8th IAEA DEMO Programme Workshop
30 August – 2 September 2022, Vienna International Centre, Vienna, Austria

Session 3: “Efficiency: coolant selection, cost and delivering time”

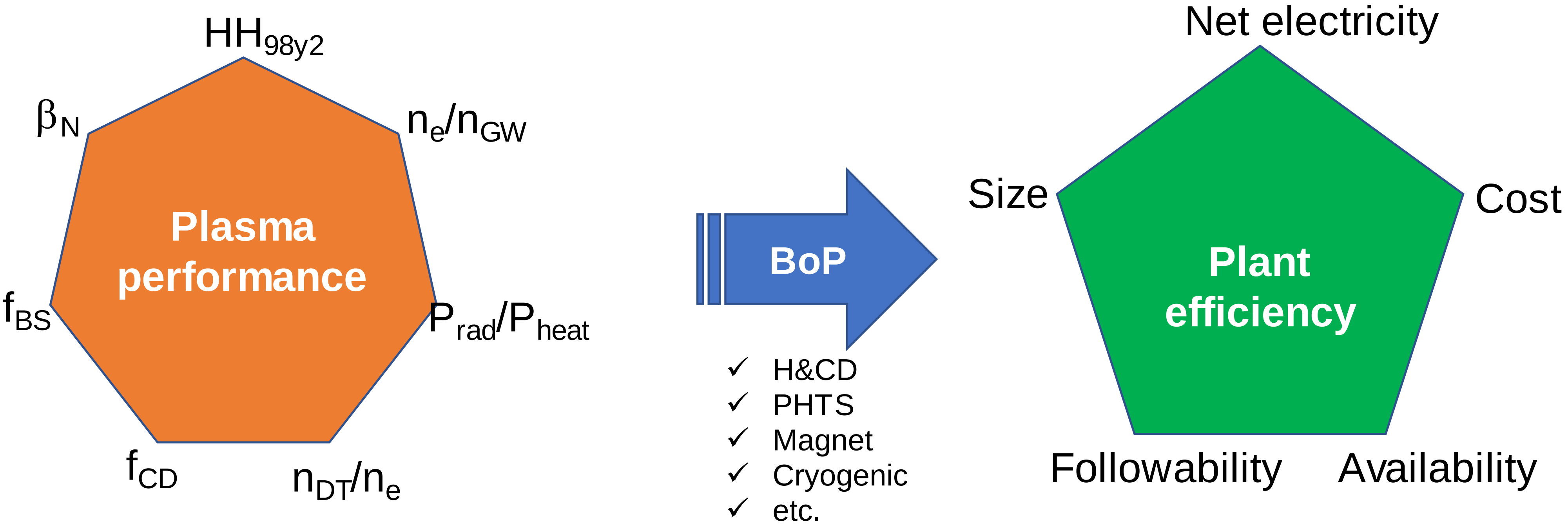
Plasma physics performance and impact on plant efficiency

Yutaka KAMADA and Yoshiteru SAKAMOTO

QST

Introduction: Plasma performance and Plant efficiency

- Plasma performance defines the fusion power for the DEMO and is directly related to net electricity by considering the bootstrap current fraction.
- In addition, plasma operational performance and operational flexibility impact on overall plant efficiency, including load followability, availability, and cost.



HH_{98y2}

β_N

n_e/n_{GW}

Plasma performance

f_{BS}

P_{rad}/P_{heat}

f_{CD}

n_{DT}/n_e

BoP

- ✓ H&CD
- ✓ PHTS
- ✓ Magnet
- ✓ Cryogenic
- ✓ etc.

Net electricity

Size

Cost

Plant efficiency

Followability

Availability

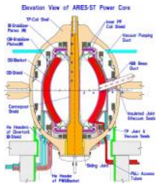
Contents

In order to discuss the plasma physics performance and impact on plant efficiency, following contents are presented.

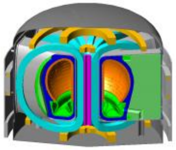
- **Key physics design drivers**
  - ✓ κ, n_{GW}, β_N, f_{BS}, f_{rad}
  - ✓ Integrated plasma performance
- **Uncertainty in fusion power**
  - ✓ Impacts of modified parameters and uncertainty on DEMO design
  - ✓ Uncertainty in plasma transport
- **Burn control**
  - ✓ by fueling pellet
  - ✓ by non-axisymmetric magnetic field
  - ✓ Integrated burn control simulation
- **Summary**

Key Physics Design Drivers

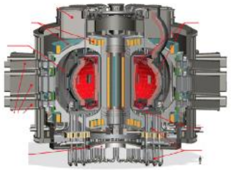
Variation of DEMO concepts and their key parameters



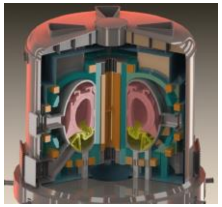
S. Nishio (IAEA2002)



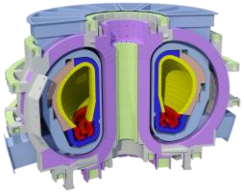
K. Tobita (NF2007)



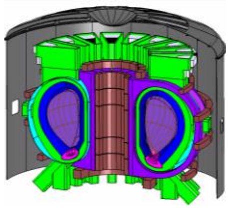
K. Kim (NF2015)



G. Zhuang (NF2019)



Y. Sakamoto (IAEA2014)



G. Federici (NF2019)

	ARIES-ST	**VECTOR**	**SlimCS**	**K-DEMO**	**CFETR**	**JA DEMO**	**EU DEMO**
	ST	Low A		Conventional A			
R/a	3.2/2	3.2/1.4	5.5/2.1	6.8/2.1	7.2/2.2	8.5/2.4	9.0/2.9
A	1.6	2.3	2.6	3.2	3.3	3.5	3.1
δ_{95} / κ_{95}	0.61/3.0	/2.35	/2.0	0.63/1.8	/2.0	1.65	0.33/1.65
Ip	27.3	14.6	16.7	12.3	13.78	12.3	17.8
B_T/B_{Tmax}	2.55/	5.0/19.6	6.0/16.4	7.4/16	6.5/14	5.94/12.1	5.9/
q_{95}	$(2.93)_{circ}$	6.0	5.4	7.0	5.54	4.1	3.89
P_{fus}	2980	3200	3000	2200-3000	2192	1462	2012
β_N	7.69	6.0	4.3	~4.2	3.0	3.4	2.5
f_{BS}	~1	0.78	0.77	~0.6	0.75	0.61	~0.35
n_e/n_{GW}	1.36	0.83	0.97		0.96	1.2	1.2
HH_{98y2}	$(1.42)_{H97}$	1.44	1.3		1.42	1.3	0.98
Operation	S.S.	S.S.	S.S.	S.S.	S.S.	S.S.	Pulse
Div. config	DN	DN	SN	DN	SN/DN	SN	SN
Physics Challenges	Non-inductive Ip ramp Div. heat handling, etc			Div. heat handling, etc			

Plasma elongation κ

- **Plasma elongation κ** is one of the key design parameters for absolute plasma performance, where upper limit is determined by **Vertical Stability**.

