Colloquium of Max Planck Institute fur Plasma Physics

March 8, 2001

JT-60 Modification Plan for Long Pulse Advanced Tokamak Research

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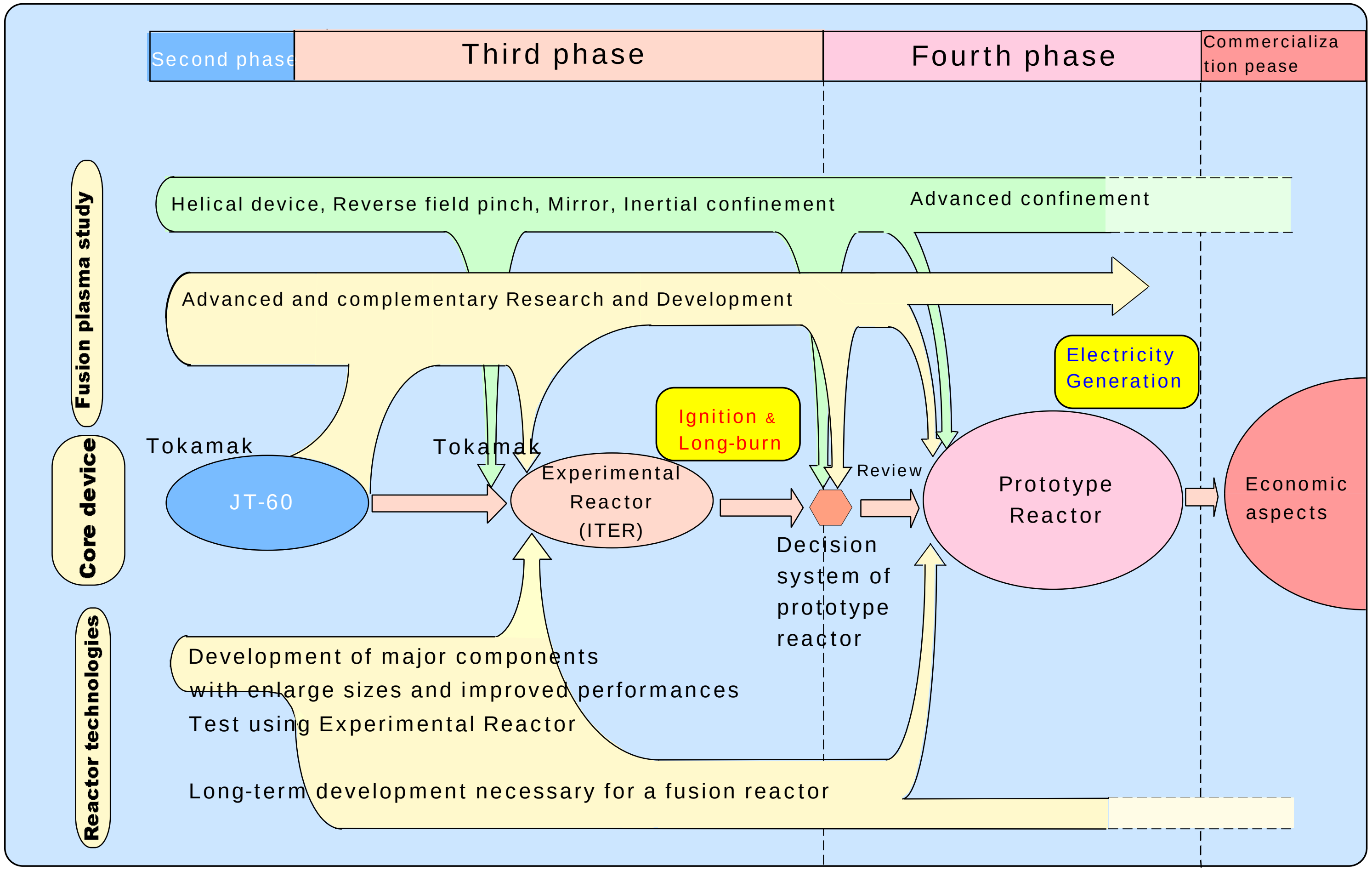
OUTLINE OF TALK

- Fusion Development Strategy
- Progress of Confinement and ITER as one step to DEMO
- Advanced tokamak researches
- Scientific achievements of JT-60 and its Infrastructures
- Proposed Modifications
- New research area and Significance of Long Pulse Experiments
  - Q~1 sustainment
  - Long sustainment of full CD plasma
  - Long sustainment of high β_N plasma
  - Advanced Divertor
  - Technological Research Subjects
- Summary

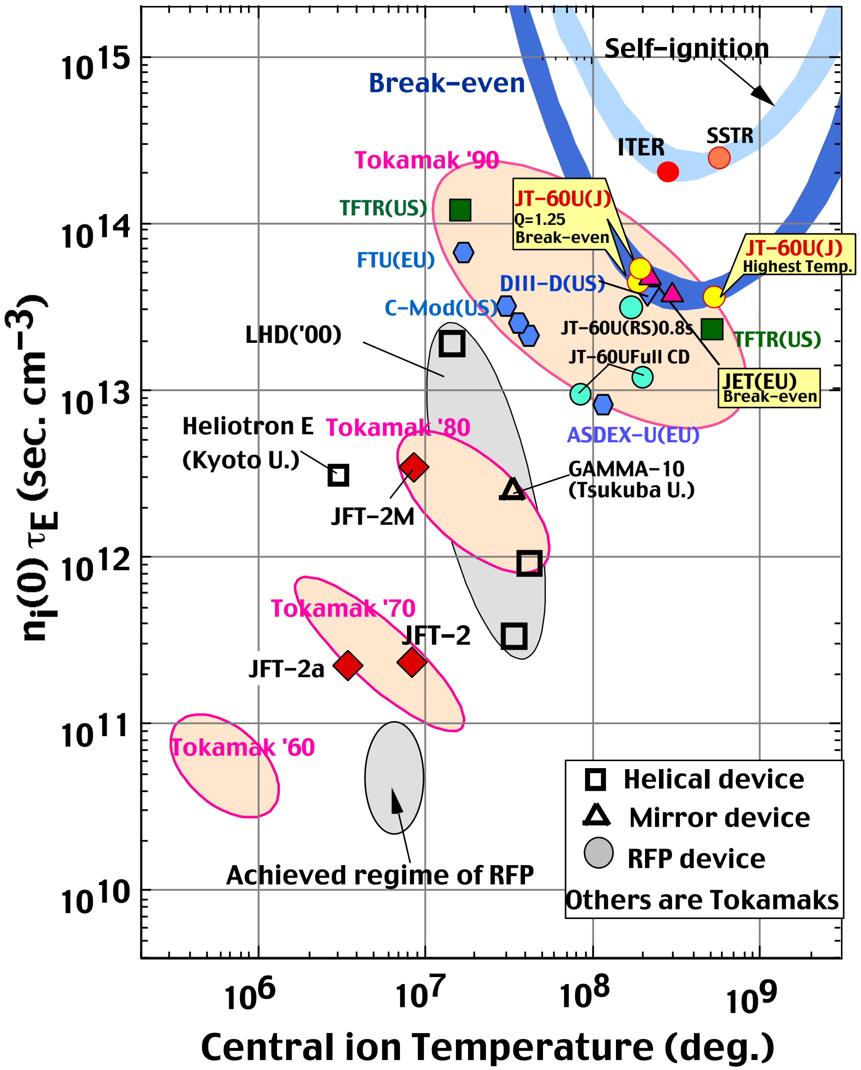
Fusion Development Strategy

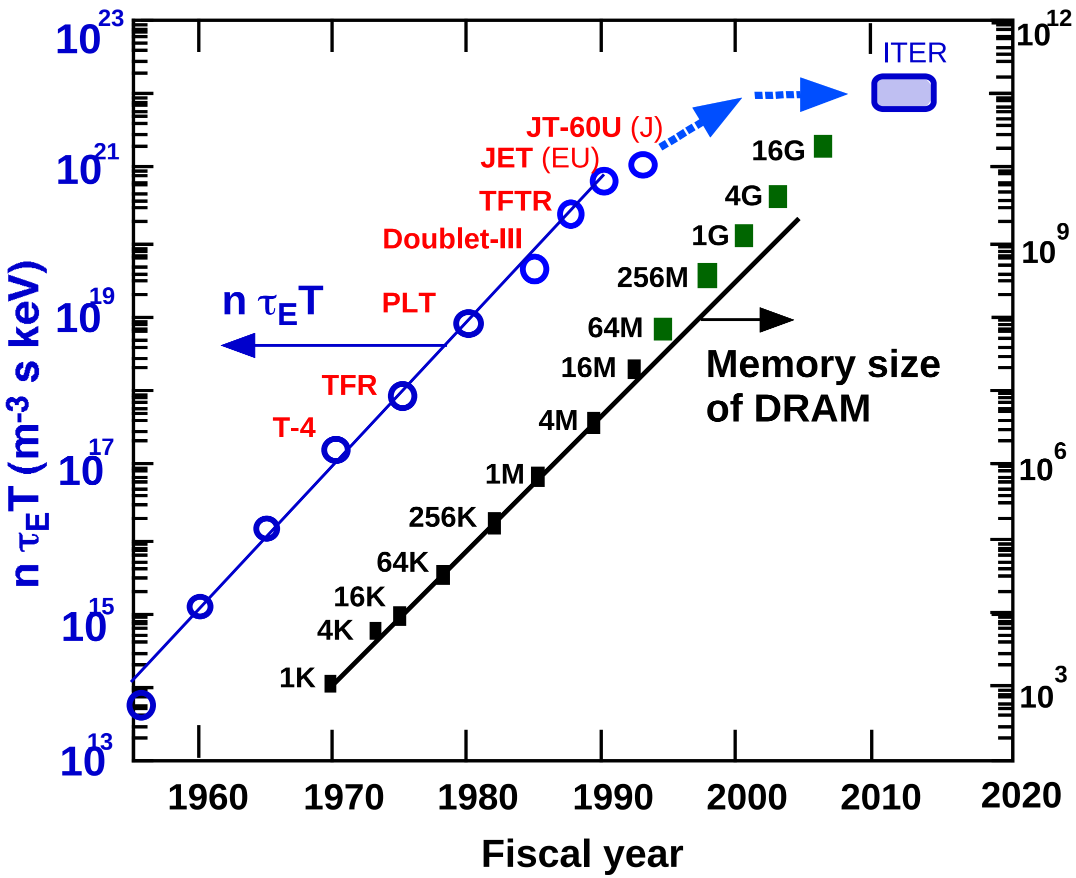
The subcommittee on fusion development strategy (N. Inoue chair) identified fusion development strategy in its report to the ITER special committee.



- Reprot on the technical feasibility of fusion energy, May17,2000

Progresses of plasma confinement is extremely fast (similar to DRAM) and is ready to high Q burning expl.





