Operation Window with Mutually Consistent Core-SOL-Divertor Conditions in ELMy H-Mode: Prospects for Long Pulse Operation in ITER and DEMO

G.W. Pacher[1], H.D. Pacher[2], G. Janeschitz[3], A.S. Kukushkin[4]

[1]Hydro-Québec, Varennes, Québec, Canada , [2]INRS-EMT, Varennes, Québec, Canada,
[3]FZ Karlsruhe, Karlsruhe, Germany, [4]ITER Organization, Cadarache, France

e-mail: pacher.guenther@ouranos.ca

Abstract. The operation window of ITER and DEMO in ELMy H-mode is investigated with near-axis and off-axis heating and current drive with emphasis on the characteristics of long-pulse operation in this mode. For both devices, conditions investigated are far from steady state. Off-axis current drive significantly increases the burn duration of ITER as well as the neutron fluence per pulse. A moderate reduction of plasma current further enhances the relevance of this mode of operation for the ITER testing mission. The number of discharges required to achieve the fluence goal is thereby reduced by a factor of ~4 to 5900. The preliminary exploration of DEMO operation indicates appreciable flexibility in reactor-like operation in ELMy H-mode.

1. Introduction and Description of the Model

A recent publication [1] described the exploration of the operational space of ITER through systematic scans of fuelling and additional heating such that mutually consistent conditions are obtained throughout the plasma from the centre through pedestal and scrape-off layer to the divertor plates. Analysis of the results of the scans led to the identification of limits to ITER performance, thus defining the operating window for ITER parameters [1,2].

Modelling is carried out with the 1.5D Astra code, in which the Integrated Core-Pedestal-SOL (ICPS) model has been implemented. The characteristics of the model are described in detail in [1]. Briefly, in ICPS modelling, the edge parameters of the core region are derived from B2-EIRENE modelling scans [3] of the edge and divertor plasma as a function of the core parameters so that core, SOL, and divertor conditions are mutually consistent. The operating space is traced out by trajectories at constant additional heating power with stepwise variation of density, achieved mainly by core-fuelling. The peak divertor power load is held at or below the desired value (10 MW/m^2 for ITER, 7.8 MW/m^2 for DEMO) by controlling the throughput on which it depends according to the edge modelling, and this is done by adjusting the gas puff. The core plasma is modelled with anomalous energy transport from the MMM95 transport model [4], stabilized by ExB and magnetic shear. The time-averaged effect of ELM's is simulated by increasing transport so as to limit the pressure gradient to the ballooning limit. Stabilization and ballooning limit coefficients are adjusted to reproduce the observed ELMy H-mode pedestal for JET conditions, and are then kept invariant. Anomalous particle diffusion is taken proportional to the sum of anomalous energy transport coefficients. This model is calibrated to JET [1,5] (an anomalous pinch is not used) and then also fits AsdexUG, as well as the pedestal scaling from an experimental database by Sugihara et al [6], as shown in [1].

In the previous work [1,2], an ad hoc reduction of the bootstrap current by 50% in the ELM-affected zone had been applied so as to provide an increase of effective resistivity due to the

ELMing cycle. However, since the calculated profiles represent the time-average over the ELM cycle, the resulting bootstrap current also represents the time-averaged value, i.e. the ad hoc reduction above is probably not required and is not used in the present work. The JET profile is fitted as before, by recalibrating the parameters for the stabilization. The recalibrated parameter combination (see [1] for definition) of t=0.25 and G=0.4 corresponding to full bootstrap current fits to experiment equally well and results in essentially the same operating space for ITER for all the variation treated in [1].

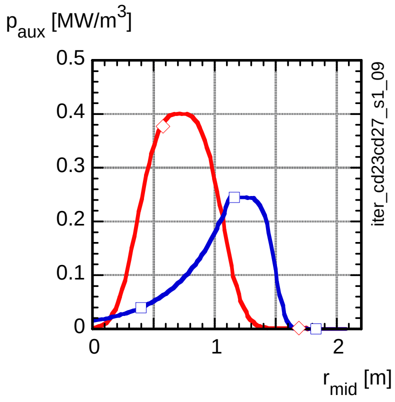


Fig. 1 - Additional power density profiles: red - "near-axis 0.3a", blue - "off-axis 0.7a"

The ballooning limit calculated from theoretical formulas including aspect ratio, elongation, and triangularity [7] is multiplied by an enhancement factor F_α of two so as to fit experiments on JET and Asdex-UG with beam heating. Recent experiments indicate that the absence of toroidal rotation produced by toroidal momentum input may lower the pedestal, corresponding to a reduction of confinement by ~10%. For the JET simulation, a confinement reduction of this order is obtained if the enhancement factor F_α is reduced from 2.0 to 1.0 i.e. the limit then corresponds to the theoretical value for ballooning stability. For ITER and DEMO, which are predominantly heated by alpha particles so that external toroidal momentum input is small, an enhancement factor of 1.0 has therefore been used in [1,2] and in the present work.

