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Steady State High β_N Discharges and Real-Time Control of Current Profile in JT-60U

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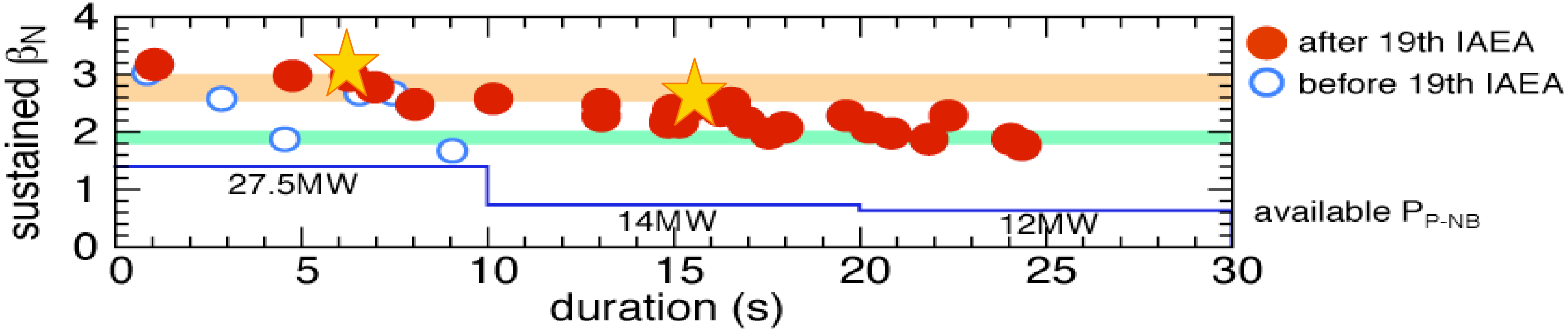
Introduction

- Current profile is essential in stability of tokamak.
  - j(r)change by j_{BS} or j_{CD} ➔ appearance of instability
    steady j(r) w/o instability must be realized.
  - appropriate current profile for higher β_N
  - realization of controlled j(r).

- High β_N with steady j(r) has not been achieved at low ρ_i^*, ν_e^* regime close to ITER.

Outline of this talk

JT-60U



- High β_N ~2.5 with steady current profile at low ρ_i^*, ν_e^* regime.
  - $\rho_i^* \sim 6\text{x}10^{-3}$ ($3\rho_i^*{}_{ITER}$), $\nu_e^* \sim 6\text{x}10^{-2}$ ($3\nu_e^*{}_{ITER}$)
  - “long-pulse modification” in 2003
- Increase of quasi-steady β_N up to 3.
  - avoiding NTM optimizing q(r)
- Real-time control of current profile for “controlled” steady high performance plasma.
  - real-time evaluation of q(ρ) using MSE
  - CD location control by $N_{//}$ control of LH waves

Evolution of current profile was found to dominate sustainable period at high β_N.

