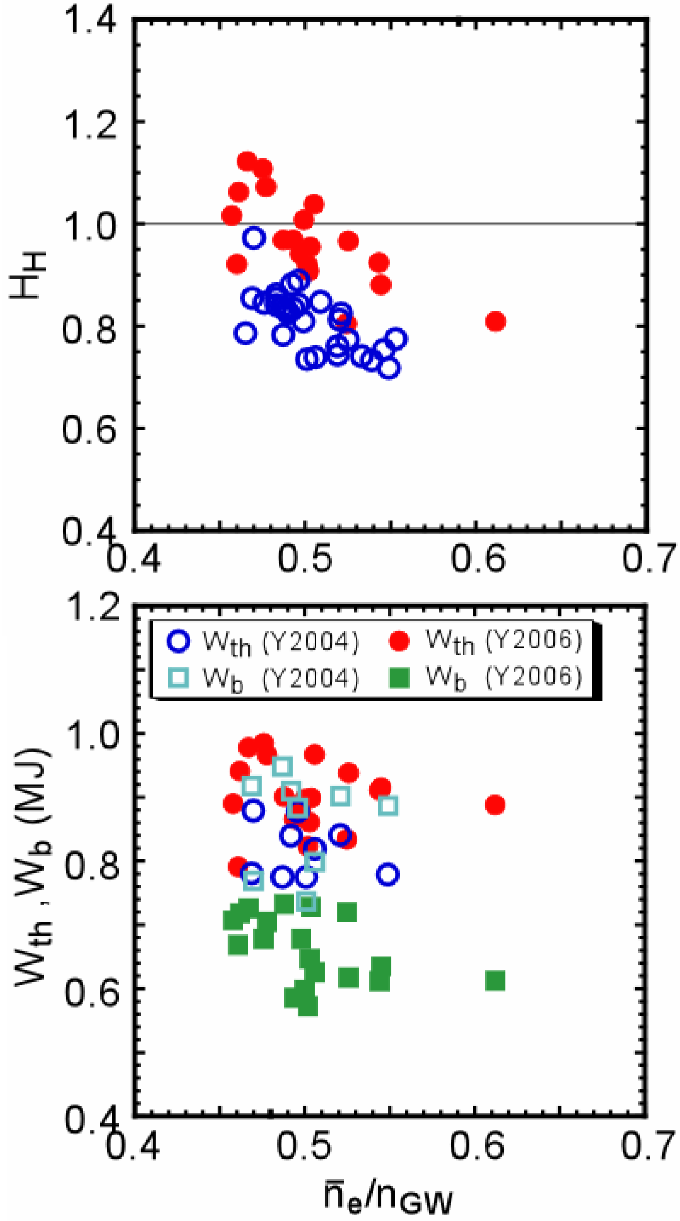
Both better confinement and larger P_{abs} contribute to reduce required NB units, which help to extend the sustained duration



co-rotation helps to form stronger T_e-ITB

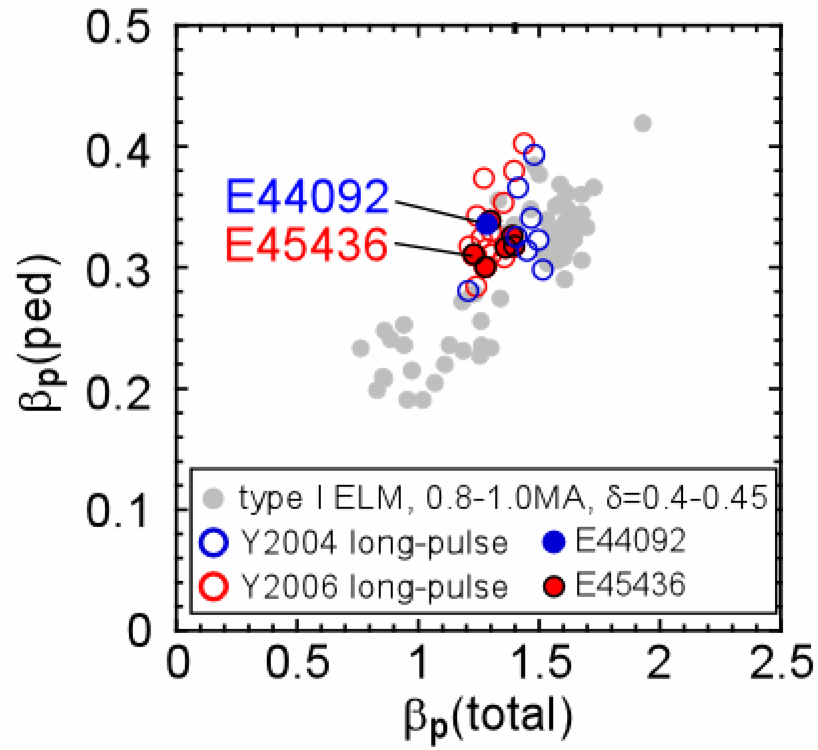
Larger thermal component sustained by improved ITB gives higher H_H



