February 22, 2006
Before NSTX PAC

Recent Results and Plans of JT-60U, and the Status of JT-60U Modification

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Contents

- Recent Results and Plans of JT-60U
    - Plasma operation with small toroidal ripple reduced by ferritic steel installation
    - Operation plan in 2006
    - Collaborative research

- Status of JT-60U Modification
    - Status after the JA-EU Satellite Tokamak Working Group discussions

Introduction

JT-60U

ITER

β_N<~no wall ideal limit

f_{BS}< 60%

$\tau_{operation}$~400-3000s

Steady-state tokamak reactor

β_N > no wall ideal limit

➔requires suppression of resistive wall mode (RWM)

f_{BS} > 70%

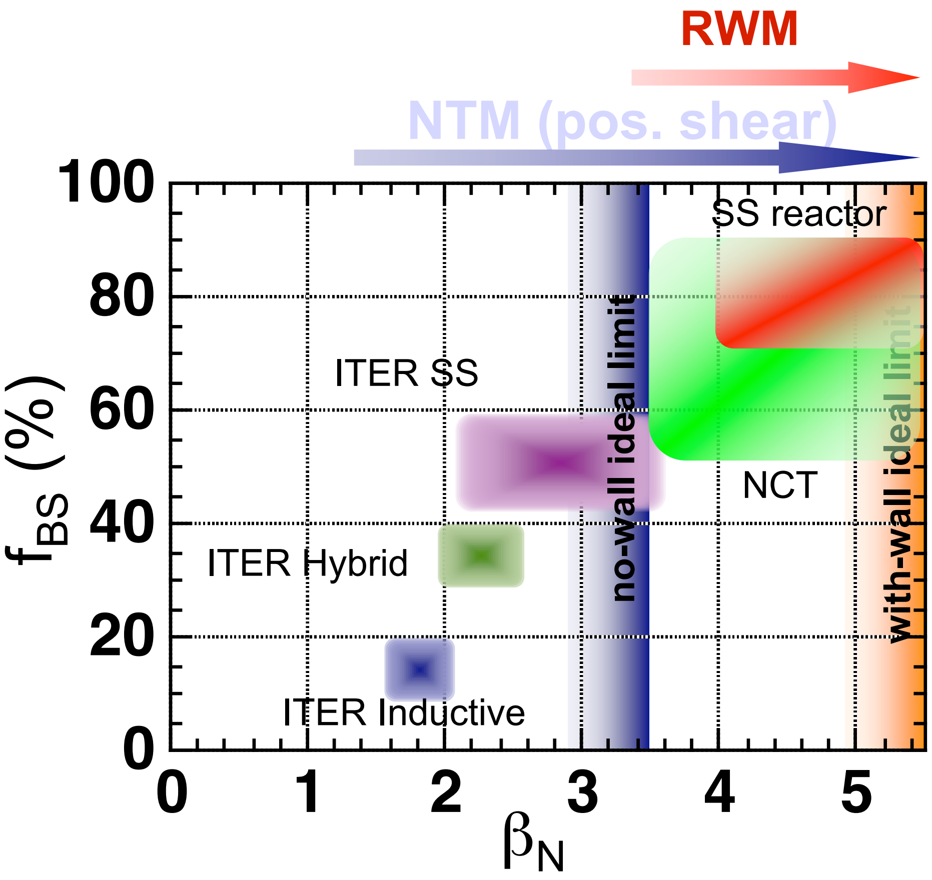
Strong linkage of $j_{BS}(r)$, $j_{total}(r)$ and transport

➔requires highly-integrated plasma control

$\tau_{operation}$~1 year

➔requires understanding of plasma-wall interactions with a long time scale

Expected Operational Space



Large toroidal field ripple constrains the operations in JT-60U

- High β_N operation above no wall ideal limit
  - Wall stabilization effect
- High integrated plasma control
  - current profile control
    - Real time MSE measurement + LHCD

require the large volume configuration close to the outer wall.

In JT-60U,

large toroidal ripple ➔ large fast ion loss

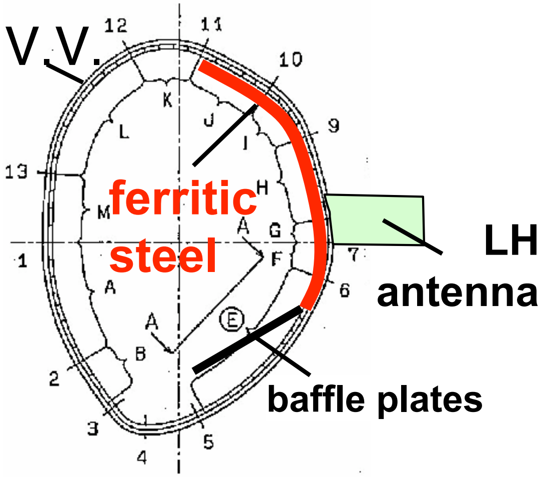
- Reduction of net heating power
- Confinement degradation due to counter rotation or Er produced by large fast ion loss fraction
- Limitation of the LH operation due to large heat load on LH anntena

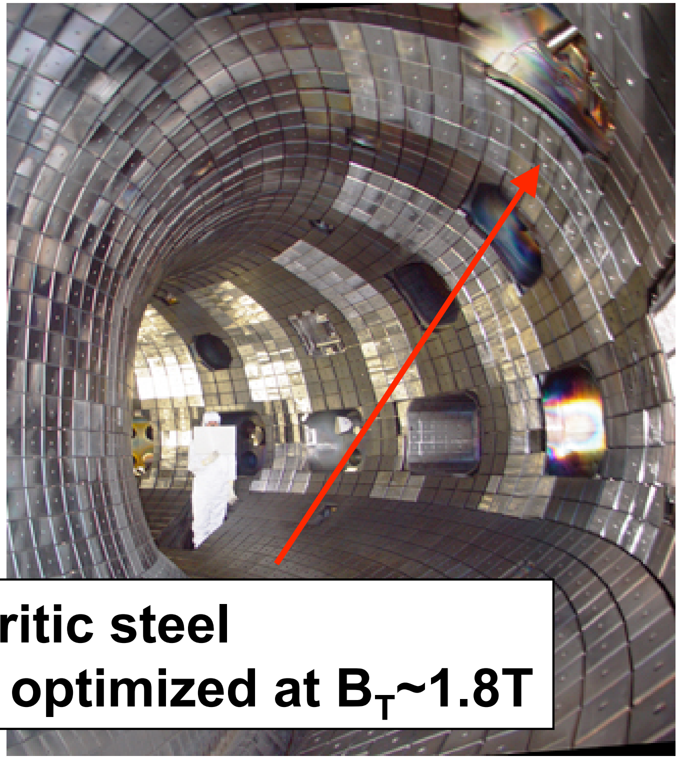
Ferritic steel installation

- JT-60U had suffered from large toroidal field ripple ➔ high energy ion loss
  - loss of net absorbed NB power
  - large heat load to LHRF launcher
  - etc…
- Ferritic steel were installed in the vacuum vessel (~10% of the surface) to reduce the ripple.
- With ferritic steel expected are:
  - net increase in P_{NB}^{abs} (especially in a plasma close to the outboard wall).

    ➔ high β_N over no-wall limit
  - reliable use of LHRF with high NB heating

    ➔ j(r) control in a high β_N plasma





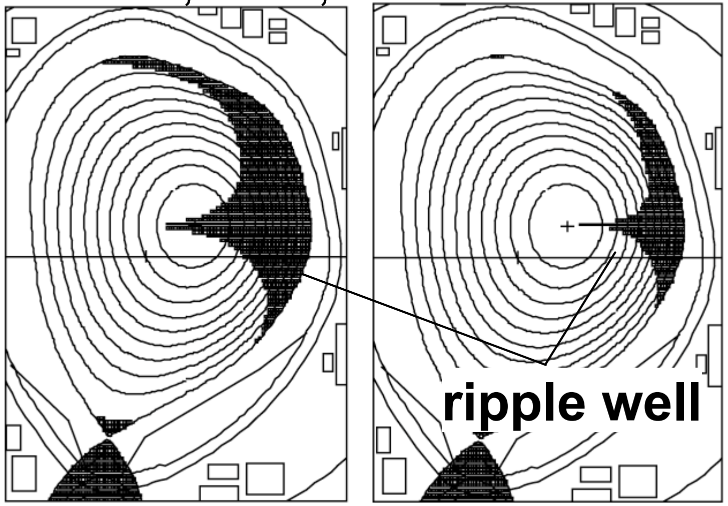
Ferritic steel optimized at B_T~1.8T

30% increase in net heating power was expected.