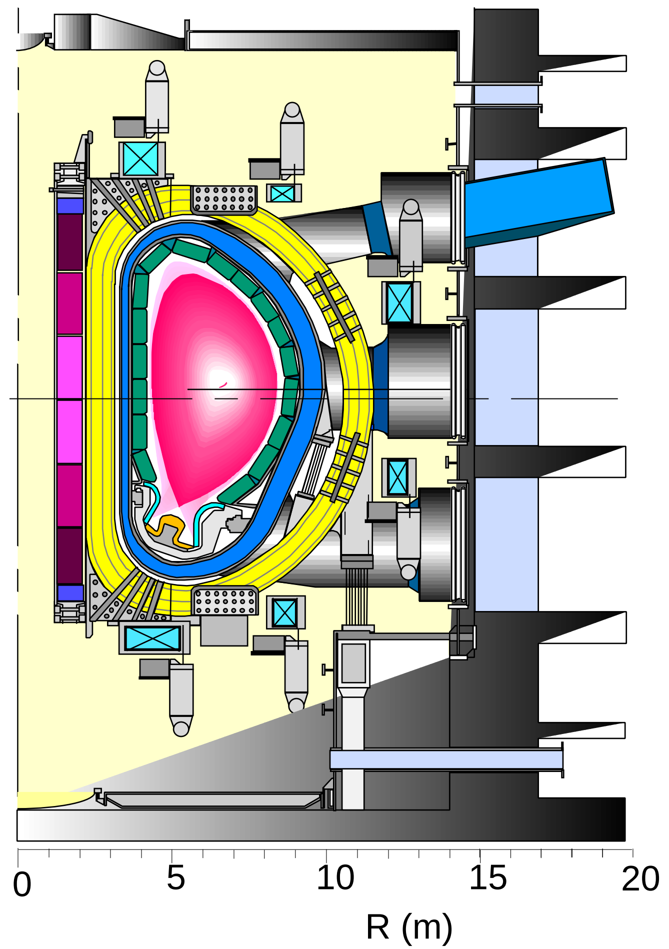
ITER-FEAT as one step to DEMO

[1] Tokamak is ready for α-dominant burning experiments".

ITER-FEAT design is sufficient to sustain burning plasma with Q=10- infinity.

[2] Tokamak is most advanced in scientific understanding.

ITER-FEAT provides new scientific regime of self-heated plasma.



Tokamak still needs improvement to become an attractive fusion reactor.

ITER-FEAT design places more emphasis on steady-state operation expecting future advances in tokamak researches.

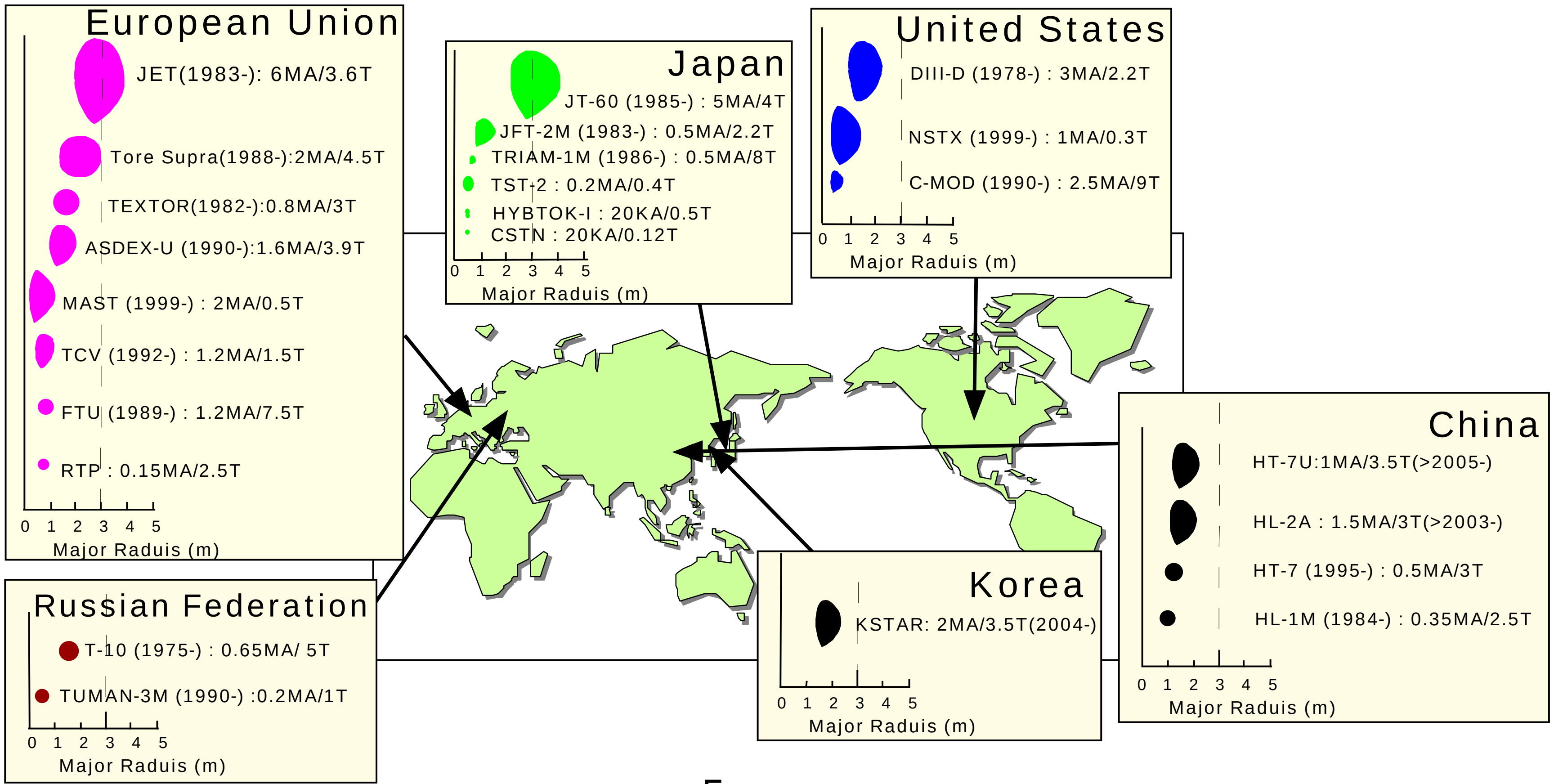
Advanced Tokamak Researches

[1] AT research : Significance of large number of tokamaks

[2] JT-60 research : High bootstrap full CD, ITB for steady-state tokamak

[3] Continuation of JT-60 program : important to keep Japanese potential

[4] JT-60 Modification : advance SS Tokamak further (ITER, SSTR)



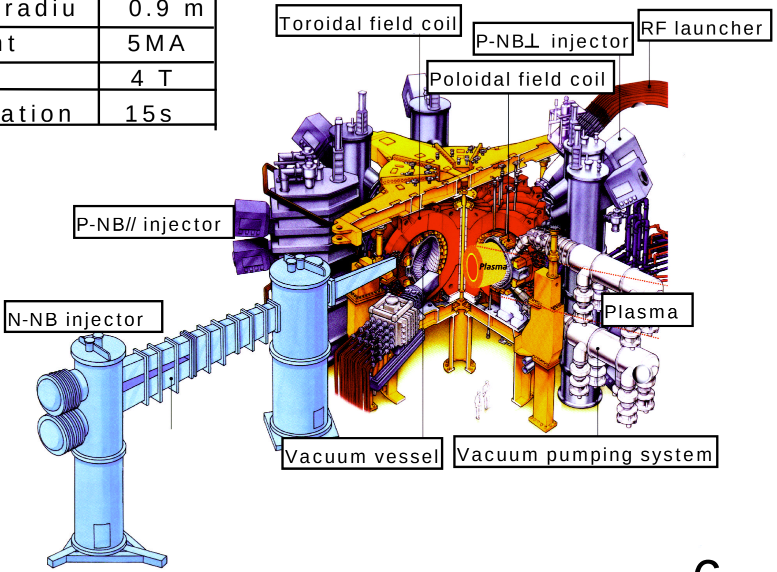
Scientific Achievements of JT-60

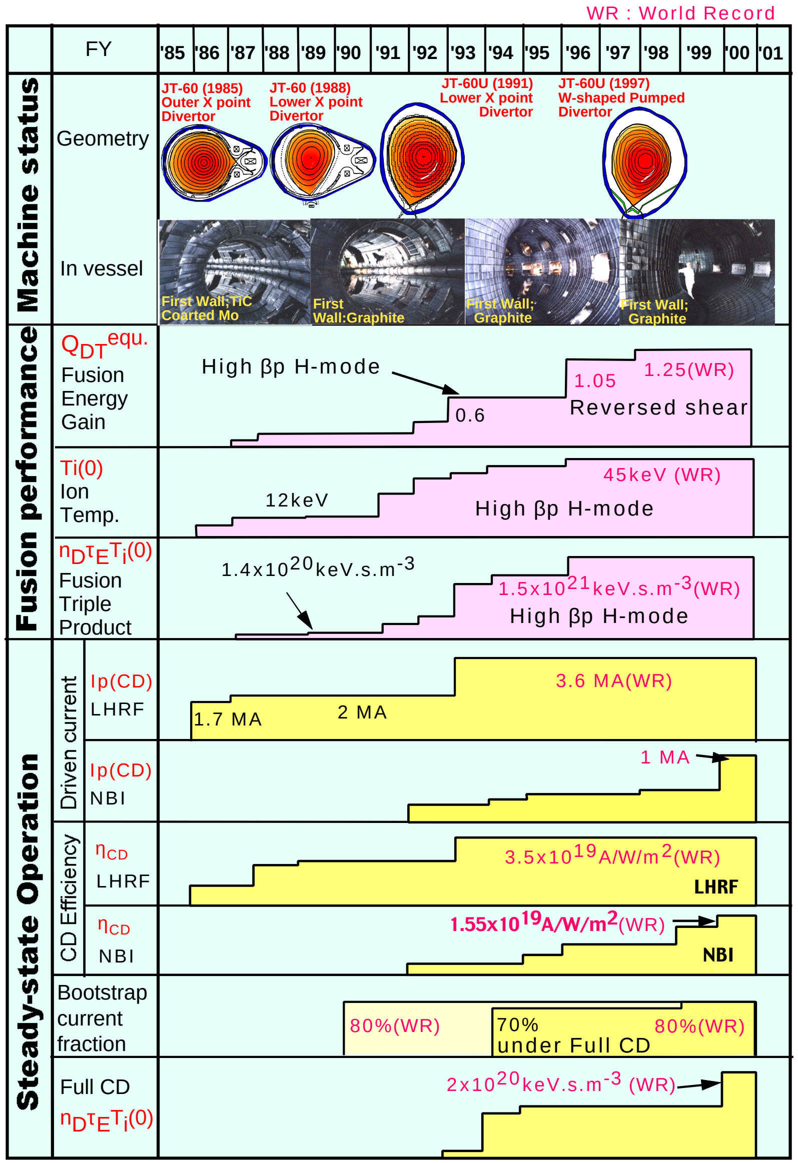
- Significant progresses has been made on fusion performance and steady state operation in these 16 years .

