Heating scenarios for the new staged-approach of the ITER research plan

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1. Introduction

The ITER revised schedule entails a staged approach strategy allowing a progressive transition from first plasma to fusion power production. The ITER research plan has been revised accordingly. Heating and Current Drive (H&CD) scenarios [Polevoi-2013] have been readdressed for each stage with the aim of achieving essential milestones with a dedicated physics program. The review of these scenarios is presented here with an emphasis on the H&CD performance and H-mode access capabilities, given the functionalities of the Electron Cyclotron Resonance Heating (ECRH, f=110-170 GHz), Ion Cyclotron Radio Frequency (ICRF, f=40-55 MHz) and Neutral Beam Injection (NBI, $E_{b,max}$=0.87 (H^0), 1 MeV(D^0)) systems. The ITER 4-Stage approach is described in *Table 1.* It consists of a first plasma in H with only 6.7 MW of EC power; a Pre-Fusion Power Operation 1 (PFPO-1) including 20 MW of EC and a proposed 10 MW of IC power in H and ^{4}He; a Pre-Fusion Power Operation 2 (PFPO-2) including the baseline auxiliary power (73 MW) in H and ^{4}He; and the Fusion Power Operation (FPO) with the same H&CD capabilities for D and DT.

	Main species	ECRH	ICRF	NBI	Total H&CD
1st plasma	H	6.7 MW	-	-	6.7 MW
PFPO-1	H, ^{4}He	20 MW	10 MW*	-	30 MW*
PFPO-2	H, ^{4}He	20 MW	20 MW	33 MW	73 MW
FPO	D, DT	20 MW	20 MW	33 MW	73 MW

Table 1 – The ITER 4-Stage Approach (*the availability of one IC antenna for PFPO-1 is still under evaluation).

2. The ITER Pre-Fusion Power Operation phase (PFPO)

The main goal of the Pre-Fusion Power Operation phase is to commission available H&CD systems, fuelling capabilities, core-edge plasma control (magnetics, ELM, divertor heat flux, NTMs, etc.), disruption prediction and mitigation system, and all installed diagnostics to provide routine operation in L-mode at 15 MA/5.3 T and H-mode at 7.5 MA/2.65 T for a pulse duration typically of the order of 50 s. Current drive capabilities in view of long pulse operation will be assessed, and key aspects of plasma-wall interactions (PWI) will also be characterized during this phase. Plasma fuelling will be limited to H or ^{4}He to eliminate the neutron production. Whenever possible, H will be favoured due to similar fuelling, transport, ELM and recycling properties as D and T and to the possible unfavourable impact of ^{4}He plasmas on plasma facing materials.

However, since the H-mode power threshold is expected to be about 1.5 to 2 times lower in ^{4}He than in H, ^{4}He operation may be necessary for a high quality H-mode to enable ELM control and mitigation during the PFPO phases. Hence, scenarios have been designed for both H and ^{4}He plasmas. Several operational points have been identified as baseline and optional scenarios. They will be adjusted according to experimental observations and achievements. Scenarios at 1.8 T are planned to access H-mode confinement regimes for the PFPO-1 phase with the available auxiliary heating (~30MW). *Figure 1* shows a basic estimate of the operational range for each H&CD system for different values of magnetic field and plasma current. The strategy is to progressively increase the magnetic field and plasma current (in this order) to mitigate disruption risks while ensuring q_{95} = 3−4 for ELM control and deleterious MHD avoidance. Resonance conditions for central absorption of ECRH and ICRF waves imply constraints in toroidal magnetic field. The NBI system operation is constrained by the minimum plasma density required to limit shinethrough power losses. Steps towards 15 MA can be grouped in six categories: (i) first plasma (100 kA / 2.65 T); (ii) first divertor plasma (3.2 MA/2.65 T) to establish initial divertor operation; (iii) first q_{95}=3 plasma (7.5 MA/2.65 T); (iv) first H-mode plasma (5 MA/1.8 T); (v) steps towards full current, (vi) first 15 MA/5.3 T plasma. For all these cases, H operation will be developed first, followed by ^{4}He operation where necessary, i.e. when a good H-mode cannot be achieved in H.

