Nonsolenoidal Startup and Plasma Stability at Near-Unity Aspect Ratio in the Pegasus Toroidal Experiment

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Abstract: Initiating and growing the current channel without a central solenoid is a critical problem facing the spherical tokamak, and may be relevant to future tokamak reactors. In the Pegasus ST experiment, small plasma arc current sources are placed in the periphery as DC helicity sources, which may offer a technically attractive means of creating an ST plasma. A model invoking null formation, helicity balance, and Taylor relaxation describes the plasma formation via localized current injection at the plasma edge. Experiments on Pegasus have confirmed elements of this model, and demonstrated achievement of $I_p \sim 0.17$ MA for a gun-injected current of $I_{inj} \leq 4$ kA. Projection to higher performance and larger experiments are enhanced by the observation that passive electrodes are as effective as the active arc sources once the tokamak discharge is formed. Plasmas evolved using the edge helicity injection generally have hollow j(R) profiles, with sufficient internal magnetic shear to mitigate large-scale tearing modes. This and more flexible field control has expanded the operating regime past the previous limit of $I_p/I_{TF} \leq 1$ to $I_p/I_{TF} > 2$, or $I_N > 10$. Operation at $A \sim 1$ offers high I_p at very low B_T, giving high values of $j_{edge}/B \sim 1$ MA/m^2-T, where peeling instabilities are excited. These instabilities show filaments that accelerate while moving radially outward, similar to that seen with Type-I ELMs. The mode amplitude increases with increasing peeling drive, j_{edge}/B.

1. Introduction

The PEGASUS Toroidal Experiment is a mid-size Spherical Tokamak (ST) with an outer vacuum vessel wall radius of 1 m and a center-column radius of 5.5 cm for operation at a minimum aspect ratio A ($=R_0/a$) of 1.13. Typical PEGASUS operating parameters are given by: $I_p < 0.3$ MA, 0.2 m $< R_0 < 0.45$ m, $\kappa < 3.5$, $\beta_T < 25\%$, and $\tau_{shot} < 0.035$ s. Operation at ultra-low aspect ratio allows the achievement of high stable β_T ($\beta_T = \langle p \rangle/(B_0^2/2\mu_0)$), which improves fusion power plant economics by reducing recirculating power requirements. High β_T operation can be achieved via high toroidal field utilization (I_p/I_{TF}), equivalent to high normalized plasma current ($I_N = I_p/aB_T$) due to the Troyon beta limit scaling $\beta_T = \beta_N I_N$. The PEGASUS ultra-low aspect ratio allows access to $I_N > 10$ while maintaining stability to the external kink mode without a nearby conducting wall.

The thin central column in PEGASUS and other STs leaves very little room for an ohmic solenoid. Nonsolenoidal techniques of heating and current drive are required to start up and/or sustain discharges and to increase plasma performance in STs. This is actually a general tokamak problem, which must be solved before designing an economically viable fusion-grade tokamak-based reactor. To that end, non-solenoidal plasma startup via point-source DC helicity injection is being developed on PEGASUS [1,2]. This technique has been used to create non-solenoidal targets with toroidally-averaged closed flux and toroidal plasma current in excess of 0.15 MA. Successful coupling to ohmic drive results in proportional reduction of the ohmic flux required to achieve a given I_p, and shows that helicity-startup plasmas couple easily to other current drive techniques. Projections for such helicity injection systems on fusion-scale tokamaks or STs are relatively compact, technically simple, and employ injectors that can be retracted from the confinement region after the startup phase.

Filamentary edge perturbations are observed during ohmically driven plasmas with high edge current density. Due to the high edge current, low magnetic field, low edge pressure, and the observed characteristics of the modes, the observed filaments are identified to be peeling modes, the low-pressure manifestation of the peeling-ballooning instability. Peeling-ballooning modes are generally thought to be responsible for the observed Edge Localized Modes (ELMs) in high-performance tokamaks. The relatively short pulse lengths and low edge temperatures and densities in PEGASUS discharges allow direct measurement of the current and pressure profiles with high spatial and temporal resolution, enabling direct experimental tests of peeling-ballooning theory.