$q_a = \frac{2\pi}{\mu_0}\sqrt{\frac{1+\kappa^2}{2}}\frac{1}{A}\frac{aB_T}{I_p}$ → increase I_p → increase n_{GW} → increase P_{fus} at fixed q_a

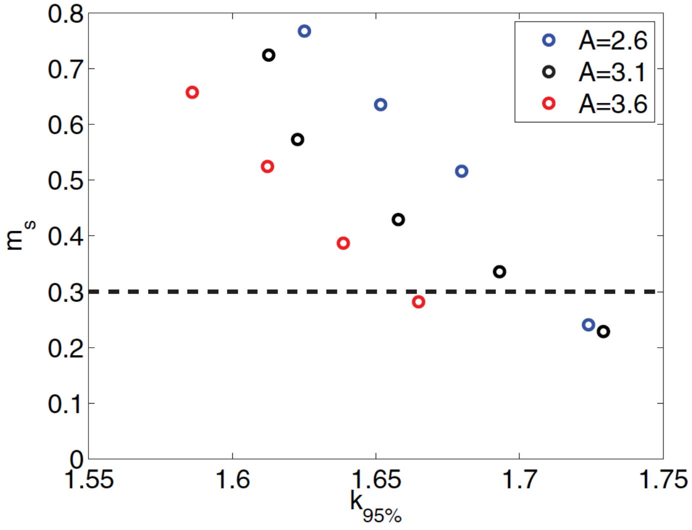
$q_a\beta[\%] = 5\sqrt{\frac{1+\kappa^2}{2}}\frac{\beta_N}{A}$ → Increase β → increase P_{fus} at fixed beta limit (β_N)

$\tau_{E,th}^{IPB98(y,2)} = 0.0562 M^{0.19} I_p^{0.93} B_t^{0.15} R^{1.39} a^{0.58} \kappa_a^{0.78} n_{19}^{0.41} P^{-0.69}$ → Long τ_E and large Q → improve P_{net}

- Lower aspect ratio contributes higher κ.
  - ✓ Stability margin of VS improves with increasing A.

DEMO difficulty:

- **Less effect of vacuum vessel as a conducting wall** on vertical stability due to large distance from plasma surface.
- **In-vessel coil is unlikely/ impossible** due to large neutron irradiation and maintainability.



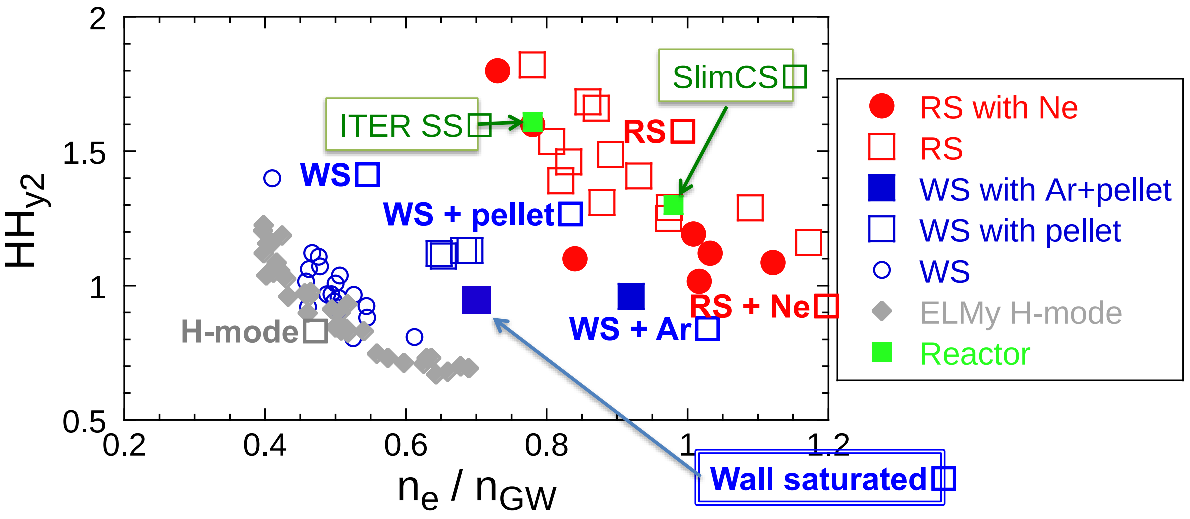
R. Wenninger, NF2015

Greenwald density n_{GW}

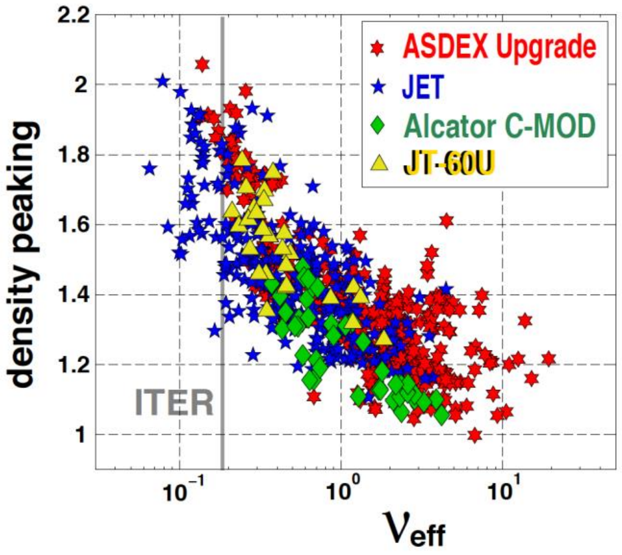
- High density operation is favorable for DEMO design to achieve high P_{fus} and compatibility with detached divertor plasma to suppress target erosion.
- **Greenwald density n_{GW} is the upper density limit, which scales $1/R_p$, leading to high $n_{GW}>1$ is necessary for large size DEMO concept.**
- Density peaking in low collisionallity region is observed in many devices
  - ✓ $n_e/n_{GW} > 1$, but $n_e^{ped} < n_{GW}$

$$n_{GW} = \frac{I_p}{\pi a^2} = \frac{2B_T}{\mu_0 q_a R_p}\sqrt{\frac{(1+\kappa^2)}{2}}$$

- It should be noted that confinement degradation is observed with increase in density.



Y. Sakamoto (JPFR2010)



C. Angioni

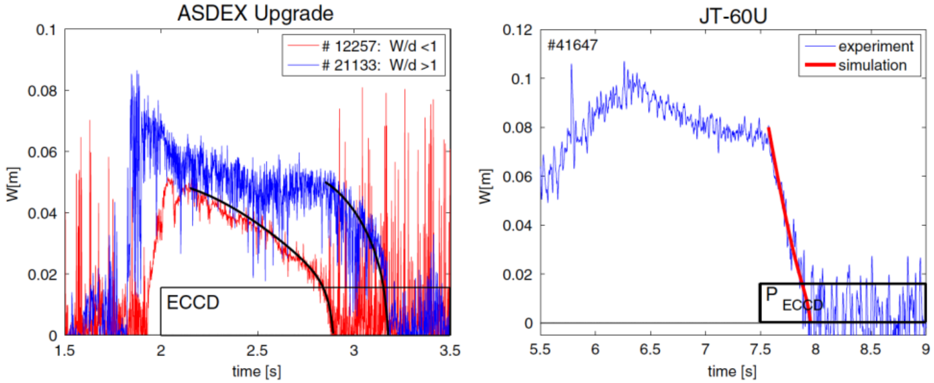
Normalized beta β_N

- **Normalized beta β_N** is one of the key performance factors that determine the economics of a DEMO reactor (Size & P_{fus})
- **Upper limit of β_N is determined by MHD Stability, leading to direct impact on plant efficiency.**

Major MHD instabilities to be considered in DEMO:

Neo-classical Tearing Modes (NTMs), destabilized below no-wall beta limit

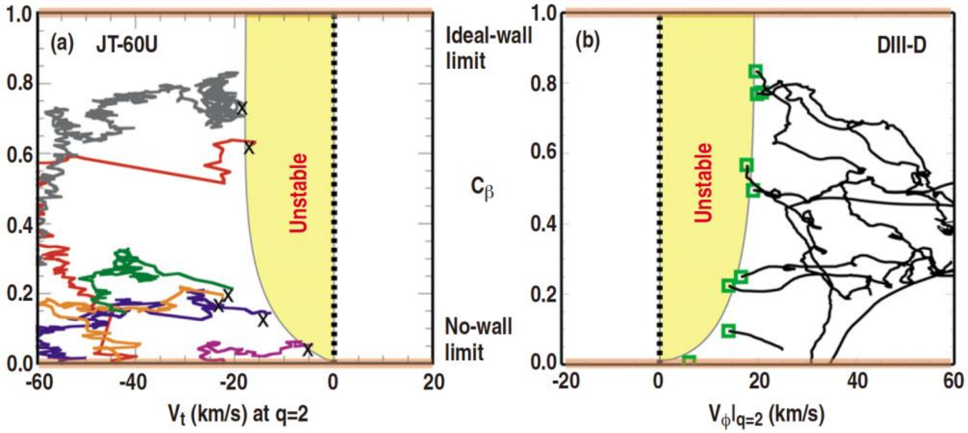
- ➢ Optimization of **p(r) & j(r)**
- ➢ Active feedback by **ECCD**



