# Overview
# of the JT-60SC Program

Presented by

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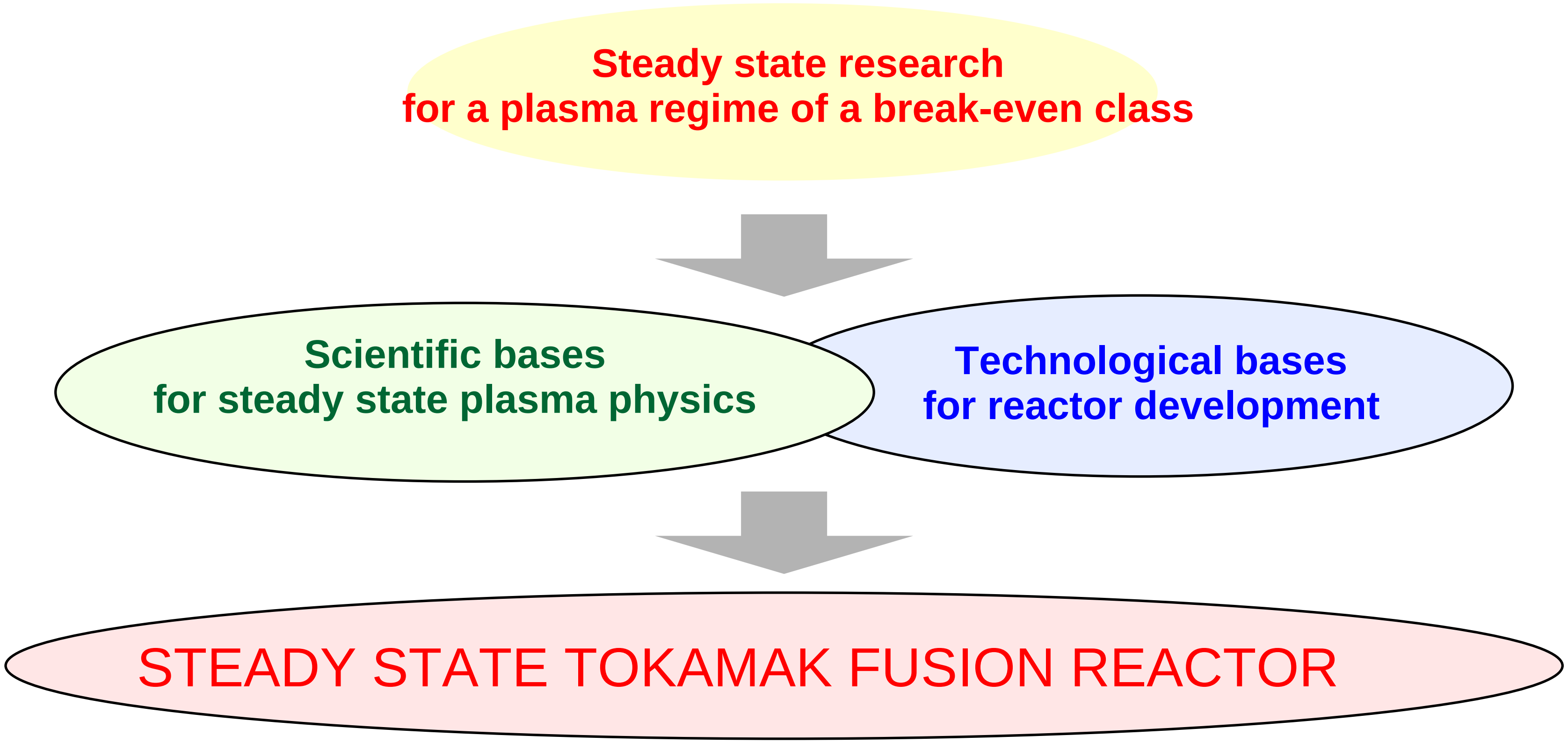
# OUTLINE OF TALK

- Mission of the JT-60SC
- Key concepts
- Place of JT-60SC
- Plasma research issues
- Directions of concept optimization
- Necessary plasma size and duration
- Utilization of JT-60 facilities
- Proposed machine parameters
- Research goals and issues;
    - High beta plasma control
    - Steady state plasma control
    - Heat and particle control
- Summary

# MISSION OF THE JT-60SC PROGRAM

- MISSION

**Establish scientific and technological bases through steady-state research for a high performance plasma regime of a break-even class in a duration sufficiently exceeding a current diffusion time as a necessary step towards a steady-state tokamak fusion reactor .**



**Steady state research
for a plasma regime of a break-even class**

**Scientific bases
for steady state plasma physics**

**Technological bases
for reactor development**

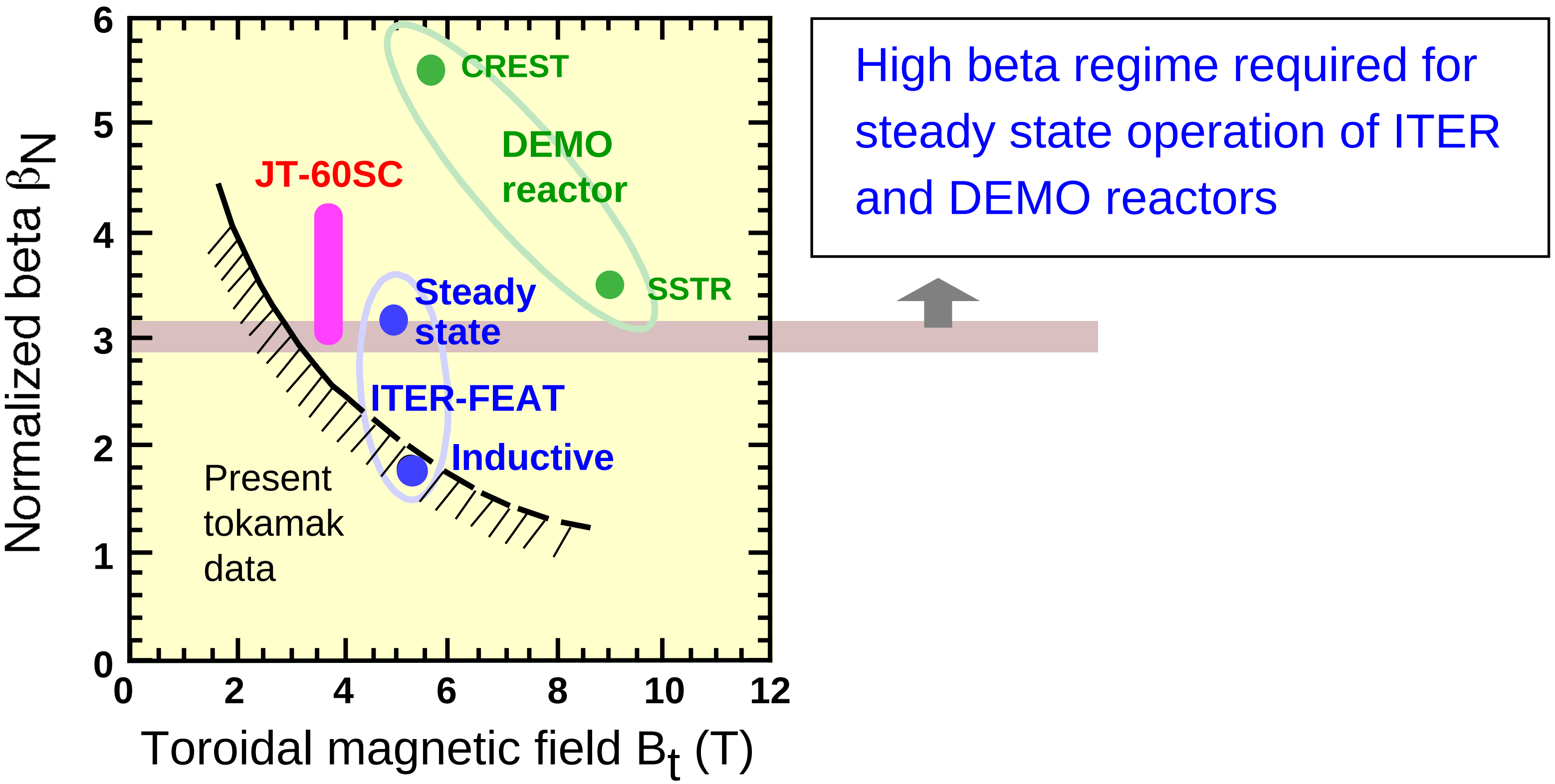
STEADY STATE TOKAMAK FUSION REACTOR

# KEY CONCEPTS

- For the fusion reactor, the steady state research is necessary in the directions of;

**Compact ➡High beta, High toroidal field**

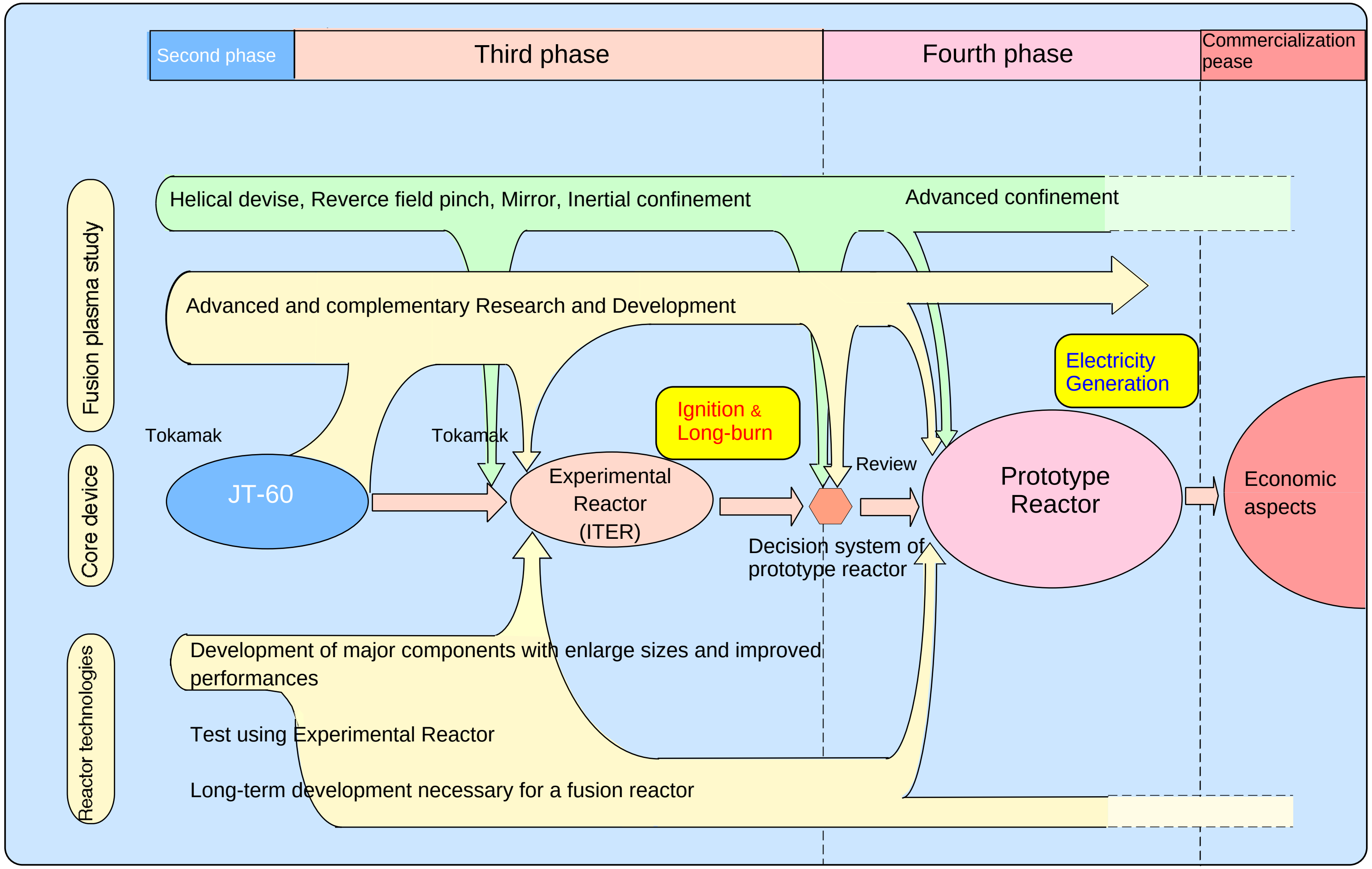
**Low circulating power ➡High bootstrap fraction**



High beta regime required for steady state operation of ITER and DEMO reactors

# PLACE OF JT-60SC IN TOKAMAK FUSION DEVELOPMENT

Fusion energy development and scenarios toward the fusion power plant



The subcommittee of the Fusion Council for Fusion Development Strategy, Report on Technical Feasibility of Fusion Energy and Extension of the Fusion Program and Basic Supporting Researches, May 17, 2000.

