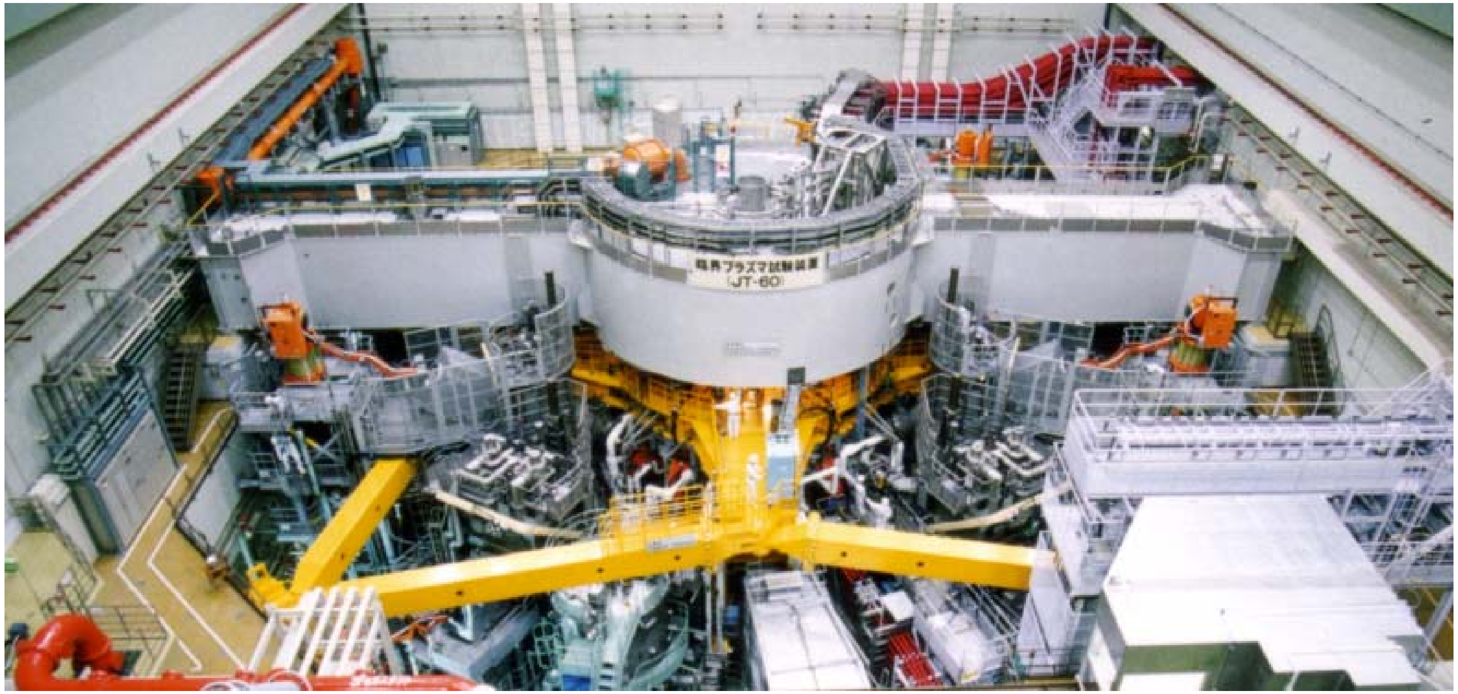
9th Workshop on MHD Stability Control
"Control of MHD Stability: Back to the Basics"
Nov. 21-23, 2004, PPPL

Stability Control for Steady-State High-Beta in JT-60U

A. Isayama for the JT-60U team

JT-60



Contents

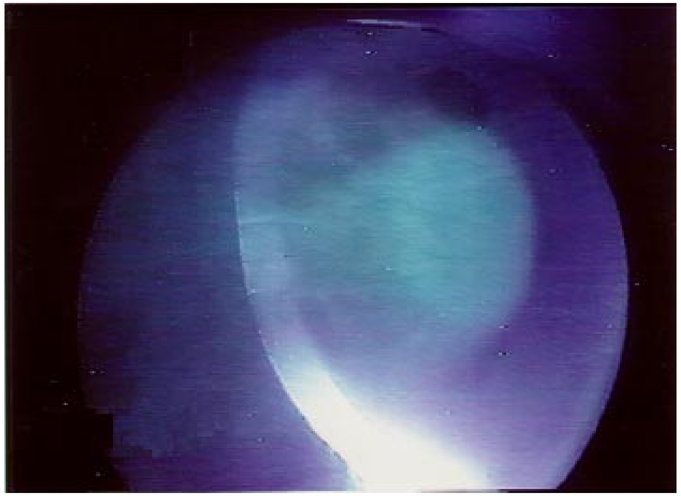
- Introduction
  -- Modification of JT-60U
  for long duration (65s) discharges

- Long-duration high-β_N plasma
  (β_N=2.5 for ~10τ_R, β_N=1.9 for ~15τ_R)

