Integrated Performance and Critical Issues Towards Steady-State Operation in JT-60U

Y. Sakamoto and the JT-60U team

Japan Atomic Energy Agency

18th International Toki conference (ITC18)

on Development of Physics and Technology of Stellarator/Heliotrons en root to DEMO

9-12 December 2008, Toki Japan

Introduction

JT-60U

JT-60U: One of the largest Tokamak.

High fusion performance was achieved so far.

- Record value of fusion triple product : $n\tau T = 1.53 \times 10^{21}$ m^{-3}skeV
- Record value of DT equivalent fusion gain: $Q_{DT}^{eq} = 1.25$

Towards steady-state operation :

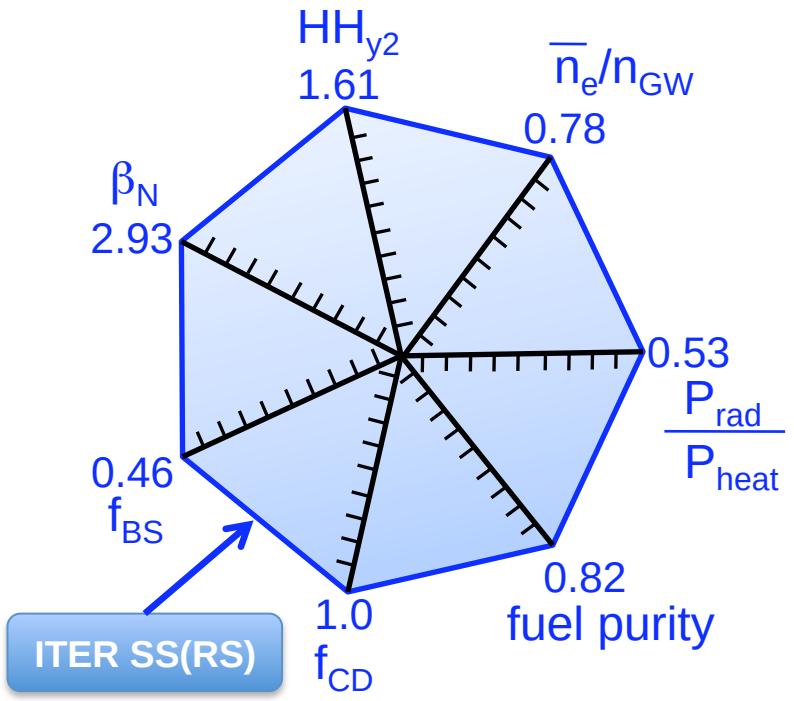
High integrated performance is required.

High values of β_N, HH_{y2} (H_{89}), f_{BS}, f_{CD}, $n_e/n_{GW,}$ fuel purity, P_{rad}/P_{heat}.
should be sustained for long time.

Other reactor conditions:

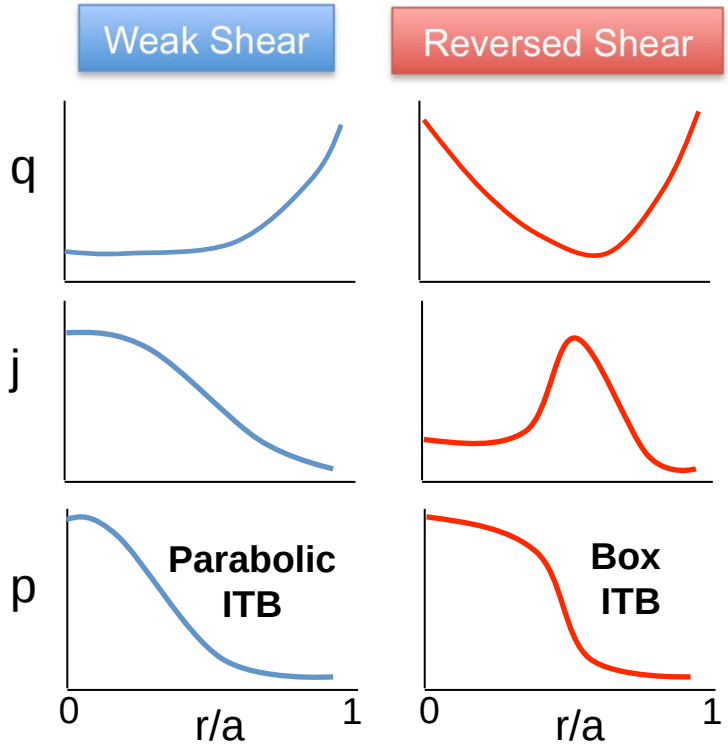
q_{95}~5, T_e~T_i, low momentum input, etc.

In JT-60U,
Weak Shear (WS) and Reversed Shear (RS) plasmas have been optimized towards high integrated performance.



Introduction (cont.)

JT-60U



Low	Confinement	High
High	Stability	Low
Low	BS current	High
Easy	Sustainment	Difficult

Critical issues for the integrated performance:

- **High beta and high confinement**
  - Enhancement of fusion performance directly.
- **Compatibility of high density with high confinement**
  - Large amount of particle fueling by gas-puffing degrades temperature in the core region.
- **Long sustainment**
  - Demonstration of steady-state plasma with high non-inductive current drive fraction over characteristic time scales (τ_E, τ_R, (τ_W)) is required.

Contents

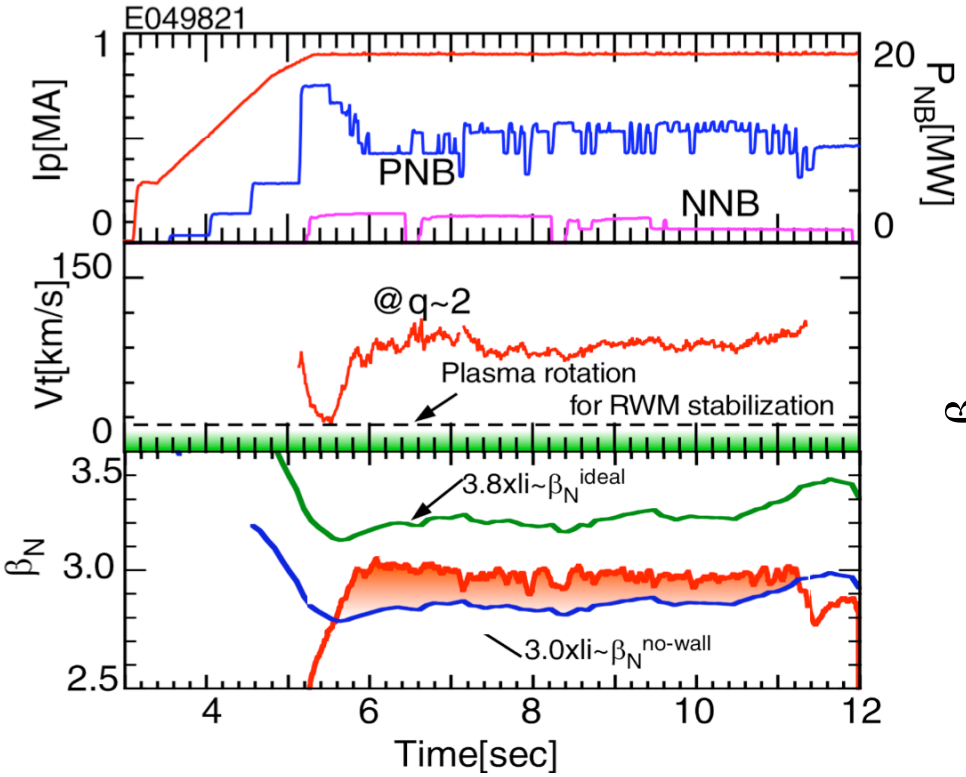
1. High beta operation above no wall beta limit

