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MHD and Current Drive Analysis of Demo-plant Core Plasma for Early Realization of Electric Power Generation

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1. Introduction

The normalized beta (β_N) is the most important parameter to reduce cost of electricity (COE) of tokamak power plant. The authors and the colleagues have proposed an economical fusion plant CREST [1], where a beam driven reversed shear plasma with β_N=5.5 stabilized by a closed conductive shell was assumed. The CREST (major radius R_0=5.4m, aspect ratio A=3.4) has been proposed as a commercial reactor, and is not pertinent to a demo-plant which follows the ITER.

Recently, we have proposed a demo-plant 'Demo-CREST (R_0= 7.25m, A=3.4)' as a fast path to realize CREST-like commercial plants. The wide parameter survey for plasma design of Demo-CREST was done[2,3]. In the initial (basic) operation stage, the Demo-CREST is operated with a moderate β_N (1.9~3.4) and with a blanket designed by a conservative standard to demonstrate net electric output in plant scale as early as possible. This plasma is expected to be stable without closed conductive shell for stabilization of the low n kink modes. In the second (advanced) operational stage of the Demo-CREST, β_N is increased as high as possible up to the range of 4.0 ~ 5.4 in order to establish economical feasibility by advanced tokamak operation. This is a challenging target toward attractive commercial reactors by fusion energy. Based on an analysis of world energy scenario [4], it has been shown that the break-even price of electricity for introduction of fusion energy is not satisfied with β_N less than 3, and β_N over 5 is very desirable for early realization of fusion power plants[5]. In order to achieve β_N higher than 4, profile control of currents (beam driven and bootstrap) and the position of a conductive shell to stabilize ideal kink modes are critical issues.

In the engineering point of view, the position of the shell, defined as $R_{ext} = a_w /a$, is a key parameter, where a_w and a are the minor radii of shell and plasma at mid plane, respectively. If R_{ext} >1.3 is allowable, the shell can be placed at the "back" of breeding blanket or it might be expected that the permanent shield works as a kind of stabilization shell. It is no doubt desirable to simplify the design of breeding blanket and to reduce electro-magnetic force. On the other hand, if R_{ext} < 1.3 is required, the shell should be placed "in" the breeding blanket.

In this paper, it is shown that, in the basic stage, the breeding blanket without the inside-shell is acceptable at β_N < 3.0 and the case of β_N =3.4 is marginal. In the advanced stage where β_N > 4.0, it is necessary to install the conductive shell in the breeding blanket for stabilization of the low n kink. Then, the blankets should be replaced by advanced ones before the advanced stage. The RWM (resistive wall modes) can be destabilized in such wall-stabilized equilibrium [6,7]. The technique to control the RWM is not completed yet, but in progress[8,9]. Active coils for the RWM control might be required, but are not considered in this design study. The replacement process with the advanced blanket will result in a suitable demonstration of the maintenance scenario of power plants. Such step-up operation scenario is a rational approach for demonstration reactor.

2. Equilibria for the basic operation stage

The result of an ideal MHD analysis for Demo-CREST design in the basic operation stage is summarized in Fig. 1, where A=3.4, elongation κ=1.85, triangularity δ=0.35 and $q_\psi \approx 5$

are assumed. Other plasma parameters of the Demo-CREST are listed in Table 1. A broadening current profile corresponds to an increase in q value on axis (= q_0).

Without the ideal conductive shell, the β_N limit against n=1 kink and high n ballooning modes is maximized with q_0 close to unity, and a larger q_0 (i.e. broader current profile) results in a lower beta limit. On the other hand, with the conductive shell, the β_N limit increases with q_0 in the range of q_0<2.1, where R_{ext}=1.3 is assumed.

The feasibility of a current profile driven by a neutral beam (NB) and BSC (bootstrap current) is investigated for the stable MHD equilibria. This current drive analysis has been done consistently with the MHD analysis [10]. The current profile driven by NB is adjusted to the stable profile by changing each power of on- and off-axis beam (shown in Fig. 2). Through the iterative calculation, the beam and alpha pressures are taken into account and the density profile is determined consistently with a specified temperature profile. In this study, $T=T_0(1-x^2)^{1.3}$ is assumed.