- High-β_N (~3) by NTM suppression

- Measurement of NTM structure

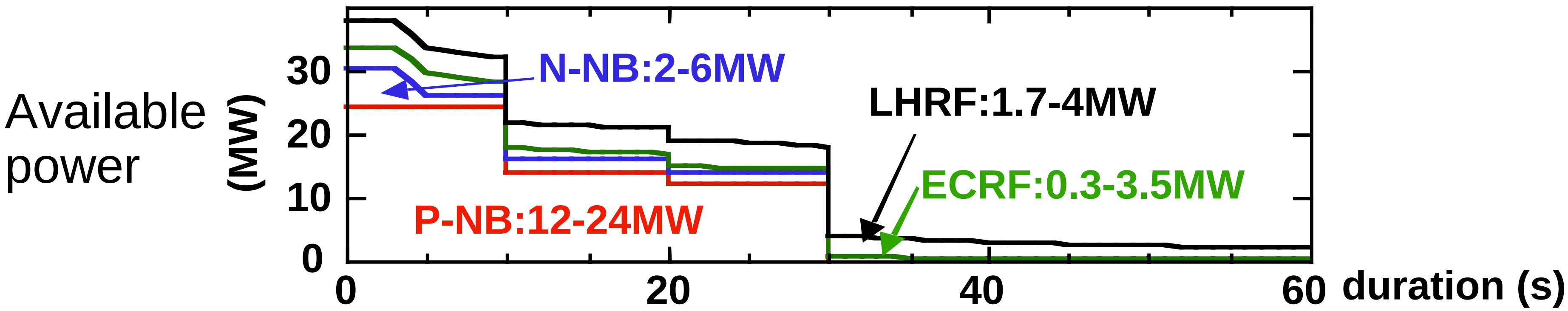
- Summary

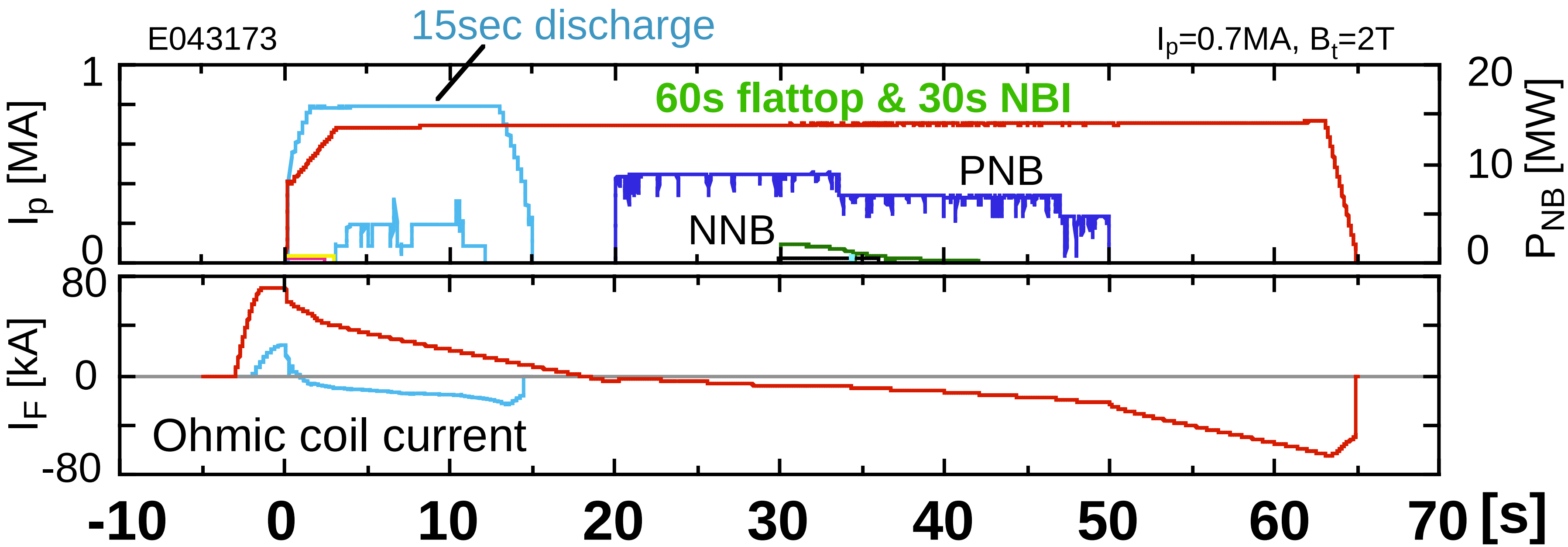


Extension of discharge duration to 65s

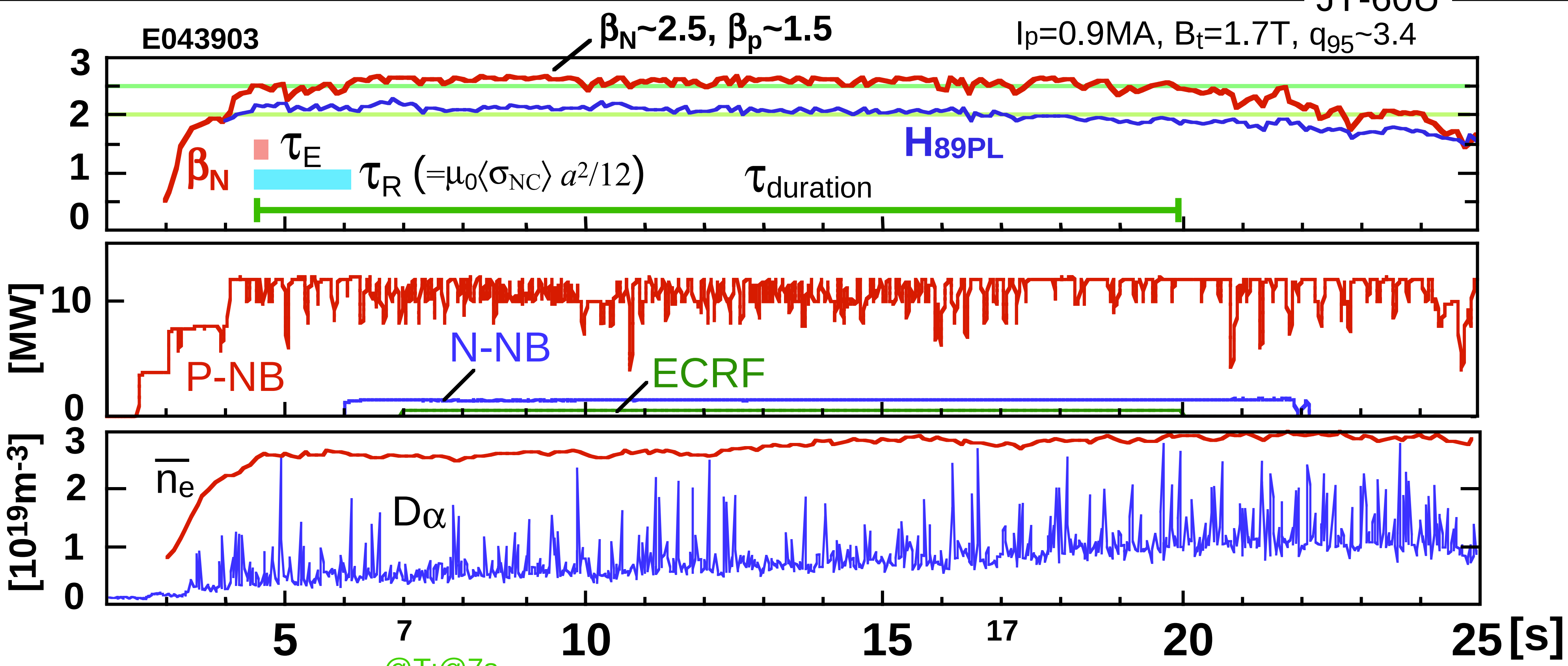
JT-60U

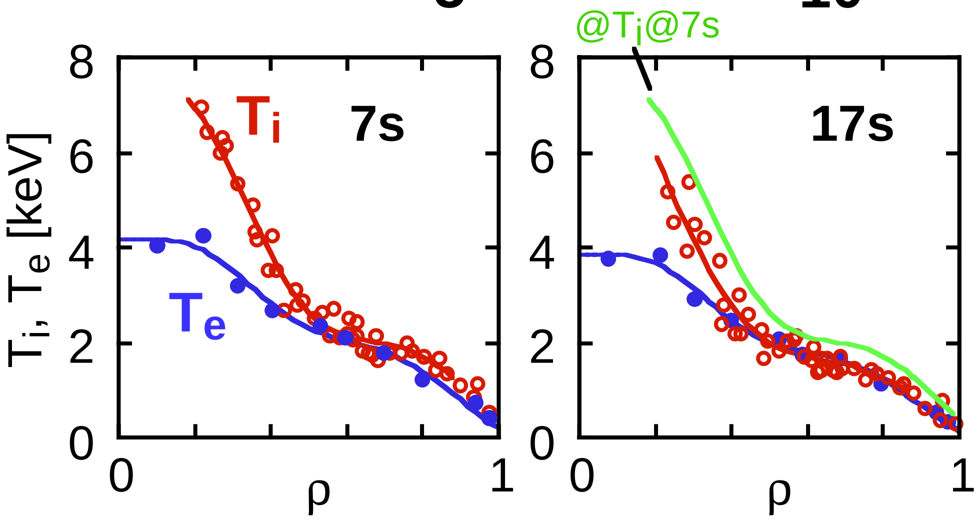
Toroidal field : **3.3T for 30s, 2.7T for 65s**
Tangential P-NB (4 units): **30s injection** (<- formerly 10s)
N-NB: **~2MW for 30 s**





β_N~2.5, H_{89PL}~2 have been sustained for 15.5s (~9.5τ_R)



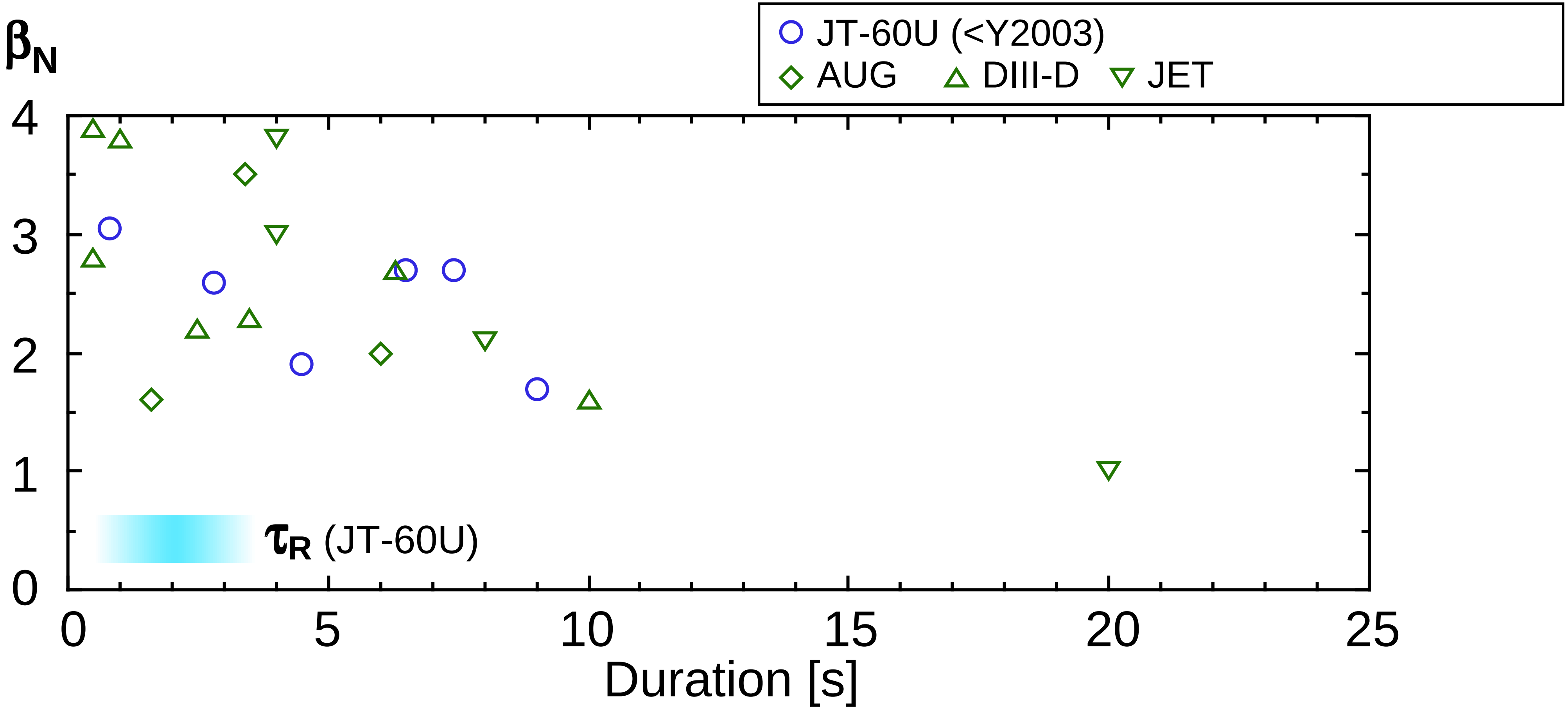


- β_N**~2.5** for 15.5s: **9.5τ_R** , **~78τ_E**
  H_{89PL}~2 ➡ **$\beta_N H_{89PL}/q_{95}^2$~0.4** **~ITER baseline scenario**
- ITB and ETB for >10s
- Confinement degradation at t=~17s:
  density rise & ETB degradation

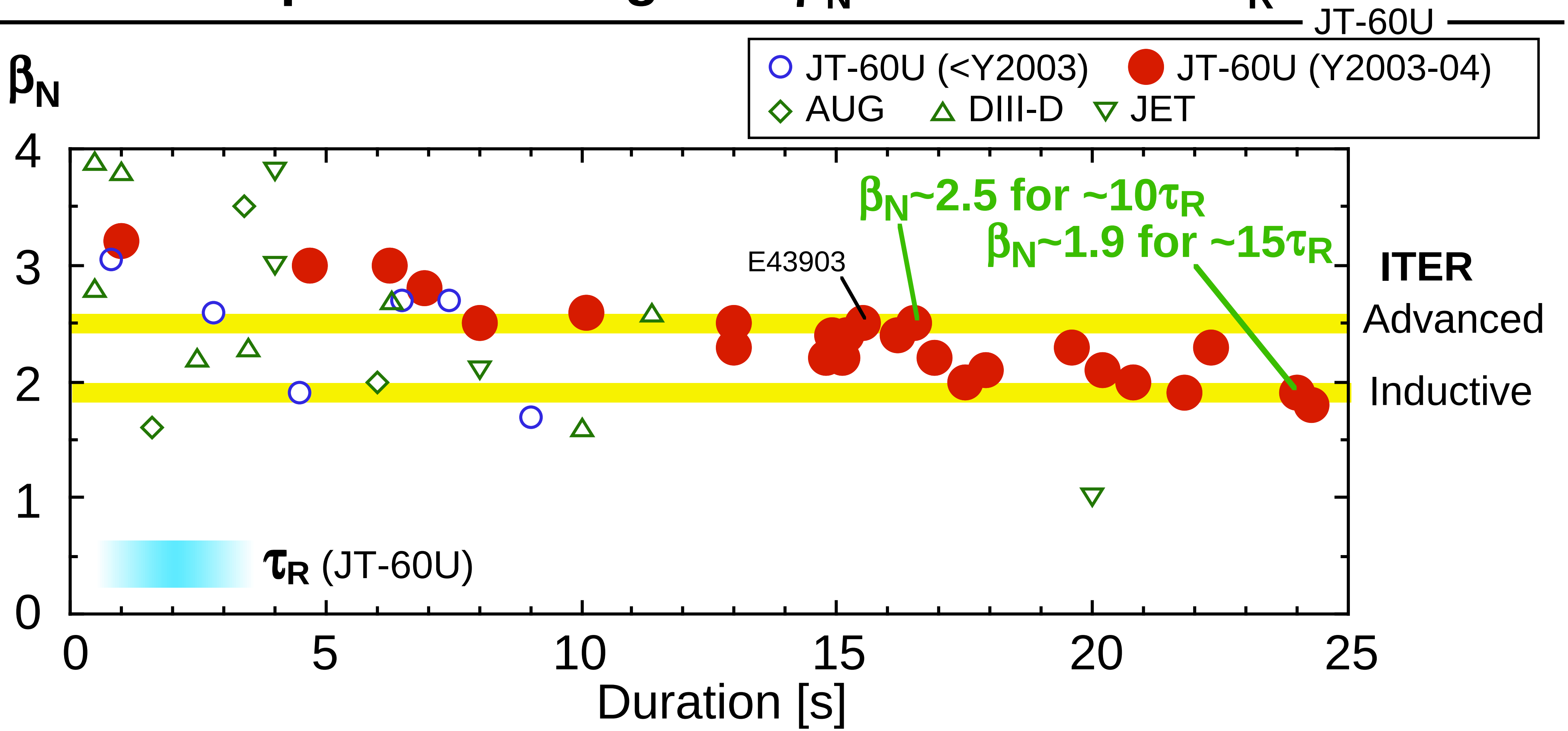
$\tau_R = \mu_0 <\sigma_{NC}> a^2/12$
(D.R. Mikkelsen Phys. Fluids B **1** (1989) 333.)