- **Key operations:**
  - **Suppression of Neoclassical Tearing Mode (presented by A. Isayama on Tuesday)**
  - **Stabilization of Resistive Wall Mode (RWM) by toroidal rotation**

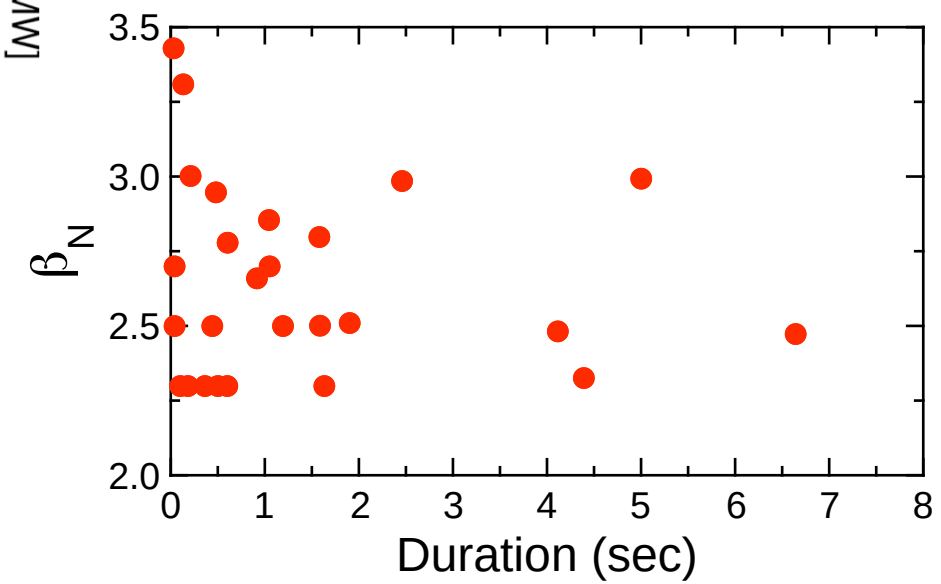
High β_N ~3 above no wall beta limit was sustained for 5s on WS plasma

JT-60U

- For the RWM stabilization, plasma rotation should be kept above critical rotation.
- In some discharges, duration is limited by
  - Energetic particle driven wall mode (EWM), which is the coupling between energetic particle and RWM.
  - RWM precursor, which reduces toroidal rotation and/or its shear.



