INSTITUTE OF PLASMA PHYSICS

NAGOYA UNIVERSITY

COMMENTS ON THERMAL RUNAWAY EXPERIMENTS IN SUB-IGNITION TOKAMAKS

K. Yamazaki

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RESEARCH REPORT

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Further communication about this report is to be sent to the Research Information Center, Institute of Plasma Physics, Nagoya University, Nagoya 464, Japan.

ABSTRACT

Justification of deuterium-tritium opoerations is discussed from the physics viewpoint and optimal thermal runaway experiments in high-field, high-density compact tokamaks are suggested within the minimization of the induced radioactivation.

1. INTRODUCTION

In the near future, tokamak experiments with deuterium-tritium reactions will give us a lot of new informations on alpha particle physics.[1] At present four big tokamaks (TFTR, JET, JT-60, T-15) are aiming at the break-even point and several projects (for example, INTOR, FER, ETF/FED, Zephyr/CITR, etc.) are/were conducted toward ignition break-through no matter how standard or compact. However there still remains a big gap between break-even experimental plans and ignition projects, because of the constraints of technology, budget and safety problems. At this moment, it is impossible to justify the construction of ignition devices only from the physics viewpoint and such big plans should be decided from the stand-point of engineering, technology, budget and safety. However it seems to be a nice strategy to build a medium-sized D-T device between the break-even and the ignition partially based on the physics interest in burning plasmas, and to study critical issues related to fusion reactor physics and engineering as soon as possible.

In this note, we will discuss the rough condition for thermal runaway due to alpha-particle heating for the purpose of justifying D-T operation of medium-sized tokamak.

2. JUSTIFICATION OF REACTING PLASMA EXPERIMENTS

Burning plasma experiments with tritium handling may give rise to a great deal of difficulties related to technological, social and political constraints. We should take a careful choice to go to a D-T burning experiment taking various factors into account. Figure 1 shows rough sketch of merits/demerits of burning plasma experiments as a function of break-even parameter Q.

From the stand-point of physics interests, four items are shown in this figure. Even in the range of low Q value we may study single particle behavior of alpha particles *which can be simulated* by pure D discharges[2)] and does not lead to a strong justification of D-T reaction experiments.[3)] The possibility of the occurrence of alpha-particle-driven microinstabilities is one of key issues of burning plasma physics. Although these instabilities may be excited in adiabatic compression tokamaks,[4)] we may not expect them in the operation regime of commercial fusion power plants.[5,6)] The most important issue to justify tritium operation from the physics viewpoint is the heating effect of alpha-particles. The break-even condition (Q = 1) is equivalent to that 20 percents of total heating input power is due to alpha-particle heating. Therefore it is very important to reach the break-even point for detecting some effects of alpha particle heating as well as for demonstrating the so-called scientific feasibility politically. The strongest justification of burning plasma experiments is undoubtedly to demonstrate the ignition state (Q = ∞). Even in sub-ignition states there is a possibility of thermal runaway and we need burn control, which can also lead to a strong justification of reacting plasma experiments from the physics viewpoint.

As for engineering issues, tritium handling, shielding, blanket and material test experiments are interesting items. Aside from these academic interests, we should consider critical constraints on the burning plasma experiment, that is, tritium restriction, budgetary limitation and safety problems.

If we want to go to a high-Q scenario of the experiment, we will come across a lot of difficulties to overcome. Therefore, the objective of the experiment should be clarified, and then we should take into account which levels of Q value and how long pulse width of D-T discharges are required for that purpose. Some conditions for justifying D-T operation have been discussed related to the appropriate alpha heating$^{3)}$ and the possible usage of thermonuclear instabilities.$^{4)}$

In the following section, we will discuss the condition of design parameters for thermal runaway in sub-ignition states of the range of $1 < Q << \infty$.