JT-60U

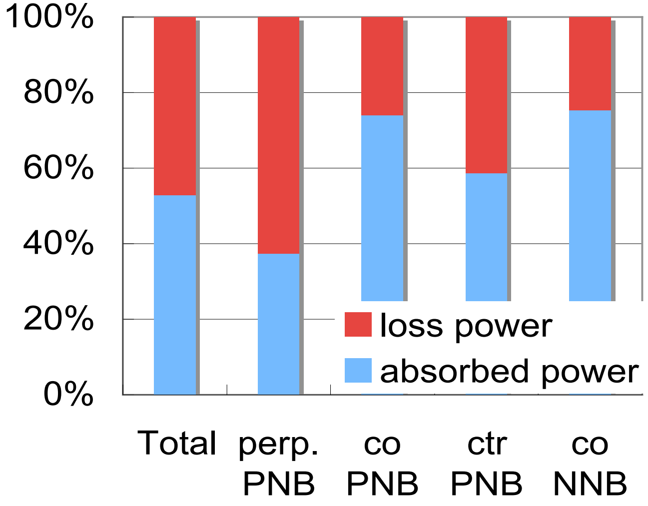
- **Monte-Carlo simulations for fast ion behavior indicated that total absorbed power is increased by 30% in the large volume configuration (by 50% for perpendicular NB).**

1.1MA,1.86T, normal shear

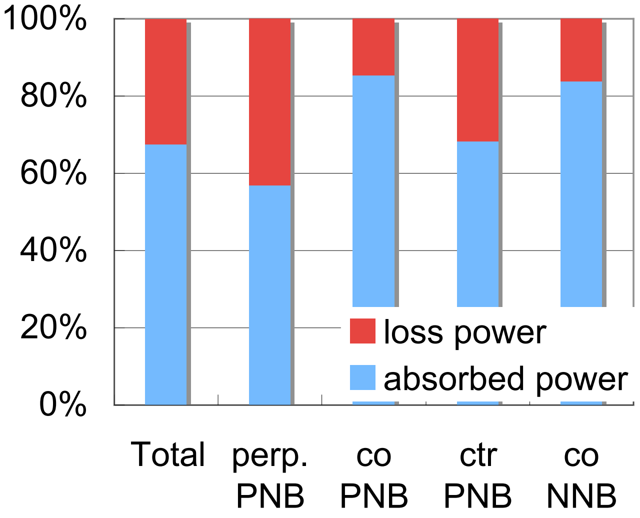


w/o ferrite **w/ ferrite**

w/o ferritic steel



w ferritic steel

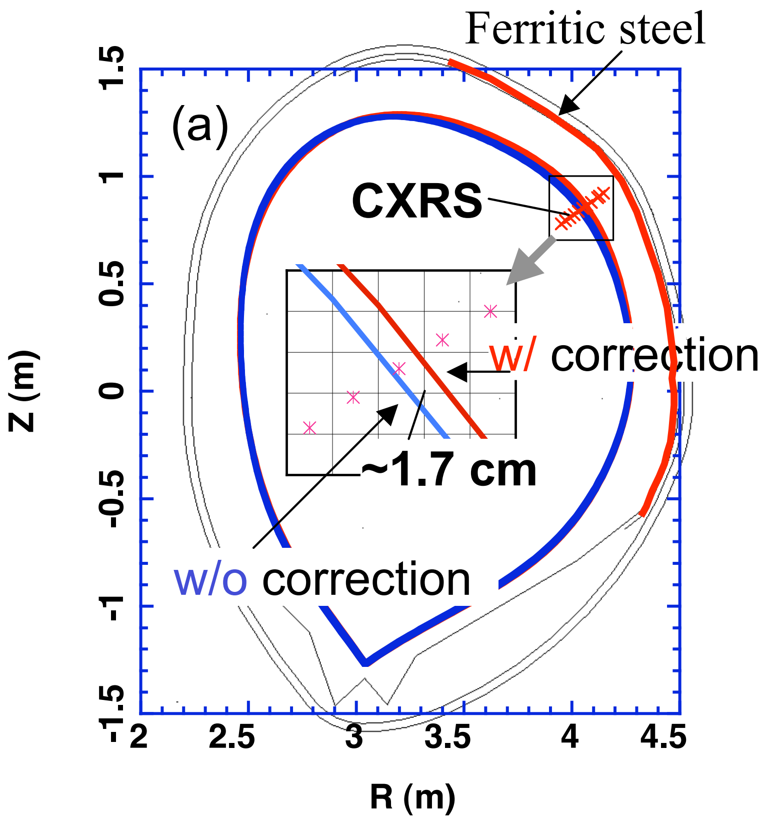


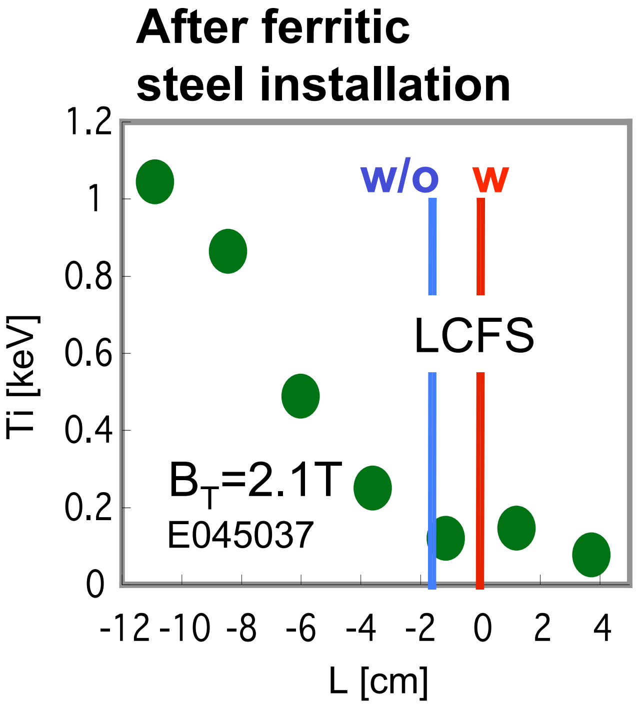
- **Reduction of heat load to the outer baffle plate due to the ripple loss was observed (e.g., 0.2 MW/m^2 with ferritic inserts, while 1MW/m^2 without ferritic inserts)**

Plasma shape detection is consistent with T_i measurement.

JT-60U

- **Plasma shape is detected with correction for magnetic flux produced by the ferritic steel.**
- **Plasma expands for ~2 cm in outer-upper region.**
- **The last closed flux surface (LCFS) location evaluated from CXRS was consistent with the reconstructed LCFS in an H-mode phase.**

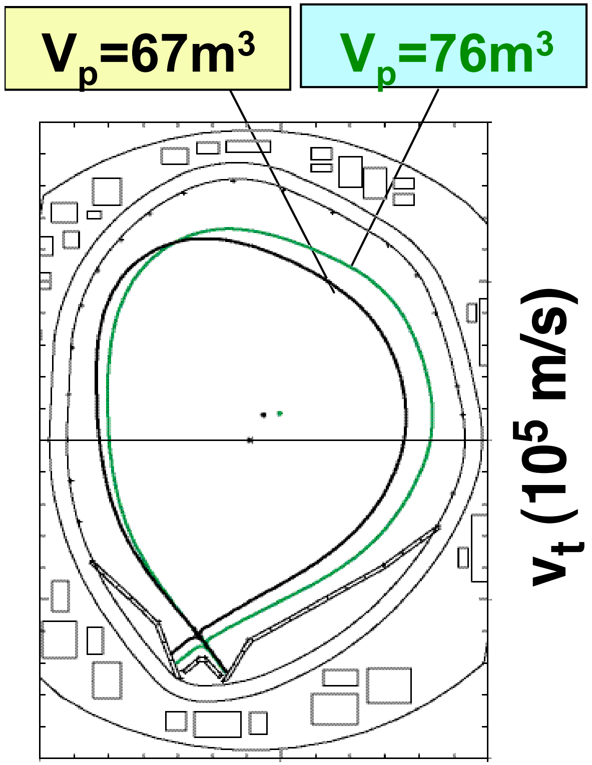




Counter rotation velocity decreases with ferritic steel.

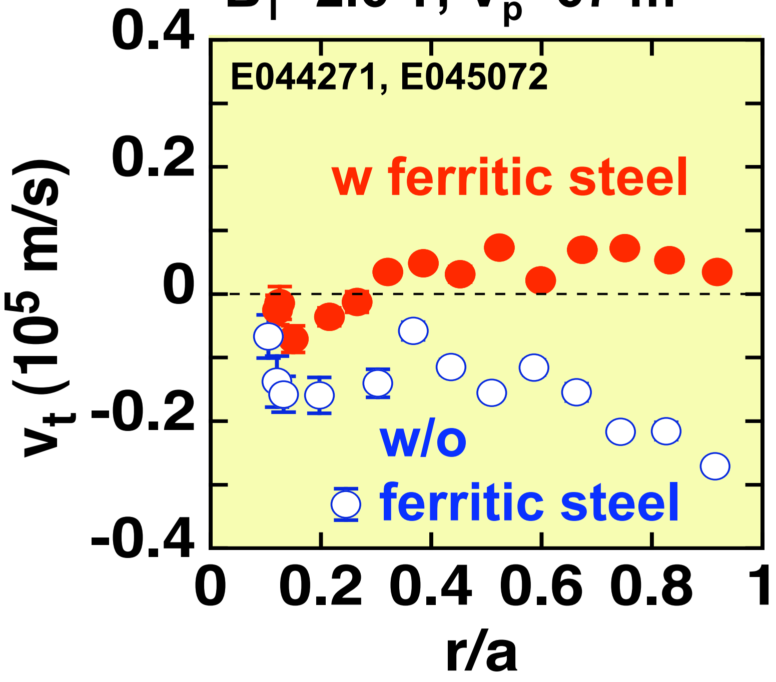
JT-60U

- Reduction of the radial electric field attributed to decrease in the fast ion loss made the counter rotation small.
- Nearly zero rotation with perpendicular NB injection and co-rotation with CO-NB injection were observed.

