

Experiments on Tokamak ADITYA

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Abstract: It is well known that the Greenwald limit is in reality a limit on edge particle confinement that leads to the loss of edge thermal equilibrium. While the radiative collapse is relatively well understood, questions remain about the exact dynamics of convectively driven collapse. We have examined the role of the Molecular Beam Injection (MBI) and the Gas Puff fuelling methods in the determination of the density limit when such a collapse is imminent. It is seen that, broad pulses of MBI, when fired in quick succession, generate a limit close to that in the case of gas-puff. Short pulses with larger separation in time lead to a significantly higher limiting density. Very large turbulent flux $\langle \tilde{n} \tilde{v}_r \rangle$ appears just before the collapse along with rapid changes in the scrape-off-layer scalelength for the former cases, unlike the case with smaller, widely spaced MBI pulses.

1. Introduction

It is well known that there occurs a dramatic deterioration of particle confinement in tokamaks as one approaches the Greenwald limit ($n_G [10^{20}] = I_p [MA] / p a^2 [m^2]$) [1]. It is also well known that this limit is actually a limit on edge density, i.e. if we were to fuel the core region directly, it would be possible to reach average densities beyond the Greenwald limit. Operation at trans-Greenwald densities is of great interest, as it will significantly improve fusion power performance [2], hence, investigation of limiting mechanisms, which causes the density limit disruption, is a crucial area of tokamak research.

Several authors [1,3-4] have investigated the phenomenology of the events leading to density limit disruption. While it is understood that ultimately it is the MHD instability, which kills the plasma, the variety of possible routes the plasma takes to reach an unstable point remains to be understood. For example, a radiative collapse of the thermal equilibrium can cause the current channel shrinkage, necessary for the onset of the MHD instability. But the same effect can also be achieved by an enhanced convective loss of heat and particles, eventually creating disruptive conditions. Recently Tokar [5] has investigated the issue of synergy between anomalous transport and radiative losses, where the edge temperature is shown to scale as n^{-8} . From these studies, it appears that an improved understanding of the conditions just preceding the disruption is necessary, especially on the issues of turbulent transport, associated scalelengths and convective cooling. One of the approaches, therefore, is to modify actively the scalelengths by using different fuelling mechanisms.

The Molecular Beam Injection (MBI) technique was shown to be a very effective fuelling method by Yao et al. [6] as it leads to deeper fuelling and more peaked density profiles compared to fuelling by the gas-puff. Recently, Bhatt et al. have developed a similar system for the ADITYA tokamak. The system has been described elsewhere [7].

Our objective in this paper, is to investigate the behavior of density-limit disruptions caused by different methods of plasma fuelling. ADITYA Tokamak

($R/a = 0.75/0.25$ m, $I_p \approx 60 - 80$ kA, $B_T = 0.8$ T) was fuelled with Gas-Puff (GP) and Molecular Beam Injection (MBI) technique. It can also be operated with a fixed pre-fill pressure (Normal - case) in which plasma-limiter interactions can cause an increase of density due to desorption of hydrogen from graphite tiles. All the three cases contain shots, which terminate in a density limit disruption when the density is ramped. In the MBI fuelling experiments reported here, we have examined the effect of changing pulse repetition time and width on the behavior of density limit disruption.

2. Experiments with GP and MBI:

Experiments with GP and MBI were carried out in ADITYA tokamak for understanding of the density limit. The pulse width and the gap between pulses were varied in different discharges. The quantity of gas (H_2) passing through the nozzle of 0.5 mm diameter was calculated using the formula in Ref. [6] and found to be $\approx 4.2 \times 10^{21}$ particles/sec at the gas source pressure of 10^5 Pa. At present the influx from the plasma-wall interaction cannot be measured, but is expected to play a role in the rate of rise of density. It may be noted that for typical gas source pressure ($< 10^5$ Pa) and typical edge density ($< 10^{19}$ m $^{-3}$) the penetration depth of the beam can be $v_b/v_i \sim 0.1$ m (for beam velocity $v_b \sim 300$ m/s & ionization frequency $\nu_i \sim 3 \times 10^3$ s $^{-1}$) which is also the location of the interferometer chord ($r = a - 0.1 = 0.14$ m).

