Non-Solenoidal Tokamak Startup Using High-Field-Side Local Helicity Injection on the Pegasus ST

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Local Helicity Injection (LHI) Achieved Using Low-Field-Side and High-Field-Side Injectors

- Edge current extracted from injectors
- Relaxation to tokamak-like state via helicity-conserving instabilities

\[ V_{LHI} \approx \frac{A_{inj} B_{\varphi,inj} V_{inj}}{\Psi_p} \]
Injector Geometries Emphasize Different Current Drives

Low-Field-Side Injection:
- Injectors on outboard mid-plane
- High $R_{inj} \rightarrow$ low $V_{LHI}$
- Dynamic shape $\rightarrow$ strong $V_{IND}$

High-Field-Side Injection:
- Injectors in lower divertor
- Low $R_{inj} \rightarrow$ strong $V_{LHI}$
- Static shape $\rightarrow$ minimal $V_{IND}$

Confinement Properties Set the Current Drive Scaling for HFS Injection

• Ohmic and stochastic confinement scalings predict non-linear $I_p - V_{LHI}$ relationships

$$V_{LHI} = I_p R_p \rightarrow T_e^{3/2}$$

• Experiment shows $I_p$ proportional to $V_{LHI}$
  – Suggests fixed $\langle \eta \rangle$

• However, may not be fully representative
  – Experiment conducted at low $B_t \sim 0.045$ T
  – Short $I_p$ flat top
  – $n_e$ was not controlled
$T_e$ Profile Structure Suggests Varying Degrees of Current Stream Structure in the Plasma Edge

- In LFS discharges, profile structure depends on attachment of plasma to the injectors
  - Peaked when attached
  - Hollow when detached

- In HFS discharges, profile structure depends upon the level of $B_t$
  - Peaked at max $B_t$
  - Hollow at reduced $B_t$
Operation at Max $B_t$ is Critical to Scale LHI to Larger Facilities

- HFS injection more difficult at max $B_t$
- Increased $B_t$ causes injector streams to pass closer to the other injector
- Cathode spots are more likely to occur early in the discharge at max $B_t$

Current streams in an unrelaxed discharge

Cathode spots on the outside of the injector

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LFS to HFS Injection Handoff Enables Routine Max $B_t$ Operation

- Additive nature of helicity means HI systems can be combined

- Startup with LFS injection at max $B_t$
  - Eases relaxation requirements
  - Favorable geometry for divertor injectors

- Handoff to HFS injection when presented with full size plasma
  - Mitigates PMI issues

- Proof of principle of the handoff technique
• Core $T_e$ increases during the HFS drive phase to > 100 eV

• Trade-off between $n_e$, $T_e$, and $I_p$; can operate at higher $n_e$ but requires more input power

• Similar results have been observed with HFS injection-only discharges at max $B_t$
Abrupt Transition in MHD Behavior During HFS Injection

- Large-amplitude, low freq. in early phase
  - Large scale n=1 at 20-80 kHz
  - Line-tied kink of current streams
- Reduction in low frequency activity later in the discharge
  - Low MHD: up to 50% more $I_p$
  - Interpreted as kink stabilization
- Mechanisms behind this transition are unclear; under investigation

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J.M. Perry et al 2018 Nucl. Fusion 58 096002
• HFS injection has been used to create discharges driven purely by helicity injection

• LFS to HFS startup successfully implemented to routinely create high $I_p$ discharges at max $B_t$

• Peaked $T_e$, $n_e$, and $p_e$ profiles observed in purely helicity driven plasmas

• $T_e$ profile suggests varying degrees of current stream thermalization in the plasma edge

• Operating regime with reduced $n=1$ activity; increased current drive efficiency discovered