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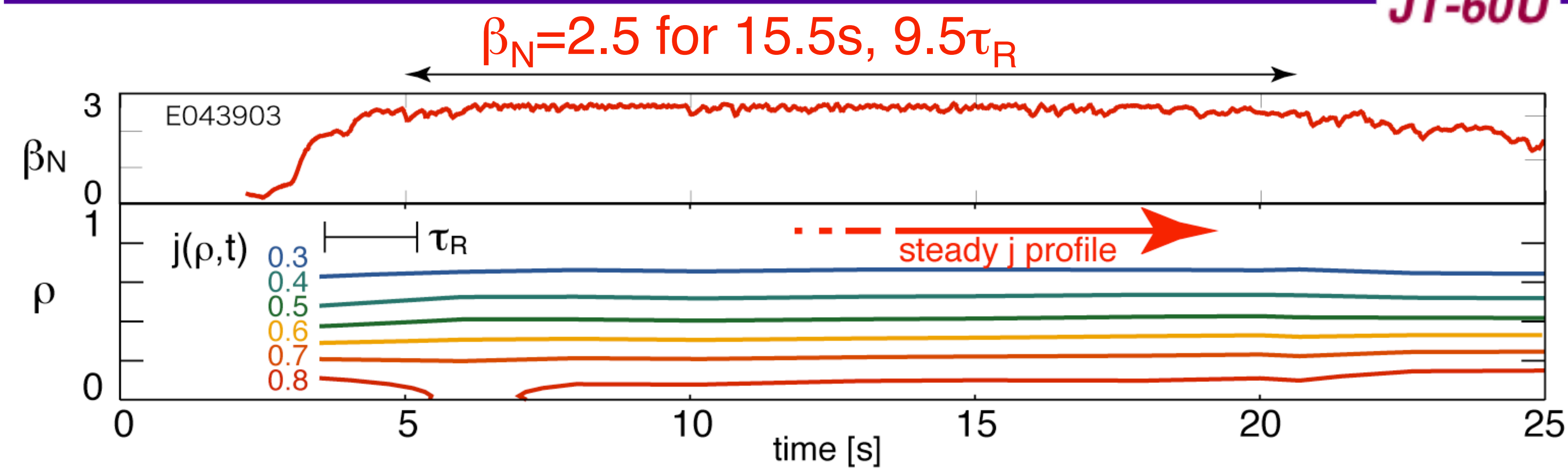

- NTM appeared after 6.5s(3.6τ_R) of β_N=2.7 sustainment.
- Gradual relaxation of Ohmic field changed j(r).
- The sustained period of 6.5s was not enough for j(r) relaxation.
- Now, β_N=2.5 for 15.5s (9.5τ_R); current profile is in steady state.
  ⇨No NTM will appear later.

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

Sustainment of $H_{89P}\beta_N/q_{95}^2>0.4$ for 15.5s, exceeding ITER standard scenario(Q=10).

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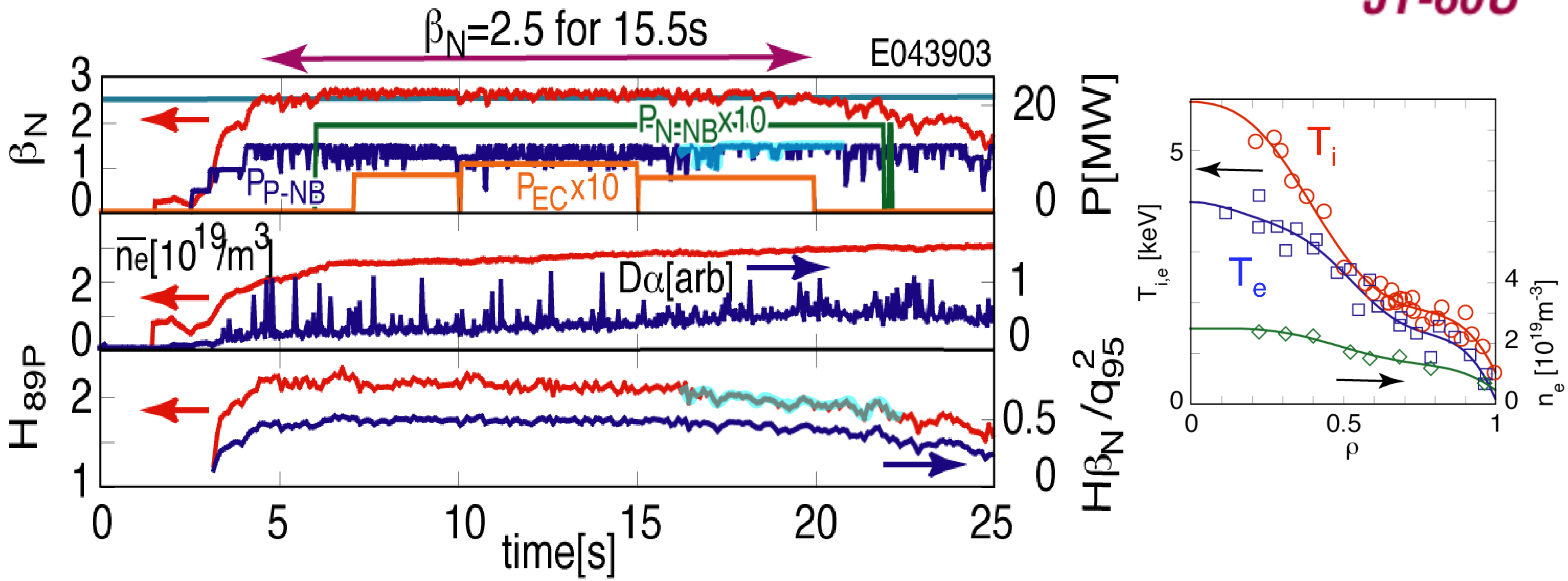

