SOFE05
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Current Status of Experimental Study and Device Modifications in JT-60U

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Outline

1. Modifications for Long Pulse Operation
   15 s =>65 s
   - Field Coil Power Supplies
   - Heating Devices: P-NBI, N-NBI, ECH, LHH
2. Extension of Advanced Tokamak (AT) Operation
3. Exploration to AT Operation with a Higher β_N and f_{BS} Steady-state Plasma
   3.1 Precise Plasma Equilibrium Observer
   3.2 Current Profile Feedback Control
   3.3 Ferritic Steel Tiles Insertion for TF Ripple Reduction for AT Research
4. Summary

Steps toward a Steady-State Reactor

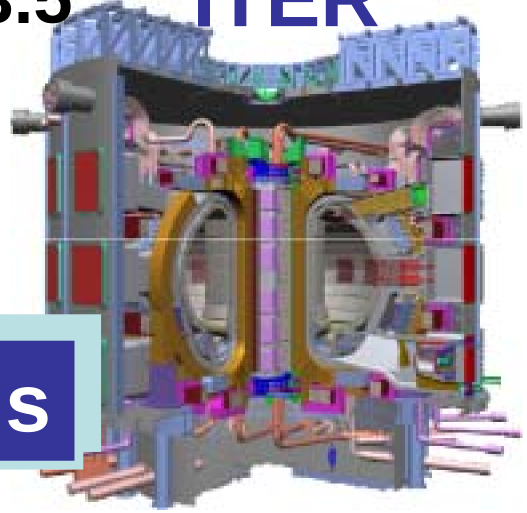
Advanced Tokamak should achieve

- **Bootstrap current fraction: $f_{BS} > 70\%$**
- **Normalized β: $\beta_N \sim 3.5$**

Pulse Duration=?

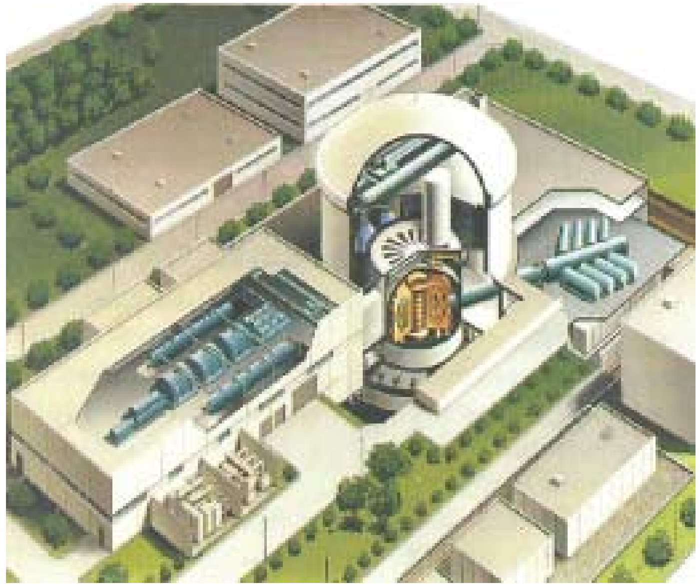
Performance

ITER



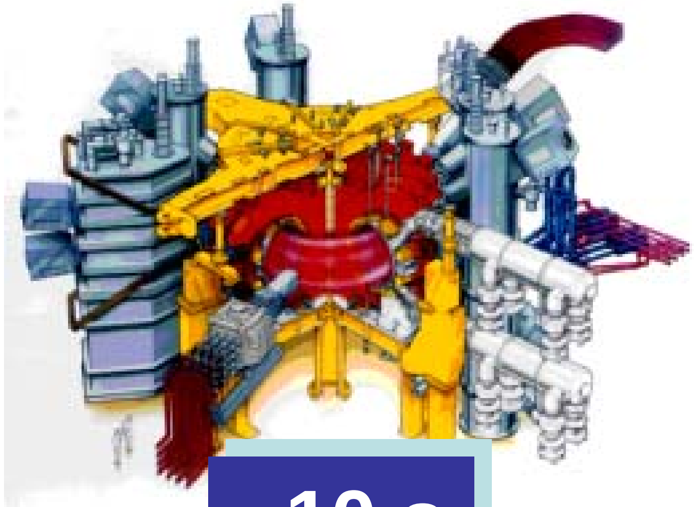
>1000 s

DEMO Reactor

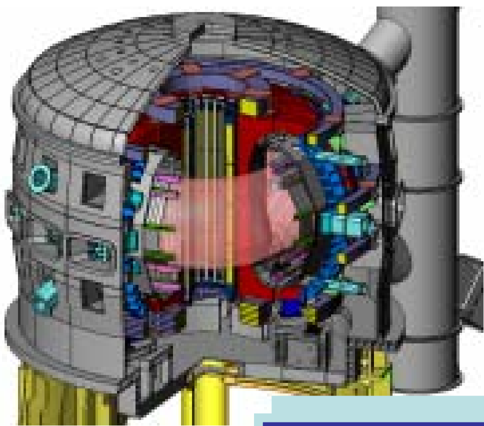


~1 year

JT-60U



~10 s



NCT

>100 s

Pulse Duration

Steps toward a Steady-State Reactor

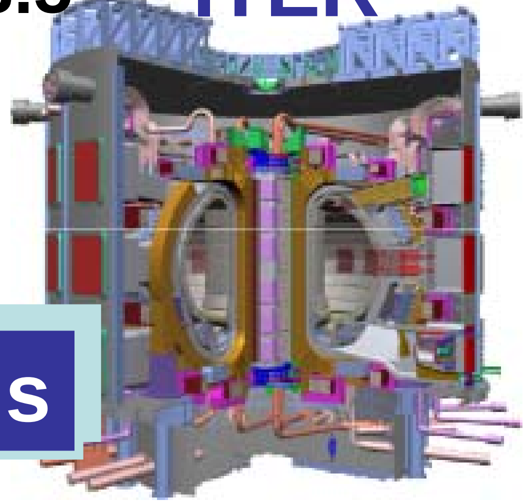
Advanced Tokamak should achieve

- Bootstrap current fraction: f_{BS} > 70%
- Normalized β: β_N〜3.5

Pulse Duration=?

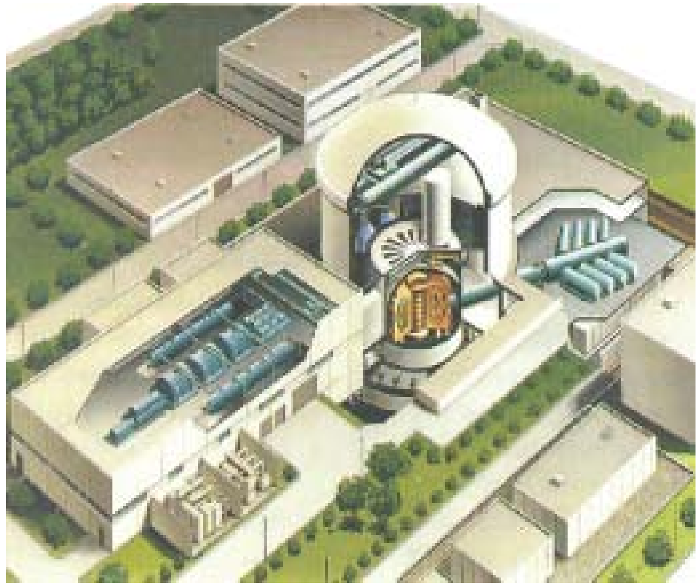
Performance

ITER



>1000 s

DEMO Reactor



~1 year

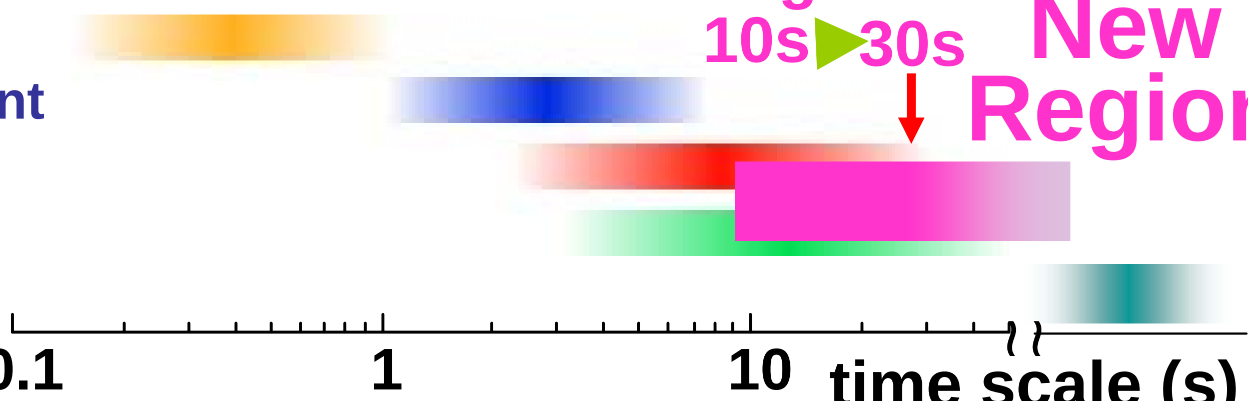
JT-60U

Key characteristic time scales

- Energy confinement
- Effective particle confinement
- Current profile relaxation
- Plasma-wall interaction
- Material erosion

