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Consideration on the core plasma control For a tokamak fusion reactor

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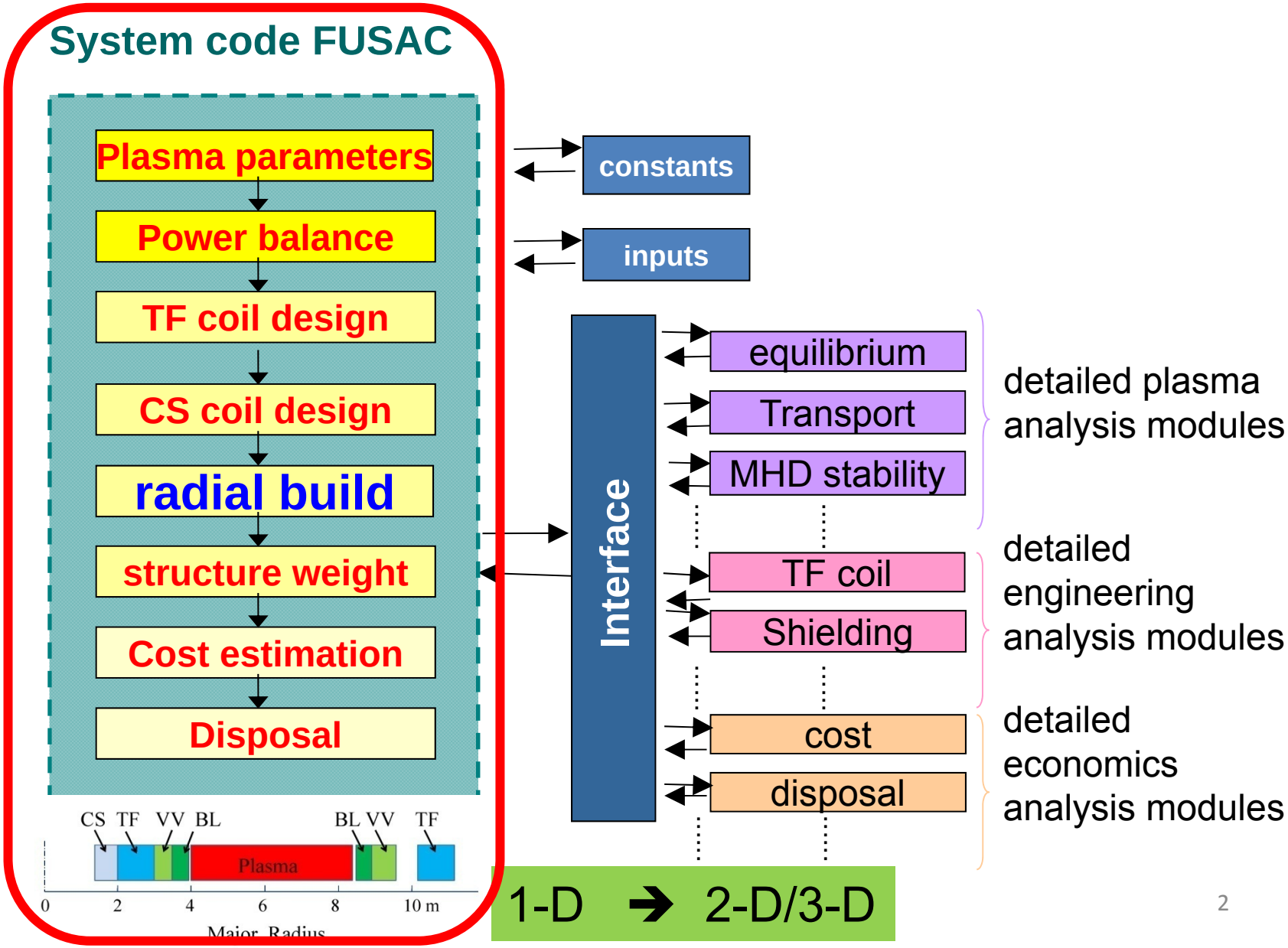
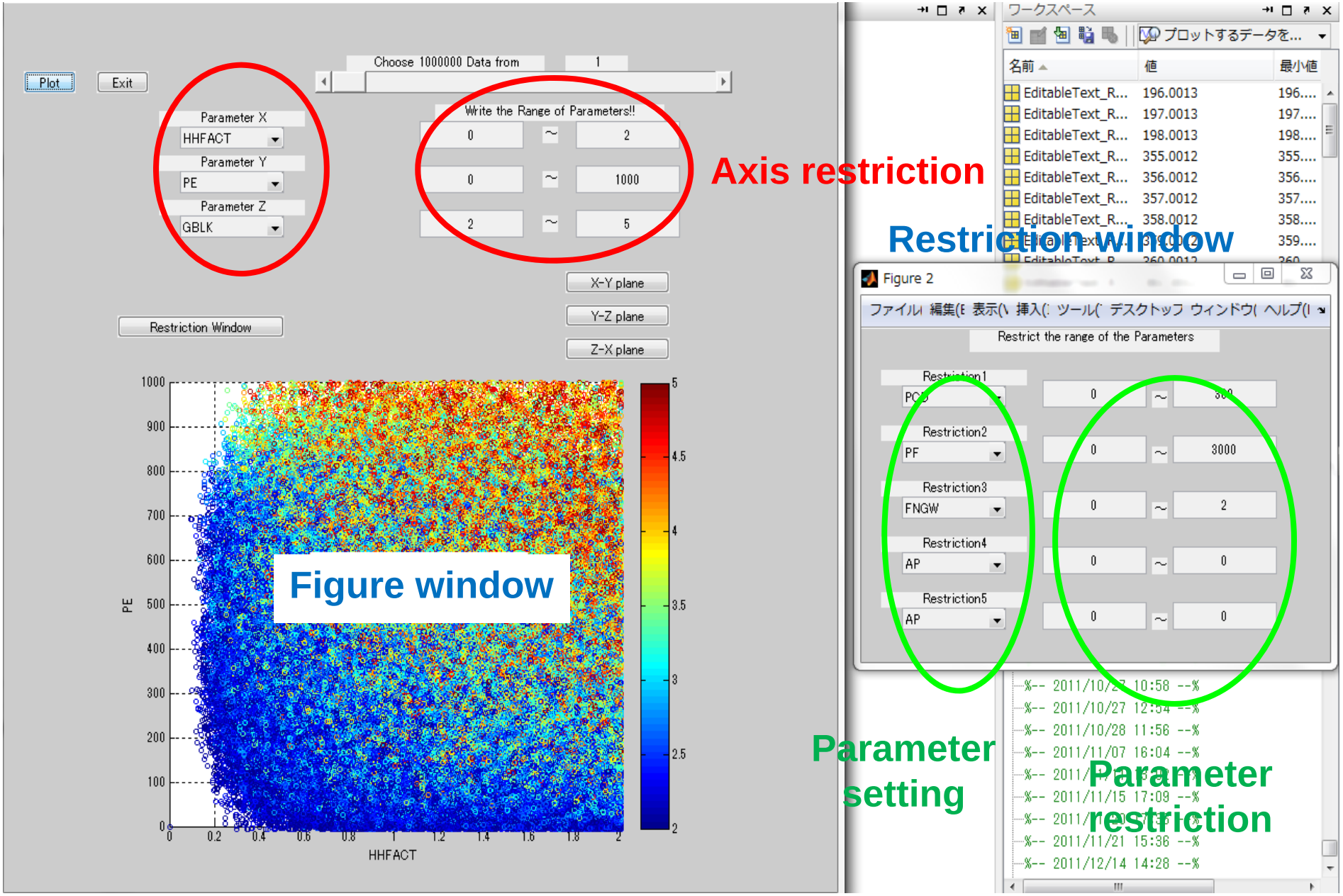
Acknowledgements : Mrs. Y. Miyoshi and K. Mitsueda