Similar achieved β_N,
but higher H_H for a given density

Y2004 (w/o FSTs) $W_{th} \leq W_{beam}$

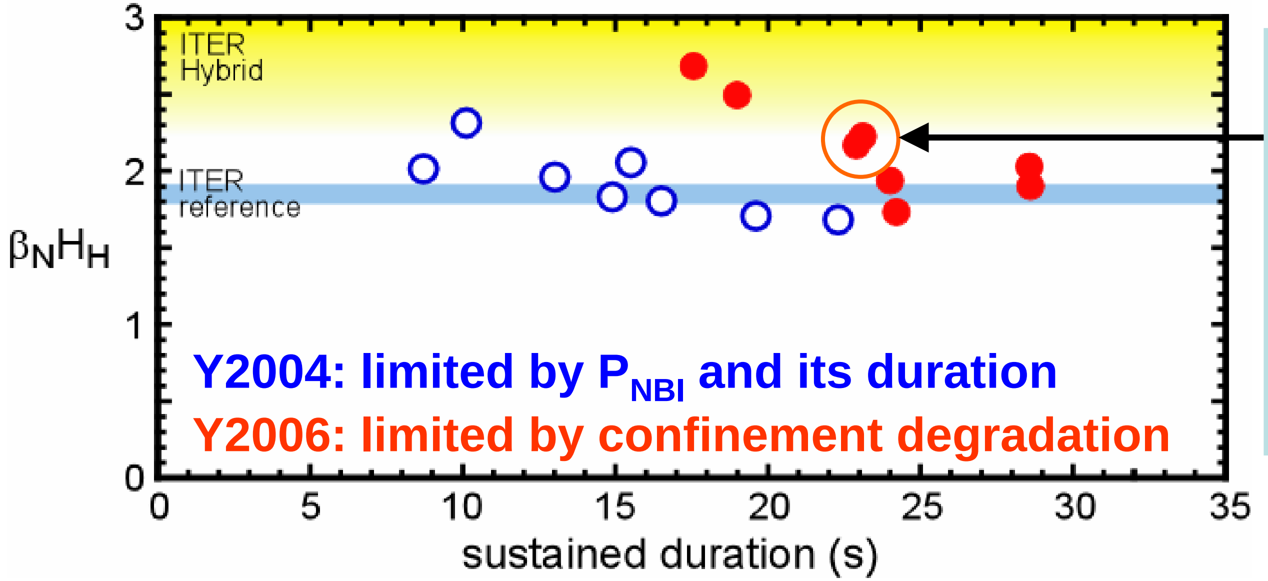
Y2006 (with FSTs) $W_{th} > W_{beam}$



pedestal contribution was small

$\beta_N H_H$>2.2 has been sustained for 23.1s (~12τ_R) at q_{95}~3.3

JT-60U

