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Naka Fusion Research Establishment,
Japan Atomic Energy Research Institute

Stationary high confinement plasmas with large bootstrap current fraction in JT-60U

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H. Takenaga, N. Oyama, Y. Kamada and the JT-60 Team

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Steady-state operation of tokamak: Full CD + large f_{BS}

In JT-60U, optimizing advanced tokamak for 10 years

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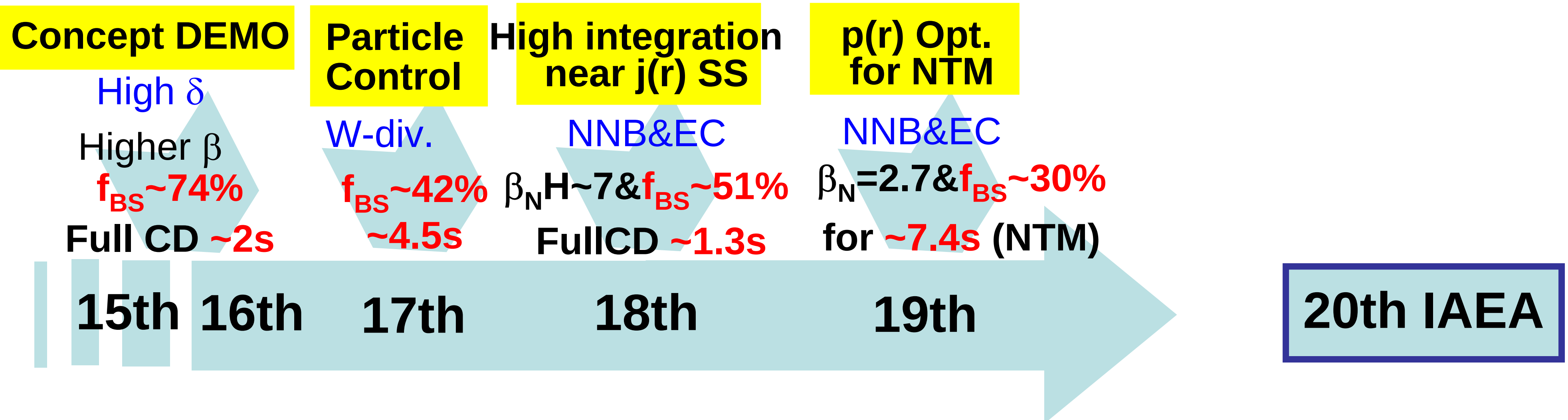

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JT-60U

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In JT-60U, optimizing advanced tokamak for 10 years

High β_p H mode (WS regime): Steady-State / Hybrid

Concept DEMO
High δ
Higher β
f_{BS}~74%
Full CD ~2s

Particle Control
W-div.
f_{BS}~42%
~4.5s

High integration near j(r) SS
NNB&EC
β_NH~7&f_{BS}~51%
FullCD ~1.3s

p(r) Opt. for NTM
NNB&EC
β_N=2.7&f_{BS}~30%
for ~7.4s (NTM)

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f_{BS}~23%
Full CD ~1.5s
LH
RS&ITB Sustain

f_{BS}~80%
Full CD ~2.7s
RS + ELMy H
SS RS near j(r) SS

f_{BS}~62%
Full CD ~0.8s
NNB&LH
j(r) Controlability

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Target:

Long sustain (>τ_R)
Large f_{BS}
Full CD

Reversed shear H mode (RS regime): Steady-state

Progress of long sustainment of large f_{BS} under nearly full non-inductive CD

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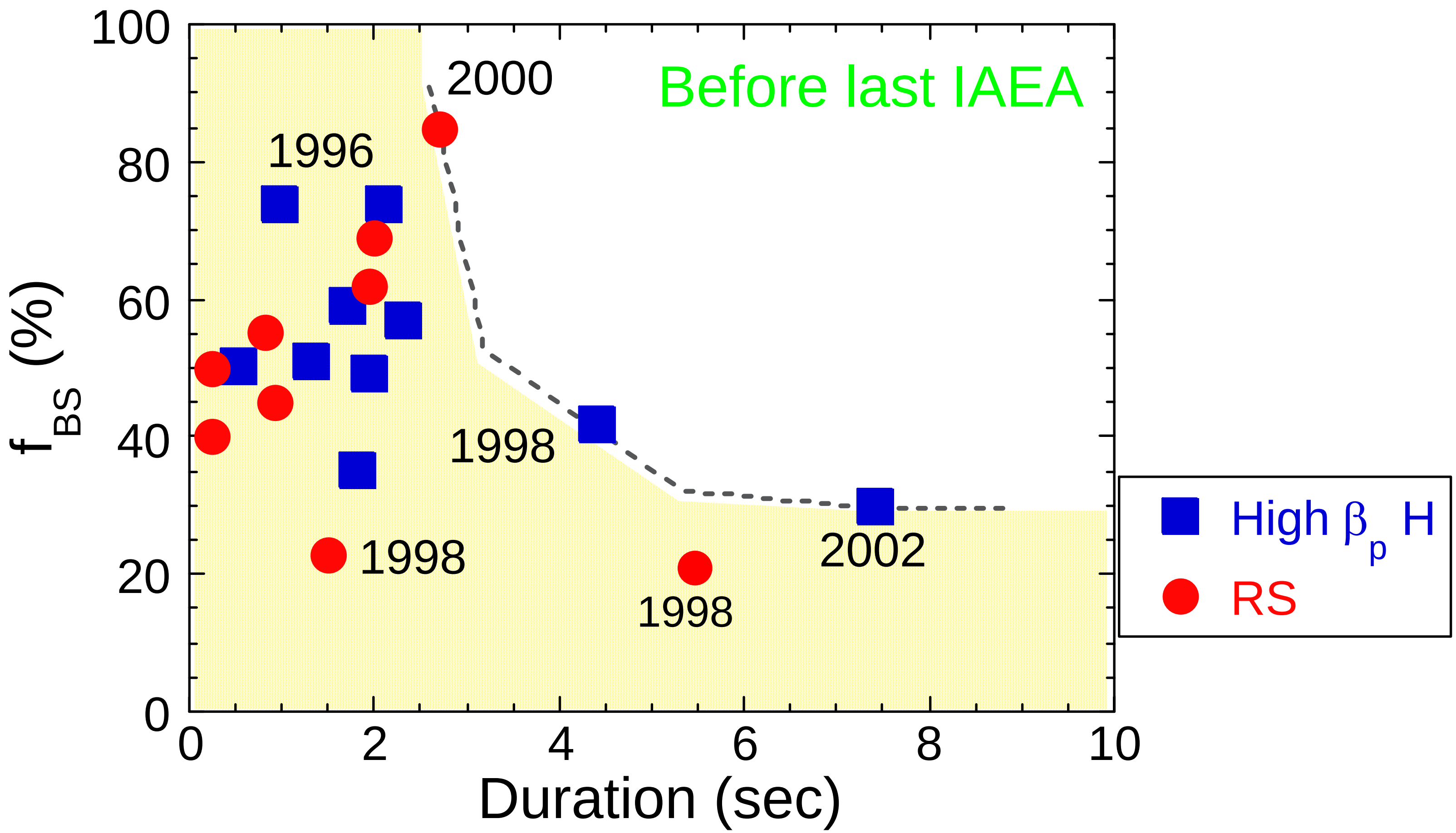

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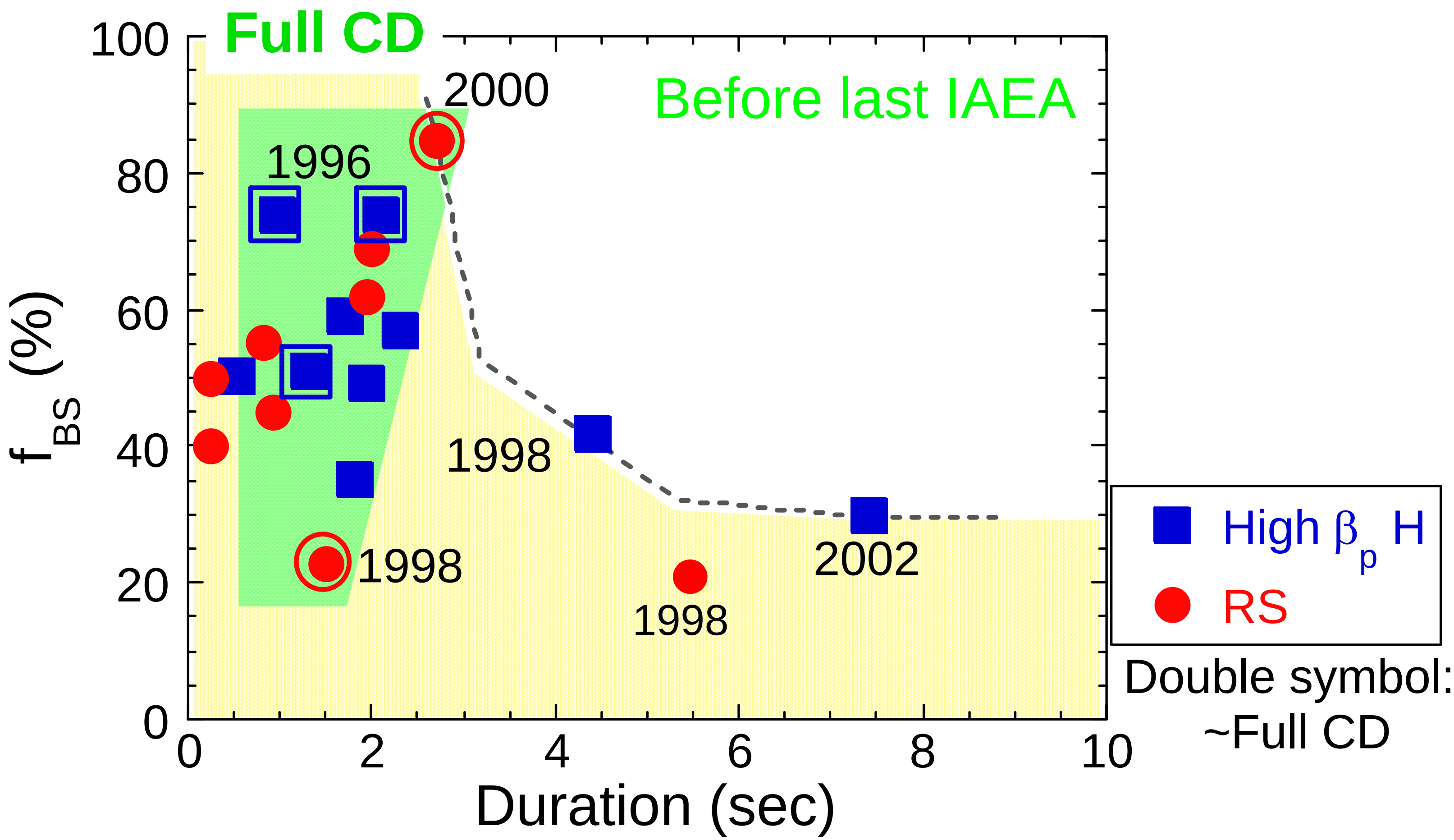