JT-60 heating limit 10s ▶ 30s

New Region



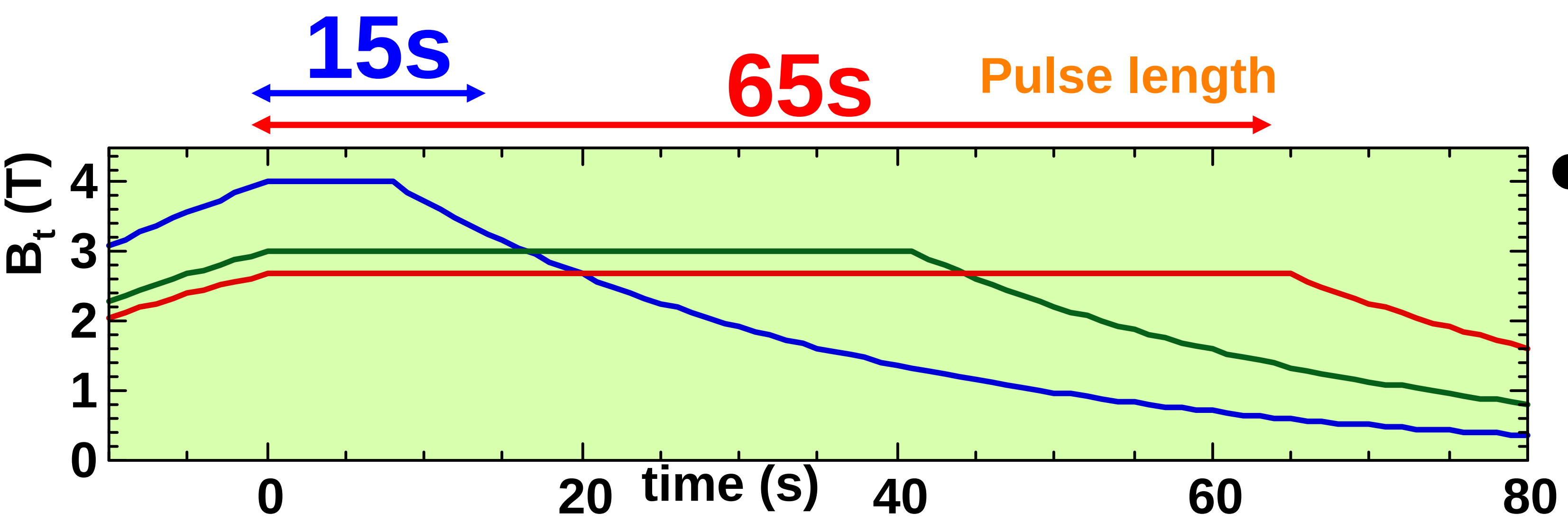
1. Modifications for Long Pulse Operation

1.1 Modifications for the Field Coil Power Supplies

a. Poloidal Field Coil Power Supplies
- Pulse heat load (I^2t) for the SCR circuit be unchanged for 65 s operation by **decrease in the primary voltage from 18 kV to 11 kV**.

b. Toroidal Field Coil Power Supply
- Pulse heat load (I^2t) for TF coil be unchanged in 65 s operation by **decrease in Bt strength**.

c. The **1000-s** Integrators for magnetic measurements (the original capability < 10 s.) have been installed.



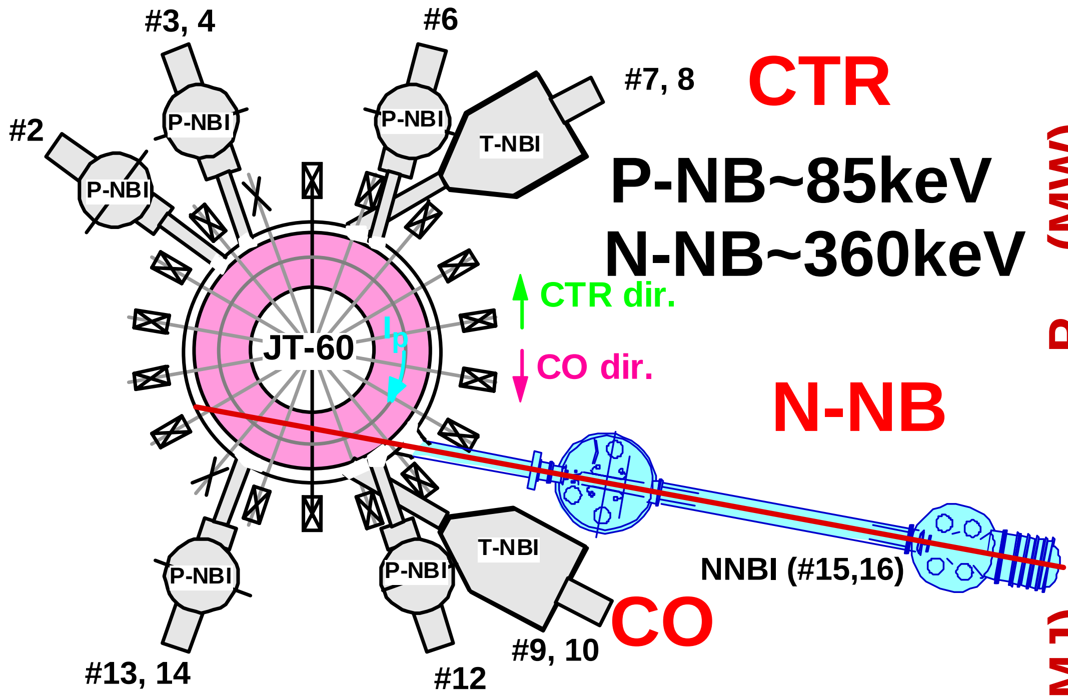
- B_t flat top

4Tx8s ⇨

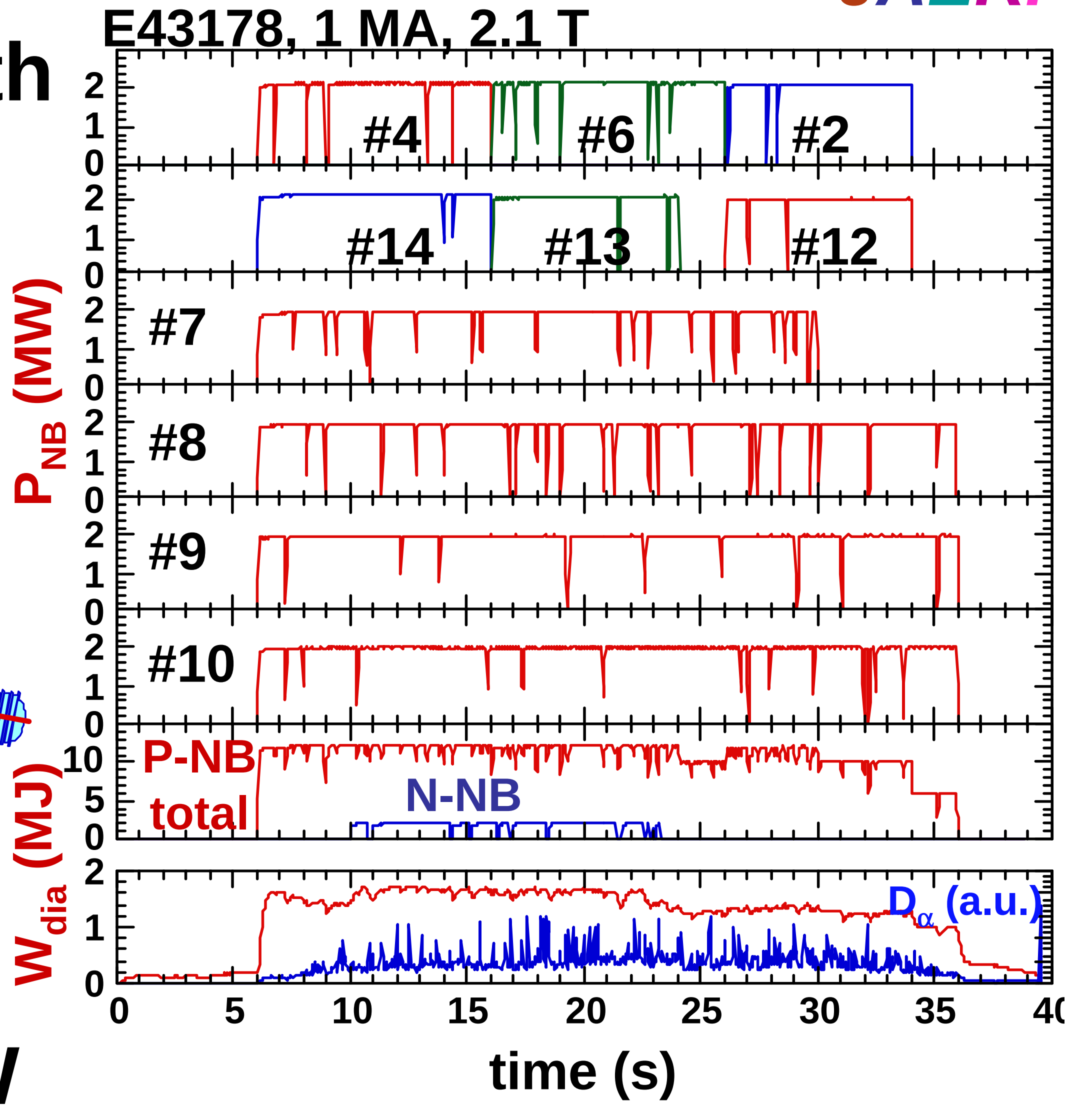
~2.7Tx65s

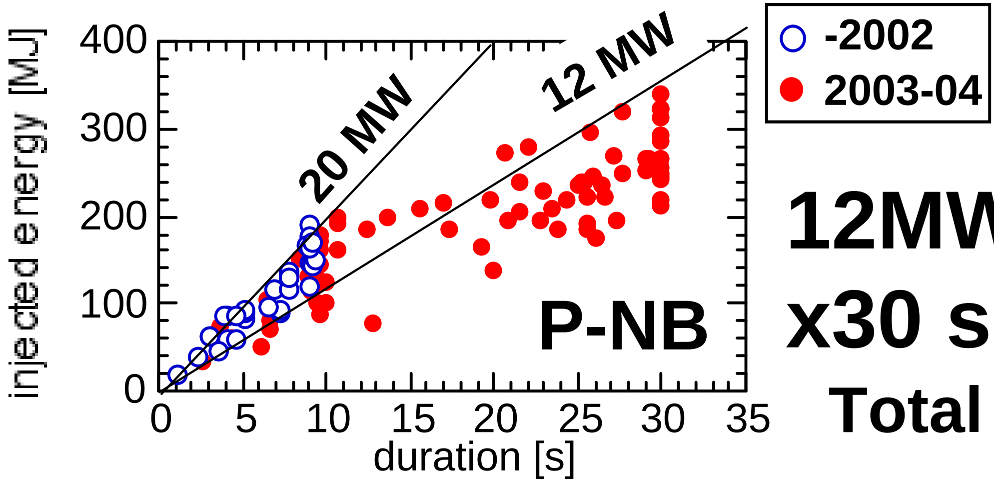
1.2 Improvements in NB Systems (P/N-NB)

