Paths to ignition by rf heating during the B-field ramp

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September 1999

(submitted to Physics of Plasmas)

LRC-99-75

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To conserve transformer volt-seconds, power to toroidal magnetic field coils, and to trigger an early transition into H-mode, where the requirements on auxiliary power are lower, rf heating during the B-field ramp phase of ignition-class tokamaks is considered. The scheme is analyzed by modifying the usual plasma operating condition (POPCON) diagrams to apply to the ramp phase where the magnetic field, plasma current and density are changing. It is shown that ICRF direct electron heating during the ramp phase of IGNITOR, as proposed by Majeski, may be useful in optimizing the operating condition path to ignition.

PACS: 52.55.Fa, 52.50.Gj, 52.55.Pi

An important milestone for the fusion program is the construction of a low-cost tokamak that can demonstrate ignition and allow investigation of the physics of burning plasmas. One approach is that of high density, high B-field compact machines such as IGNITOR[1] and FIRE.[2] Obviously costs are reduced by achieving the best possible plasma confinement (e.g. H-mode), minimizing the required power of auxiliary heating systems and designing for the shortest pulse length that is compatible with the physics that must be explored. These objectives may be enhanced by triggering an H-mode transition in the plasma during the startup or ramp phase of the discharge where the magnetic field B, plasma current I_p and central density n_0 are low and simultaneously increasing. The early H-mode creates a high performance discharge lasting for the maximum time. Since the H-mode threshold power is generally believed to be an increasing function of B and n, transition during the ramp can reduce the power requirement of the auxiliary heating system. The latter is often dominated by the H-mode transition power, not flat-top heating requirements which become minimal as ignition conditions are approached.

For ion cyclotron range of frequencies (ICRF) heating during the B-field ramp, the difficulty, not faced in conventional present day tokamaks, is that the ion cyclotron resonance locations are moving for a fixed rf frequency. To circumvent the difficulties associated with undesirable edge resonances (especially near the antenna) and/or with engineering an rf system that uses variable or multiple frequencies, a direct electron heating scheme was been proposed by Majeski[3] and is the heating scheme we consider in the present study. While high field ignition or burn class tokamaks generally provide good target plasmas for ICRF heating because their high density usually implies good single pass absorption, this may not be the case for the cooler, less dense plasmas present in the ramp phase. Thus, the question arises as how to best optimize rf absorption and analyze rf power requirements together with the complicated possibilities for operating condition paths to ignition.

To address these questions we have developed a new kind of ramped-POPCON diagram, hereafter referred to as a RAMPCON diagram, in which the "y-axis" representing increasing n_0 is also used to represent increasing B and I_p. The x-axis is temperature as for the usual POPCONs. This allows consideration of startup scenarios. The topology of the P_{aux} (auxiliary power) contours for the RAMPCON diagrams is similar to that of conventional POPCONs, but the shape of the H-mode power threshold curves is different because of the dependence on density and B-field.

We have considered RAMPCONs for various scaling laws as applied to nominal IGNITOR parameters: R_0 = 1.32 m, a = 0.47 m, δ = 0.4, κ = 1.87, B_{0max} = 13 T, I_{pmax} = 11 MA, Z_{eff} = 1.2, Z_{imp} = 6 (i.e. pure carbon impurity) and the profile peaking factors

$\gamma_n = 2$, $\gamma_T = 2$, [e.g. $n = n_0(1-x^2)^{\gamma_n}$ with x a normalized radial variable]. For the Improved Ohmic Confinement (IOC) scaling law[4] we find that Ohmic ignition occurs near the top of the ramp, without the application of auxiliary rf power.

For a high field machine, the IOC law is much more optimistic than ITER-89p L mode scaling,[4] which we now consider (even though its application to high field tokamaks is arguably unduly pessimistic). In L-mode we find that Q remains less than 5 over the accessible parameter space. Consequently, interesting performance requires an H-mode transition or performance with an effective H factor greater than one (relative to ITER-89p). We find that H = 1.8 is sufficient to yield ignition for the assumed case. A sample RAMPCON diagram for the nominal IGNITOR parameters is shown in Fig. 1 which fixes H = 1.8 (a generalization will be considered subsequently) and employs a linear n_0, B, I_p ramp over the range $n_0 = 0 - 1.2 \times 10^{21}$ m^{-3}, B = 5 - 13 T and I_p = 0 - 11 MA. The gray and black shaded contours correspond to P_{aux} (0, 10, 20, 30, 40, 50 MW); Q (5, 10, ∞) contours are gold, where $Q = P_{fusion}/(P_{aux}+P_{oh})$; and the Troyon beta limit is shown in green. The RAMPCON diagram of Fig. 1 (as well as all such diagrams presented in this paper) satisifies the Greenwald density limit at all times. The H-mode power threshold using a recent empirical data base for diverted tokamaks[5] is shown in dashed blue, and the contours of single pass absorption (f_{sp}) for direct electron heating are shown in blue (cyan). The rf single pass absorption was calculated from the FREMIR[6] code for 400 MHz rf with $k_{||} = 0.4$ cm^{-1}. If a confinement enhancement of H = 1.8 over ITER-89p L mode scaling is only possible by achieving an H-mode transition, then Fig. 1 is self-consistent to the right of, and below, the dashed blue contour. This requires about 20 MW of absorbed rf power, after which ignition is readily achieved.