2. Non-Solenoidal Discharge Formation via DC Helicity Injection

Local current sources in the plasma scrapeoff region can inject magnetic helicity and drive toroidal current, thereby creating a ST plasma without using an ohmic solenoid [3,4,5]. A discharge begins by driving current along the helical vacuum magnetic field created by combined toroidal and vertical external fields. If conditions for magnetic relaxation and tokamak radial force balance are met, this force-free current can relax through helicity-conserving magnetic turbulence to form a tokamak-like plasma. Once a tokamak-like discharge is formed, it is grown by continuing helicity input to produce a net I_p compatible with helicity balance and magnetic relaxation constraints. Here, tokamak-like is used to describe the toroidally averaged properties of the plasma, although the field lines are at least partially stochastic during the driven phase.

To first order, all injected helicity is found to be converted to helicity in the tokamak plasma, and that helicity is mainly lost though resistive dissipation [NE thesis]. Resistivity and I_p are thus tightly coupled through the plasma heating and confinement properties. To sustain a tokamak-like plasma of current I_p, the total effective loop voltage provided by helicity injection and poloidal field induction is required to equal the loop voltage for a conventional inductively driven tokamak plasma at I_p. The achievable current is thus limited by helicity injection and confinement properties to:

$$I_p \leq \frac{1}{2\pi\langle\eta\rangle}\left(\frac{A_p V_{loop}}{R_0} + \frac{A_{inj} V_{bias}}{R_{inj}}\right) \quad where \quad \frac{dK}{dt} \geq 0,$$

A_p is the plasma cross-section, η is the plasma resistivity, A_{inj} is the total area of the emitting electron source normal to the local field, R_{inj} is the major radius of the current source, and V_{bias} is the injector bias potential. Physically, the first term is inductive drive from external poloidal field variations; the second term is helicity injection drive. The maximum I_p allowed by helicity balance is inversely related to resistive dissipation, and thus strongly related to T_e.

Helicity injection current drive relies on the relaxation of unstable plasma to the lowest energy state (the "Taylor" state) via non-axisymmetric magnetic perturbations [6]. This Taylor relaxation process imposes an upper limit on the achievable I_p for a given injector, by seeking the Taylor state while conserving helicity on a resistive dissipation timescale. Force-free equilibrium fields are characterized by $\nabla \times B = \mu_0 J = \lambda B$, where λ is the inverse scale length of the local field line helicity ($\lambda = \mu_0 J_{\parallel}/B$), and λ is uniform in the Taylor state. For systems with edge current drive, the maximum λ is set by the injector properties, edge conditions, and discharge geometry. Assuming that current and field are distributed uniformly in a turbulent edge region of thickness w, the maximum I_p that can be achieved by relaxation is estimated by

$$\bar{\lambda}_p \le \bar{\lambda}_{edge} \rightarrow I_p \le \frac{\Phi I_{inj}}{2\pi R B_p w} \rightarrow I_p \le f_G \sqrt{\frac{\kappa \varepsilon A_p I_{TF} I_{inj}}{2\pi R_0 w}}$$

where λ_p and λ_{edge} are the values of λ corresponding to the main discharge and the edge region, overbars indicate average values, B_p is the poloidal field at a location with major radius R, ε is the inverse aspect ratio, Φ is the toroidal flux, I_{TF} is the total toroidal field current, and f_G is a dimensionless function of shape parameters (ε, κ, and triangularity δ). The value of f_G varies from unity, in the circular cross-section large-A limit, to ~2.5 for typical low-A, shaped plasmas. The maximum achievable I_p using point-source helicity injection is thus either this upper limit set by relaxation, or a lesser value consistent with the helicity injection rate.

Experiments on Pegasus have demonstrated, for the first time, non-solenoidal, high-current spherical tokamak startup via localized helicity injection in the plasma scrapeoff region. Point-source DC helicity injection is performed by biasing a set of 3 washer-stack, arc current sources ("plasma guns") with respect to an external anode, which is magnetically connected to the plasma guns in the vacuum magnetic field. Each gun is capable of sourcing up to 1.5 kA of current parallel to the helical vacuum field at up to V_{bias} = 2 kV.

