Local Helicity Injection Startup and Edge Stability Studies in the Pegasus Toroidal Experiment

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Abstract: Studies on the Pegasus ultralow aspect ratio tokamak are exploring: non-solenoidal startup using localized magnetic helicity injection; and edge peeling mode stability and dynamics. The helicity injection operating space is constrained by helicity injection and dissipation rates and a geometric limit on plasma current. Bursts of MHD activity, consistent with driving low-n kink modes line-tied to the injector, are observed during helicity injection, and correlate with rapid equilibrium changes, including inward motion of the magnetic axis and redistribution of toroidal current density. Internal magnetic measurements show the creation of a poloidal null prior to the formation of a tokamak-like equilibrium, and the redistribution of current into the core region as the plasma evolves. The MHD activity results in strong ion heating, with observed ion temperatures as high as 1 keV, and emission line splitting indicating bi-directional flows. The plasma arc injector impedance is consistent with a double-layer sheath at the current extraction aperture. The increasing understanding developed in these studies support scalability of the helicity injection startup technique to large devices. Operation at near-unity aspect ratio with high plasma current relative to the toroidal field allows study of peeling modes, a cause of Edge Localized Modes (ELMs) in larger devices. Peeling modes in Pegasus appear as coherent edge-localized electromagnetic activity with low toroidal mode numbers and high poloidal mode numbers. Internal magnetics and fast framing images show the formation of current-carrying field-following filamentary structures, which briefly accelerate radially, detach from the plasma edge, and propagate radially at a constant velocity. The acceleration and propagation velocity of the filaments correspond to the predictions of electromagnetic blob theory.

1. Introduction

Studies of ultralow aspect ratio tokamak plasmas in the Pegasus Toroidal Experiment [1] are presently concentrating in two areas: non-solenoidal startup via edge current injection as a source of magnetic helicity input; and edge peeling mode dynamics. Past startup experiments used a combination of localized helicity injection and poloidal field induction to transiently form tokamak-like plasmas with I_p up to 0.17 MA without using induction from a central solenoid [2,3]. This non-solenoidal operating space is constrained by the helicity injection and dissipation rates and a geometric limit on I_p predicted by Taylor's magnetic relaxation theory [4,5]. The Taylor limit relates the maximum I_p to the total toroidal field coil current I_{TF}, the current I_{inj} from the compact injector, the radial width *w* of the injector-driven region, and the plasma geometry according to

$$I_p = f(\epsilon, \delta, \kappa)\sqrt{\frac{\kappa A_p I_{\mathrm{TF}} I_{\mathrm{inj}}}{2\pi R_0 w}}$$

where A_p is the plasma cross-section, R_0 is the plasma major radius, and *f* is a dimensionless function of order unity of the dimensionless shaping parameters ε, δ, and κ. These combined constraints project to MA-class startup with reasonable hardware requirements.

To extrapolate this technique to NSTX-U and beyond, the Pegasus program is focused on extending the technique of helicity injection startup and growth to I_p ~ 0.3 MA and relatively long pulse length. For a given fusion device, poloidal field induction provides a finite amount of V-sec, and this induction may be further constrained by the use of superconducting coils. Hence, it is necessary to grow I_p with helicity injection as the primary drive mechanism. Then, the external circuit driving the helicity injector is the source for the bulk of the V-sec used to form the discharge and grow the toroidal plasma current. Developing a predictive understanding of this helicity injection technique, and confidently designing a high-current local helicity injection startup system for any device, requires evaluating the helicity dissipation mechanisms at increasing electron temperatures to distinguish between stochastic and tokamak confinement in the driven discharge.

Experiments show that the plasma responds equally to active plasma sources or passive electrodes as the current source for edge helicity drive once the tokamak is formed [3]. Compact injectors act as local sources of toroidal current and magnetic helicity, and provide effective toroidal loop voltage proportional to the product $V_{inj}A_{inj}$, where V_{inj} is the bias voltage on the injector provided by an external circuit and A_{inj} is its cross-sectional area [4]. Shaped electrodes can simultaneously optimize the helicity input rate (via large injector cross-section A_{inj}) and the Taylor-relaxation current limit (via relatively small w). Initial tests on Pegasus at low I_p have demonstrated the feasibility of starting and sustaining plasmas with negligible poloidal induction. As an example, Figure 1(a) shows a discharge whose early phase is driven using plasma arc injectors, while the later phase is purely electrode-driven. This proof-of-principle discharge demonstrates a viable approach to forming and sustaining discharges using only helicity injection current drive, with any particular target I_p achievable through appropriate scaling of the evolving vertical field and injector current, assuming sufficient stored energy in the external power supply. Improvements to the radial position control and injector configuration will enable helicity-driven discharges to reach higher I_p and thereby test the physical understanding of this startup technique.

