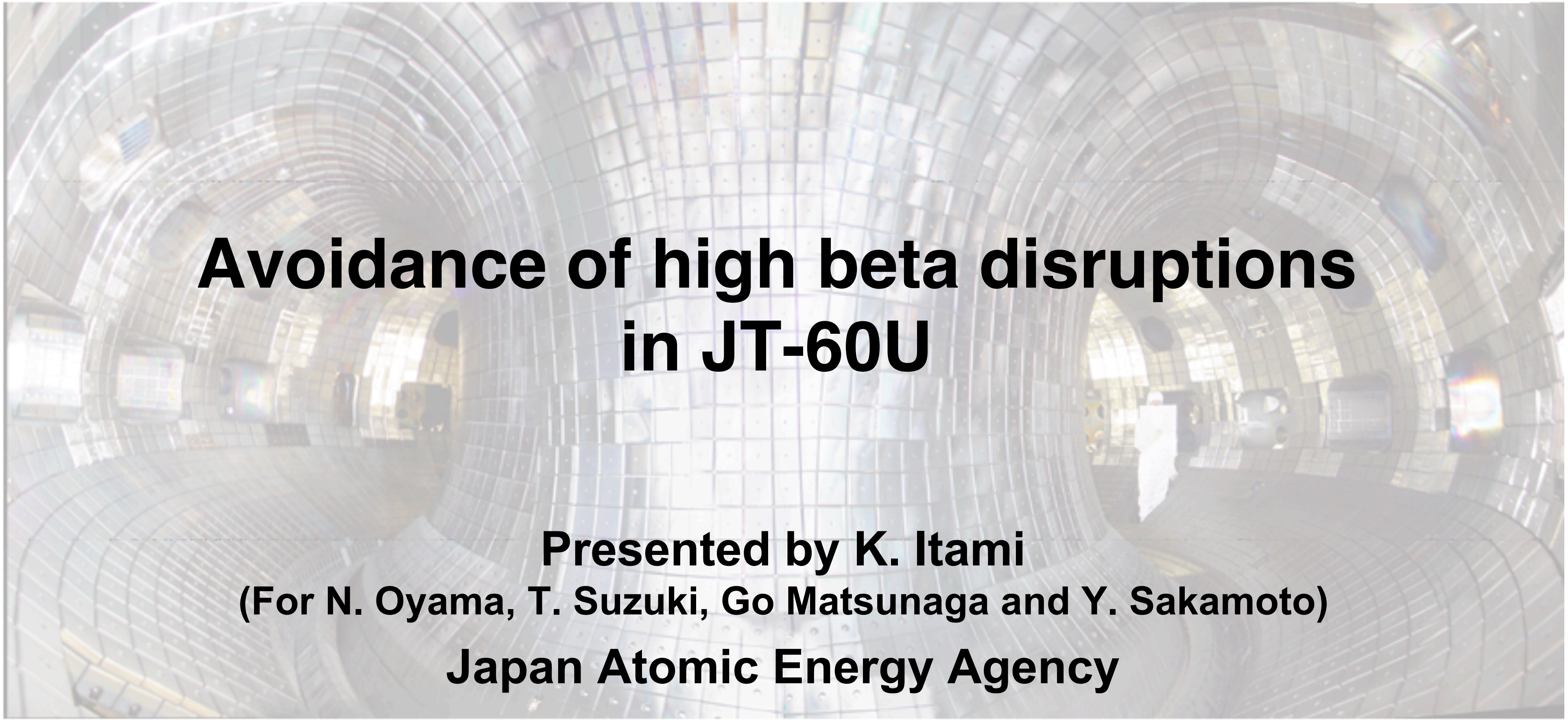


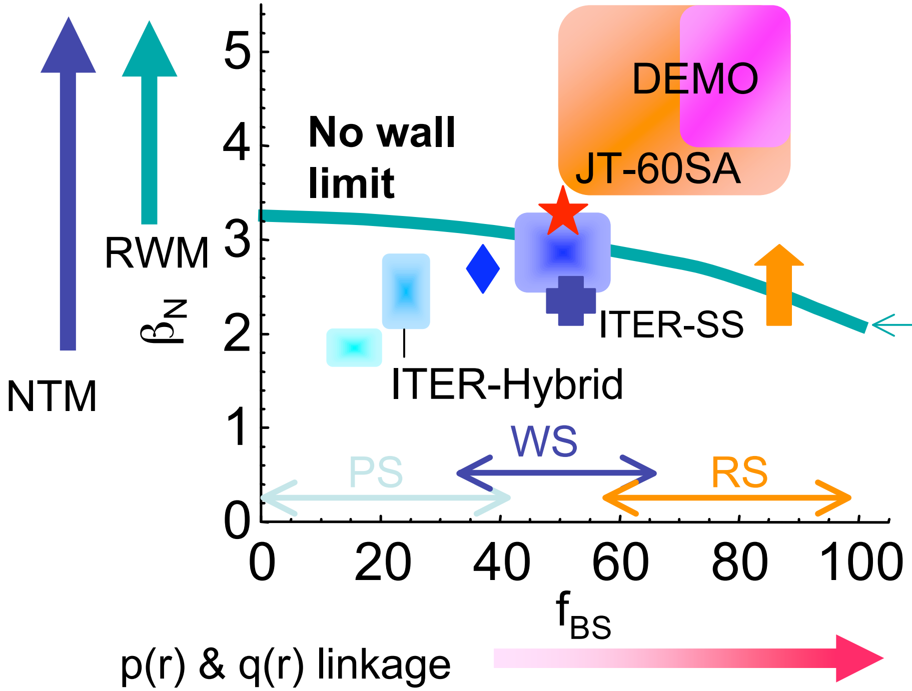
Avoidance of high beta disruptions in JT-60U

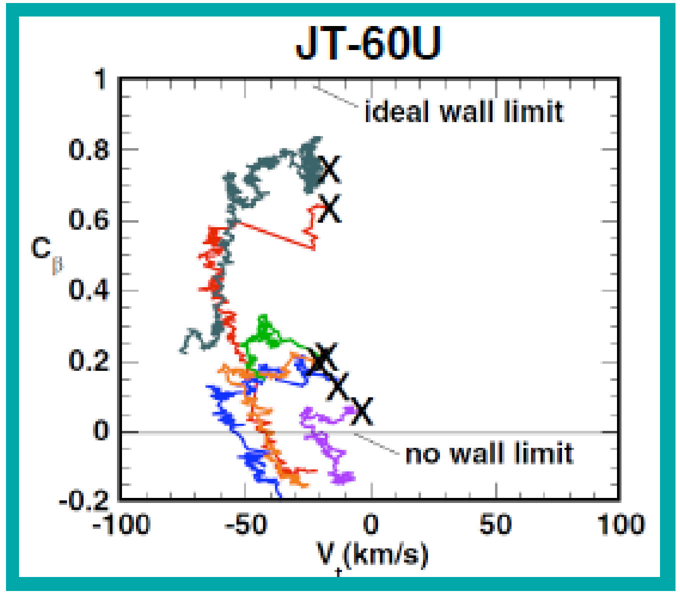
Presented by K. Itami
(For N. Oyama, T. Suzuki, Go Matsunaga and Y. Sakamoto)
Japan Atomic Energy Agency

US-Japan Workshop on MHD Control, Magnetic Islands and Rotation, Austin, U.S.A. , Nov. 23, 2008

Avoidance of high β_N disruption was essentially important to extend Avanced Tokamak plasma research in JT-60U.

JT-60U





M. Takechi et al., PRL 98, p.055002(2007)

- ITER Hybrid scenario oriented
  - ◆ High $\beta_N H_H$ in long hybrid discharge with NTM-free plasma profiles
- ITER SS scenario oriented
  - ✚ Formation of fully non-inductive current profile in steady state
  - ★ Long sustainment of high β_N above no wall limit
- DEMO oriented
  - ⬆ RS plasmas with both high β_N and high f_{BS} toward DEMO

Outline

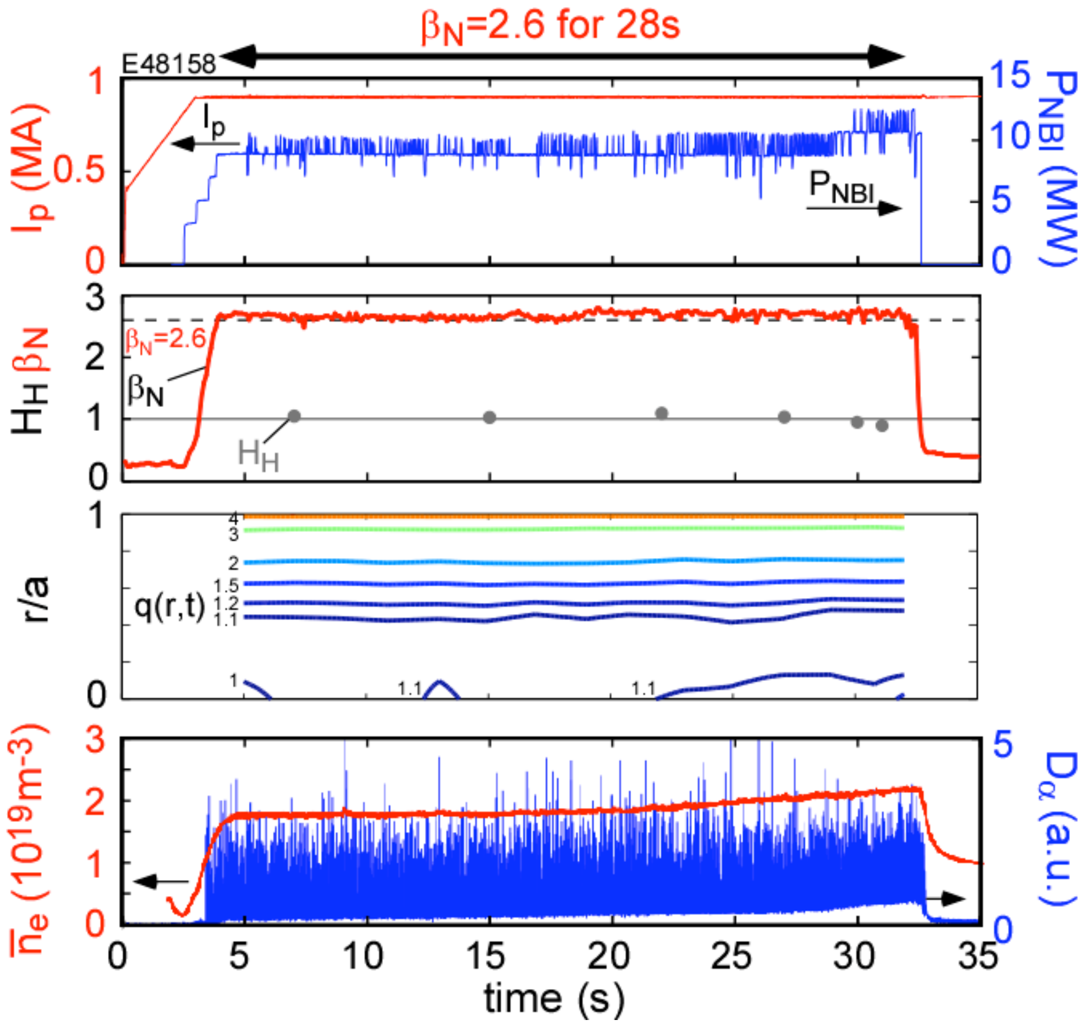
1. High $\beta_N H_H$ in long hybrid discharge with NTM-free plasma profiles.
2. Formation of fully non-inductive current profile in steady state.
3. Long sustainment of high β_N above no wall limit.
4. RS plasmas with both high β_N and high f_{BS} toward DEMO.

