What are Issues for realizing fusion power plant?

Why do we need fusion?

Requirements for fusion as a future energy source

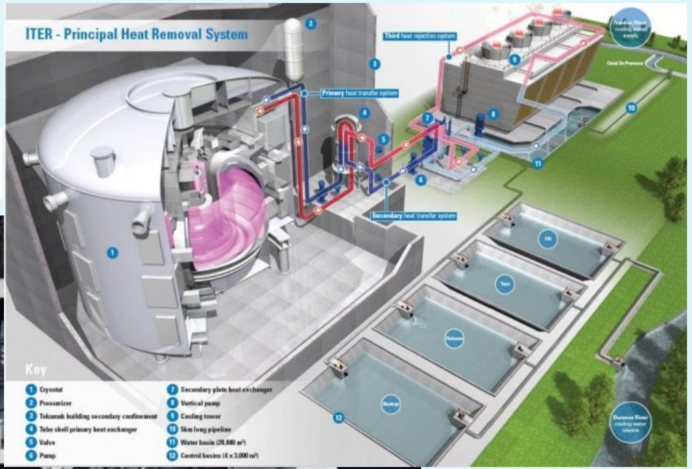
Setting GOAL!

Where are we?

What are Issues for realizing fusion power plant?

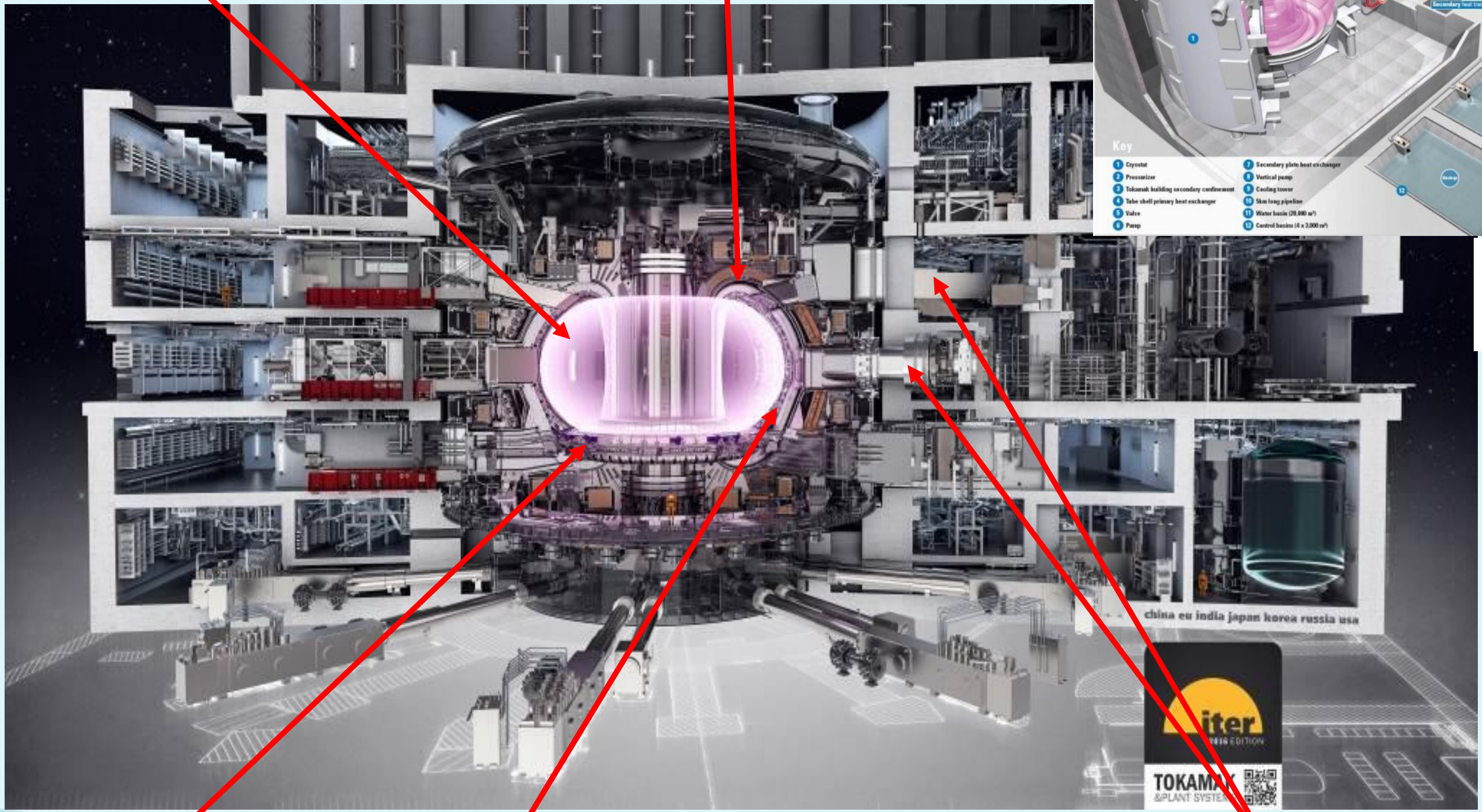
What are Issues for realizing fusion power plant?