# PLASMA RESEARCH ISSUES FOR A STEADY-STATE REACTOR

- HIGH BETA PLASMA CONTROL

  Realize a high pressure plasma stably at a high beta and a high field by optimized control for plasma shaping and current and pressure profiles

- STEADY STATE PLASMA CONTROL

  Establish control technology for a high-density and high-confinement plasma non-inductively sustained with a high bootstrap fraction

- DIVERTOR HEAT AND PARTICLE CONTROL

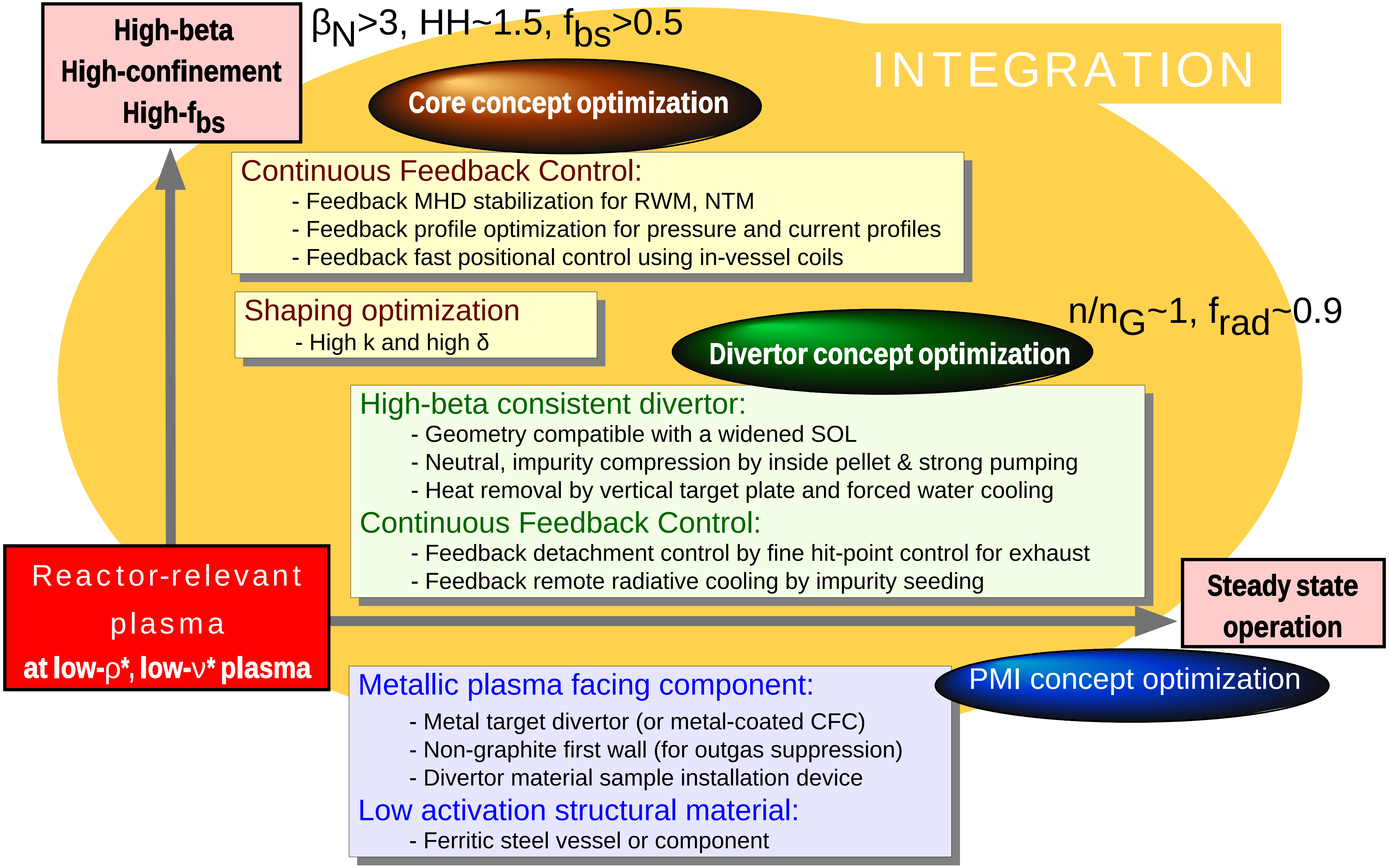
  Realize heat and particle control required for the steady state operation by optimizing the divertor to be compatible with the high-density and high-confinement plasma

- PLASMA TEST FOR MATERIAL TECHNOLOGY

  Test and demonstrate the concept of plasma material interaction and structural material required for a steady state reactor

- DEMONSTRATE AN INTEGRATED TOTAL PLASMA
- SUSTAIN THE PLASMA WITH FEEDBACK STABILIZATION AND CONTROL

# DIRECTIONS OF TOKAMAK CONCEPT OPTIMIZATION FOR A STEADY STATE REACTOR



**High-beta**
**High-confinement**
**High-$f_{bs}$**

$\beta_N>3$, HH~1.5, $f_{bs}>0.5$

INTEGRATION

**Core concept optimization**

Continuous Feedback Control:
- Feedback MHD stabilization for RWM, NTM
- Feedback profile optimization for pressure and current profiles
- Feedback fast positional control using in-vessel coils

Shaping optimization
- High k and high δ

$n/n_G$~1, $f_{rad}$~0.9

**Divertor concept optimization**

High-beta consistent divertor:
- Geometry compatible with a widened SOL
- Neutral, impurity compression by inside pellet & strong pumping
- Heat removal by vertical target plate and forced water cooling

Continuous Feedback Control:
- Feedback detachment control by fine hit-point control for exhaust
- Feedback remote radiative cooling by impurity seeding

Reactor-relevant plasma
**at low-ρ*, low-ν* plasma**

**Steady state operation**

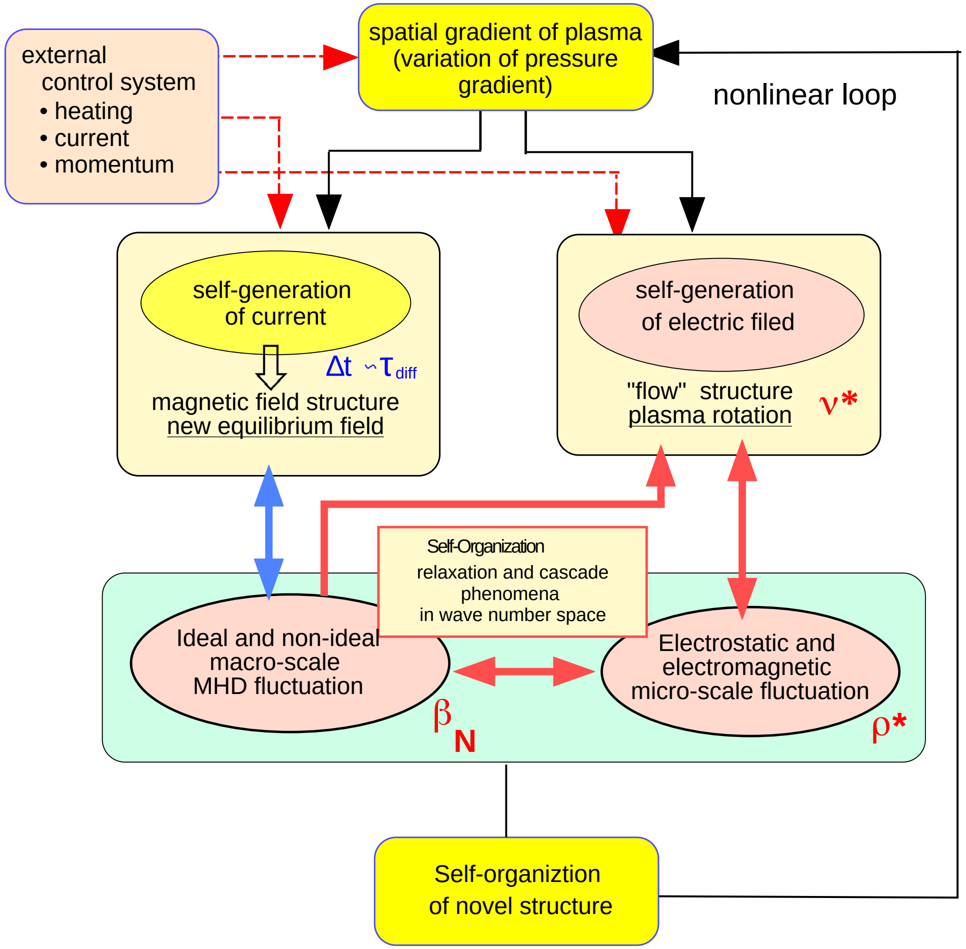
PMI concept optimization

Metallic plasma facing component:
- Metal target divertor (or metal-coated CFC)
- Non-graphite first wall (for outgas suppression)
- Divertor material sample installation device