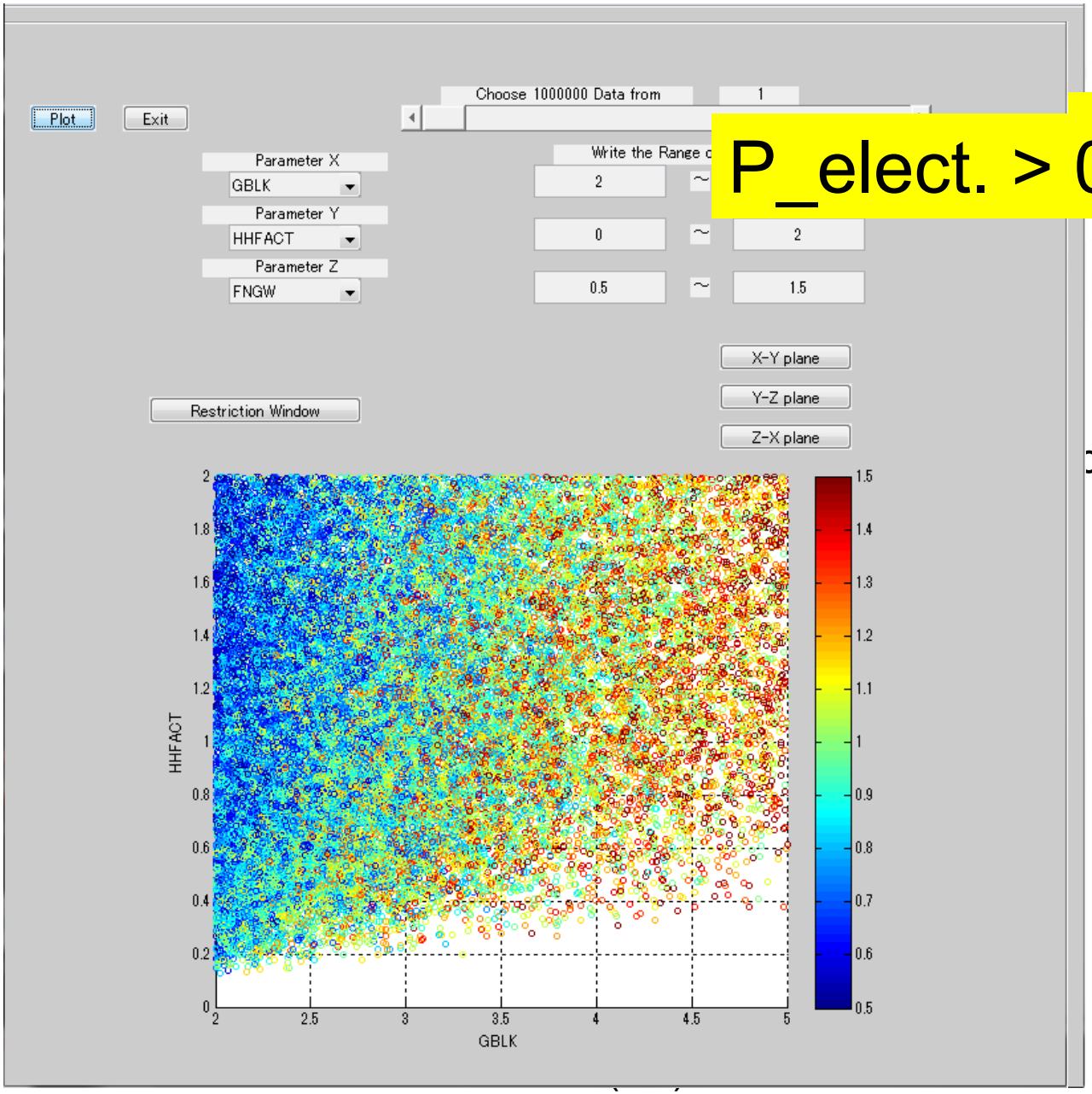
Platform of the Integrated Design Code



Visualization of system code results (1)



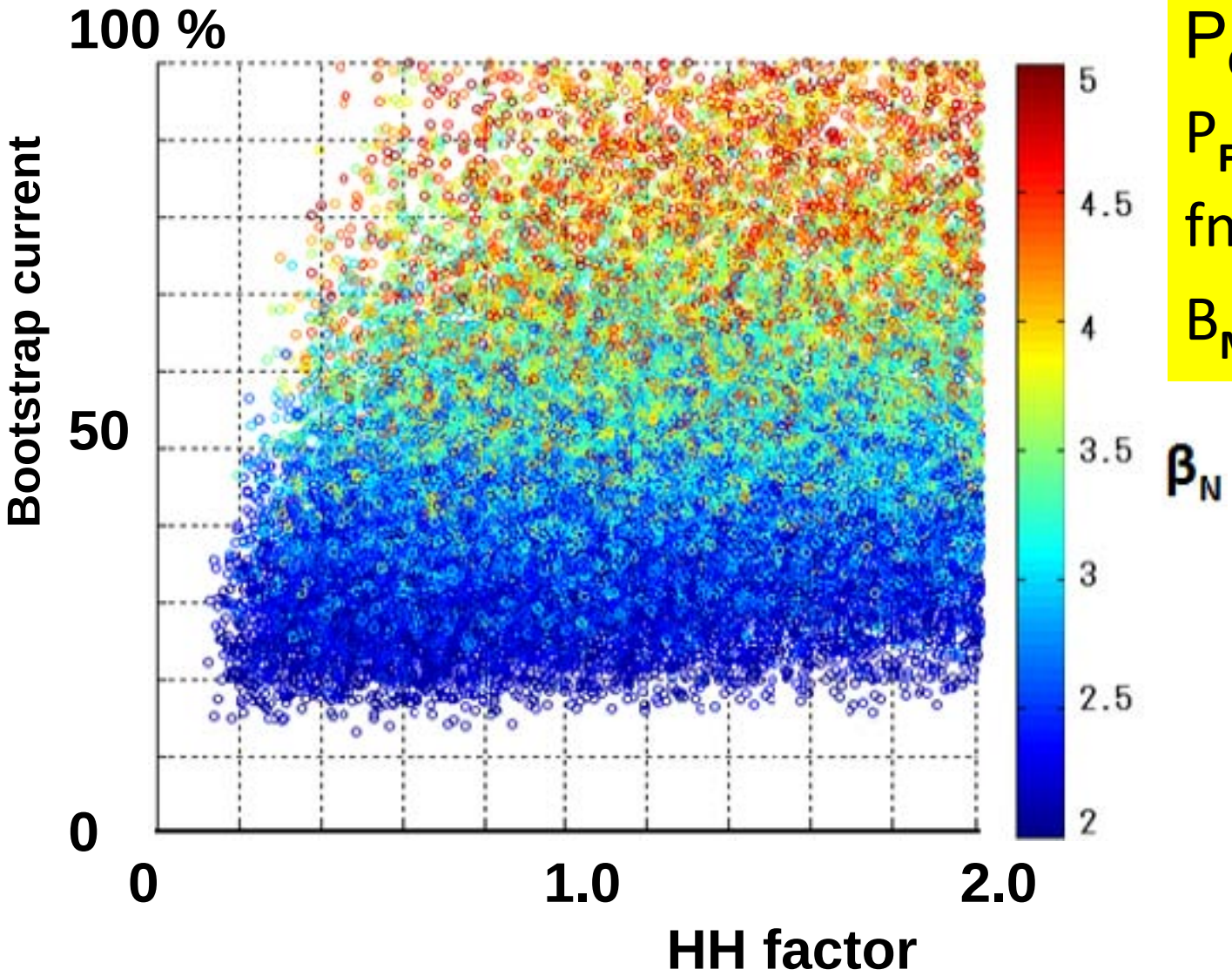
Visualization of system code results (2)