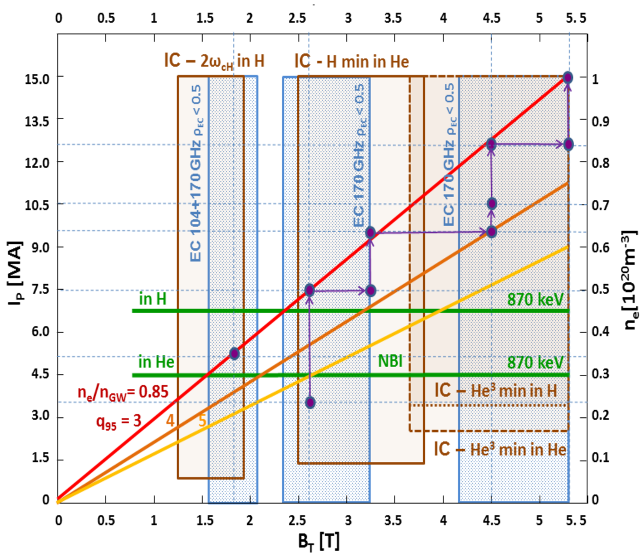

Figure 1 - Operational range of H&CD systems over B_T , I_p and density ranges in ITER. EC/IC/NBI ranges are in blue/brown/green respectively.

Two areas for H&CD systems are under R&D studies to meet the requirements of the 4-stage approach: 1) an additional low EC frequency would enable successful EC-assisted breakdown and burnthrough at 1.8T. Indeed, 2nd harmonic (X2) EC assistance is recommended while 170 GHz gyrotrons can only offer 3rd harmonic (X3) EC assistance at 1.8T. Hence, low frequency gyrotrons (f=100-110 GHz) are under investigation, though their power and duration may be limited; 2) the acceleration of the installation of one IC antenna (~10 MW) to be available for the PFPO-1 phase. All of the main scenarios foreseen for first plasma and the two Pre-Fusion Power Operation phase are displayed in *Table 2*. Ohmic scenarios will be operated first, but they are not listed here. The L-H power thresholds in H and D are calculated according to [Martin-2008]. The L-H threshold in DT is assumed to be 25% lower than in D, while in ^{4}He it is considered to be 1 to 1.5 times larger the one in D. Densities are set to the minimum L-H threshold densities $n_{e,min}$ as scaled in [Ryter-2014]; $n_{e,min}$ typically represents between 0.34 and 0.4 times the Greenwald density for q_{95}=3-4; ^{4}He plasmas are not considered at high (B_T,I_p) because of limited fuelling, while H plasmas are more easily fuelled with pellets. Furthermore, ^{4}He plasmas are performed only when an H-mode is achievable.

	Species	B_T (T)	I_p (MA)	P_{L-H}(MW) at $n_{e,min}$	Mode	P_{AUX} (MW)	EC @100-110 / 170 GHz	IC best schemes	NB energy (keV) & power limits (MW) @ $n_{e,min}$	
1st plasma	H	2.65	0.1	-	-	6.7	UL only, X2	No ICRF	No NBI	
PFPO-1	H	2.65	3.2	26	L	20	O1 / X2	Not foreseen	No NBI	
		2.65	7.5	32	L	20	O1 / X2	FWEH		
		1.8	5	18	L, ~H	30	X2 / X3	n=2 H		
		3.3	7.5 to 9.5	42 to 44	L	30	O1 / X2	n=1 (^{3}He)-^{4}He*		
		4.5	7.5 to 9.5	61 to 64	L	30	- / O1	n=1 (^{3}He)		
		5.3	7.5 to 9.5	75 to 80	L	30	- / O1	n=1 (^{3}He) n=1 (^{4}He) n=1 (^{3}He)-^{4}He*		
	^{4}He	2.65	7.5	16 to 24	L, ~H	30	O1 / X2	n=1 (H) n=2 ^{4}He		
		1.8	5	9 to 14	L, H	30	X2 / X3	n=2 (H)		
PFPO-2	H	2.65	7.5	32	L	32	O1 / X2	FWEH	530	9
		1.8	5	18	L, H	47	X2 / X3	n=2 H	500	8
		3.3	7.5 to 9.5	42 to 44	L	52 to 57	O1 / X2	n=1 (^{3}He)-^{4}He*	570 to 600	11 to 13
		4.5	9.5 to 12.5	66 to 70	L	50 to 60	- / O1	n=1 (^{3}He)	680 to 720	18 to 21
		5.3	12.5 to 15	85 to 90	L	60 to 66	- / O1	n=1 (^{3}He) n=1 (^{4}He) n=1 (^{3}He)-^{4}He*	760 to 800	24 to 27
	^{4}He	2.65	7.5	16 to 24	L, H	62	- / X2	n=1 (H) n=2 ^{4}He	660	17
		1.8	5	9 to 14	L, H	52	- / X3	n=2 (H)	540	10

Table 2 – H&CD schemes for main scenarios of ITER non-active phase; ~H means possible low quality H-mode; n is the ion cyclotron harmonic $\omega=n\omega_c$.; FWEH = Fast Wave Electron Heating; *Needs ~10% ^{4}He for ^{3}He heating [Kazakov-2015].