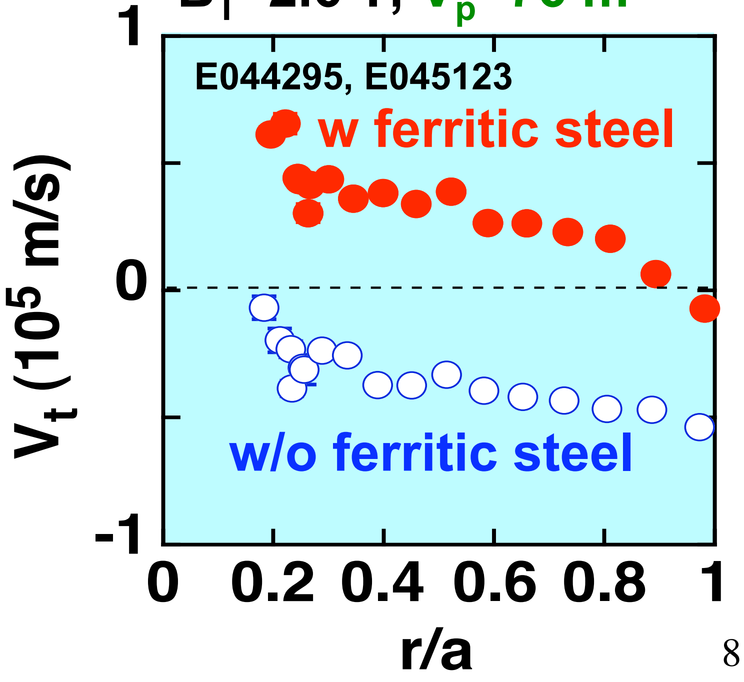


$P_{P\text{-}NB}$=3.9 MW

B_T=2.6 T, V_p=67 m^3



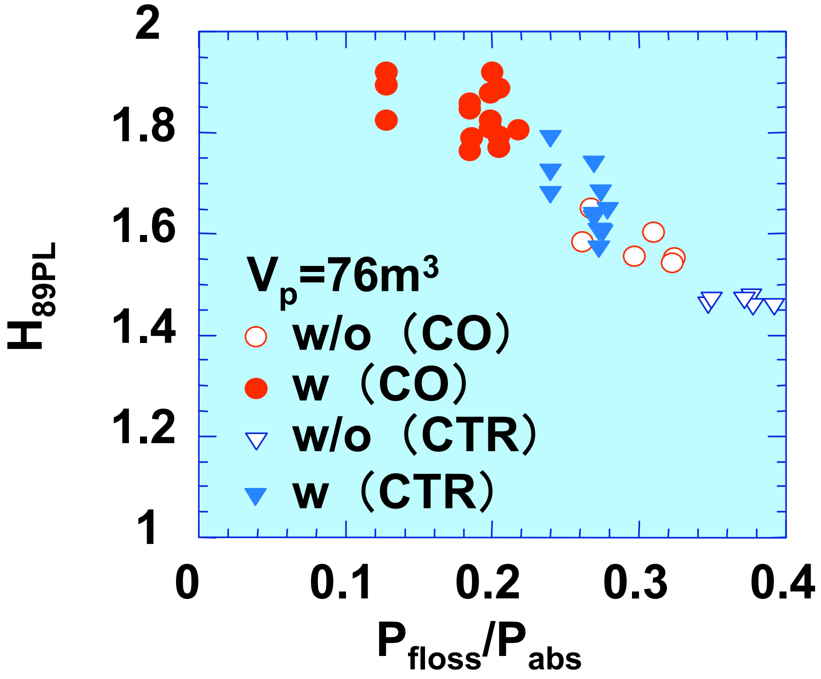
$P_{P\text{-}NB}$=8.3 MW &
$P_{CO\text{-}NB}$=3.9 MW
B_T=2.6 T, V_p=76 m^3

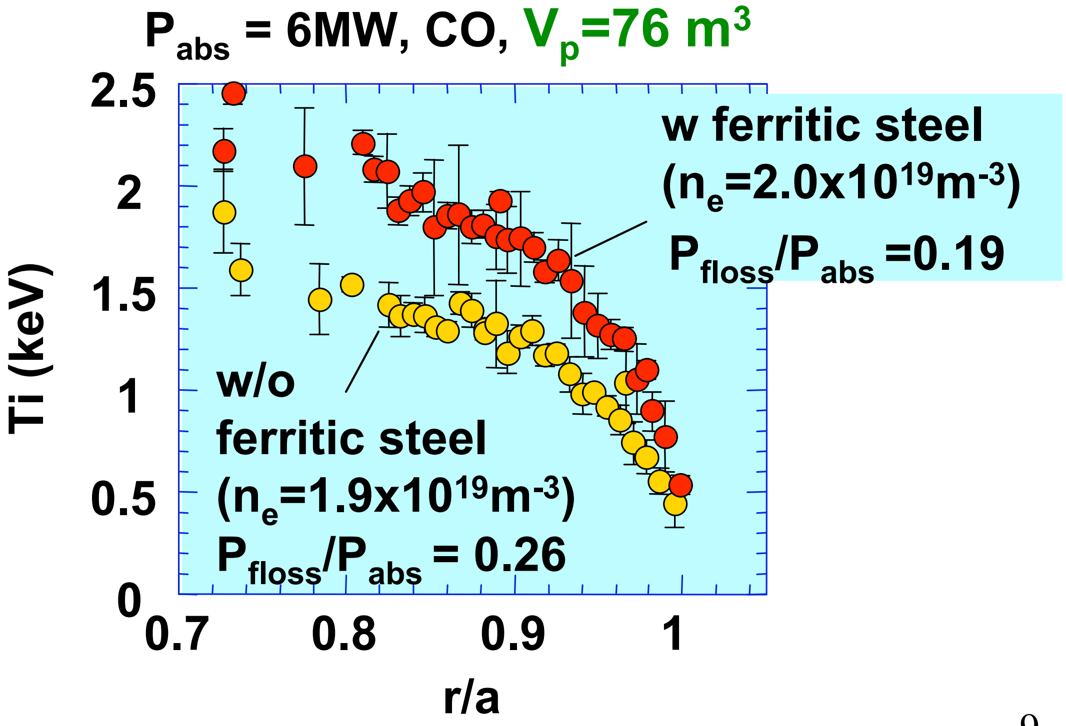


H-mode confinement was improved with ferritic steel.

JT-60U

- **With decreasing the fast ion loss fraction by installing the ferritic steel, the H-mode confinement was clearly improved.**
- **Pedestal temperature explicitly increased by the existence of ferritic steel.**
- **Relation to the toroidal rotation and/or the radial electric field is under investigation.**