P_elect. > 0 GW

ction

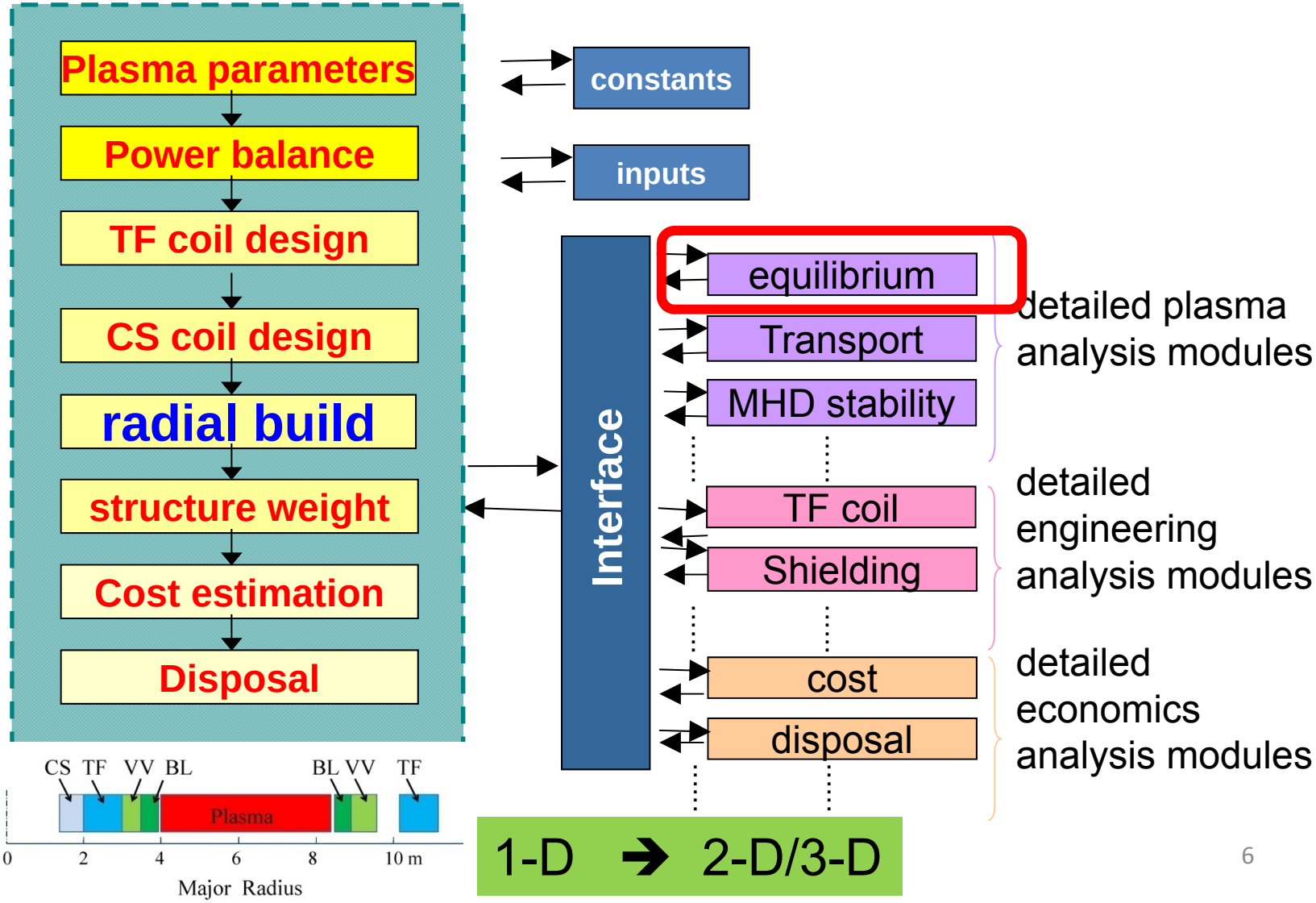
Relation between HH, β_N and f_{bs}



P_{CD} < 300MW,
P_F ~ 3GW,
fn_{GW} 0.5～1.5 ,
B_{MAX} =16±0.5T

Platform of the Integrated Design Code

System code FUSAC



Automatic Optimization of PF coil positions and currents

@Given parameters

Rp, a, Δ, Hmax

κ, δ

b = κ a, c = δ a

@ category of PF coils

* Divertor coil

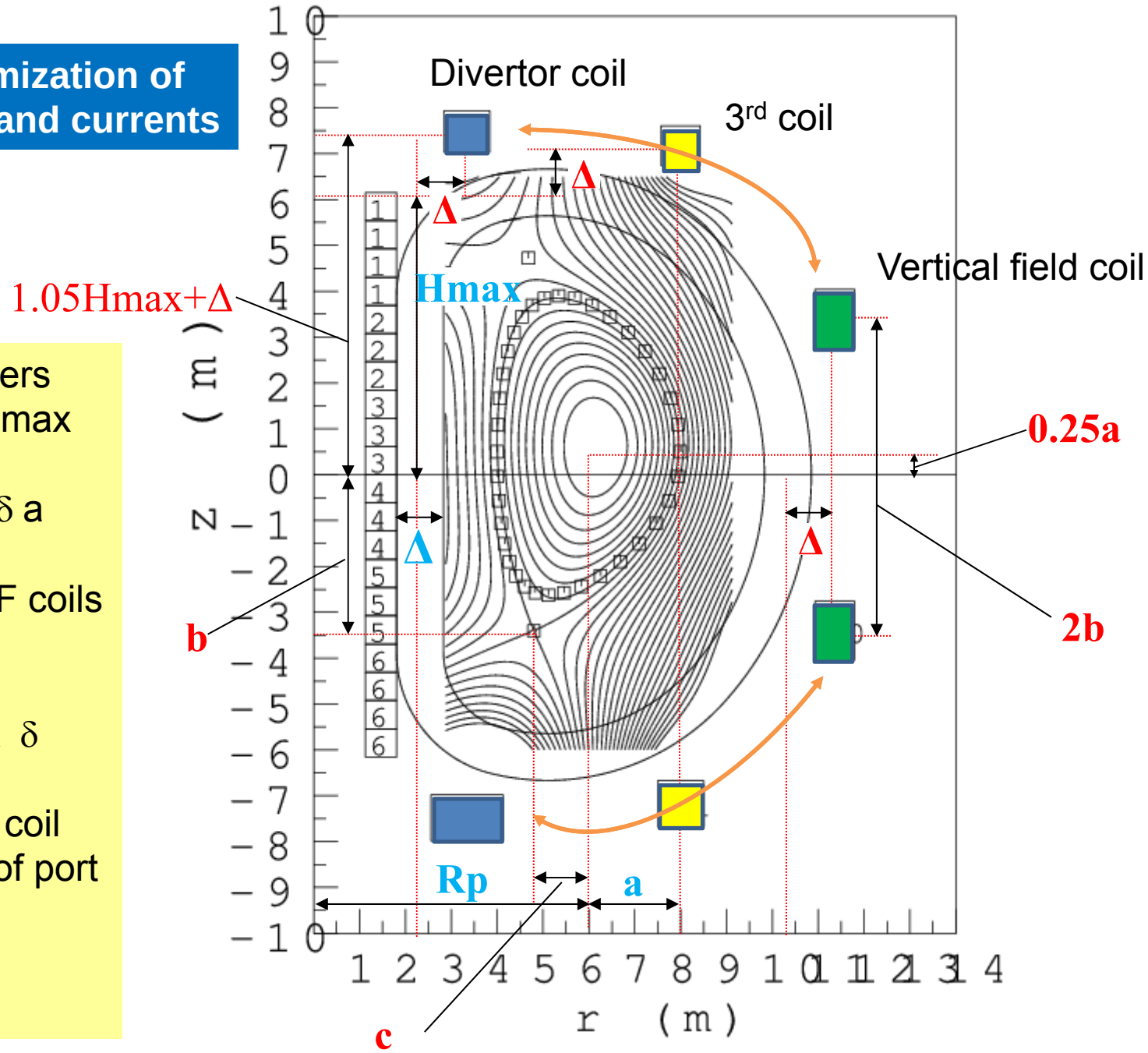
X-point, κ δ

* Vertical field coil

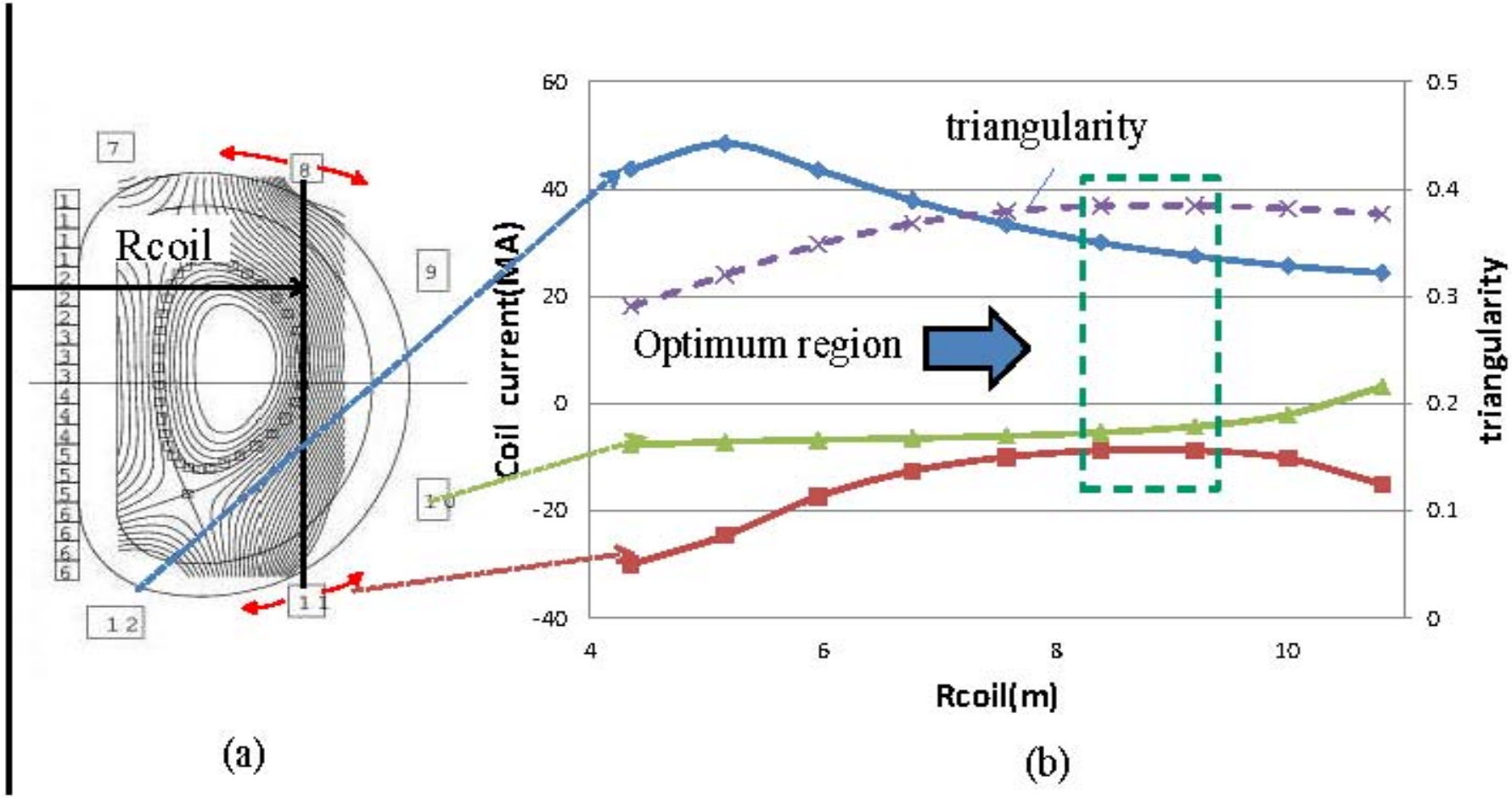
Opening of port

* 3rd coil