Is ITER sufficient?



Plasma Performances

Superconducting Magnets



Coolant System
→ BoP

Divertor: Heat Removal

Blanket → Breeding Blanket, Heat exchange

Heating & Current Drive Systems

What are Issues for realizing fusion power plant?

1. Do we have enough plasma performance?
2. Can we sustain fusion reactor condition stably?
3. Can fusion power be handled by surrounding wall?
4. Can we supply enough fuel?
5. Can we operate reactor without severe environmental problems? Safety, blanket technology
6. Can we reactor with reduced cost?
7. Integrated DEMO design and system development? Modelling and simulation
8. Alternative concepts to resolve any remaining problems?
9. Investment for R&D and demonstration?
10. License, code and standards, Public acceptance

Let's design our own fusion reactor system

0. Setting goal: Term paper topics from fusion reactor technology 1 of last semester

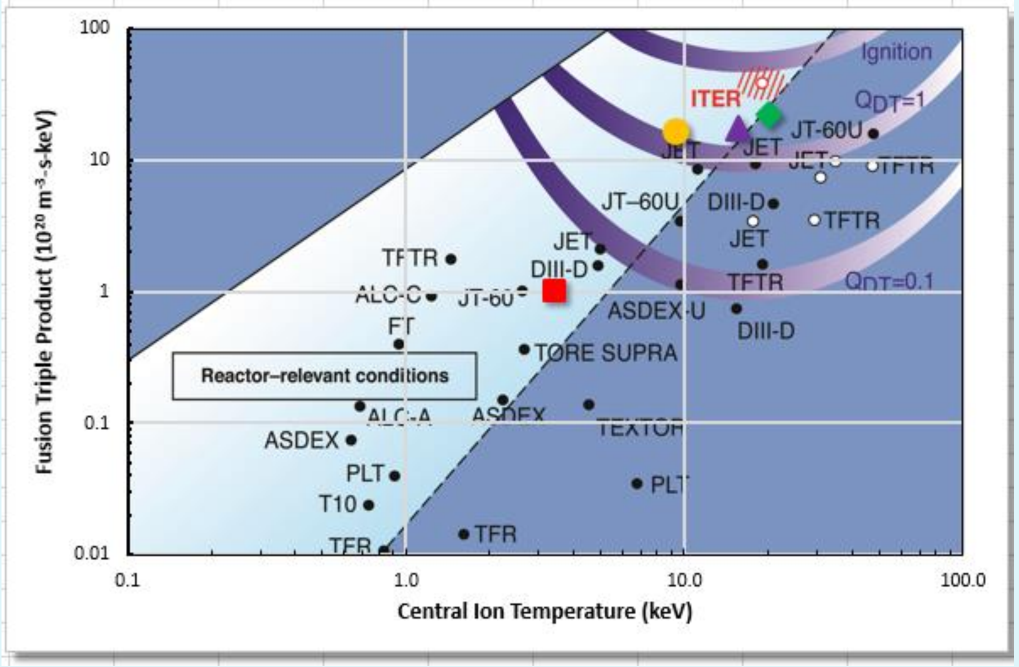
- Physics Validation Tokamak
- K-DEMO-based fusion reactor
- EU DEMO2-based fusion reactor
- Small fusion power plant (reference : SMART of fission)
- Hybrid reactor
- Spacecraft fusion reactor
- ST (Spherical Torus) fusion neutron source
- Negative Triangularity Tokamak
- SPARC-based compact fusion reactor