- β_N~2.5 sustained for 15.5s=9.5τ_R in high β_p H-mode plasma
  - H_{89P}=2.3-1.9, $H_{89P}\beta_N/q_{95}^2$=0.5-0.4, q_{95}~3.4, f_{GW}~0.6-0.8, f_{BS}=0.39
  - Fine tuning of stored energy FB by P-NBs.
  - Duration limited by heating capability, not instability (no NTM).
- Confinement degraded with n_e due to enhanced recycling.

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β_N=3 was sustained for 6.2s (4.1τ_R) at low q_{95}=2.2 weak shear plasma.

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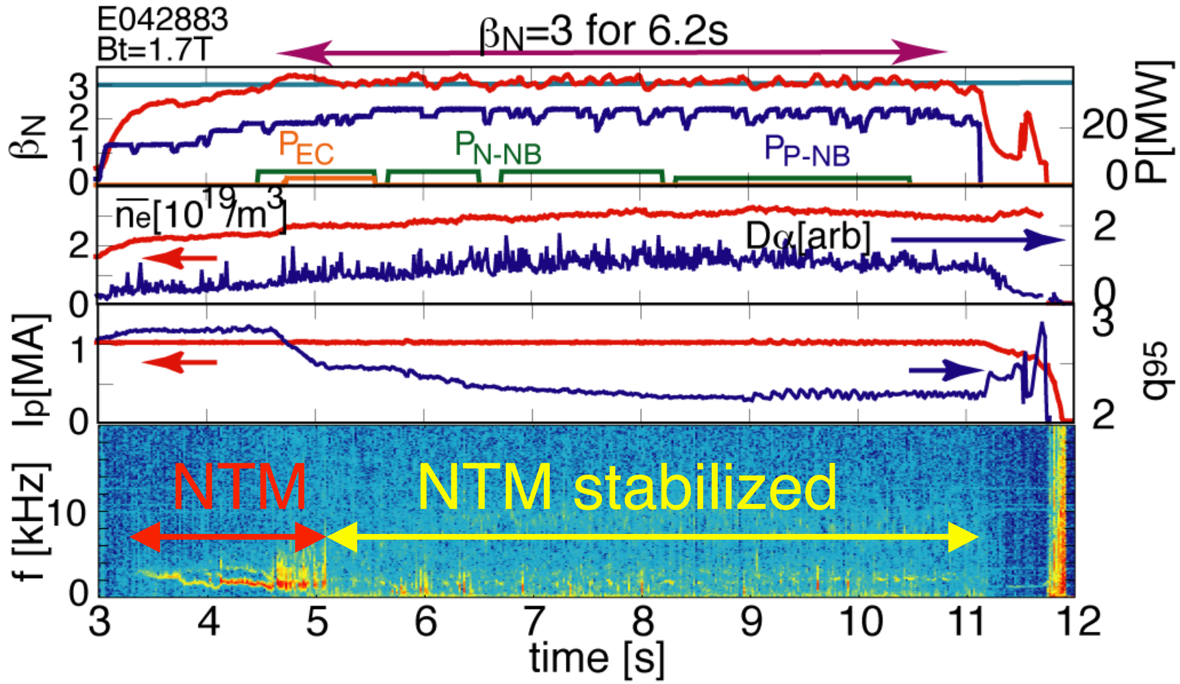
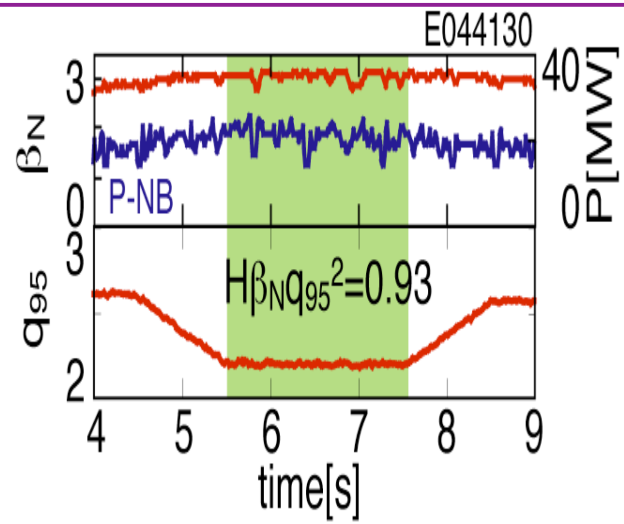
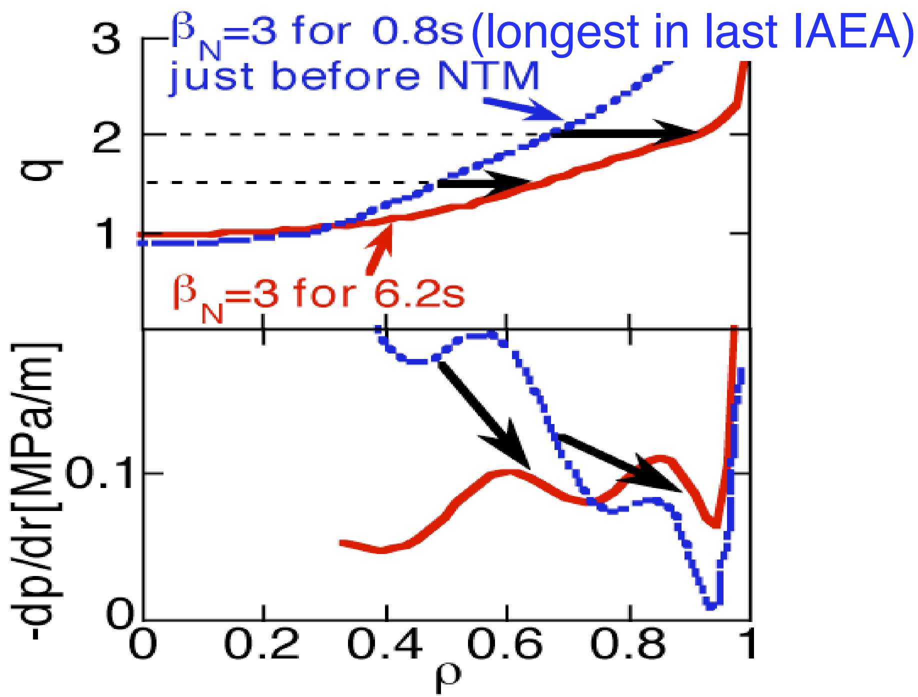


