Physics Design Issues on DEMO

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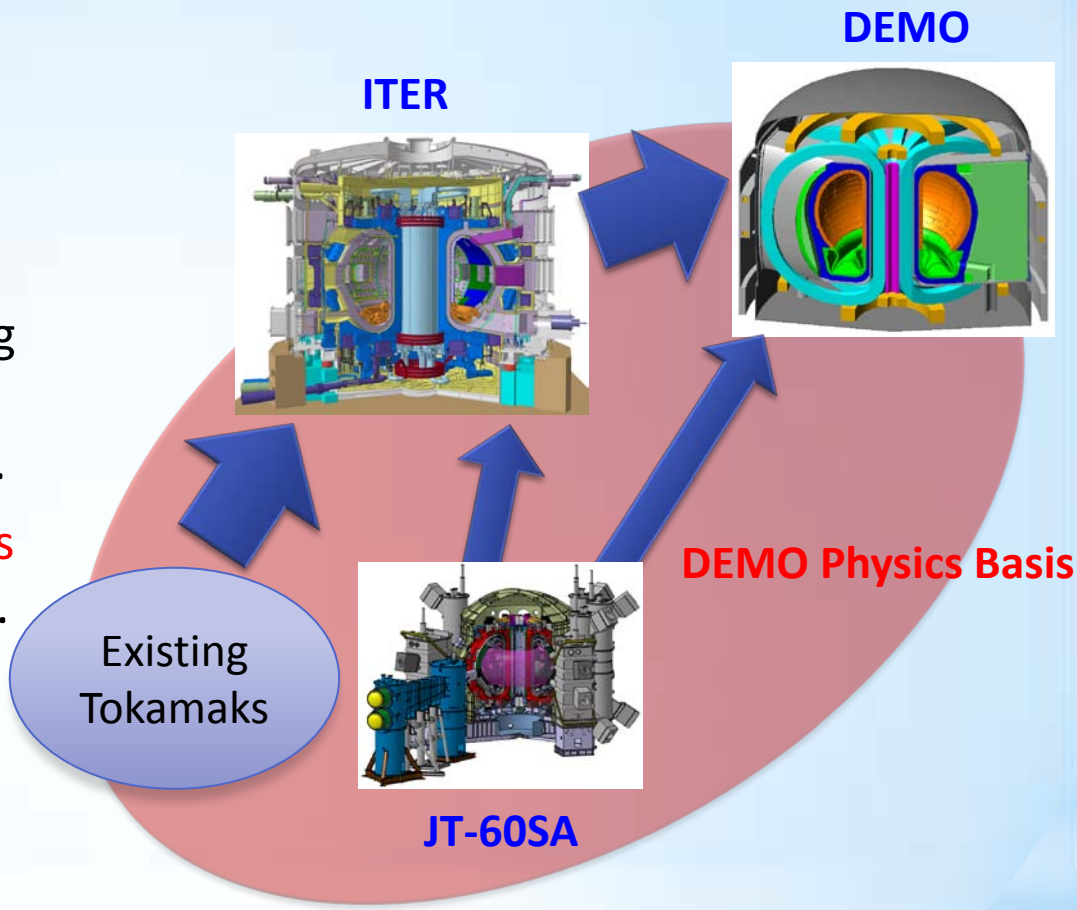
Introduction

- DEMO should be fully-optimized device by integrating plasma physics and reactor engineering.
- DEMO Physics Basis have to be demonstrated in ITER and existing & newly-constructed tokamaks under the engineering constraint.
- A lot of attractive DEMO concepts have been proposed in the world.

➢ It is important to clarify what are the future physics R&D issues towards the DEMO.