- Operation of present JT-60 will be completed with 17 years of research, end of 2001.

Major parameters of JT-60

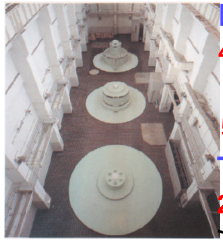
Plasma major radius	3.4m
Plasma minor radiu	0.9 m
Plasma current	5MA
Toroidal field	4 T
Discharge duration	15s





JT-60 Infrastructure is valuable Properties for Fusion

Motor-generators

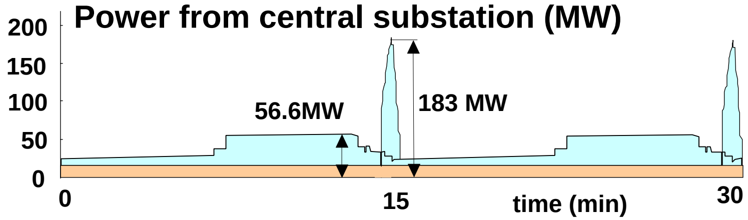


H-MG:
400MVA, 2.6GJ
P-MG:
500MVA, 1.3GJ
T-MG:
215MVA, 4GJ

2ndary cooling system

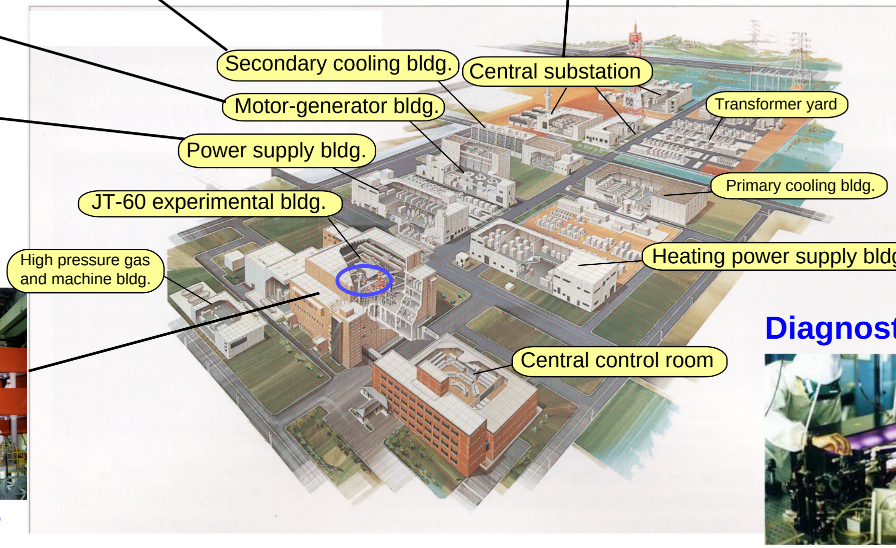
Evaporation:
100ton/hr
40MW

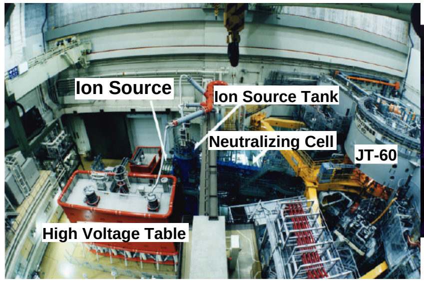
Central sub-station(275kV, 183MW)

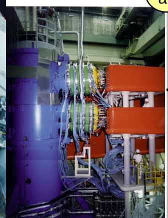


Transformer yard

P-P/S: 1GW
T-Diode P/S : 340MW





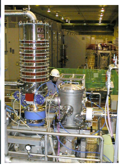


Ion Source

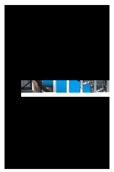
JT-60 N-NBI system(0.5MeV, 10MW)

RF heating system

ECRF
120GHz
4MW

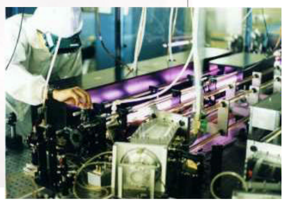


LHRF
2GHz
16MW



ICRF
112MHz
8 MW

Diagnostics system



Ruby laser TS
YAG laser TS
FIR/CO2 interferometer
CXRS(Ti,Vt,Vp)
MSE(Bp,q,J)
CX-NPA (MeV)
γ-ray PHA
IRTC(ripple loss, divertor)
Thermo couple

Neutron(14MeV, activation, spectrometer)
Heterodyne reflectometer
ECE(fourier, poly., heterodyne)
Hard X-ray, Soft X-ray, Bol.
VUV, Grazing incidence mono.
X-ray TV, Zeff(V.B.)
CO2 collective scattering
Magnetic Probes(Eq. Bdot)
Divertor
Langumuir probe:fixed, recipro
Interferometer, Vis. spectro.
VUV spectrometer, Dα/Hα,
Impurity, neutral pressure

Proposed JT-60 Machine Modifications

Major Modifications

[1] All superconducting magnets for long pulse.

[2] 4MA plasma current for Q~1 plasma.

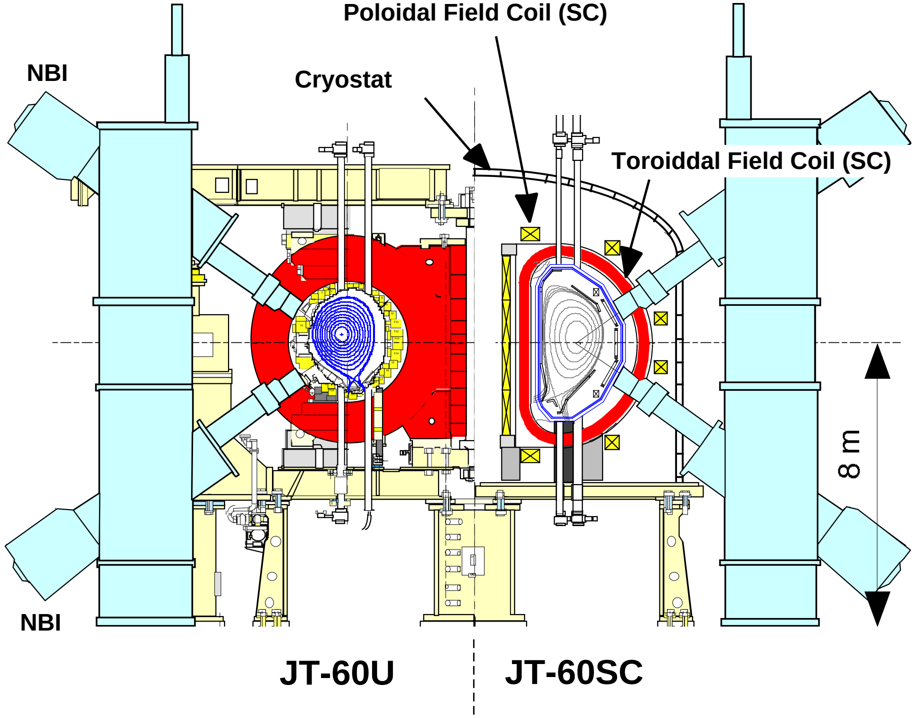
[3] Improved shaping, ECCD and RWM coils for AT operation.

[4] N-NBCD+ECCD for reactor relevant current drive.

[5] use of RAF(in-vessel components) for DEMO.

Parameter	JT-60U	JT-60SC	ITER-FEAT Pulse	ITER-FEAT Steady-State
Pulse length	15 s	100 s	400 s	Steady
Maximum input power	40 MW (10 s)	40 MW (10 s) ≥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 κ_{95}	1.8 (δ_{95}=0.06)	≦1.9 (1.7*)	1.7	2.0
Triangularity δ_{95}	0.4 (κ_{95}=1.33)	≦0.45 (0.35*)	0.35	0.35

* Nominal



New Research Area of JT-60 Modification

[1] Long sustainment of Q~1 plasma (100s, $\tau_{dis.} > \tau_{skin}$) .

(${\rho_p}^*$ and ν^*close to ITER ss operation)

[2] Long sustainment of Full CD plasma (100s).

(RS, weak positive shear, N-NBI)

[3] Long sustainment of high beta (β_N~3-4.2) plasma.

(shaping (high κ & δ and local pitch-dν/dr), ECCD for NTM, Mode-control-coil for RWM)

[4] Divertor optimization

(compatibility with high δ and β, metallic PFC, forced cooling divertor, long particle exhaust)

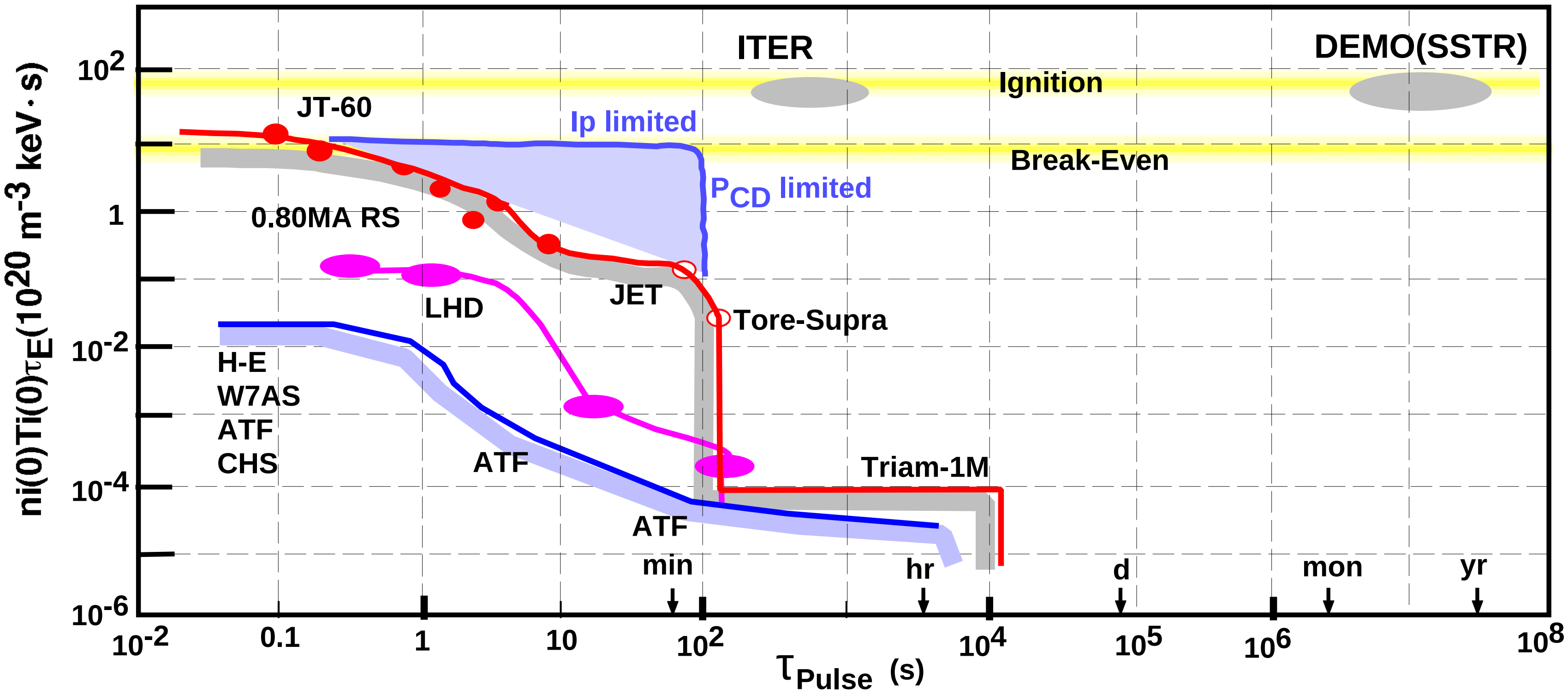
[5] Reduced Activation Ferritic steel for PFC components

Significance of Long Pulse Experiments

[1] Long sustainment is key mission of ITER and it will be realized in ITER.