In the actual design of a reactor, the power capacity of NB system is determined by the maximum power requirement. Therefore it is desirable to minimize the change in each beam power throughout the operating range. The reference equilibria for the basic stage, shown by circles in Fig. 1, are results of a survey in which the powers of the on- and off- axis beams have been kept nearly constant. The beam powers are shown in Fig. 2, where E_b =1.5MeV have been used. The equilibria up to β_N=3.4 can be sustained with an 1.5 MeV NB system by increasing q_0 according to the increment of β_N. The changes of on- and off- axis beam powers are kept in the range of +/- 5 MW and +/- 2 MW, respectively. The BSC is effectively utilized for achieving stable profiles without changing the beam powers.

β_N	1.9	2.5	3.0	3.4
q_ψ	5.0	5.0	5.0	5.2
q_0 / q_{min}	1.3/-	1.7/-	2.1/-	2.3/-
R (m)	7.25	←	←	←
a (m)	2.13	←	←	←
R/a	3.4	←	←	←
κ	1.85	←	←	←
δ	0.35	←	←	←
B_t (T)	8.0	←	←	7.8
I_P (MA)	15.9	15.4	15.6	14.7
I_{BS} / I_P (%)	23.7	34.4	40.1	49.7
β_P	1.11	1.55	1.86	2.15
<Te> (keV)	17.9	18.7	20.7	18.4
<Ti> (keV)	18.8	19.5	21.5	19.2
Z_{eff}	1.7	←	2.1	←
$\langle n_e \rangle$ ($10^{20}m^{-3}$)	0.625	0.789	0.873	1.05
HH_{98}	0.96	1.1	1.2	1.2
$\langle n_e \rangle$ / n_{GW}	0.56	0.73	0.80	1.02
E_b (MeV)	1.5	←	←	←
P_b (MW)	188	190	185	191
on axis (MW)	164	163	157	166
off axis (MW)	24	27	28	25
P_f (MWth)	1260	1940	2460	2840
Q	6.7	10.2	13.3	14.9

Table 1 Parameters in the basic stage

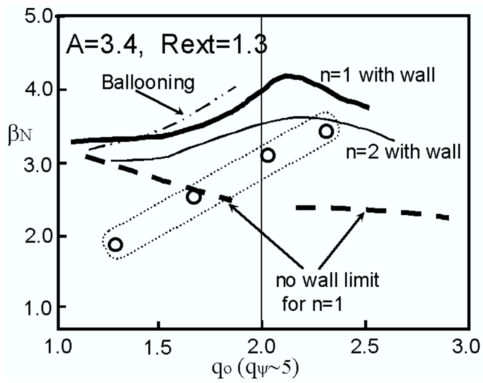

Fig.1 MHD equilibria for the basic operation stage. The reference operation points are shown by circles.

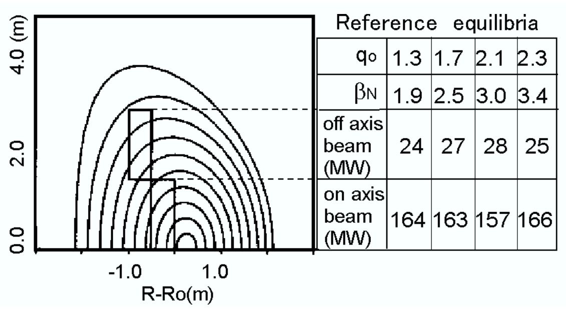

Fig. 2 Beam powers for the reference equilibria shown in Fig. 1, where E_b=1.5MeV.