Low activation structural material:
- Ferritic steel vessel or component

# UNKNOWN PHYSICS PROCESSES IN HIGH BOOTSTRAP STEADY STATE OPERATION

- A prominent structure formation in a self-organized plasma
- A new plasma state would be emerged from physics processes with different time and spatial scales and self-organized plasma dynamics



external control system
- heating
- current
- momentum

spatial gradient of plasma (variation of pressure gradient)

nonlinear loop

self-generation of current

$\Delta t \sim \tau_{diff}$

magnetic field structure
new equilibrium field

self-generation of electric filed

"flow" structure
plasma rotation

$\nu^*$

Self-Organization
relaxation and cascade phenomena
in wave number space

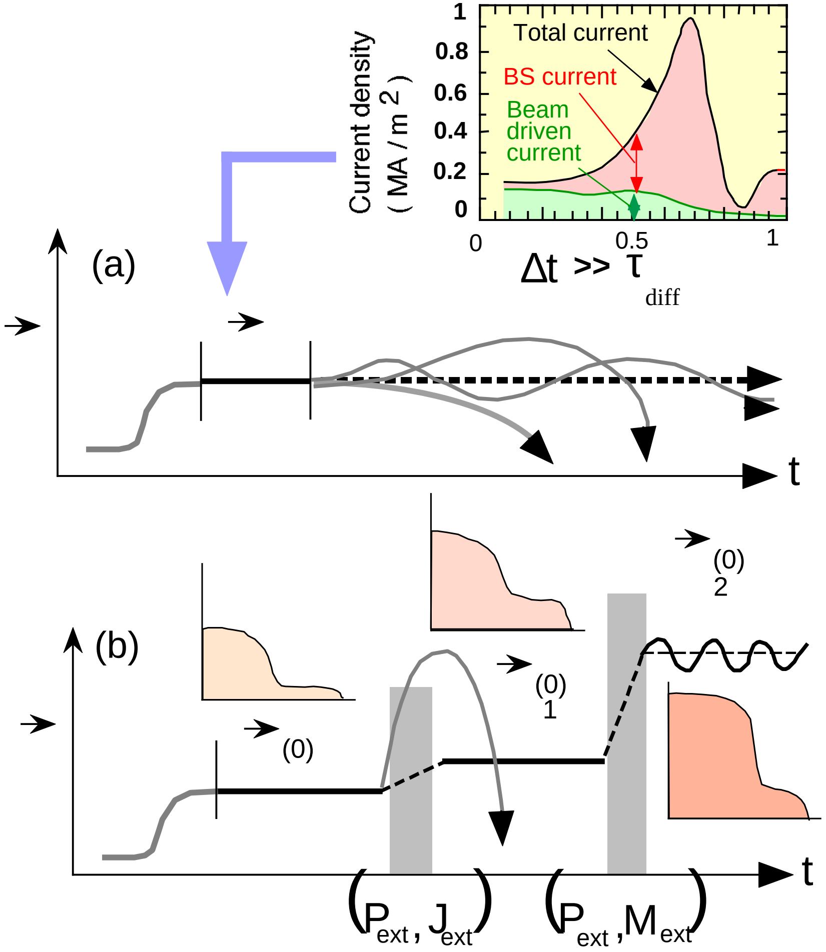
Ideal and non-ideal macro-scale MHD fluctuation

$\beta_N$

Electrostatic and electromagnetic micro-scale fluctuation

$\rho^*$

Self-organiztion of novel structure

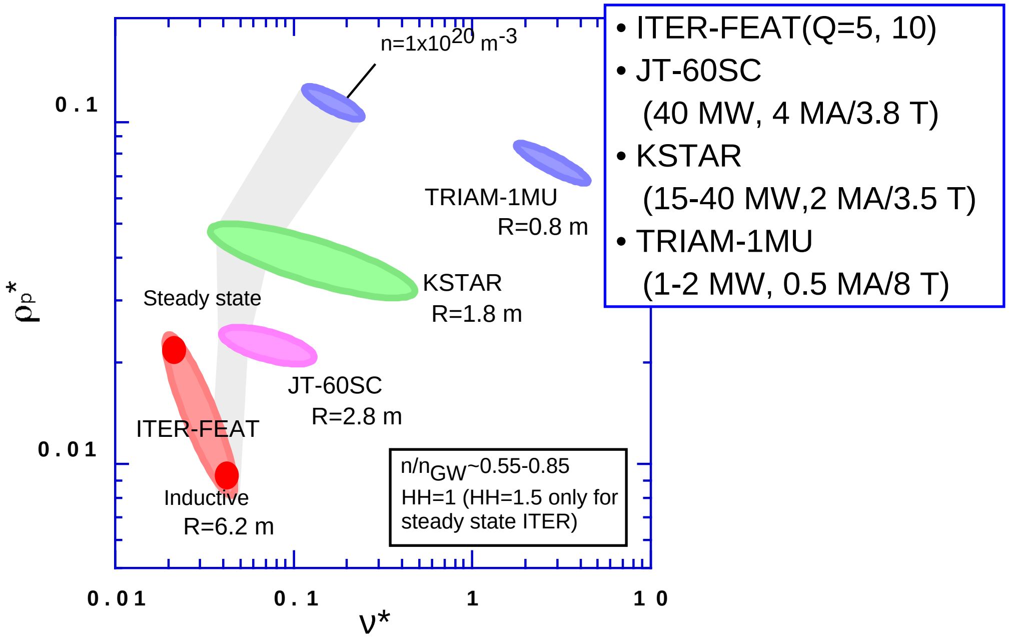


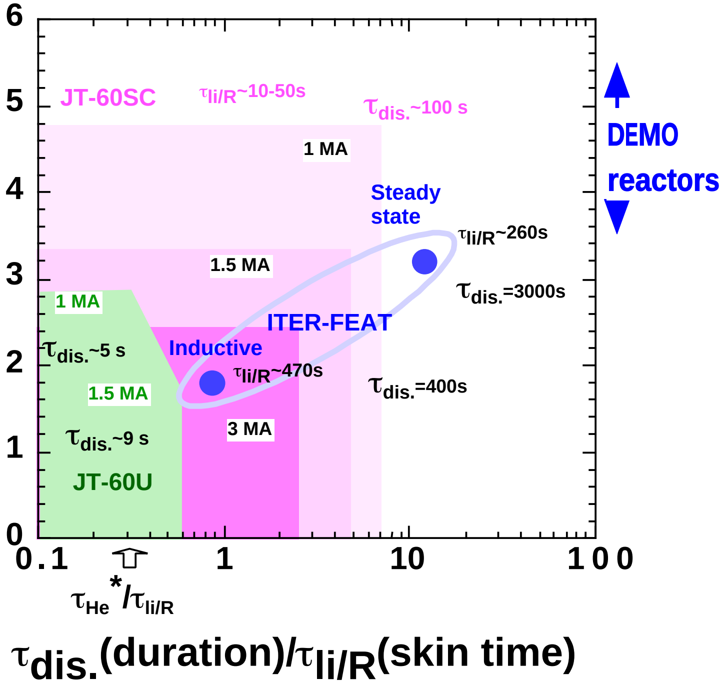
# PLASMA SIZE AND DURATION NECESSARY FOR ACCOMPLISHMENT OF THE MISSION

- Major radius of ~3 m

  The plasma regime of a break-even class with a major radius of ~3 m can produce low normalized collisionality and Larmor radius closely approaching a reactor plasma regime as JT-60, JET and TFTR have produced.
- Duration of ~100 s

  A plasma duration of ~100 s is required to sufficiently exceed a current diffusion time scale for the plasma of this class.





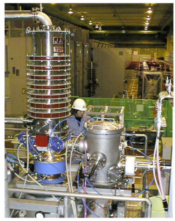
# MAXIMUM UTILIZATION OF JT-60 FACILITIES FOR THE JT-60SC PROGRAM

- Effective use of JT-60 facilities

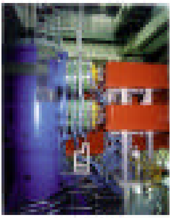
  Most of the JT-60 facilities surrounding the JT-60U device are available for the implementation of the JT-60SC program

- Nominal major radius of 2.8 m

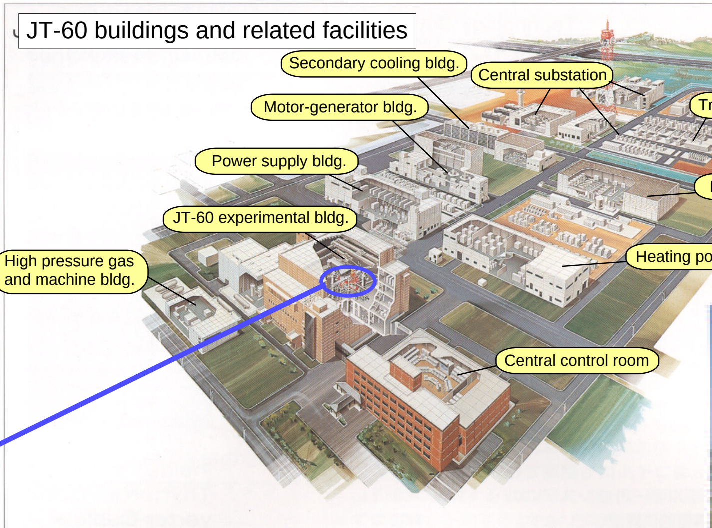
  Taking a major radius of 2.8 m allows central heating from the existing neutral beam injectors as well as effective use of the existing plasma diagnostics.



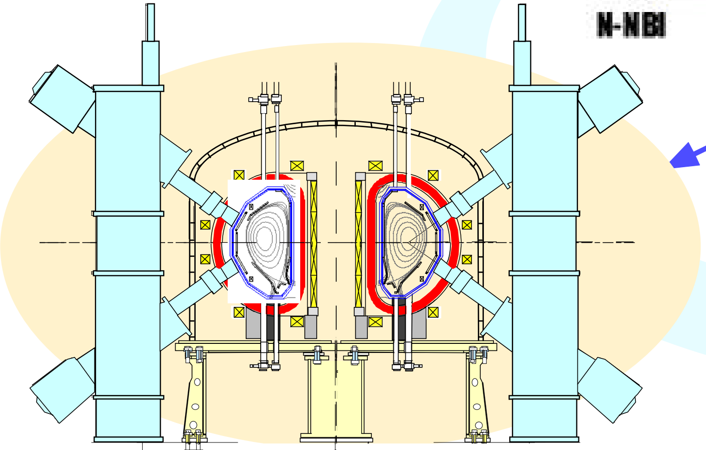
**RF**



**N-NBI**

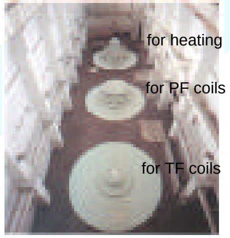


Central substation



JT-60SC

Transformer yard



Motor-generators

# PROPOSED MACHINE PARAMETERS FOR JT-60SC

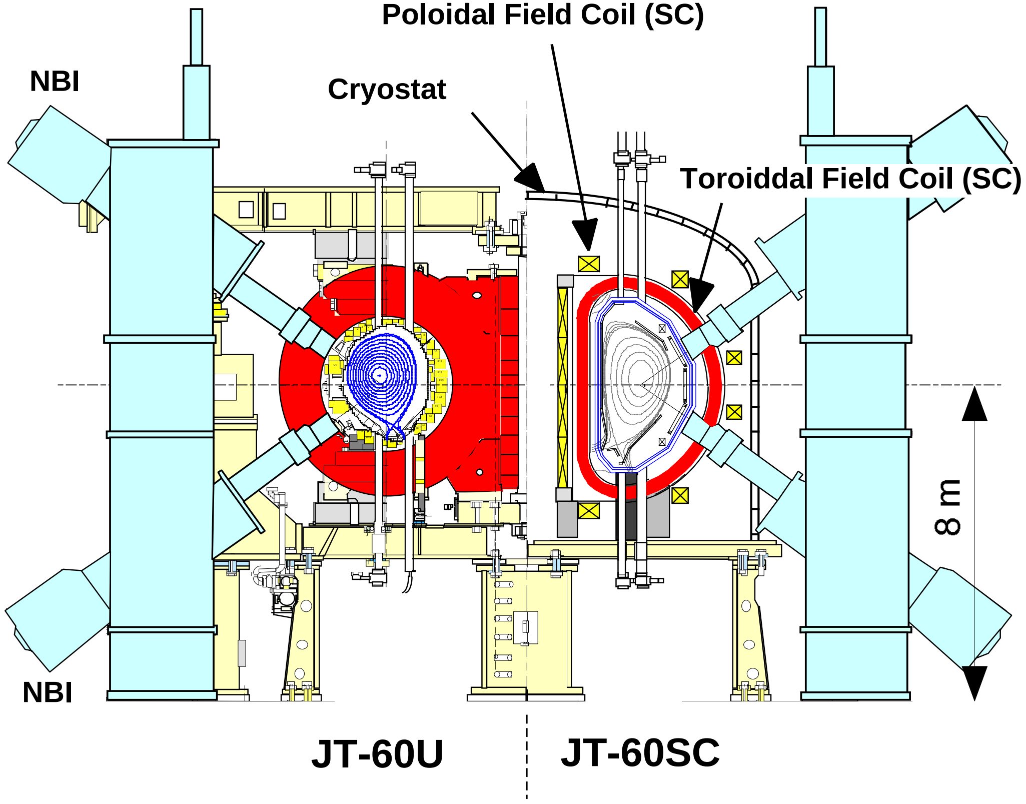
- Baseline of the JT-60SC design

1) Superconducting toroidal and poloidal coils to extend an inductive duration to ~100 s at 4 MA for the current flat top (not excluding a longer duration)
2) Selection of a nominal major radius of 2.8 m for central neutral beam heating
3) Plasma shaping control enabling a high triangularity and elongation shape
4) Extension of the heating and current drive duration to ~100 s for NBI and EC
5) Feedback MHD stabilization for RWM and NTM
6) High-beta consistent divertor geometry with a sufficient pumping speed

