Current Profile Modification Influence on MHD and Non-Solenoidal Plasma Startup in the Pegasus Toroidal Experiment

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Abstract: The Pegasus Toroidal Experiment operates at A<1.3 and has achieved record high normalized plasma current for a tokamak, $I(N)$ > 12. Operation at high I(N) allows access to high beta(t) and requires j(r) modification to avoid deleterious MHD. Very broad, stable current profiles are obtained when washer-stack current sources (plasma guns) are used to initiate non-inductive discharges via DC helicity injection. This startup technique is scalable and requires no modification of the vacuum vessel. Equilibrium reconstructions of divertor gun discharges show high edge current ($l(i)$ = 0.2) and elevated q ($q(min)$ > 6), which allow access to the high $I(N)$ regime. Plasma gun discharges relax into a tokamak-like configuration with toroidally-averaged closed flux surfaces, large n=1 activity and toroidal current amplification up to 30 times the vacuum windup. Maximum I(p) is determined by helicity balance and up to 80 kA of toroidal current has been generated with this technique. Experimental evidence of flux amplification includes: reversal of the edge poloidal magnetic flux; increase of the toroidal plasma current over that of the vacuum geometric windup; plasma position subject to radial force balance; and persistence of the plasma current after gun shut-off. Coupling gun discharges to other current drive is straightforward. Gun-only plasmas which reach a maximum plasma current of 60 kA have been coupled to Ohmic drive applied at the time of the plasma gun turn-off and ramped up to 110 kA. Observed edge filaments are thought to be due to peeling instability, but the full mode structure is still being determined.

1. Introduction

Operation at low aspect ratio ($A=R_0/a$) 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 as measured by 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 Toroidal Experiment operates at low aspect ratio (A<1.3) which allows access to I_N > 10 while maintaining stability to the external kink mode without a nearby conducting wall.

Past Pegasus operations with limited Ohmic flux and crude coil waveform control led to performance limitations due to deleterious MHD [1,2]. Low-order rational surfaces in regions of low magnetic shear lead to large tearing modes, which would limit the achievable plasma current. These modes could be mitigated through crude discharge evolution control by allowing the discharge to heat up before the appearance of low-order rational surfaces. Control of these modes makes the available heating and current drive power the ultimate limitation on Pegasus performance.

The relatively thin central column in Pegasus and other spherical tokamaks (STs) leaves very little room for an Ohmic solenoid. Additional sources of heating and current drive are required to continue to increase performance, assuming successful mitigation of tearing mode activity. In order to make more efficient use of the available Ohmic flux, non-solenoidal plasma startup via DC helicity injection has been developed on Pegasus [3,4]. This technique has been used to create non-solenoidal targets with toroidally-averaged closed flux and toroidal plasma current in excess of 80 kA. Successful coupling to Ohmic drive results in significant reduction of the Ohmic flux required to achieve similar plasma current.

Filamentary edge perturbations are observed during both Ohmically driven and gun initiated plasmas. Due to the high edge current and low pressure gradient, as well as the observed characteristics of the modes, the observed filaments are thought to be peeling instabilities. There are magnetic fluctuations associated with these filaments, but their detailed structure remains unclear.

2. Experimental Facility

The Pegasus Toroidal Experiment is a mid-size spherical tokamak experiment as shown in Figure 1. The outer vacuum vessel wall radius is 1 m with a center-column radius of 5.5 cm. A poloidal limiter at R = 0.8 m allows for operation at a minimum A of 1.13 Typical operating parameters are given by: $I_p < 200$ kA, 0.2 m $< R_0 <$ 0.45 m, $\kappa < 3.5$, $\beta_t < 25\%$, $\tau_{shot} < 0.035$ s. Magnetic equilibria are constrained by a set of magnetics diagnostics consisting of: 32 poloidal flux loops, 35 poloidal magnetic field pickup coils, a plasma Rogowski, and diamagnetic flux loop [2].