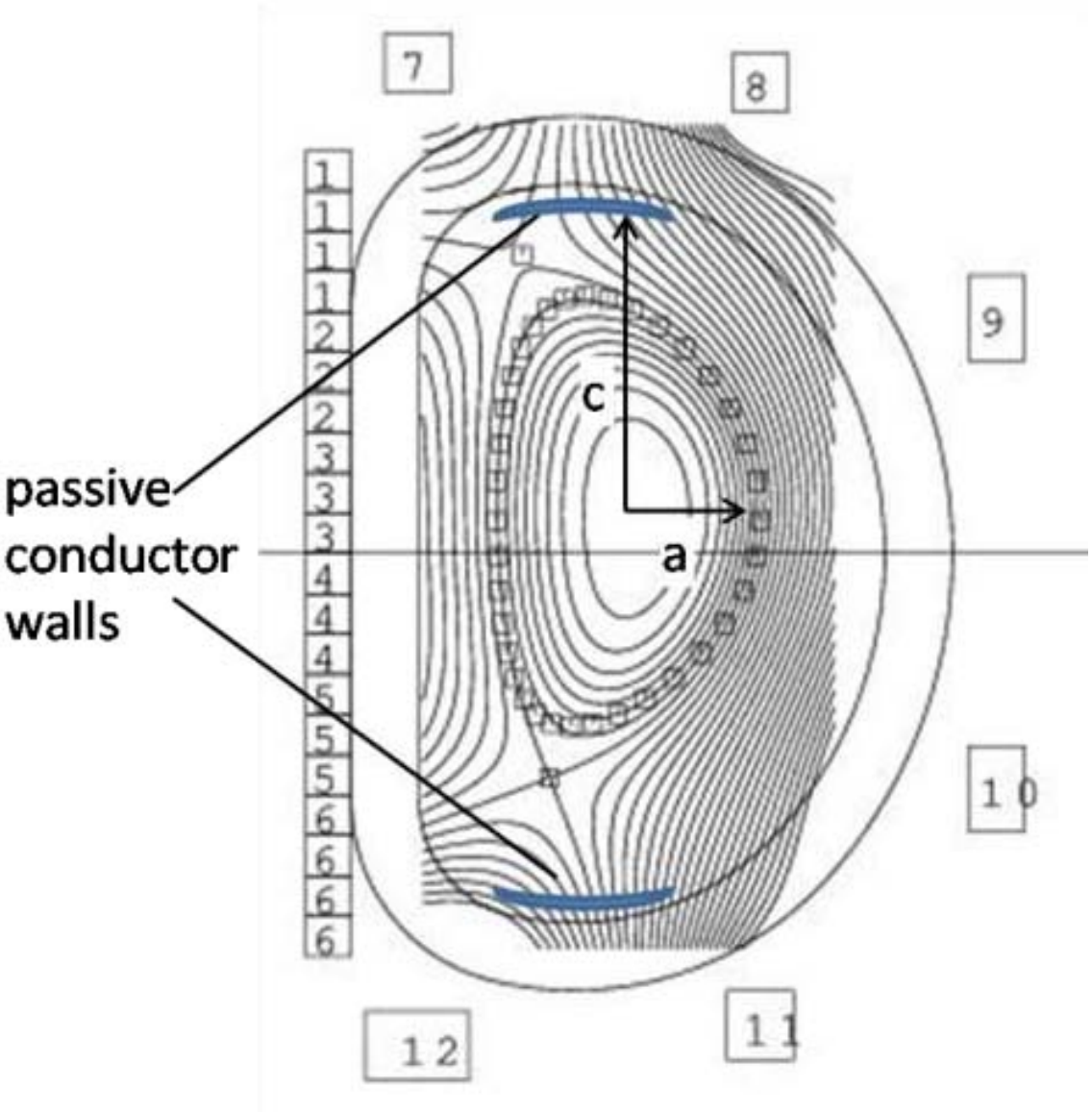
, κ δ



Optimization of PF coil position



Consideration on the vertical instability



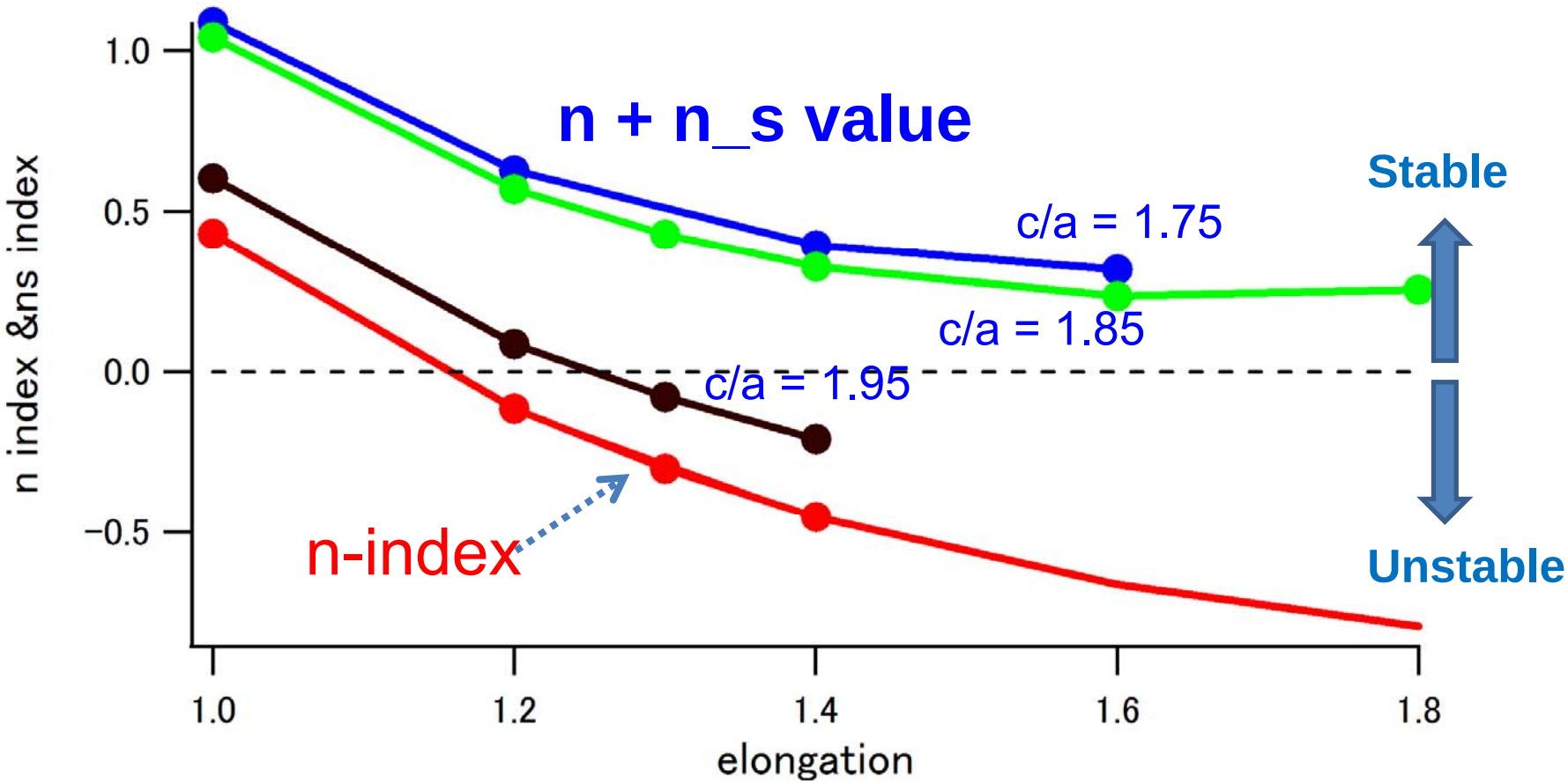
$$n = -\frac{R}{B_Z}\frac{\partial B_{Z(EQ)}}{\partial R}$$

$$n_s = -\frac{R}{B_Z}\frac{\partial B_{Z(Shell)}}{\partial R}$$

Stability condition
on the vertical instability

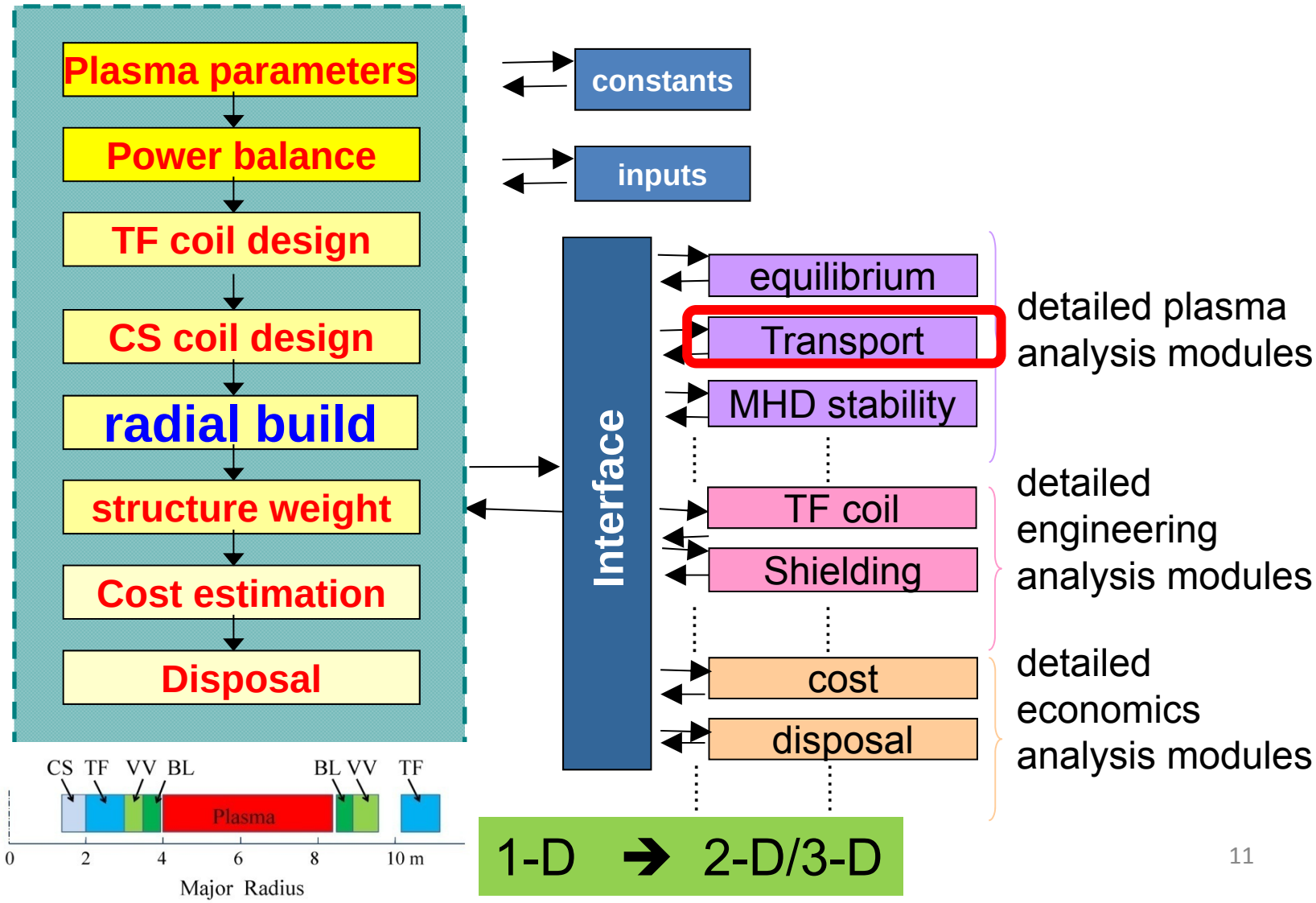
$$n + ns > 0$$

Consideration on the vertical instability(2)



Platform of the Integrated Design Code

System code FUSAC



Installation of 1.5-D transport code

2-D Equilibrium (Grad-Shafranov equation)

$$R^2 \frac{\partial}{\partial R}\left(\frac{1}{R^2}\frac{\partial \Psi}{\partial R}\right) + \frac{\partial^2 \Psi}{\partial Z^2} = -R^2 \frac{dP}{d\Psi} - \frac{d}{d\Psi}\left(\frac{I^2}{2}\right)$$

1-D Transport

$$\frac{\partial n_j}{\partial t} = \frac{dr}{dV}\frac{\partial}{\partial r}\Gamma_j + \langle S_j \rangle$$

$$\frac{3}{2}\frac{\partial p_j}{\partial t} = \frac{dr}{dV}\frac{\partial}{\partial r}\left(q_j + \frac{3}{2}\Gamma_j T_j\right) + \langle Q_j \rangle + \frac{3}{2}\langle T_j S_j \rangle$$