Operational regime before 2003

JT-60U



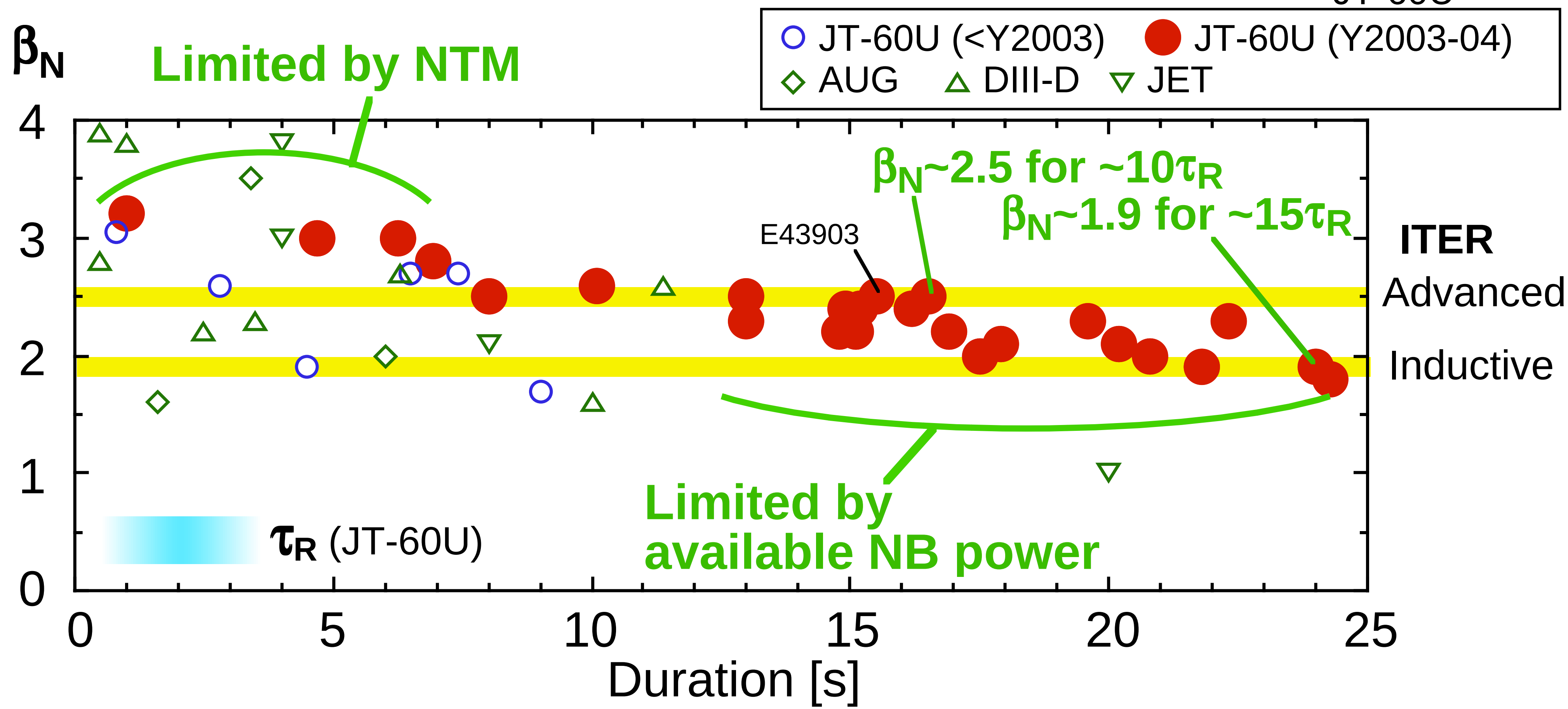
New operational regime: β_N=2-2.5 for >10τ_R



- **Region of sustained beta has been significantly extended.**
  - **β_N~2.5** (~advanced operation in ITER) for 16.5s, ~**10τ_R**
  - **β_N~1.9** (~inductive operation in ITER) for 24s, ~**15τ_R**
- Low collisionality & Larmor radius regime: **$\nu*/\nu*_{ITER}$~3, $\rho*/\rho*_{ITER}$~3**
- NTM in longtime scale: **not** observed so far (at β_N~2.5)

New operational regime: β_N=2-2.5 for >10τ_R

JT-60U



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Issue for reaching high beta region = NTM suppression

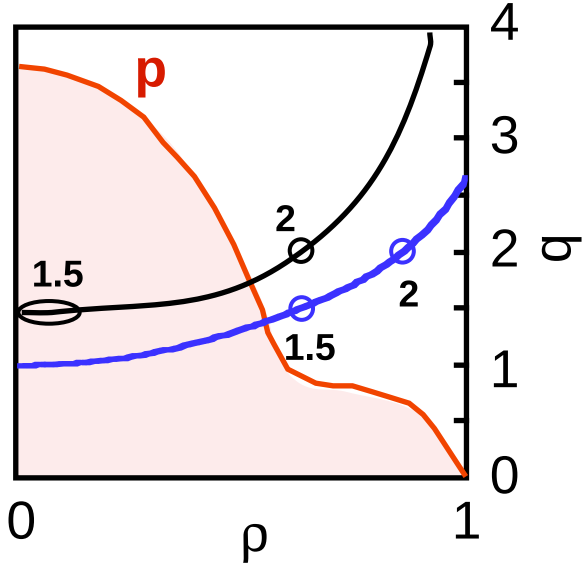
JT-60U : Two scenarios for NTM *suppression*

NTM *avoidance* : Optimization of p(r) & q(r)

This talk

- Hybrid Scenario regime (q_{95}~4.5)
  q=1.5 at the center, q=2 at ρ >~ 0.7
- Low-q regime (q_{95}~2.2)
  q=1.5 and 2 at ρ >~0.7

Capability of various heating profile & plasma shape control in JT-60U



NTM *stabilization* : Active suppression with EC wave

- Early ECCD
  ECCD **before** the NTM onset (or **just after**)
- Late ECCD
  ECCD **after** the NTM saturation

Highlights in 2004

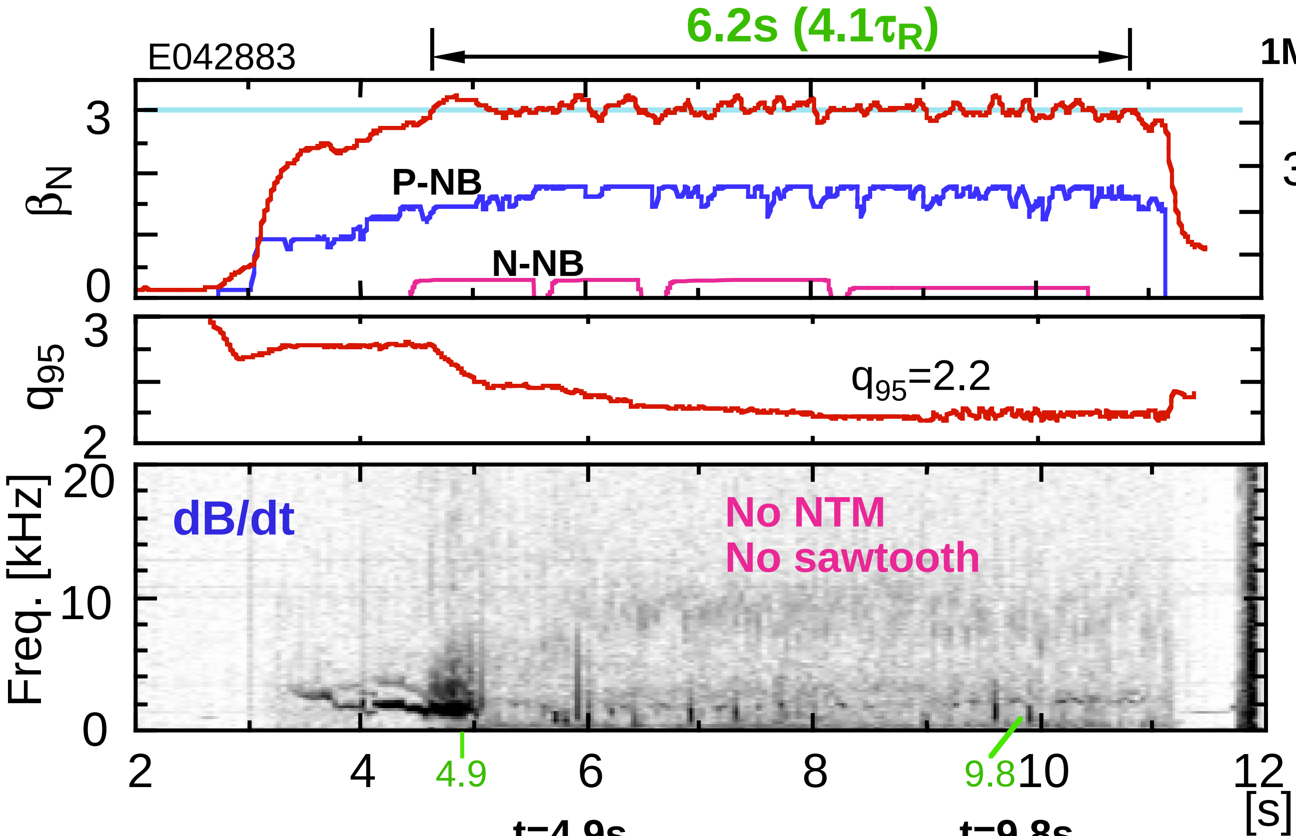
High β regime (β_N~3)

2nd harmonic X-mode EC wave

New attempt in JT-60U

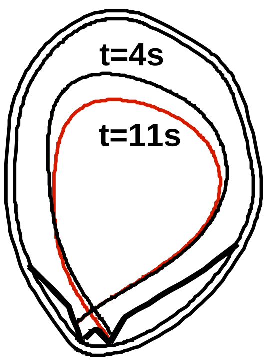
Stationary high-beta with β_N~3 for ~4τ_R at q_{95}~2.2