Progress of long sustainment of large f_{BS} under nearly full non-inductive CD

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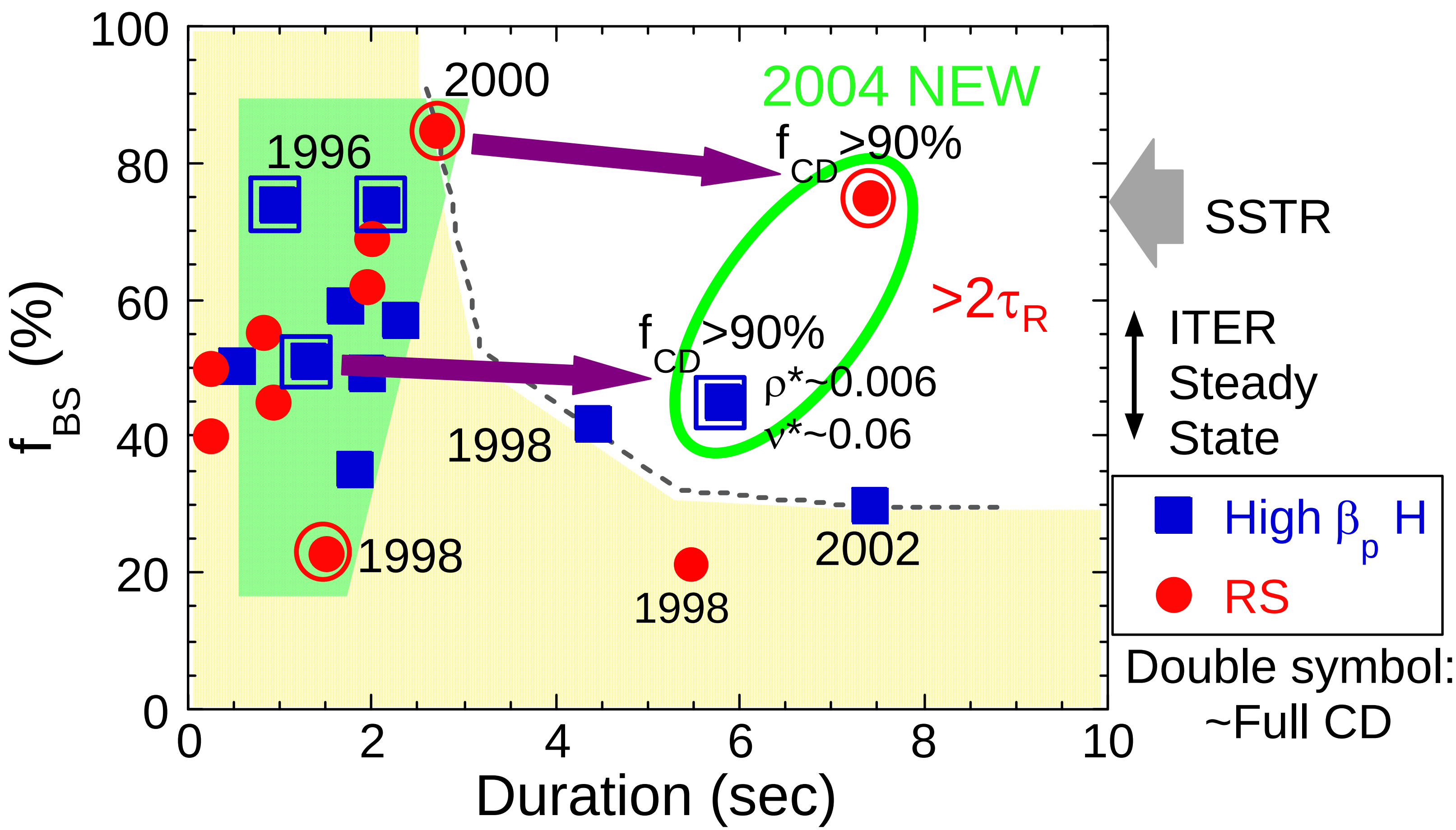
Achieved region of large f_{BS} has significantly been extended.



Weak shear plasma regime towards ITER steady state scenario

Issue :

Avoidance of NTMs

Key :

Optimization of q profile (q_{95}~4.5)

Quite low q_{95}~2.2 (T. Suzuki, EX1-3)

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

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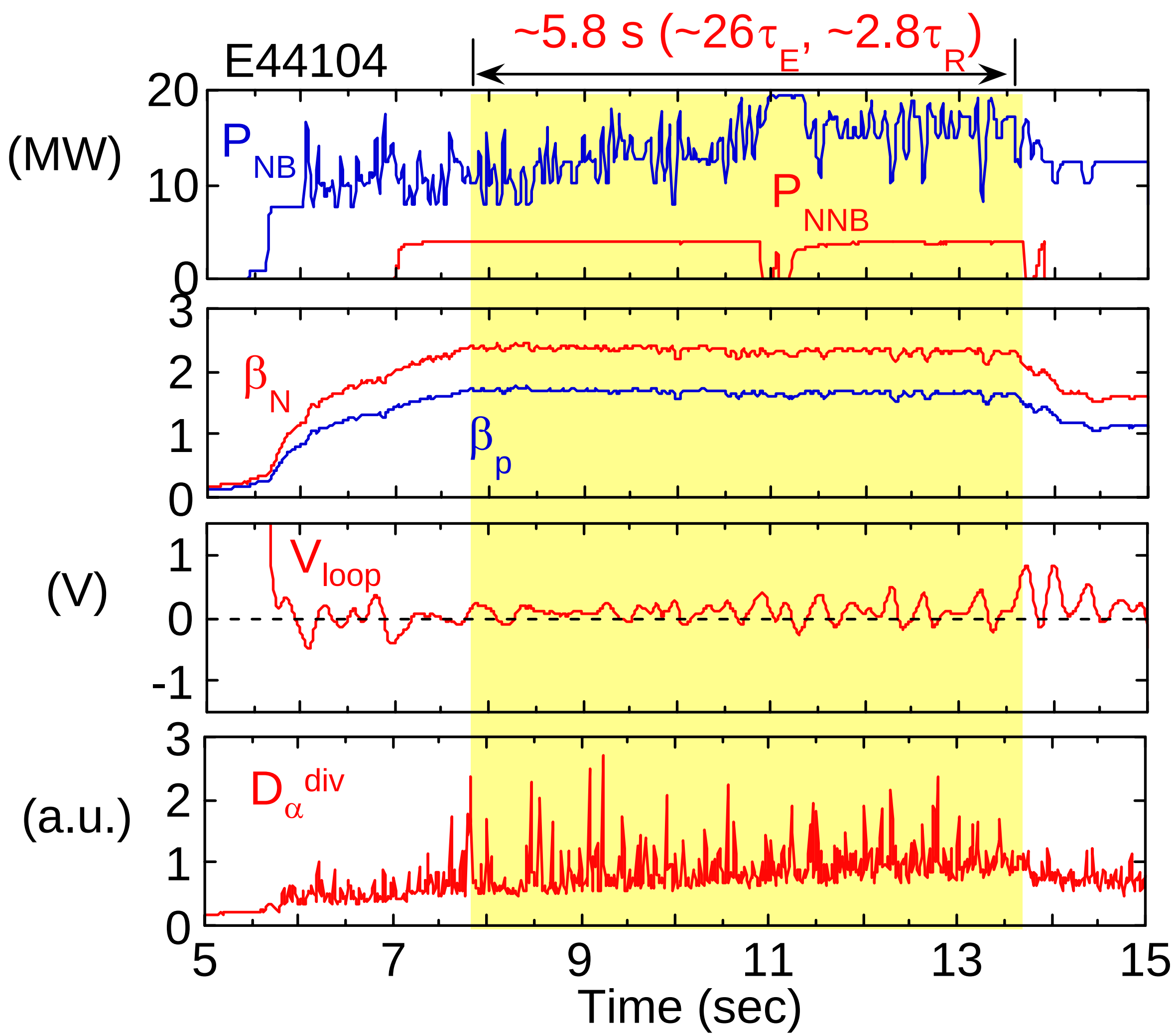
Scenario: High β_p ELMy H-mode (2.4T, 1MA, q_{95}~4.5, δ~0.5)