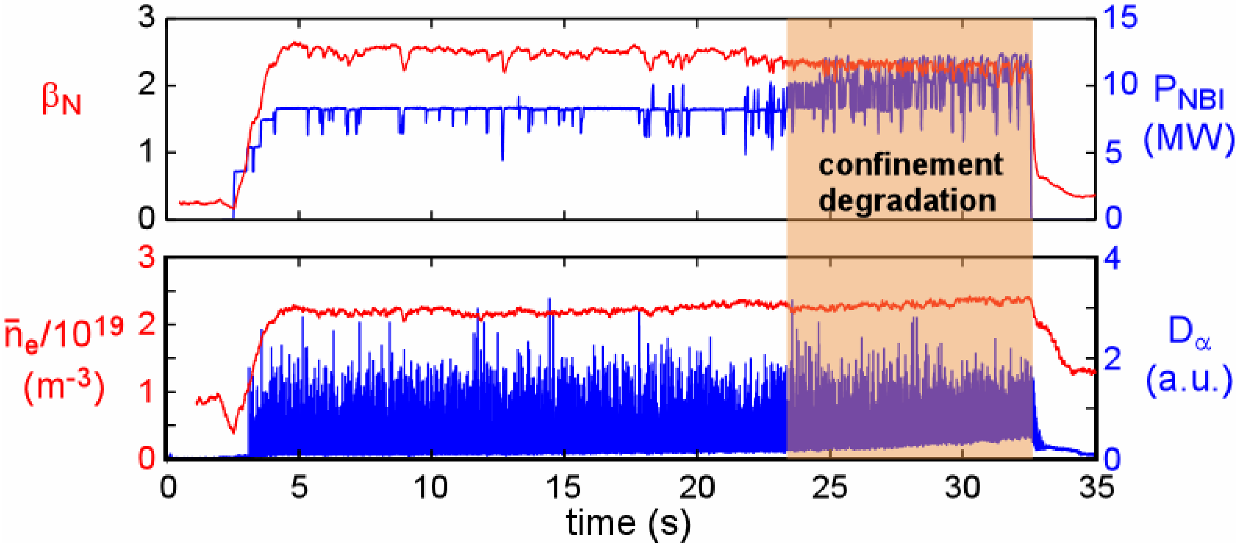


Y2004: limited by P_{NBI} and its duration

Y2006: limited by confinement degradation

$\beta_N H_H/q_{95}^2$>0.20
$\beta_N H_{89}/q_{95}^2$>0.42
f_{BS}~36-45%, τ_R~2s
⇓
candidate for ITER Hybrid scenario

What parameters do limit the sustained time duration?