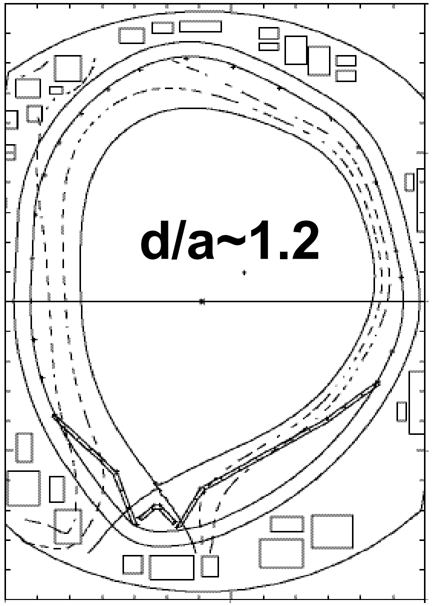


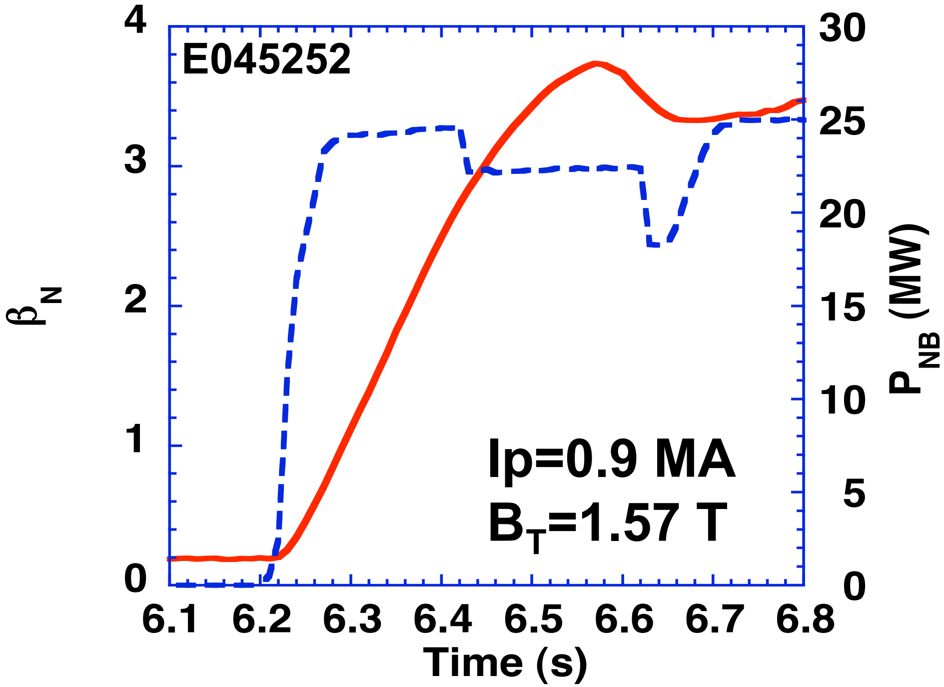


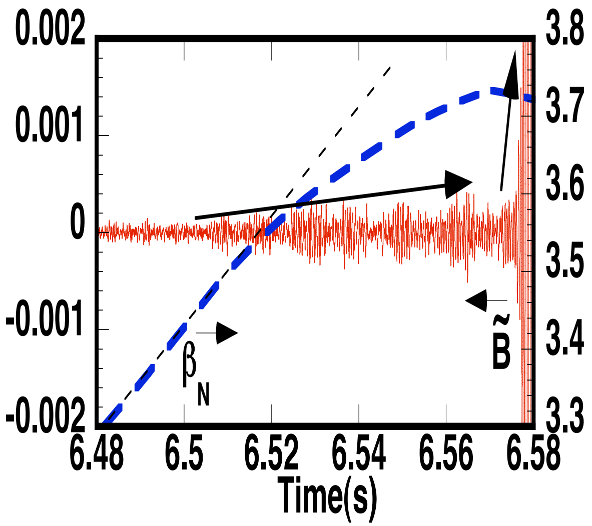
High β_N of 3.7 exceeding no-wall ideal limit was achieved with RWM.

JT-60U

- Increase in net heating power and confinement improvement by reducing the fast ion loss in the large plasma configuration close to the outer wall allowed to access high β_N regime exceeding no-wall ideal limit.
- High β_N was terminated by mini collapse.
- The m/n=3/1 mode started at β_N~3.2. Its amplitude increased gradually and then increased rapidly with τ ~2ms (L/R_{wall}~10 ms).



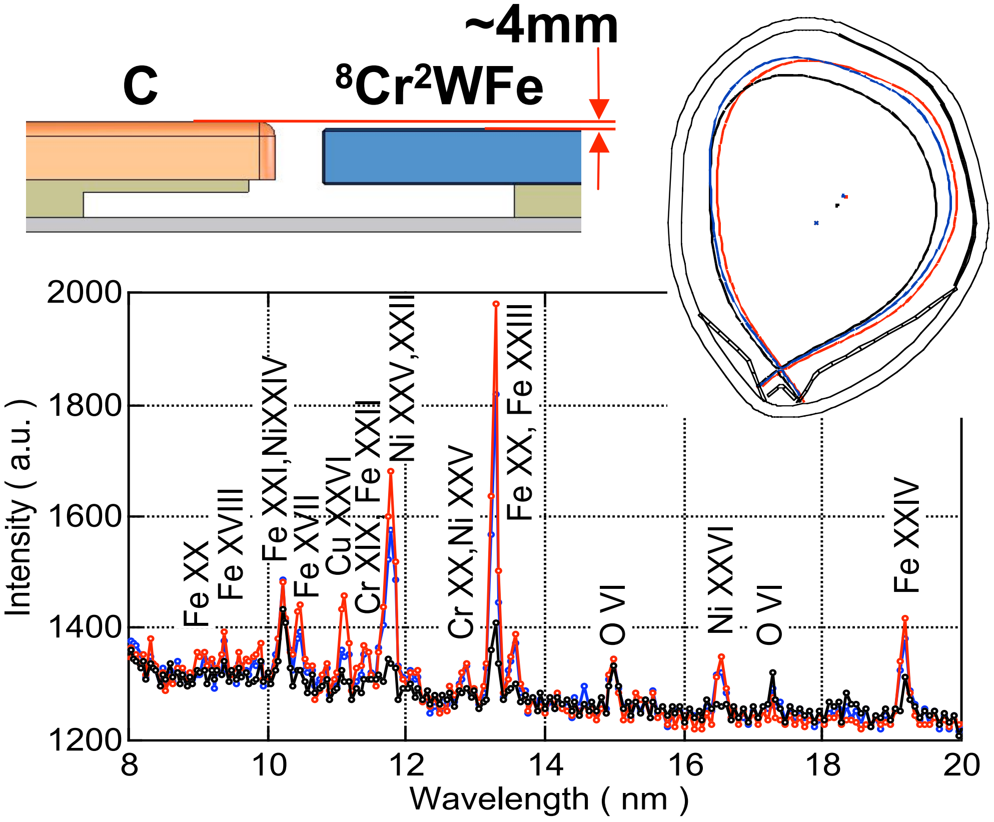




No serious effect of impurities was observed with the ferritic steel.

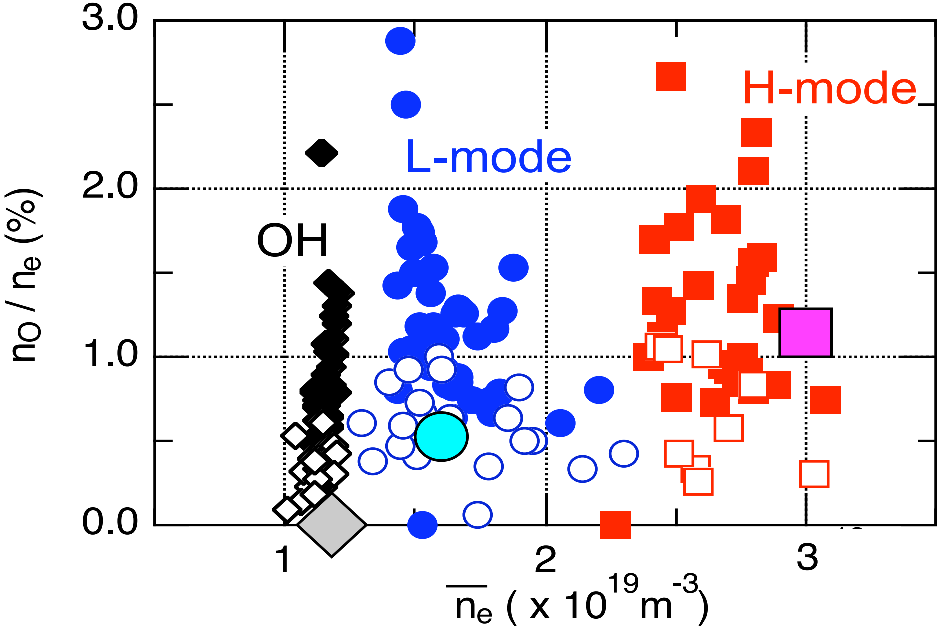
JT-60U

- **Metal impurity lines were observed in the large plasma configuration close to the outer wall.**
- **Contribution of metal impurity to the radiation was small.**
- **No increase in oxygen impurity was observed with ferritic steel.**



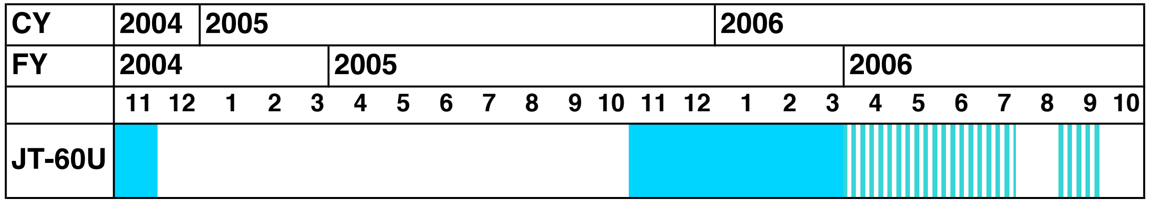
Open symbols : within 50 shots after boronization

Large symbols : w ferritic steel



JT-60U Operation Plan

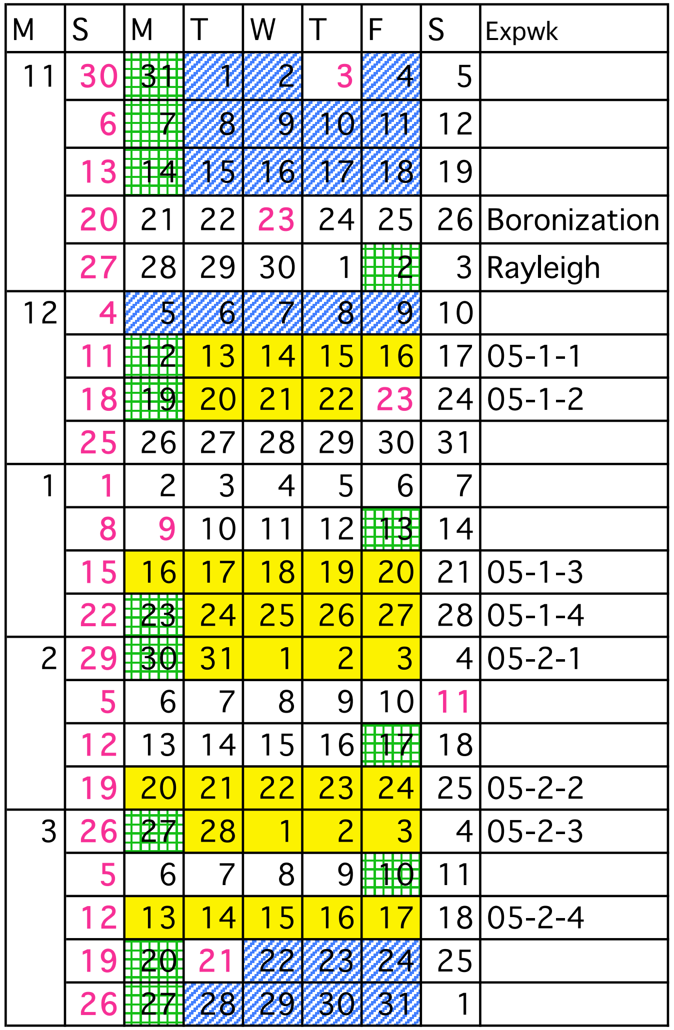
- Operation in FY2005 starts on Nov. 1 and continues until Mar. 2006.
- 8 weeks experimental operation and several weeks conditioning operation in FY2005.
- Schedule in FY2006 is not yet decided officially, but operation will continue until Sep. 2006, with a similar number of weeks as in FY2005.



