JT-60SA
Advanced Superconducting Tokamak
BA-Satellite Tokamak Program

Plans for long-pulse operation in JT-60SA

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IAEA TM on Long-Pulse Operation of Fusion Devices,
14-17 November 2022, Vienna

Contents

- JT-60SA and long pulse operation (LPO)
- Machine capabilities of JT-60SA for LPO
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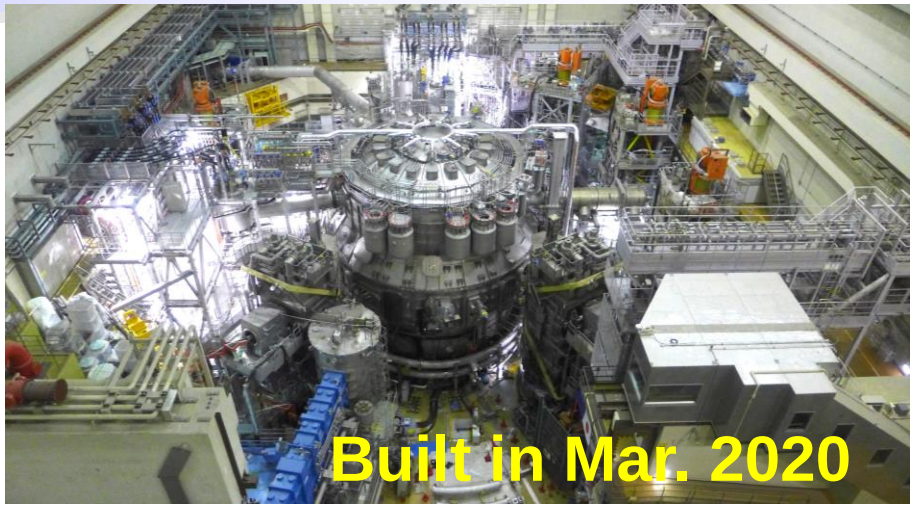
JT-60SA Project for ITER and DEMO

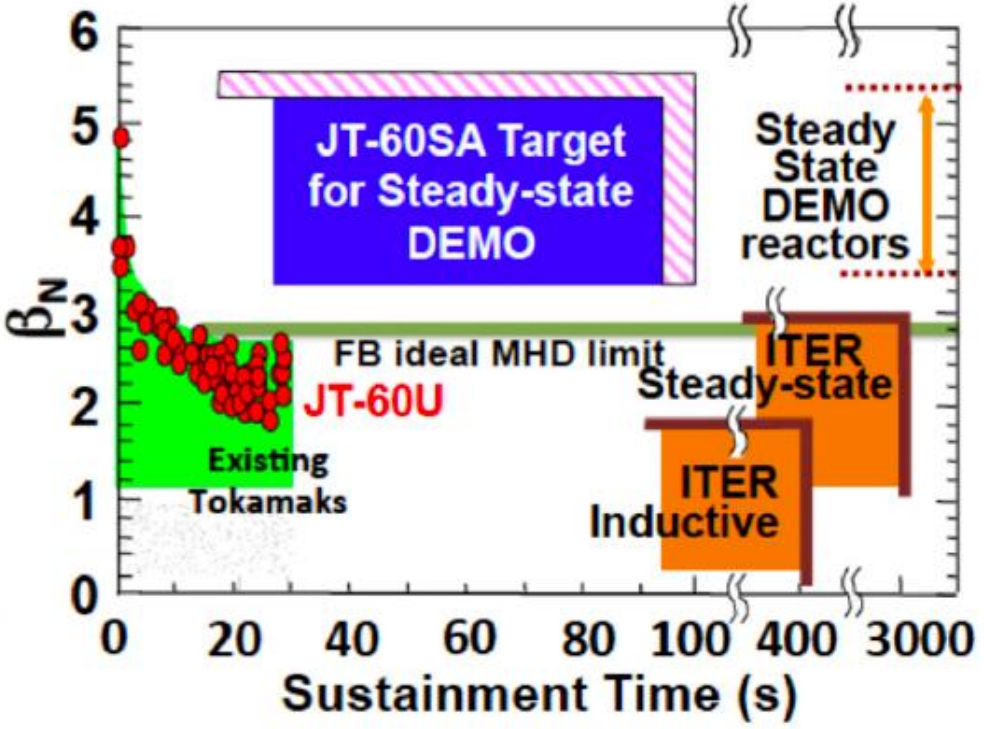
JT-60SA:

- Large superconducting: R_P~3.0 m, a_P~1.2 m
- High plasma current: I_P/B_T=5.5 MA/2.3 T
- High power and long pulse: 41 MW × 100 s
- Highly shaped: $S=q_{95}I_P/(a_PB_T)$ ~7, A~2.7, κ_x ~1.9, δ_x ~0.5



Mission:

- Contribute to the early realization of fusion energy by addressing key physics issues for ITER and DEMO
- Aim at fully non-inductive steady-state high β_N operations above the no-wall ideal MHD stability limits, for long time (~3-4τ_R)



Machine enhancement and staged approach

JT-60SA

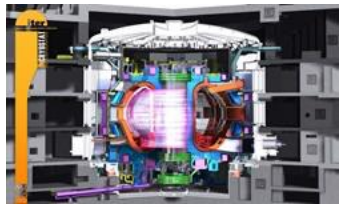
	Phase	Expected operation schedule		Annual Neutron Limit	Remote Handling	Lower Divertor (wall material)	P-NB Perp.	P-NB Tang.	N-NB	NB Energy Limit	ECRF 110 GHz & 138 GHz	Max Power
Initial Research Phase	phase I	2020-2023	H	- (N2)	R&D	-	0	0	0	0	1.5MWx5s	1.5MW
		2025				Carbon Div. Pumping (Carbon)	3MW	3MW	10MW	23MW x 14s duty = 1/30	1.5MWx100s + 1.5MWx5s	19MW
	phase II	2025	D	3.2E19 (N2)			6.5MW	7MW				26.5MW*
		2026										
	phase III	2027					13MW					33MW*
Integrated Research Phase	phase I	2029 - 2032	D	4E20 (water)		Actively cooled Carbon Div.Pumping (10MW/m2 ss, 15MW/m2x5s) (Carbon)				20MW x 100s 30MW x 60s duty = 1/30	7MW x 100s	37MW
	phase II	2033 -	D	1E21 (water)	Use	Actively cooled Tungsten Div.Pumping (Tungsten)						
Extended Research Phase		>5y	D	1.5E21 (Boron)		Actively cooled Tungsten Advanced Structure (U. Div. to be considered) (Tungsten)	16MW	8MW		34MW x 100s		41MW

(filler in the VV double wall)

Upper Open Carbon Divertor (very limited heat handling capability) is always ready

*Real Injection: ~ 26MW x 2-3 sec limited by divertor cooling

ITER

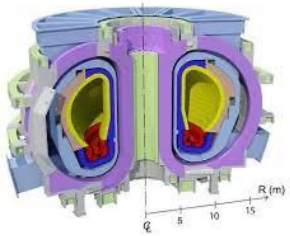


PFPO-1

PFPO-2

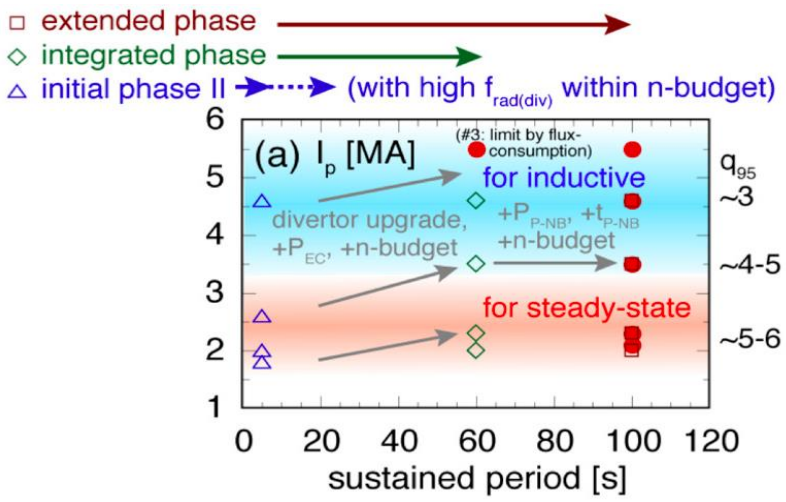
FPO-1

DEMOs

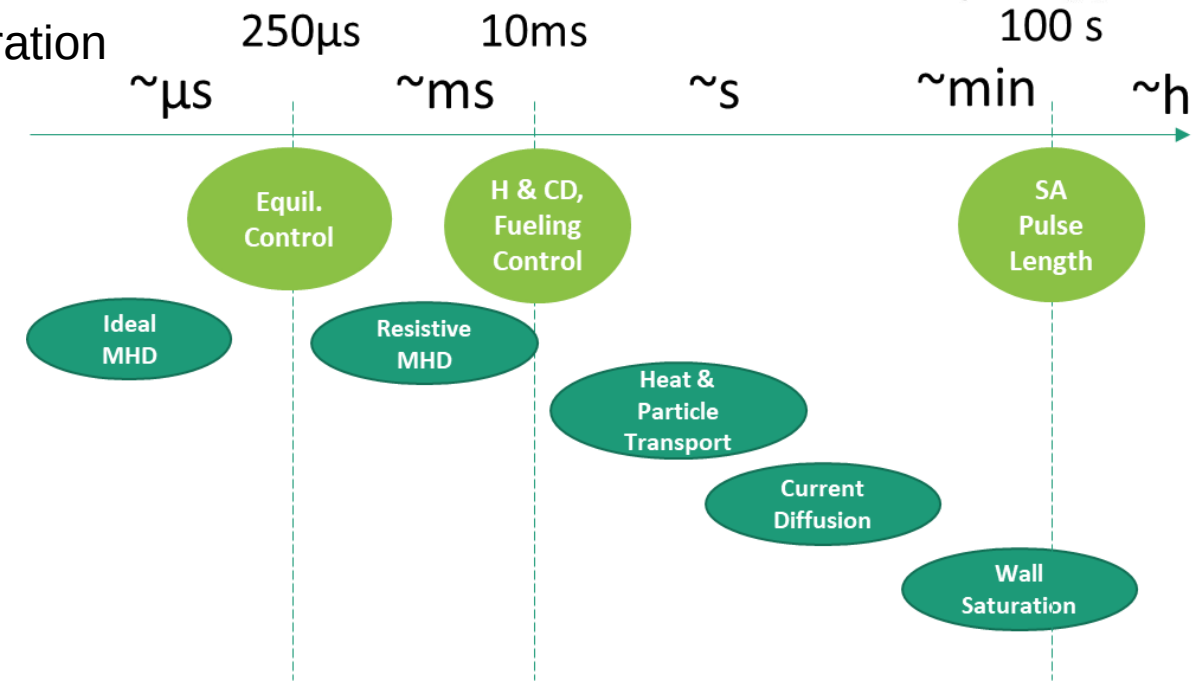


Objectives for long pulse operations in JT-60SA

- JT-60SA aims to demonstrate the real-time control in long pulse discharges exceeding *the time scales governing the plasma system*
  - MHD : ~ 10^-6 s (ideal), ~ 10^-3 s (resistive)
  - Transport: 10^-2 ~ 10^0 s
  - Current diffusion : ~ 10^1 s
  - Wall saturation : ~ 10^2 s