- Extension of Pulse Length



P-NB~85keV
N-NB~360keV





12MW x30 s

N-NBI: 1.5MWx20 s

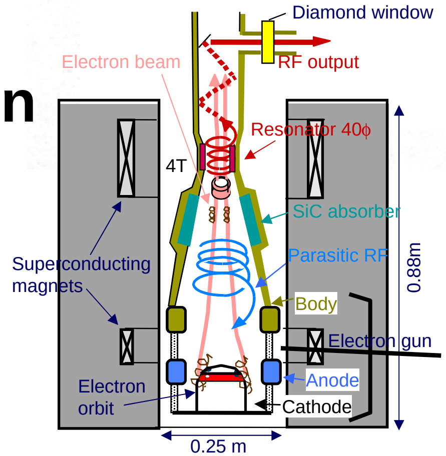
Total Energy (P-NB + N-NB) =350 MJ

1.3 Improvements in RF Systems (EC, LH)

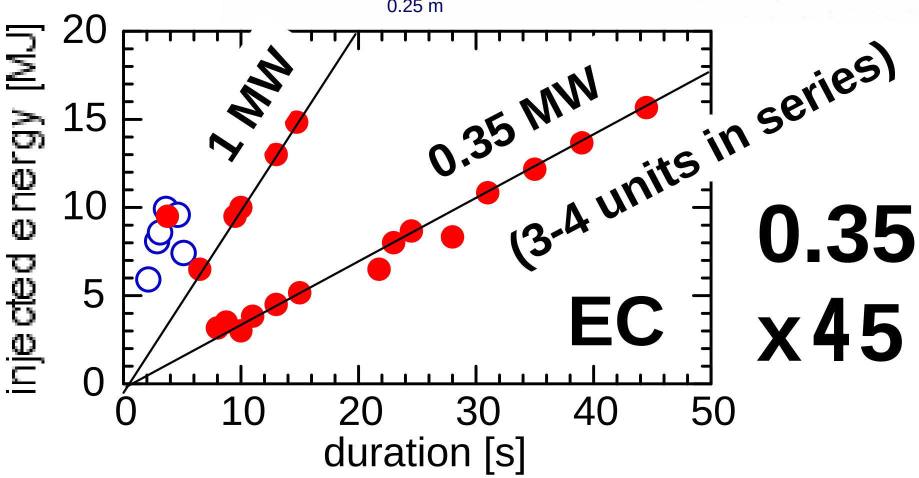
ECRF (110 GHz)

- 17-s continuous oscillation was achieved with anode voltage control.

Gyrotron



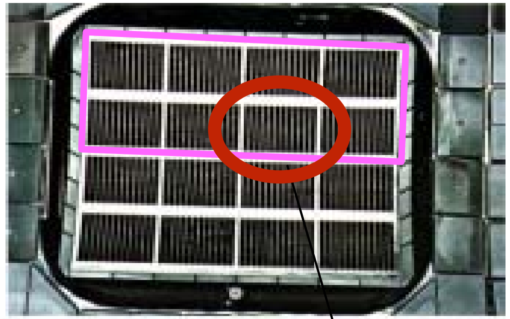
Anode



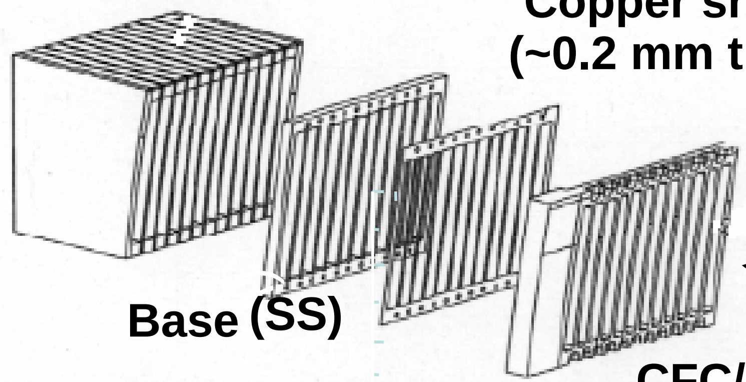
0.35MW x45 s

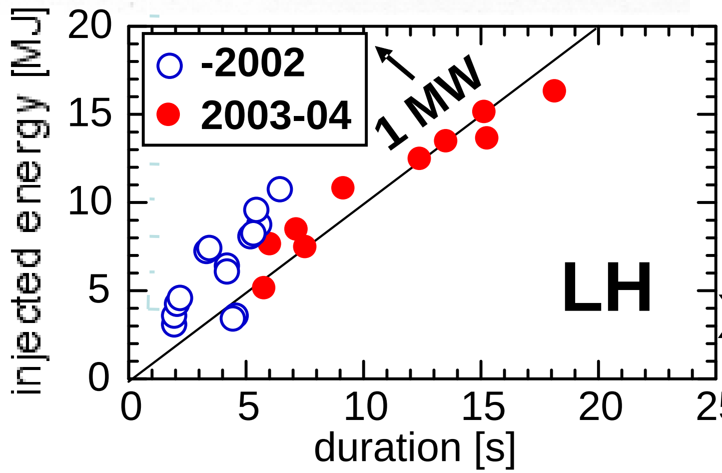
LHRF (2 GHz)

- Multi-junction SS antenna
- Carbon grill



Original antenna mouth (Stainless steel (SS))





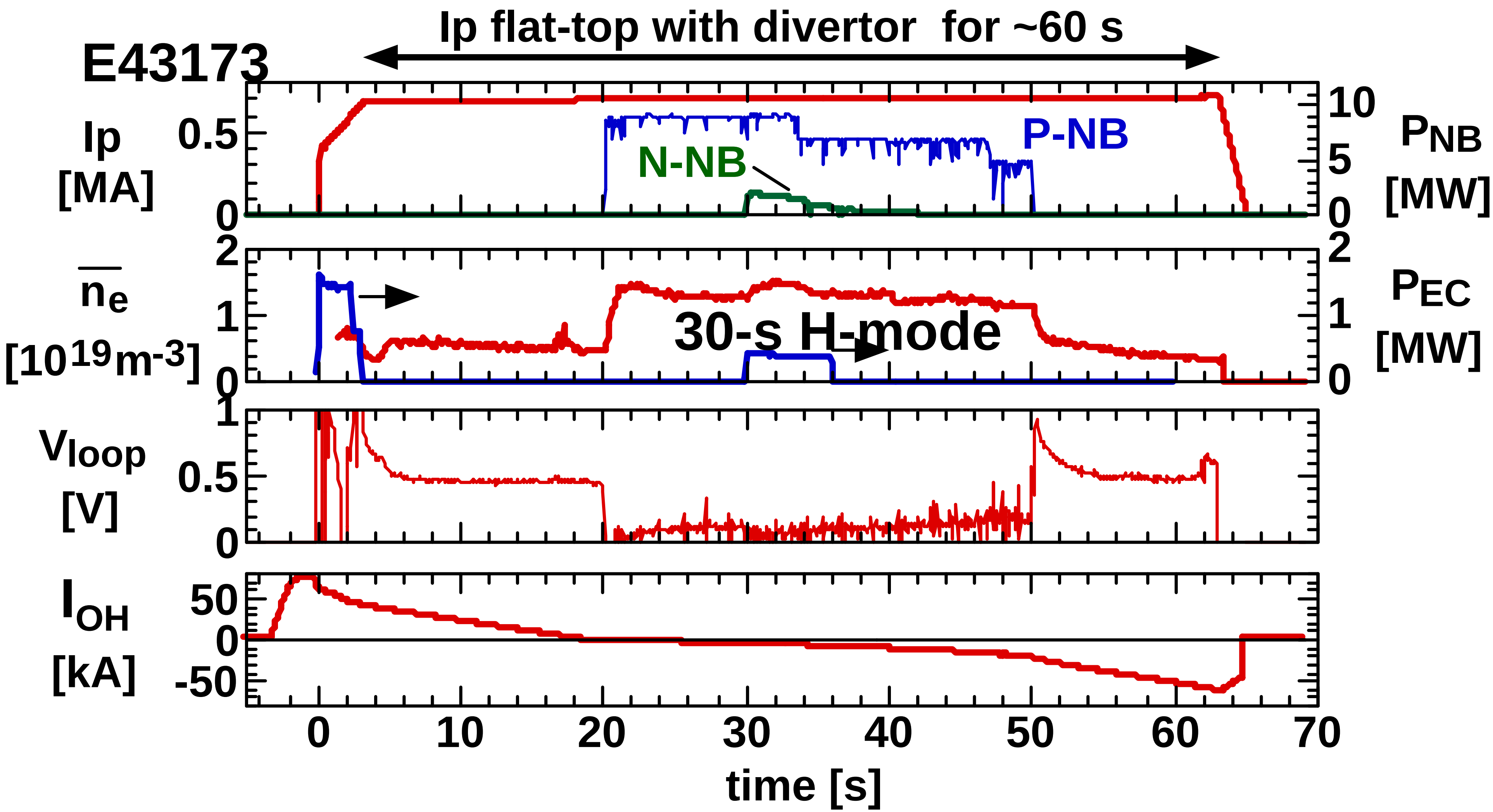
1MW x18 s

2. Extension of Advanced Tokamak Research

65-s discharge was successfully achieved.

Ip=730 kA, B_t=2 T, P_{NBI}=9 MW, P_{ECRF}=0.48 MW

ELMy H-mode was sustained for 30 s.