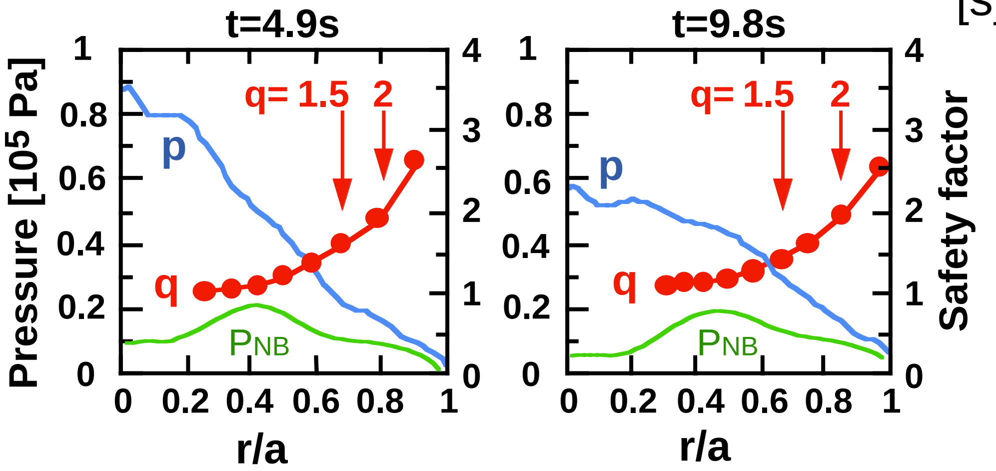
JT-60U

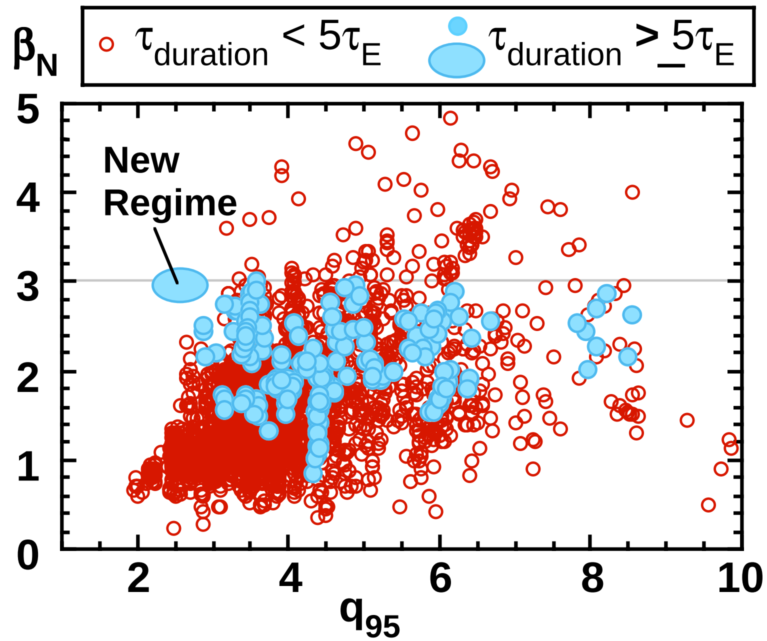


- β_N=3, β_t=2.4%
- $\beta_N H_{89PL}/q_{95}^2$~0.75

- Low-q in NB phase
- l_i ~ 0.8 (4.3s) ➞ 0.7 (4.9s)
  β_N / l_i ~ 4

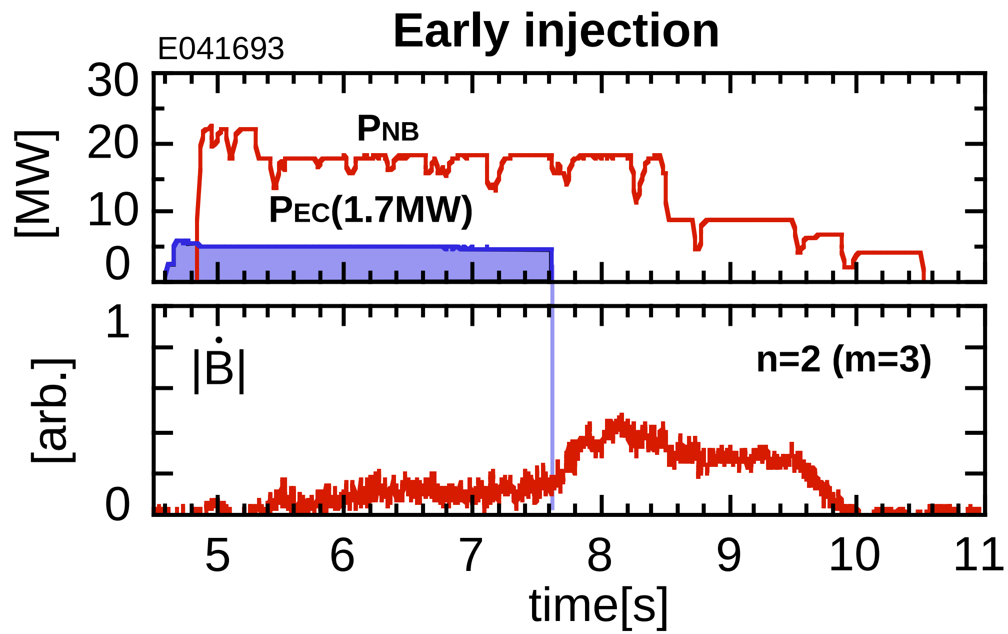


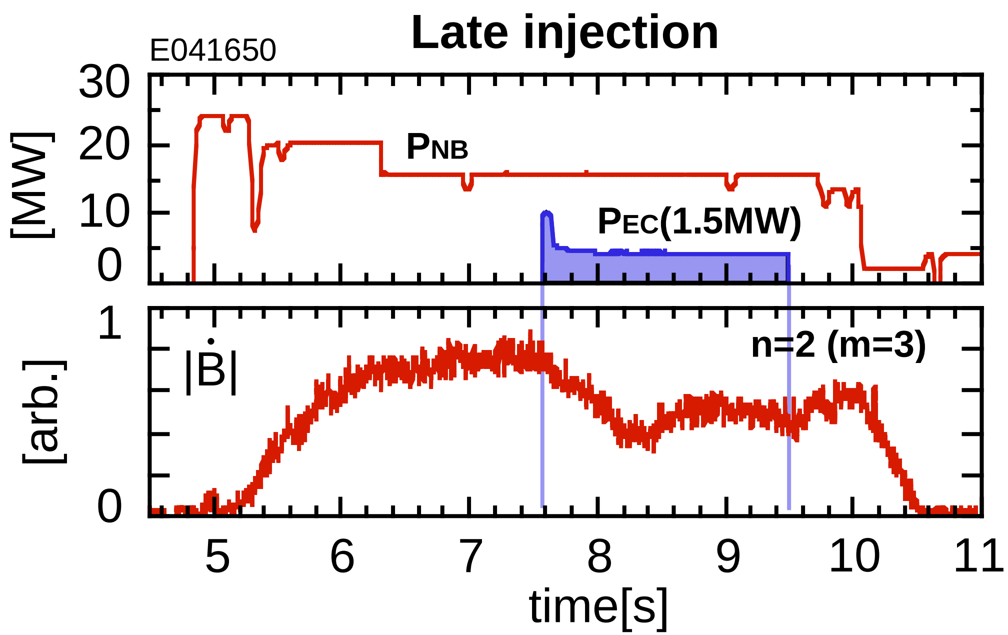


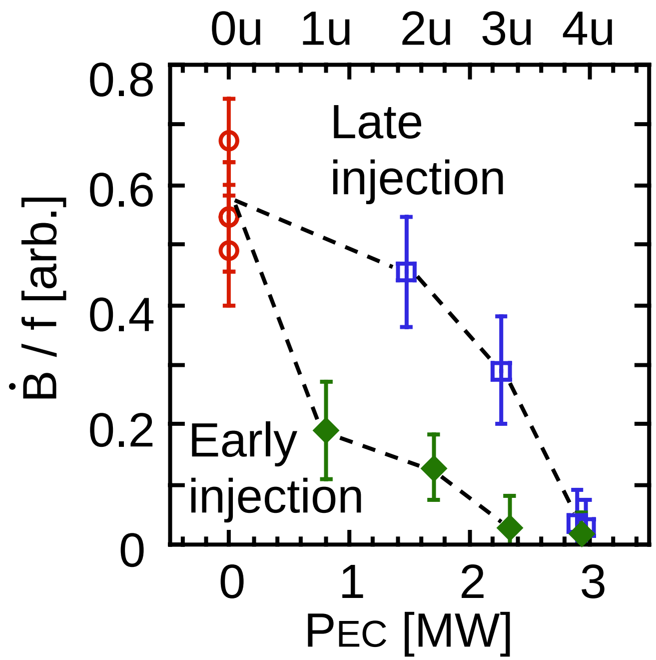


Early injection with fundamental O-mode EC wave

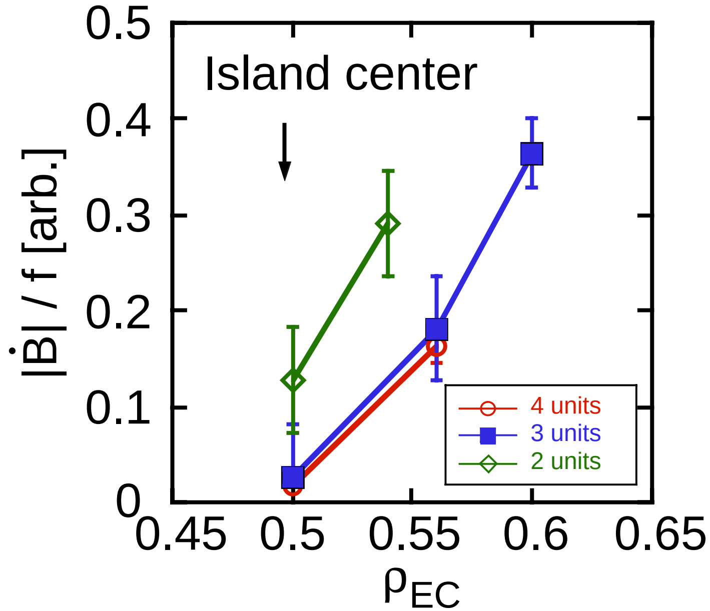
JT-60U







Ḃ/f is more efficiently suppressed by the early injection

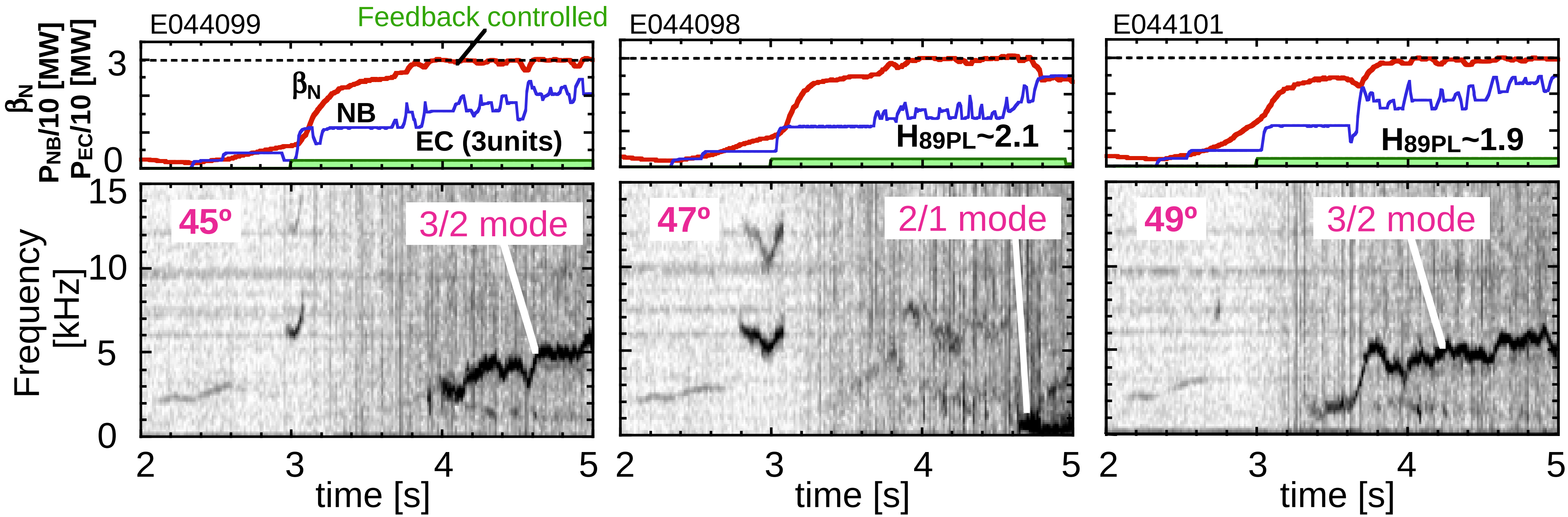


Precise adjustment of EC injection angle is required also in early injection.

