

JT-60 plan for the Advanced Tokamak

**Presented by
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Advanced Tokamak Workshop

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Outline

JT-60U

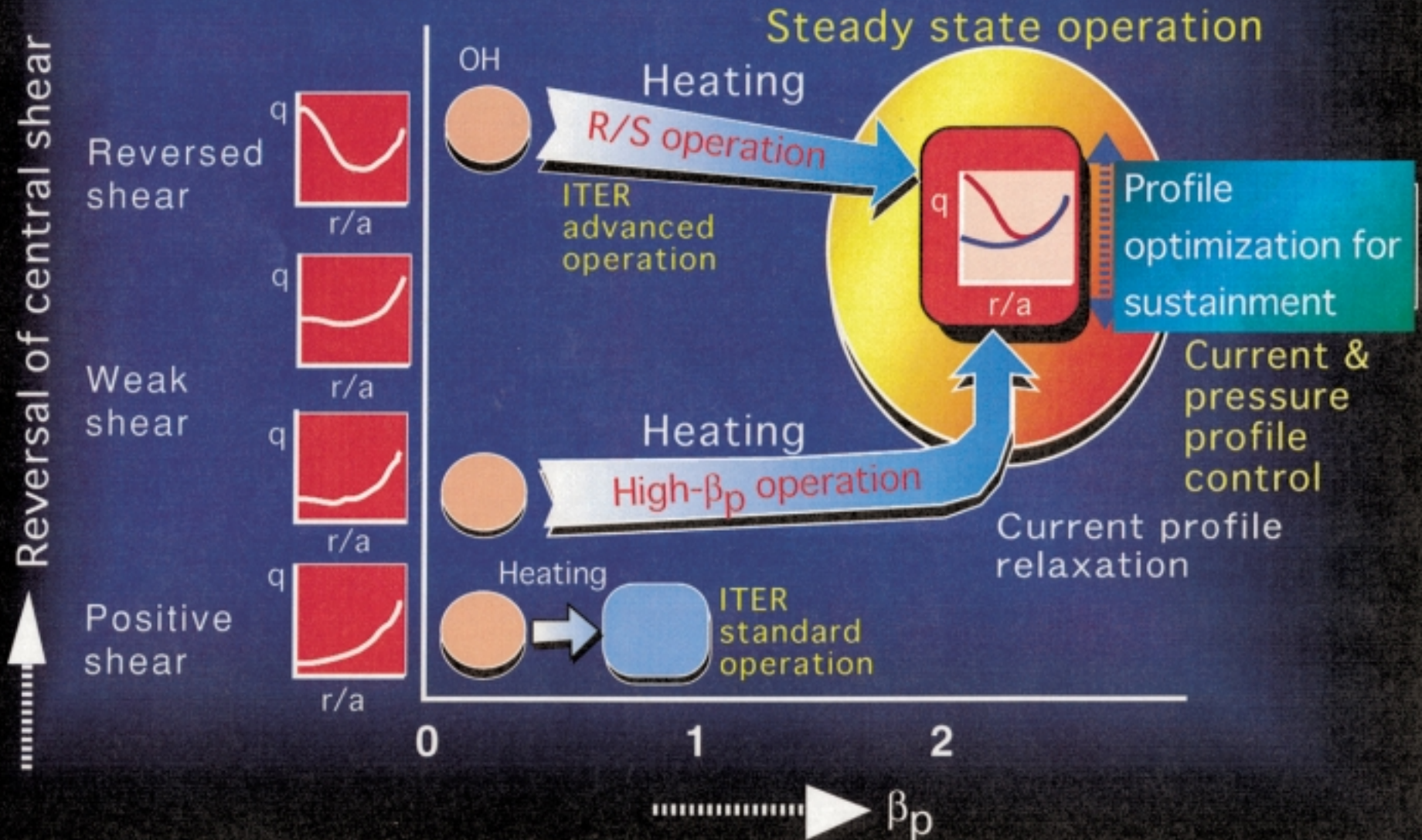
- **Objectives of JT-60U**
 - **Approach to steady state operation**
- **Progress for Advanced Tokamak;**
 - **Reversed shear operation**
 - **High beta-p operation**
- **Short term plan related to AT**
- **Long term prospect**

Objectives of JT-60U

JT-60U

- **Establish a steady-state operation for SSTR**
- **Approach to steady-state operation in JT-60**
 - High beta-p operation
 - Reversed shear operation
- **Key Issues for steady-state, high performance;**
 - Stability
 - Confinement
 - Current drive & Bootstrap
 - Divertor

Approaches toward Steady State Operation



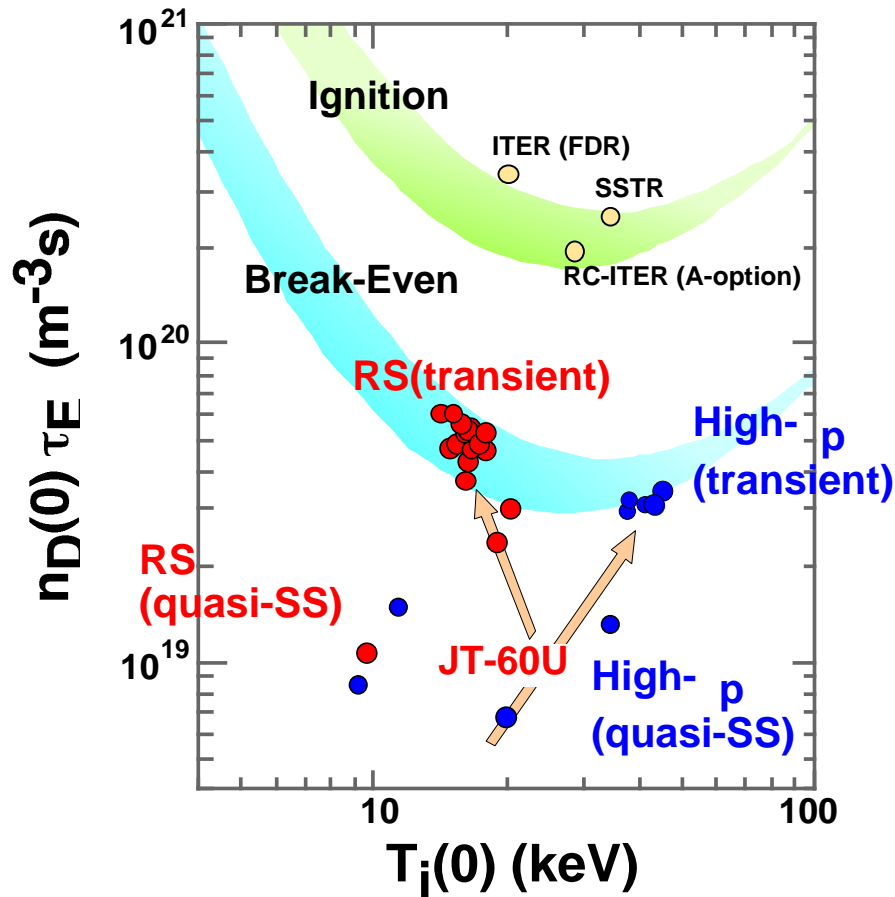
Progress in JT-60

JT-60U

- ~1987 High p operation started in JT-60
- 1989 80% bootstrap current in high p
- 1990 SSTR design proposed
- JT-60 upgraded (JT-60U)
- 1992 RS operation proposed in SSTR
- ~1995 RS operation started in JT-60
- 1996 $Q_{DT}^{eq} > 1$ in RS
- 1997 W-shaped Divertor
- Steady-state operation in high p
($I_p=1.5\text{MA}$, $dt\sim 9\text{sec}$, Total heating energy input 203MJ)
- 1998 World record ($Q_{DT}^{eq}=1.25$) in RS

Recent progress for steady-state reactor plasma

JT-60U



- **World records** of equivalent fusion amplification factor was achieved in RS operation.
- High fusion performance has been achieved in **advanced regimes** of high- β and reversed shear discharges for steady state tokamak operation.