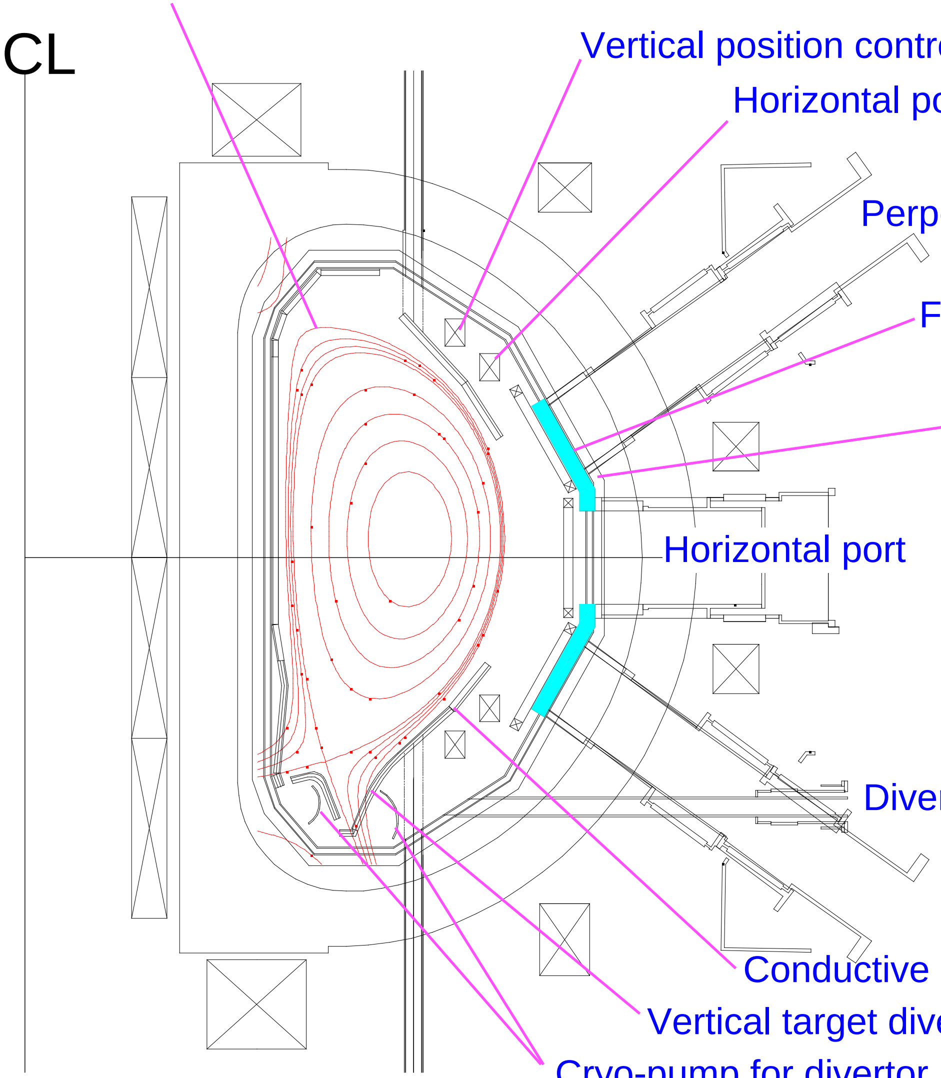
## MAIN PARAMETERS

| Parameter | JT-60U | JT-60SC | ITER-FEAT | |
|---|---|---|---|---|
| | | | Pulse | Steady-State |
| Pulse length | 15 s | 100 s | 400 s | Steady |
| Maximum input power | 40 MW (10 s) | 40 MW (10 s)<br>≥10MW (100 s) | 73 MW | 73 MW |
| Plasma current Ip | 3-5 MA | 4 MA | 15 MA | 7.8 MA |
| Toroidal field Bt | 4 T | 3.8 T (Rp=2.8 m) | 5.3 T | 4.98 T |
| Major radius Rp | 3.4 m | 2.8 -3 m (2.8 m*) | 6.2 m | 6.6 m |
| Minor radius ap | 0.9 m | 0.7-0.9 m (0.85*) | 2.0 m | 1.6 m |
| Elongation $\kappa_{95}$ | 1.8 ($\delta_{95}$=0.06) | ≦ 1.9 (1.7*) | 1.7 | 2.0 |
| Triangularity $\delta_{95}$ | 0.4 ($\kappa_{95}$=1.33) | ≦ 0.45 (0.35*) | 0.35 | 0.35 |

* Nominal



# SCHEMATIC VIEW OF A CROSS SECTION VIEW FOR JT-60SC



A flux surface for a SOL width of 3 cm at the midplain
to be closed for heat and particle control at divertor

Vertical position control coil (Copper)

Horizontal position control coil (Copper)

Perpendicular NBI port

Ferritic steel plate for TF ripple reduction (1% to 0.4%)

Vacuum vessel (neutron shield)

Horizontal port

Divertor material sample installation device

Conductive baffle plates for vertical stability and ideal MHD stability

Vertical target divertor

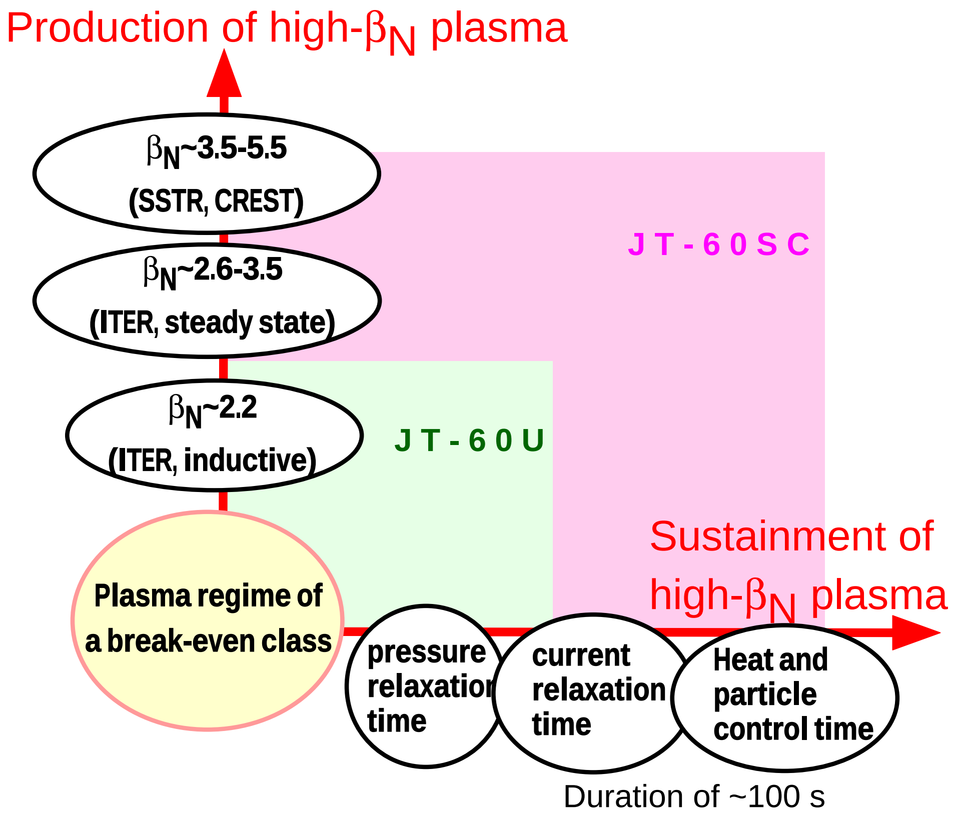
Cryo-pump for divertor pumping

| Neutron budget | JT-60U | JT-60SC |
|---|---|---|
| Max. neutron rate (n/s) | $2\times10^{17}$ | $4\times10^{17}$ |
| Weekly limit (n/week) | $3.1\times10^{18}$ | $4\times10^{19}$ |
| Three month limit (n/3M) | $2.1\times10^{19}$ | $1.5\times10^{20}$ |
| Annual limit (n/year) | $3.1\times10^{19}$ | $2\times10^{20}$ |

An equilibrium configuration for a plasma with 4 MA and $\beta_N$=3

# RESEARCH GOAL FOR HIGH BETA PLASMA CONTROL IN JT-60SC

- Goals
  - Produce a high normalized beta plasma ($\beta_N > 3$) required for steady state operation in experimental and DEMO reactors and sustain it for a sufficiently long duration
  - Establish the feedback MHD stabilization technology for resistive wall mode and neoclassical tearing mode



Production of high-$\beta_N$ plasma

$\beta_N$~3.5-5.5 (SSTR, CREST)

$\beta_N$~2.6-3.5 (ITER, steady state)

$\beta_N$~2.2 (ITER, inductive)