2. Helicity Injection Studies

Complex MHD activity is present throughout the helicity injection process, consistent with expectations from Taylor relaxation. During periods of plasma growth, short-duration (~0.1 ms) bursts of coherent n=1 magnetic activity are observed. Until recently, the compact helicity injector has been located near the main limiter in the Pegasus device, and Figure 1(b) shows the toroidal variation in amplitude of the bursty MHD fluctuations in a typical injector-driven discharge with that injector location. The fluctuations are measured using a toroidal array of wall-mounted Mirnovs and an insertable toroidal array of Mirnovs. Figure 1(c) shows a corresponding dataset for a more recent injector-driven discharge, with the compact injector located 180^{o} toroidally on the other side of the Pegasus device. These plasmas had approximately the same plasma current evolution, and in each case, the bursty MHD was found to have an n=1 structure with a frequency of approximately 16 kHz. Both of these figures include the fluctuation amplitude (in red) and the fluctuation amplitude scaled by the local toroidal field (in blue), versus the toroidal location of each Mirnov, with the Pegasus main limiter defined to be at zero, and the vertical line is approximately the location of the front of the injector in each discharge. Note, even though the fluctuation amplitudes are roughly comparable in magnitude in these two discharges, the toroidal distribution of the activity is not identical. Instead, the minimum for the n=1 magnetic fluctuations corresponds to the location of the injector, suggesting that the magnetic structure is a line-tied kink mode on the open flux tube driven by the injector. The mode would then be “line-tied” in the sense that the driven flux tube is connected to the injector face, which has a compact and well-defined location, thereby constraining the field line in the vicinity of the injector. Far away from the injector, the unstable flux tube can more freely move, and the corresponding magnetic fluctuation amplitude is a factor of two larger.

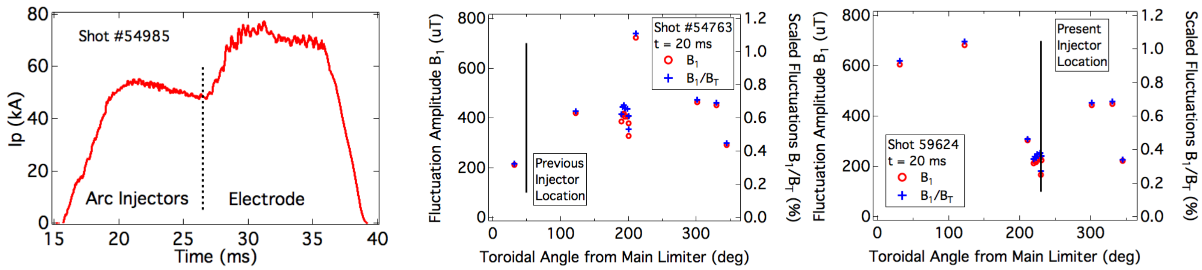

Figure 1: (a) Nonsolenoidal startup and sustainment with minimal poloidal induction; (b) amplitude of MHD activity vs toroidal angle for previous injector location; (c) MHD amplitude vs angle for present location

A line-tied kink structure with bursts of activity is reminiscent of recent time-dependent resistive MHD simulations using the NIMROD code [6]. These simulations show a helical plasma stream connected to the compact injector, and making multiple toroidal transits before reaching the current return. Adjacent turns in the helical stream interact, pulling together to form a transient reconnection region, which then generates and expels an axisymmetric plasma ring. These rings are expelled radially inward, and under the proper conditions could form often enough to merge into and sustain an axisymmetric equilibrium against resistive dissipation. Direct observation of the reconnection and formation of axisymmetric rings is experimentally challenging, but features of injector-driven Pegasus discharges correspond to this paradigm. Empirically, we find that each burst of MHD activity in an Pegasus injector-driven discharge corresponds to: a rapid increase in I_p; rapid growth of the plasma cross-section, which creates a corresponding inward radial motion of the plasma; and, a drop in l_i, suggesting a significant redistribution of the current density profile. These calculations motivate further study of the full 3D magnetic structure of injector-driven discharges, including high-time-response local magnetic measurements toroidally opposite to the injector, in regions that may potentially exhibit reconnection activity.