[2] Extension of long sustainment of high fusion performance ($n\tau T \sim 10^{20}$-10^{21} keVsm^{-3}) will certainly contribute to optimize long pulse operation of ITER.

[3] Furthermore, long sustainment of non-inductively driven (high bootstrap) discharges will have a great impact to the realization of steady-state tokamak reactor.



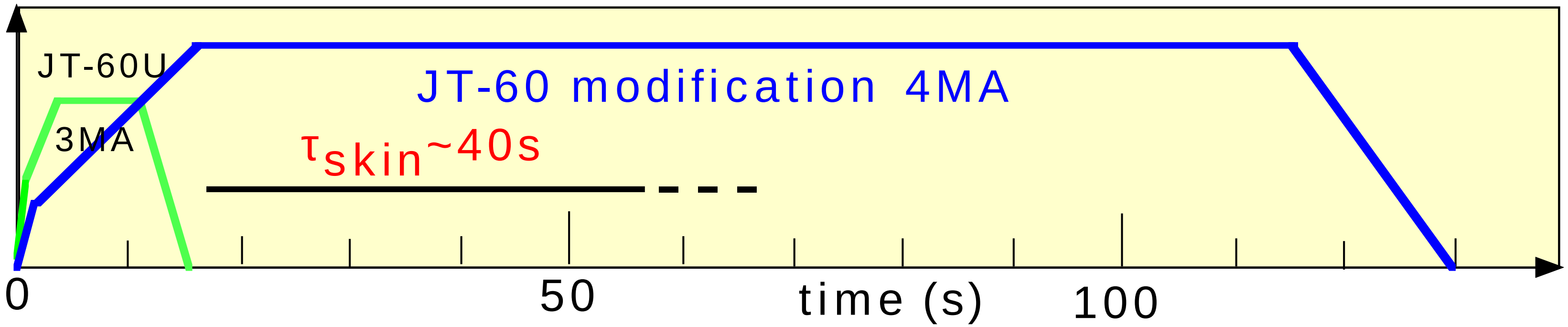
New research area #1

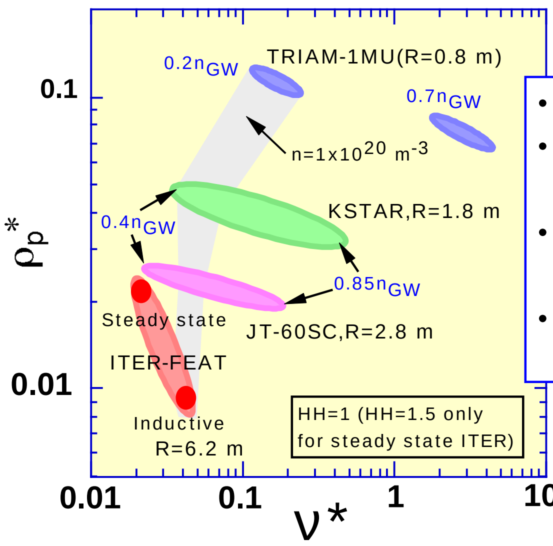
Q~1 sustainment much longer than τ_{skin}

[1] JT-60SC : $\tau_{dis.}$ > τ_{skin} of Q~1 plasma

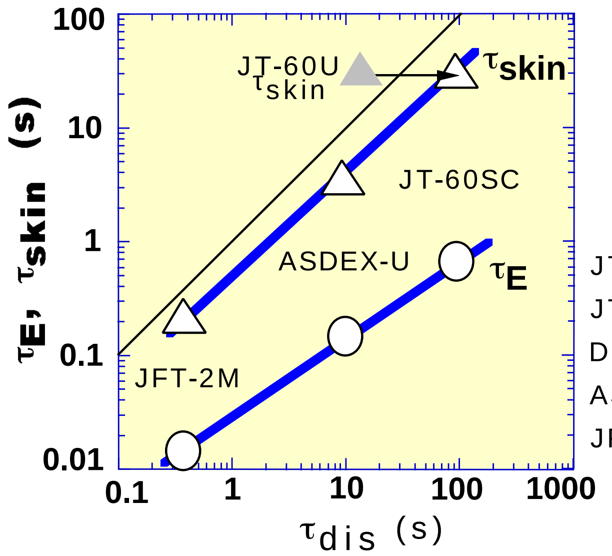
(JT-60U, JET: limited pulse length , $\tau_{dis.} < \tau_{skin}$)

[2] ρ_p^* and ν^* : close to ITER steady-state operation





- ITER-FEAT(Q=5, 10)
- JT-60SC
  (15-40 MW, 4 MA/3.8 T)
- KSTAR
  (15-40 MW,2 MA/3.5 T)
- TRIAM-1MU
  (1-2 MW, 0.5 MA/8 T)

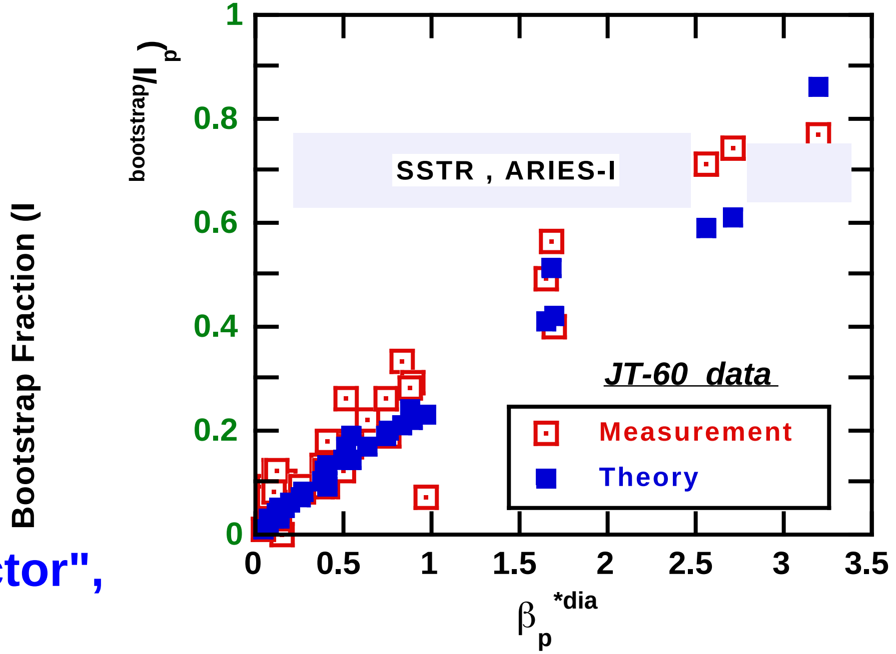


JT-60U : 3.0m
JT-60SC : 2.8m
DIII-D : 1.67m
ASDEX-U : 1.65m
JFT-2M : 1.3m

Steady-state Research

Historical remarks on steady-state researches

1971: Theory of bootstrap current
(Nature Phys. Sci., R.J. Bickerton)
1988: Observation of bootstrap current
(TFTR:M. Zarnstorff)
1990: 80% bootstrap current (JT-60)
1990: SSTR : M. Kikuchi
ARIES-I :R. Conn
1992: Theory of reversed shear operation
for SSTR, T. Ozeki
1993: "Prospect of a Stationary Tokamak Reactor",
EPS invited paper, PPCF, M. Kikuchi
1995: "Experimental evidence for the bootstrap
current", PPCF review paper, M. Kikuchi, M. Azumi



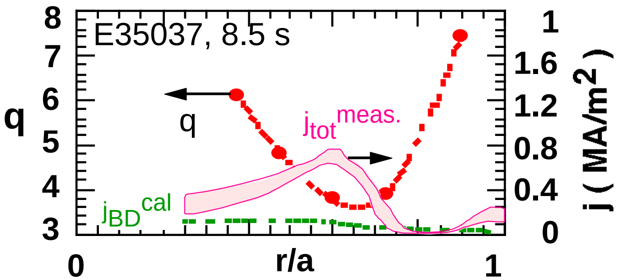
1992-2000; For all IAEA fusion energy conferences,
JT-60 team reported progresses towards steady-state
operation of tokamak.

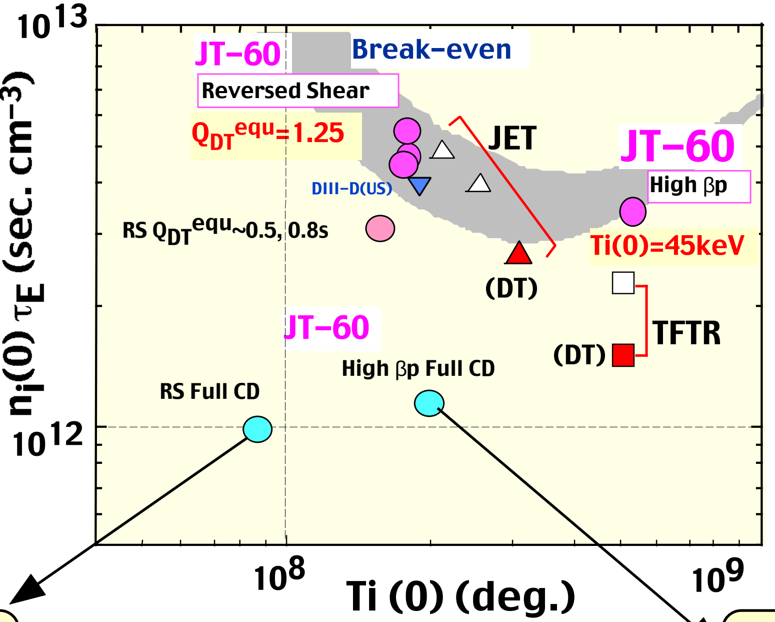
High Performance Full CD Regime in JT-60U

Both weak shear and negative shear regimes are proposed for SSTR.
JT-60U results are quite promising for both scenarios.

