Plasma Operation of RTO/RC ITER

H. Matsumoto[1], D. Boucher[2], V. Mukhovatov[2]

[1]*ITER Joint Central Team, Garching Joint Work Site, D-85748 Garching, Germany*
[2]*ITER Joint Central Team, Naka Joint Work Site, Naka, Ibaraki-ken, 311-01 Japan*

1. INTRODUCTION

The options of the Reduced Technical Objectives/Reduced Cost (RTO/RC) ITER aimed at a target of 50 % of the cost of the present ITER design while maintaining its overall programmatic objective are under study now. The physics goals of the RTO/RC ITER are:

- to achieve extended burn in inductively driven plasma with $Q=P_{fus}/P_{aux}$ 10 for a range of operation scenarios and with a duration sufficient to achieve stationary conditions on the time scales of plasma processes; and
- to aim at demonstrating steady-state operation using non-inductive current drive with Q of at least 5.

Also, the possibility of controlled ignition should not be precluded.

Two options, i.e., Low Aspect Ratio Machine (LAM) and Intermediate Aspect Ratio Machine (IAM), which satisfy to above requirements are discussed in this paper. The major parameters of LAM and IAM are shown in Table I.

Table 1. Main parameters of IAM and LAM

Parameters	IAM	LAM	Parameters	IAM	LAM
R[m]	6.20	6.45	Plasma surface S_{surf} [m^2]	632	824
a[m]	1.90	2.33	Plasma cross-section [m^2]	19.40	30.12
I_p[MA]	13.3	17	Plasma volume [m^3]	726	1177
B_o[T]	5.51	4.23	Elongation @95%	1.68	1.74
Aspect ratio	3.26	2.77	Elongation at separatrix	1.83	1.92
q_{95}	3.00	3.00	Average triangularity at separatrix	0.43	0.49

2. RTO/RC ITER PLASMA PERFORMANCE

The modeling of the plasma performance in IAM and LAM was performed using the 1.5D transport simulation code PRETOR. The physics assumptions are basically the same as those used in ITER FDR [1]. The key quantities that determine the plasma performance are: (i) the thermal energy confinement time, τ_E, (ii) the impurity level in the main plasma, (iii) the normalized plasma density, n_e/n_{GW} with $n_{GW}=I_p/(\pi a^2)$, (iv) normalized plasma pressure, $\beta_N=\beta(aB_o/I_p)$, and (v) normalized power crossing the plasma separatrix, P_{loss}/P_{LH}, where P_{LH} is the H-mode power threshold. None of these quantities is known exactly but a range can normally be estimated. The fusion performance is expressed as a domain indicating how key figures of merit such as total fusion power or Q vary within the plausible range of input parameters. The IPB98(y,1) ELMy H-mode confinement scaling law [2]

$$\tau_{E,th}^{IPB98(y,1)}(s) = 0.0503 H_{H98y1} I_{MA}^{0.91} B_T^{0.15} P_{MW}^{-0.65} n_{19}^{0.44} M^{0.13} R_m^{2.05} \varepsilon^{0.57} \kappa_a^{0.72}$$

is used for normalization of heat transport coefficients. The impurity level is determined with the same divertor model as previously used for the ITER FDR after renormalisation to take into account the new geometry of the divertor, updated pumping speeds and target plate surfaces.

2.1 Inductive Operation

Results of modeling of ELMy H-mode D-T discharges at $q_{95}=3$ in IAM and LAM are shown in Table 2.

Table 2. Main plasma parameters of IAM and LAM at inductive Q=10 operation

Parameter	IAM	LAM	Parameter	IAM	LAM
$<n_e>$ ($10^{19}m^{-3}$)	10	8	τ_{He} / τ_E	5	5
$<T>$ (keV)	11	11	n_e / n_{GR}	0.8	0.8
Z_{eff}	1.9	2.0	H_H	1.0	1.0
P_{aux}(MW)	50	50	β_N	2.1	2.2
P_{fus}(MW)	500	500	P_{fus} / S_{surf} (MW/m^2)	0.8	0.6
τ_E (s)	3.2	4.2	Loop voltage (mV)	70	80

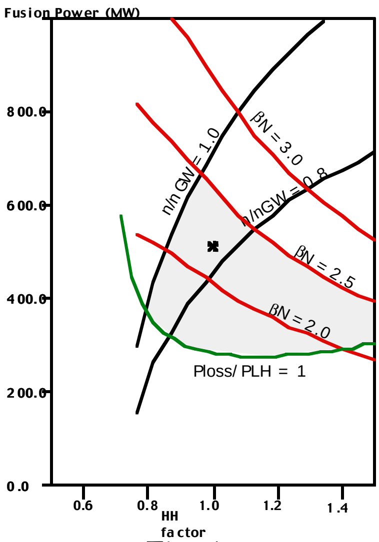

Fig. 1.