In order to focus on the role of convection rather than the role of radiative loss in causing the disruption, we have selected only those shots, which show a marked increase in the H_a signal with the rise in density and are relatively free from significant MHD activity during this phase. When put together on the Hugill-plot, the MBI driven discharges fall in two distinct clusters which we call type I and type II, as shown in Fig.1. The type I shots are the ones which have broad (3 – 3.5 ms) width and short (2 – 5 ms) time gap between the pulses. The type II shots have typically a pulse width of 2 ms and a gap of 8 ms.

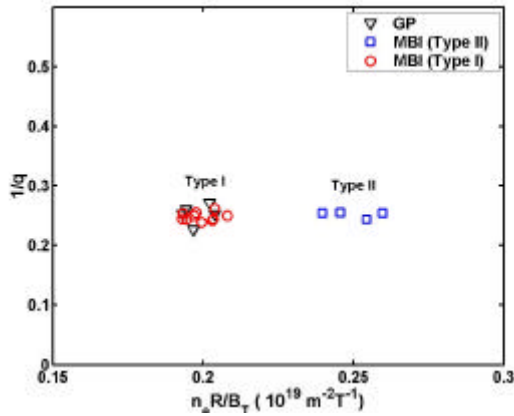


FIG. 1. Hugill Plot for ADITYA

The time evolution of a typical type I and II discharges has been shown in Fig.2, where, plasma current, chord averaged plasma density for central chord, H_a and bolometer signal have been shown in 2a (2b) for type I (type II) discharge. From the central chord measurements the rates of increase of density for the GP (#15040), MBI type I (#14676) and type II (#14732) cases are 2.4×10^{21} , 3×10^{21} & 2.4×10^{21} m $^{-3}$ s $^{-1}$ respectively. The pulse duration being small, such high rates (when compared to Yao et al [6]) can be accommodated.

The traces shown in Fig. 3a and 3b show an expanded view of the H_a and Mirnov signal where we note that in type I case, the rise of H_a signal is quite dramatic with a simultaneous rise in the MHD activity just before the disruption. We consider this to be a signature of strong convection where a lot of recycling takes place on the limiter surface due to a reduced particle confinement time. This may also be a cause of its lower value of critical density.

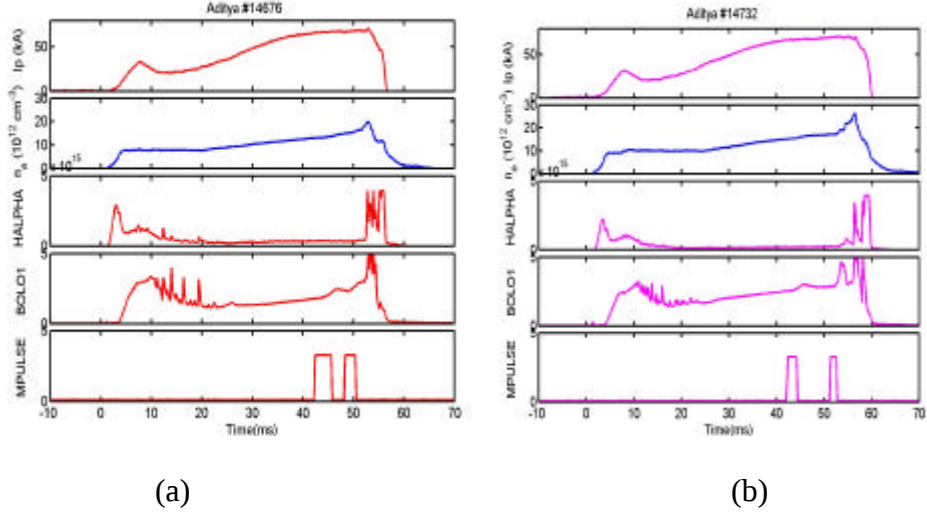


FIG. 2. Plasma current (I_p), plasma density (n_e), H_α (HALPHA), bolometer signal (BOLO1), MBI pulses (MPULSE) for (a) type I and (b) type II discharges.