Non inductive CD: P_{NB}^{inj}(co)~4.5MW & P_{NNB}^{inj}~4MW & Bootstrap



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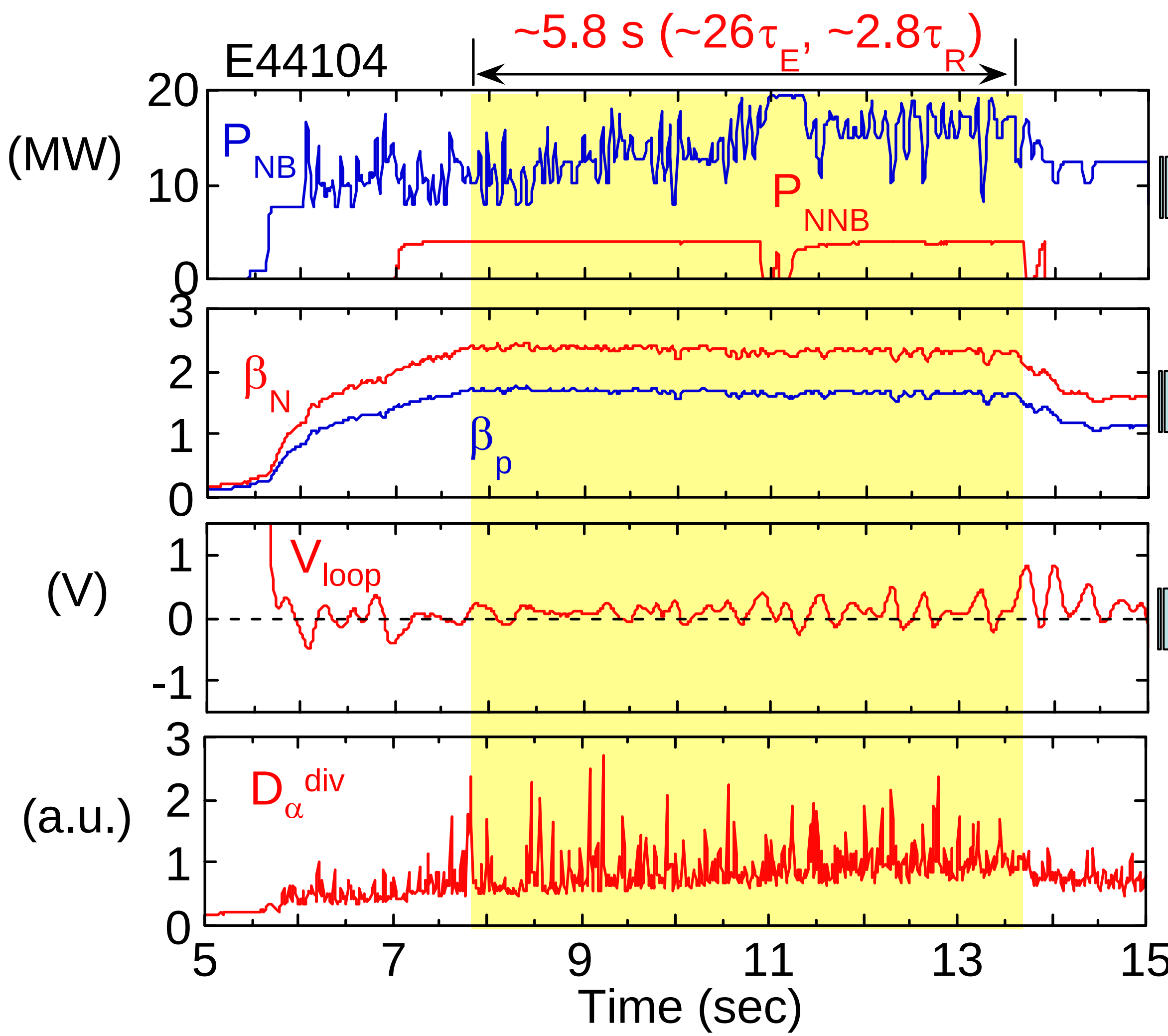

Duration was limited by NNB

β_N~2.4, β_p~1.75 were kept constant by feedback control of stored energy

Loop voltage is almost zero,

➡ Nearly full CD

f_{CD}=90-100% for ~5.8s

(f_{BS}~50-43%, f_{BD}~52-47%)

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

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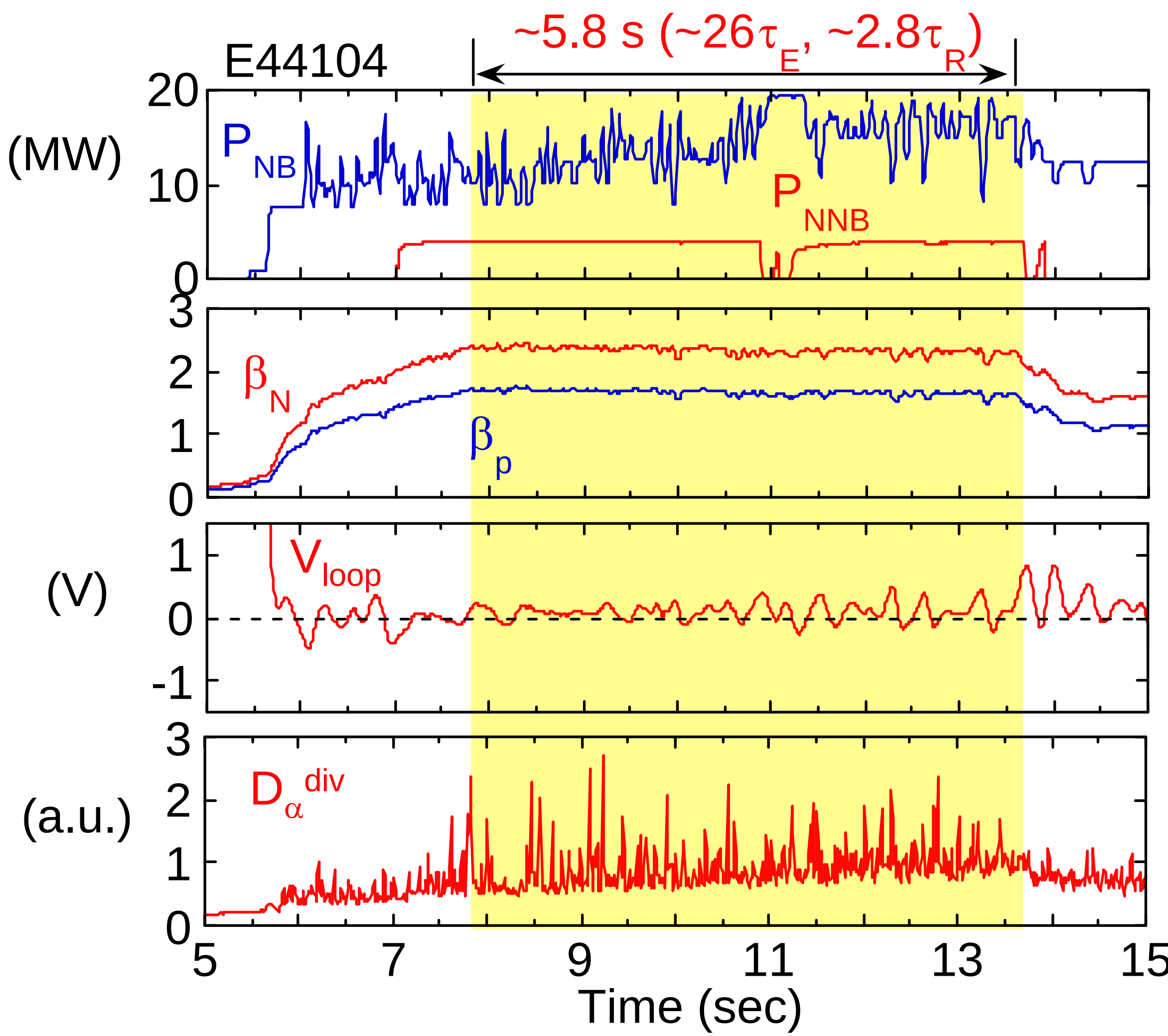
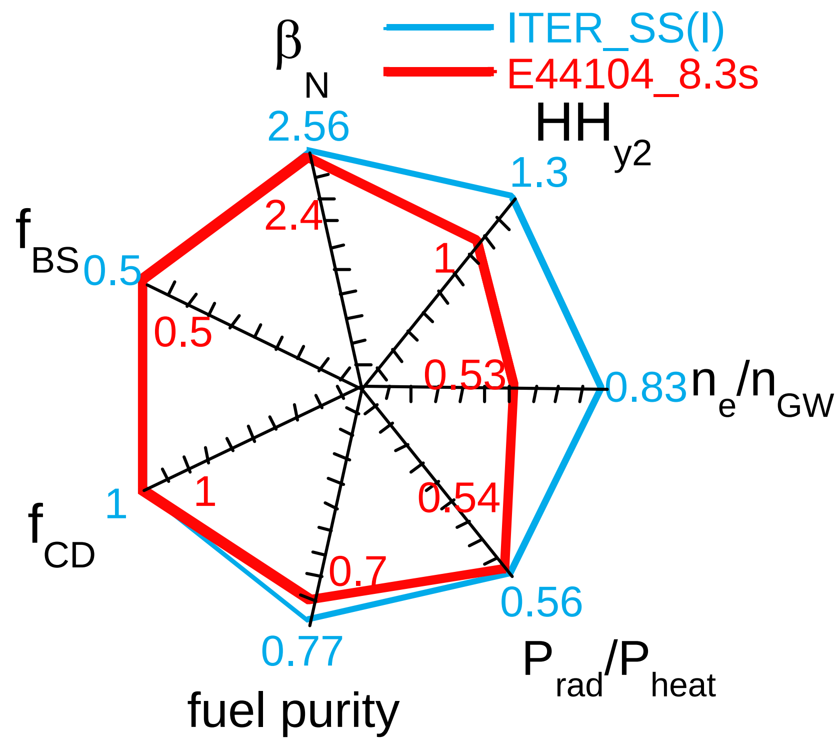