The modest plasma parameters and short pulse lengths of Pegasus plasmas permit direct measurement of internal magnetic fields using an insertable array of Hall-effect sensors, with a time response appropriate for studying the evolution of the driven magnetic equilibrium [7]. This array provides $B_z(R)$ measurements that have confirmed: the creation of a local poloidal field null preceding the initial transition from the open-field-line state to the MHD turbulent tokamak-like state; rapid relaxation of the current profile during the early evolution of the tokamak-like state; and, evolution to a more typical tokamak-like current profile late in the discharge. Figure 2(a) shows B_z measurements versus major radius at four times during the evolution of an injector-driven discharge. Chronologically, the first trace (in red) is from shortly after the formation of the tokamak-like equilibrium, and still shows a clear poloidal field null. As the discharge evolves, the measured vertical field profile increases and changes, from red to blue to green. The final vertical field distribution (in gold) is measured shortly after the plasma has disengaged from the injector, and is thus no longer being driven. Figure 2(b) shows the calculated estimates for the local toroidal current J_ϕ for the same diagnostic times, where the colored bands are confidence intervals based on the estimated errors in the measured fields. The current profile is initially rather hollow (in red), but as the plasma evolves the toroidal current rapidly redistributes inward. The core current density continues to rise (blue and green), showing that the core plasma current is being driven by the external injection and the magnetic relaxation activity. After the plasma disengages from the injector, the current distribution becomes a typical peaked tokamak distribution (in gold).

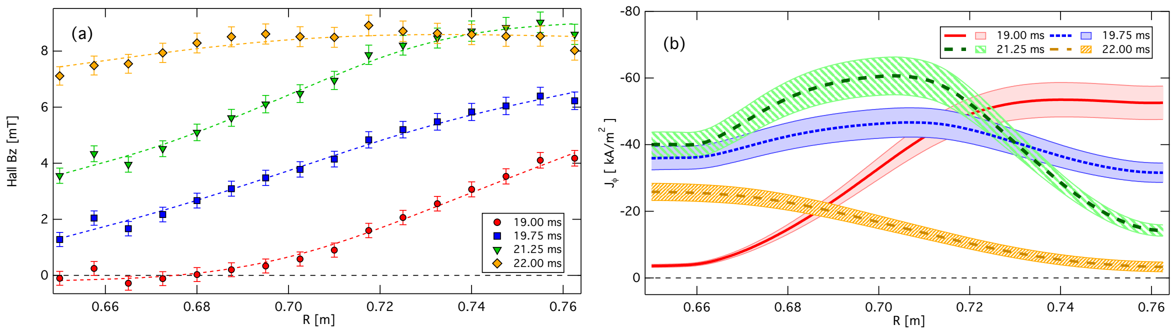

Figure 2: (a) Measured vertical fields at four times during the evolution of an injector-driven discharge; (b) Corresponding toroidal current density profiles.

Previous studies have shown that injector-driven plasmas are approximately at a Taylor limit throughout their evolution, and that calculated Taylor limits correspond to the empirically observed maximum plasma currents in sets of Pegasus discharges [3,4]. Recent technological tests of the Pegasus injector structure placed the active injection surface farther away from the plasma edge than before (see paper FTP/P1-19, this meeting), effectively increasing the width *w* of the injector-driven region by at least a factor of three, and correspondingly reducing the maximum plasma current I_p. Experimental variations in the TF current and bias current have confirmed the expected Taylor-limit scalings for this test injector, and motivated the next iteration of the injector design with a much more narrow effective *w*.

The large-amplitude MHD activity during helicity injection gives rise to strong ion heating and toroidal flows, where passive ion spectroscopy shows ion temperature T_i can reach well above 1 keV, even as T_e stays relatively low. Figure 3(left) shows the amplitude of MHD activity as measured on the outboard midplane, T_i measured from Doppler-broadened CIII emission lines, the injector bias voltage, and the plasma current vs time for a typical helicity injection discharge. Also shown is a typical Gaussian fit to the observed emission spectrum at one particular time in this discharge. The strong ion heating is indicative of magnetic reconnection, and evidence that this reconnection activity plays a role in helicity injection current drive. The field stochasticity inherent in this startup and sustainment technique keeps the electron temperature low, which allows low charge state impurities to be observed in the core plasma [4]. Spectroscopic analysis indicates that the observed impurity ion distributions are consistent with $T_e \sim 50$-100 eV.