In this paper, we concentrate on the potential of the base operation of ITER, ELMy H-mode, for attaining long pulses, and its adequacy for performing the technical testing mission of ITER [8, chapter 1] and attaining reactor-like operation of DEMO. Long-pulse operation is obtained by using the external heating power to drive current with a local efficiency varying as the power density, decreasing with local electron density, and increasing with local electron temperature:

$$j_{CD}\ [MA/m^2] = 0.2 \times 2\pi \times \frac{p[MW/m^3]}{n_e\ [10^{20}/m^3]} \times \frac{T\ [keV]}{10}$$

Its magnitude is set so that the resulting global current drive efficiency is ~$0.25\mathrm{x}10^{20}$ $AW^{-1}m^{-2}$ at 10 keV, which is in the expected or moderately optimistic range for LH, EC, or NB current drive in ITER [8, chapter 6, sect. 4]. Two power deposition profiles are investigated, identified as “near-axis” and “off-axis” in the following text and shown in figure 1.

2. Long-Pulse Operation for ITER

The operating space of ITER is explored with successive simulations at constant heating power up to 100 MW. At a given value of heating power, the plasma density is varied in a stepwise fashion by adjusting the core fuelling, while the peak divertor power load is held at the specified value by regulating the gas puff (the divertor power load may be smaller than the specified value – the gas puff is then fixed at zero). Conditions are maintained at that density until core and SOL conditions relax to a quasi-steady state. The impurity density at the separatrix is calculated self-consistently from the scaling law for the intrinsic impurity carbon (the only divertor plate material considered in this paper). Outputs of the simulations are notably the alpha-particle power, the power conducted into the SOL, and the normalised edge density f_{sat_n}, (normalised such that full detachment of either divertor occurs at 1.0, see full description in [1], [3]).

As developed in [1], the operational space of ITER is restricted by the following five limits:

1. The maximum attainable alpha particle power P_{α_max} at given auxiliary power, caused by the combination of decreased fusion cross-section at low ion temperature and increased radiation at high density.
2. The desired Q consistent with the ITER mission. This is $Q \geq 5$
3. The edge density limit discussed in [3] and references therein. This is taken to be 90% of the density required to produce full detachment of the inner divertor in ITER, i.e. $f_{sat\_n} \equiv \mu^{0.43} = 0.9$ (μ is the normalised divertor neutral pressure [3]); only densities below this are allowed.
4. The ratio of the SOL power to the LH threshold. The back transition from the H-mode to the L-mode is usually found to occur at a power one-half that of the forward transition, but the limit is taken to be equal to the forward transition here in order to maintain a margin of the order of 2, i.e. P_{SOL}/P_{LH}.
5. The available auxiliary power. This is taken to be $P_{aux} = 73$ MW for ITER.