Plasma regime of a break-even class

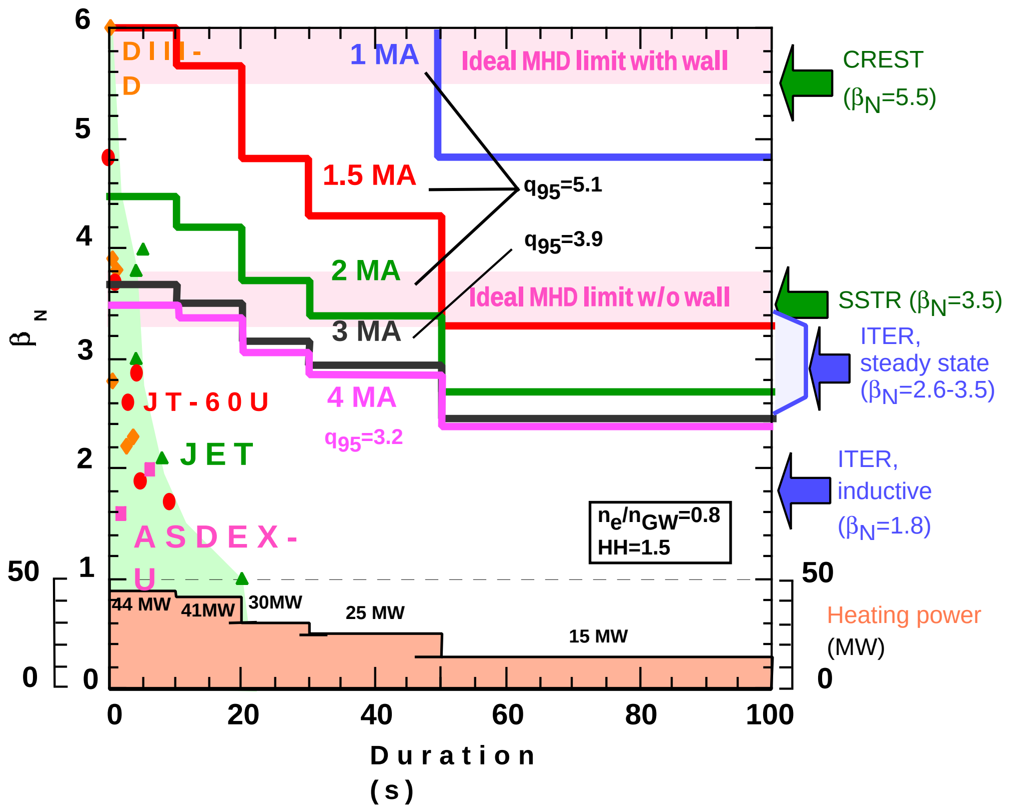
Sustainment of high-$\beta_N$ plasma

pressure relaxation time

current relaxation time

Heat and particle control time

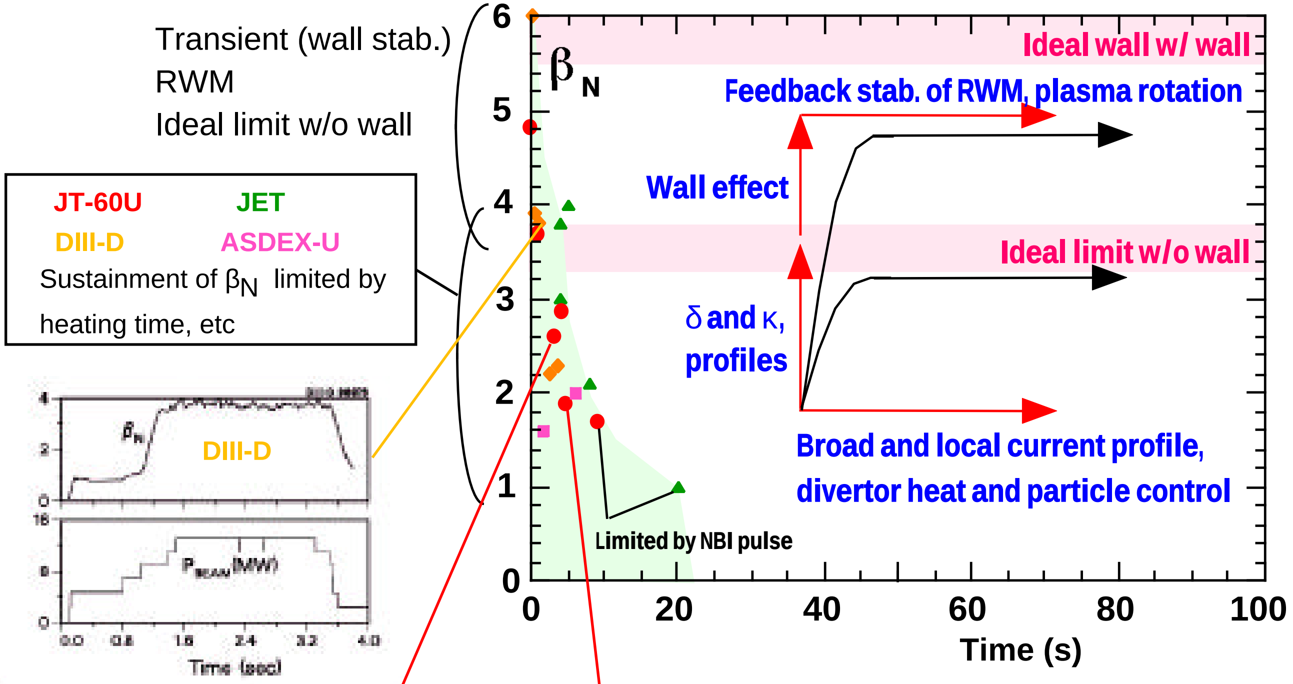
Duration of ~100 s



# RESEARCH ISSUES FOR HIGH BETA PLASMA CONTROL IN JT-60SC

- Issues

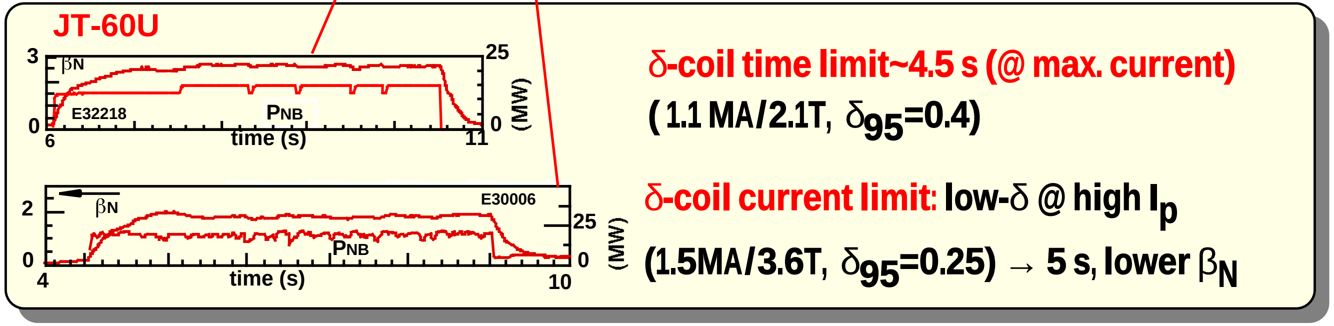
Effective shaping and profile control, divertor heat and particle control, feedback MHD stabilization are required for long sustainment of the high beta plasma as shown below.



- Region above Ideal MHD limit
  - High beta (<1 s) only achieved tranjiently
- Region below Ideal MHD limit

-for positive or weak negative shear :
  - Limited by heatng time, etc
  - Limited by onset of resistive modes at higher performance

-for negative shear :
  - Onset of ideal or resistive modes due to current profile change



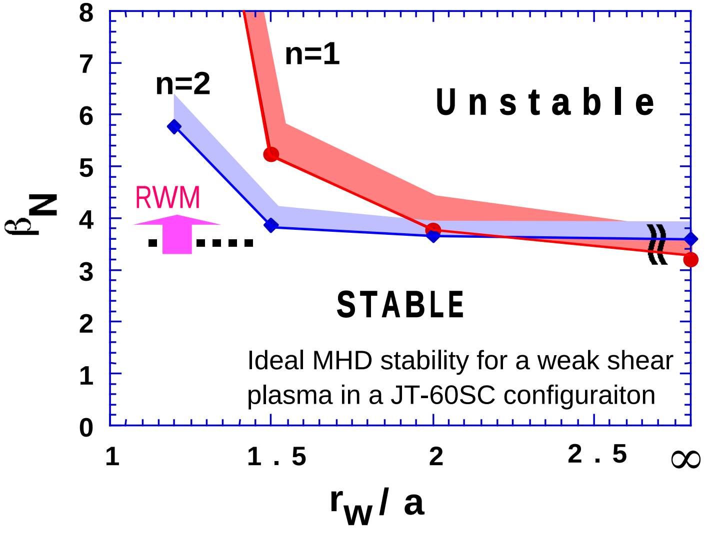
**δ-coil time limit~4.5 s (@ max. current)**
**(1.1 MA/2.1T, $\delta_{95}$=0.4)**

**δ-coil current limit: low-δ @ high $I_p$**
**(1.5MA/3.6T, $\delta_{95}$=0.25) → 5 s, lower $\beta_N$**

# FEEDBACK STABILIZATION OF RESISTIVE WALL MODE

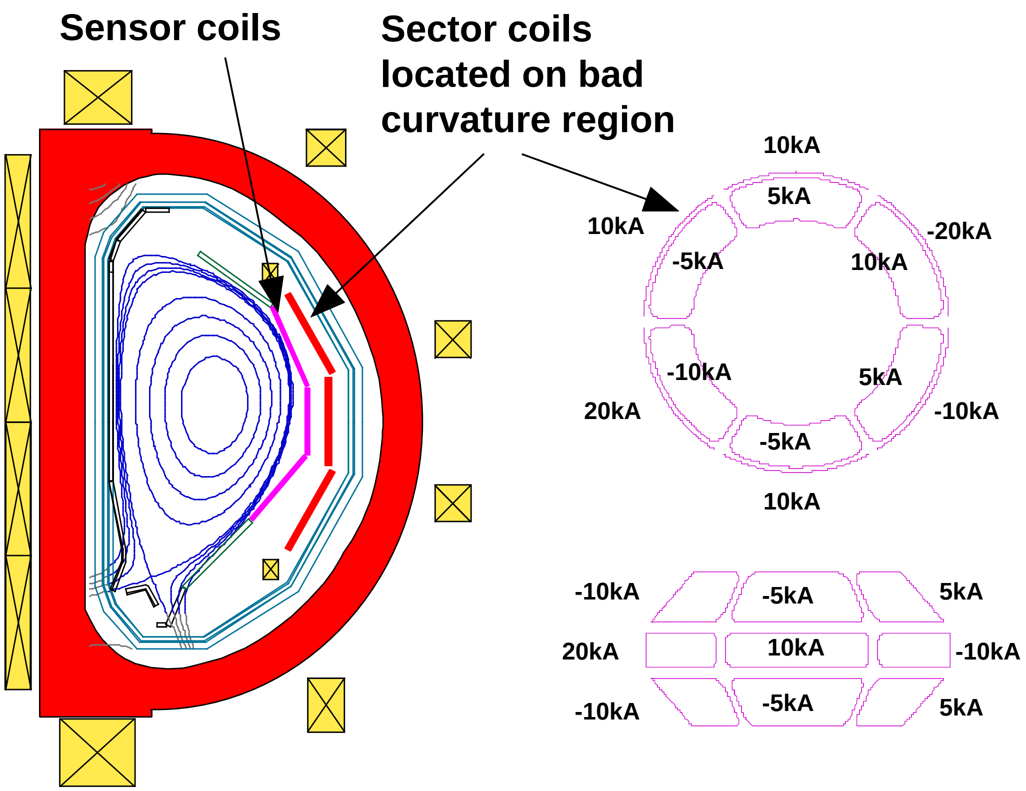
- Wall stabilization
  is required to improve an ideal MHD limit with conductive baffle plates close to the plasma in the vacuum vessel

- Resistive wall mode
  is needed to be stabilized for sustainment at a higher beta than the ideal MHD limit w/o wall