Triple product

$$n_D \ E T_{i0} = 1.53 \times 10^{21} \text{ m}^{-3} \text{ keVs}$$

was obtained in high- β

$Q_{DT} = 1.25$ was obtained in RS

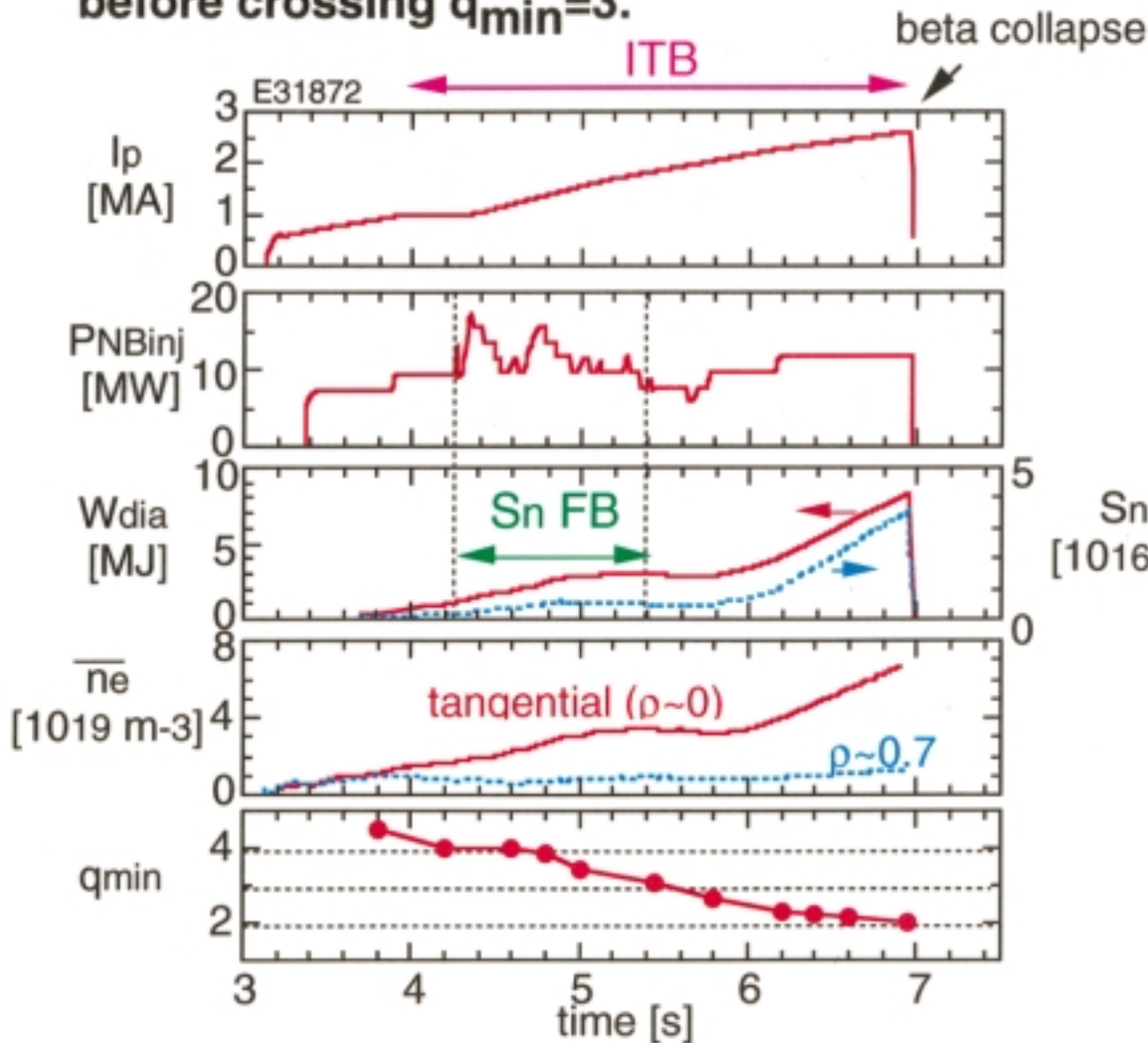
Reversed shear operation significantly improves fusion amplification factor

[T.Fujita, et al., Fusion Energy, IAEA Yokohama 1998 EX1/2]

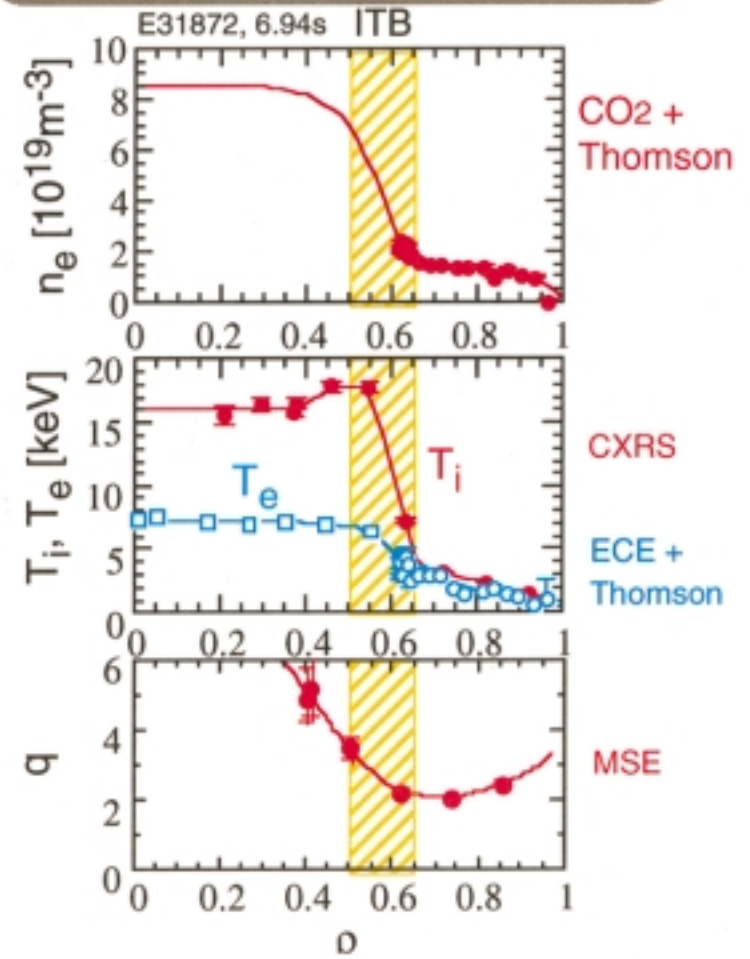
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- Current ramp-up with **persistent ITB**.
- **Sn feedback with NB power** before crossing $q_{min}=3$.

$Q_{DT}^{eq}=1.25$, $S_n = 3.6 \times 10^{16} /s$
 $W_{dia} = 8.2 \text{ MJ}$, $\tau_E = 1.07 \text{ s}$
 $H_{ITER89P} = 3.2$, $\beta_N = 1.53$

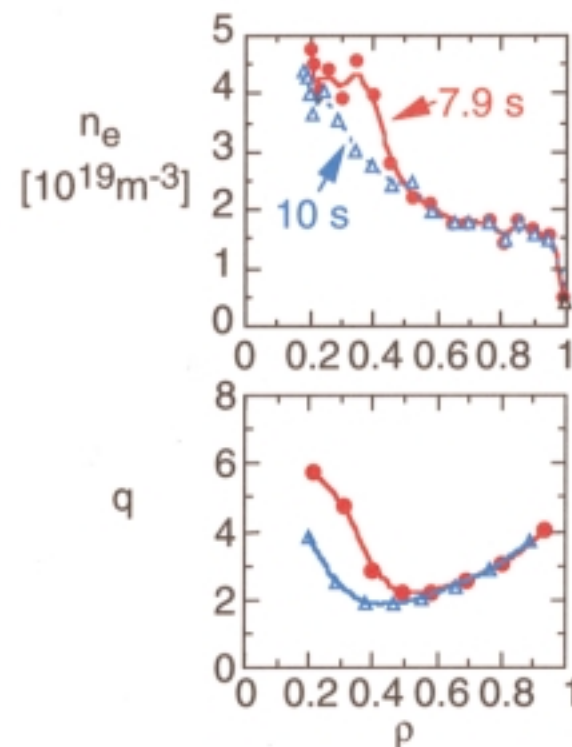
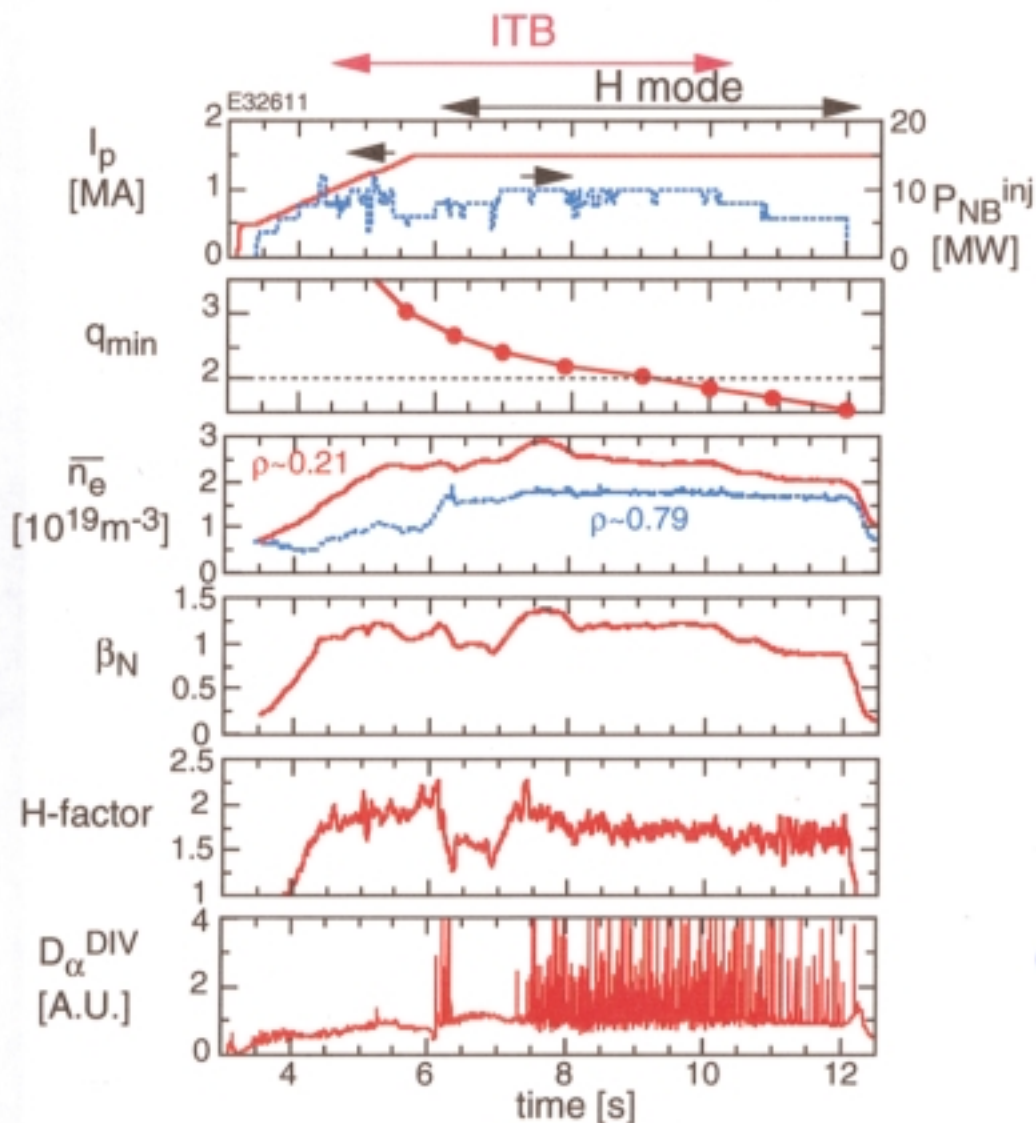