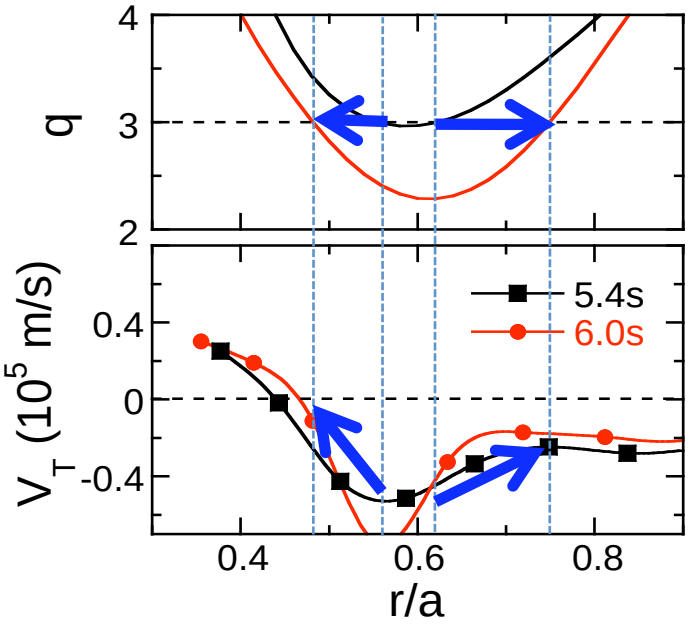
WS plasmas above no wall beta limit

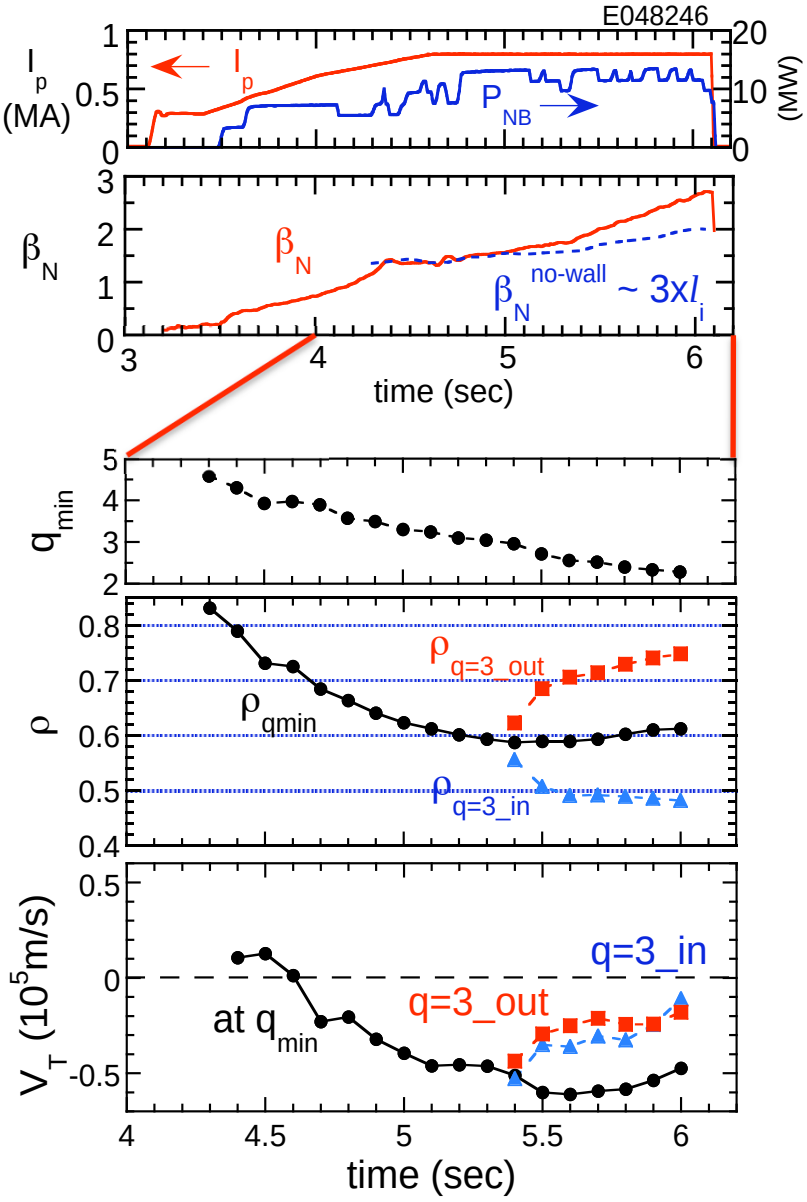


High confinement RS plasmas with high β_N above no wall beta limit

JT-60U

- β_N~2.7, HH_{y2}~1.7, f_{BS}~90% were simultaneously achieved.
- q_{min} decreases towards stationary.
  - Inner q=3 surface moves inward,
  - Outer q=3 surface moves outward.
- V_T at q=3 is reduced.
- Destabilization of RWM seems to be attributed to decrease in toroidal rotation at q=3 surfaces.

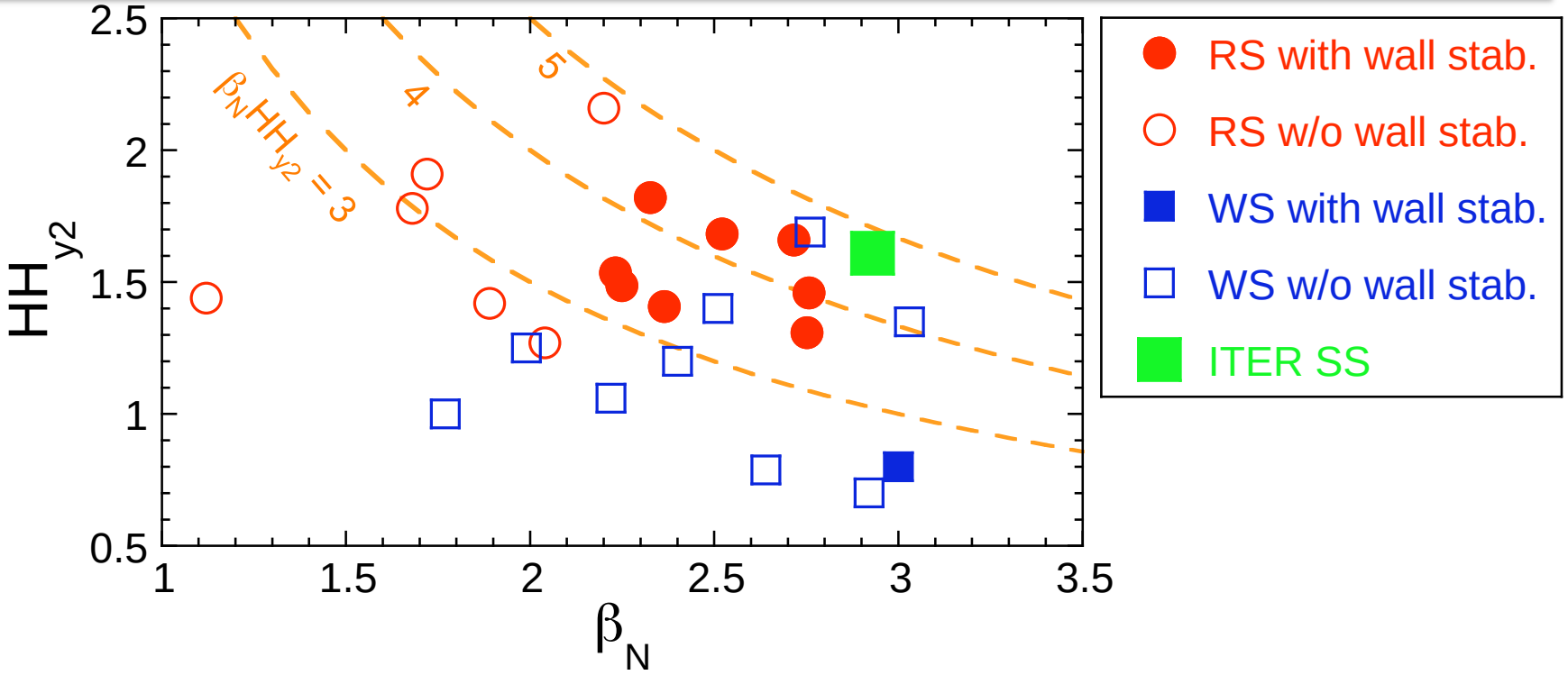




Simultaneous achievement of high beta and high confinement

JT-60U

- Beta limit was improved by RWM stabilization, especially in RS plasma with keeping high confinement.
- High β_N expected in ITER was achieved with high confinement.
- In WS plasma, high β_N with high confinement was obtained without wall stabilization.
- Lower confinement in WS plasma with wall stabilization is attributed to the lack of strong central heating.