⇨ **Compact ST fusion power plant (fusion version of SMART)**

Let's design our own fusion reactor system

0. Setting goal: Compact ST fusion power plant (fusion version of SMART)

- Power from SMART: 330 MW_{th}, $100MW_e$
- Size of reactor from SMART: H=2m, D=1.83m → R=1.2m, a=0.8m, κ=2.0



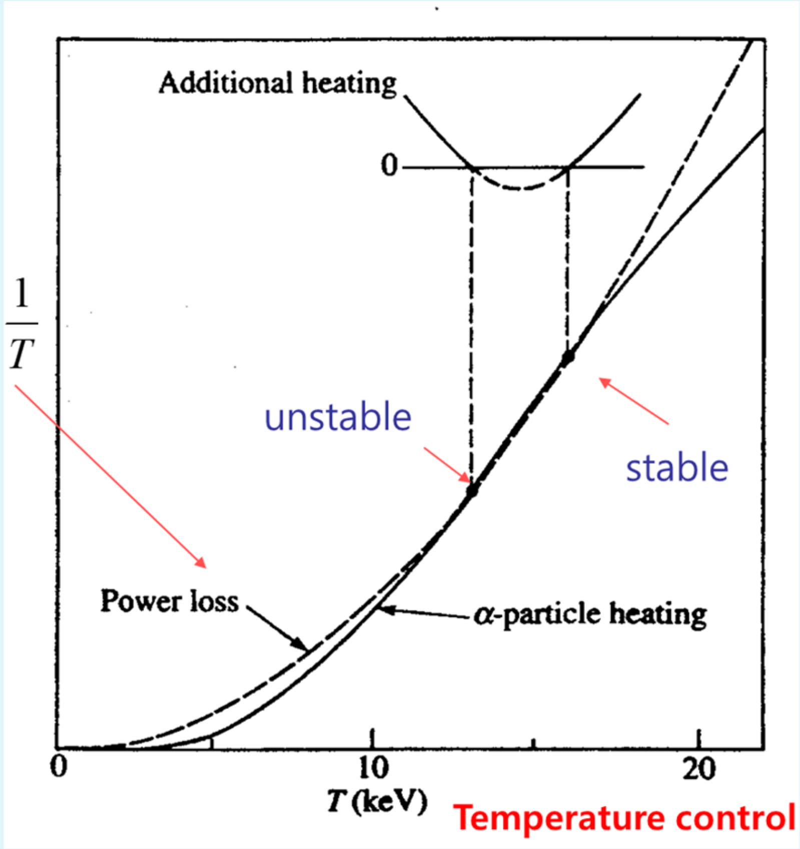
	Parameter	Unit	Symbol	Equation	KSTAR	ITER	K-DEMO	Compact ST
					■	●	◆	▲
	Major Radius	m	R_0		1.8	6.2	6.8	1.2
	Minor Radius	m	a		0.5	2.0	2.1	0.8
	Elongation		κ		1.8	1.7	1.8	2.0
	Plasma Current	MA	I_p		2.0	15.0	12.0	5.0
	Toroidal Magnetic Field	T	B_T		3.5	5.3	7.4	9.0
D	Normalized Beta	-	β_N		5.0	1.8	4.0	7.0
E	Internal Inductance	-	l_i		1.0	1.0	1.0	0.8
S	Sfaety factor		q_{eng}		2.19	1.94	3.6	9.6
I	Average Ion Temperature	keV	T		3.42	9.31	20.22	15.74
G	Energy Confinement Time	s	τ_E		0.12	1.82	1.06	0.45
N	Average Ion Density	$10^{20}m^{-3}$	n		2.55	0.95	1.04	2.49
	Toroidal Beta	%	β_T	$\beta_N l_i I_p/aB_T$	5.71	2.55	3.09	3.89
	Fusion Power	MW	P_f		0.318	513	3674	363
	Loss Power	MW	P_{loss}	pV/τ_E	38	130	677	84
	Aux. Heating Power	MW	P_H		28	73	120	10
	Required current drive po	MW	P_{NCD}		15.3	112.5	28.8	7.5
	Q			P_f/P_H	0.01	7	31	36
	Troyon Beta Limit	%	β_{Troyon}	$\beta_N l_i I_p/aB_T$	5.71	2.55	3.09	3.89
	H-mode scaling law	s	τ_{H98y}		0.12	1.82	0.66	0.18
	Greenwald Density limit	$10^{20}m^{-3}$	n_G	$I_p/\pi a^2$	2.55	1.19	0.87	2.49
	H factor		H		1.0	1.0	1.6	2.5
	Greenwald density factor		f_G		1.0	0.8	1.2	1.0
	Bootstrap fraction		f_B		0.0	0.24	0.83	0.7
	Fusion Triple Product	$10^{20}m^{-3}$-s-keV		$nT\tau_E$	1.0	16.2	22.3	17.6