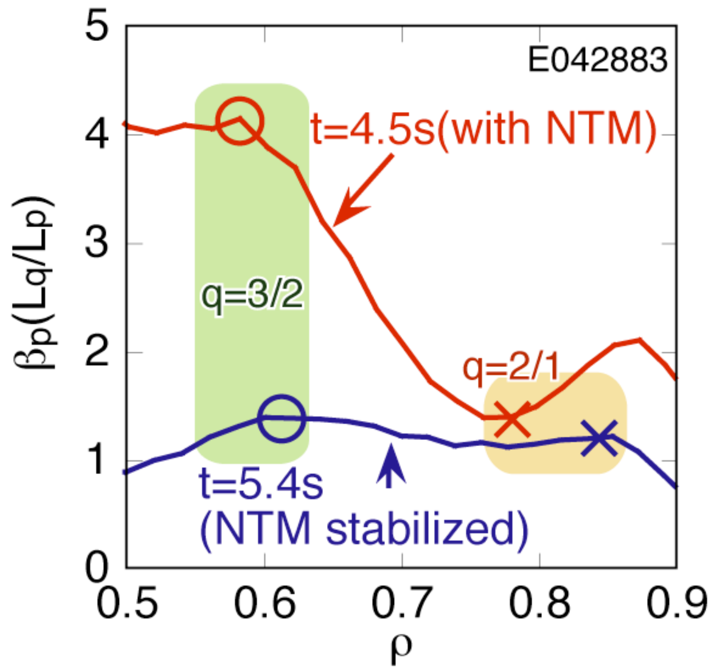


Further increase of $H_{89P}\beta_N/q_{95}^2$ without NTM

- Decrease of q_{95} down to 2.2 stabilized NTM after t=5.1s, without NTM stabilization by EC waves.
- No sawtooth activity even at the low q_{95}.
- β_N=3 for 6.2s, 4.1τ_R limited by heating capability (23-25MW).
- $H_{89P}\beta_N/q_{95}^2$ reached 0.75 at n_e/n_{GW}~0.6.

Misalignment of rational surfaces to steep pressure gradient stabilizes the NTM.





- Control of q=m/n location was essential in stabilizing NTM.
  - Decrease in q_{95} ⇨ Rational surfaces (m/n=3/2, 2/1) move outward (small ∇p).
  - Decrease of $\beta_p(L_q/L_p)$: a measure of bootstrap current destabilization term

⇨ q(r) control

Multi-channel MSE & $N_{//}$ controlled LHCD are keys in real-time q(r) control.

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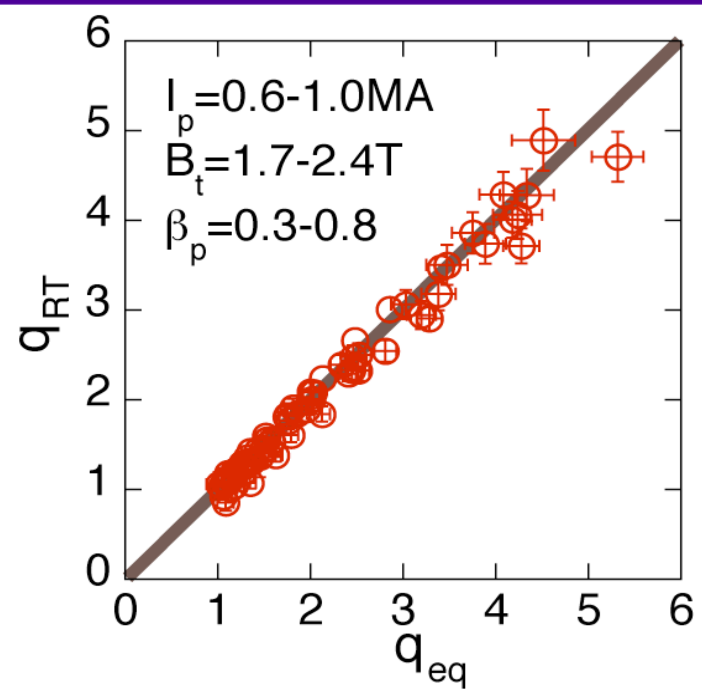