- There are many issues to be studied for long pulse operation
  - Compatibility of radiative divertor with high performance core plasma
  - Control of current/pressure profiles under high f_{BS} condition
  - Impurity accumulation
  - Long sustainment of high-beta plasma that exceeds no-wall limit
  - etc…



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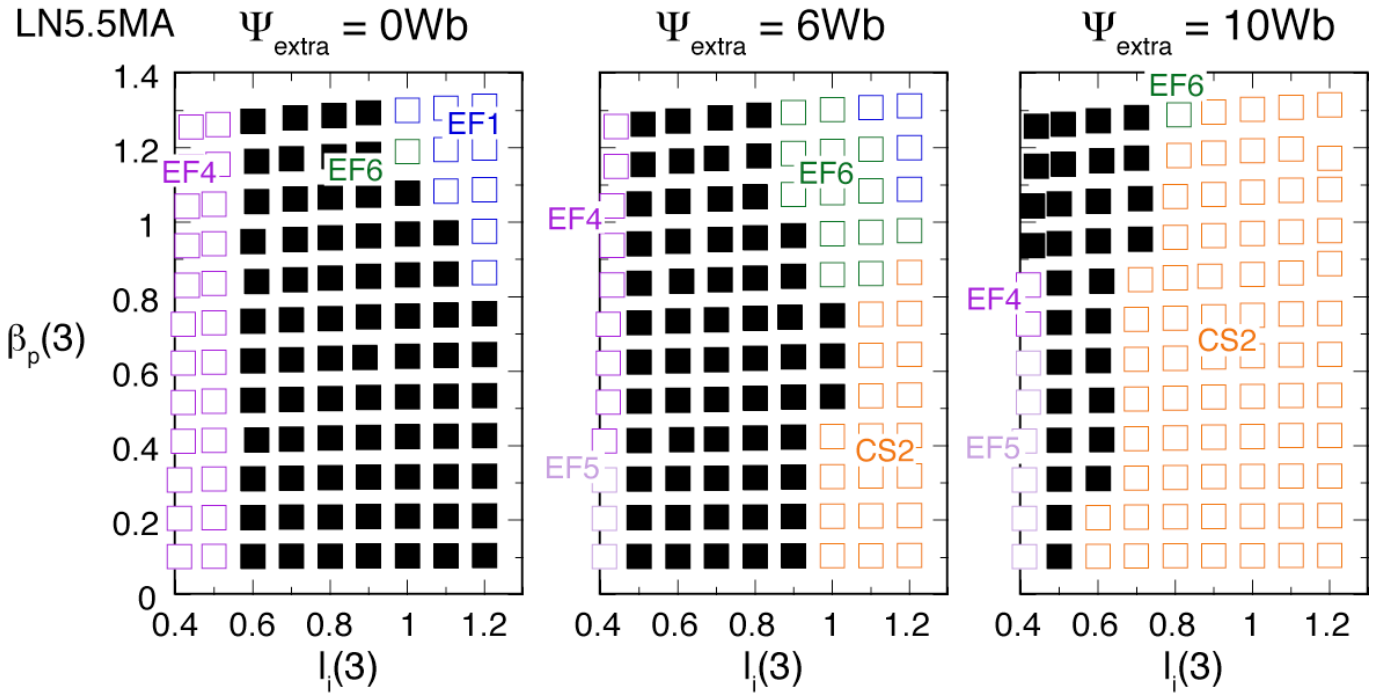
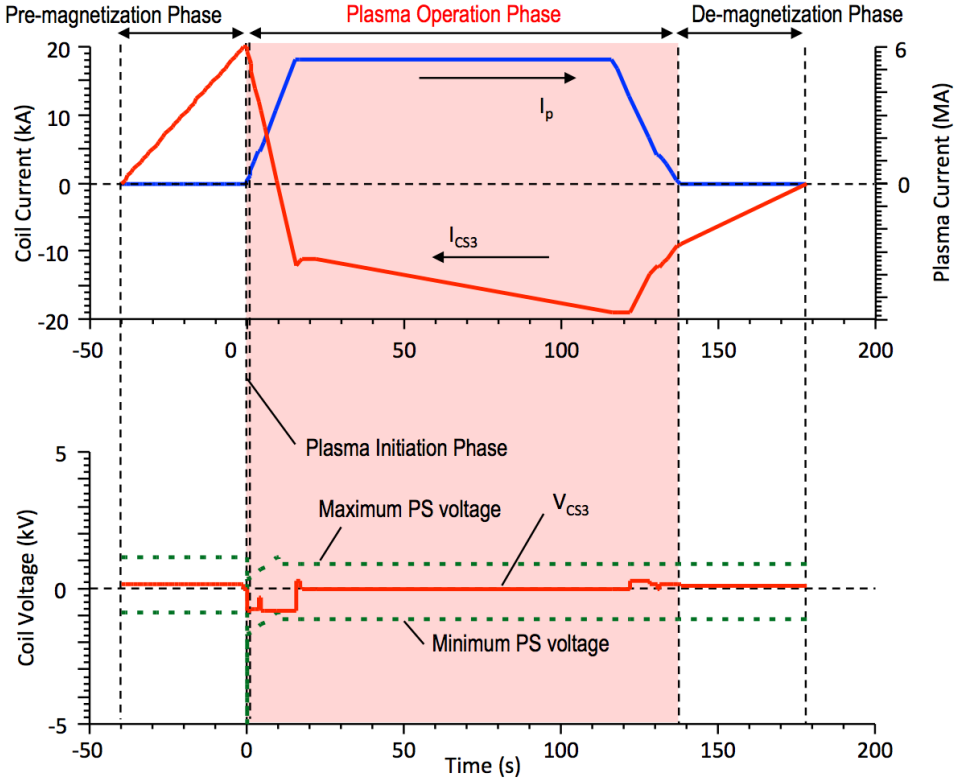
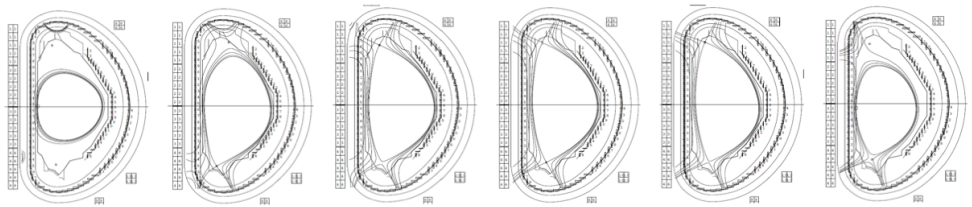
Coil flux usage for LPO

- In nominal 5.5 MA scenario, ~ 9Wb is remained for flux swing in current flattop
  - Assumption for resistive flux consumption : $0.45\mu_0 R I_p$
  - Loop voltage at I_p flattop is predicted as ~0.06 V
    - Flattop duration ~ 100s will be possible







(i) 0.9s (ii) 5.7s (iii) 9.8s (iv) 21.6s (v) 112.4s

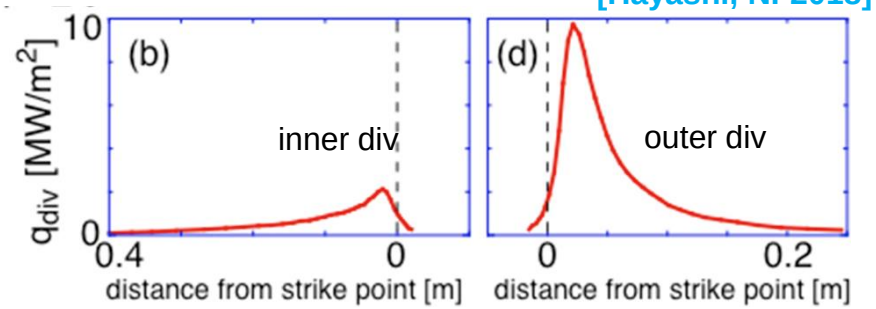
Heat handling capabilities of Divertor

- Actively cooled divertor for integrated research phase is under design
  - 10 MW/m^2 for steady-state
    - For high β_N steady-state
      - Need to develop radiative divertor scenario that is compatible with high core performance
  - 15 MW/m^2 for 5 s
    - To allow flexible experiments for ITER physics and risk mitigation experiments
      - e.g., enhance core performance without impurity seeding

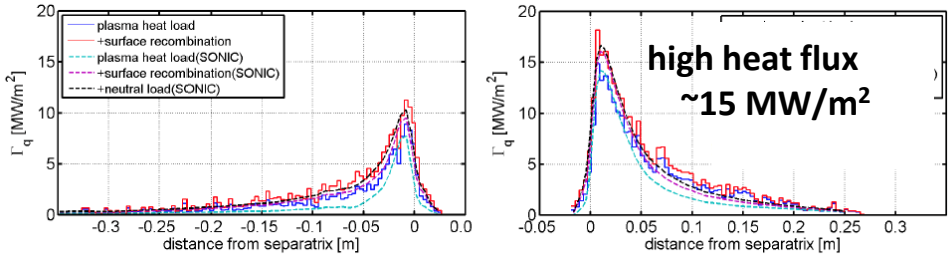
Graphite tile
+
TZM heat sink

High β_N steady-state (w/ Ar seeding)

[Hayashi, NF2018]



ITER Standard Op. (No imp. seeding)