K. Nagasaki et al., Nucl. Fusion **43** (2003) L7

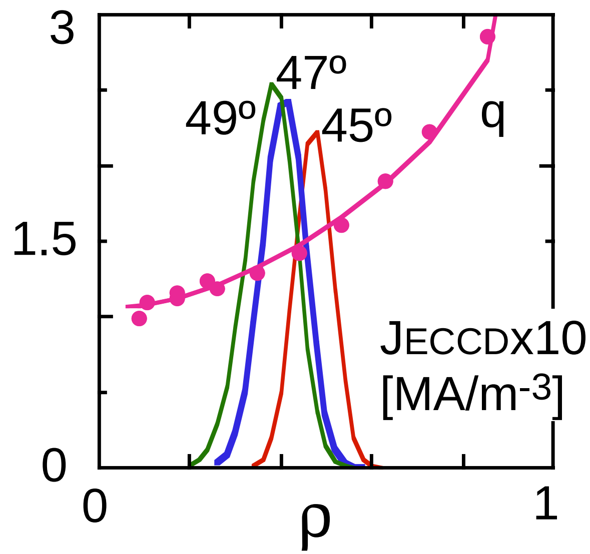
NTM stabilization with early ECCD in β_N~3 regime

JT-60U



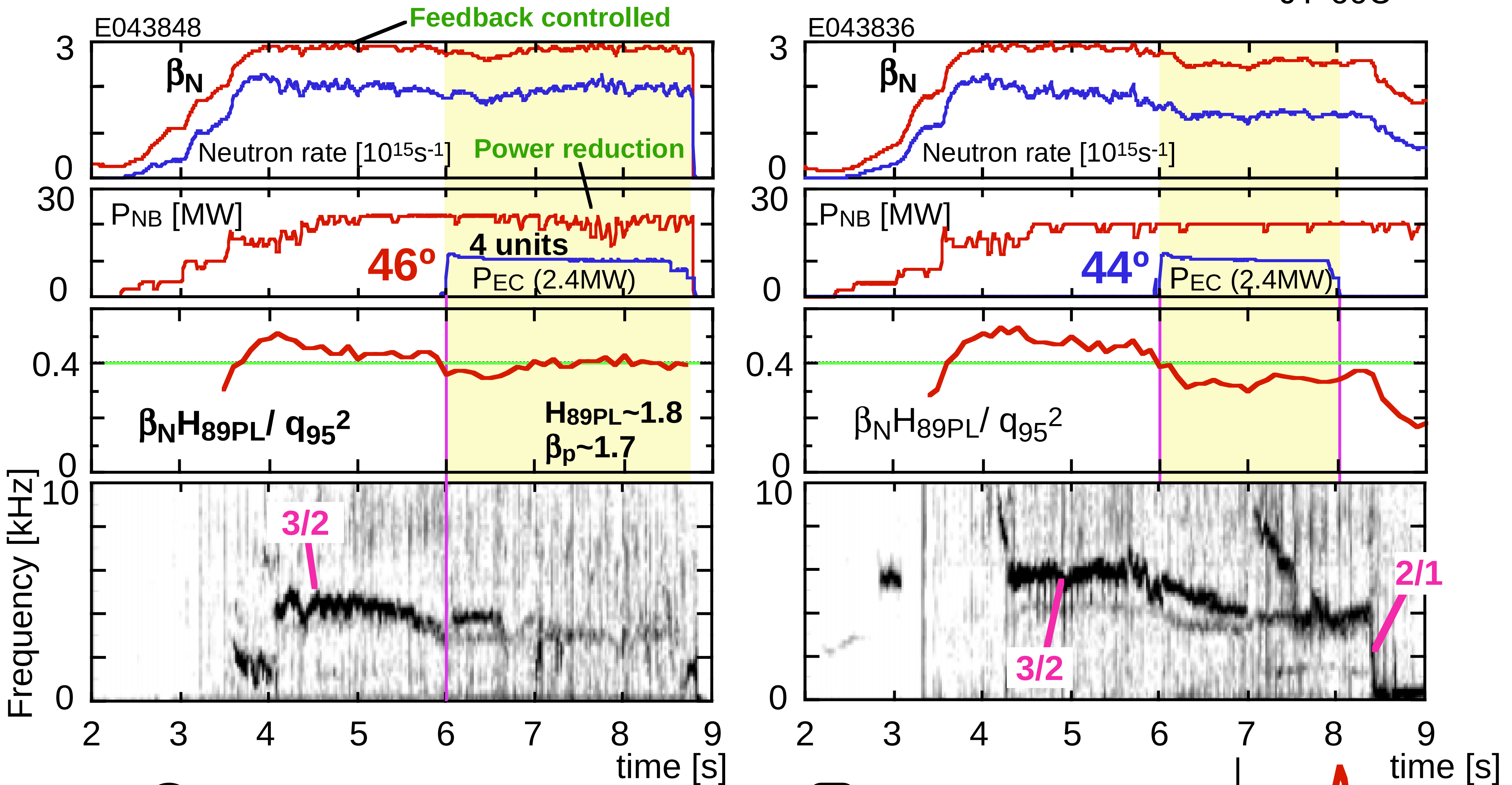
- Complete stabilization at β_N ~3 (β_p ~1.8)
  with smaller NB power than for late ECCD
- Confinement improvement by NTM stabilization
- Requirement for complete stabilization:
  - J_{ECCD}~J_{BS} at q=3/2
  - High accuracy of ECCD location