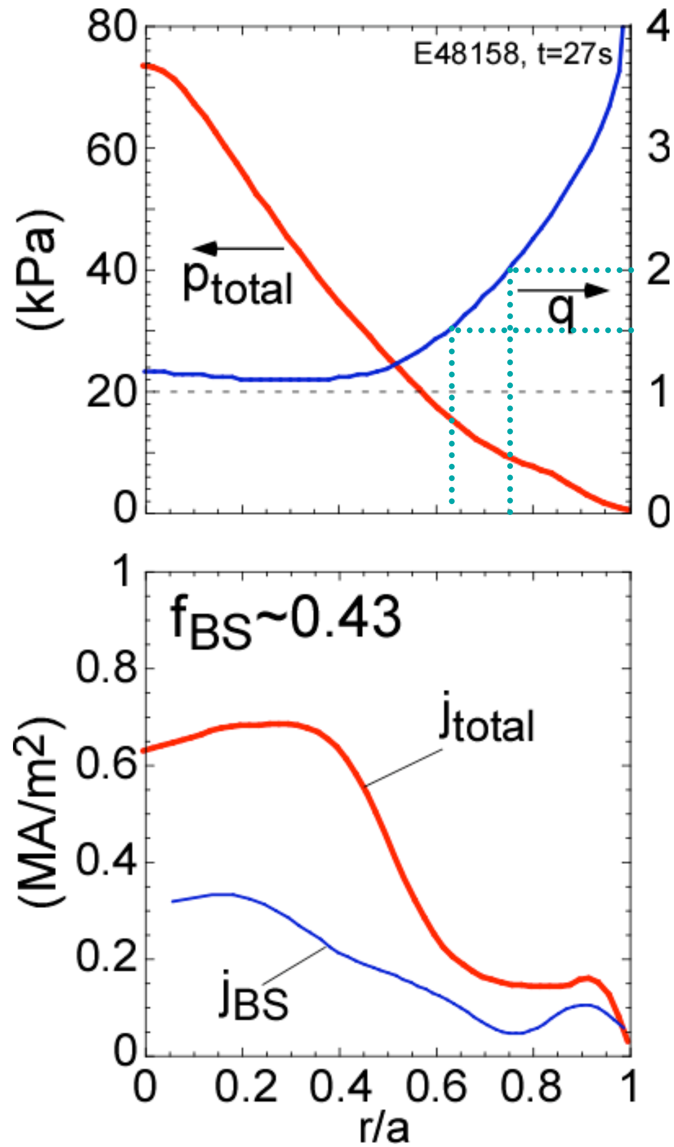
1. High $\beta_N H_H$ in long hybrid discharge with NTM-free plasma profiles

Profiles with NTMs free up to β_N ~ 3 was sustained with controlled wall recycling: β_N = 2.6 is sustained for 28s.

JT-60U

- **NTMs free up to β_N~3, Infrequent sawtooth**
- **Wall recycling was controlled to low level.**

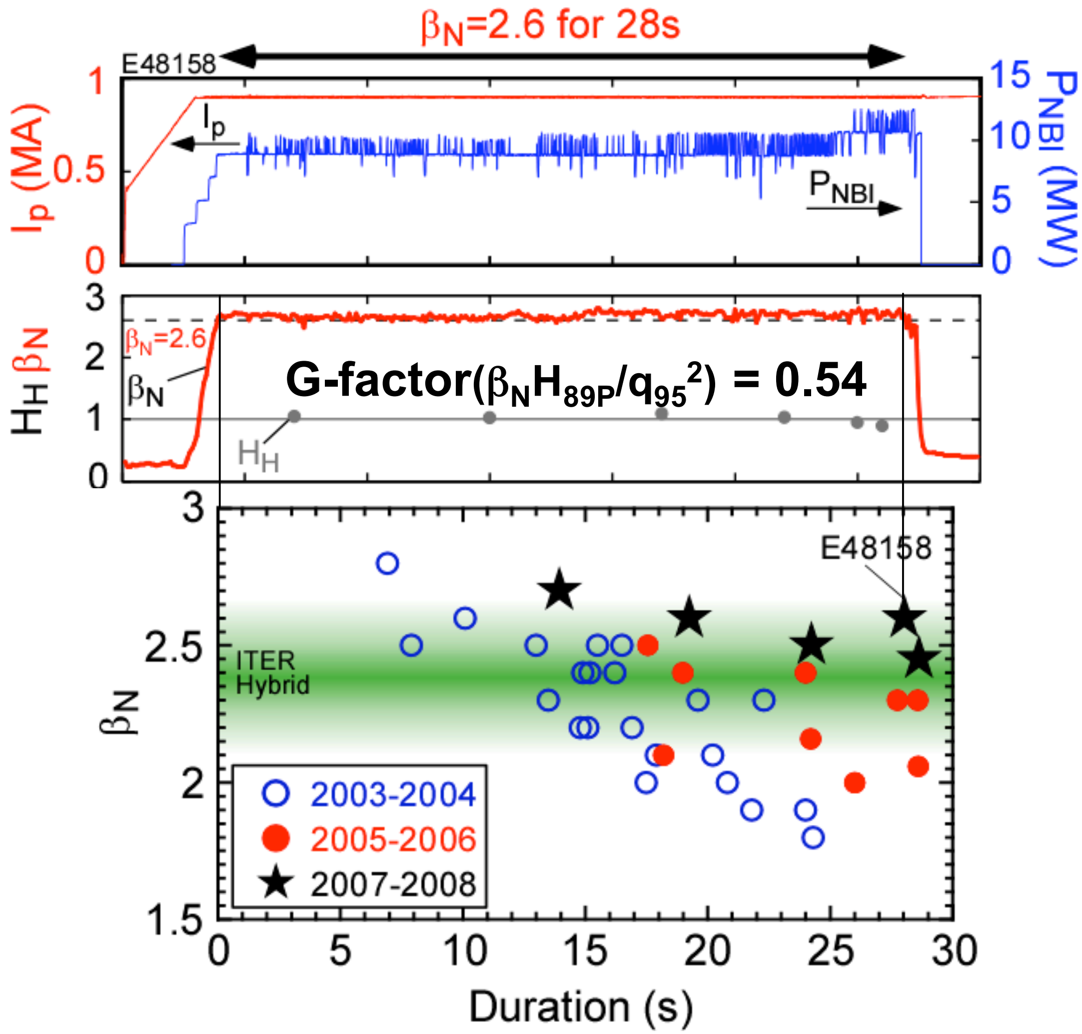


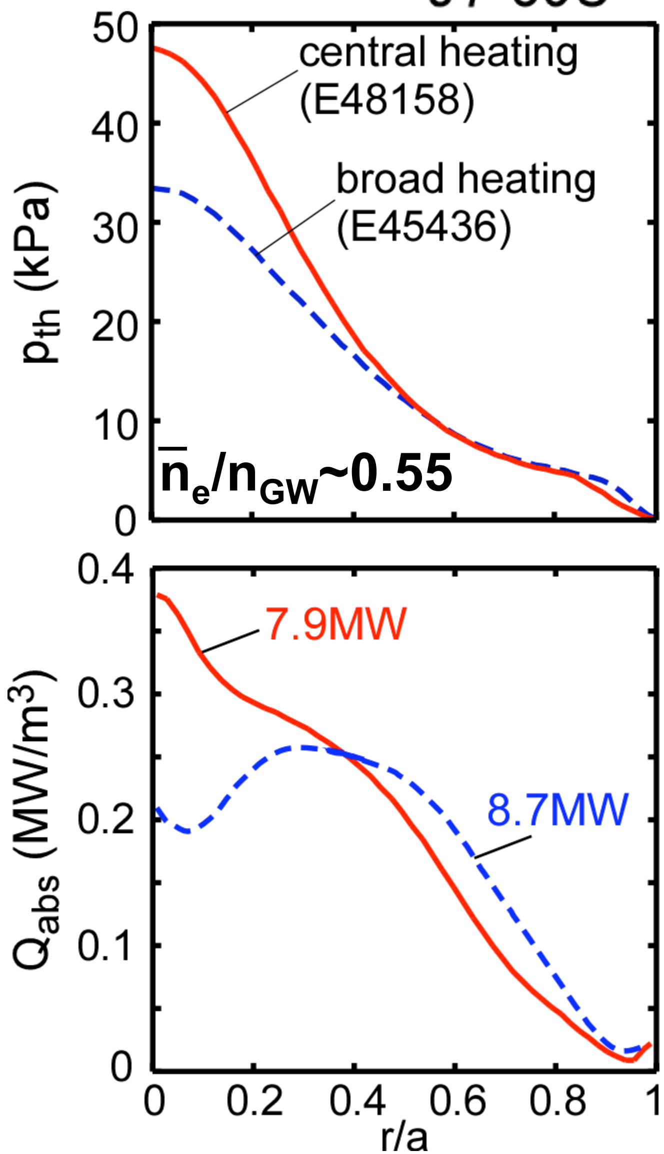


Peaked pressure has been kept with smaller P_{net} by central heating. $\beta_N H_H$>2.6 is sustained for 25s (~14τ_R).

JT-60U

Three PERP-NBIs for central heating was upgraded to enable 30s-injection.

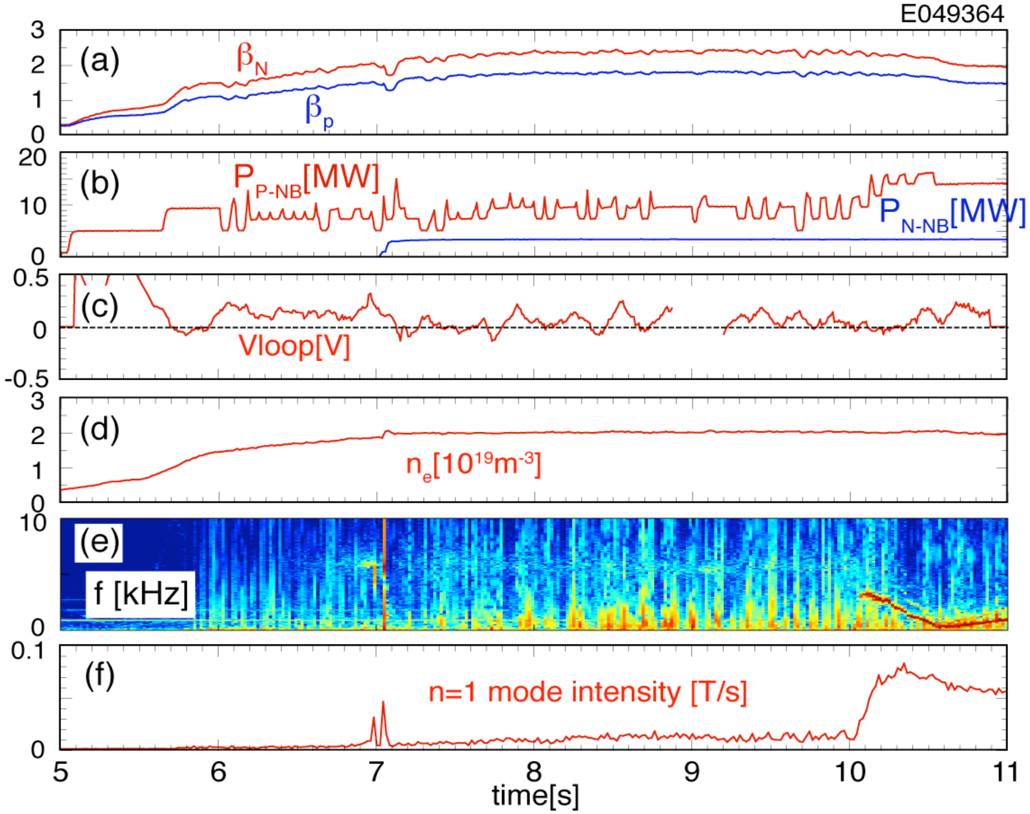


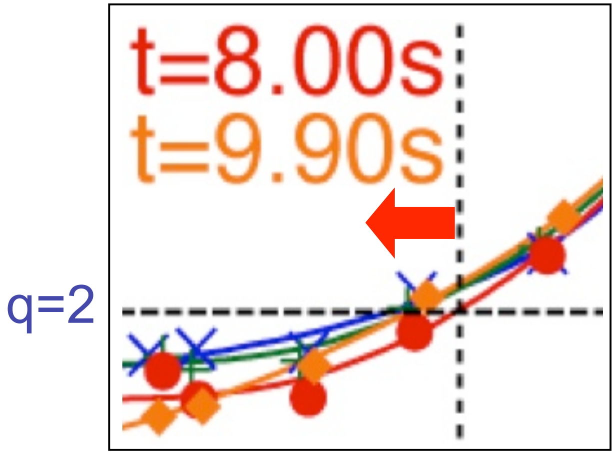


Almost non-inductive CD discharge (f_{CD}=0.97) was sustained with NBCD and β_N=2.4 (W_{store} feed back: f_{BS}=0.52) for ~ τ_R.