2. High density operation with high confinement

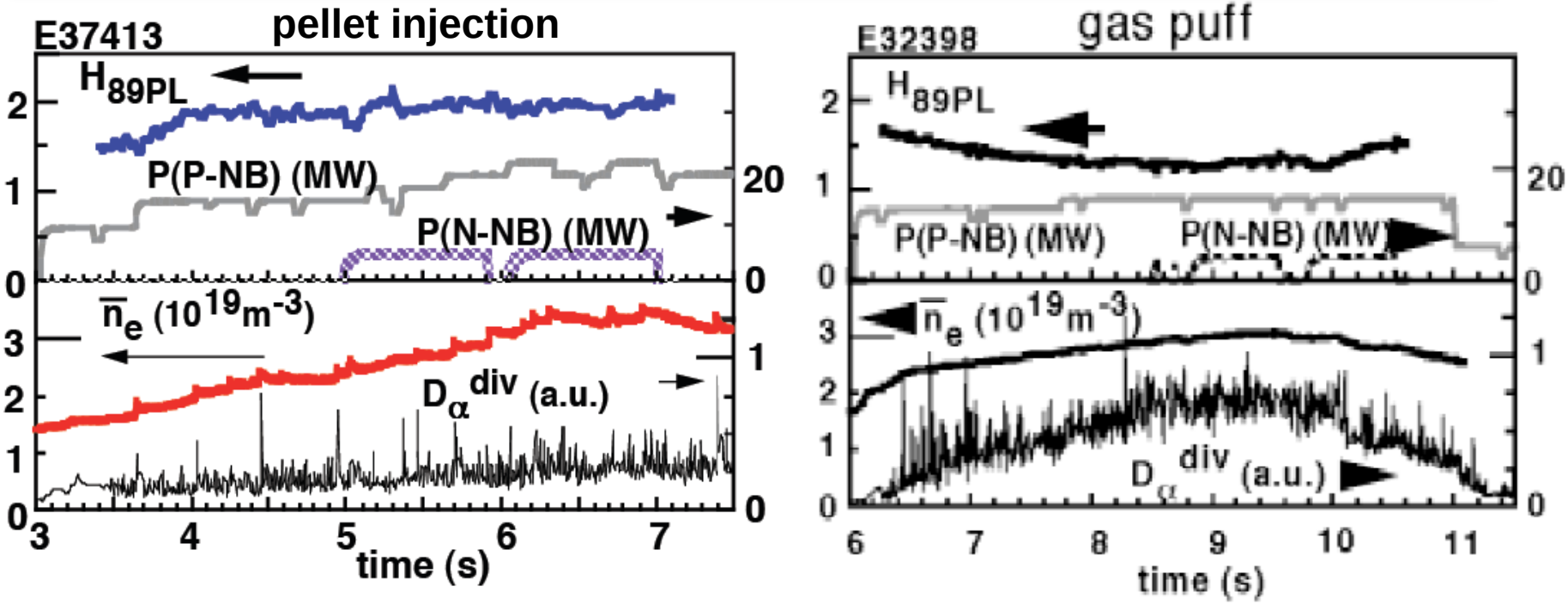
- **Key operations:**
  - **Pellet injection in WS plasma**
  - **Wide ITB in RS plasma**

High confinement was obtained at high density by pellet injection in WS plasma

JT-60U

Weak shear plasma (3.6T, 1.0MA, q_{95}~6.5, δ~0.45)

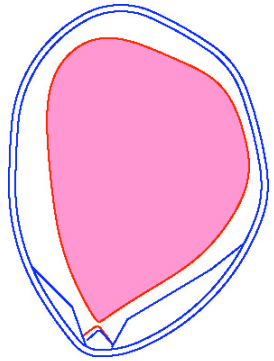
- Pellet injection (HFS(top)).
- HH_{y2}=1.05, β_N=2.2 and f_{BS}~60% at n_e/n_{GW}=0.7.
- Confinement was degraded with gas puffing at similar density.
- High confinement by pellet injection is attributed to keeping high pedestal temperature at similar pedestal density.

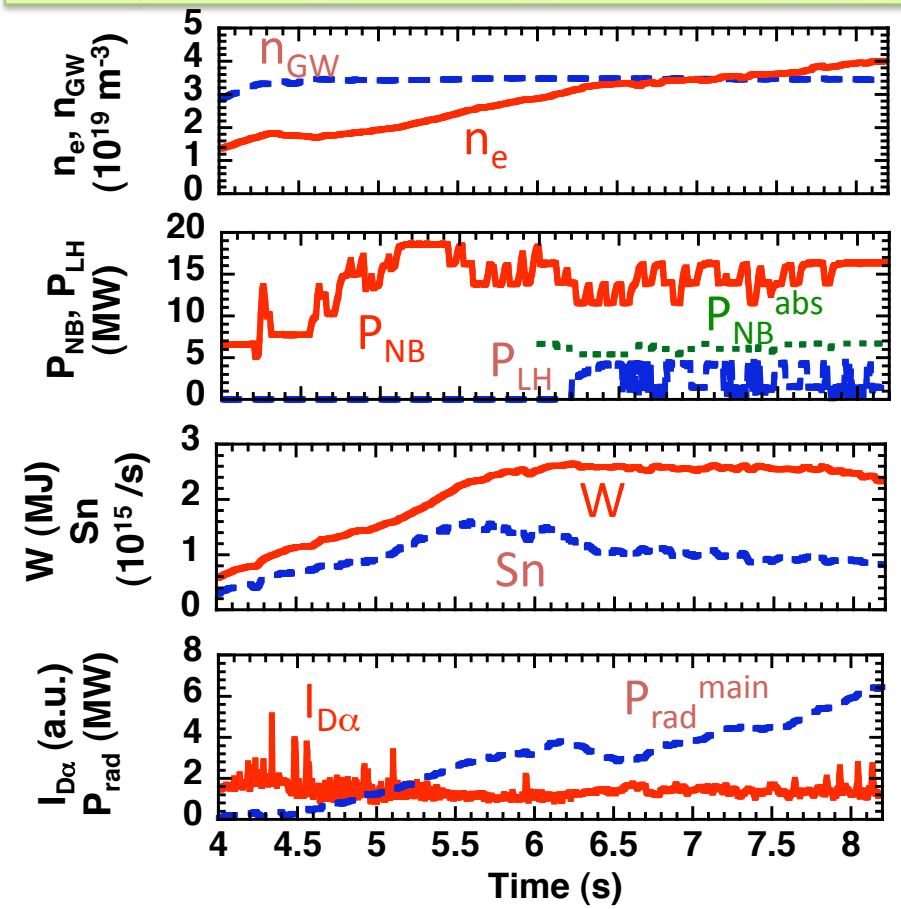


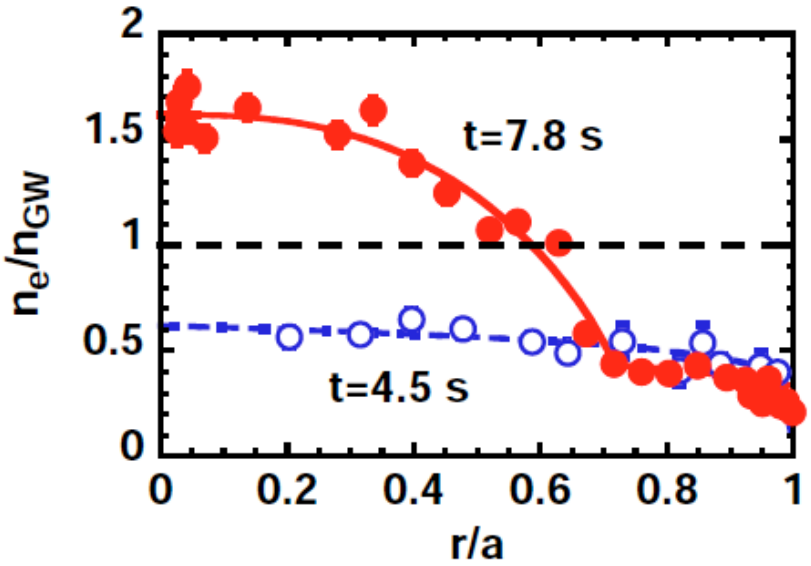
High density above n_{GW} in RS plasma

JT-60U

- Reversed shear plasma (2.5T, 1.0MA, q_{95}~6.1, δ~0.45)
- Large volume configuration for wide radius of density ITB.
- NB fueling only.
- HH_{y2}=1.3, β_N=2 and f_{BS}~70% at n_e/n_{GW}=1.1.