3. Equilibria for the advanced operation stage

For the advanced stage, higher beta equilibria with reversed shear (RS) configuration stabilized by a closed shell are considered. Three RS equilibria with β_N =4.0 is listed in Table

2, where q_ψ = 5.2, 5.85 and 6.5 respectively. Because of engineering restriction in the design, the fusion output P_f are limited up to 3 GW. In the cases of q_ψ = 5.2 and 5.85, the toroidal field on axis B_{t0} is reduced in order to keep this output limit. At q_ψ = 6.5, B_{t0} attains its design value, i.e., 8 Tesla (15.5 Tesla on TF coil). Since increasing q_ψ results in higher BSC rates and lower beam powers, the attainable Q (=P_f/P_b) increases with q_ψ, where P_b is the beam power. At q_ψ = 6.5, Q ~ 30 is achievable. This value is equivalent to a target for commercial power plant. On the other hand, an equilibrium with a higher q_ψ requires a closer shell. At q_ψ = 5.2, R_{ext} =1.4 is allowable while R_{ext} =1.25 is required at q_ψ = 5.85 and 6.5. The plots in Fig. 3 shows R_{ext} vs the eigen value ($-\omega^2$) of instability in the case of q_ψ = 5.85, where n is the toroidal mode number.

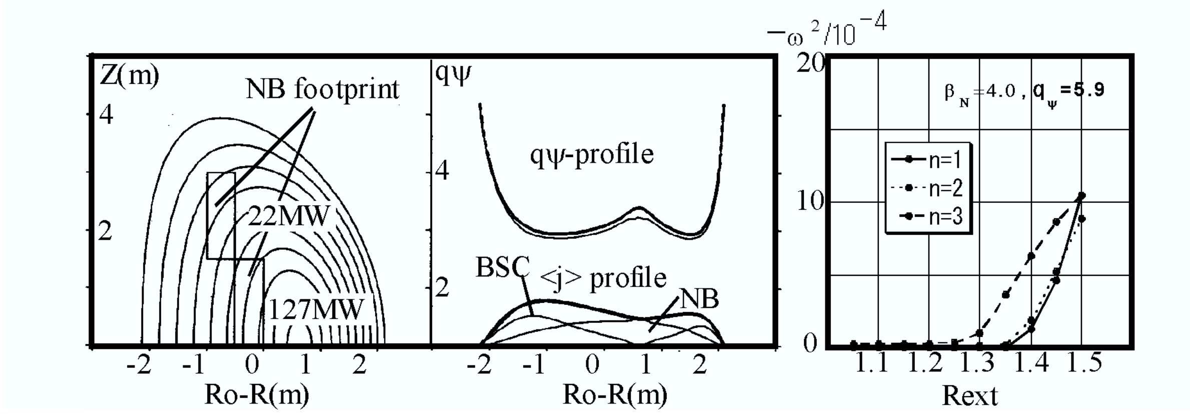

Fig.3 RS eqilibrium at q_ψ = 5.85 and the stability analysis.

The highest β_N equilibrium in Table 2 is an example for CREST-like operation mode, where β_N = 5.4 and B_{t0} is reduced down to 5 Tesla in order to keep the 3 GW limit in the fusion output. Note that, in order to achieve this parameters, higher plasma shaping factors, i.e. κ = 2.0, δ = 0.5 are necessary. This means that a further advanced blanket may be necessary as well as plasma shaping coils and plasma-position stabilizer which were proposed in the CREST original design[1]. The aim of this mode is just to test the highest β_N equilibrium for the first commercial reactor (like CREST) which follows the demonstration plant. From a view point on the achievable Q value, there is no merit in this mode, that is, Q = 25.1 with this mode while Q = 29.7 is possible with β_N=4.0 at q_ψ=6.5. This is because R_0 = 7.25m is inappropriately large to operate at such high β_N using 1.5 MeV beam.

4. Summary of step-up scenario

The step-up operation scenario of Demo-CREST is summarized in Fig.4. In the basic stage, the conventional design blanket without closed conductive shell is installed in the plant. The β_N is gradually increased up to 3.0 or 3.4 (operation mode 1 to 4 in Fig.4). The blanket design is based on the pressurized water cooling by 330°C and the thermal efficiency is 30% [11]. The net electric outputs in reactor-relevant range can be expected at the end of this stage: 600 MWe at β_N =3.4 (mode 4) or 450 MWe at β_N =3.0 (mode 3), but nearly zero at β_N =1.9 (mode 1). Throughout this stage, the powers of on- and off-axis beams are nearly constant; ~160 MW and ~25 MW, respectively.