Figure 3(right) shows evidence for bi-directional toroidal velocity flows on the BIV line during helicity injection. Bi-directional flows have been observed on reconnection experiments such as TS-3 in Japan [8]. Such flows are directed out of the x-point as field lines break and magnetic field-line energy in converted into plasma kinetic energy. Sweet-Parker reconnection theory, for instance, predicts that plasma outflows from the x-point are bi-directional, with a speed equal to the Alfven velocity. In Figure 3(right)(a), the BIV doublet (wavelengths 2824 A and 2825.8 A) has split into two pairs of lines, with the splitting in each line being slightly and significantly asymmetric. The splitting in these lines indicates a toroidal velocity of ±57 km/s, while the Alfven velocity near the injector is in the range 50-150 km/s during the injection drive. This preliminary data motivates the deployment of poloidal viewing chords to further explore the 3D ion velocity distribution, and to better compare measurements to reconnection theory. In any case, the observed ion energies and flows during helicity injection are broadly consistent with reconnection-drive ion heating and flows, which can significantly affect the overall power balance and plasma evolution, and must be considered in a predictive model of this startup technique.

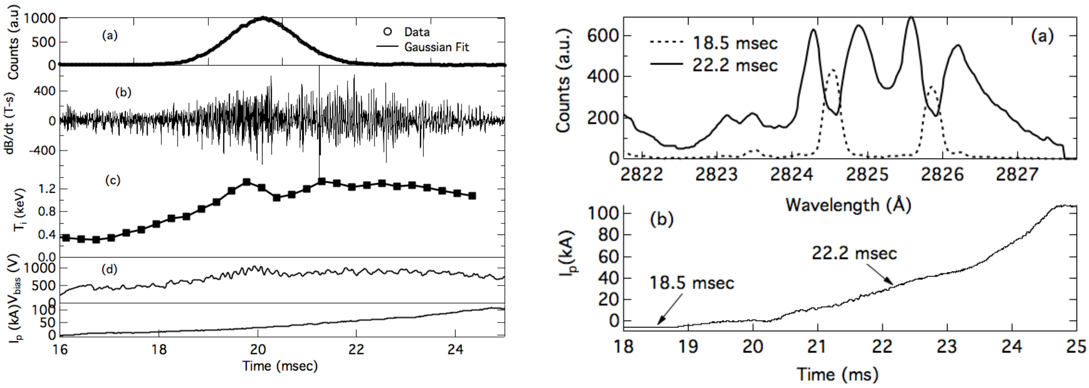

Figure 3: (left) (a) Sample Gaussian fit for a particular timeslice and (b)-(e) MHD fluctuation amplitude, ion temperature, injector bias voltage, and plasma current versus time for a typical injector-driven discharge; (right) (a) Emission spectrum for two times in a typical discharge, and (b) plasma current vs time, showing emission line splitting for a BIV line doublet.

An accurate model for the impedance of the helicity injectors is needed to define power supply requirements for the desired current drive capability. To that end, the impedance of the active arc sources appears consistent with an interpretation based upon the physics of a double-layer sheath near the electron injection region. Injector current-voltage characteristics at low voltage exhibit an approximate $I_{inj} \sim V_{inj}^{3/2}$ scaling. At high V_{inj}, the scaling changes to $I_{inj} \sim V_{inj}^{1/2}$, consistent with sheath expansion [9]. The observed impedance also varies inversely with the local electron density. Figure 4(a) shows trajectories of measured injector current I_{inj} and injector bias voltage V_{inj} for six gas fueling rates (expressed in terms of plenum backpressure), from a set of otherwise identical gun-driven Pegasus discharges. The trajectories show the transition from the low-voltage regime to the expanding-sheath regime, and the effect of fuelling. A related model is under development for helicity injection using a passive electrode.