JT-60U

I_p=0.8MA, B_t=2.1T, q_{95}=4.3, β_N=2.4, β_p=1.8, f_{GW}= 0.53, Z_{eff}=2.5, H_{89P}=2.2, H_{H98y2}=0.89 (f_{th}=0.50), f_{BS}=0.52, f_{BD}=0.46, f_{CD}=0.97, τ_R=2.1s



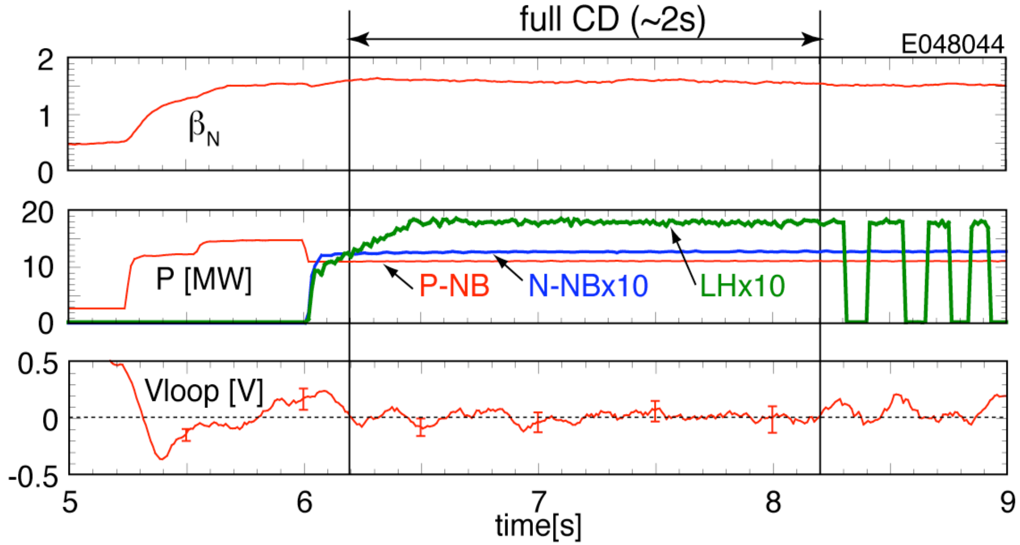


Off-axis current driver was needed.

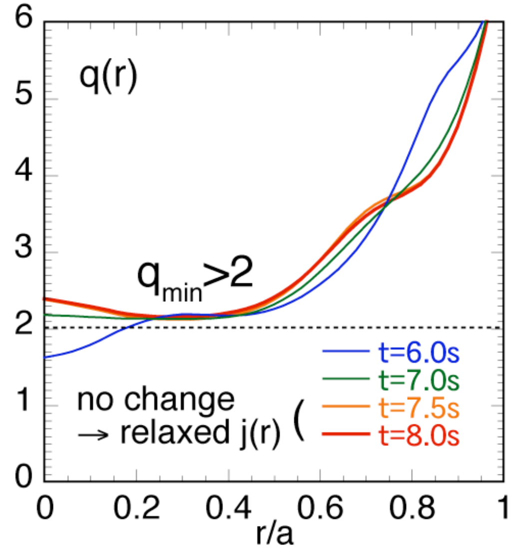
Relaxed and fully non-inductive j(r) with f_{BS}=0.5 was formed in weak-shear regime using NBCD (on-axis) + LHCD (off-axis).

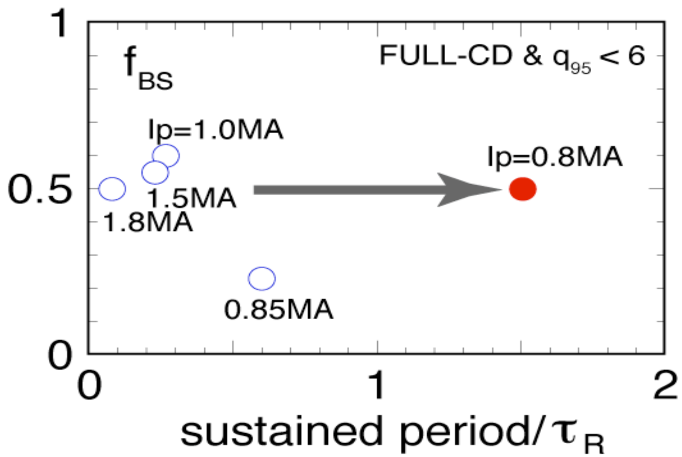
JT-60U

Ip=0.8MA, Bt=2.3T, f_{GW}=0.61, β_N~1.6, β_p~1.5 , H_{89P}=1.5, H_{H98y2}=0.64, τ_R=1.3s, $N_{//}$=1.9



MHD instability free and steady- state q profile





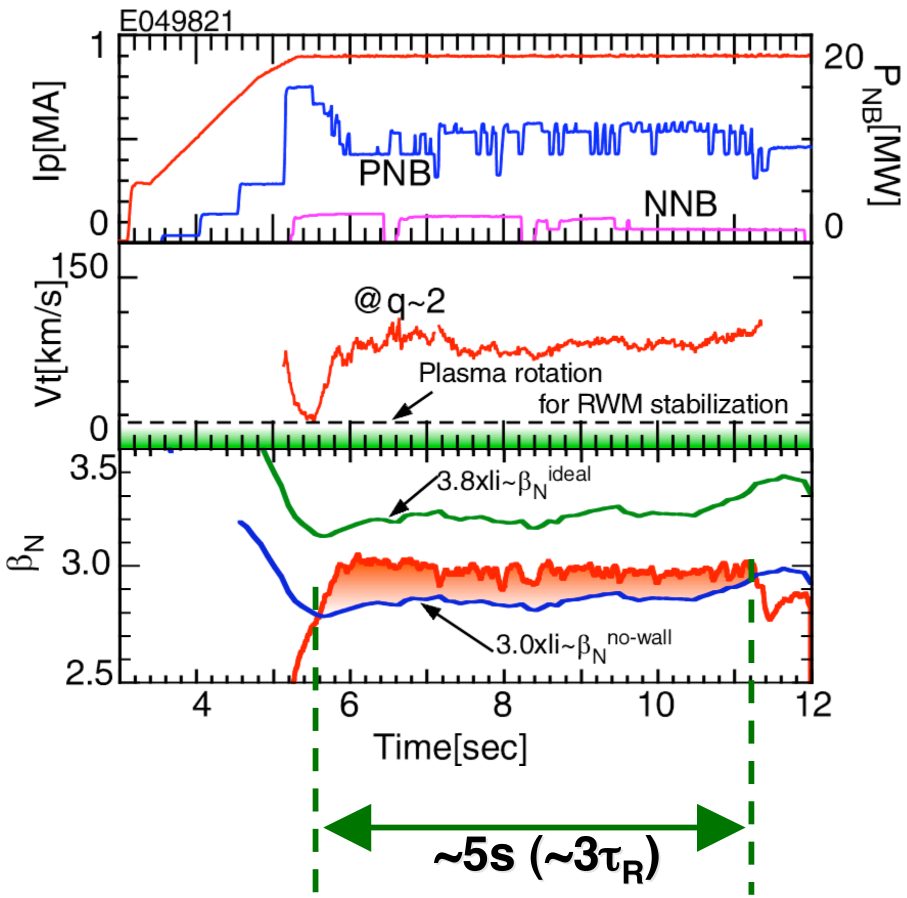
Non-inductive and Steady state with high f_{BS} extended

3. Long sustainment of high β_N above no wall limit.

β_N ~ 3.0 above the no wall limit (C_β ~ 0.4) was sustained for ~ 5 s, when the plasma rotation had some margin above V_t^{cri} and perp-NB power was minimized.

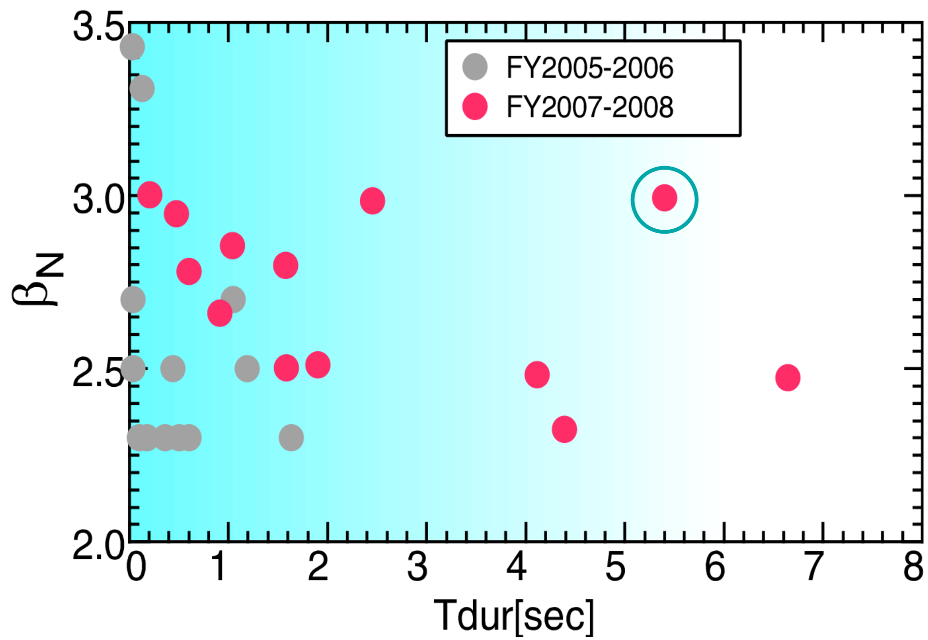
JT-60U

f_{CD}≥80% and f_{BS}~50% (ACCOME code)



☺**Reduction of fast ion loss**
=> keep co-rotation > V_c

☺ **To minimize risks to trigger RWM despite V_t > V_t^{cri}**

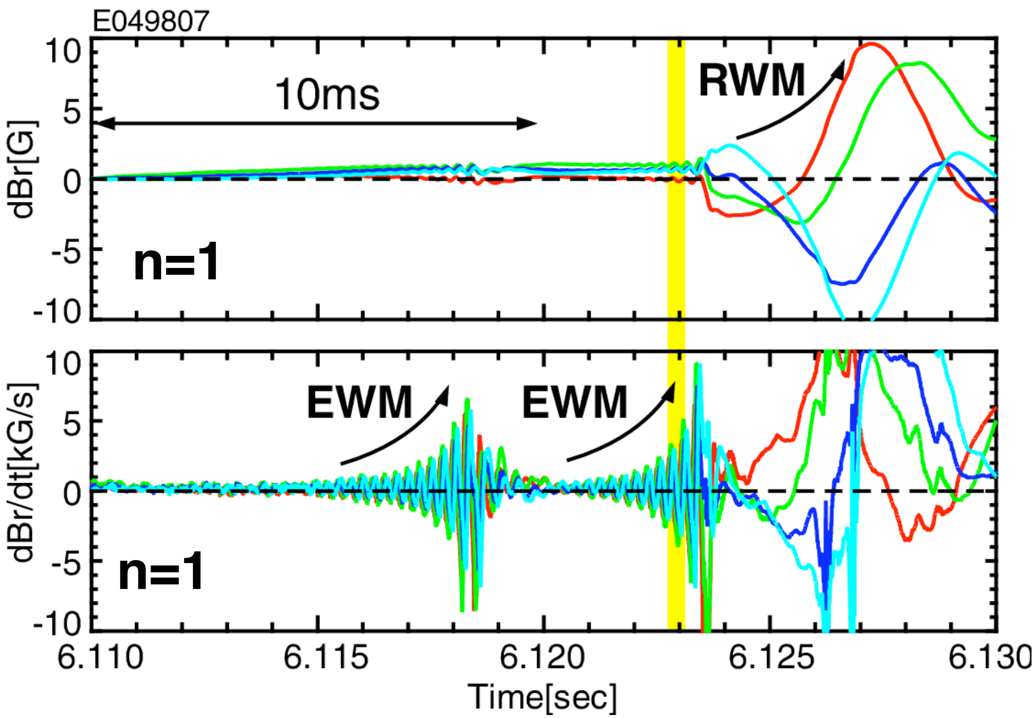


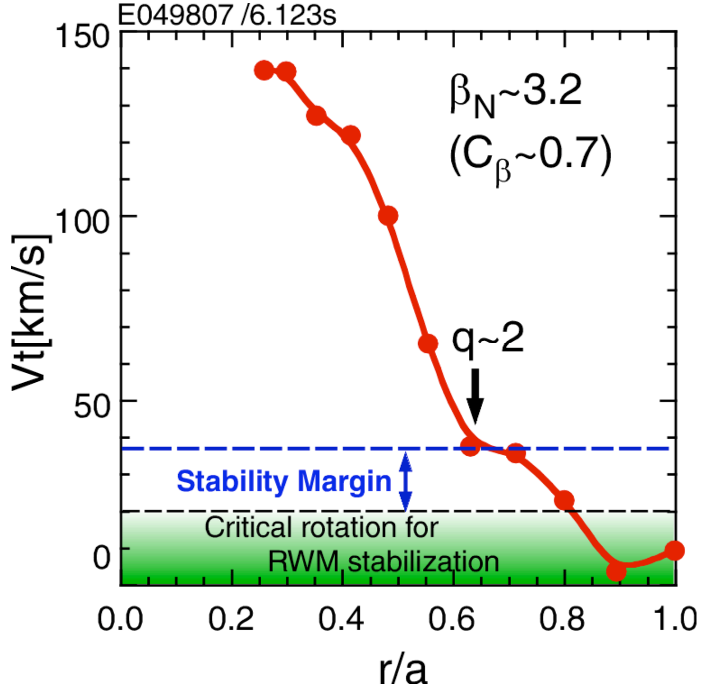
Observation of MHD instabilities at $\beta_N > \beta_N^{no\text{-}wall}$

Energetic Particle driven Wall Mode (EWM)

EWM can directly induce RWM, even though, rotation is enough

In the wall-stabilized high-β_N region, Energetic particle driven Wall Mode (EWM) is newly observed.