L. Urso, NF2010

Resistive Wall Modes (RWMs), destabilized above no-wall beta limit

- ➢ Stabilized by **plasma rotation**
- ➢ Active feedback by **non-axisymmetric coils**



M. Takechi, PRL2007

H. Reimerdes, PRL2007

Bootstrap current fraction f_{BS}

- Non-inductive current drive power (P_{CD}), accounts for a large fraction of the recirculating power in a DEMO plant.
- **Large f_{BS} contributes to reduce the P_{CD}, leading to direct impact on plant efficiency.**
- Depending on f_{BS}, the plasma operation mode can be categorized as follows:

Flat Magnetic Shear (f_{BS}<50%)

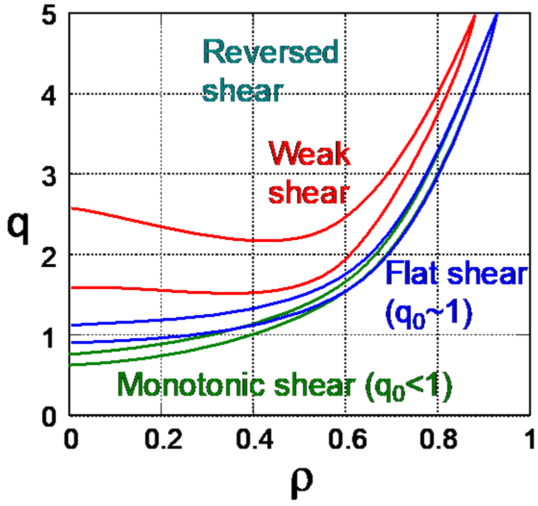
⇒advanced inductive (Hybrid Ope.): High fusion power

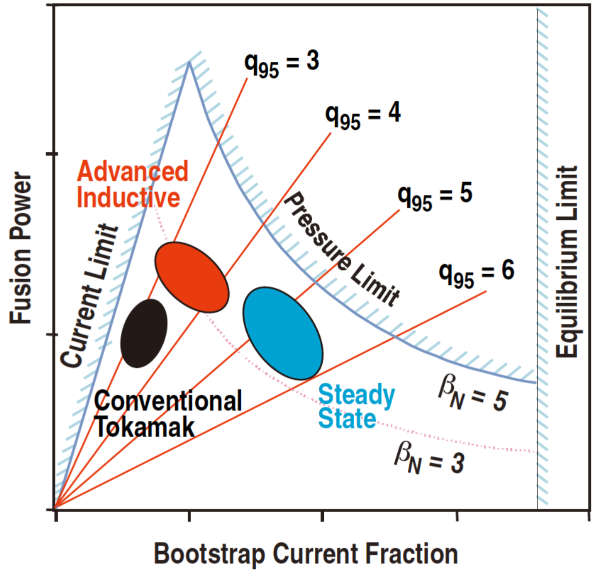
Weak Magnetic Shear (40%<f_{BS}<70%)

⇒Steady State : Good compatibility with non-inductive CD *& Good confinement with weak ITB*

Reversed Magnetic Shear (60%<f_{BS})

⇒Steady-State : Very Good Confinement, but *narrow MHD stability window*





T. Luce, PoP2011

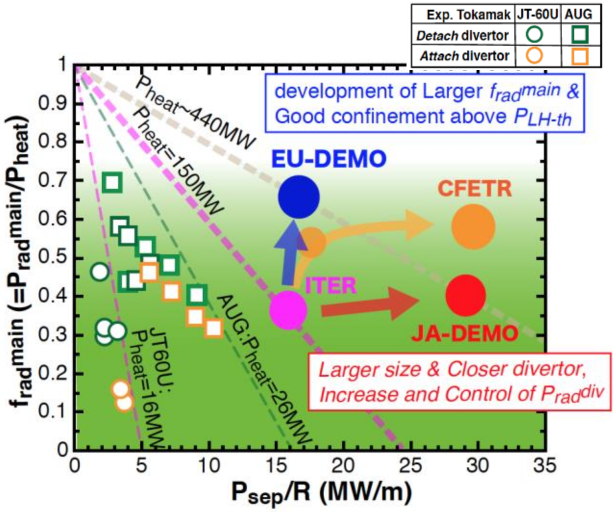
Radiation power fraction f_{rad}

- High P_{fus} requires the large f_{rad} to reduce the heat flux onto the divertor target.
- Large f_{rad} in main plasma degrades energy confinement.

➢ **P_{fus} would be limited by the tradeoff between confinement and f_{rad} and/or divertor heat removal capability.**

Conventional divertor configuration

✓ Approaches of increasing f_{rad}^{main} and f_{rad}^{div} *in larger* P_{sep}/R are necessary.



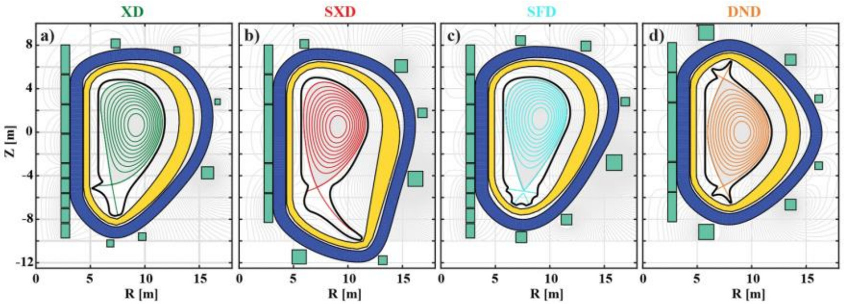
N. Asakura, PSI25

Advanced divertor configurations

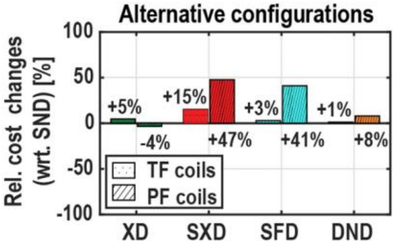
✓ Tradeoff between physical benefit and engineering difficulties.

➢ Higher P_{rad} achieved with the same impurity concentration, without degrading core performance.