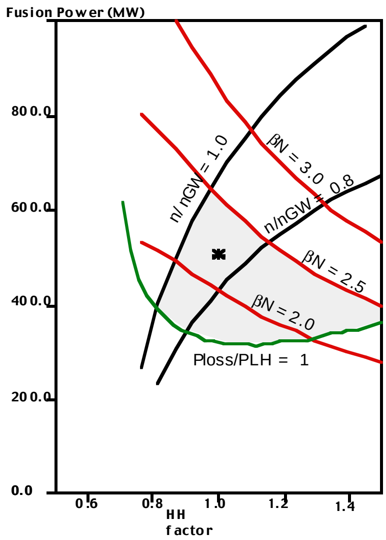

Fig. 2.

Figs.1 and 2 indicate the domain for Q=10 for LAM and IAM respectively. Each point of the domain corresponds to Q=10. The shaded area indicates the region in terms of fusion power and H_H factor that obeys the following limits: $n/n_{GW} < 1$, $P_{loss}/P_{LH} > 1$ and $\beta_N < 2.5$.

2.2 Non-Inductive Operation

Prediction of plasma performance at non-inductive steady-state operation has inherent difficulties arising from the following facts. The total driven plasma current depends on profiles of plasma parameters which inter-relate to each other. The confidence in prediction of the density profile and plasma purity is rather low due to the density peaking often observed in these regimes which could decouple the edge density from the volume averaged density. The control of current density profile, which should satisfy equilibrium and stability criteria, is not easy, and optimisation of non-inductive operation in terms of the fusion output, Q, is not trivial.

2.2.1 Monotonic q profile scenario

The simplest scenario of non-inductive operation would be a monotonic q operation by injecting momentum and energy at the center of the plasma. Almost the best current drive efficiency can be obtained at the hottest core of the plasma, and also the power is coupled to the most efficient spot for fusion reactions. However, excessive current density at the center of the plasma would create strong and frequent sawtooth oscillations, and contribution of bootstrap current is rather small due to the more centrally peaked pressure profile. In this section, a steady-state scenario for IAM with centrally driven current and modest confinement improvement is considered. In the simulations, a generalised current drive module was used. In this module, instead of computing current drive efficiency of each current drive scheme, current drive efficiencies and profiles were given to the code as input.

Assumptions and input to the simulations:

- 80 MW of the CD power (50% coupling to electrons and 50 % to ions).
- Width of the CD power deposition profile: 25% in minor radius around the plasma centre.
- The CD efficiency : γ=0.20 MA/MW/m^2 at T_e=10 keV.
- H_H =1.1.

Results of simulations for a middle of the sawtooth period:

Q = 4.8, β_N = 2.5, β_p = 1.4, $<T_e>$=10.7 keV, $<T_i>$=9.5 keV, $<n_e>$ = 8.8×10^{19}m^{-3}, Z_{eff}=1.7.

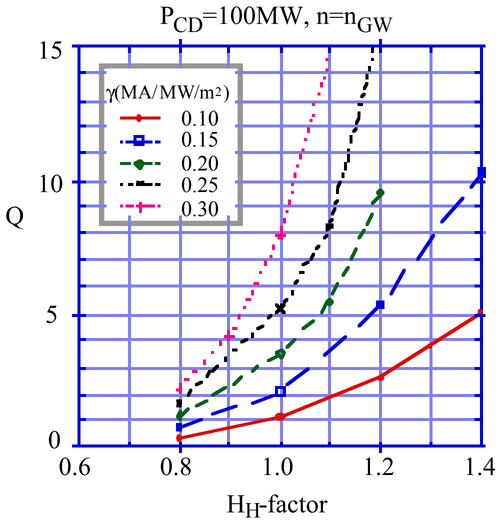

Fig. 3.

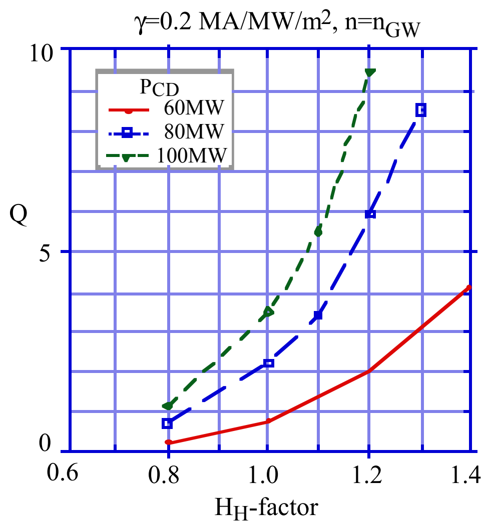

Fig 4.

Dependence of Q on the confinement improvement factor H_H with the current drive efficiency γ as a varying parameter are shown in Figs. 3 and 4. When the current drive power of 100 MW is available, either very high current drive efficiency, γ = 0.25MA/MW/m^2 at H_{H98y1}=1, or a moderate confinement improvement, H_{H98y1}=1.2, at conservative current drive efficiency of γ = 0.15MA/MW/m^2 will be needed to reach Q=5 region.

- Reversed magnetic shear configuration

Typical parameters for IAM and LAM devices under Q=5 steady-state reverse magnetic shear operation are shown in Table 3.