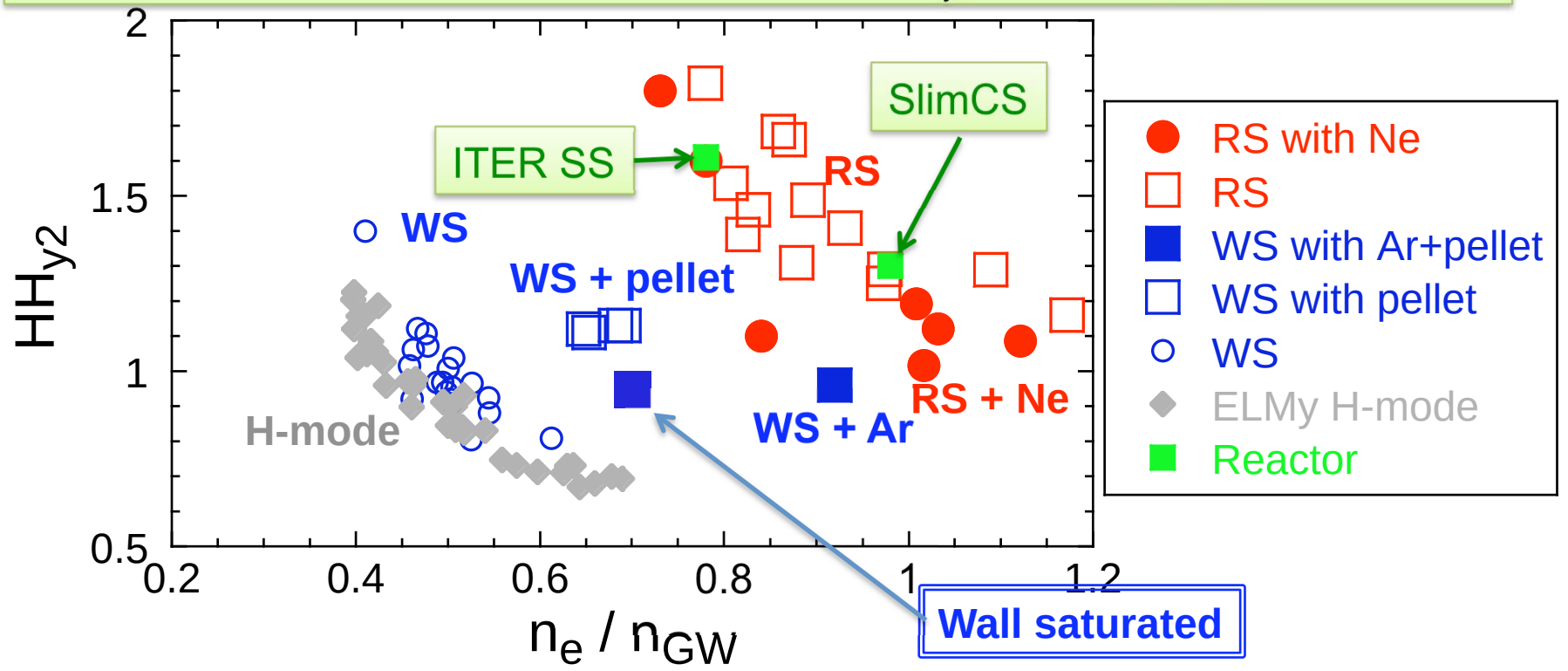




Compatibility of high density and high confinement

JT-60U

- High density operation region was obtained at n_e/n_{GW} ~ 1 with high confinement, especially in RS plasmas.
- In WS plasmas, high density operation region was extended by pellet injection or impurity seeding with small degradation of confinement.
- In the cases of impurity seeding (Ar or Ne), high radiation loss fraction (f_{rad} > 0.9) was also obtained.
- Furthermore, in the wall saturated condition, HH_{y2}~0.95 at n_e/n_{GW}~0.7.



3. Long sustainment with high non-inductive current drive fraction

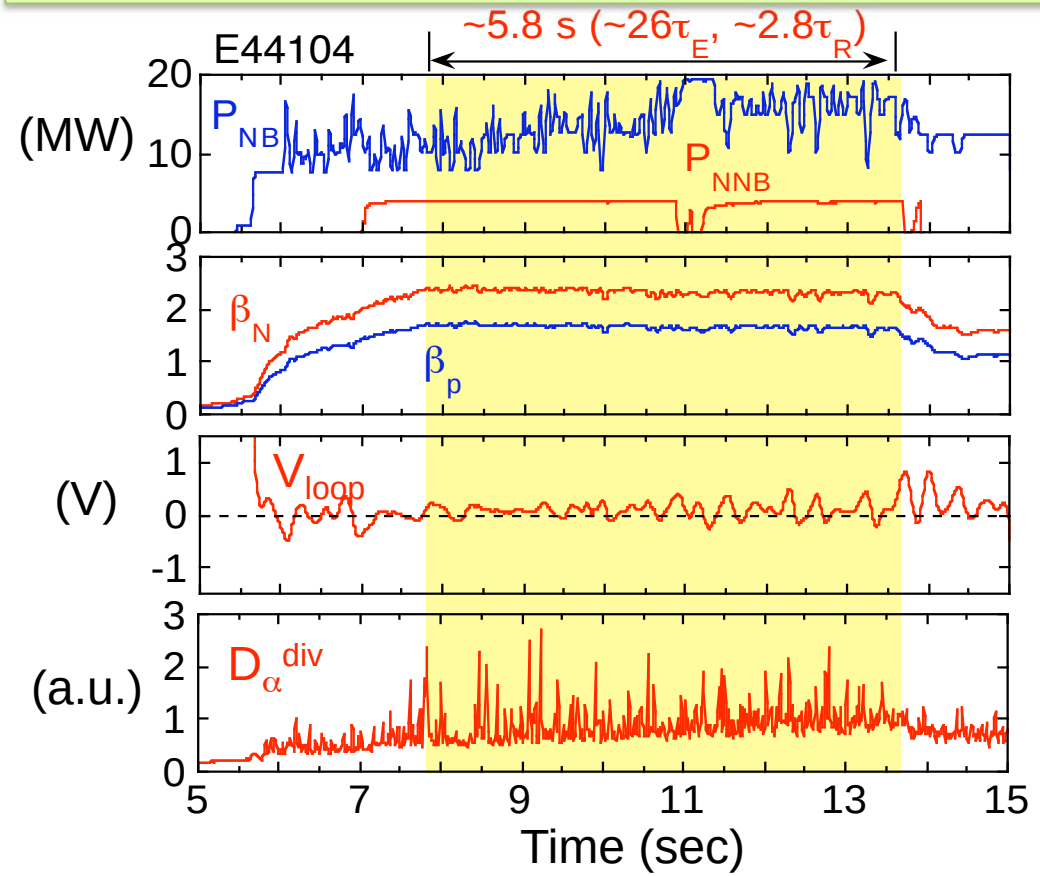
- **Key operations:**
  - **NTM suppression in WS plasma**
  - **ITB control in RS plasma**