➢ Magnetic forces on TF coils, large divertor coil, capital costs



R. Ambrosino, FED2019

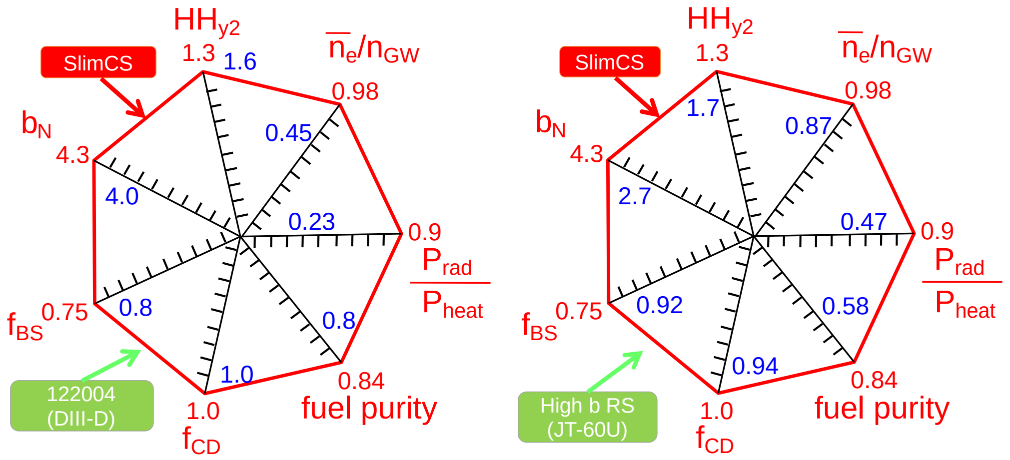


H. Reimerdes, FED2019

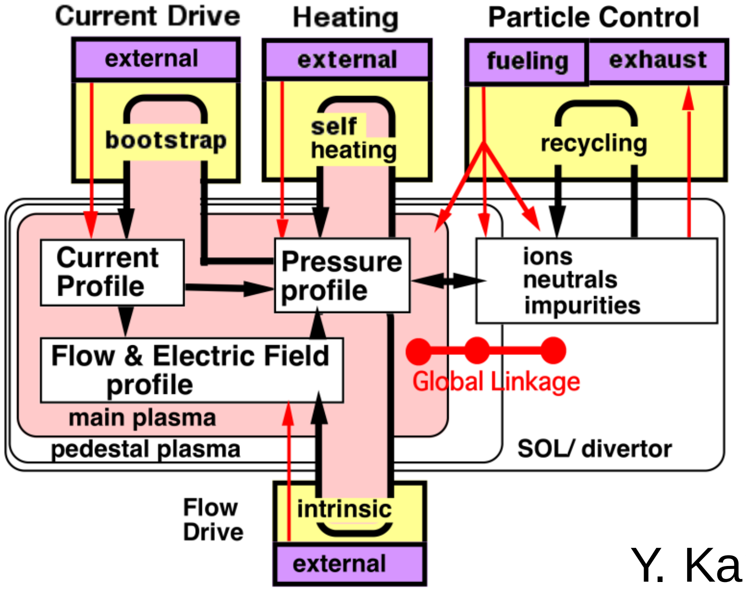
Integrated performance in self-regulating system

- All physics design parameters have to be achieved simultaneously.
- It should be noted, however, that the existence of such stationary solutions is not obvious in a fusion plasma.
- Fusion plasma is characterized by **highly self-regulating combined plasma system** in which the plasma itself determines by self-heating, bootstrap current, and intrinsic rotation.

➢ **Are there any experimental results that have achieved integrated normalized performance designed in various DEMO concepts?**
  - ✓ It is important to demonstrate the integrated normalized performance designed for the DEMO, or
  - ✓ It would be important to design DEMO plasma based on achieved or well foreseeable normalized integrated performance.



Y. Sakamoto (PFR2010)



Y. Kamada

Uncertainty in fusion power

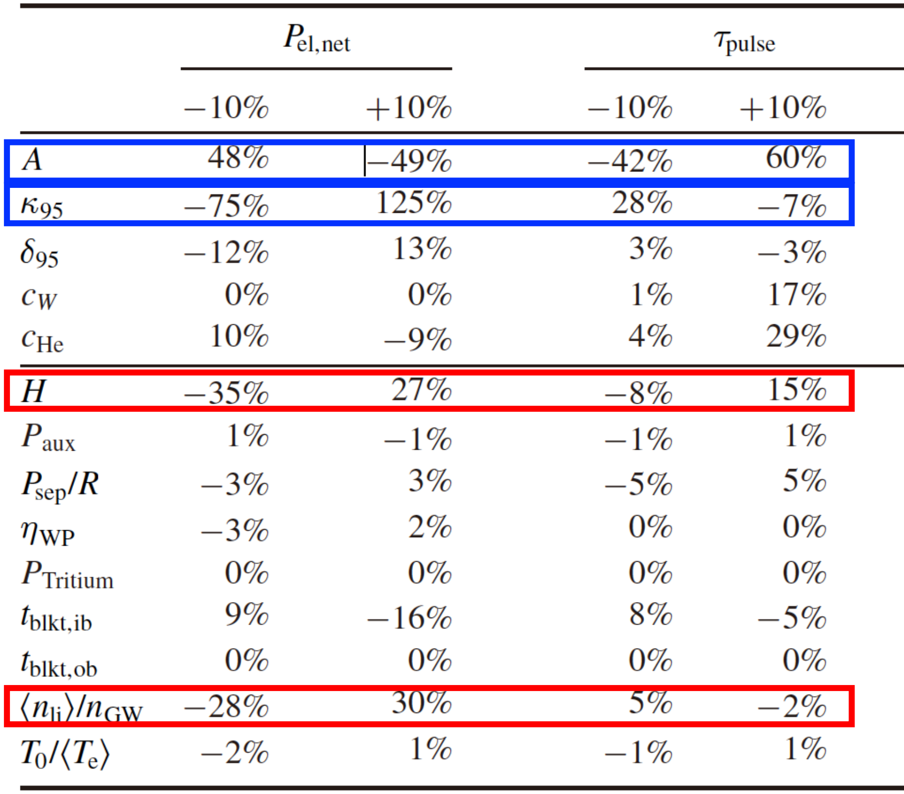
Relative impact of 10% modified parameters on P_{net} and τ_{pulse}

Aspect ratio, A, has a significant impact on P_{net} and τ_{pulse}

- ✓ The tradeoff is due to relation between plasma volume (~P_{net}) and CS size (~τ_{pulse}) with fixed R_p.

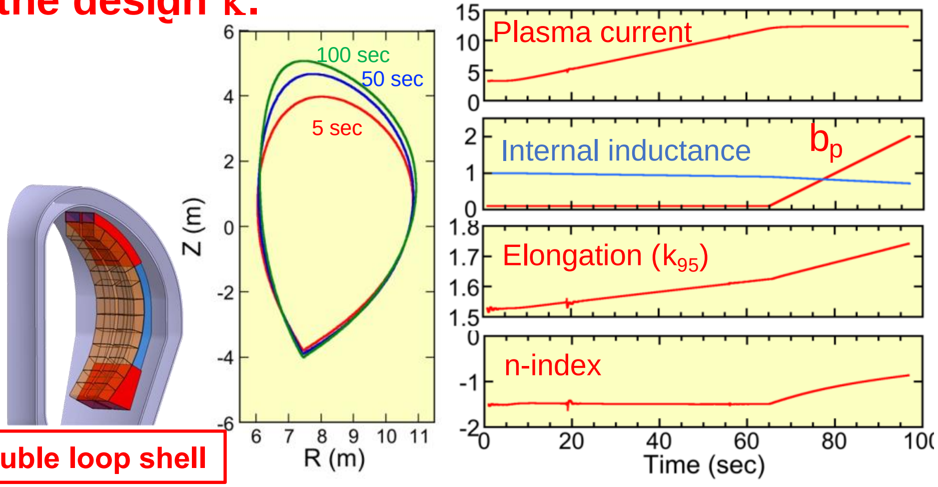
Plasma elongation, κ_{95}, has the significant impact

- ✓ Mainly due to change in I_p with fixed q_{95}, leading to change in τ_E (H) and n_{GW}.
- ✓ Controllable κ depends on 3D conducting structure and PF coil system.
- ➢ **Detail analysis by equilibrium simulator with 3D conducting structure is required to determine the design κ.**



	$P_{el,net}$		τ_{pulse}	
	−10%	+10%	−10%	+10%
A	48%	−49%	−42%	60%
κ_{95}	−75%	125%	28%	−7%
δ_{95}	−12%	13%	3%	−3%
c_W	0%	0%	1%	17%
c_{He}	10%	−9%	4%	29%
H	−35%	27%	−8%	15%
P_{aux}	1%	−1%	−1%	1%
P_{sep}/R	−3%	3%	−5%	5%
η_{WP}	−3%	2%	0%	0%
$P_{Tritium}$	0%	0%	0%	0%
$t_{blkt,ib}$	9%	−16%	8%	−5%
$t_{blkt,ob}$	0%	0%	0%	0%
$\langle n_{li}\rangle/n_{GW}$	−28%	30%	5%	−2%
$T_0/\langle T_e\rangle$	−2%	1%	−1%	1%