Negative shear for SSTR:
T. Ozeki, IAEACN-56/D4-1(1992)

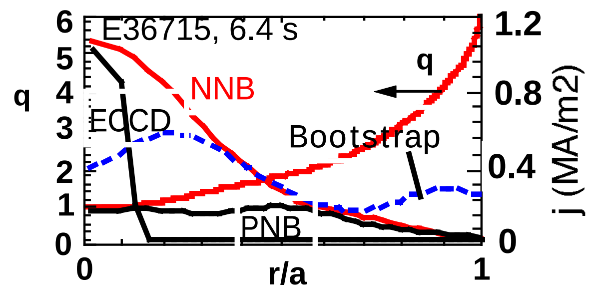
Negative shear with 80% bs:
T. Fujita, IAEACN-77/EX4-1(2000)

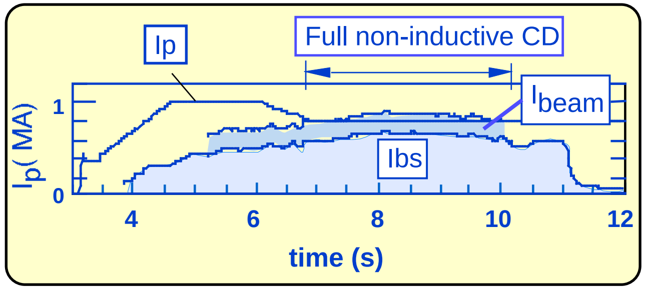




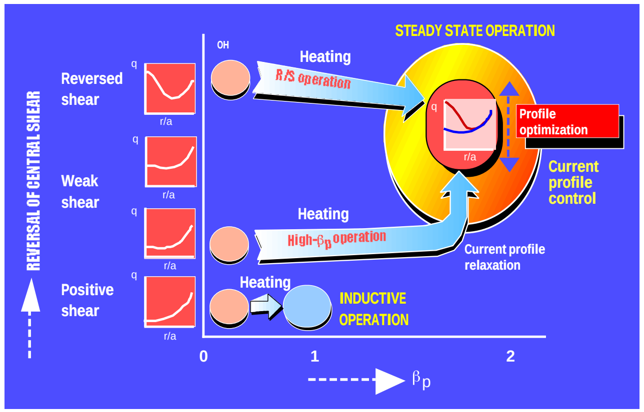
Weak positive shear:
(original SSTR)
M. Kikuchi, N.F. 30(1990)265.

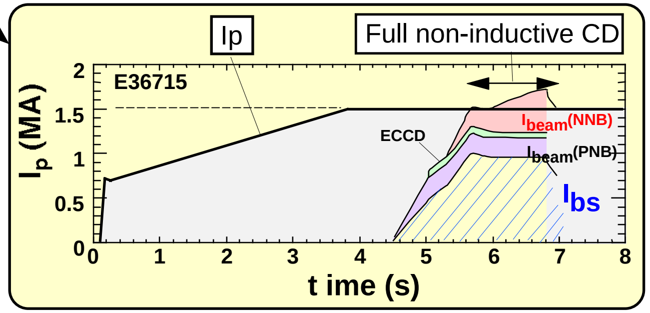
Weak shear with 51% bs:
T. Oikawa, IAEACN-77/EX8/3(2000)





0.8MA/ 3.4T, q95=9.3, δx~0.43, off-axis NBCD (25%), BS~80-88%, H89P3.3-3.8, HHy22.1-2.3, βp=2.6-3.2, βN =1.9-2.2- for 2.6s





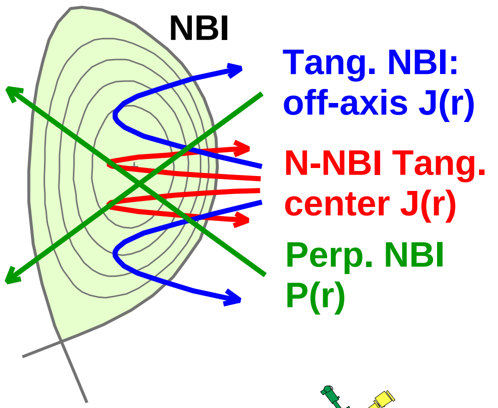
1.5MA/ 3.7T, q95=4.8, NNB (360keV,~4MW), ECH (~1.6MW), I_{NB}~0.61MA(η_{CD}=1.5x10^{19}m^{-2}A/W), I_{PNB}~0.26MA, I_{BS}~0.76MA, H_{89P}~2.9, HH_{y2}~1.4, βp=1.9, β_N =2.5 for 1.3s

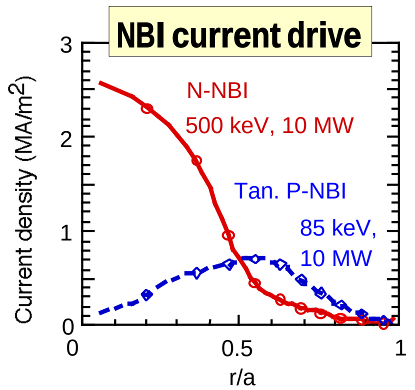
Heating and CD System

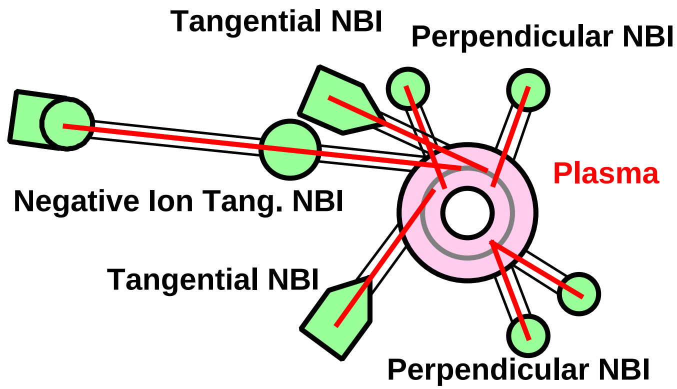
Current Drive with N-NB (& ECRF) is a unique feature of JT-60 which is most reactor-relevant from engineering point of view.

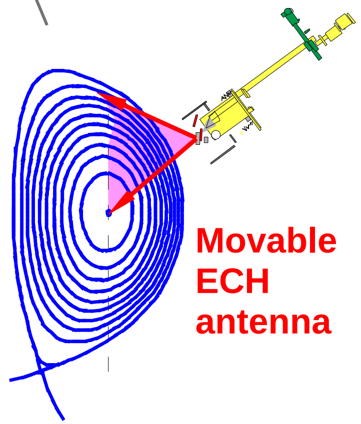
Present H&CD system becomes powerful for long pulse experiments through minor modifications.

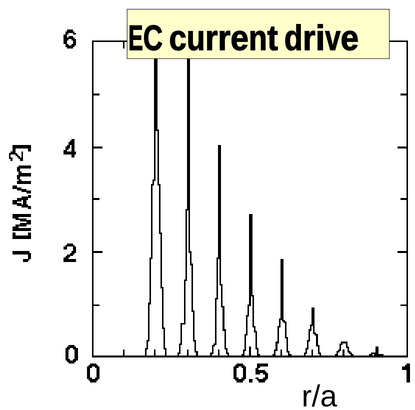
	10 sec	30 sec	100sec
Perpendicular NBI (85keV)	20MW	13.3MW	6.7MW
Tangential NBI (85keV)	10MW	6.7MW	3.3MW
Negative Ion Tang. NBI (500keV)	10MW	7MW	3MW
ECH (110GHz)	4MW	3.1MW	1.7MW
Total	44MW	30MW	14.7MW









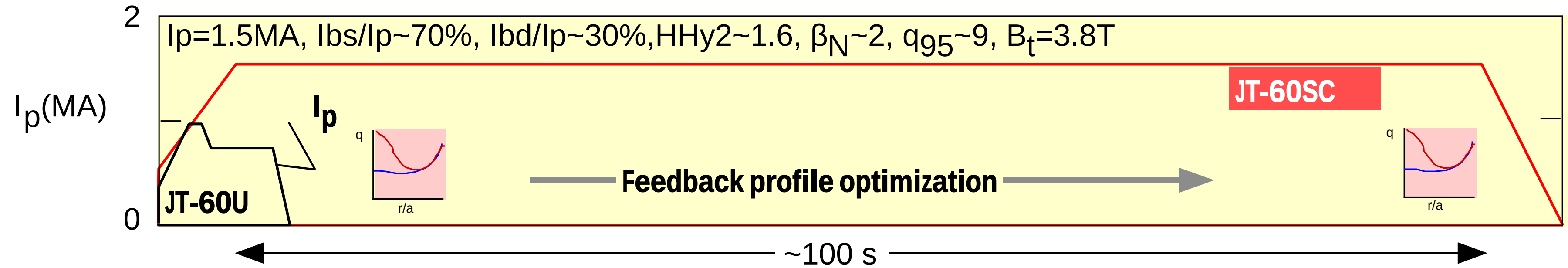


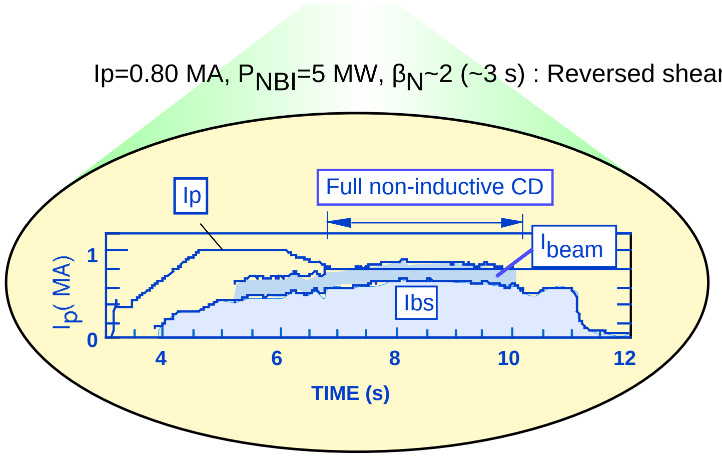
New research area #2

Long Sustainment of Full CD plasma(>100s)

Full non-inductive sustainment of high-bootstrap plasma sufficiently exceeding τ_{skin}.