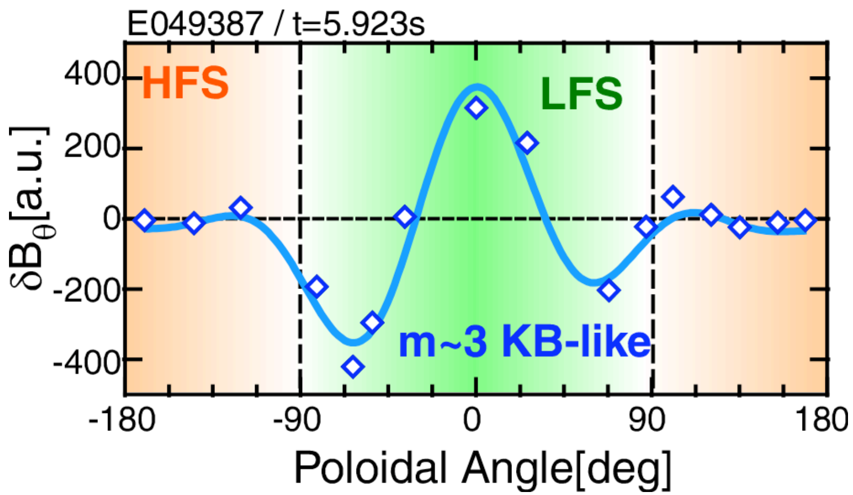


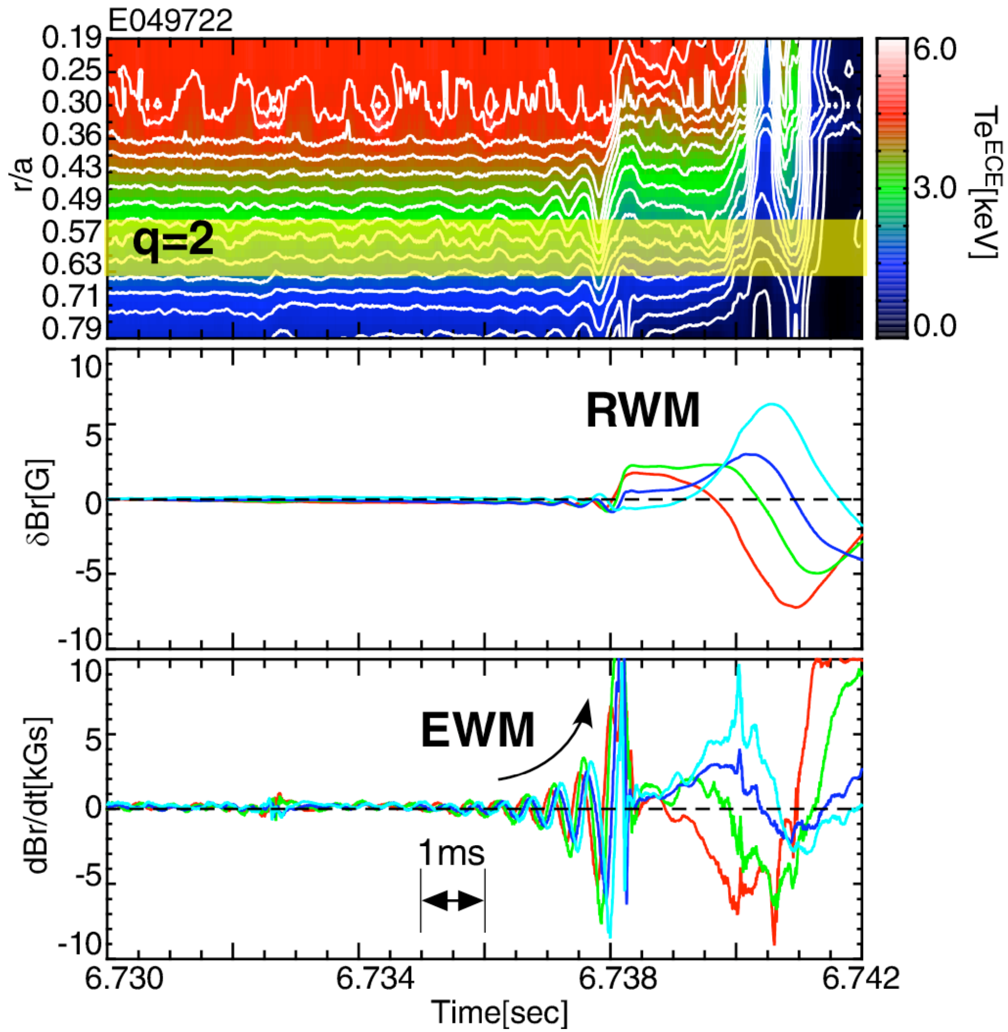
At RWM onset, rotation was enough for stabilization.

The EWM is dangerous for RWM

EWM has globally-spread structure

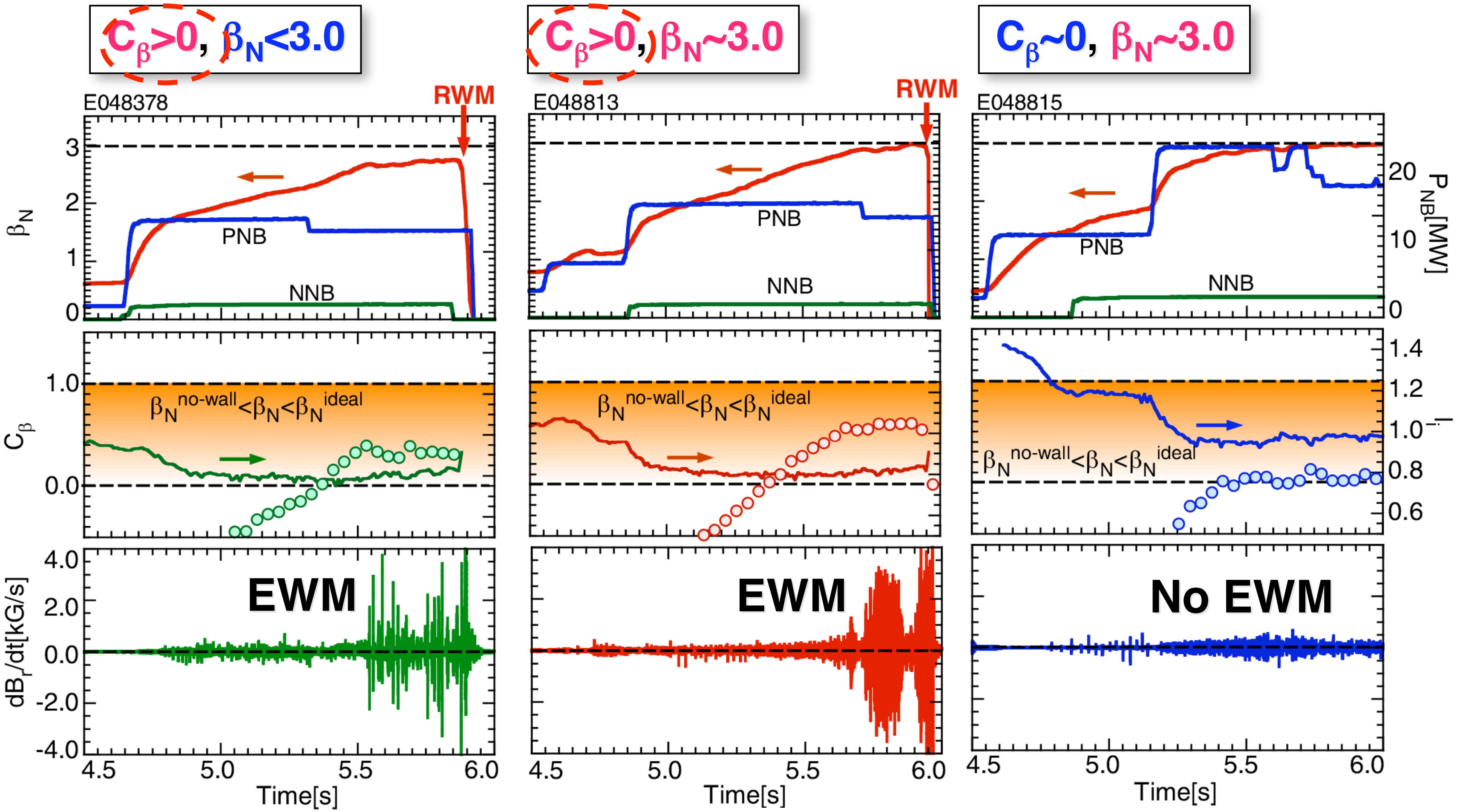
- **Toroidal mode number**
  n=1
- **Poloidal mode number**
  m~3 (Kink Ballooning-like)
- **Radial mode structure**
  globally-spread
- **Growth time**
  1~2ms ~ τ_w





EWM is only observed in the wall-stabilized region $C_\beta>0$

- The EWM were observed in high-β_N plasmas.
- However, the EWM requires $C_\beta>0$, NOT only high-β_N.



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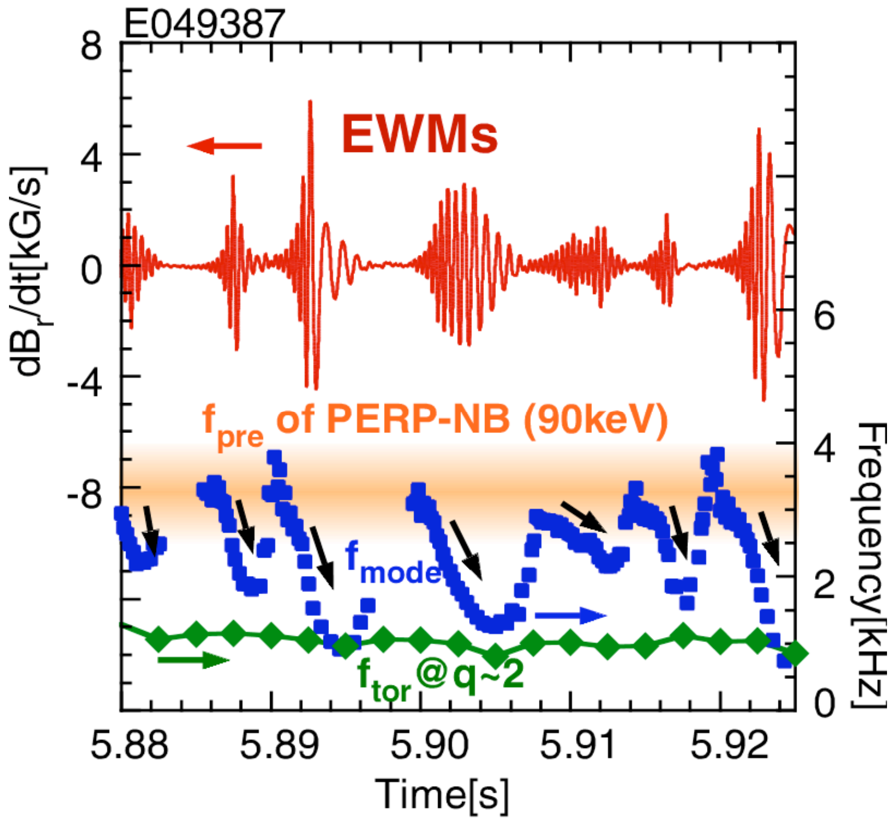
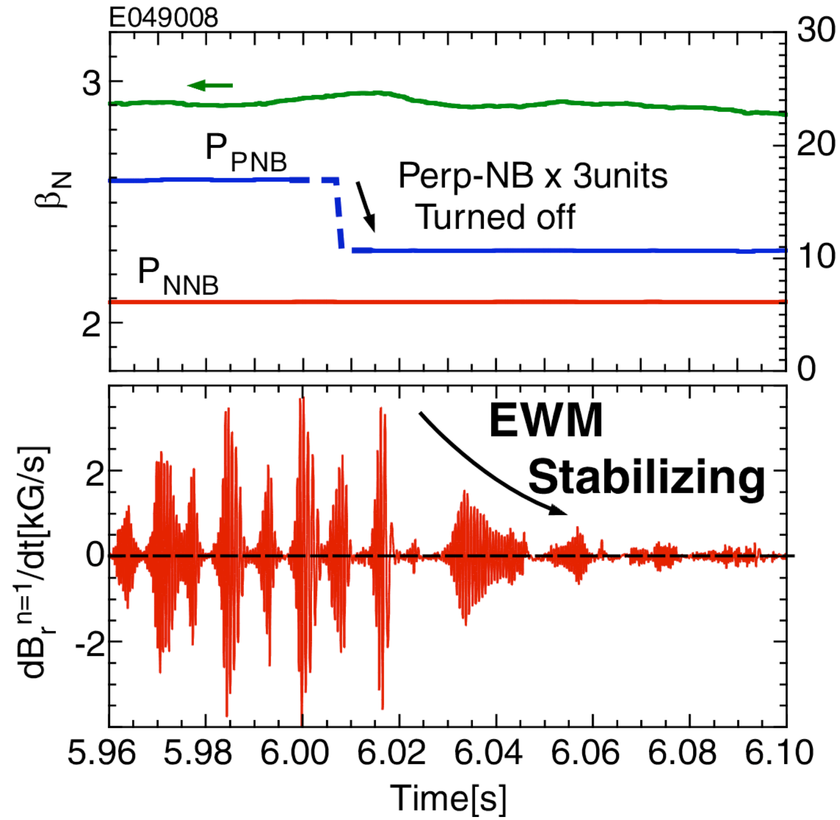
EWM is destabilized by trapped energetic particles

- EWM frequency was chirping down as amplitude was increasing.
- Initial frequency corresponds to precession freq. of PERP-NB (~90keV)



- PERP-NB power was turned off with keeping high-β_N.