Same as 1st O-mode



Successful NTM stabilization in β_N~3 regime

JT-60U

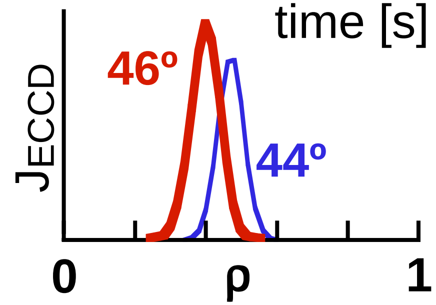


Successful

Recovery of β & H-factor

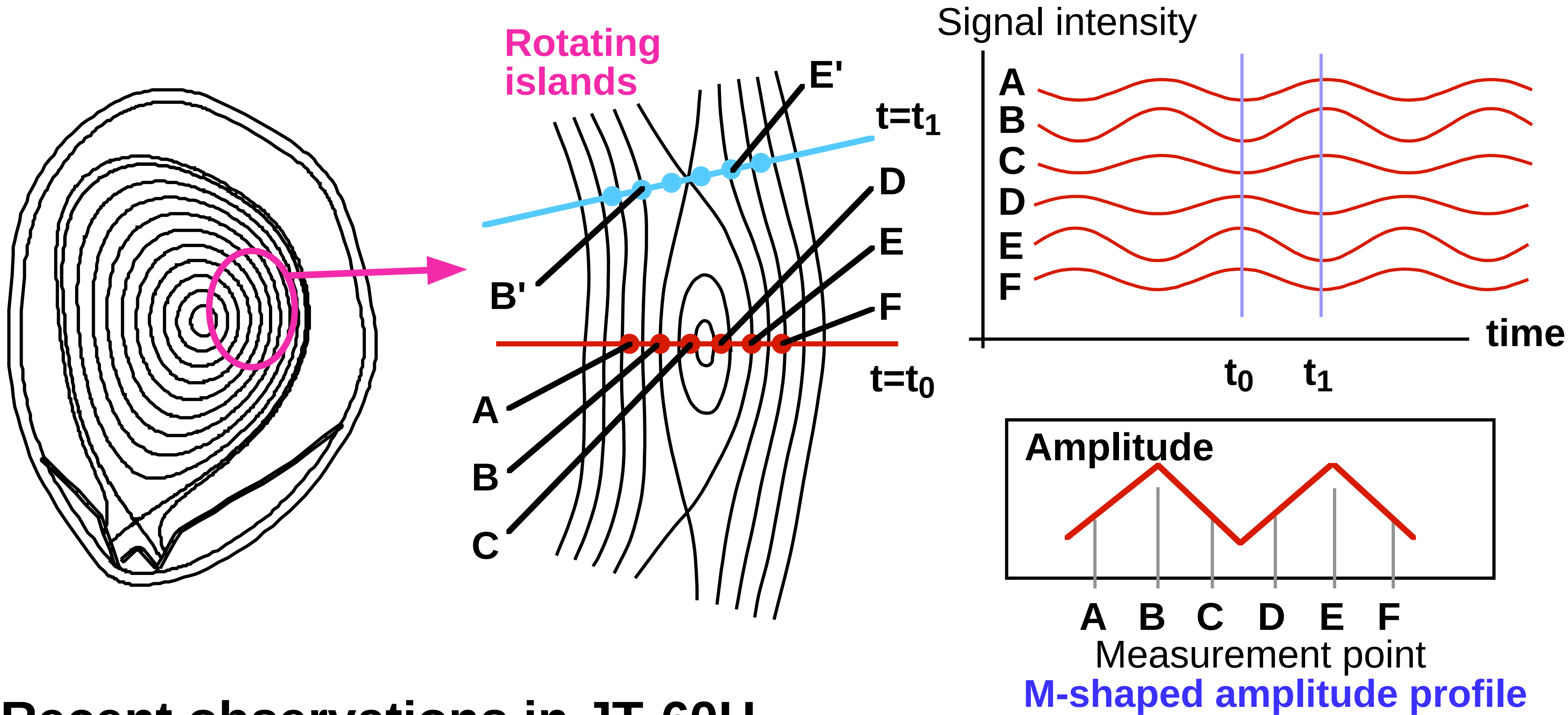
Unsuccessful

Misaligned ECCD



Detailed measurement of NTM structure

NTM: Magnetic island formation



Recent observations in JT-60U

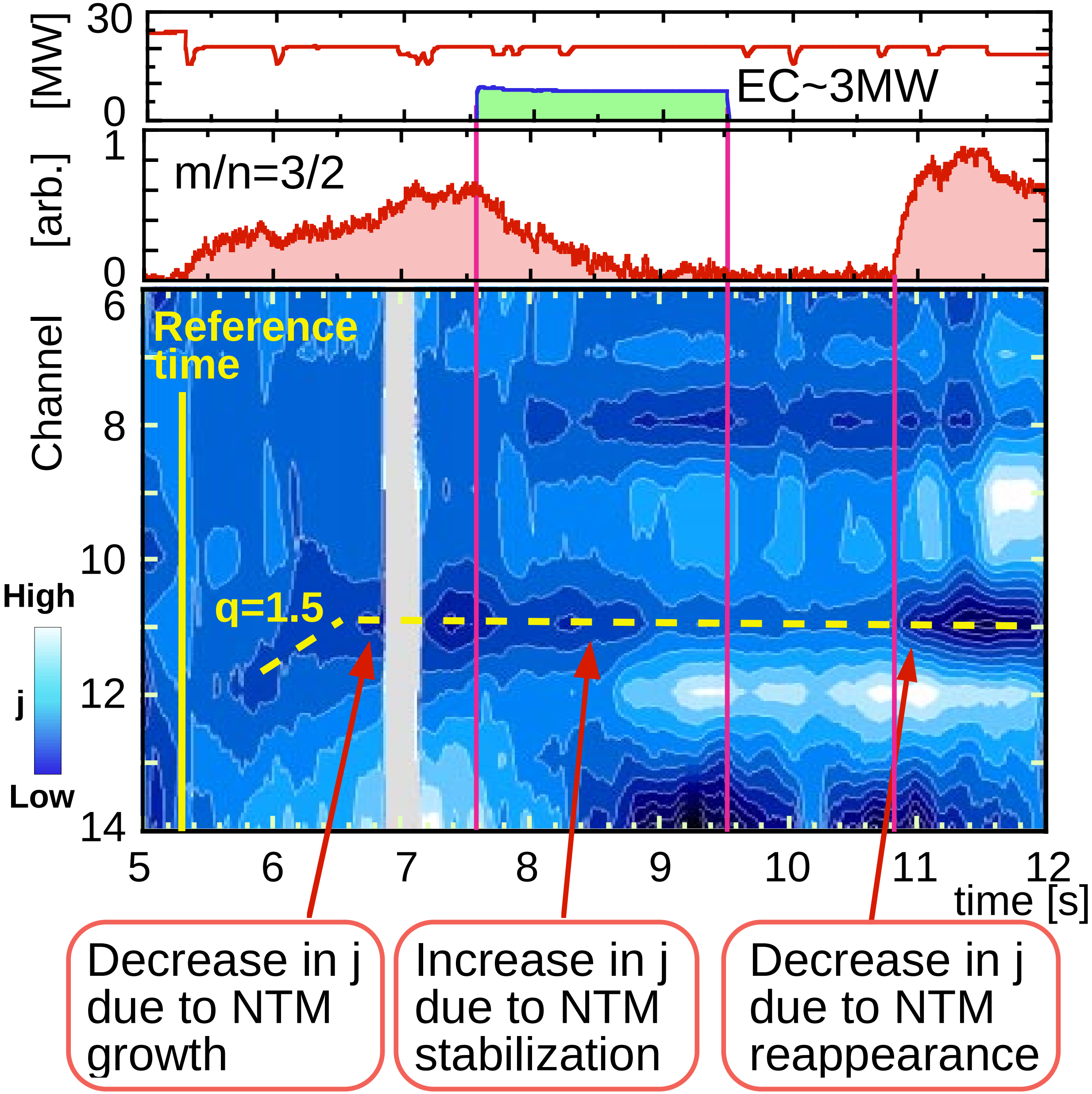
- Change in J(r) during NTM growth/stabilization
- NTM structure in $\tilde{T}_e$ during stabilization

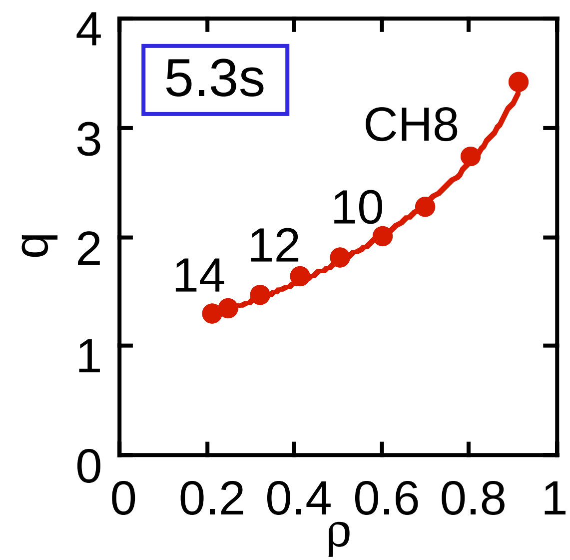
MSE

ECE

Localized change in current density has been observed during NTM growth/suppression

JT-60U



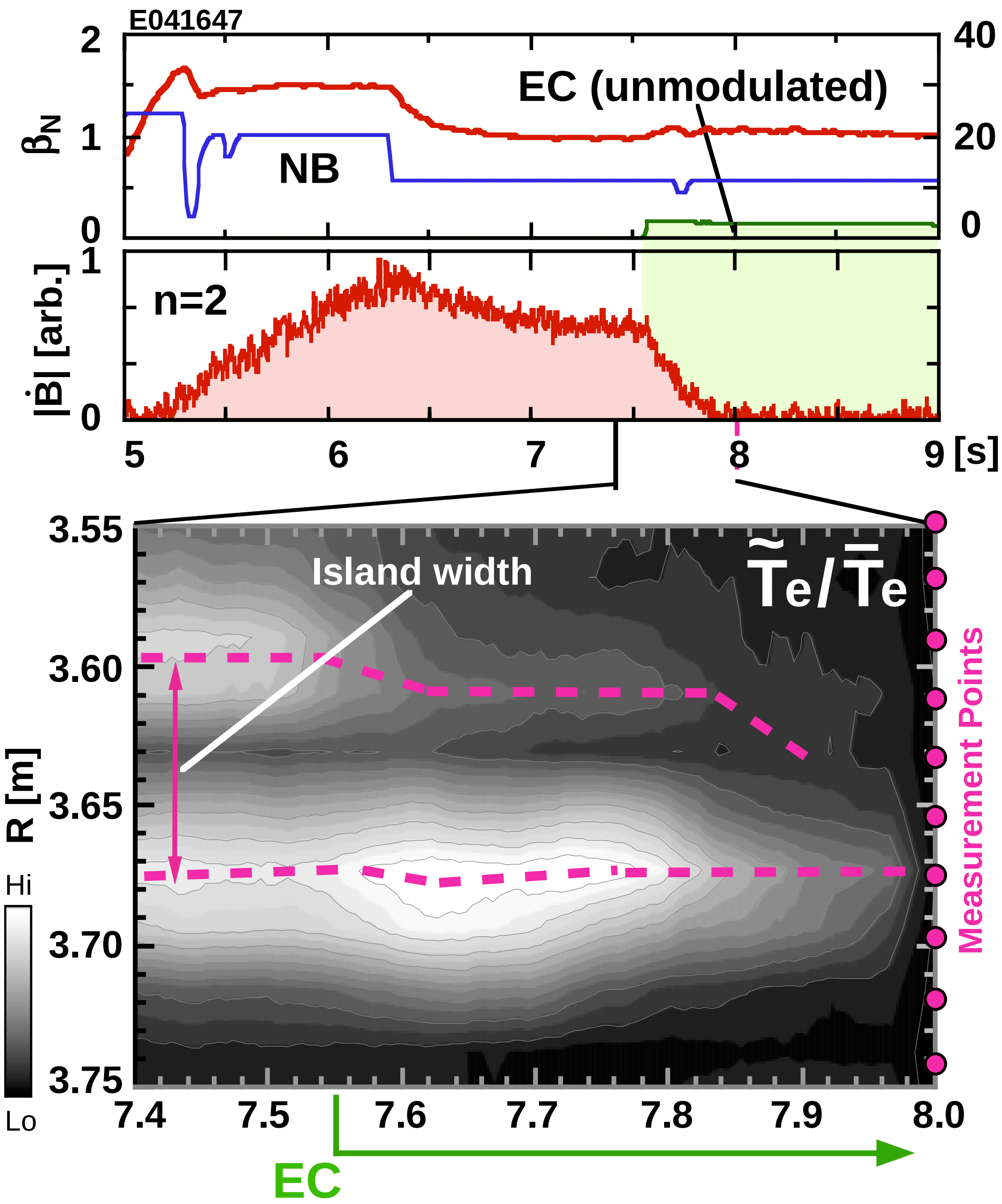


- If configuration & β ~ const, change in MSE signal = change in j(r)
  → direct measurement of δj

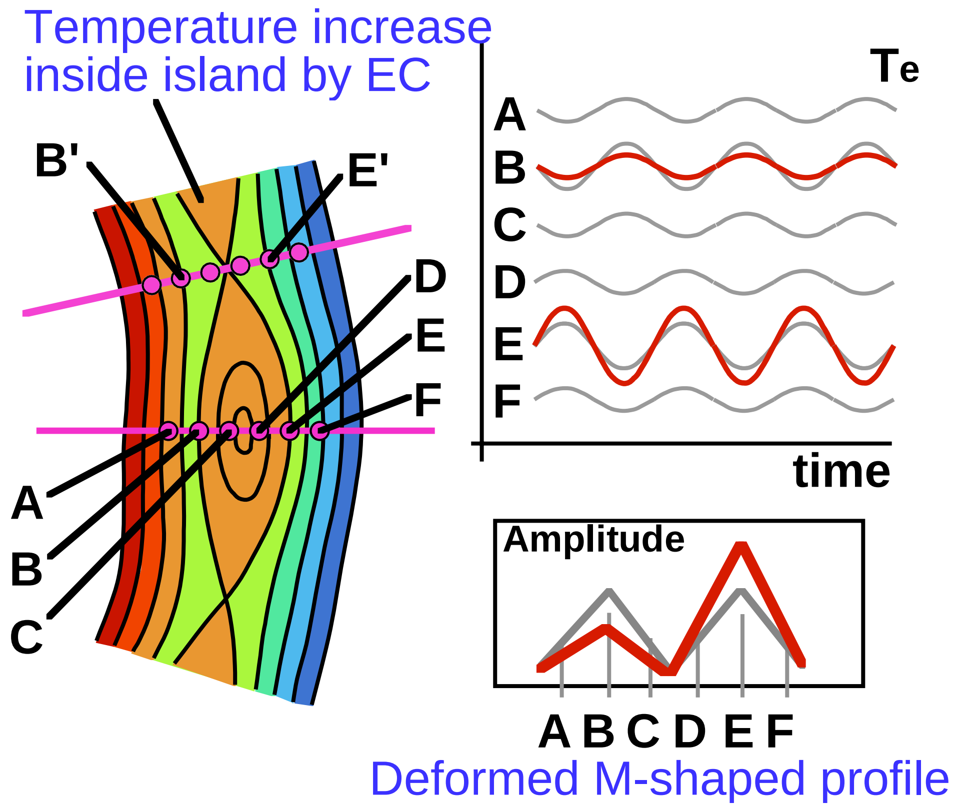
Decrease/increase in bootstrap current due to NTM growth/suppression