It can be seen from Fig. 1 that the single pass absorption is excellent (> 75%) once T exceeds 10 keV and one is at least 1/3 the way up the ramp ($n_0 > 4 \times 10^{20}$ m^{-3}, B > 8 T and I > 4 MA). However, single pass absorption appears to be an issue during the early startup phase when the plasma is cold, and or the density is very low, since it fundamentally scales with the electron beta, β_e, and $k_{||}v_e/\omega$ where v_e is the electron thermal velocity.

To analyze the start-up phase and possibility of an rf-assisted H-mode transition in more detail, we must further complicate Fig. 1 by including a bifurcation in the confinement law using H = 1.0 below threshold and H = 1.8 above it. We wish to take into account the different confinement and rf absorption properties of three different phases: Ohmic, rf-heated L-mode, and H-mode. For this analysis, it is more transparent to consider an alternative presentation of the diagram in which we fix P_{aux} and plot contours of the energy growth rate $\lambda = W^{-1}\, dW/dt$, where $W = \langle nT \rangle$.

The resulting RAMPCON with λ contours {-4, -2, -1.5, -1., -0.5, 0, .5, 1., 1.5, 2., 4}s^{-1} is presented in Fig. 2 for P_{aux} = 20 MW (absorbed into the core plasma) and parameters other than H the same as in Fig. 1. Again a linear ramp in n_0, B, I_p is employed as for Fig. 1, but for simplicity only n_0 is shown in the y-axis label. On the left of the diagram we have a region with H = 1.0 which terminates at the H-mode power threshold (heavy dashed line). On the right we have a region with H = 1.8 which begins at the H-mode power threshold. Here we assume the H-mode transition occurs when the conduction power equals the H-mode threshold power. The thick black lines are steady state ($\lambda = 0$) and the plasma is heated ($\lambda > 0$) in the red shaded region and cooled ($\lambda < 0$) in the blue shaded region. The diagram shows that there is a scenario to get to ignition, but it requires that the H-mode transition occur about half way or earlier up the ramp (where the plasma remains below 6×10^{20} m^{-3}). This follows from the figure because further up the ramp, the plasma is cooled $\lambda < 0$ at the H-mode transition boundary and therefore evolves away from the boundary to the left, back towards the heavy black $\lambda = 0$ contour. To make the transition at these higher values of n_0 and B would require $P_{aux} > 20$ MW. Assuming the operating point is moved to the transition boundary in the red region, the H-mode transition occurs. Once the transition is made, the burning and ignited plasma regimes are accessible. The gold contours shown in the figure are Q = {5, 10, 20}.

The cyan rf absorption contours of Fig. 1 do not depend on the confinement properties of the plasma (i.e. the H value), and may be mentally overlaid on Fig. 2. The Ohmic target plasma at the bottom of the ramp is low density and cold, and is therefore a poor absorber: we find that absorption becomes significant ($f_{sp} > 25\%$) about half way up the ramp. Now applying rf, as the plasma heats, absorption improves to $f_{sp} \sim 50\%$ for 20 MW absorbed power at $n_0 = 6 \times 10^{20}$ m^{-3}, implying T_0 = 7 keV. This puts the plasma at the H-mode threshold. Once the transition to H-mode occurs, T_0 increase to about 12 keV, rf absorption is excellent, and there is a clear path to ignition for H ~ 1.8.

We complete our analysis with discussion of some additional rf considerations. The base case results discussed above were for the choice $k_{||} = 0.4$ cm^{-1}. The effect of varying $k_{||}$ has also been studied. Except at very low n_0, B, I_p (small values along the y-axis of the RAMPCON diagram) absorption is an increasing function of $k_{||}$ in the range $k_{||}$ = 0.2 to 0.4 cm^{-1}. Fig. 3 shows the absorption vs. $k_{||}$ for a fixed value along the y-axis of y = 0.45 (i.e. 45% up the ramp where $n_0 = 5.4\ 10^{14}$ cm^{-3}, B = 8.6 T) and for a fixed T_e = 6 keV. Significantly, at still higher values of $k_{||}$ the accessibility of the rf wave becomes an issue due to the FW cutoff.

