Programmatic issues to be studied in advance for the DEMO planning

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Preface

Fusion is an attractive long range big project.

For such a long range and unprecedented physics and engineering convolution development, two approaches are necessary.
The polar method

A firm view on the present basis
Reality

We can go up, step by step. But the peak we may reach may not be the right one.
View from the air

Two views should be combined
Many countries define that “DEMO is the last integrated R&D machine” in the Fusion reactor development.
If the DEMO is so defined,

• Critical Issues to be challenged and overcome as an energy system

1) Plan for development of the control system for the fusion power plant;
   * How to maintain a constant fusion output.
   Development of a program by integrating plasma physics, diagnostics, actuators, simulation codes, and control system

2) Diverter concept and its physics and engineering feasibility:
   * How to handle heat and particles

3) Technical feasibility of the breeding blanket and long range plan:
   * Technical feasibility and scenario of the blanket handling high grade heat
4) Maintenance of the in-vessel components including hot cell design, recycling and back-end management scenario:
   * Design a large hot cell (factory) in line with development of scenarios for the replaced components, recycling and radioactive waste management.

5) Overall scenario for developing QA system:
   * Development of the design code and standard, safety regulation, operation and maintenance scenario, etc., taking into account of the feature of the fusion system.
Issue 1  Fusion Output Control
from the airplane view

DEMO is the first demonstration machine of electricity production.

Whether or not the fusion is really attractive and worthy for commercial use is an crucial question?

This evaluation will be made not by fusion researchers, but from the users (utility company, industry, public etc.).

Accepting the advantage of the fusion characteristics, yet if the plant system is too much complicated, the users may not show interest in fusion plant.

Now, what are required for fusion as an energy plant?
#1 Fukushima No3 plant
Simple start up, and much simpler control
About 80% of the total plant are for safety relevant systems.
Requirements for the control of DEMO and beyond

1. Steady Electric Power generation = steady fusion thermal output ⇒ \( P_f = \text{constant} \)

2. The control system should be as simple as possible. Actuators should be minimum.

3. The frequency of the sudden stop must be lowest, once a year or less.

4. Plasma detection and heating/fueling systems will be severely restricted in a high neutron environment and space.

Recalling that fission control is just to keep recirculation water flow rate,
The fusion thermal output \( P_f \) must be expressed in terms of a function of the actuators \( A_i (i=1,2,3\cdots) \) as

\[
P_f = f(A_1, A_2, A_3 \cdots), \text{ precisely, } A_i \text{ is a command signal.}
\]

Q1 Can we establish such a functional form of \( f \) by the time of completion of the DEMO reactor?

\( \rightarrow \) Simulation codes system should include both prediction and real-time feedback control function.

The codes should be able to express most of the plasma behavior, validated existing machines and by ITER before final application to DEMO.

Such an integrated code system can be developed only by a long range, strategic manner, and require significant resources.
DEMO plant

Conceptual Design  Engineering Design  Construction  Operation

ITER burning plasma

Satellite Machines

Development of Codes
Role of DEMO

Demonstration of Electricity Generation
Find a single scenario to start up and to maintain burning
Find a minimum set of actuators and diagnostics
Suggestion for future improvements

Diagnostics for Control

Q: what is a minimum set of diagnostics?

Concern: High neutron flux and fluence, induced gamma ray radiation, limited space and access competing with breeding blanket and shield.
Figure 3.2- 1b Neutron and Gamma-ray fluxes during operation Outboard Side

ITER EDA Final Design Report
Particular concern:
+ magnetic flux measurements for control
+ optical measurements

Neutron flux: $2.5 \times 10^{15} ncm^{-2}s^{-1}$ (Y. Someya)

RIC: Radiation Induced Conductivity
RIED: Radiation Induced Electrical Degradation
RIEMF: Radiation Induced Electrical Motive Force

Tolerance for neutron flux and fluence
Influence of the structural materials and magnetic materials

Sensitivity strongly depends on the location of the sensors.

Find the sensor position and evaluate the feasibility.
In Japan, we launched a working body for “Sensing and Diagnostics coupled with Control of DEMO plant”

A total of 30-40 members form the fields of, plasma control, diagnostics, remote handling, blanket, in vessel components, reactor structure, and reactor design get together to discuss in a coordinated way.

Report will be completed a year later.
Issue 2  Divertor

Can we mitigate the heat load to the solid material wall?