Let's design our own fusion reactor system

Plasma performances vs. Machine operation limits

β_N	$\beta = \beta_N I_p / a B_o$ $<p> = \beta B_o^2 / 2 \mu_o$	I_p
	$q = 2\pi a^2 B_o / R \mu_o I_p$	B_o
f_b	$f_b \sim \varepsilon^{1/2} \beta_p$	P_{CD}
	$I_p*(1-f_b) < I_{CD} = \gamma_{CD} * P_{CD} / n_{e,20} R$	P_H
H factor	$\tau_E \equiv <p>/P_{loss} = \tau_{Eth}^{ELMy} H$ $P_H = P_{loss}$	
n_G	$n = n_G I_P/\pi a^2$	n

$\tau_E \propto \frac{1}{T}$



But, optimal temperature ~15keV

$$P_f = P_n + P_\alpha = n_D n_T <\sigma v> E_f$$
$$= N_D N_T (B^4 / 16\mu_0^2)\, \beta^2\, E_f <\sigma v>/k^2 T^2$$

$Q = P_f / P_H$

Let's design our own fusion reactor system

1. Do we have enough plasma performance?

- Sufficient fusion power for net electricity generation as required: $P_f > 330\ MW_{th}$, $P_{net} > 100MW_e$
- Sufficient heating power for required current drive power: $P_H > P_{CD}\ (f_b)$
- Sufficient alpha heating power compared to power loss: $P_\alpha + P_H > P_{loss}$ (H factor)

- High field, high current, low density limit, low bootstrap fraction and low β_N gives low net electricity
  I_p=10MA, B_o=9.0T, P_f=363MW, P_H=50MW, β_N=3.5, H=2.2, n_G=0.5, f_b=0.5, η_e=0.4, P_{net}=71MW
- High current/low field, high β_N, low density limit and high bootstrap fraction meets most requirements
  I_p=10MA, B_o=4.5T, P_f=363MW, P_H=25MW, β_N=7, H=2.5, n_G=0.5, f_b=0.7, η_e=0.4, P_{net}=95MW
- High field/low current, high β_N, high H factor and high bootstrap fraction meets most requirements
  I_p=5MA, B_o=9.0T, P_f=363MW, P_H=10MW, β_N=7, H=2.5, n_G=1.0, f_b=0.7, η_e=0.4, P_{net}=113MW