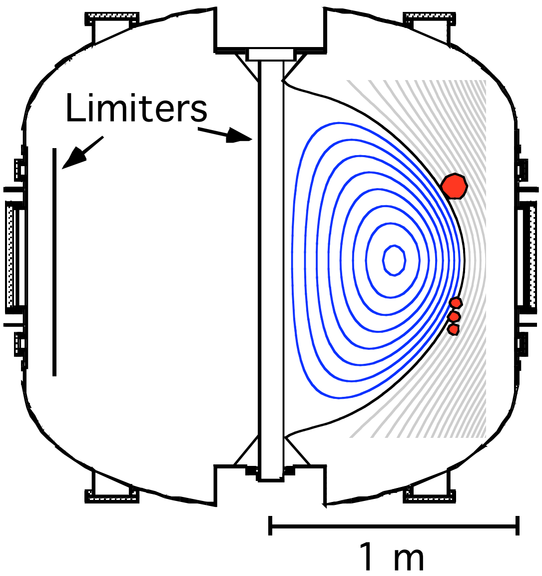

Figure 1: The Pegasus vacuum vessel

Experimental flexibility is achieved through fully programmable, fast-switching power supplies for all coil currents. These power supplies feedback on the measured coil current and operate with a switching frequency of 6 kHz, allowing sub-millisecond time response to requested changes or perturbations in the measured coil current. The low-inductance toroidal field (TF) coil has twelve turns, and is capable of ramping from full current (288 kA TF rod current or ~2 kG at the vessel R_0) to zero in 5 ms. This fast-ramp TF capability allows for variations of the TF during the shot.

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 2 kA of current parallel to the helical vacuum field at up to 1200 V. The plasma flux surfaces shown in Figure 1 represent a typical plasma gun startup discharge with a total of 80 kA of toroidal plasma current being sustained by 2 kA total of injected gun curent. The location of the plasma guns and anode are shown by the circles over-layed on the gun-plasma flux plot in Figure 1. The three small circles below the midplane represent the locations of the 3 gun apertures. The larger circle above represents the location of the anode. By initiating the discharge with this tool, the Ohmic flux can be conserved for heating and driving current in the already established target.

3. Paths to Achieve High-I_N

Using non-programmable, capacitor-based coil power supplies limited the achievable operation due to the appearance of large internal MHD [1,2]. This finding motivated facility upgrades to overcome these modes. All coil power supplies have been upgraded to allow current feedback control on all PF and TF coils as well as the Ohmic solenoid. The enhanced control allows for manipulation of the discharge evolution to prevent the large internal MHD from limiting the achievable I_N. Additionally, capability for non-solenoidal startup via point-source DC helicity injection has been deployed. This allows for startup over a very wide range of toroidal field and provides a very hollow plasma current source with favorable stability properties.

The operating space accessed by these methods is shown in Figure 2. This figure shows normalized current that has been achieved in Pegasus versus the plasma current for both Ohmically created and non-solenoidal plasma gun discharges. Achievement of high I_N indicates high toroidal field utilization since I_N=5A(I_p/I_{TF}). The highest current discharges are able to achieve I_N in excess of 6, or $I_p/I_{TF} \sim 1$, but I_N > 12 has been accessed at lower plasma current in both Ohmic and plasma-gun discharges.

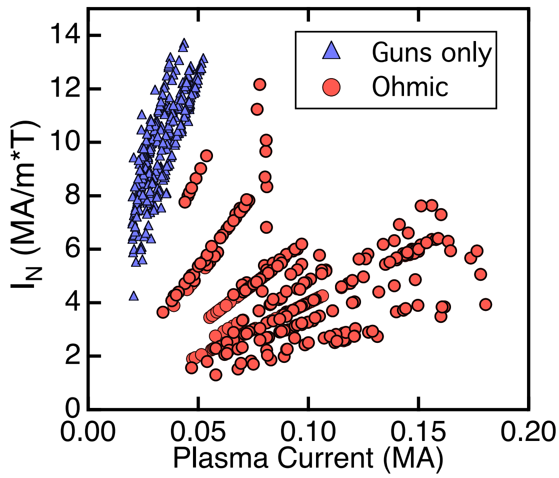

Figure 2: I_N vs. Plasma Current for Pegasus

A variety of discharge evolution variations have been used to achieve $I_N > 5$. They are:

1) Plasma gun pre-ionization:
Operation at lower TF increases I_N at the same I_p, and less power should be required to achieve the lower I_p. This leads to one path where high I_N might be realized by de-rating the plasma current at lower TF in order to have excess heating power. Low-TF operations has typically been difficult to achieve due to the increased sensitivity to a good poloidal field null for breakdown and the need for μwave pre-ionization. Lowering the TF rod current below 70 kA places the pre-ionization resonance outside of the vacuum chamber, so this was the minimum operable TF current.