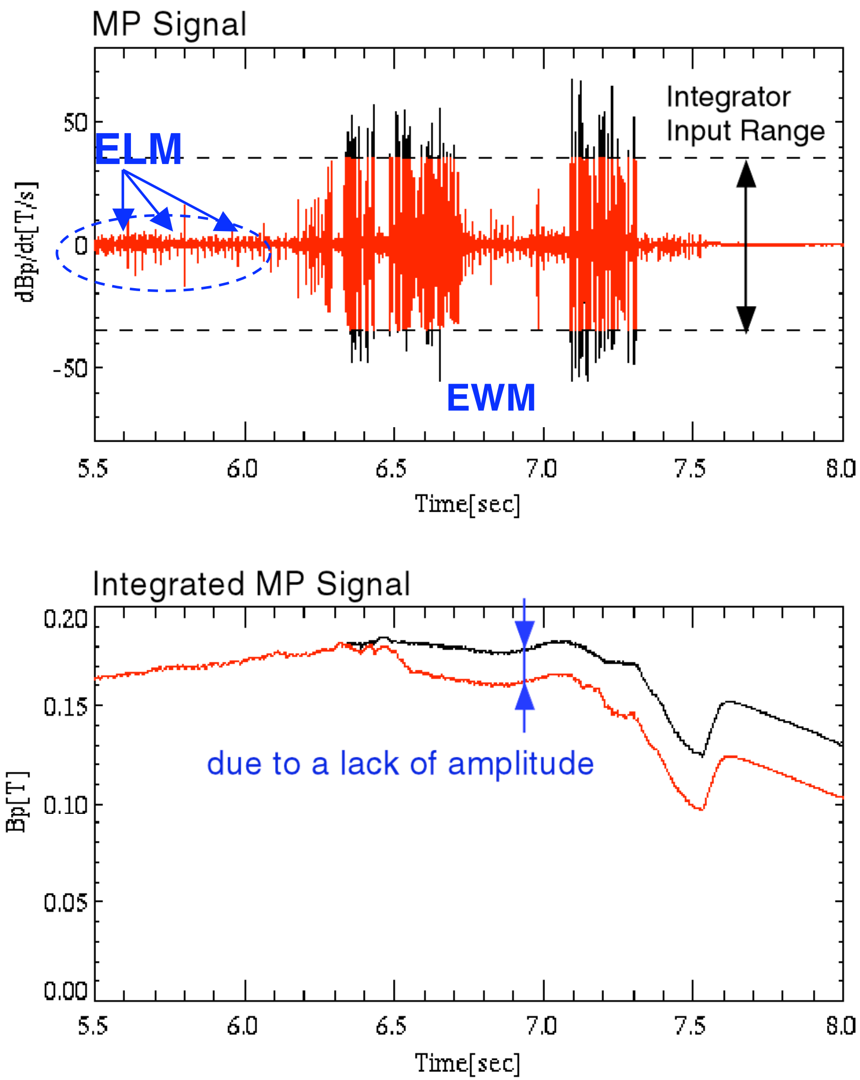
-> EWM can be stabilized.



EWM is destabilized by trapped energetic particle

Large EWM amplitude caused inaccurate plasma control

- **Finally, the integrator gain was reduced to avoid this problem.**
- **Although this is basic problem, we should pay attention.**



Observation of MHD instabilities at $\beta_N > \beta_N^{no\text{-}wall}$

RWM Precursor

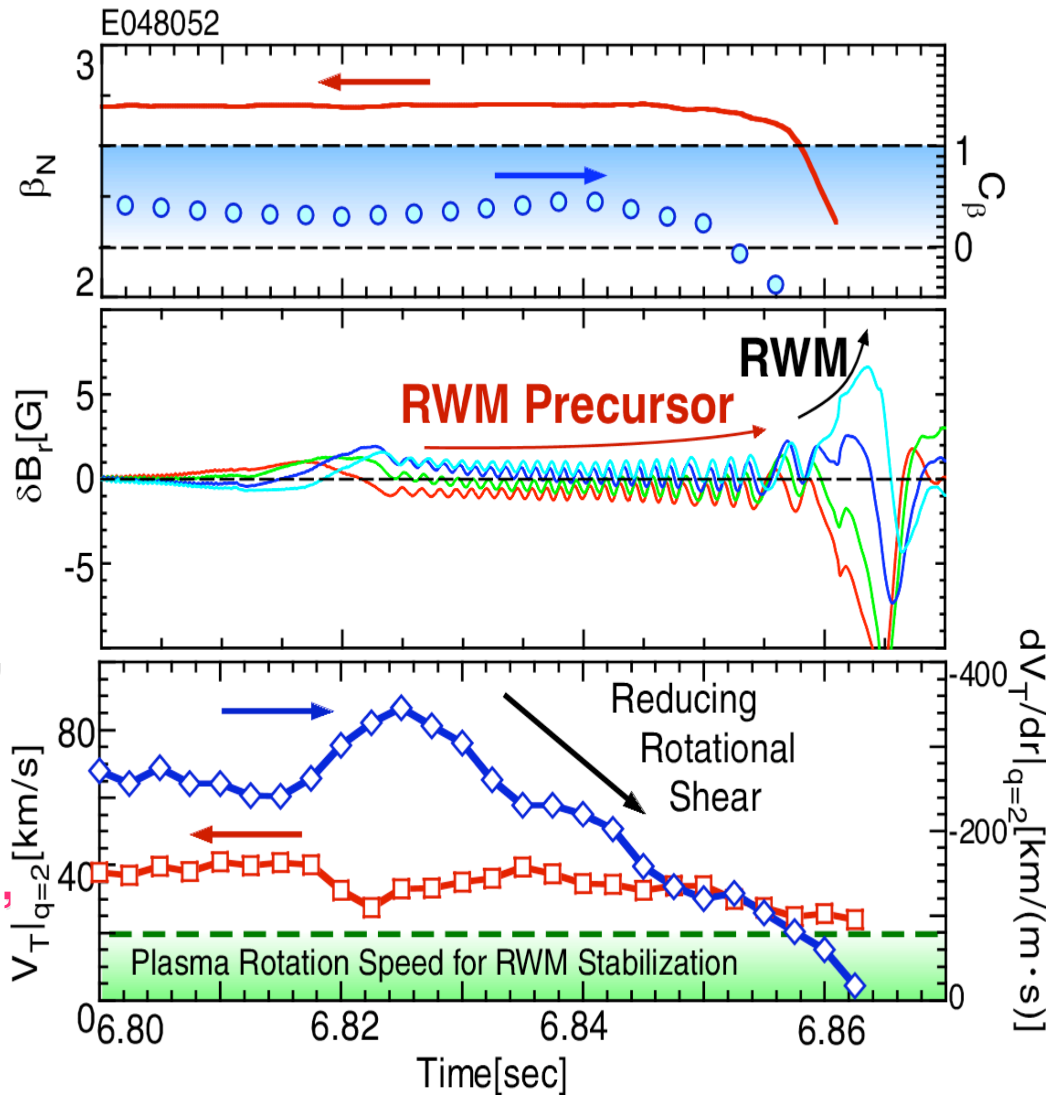
RWM precursor can strongly affect Vt-profile at q=2

In the wall-stabilized high-β_N region, a slowly growing precursor is observed just before RWM onset.

RWM Precursor

Main features:

- Growth time ~50ms ~ τ_{TM},
- Toroidal mode number n=1,
- Confinement is not much degraded,
- It is triggered by ELM or EWM,
- Finally, rapidly growing (RWM),
- Vt-profile at q=2 is strongly affected,
- Mode frequency does not correspond to Vt at q=2.

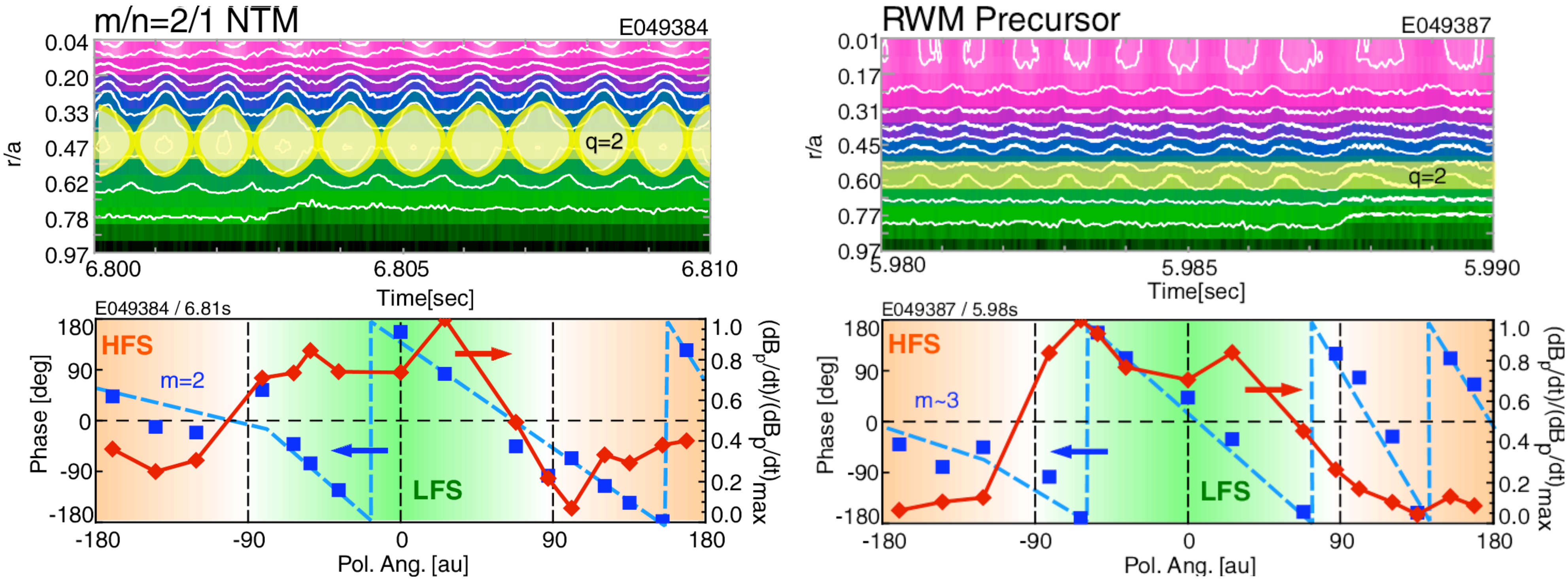


RWM precursor is quite different from NTM

RWM precursor looks like NTM (growth time ~50ms, affected location).
However, according to mode structure comparison,

- **RWM precursor does not have any clear islands at q=2.**
- **Rather, poloidal mode structure is m~3 at the wall.**

RWM precursor is different from m/n=2/1 NTM



JT-60U

Rotational shear was lost and finally RWM became unstable

RWM precursor :