H & CD in long pulse up to 100 s is possible

NB systems

Positive-ion-source NB

85 keV, 24 MW

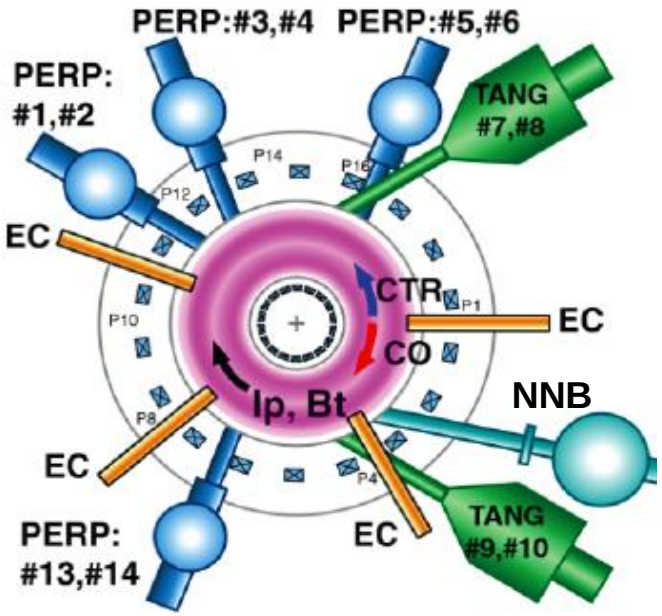
CO:2u, CTR:2u, PERP:8u

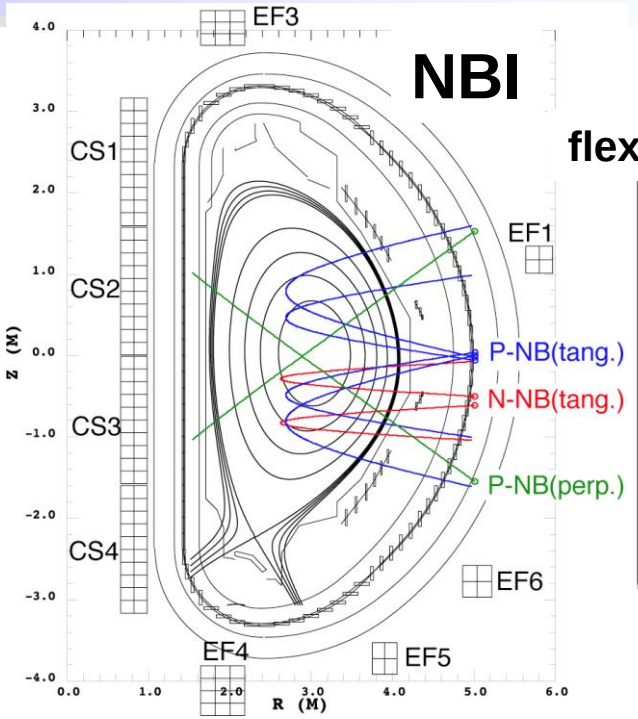
Negative-ion-source NB

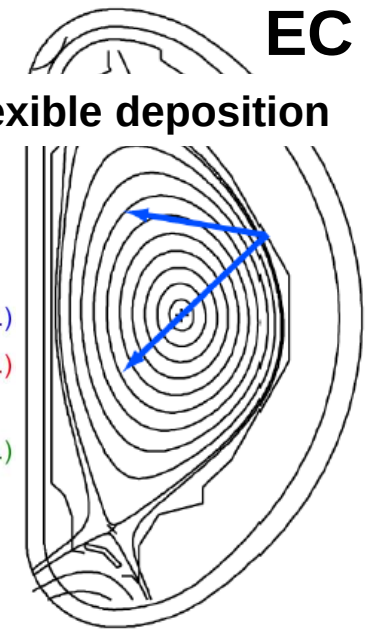
500 keV, 10 MW, Off-axis

EC systems

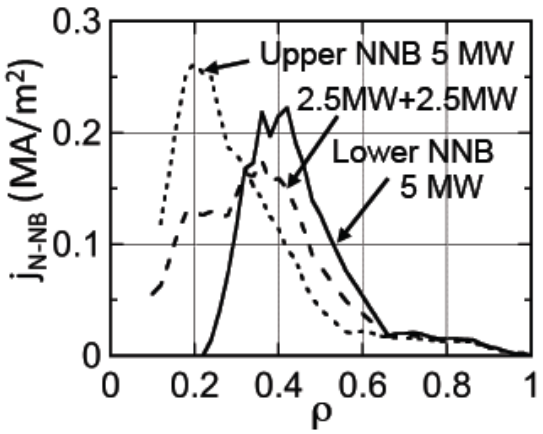
7 MW (9 Gyrotrons, 4 Launchers, movable mirror) (82), 110, 138 GHz, > 5 kHz modulation (NTM)