Sn
 $[10^{16} /s]$



Sustainment of RS discharge with ELMy H-mode

JT-60U



$B_T = 3.5$ T, $I_p = 1.5$ MA,
 $q_{95} = 4.3$, $\delta \sim 0.26$

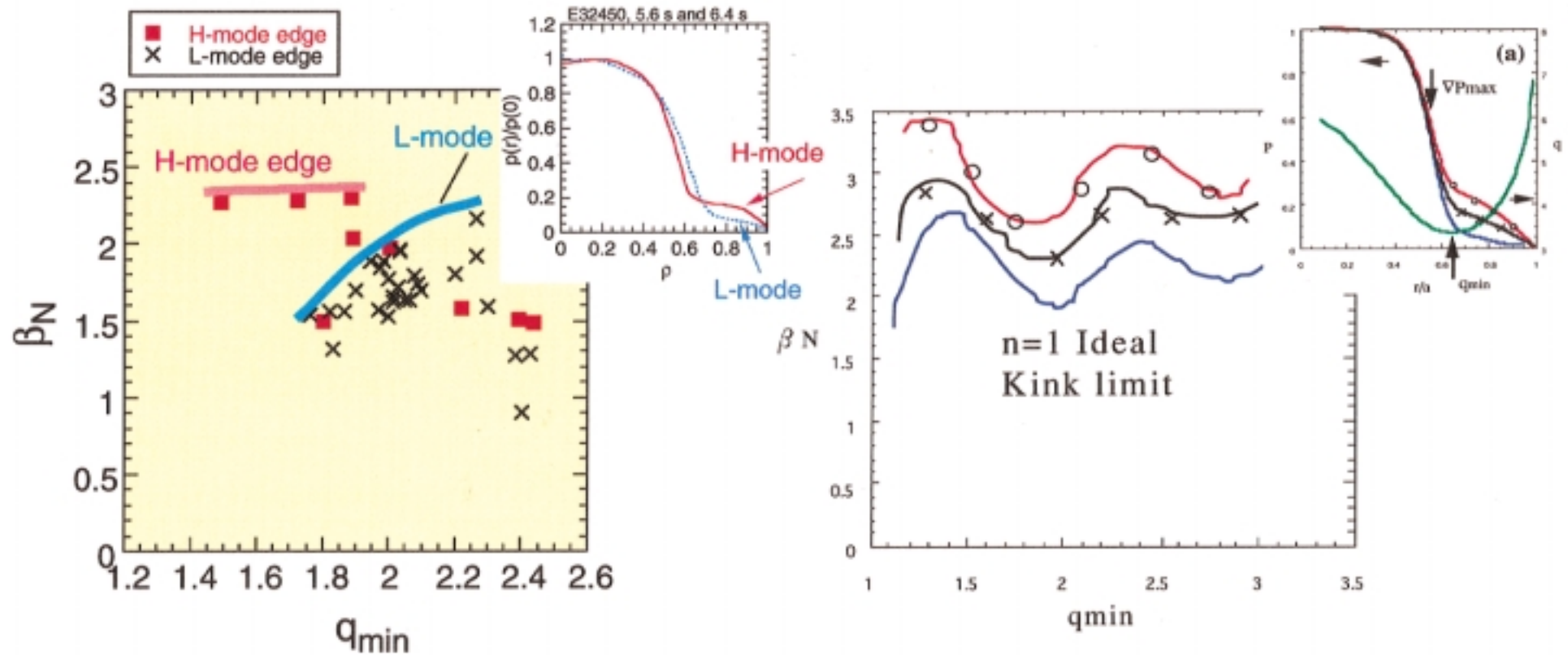
- $\beta_N = 1.0-1.4$, $H_{ITER89P} = 1.5-2.0$ for 5.5 s

- Achievement of quasi-steady reversed shear discharges has made confinement and transport analyses possible without dW/dt correction

[T.Fujita, et al., Fusion Energy, IAEA
 Yokohama 1998 EX1/2]

The performance was limited by the ideal MHD stability

JT-60U

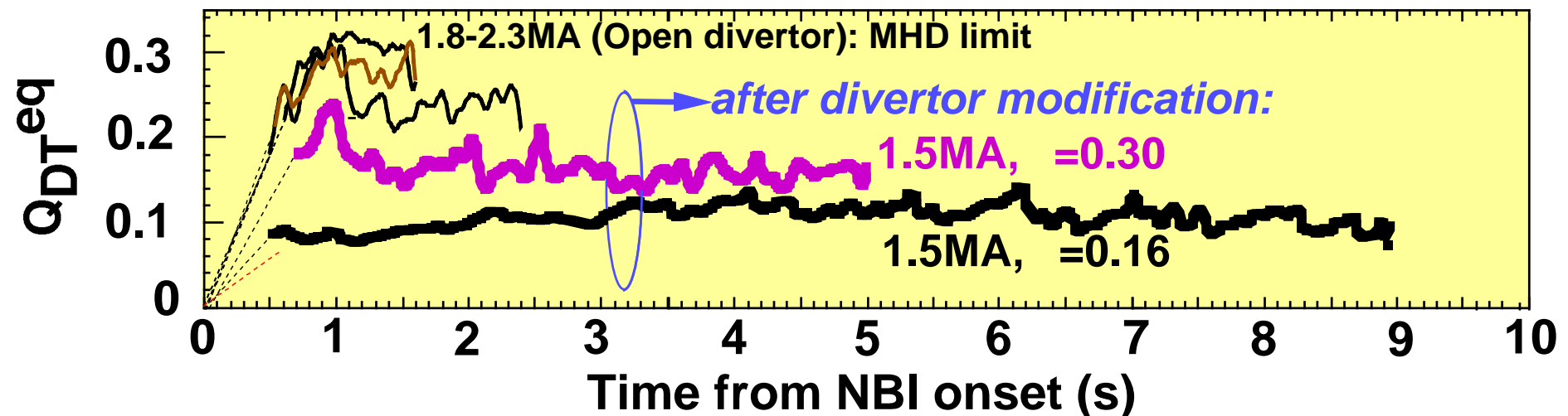


- Increase in the edge pressure improves the beta limit by low n kink.
- Optimizaton of the pressere profile is effective for the beta improvement.

[T.Fujita, et al., IAEA Yokohama 1998 EX1/2, Y.Ishii, Plasma Phys. cont. Fusion (1998) 1707]

Long pulse high performance in high- β regime with W-shaped divertor and high triangularity

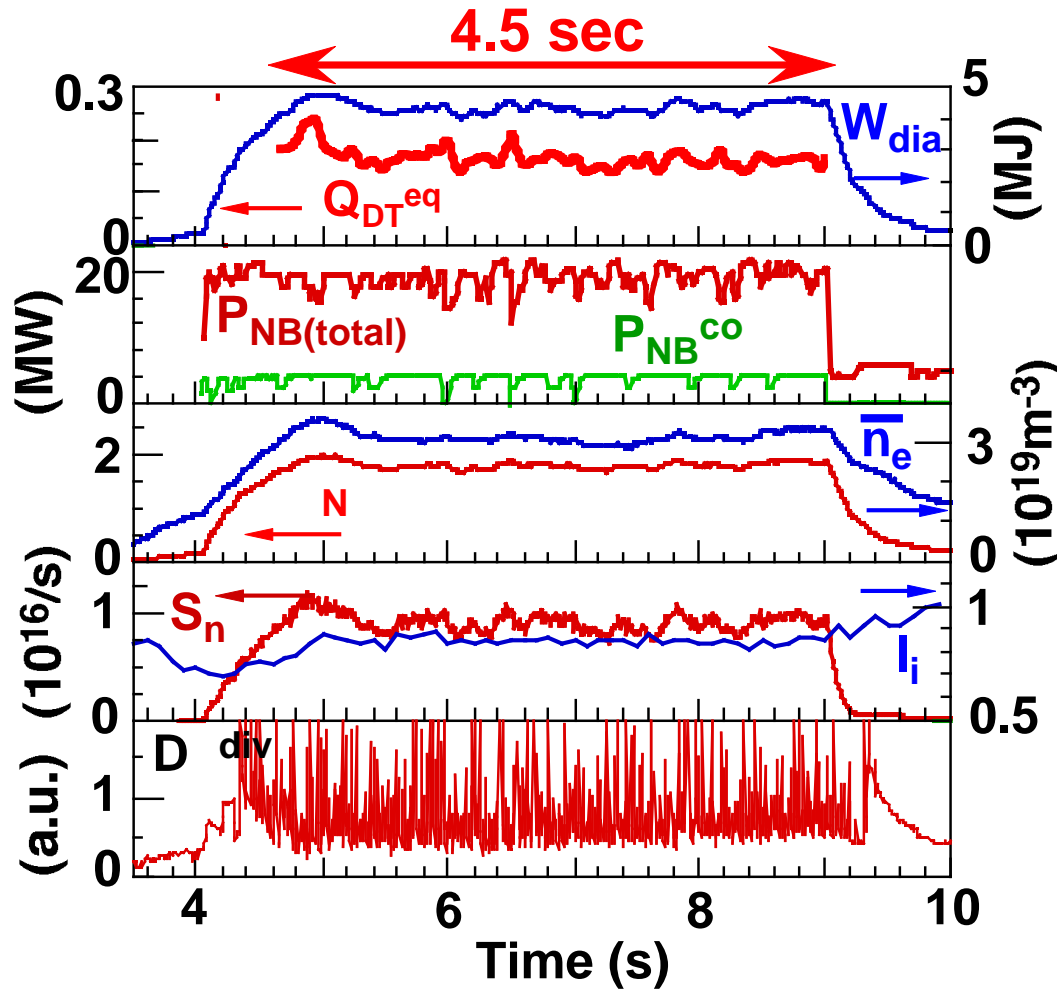
JT-60U



- **W-shaped divertor** improves heat and particle control; long sustainment 203 MJ of heating energy
- **High triangularity** shaping improves stability and confinement; stability margin higher sustained performance