Plasma stability with high beta limits : high β_N instead of high I_p

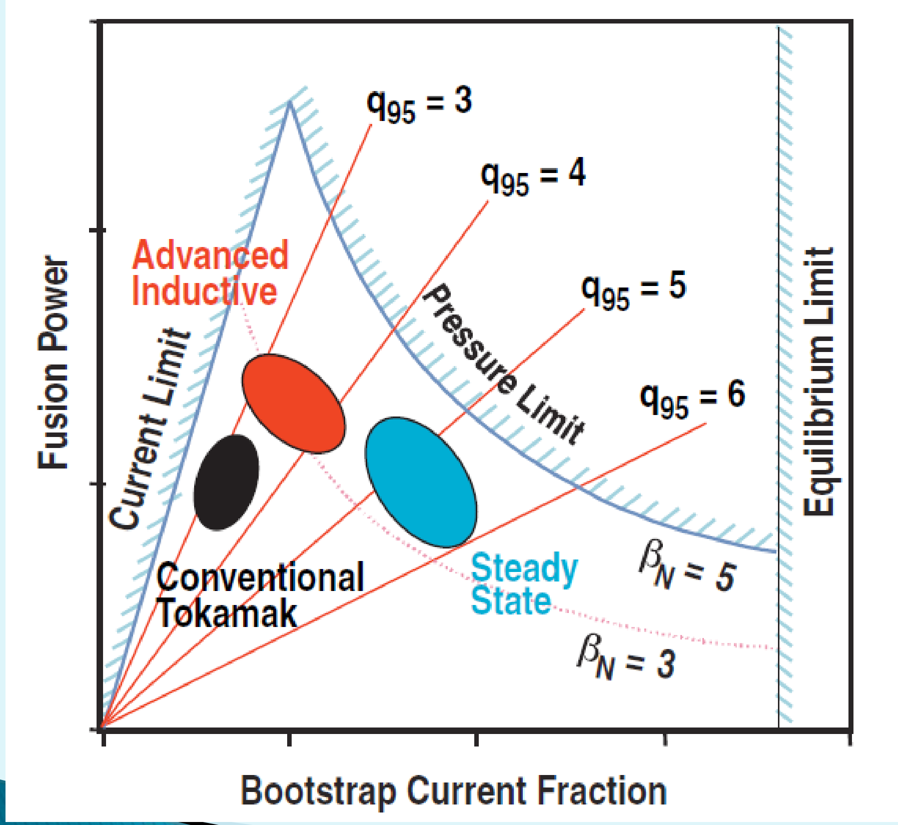
Steady-state with high f_b : high q_a with low I_p (high density limit)

Plasma confinement with high τ_E : high H factor

Let's design our own fusion reactor system

1. Do we have enough plasma performance?

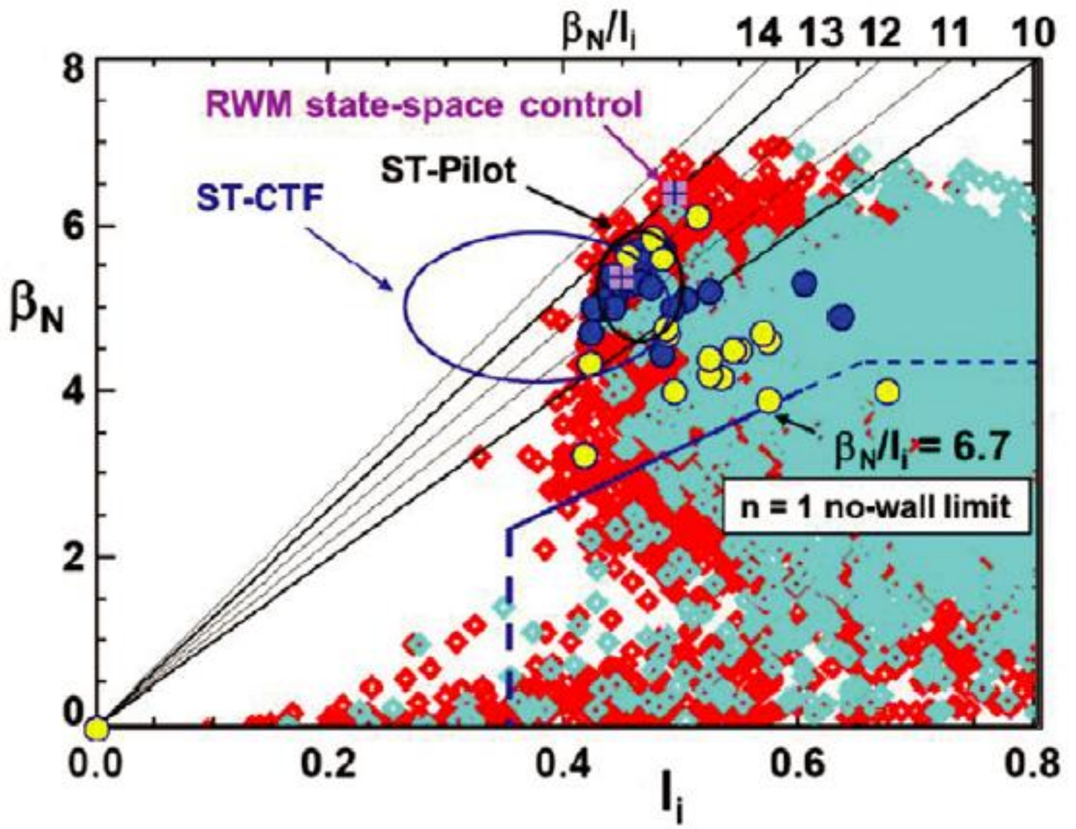
- Plasma stability with high beta limits : high β_N instead of high I_p