In principle, point-source current injectors can be placed anywhere in the plasma boundary region. The only gun requirements are sufficient port access and appropriate heat-handling capability on the gun structures. The main disadvantage of using guns is their small aperture. This follows from the definition of the helicity injection rate: $dK/dt = 2V_{bias}\Psi_{inj}$, where Ψ_{inj} is the magnetic flux intersecting the cross-sectional area of the current source. Small gun apertures require a high V_{bias} to provide a large dK/dt. To optimize net current drive, most experiments were performed with the plasma guns on the low-field side of the plasma, near the outer midplane, where poloidal field induction can add to the current drive available from the helicity sources.

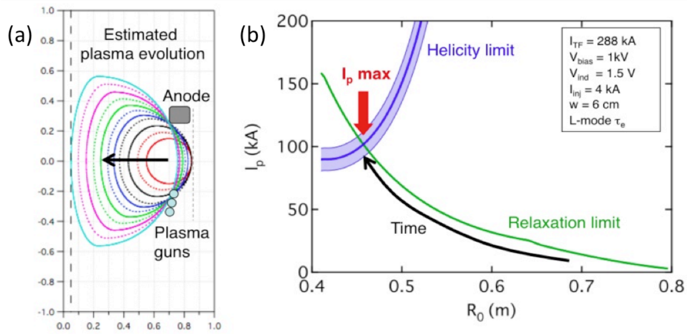

Fig. 1. (a) Geometric evolution with midplane startup. (b) I_p evolution with helicity and relaxation limits.

Midplane-gun discharges form at large major radius, limited on the gun and anode structures, and evolve inward until limiting on the centerstack and filling the confinement volume. Figure 1(a) indicates the time-evolution of the plasma as it grows inward. Given sufficient helicity input rate, the plasma follows the trajectory indicated in Fig. 1(b), where I_p is limited by the Taylor relaxation limit as it grows inward, until it reaches a maximum I_p set by the net helicity injection rate or by decoupling of the plasma from the edge current source.

Experiments using these midplane gun arrays complemented earlier divertor gun results, replicating many of the features of the divertor-injection experiments [1]. In particular, relaxation of driven helical currents to the axisymmetric tokamak-like state depend upon the formation of a poloidal field null by combining the vertical field with the poloidal field induced by the injected current. [3] Before this null formation and consequent relaxation, the net I_p is limited to the injected current multiplied by the field windup factor.

Midplane-injection experiments confirm that the I_p evolution can be determined by either the helicity injection rate or the Taylor relaxation limit [3], with I_p falling below the Taylor limit if the helicity input is insufficient. I_p typically rises monotonically and rapidly until the plasma fills the vacuum vessel. The plasma subsequently disconnects from the gun. Figure 2 shows an equilibrium reconstruction for a typical midplane gun discharge when the plasma is filling the confinement region, and is limited on both the central column and the outboard gun/anode structures. Vertical field ramps necessary for radial force balance also provide inductive drive, supplementing the helicity-driven V_{eff}. The net volt-seconds from the gun drive and poloidal field induction are typically comparable.

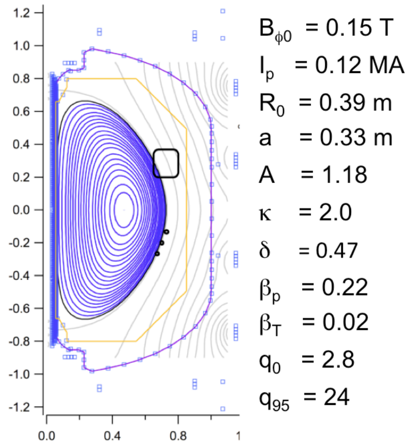

Fig. 2 equilibrium reconstruction for fully formed plasma.