When the density at the edge is low and $k_{||}$ is large the existence of the FW cutoff becomes important. This occurs at the start of the ramp, and is particularly an issue when the density profile is highly peaked, so that the edge to central density ratio is small. In the preceding discussion, it was shown that increasing $k_{||}$ generally leads to improved absorption in the parameter range of interest. But this improvement comes at the cost of a greater difficulty in coupling to the wave, because the fields launched at the antenna/waveguide must tunnel through the evanescent layer that occurs between the plasma surface and the FW cutoff.

To study the optimization of $k_{||}$ would require a coupling code, capable of modeling the rf launcher. While this is beyond the scope of the present study, an estimate of the acceptable range of $k_{||}$ can be deduced from a simple computation of the width of the evanescent layer. In the vacuum, the evanescent scale length (for $k_y = 0$) is $k_{||}^{-1}$, thus for acceptable coupling we expect that $k_{||} \Delta < g$ must pertain, where Δ is the layer width and g is a number of order unity, perhaps 2 or 3 at most. Calculations[7] suggest that the useful range of $k_{||}$ will be restricted to less than 0.5 cm^{-1}.

The relatively poor absorption at the bottom of the ramp in the preceding studies is due to the low β_e of the startup plasma. Direct electron absorption at fixed n_0 and T_e is, to an excellent approximation, linearly proportional to $1/B^2$ when the single pass absorption is small compared to one. (This has been checked numerically for the parameters of interest here, but is not illustrated.) Thus a possible method of further improving the absorption in the lower half of the ramp would be to consider scenarios where the density ramp begins at B values below 5 T. If this philosophy is to be pursued, other physics and engineering aspects of the ramp-up scenario would need to be re-examined, e.g. the Greenwald density limit and MHD stability limits.

In related work[7] we have analyzed ICRF edge interactions for conventional antennas operating in the high density environment of IGNITOR and FIRE. We find that rf-sheath power dissipation considerations, which impact both antenna efficiency and heat load on the antenna structure, impose a limitation on the allowed density at the antenna surface. Typically, the latter constraint is the most restrictive. For IGNITOR, taking the requirement that the peak heat load satisfy $Q_{sh} < 10$ MW/m^2 implies the density requirement $n_e < 2 \times 10^{18}$ m^{-3}. The density restriction can be met by placing the antenna sufficiently far away from the plasma surface, and/or by employing antenna protection limiters with sufficient radial extent. In either case, the impact on antenna coupling must be assessed.

The present study, requiring higher frequency, shorter wavelength rf, motivates investigations of non-conventional ICRF launching techniques such as dielectric-filled and folded waveguides, possibly launching through a window. The latter would simplify hardware structures in the ignition plasma environment. The issues of obtaining sufficient

$k_{||}$ for direct electron heating during the ramp (e.g. appropriate toroidal launch angles) and the role of wall - SOL physics in the presence of intense fields in these launching scenarios is an important area of for future research.

In conclusion, we have presented a method of analyzing plasma operating conditions during a B-field ramp, and employed the resulting RAMPCON diagrams to assess the feasibility of direct electron heating during the ramp phase of IGNITOR. The direct electron heating scheme appears to be feasible, based upon the results of this preliminary study. The main issue is the creation of an Ohmic target plasma which has sufficient single pass absorption to allow the heating to proceed, and hence the plasma to evolve to the higher T_e, where the direct electron absorption is better. A 400 MHz rf system is expected to perform best when the launched wavenumbers are in the approximate range $0.2\ cm^{-1} < k_{||} < 0.5\ cm^{-1}$.

Under optimistic assumptions about the global energy confinement scaling (IOC scaling law) we find that IGNITOR ignites Ohmically, and the use of rf heating is not required. Under pessimistic assumptions (ITER-89p L mode scaling) interesting machine performance requires an H-mode transition. We find that the transition can be assisted by direct electron heating during the ramp. This strategy allows one to achieve H-mode access by making the transition at low density and B-field, where the threshold power for the transition is expected to be lower than for top-of-the-ramp parameters.