T.C. Luce, Phys. Plasmas 18, 030501 (2011)

High β_N

Stability



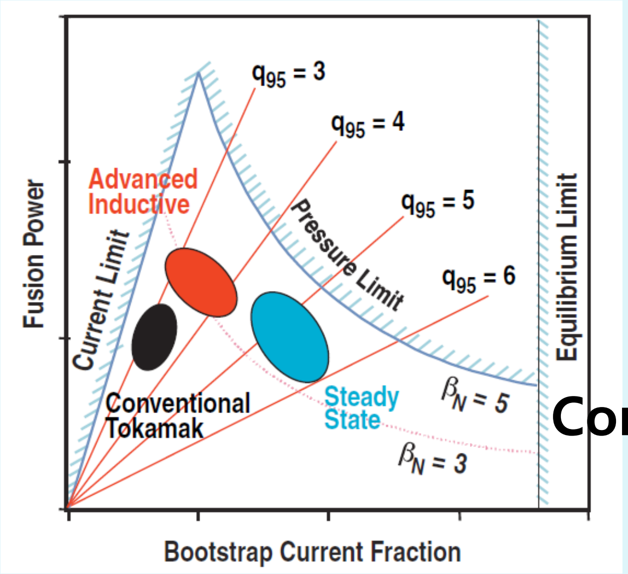
S.A. Sabbagh et al, Nucl. Fusion 53, 104007 (2013)

OK for high β_N in ST ?

Let's design our own fusion reactor system

1. Do we have enough plasma performance?

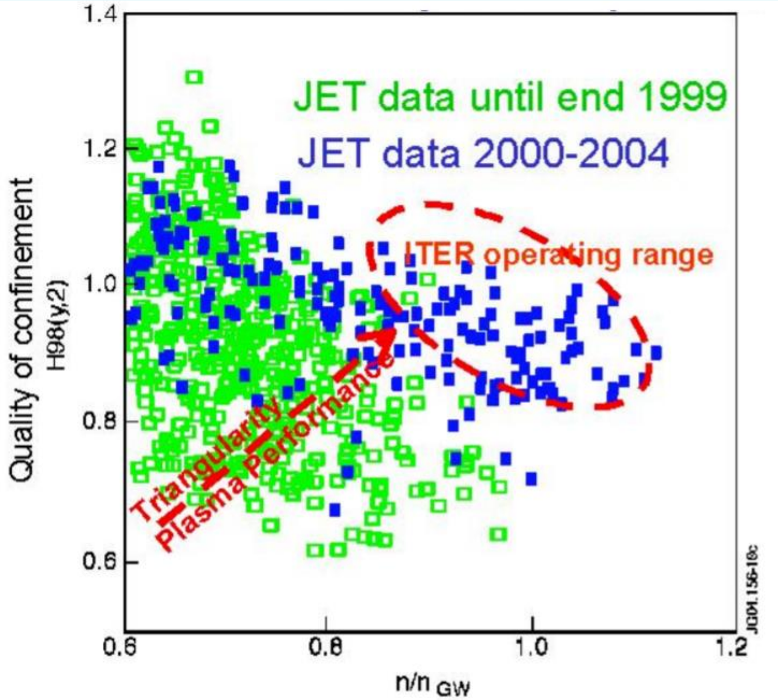
- Plasma stability with beta limits : high β_N
- Steady-state with high f_b and low fusion power : high q_{95}, low $P_{H\&CD}$ → high H