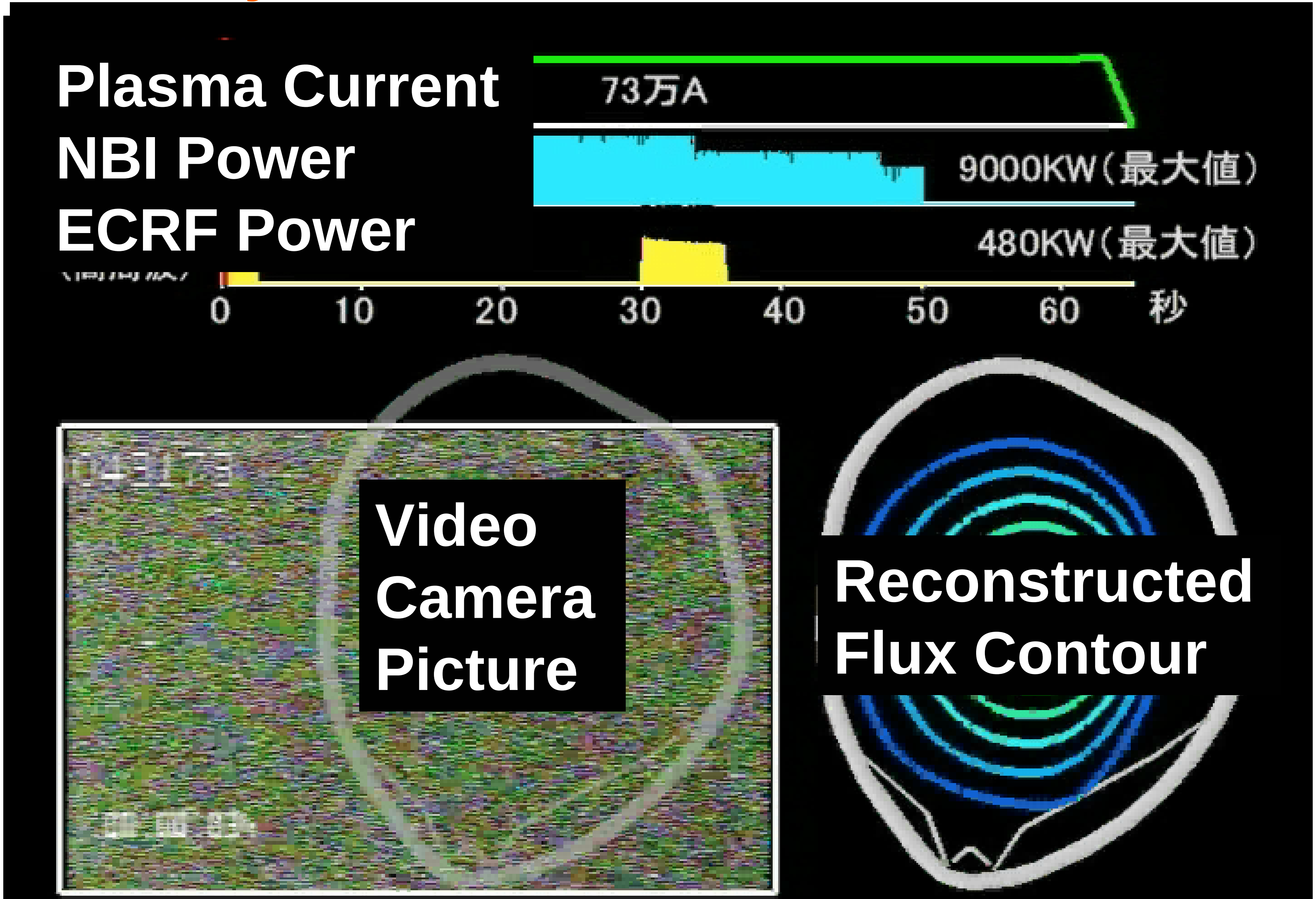
Movie

65-s Discharge Movie

Ip=730 kA, B_t=2 T, P_{NBI}=9 MW, P_{ECRF}=0.48 MW

ELMy H-mode was sustained for 30 s.

Ip
P_{NBI}
P_{ECRF}



2.1

Long Sustainment of High β_N - High β_p H-mode Extended Pulse -

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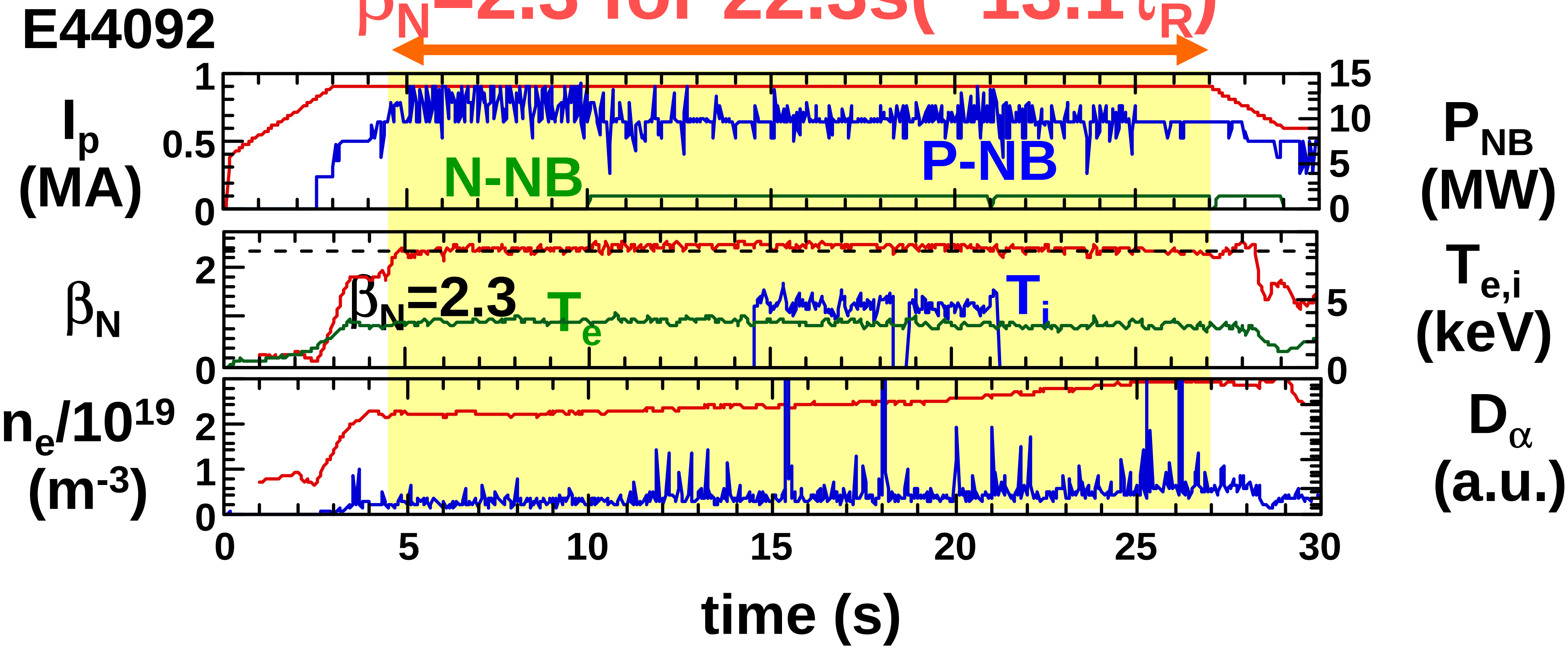
Ip = 0.9 MA, B_t = 1.56 T, q_{95}~3.1-3.2, H_{89PL}~1.9

β_N=2.3 for 22.3s(~13.1τ_R)



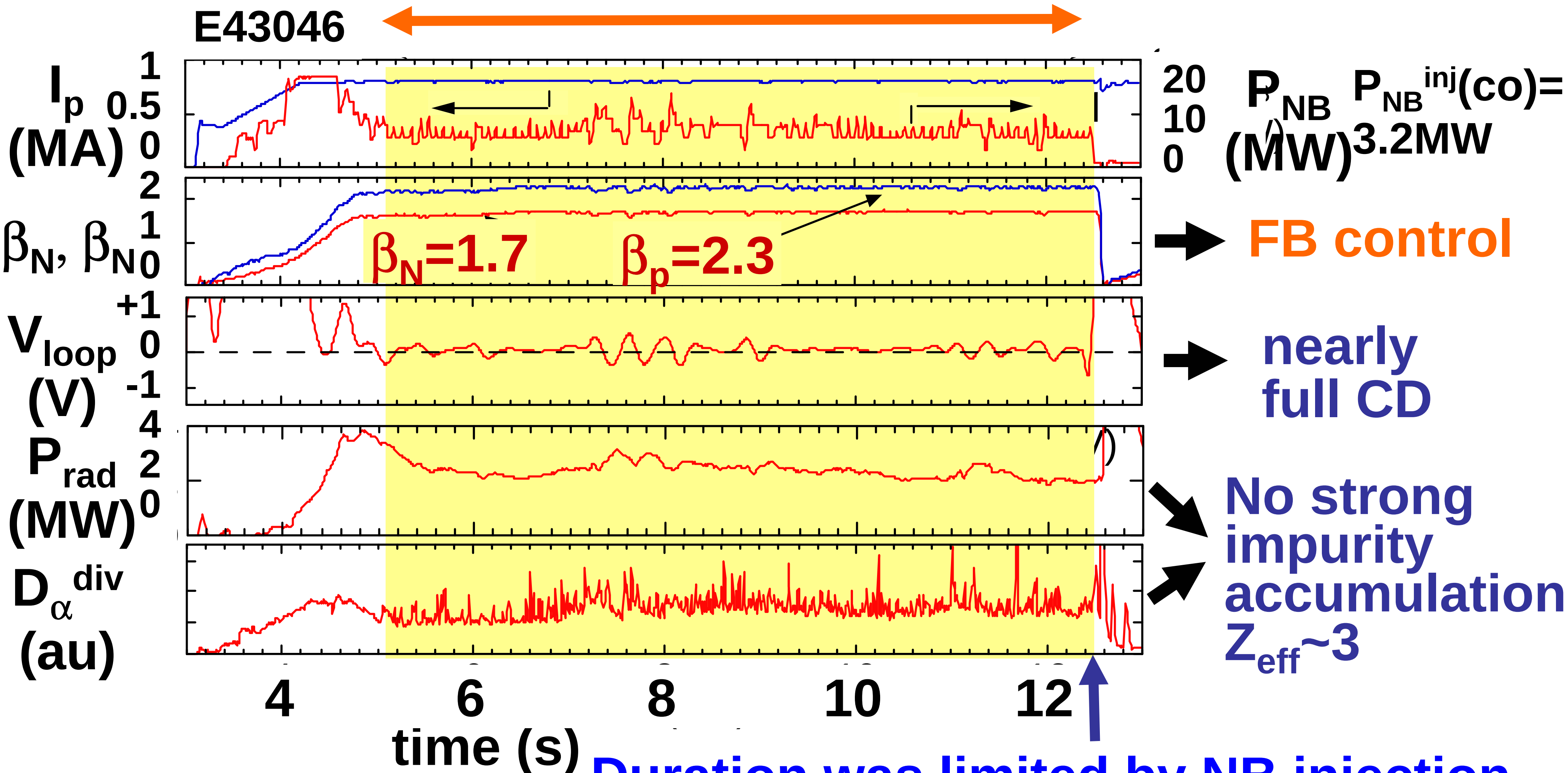
$\tau_R \equiv \mu_0 \langle\sigma_{NC}\rangle a^2/12$ D.R. Mikkelsen, Phys. Fluids B 1 (1989) 333.