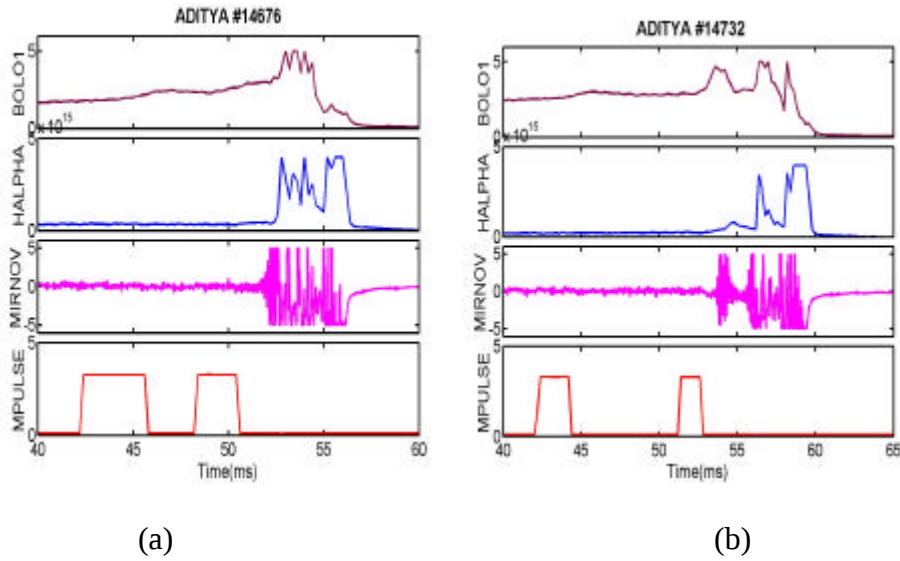


FIG. 3. Expanded view of the bolometer signal, H_α , Mirnov signal (MIRNOV), MBI pulses for (a) type I and (b) type II discharges.

3. Density Profile and Scalelength Evolution

Curves shown in Fig.4 are generated from the three channels of the microwave interferometer (central chord and two more at $r = \pm 0.14$ m) and the two Langmuir probes (at $r = 0.244$ m and $r = 0.25$ m) on the outboard side. The curves are drawn with a polynomial fit to ‘guide the eye’, with the inner boundary point reflected from the outer boundary.

In order to gain an understanding of the density profile evolution, we define a generalized dimensionless scalelength parameter L as: $L = [\ln(n_1/n_2)]^{-1}$ where the density $n = n_1$ at $r = r_1$ and $n = n_2$ at $r = r_2$, r being the minor radius with $r_1 < r_2$. Note that, in the limit