High integrated performance was achieved towards ITER SS



No NTM was observed

Avoidance of NTM by optimization of q(r)

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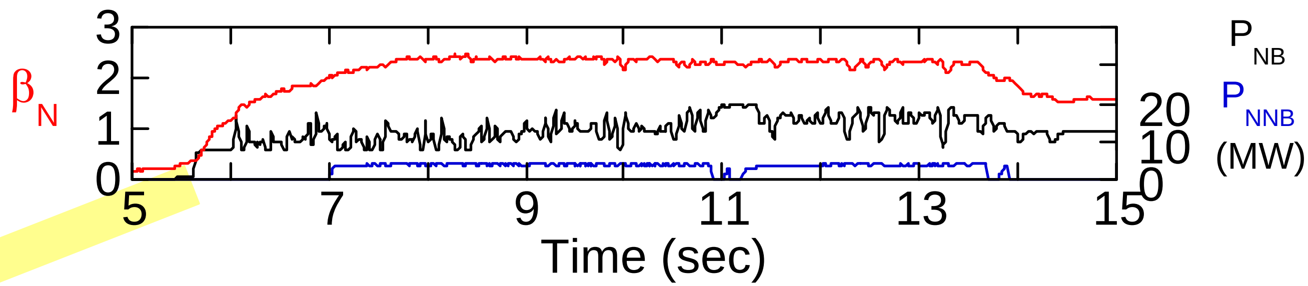
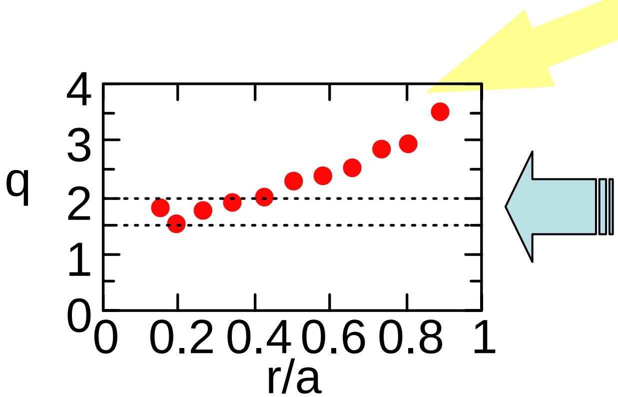
Avoidance of NTM: alignment of ∇p and q=m/n (3/2, 2/1,..)

p(r) and q(r): optimized by feedback control of W_{dia} and injection timing of NBs





NB injection before penetration of current
q(r)>1.5

Avoidance of NTM by optimization of q(r)

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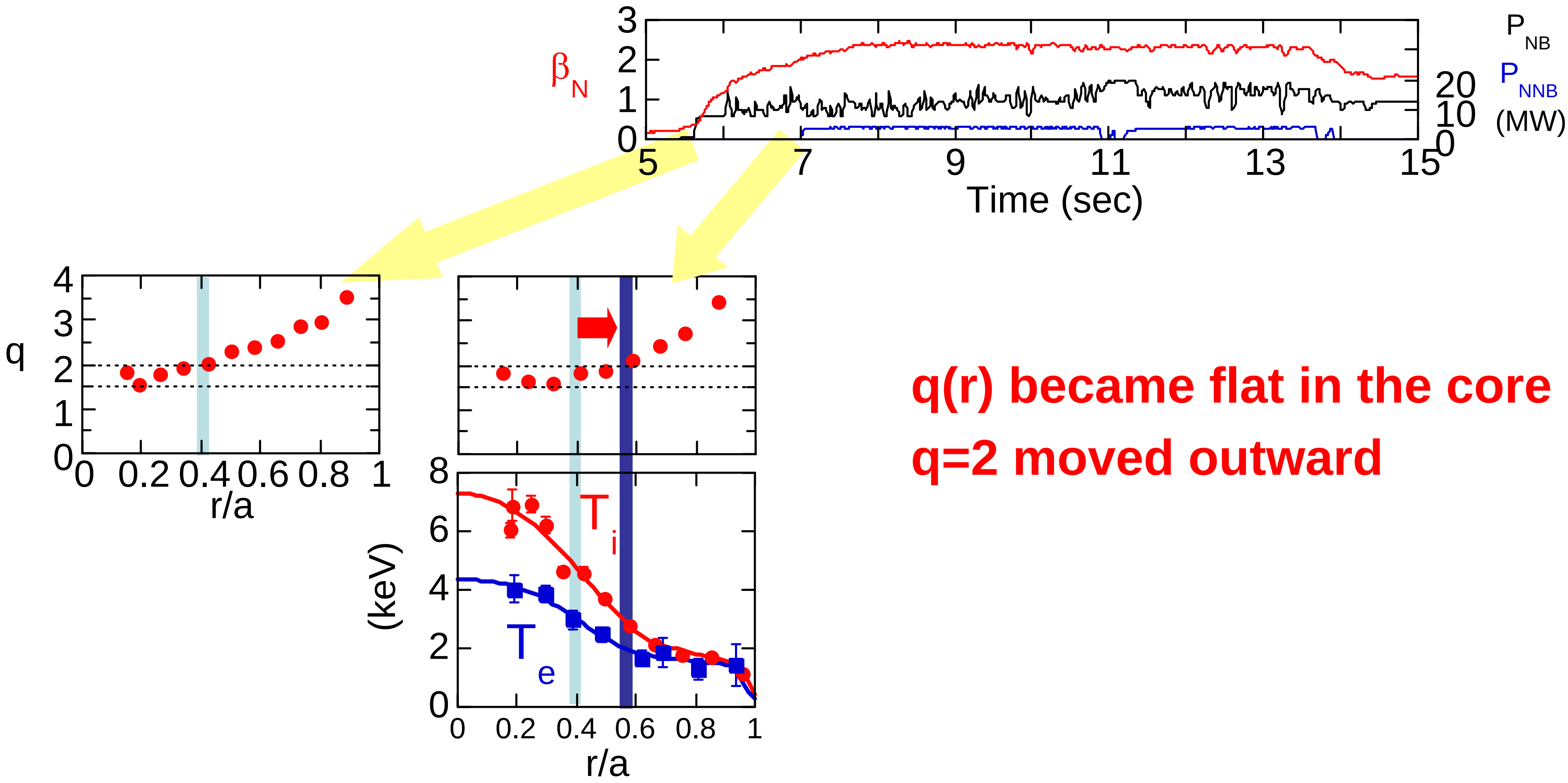

q(r) became flat in the core

q=2 moved outward

Avoidance of NTM by optimization of q(r)