2.2 Long Sustainment of High f_{BS}

- Reversed Shear ELMy H-mode, Nearly Full CD -

Ip=0.8MA, Bt=3.4T, q_{95}~8.6, n_e/n_{GW}~0.55

β_N~1.7, f_{BS}=75%, f_{CD}=20% for 7.4s (~2.7τ_R)



Duration was limited by NB injection.

2.3 Quasi Steady State High β_N Plasma

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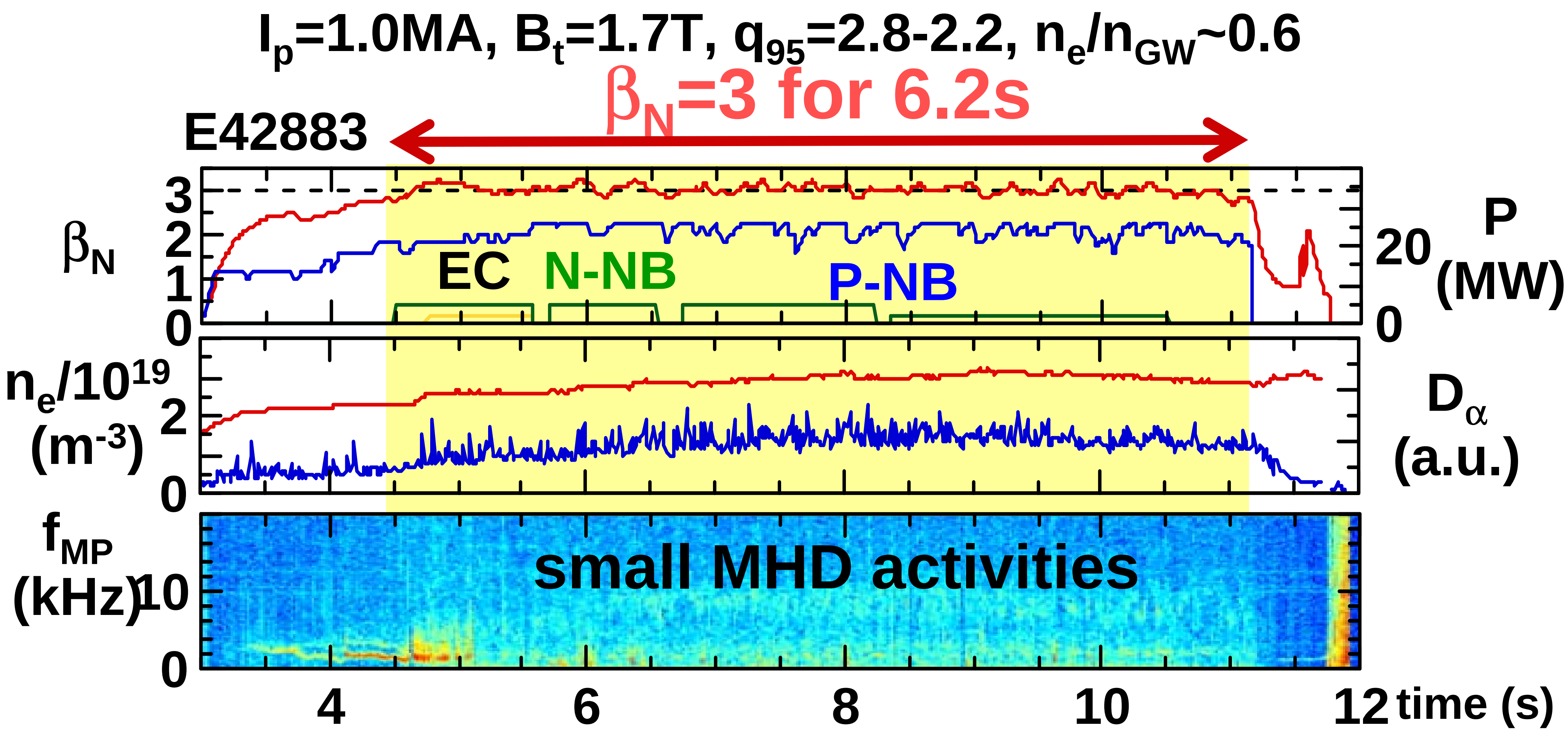
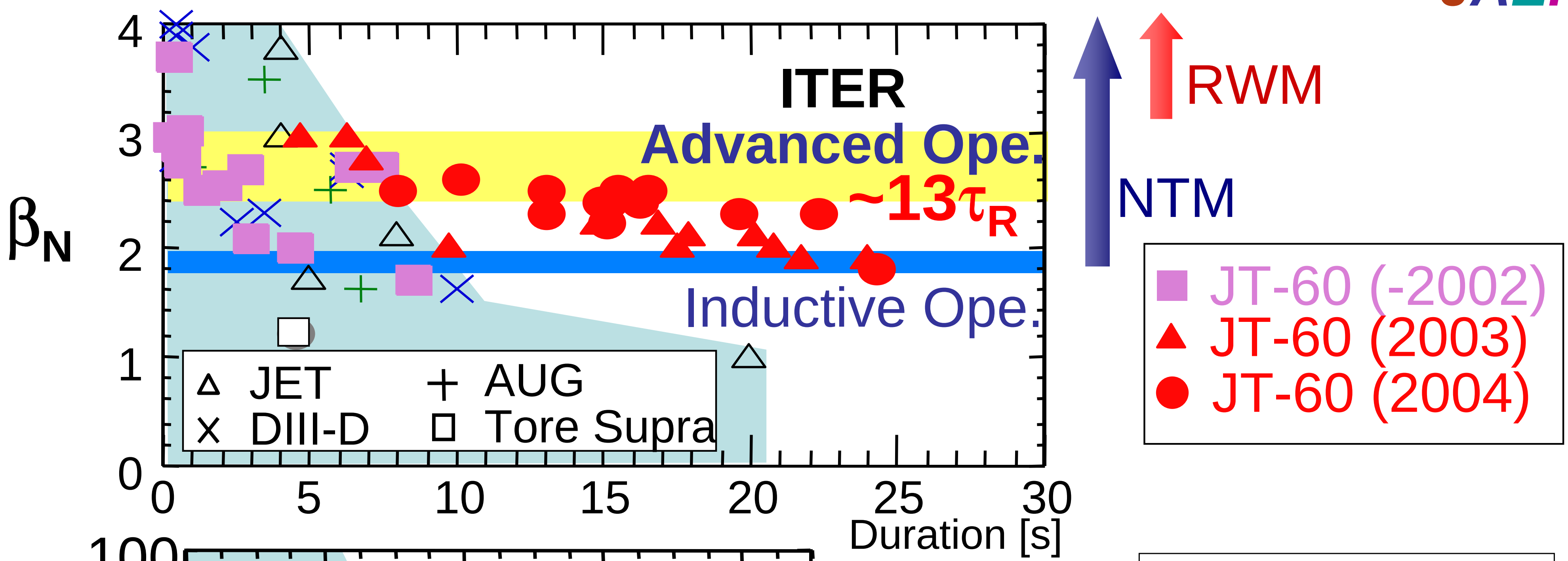
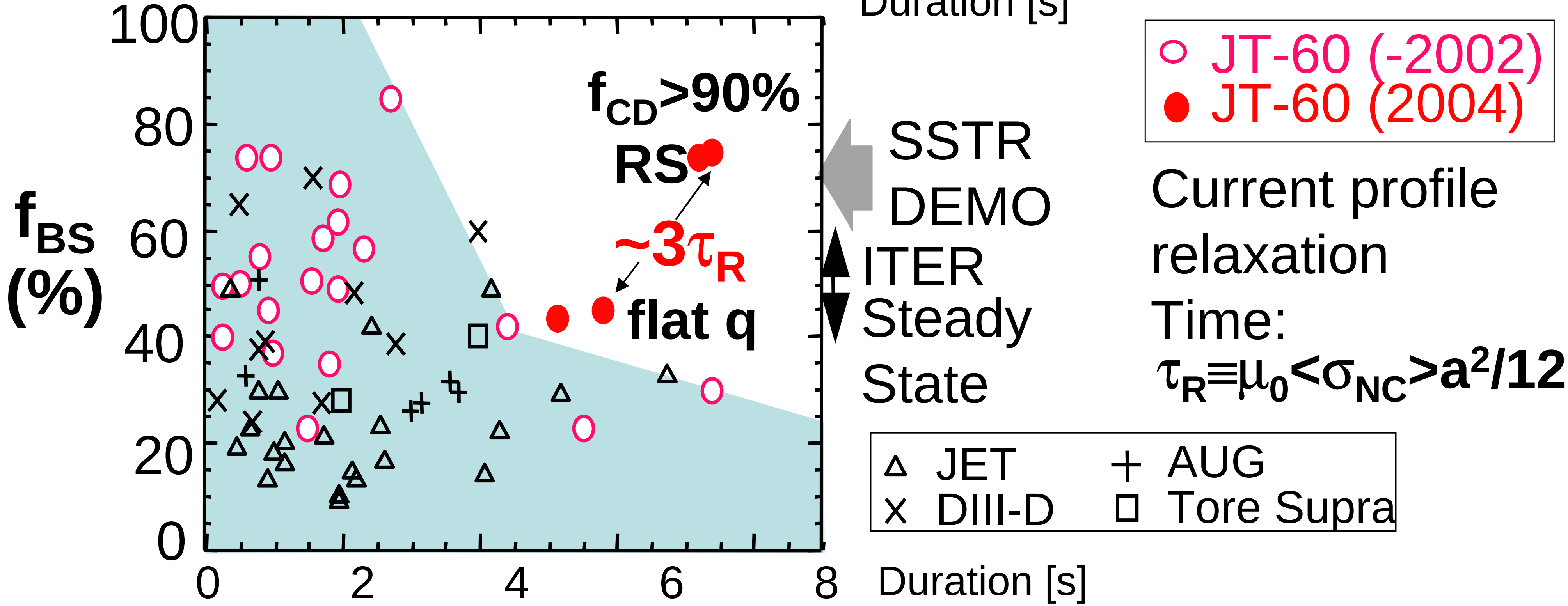


Method 1: Avoid putting the NTM resonance surface on the steep pressure gradient area by flattening q profile (q_{95} = 3.0 => 2.2-2.8).