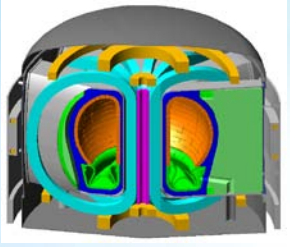
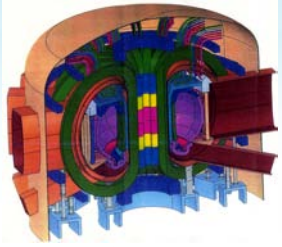
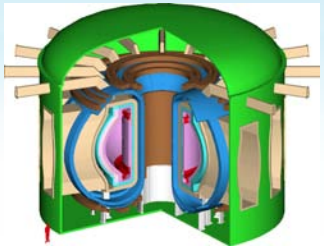
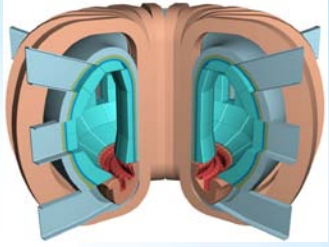
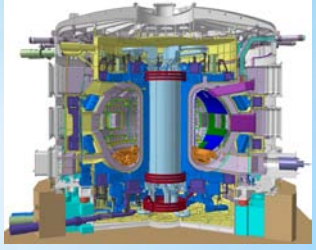
Physics design issues will be discussed from the viewpoints of

✓ difference of fusion performance between ITER & DEMO,

✓ gap between achieved integrated plasma performance and DEMO design parameters.

Proposed DEMO concepts: challenging

	Slim CS	Demo-CREST	ARIES-AT (-RS)	PPSC-D (-A)	ITER std (SS)
P_{fus} (GW)	2.95	1.3 – 3.2	1.755 (2.17)	2.53 (5.0)	0.4 (0.35)
Fusion Gain	30 – 49	1 – 30	47 (26)	35 (20)	10 (6)
R_p (m)	5.5	7.25	5.2 (5.52)	6.1 (9.55)	6.2 (6.35)
B_T / B_{max} (T)	6.0 / 16.4	8.0 / 16.0	5.8 / 11.5 (7.98 / 16)	5.6 / 13.4 (7.0 / 13.1)	5.3 / 11.8 (5.18 / 11.8)
I_p (MA)	16.7	15.9 – 13.2	13 (11.32)	14.1 (30.5)	15 (9.0)
HH	1.3	1.0 – 1.4	1.4 ( )	1.2 (1.2)	1.0 (1.57)
β_N	4.3	1.9 – 4.0	5.4 (5.0)	4.5 (3.5)	1.8 (2.95)
f_{BS}	0.75	0.24 – 0.73	0.91 (0.88)	0.76 (0.45)	0.15 (0.48)
f_{GW}	1.0	0.5 – 1.3	0.96 (1.1)	1.5 (1.2)	0.85 (0.82)

Main difference btw ITER and DEMO

Main difference in physics design parameters between ITER and DEMO, that shows physics design issues:

Fusion output (ITER: 0.5GW, DEMO: 2-3GW)

- ✓ Continuous large heat/neutron load to plasma facing components
- ✓ Significant impact of disruption to in-vessel components
- ✓ Significant impact of pulsed heat load induced by ELM on the divertor

Fusion gain (ITER: 10-5, DEMO: >30)

- ✓ Less controllability with limited power of external heating and sensors
- ✓ Plasma with self-organized system (linkage among profiles of current, heating and rotation)

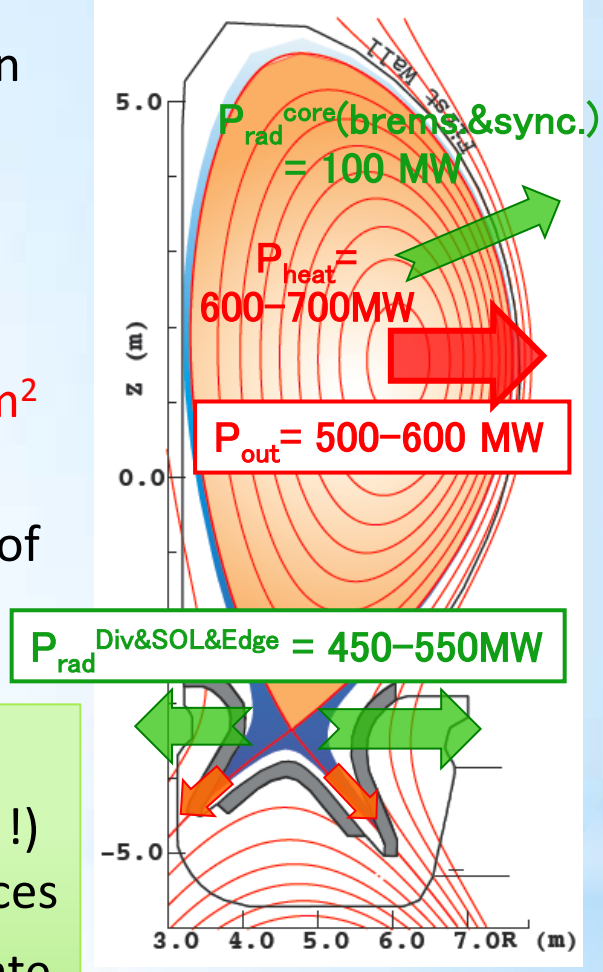
Integration of normalized plasma performance (ITER < DEMO)