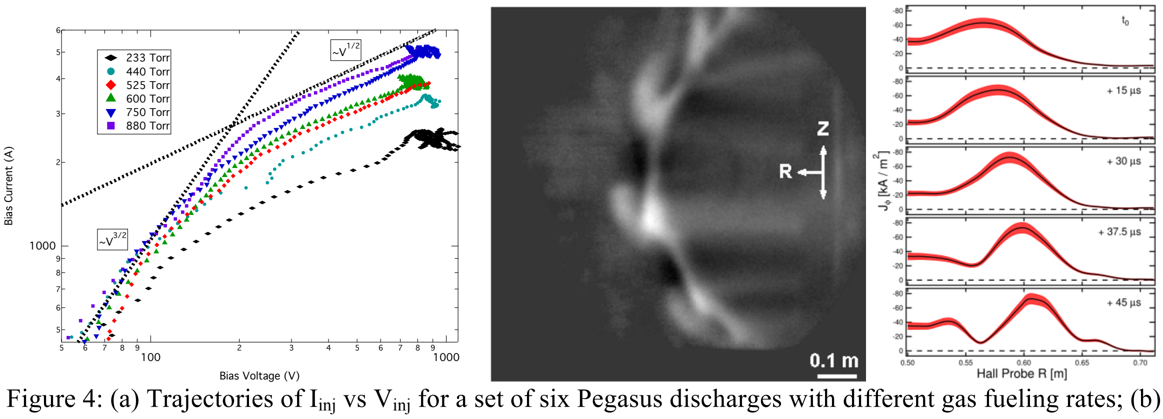

Figure 4: (a) Trajectories of I_{inj} vs V_{inj} for a set of six Pegasus discharges with different gas fueling rates; (b) Visible image (δt = 10 μs) of peeling-mode filaments on surface of a Pegasus plasma; and (c) Formation of current filament and current hole due to peeling mode.

3. Edge Stability Studies

Tokamak operation at near-unity aspect ratio provides a unique laboratory for detailed tests of theories underlying Edge Localized Mode (ELM) physics, which is a major concern for the future operation of ITER. Experiments at A ~ 1 naturally involve high I_p at very low B_T, with correspondingly high edge values for J_{edge}/B to provide experimental access to the peeling mode [10]. Peeling modes in Pegasus appear as coherent, edge-localized electromagnetic activity with low toroidal mode number n (≤ 3) and high poloidal mode numbers, as observed in both magnetic diagnostics and fast-frame visible imagery. Figure 4(b) shows a visible image of a peeling-mode structure in a typical Pegasus inductively-driven discharge, clearly exhibiting a field-line pitch corresponding to low toroidal mode number and high poloidal mode number. Peeling-mode fluctuation amplitudes depend strongly on j_{edge}/B, consistent with the theoretical drive for peeling modes [10]. Mode onset agrees with ideal MHD predictions from DCON stability analysis of the magnetic equilibrium [11].

The peeling instability nonlinearly generates ELM-like, field-aligned filamentary structures on a 40-50 μs timescale. These filaments detach from the tokamak edge and transiently accelerate radially outward, then propagate radially at constant velocity. Time-resolved J_{edge} measurements and high-speed image analysis confirm a theoretical picture that the filaments are formed from an initial “current-hole” perturbation and carry net toroidal currents $I_f \sim$ 100-200 A, less than 0.2% of the plasma current, as seen in Figure 4(c). The longer-timescale radial speed is within a factor-of-two agreement with predictions from electromagnetic blob theory.

4. Conclusions

The Pegasus program is focused on extending non-solenoidal helicity injection startup and growth to ~0.3 MA plasma currents, using passive electrodes to grow discharges for relatively long pulse lengths. Shaped electrodes serving as current and helicity sources can be optimized with respect to both helicity and relaxation constraints. Bursts of MHD activity are observed during helicity injection, and correlate with rapid equilibrium changes, including inward motion of the magnetic axis and redistribution of the toroidal current. The structure of these bursty modes is that of a line-tied low-n kink mode, and the phenomenology is similar to that of resistive MHD plasma simulations. Internal magnetic measurements show the creation of a poloidal null prior to the formation of a tokamak-like equilibrium, and the redistribution of toroidal current into the core region as the plasma evolves. The MHD activity results in strong ion heating, with observed ion temperatures as high as 1 keV, and also exhibits the bi-directional flows that would be expected with significant reconnection activity. The plasma arc injector impedance is consistent with a double-layer sheath at the current extraction aperture. The increasing understanding developed in these studies support scalability of the helicity injection technique to large devices.

Operation at near-unity aspect ratio with high plasma current relative to the toroidal field allows study of peeling modes, a cause of Edge Localized Modes (ELMs) in larger devices. Peeling modes in Pegasus appear as coherent edge-localized electromagnetic activity with low toroidal mode numbers and high poloidal mode numbers. Internal magnetics and fast framing images show the formation of current-carrying field-following filamentary structures, which briefly accelerate radially, detach from the plasma edge, and propagate radially at a constant velocity. The acceleration and propagation velocity of the filaments correspond to the predictions of electromagnetic blob theory. This access to Advanced Tokamak (AT) physics studies shows that the Pegasus Toroidal Experiment can serve as a unique testbed for detailed comparisons between theoretical models of ELM dynamics and experimental measurements.

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