Midplane gun discharges exhibit significant MHD activity during helicity drive while I_p is increasing. This activity appears as bursty, low-n oscillations with frequencies in the 30–50 kHz range and amplitudes falling dramatically but not vanishing between bursts. These bursts correspond to rapid inward movements of the current centroid and increases in I_p.

The Taylor relaxation limit on I_p scales as $(I_{TF}I_{inj})^{1/2}$. These scalings are supported by the measurements by Battaglia [3,4], where the maximum I_p was shown to follow the Taylor limit scalings with $(I_{TF})^{1/2}$, and $(I_{inj})^{1/2}$ for otherwise fixed parameters and even when excess helicity input was applied via ohmic heating.

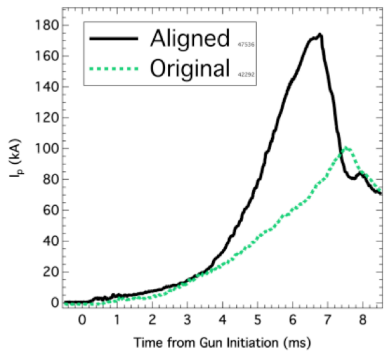

Fig. 3 I_p for aligned ($w \approx 2$ cm) & original gun structure ($w \approx 6$ cm).

The Taylor relaxation limit on I_p also scales inversely with $\sqrt{w}$. One-gun and three-gun discharge comparisons indicated that the effective width w in three-gun discharges was approximately three times the width of one-gun plasmas, implying that the three-gun relaxation limit was a factor of $\sqrt{3}$ lower than would have otherwise been possible. In addition, equilibrium reconstructions indicated that the gun array was not well-aligned with the plasma edge, resulting in a relatively wide gun-driven edge region. The gun array was realigned in 2009 to place all guns along the last closed flux surface. As shown in Figure 3, the relaxation limit was observed to increase by $\sim\sqrt{3}$, from the previously observed maximum I_p of 0.10 MA to 0.17 MA.

At the relatively low I_p and B_T levels for which experiments have been performed to date, it is not possible to distinguish between competing confinement models to apply to helicity dissipation estimates. In particular, estimates of I_p limits set by either L-mode confinement or field stochasticity (*i.e.,* uniform T_e) are comparable within considerable error bars for the I_p < 0.12 MA database presently available. This illustrates the need to achieve high I_p to clearly develop an appropriate confinement model for the tokamak-like state.

Point-source helicity injection provides an attractive target for additional current drive techniques. This is demonstrated by coupling gun-produced plasmas to ohmic solenoid induction after gun shutoff. Figure 4(a) shows I_p, V_{loop}, and I_{inj} for a discharge which used helicity injection startup to reach $I_p \approx 0.13$ MA, followed by solenoidal induction to ramp up to I_p = 0.22 MA. Notably, the generally hollow j(r) due to the helicity injection technique completely avoids n = 1 internal tearing activity typical of ohmic plasmas in Pegasus. Figure 4(b) is the signal from an external poloidal Mirnov in this same discharge, showing both the strong mode activity during the gun phase and the very quiescent ohmic phase.

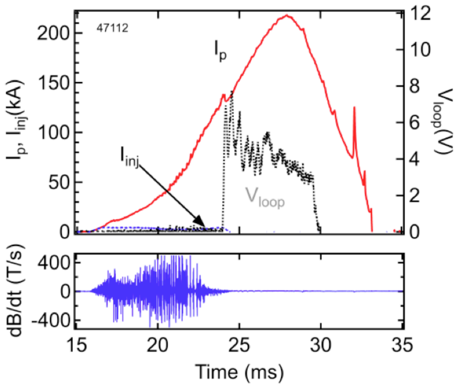

Fig. 4. (a) HI target coupled to ohmic drive; (b) n=1 mode activity.

These coupling studies found that efficient handoff from helicity injection to other current drive at high I_p requires the gun-driven current rampup to be as slow as possible. This appears to allow the current density profile to evolve from a very hollow edge-driven skin current to a current profile with an increasing amount of central current and energy. This is supported by j(R) profiles estimated in fitted MHD equilibria, for two representative gun-startup Pegasus discharges, at the moment of gun shutoff. A mildly hollow profile is found for the case of a slow current evolution and smooth handoff to ohmic drive (Fig. 4(a)). A more hollow current profile is indicated for fast ramp cases, such as the 0.17 MA discharge shown in Fig. 3.