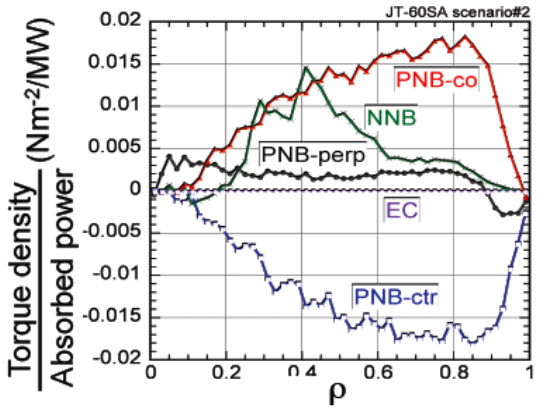




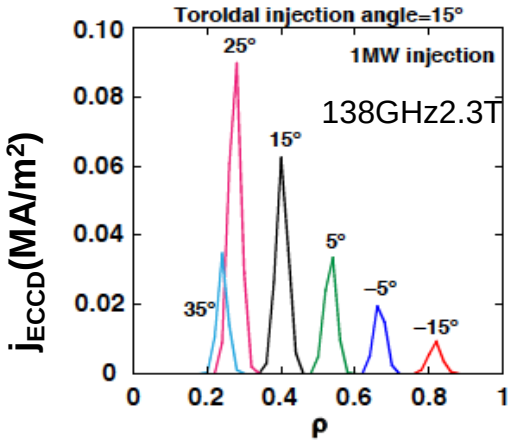
N-NB driven current



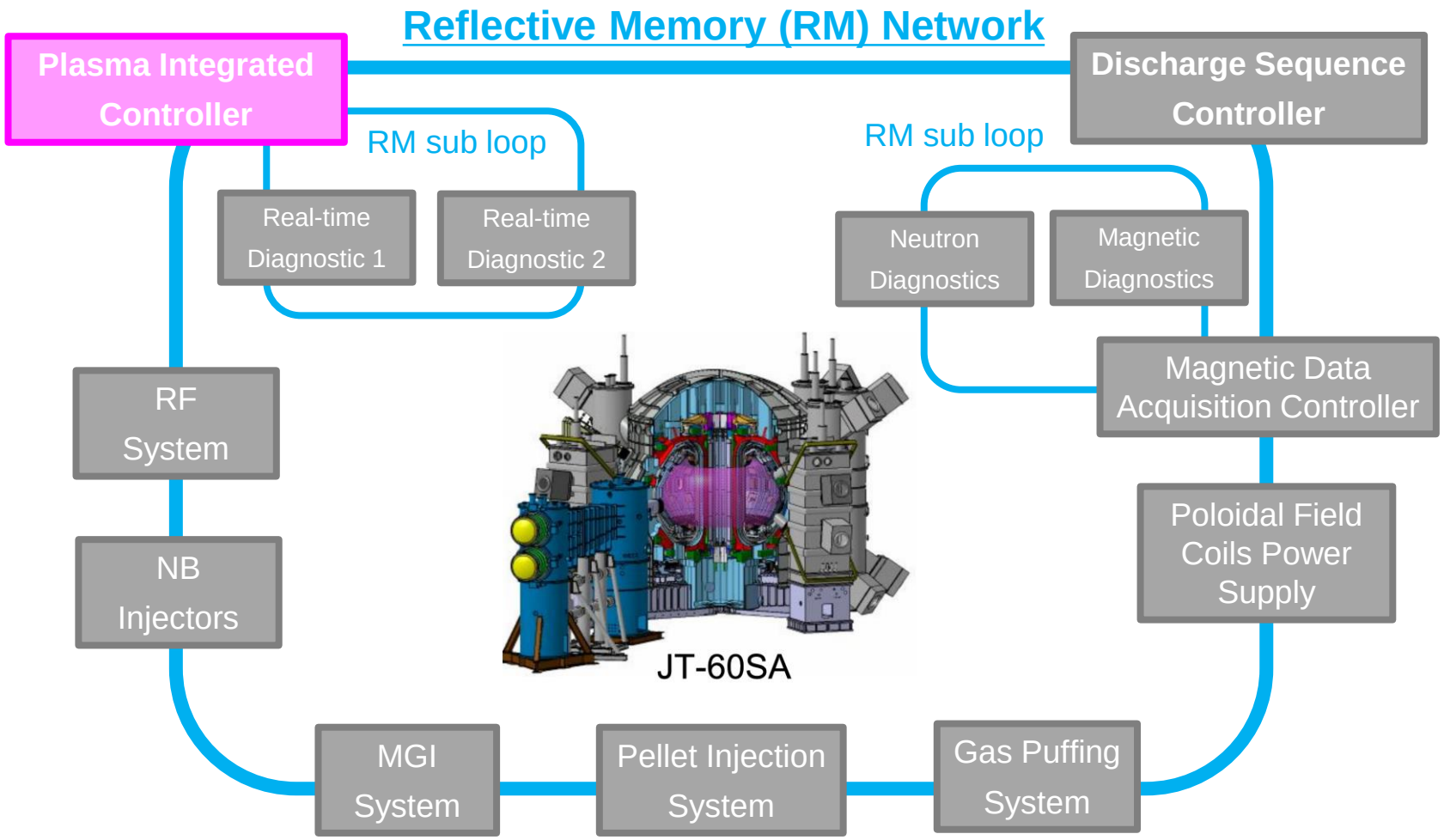
Torque input



EC current drive



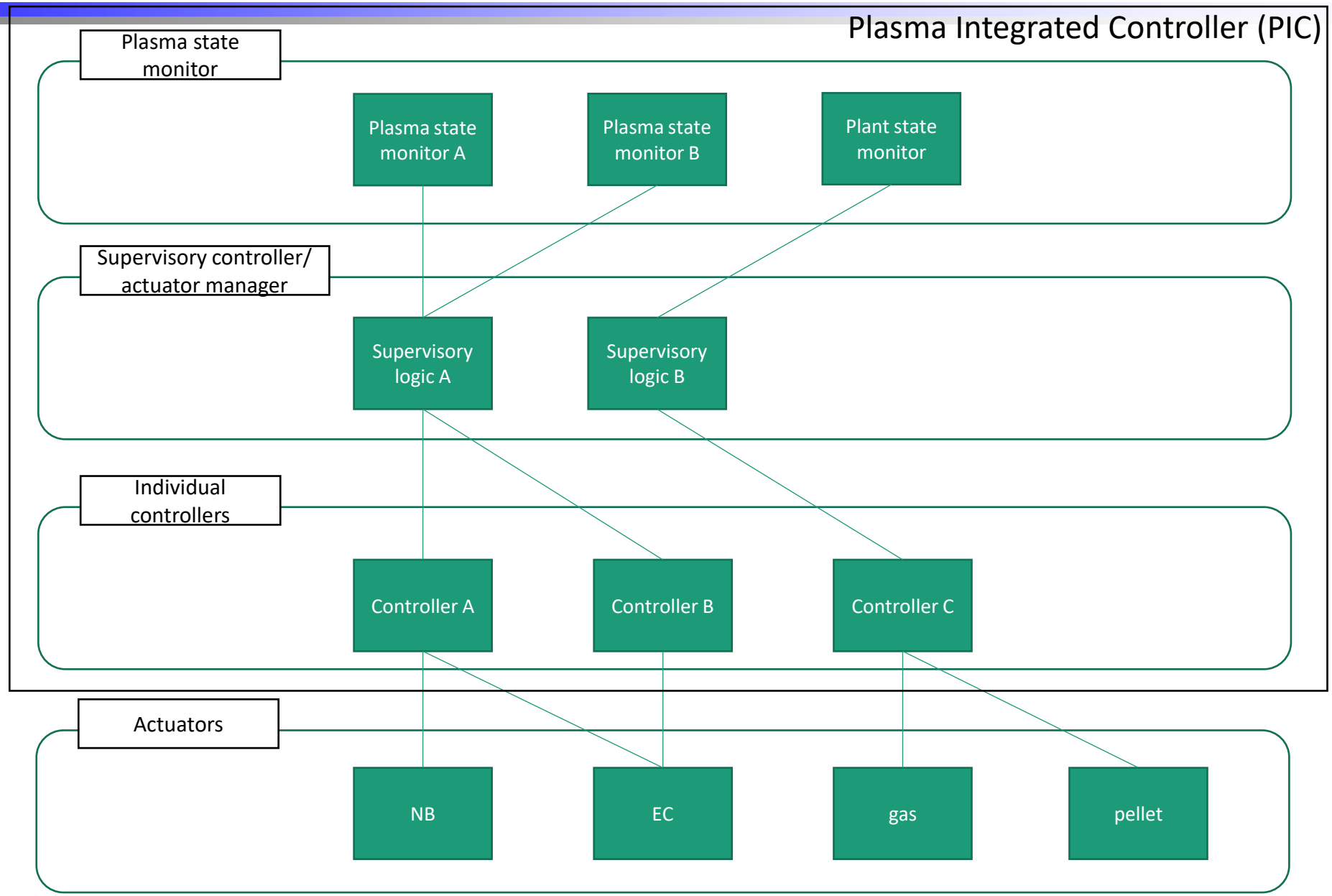
Real-time control system architecture



- Plasma Integrated Controller (PIC) sends commands to
  - PF coil power supply system for I_p/shape control
  - Gas puff, pellet and MGI systems for fueling
  - RF and NB systems for heating
- Real-time diagnostics are connected to inner RM sub loop
- High level functions (e.g., actuator manager, plasma state monitor) will be implemented in PIC

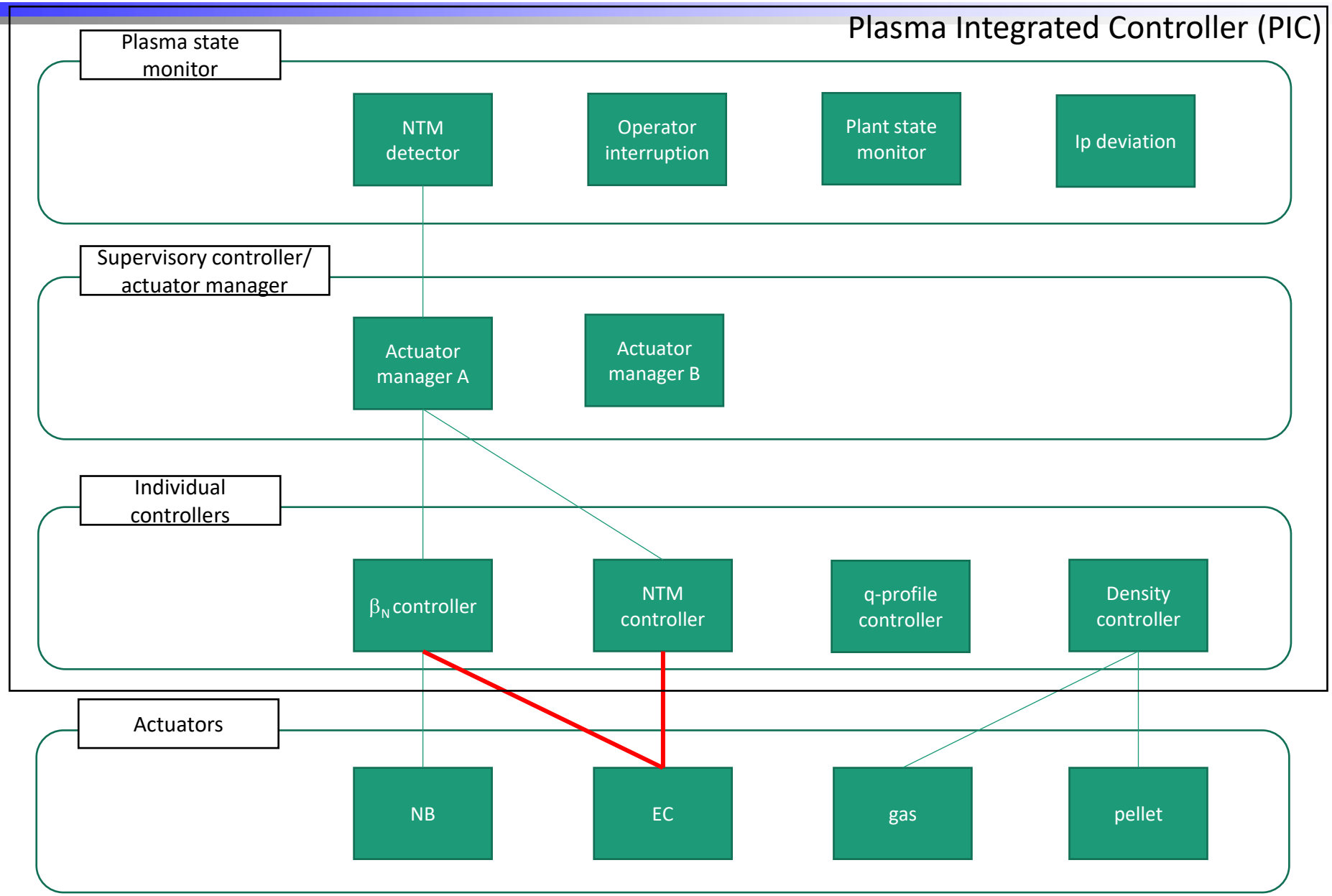
*Clock signals and interlock signals are distributed by other hard-wired networks