Ideal MHD stability for a weak shear plasma in a JT-60SC configuraiton

- Feedback RWM stabilization



**Sensor coils**

**Sector coils located on bad curvature region**

Control of RWM for n=1,2 modes

# FEEDBACK STABILIZATION OF NEOCLASSICAL TEARING MODE

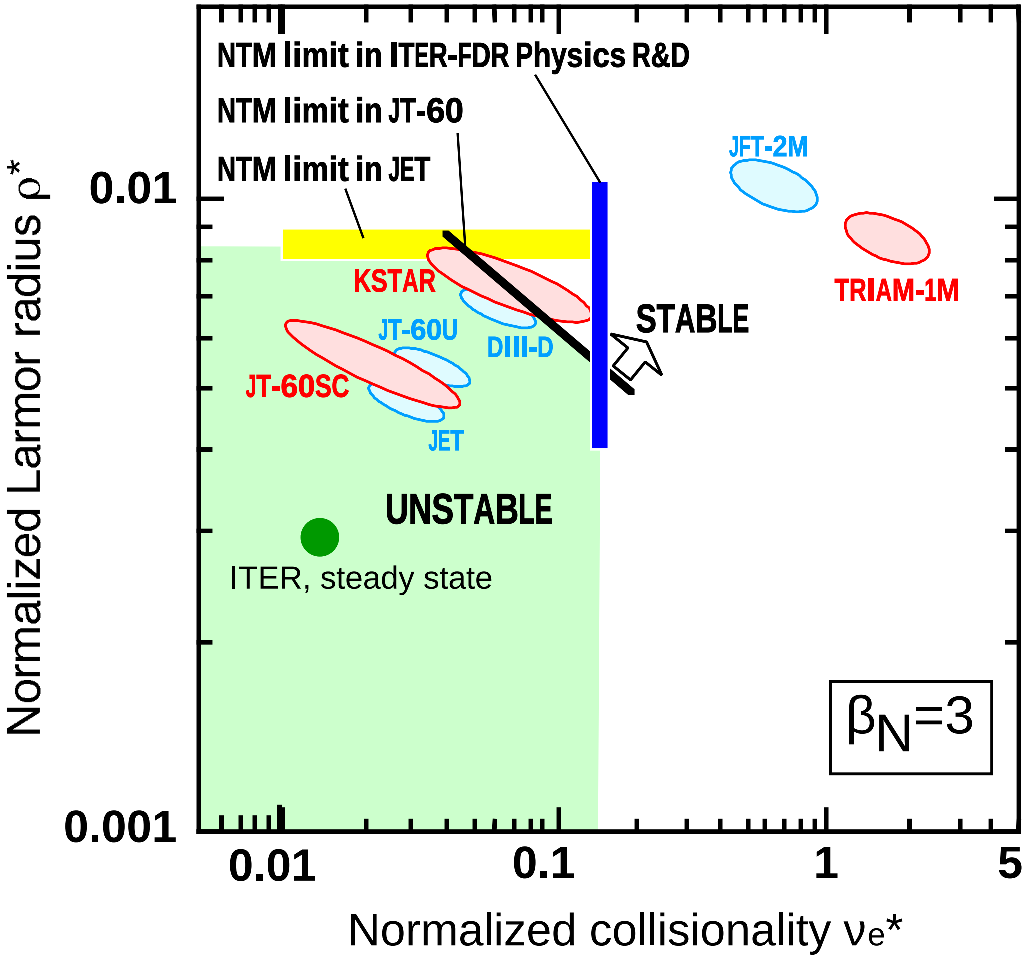
- Stabilization of NTM

  is an critical issue for steady state operation at high beta.

- Objectives

  Establish the feedback NTM stabilization technology for reactor relevant conditions;

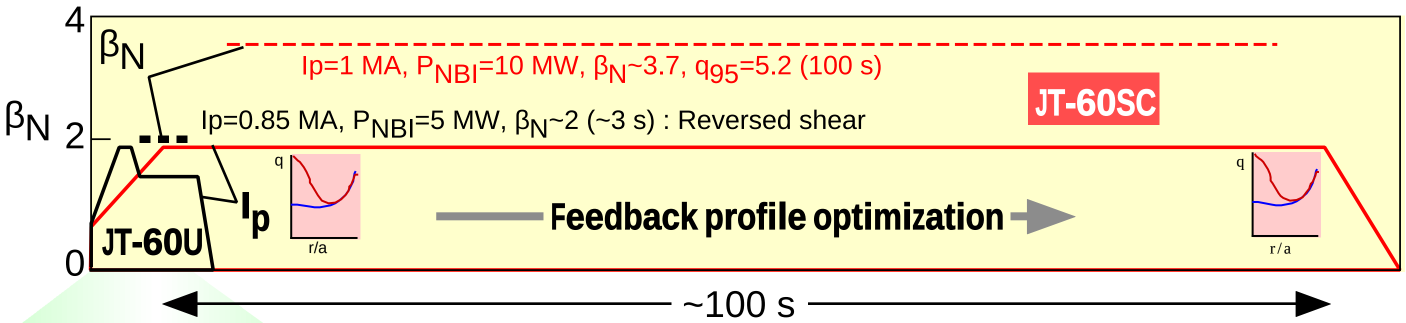
  - at a high beta-N
  - during fully non-inductive CD with a large bootstrap fraction
  - in a steady state where the duration exceeds a current diffusion time
  - in a regime of low collisionality (high temperature) and small Larmor radius (large size and high field)

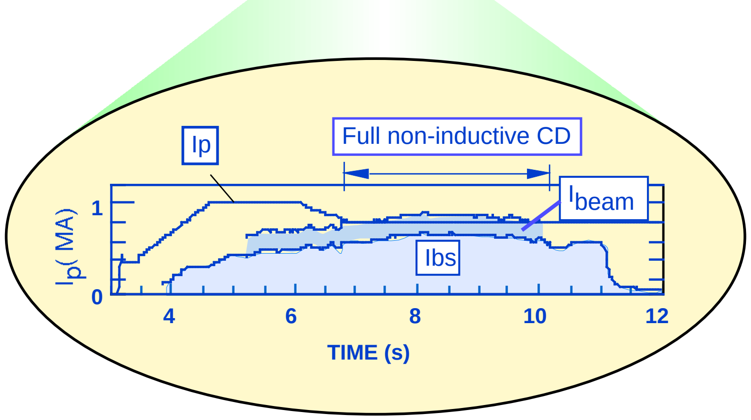


NTM stabilization by ECH/ECCD with a movable antenna (4 MW, ECCD~150 -350kA)

# RESEARCH GOAL OF STEADY STATE PLASMA CONTROL RESEARCH IN JT-60SC

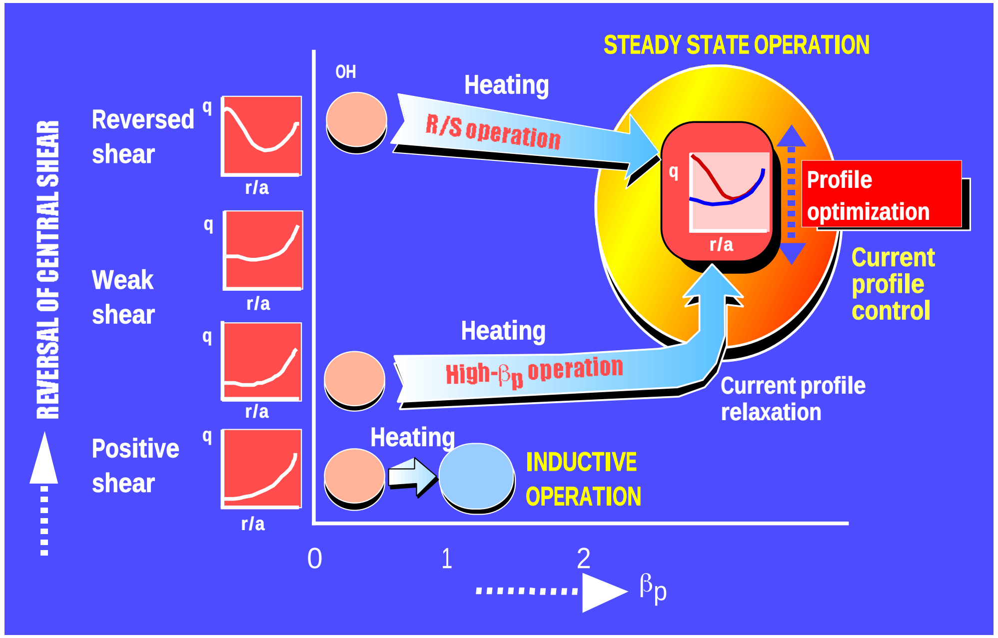
- Goals
  - Realize full non-inductive sustainment of a high-beta and high-bootstrap plasma based on high-$\beta_p$ H-mode and reversed shear mode sufficiently exceeding a current diffusion time.
  - Establish the feedback optimization technology for pressure and current profiles





**Full non-inductive CD with a reversed shear plasma in JT-60U (~2.7 s)**

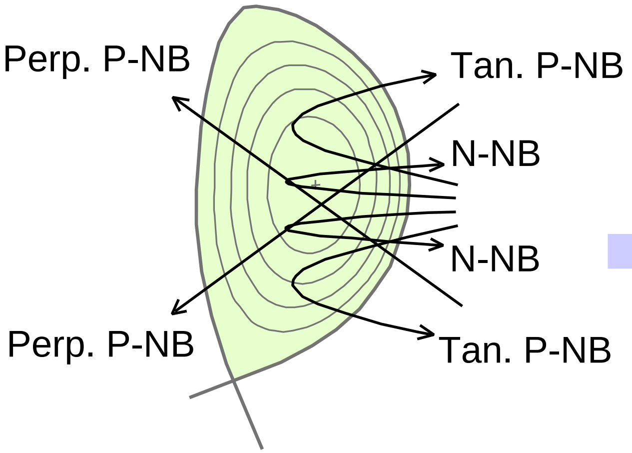
**Reversed shear: $\beta_N$=2, HH=2.2, $f_{bs}$=80%, $q_{95}$~8.5**



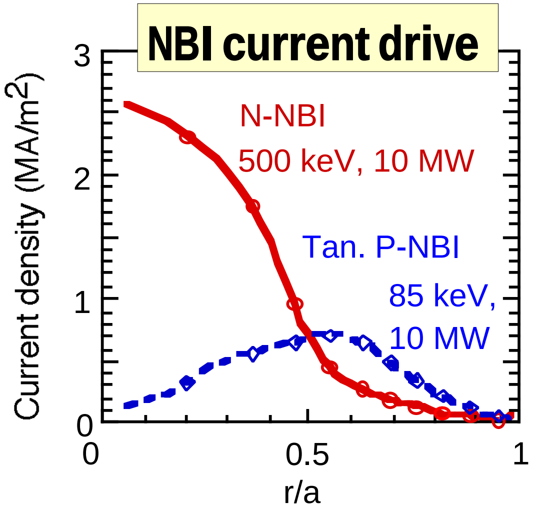
# GLOBAL AND LOCAL PROFILE CONTROL USING INTENSE NBI AND ECH

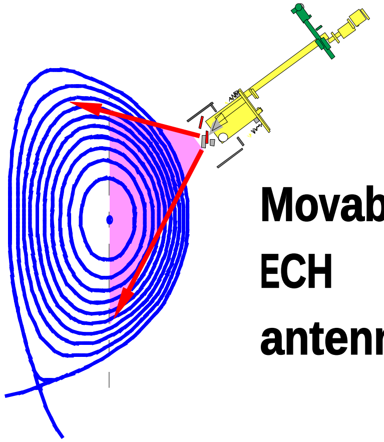
- Heating and current drive performance

  Pursue long sustainment of a high performance plasma in combination with NBI and ECH systems equipped for JT-60U by extending the pulse length of these systems to ~100 s