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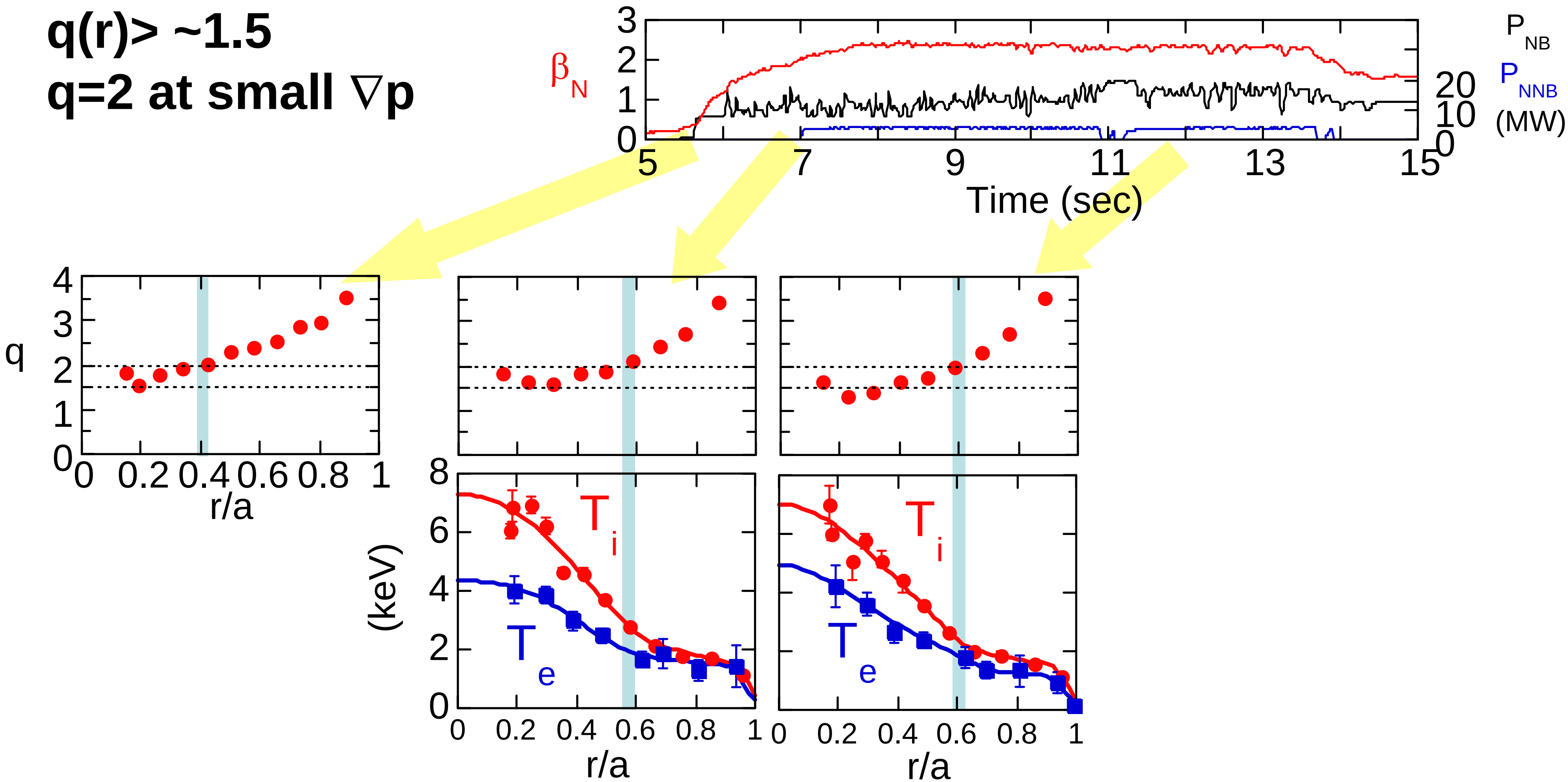
Avoidance of NTM: alignment of ∇p and q=m/n (3/2, 2/1,..)

p(r) and q(r): optimized by feedback control (W_{dia}) and injection timing of NBs

q(r)> ~1.5
q=2 at small ∇p



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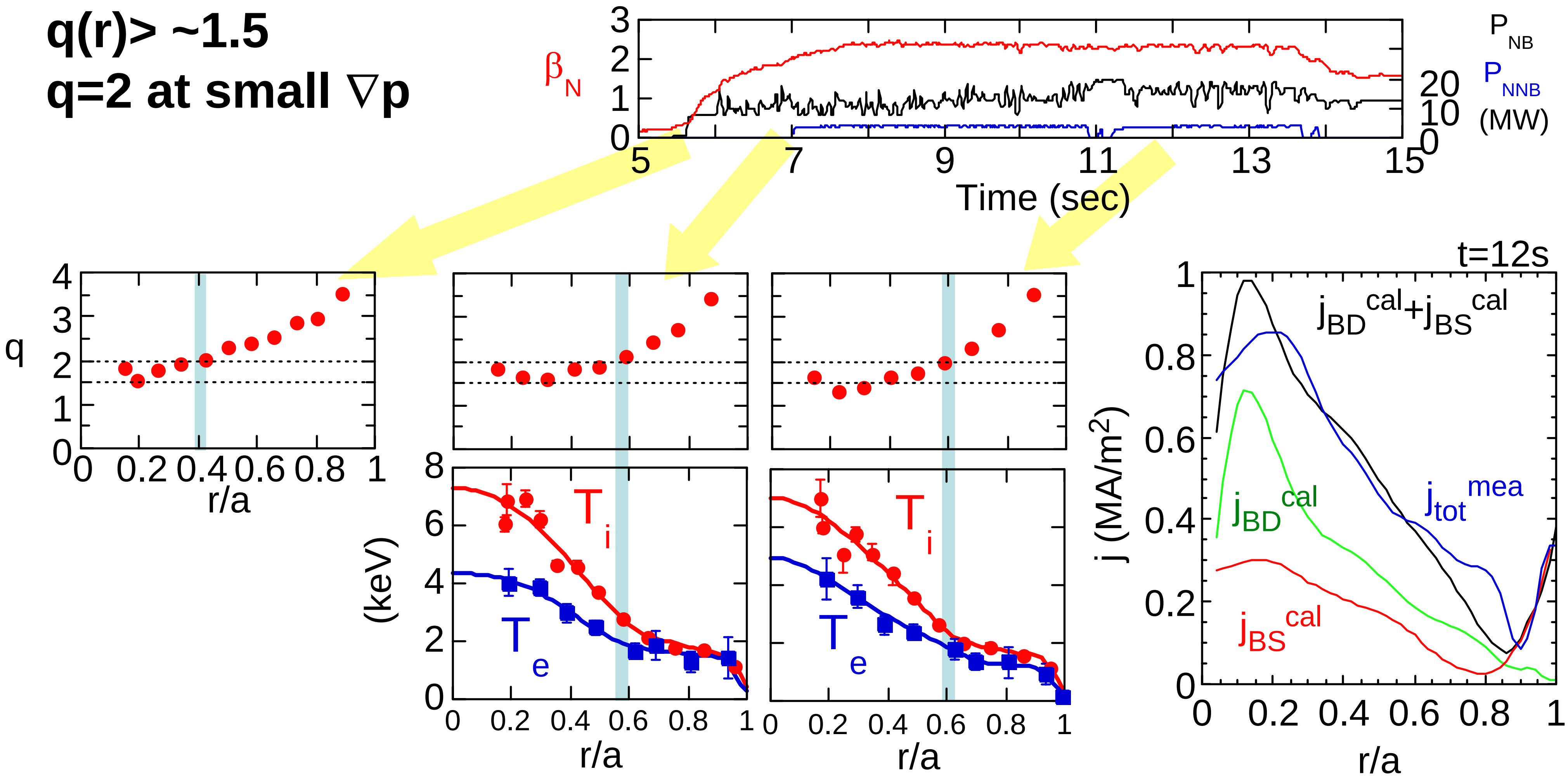


Reversed shear plasma regime with larger bootstrap current fraction

Target :

Long sustainment (>τ_R)

large f_{BS} under full CD

Issue :

ITB control

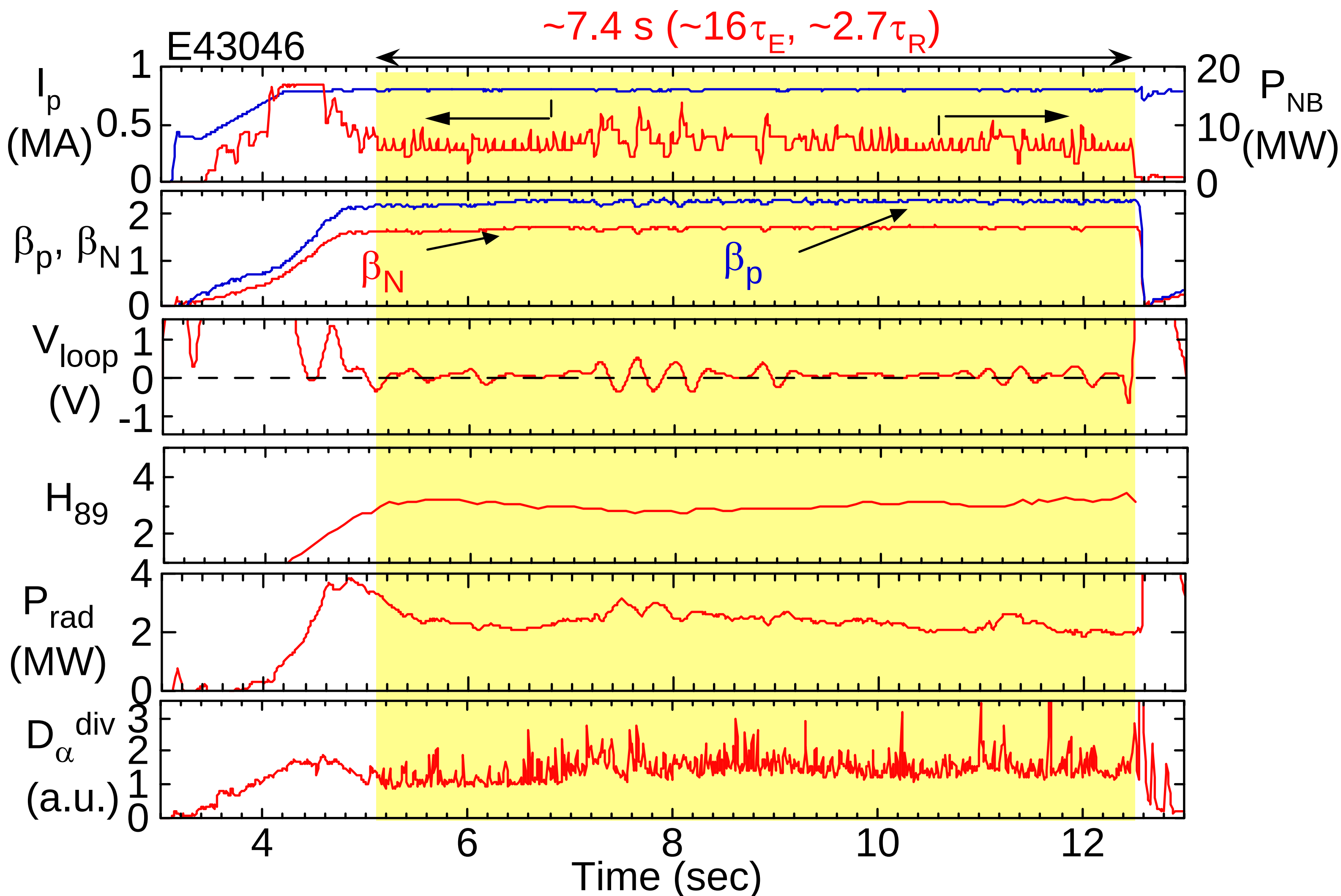
under the plasma with large f_{BS} characterized by strong linkage between p(r) & j(r).