CY	**2004**		**2005**												**2006**									
FY	**2004**					**2005**												**2006**						
	11	**12**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
JT-60U	■												■	■	■	■	■	▥	▥	▥	▥		▥	

maintenance operation

FY2005



M	S	M	T	W	T	F	S	Expwk
11	30	31 🟩	1 🟦	2 🟦	3	4 🟦	5	
	6	7 🟩	8 🟦	9 🟦	10 🟦	11 🟦	12	
	13	14 🟩	15 🟦	16 🟦	17 🟦	18 🟦	19	
	20	21	22	23	24	25	26	Boronization
	27	28	29	30	1	2 🟩	3	Rayleigh
12	4	5 🟦	6 🟦	7 🟦	8 🟦	9 🟦	10	
	11	12 🟩	13 🟨	14 🟨	15 🟨	16 🟨	17	05-1-1
	18	19 🟩	20 🟨	21 🟨	22 🟨	23 🟨	24	05-1-2
	25	26	27	28	29	30	31	
1	1	2	3	4	5	6	7	
	8	9	10	11	12	13 🟩	14	
	15	16 🟨	17 🟨	18 🟨	19 🟨	20 🟨	21	05-1-3
	22	23 🟩	24 🟨	25 🟨	26 🟨	27 🟨	28	05-1-4
2	29	30 🟩	31 🟨	1 🟨	2 🟨	3 🟨	4	05-2-1
	5	6	7	8	9	10	11	
	12	13	14	15	16	17 🟩	18	
	19	20 🟨	21 🟨	22 🟨	23 🟨	24 🟨	25	05-2-2
3	26	27 🟩	28 🟨	1 🟨	2 🟨	3 🟨	4	05-2-3
	5	6	7	8	9	10 🟩	11	
	12	13 🟨	14 🟨	15 🟨	16 🟨	17 🟨	18	05-2-4
	19	20 🟩	21	22 🟦	23 🟦	24 🟦	25	
	26	27 🟩	28 🟦	29 🟦	30 🟦	31 🟦	1	

🟩	Maintenance
🟨	Exp. Operation
🟦	Cond. Operation

Major Targets of JT-60U Experiments during 2005-2006

1. **Achievement of longer sustainment (> 25 s) of β_N = 2-2.5 and HH~1.**
2. **Achievement of high beta exceeding the free-boundary stability limit (β_N >~3.5).**
3. **Extension of duration of high bootstrap current fraction (70-80%) and development of control schemes of self-organized plasmas.**
4. **Extension of performance under quasi-steady fully non-inductive current drive condition.**
5. **Extension of fusion triple product in long pulse discharges (aiming at 5×10^{19} m^{-3}skeV x 20 s)**
6. **Achievement of stationary sustainment of high confinement under saturated wall conditions by active divertor-pumping.**

Status of Contribution to ITPA from JT-60U

- The Fourth IEA Large Tokamak Workshop (W62) on "Implementation of the ITPA Coordinated Research Recommendations" was held on November 1-2, 2005, in General Atomics.
- The number of proposals which need JT-60U is 34.

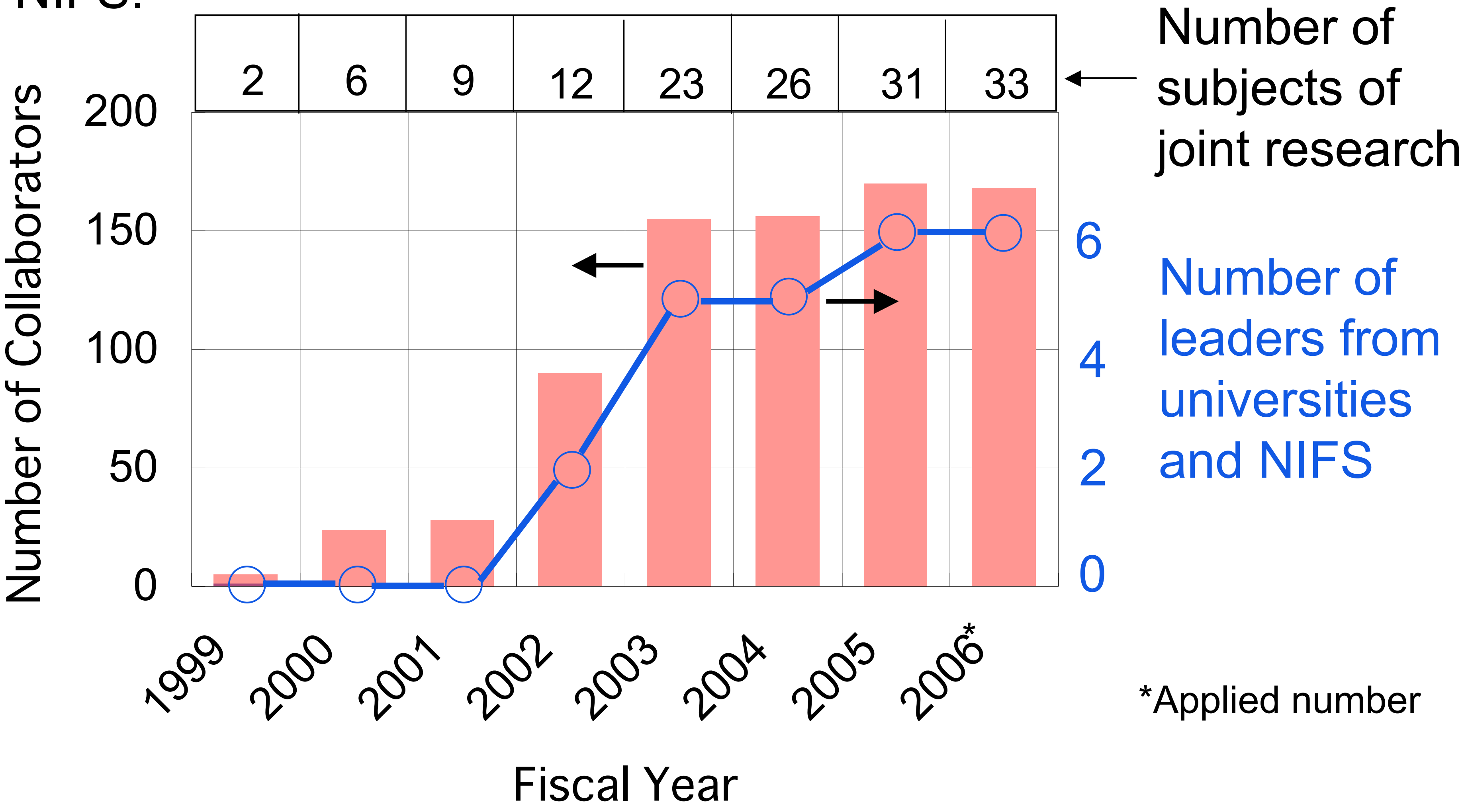
ITPA/IEA Joint Experiments between Various Tokamaks

Topical Group	Number of proposals	Discussion Results	Number of proposals which need JT-60U
Confinement Database and Modelling	5	E(3), E/D(1), D(1)	2
Transport Physics	15	E(14), D(1)	9
Pedestal and Edge Physics	10	E(10)	4
Scrape-off Layer and Divertor Physics	13	E(11), P(2)	7
MHD, Disruption, and Magnetic Control	9	E(9)	4
Steady-State Operation	8	E(6), D(1), P(1)	8
Total	60	E(53), E/D(1), D(3), P(3)	34

・E:The IEA program leaders accepted this item as a well defined joint experiment
・D:The proposed activity appears to be a joint experiment but further definition is required
・P:The item proposed was judged to be important programmatic activity appropriate to the research of the ITPA but not a joint experiment

