Non-solenoidal startup as a path to high normalized current operations in the PEGASUS Toroidal Experiment

A.J.Redd, M.W.Bongard, R.J.Fonck, E.T.Hinson, and D.J.Schlossberg

University of Wisconsin Madison, Madison, Wisconsin USA

Abstract: The PEGASUS Toroidal Experiment is an ultra-low aspect ratio spherical tokamak (R=0.45m, a=0.40m) exploring non-solenoidal startup and the physics of the high-I_N high-β_T operating regime. Achieving high I_N in PEGASUS requires a non-solenoidal method of driving plasma current and controlling the current density profile. PEGASUS uses compact high-current plasma guns as DC magnetic helicity injectors for non-solenoidal startup, and helicity injection discharges can be coupled to inductive drive for further I_p rampup and sustainment. To date, helicity injection alone has produced I_p=0.17 MA, while gun-Ohmic coupling has produced 0.135 MA of handoff current and peak I_p=0.22 MA. Further optimization will enable production of high-density, high-I_N target plasmas for high-β_T studies.

The PEGASUS Toroidal Experiment is a mid-size (R=0.40-0.45m, a=0.35-0.40m), extremely low aspect ratio tokamak (A<2), designed and built with a minimal central column, and thus having a correspondingly small amount of Ohmic flux available [1]. Figure 1 shows a cross-section of the PEGASUS device and support structures, along with flux surfaces of a model equilibrium. Very low aspect ratio ($A \rightarrow 1$) naturally leads to accessing large values of the normalized plasma current, $I_N = I_p/aB_T$, or toroidal field utilization factor I_p/I_{TF} ($I_N = 5AI_p/I_{TF}$). Confinement and stability modeling show that the regime of interest (high β_T and I_N) is attained at high field utilization, $I_p/I_{TF} > 1$, and high $I_p > 0.2$ MA. A primary goal of PEGASUS discharge development is simultaneously achieving high I_p and I_p/I_{TF} at high particle density to study the stability properties of this regime.

A precondition for accessing high I_N and/or β_T regimes is mitigation of low-order tearing modes observed in early PEGASUS experiments [2]. These modes effectively limited the accessible I_p for a given ohmic flux swing. Recent experiments and analyses have conclusively shown that the previously observed limit $I_p/I_{TF} \leq 1$ is not intrinsic, but can be readily surpassed by active manipulation of the j(r) profile [3]. Experimentally, low-m, n=1 internal modes were suppressed or at least mitigated by avoiding the formation of very low-shear regions near low-order rational flux surfaces.

Hence, accessing the high-I_N high-β_T operating regime in PEGASUS requires a non-solenoidal technique for driving toroidal current and controlling the current density profile. Helicity Injection Current Drive (HICD) is a class of non-solenoidal techniques for driving toroidal current in magnetized plasmas, which tend to produce equilibria with flat or hollow current density profiles and strong shear.

Current drive in toroidal magnetized plasmas can be described in general terms as the injection of magnetic helicity, where HICD relies on the relaxation of unstable plasma to the lowest energy state (the "Taylor" state) via non-axisymmetric magnetic perturbations, a relaxation process that conserves helicity on resistive dissipation timescales [4]. In PEGASUS, an array of local current sources in the plasma scrapeoff region is used to inject magnetic helicity and drive toroidal current, creating ST plasmas without using the ohmic solenoid [5]. Experimentally, we find that all injected helicity is converted to helicity in the tokamak plasma, and that helicity is only lost though resistive dissipation [6]. Assuming a sufficient helicity injection rate, the Taylor relaxation process imposes an upper limit on the achievable I_p for a given injector. A simple algebraic expression has been developed for the maximum I_p allowed by relaxation, in terms of measureable quantities, including the total TF coil current and the plasma gun bias current, and is supported by PEGASUS experimental observations [5].

