New Understanding and Achievements from Independent Injector Drive Experiments on HIT-SI

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International Workshop on Spherical Tori
October 22nd, 2009
Madison, Wisconsin
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Highlights

- New HIT-SI results with independent injector operation (different voltage & flux amplitudes) gives highest spheromak current (38 kA) and current amplification ($i_{\text{tor}}/i_{\text{inj}} \approx 2$) to date

- Each injector has a preferred spheromak current direction related to the sign of the helicity and its orientation relative to the confinement volume

- Spheromak current degrades in time, probably due to symmetric flux loss leading to spheromak current flipping
Outline

1. Introduction
2. HIT-SI Device
3. Independent Injector Experiments
4. Summary
Previously, HIT-SI was exclusively run with identical injector amplitudes $\approx$ equal helicity injection

Best equal helicity injection results:
- Spheromak currents up to: 33 kA ($\sim$7.5 MW input)
- Current amplification ($I_{\text{tor}}/I_{\text{inj}}$) up to: 1.5

New results with unequal helicity injection allowed for a higher X-injector loop voltage, yielding higher spheromak currents & current amplification
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Injection of Magnetic Helicity is Equivalent to Current Drive on Toroidal Plasmas

- Magnetic helicity, $K$, is the best constant of motion in a magnetized plasma.

- Force-free equilibrium $\nabla \times \mathbf{B} = \mu_0 \mathbf{J} = \lambda \mathbf{B}$ has minimum energy, while conserving $K$, when $\lambda$ is constant.

- Helicity-conserving magnetic activity dissipates free energy by producing a more uniform $J/B$ profile:

  ⇒ Drive $J/B$ high in an experimentally appropriate location to produce current drive in a closed flux region.
In each injector, the voltage and flux can be independently feedback controlled yielding equal or unequal helicity injection. Two injectors allow for constant helicity injection.
Close fitting ‘bow-tie’ flux conserver gives stability to global modes

‘Bow-tie’ flux conserver and hollow current profile raises the $\beta$ limit
AC drive produces a DC equilibrium with $I_{\text{tor}}$ up to 38 kA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>$R_0$</td>
<td>0.33 m</td>
</tr>
<tr>
<td>axial length</td>
<td>0.57 m</td>
</tr>
<tr>
<td>$f_{\text{inj}}$</td>
<td>5.8 kHz (172 $\mu$s)</td>
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<tr>
<td>$I_{\text{inj}}$</td>
<td>$\leq$ 30 kA</td>
</tr>
<tr>
<td>$V_{\text{inj}}$</td>
<td>250 – 450 V</td>
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<tr>
<td>$\psi_{\text{inj}}$</td>
<td>$\leq$ 1.7 mWb</td>
</tr>
<tr>
<td>$P_{\text{inj}}$</td>
<td>$\leq$ 8 MW</td>
</tr>
<tr>
<td>$n_e$</td>
<td>$\sim 3 \times 10^{19} \text{ m}^{-3}$</td>
</tr>
</tbody>
</table>
Current Amplification of \( \approx 2 \) Achieved with Unequal Helicity Injection

- \( \approx 6 \) MW input power
- Peak spheromak current up to 38 kA
- \( \approx 2 \) current amplification (\( I_{\text{tor}}/I_{\text{inj quad}} \))
- Poloidal flux amplification (\( \psi_{\text{pol}}/\psi_{\text{inj}} \)) > 6
Current Amplification of \( \approx 2 \) Suggests Improved Confinement

- Taylor state equilibrium accurately predicts magnetic profiles in HIT-SI [T. R. Jarboe et al. IAEA 2008]
- Superposition of Taylor states of one injector & the equilibrium assuming:
  - \( \lambda_{\text{inj}} = \lambda_{\text{sph}} \sim 10.3 \, \text{m}^{-1} \)
  - \( I_{\text{tor}}/I_{\text{inj}} = 2 \)
- Taylor state has significant closed flux that does not link the injector
Each Injector has a ‘Preferred’ Direction of Spheromak Current

- Preferred current direction *not* predicted by single-fluid MHD
- Opposite current preference is the result of injectors mounted on opposing sides of the confinement volume
Injector Preference Determined by the Polarity of the Helicity

Both shots with only X injector:
- Positive helicity: voltage & flux in the same direction
- Negative helicity: voltage & flux in opposing directions
Spheromak Current ‘Flipping’ a Consequence of Opposing Injector Preference

- Current flipping occurs during dual injector operations
- Injectors trade dominance of the toroidal current direction

*Negative Helicity Shots
Degradation of current in one toroidal direction probably due to equilibrium flux loss

Flipping occurs when opposite direction has lower dissipation of current on open flux $\rightsquigarrow$ yielding larger currents late in time
Injecting opposite helicity has same preferred current direction but results in no significant spheromak current because of helicity balance.
New HIT-SI Configuration Will Yield More Efficient Current Amplification

- Injectors on the same side of the confinement volume:
  - Gives same polarity of helicity and preferred spheromak current
  - Injectors will work together & eliminates flipping

- Equilibrium flux control:
  - Provide favorable flux boundary conditions for spheromak
  - Reduce spheromak degradation in time
Three Injector Concept Takes Advantage of New Understanding

- 50% more helicity injection for the same voltage & flux amplitudes
- Generates a rotating magnetic structure without crossing the injectors
- Improved flux conserver:
  - Smaller injector openings
  - Solid back plate (available for diagnostics and/or diverter)
Summary

- New HIT-SI results with independent injector demands gives highest spheromak current (38 kA) and current amplification $\left( I_{\text{tor}}/I_{\text{inj}} \approx 2 \right)$ to date.

- Each injector has a preferred spheromak current direction related to the sign of the helicity and its orientation relative to the confinement volume.

- Spheromak current degrades in time, probably due to symmetric flux loss leading to spheromak current flipping.

- **Future Plans:** New HIT-SI configuration with three injectors on the same side and equilibrium flux control will produce more efficient current drive.