JT-60U as a Core National Device for Joint Research

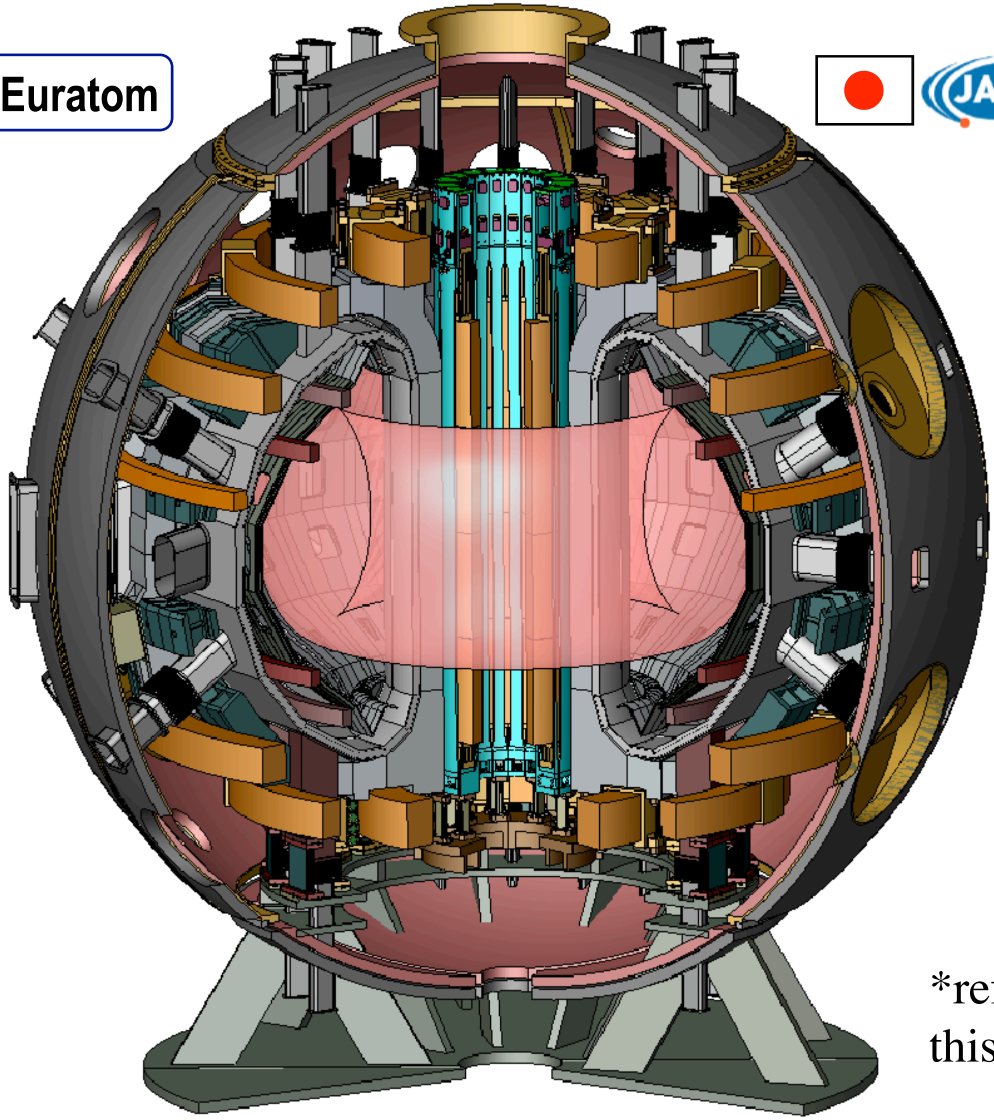
- JAEA is striving for research collaboration with the universities and NIFS.



*Applied number

Status of
JT-60U Modification*

Euratom



*referred as NCT tentatively in this document.

JA-EU Satellite Tokamak Working Group

Terms of Reference

1. Review JA technical proposal and estimated costs of JT-60 modification program in order to assess the suitability of the proposed changes for the use of JT-60 as a satellite tokamak to ITER in the BA context;
2. Identify possible areas of contribution by the EU to the procurement of the modifications and in the subsequent exploitation of the machine in the BA context;
3. Envisage the organization of the exploitation of the modified JT-60, including the possible role of the EU;
4. Identify elements for a joint scientific programme of exploitation in the BA context;
5. Submit a joint interim report by Mid November 2005 containing its findings and recommendations.

Members

Chair: S. Matsuda (JAEA)
JA members: M. Kikuchi (JAEA, Contact Person), Y. Miura (JAEA), Y. Takase (U. Tokyo), M. Matsukawa (JAEA), S. Sakurai (JAEA)
EU members: F. Romanelli (ENEA, Contact Person), J. Pamela (EFDA), D. Campbell (EFDA CSU), C. Sborchia(IPP), J.J. Cordier (CEA), S.Clement-Lorenzo (EC).

Meetings

1. Informal meeting: September 20, 2005 at Genova
2. 1st meeting: October 5,6, 2005 at NAKA
3. 2nd meeting: November 3,4,5 at Garching
4. 3rd meeting: November 14,15 at NAKA

Role of Satellite Tokamak in the Broader Approach

The EU and JA have agreed that within the “Broader Approach”, the Satellite Tokamak should serve the following functions:

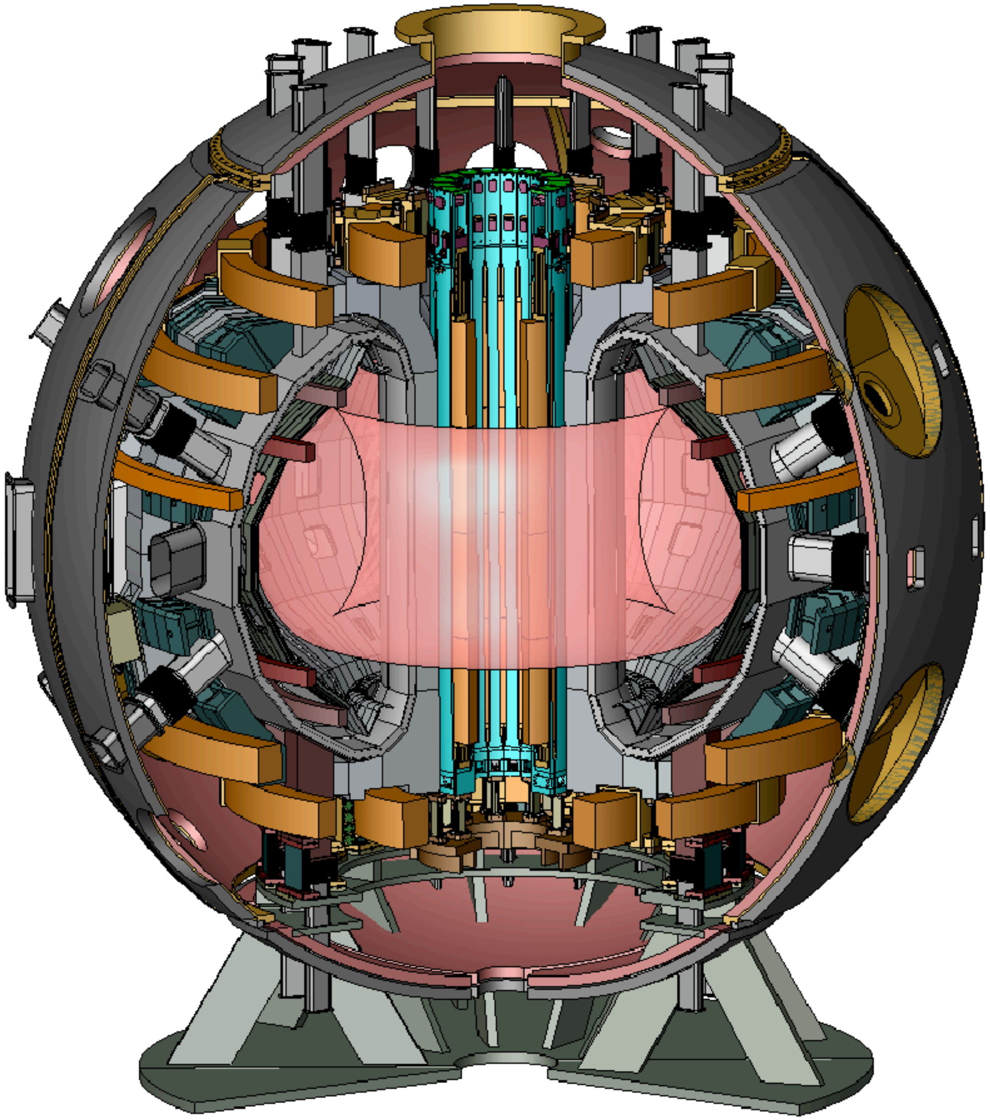
- **During ITER construction:**
  - to optimize operation scenarios for ITER
  - to optimize ITER auxiliary systems which come later in the construction of ITER
  - to train, in an international environment, scientists, engineers and technicians in view of the integrated operation and scientific exploitation of ITER

- **During ITER operation:**
  - to support further development of operating scenarios and the understanding of physics issues
  - to test possible modifications before their implementation on ITER

- **The main functions in support to DEMO will be to explore operational regimes and issues complementary to those being addressed in ITER. In particular these will include:**
  - steady state operation
  - advanced plasma regimes (higher normalized plasma pressure: β)
  - control of power fluxes to walls.