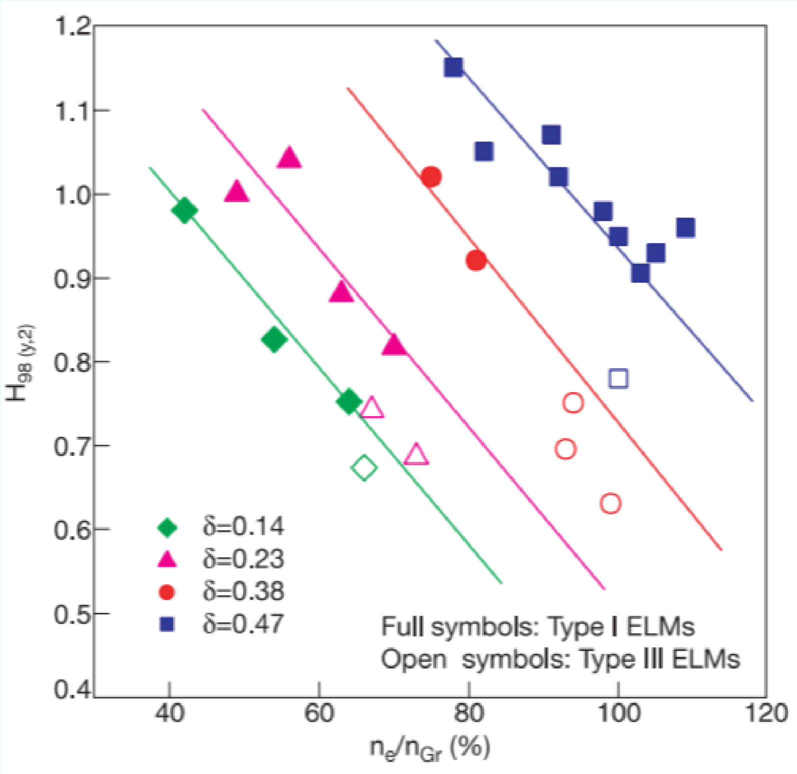


T.C. Luce, Phys. Plasmas 18, 030501 (2011)

High H

Confinement





G. SAIBENE et al., Plasma Phys. Control. Fusion 44, 1769(2002)

Difficulty in H factor, but uncertainties in scaling law ?

Let's design our own fusion reactor system

1. Do we have enough plasma performance?

- Plasma stability with beta limits : high β_N
- Steady-state with high f_b and low fusion power : high q_{95}, low $P_{H\&CD}$ → high H
- Plasma confinement with high τ_E : high H factor with selected scaling law

Uncertainties in scaling law ?

$$\tau_E^{IPB(y,2)} = 0.1445 H_{98}(y,2) M^{0.19} I_p^{0.93} R^{1.97} B_T^{0.15} \varepsilon^{0.58} \kappa_a^{0.78} \overline{n_{e20}}^{0.41} / P_{loss}^{0.69}$$