However, these studies were hampered by the relatively short helicity injection pulse lengths, and by difficulty in controlling the plasma radius via external coils and open-loop control. The consequent slow continuous rise in vertical field inside the vessel resulted in the plasma being crushed into the central column. More complete validation studies of the plasma startup and growth require active radial position control using internal coils and a closed-loop feedback system, which are planned for Pegasus in the next biennium.

It is important to note that the helicity injection physics is agnostic concerning the specific source of edge current. Once a tokamak-like plasma is formed by a minimal gun system, it is plausible that the confined plasma itself could provide sufficient charge carriers in the scrapeoff layer to allow simple electrode structures to drive I_{inj}. The cross-sectional area of the electrodes can be significantly larger than the aperture of a plasma gun, allowing a large helicity injection rate with a moderate bias potential V_{bias}. The shape and position of these electrodes may be tailored to provide an optimal combination of high helicity injection rate and high Taylor relaxation limit. From a technical standpoint, shaped electrodes are far easier to deploy than arrays of active plasma arc sources for the same helicity injection rate. Hence, there is a need to understand combinations of plasma gun sources and electrodes to maximize the achievable I_p with minimal requirements on machine access, power supplies, and physical and operational complexity.

Preliminary experiments to support this conjecture were conducted by fitting the plasma gun arc supplies with crowbar switches, enabling rapid extinguishment of the internal gun arc. Initial experiments demonstrated that the guns can continuously source injected current through the sharp transition from active current sources to passive electrodes without an additional influx of impurities.

Further experiments included modification of the electrode faces of the guns themselves, to narrow slots as wide as the arc-channel aperture, with the three slots aligned to approximate a single narrow electrode. The equivalence between injection by guns and injection by the passive electrode faces was shown by creating matched pairs of discharges, where in one discharge the arc current is switched off early in the plasma evolution. Figure 5 shows plasma current, bias current, and bias voltage for such a matched pair of discharges, where the arc current is switched off at 18 ms in the guns-as-electrodes case (solid curves). These results imply that the tokamak-like plasma is indeed providing sufficient charge carriers to source I_{inj} without an active plasma arc, and more flexible electrode geometries are possible.

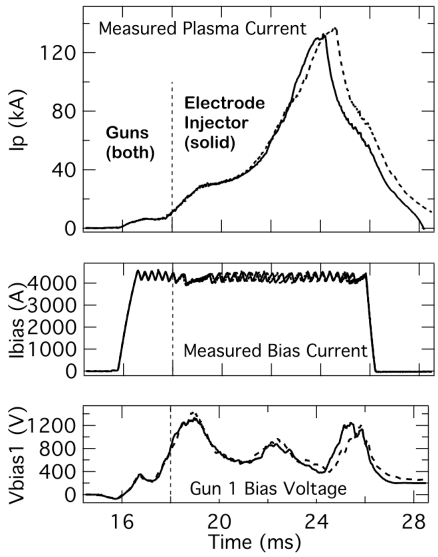

Fig. 5. Arcs off @18 ms; I_p growth by passive electrode (solid). Full-arc-on traces (dashed) shown for comparison.

Finally, initial ion spectroscopy measurements in gun-driven discharges indicate that the ions are strongly heated during the drive phase, as observed in other experiments with significant magnetic reconnection [7].The ion temperature, measured by the Doppler-broadened profile for N-III emission lines, is ~0.5 keV greater in the drive phase than without gun drive. The dominant impurity emissions from these helicity injection plasmas, N-IV and O-V, suggest T_e ~30–70 eV, indicating that during the helicity injection $T_i >> T_e$, in stark contrast to typical ohmic plasma conditions.