Table 3. Typical parameters for IAM and LAM devices under steady-state reverse magnetic shear operation.

Parameter	IAM	LAM	Parameter	IAM	LAM
R (m)	6.37	6.62	n/n_{GW}	1.0	1.0
a (m)	1.73	2.16	β_N	3.4	3.6
B_T (T)	5.38	4.14	P_{loss}/P_{LH}	2.3	2.9
κ_x	1.93	1.93	$<n_{e19}>$	9.9	7.8
I_p (MA)	9.1	11.1	$<T>$ (keV)	11.3	10.9
q_{95}	4.4	4.1	β_p	1.98	1.63
f_{bs}	0.44	0.40	P_{fus} (MW)	500	500
H_H	1.25	1.25	P_{CD}(on/off axis) (MW)	20 / 80	20 / 80

Fig. 5 plots β_N as a function of ($\gamma \times P_{CD}$) for three values of the H_H factor: 1, 1.25 and 1.5. For Q = 5, the required values of β_N decrease significantly with the ($\gamma \times P_{CD}$) product. At the low end of ($\gamma \times P_{CD}$) (< 15), high β_N = 3.5-4 are required. This, combined with a requirement of significant confinement improvement, will need an advanced tokamak mode of operation. At higher values of ($\gamma \times P_{CD}$) (> 20), the required β_N are smaller (3-3.5) and only modest confinement improvement is required. Fig. 5 also indicates that the required values of β_N are systematically about 10% lower for IAM than for LAM at fixed Q. This systematic difference has to be attributed to the higher aspect ratio leading to lower plasma current and higher bootstrap current fraction.

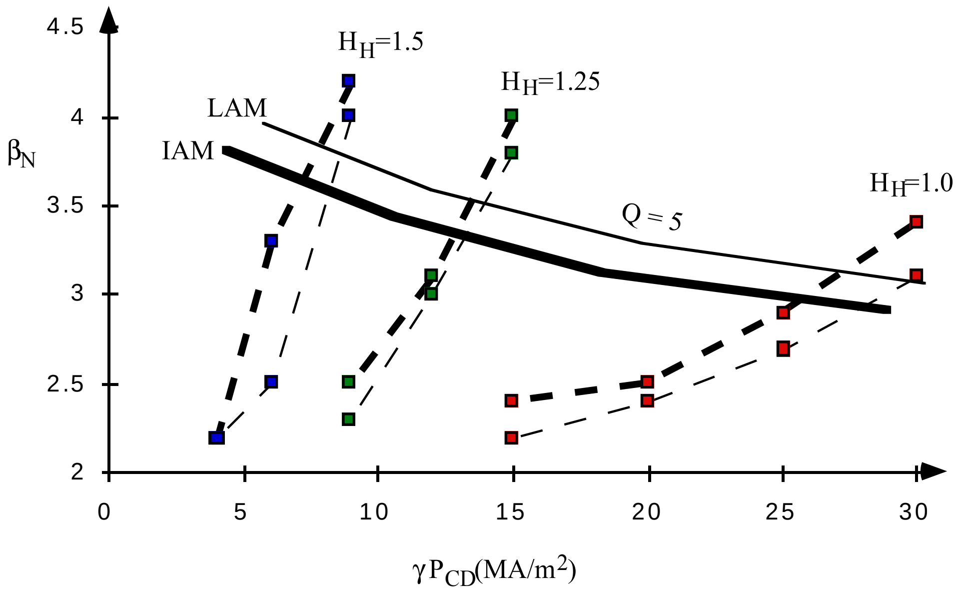

Fig. 5. Required β_N values as a function of current drive figure of merit ($\gamma \times P_{CD}$). Dotted lines indicate the constant H_H factor contours and solid lines indicate the constant Q = 5 contours. IAM: thick lines, LAM: thin lines. 2% of carbon impurity is assumed.

3. CONCLUSIONS

- The IAM and LAM options of the RTO/RC ITER can achieve Q=10 in inductive operation at H_H=1 with conservative values of operating density ($\cong 0.85 n_{GR}$), normalised beta ($\beta_N \cong 2.2$), and P_{loss}/P_{LH} > 1.4. The operation domain for LAM is marginally larger than that for IAM.
- Values of Q achievable at steady-state non-inductive operation are sensitive to the current drive efficiency and injected power and to the level of the confinement improvement over ELMy H-mode scaling prediction.
- With an efficient current drive system and power of about 100MW only a modest confinement improvement (H_H > 1 - 1.2) would be required to achieve Q = 5 in either IAM or LAM at steady-state operation. Due to its higher aspect ratio, IAM as compared to LAM needs marginally smaller (by ~10%) values of H_H and β_N to achieve Q=5.

REFERENCES

[1] "Technical Basis for the ITER Final Design Report, Cost Review and Safety Analysis," *1998 ITER EDA Documentation Series No.16* (Vienna: IAEA)
[2] ITER Physics Expert Groups *et al Nucl Fusion* to be published