The arcs inside the plasma guns do not require a magnetic field to operate and provide an excellent pre-ionization source. Using plasma guns for pre-ionization removes the minimum operating field restriction, and also removes the need to create a poloidal field null. This increased flexibility was used to expand the operating space as planned. The plasma current remained below 100 kA, but these discharges reached I_N of ~ 10 by using the excess of Ohmic power to increase I_p even in the presence of tearing modes.

2) TF rampdowns:
Discharges have been created with very high TF to remain stable during I_p ramp-up, with a subsequent TF decrease over the period of a few energy confinement times. The motivation for this technique was that by forming the discharge at elevated TF, the electron temperature would increase quickly, leaving a lower-resistivity plasma not as susceptible to large magnetic islands. This technique results in discharges with hollow current profiles due to the poloidal current induction of the TF ramp down as

evidenced by a reduction in ℓ_i by 20%. These discharges are at high plasma current (I_p > 0.15 MA), but the rapid decrease in TF eventually leads to a loss of plasma current and I_N < 8 is the maximum achieved with fast TF ramps at high plasma current.

The highest inductively achieved I_N was with a TF ramp-down of a lower plasma current target. This approach allowed the current profile to evolve for several energy confinement times before the TF rampdown. These points are those at 70-80 kA and 8-12 I_N on Figure 2. The slower discharge evolution allows more current penetration to the core of the discharge. As the plasma current was ramped down, the core remained stable longer than in the higher current, faster Ip ramp-up cases. This allowed this technique to access the highest inductive I_N in Pegasus.

3) Non-solenoidal startup with plasma guns:
The physics of non-solenoidal discharge formation will be discussed in more detail in section 4, but discharges created by the plasma guns can have very high I_N. Discharges created with plasma guns located in the lower divertor region achieved I_N > 12, with a maximum toroidal plasma current of 50 kA. Magnetic equilibrium reconstructions of gun-driven discharges show very broad current profiles with ℓ_i < 0.3. These discharges form around the center column, in the high-field region, maximizing I_p/I_{TF} and thereby I_N for this startup technique. Extension of this startup technique to higher current is an active area of research and will be discussed further in the next section.

The proposed methods for accessing high I_N have been evaluated and shown to work within limitations. For further advances, Pegasus must develop alternative means for heating and current drive, or find more efficient use for the available methods. Non-inductive startup provides a tool to create target plasmas with significant I_p before Ohmic heating is applied. Coupling these two techniques and utilizing the flexibility of the fast-ramp TF gives Pegasus the ability to increase β_t by maintaining I_N.

4. Non-Solenoidal Discharge Formation via DC Helicity Injection

Magnetic helicity is defined by a linkage of magnetic flux [5]. Current drive in a tokamak is equivalent to injection of magnetic helicity into the system since the toroidal current creates a poloidal flux that links the vacuum toroidal field. Ohmic induction is a form of AC helicity injection and DC helicity injection can be accomplished by driving current parallel to the magnetic field [6,7].

This is accomplished in Pegasus by creating a helical vacuum magnetic field with static poloidal and toroidal fields. Localized current sources are placed along a magnetic field that connects with an external anode. An applied voltage between the current source and anode is used to extract an electron current parallel to the magnetic field. The relative field strengths determine the number of toroidal transits the current filament makes before striking the anode, referred to as the geometric windup (G).

As long as the self-field from the extracted current remains below the field required to cancel the vacuum magnetic field, the total measured I_p is limited to the extracted current (I_{inj}) times G. When the self-field from the plasma current is able to overwhelm the applied vacuum field, relaxation into a tokamak-like state is observed. After relaxation occurrs, I_p is able to increase far beyond the vacuum field geometric windup.