- ✓ Confinement enhancement factor (HH)
- ✓ Normalized beta (β_N)
- ✓ Bootstrap current fraction (f_{BS})
- ✓ Density normalized by Greenwald limit (f_{GW})
- ✓ Radiation power normalized by heating power including α heating (f_{rad})

Physics design issues: Heat removal

- Heating power of 650MW (P_α+P_{ax}=590MW+60MW) in DEMO (SlimCS with R_p=5.5m) is larger than that of 120MW (P_α+P_{ax}=80MW+40MW) in ITER (R_p=6.2m), which is heat source to the components.
- Nevertheless, acceptable divertor heat load of ~6MW/m^2 in DEMO is smaller than that of ~10MW/m^2 in ITER.

➢ Power of ~500MW should be radiated in the regions of plasma edge, SOL and divertor (~100MW in core plasma through brems. & sync.)



- Physics design issues of heat removal are
  - ✓ to establish high radiative plasma operation (f_{rad}~0.9 !) by impurity seeding with keeping plasma performances
  - ✓ to develop the divertor simulation code and to validate it by experiments
  - ✓ to develop improved/advanced divertor configurations

Physics design issues: Disruption

- Disruption could be caused by VDE, several MHD modes, high density/ radiation operation, machine trouble…
- ❖ Total exclusiveness of the disruption might be impossible.
- A huge amount of the plasma stored energy of 1.24GJ in DEMO, while that of 0.35GJ in ITER, ~0.01GJ in the existing tokamaks.
- Disruption (thermal & current quench) potentially cause enormous damage to the tokamak device through thermal shock, halo current, runaway electrons.
  - ✓ Melting/ ablation of armor materials and divertor
  - ✓ Deformation/ fracture of in-vessel components and structures