Before starting in the advanced stage, the blanket is replaced by advanced one based on the super-critical water cooling [12] (~480°C, ~40% in thermal efficiency). This blanket will have an inner shell at R_{ext} = 1.25. The engineering design of the advanced blanket system is in progress [13] . The thermal efficiency expected is 40%. By increasing q_ψ up to 6.5, the NB power for current drive can be reduced down to 106 MW (mode 7) from 182 MW at q_ψ = 5.2 (mode 5). The net electric output up to 1100 MWe can be expected with mode 7. If further advanced plasma shaping and control are successful, the CREST-like mode can be tested in Demo-CREST. However, an additional replacement of blanket system might be necessary because of the higher plasma elongation and its positioning control.

β_N	4.0	←	←	5.4
q_ψ	5.2	5.85	6.5	4.3
q_0	3.5	3.5	3.8	2.9
q_{min}	2.9	3.1	3.6	2.3
R (m)	7.25	←	←	←
a (m)	2.13	←	←	←
R/a	3.4	←	←	←
κ	1.85	←	←	2.0
δ	0.35	←	←	0.5
B_{tmax} (T)	14.0	14.5	15.5	9.7
B_{t0} (T)	7.25	7.50	8.00	5.0
I_P (MA)	14.0	13.7	13.2	14.9
I_{BS} / I_P (%)	57.7	64.0	72.5	65.4
β_P	2.44	2.61	2.84	2.43
<Te> (keV)	17.1	17.3	17.3	18.6
<Ti> (keV)	18.0	18.2	18.2	19.5
Z_{eff}	2.1	←	←	←
$\langle n_e \rangle$ ($10^{20}m^{-3}$)	1.21	1.20	1.21	1.08
HH_{98}	1.28	1.34	1.42	1.34
$\langle n_e \rangle / n_{GW}$	1.21	1.25	1.31	1.04
E_b (MeV)	1.5	←	←	←
P_b (MW)	182.0	148.0	106.6	126.4
on axis (MW)	152.3	127.3	93.4	93.9
off axis (MW)	29.8	21.7	13.2	32.5
P_f (MWth)	3130	3150	3160	3170
Q	17.2	21.3	29.7	25.1

Table 2 Parameters in the advanced stage

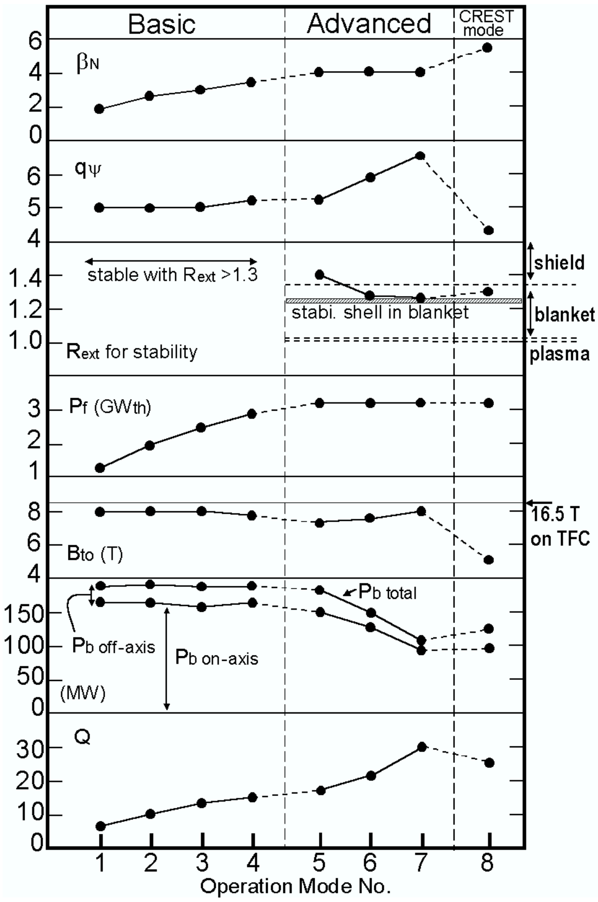

Fig. 4 Step-up scenario of Demo-CREST

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