3. THERMAL RUNAWAY CONDITION IN SUB-IGNITION STATES

In order to estimate the condition for thermal runaway a simplified zero-dimensional model is adopted,

$$3n \frac{d}{dt} T = \frac{n^2}{4} <\sigma v> W_\alpha + P_{in} - \frac{3nT}{\tau_E} , \qquad (1)$$

where n, T, $<\sigma v>$, W_α, P_{in} and τ_E denote plasma density, temperature, fusion reactivity, alpha-particle energy, external input heating power and plasma energy confinement time, respectively. By linearizing this equation ($T = T_o + \delta T$), we obtain the growth rate of thermal instability,

$$\gamma_T = \frac{1}{3n}\frac{d}{dT}\left(\frac{n^2}{4}<\sigma v>W_\alpha + P_{in} - \frac{3nT}{\tau_E}\right)_{T_o} , \tag{2}$$

Here we will assume

$$\frac{dP_{in}}{dT} \sim 0 ,$$

and

$$\tau_E \propto T^s ,$$

then,

$$\gamma_T\tau_E = \frac{Q}{Q+5}\frac{d\ln<\sigma v>}{d\ln T} + s - 1 . \tag{3}$$

A critical Q value for marginal stability against thermal runaway is given by

$$Q^{cr} = \frac{5\ (1 - s)}{\frac{d\ln<\sigma v>}{d\ln T} - (1 - s)} . \tag{4}$$

When the Alcator scaling is acceptable even in nearly ignited states, the change of the energy confinement time due to temperature rise can be neglected ($s = 0$). If the neoclassical loss is dominant ($s = 1/2$), the system is more unstable against thermal runaway. The growth rates for these two cases are given in Fig.2. Marginal Q values for thermal instability excitation, Q^{cr}, are shown in Fig.3. It should be noted here that in rather low Q (Q = 2-3) low temperature (T = 5 keV) regime, we may except onset of weak thermal runaway ($\gamma_T^{-1} = (2\text{-}5)\cdot\tau_E$) which may be detectable in the experiment when the radiation energy loss is not dominant.

4. OPTIMAL THERMAL RUNAWAY EXPERIMENTS

As pointed out above, burning plasma experiments are bounded by various technological and social constraints, especially cost and safety. Here some aspects on the design of medium-sized burning tokamak devices will be presented in relation to the induced radioactivation and safety problems.

The radioactivation due to fusion-generated neutrons makes maintenance of the device difficult and gives rise to various problems when the remote handling technique is not established. In the physics-oriented burning plasma experiments hence we should reduce total amount of neutron flux as much as possible within the range of the experimental objective. Roughly speaking, the accessibility and safety of the device against induced radioactivation may be inverse-proportional to the total neutron flux,

$$\text{safety \& accessibility} \propto (NQ\tau)^{-1} , \tag{5}$$

where N and τ mean total burning shot number and burning pulse width, respectively. When we want to do experiments for thermal runaway described in the previous section, for instance, pulse length should be as long as

$$\tau \sim 5(\tau_E + \gamma_T^{-1}) . \tag{6}$$

Rather high Q operations make it possible to detect the thermal runaway in the experiment with short pulse discharge, while rather low Q operations demand a long pulse experiments. In both cases, radioactivation induced by fusion-produced neutrons proportional to $Q\tau$ may not be minimized. We can say that the most effective thermal runaway experiment should be carried out under the condition:

$$Q \sim 2Q^{cr} ,$$

and (7)

$$\tau \sim (5\text{-}10)\tau_E .$$

which was derived with the minimization of the value $Q\tau$ by fixing the confinement time τ_E. For example, for T = 5 keV, Q = $\sim$3, and for T = 10 keV, Q = $\sim$5. According to this discussion, rahter low-temperature high-density operation scenario like compact high-field tokamaks (e.g., Zephyr) is more effective for thermal runaway experiments than high-temperature medium-density scenario like standard tokamaks (e.g., TFTR, INTOR). Some examples of these high-field devices are listed in Table 1. Here the right-hand terms of Eq.(1) with parabolic density and temperature profiles were used for calculating Q values in this table. As for global energy confinement time τ_E, Alcator scaling for electron confinement, τ_{Ee}, and neoclassical scaling with 1.5 times thermal conductivity for ion confinement were assumed and bremsstrahlung radiation loss was taken into account. The high-field tokamak devices with the toroidal magnetic field of 8 or 9 tesla, whose major radius is same as that of the PLT device, may enable us to investigate thermal runaway phenomena effectively within the minimization of radioactivation induced by fusion neutron flux.