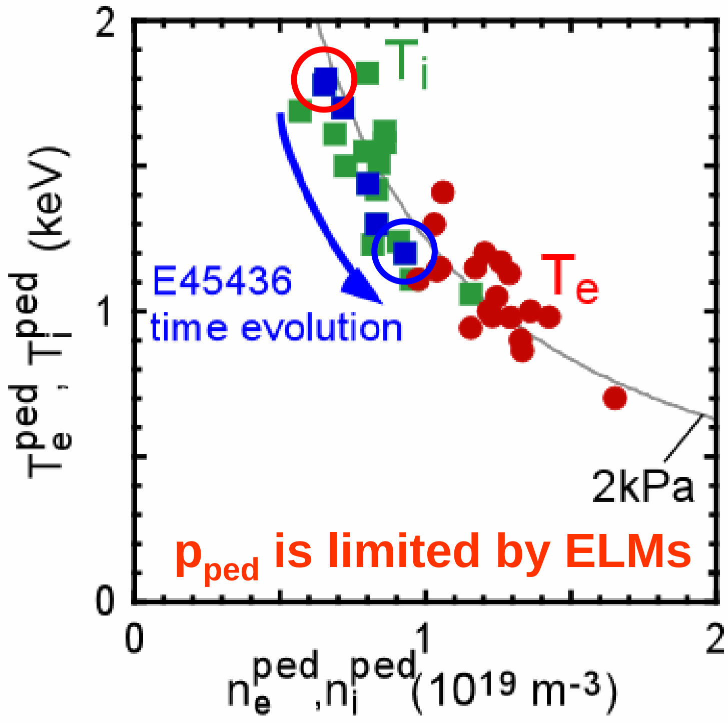


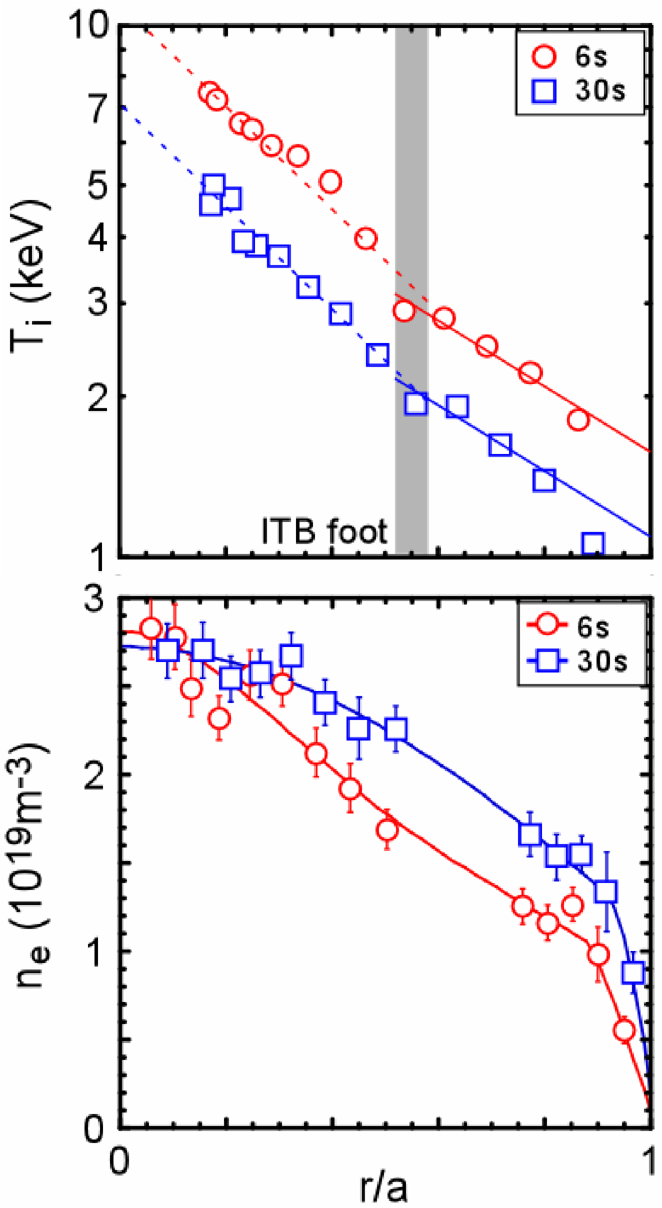
Not P_{NBI} limit
- No help from higher P_{NBI}