$\tilde{T}_e$ profile suggests temperature increase INSIDE island

JT-60U



Hypothesis



The hypothesis well explains

- Decrease at inner-half region
- Increase at outer-half region
- Fast response time (<< τ_R)
- No asymmetry for misaligned ECCD

Details are under investigation

Reduced heat transport inside the island in LHD

Estimation of $\chi_\perp$ from cold pulse propagation $\chi_\perp^{in}/\chi_\perp^{out}$ ~1/10

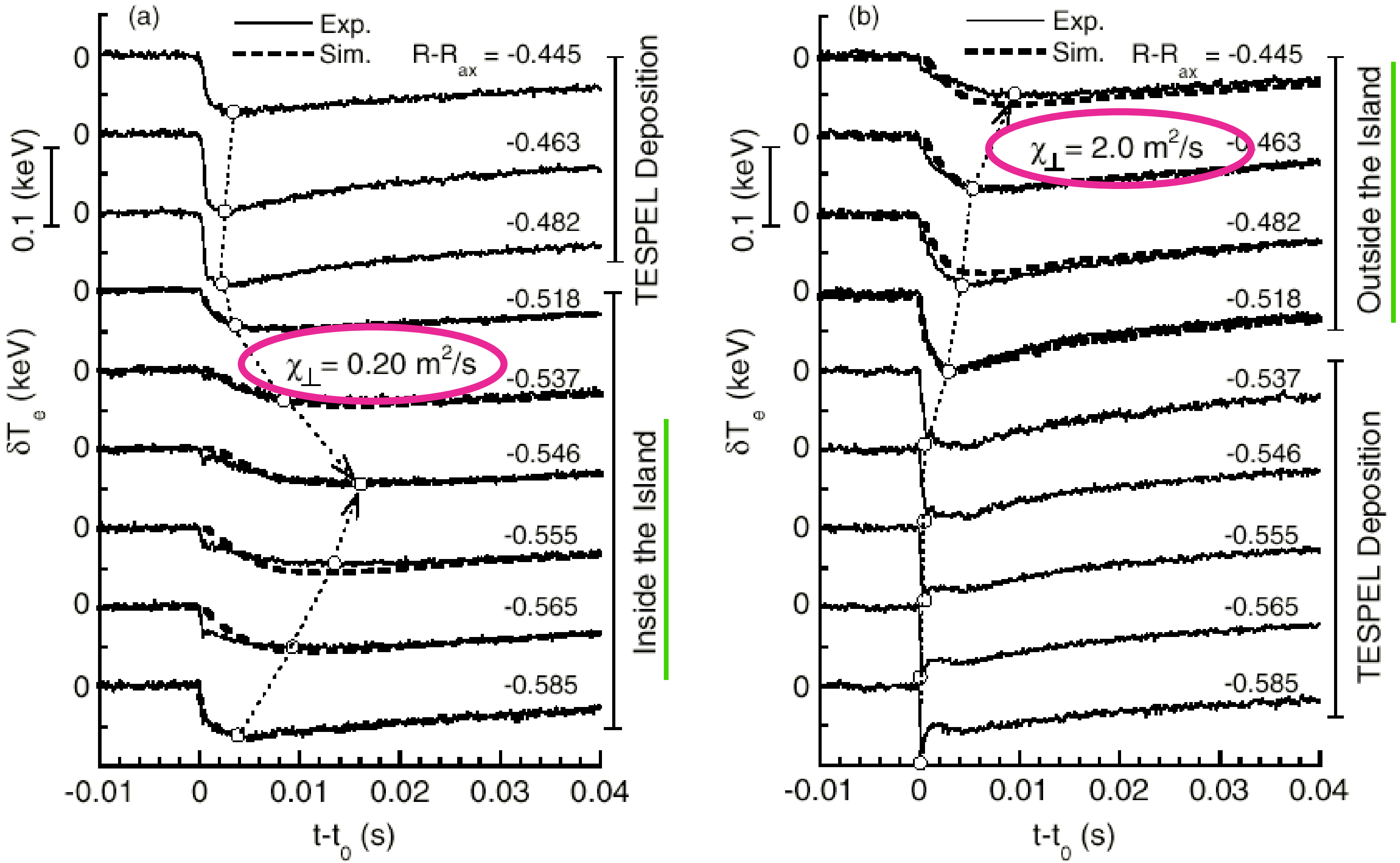
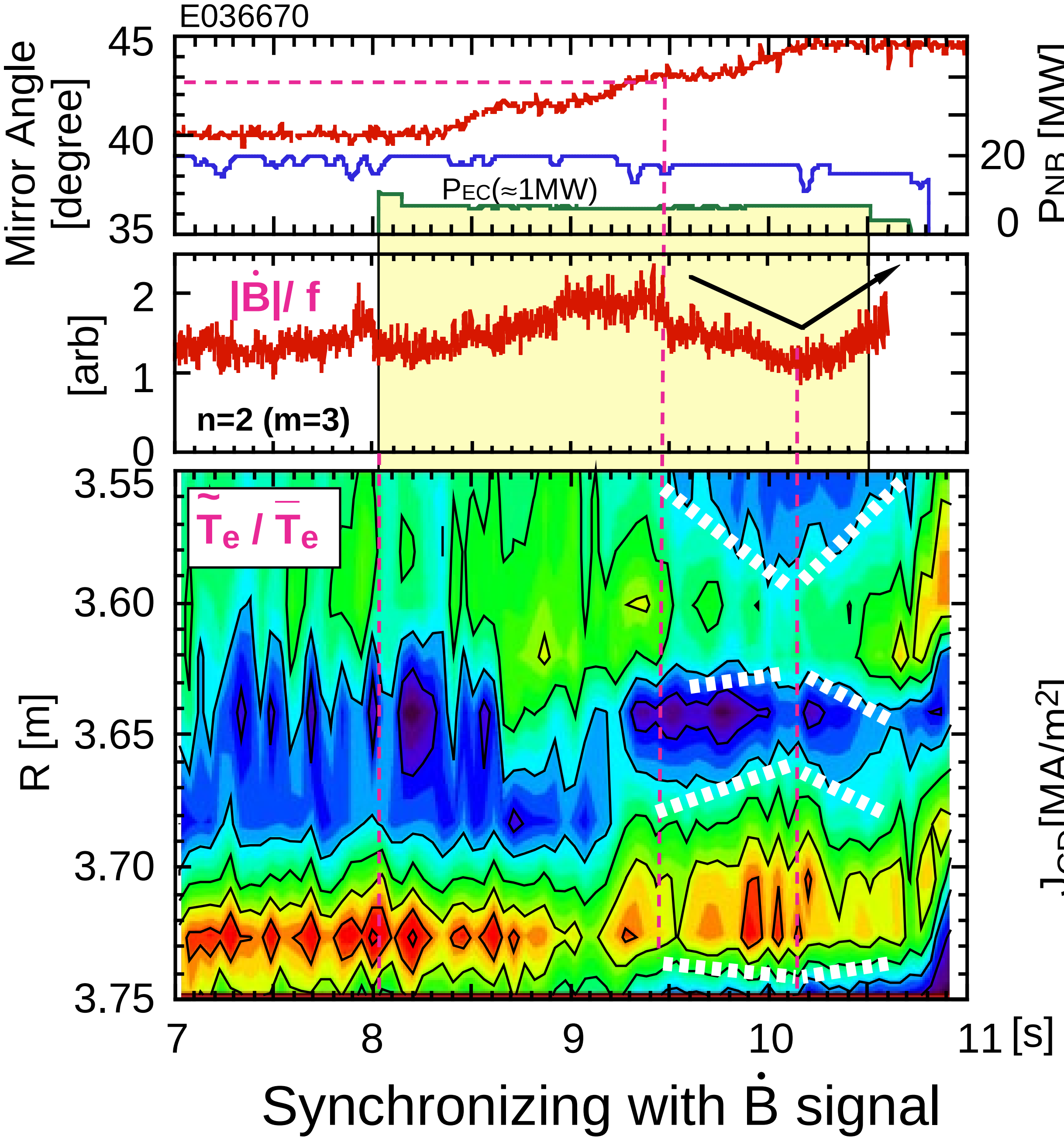


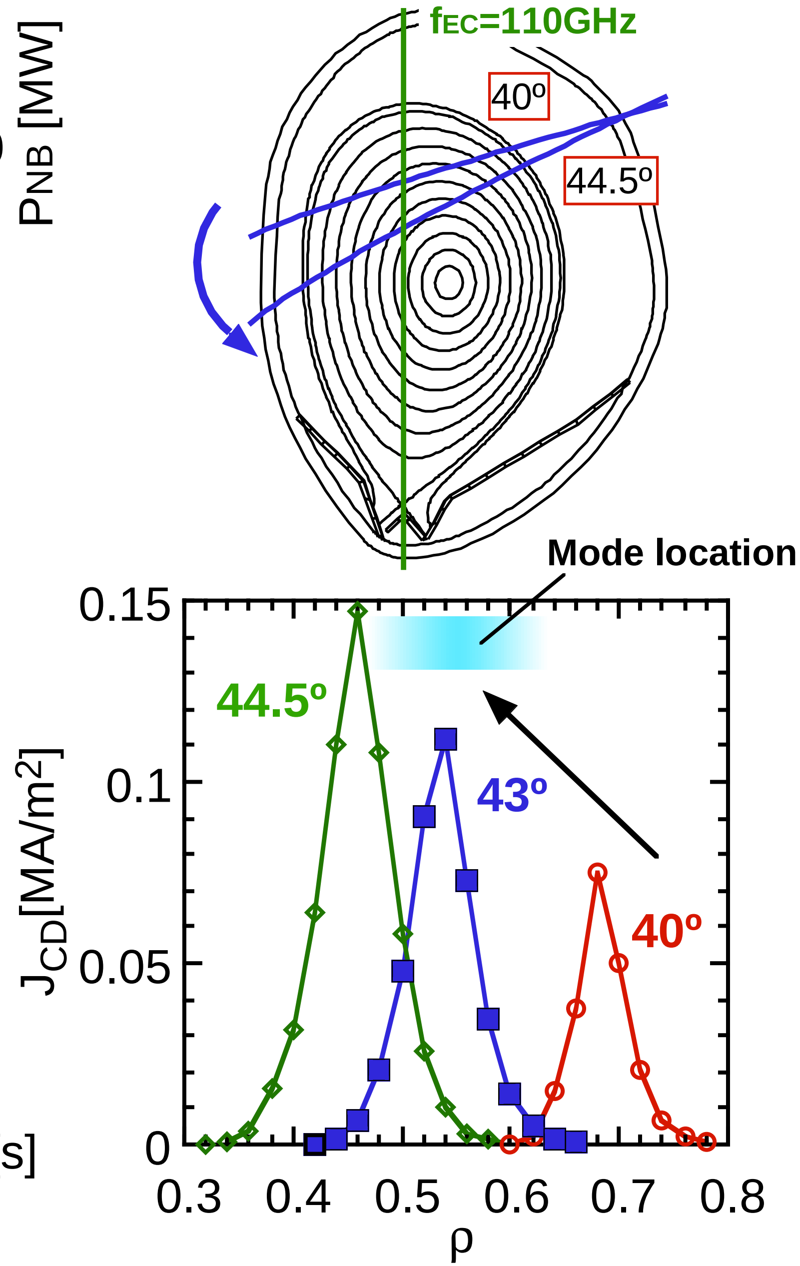
FIG. 3. Comparison of temperature perturbation between experiment and simulation. The time evolutions of the measured (sold line) and the simulated (broken line) temperature perturbation at different radii in the same discharges as (a) Fig. 1 and (b) Fig. 2, respectively.