Even for ITER, it may be marginal.
How to handle heat load in DEMO?
**SlimCS**

- $P_{\text{fusion}} = 2.95$ GW
- $P_{\text{heat}} = P_\alpha + P_{\text{ax}} = 600 \sim 700$ MW
- $P_{\text{out}} = 500 \sim 600$ MW
- $P_{\text{rad}} = 450 \sim 550$ MW
- $P_{\text{target}} < 50$ MW

**ITER**

- $P_{\text{fusion}} = 0.5$ GW
- $P_{\text{heat}} = P_\alpha + P_{\text{ax}} = 150$ MW
- $P_{\text{out}} = 100$ MW
- $P_{\text{rad}} \sim 50$ MW
- $P_{\text{target}} \sim 50$ MW

**Parameters**

**SlimCS**
- Major radius: $R_p = 5.5$ m
- Minor radius: $a_p = 2.1$ m
- Plasma current: $I_p = 16.7$ MA
- Toroidal field: $B_t = 6.0$ T
- Plasma volume: $V_p = 941$ m$^3$

**ITER**
- Major radius: $R_p = 6.2$ m
- Minor radius: $a_p = 2.0$ m
- Plasma current: $I_p = 15$ MA
- Toroidal field: $B_t = 5.3$ T
- Plasma volume: $V_p = 830$ m$^3$
A plane view on the power deposition

\( P_{fusion} \): fusion output
\( P_{target} \): power to the divertor plate
→ the stationary power to be absorbed in the wall of the reactor:

\[
\left( \frac{1}{5} + \frac{1}{Q} \right) \times P_{fusion} - P_{target} \sim 650 \text{MW}
\]

(Assume \( Q \sim 30 \), \( P_{fusion} = 3000 \text{MW} \), \( P_{target} \sim 50 \text{MW} \))

SlimCS

total surface area of the first wall: \( 880 \text{m}^2 (670+210) \text{ m}^2 \)
if the radiation spreads into the plasma facing wall, the average power density: \( \sim 0.7 \text{ MW/}\text{m}^2 \)
non-uniformity factor: assume \( f \sim 3 \)
→ the peak heat load to the 1\text{st} wall: \( 2.2 \text{MW/}\text{m}^2 \)
in addition to the neutron wall load and divertor
If we confine the radiation due to detached plasma in the divertor region, the average power loading will be

\[
\frac{(650\,MW - 50\,MW)}{210\,m^2} = \sim 3\,MW/m^2
\]

assume non-uniformity factor \( f \sim 3 \),
the peak heat flux to the divertor region would be

\[
\sim 9\,MW/m^2
\]

in addition to the normal divertor heat load.

→ Balancing of radiation into the first wall and the divertor region is inevitable, yet still it is marginal to handle these power levels.
Handling the Pulsed Heat Load

1) Thin plate approximation (1D)

This model can be applied when the heat can be dissipated in the direction of the plate thickness in a time scale of interest, and the temperature gradient is negligible;

\[ \Delta t : \text{heat pulse width [s]} \]
\[ \delta_0 : \text{plate thickness [m]} \]
\[ q_0 : 1\text{D heat flow [W/m}^2\text{]} \]
\[ \rho[kg/m^3], \ c[J/kgK] \]

\[ \rho c \delta_0 \Delta T = q_0 \Delta t \]

Then, the condition for melting of the plate is

\[ q_0 \Delta t \geq \rho c \delta_0 (T_{\text{melt}} - T_0) \quad [J/m^{-2}] \ldots \ldots (1) \]
2) Heat conduction in a 1D infinite solid

\[
\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial x^2} \quad a = \frac{\lambda}{c \rho} \quad \text{heat diffusion rate (} m^2/s \text{)}
\]

\[\rho \ (kg/m^3), \ c(J/kgK), \ \lambda \ (W/mK)\]

\[\xi = \frac{x}{2\sqrt{at}} \quad \text{is non-dimensional quantity, then}\]

\[
\frac{d^2 T(\xi)}{d\xi^2} + 2\xi \frac{dT(\xi)}{d\xi} = 0 \quad \rightarrow
\]

\[T = \text{erf}(\xi) = \int_0^\xi \exp(-u^2) \, du\]

if the surface heat flux is \( q_0 \),

\[T - T_0 = \frac{2q_0\sqrt{at}}{\lambda} \text{ierf}(\xi)\]

the surface temperature \( T_s = T_0 + \frac{2q_0\sqrt{at}}{\sqrt{\pi}\lambda} \)
Putting $\Delta T = T - T_0$, $\Delta t = t$,
the condition for the excess heat is
\[ q_0 \sqrt{\Delta t} \geq \frac{\Delta T}{2} \sqrt{\pi c \rho \lambda} \left[ J m^{-2} s^{-1/2} \right] \] ................ (2)
for melting $T = T_{\text{melt}}$
for elastic-plastic change $T = T_{\text{crit}}$