R. Wenninger (NF2017)



Double loop shell

Y. Sakamoto (IAEA2018)

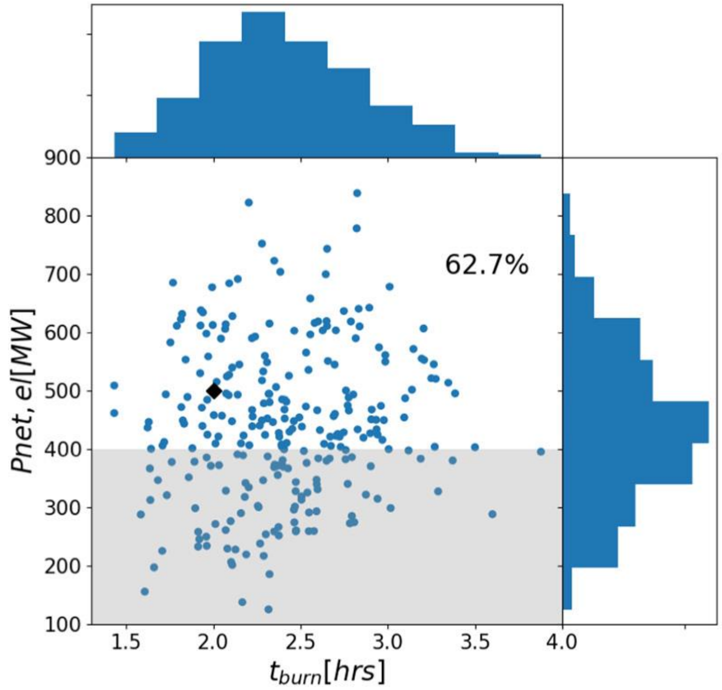
Implications of uncertainties on DEMO design

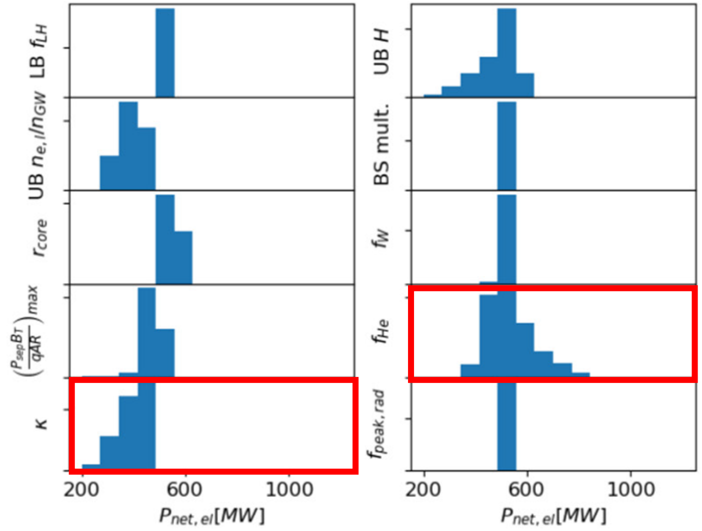
- Predicted performance for EU DEMO 2017 (P_{net}=500MW, t_{burn}=2hrs) baseline assuming the following range of uncertainties.
  - ✓ Elongation: lower half Gaussian (mean 1.85, std 0.05)
  - ✓ Density limit: lower half Gaussian (mean 1.2, std 0.1)
  - ✓ H factor: lower half Gaussian (mean 1.2, std 0.1)
  - ✓ He fraction: Gaussian (0.1, std 0.025)
  - ✓ W fraction: Gaussian (10^{-4}, std 5×10^{-5})
  - ✓ etc.

➢ Only ~63% of the scenario have an acceptable performance (P_{net}>400MW, t_{burn}>1hr).

Analysis indicates that

- ✓ **Uncertainties in elongation and impurity fractions having a significant impact on the performance**
- ✓ **future work should focus on reducing these.**



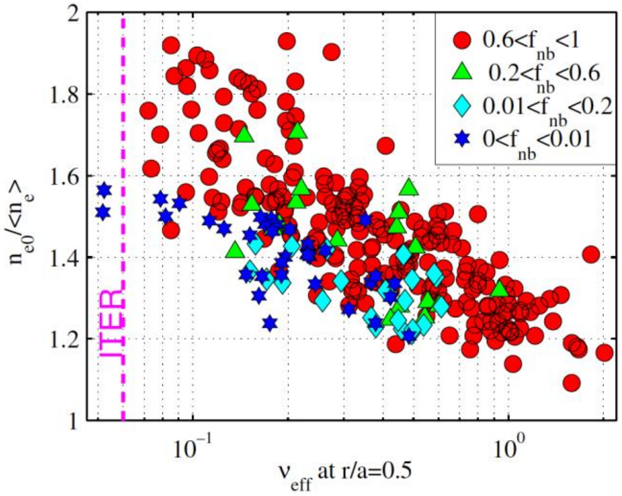


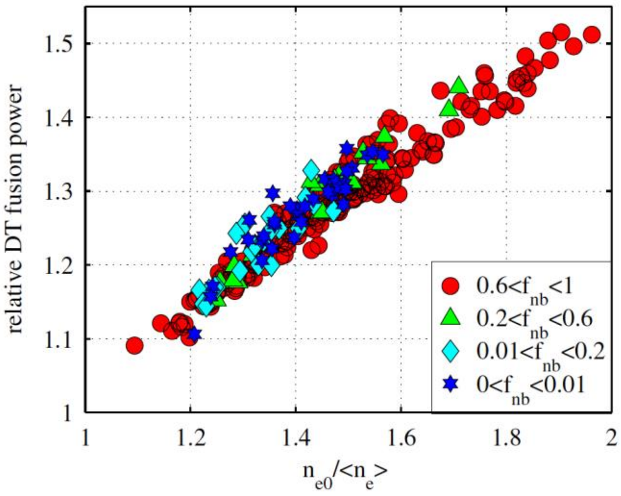
H. Lux (NF2019)

Uncertainty in Particle transport

- In addition to zero-dimensional parameters, uncertainties in the plasma profile also have a significant impact on fusion power.
- For example, it is known that the density peaking due to turbulence-driven inward pinch in the low collisionality regime.
- Density peaking contributes to increase fusion power, but the extent to which it peaks is not yet known.
- Transport helium ash and radiative impurities such as Ze, Ar and Ne are also not well understood.

Experimental data and modeling in ITER close to DEMO plasma performance are extremely important to reduce the uncertainty.