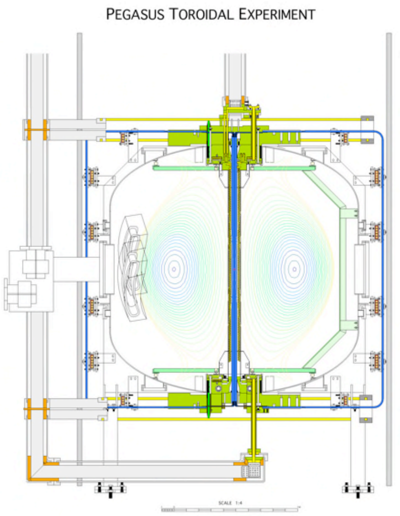

Figure 1: The PEGASUS device

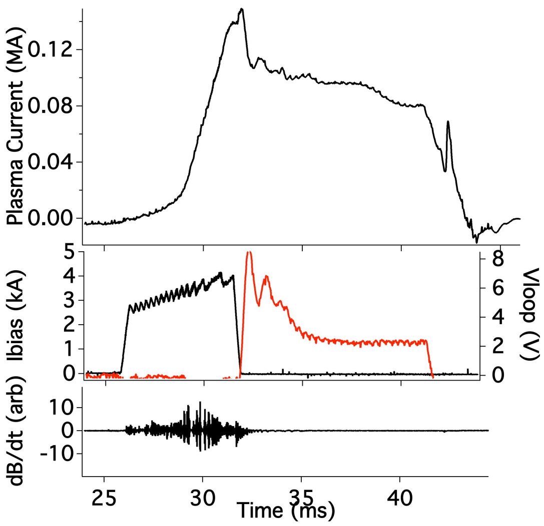

Figure 2: Time traces for discharge #46135

Figure 2 shows time traces for helicity injection discharge #46135, a typical early attempt at using a helicity injection startup with inductive sustainment. The time traces include the plasma current I_p, the plasma gun bias current I_{inj} during the helicity injection phase, the applied loop voltage V_{LOOP} during the inductive phase, and the magnetic field fluctuations measured by a wall-mounted Mirnov sensor. During helicity injection, the measured fields are turbulent, and exhibit bursts of n=1 MHD activity with frequencies in the range of 40-60 kHz. After gun shutoff, the plasma is relatively quiescent, which is a common feature of high-I_p helicity injection startup plasmas. The majority of the I_p rise during startup occurs in less than three milliseconds, for a current ramp rate in excess of 40 MA/s. This short time interval is not adequate for the current density to significantly migrate inward from the plasma edge.

Figure 3 shows similar time traces for PEGASUS discharge #47112, which uses a relatively slow helicity injection startup to achieve I_p=0.135 MA (the so-called "handoff" current), and inductive drive to further ramp up and sustain the plasma current, reaching a peak I_p of 0.22 MA. As with discharge #46135 above, the measured field is turbulent during helicity injection, with bursty MHD activity, up to the gun shutoff at 24 ms. During the inductive phase, the plasma is remarkably quiescent, with no evidence of low-n tearing modes, despite the rapid and substantial increase in I_p, at a rate above 20 MA/s for several milliseconds. Equilibrium reconstructions throughout the inductive phase show that the slow helicity injection startup produces a strongly sheared discharge with a less hollow current profile (l_i > 0.4), and that this magnetic shear is "frozen into" the discharge throughout the inductive phase. The primary consequence of this sheared profile is that the n=1 tearing modes remain stabilized, so that the only operational limits on I_p are set by the PEGASUS power supplies.