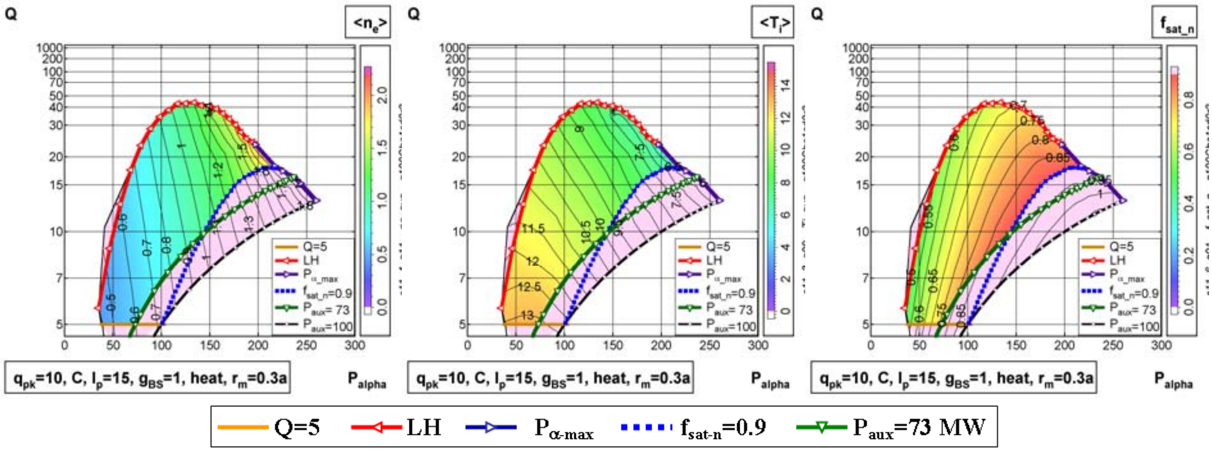


Fig. 2 - Operating space for ITER in ELMy H-mode at 15 MA with near-axis heating plotted in the Q-P_{alpha} plane. Average electron density (left), average ion temperature (center) and normalised separatrix density right. The five limits relevant to the operation space are indicated.

Figure 2 illustrates the typical operating space for operation at 15 MA with near-axis heating in the plane *Q*-P_{alpha}, the most interesting for judging plasma performance. Long-pulse operation in ITER is especially important for the testing mission, for which the desired neutron wall load is ≥ 0.5 MW/m^2 [8], corresponding to ~100 MW alpha power. Provided this value of neutron wall load is attained, it is interesting to optimise the neutron fluence (product of wall load and time). For the testing mission, it is appropriate to consider burn duration and fluence per discharge as performance indicators. From 0-D estimates, a flux of 39 volt-seconds is available for burn at 15 MA plasma current, which corresponds to the burn duration shown on figure 3 (left, top) and total fluence (left, bottom) per discharge for the on-axis heated discharge. At the desired average neutron wall load corresponding to 100 MW alpha power and Q = 7 (73 MW auxiliary power), the burn duration is ~800 s and the fluence is ~330 GJ. The desired total neutron fluence for the testing mission is 0.3 MWa/m^2 [8] which translates to a total integrated fluence of 7.6x10^6 GJ. Thus 23000 pulses are required at full current without current drive.

With current drive, both pulse duration and fluence per discharge increase appreciably, as shown on figure 3 for (centre) near-axis and (right) off-axis current drive. Comparing again at P_{alpha} = 100 MW and Q = 7, they increase to ~1400 s and 500 GJ with near-axis and to ~2000 s and 800 GJ with off-axis current drive.