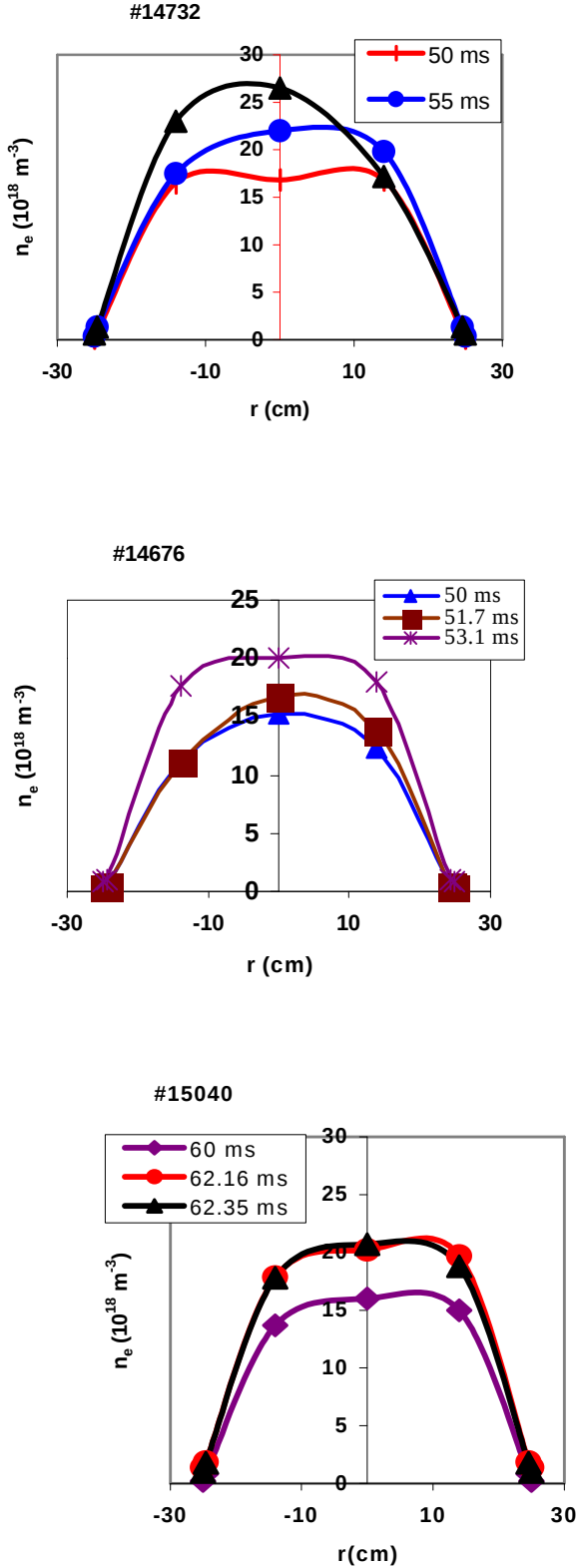


FIG. 4. Radial profiles of plasma density (a) with MBI (type II), (b) with MBI (type I), (c) with GP.

$\Delta \rightarrow 0$ (where $\Delta \equiv r_2 - r_1$), we have $L \rightarrow L_n / \Delta$, with the conventional scalelength L_n defined as $\frac{1}{n} \frac{dn}{dr}$. We have four radial locations ($r = 0, 0.14, 0.244$ and 0.25 m) at which density is measured; therefore we can define three scalelengths as L_C, L_E & L_S to represent respectively the ratios of density at successive locations (viz. $L_C = [\ln(n(r=0)/n(r=14))]^{-1}$ etc.) in the core, edge and SOL (Scrape-Off-Layer region). The inverse of logarithm provides a sensitive ‘diagnostic’ to probe whenever the density ratio hovers around unity. The time evolution of L_C, L_E & L_S for the gas puff case (#15040), MBI type I case (#14676) and MBI type II case (#14732) has been shown in Fig. 5. Positive (negative) values of L indicate that density is decreasing (increasing) as one moves radially outwards. Furthermore, for ADITYA parameters the density profile index n (with $n = n_0(1 - r^2/a^2)^n$) can be related to L_C by $n = 2.4/L_C$. An examination of the time evolution of these parameters reveals an interesting picture of the pre-disruption phase.

In the GP case, we note that a fluctuation of about 10 – 20 KHz in L_C correlates well with the onset of rapid rise in L_S . The fluctuation in L_C appears to be correlated with Mirnov oscillations just before the disruption. MHD reconstruction of this equilibrium shows that the 0.14 m interferometer chord is very close to $q = 2$ surface, thereby allowing it to track changes in the density profile near this region. In contrast to this, the MBI type II shots (#14732) shows a ‘quiet’ signal of L_C , except for the partial crash of central temperature preceding about 2 ms before the disruption.

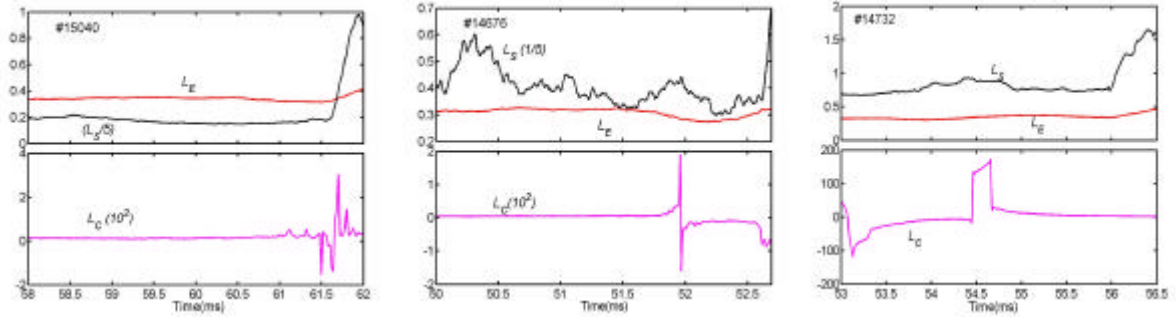


FIG. 5. Time evolution of L_C , L_E & L_S for the gas puff case (#15040), MBI type I case (#14676) and MBI type II case (#14732)

The negative spike in L_C at about 53 ms indicates that profile is becoming hollow ($n_{14\text{cm}} > n_{0\text{cm}}$) and stays so, for about 1.5 ms. The behavior of L_E (≈ 0.3) is nearly steady in all the three cases under consideration, suggesting a significant drop in the density ($e^{1/0.3} \sim 20$) as one goes from $r = 0.14$ m to $r = 0.244$ m in the minor radius. The distinguishing feature of MBI type II when compared to GP is a rapid increase in density closer to the core region. However, in the case of MBI type I discharges, which disrupt at low values of density, the profile remains somewhat flatter. The most striking behavior is of L_S in these discharges. Here, not only the value of L_S remains high, it also shows fine structure (about 10 – 20 KHz) riding on the top of a larger amplitude waveform of 1 – 2 KHz (probably due to ionization related effects). The rise in L_S at the end is much faster than in the GP and MBI type II cases, and is once again probably correlated with Mirnov activity (at about 10 KHz).