Modified JT-60U Facility

Euratom

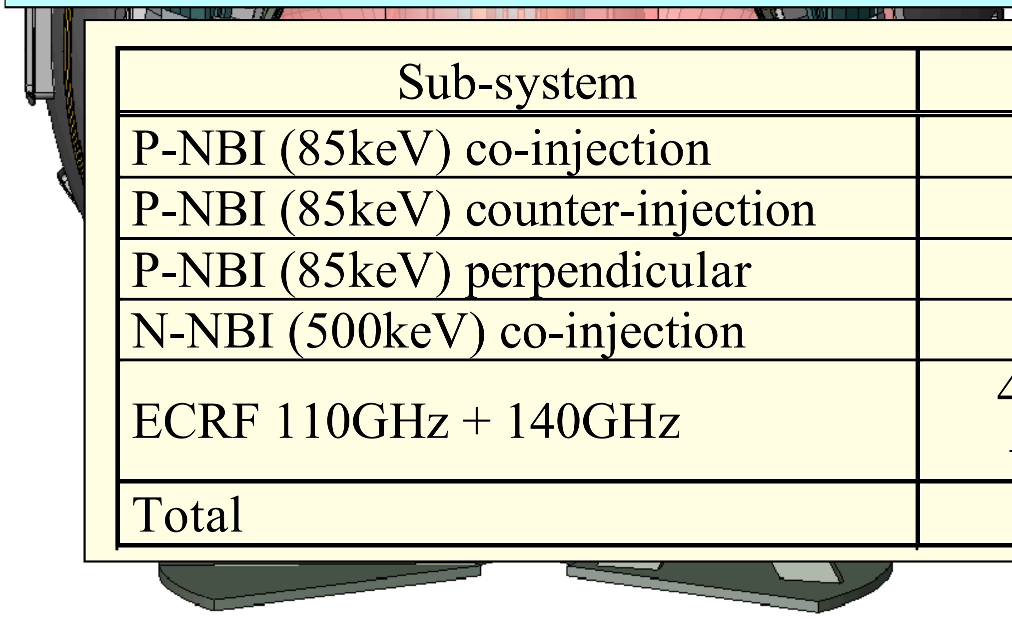


NCT parameters	
Plasma Current	5.5MA/3.5MA
Major Radius	3.01m / 3.16m
Minor radius	1.14m / 1.02m
Elongation κ_{95}	1.83 / 1.7
Triangularity δ_{95}	0.57 / 0.33
Toroidal field B_t	2.72 / 2.59
Safety factor q_{95}	3.77/ 3.0
Flat top	100s (8hours)
H&CD power	41MWx100s
Perp NB	16MW
Co P-NB	4MW
CTR P-NB	4MW
N-NB	10MW
ECRF	7MW
PFC heat flux	10MW/m^2
Annual neutron	4x10^{21}

Modified JT-60U Facility

- Extension of the heating and current drive (H&CD) capability to **41MW for 100s**, involving improvements in the performance of the neutral beam and electron cyclotron heating systems;
- Inclusion of **an option for upgrading to metallic Plasma Facing Components**, while ensuring a high power handling capability;
- Increase in the neutron budget by an order of magnitude with respect to the original proposal to allow for a comprehensive exploitation of the device capabilities, which requires **the in-vessel components to be remote handle-able**.

Sub-system	Composition	Torus input
P-NBI (85keV) co-injection	2units x 2MW	4MW
P-NBI (85keV) counter-injection	2units x 2MW	4MW
P-NBI (85keV) perpendicular	8units x 2MW	16MW
N-NBI (500keV) co-injection	2units x 5MW	10MW
ECRF 110GHz + 140GHz	4units x 0.75MW +5unitsx0.8MW	7MW
Total		41MW

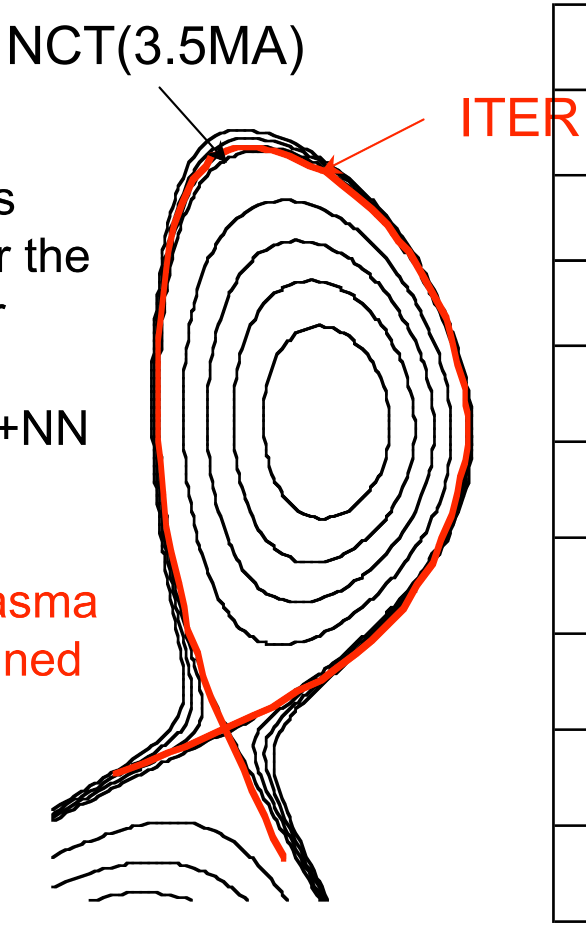


Annual neutron	4×10^{21}

Scenario (*ELMy H-mode and Hybrid Operation*)

Analysis of NCT's capability for exploration of ELMy H-mode and hybrid scenarios indicates that it can explore a wide range of ITER-relevant issues. In particular, the possibility to operate in long-pulses (~100s) with ITER-shaped plasmas at 3.5MA/2.42T.

- TOSCA calculation shows that the necessary flux for the flat top plasma current for 3.5MA,100sec (30MW, CO(4)+CTR(4)+Perp(16)+NNB(6)) is about 13Wb.
- It is estimated that the plasma current of 3.5MA is sustained for 100sec.

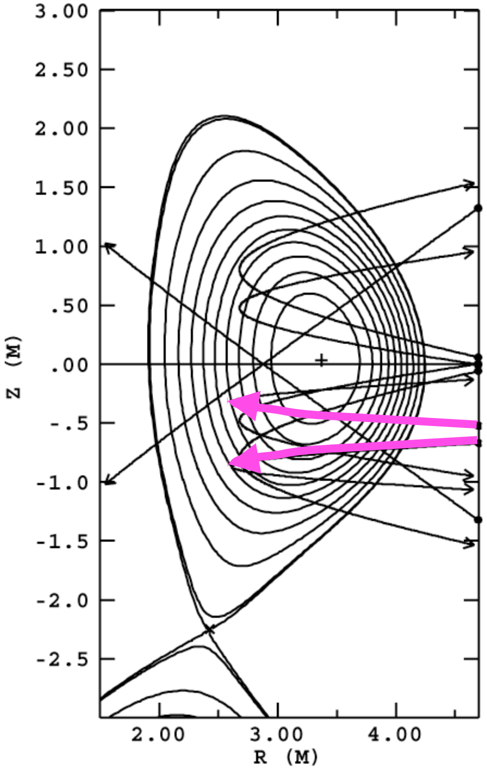


	ITER	NCT 3.5MA
R	6.2	3.16
a	2	1.02
A	3.1	<-
κ_{95}	1.7	<-
δ_{95}	0.33	<-
B_T	5.3	2.42
I_P	15	3.5
q_{95}	3	<-
n_{GW}	1.19E+20	1.07E+20

Scenario (*Non-inductive steady-state operation)*

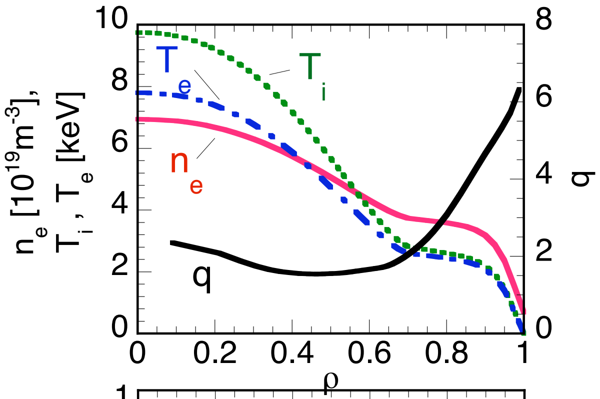
- The analysis of NCT's capability for exploration of a full current drive scenario shows that 3 MA/2.44T full current drive with a Greenwald fraction f_{GW} of 0.55, bootstrap current fraction, f_{BS} of 0.56, HH_{98y2} = 1.30 and q_{95}=5.3 is possible using the total power of 41 MW (24MW P-NBI, 10 MW N-NBI and 7 MW ECRF). The achievable normalized beta, β_N, is 3.6.