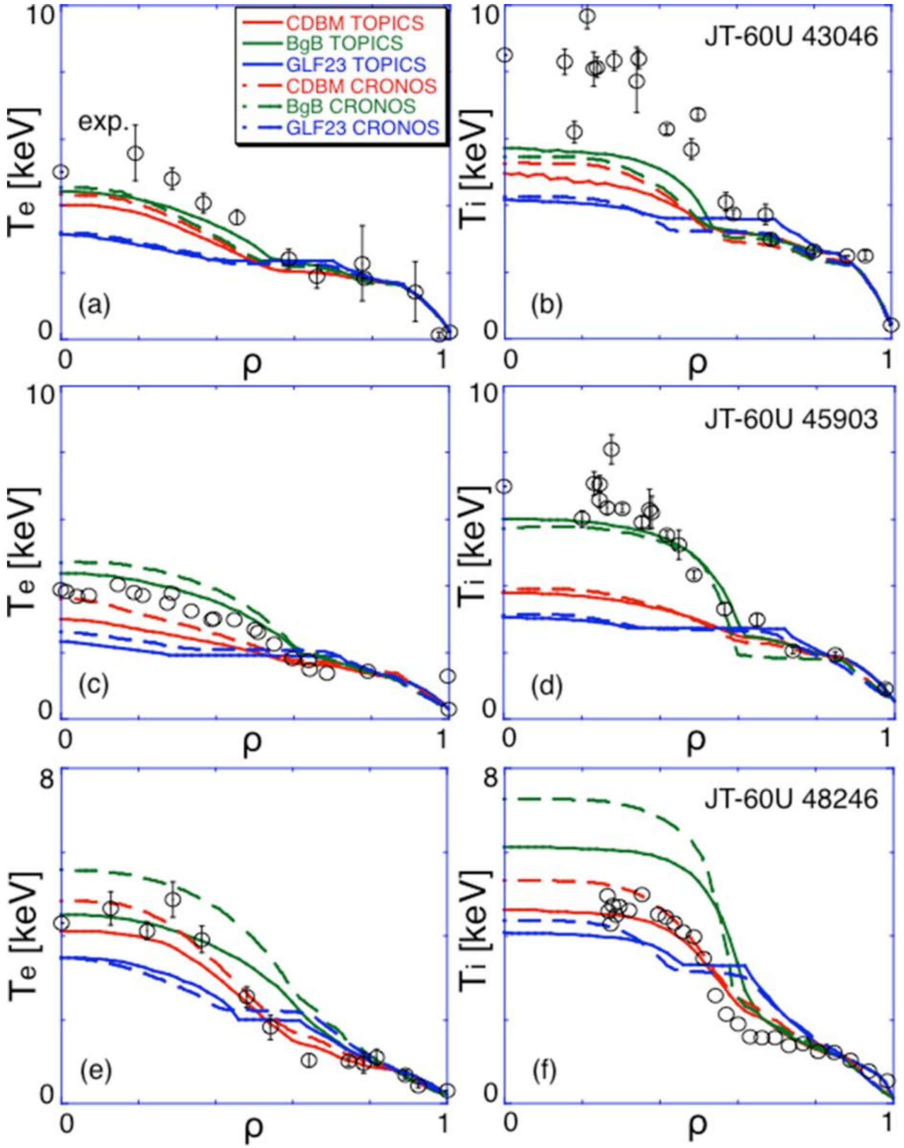


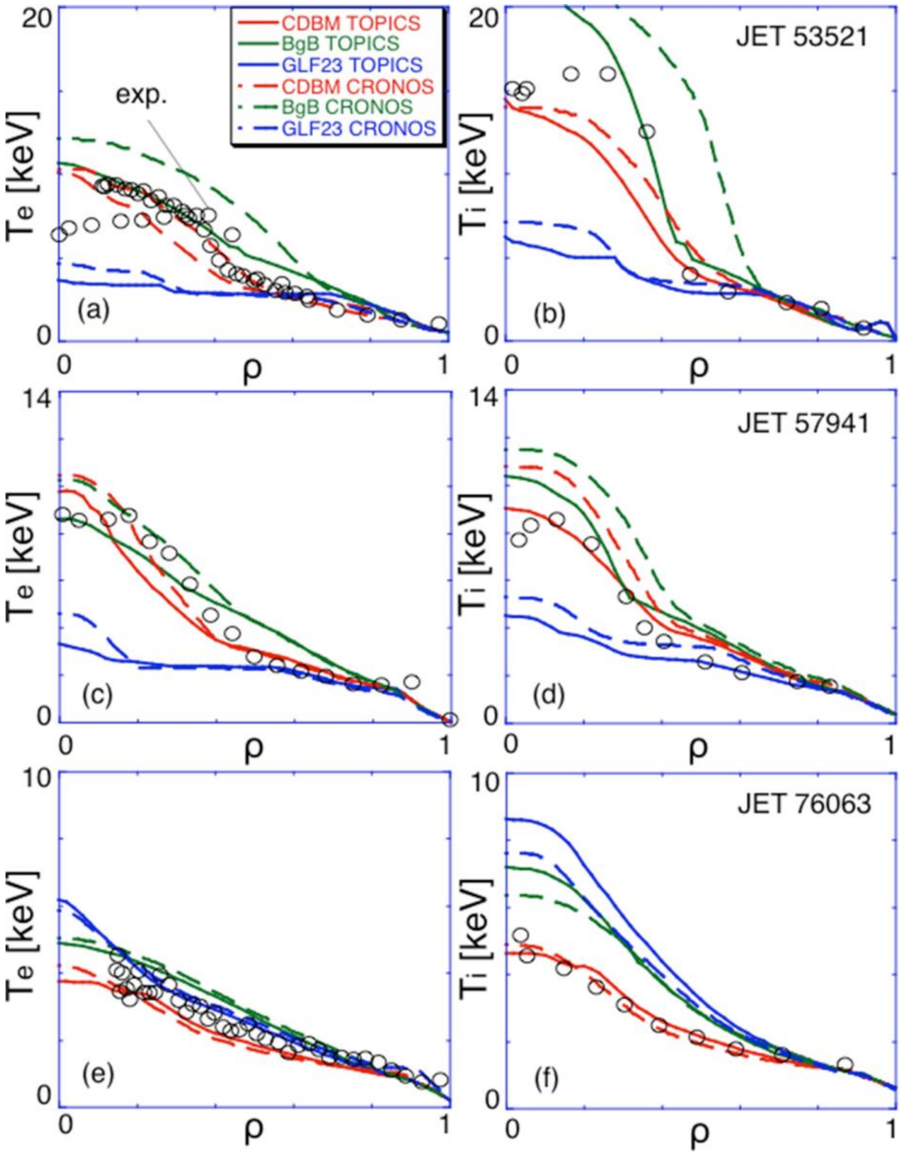


H. Weisen, PPCF2006, NF2005

Uncertainty in Thermal transport

N. Hayashi (NF2017)





Need burn control to accommodate a range of P_{fus}

- The followings are needed to reduce the uncertainty in fusion power
  - ✓ Efforts to reduce uncertainty in high-impact parameters
  - ✓ Studies on controllability to compensate the uncertainty

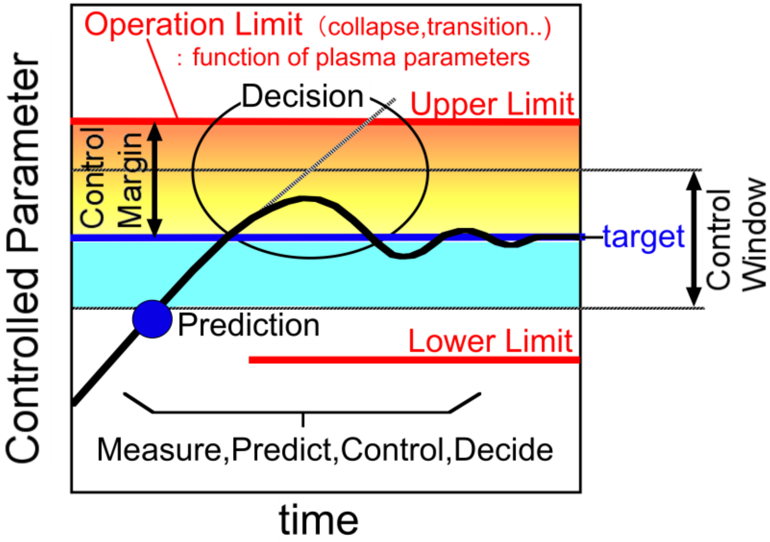
- Problem on controllability of DEMO plasmas
  - ✓ Design parameters are usually chosen near the operational limits (κ, β_N, n_e/n_{GW}).
  - ✓ the plasma design have to ensure an appropriate control margin so that uncertainties can be compensated.

➢ It is important to consider controllability of the burning plasma in next step plasma design.

Burn control

Burn Control in DEMO

- DEMO burning plasma should be controlled by using all (but limited) actuators such as H&CD (NBI/ ECRF), fueling (pellets/ gas-puff), impurity seeding, (rotation),,,
- Plasma parameters should be measured by dedicated diagnostics or should be evaluated based on measured parameters.
- The followings should be considered in control scheme.
  - ✓ Wide range of timescales
  - ✓ Spatial linkage among core - pedestal - SOL – divertor
  - ✓ Parameter linkage among p(r) & j(r) & V_ϕ(r)
  - ✓ Control margin against operation boundaries