One limit on the maximum I_p that can be sustained using this technique is determined by the DC magnetic helicity injection rate (K_{DC}) by the gun, as given by equation 1.

$$K_{DC} = 2\int_A \Phi B \cdot ds \approx 2V_{inj} B_n A_{inj} \quad [1]$$

Here V_{inj} is the bias voltage required to extract the injected current from the arc, B_n is the magnetic field normal to the gun aperture, and A_{inj} is the area of the injection aperture. This quantity can be enhanced by the effective voltage on the plasma as the PF is increased to maintain radial force balance with the discharge and is balanced by dissipation within the discharge.

Previous study of DC helicity injection with coaxial geometry [6] indicates that the toroidal current driven in this fashion can penetrate into the central plasma through the process of Taylor relaxation. Taylor relaxation requires that there be a sheet at the plasma edge with λ ($\lambda=\mu_0 J/B$) greater than the value of λ in the bulk of the plasma [5]. Assuming a flat λ profile across the plasma, the maximum I_p that can be sustained and still maintain current drive via Taylor relaxation is given by equation 2.

$$I_p < \varepsilon I_{TF} \left[\frac{N_{inj} I_{inj}}{I_{TF}} \frac{R_0}{R_L} \frac{L}{2\pi\delta} \right]^{1/2} \quad [2]$$

Discharges formed via this technique show evidence of relaxation into a tokamak-like state. Since current is being driven on open field lines, it is unsure if truly closed magnetic flux surfaces exist, but the plasma behaves as if closed flux surfaces exist in the toroidally averaged sense. Density measurements indicate an increase in particle confinement in relaxed discharges and the discharge decay time is much slower than the I_{inj} turn-off time.

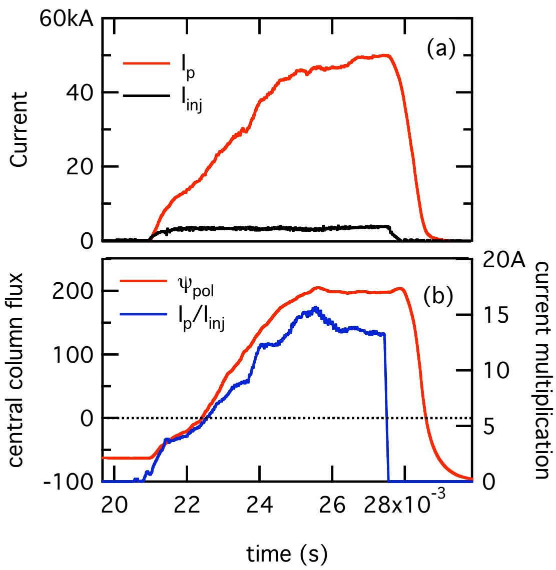

Figure 3: Plasma current and gun injected current for a divertor gun discharge (a). The center column poloidal flux and current multiplication factor (b) showing flux reversal as current multiplication exceeds geometric windup.

The time evolution of a relaxed, center-column limited discharge initiated by plasma guns located in the lower divertor region and biased with respect to an anode plate mounted in the upper divertor are shown in Figure 3. This discharge shows multiple characteristics that indicate relaxation to a tokamak-like state with poloidal flux amplification. Figure 3(a) shows the total measured I_p and the injected current from the plasma gun (I_{inj}), (b) the measured center column poloidal flux and the current multiplication factor. In this discharge, 50 kA of toroidal current was created, as shown in Figure 3(a), and discharges with I_p > 80 kA have been created using this technique. Figure 3(b) shows that the injected gun current is zero with over 40 kA of plasma current remaining. This current persistence after the gun current shut off and the approximately 1 ms decay time for I_p after this coincide with visible images of the collapse of a tokamak-like discharge. This discharge is limited on the inboard side. The geometric windup from the vacuum fields (($G=I_p/I_{gun}$)) was 5. As shown in Figure 3(b), center column poloidal flux shows reversal at the same time that the current multiplication factor exceeds G.