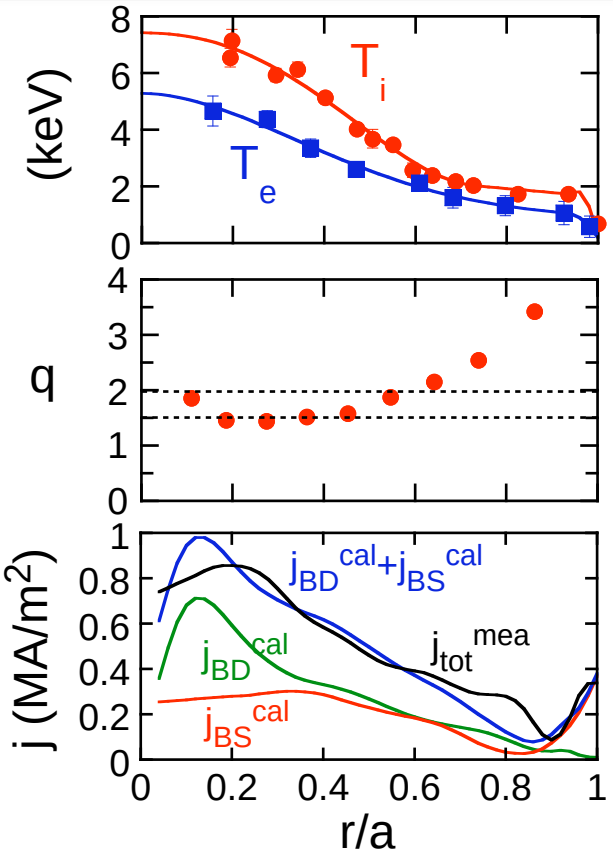
f_{BS}~45% sustained for ~5.8s (~2.8τ_R) under nearly full CD in WS plasma

JT-60U

Weak shear plasma (2.4T, 1.0MA, q_{95}~4.5)

- Removal of q=1.5 for 3/2 NTM suppression by p(r) & j(r) optimization using FB control of stored energy and injection timing of NBs.
- β_N~2.4, f_{BS}~45% and HH_{y2}~1 for 5.8s
- $j_{BS}+j_{BD}$ = 90-100% is close to j_{tot}^{mea} ⇒ Nearly full CD



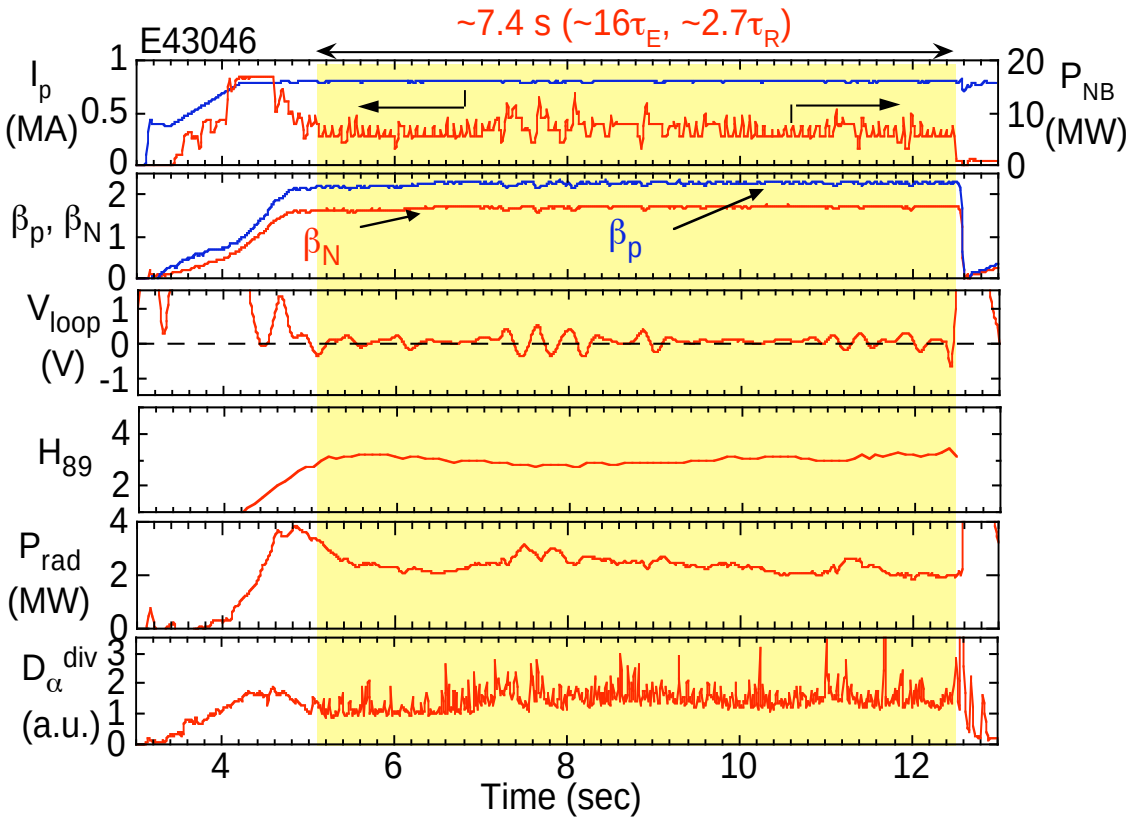


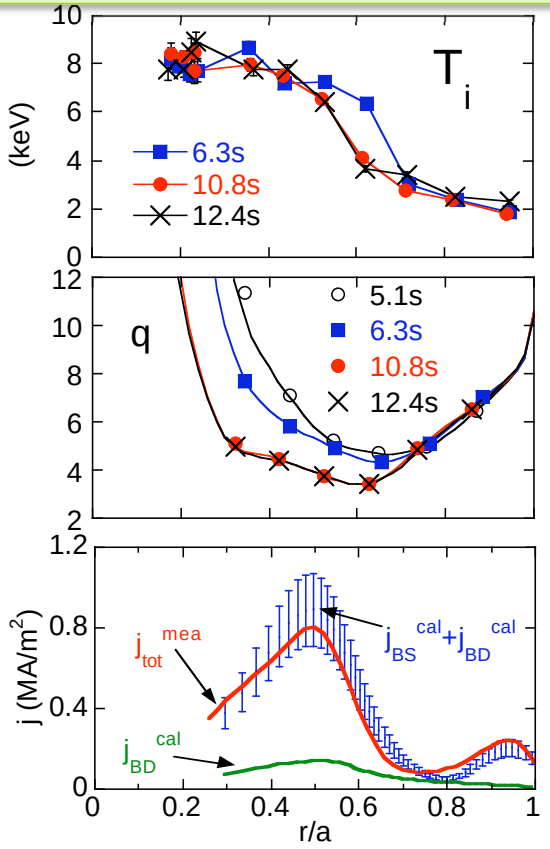
f_{BS}~75% sustained for ~7.4s (~2.7τ_R) under nearly full CD in RS plasma