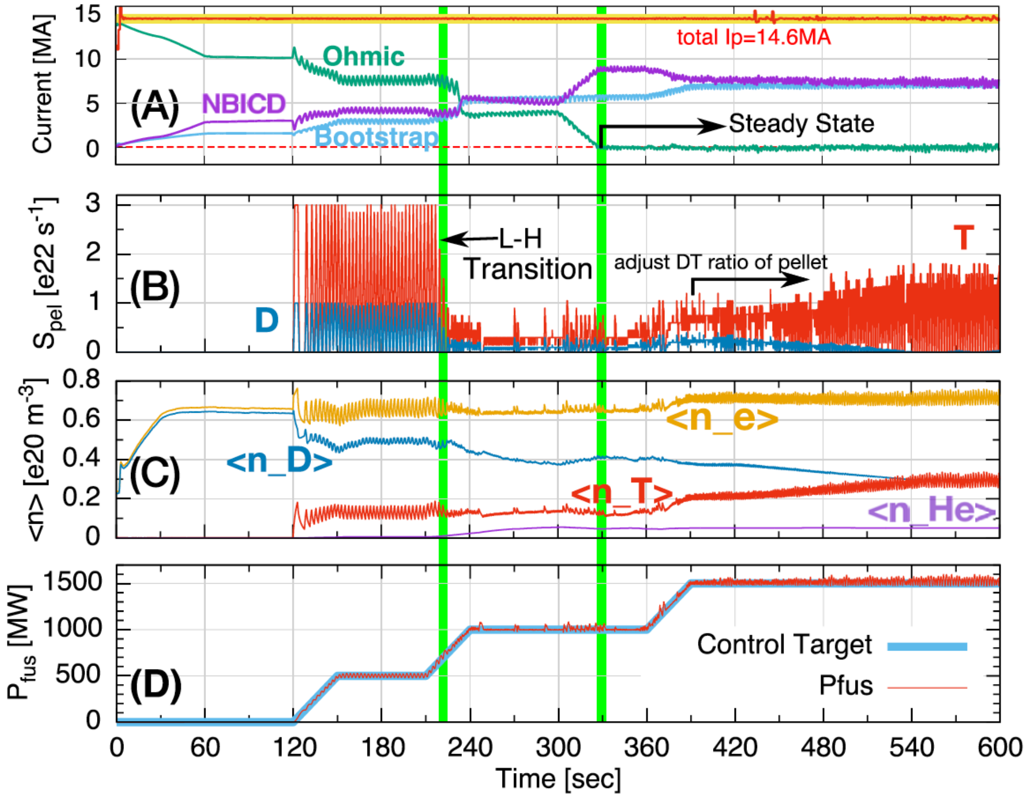


Burn control by fueling pellet

- **Density control by pellet injection**
  - ✓ most likely burning control method for fusion reactors
  - ✓ it is necessary to pay attention to the density limit and to keep divertor detachment.

- **Control of DT concentration**
  - ✓ P_{fus} can be control with keeping density.
  - ✓ Needs separate pellets of D and T

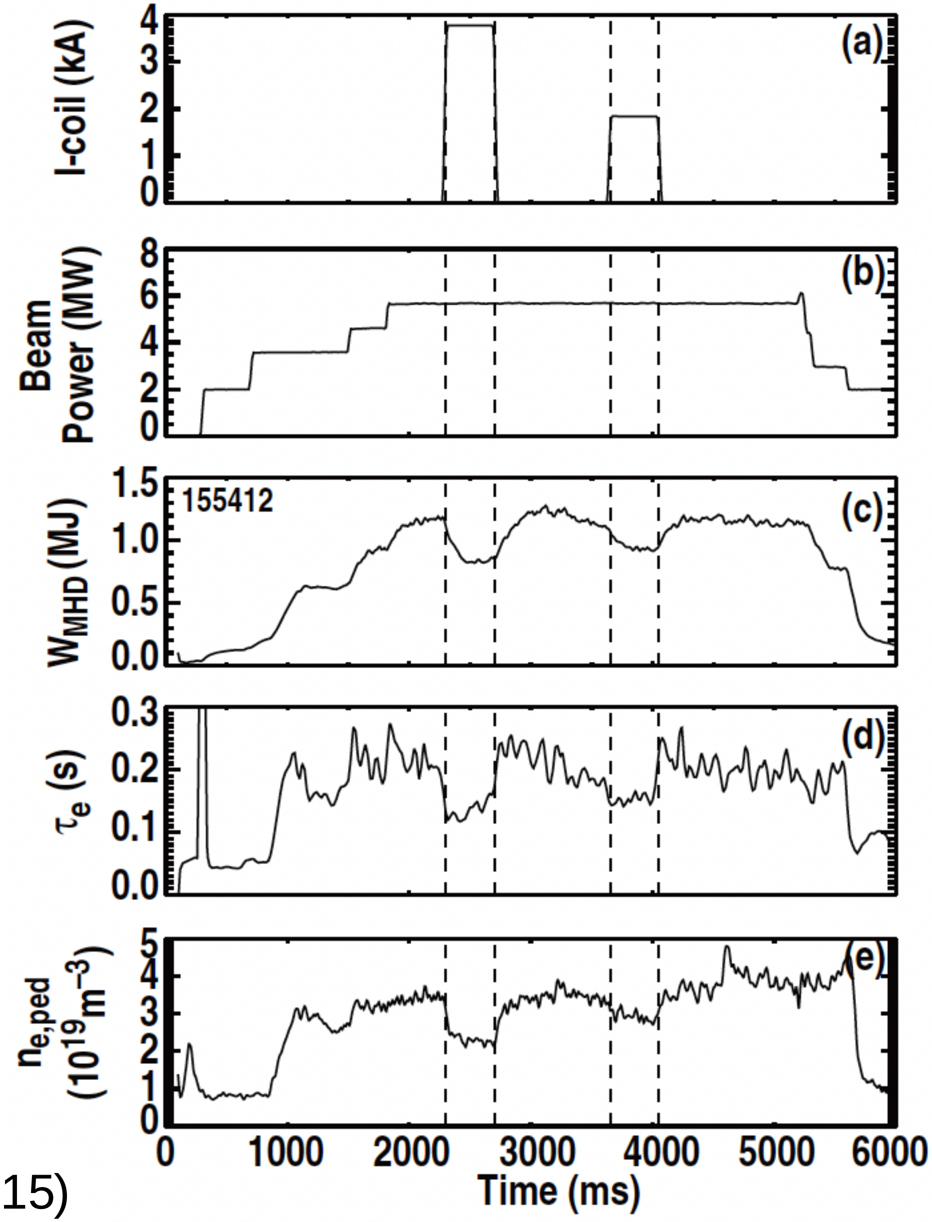
Control of the P_{fus} changes the alpha heating, so various physics quantities have to be controlled to maintain a favorable quasi-steady state, including β_N, detached divertor and radiation loss.