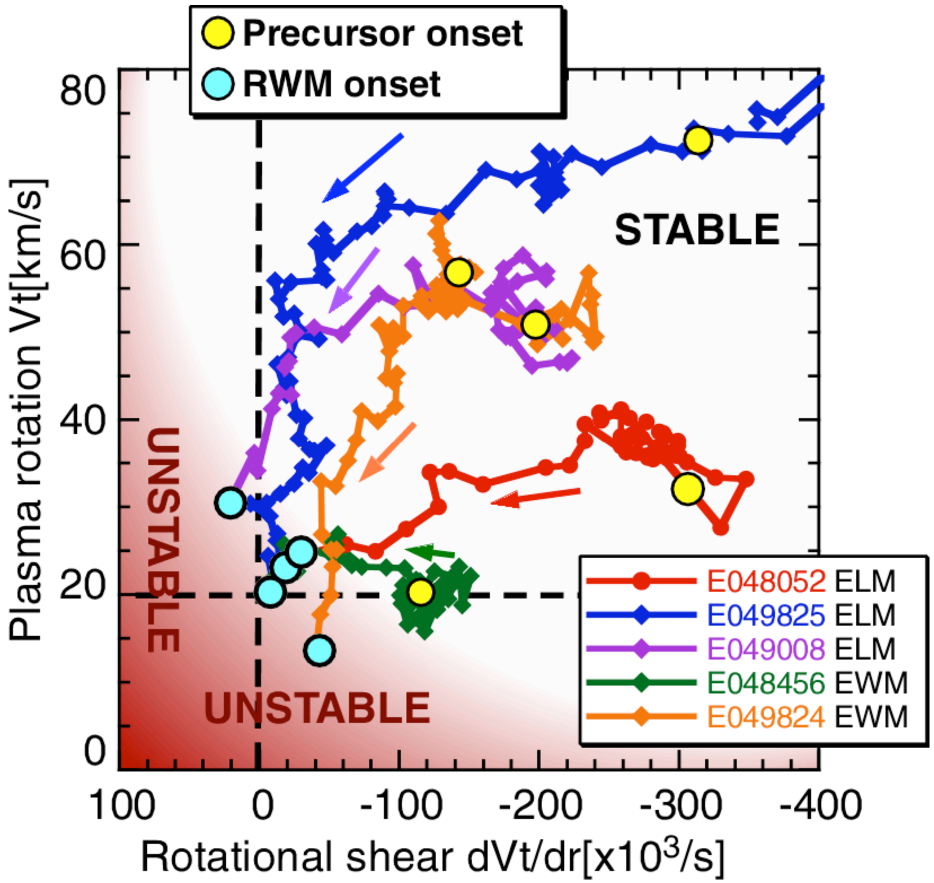
- Different from NTM, (No clear island)
- Mode struct. : n=1, m~3 (KB-like),
- f_{mode} : NOT correspond to Vt at q=2,

  These are RWM-like behaviors.

  RWM precursor is thought to be fundamentally the same as RWM (Growth time is further slowdown)

- RWM precursor can strongly reduce V_t and/or dV_t/dr at q=2,
- When $V_t \rightarrow V_t^{cri}$ or $dV_t/dr \rightarrow 0$,

  Finally, RWM onset.



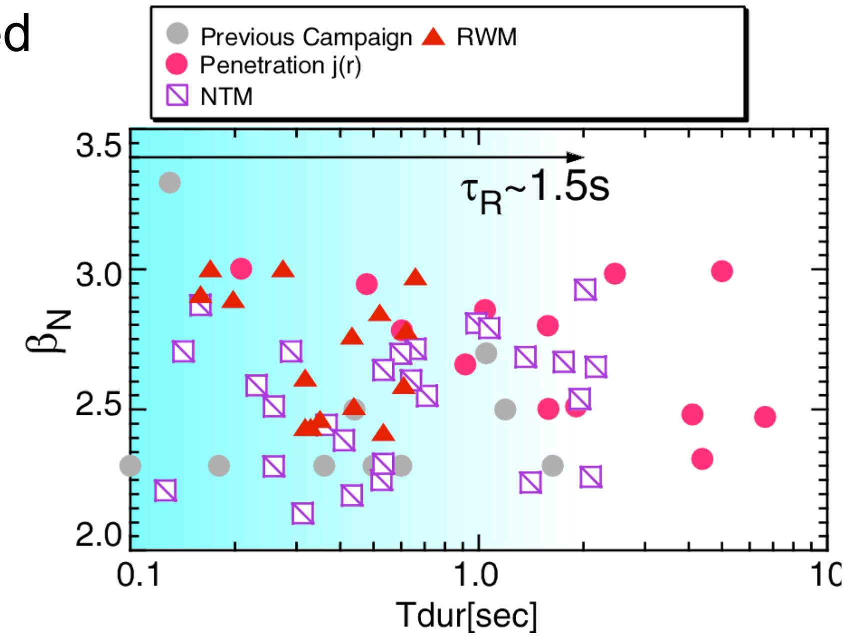
Rotational shear is important for RWM stability as well as rotation speed

EWMs must be avoided to reduce risks to induce disruptions caused by RWM despite $V_t > V_t^{cri}$.

JT-60U

Discharges with $\beta_N > \beta_N^{no\text{-}walll}$ were limited by

- Resistive Wall Mode (RWM)
- Neoclassical Tearing Mode (NTM)



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JT-60U

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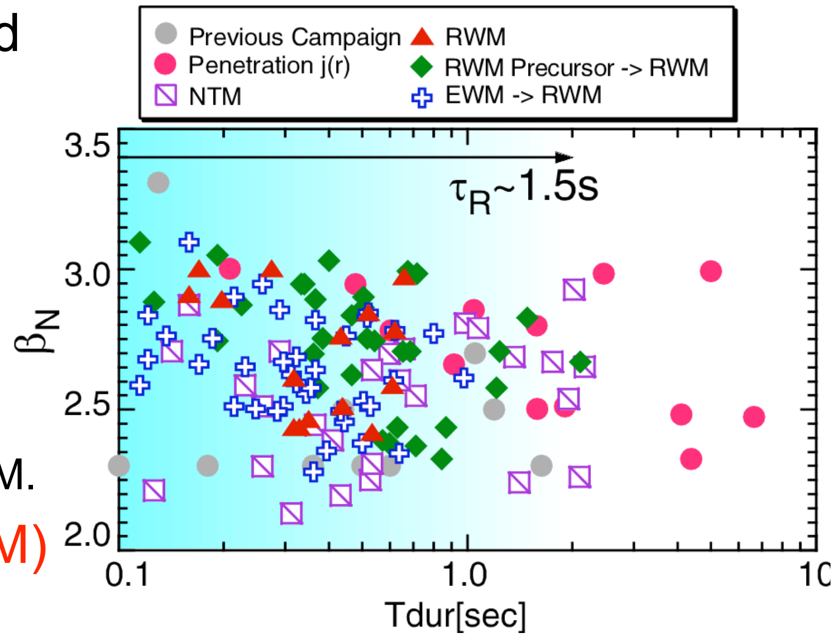
RWM were induced, despite $V_t > V_t^{cri}$, by

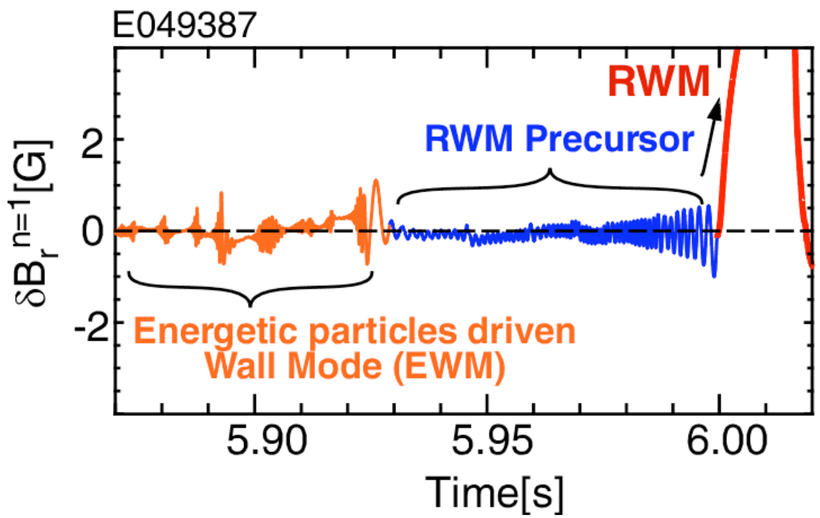
•RWM Precursor

- RWM pecursors are triggered by EWM and ELM.

•Energetic particle driven Wall Mode (EWM)

- EWM may directly trigger RWM





EWMs must be avoided to reduce risks to induce disruptions caused by RWM despite $V_t > V_t^{cri}$.

JT-60U

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- Resistive Wall Mode (RWM)
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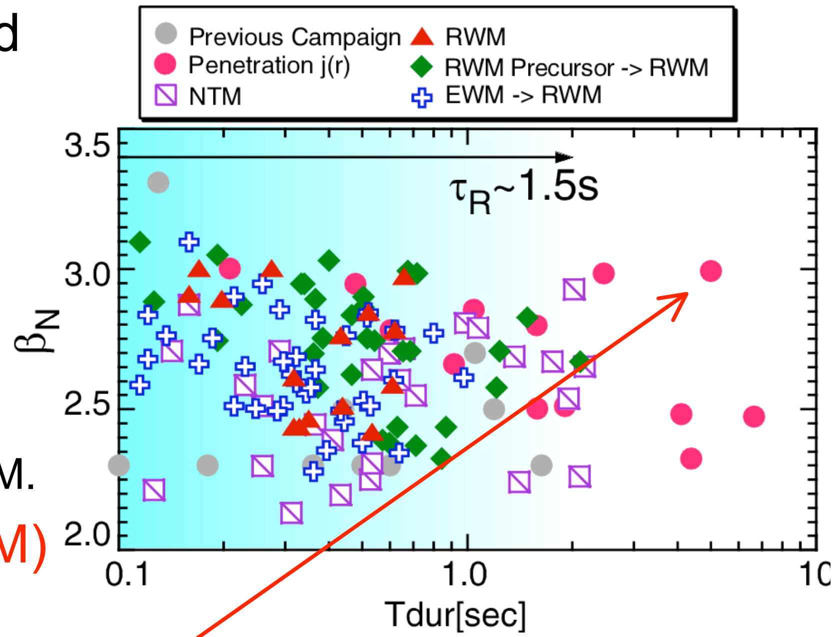
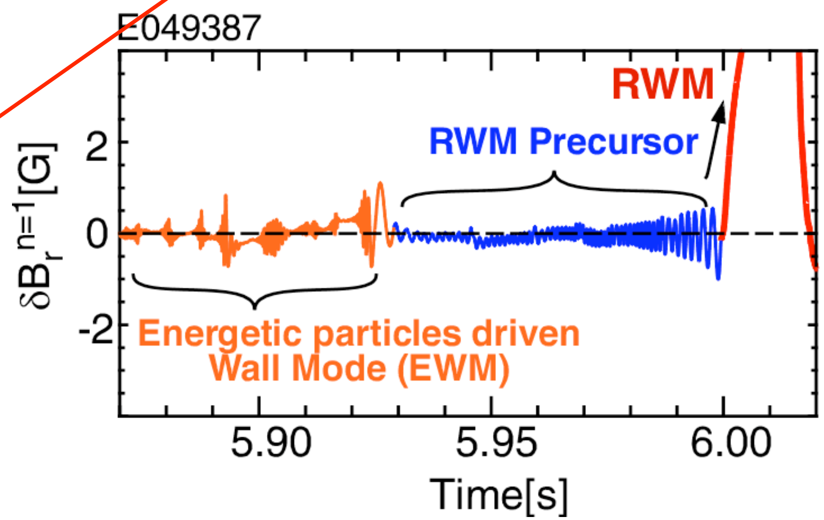




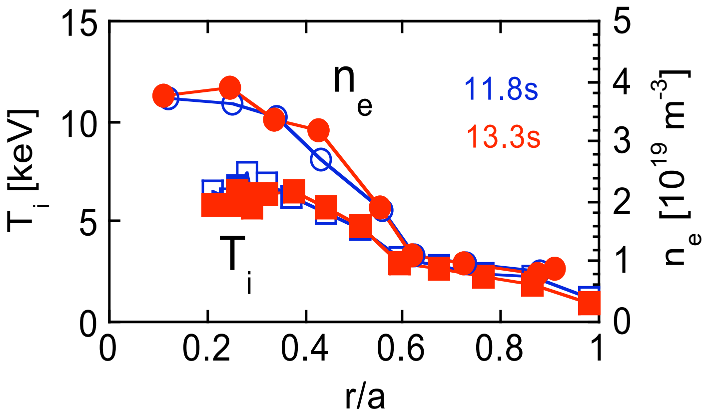
EWM must be avoided to reduce risks to induce disruption by RWM