Structure of control integration



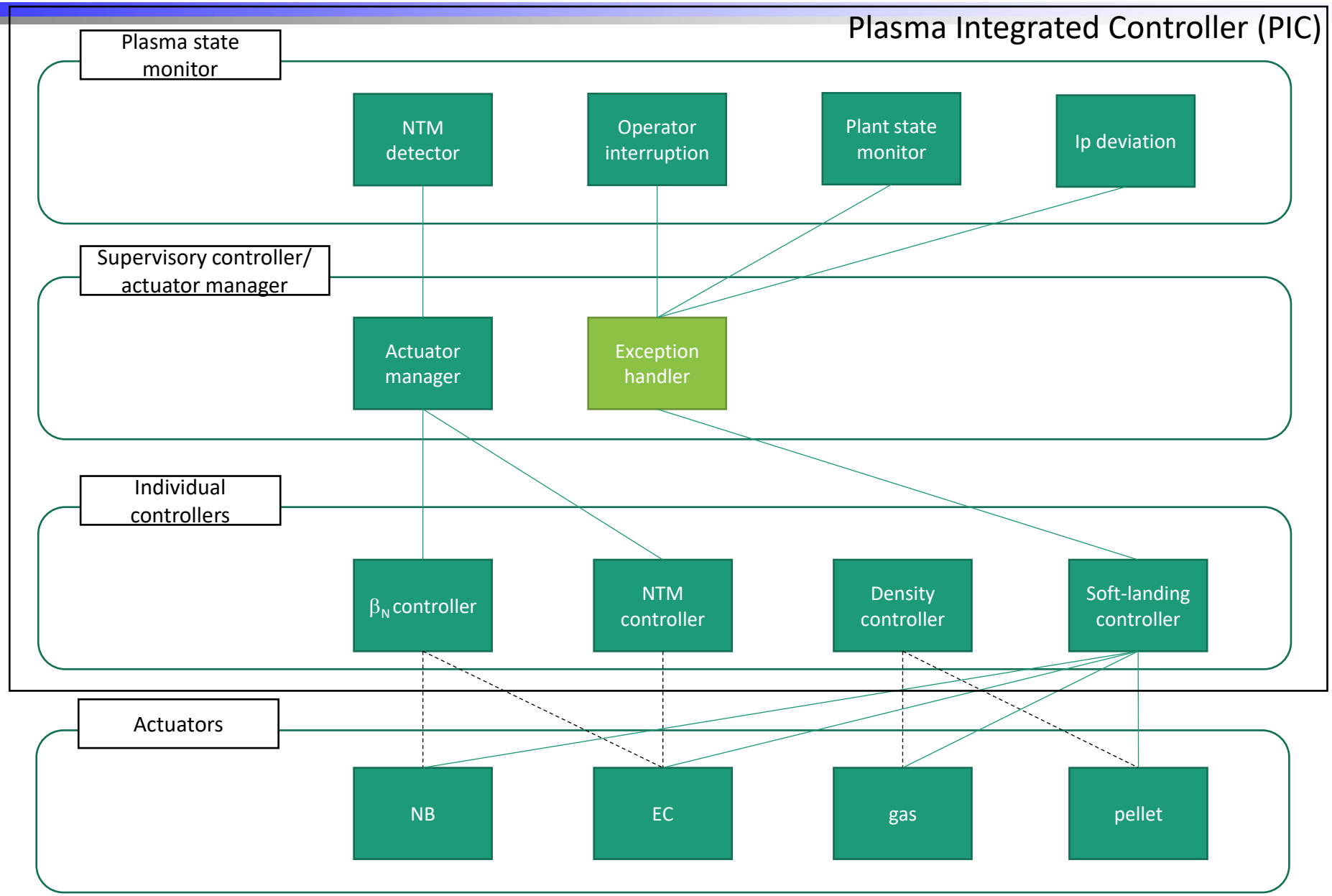
Example: actuator manager

If an actuator is shared with some controllers, actuator manager is required



Example: soft landing logic

If an exception like I_p deviation happens, soft-landing controller takes over



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Scenario development

Target plasmas

- ITER standard (q_{95}~3)
- ITER hybrid (q_{95}~4-5)
  - Reduced current, improved confinement operation
  - Candidate of longer pulse high performance operation in ITER
- DEMO steady-state (q_{95}~5-6)
  - Higher beta (β_N > 4), fully-noninductive operation

Target scenarios are investigated

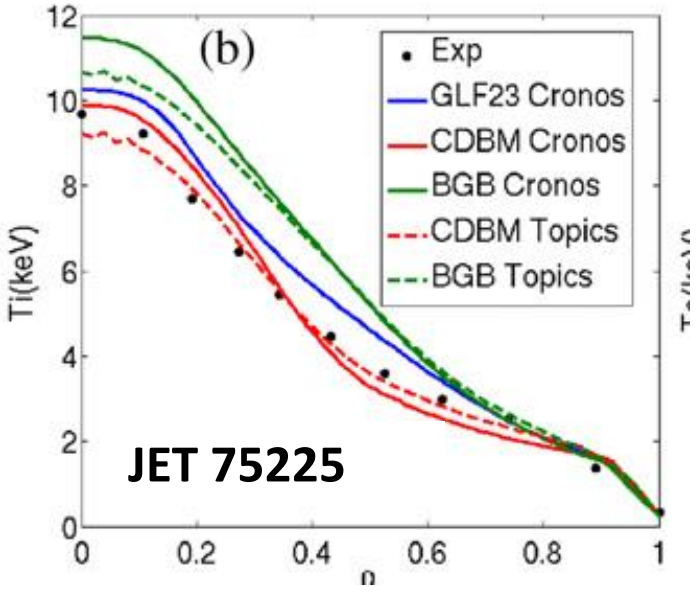
- Serve as workhorses for long pulse operation development

Scenario prediction basis for JT-60SA

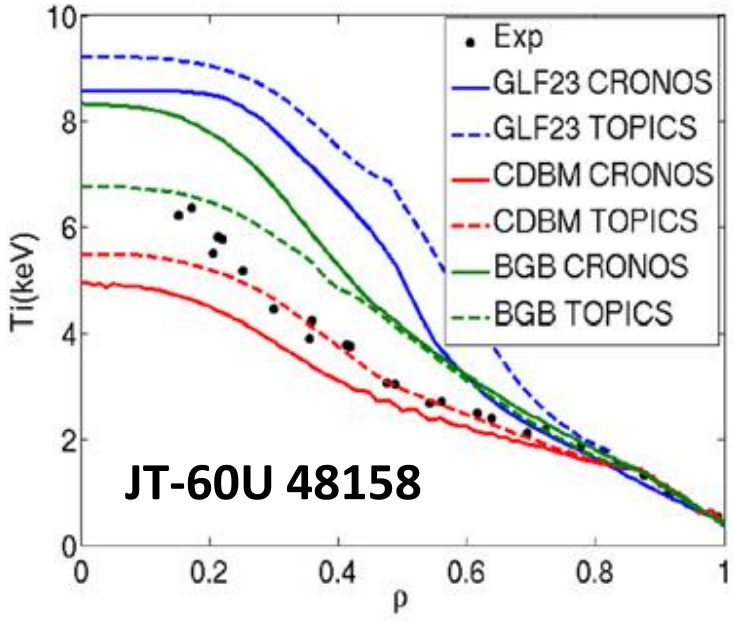
Model validation & verification (V&V) has been done with JET & JT-60U AT scenario exp.

- **Integrated codes used : TOPICS, CRONOS, JINTRAC, ASTRA, METIS**
- **Anomalous transport model : GLF23, CDBM, Bohm/gyro-Bohm**

Hybrid Scenario



q_{95} = 4.0, β_N = 3.0, f_{GW}= 0.45



q_{95} = 3.2, β_N = 2.6, f_{GW}= 0.50

CDBM predicts or underpredicts exp.

->

can be used for conservative prediction

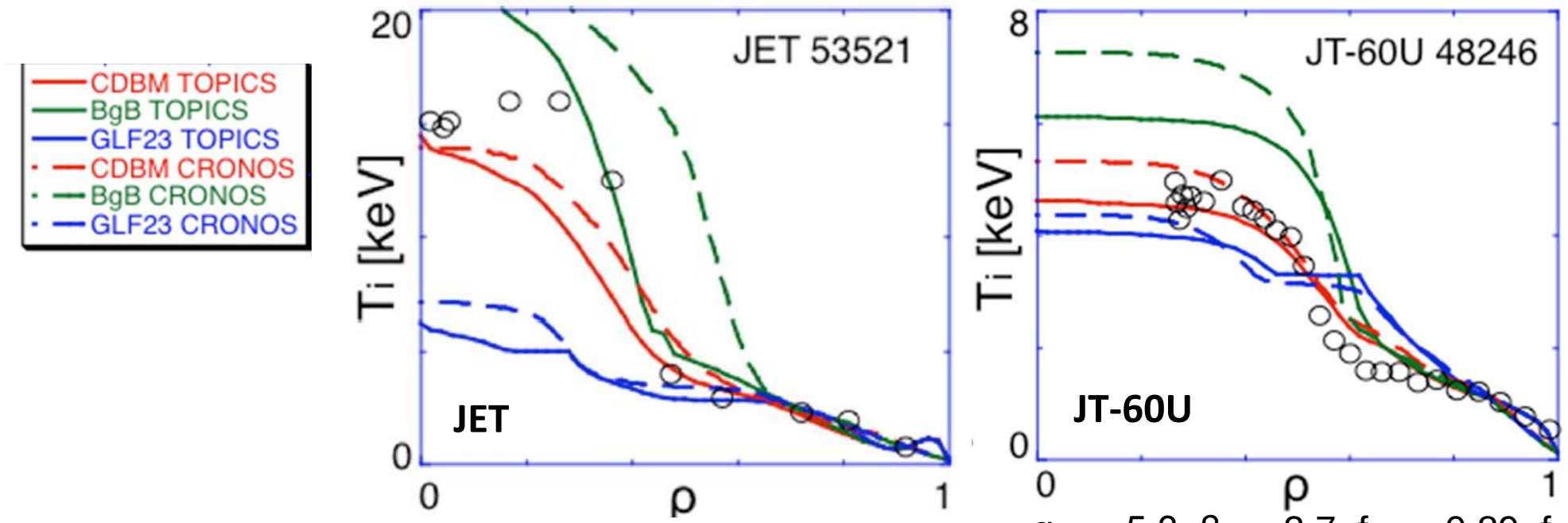
Garcia NF2014, Hayashi NF2017

Scenario prediction basis for JT-60SA

Model validation & verification (V&V) has been done with JET & JT-60U AT scenario exp.

- **Integrated codes used : TOPICS, CRONOS, JINTRAC, ASTRA, METIS**
- **Anomalous transport model : GLF23, CDBM, Bohm/gyro-Bohm**

ITB plasmas



q_{95} = 5.8, β_N = 1.5, f_{GW}= 0.40, f_{BS} = 0.38

q_{95} = 5.3, β_N = 2.7, f_{GW}= 0.89, f_{BS} = 0.84

CDBM predicts or underpredicts exp.

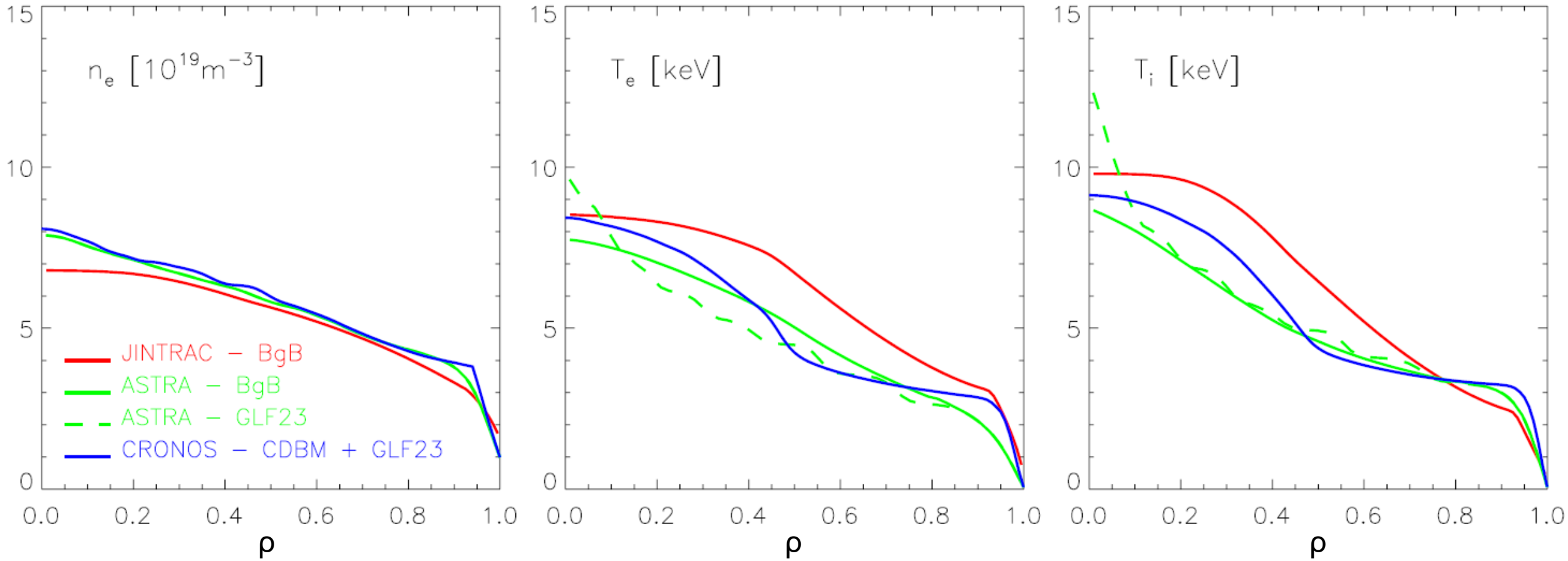
->

can be used for conservative prediction

Garcia NF2014, Hayashi NF2017

Hybrid scenario with high β_N~3 is envisioned

- I_p/B_T=3.5 MA/2.3 T



- Prediction (CDBM+GLF23) : β_N = 3.2, H_{98}= 1.3, f_{BS}= 0.40
- 29 MW NB with 7 MW EC (138GHz)