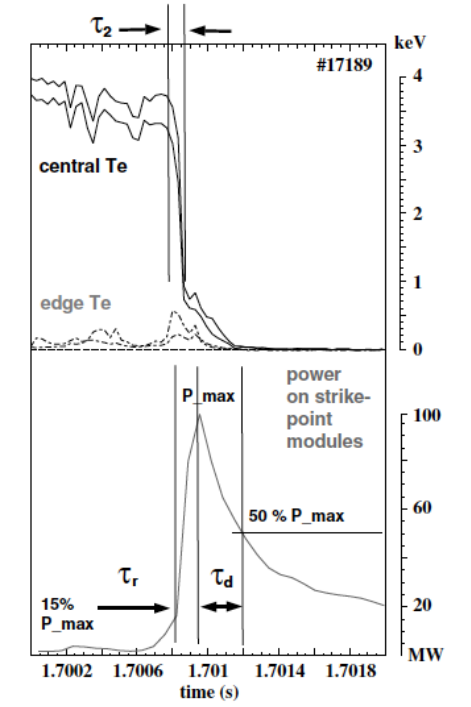


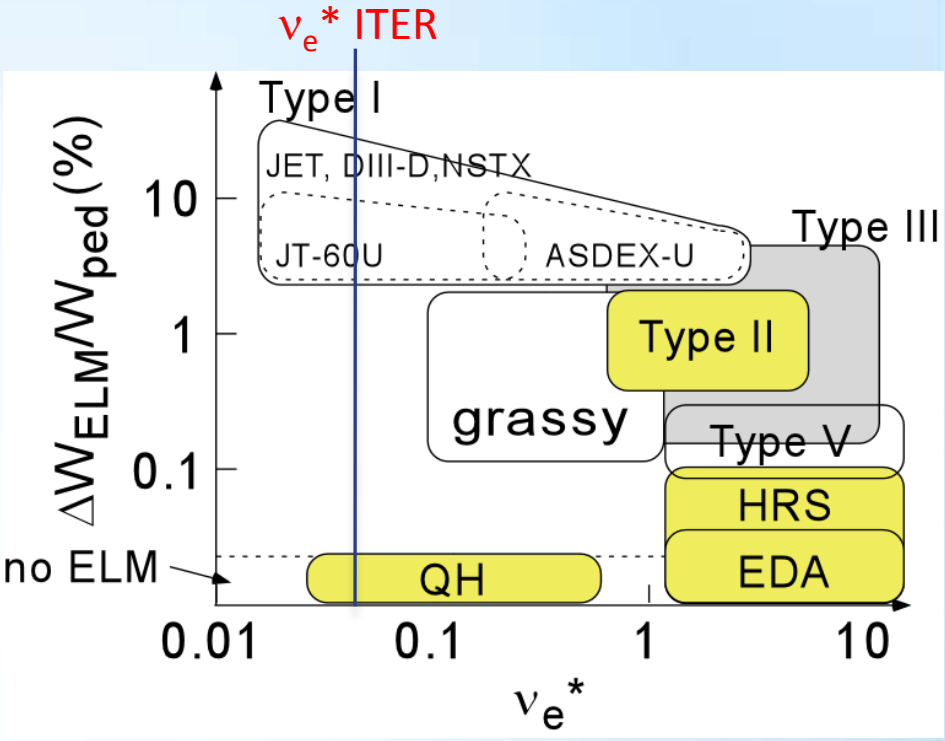
Figure 38. Plasma temperature and divertor target power data from ASDEX Upgrade.

- Physics design issues of disruption is to establish fully-operational control system.
  - ✓ Prediction technique, e.g. neural network, tokamak simulator
  - ✓ Avoidance technique, e.g. operation margin, active MHD control
  - ✓ Mitigation technique, e.g. massive gas injection, killer pellet

Physics design issues: ELM

- ELMs are the basic nature of plasmas with H-mode edge.
- Typically, about >10% of pedestal stored energy by type-I ELM is periodically released to SOL and Divertor.
- ΔW_{ELM}~50MJ in DEMO, ~22MJ in ITER and ~1MJ in the large tokamaks, while ~1MJ would be acceptable in ITER (or DEMO).

➢ $\Delta W_{ELM}/W_{ped}$ < ~1% is required.

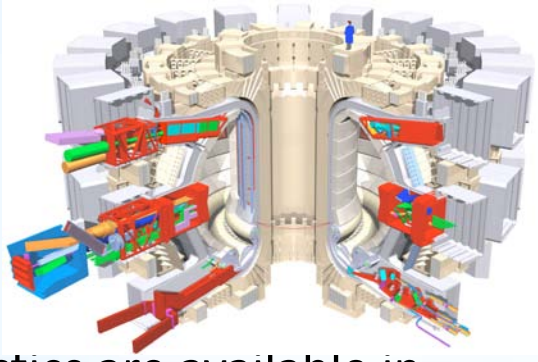


- Physics design issues of ELM are to eliminate or mitigate large ELMs
  - ✓ QH mode: to clarify operation condition (V_ϕ, n_e^{ped}, outer gap,,,)
  - ✓ Grassy ELM / Type II ELM: to expand its operation regime into DEMO
  - ✓ Active ELM control for ELM mitigation: pellet pace making, Resonant Magnetic Perturbation,,,