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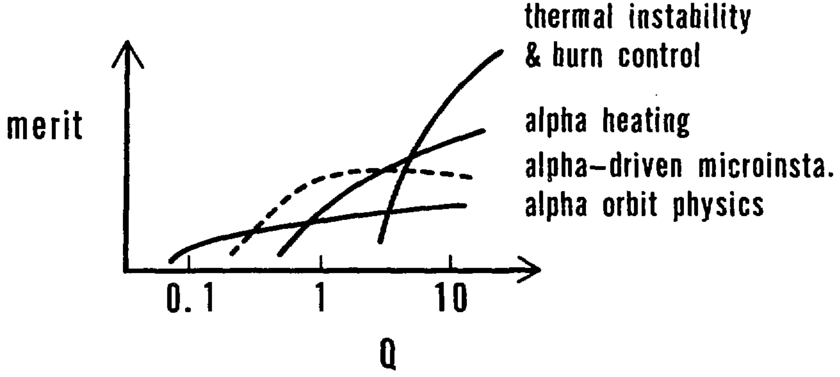
Table I. Typical performance of high-field compact tokamaks for thermal runaway experiments.

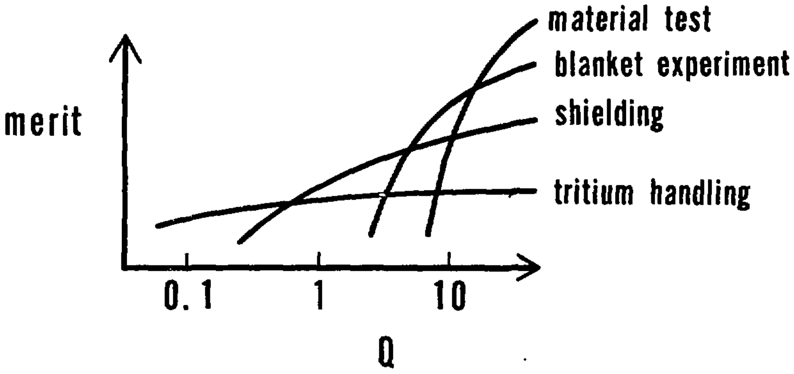
$R = 1.4$ m, $q_a = 2.5$,
$R/a = 3.5$, $T_e = T_i = 8$ keV,
$b/a = 1.5$, $\beta = 5.0$ %

B_T(T)	7	8	9
n (cm^{-3})	2.5×10^{14}	3.3×10^{14}	4.2×10^{14}
τ_E (s)	0.13	0.15	0.17
P_H (MW)	18.4	16.6	13.2
P_α (MW)	7.0	11.9	19.1
I_p (MA)	2.6	3.0	3.3
τ_E/τ_{Ee}	0.63	0.56	0.49
Q	1.9	3.6	7.3
Q/Q^{cr}(s = 0-1/2)	$0.7 \sim 1.8$	$1.4 \sim 3.4$	$2.7 \sim 7.0$
$\gamma_T \tau_E$(s = 0-1/2)	$0 \sim 0.29$	$0.26 \sim 0.71$	$0.71 \sim 1.21$