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

JT-60U

Scenario: Reversed shear ELMy H-mode (3.4T, 0.8MA, q_{95}~8.6, δ~0.42)

Non-inductive CD: Bootstrap dominant & P_{NB}^{inj}(co)=3.2MW



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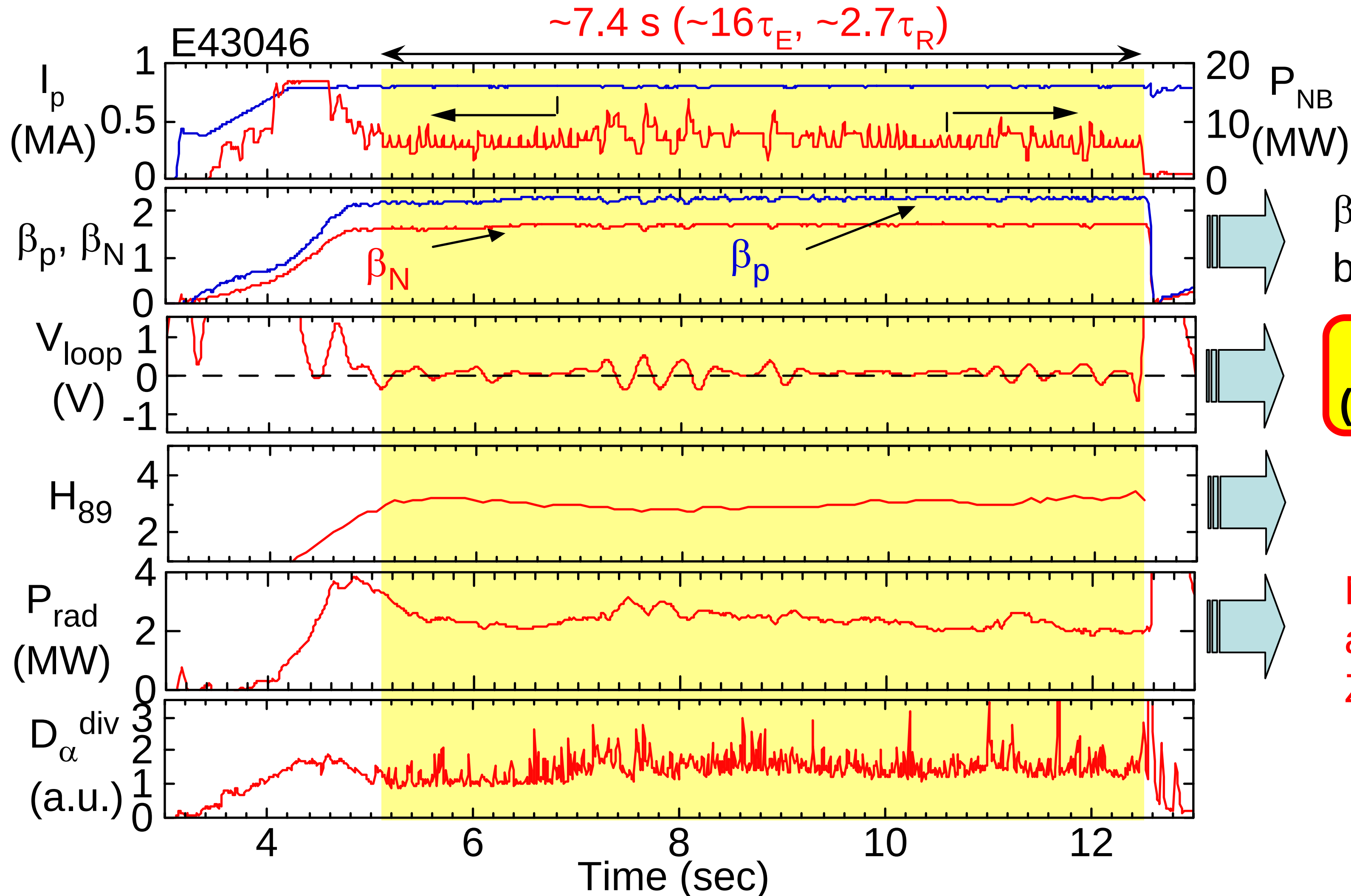


Duration was limited by NB injection.

β_N~1.7, β_p~2.25 by feedback control

f_{CD}=95% for ~7.4s (f_{BS}~75%, f_{BD}~20%)

H_{89}~3, HH_{y2}~1.7

No strong impurity accumulation
Z_{eff}: constant (~3)

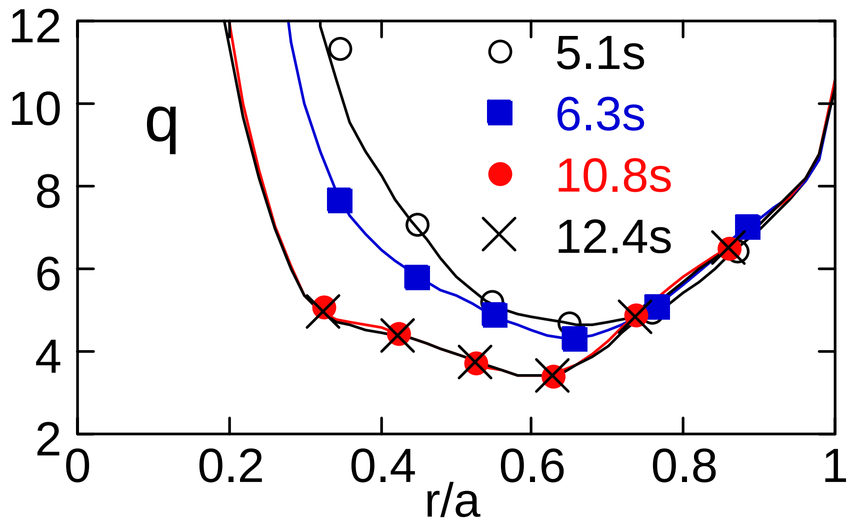
q and pressure profiles reached stationary condition with f_{BS}~75%

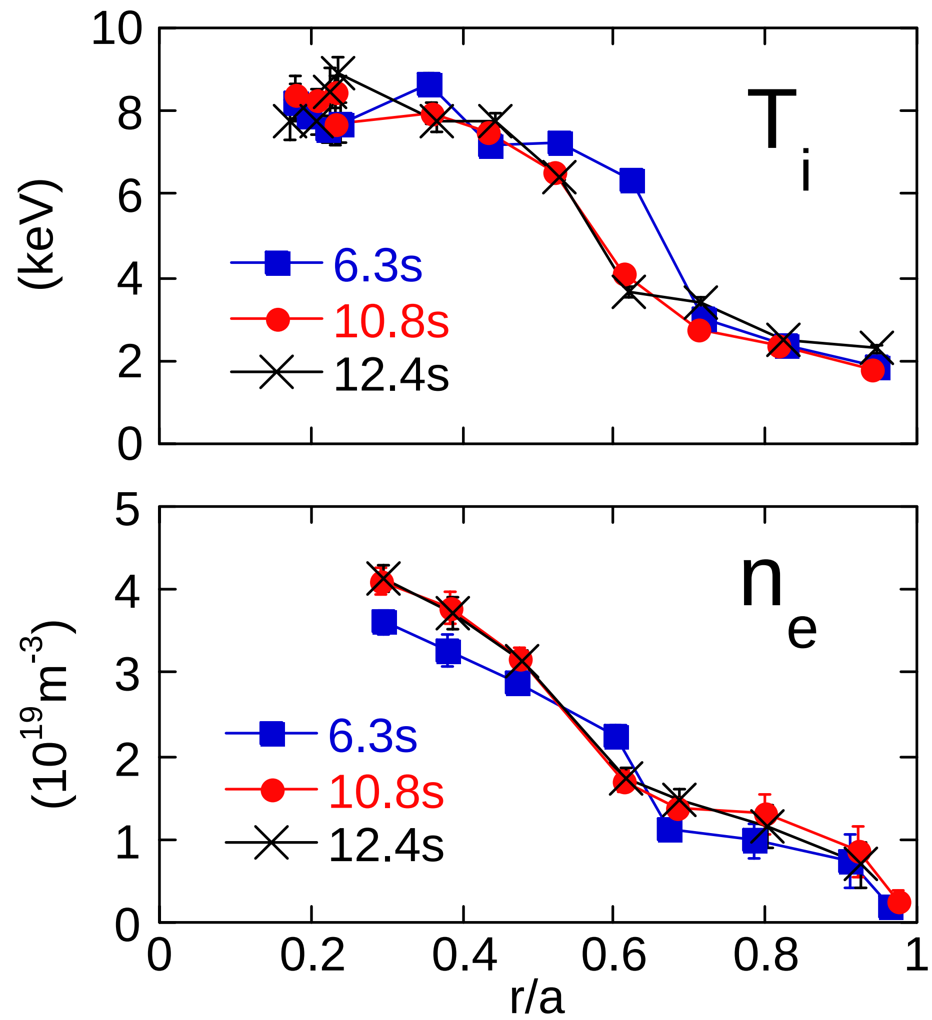
JT-60U

Strong RS (s~-1.5) --> Weaker (s~-0.8)