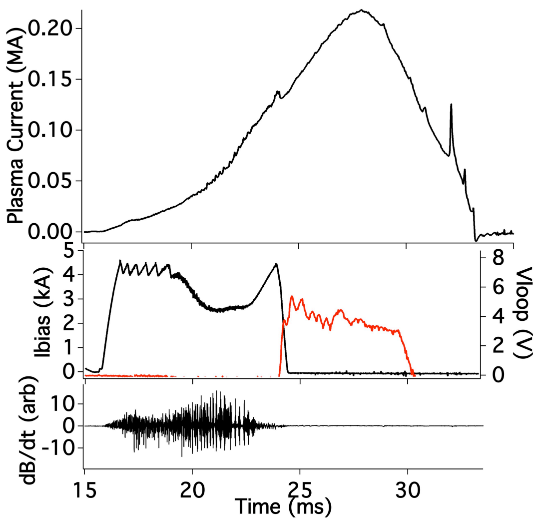

Figure 3: Time traces for discharge #47112

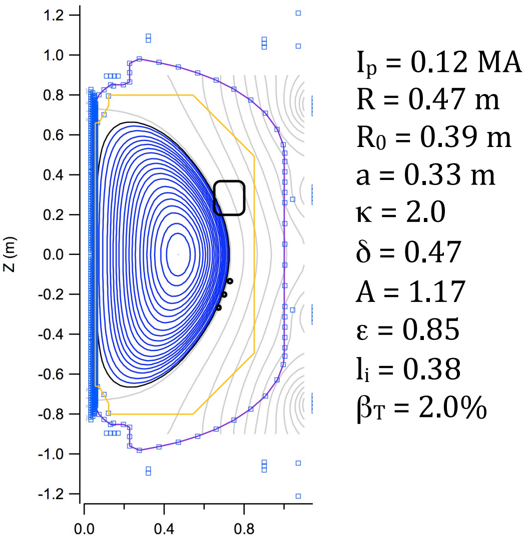

Figure 4: Flux surfaces for equilibrium reconstruction of #47112 at 23.55 ms.

As an example, Figure 4 shows a poloidal flux plot for an MHD equilibrium reconstruction of #47112 at time 23.55 ms, along with a table of key equilibrium parameters. Throughout most of the helicity injection phase, the plasma is limited on the outboard gun array and corresponding anode structure, where the positions of these structures are indicated in Fig. 4. At the time of the reconstruction, the plasma is also limited on the central column, so that the plasma is filling the available cross-section of the confinement region.

Reconstructions of later times in the same discharge indicate that the plasma is crushed into the central column by ramping vertical fields during the inductive drive phase. Further optimization efforts produced discharges that have the same handoff current (0.135 MA) but fill the confinement region throughout the inductive phase, at the cost of slightly lower peak plasma current (*e.g.*, 0.19 MA in discharge #47344).

Figure 5 compares current density profiles from equilibrium reconstructions of gun-only discharge #45736 and handoff discharge #47112, at the end of the helicity injection phase. Shot #45736 has a rapid I_p ramp, similar to that in #46135. Note that the current density profile is considerably more hollow in #45736, while the slower current evolution in discharge #47112 has produced a flatter current density profile.

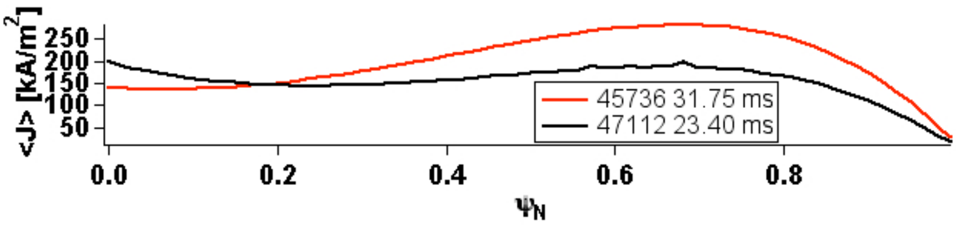

Figure 5: Reconstructed current density profiles at the end of helicity injection for a rapid Ip ramp case (#45736, in red) and a slower ramp case (#47112, in black)

Helicity injection current drive provides non-solenoidal tokamak plasma startup in the PEGASUS Toroidal Experiment, which can then be coupled to inductive drive for further I_p rampup and sustainment. Present experiments have demonstrated that a slow current evolution is necessary for a good handoff to inductive drive, and a peak I_p of 0.22 MA (with corresponding ratio I_p/I_{TF} of 0.7) has been achieved in a combined HICD/inductive scenario. Equilibrium reconstructions indicate that the strongly sheared profile of the helicity injection startup plasma is "frozen into" the inductive phase, stabilizing the plasma to the low-n tearing modes that limited I_p in early PEGASUS operations. Further optimization of the existing HICD/inductive scenarios will improve the handoff current, the duration of high current, and the peak I_p, with the goal of producing targets for high-I_N high-β_T studies.

1. G.D. Garstka *et al.*, Nuclear Fusion **46**, S603 (2006).

2 G.D. Garstka et al., Physics of Plasmas **10**, 1705 (2003).

3. "Accessing high normalized current in an ultra-low-aspect ratio torus," E.A. Unterberg, Ph.D. dissertation, University of Wisconsin–Madison (2007).

4. J.B. Taylor, Reviews of Modern Physics **58**, 741 (1986).

5. D.J. Battaglia *et al.*, Physical Review Letters **102**, 225003 (2009).

6 "Non-inductive startup of the PEGASUS spherical torus using localized washer-gun current sources," N.W. Eidietis, Ph.D. dissertation, University of Wisconsin – Madison (2007).