Quasi-steady sustainment of high performance with ~65% CD at a high triangularity in high- ρ regime

JT-60U



High- ρ operation:

- ~ 0.3 , $I_p = 1.5$ MA, $B_t = 3.5$ T
- higher density $n_e/n_G \sim 43\%$

High non-inductive CD rate:

- $\sim 65\%$ (43%BS+22%NBCD)

Sustainment for ~ 4.5 s;

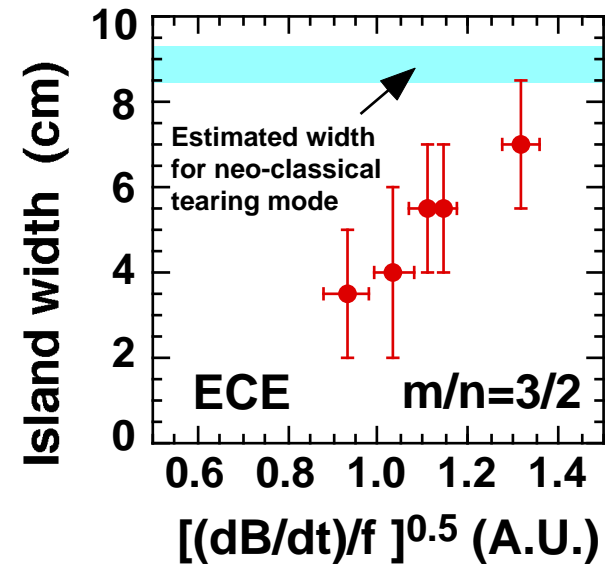
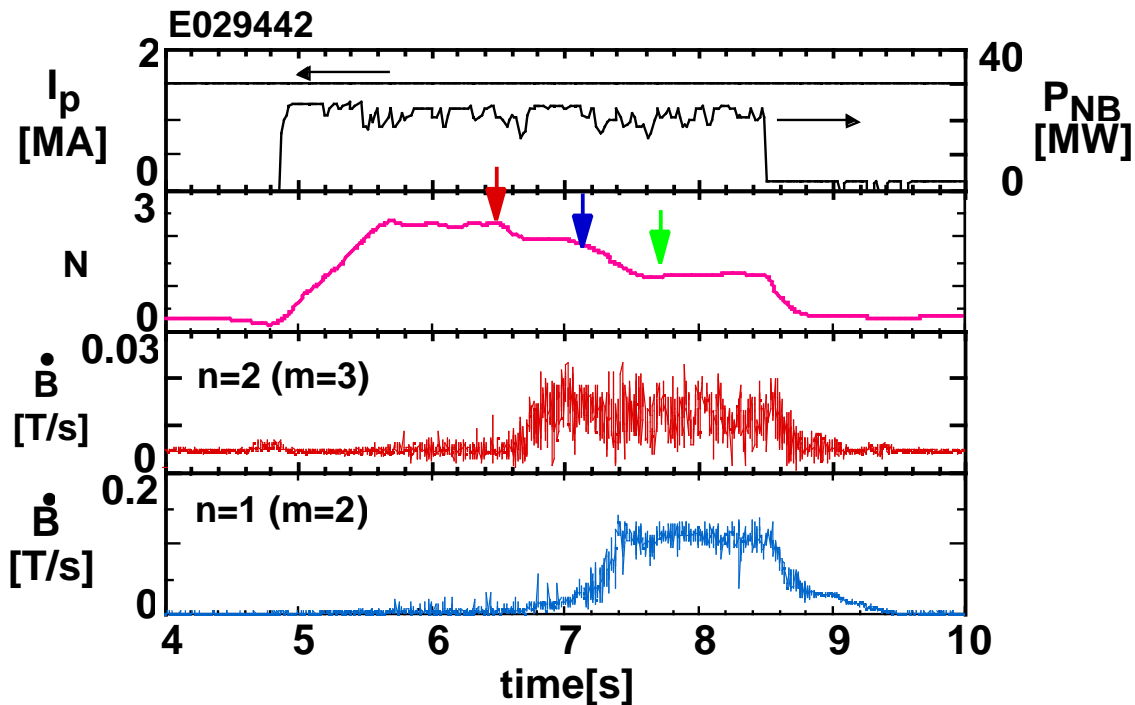
- $H_{ITER89P} \sim 2.2$
- $N \sim 1.9$
- $Q_{DT}^{eq} \sim 0.16$
- limited by coil turn-on time

Sustainment of High- ρ ELMy H-mode:

[Y. Kamada et al, Fusion Energy, IAEA
Yokohama 1998 CD2EX92]

Resistive modes limit the sustainment of high performance

JT-60U



- Degraded with **continuous resistive modes (m/n=3/2, 2/1, etc)**
- **Neo-classical tearing mode** is a candidate for the resistive modes.
- **ECCD** to control the local current profile could be effective for suppression of neo-classical modes

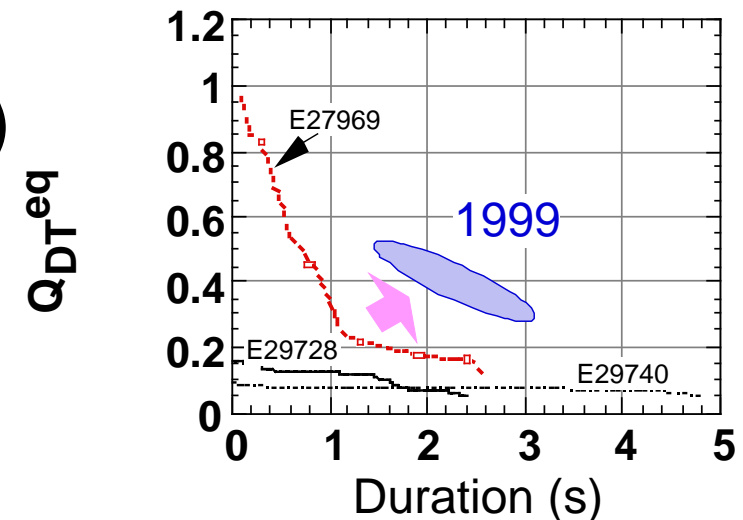
[Asayama et al, Plasma Phys and Fusion (1998)]

Short Term plan related to AT in JT-60

1. Extension of operational regimes

JT-60U

- High performance full-CD in high p ;
 - Demonstrate the concept of SSTR (high p , high confinement, full CD) with higher I_p
 - $I_p > 2\text{MA}$
 - $Q_{DT}^{eq} > 0.3$ (using NNB)
- Long sustainment of high Q_{DT}^{eq} in RS;
 - $Q_{DT}^{eq} > 0.5$ for $>1\text{sec}$



**Optimized use of NNB, LH and EC
with W-shaped divertor**

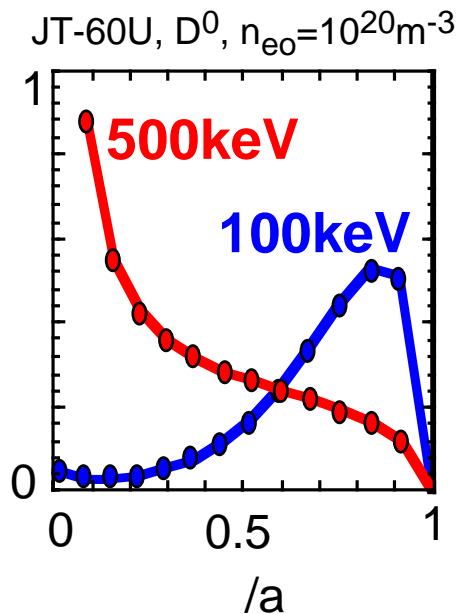
Negative ion based Neutral Beam

JT-60U

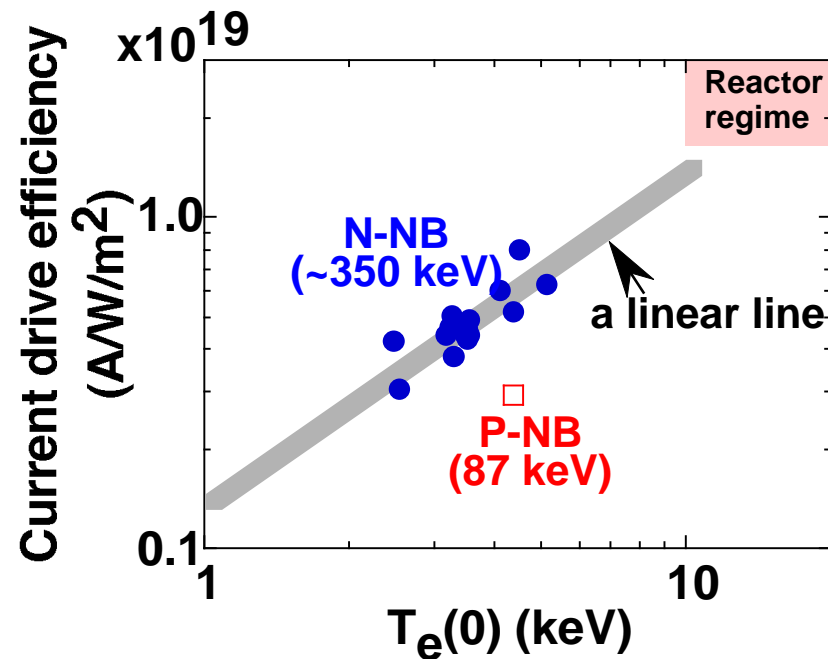
N-NBI is useful for **a central heating and a central current drive**

- N-NBI experiments:
 - evaluate CD efficiency in $T_e(0) \sim 2.5-5$ keV at ~ 350 keV.

Power Deposition(a.u.)