S. Inagaki et al., Phys. Rev. Lett. 92 (2004) 055002

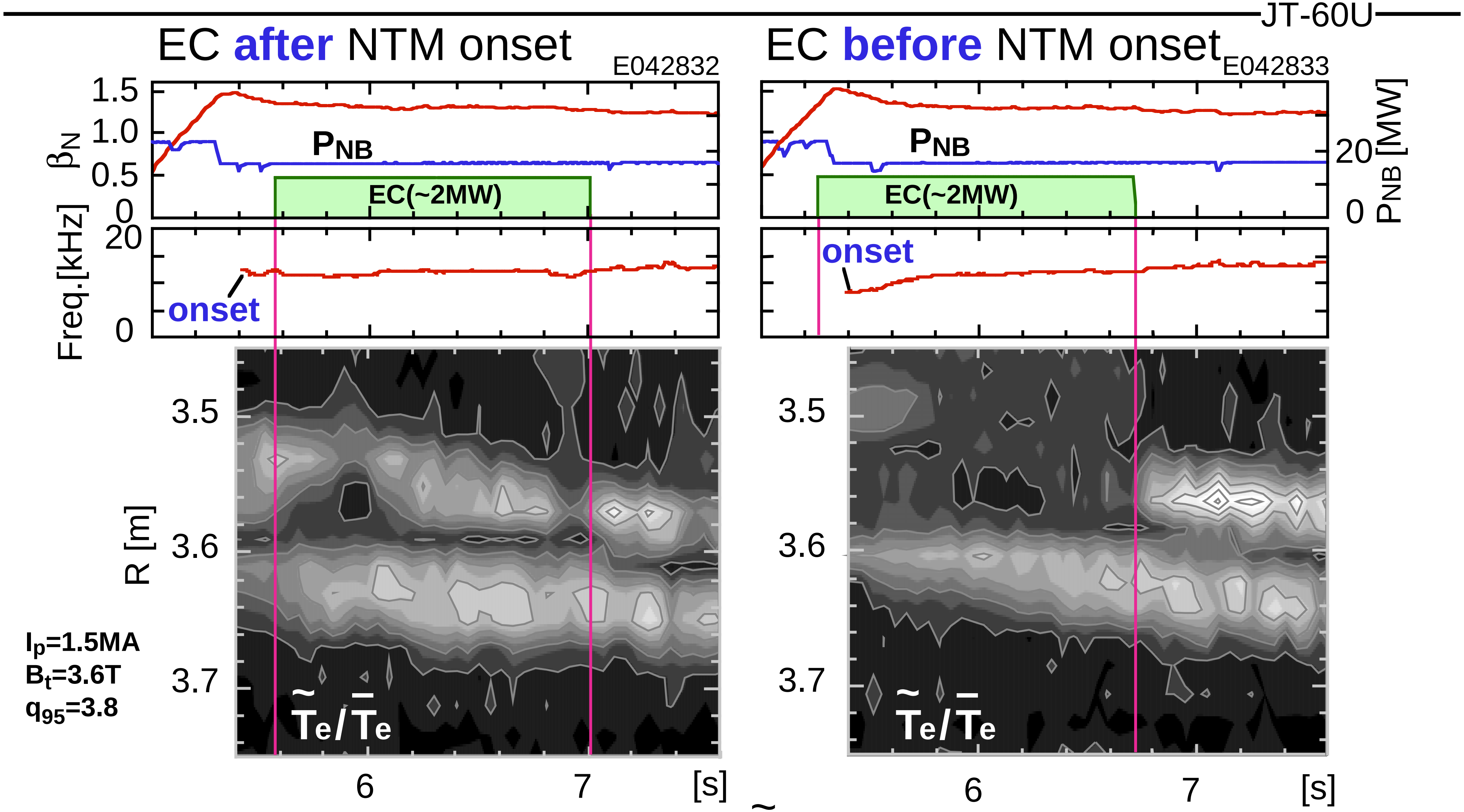
Similar asymmetry was observed during EC mirror scan.

JT-60U





EC before the NTM onset suggests more efficient deposition inside island.



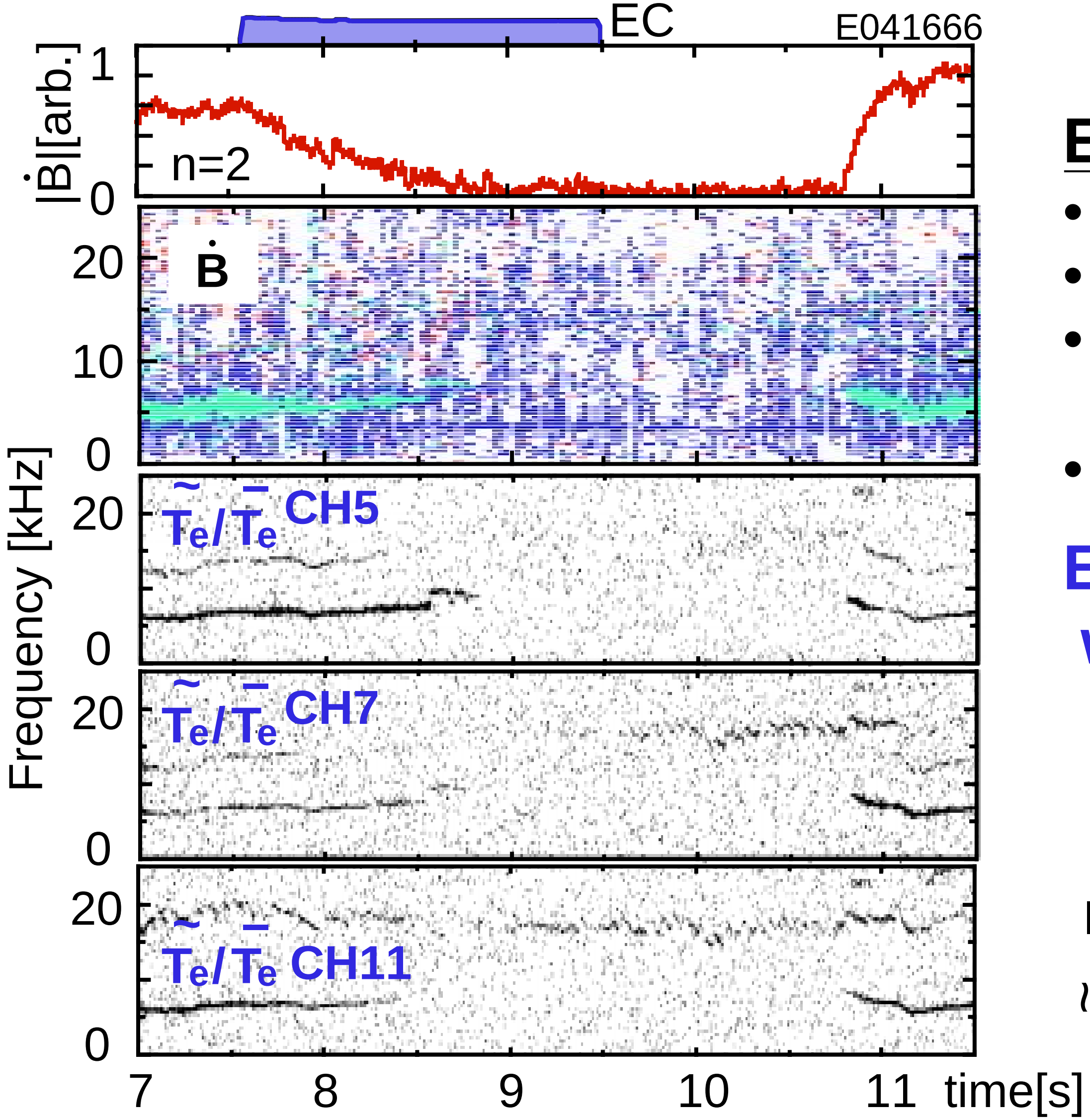
- Hypothesis leads to "One peak in $\tilde{T}_e$ = deposition inside island"
  → 'ECH/ECCD before NTM onset is more efficient'

Further investigation required

NTM onset physics is the most challenging

JT-60U

- 'NTM: Seed island formation by sawtooth and fishbone ➞ growth'
- However, NTM can appear without clear MHD event

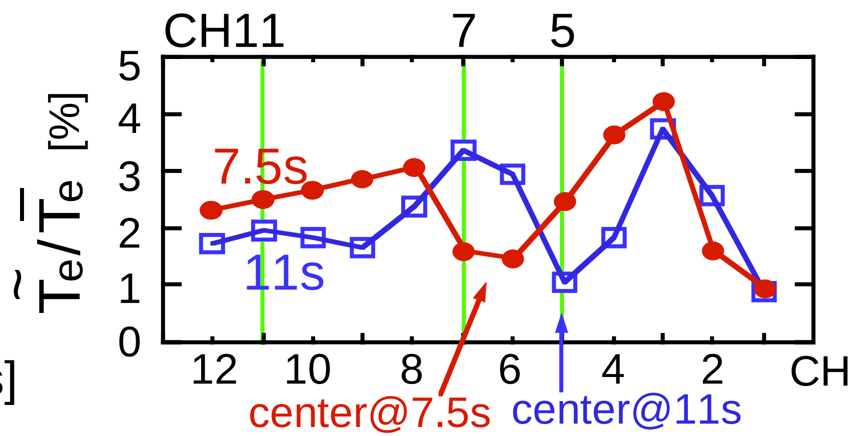


Spontaneous NTM

Example in JT-60U

- Reappearance of NTM at t=10.7s
- Constant NB power
- β_N~1.5 (7.5s) ➞ 1.67 (10.7s): small increase
- No sawtooth, no fishbones

Experimental & theoretical works required



Summary

Long-duration high-β_N discharge

- β_N=2.5 for ~**$10\tau_R$**, ~$80\tau_E$; β_N=1.9 for ~**$15\tau_R$**, >$100\tau_E$
- No NTM in long timescale at β_N<~2.5 Low ν^* & ρ^* regime

NTM suppression at β_N~3 regime

- NTM avoidance at q_{95}~2.3: **importance of p(r) & q(r)**
- NTM stabilization by early ECCD:
  f_{BS}~f_{ECCD} for 2X & 1O; **reduced EC power for stabilization**
- Confinement improvement & stationary sustainment
  by NTM stabilization (β_N~2.9, H_{89PL}~1.8)

Measurement of NTM structure

- Decrease/ increase in J(r) during NTM growth/ suppression
- Asymmetry in δT_e during NTM stabilization
  Hypothesis: 'temperature increase inside island'