Acknowledgments

We wish to thank R. Majeski (PPPL) for discussions of the high-frequency electron heating scenario for IGNITOR, and D. Russell (Lodestar) for providing some of the coding used in the present analysis. This work was supported by Raytheon/Lodestar subcontract No. 53250.420 7001; however this support does not constitute an endorsement by either Raytheon or the USDOE of the views expressed herein.

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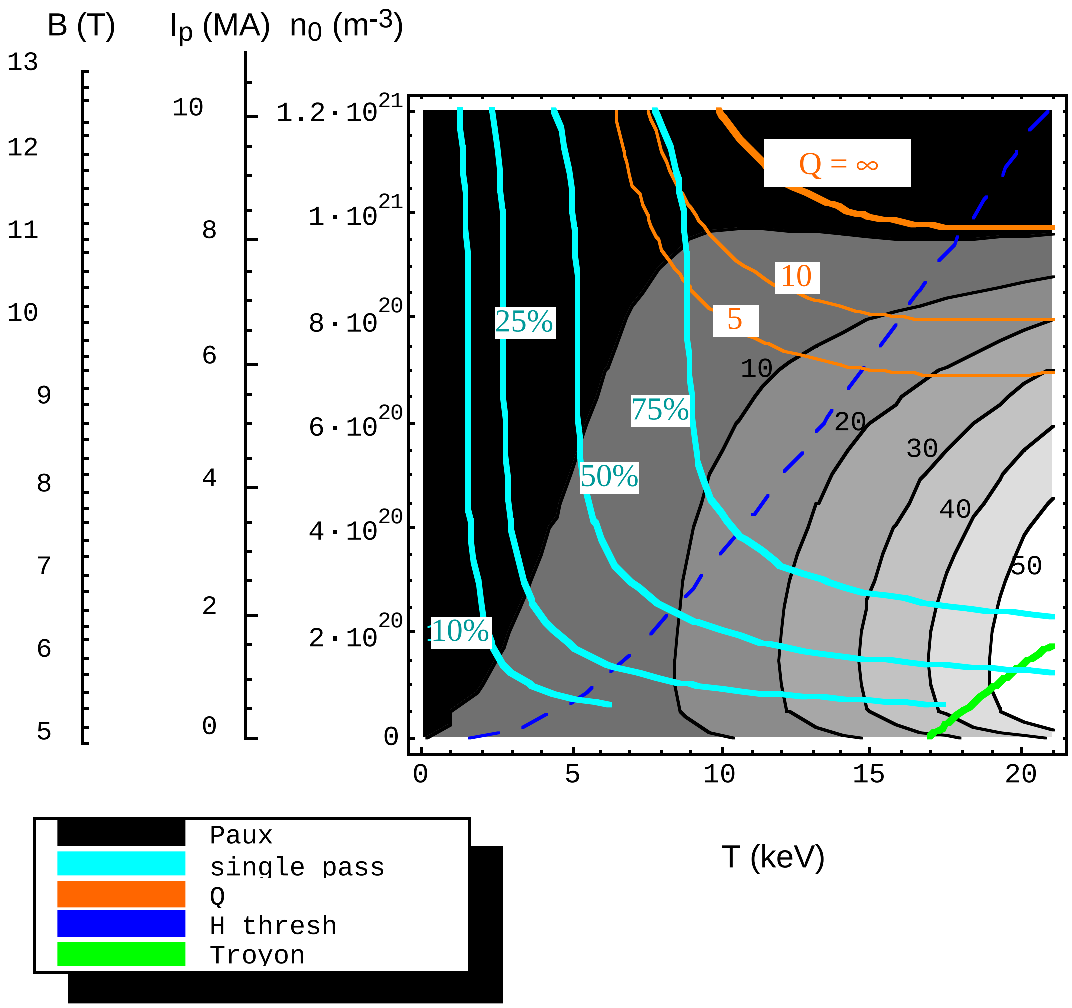
Figure Captions

1. RAMPCON diagram for IGNITOR under the ITER-89p scaling law with H = 1.8. Black shaded contours are P_{aux} (MW), cyan are single pass absorption f_{sp}, gold are Q. The Troyon β limit is shown in green (unstable below the curve) and the Thomsen H-mode power threshold is shown in dashed blue (H mode below and to the right of the line).
2. Bifurcated RAMPCON diagram for IGNITOR under the ITER-89p scaling law showing the L-H transition (H = 1.0 left, and H = 1.8 right), with contours of the stored energy growth rate λ (s^{-1}).
3. Single pass absorption f_{sp} vs. $k_{||}$ (cm^{-1}) for n_0 and B corresponding to 45% of the way up the ramp, for T_e = 6 keV.