ITB & ETB are formed.

ITB radii decrease by change in q(r).





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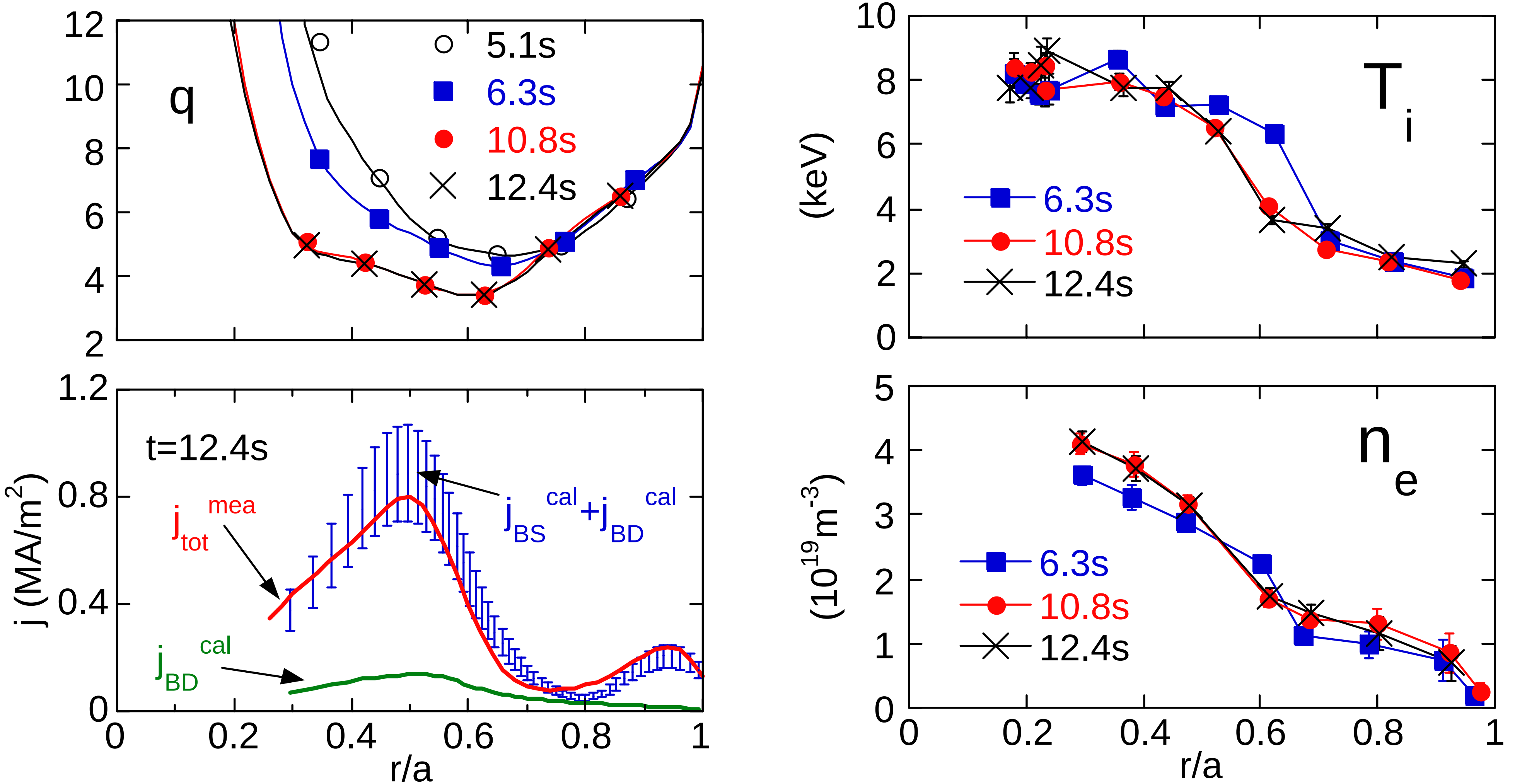
JT-60U

Strong RS (s~-1.5) --> Weaker (s~-0.8)

$j_{BS} + j_{BD}$ agrees well j_{tot} --> j_{OH} is small

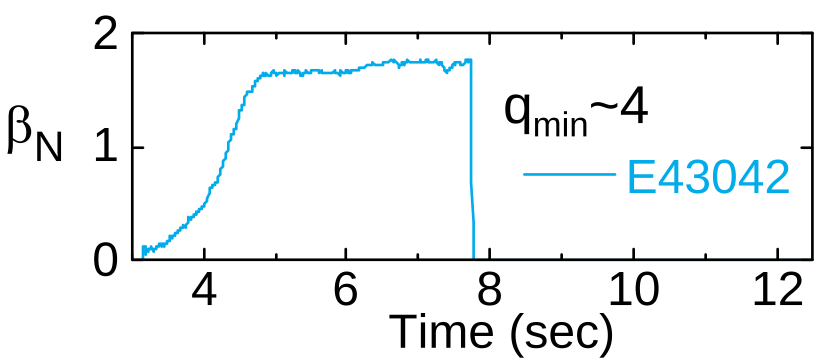
ITB & ETB are formed.

ITB radii decrease by change in q(r).



∇T_i reduction at ITB through rotation control enable long sustainment

Reversed shear plasma frequently disrupted at q_{min}~integer.



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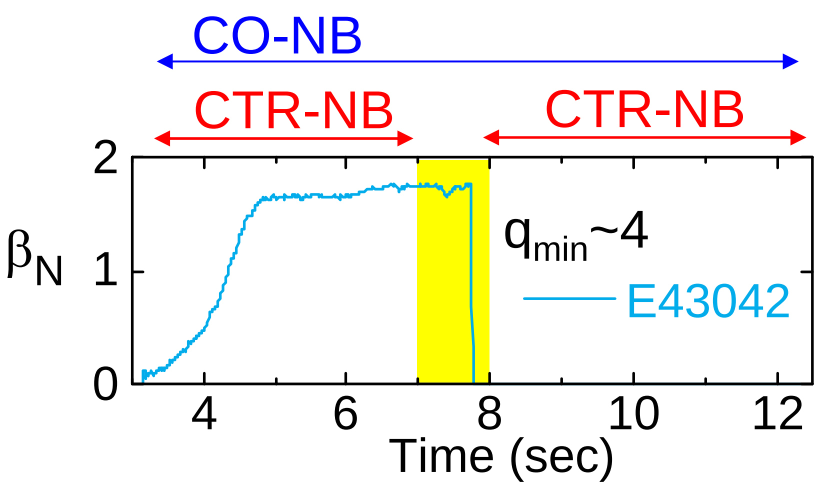
ITB control by toroidal rotation to avoid disruption for the plasma with strong linkage between p(r) & j(r). ⬅ ITB control by V_T: IAEA 2000 (Y. Sakamoto)



In this phase,
combination of tang-NB was changed
from CO(~3MW)+CTR(~0.8MW)
to CO(~3MW) + no CTR.
This change drives CO rotation.