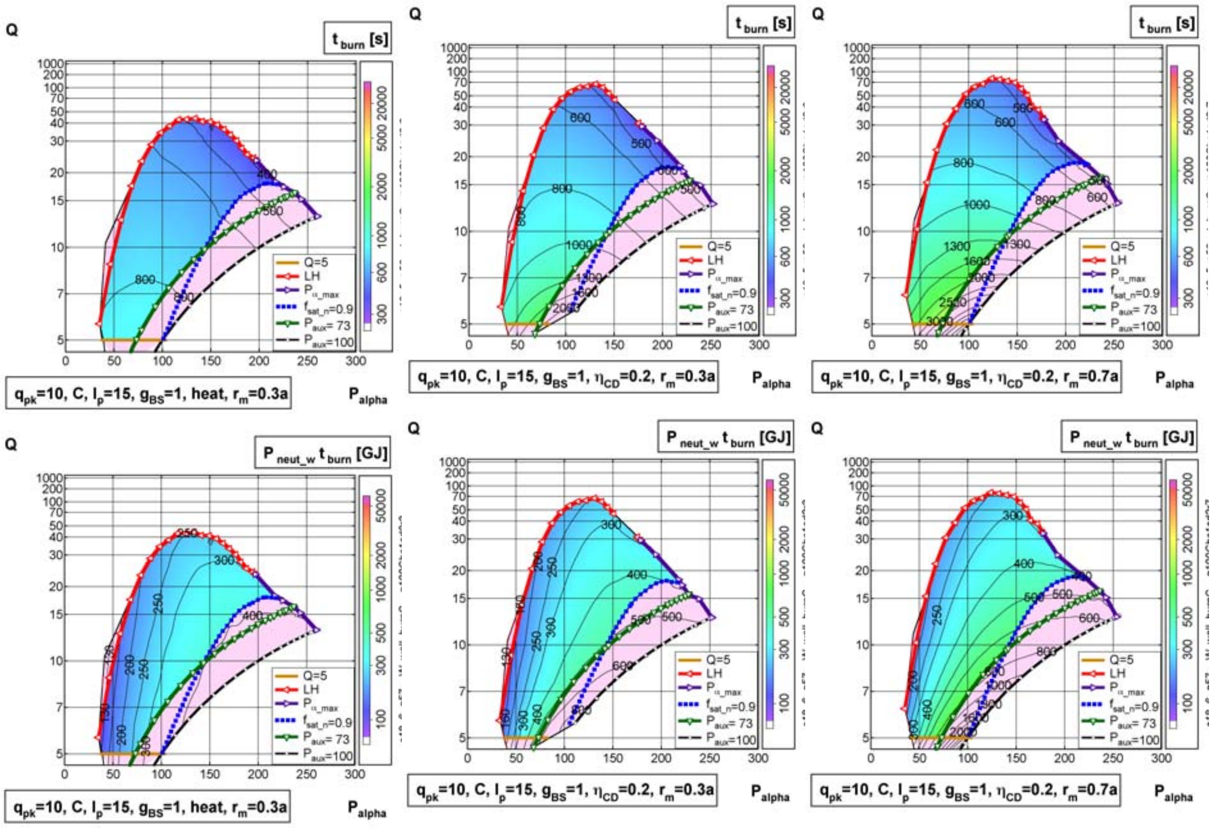


Fig. 3 - Operating space for ITER in ELMy H-mode at 15 MA with near-axis heating (left), near-axis current drive (centre), and off-axis current drive (right) Top row burn duration, bottom row total fluence per discharge for 39 Vs available for burn..

The maximum values for a specific case are clearly always attained somewhere along the line composed of minimum Q, maximum additional power, and maximum allowed density (i.e. the downward-facing limits of Fig. 3: the yellow, green, and blue lines). It is thus convenient to compare the different cases by examining the values obtained along this trajectory.

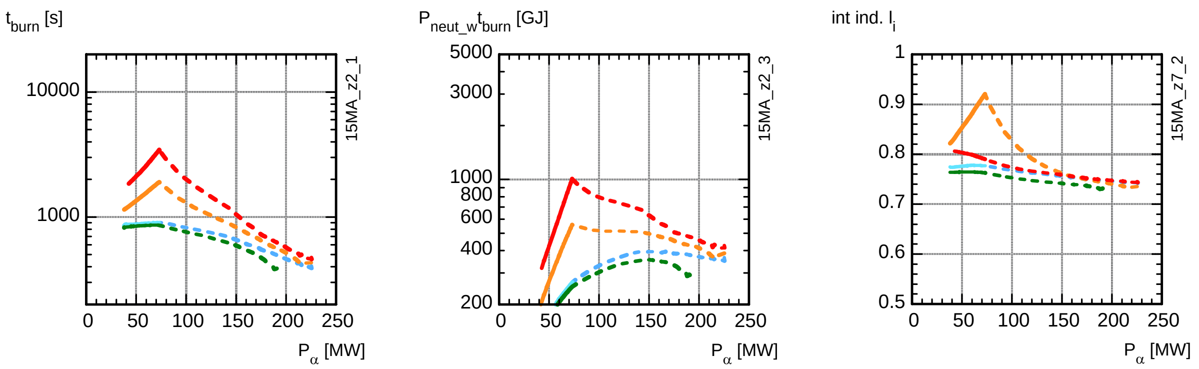
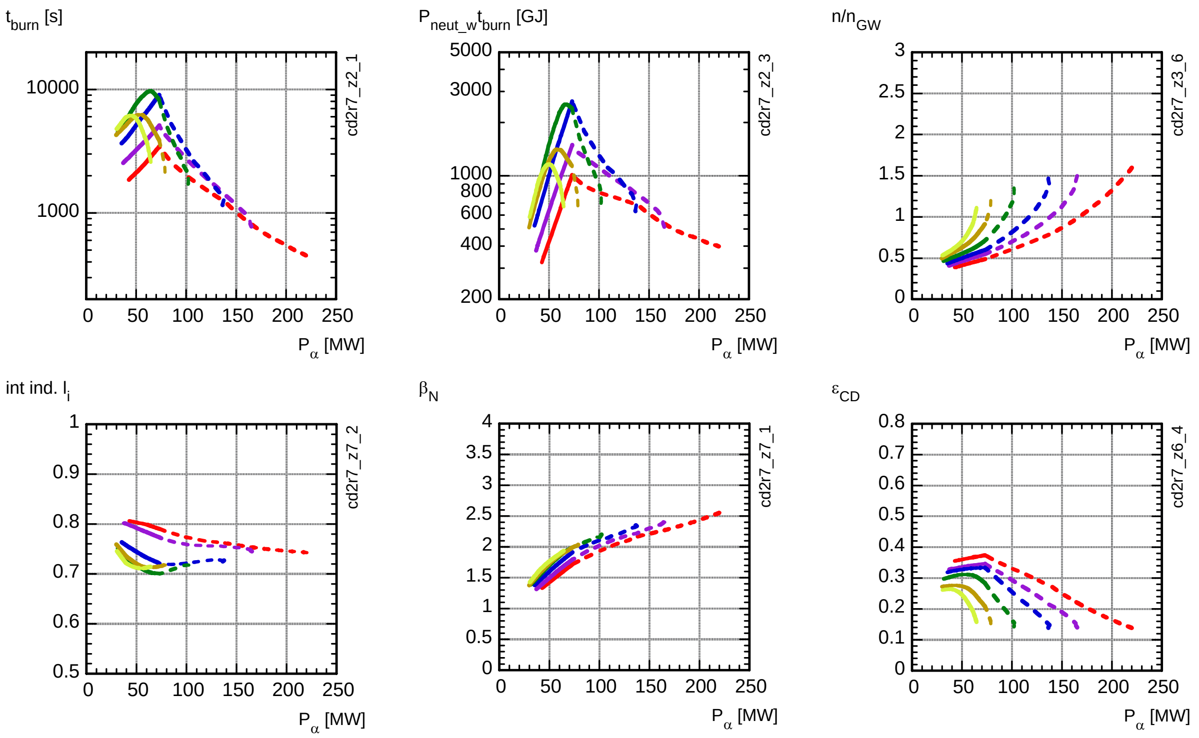