Pegasus data has been used to test the two criteria of helicity balance and Taylor relaxation discussed previously. The limiting plasma current predicted by these conditions is consistent with the observed maximum current within error. Divertor-mounted plasma guns operate in a regime where helicity balance determines the achievable plasma current. These discharges are center-column limited and grow outward into the low-field region. Figure 4 shows the scaling of the toroidal current with the driving helicity normalized to B_{TF}. All are discharges with static PF, so the maximum I_p is fully determined by the magnetic helicity injection rate. The upper limit achieved agrees with the calculated helicity balance.

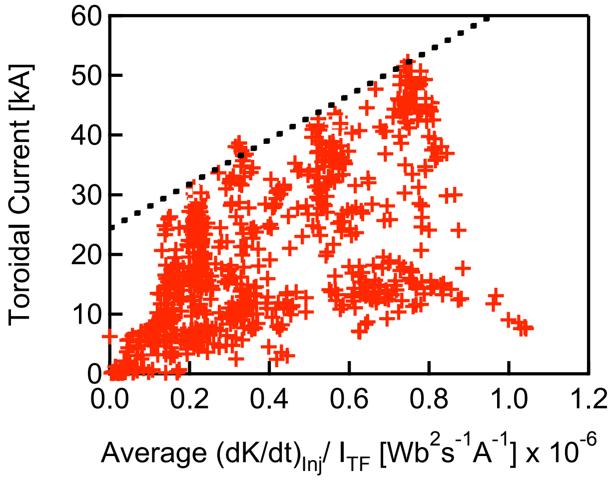

Figure 4: Helicity injection rate normalized to toroidal field.

Reconfiguring the geometry of the plasma guns to create an outboard limited condition allowed access to an operational regime where the maximum I_p is limited by Taylor relaxation requirements for power to flow from the gun to the plasma. Discharges initiated with the guns located near the outboard side of the plasma, as shown in Figure 1, have a maximum I_p consistent with equation 2.

These discharges start in an outboard limited configuration and grow inward to the high field region. The time evolution of one of these discharges is shown in Figure 5. Figure 5(a) shows the time evolution of the plasma current as well as magnetic fluctuations measured at the outboard midplane. The current injected by the plasma gun ramps up at 21 ms and drives the plasma until 28 ms. During the gun-drive phase, steady MHD is observed and may be related to current penetration. The reconstructed shape parameters shown in Figure 5(b) indicate that this technique results in a large, low-A plasma with high shaping. Figure 5 (c) shows the energy parameters for the plasma. The normalized pressure is low since these discharges require operation at full TF, but the increase in stored energy up until the gun shut off and confinement of that energy after the gun turns off are

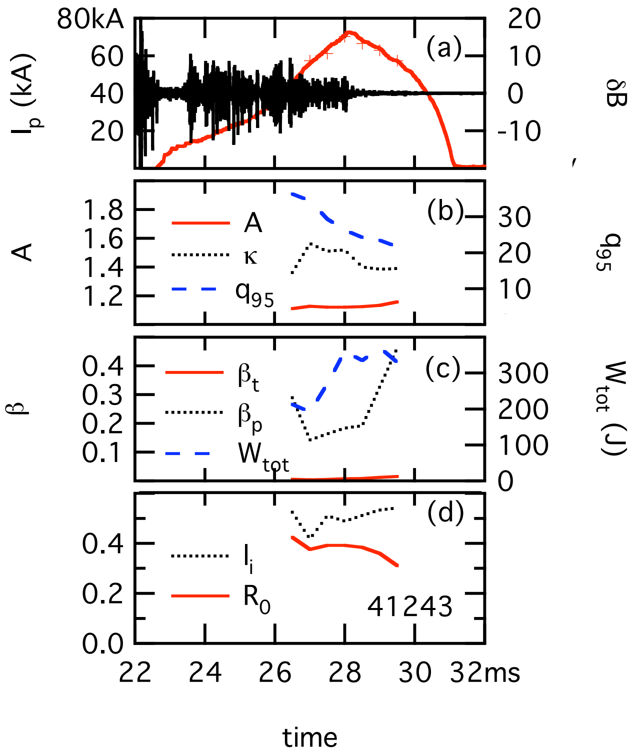

Figure 5: Time evolution of a 3-gun plasma

consistent with Ohmic confinement scalings. Present studies have applied Ohmic induction to drive these targets after gun shut-off, but other current drive techniques need to be tested.