- The ECRH low frequency gyrotrons, if used in ITER, will be in the range of 100-110 GHz. The eight low frequency gyrotrons are here assumed to have dual frequency capabilities enabling to switch to 170 GHz (their performance will be reduced). Their resonance is outside the plasma for B_T > 4 T, hence no power from low frequency gyrotrons is considered above 4 T.
- The best ICRF heating schemes are listed in *Table 2*. No efficient IC scenario is available at 2.65 T in H plasmas [Lerche-2012]; hence optional off-axis heating scenarios at slightly higher magnetic fields in H are proposed and described in [Schneider-2017]. Not all ICRF heating schemes have been investigated yet, especially at intermediate magnetic fields.
- The NBI energy and power limits to limit shinethrough losses are calculated according to [Singh-2017, Kim-2017] using the perveance matching constraint $P_{NB} \sim E_{NB}^{2.5}$ and the fact that the minimum energy is 500 keV, due to degraded beam divergence at lower energies leading to higher heat loads on the duct-liner.

3. The ITER Fusion Power Operation Phase (FPO)

The ITER FPO phase involves both D and DT plasmas with the project mission goals of achieving Q ≥ 10 for 300−500 s and Q ≥ 5 in non-inductive operations for up to 3000 s. H&CD systems, fuelling and extra diagnostics need to be (re-)commissioned for D plasmas. Tritium transport, fuelling and mixture control strategies for DT operation will be assessed. The control strategy will be refined for high plasma energies, including event handling, MHD and burn control. The PWI key aspects will be further characterized for long pulse operation.

The FPO phase will be divided in four steps: initial D and Trace-T operation for pulses of ~50 s, two DT phases for pulses of ~300 s to 1000 s, and long pulse DT operation. The same target scenarios as in PFPO-2 will be reproduced, as shown in *Table 3*. The main H&CD modification is H^0 870 keV beams replaced by D^0 1 MeV beams. No beam shinethrough limitation is expected in this phase due to higher ionisation efficiency. If low frequency gyrotrons are used in the non-active phase (for successful breakdown / burnthrough at 1.8T), they will be replaced by 170 GHz gyrotrons between the PFPO-2 and FPO phases. Several upgrade options are foreseen for H&CD systems leading to P_{AUX}=130 MW enabling advanced steady-state scenarios and long pulse operation. An example of these scenarios is shown in *Table 3*.

	Species	B_T (T)	I_p (MA)	P_{L-H}(MW) at $n_{e,min}$	Mode	P_{AUX} (MW)	EC @100-110 / 170 GHz	IC best schemes	NB energy (keV) & power limits (MW) @ $n_{e,min}$	
FPO	D	2.65	7.5	16	L, H	73	O1 / X2	n=1 (H)	1000	33
		3.3	7.5 to 9.5	21 to 22	L, H	73	O1 / X2	n=1 (H)		
		4.5	9.5 to 12.5	33 to 35	L, H	73	- / O1	n=1 (^{3}He)		
		5.3	12.5 to 15	43 to 45	L, H	73	- / O1	n=1 (^{3}He)		
	DT	2.65	7.5	12	L, H	73	X2	n=1 (H)		
		3.3	7.5 to 9.5	16 to 17	L, H	73	X2	n=1 (H)		
		4.5	9.5 to 12.5	25 to 27	L, H	73	O1	n=1 (^{3}He) + n=2 T		
		5.3	12.5 to 15	32 to 34	L, H	73	O1	n=1 (^{3}He) + n=2 T		
Upgrades	DT	5.3	9	30	L, H	130	O1	n=1 (^{3}He) + n=2 T	1000	33 to 50

Table 3 - H&CD schemes for main scenarios of the active phase of the ITER research plan.

4. Conclusion

Optimizing H&CD systems and associated scenarios to enable the success of ITER mission goals for the various phases of the ITER research plan is a continuous challenge that will be met over the next years via dedicated R&D studies and appropriate experiments and modelling efforts.

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5. References

[Polevoi-2013] A.R. Polevoi et al, NF 53 (2013)
[Martin-2008] Y.R. Martin et al, J. Phys., 123 (2008)
[Ryter-2014] F. Ryter et al, NF 54 (2014)
[Singh-2017] M. Singh et al, New J. Phys 19 (2017)
[Kim-2017] S.H. Kim et al, accepted NF (2017)
[Lerche-2012] E. Lerche et al, PPCF 54 (2012)
[Schneider-2017] Subm. to EPJ Web of Conf. (2017)
[Kazakov-2015] Ye.O. Kazakov et al, NF 55 (2015)