Fig. 4 – Parameter variation along trajectory (see text) for): burn time, fluence, and internal inductance. Cases shown (all with 15 MA plasma current) are: near-axis ((turquoise) and off-axis heating (green), and near-axis (orange) and off-axis (red) current drive. Solid lines at Q = 5, dashed .lines at P_{add}= 73 MW or $f_{sat\text{-}n}$=0.9

Figure 4 compares the performance with near- and off-axis heating with that with near- and off-axis current drive at the nominal 15 MA current. With heating alone, little difference appears between near-axis and off-axis deposition, although the former is marginally better. The current-driven cases are both appreciably better, and the best situation for the parameters considered here is the off-axis current drive case, which has maximum burn duration (3400 s) and fluence (1000 GJ) at P_{alpha}=73 MW (equal to P_{aux}).This maximum occurs somewhat below the desired P_{alpha} of 100 MW, for which the values would be 2000s and 800 GJ, respectively, so that 9500 pulses are required for the testing mission. A major difference between the two current drive locations is the high value of internal inductance with near-axis deposition, but it is not critically low for the other cases. Off-axis current drive appears to be beneficial because it reduces the radius of the q=1 surface, inside which the temperature profiles are flattened.

Until now, all cases examined have been at the nominal plasma current of 15 MA. However, the volt-seconds available for burn are estimated to increase by 16.5 Vs for every MA reduction of plasma current below 15 MA, so that the longer pulse possible at lower current may be advantageous for the testing mission. Accordingly, similar scans have been carried out at lower plasma currents down to 11 MA.



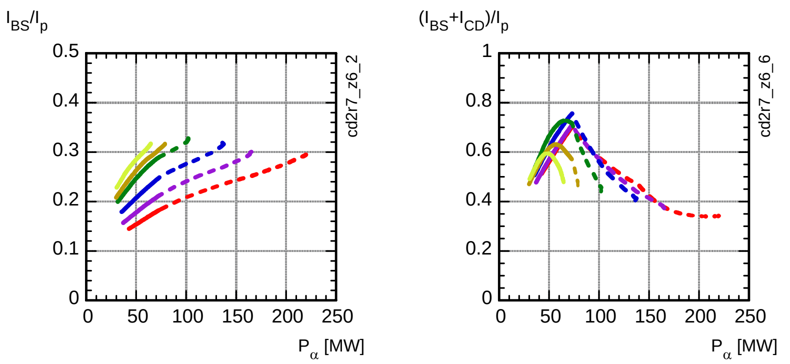


Fig. 5 – Parameter variation along trajectory with off-axis current drive for different plasma currents: 15 (red), 14 (purple), 13 (blue), 12 (green), 11.5 (brown), and 11 (yellow) MA: burn time, fluence, density normalised to Greenwald; internal inductance, normalised beta, current drive efficiency; bootstrap current fraction, non-inductive current fraction. Line types as in fig. 4