3. Low-m/n Mode Suppression and High Field Utilization Access

To realize the very high β_T regime at near-unity A requires operation at high normalized current, or equivalently high toroidal field utilization factor, $I_p/I_{TF} \approx I_N/5$. Earlier experiments with limited waveform control of the ohmic and field coil currents found that the field utilization factor I_p/I_{TF} was limited by the onset of large m/n = 2/1 internal modes that coincided with the existence of a large radial region with $q \approx 2$ and little to no shear. This led to a "soft" limit of $I_p/I_{TF} \leq 1$ for accessible operation space. Newer experiments indicate that large low-m, n=1 internal modes often persist in ohmic inductive startup plasmas even at increased B_T, where q(0) is readily maintained above 2. The large-scale n=1 modes appear with m roughly consistent with the estimated central q values.

Three methods to achieve high toroidal field utilization have expanded the Pegasus operating space significantly past the earlier "soft limit" of I_p/I_{TF} = 1, as shown in Figure 6. These methods vary the internal j(r) profiles, at least in transient manners, by: I_{TF} rampdowns; fully noninductive startup via DC helicity injection; and extremely low I_{TF} ohmic operations enabled by gun preionization. In all cases, magnetic reconstructions suggest that the j(r) profile was broadened and some internal shear was present. These experiments confirm that

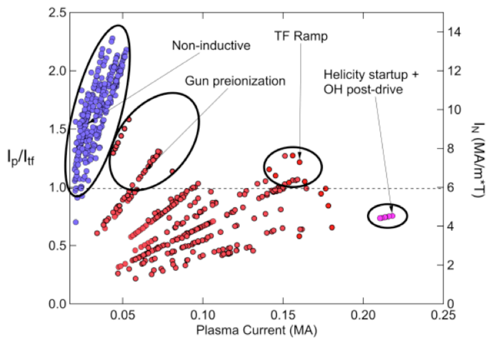

Fig. 6. j(r) modification techniques allow achievement of high I_p/I_{TF}.

$I_p/I_{TF} = 1$ is not associated with an intrinsic physics limit, and achieving high I_N and β_T should become possible at high I_p/I_{TF} as these tools are expanded and exploited.

Most dramatically, experiments with ohmic induction following helicity-driven startup have shown that these large internal modes can be essentially eliminated, given sufficient helicity drive and/or pulse length to effectively evolve the current profile. In particular, the helicity injection startup technique appears to produce plasmas with a broad current profile, but with sufficient internal shear to evolve to a high I_p plasma with minimal n=1 activity, as shown above in Figure 5. To reach the desired high values of I_p/I_{TF} with the finite V-s available from ohmic induction, the helicity injection current drive capability and plasma pulse length need to be extended, with finer control of the vertical field (and radial position) evolution. This will allow the establishment of a high-I_p plasma via helicity injection only, with sustainment via induction as B_T is lowered. Conversely, high I_p/I_{TF} will be more directly accessible at low B_T as the helicity injection system capability is increased to provide sufficiently high dK/dt at low B_T.

4. Characterization of High j_{edge}/B Instabilities

Characterization of edge instabilities present under varying j_{edge}/B values is presently being pursued. These ohmically driven discharges exhibit ELM-like peeling edge instabilities during periods of strong positive dI_p/dt (~25 MA/s) during current rampup, large low-m/n=1 internal tearing activity at peak I_p, and typical L-mode turbulence in MHD quiescent periods induced by I_p rampdowns. Radially scanning Mirnov coils and fast Langmuir probes at the plasma edge indicate turbulent power spectra during the peeling and MHD quiescent phases. A coherent electromagnetic signature was observed during the peeling phase, typically in the 20-100 kHz frequency range. Imaging studies during the peeling phase revealed larger filament virulence at lower values of I_{TF}, with dI_p/dt, shape, fueling, and V_{loop} fixed, consistent with increased peeling drive through higher j_{edge}/B.

A radially scannable array of Mirnov coils with small toroidal angular spacing typically show an n = 1 to 4 EM signature during a peeling phase at a position ~20 mm outside the confined plasma edge, with n= 1 being most common. A second Mirnov coil with a 10 mm vertical displacement indicates m = 20–40, consistent with typical values for edge-q in these discharges. This peeling signature vanishes rapidly with distance from the edge, consistent with the identification of high m.