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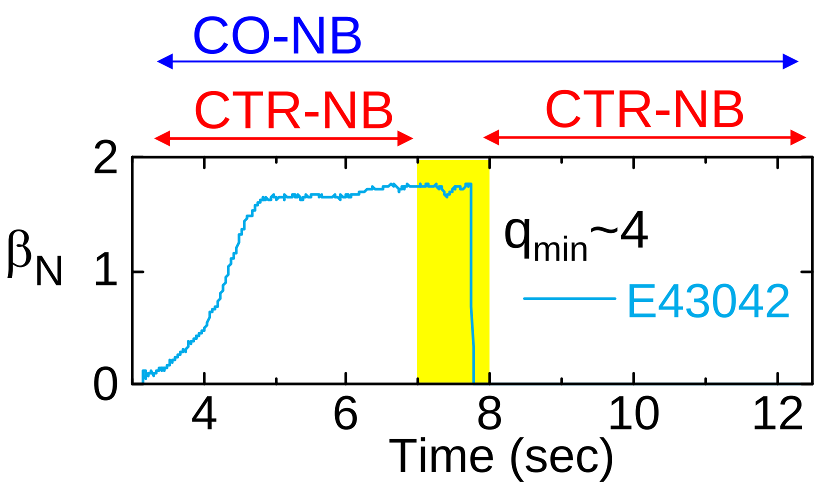

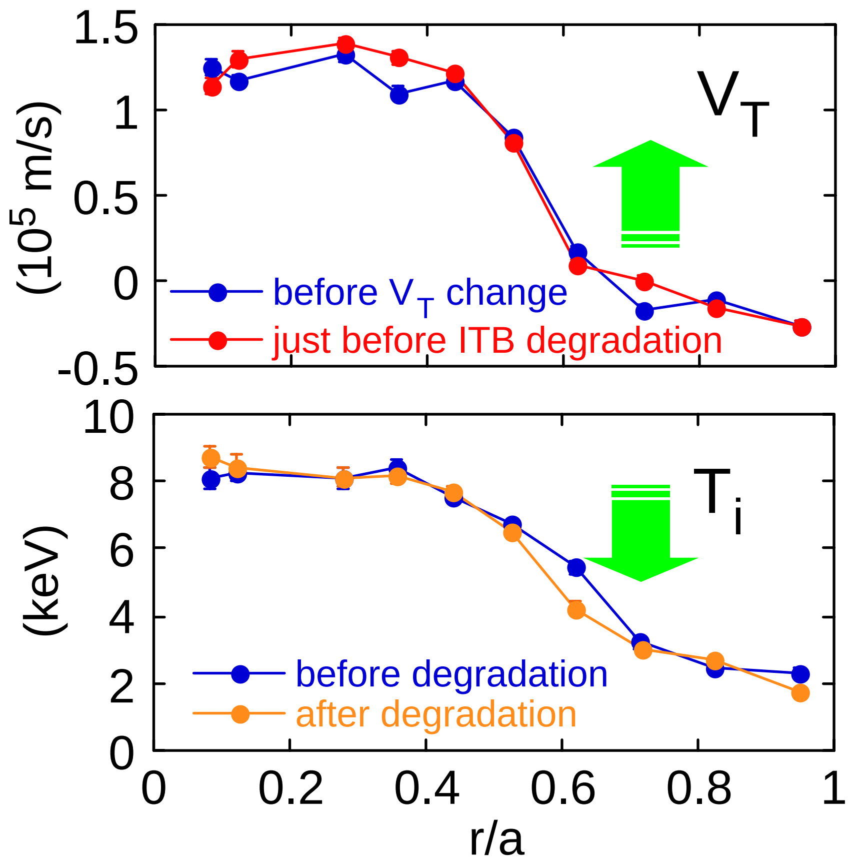

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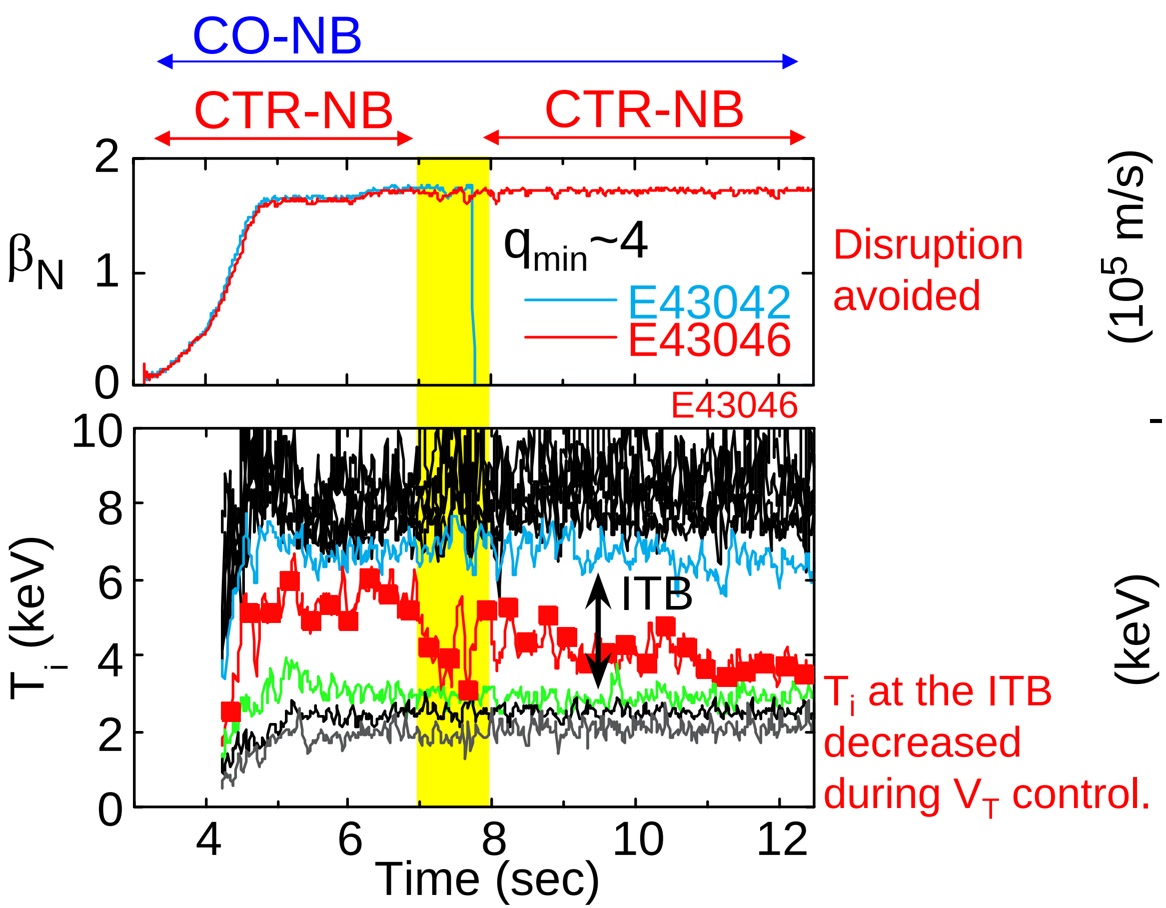

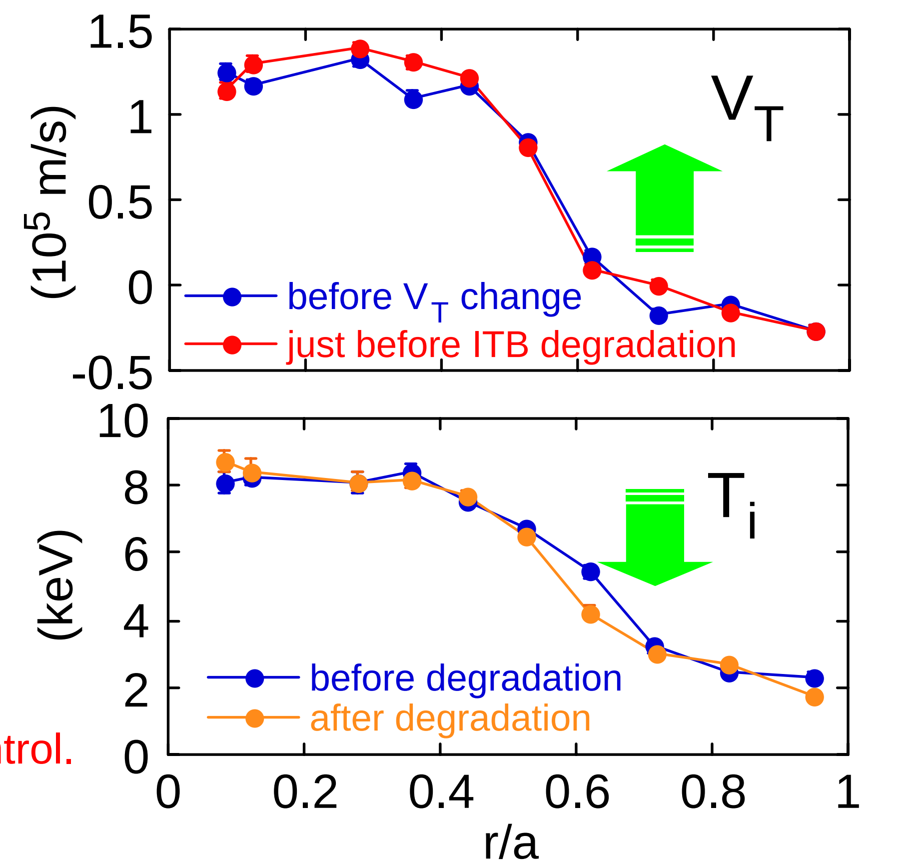

Summary

Towards steady state operation of tokamak,

JT-60U has made significant progress in terms of

long sustainment of plasmas with large f_{BS} in two regimes.

(1) Weak shear regime

High integrated performance plasma with f_{BS}~45% was sustained for ~5.8s (~2.8τ_R) under nearly full non-inductive CD.

(2) Reversed shear regime

Quite high confinement (HH~1.7) plasma with f_{BS}~75% was sustained for ~7.4s (~2.7τ_R) under nearly full non-inductive CD.

ITB control through rotation for the plasma with strong linkage between p(r) & j(r) was demonstrated, which enable long sustainment.