Since off-axis current drive has been seen above to be favourable, only this case is examined for the plasma current variation in figure 5. As plasma current is reduced and the volt-seconds available for burn increase, both burn duration and fluence are seen to increase, attaining 10000 s and 2500 GJ. Both peak for all currents at or just below the alpha power of 73 MW (below the desired value of 100 MW), with the 12 and 13 MA cases almost equivalent. At lower currents, both duration and fluence decrease relative to this optimum. However, at an alpha power of 100 MW, the 13 MA case is clearly superior to the 12 MA case, with 3200s and 1300 GJ, and the 14 MA case is almost equivalent. The entire testing mission would then require approximately 5900 such pulses. If the somewhat lower wall load near 70 MW alpha power is acceptable, the number of discharges is reduced dramatically, to about 3000. Note that a density equal to the Greenwald density is not attained until P_{alpha} =150 MW, so that the best performance for the testing mission is well below the Greenwald density.

For all cases, the normalised β_n is near 2 at the fusion powers of interest, so that the resulting bootstrap fraction is low, no bigger than 30 % at best. The total non-inductive current fraction reaches 75 % at the maximum fluence, and is near 60% at 100 MW, so that operation is still fairly remote from steady state.

3. Preliminary Results for DEMO

DEMO operations, which are to be reactor-like, have operational limits different from an experiment such as ITER. Specifically, enough alpha particle power is always available so that the LH back-transition is prevented and this limit becomes irrelevant. Furthermore, the ion temperature always remains sufficiently high that the limit on maximum alpha particle power mostly due to degradation of the fusion cross-section is not accessed for DEMO. However, economic considerations will impose a lower limit on Q higher than that required for ITER, say 20 or higher. To achieve controllability of the discharge and to obtain sufficient driven current, Q should not exceed a maximum value, say 50. Reasonable minimum and maximum values to delimit the operating window might thus be Q = 20 and Q = 50 respectively. Other limits will include desired maximum and minimum values of fusion power, and the edge-based density limit as for ITER.

As an illustration, we have examined the operating diagram of a machine with the typical DEMO parameters (R = 8.1 m, a = 2.8 m, I ≤ 21 MA, B = 5.7 T) we had used in a previous study of impurity seeding [9]. In order to permit comparison with the ITER cases above, no impurity seeding is used for the DEMO simulations presented here, and the divertor plate material is taken to be carbon as for ITER (Calculations with carbon-free walls and impurity seeding have not yet been done). The maximum power load on the divertor plates is limited for DEMO to ~7.8 MW/m^2 by gas puffing when required (with this power load, a helium-cooled divertor is an option). Only full plasma current, 21 MA, has been examined in this preliminary investigation. As for ITER, scans at variable density are carried out at different heating (current-drive) power from 10 to 100 MW. Near-axis heating, as well as near- and off-axis current drive with deposition profiles as for ITER are examined.

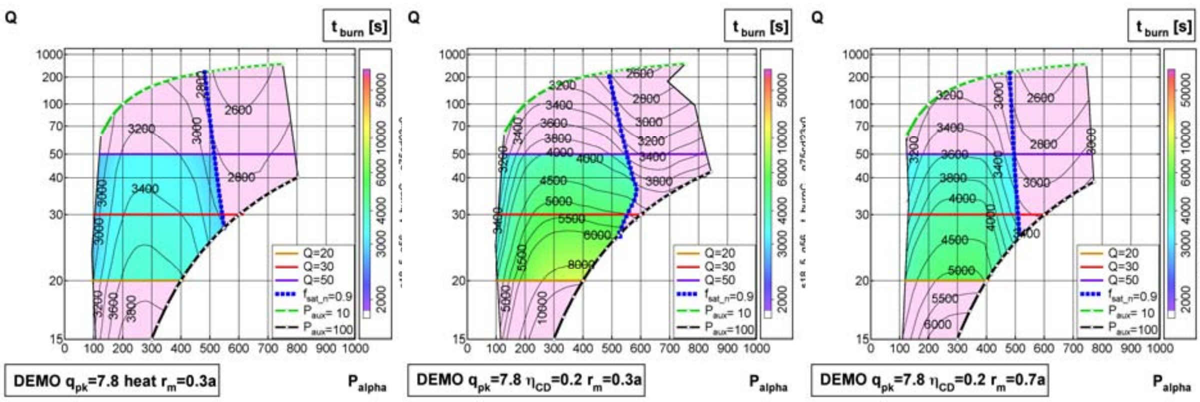


Fig. 6 - Operating space for DEMO in ELMy H-mode at 21 MA plotted in the Q-P_{alpha} plane. Burn duration for 100 Vs for near-axis heating (left), near-axis (centre), and off-axis current drive (right).