Thus, although one has used a deep fuelling technique, the fuelling appears to have been too rapid to allow relaxation of the density profile (presumably by some pinch mechanism) into a more peaked form. It is possible that the edge density quickly approaches its limiting value on account of a ‘two-way’ fuelling (firstly from the usual flow of neutrals from the LCFS towards the edge and secondly from the ‘outward’ flow of excess plasma density from the core side). In fact, we note that in the MBI cases the density pulse (defined here as the peak of the density trace) seems to travel both ways (inwards and outwards) from a middle location, in contrast to GP case where its arrival is noticed first on the outboard probes and subsequently at inner radial locations. This is shown in Fig. 6.

The speed of propagation of peak in the MBI case is about 70–80 m/s, when compared with the normal pinch velocity $v_p \sim E_f / B_q$, it is about 8 times greater for the parameters $I_p \sim 70$ kA, $V_{\text{loop}} \sim 3$ V. It is well known that the pinch effect leads to peaking of density profiles, however it may develop differently in the MBI and GP cases possibly due different levels of turbulence. More detailed analysis as in [3] is needed to estimate perturbed diffusivity and pinch velocity contributions.

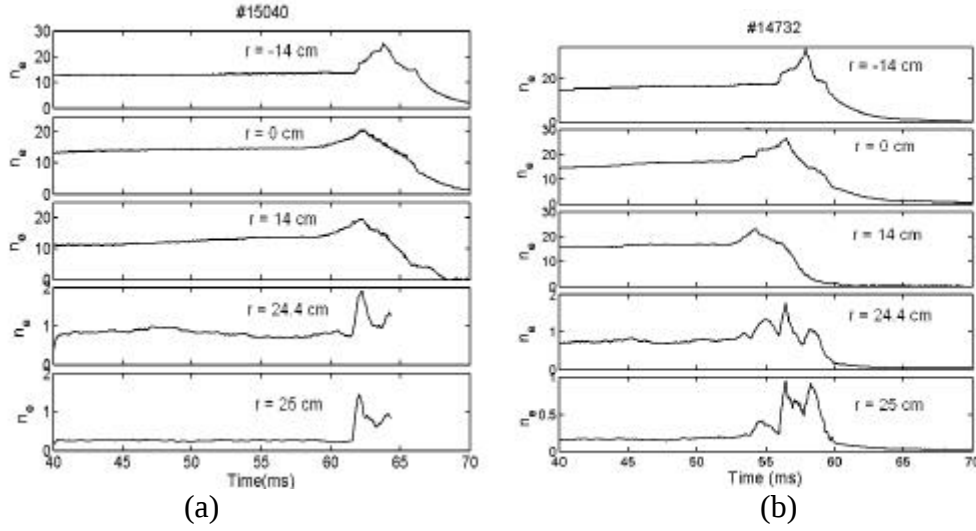


FIG. 6. Time evolution of density as measured at different radial locations.

The turbulence driven radial flux $\Gamma_{ExB} = \langle \tilde{n} \tilde{v}_r \rangle$ was calculated by a poloidal array of Langmuir probes measuring potential and density perturbations alternately. The turbulent flux