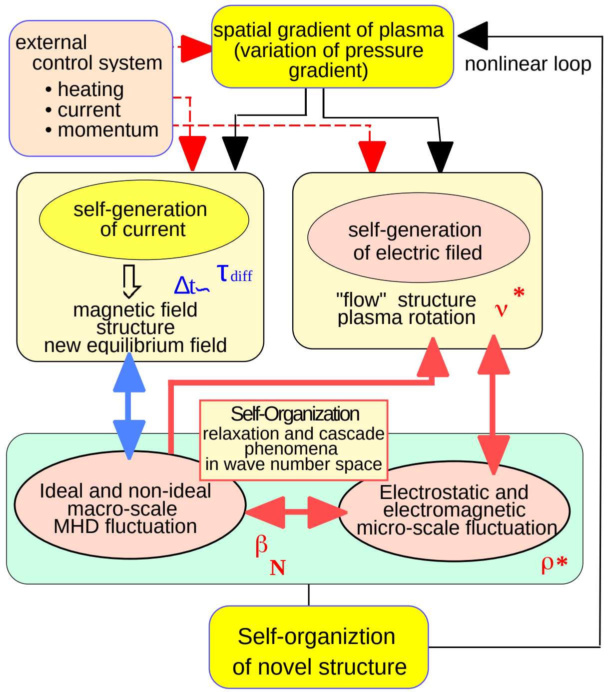
Physics of non-linear loop (J_{bs}-P-Er') in high-bootstrap plasma.





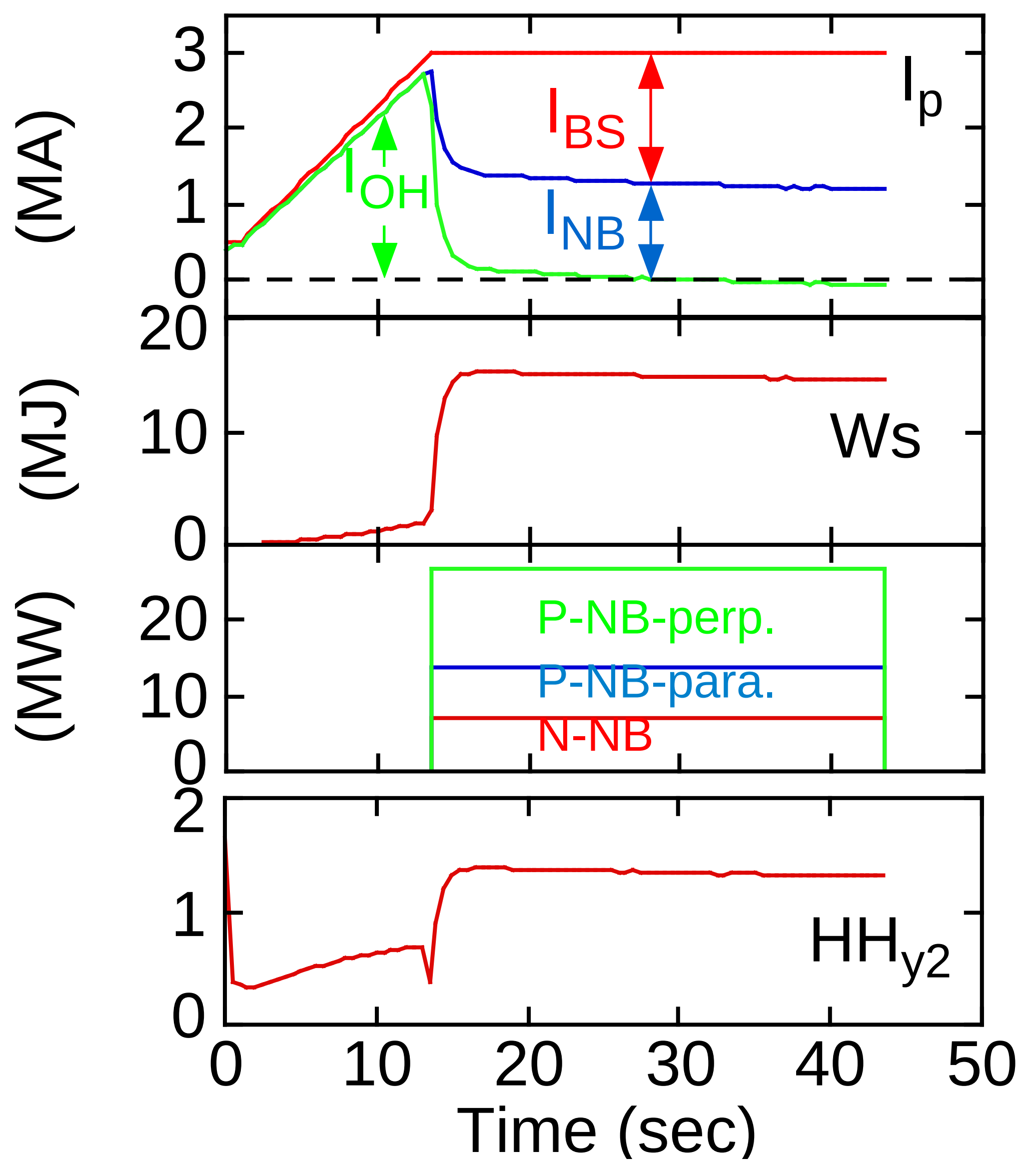
Full non-inductive CD with a reversed shear plasma in JT-60U (~2.7 s)

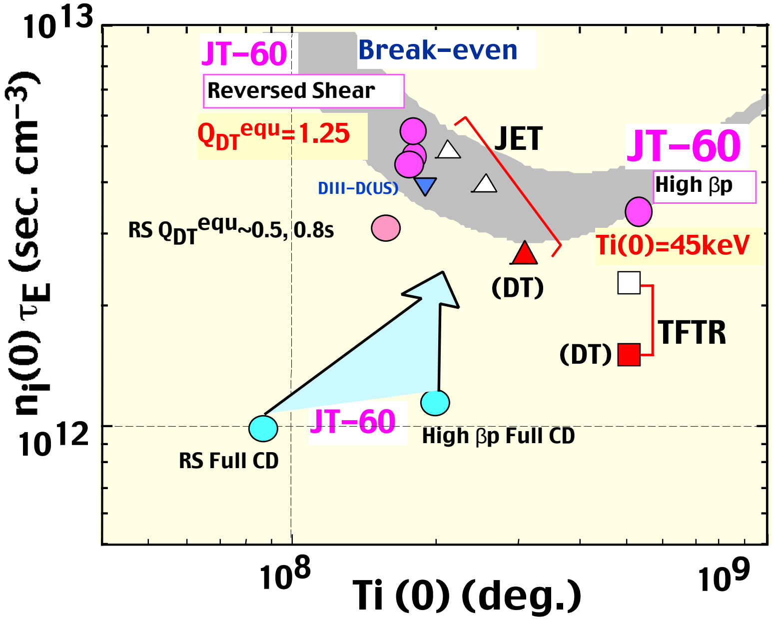
N-NBCD:	~3MW
P-NBCD:	~3.3MW
P-NBH :	~6.7MW
ECCD :	~1.7MW
Total :	~15MW



High performance 3 MA Full CD

Time Dependent TOPICS with Multi-Beam 1D Fokker-Planck NBCD code





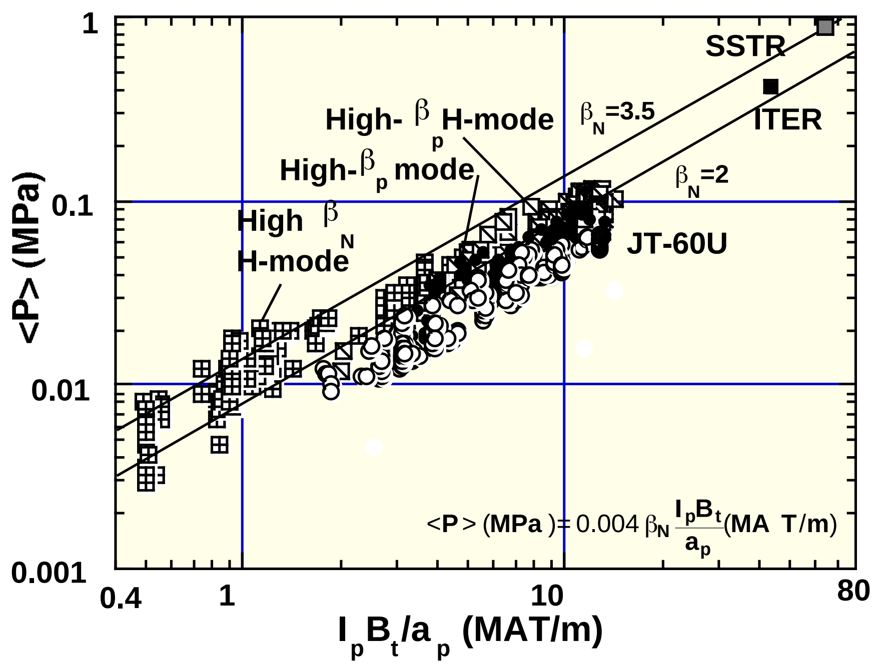
Simulation result:
I_p=3MA, R_p=2.85m, a_p=0.85m,
τ_E=0.54s, β_N=2.6, $n_d(0)\tau_E T_i(0)=5\times10^{20}$keVs/m^3,
Ti(0)=19.3keV, f_{bs}=0.6, f_{bd}=0.42, HHy2=1.4

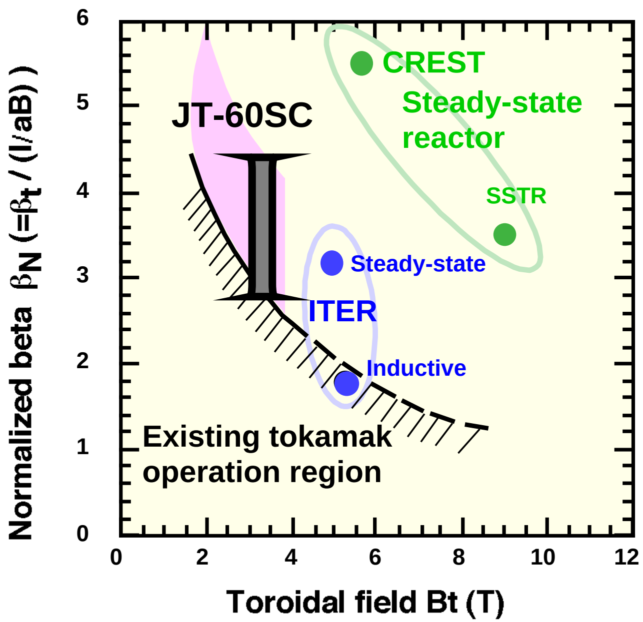
High Pressure towards Compact Reactor needs high βN and B_t

The economically viable fusion reactor requires average plasma pressure <P> of ~1MPa(10atm.) to produce high fusion power density ($P_f \sim \langle P \rangle^2$) .