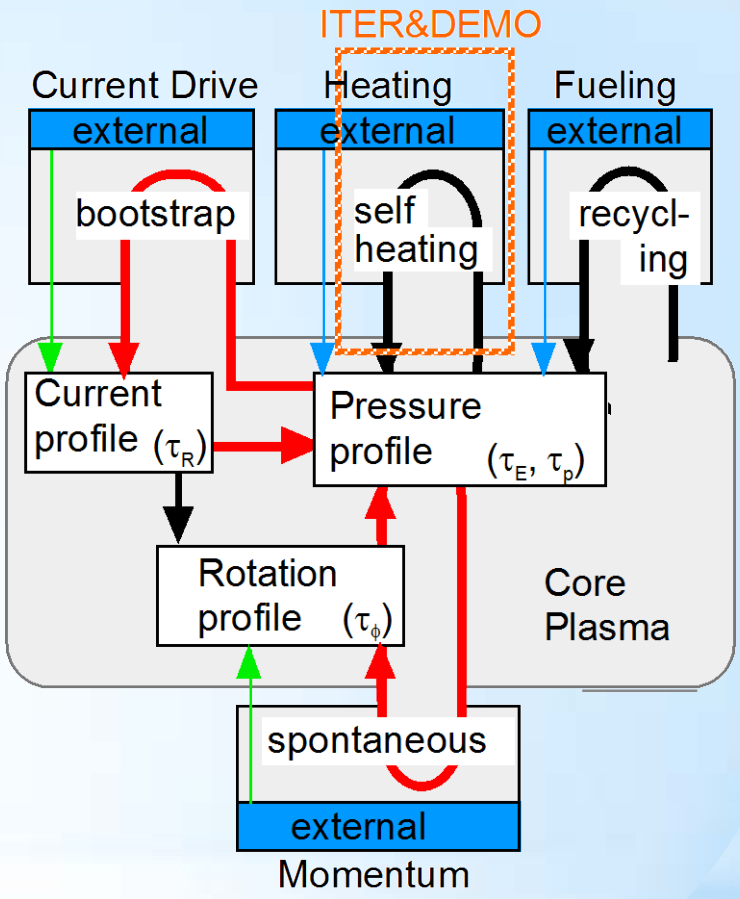
Physics design issues: Controllability

- Important core plasma profiles are j(r) & p(r) & $V_f(r)$, which are linked each other.
- External fractions of current drive power & heating power & momentum input & fueling are very small in DEMO.
- ➢ Such self-organized plasma have less controllability.

About 50 individual measurement system in ITER will help to control, evaluate and optimize plasma performance.



- What kind of diagnostics are available in DEMO?



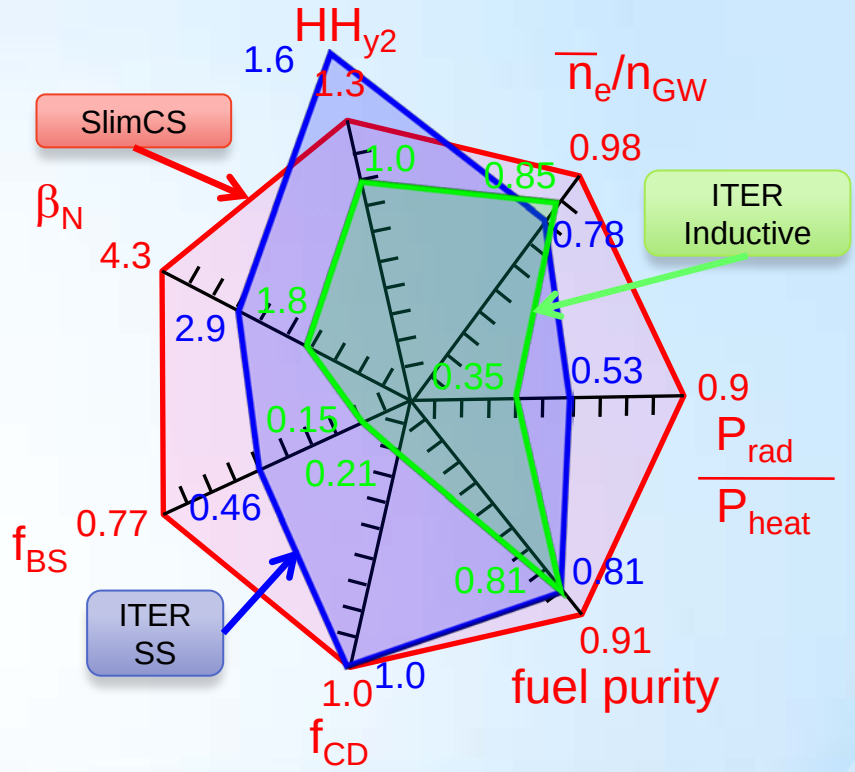
- Physics design issue of controllability is to clarify the minimum set of actuators and sensors for self-organized plasma, that should be examined in the experiments.