JT-60 high density case

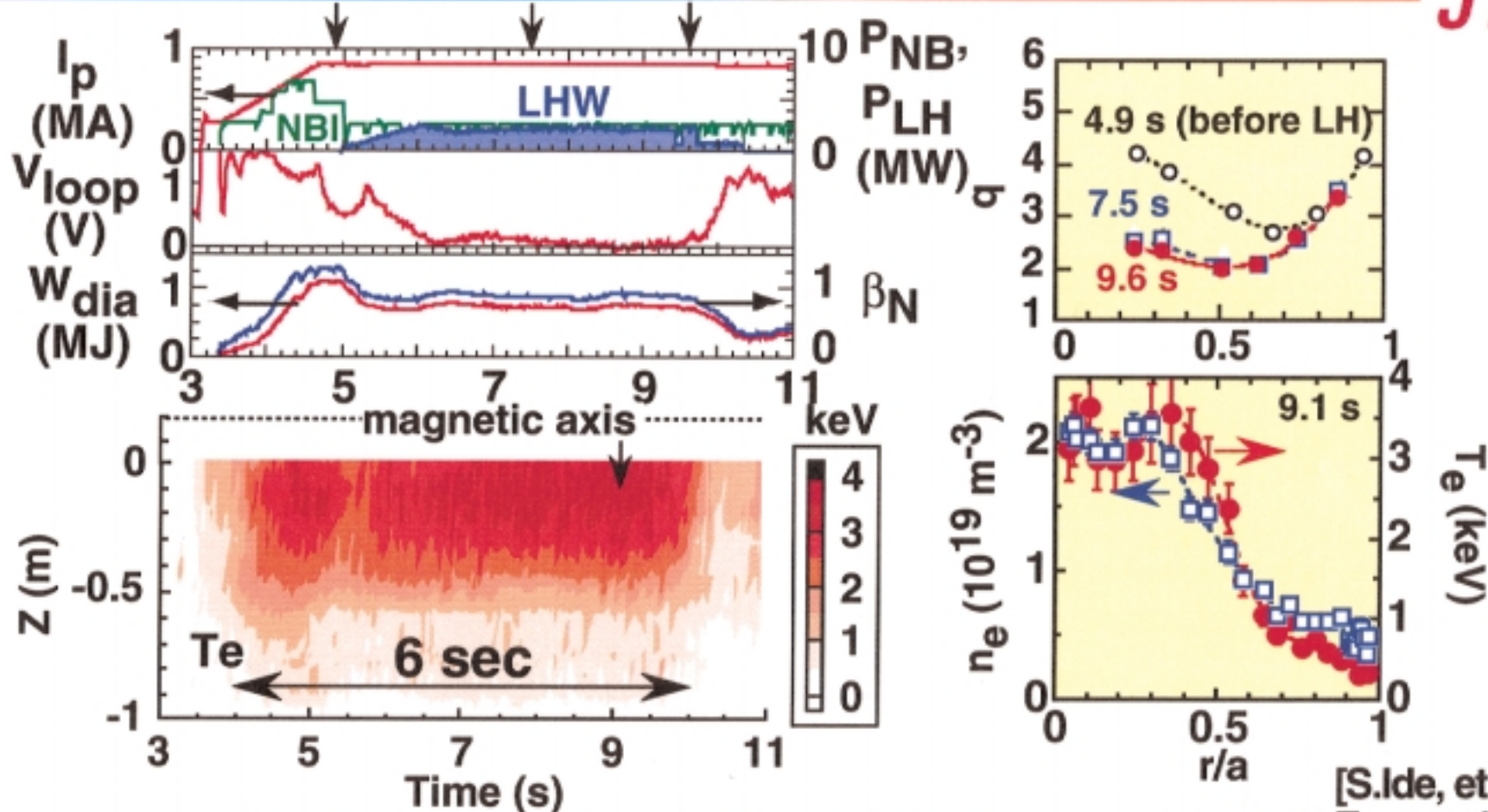


- NNBCD efficiency is almost linearly increased with electron temperature

CD efficiency in a reactor regime would be possible above 10 keV in JT-60U

Steady sustainment of reversed shear discharge with ITB by full non-inductive current drive during LHCD

JT-60U



$I_p=0.85 \text{ MA}, B_t=2.0 \text{ T}, P_{LH}\sim 2.3 \text{ MW}, P_{NB}=2.5 \text{ MW}$

[S.Ide, et al., Fusion Energy, 1998 CD1/4]

- LHCD at off-axis **controls** a reversed shear configuration
- ITB **sustained for ~6 s** at almost constant location ($r/a\sim 0.6$) until LH off
- **Full non-inductive current drive** with LH (78%)+BS (22%).

2. Topical issues for a steady state

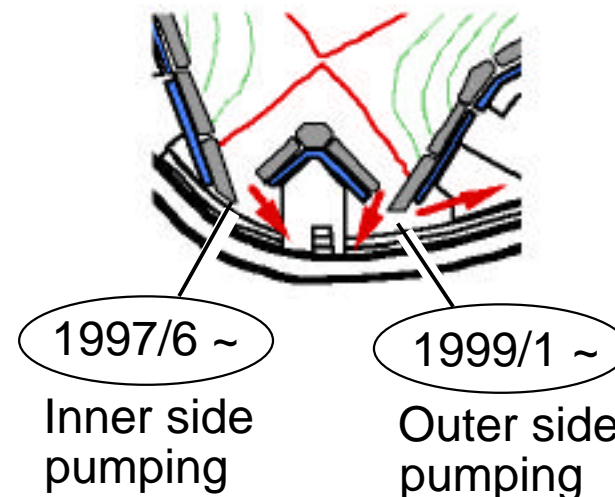
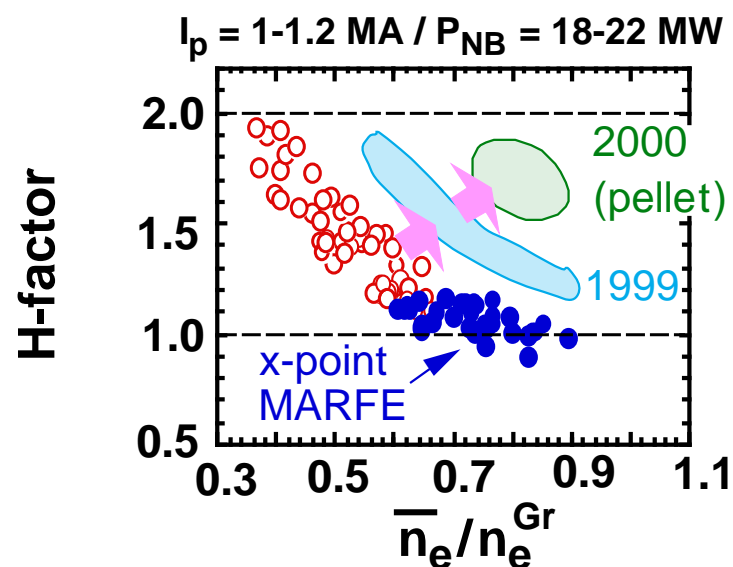
JT-60U

- **Pressure and current profile control under high bootstrap current fraction**
 - Investigation and control of ITB
 - Current profile control by NNB, LH and EC
- **MHD stability**
 - N scaling of neoclassical tearing modes and their stabilization with ECCD.
 - Ideal and resistive MHD in RS-mode.
(Investigation of the wall stabilization?)
- **Confinement;** Investigate the reactor relevant plasmas by NNB and EC (electron heating et al.)

3. Integration of high density, high confinement and radiative divertor

JT-60U

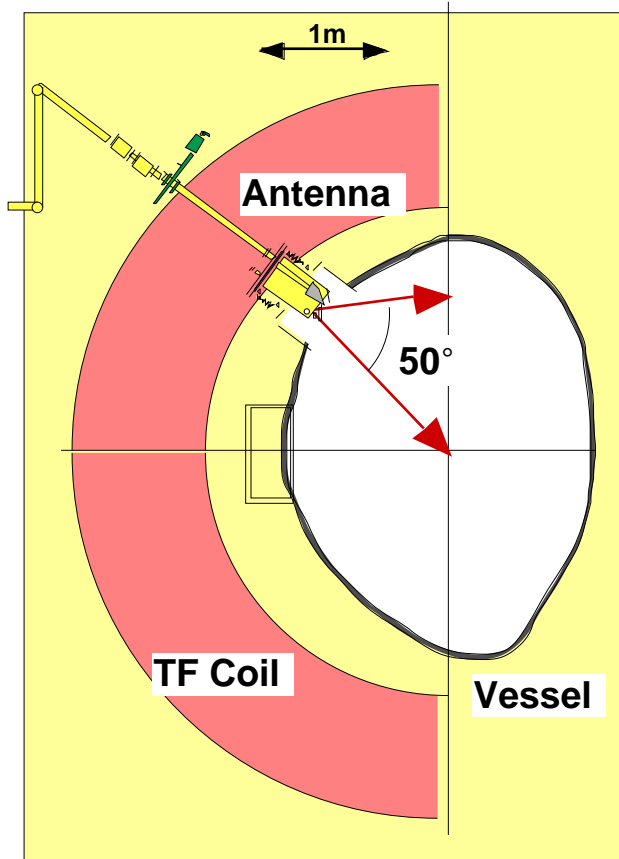
- High confinement with high density, using both side divertor pumping from Feb. 1999;
to improve exhaust capability
to control SOL flow at outer divertor for puff&pump



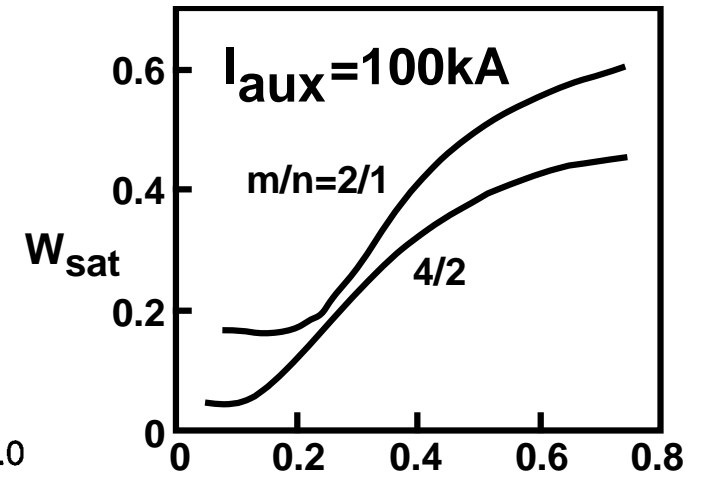
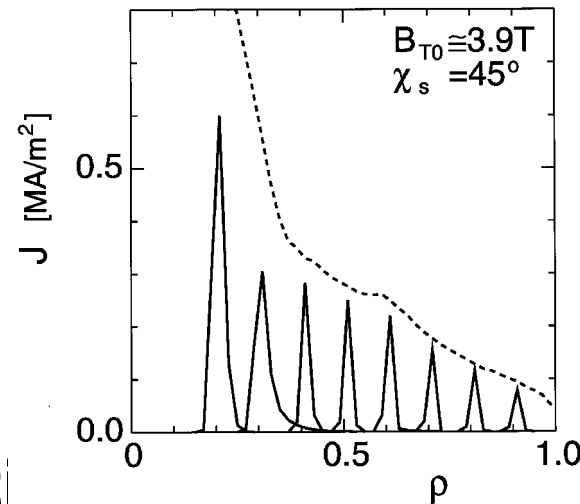
- Repetitive pellet injector is under development.