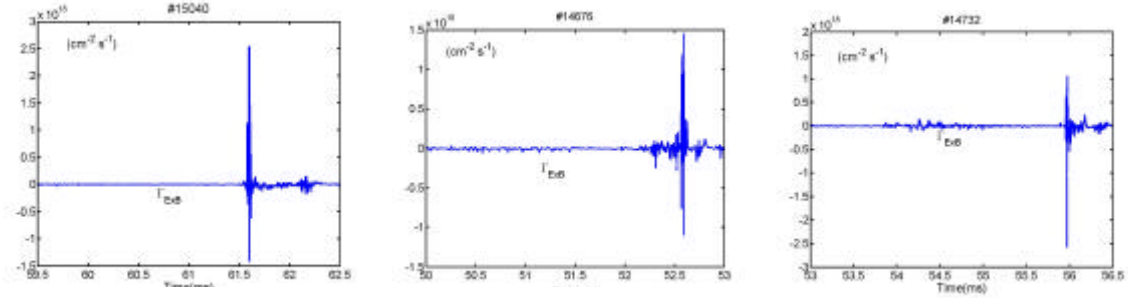


FIG. 7. Turbulent and steady flux for the three cases

is seen to be quite large at the time of disruption (FIG. 7) in the GP and MBI type-I cases, and is relatively small in the MBI type-II cases. This may explain why the H_α signal rose rapidly in the former two cases. In order to understand the turbulent flux in the two types of discharges we have also carried out correlation analysis.

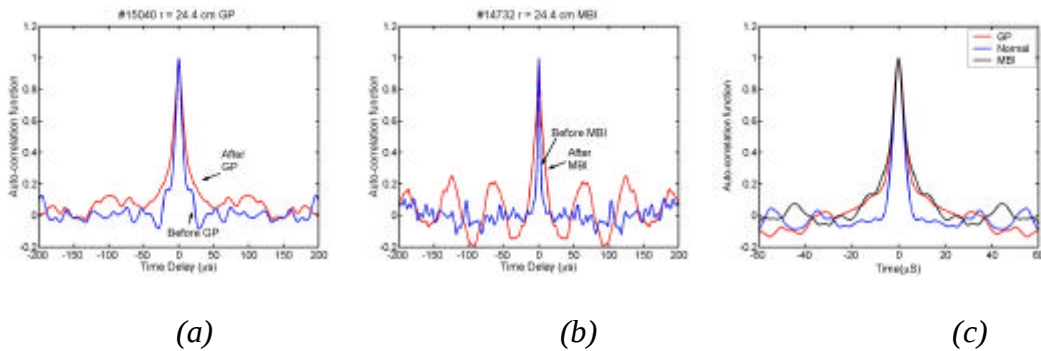


FIG. 8. Auto-correlation functions of Langmuir probe signals (a) Experimental (GP) (b) Experimental (MBI) (c) Modeling (GP and MBI).

Fig. 8 shows the autocorrelation function. We see that there is a broadening of the autocorrelation function in general after the MBI/GP, however, the oscillatory nature seen in the type II case probably indicates the formation of coherent structures. Preliminary studies with the coupled SOL (open field line) – edge (closed field line) simulations (extending the earlier 2-D SOL turbulence code FDUT [8] to mock-up the 3-D effects) show an encouraging qualitative match with experimental observations (FIG. 8c)

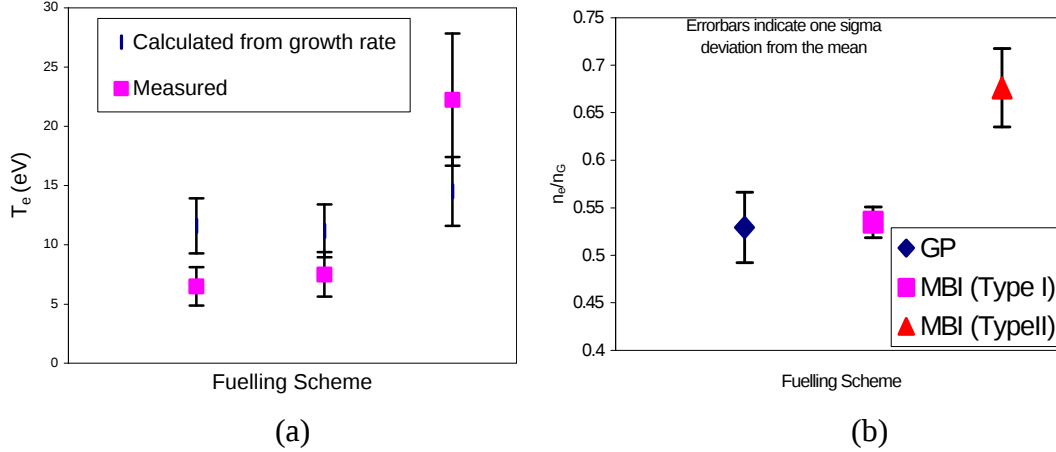


FIG. 9. Edge temperature and critical Greenwald parameter for different fuelling scheme