Physics design issues: Integration of normalized plasma performance

- Physics design parameters should be sustained simultaneously in the DEMO plasma.
- Radar-screen diagram is used to visualize the achieved integrated performance so far, where the full scale of each corner represents SlimCS.
- Large gaps between ITER and SlimCS
- JT-60SA is similar to SlimSC on the diagram.

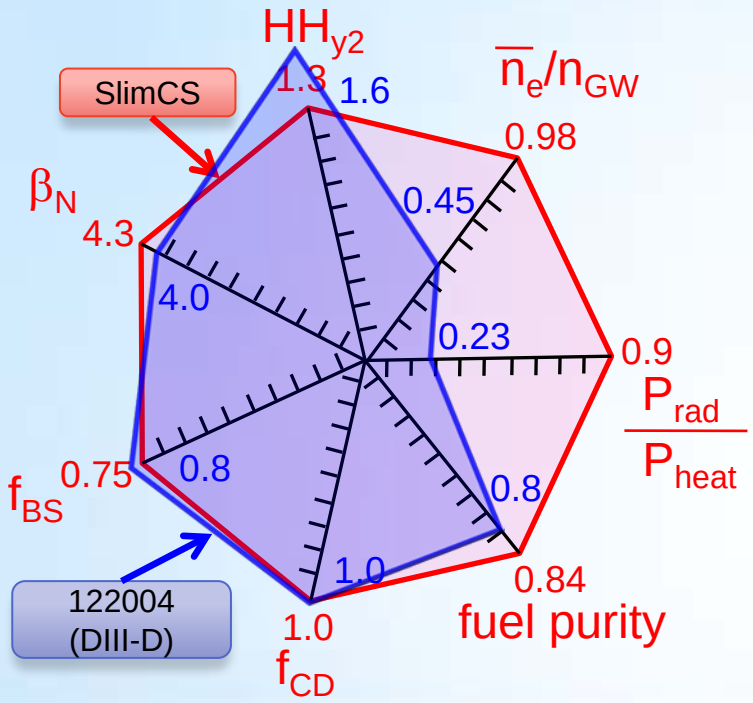
➢ JT-60SA must bridge between ITER and SlmiCS.

- High performance was obtained in Reversed shear and Weak positive shear plasmas so far.