110GHz ECH/ECCD system

JT-60U



	1999~	<i>Upgrade</i>
Frequency	110GHZ	
Max. power	1MW	<i>4 MW</i>
Pulse length	5s	<i>10s</i>
Unit	1	<i>4(3)</i>
Injection mode	Low field side O-mode	
Injection angle	Real time control on poloidal inj. angle	



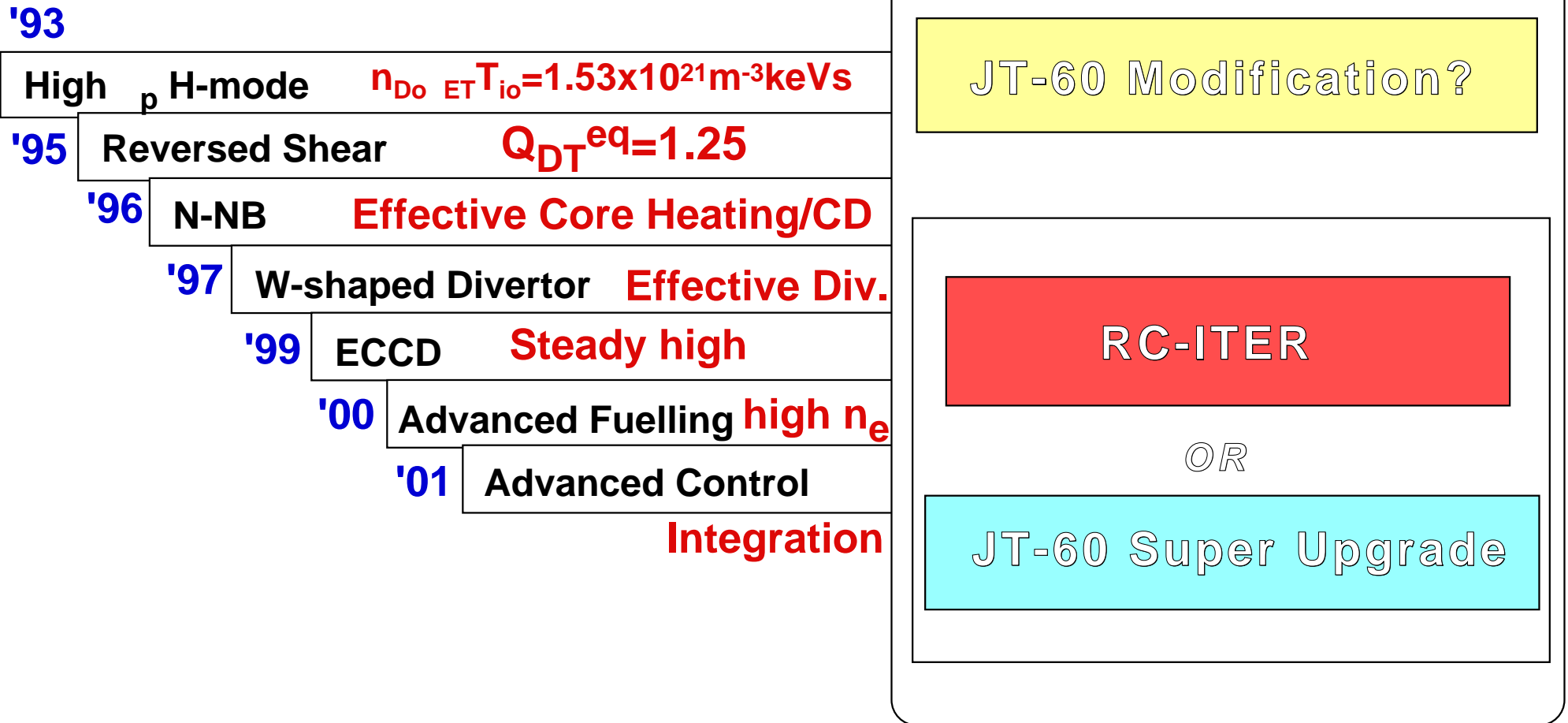
Ray tracing calculat

Localized current can be expected. $\sim 0.25\text{MA/m}^2$, $P_{\text{in}}^J = 1\text{MW}$

Long Term Prospect

JT-60SU

~ '02



Goal: Advanced-SSTR

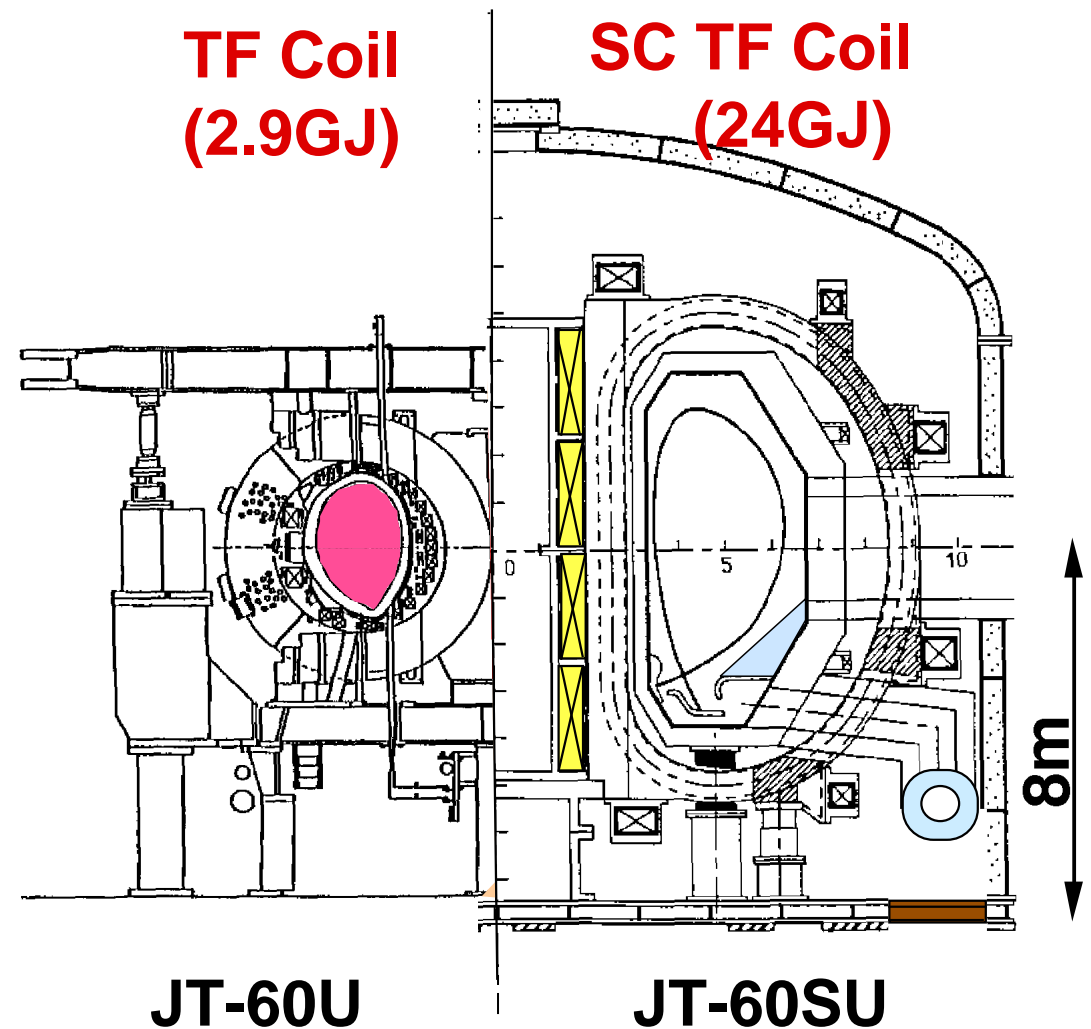
Objectives of JT-60SU

JT-60SU

1. Establish scientific basis of steady-state operation
2. Contribute next generation tokamak
 - long pulse, advanced steady-state operation

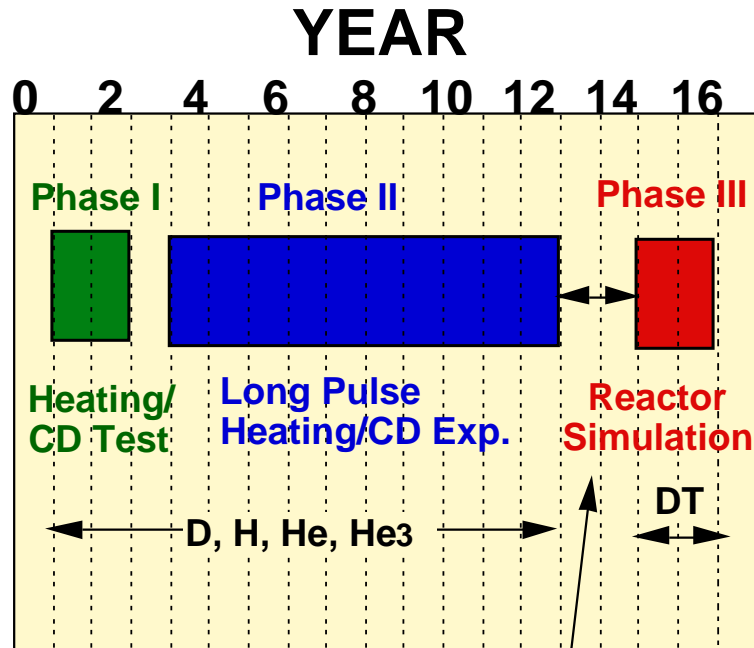
Energy confinement	few sec
Divertor heat removal	~10sec
Particle pumping	~10sec
Diffusion of current	few100sec
First wall temperature saturation	500-1000sec