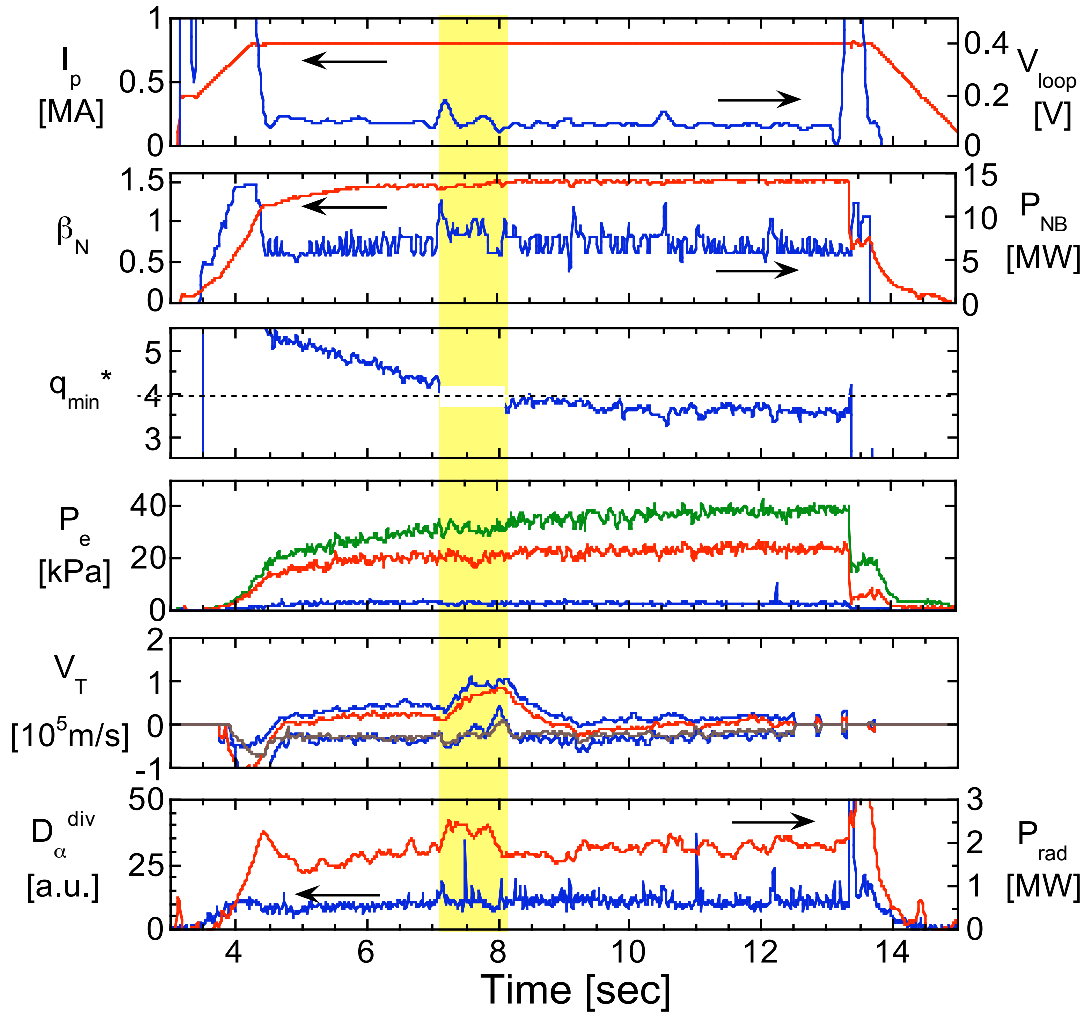
Minimize Perp-NB power!

By utilizing real time control logic to avoid disruptions with q_{min} = 4, f_{BS}~70% was sustained for 8 s in 2006.

JT-60U

- 0.8MA/3.4T, q_{95}~8.5, H_{98}~1.8, β_N~1.4, β_p~2.1, f_{BS}~70% sustained for ~8 s.
- Reduction of grad-P at q_{min} = 4 by turing off CTR-NB was successfully achieved, while ITB was sustained by W_{store} feedback during 7-8 s.
- However the large f_{BS} plasma was terminated by collapse which might be attributed to increase in pressure at the center.



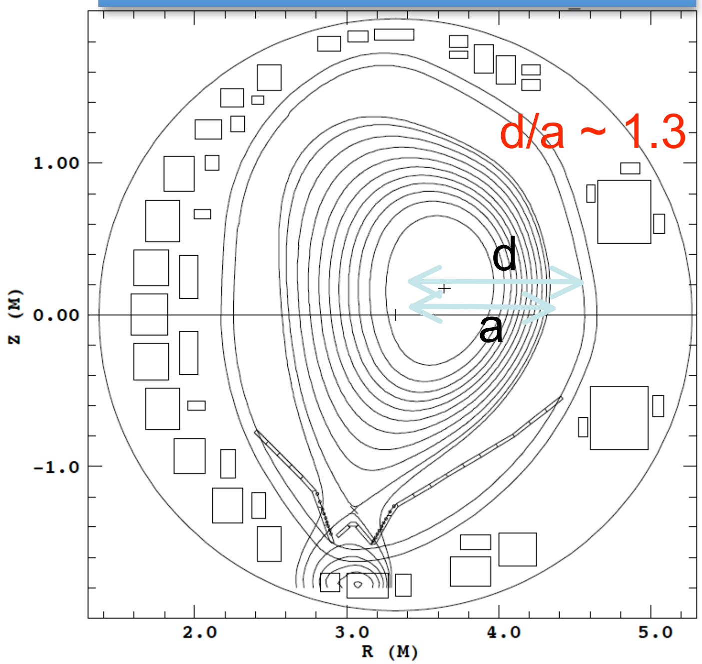


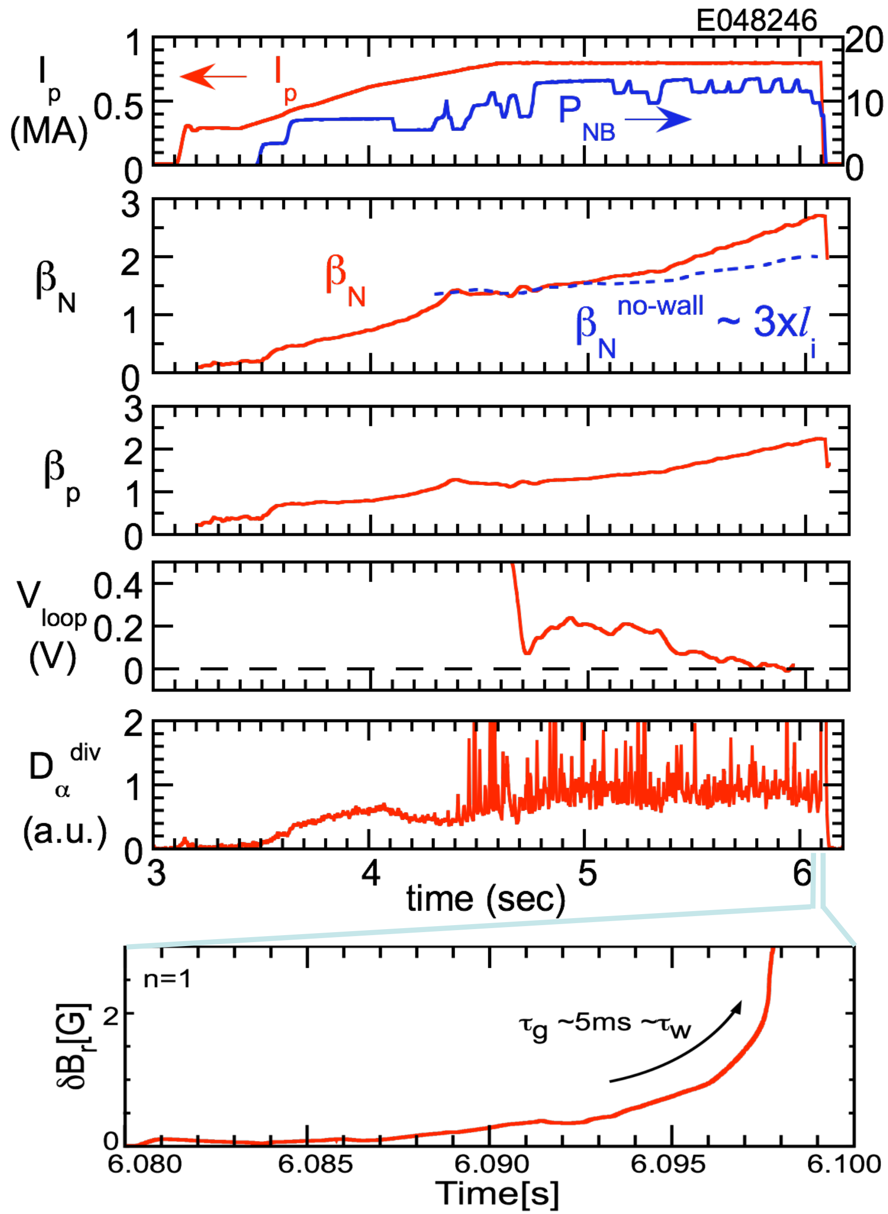
RS plasma with high f_{BS} and high β_N was obtained in 2008

JT-60U

- B_T = 2T, I_p = 0.8MA, q_{95}~5.3,
- d/a ~ 1.3 for wall stabilization
- Early heating for RS configuration
- β_N~2.7 (> no wall beta limit), β_p~2.3 (f_{BS}~90%) were achieved.
- RWM (τ_g ~ 5ms ~ τ_{wall})

Configuration for wall stabilization





C_β ~ 0.8 was achieved and eigen-function is large in outer region of plasma

JT-60U

- According to MARG2D code, the plasma is unstable without wall.
  - $\beta_N^{no\text{-}wall}$ ~ 1.9
  - $\beta_N^{ideal\text{-}wall}$ ~ 2.9

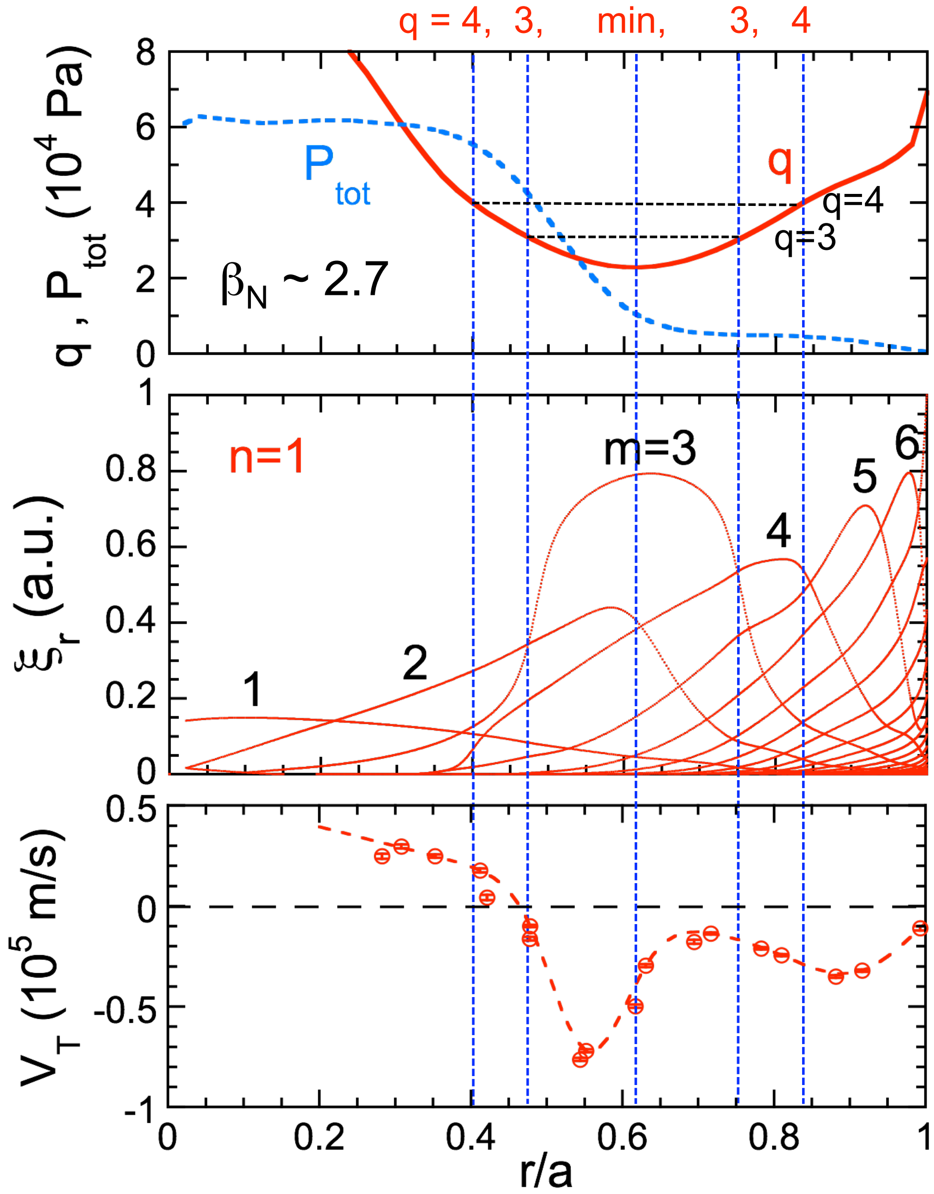
C_β ~ 0.8

$$C_\beta=(\beta_N - \beta_N^{no\text{-}wall}) / (\beta_N^{ideal\text{-}wall} - \beta_N^{no\text{-}wall})$$

- Eigen-function of RWM is large in the the outer half of minor radius including small pressure gradient region.