4. Comparison with Theory/ Simulation:

We now attempt to understand our overall observations using well known theoretical models. Rogers & Drake [9] have identified a parameter space defined by two non-dimensional parameters a and a_D , to delineate operating space for L mode, H mode and density limits. It has been pointed out that the density limit can be identified as a boundary in this dimensionless parameter space. We have calculated a and a_D for the parameters of interest here as $a = 2 \times 10^{-4} T_{eV} \cdot G / (n_G R L_n)$ and $a_D = 6.7 \times 10^{-3} T_{eV} \sqrt{R n_G} (R / L_n)^{1/4} / (B_0 \sqrt{G})$ where R is the major radius ($R = 0.75$ m), G is the Greenwald parameter defined as $G = \bar{n}_{20} / n_G$ with $\bar{n}_{20}$ being the average density measured in the units of 10^{20} m^{-3} , L_n is the scalelength defined earlier, B_0 is the toroidal magnetic field (0.8 T) and T_{eV} is the temperature in eV. As an indirect indicator of T_e in the edge zone, we have estimated T_e by calculating the growth rate of the B_θ signal and using the formula $t \sim 4 T_{eV}^{3/2} \mu\text{s}$, given by Turner and Wesson [10]. Measurements by separate set of Langmuir probes in mid-plane and 190 mm above mid-plane show rough agreement with the above estimates (FIG. 9(a)). All the shots under consideration have been depicted on this diagram (FIG.10) showing a rough agreement with the theoretical prediction. The a , a_D parameters were calculated just before the disruption. The continuous trace shows the time evolution of the shot #14732.

It may be noted that due to higher edge temperature, the a_D parameter is large for the MBI type II cases. However, its weak scaling on L_n vis-à-vis the contrasting experimental observations of strong dependence on L_n , leaves the question of identifying the right parameters open. Recently, Singh et al. [11] have suggested that the above parameter may be

quite important for describing the dynamics of drift resistive ballooning mode (DRBM) driven turbulence and zonal flows, through finite larmor radius effects.

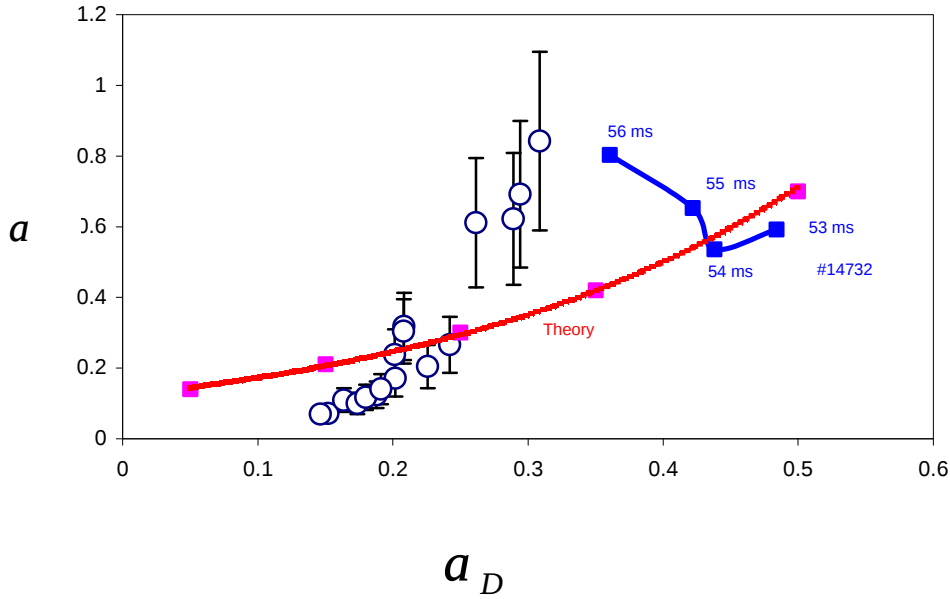


Fig. 10. Phase space plot for Aditya discharges

In conclusion, experiments on ADITYA tokamak with gas-puff and two difference schemes of MBI reveal the role of turbulence transport in deciding the density limit. The MBI shots with closely spaced and broad pulses (type I) are seen to result in discharges similar in nature to those with gas-puff. Such discharges disrupt at lower densities compared to MBI shots with widely spaced and shorter pulse width (type II) (FIG.9b).

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