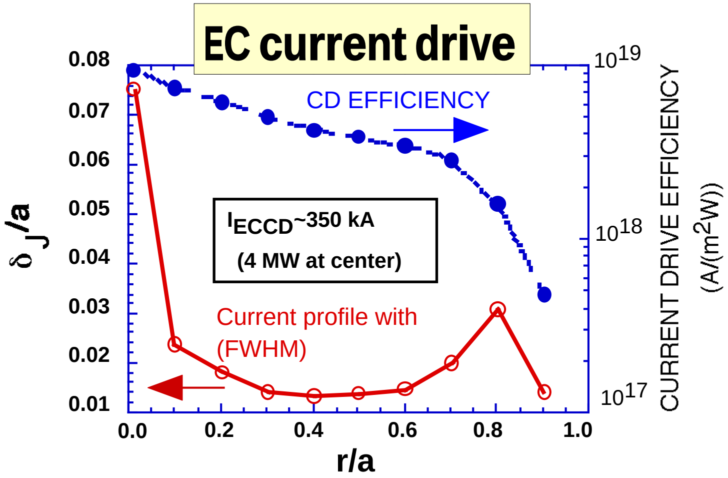


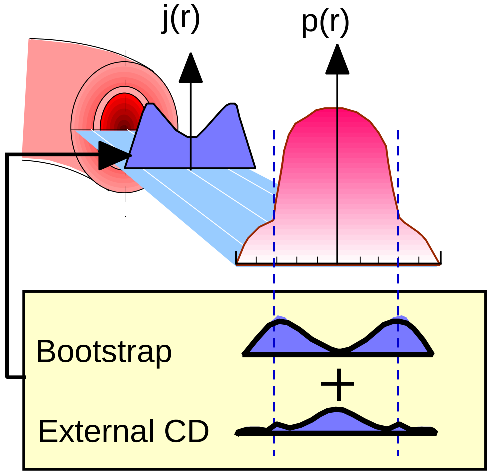
Neutral beam configuration for JT-60SC





**Movable ECH antenna**





**Profile control for long sustainment**

# LONG PULSE CAPABILITY OF BEAM CURRENT DRIVE AND ECH/ECCD

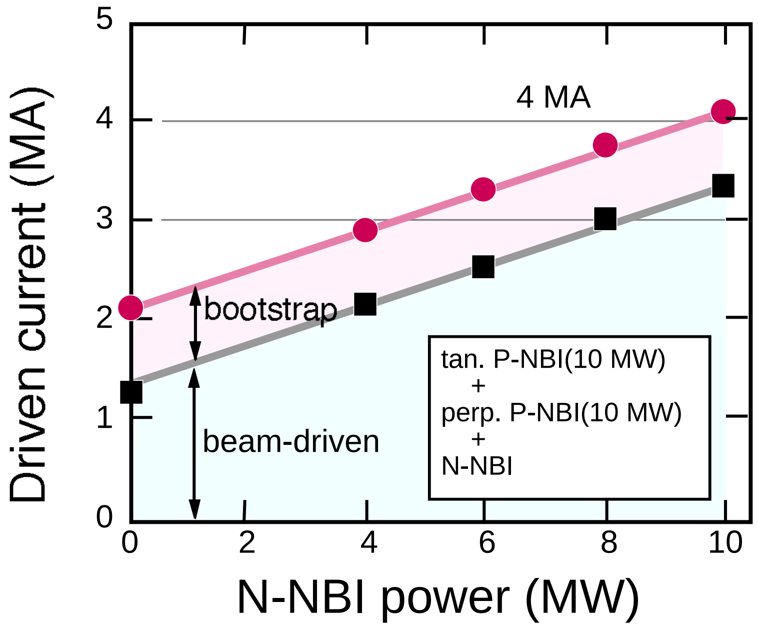
- The present NBI and ECH systems are capable of long pulse heating and current drive depending on the power and pulse length;

10 s → Full current drive at Ip= 4 MA
( 10 MW N-NBI + 10 MW tan. P-NBI + 4 MW ECCD )

30 s → Full current drive at Ip=3 MA
( 7 MW N-NBI + 6.7 MW tan. P-NBI + 3.1 MW ECCD )

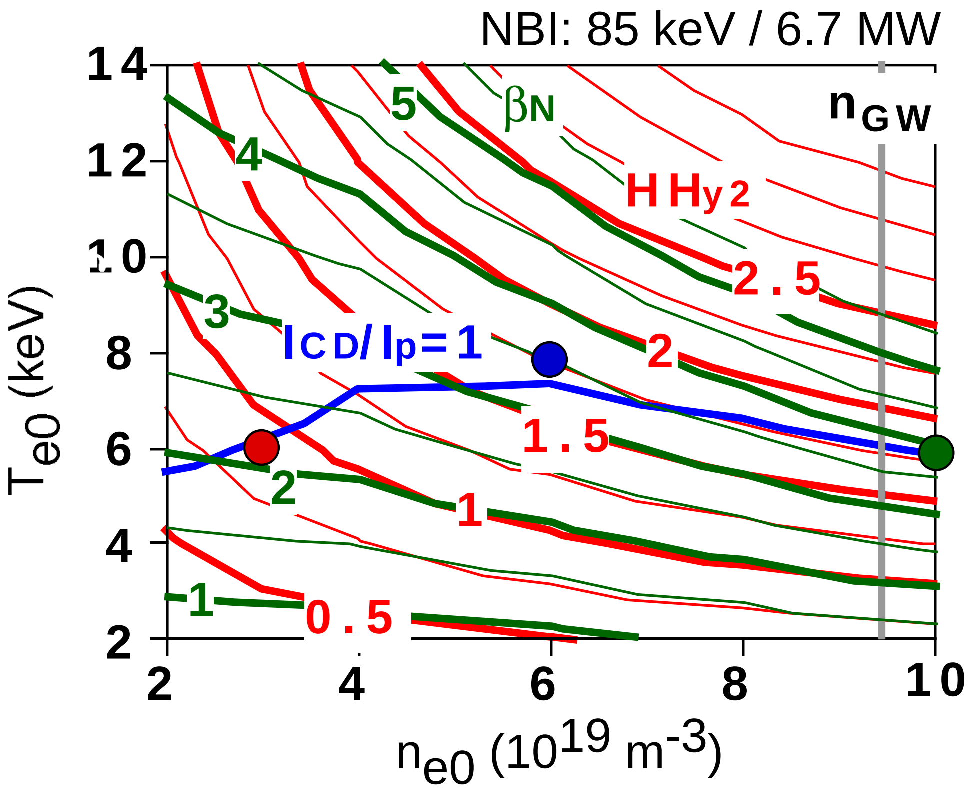
100 s → Full current drive at Ip=2 MA
( 3 MW N-NBI + 3.3 MW tan. P-NBI + 1.7 MW ECCD )

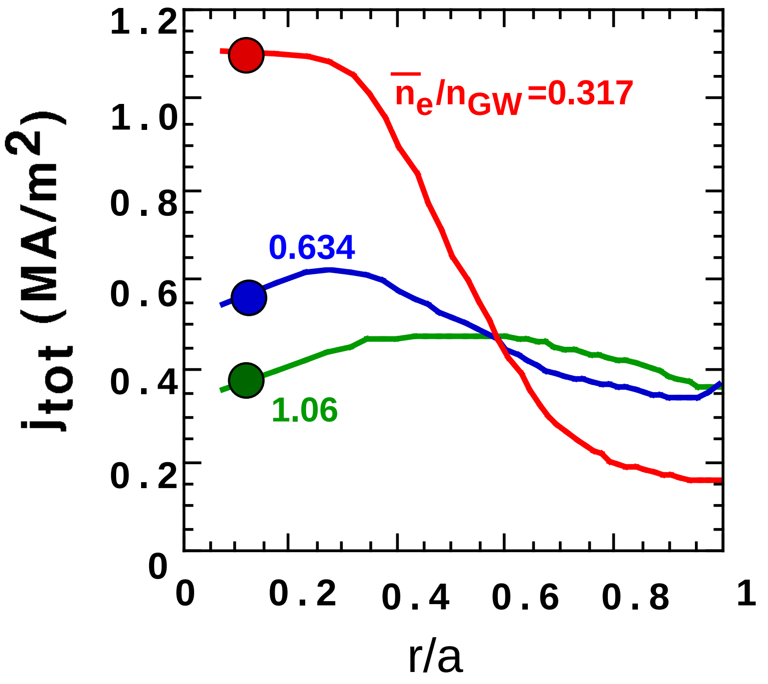
| | 10 s | 20 s | 30 s | 50 s | 100 s |
|---|---|---|---|---|---|
| Perp. P-NBI | 20MW | 20MW | 13.3MW | 13.3MW | 6.7MW |
| Tan.-NBI | 10MW | 10MW | 6.7MW | 6.7MW | 3.3MW |
| N- NBI | 10MW | 7MW | 7MW | 3MW | 3MW |
| ECH | 4MW | 3.75MW | 3.1MW | 2.4MW | 1.7MW |
| Total | 44MW | 40.75MW | 30MW | 25.4MW | 14.7MW |



# FULL CURRENT DRIVE PERFORMANCE DURING 100 S

- ACCOME code analysis
  - Full current drive performance is widely confirmed up to 4 MA by ACCOME code calculations
  - Full CD up to 2 MA for 100 s is possible within the power of NBI and ECH systems.
  - Full CD at 1.5 MA for 100 s is possible for a wide range of density up to $n_e \sim / n_{GW}$ where $HH_{y,2}$=0.8-1.8 and $\beta_N$<4 at 2.8 T





# RESEARCH GOAL OF DIVERTOR HEAT AND PARTICLE CONTROL IN JT-60SC

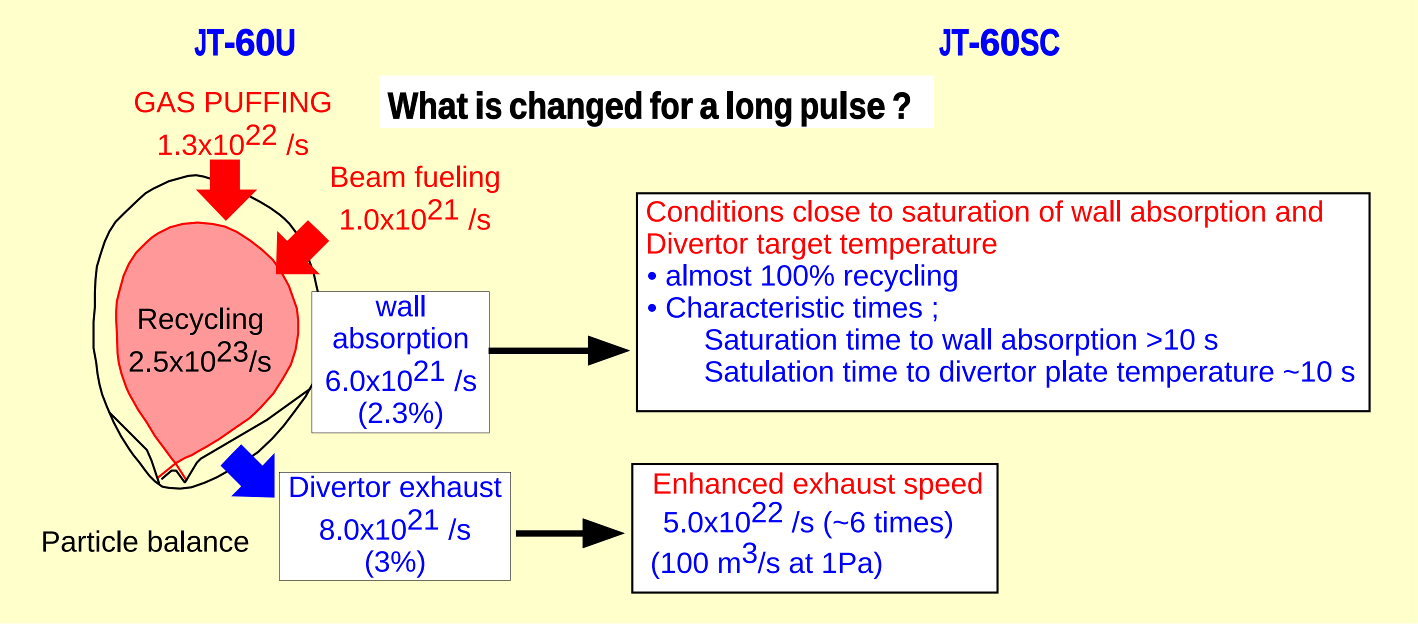
- Goal

  Production and long sustainment of a high-density and high-confinement plasma compatible with a cold and dense divertor plasma required for a steady state reactor