Fig. 6 and Fig. 7 show the burn duration for these three DEMO heating/current-drive scenarios in ELMy H-mode operation, assuming 100 Vs are available for burn at the full plasma current of 21 MA. In contrast to the ITER simulations, the longest burn duration is obtained not with off-axis, but with near-axis current drive. Here, near-axis current drive actually reduces the q=1 radius more than off-axis current drive. The DEMO operation investigated here is at high Q, versus low-Q for ITER, and as a result, the driven current fraction is smaller, ~10% vs. 30-50% for ITER, the current profile is then less peaked for the near-axis current drive case than for ITER and therefore the q=1 surface shrinks. This causes an increase in the central temperature and thus enhances the driven current (Fig. 7).

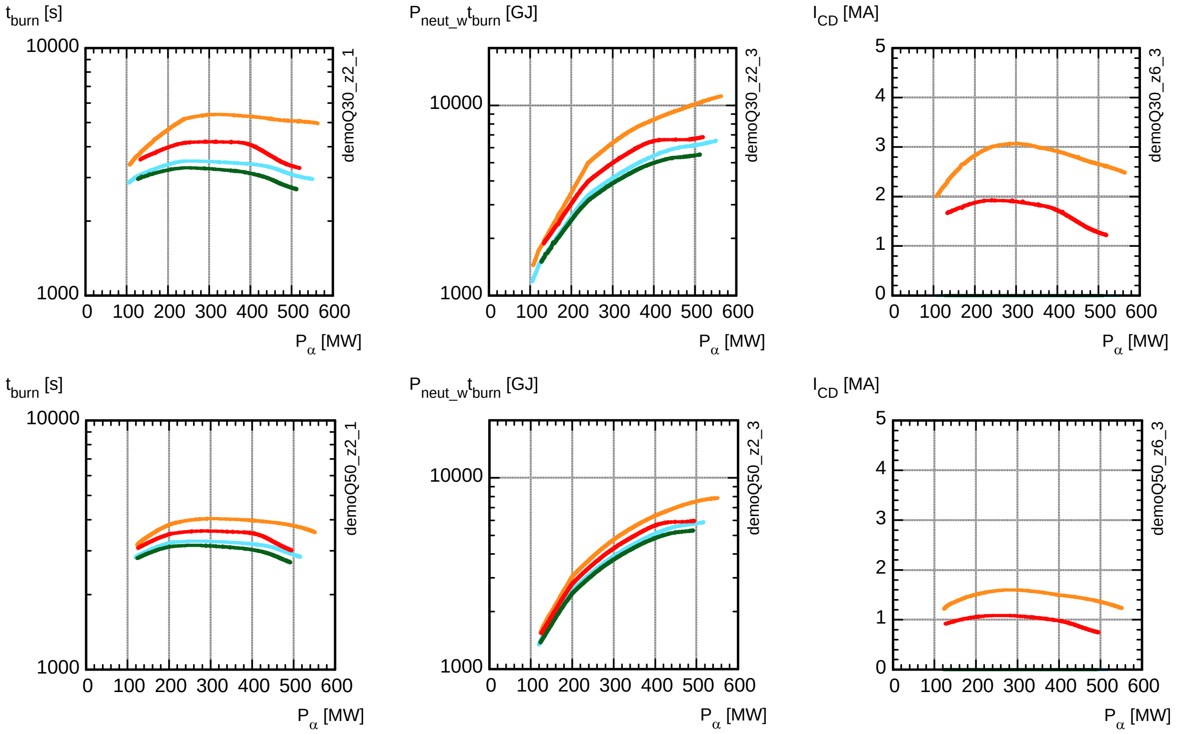


Fig. 7 - Parameter variation at Q=30 (top) and Q=50 (bottom) for DEMO at 21 MA for burn time, fluence, and driven current. Cases shown are: near-axis (turquoise) and off-axis heating (green), and near-axis (orange) and off-axis (red) current drive.