Long pulse over 1000s is necessary



Operation plan and parameters in JT-60SU

JT-60SU



operation parameters	DD		DT
plasma current I_p (MA)	5	10	6.2
toroidal field B_t (T)	6.25	6.0	5.77
major radius R_p (m)	4.8	5.0	5.2
minor radius a_p (m)	1.3	1.5	1.35
ellipticity	1.8	1.8	1.8
triangularity	0.4	0.4	0.4
safety factor q_{95}	6.2	3.8	4.5
density $\langle n_e \rangle$ (10^{19} m^{-3})	8.8	10.0	8.4
-particle fraction	----	----	0.05
beam power P_{NB} (MW)	60	60	50
fusion gain Q_{DT}	----	----	5.0
confinement time τ_E (s)	1.54	3.24	1.71
beta (%)	1.24	1.83	2.39
normalized beta β_N	2.01	1.65	3.0
poloidal beta β_p	1.73	0.79	2.0
bootstrap current I_{BS}/I_p	0.50	0.23	0.51
beam driven current I_{BD}/I_p	0.50	0.22	0.49

AT Operation in DT;
 $f_{BS} \sim 0.7$ $\beta_N \sim 2.5$, $Q_{DT} = 4$
and H=HELMfree

Progress of physics design for a steady-state advanced operation

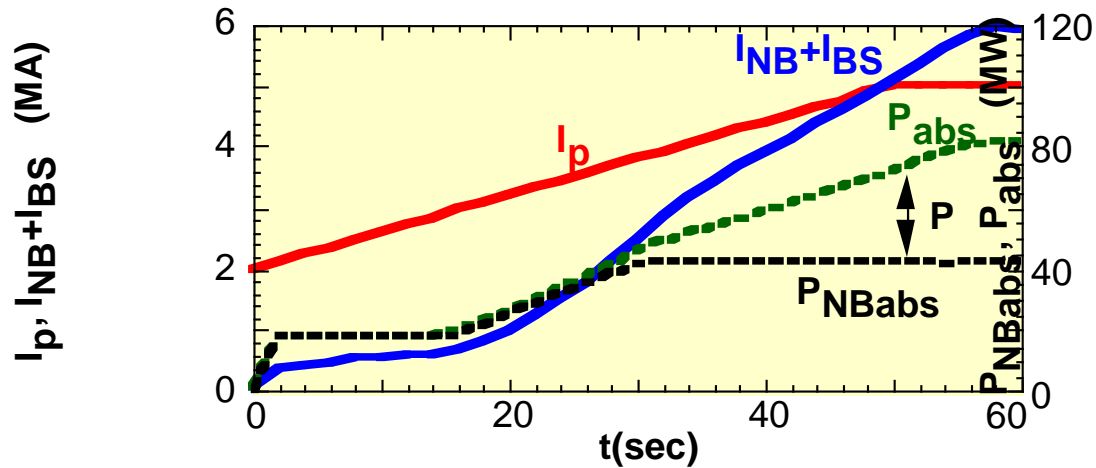
JT-60SU

- **A transport code simulation has confirmed that a full CD reversed shear plasma with $IBS/I_p \sim 0.7$, $\beta_N \sim 2.5$, $Q_{DT} = 4$ and $H \sim H_{ELMfree}$ (central NBCD) can be sustained for $> 1000s$ without any additional active control**
- **Burn control by local current profile control**
- **MHD stability in advanced operation**
- **Dynamic simulation of the vertical displacement events**

[K.Ushigusa, et al., Fusion Energy, IAEA Yokohama 1998 FTP/12]

Start-up of RS and ITB

JT-60SU

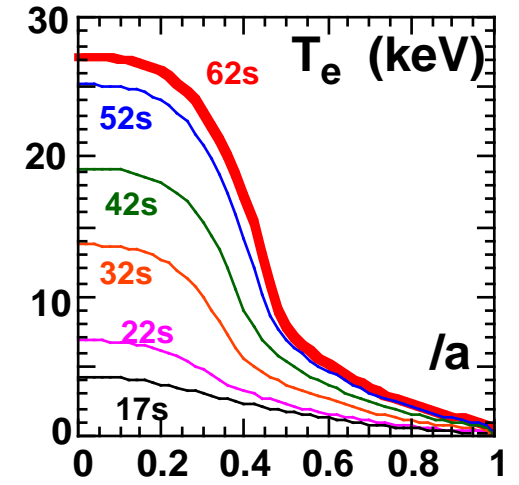
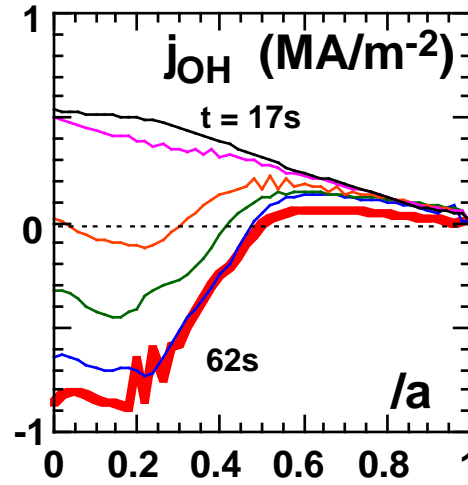
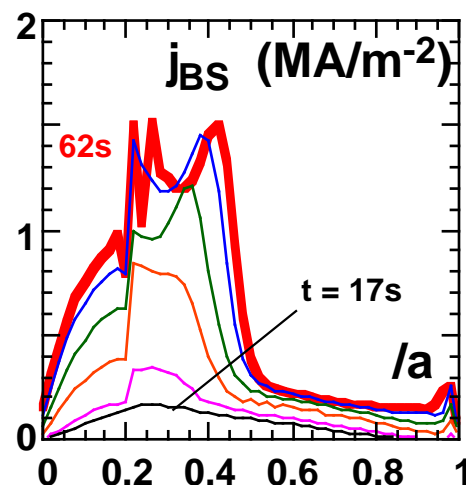
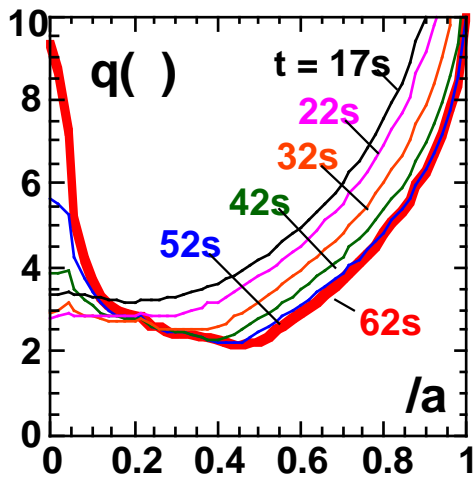


Assumption:

Xe,i of ITB is neo-classical
Xe,i of other region is L-mode level

Xe,i is minimum at s=0.