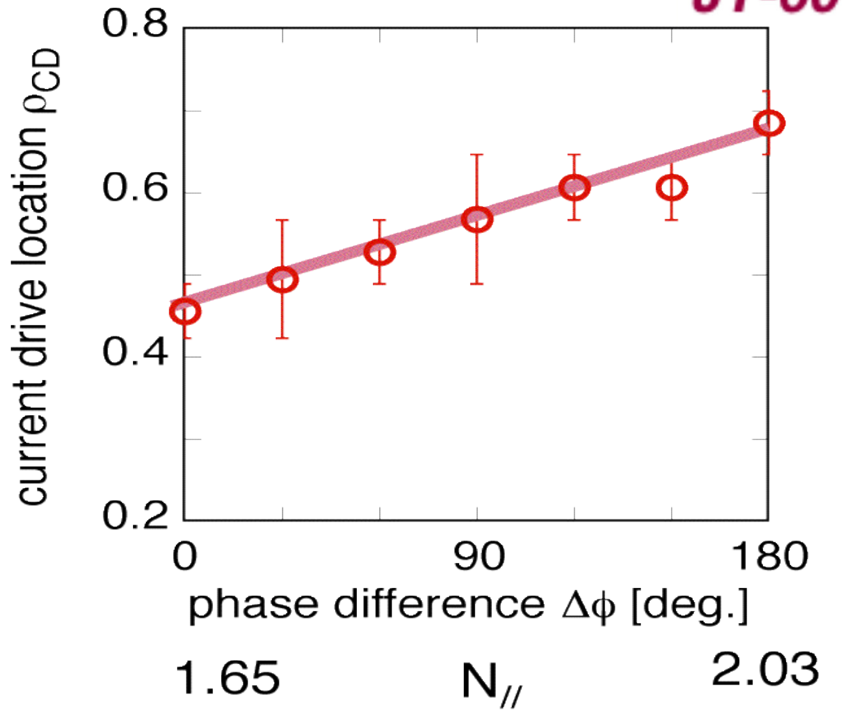

- High accuracy real-time q(r) using MSE(9ch) within 10ms
  - applicable to wide plasma parameters

- Direct control of LHCD location by $N_{//}$
  - LH power is also controlled to fix LH driven current.

q profile control (q(0)~1⇨1.3) was demonstrated.

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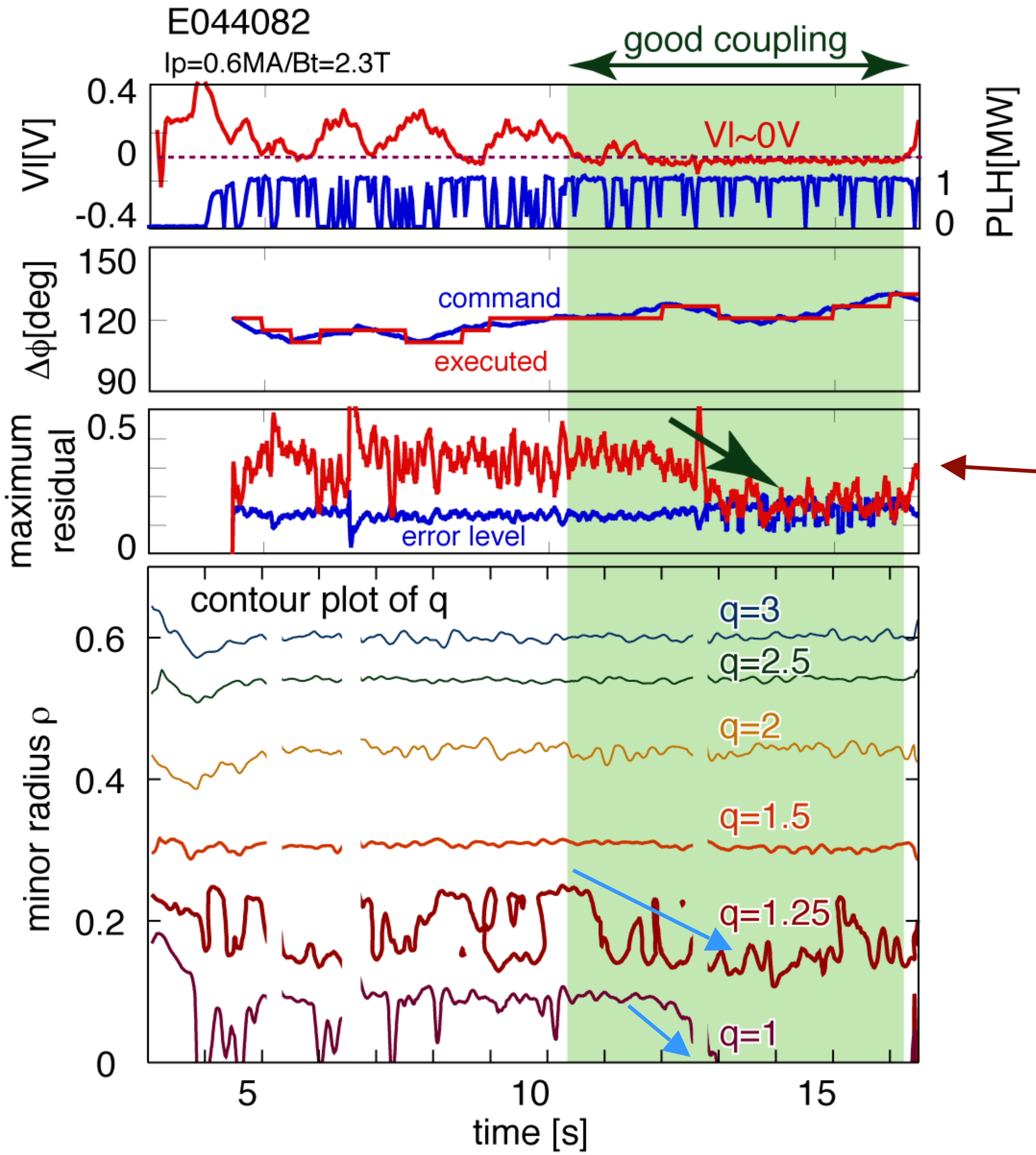