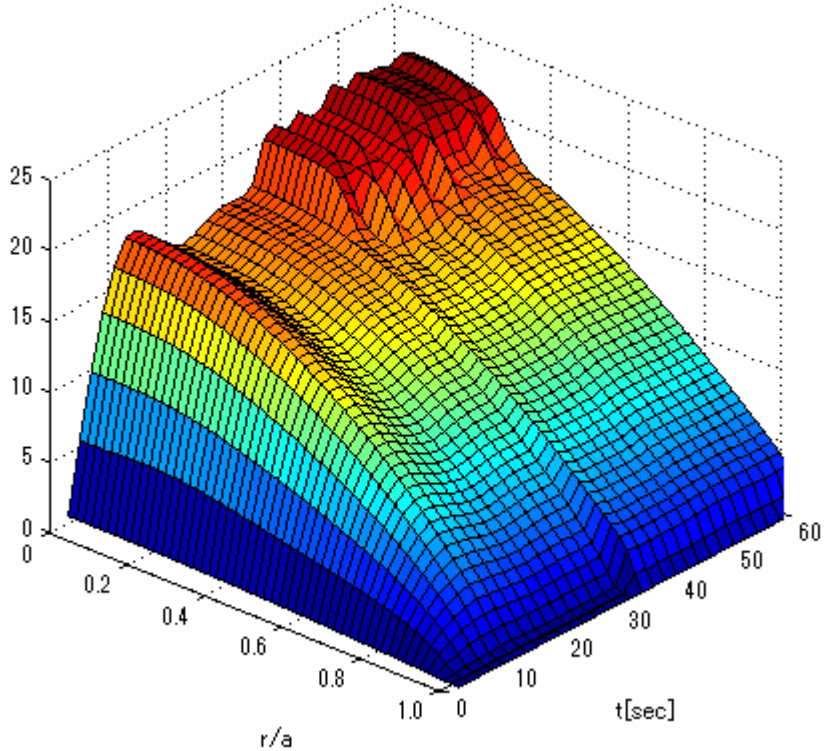
Particle flux $\Gamma_j = V' \langle |\nabla r|^2 \rangle \left(D_j \frac{\partial n_j}{\partial r} + n_j U_j \right)$

Heat flux $q_j = V' \langle |\nabla r|^2 \rangle \left(n_j \chi \frac{\partial T_j}{\partial r} + n_j U_j T_j \right)$

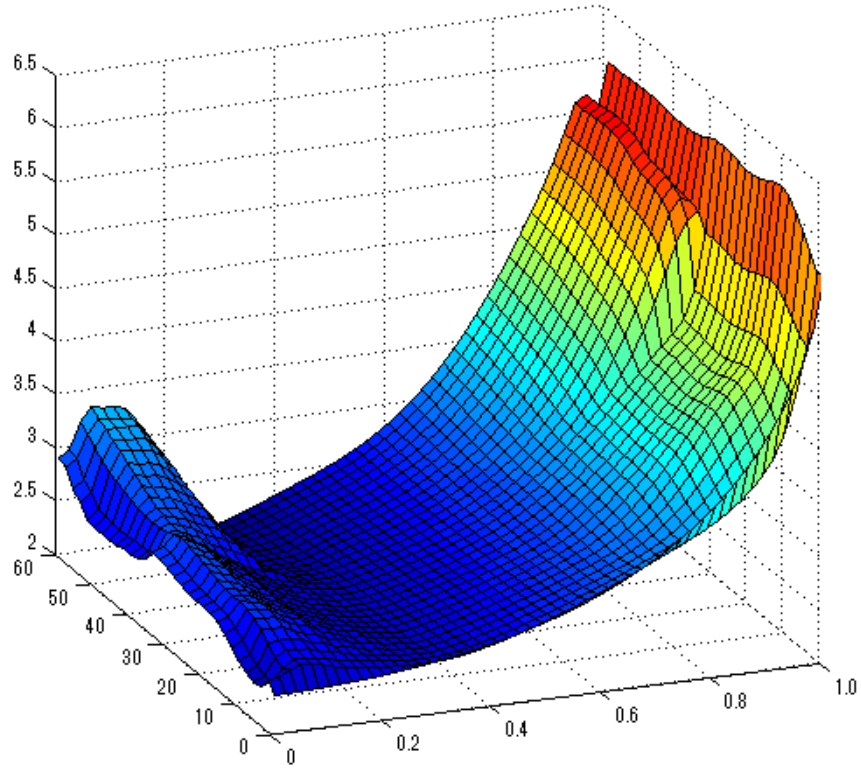
$$\langle Q_j \rangle = \langle Q_{j=e}^{joul} \rangle + \langle Q_j^{heat} \rangle + \langle Q_j^{fus} \rangle - \langle Q_{j=e}^{rad} \rangle + \sum_k \langle Q_{j,k}^{equip} \rangle$$

Temperature and safety factor profiles

Temperature



Safety factor

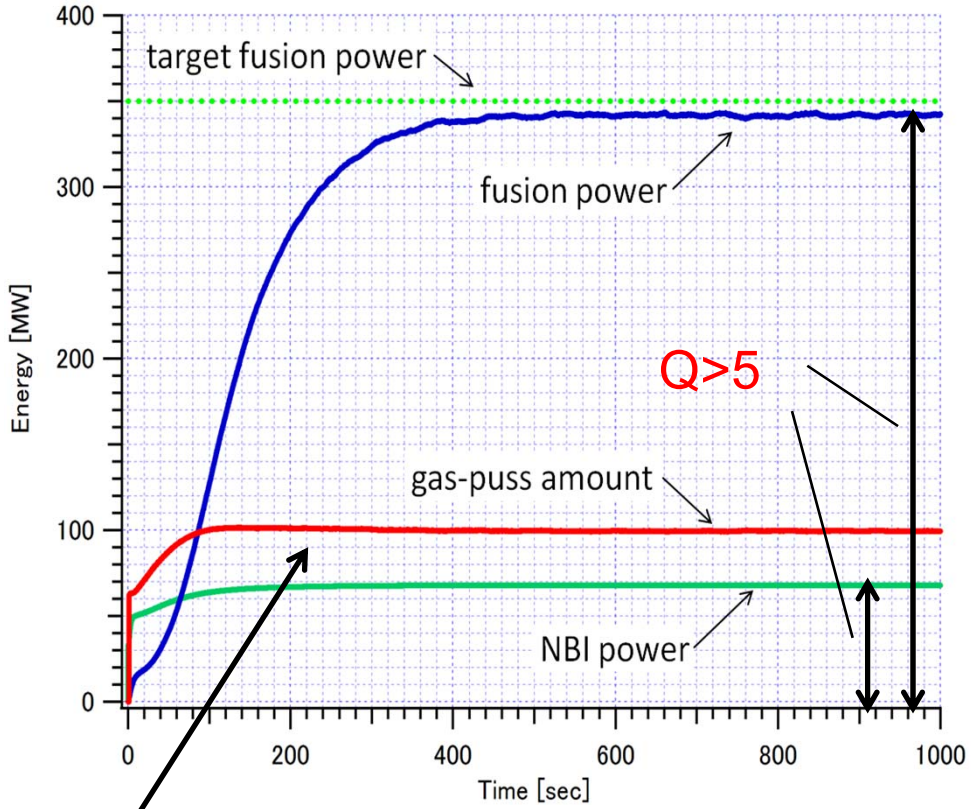


Fusion power control (1)