(a) Physics issues



(b) Engineering issues



(c) Social constraints

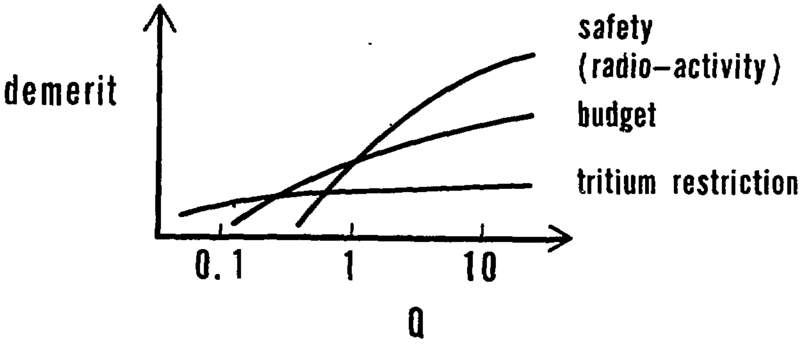
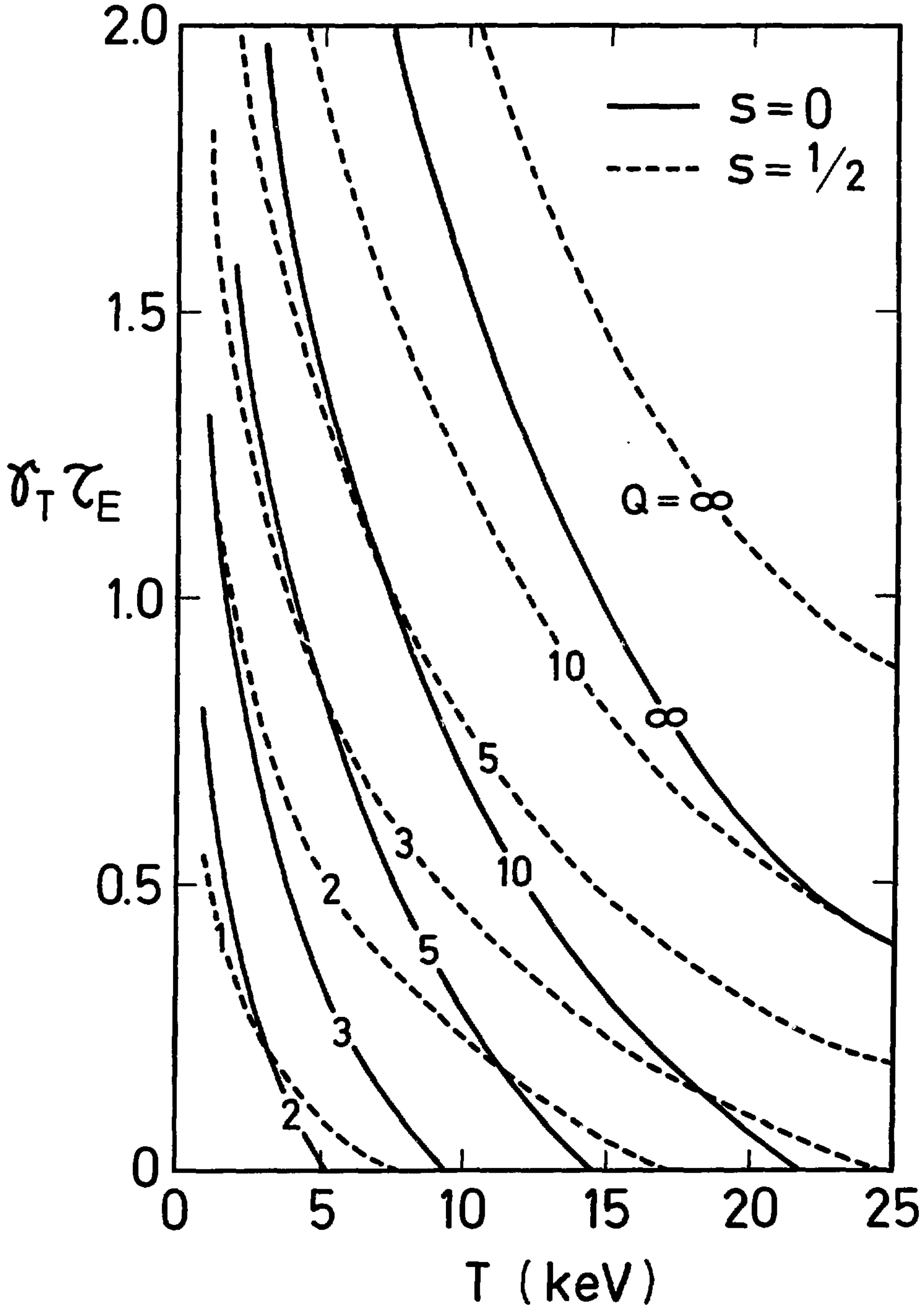


Fig.1 Merits and demerits of D-T burning plasma experiments as a function of fusion energy gain Q.