Not MHD limit
- No NTMs appeared

V_T was unchanged

Broad n_e profile caused smaller p_{th} through pedestal <-> core interplay





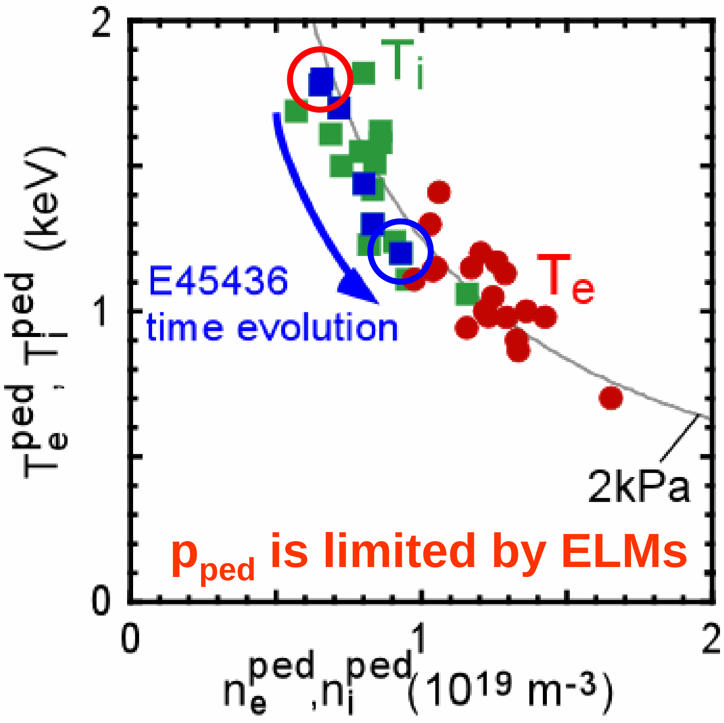
n_e^{ped} increased by ~30%

=> T_i^{ped} decreased by ~30%

=> core T_i also decreased by ~30% (stiff profile)

But, n_e became broader!

Broad n_e profile caused smaller p_{th} through pedestal <-> core interplay



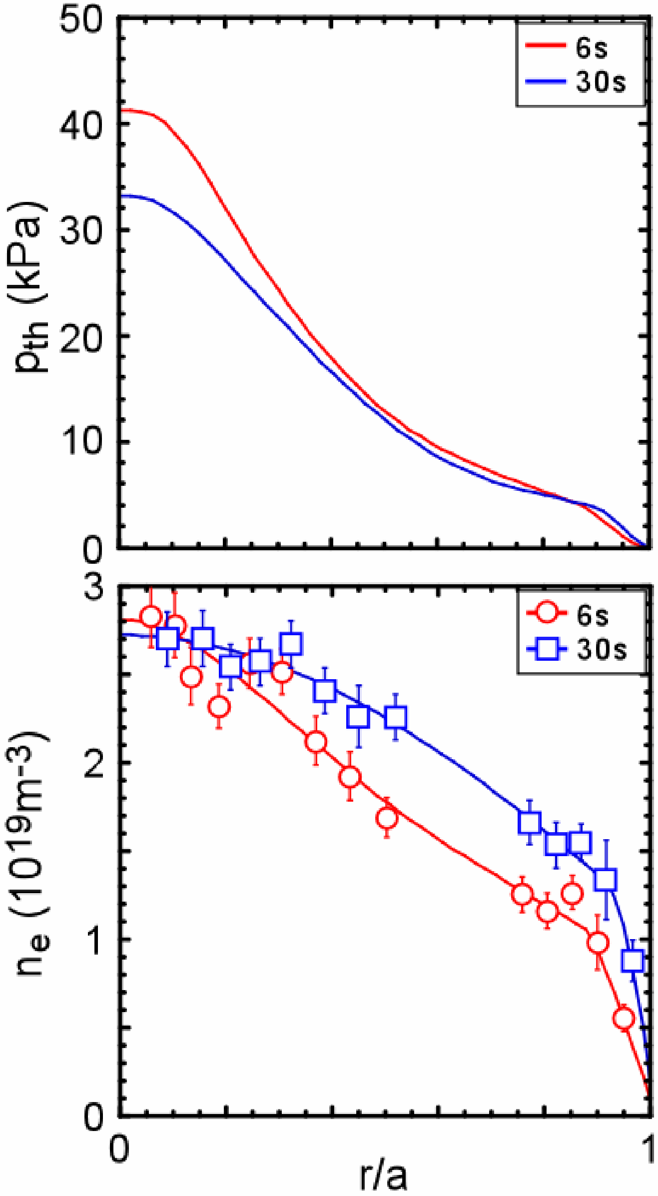
p_{ped} is limited by ELMs

n_e^{ped} increased by ~30%

=> T_i^{ped} decreased by ~30%

=> core T_i also decreased by ~30% (stiff profile)

But, n_e became broader!