High-speed image analyses show the peeling filaments to have high poloidal coherence lengths, rotate poloidally, detach from the edge after ~50 μs, and accelerate radially outward. Figure 7 shows the radial propagation of peeling filaments over a period of 60 μs. The data shows v_r, = 940 ±100 m/s, as well as a clear radial acceleration a_r = 2.80 ±.21 $\times 10^7$ m/s^2, which is comparable to that seen in type I ELMs in MAST [8].

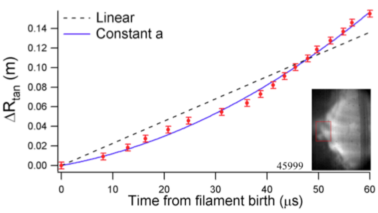

Fig. 7. Radial propagation and acceleration of peeling filament.

A Hall probe array measures internal $B_z(R,t)$ to constrain j(R) in equilibrium reconstructions. Strong wall currents complicate reconstructions in the early low-I_p peeling phase of the discharge. However, the local j(R,t) can be estimated directly from the radial Hall probe array using Ampere's law and an elliptical approximation to the plasma cross-section [9]. Figure 8(a) shows the current profile in the edge region for three I_p ramp rates at I_p ~ .065MA, confirming that large j_{edge}/B, the effective peeling drive, is quite sensitive to dI_p/dt. The fluctuation power of the peeling mode EM bursts increases strongly with this peeling drive, as indicated in Fig. 8(b) where the power is plotted versus the normalized current ramp rate. Detailed comparisons of the local edge stability to low-to-moderate-n peeling modes requires more complete equilibrium reconstructions during the peeling phase and are in progress.

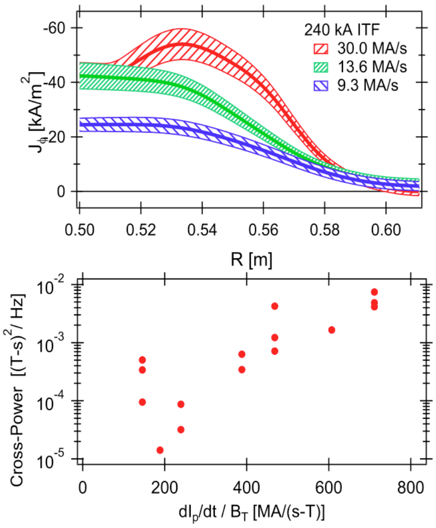

Fig. 8. (a) j_edge(R) variation with dI_p/dt; (b) Peeling EM fluctuation power increasing with j_edge/B.

6. Conclusions

Non-solenoidal startup using point-source DC helicity injection is demonstrated to create plasmas with $I_p \sim 0.15$ MA with < 4 kA injected. Given the proper conditions for null formation and relaxation to a tokamak-like state, the ultimate I_p that can be achieved must satisfy constraints from magnetic helicity or confinement balance and Taylor relaxation. Some outstanding issues are: confinement during gun drive and the corresponding helicity dissipation rate; the source impedance in the turbulent edge region; and the dynamics of the current density in the plasma periphery.

Plasmas evolved using the edge helicity injection generally have hollow j(R) profiles, with sufficient internal magnetic shear to mitigate the large-scale tearing modes. This and more flexible field control has expanded the operating regime past the previous "soft limit" of $I_p/I_{TF} < 1$ to $I_p/I_{TF} > 2$, or $I_N > 10$. High I_N, β_T studies will become accessible at high I_p/I_{TF} as these discharges are pushed to higher I_p.

Operation at near-unity aspect ratio results in relatively high values of j_{edge}/B. This high peeling mode drive coincides with high-m, n ~ 1-4 magnetic modes that have characteristics related to ELM-precursors. Increasingly detailed measurements of j_{edge} and operation at higher pressures may offer the possibility of detailed tests of peeling-ballooning theory.

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