JT-60U

Reversed shear plasma (3.4T, 0.8MA, q_{95}~8.3)

- β_N~1.7 & f_{BS}~75% were kept constant by feedback control of stored energy.
- Although q_{95} is high, stationary condition of p(r) & j(r) was confirmed.
- $j_{BS}+j_{BD}$ = 95% is close to j_{tot}^{mea} ⇒ Nearly full CD

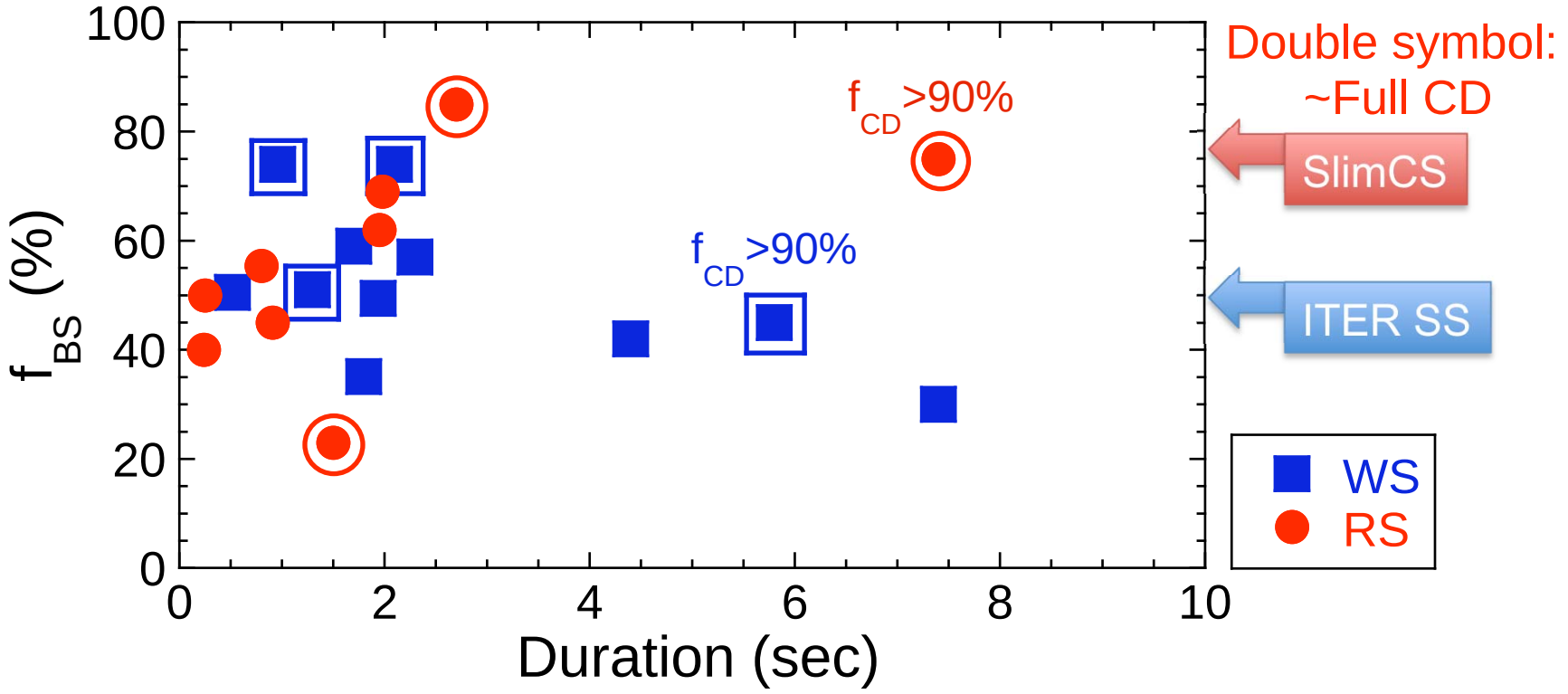




Long sustainment of high f_{BS} plasmas under nearly full-CD

JT-60U

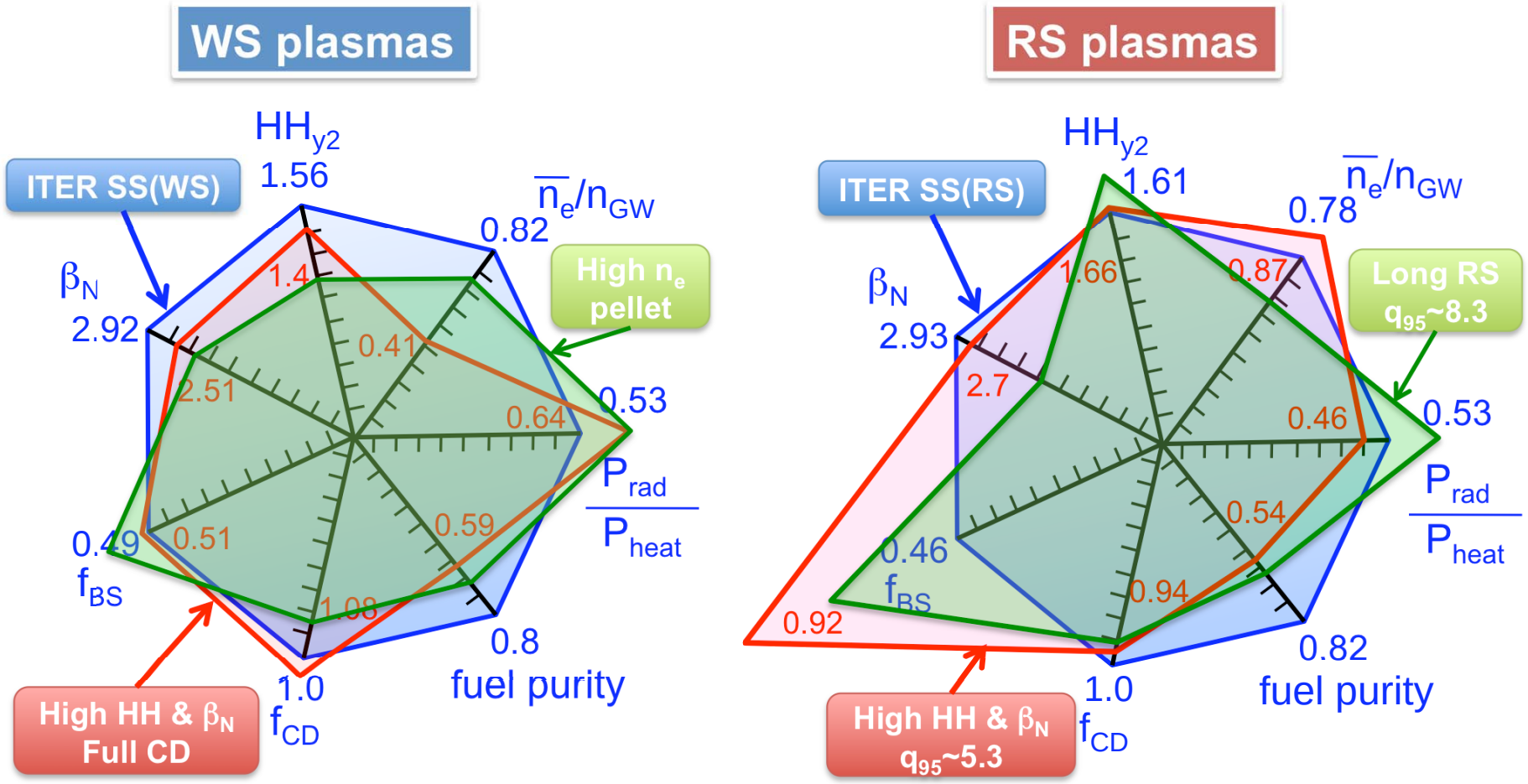
- By optimizing high confinement WS and RS plasmas, sustained duration of high f_{BS} is extended under the nearly full-CD condition.
- High f_{BS} expected in ITER steady state scenario and DEMO reactor is sustained for longer than current diffusion time scale (τ_R).
- Durations are limited by pulse length of NB or NNB.



4. Integrated performance towards DEMO reactor

High integrated performance achieved in WS and RS plasmas

JT-60U



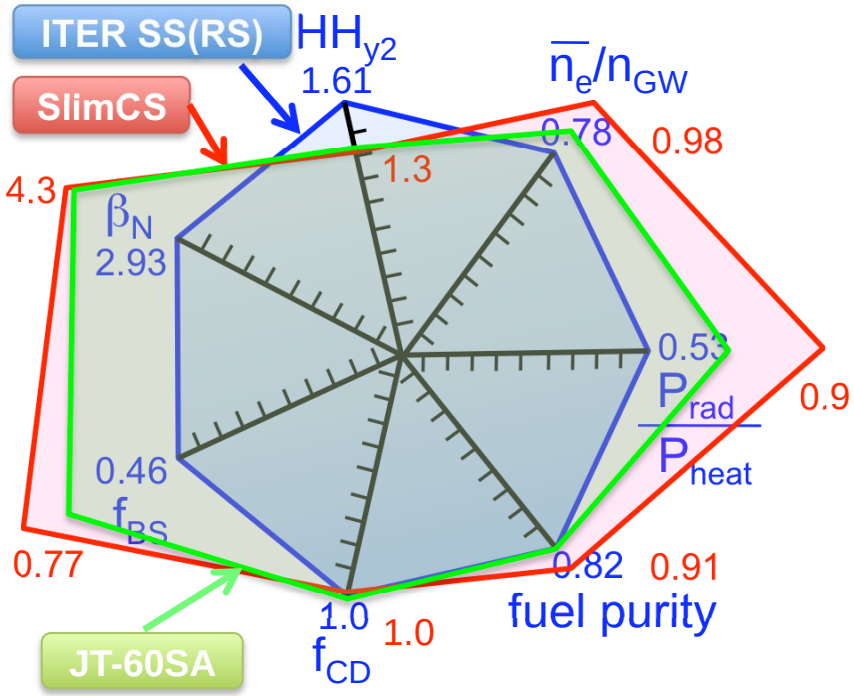
- Some parameters are not satisfied simultaneously
- Long sustainment

: Remaining issues