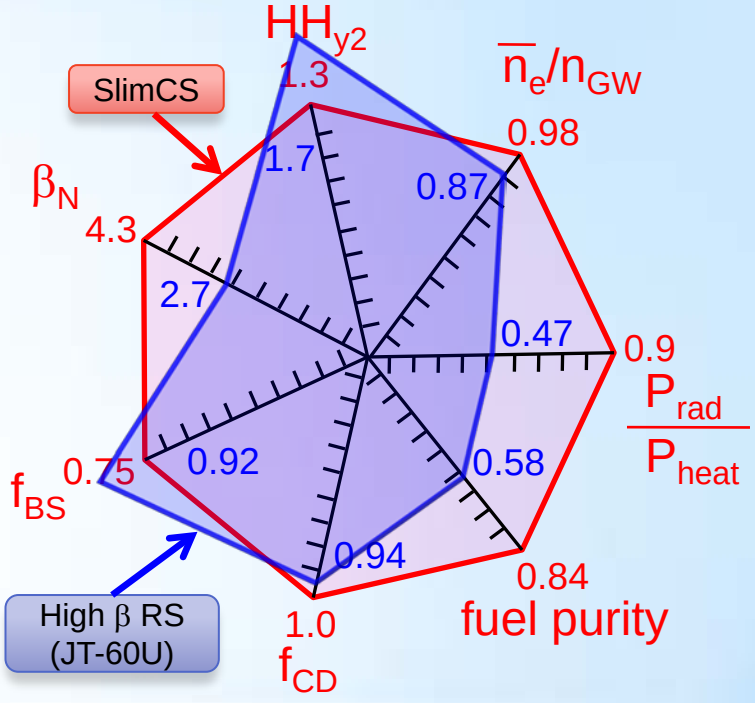


Achieved integrated performances in RS

- Two examples in Reversed Shear plasma regime



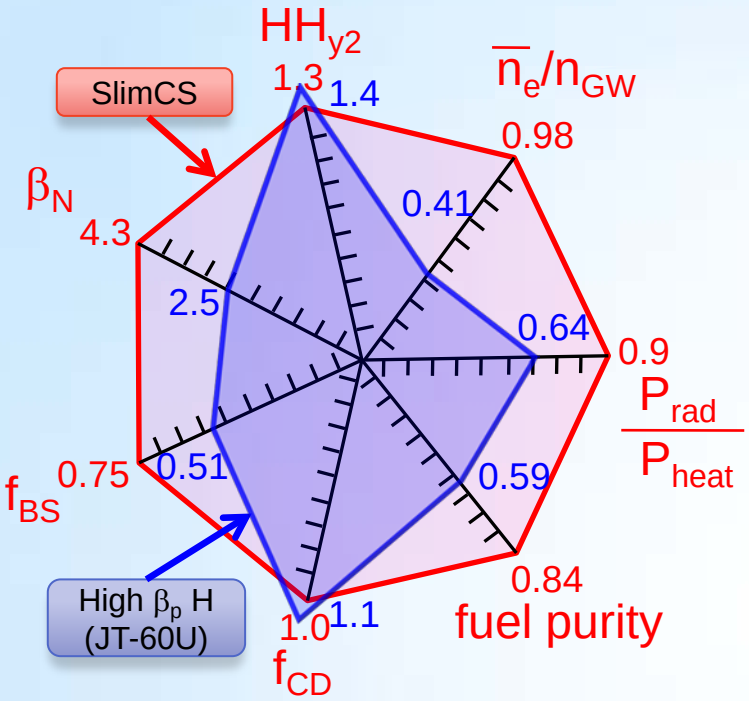
Reversed shear Plasma/ DIII-D
~1.35MA, ~1.7T, q_{95}~5.0
Transiently obtained (no disrupt.)
High beta by wall stabilization



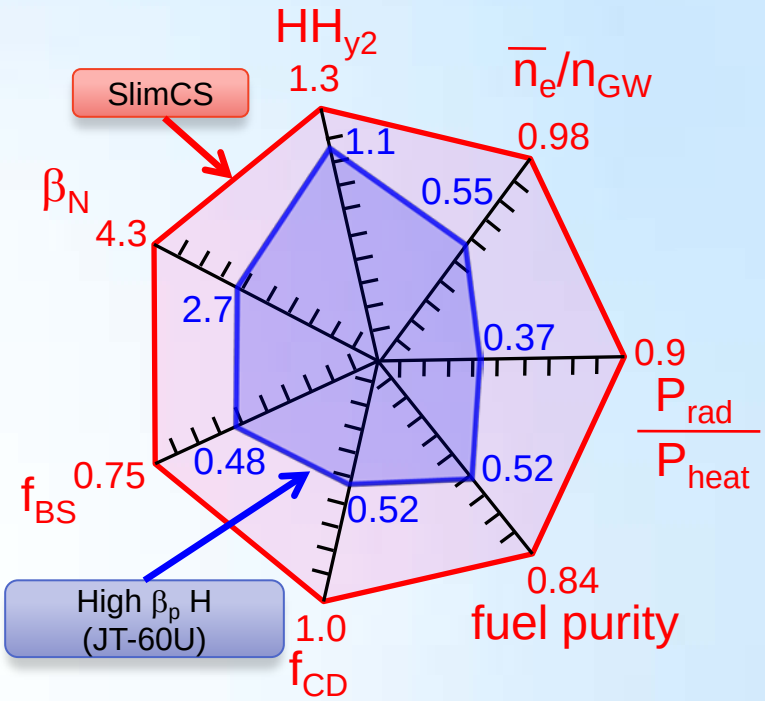
Reversed shear Plasma/ JT-60U
0.8MA, 2.0T, q_{95}=5.3
Transiently obtained (disrupt.)
High beta by wall stabilization

Achieved integrated performance in WS

- Two examples in Weak positive Shear plasma regime



High β_p H mode plasma/ JT-60U
1.5MA, 3.74T, q_{95}=4.75
Quasi-steady (1.3s, ~$3.3\tau_E$)/ Full CD by NNBI