Method 2: ECCD at q integer surface with excited magnetic islands.

Achievements of High β_N & f_{BS}





Current profile relaxation Time:
$\tau_R \equiv \mu_0 <\sigma_{NC}> a^2/12$

3. Exploration to AT operation with a higher β_N and f_{BS} steady-state plasma

For a higher β_N and f_{BS} steady-state plasma, Requirements are listed:

- Wall stabilization
- Current profile control → better LHCD

→ Enlarge a plasma size

⇒ - Real-time Precise Equilibrium Observer (3.1)
- Current Profile Feedback Control (3.2)

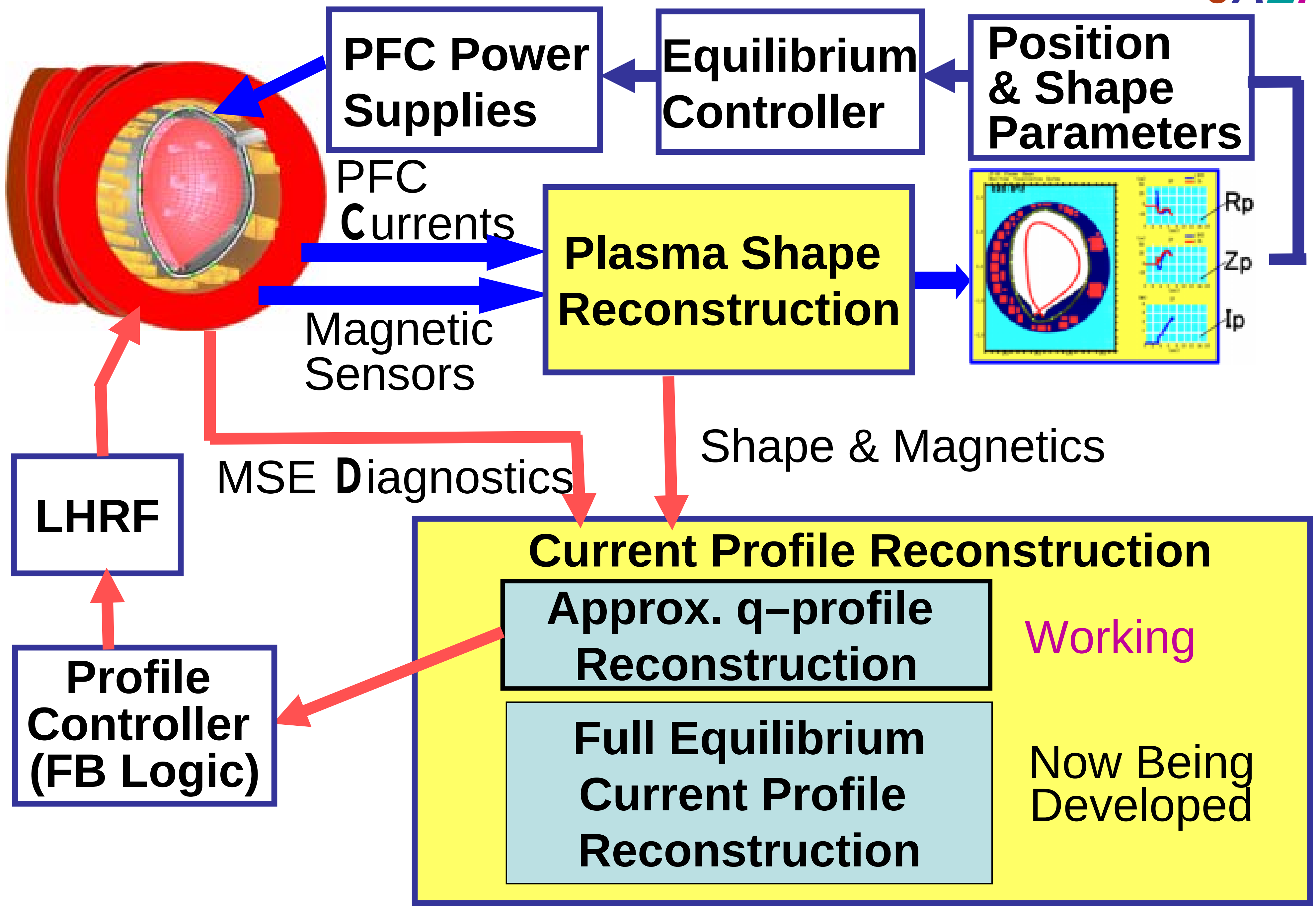
- More absorbed heating power

→ decrease ion loss & heat load on LH antenna

→ **Ripple reduction**

⇒ - Ferritic Steel Plate Insertion (3.3)

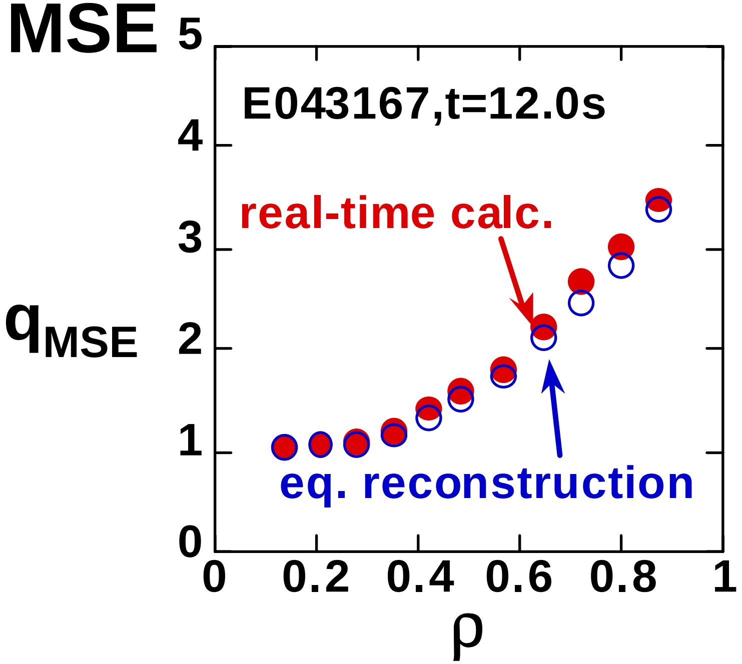
3.1 Real-time Precise Equilibrium Observer



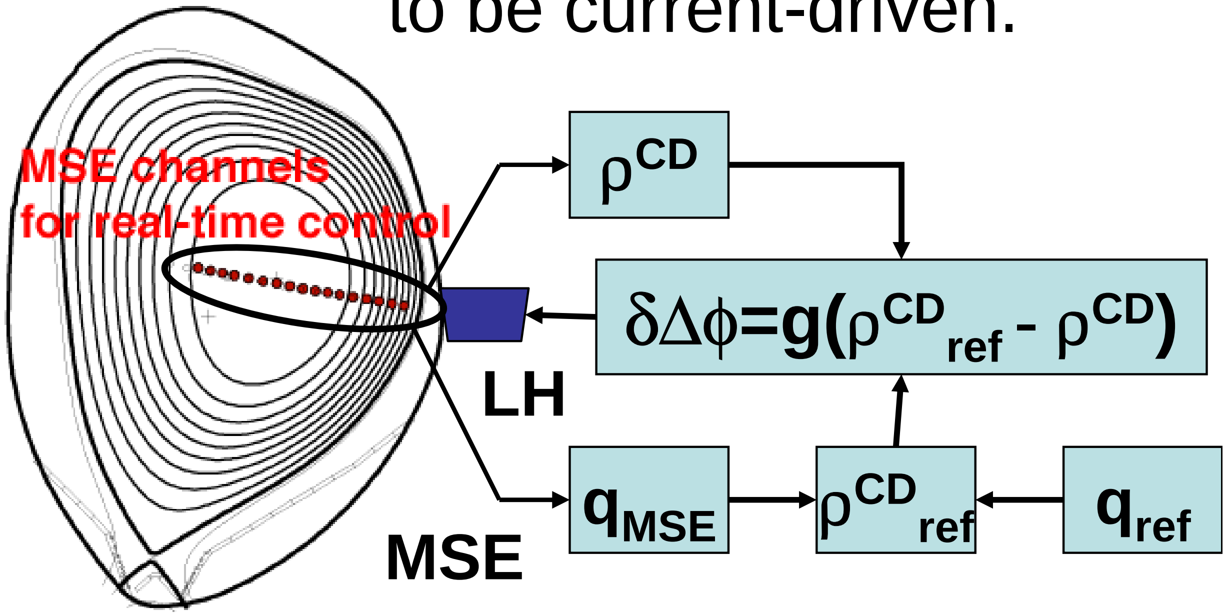
3.2 Current Profile Feedback Control

Real-time control of q(r)