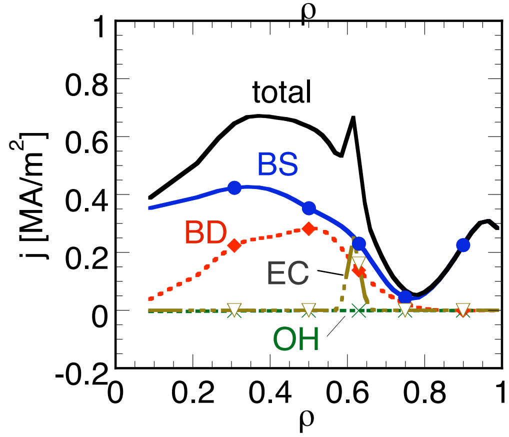
- A higher β_N of 4.4 at f_{GW} =0.88, f_{BS}=0.70, HH_{98y2} = 1.32 and q_{95}=5.5, (which is similar to JA designed DEMO J05, slim CS), is possible at 2.4MA/1.79T with the total power of 41MW.



41 MW (P-NB: 24MW(BAL),
N-NB: 10MW, EC: 7MW),
A~2.65, 2.4 MA, 1.79T, q_{95}=5.5,
HH_{98y2} = 1.32, f_{BS} = 70%, β_N=4.4,
f_{GW}~0.88.

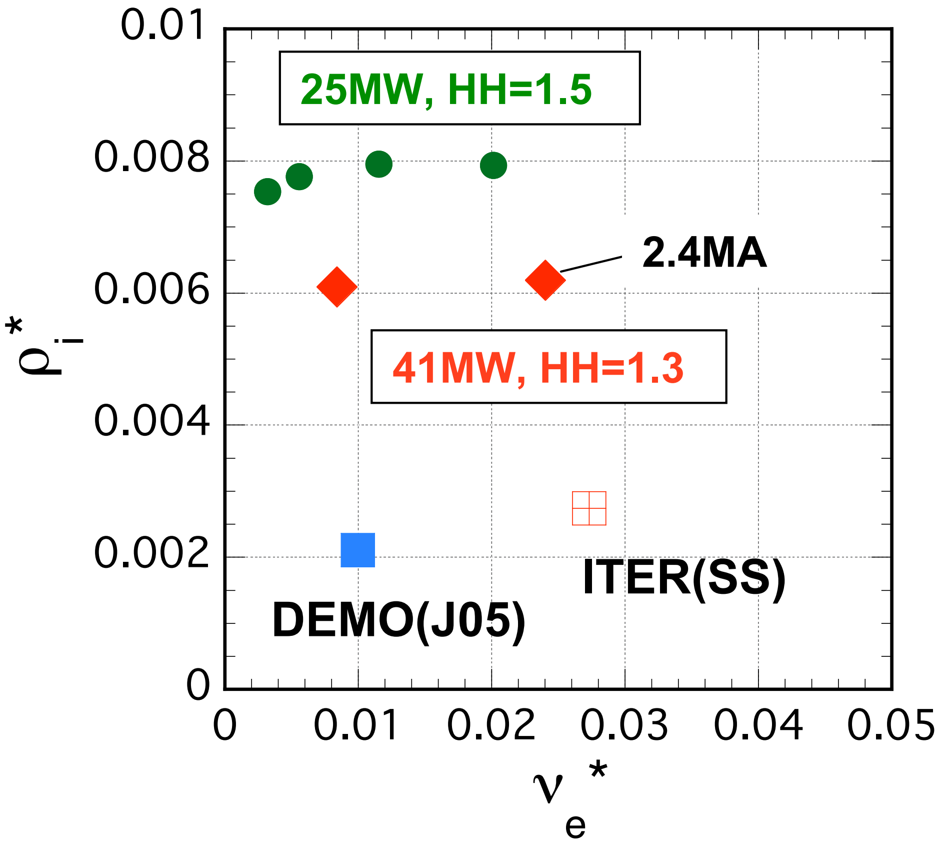
NNB
500keV,
10MW,
Z=-0.6m





Comparison with DEMO J05, slim CS

- $\rho_i^* / \rho_i^{*DEMO}$ **=3**
- ν_e^* / ν_e^{*DEMO} **=2.4**

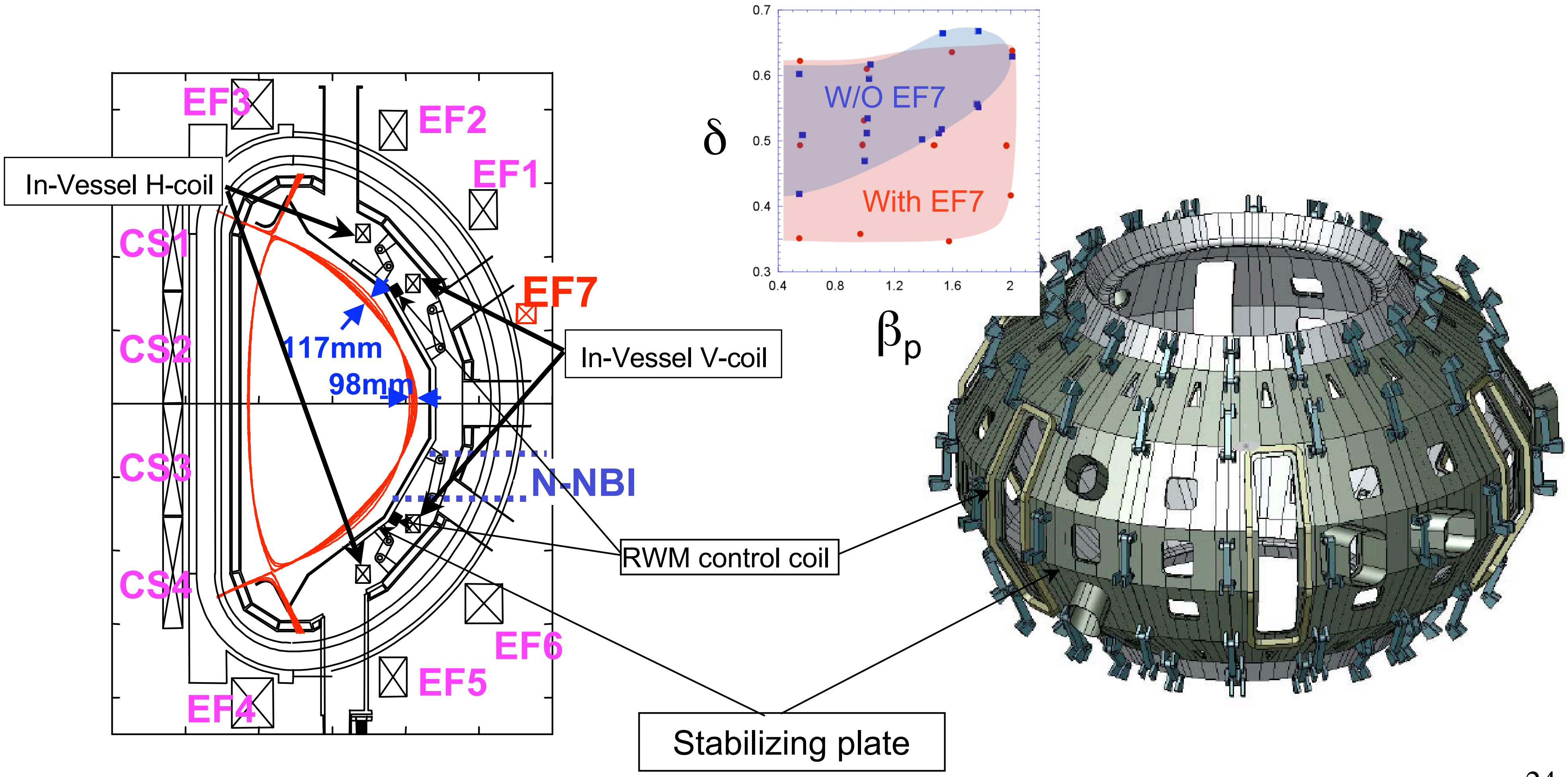


	NCT 41 MW	DEMO(J05, slim CS)
I_p [MA]	2.4	16.7
B_t [T]	1.79	6.0
R_p [m]	3.08	5.5
A	2.65	2.6
q_{95}	5.52	5.4
κ	1.82	2
β_N	4.37	4.3
β [%]	5.0	5.7
HH_{98y2}	1.32	1.3
f_{BS}	0.70	0.77
f_{GW}	0.88	1.15
$\overline{n_e}$ [$10^{19}m^{-3}$]	5.0	12
$<T_i>$ [keV]	4.0	17
ρ_i^* [10^{-3}]	6.2	2.1
ν_e^* [10^{-2}]	2.4	1.0

Equilibrium and PF Control

NCT appears to have considerable flexibility for equilibrium variations providing access, in principle, to a wide range of physics studies:

- **Studies of vertical stability confirm the importance of the stabilizing plate.**
- **Internal coils for fast position control will provide additional flexibility**



Summary

-Recent Results and Plans of JT-60U

- **Ferritic steel was installed for reducing the toroidal field ripple.**
  - Reduction of fast ion loss and counter rotation were observed.
  - Confinement improved with decreasing fast ion loss fraction.
  - High β_N exceeding no wall ideal limit was achieved.
  - No serious impurity effects were observed.
- **International and domestic collaborative research is performed intensively**

- Status of JT-60U Modification

- Heating and current drive capability is now 41 MW for 100 sec.
- Inclusion of an option of metallic PFC.
- Increase neutron budget => in-vessel components to be remote handle-able.