P_{NET}

6.7MW=>

8.7MW

$\tau_{E,th}$

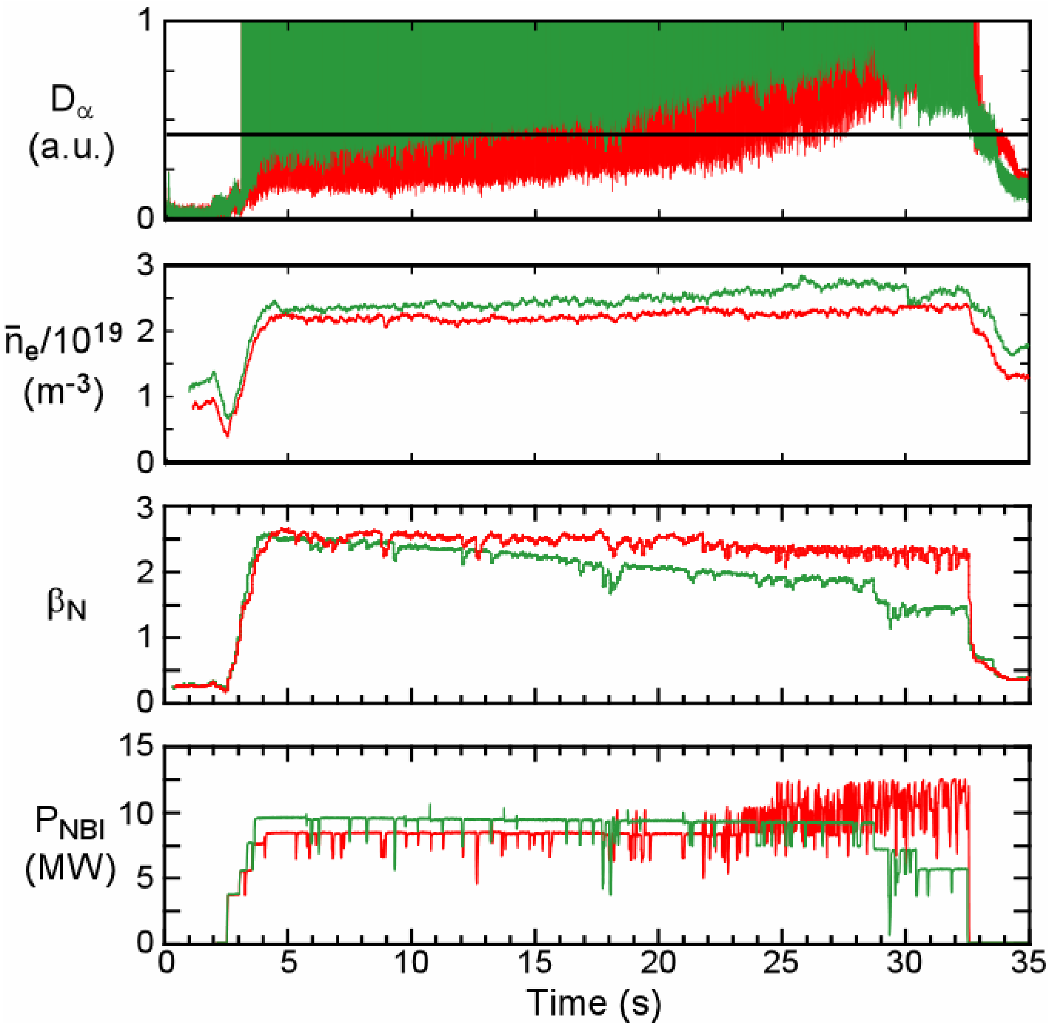
0.15s=>

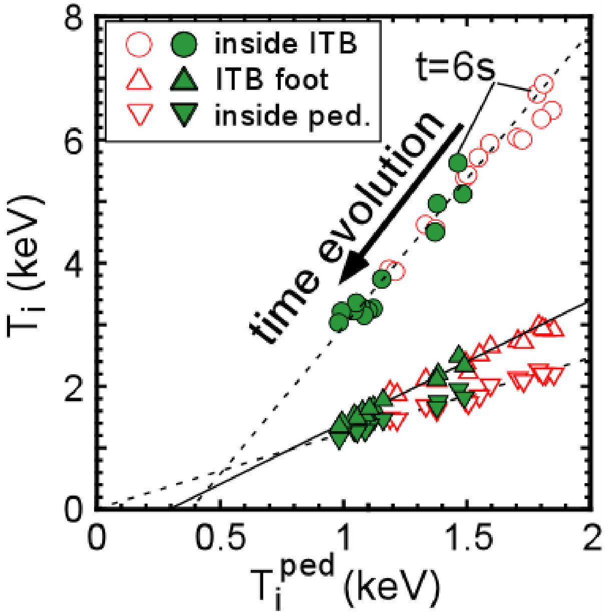
0.11s

Higher edge density due to high recycling prevented peaked pressure profile

JT-60U

Long-pulse plasma in different wall condition