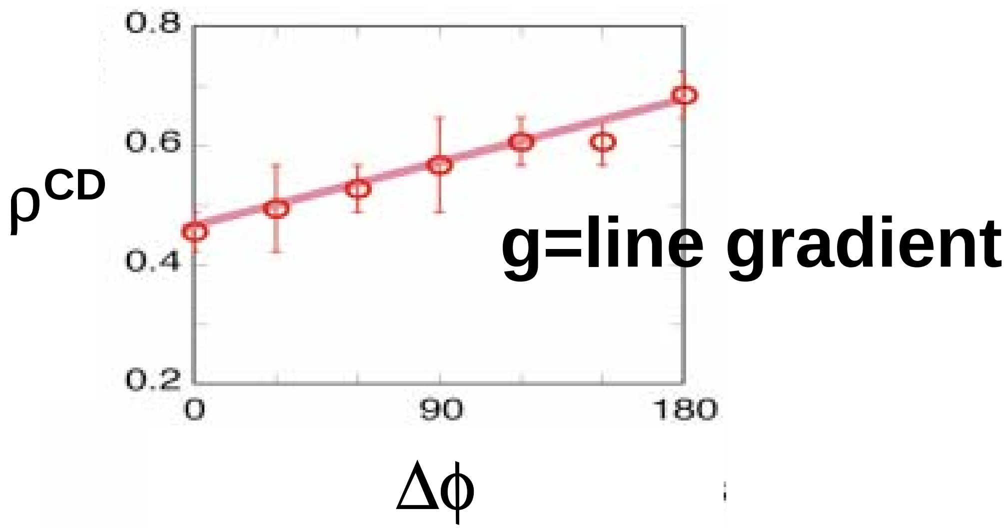
- Real-time approx. q-profile observer with MSE



ρ^{CD} : Normalized minor radius to be current-driven.

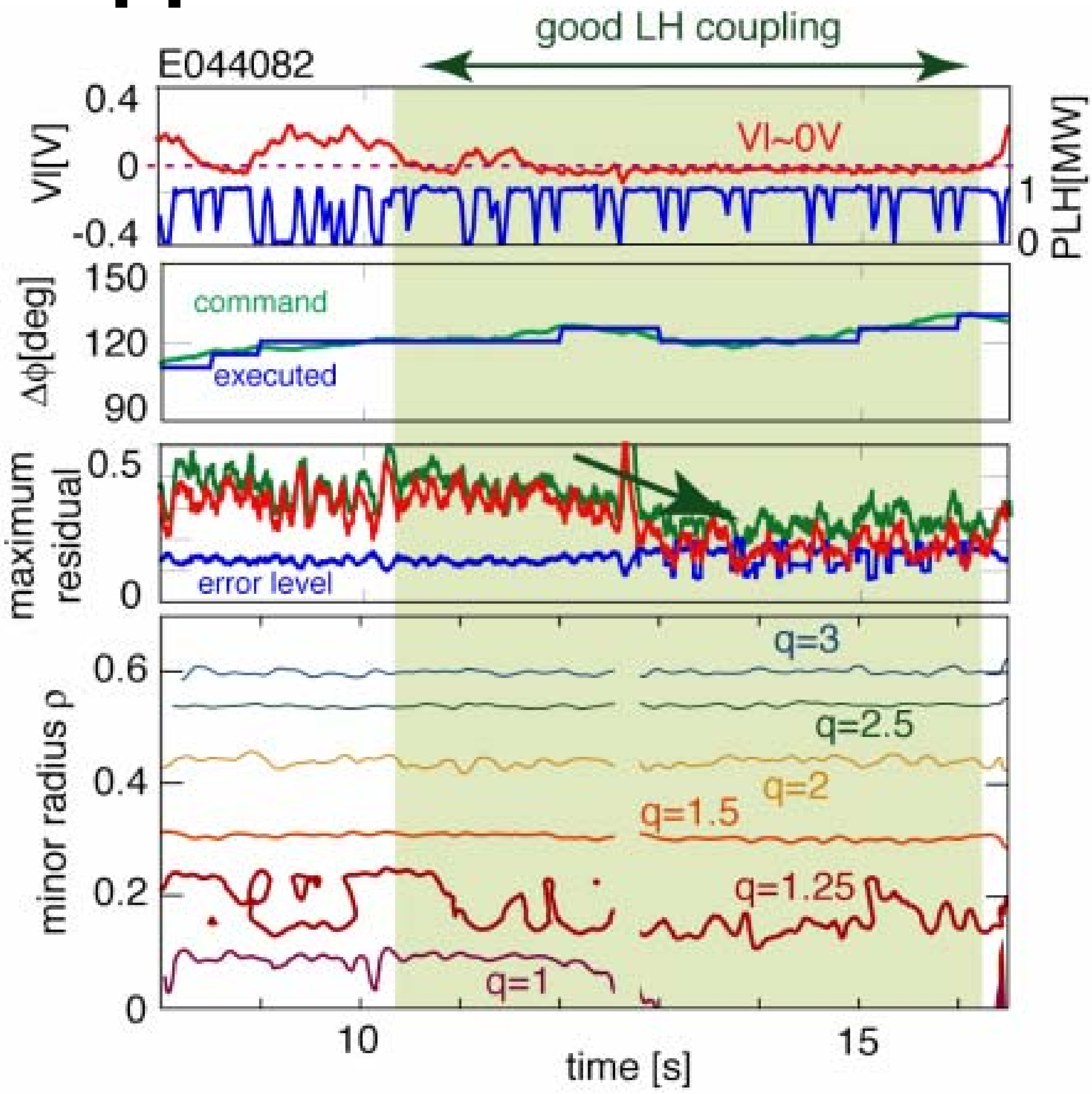


- Change CD location ρ^{CD} by LHW phase difference $\Delta\phi$.

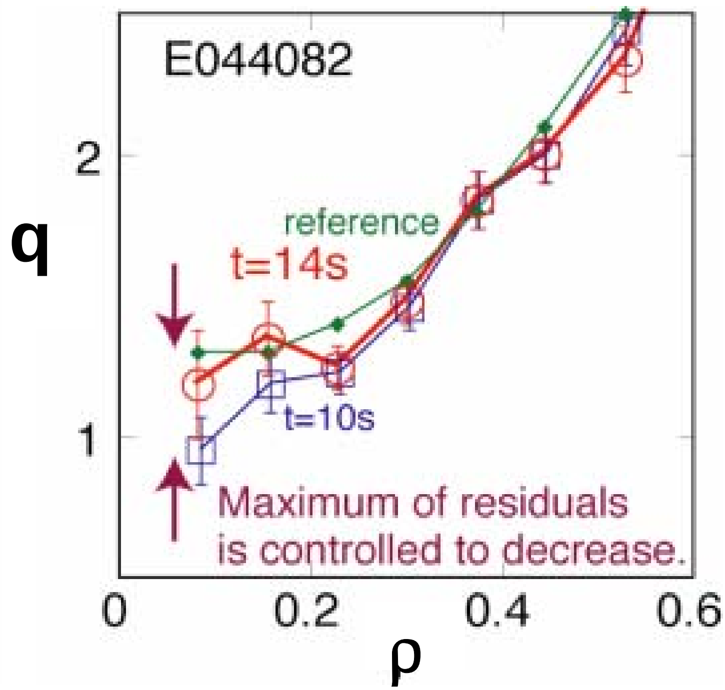


3.2 Current Profile Feedback Control (Cont'd)

q-profile FB control was demonstrated.



- $\Delta\phi$ was controlled.
- q(r) approached to the reference, and was sustained for 3s.
  - $n_e=0.5\text{x}10^{19}\text{m}^{-3}$
  - $\eta_{CD}\sim1\text{x}10^{19}\text{A/W/m}^{-2}$



q(r) control in higher f_{BS} and/or β_N plasmas is a next target.

3.3 Ferritic Plate Insertion for TF Ripple Reduction
Expected Effects in AT Research

TF ripple reduction will bring about extensive improvements in

- **MHD stability,**
- **Controllability of current profile in a longer period,**
- **Absorbed heating power,**

⇩

and provides the basis towawd

- **β_N beyond the ideal limit with the free boundary,**
- **Longer sustainment of a high-β_N plasma, and**
- **Longer sustainment of a high-f_{BS} plasma.**

3.3 Ferritic Plate Insertion for TF Ripple Reduction
Effects Comparison -with and without FP-

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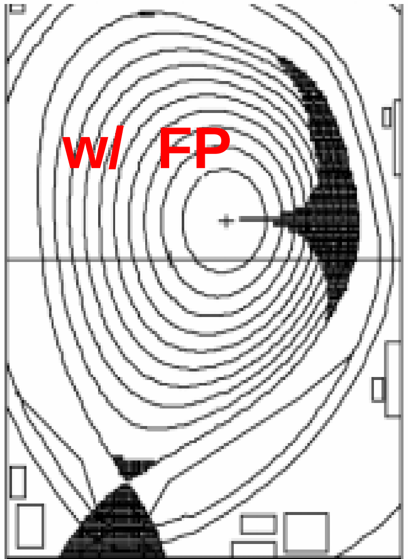
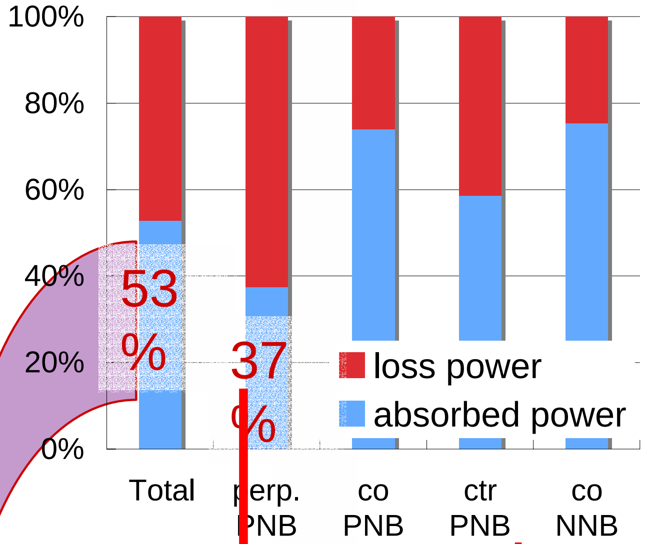
Ripple Well Area