B (T)
Ip (MA)
n0 (m-3)
T (keV)
Q = ∞
10
5
25%
50%
75%
10%
Paux
single pass
Q
H thresh
Troyon

Fig. 1

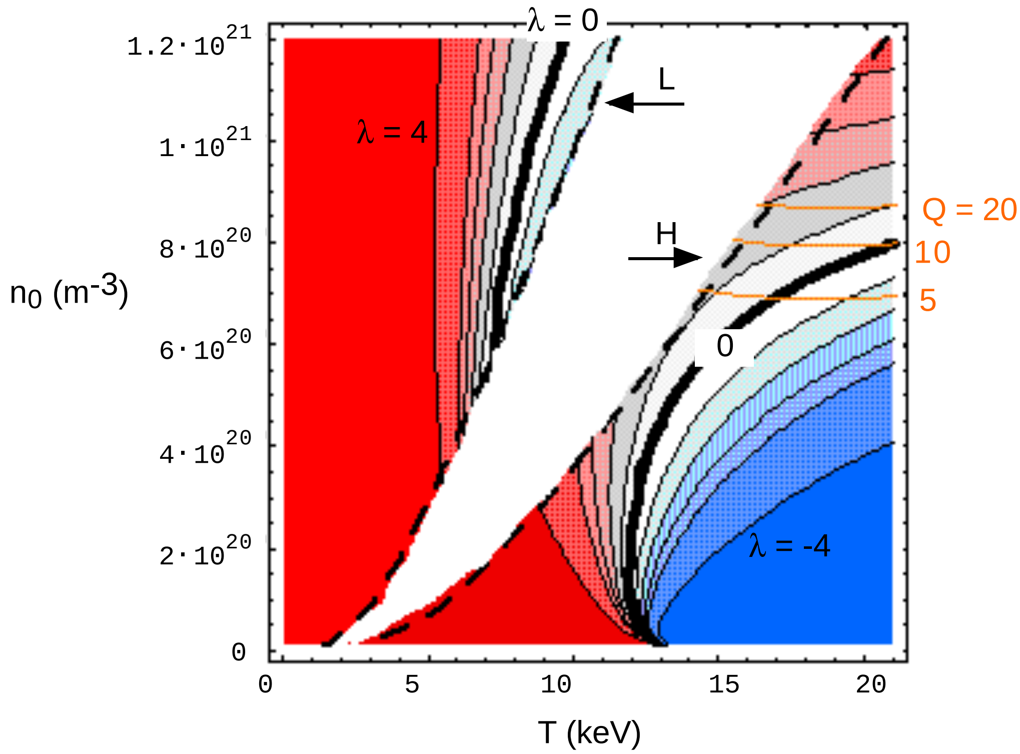

λ = 0
1.2·10^21
1·10^21
8·10^20
6·10^20
4·10^20
2·10^20
0
n0 (m-3)
λ = 4
L
H
Q = 20
10
5
0
λ = -4
0
5
10
15
20
T (keV)

Fig. 2

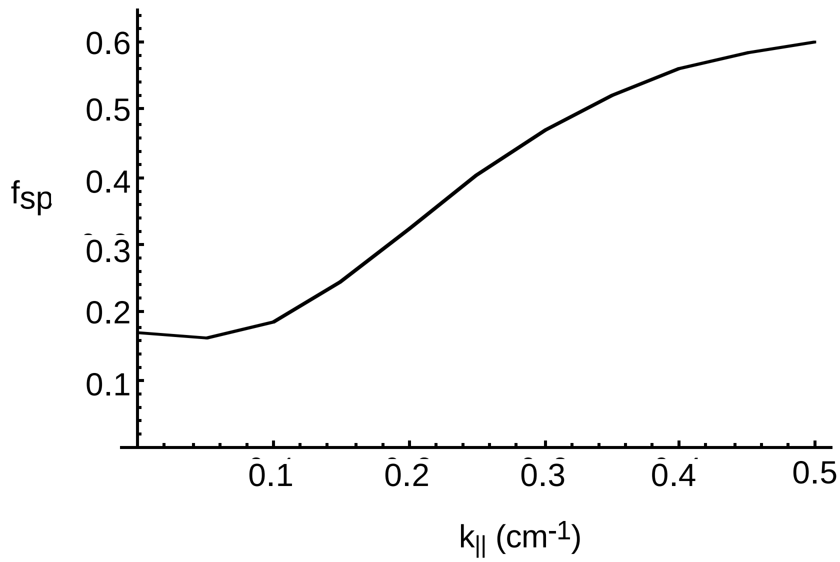


Fig. 3