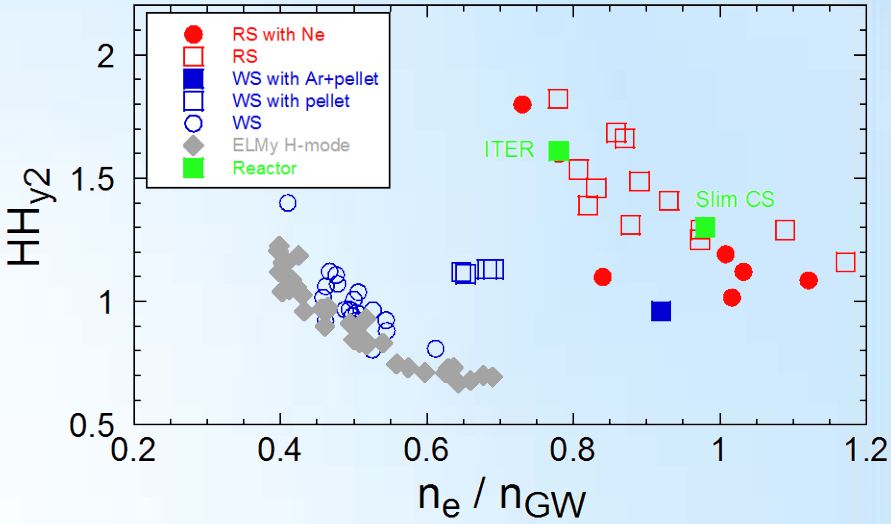


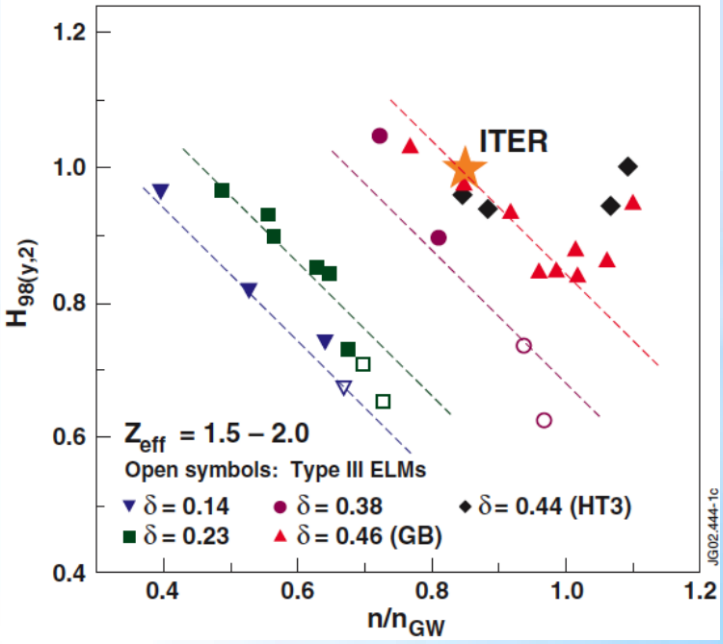
High β_p H mode plasma/ JT-60U
0.9MA, 1.54T, q_{95}=3.2
Steady (28s, ~ $14\tau_R$)/ Long NB pulse

- Physics design issue of integrated plasma performance is to reconsider a set of plasma parameter based on foreseeable parameters.

Physics design issues: Trade-off relation

- Performances of HH, β_N, f_{BS} are roughly determined by plasma operation scenario.
- ➢ Selection of plasma operation scenario is important for DEMO physics design.
- However, there are trade-off relationships when f_{GW} and f_{rad} are increased.
- ✓ Density can increase with increasing particle fueling, while it causes degradation of confinement.
- ✓ Radiation can increase with increasing impurity seeding, while it causes degradation of fuel purity and confinement.
- These kinds of trade-off relationship should be considered in physics design.





Summary

- DEMO Physics Basis have to be demonstrated in ITER and existing & newly-constructed tokamaks.
- Main difference between DEMO and ITER & existing tokamaks shows the physics design issues on (i) heat removal, (ii) disruption control, (iii) ELM control and (iv) controllability of the self-organized plasma are common to all DEMO concepts, which must be overcome before DEMO construction.
- Integrated plasma performance in the proposed DEMO concepts has not been achieved in existing tokamaks (may not in ITER). We may need to reconsider physics design parameter based on the foreseeable parameters.