5. Edge stability

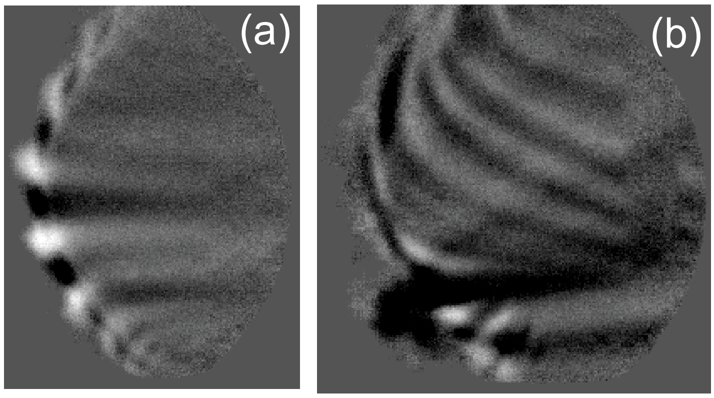

Figure 6: Visible images of an Ohmic plasma with the image taken 30 μs earlier subtracted. Frame (a) is during the I_p ramp-up, and (b) is during the plasma

High speed imaging of the plasma edge reveals the presence of spatially coherent filaments. Shown in Figure 6(a) is an image of the plasma taken from a tangential viewing angle at an exposure time of 6 μs and framing rate of 33 kHz with the previous frame subtracted to enhance the changes that occur in the 30 μs between frames. This picture is during the current ramp up with an I_p ramp rate of 33 MA/s. The left side shows the outboard side of the plasma, and several periodic perturbations are visible on the plasma edge. These appear consistent with numerical simulations of peeling mode perturbations [8]. Individual perturbations have been imaged at up to 90 kHz and show a regular growth and lifetime on the order of 100 μs or less. Radial propagation and detachment of individual filaments is visible as the perturbations become very large. Figure 6(b) is taken later in the same shot after the current has been allowed to ramp down. Filaments can be seen wrapping around the upper half of the plasma, but the edge perturbation isn't clearly visible.

Magnetic analysis with radially movable probes that can be placed near the plasma edge is in process. Correlation analysis between two probes separated by 40° toroidally show a broadband magnetic signal. Electrostatic probe measurements are being implemented to determine if some of this spectrum is due to electrostatic turbulence. During the ramp-up (Figure 6(a)) before tearing mode activity is observed, there are significant peaks in the measured cross-power spectrum between 80-100 kHz. The cross-phase analysis of those fluctuations suggests $n \leq 4$

6. Summary

Pegasus has developed three operational scenarios to overcome limiting instabilities and achieve record high normalized plasma current. These scenarios are made possible by increased flexibility of the coil systems and power supplies. Detailed waveform control allows control of the discharge size evolution and input power. Fast-ramp TF-coil capability provides the ability to quickly change the toroidal field during the discharge. These techniques allowed the creation of discharges with I_N up to 12. Low-field operations made possible by plasma gun preionization and plasma gun only discharges also were able to reach I_N up to 12. These methods require the use of a new capability which allows non-solenoidal startup in Pegasus.

Non-solenoidal startup using DC helicity injection is performed by a set of plasma guns to initiate a tokamak-like discharge. This technique creates broad, stabilizing current profiles and is easily coupled to other current drive techniques. Discharges with up to 80 kA have been created using this technique and no central induction. The total plasma current that can be achieved for a giving magnetic field configuration and a given set of gun parameters must satisfy at least two limits: magnetic helicity balance and Taylor relaxation limits.

During both the decay phase of plasma gun discharges and the driven phases of Ohmic discharges, edge filaments are observed which may be related to peeling modes. Constraint of the edge current profile during equilibrium reconstructions is presently being implemented in order to perform detailed MHD stability calculations. Magnetic measurements indicate coherent modes with $n < 4$ in the 80-100 kHz range may be due to observed filaments.

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