High βN and high Bt are required to reach such high pressure plasma.

$$\langle P \rangle \,(\mathrm{MPa}) = 0.004\, \beta_N \frac{I_p B_t}{a_p} (\mathrm{MA\ T/m})$$

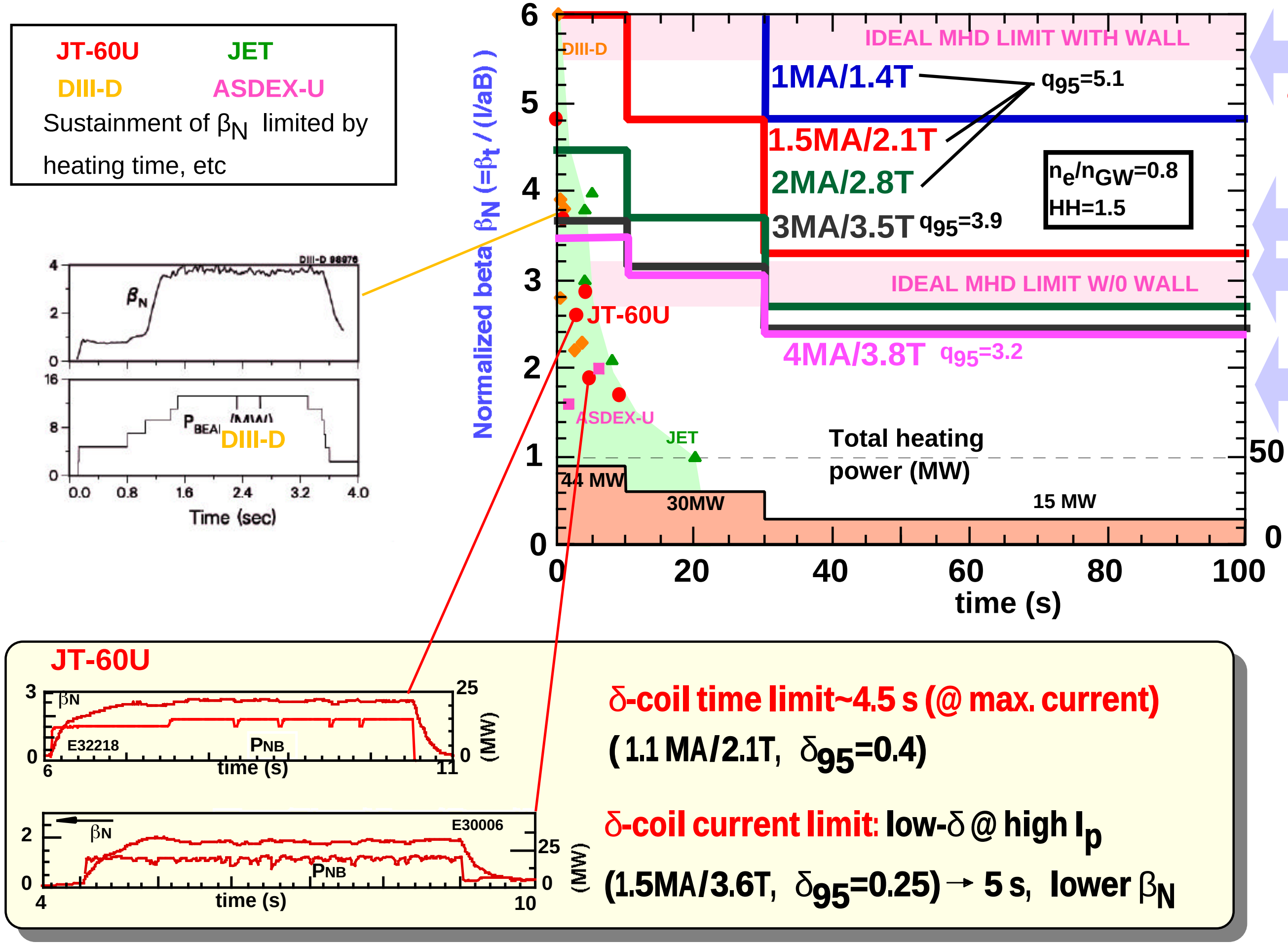




New research area #3

Long sustainment of high β_N plasma in JT-60SC

Effective shaping, profile control, and feedback MHD stabilization are required for long sustainment of the high beta plasma.



CREST(β_N=5.5)

- **Region above Ideal MHD limit**
  - High beta only achieved transiently
  - Onset of RWM

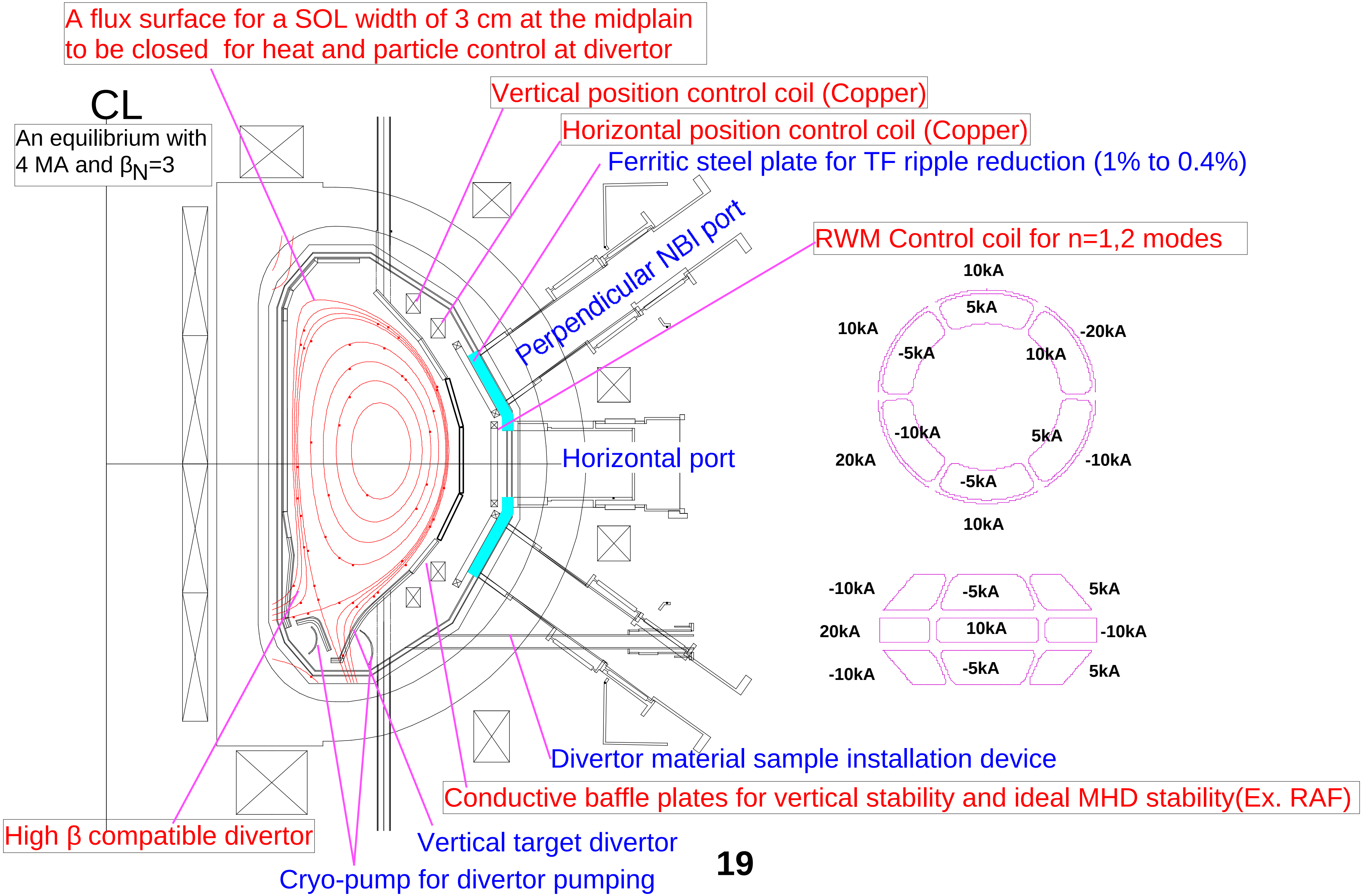
SSTR (β_N=3.5)

ITER SS (β_N=2.6-3.5)

ITER Ind. (β_N=1.8)

- **Region below Ideal MHD limit**
  - for positive or weak negative shear
    - Limited by heatng time, etc
    - Limited by onset of NTM
  - for negative shear :
    - Onset of ideal or resistive modes due to current profile change

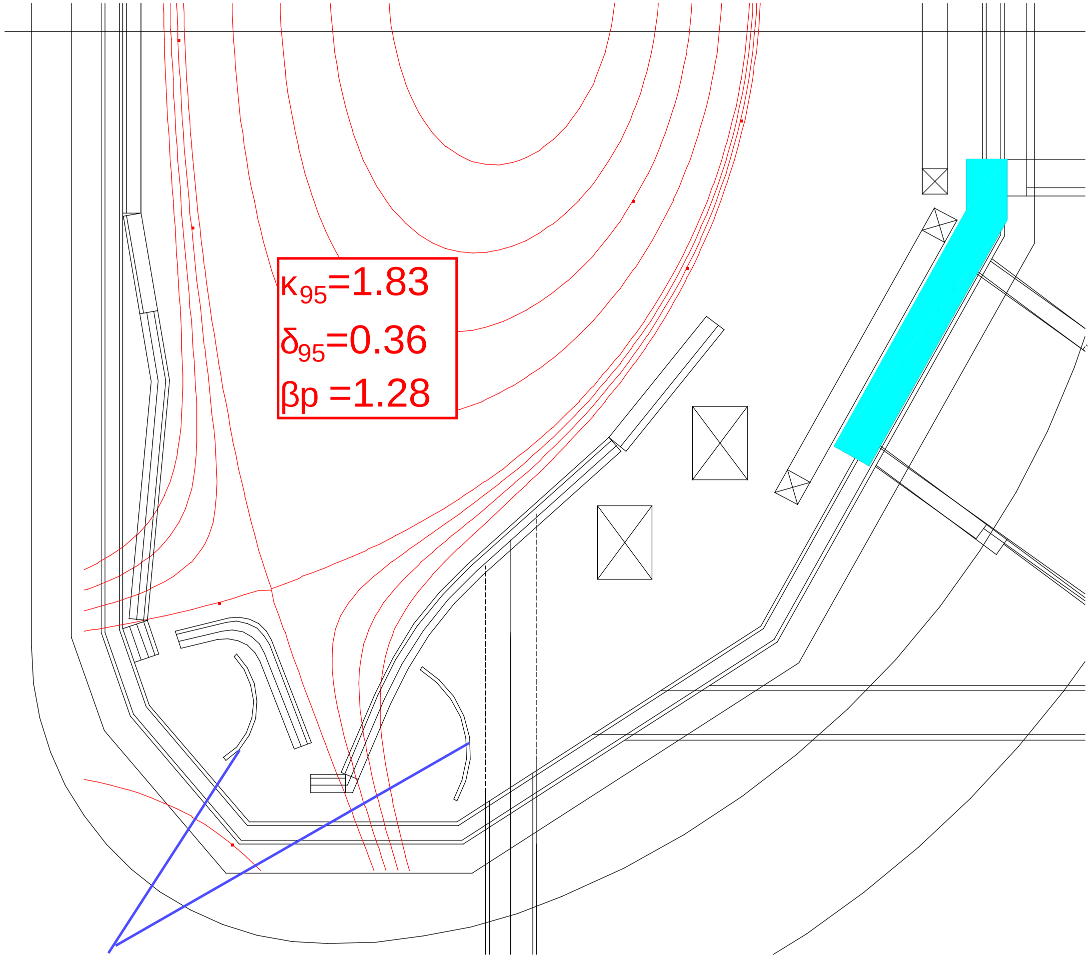
Machine Optimization for High β study in JT-60SC