In the case of $W$, put
\[ T_0 (K) \ 300K, \ \rho (kg/m^3) \ 19300, \ c (J/kgK), \ 200 (at \ 3680K), \]
\[ \lambda (W/mK) = 89(at\ 3680K), \ \text{melting temp.} \ T_c(K) \ 3680 \]

then, $\Delta T = 3680 - 300 \sim 3400 \ K$

\[ \frac{\Delta T \sqrt{\pi c \rho \lambda}}{2} = \frac{\sqrt{\pi}}{2} \times 3400 \times \sqrt{200} \times 89 \times 1.93 \times 10^4 \]
\[ = 5.6 \times 10^7 = 56 \text{ MJ/m}^2 s^{-\frac{1}{2}} \]
Time scale and thickness

Surface heating

From the curve of $i_{erf}(\xi)$, most part of the heat can be hold within a depth of $\delta (0 \leq \xi \leq 0.5)$,

$$\xi = \frac{\delta}{2\sqrt{\alpha \Delta t}} \sim 0.5, \quad \rightarrow \quad \delta \sim \sqrt{\alpha \Delta t}$$

ex. 0.4msec pulse, at 1273K W,

$$\sqrt{\alpha \Delta t} = \sqrt{\frac{\lambda}{c \rho}} \Delta t = 0.12mm$$

Note: $q_0$ from eq.(1) and eq.(2) become equal only when $\delta = \sqrt{\alpha \Delta t}$
Polar method for divertor issues
steady power handling
how to mitigate ELM peak power
N.Oyama et al;
NuclearFusion 45 (2005) 871
Peaking of ELM energy to the divertor

- T.Eich et al: Inter ELM Power Decay Length for JET and ASDEX Upgrade and Comparison with Heuristic Drift-Based Model PRL107, 215001 (2011)

Analysis of measurement for inter-ELM attached plasma.

Scaling for power spread

\[ \lambda_{int} \approx \lambda_q + 1.64 w_{pvt} \]

Power to the divertor surface is multiplied by the flux expansion factor, \( f \sim 3 \) (SlimCS), 6 (ITER)
\[ \lambda_{int} = \frac{\int[q(s) - q_{BG}]ds}{q_{max}} f_x^{-1} \]
Plane view

If it is inevitable to decrease steady state heat load to the divertor target down to a level of \( \sim 10\text{MW/m}^2 \), by developing a highly radiative detouched plasma, how does the ELM heat superposition affect the divertor loading?

ex. in Eich 2011 paper,
- time duration
  - 99% (40ms) inter ELM
  - 1% (0.4ms) ELM
- heat loading
  - \( q_{\text{max}} \sim 10\text{MW/m}^2 \)
  - \( q_{\text{peak}} \sim 80\text{MW/m}^2 \)
- base temperature of the divertor plate during inter-ELM may be about 300~500°C
- ELM power \( q_0\sqrt{\Delta t} = 80\text{MW} \times \sqrt{4 \times 10^{-4}} \sim 1.6\text{MJ/m}^{-2}\text{s}^{-1/2} \)
- and \( T_s - T_0 = \frac{2q_0\sqrt{\alpha\Delta t}}{\varepsilon_0} = 108 \degree \text{C} : \) far from melting
Q: Does the heat accumulate due to repetition?
No, because the thermal diffusion depth for 40msec is
\[ x \approx \sqrt{\alpha \Delta t} \approx 1.2\text{mm} \]

The sharp peak temperature rise (\( \Delta T \approx 110\,^\circ\text{C} \)) by one ELM propagates and decays into the deeper position and can be cooled with the bulk heat.
Whether or not the ELM gives damage to the surface of the divertor plate depends on the time contribution to one cycle, and its peak load. (A view from the plane)
It is also indicative that attention should be paid in deducing the peak heat flux from the measurement of the surface temperature.

Namely, the heat flux $q_0$ can only be obtained by knowing a precise measurement of ELM pulse length ($\Delta t$) and the materials properties, through

$$q_0 = \frac{\Delta T}{2} \sqrt{\frac{\pi c \rho \lambda}{\Delta t}}$$

The other critical issues have to be visited taking into account of the priority and timing from the view point of power plant. Thank you for your attention!