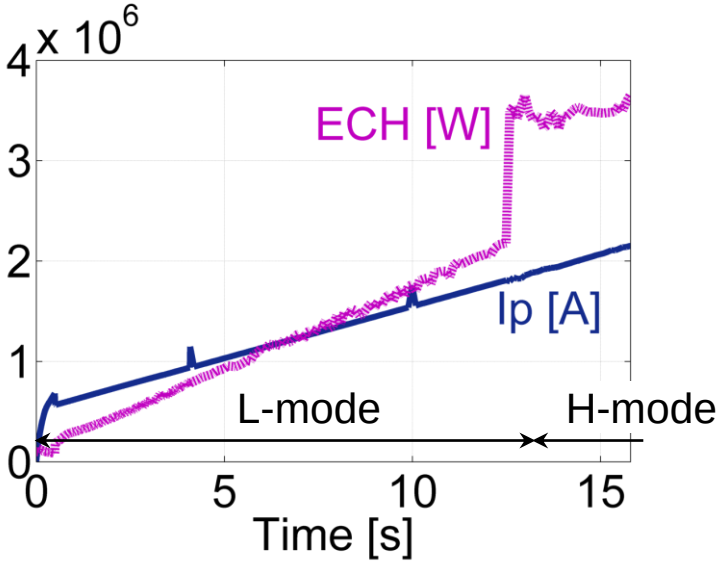
[L. Garzotti, NF2018]

Off-axis ECH Assists I_P ramp-up for Hybrid Scenario

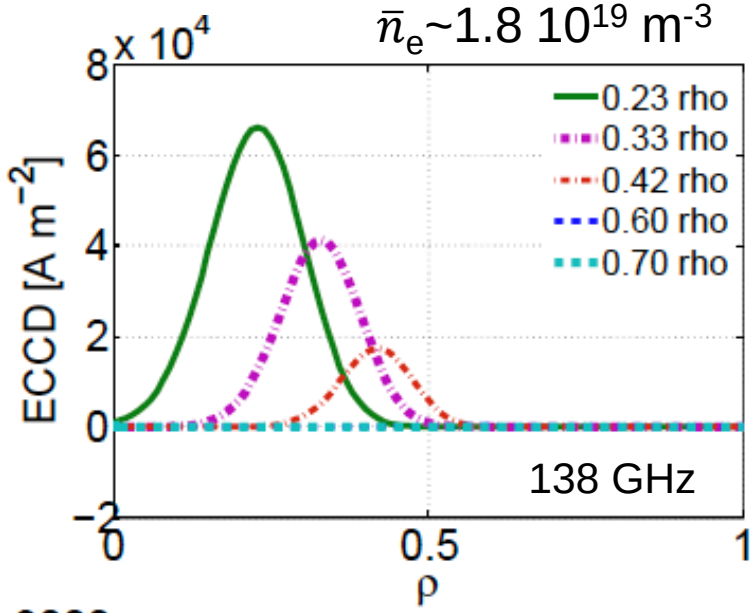
- **Current profile control during I_P ramp-up for hybrid scenario without sawtooth**
- **Favorable ECH power deposition to obtain q>1 is estimated**
  - ECH applied ρ~0.33 allows a compromise between a q>1 and high central T_e
  - $P_{ECH} \geq$ 2.2 MW to maintain q>1
- **Anomalous current diffusion (flux pumping, dynamo effect, etc) is not considered**
  - **Its effect will be studied in JT-60SA**

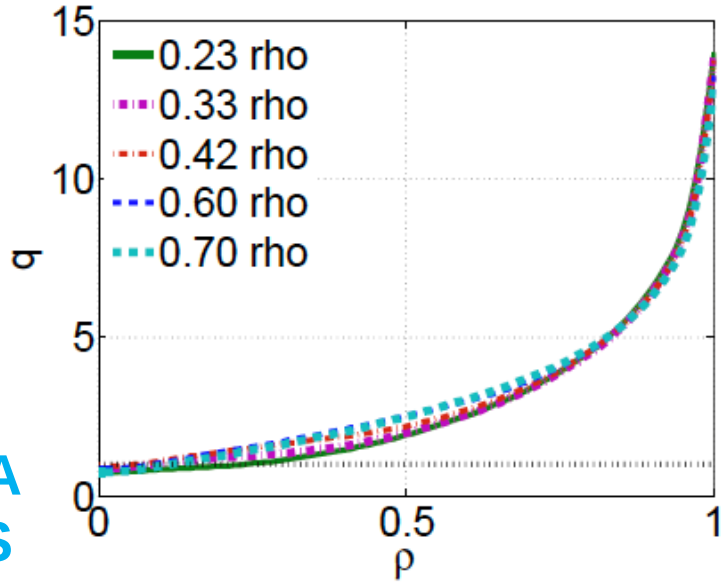
CDBM+REMA in CRONOS

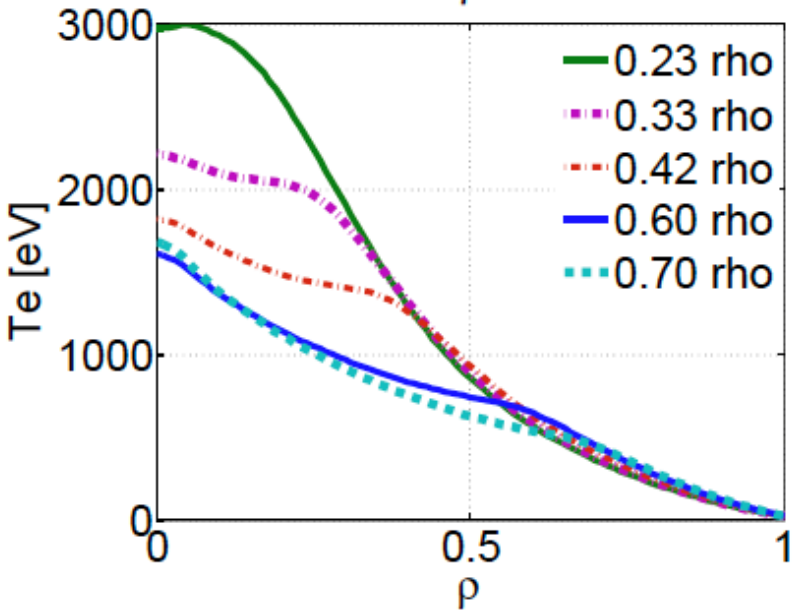
[J. Morales, PPCF2021]



$\bar{n}_e$~1.8 10^{19} m^{-3}





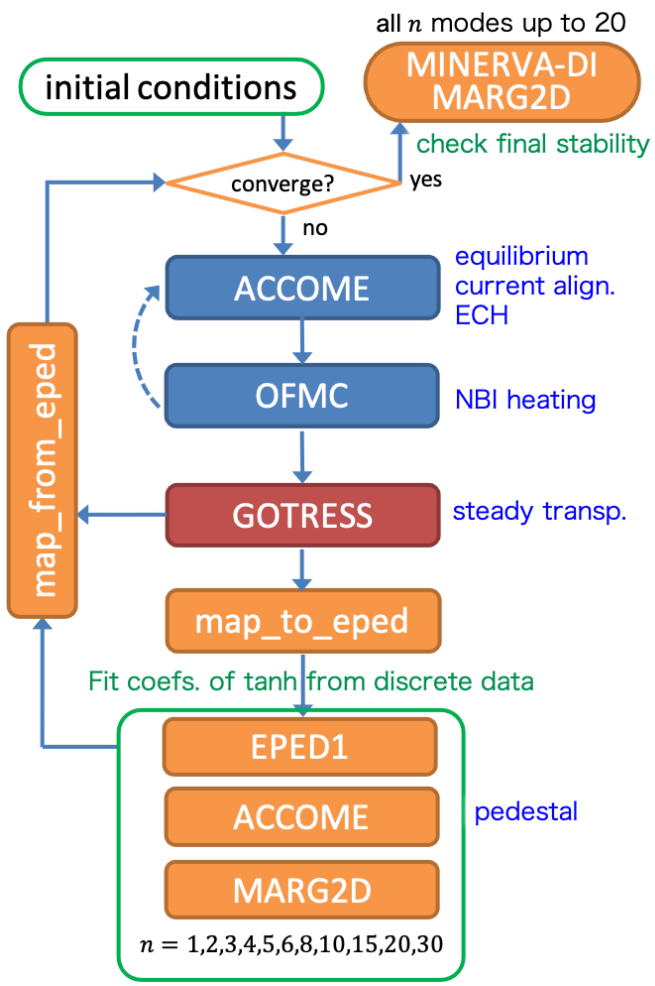


DEMO-relevant plasma can be aimed at integrated research phase I

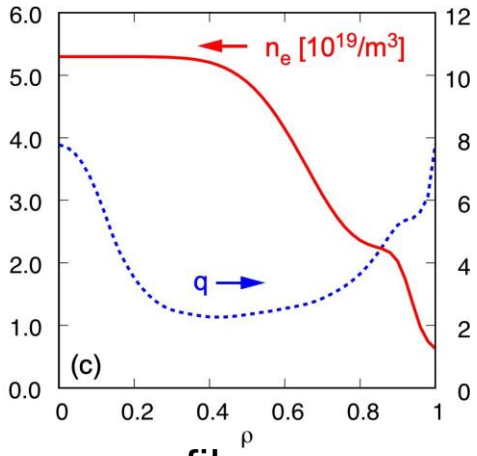
- **Integrated core-pedestal model developed incorporating with MHD**
  - Consist of transport, equilibrium, heating/CD, pedestal & MHD codes
  - Provide exact steady-stage solution