S. Tokunaga (FED2017)

Burn control through confinement by applying a non-axisymmetric magnetic field

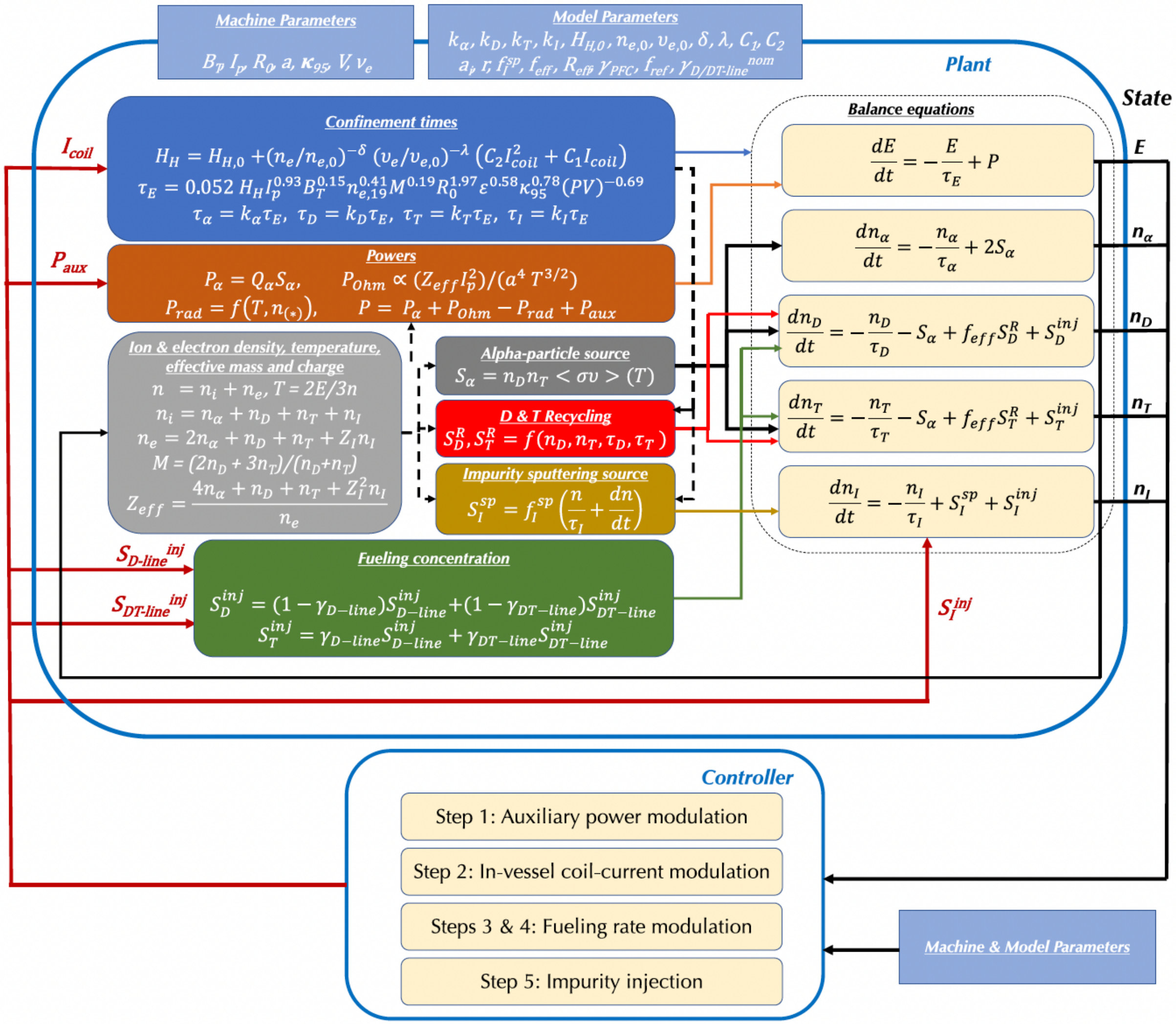
- In plasma design, energy confinement time is a required value to satisfy both power balance and plasma current balance for steady state.
- In plasma control, it is difficult to control the confinement itself.
  - ✓ Impurity seeding, rotation,
- A new approach has been experimentally demonstrated to control the stored energy by applying a **non-axisymmetric magnetic field using the in-vessel coils to modify the energy confinement time**.
  - ✓ the application of non-axisymmetric magnetic fields results in a decrease in confinement time and density pumpout.
  - ✓ the density pumpout in the pedestal was compensated by gas puffing.



R.J. Hawryluk (NF2015)

Integrated burn control simulation

- The model-based nonlinear controller is synthesized from a zero-dimensional model of the burning-plasma dynamics.
- Actuators: H&CD power, in-vessel coil-current, fueling rate, impurity injection
- A nonlinear simulation study is carried out to illustrate the successful controller performance in ITER-like scenarios in which unknown variations of the DT concentration of the fueling lines are emulated.



Machine Parameters

$B_T, I_p, R_0, a, \kappa_{95}, V, \nu_e$

Model Parameters

$k_\alpha, k_D, k_T, k_I, H_{H,0}, n_{e,0}, \upsilon_{e,0}, \delta, \lambda, C_1, C_2$

$a_i, r, f_I^{sp}, f_{eff}, R_{eff}, \gamma_{PFC}, f_{ref}, \gamma_{D/DT\text{-}line}{}^{nom}$

Plant

I_{coil}

Confinement times

$$H_H = H_{H,0} + (n_e/n_{e,0})^{-\delta} (\upsilon_e/\upsilon_{e,0})^{-\lambda} (C_2 I_{coil}^2 + C_1 I_{coil})$$

$$\tau_E = 0.052\, H_H I_p^{0.93} B_T^{0.15} n_{e,19}^{0.41} M^{0.19} R_0^{1.97} \varepsilon^{0.58} \kappa_{95}^{0.78} (PV)^{-0.69}$$

$$\tau_\alpha = k_\alpha \tau_E,\ \tau_D = k_D \tau_E,\ \tau_T = k_T \tau_E,\ \tau_I = k_I \tau_E$$

P_{aux}

Powers

$$P_\alpha = Q_\alpha S_\alpha, \qquad P_{Ohm} \propto (Z_{eff} I_p^2)/(a^4\, T^{3/2})$$

$$P_{rad} = f(T, n_{(*)}), \qquad P = P_\alpha + P_{Ohm} - P_{rad} + P_{aux}$$

Ion & electron density, temperature, effective mass and charge

$$n = n_i + n_e, T = 2E/3n$$

$$n_i = n_\alpha + n_D + n_T + n_I$$

$$n_e = 2n_\alpha + n_D + n_T + Z_I n_I$$

$$M = (2n_D + 3n_T)/(n_D + n_T)$$

$$Z_{eff} = \frac{4n_\alpha + n_D + n_T + Z_I^2 n_I}{n_e}$$

Alpha-particle source

$$S_\alpha = n_D n_T < \sigma\upsilon > (T)$$

D & T Recycling

$$S_D^R, S_T^R = f(n_D, n_T, \tau_D, \tau_T)$$

Impurity sputtering source

$$S_I^{sp} = f_I^{sp} \left(\frac{n}{\tau_I} + \frac{dn}{dt}\right)$$

$S_{D\text{-}line}{}^{inj}$

$S_{DT\text{-}line}{}^{inj}$

Fueling concentration

$$S_D^{inj} = (1 - \gamma_{D-line}) S_{D-line}^{inj} + (1 - \gamma_{DT-line}) S_{DT-line}^{inj}$$

$$S_T^{inj} = \gamma_{D-line} S_{D-line}^{inj} + \gamma_{DT-line} S_{DT-line}^{inj}$$

Balance equations

$$\frac{dE}{dt} = -\frac{E}{\tau_E} + P$$

$$\frac{dn_\alpha}{dt} = -\frac{n_\alpha}{\tau_\alpha} + 2S_\alpha$$

$$\frac{dn_D}{dt} = -\frac{n_D}{\tau_D} - S_\alpha + f_{eff} S_D^R + S_D^{inj}$$

$$\frac{dn_T}{dt} = -\frac{n_T}{\tau_T} - S_\alpha + f_{eff} S_T^R + S_T^{inj}$$

$$\frac{dn_I}{dt} = -\frac{n_I}{\tau_I} + S_I^{sp} + S_I^{inj}$$

S_I^{inj}

State

E

n_α

n_D

n_T

n_I

Controller

Step 1: Auxiliary power modulation

Step 2: In-vessel coil-current modulation

Steps 3 & 4: Fueling rate modulation

Step 5: Impurity injection

Machine & Model Parameters

A. Pajares (NF2019)

Power level adjustment by burn control

- Plasma burn control schemes could be useful not only for the compensation of uncertainty, but also for fusion power level adjustment.
- When operating a fusion reactor, it is important to ensure **load-following capability** to meet the requirements of the grid, which leads to enhance plant efficiency.
- **Power level adjustment is relatively easy for pulsed operation, but a challenge for steady-state operation due to highly self-regulating nature.**
- It should be noted that time delay for a change in thermal output to be reflected in a change in electrical output should be considered.

Summary

- Plasma physics parameters, especially κ, n_{GW}, β_N, f_{BS}, f_{rad} are key design drivers, which have large impact on P_{fus} or P_{net}.
  - ✓ It is important to demonstrate the integrated normalized performance designed for the DEMO, or
  - ✓ It would be important to design DEMO plasma based on achieved or well foreseeable integrated normalized performance.
- Uncertainty in fusion power should be reduced by experiment and modeling of the DEMO relevant plasmas.
  - ✓ the plasma design have to ensure an appropriate control margin so that uncertainties can be compensated.
  - ✓ It is important to consider controllability of the burning plasma in next step plasma design.
- Plasma burn control schemes could be useful not only for the compensation of uncertainty, but also for fusion power level adjustment.
  - ✓ When operating a fusion reactor, it is important to ensure load-following capability to meet the requirements of the grid, which leads to enhance plant efficiency.