$$P_{loss} = P_\alpha + P_{ohmic} + P_{aux} - P_{brem} - P_{cycl} - P_{line}/3$$

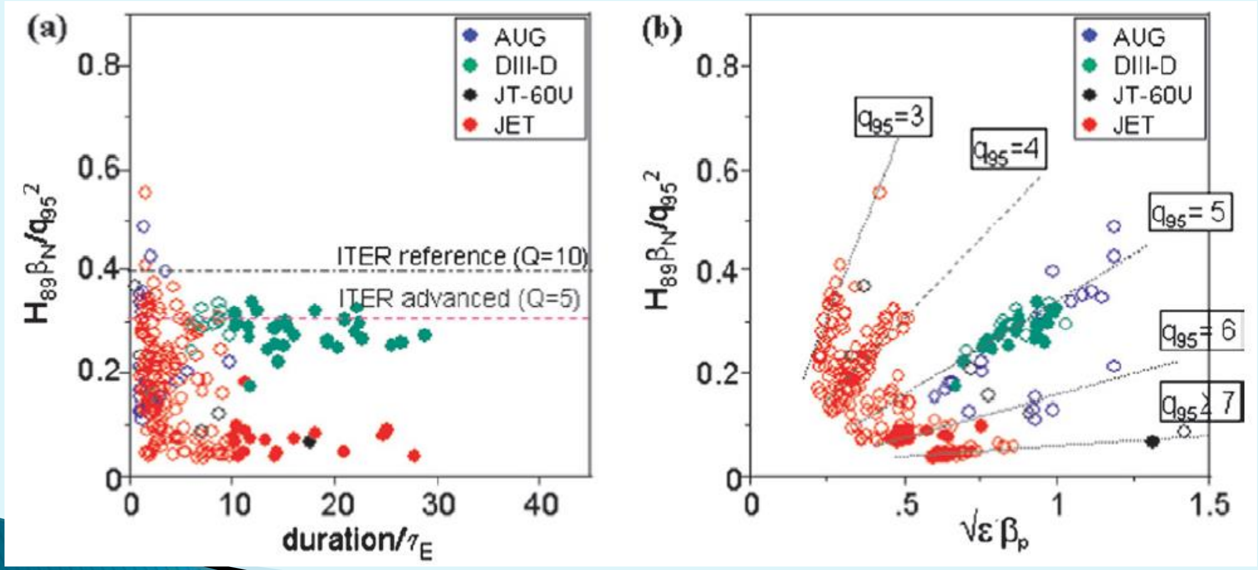
Power balance needs to be estimated carefully.
Confirmed only with simulation.

Let's design our own fusion reactor system

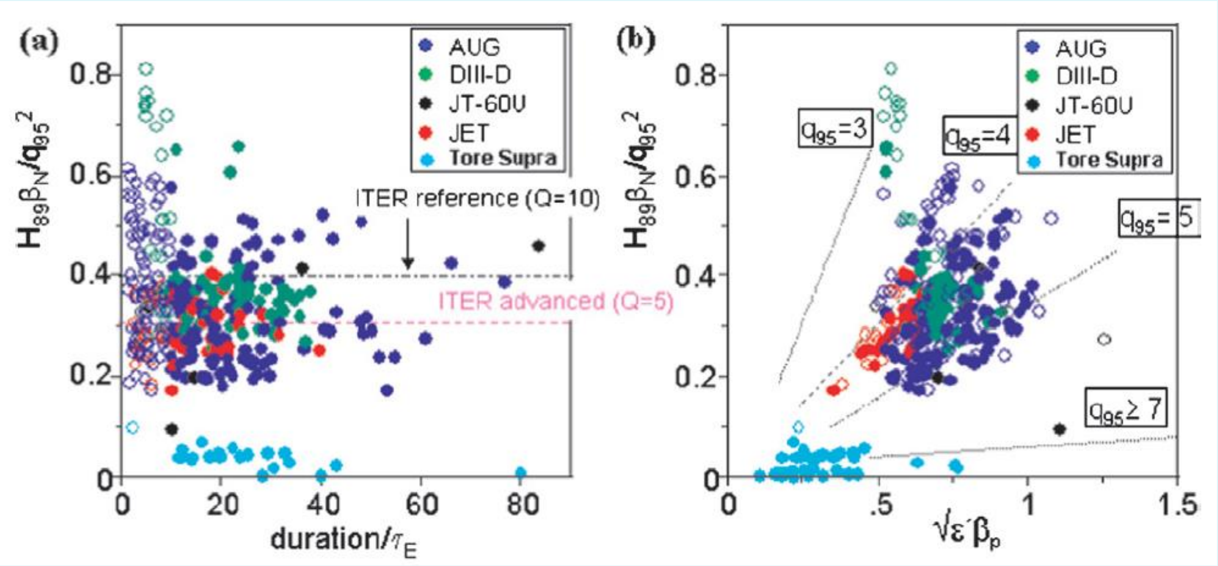
1. Do we have enough plasma performance?

- Plasma stability with beta limits : high β_N
- Steady-state at low fusion power and high f_b : high q_{95}
- Plasma confinement with high τ_E : high H factor

Reversed shear scenario



Hybrid scenario



A C C Sips et al, Plasma Phys. Control. Fusion 47, A19 (2005)

Experimental limitation?

Homework # 1

1. Plasma instabilities related to the plasma beta limit
2. Improved plasma confinement regimes
3. Tokamak plasma operation scenarios