For near-axis current drive, at Q=30 (50), a burn time of 5000s (3600s) or more is obtained for a large range of alpha power (220 - 550 MW, i.e. fusion power 1100 - 2750 MW), indicating appreciable flexibility for reactor-like operation. The difference between near- and off-axis current drive is reduced at higher Q because the current drive is then smaller. The burn time would be greatly enhanced at somewhat lower plasma current, similar to the study of [9]. Note that, for the ELMy H-mode scenarios considered here, normalised beta is below ~2.3, so that the bootstrap current fraction is ~30% maximum, i.e. this is also far from steady state.

4. Summary and Conclusion

The operating window of ITER in ELMy H-mode has been examined in order to assess the adequacy of this operational mode for the ITER testing mission. Near-axis and off-axis heating and current drive scenarios have been evaluated. The longest burn duration and the largest fluence per discharge are generally attained at low Q. However, this maximum occurs near an alpha power equal to the installed auxiliary power of 73 MW, i.e. at a neutron wall load only three-fourths of the desired value of 0.5 MW/m^2. At 100 MW alpha power, i.e. at the desired neutron wall load, the parameters are limited by the installed power (except for the lowest plasma current investigated, for which the performance is degraded). At the desired neutron wall load, which corresponds to Q~7 at the installed auxiliary power, the best performance in burn duration and fluence per discharge is obtained with a plasma current reduced by ~15% from the nominal 15 MA. The desired neutron fluence for the testing mission of 0.3 MWa/m^2 is reached with 23000 discharges with heating alone at nominal current, but with off-axis current drive and reduced plasma current, the goal can be attained with only 5900 pulses; at a reduced flux of 0.38 MW/m^2 but maximum fluence even ~3000 pulses suffice. The required plasma density for these parameters is well below the Greenwald density. The normalised beta is low for all cases, and the total non-inductive current fraction is 60% or less at 100 MW alpha power, fairly remote from steady-state operation.

The preliminary DEMO simulations reported here differ in several aspects from a previous study [9]. There, the degradation of confinement in the absence of toroidal rotation had not yet been experimentally recognized and was therefore not taken into account. In addition, the point comparison carried out there concentrated on only one high-Q operating point for auxiliary and fusion power, and the current drive efficiency was assumed higher. As a result, the burn duration reported there was a factor of two larger for a similar profile of off-axis current drive. At full current, the present simulations yield, for Q=30(50) a burn duration of ~5000 (3700) seconds with a fluence per discharge of 10000 (7500) GJ at an alpha power of 500 MW (fusion power of 2.5 GW). As in [9], reducing plasma current to free volt-seconds for burn would greatly enhance the burn duration, by a factor of two to three over that reported here. The preliminary analysis reported here indicates that appreciable flexibility for reactor operation is attained, at least for the ELMy H-mode considered, since the fusion power can be reduced by more than a factor of two from nominal without reducing the burn duration. This behaviour is expected to change as the bootstrap current becomes relatively more important. This will be investigated in future work, as will carbon-free operation with impurity seeding and operation at lower plasma current.

References

[1] Pacher, G.W., Pacher, H.D., Janeschitz, G., Kukushkin, A.S., *Nucl. Fusion* **48** (2008) 105003.

[2] Pacher, G.W., Pacher, H.D., Kukushkin, A.S., Janeschitz, G., *Proc. 34th EPS Conf. on Plasma Physics*, Warsaw (2007); http://epsppd.epfl.ch/Warsaw/pdf/P4_118.pdf.

[3] Pacher, H.D., Kukushkin, A.S., Pacher, G.W., Kotov, V., et al., “Impurity seeding and scaling of edge parameters in ITER”, to be publ. by *J. Nucl. Mater.* (2008).

[4] Bateman G., Kritz A.H., et al., *Phys Plasmas* **5** (1998) 1793.

[5] Pacher, G.W., Pacher, H.D., Janeschitz, G., Kukushkin, A.S., et al., *Nucl. Fusion* **45** (2005) 581.

[6] Sugihara M., Mukhovatov V., Polevoi A., Shimada M., *Plasma Phys. Control. Fusion* **45** (2003) L55.

[7] Igitkhanov, Yu., (1998) private communication

[8] "Progress in the ITER Physics Basis", *Nucl. Fusion* **47**, no. 6 (2007) S1.

[9] Pacher, G.W., Pacher, H.D., Janeschitz, G., Kukushkin, A.S., et al., *Nucl. Fusion* **47** (2007) 469.