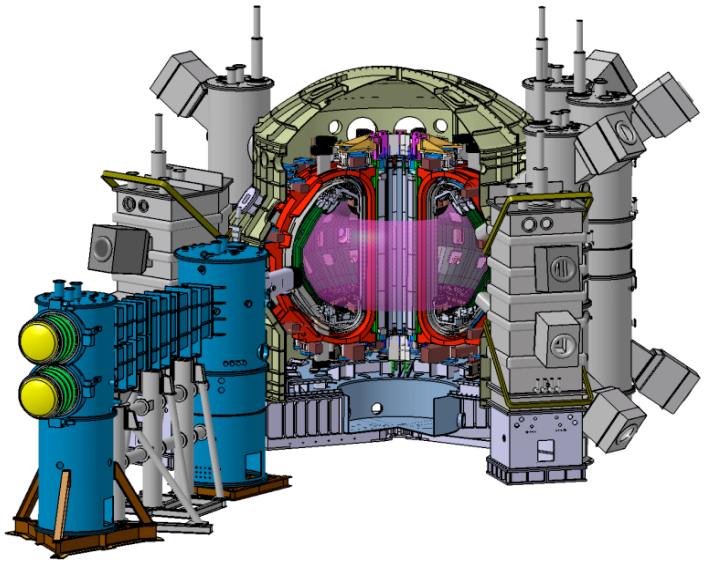
JT-60SA will bridge large gaps between DEMO and ITER

JT-60U

- SlimCS: Economical & compact DEMO reactor with high β_N and f_{BS}.
- Large gaps in design parameters between SlimCS and ITER, especially β_N, f_{BS}, P_{rad}/P_{heat}.
- JT-60SA will address key issues for DEMO, as satellite tokamak of ITER.
  - Demonstration of high beta operation by RWM control coils.
  - Heat and particle control with divertor pumping capability.
- ITER scenario can be improved by results of JT-60SA.



JT-60SA



Summary

- JT-60U tokamak optimized WS and RS plasmas towards steady-state operation of tokamak and demonstrated
  - High beta and high confinement simultaneously
  - Compatibility of high density with high confinement
  - Long sustainment
- High integrated performances were achieved in both plasma regimes.
- There are still remaining issues for high integrated performance and long sustainment.
- JT-60SA will address the remaining issues, as satellite tokamak of ITER.