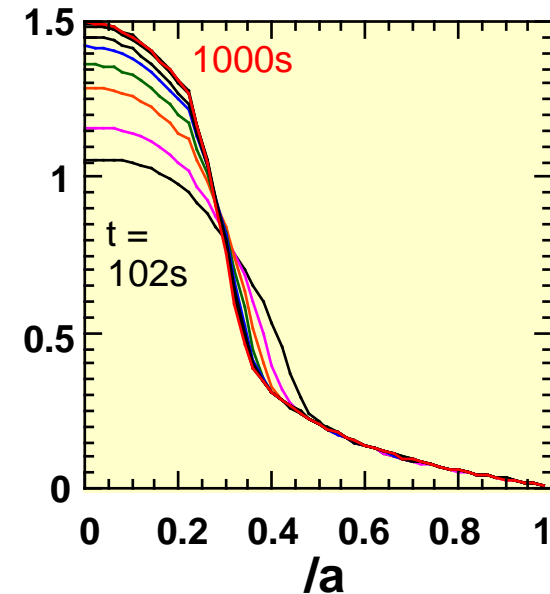
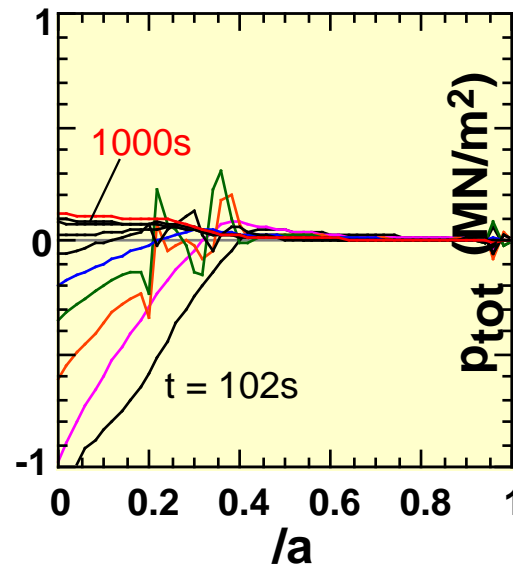
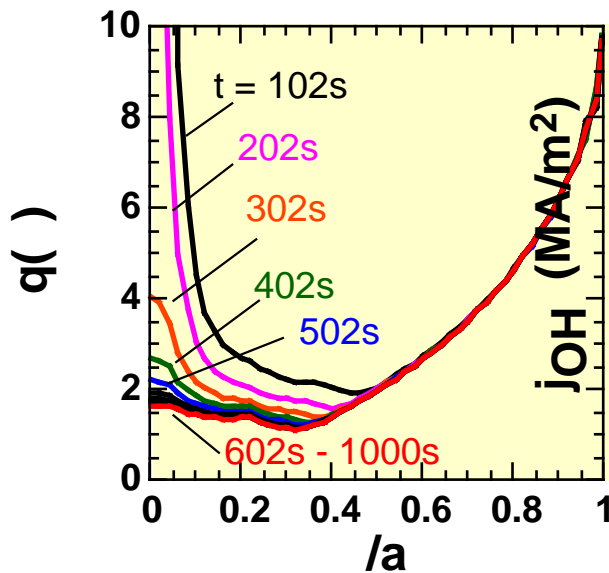
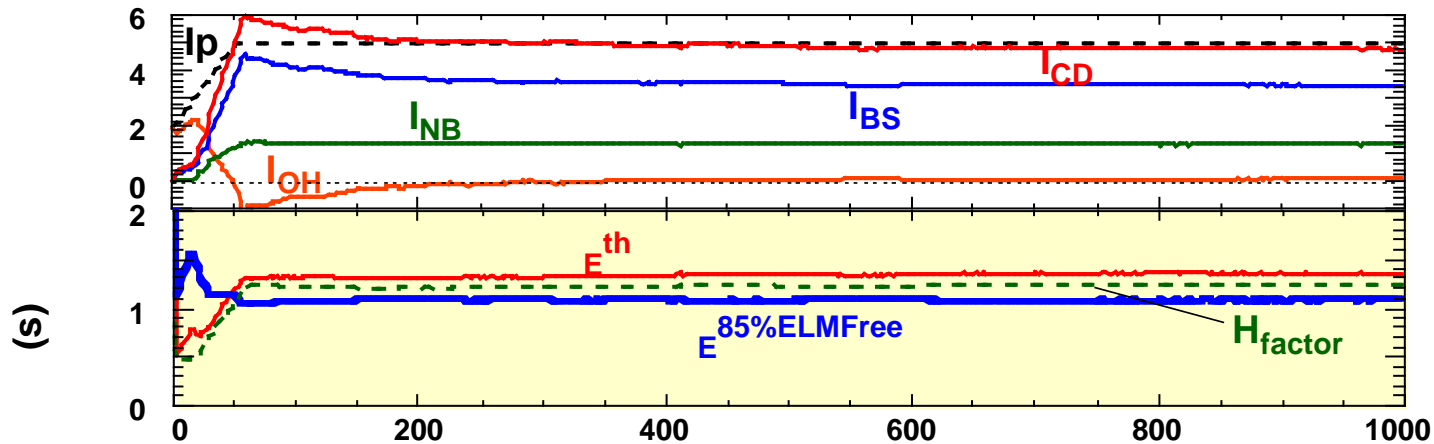
Balance of IBS, INB and I_p is a key to obtain R/S at current flat top



Sustainment of Steady-state Advanced plasma

JT-60SU

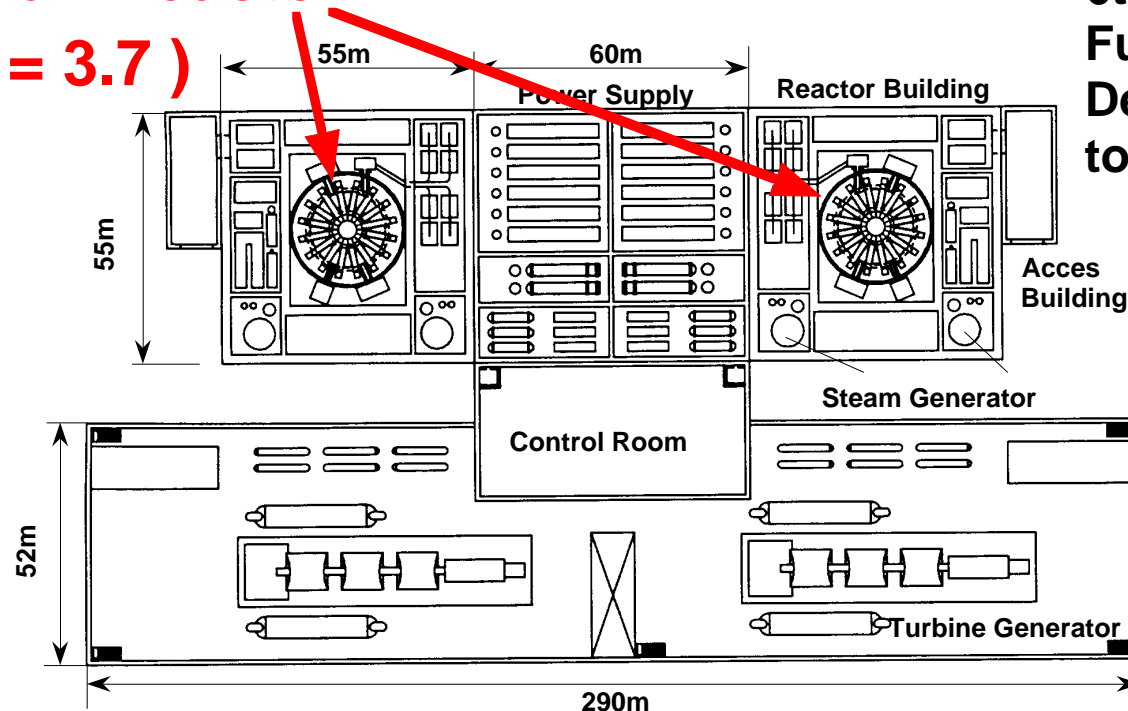
$I_{BS}/I_p = 0.7$, $I_{NB}/I_p = 0.3$, $Q_{DT} \sim 4$, $H_{factor} \sim 1.2$, $>1000s$



Goal of Steady State Reactor Advanced-SSTR

A-SSTR

- High Temperature Super conductor (27K)
- Pair Tokamak Reactor
- $N=4.2$ (or = 3.7)



M.Kikuchi, et al.
6th IAEA-TCM on
Fusion Power Plant
Design and Technology
to be published in FED

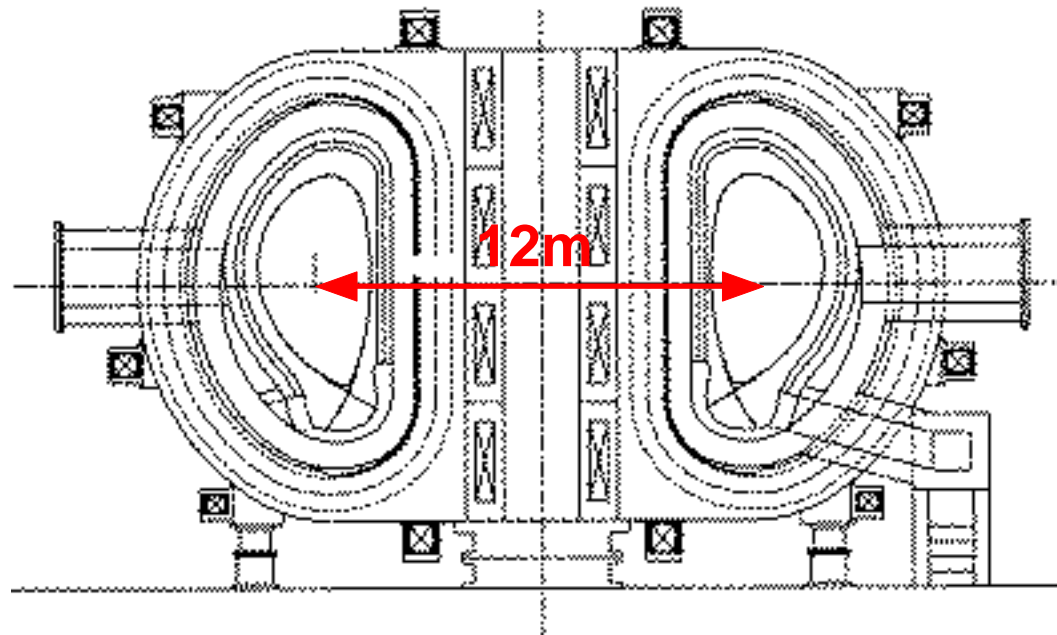
Economically competitive Tokamak Reactor

- Half construction cost / power of SSTR
- Similar to Light Water Reactor (LWR)

Target of the fusion plasma

A-SSTR

$R_p = 6m$
 $a_p = 1.5m$
 $q_{95} = 1.8$
 $q_{95} = 0.4$
 $V_p = 486m^3$
 $B_t = 11T$
 $B_{tmax} = 20.5T$
 $q_{95} = 4.8$
 $N = 4.2 \text{ (or } 3.7 \text{)}^*$
 $f_{BS} = 80\%$
 $n_{He}/n_e < 10\%$
 $\langle n \rangle = 2.1 \times 10^{20}$
 $n_e/n_{eGR} = 1.2$
 $Z_{eff} = 1.6$
 $HITER_{89} = 2.7$



$P_{fusion} = 4.5GW \text{ (or } 3.53GW \text{)}^*$
Electric power = 1.7GW (or 1.63GW)
Heating: NBI or ECCD

* Net thermal efficiency is 34.5% (or 41%)

Summary

JT-60U, JT-60SU, A-SSTR

- **Significant progress for a steady-state plasma** was obtained in the high p operation and the RS operation.
- In the short term plan; the **operational region of a steady-state high performance would be extended** by the N-NBI, EC and W-shaped divertor.
- In the long term prospect; ITER-RC, **JT-60SU**,
 - AT operation in JT-60SU was confirmed by the simulation.
 - Final Goal; **Advanced-SSTR**, $R_p = 6\text{m}$, $q_{95} = 4.8$, $N = 4.2$ (or 3.7), $f_{BS} = 80\%$, $n_e/n_{eGR} = 1.2$ and engineering development

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