Absorbed NB Power

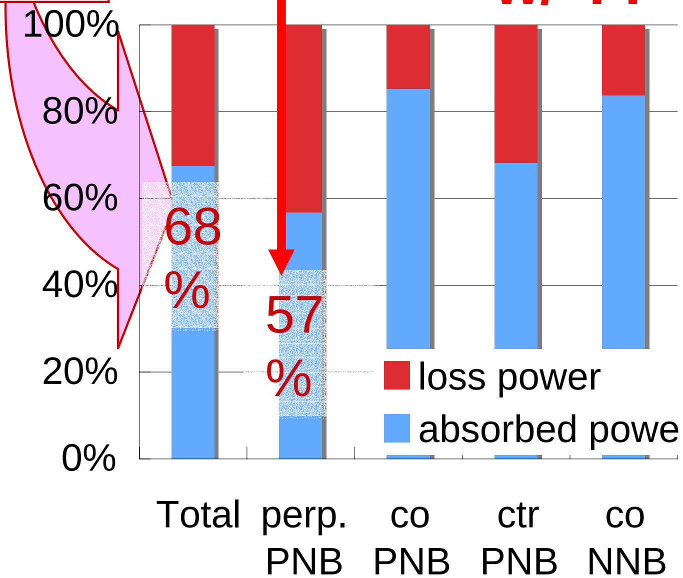


x1.3

x1.5

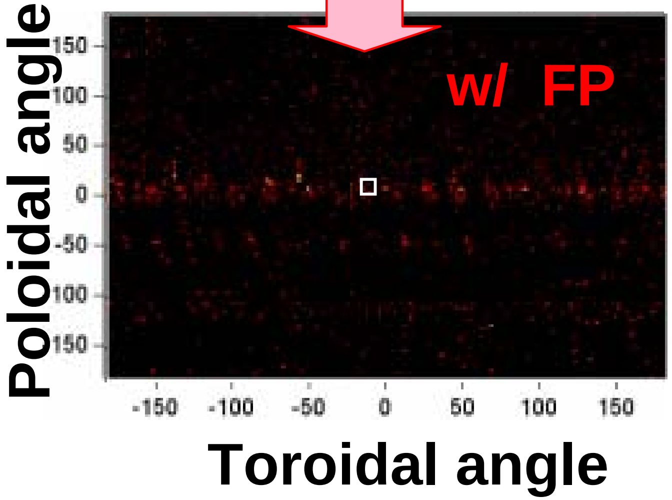
w/o FP

w/ FP



Heat Load on LH Antenna

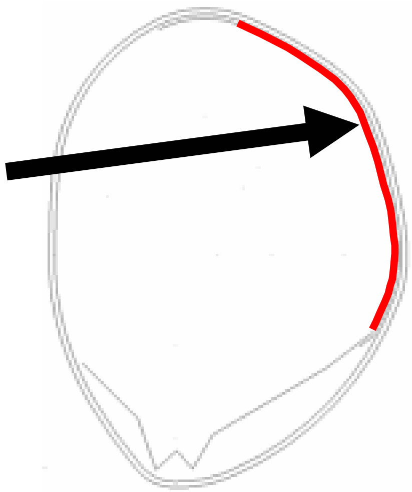
from 0.27 to 0.1 MW/m²
(for full NB injection of 20 MW)

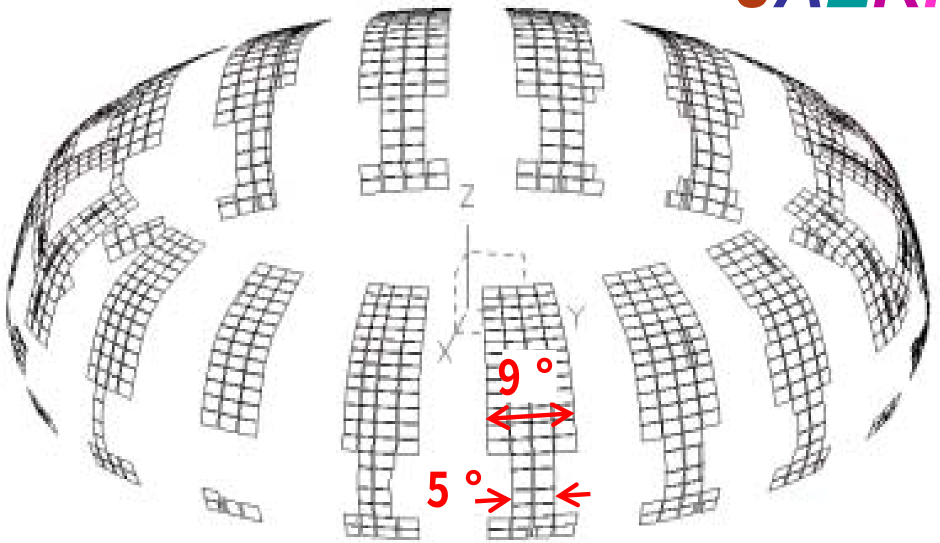


Installation of Ferritic Steel Plates (1/2)

JAERI

Material:
8Cr2W steel
Magnetization:
~1.8 T
Thickness:
23 mm





3-D View

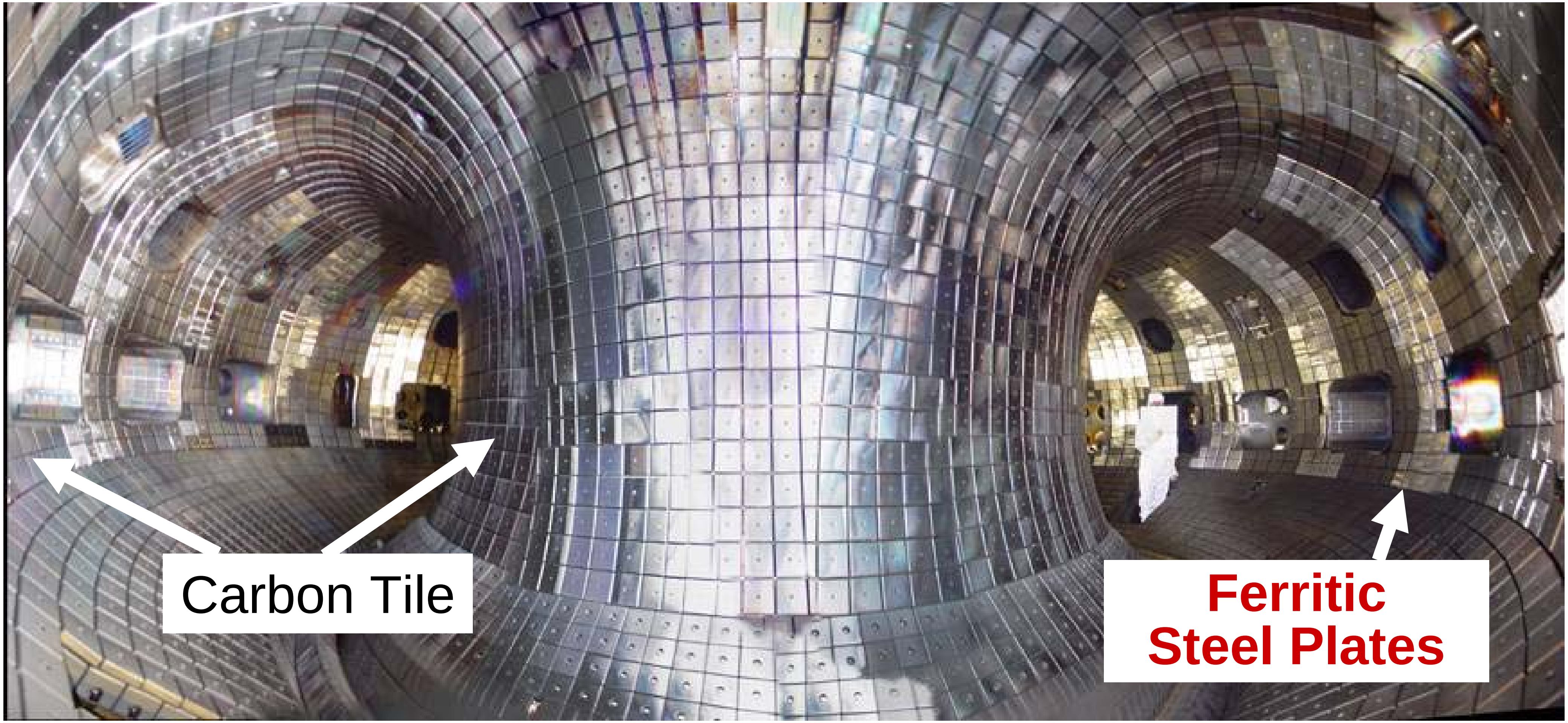
May, 2005

June, 2005

July, 2005

Installation of Ferritic Steel Plates (2/2)

The installation work has been just completed in Aug. 2005.



Summary (1/2)

- Modifications of facilities were completed: Discharge pulse length: 15 s to 65 s.

- 65-s pulse discharge has been successfully achieved with 30-s H-mode sustainment.

- In extending advanced tokamak (AT) operation, remarkable results were attained:
  - a. High β_p H-mode plasma with $\beta_N \sim 2.3$ for 22 s.
  - b. RS ELMy H-mode plasma with $f_{BS} \sim 75\%$ and $\beta_N \sim 1.7$ for 7.4 s under nearly full (95%) CD.
  - c. $\beta_N \sim 3$ for 6.2 s with suppressing NTM by ECCD or by flattening q profile.

Summary (2/2)

For AT operation with a higher β_N and f_{BS} in longer pulse discharge,

- **Plasma Precise Equilibrium Observer has been developed.**
- **Current Profile Control has been demonstrated.**
- **Ferritic Steel Tile Insertion for TF Ripple Reduction has been just completed.**

We will restart experiments in the coming Nov.

Now we are ready to make further explorations into AT plasma operation toward ITER and a fusion DEMO reactor.