- **prediction of high β_N steady-state plasma**
  - κ=1.9, δ=0.5, f_{GW}=0.85, I_p/B_T=2.3 MA/1.72 T
  - 16 MW NB with 7 MW EC (110GHz) : $H_{98,y2}$=1.6, β_N=4.3, f_{BS}=0.68 (see profiles in figure)

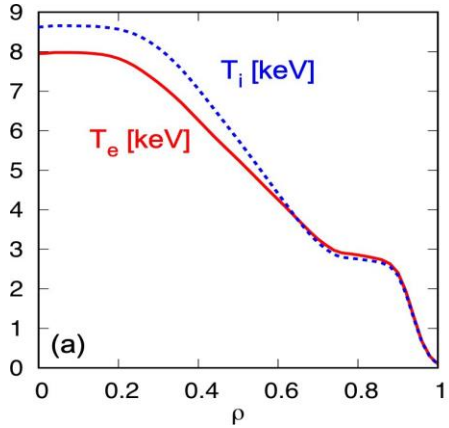
GOTRESS+ framework



[M. Honda NF2021]



n profile prescribed



CDBM transport model used

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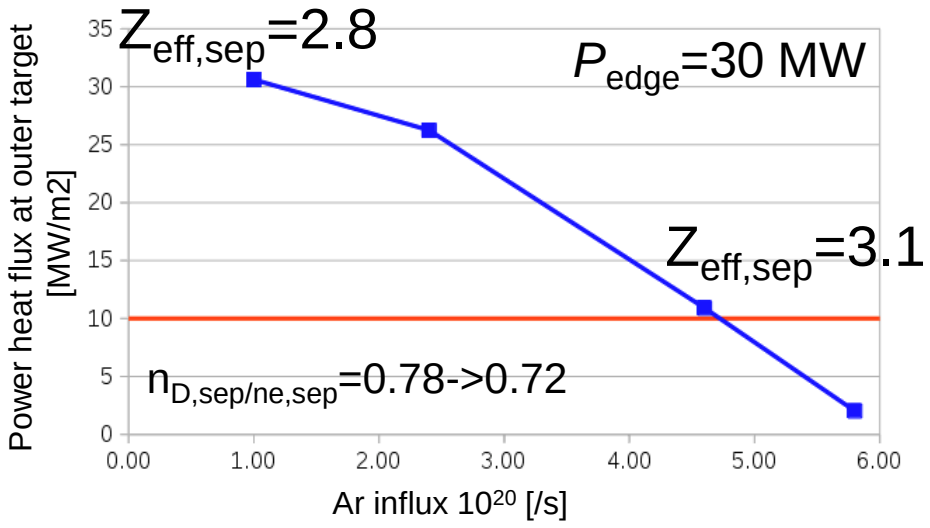
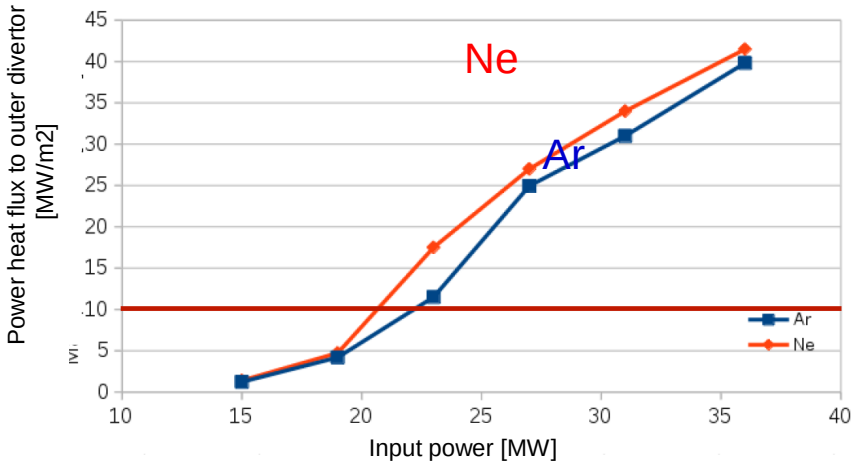
Heat handling Scheme by Impurity Seeding Investigated

- **Impurity control for heat handling to divertor plate for a long pulse discharge**
- **Divertor heat load reduction <u>in C-wall</u> by Ar seeding in I_P=5.5 MA, P_{inj}=15-35 MW, β_N~3.**
- **10 MW/m^2 is reached keeping small impurity increment at separatrix**

SOLEDGE2D-EIRENE



- **Ar is more effectively radiated at higher T_e than Ne to reduce heat load**
- **Maximum power allowable to divertor heat load is larger for Ar**



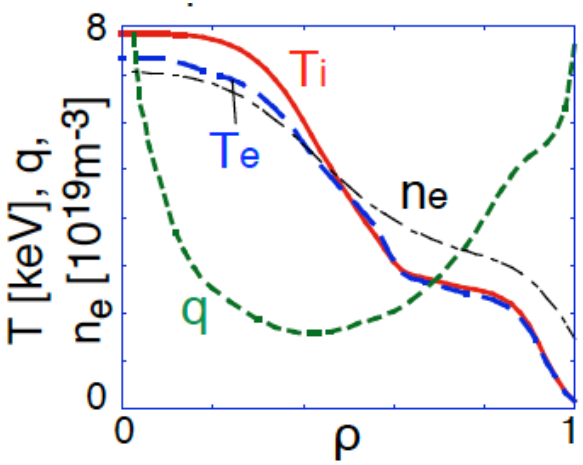
[L. Balbinot, IAEA-TMDC2019]

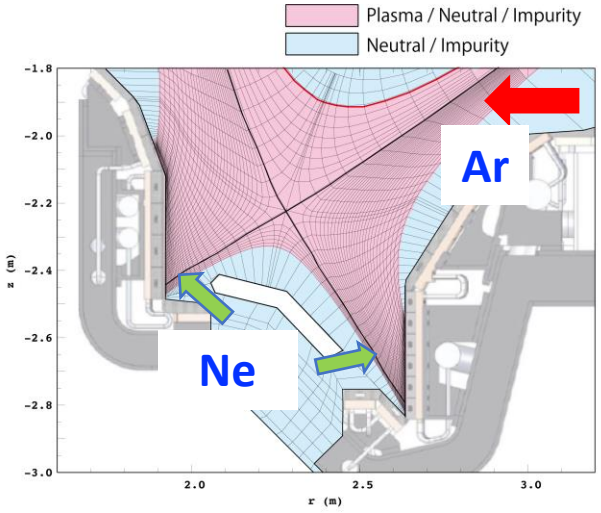
Ar+Ne Mixed-Impurity Seeding Compatibility between High β_N and High Radiation

- **Integrated divertor code extended to multi-impurity seeding simulation**
  - Kinetic treatment of impurities
- **By increasing Ne, high radiation in divertor and lower radiation in core-edge can be realized.**
  - Lower Ar puff rate in Ar+Ne seeding
  - Ar-only seeding: Ar impurities are stagnated in top of SOL
  - Ar + Ne seeding: Ar impurities are transported to inner divertor plasma

Target: $n_{e,sep}$ ~1.7x10^{19} m^{-3}, q_{div} < 10 MW/m^2
in steady-state high β_N~4 operation,
I_p=2.3 MA, P_{out} = 23 MW, $P_{rad,tot}$=13 MW

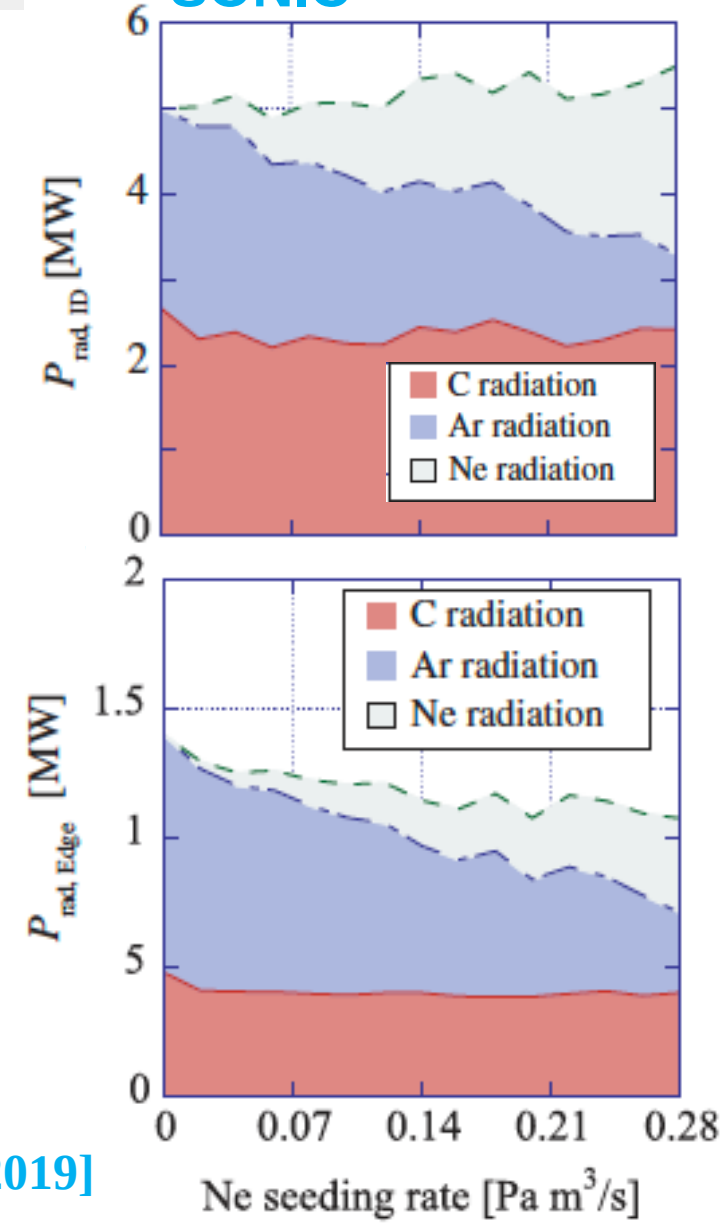
TOPICS





[S. Yamoto, PPCF2020, CPP2019]