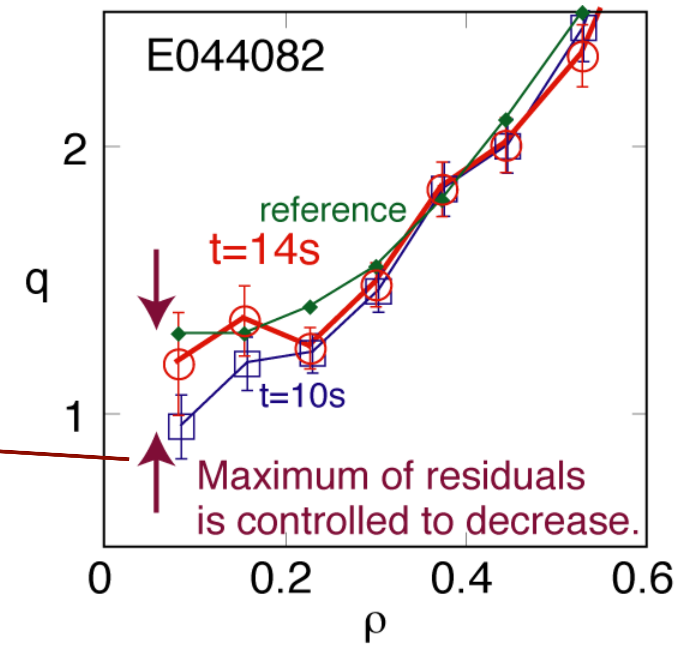

- Δϕ was controlled.
- q(r) approached to the reference at t=13s, and was sustained for 3s.
  - $n_e=0.5x10^{19}m^{-3}$

Summary

- **High β_N=2.5 sustained for 15.5s (9.5τ_R) with steady current profile in low ρ_i^*, ν_e^* regime close to ITER.**
  - Evolution of j(r) was found essential in sustainment of high β_N; NTM appeared even after sustainment for 3.6τ_R.
- **Appropriate current profile raised sustainable β_N.**
  - β_N=3.0 was maintained for 6.2s(4.1τ_R) at low q_{95}=2.2 regime.
  - Misalignment of rational surfaces and steep pressure gradient stabilized NTM.
- **Real-time control system of q(r) was developed using MSE and $N_{//}$ control of LHCD.**
  - Real-time calc. method of q(r) was developed. The result agrees with that by equilibrium calc.
  - The system raised center q to 1.3, and sustained q(r) for 3s.