- Divertor concept optimization

  - Realization of high density plasma at the edge by shaping control with high-d and high-k
  - Optimization of divertor geometry for a high-beta configuration
  - Efficient fueling and neutral/impurity flow control by inside pellets with strong pumping
  - Detachment control by hit-point control and remote radiative cooling by impurity seeding

⇒ Continuous feedback control of heat and particle flow exceeding th characteristic times of wall saturation and divertor temperature



**JT-60U**

**JT-60SC**

**What is changed for a long pulse ?**

GAS PUFFING
$1.3\mathrm{x}10^{22}$ /s

Beam fueling
$1.0\mathrm{x}10^{21}$ /s

Recycling
$2.5\mathrm{x}10^{23}$/s

wall absorption
$6.0\mathrm{x}10^{21}$ /s
(2.3%)

Divertor exhaust
$8.0\mathrm{x}10^{21}$ /s
(3%)

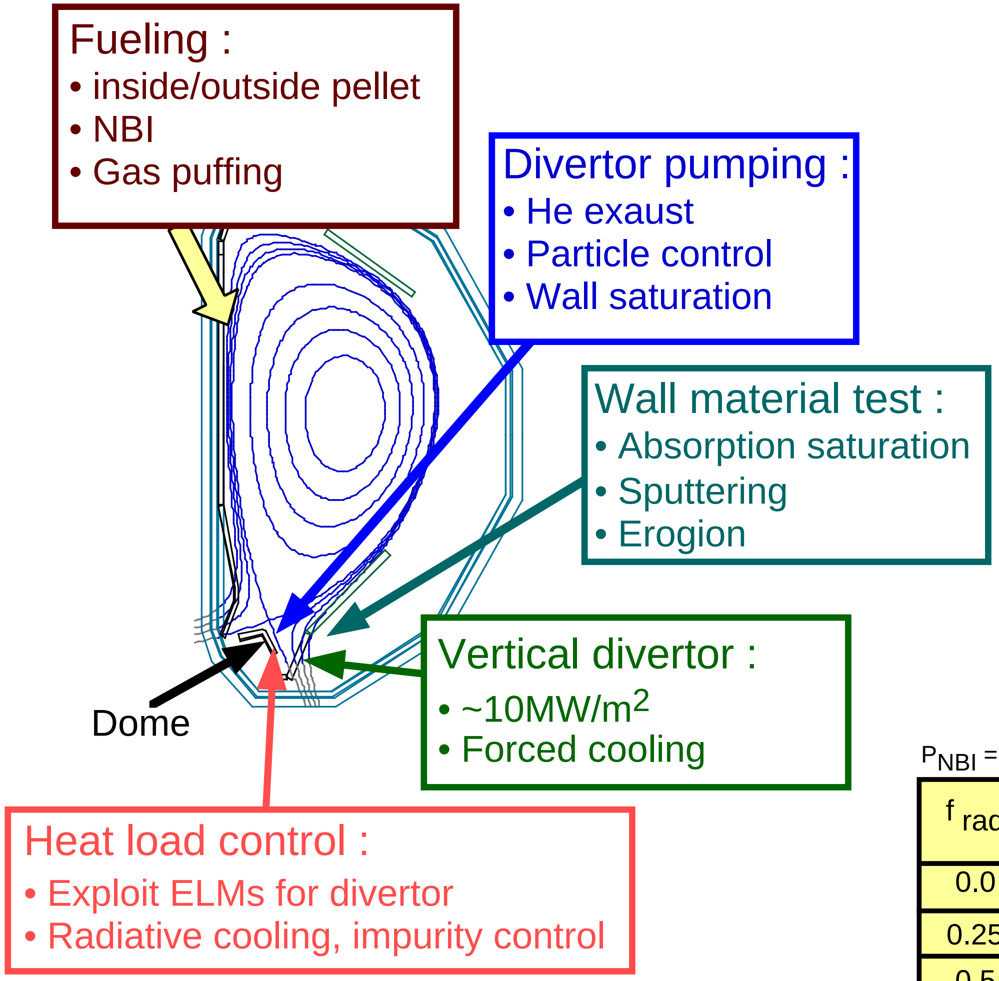
Particle balance

Conditions close to saturation of wall absorption and Divertor target temperature
- almost 100% recycling
- Characteristic times ;
  - Saturation time to wall absorption >10 s
  - Satulation time to divertor plate temperature ~10 s

Enhanced exhaust speed
$5.0\mathrm{x}10^{22}$ /s (~6 times)
(100 $\mathrm{m}^3$/s at 1Pa)

# EQUIPMENTS FOR HEAT AND PARTICLE CONTROL

- Key concepts



Fueling :
- inside/outside pellet
- NBI
- Gas puffing

Divertor pumping :
- He exaust
- Particle control
- Wall saturation

Wall material test :
- Absorption saturation
- Sputtering
- Erogion

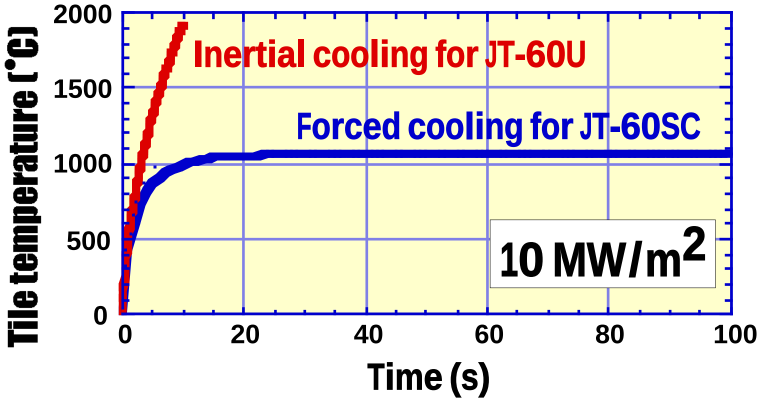
Vertical divertor :
- ~$10 MW/m^2$
- Forced cooling

Dome

Heat load control :
- Exploit ELMs for divertor
- Radiative cooling, impurity control

- Forced cooling divertor

required to suppress the increase in the target temperature against a maximum large heat load of $10 MW/m^2$ on the divertor target plate

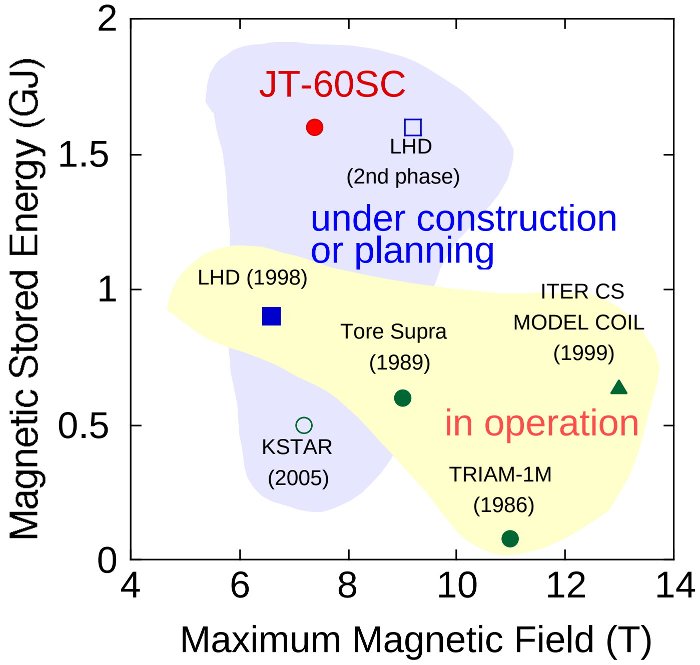


$P_{NBI}$ = 40 MW, heat flux SOL length = 1 cm (midplane), ratio of in/out power flowing = 1/2

| $f_{rad}$ | $P_{rad}$ (MW) | $P_{div, inner}$ (MW) | $P_{div, outer}$ (MW) | $Q_{div, inner}$ ($MW/m^2$) | $Q_{div, outer}$ ($MW/m^2$) |
|---|---|---|---|---|---|
| 0.0 | 0 | 12 | 24 | 8.9 | 11.0 |
| 0.25 | 10 | 9 | 18 | 6.7 | 8.3 |
| 0.5 | 20 | 6 | 12 | 4.4 | 5.5 |
| 0.75 | 30 | 3 | 6 | 2.2 | 2.8 |

# RESEARCH ISSUES FOR FUSION REACTOR TECHNOLOGY IN JT-60SC

- Metallic plasma facing component
  - Development of non-grapfite first wall and metal divertor material in terms of high heat and particle flux from the plasma, erosion, redeposition, dust, high-Z material
  - Divertor material sample installation device
    - High heat and particle flux (10 MW/m$^2$, 10$^{22\sim23}$ m-$^2$s$^{-1}$), wall material test
    - Tritium retention
- Low activation structural material
  - Elucidate the issue on plasma suitability in the use of ferritic steel for vessel or other structural component
  - Clarify effects of strong magnetized material on the plasma behaviors such as plasma build-up, mode locking, positional stability
  - Application to the toroidal field ripple reduction (1% to 0.4% at the plasma edge)



- Superconducting magnet technology
  - Development of a full superconducting fusion device ($Nb_3Al$ or $Nb_3Sn$ for TFC, $Nb_3Sn$ for CS)
  - Influence of disruption on operation
  - Quench protection technology for SC coils

# SUMMARY

| | GOALS | MEANS |
|---|---|---|
| **CORE PLASMA CONTROL** | • High-beta and high confinement: $\beta_N>3$ and HH~1.5<br>• Control of high bootstrap plasma: $f_{bs}>50\%$<br>• Clarification of self-organized physics in a steady state plasma | • Plasma shaping: high-δ and high-κ<br>→ ELMs gentle for divertor<br>• MHD stabilization by closed conductive baffle<br>• Feedback stabilization by sector coils and ECH<br>→ Stabilization of NTM, RWM<br>• Feedback control of current and pressure profiles: by NBI and ECH |
| **DIVERTOR PLASMA CONTROL** | • Compatible divertor with high-density and high-confinement: n/nG~1, HH~1.5<br>Particle control:<br>• Steady density control<br>• Effective impurity and He exhaust: $\tau_{He}^*/\tau_E<5$<br>Heat control:<br>• Radiative cooling: $P_{rad}/P_{in}$~0.9<br>• Detachment control | • Divertor geometry consistent with a high-δ and high-κ configuration at high-beta<br>→Wide SOL~3-4 cm for particle control<br>Effective closed divertor: pellet+strong pumping for neutral and impurity compression<br>• Repetitive inside pellets<br>• Strong divertor exhaust (~100 m$^3$/s)<br>• Forced water cooling of vertical divertor target plate:<br>• Impurity seeding: Ar, Ne, etc |
| **PMI** | • Suitability for the use of ferritic steel<br>• Suitability for the use of metallic plasma facing component<br>• Tritium retention | • Use of ferritic steel for vessel or other structural component<br>• Metallic first wall and divertor target plate<br>• Divertor material sample installation device |
| **Integrated demonstration** | | |