New research area #4

Divertor concept with a wide SOL at high beta

- **Based on JT-60U results, a wide SOL width at midplane is taken into account for heat particle control at divertor: ~1 cm for heat flux, ~3-4 cm for particle flux**



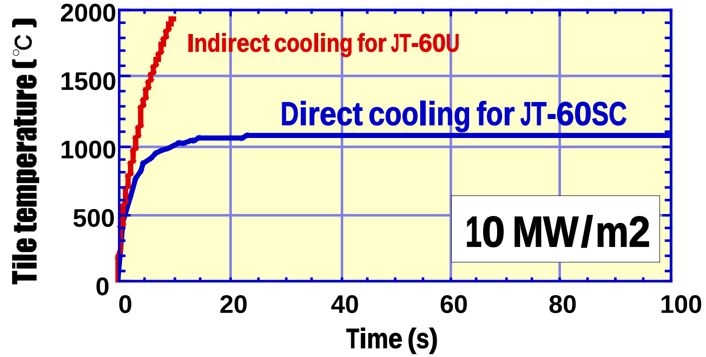
Strong pumping separately from inner and outer

Divertor Concept

- **High δ and β consistent divertor**
- **Vertical target with forced water cooling**
  $T_{surf.}$ ~ 1000 deg C at10MW/m^2
- **Metal target (or Metal coated CFC)**
- **Strong pumping (two cryo pump)**
  5.0×10^{22} /s (~6 times) (100 m^3/s at 1Pa)

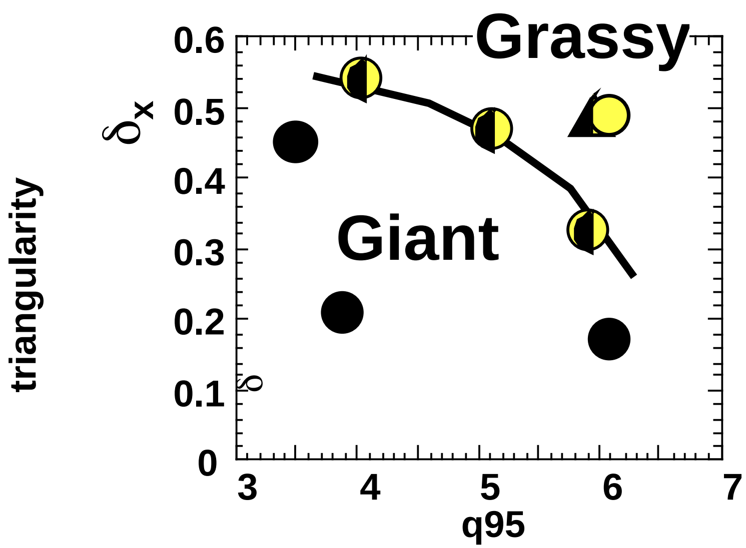
Characteristics of JT-60SC divertor

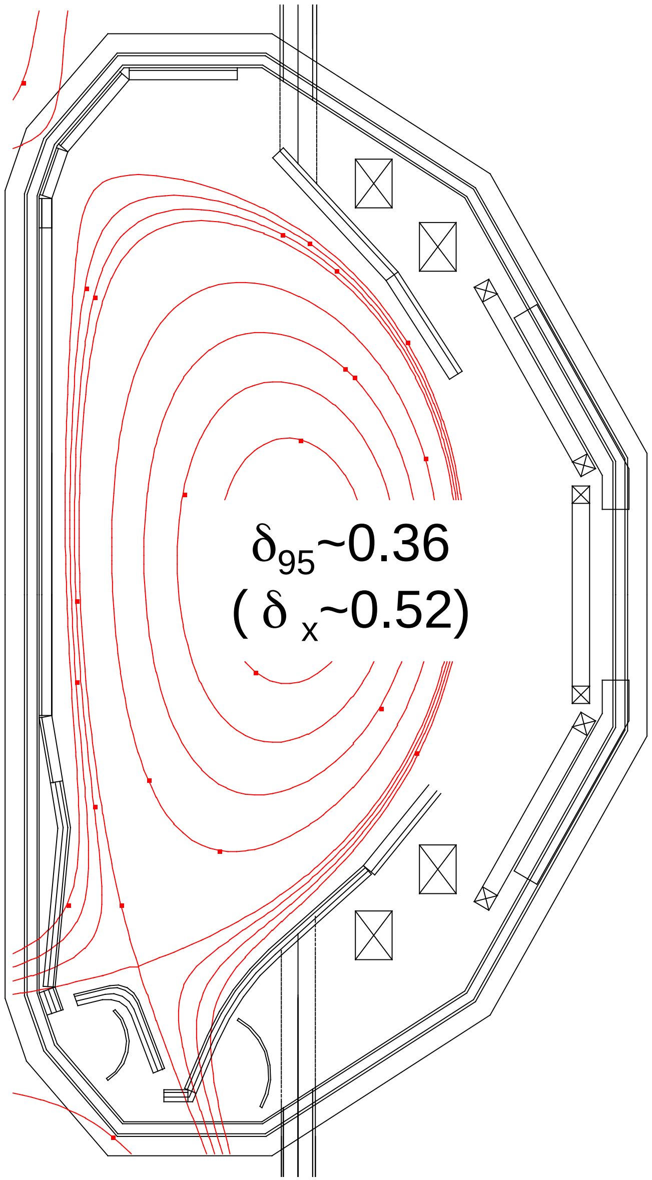
- **Almost 100% recycling**
- **Characteristic times ;**
  Saturation of wall absorption >10 s
  Satulation of divertor plate temp. ~10 s



Study of Type II (Grassy) ELM with high δ

- In JT-60U, Grassy ELMy H-mode with Full CD and HH_{y2}~1.2 is achieved.
- The parameter region of the appearance of Grassy ELM is clarified.
- δ > ~ 0.4 & q_{95} > ~ 5, β_p> ~ 1.6





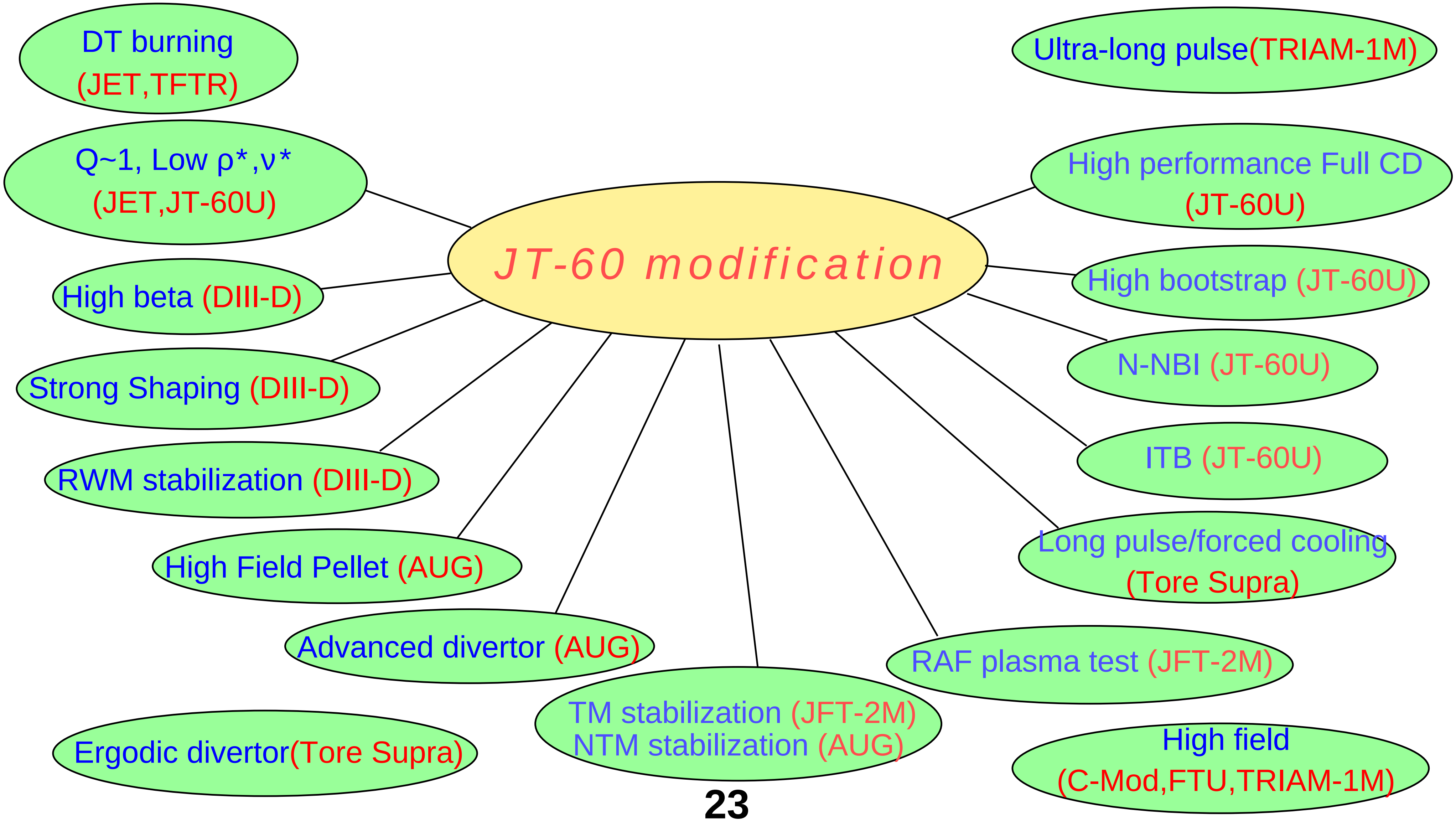
- In JT-60SC, it is necessary to find a way to lower q_{95} with δ~0.35 to have Grassy ELM.

New research area #5

Technological Research Subjects

- First wall technology
  - Development of metal divertor material and first wall 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
- Reduced Activation Ferritic test (as of JFT-2M AMTEX program)
  - Elucidate the issue on plasma in the use of ferritic steel for in-vessel 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)

JT-60 modification incorporates many advanced tokamak elements for their integration.



Summary

- JT-60 will become powerful advanced tokamak with proposed modification.

- JT-60 will become an integrated test bed of advanc tokamak for ITER and DEMO.

[1] Long sustainment of Q~1, low ρ*,ν* plasma

[2] Long sustainment of high performance full CD plasma (N-NBCD+1st harmonic ECCD for current drive)

[3] Long sustainment of high beta (strong shaping, stabilizing NTM &RWM)

[4] High δ and β compatible divertor

[5] Technology test such as RAF plasma test , forced cooled divertor target