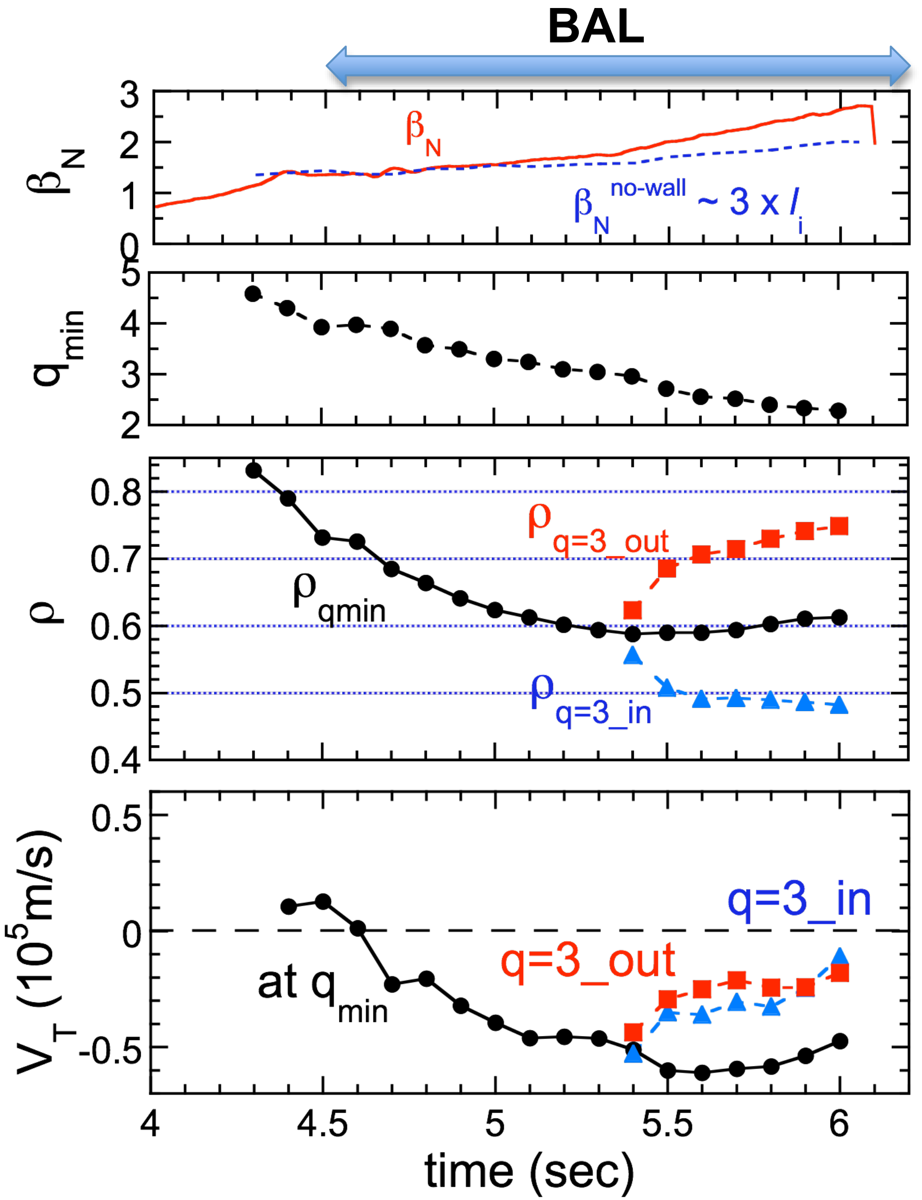
- Toroidal rotation can stabilize RWM.

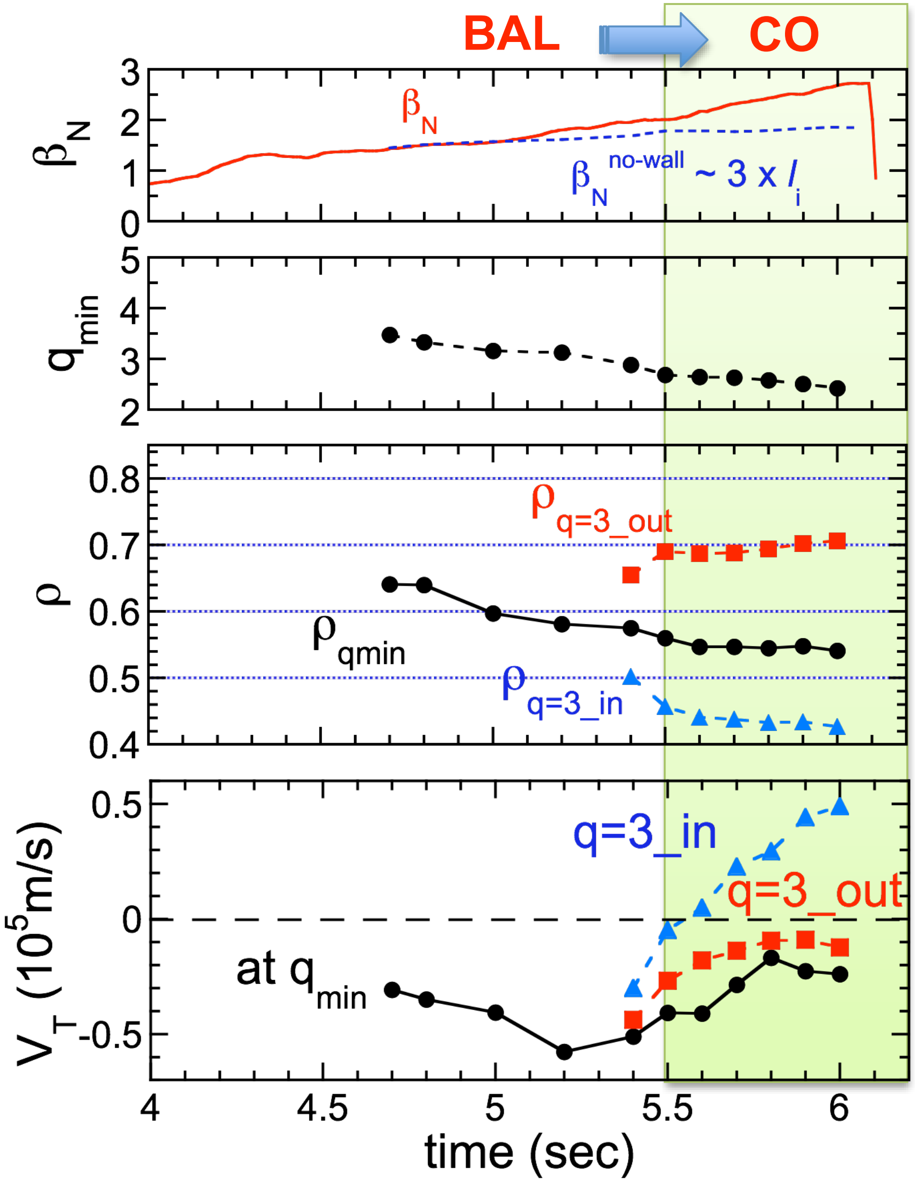
- We investigate the relation between toroidal rotation and RWM onset for RS plasmas with high f_{BS}.



Toroidal rotation at the outer half of minor radius seemed to be important for RWM stabilization

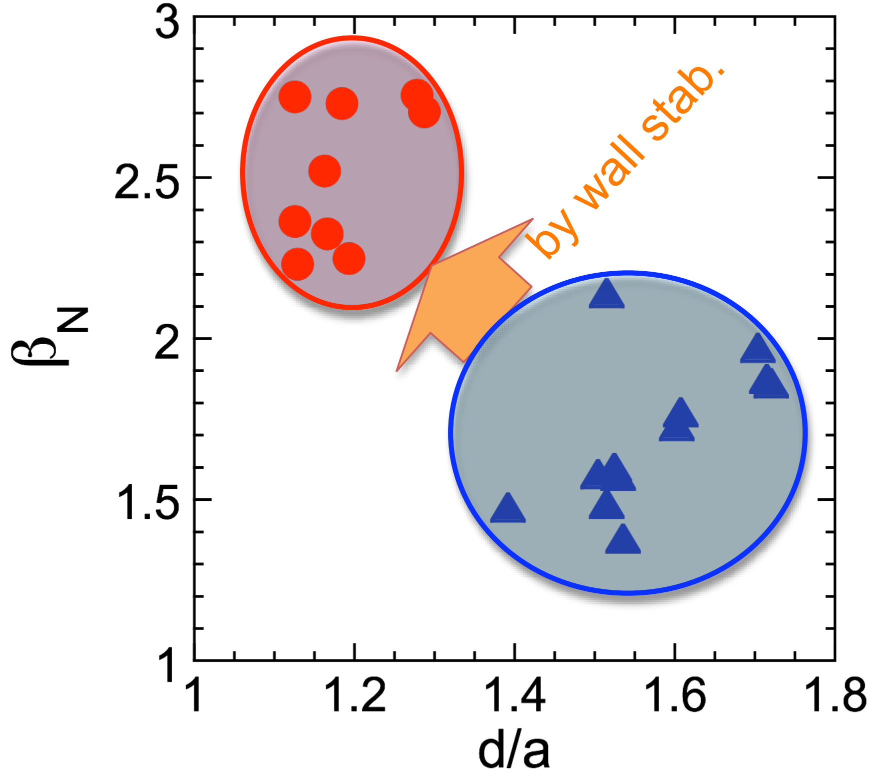
JT-60U

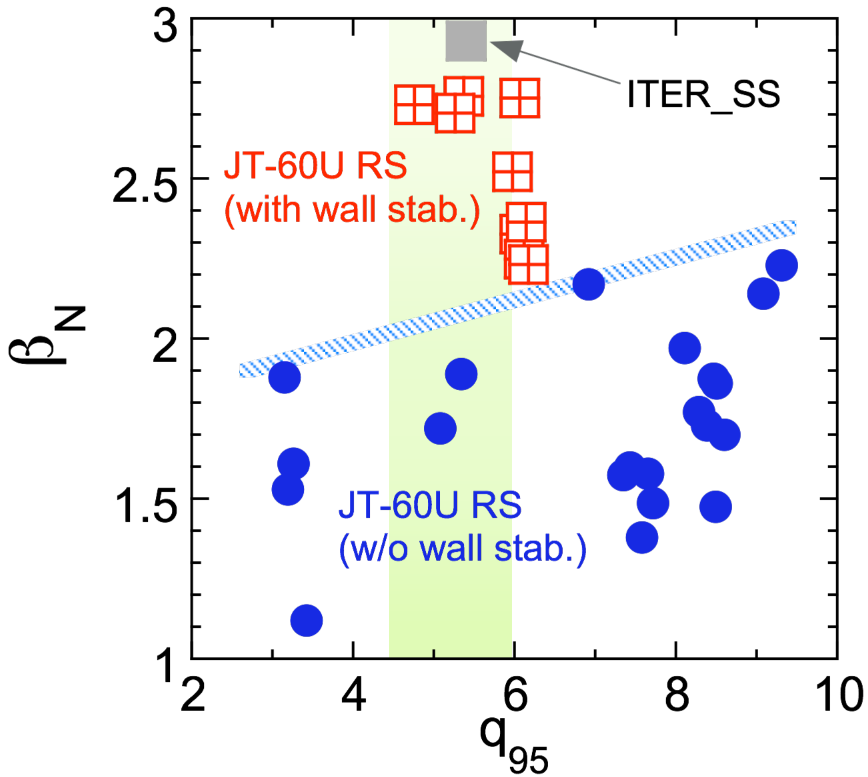




Wall stabilization of RWM successfully extended RS plasmas toward high β_N regime above no wall limit.

- By optimizing large volume plasma close to wall, beta limit of high f_{BS} plasmas is significantly improved by wall stabilization.
- As a result, high β_N expected in ITER steady state scenario has been achieved at reactor relevant q_{95} ~ 5 regime.





Summary

- Flat current profile and peaked pressure profile, which was free from NTMs free up to β_N ~ 3, was sustained by central NB heating and controlled wall recycling. $\beta_N H_H$>2.6 is sustained for 25s (~14τ_R).
- MHD stable and fully non-inductive j(r) with f_{BS}=0.5 was formed using NBCD (on-axis) + LHCD (off-axis) control.
- EWM and RWM precursor were found above the no-wall limit. It was found that these new instabilities triggered RWM despite $V_t > V_t^{cri}$. Suppression of EWM was important in addition to V_t control to sustain β_N ~ 3.0 (C_β ~ 0.4) for ~ 5 s.
- Wall stabilization of RWM successfully in RS plasma extended the operational regime toward DEMO relevant regime.