The input parameters are

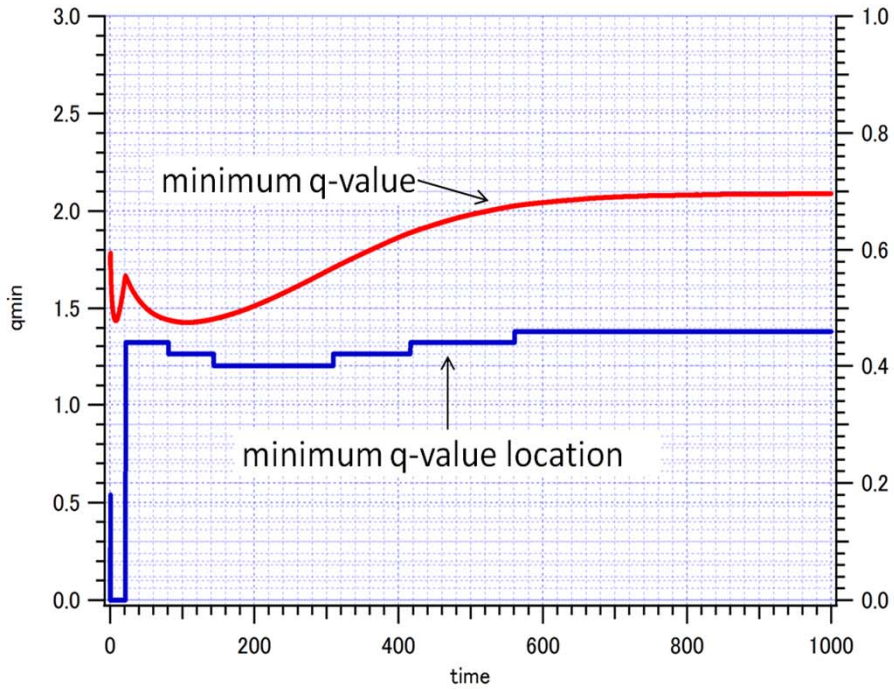
Rp=6.3m,
ap=1.75m,κ=1.8, δ=0.4
Ip=9MA, Bt=4.76T,
P_{nbi}=70MW, E_{nbi}=1MeV,

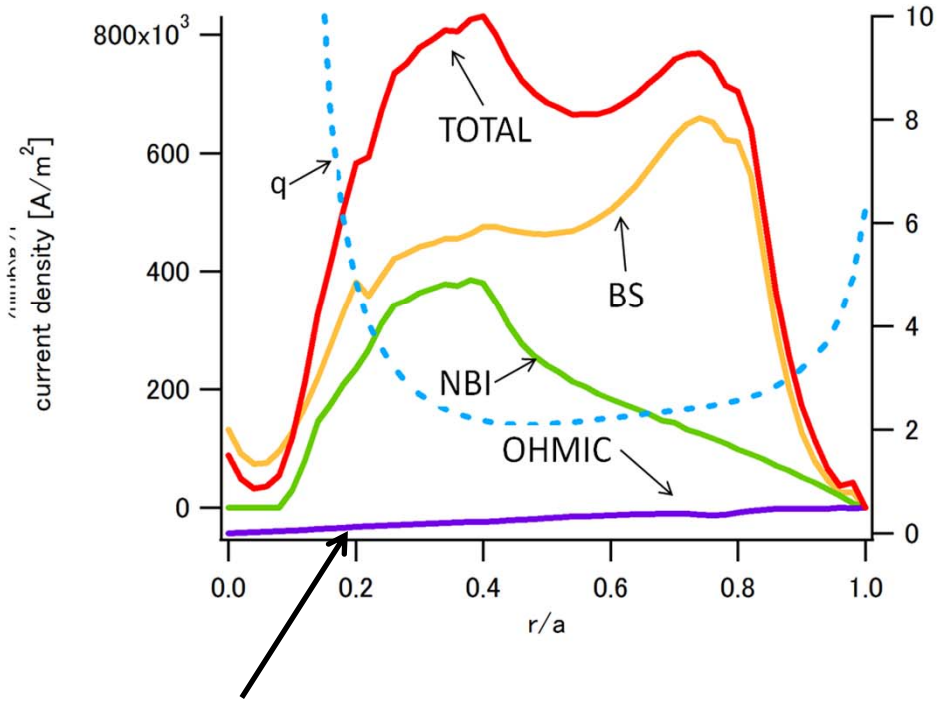
D_j=0.02/n_e(10^{20}m^{-3})
χ_j=0.08T_e(kev)/n_e(10^{20}m^{-3})



The gas-puff amount is controlled so as to keep the fusion power of Q = 5.

Fusion power control (2)





The ohmic current is nearly 0. In this case, it seems to be full steady state operation.

In this case,
f_{GW}=0.95,β_N=4.16

Control of Fusion Core Plasma

@ Which parameters should be controlled in a fusion reactor?

@ What kind of actuators are available?

@ What kind of parameters could be measured in a fusion reactor?

@ Which diagnostics could be applicable?

@ What kind of control logic could be employed?

Discussion on control parameters

Objective	control parameters
Power Plant	P_fus
Engineering issues	q_div, q_wall
Physics issues	β_N, n_GW, q_min, rotation
Plasma operation	R_p, a_p, κ, δ, d_gap

Discussion on actuators and control parameters

	gas-puff	pellet	NBI	EC	PF coil
ne	○	○	△		
Zeff	○	○			
fd,fT,fimp	○	○	△		
Ti			○		
Te			○	○	
qrad	○	○			
qelm		○			○
Ip			○	○	○
j(r)			△	○	△
Rp,ap					○
κ , δ					○
dgap					○
rotation			○		

Discussion on the feedback control

- **Control logic**

relationship between the control values and the actuators would be written as follows

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{pmatrix} \begin{pmatrix} P_{puf} \\ P_{nbi} \\ P_{pel} \\ P_{imp} \end{pmatrix} = \begin{pmatrix} P_{fus} \\ j(r) \\ n(r) \\ q_{div} \end{pmatrix}$$