T_i follows same line in both cases => const. $\nabla(\ln T_i)$

But, achieved T_i was smaller in high recycling case due to higher edge n_e

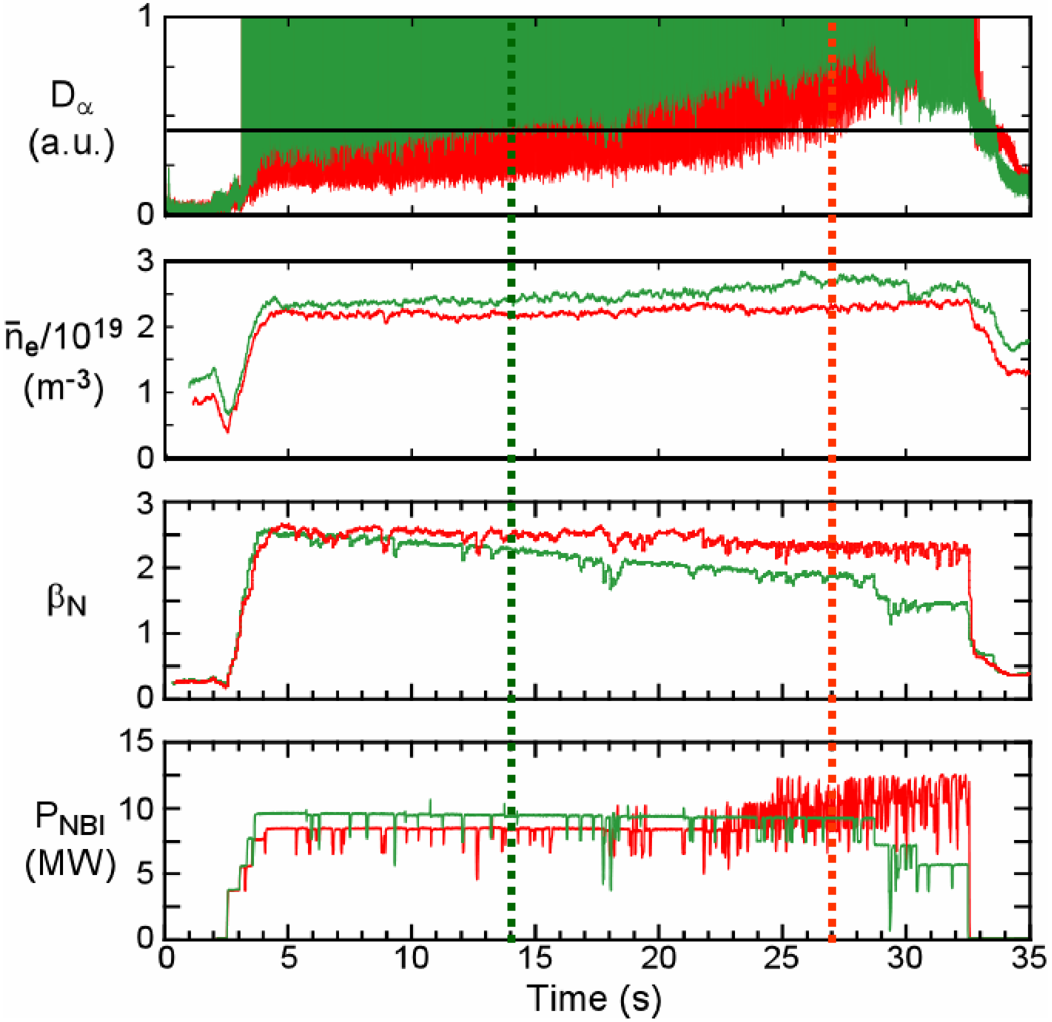
Higher edge density due to high recycling prevented peaked pressure profile