SONIC



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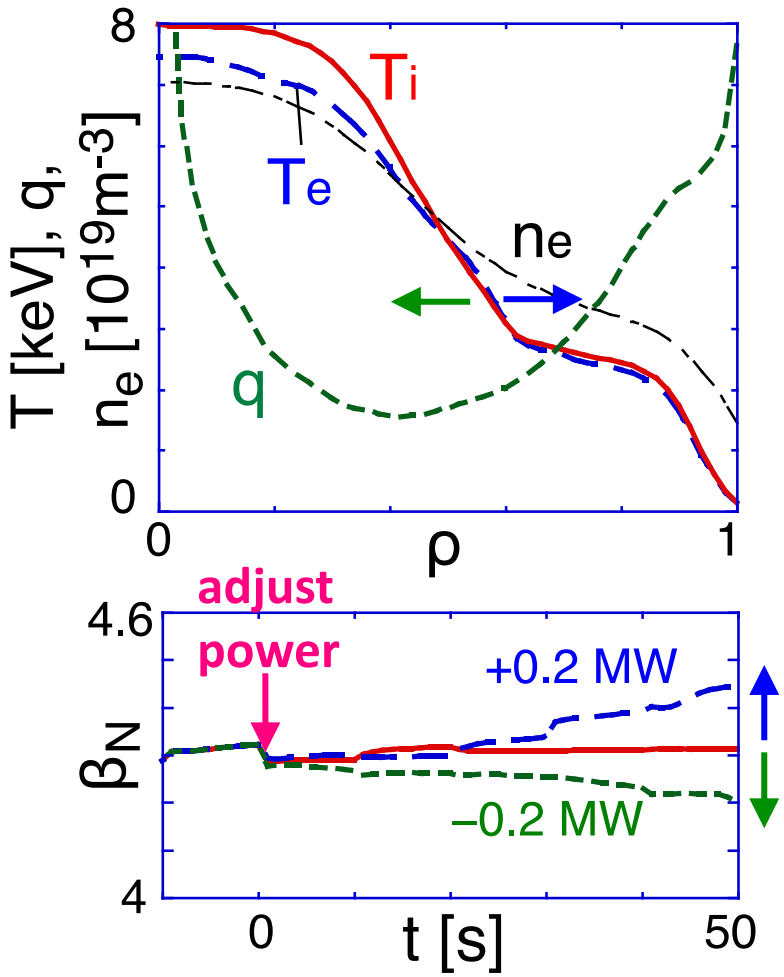
Sustainment of high-beta steady-state plasma by temporal power control of ECH or ECCD is investigated

P_{in}~26 MW ($P_{NNB/PNB/ECH}$=5/14/7MW)
β_N~4.3 (I_p/B_t=2.3MA/1.7T, f_{GW}~0.85, Z_{eff}=2 with C)



1.5D plasma profiles : TOPICS with CDBM transport model

NB fast ion : Monte-Carlo particle code OFMC

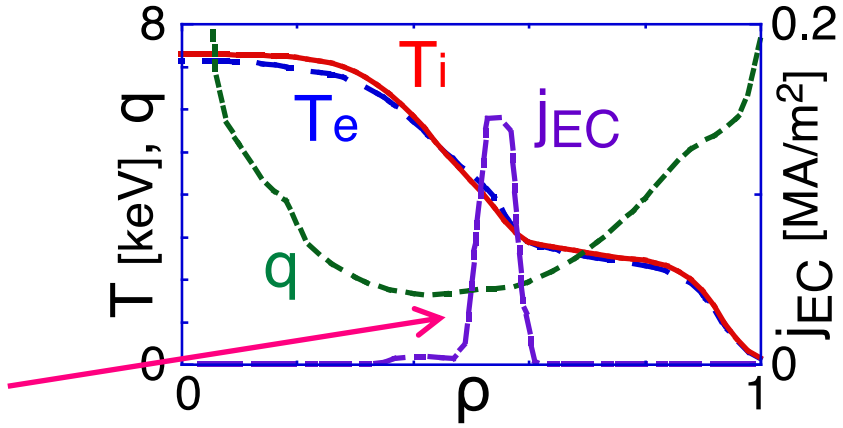
EC : Ray tracing & Fokker-Planck code EC-hamamatsu

Small power perturbations -> ITB moves out/in-ward, β_N in/de-creases with current diffusion time in ITB region (order of 10 s)

ITB sustained by enhancing/reducing power every several to ten seconds

P & j profile misalignment due to bootstrap current by ITB
-> ITB movement

ECH -> ECCD can lock ITB by making weak-magnetic-shear region close to ITB foot
(similar way to Hayashi NF2005, Garcia PRL2010)

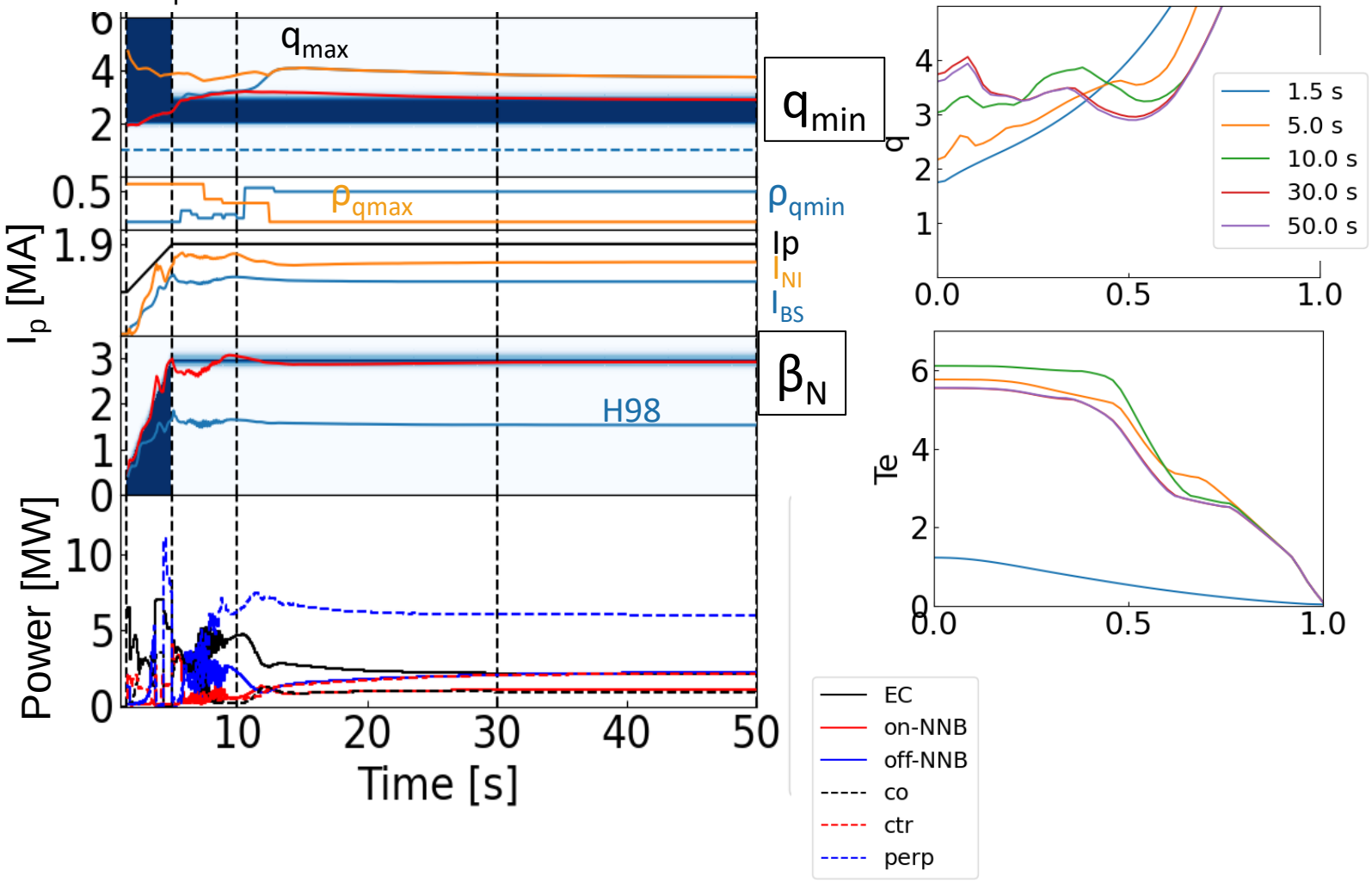


[N. Hayashi IAEA2018]

q_{min} + β_N control using reinforcement learning

- q_{min} + β_N control in ITB plasma will be challenging due to high f_{BS} fraction
- Neural-network-based control system is trained through +2000 times simulations using RAPTOR[1]
  - Target : $2 < q_{min} < 3$, $\beta_N = 3$
- Trained system is tested in simulations using TOPICS
  - Achieved stable control even for a plasma simulated with another code/model
  - Encouraging for the application of the trained system to real experiments

- I_p/B_T=1.9 MA/1.9 T



[1]F. Felici et. al. Plasma Physics and Controlled Fusion 54(2), 2012, 025002

Summary

- JT-60SA will explore long pulse operation exceeding the time scales governing the plasma system
  - Flattop duration will be 100 s
  - Divertor will handle 10 MW/m^2 for steady-state
  - 24 MW Pos-NB, 10 MW Neg-NB, 7 MW EC will be injected 100 s
  - High level functions of Plasma Integrated Controller is under development

- Strong work have been done for preparation of long pulse operation
- Target scenarios are investigated as basis of LPO development
- Heat handling using impurities (Ar, Ne) are investigated
- Performance control of highly self-regulated high-beta ITB plasma are investigated
  - Sustainment of high-beta steady-state plasma by temporal power control of ECH or ECCD
  - q_{min} + β_N control using reinforcement learning