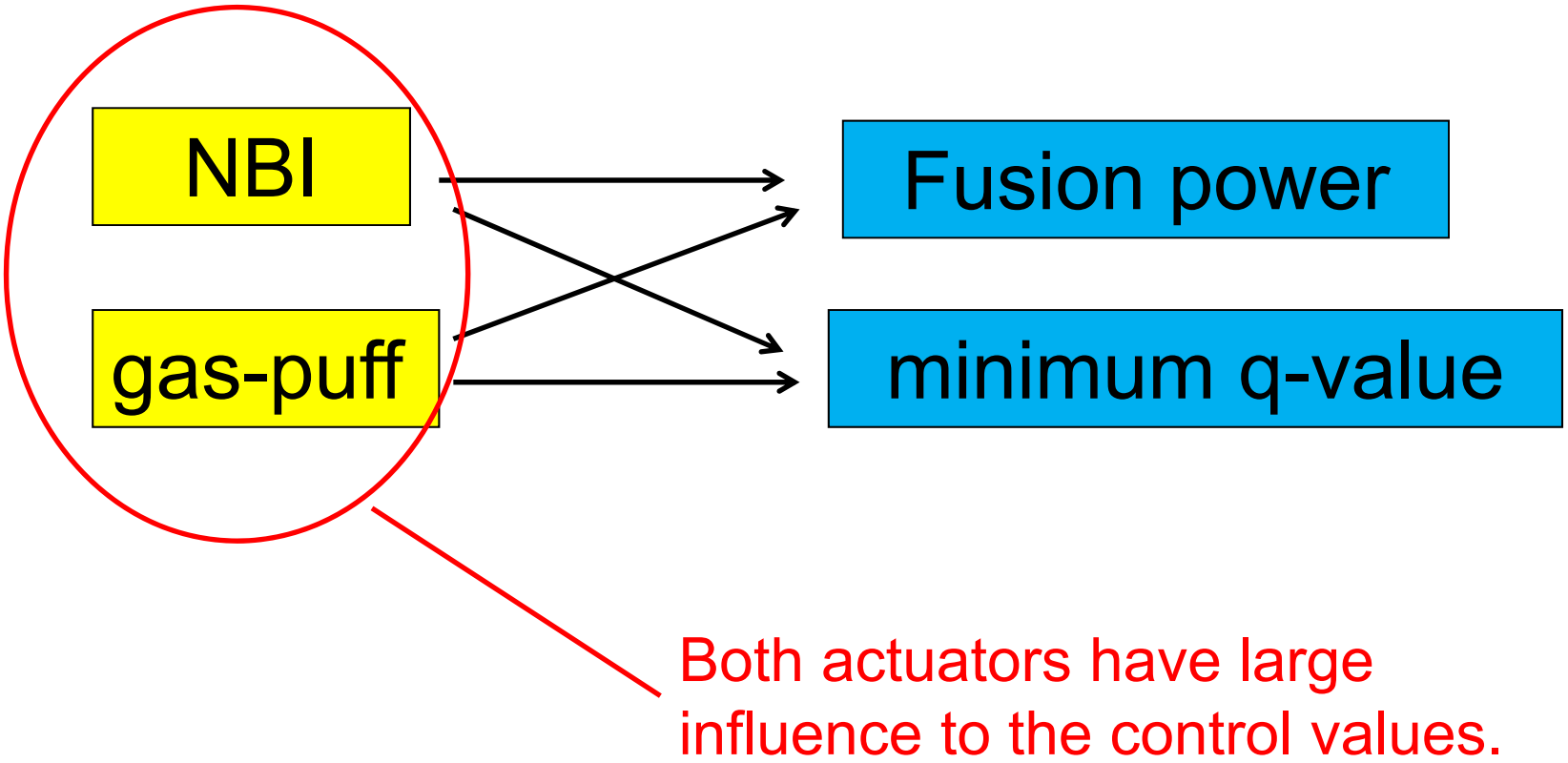
Governing tensor

Actuator vector

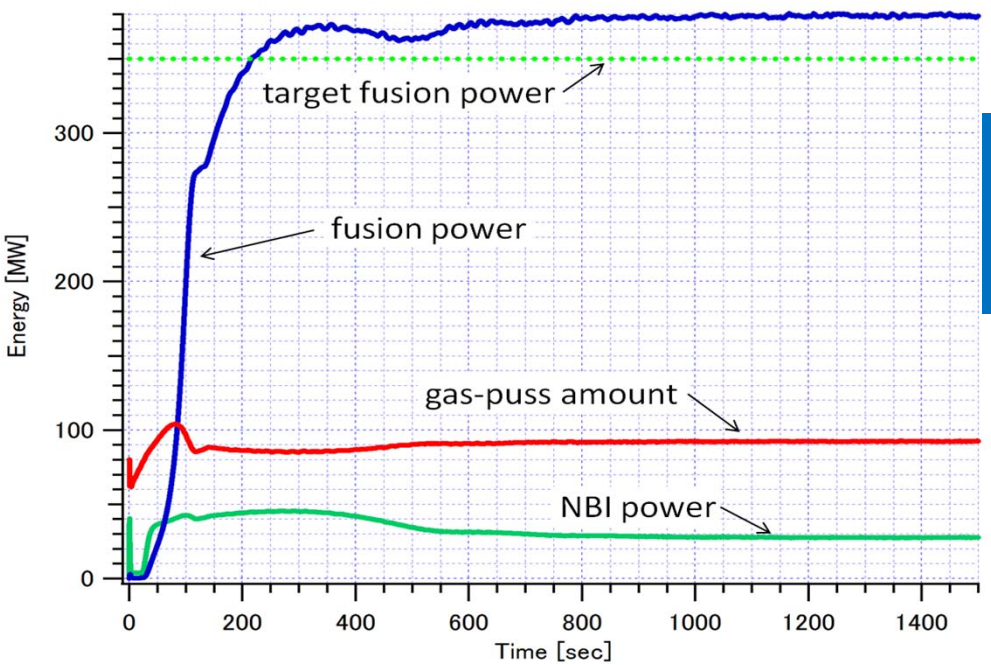
Control volume vector

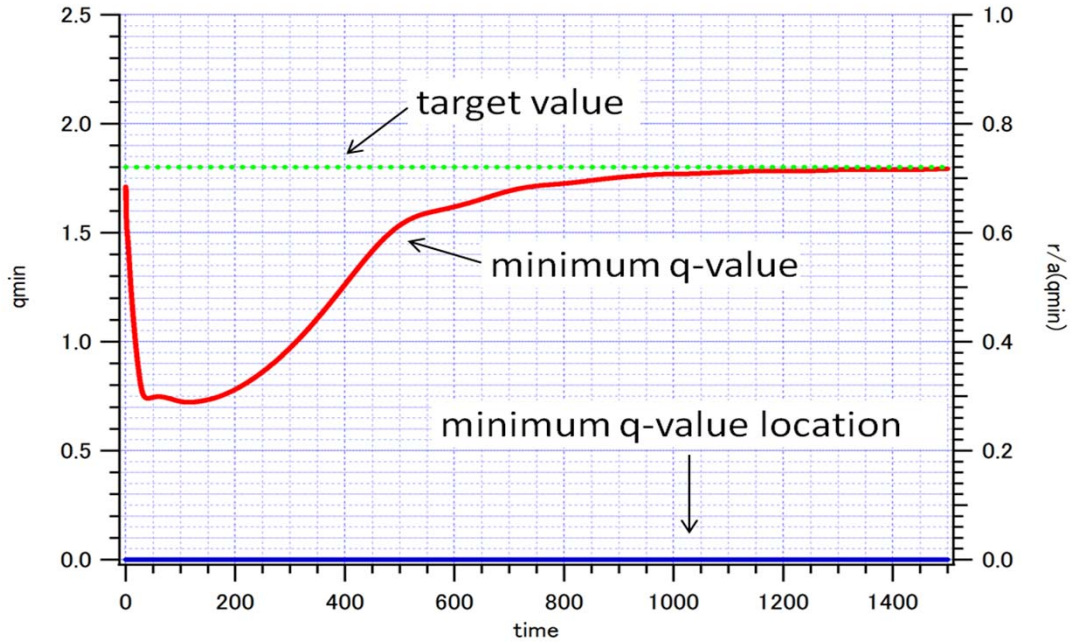
The ultimate goal is to find out the suitable components of these tensor and vectors

Simultaneous control simulation (1)



Simultaneous control simulation (3)

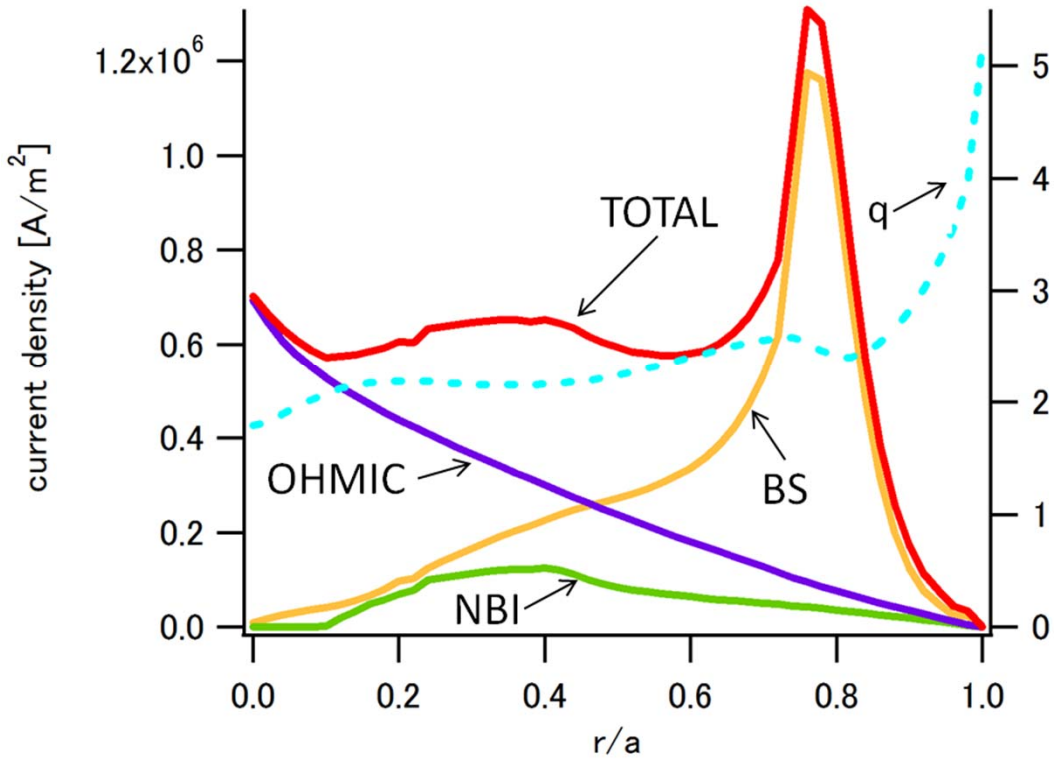




Simultaneous control simulation (4)

The ratio of ormic current is large and it is not full steady state operation

In this case, f_{GW}=1.043,β_N=3.30



The construction of more appropriate control logic is needed.