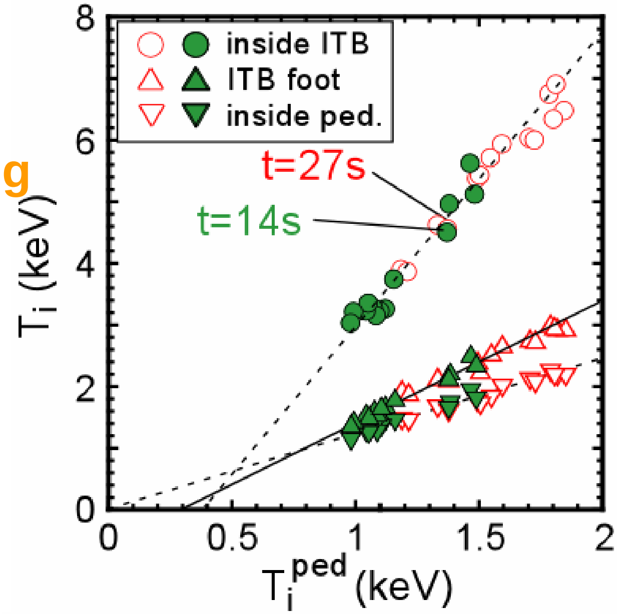
JT-60U

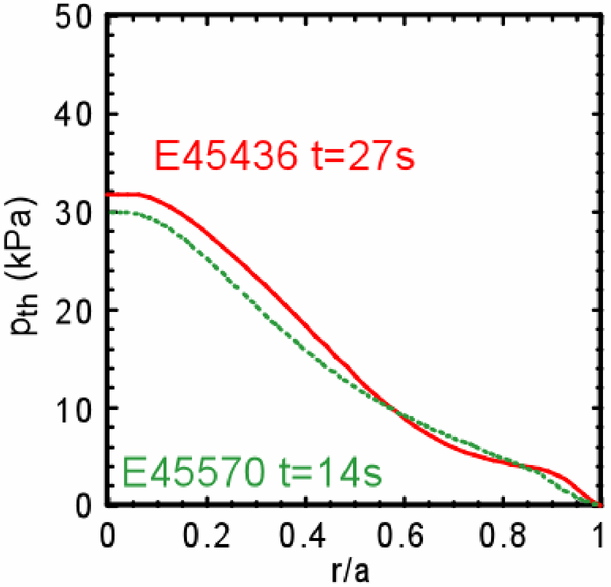
Long-pulse plasma in different wall condition

Similar recycling with similar Q_{abs} => similar p(r)

Limited capability of pumping cased enhanced recycling







Summary

- Reduction of fast ion losses by 1/2~1/3 provides higher heating power together with better flexibilities of NBI combinations and torque input profile.
- Sustained duration of $\beta_N=2.3$ has been extended to 28.6s, where smaller heating power kept peaked p(r).
- $\beta_N H_H>2.2$ with $f_{BS}=36\text{-}45\%$ was sustained for 23.1s ($\sim 12\tau_R$) at $q_{95}\sim 3.3$. These long-pulse plasmas are possible candidates for ITER hybrid operation scenario.

These long-pulse plasmas close to τ_w reveal following issues for further development of AT plasmas

  - higher edge n_e prevented peaked pressure profile
  - long sustainment of high performance plasmas with active particle control