<u>Fig.2</u> Products of the growth rate of thermal runaway γ_T and the energy confinement time τ_E for Alcator scaling (s = 0) and neoclassical scaling (s = 1/2).

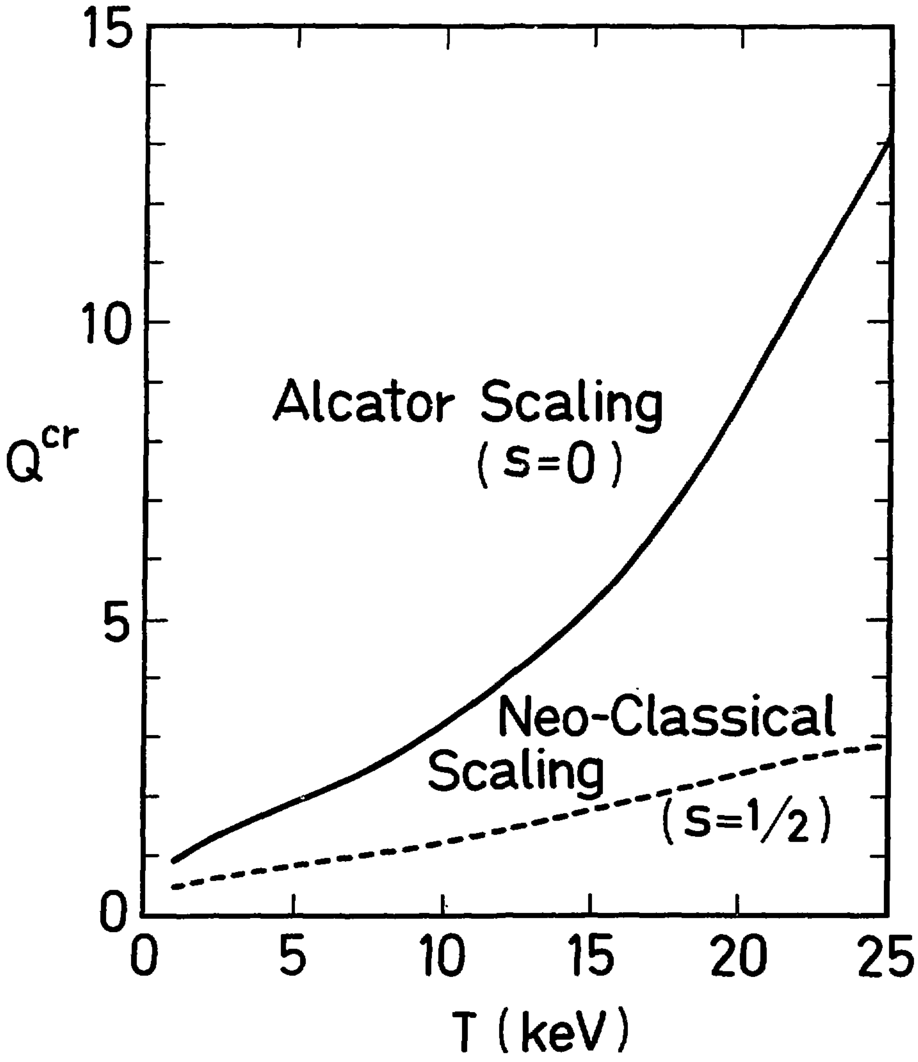


Fig.3 Critical Q values for the excitation of thermal instability.