Modifications to the HIT-SI Flux Conserver

Operation of the HIT-SI helicity injectors leads to a family of field lines that are not driven directly by the injector voltage. These fields are analogous to the closed toroidal fields inside the current sheet of a “bubble-burst” coaxial gun, but the asymmetric injector geometry on HIT-SI allows these field lines to exit the flux conserver through the midplane diagnostic gap. Furthermore, as relaxation activity arises in the vessel, toroidal modes can push field into this gap. Open field lines are helicity-dissipating\(^1\) and should be avoided.

A copper strap has been installed across the diagnostic gap. This modification makes the flux conserver more complete, reducing the quantity of helicity-dissipating flux. The effect of the strap on the magnetic structure of the plasma is shown. Recent discharges with the strap installed have produced spheromak currents up to 90% of the amplitude of the injector currents.

A “Cutaway” View of the HIT-SI Device

Midplane diagnostic ports

“X” Injector

“Y” Injector

Outer tank provides a current path across the diagnostic gap, but at high R and L

Axial diagnostic ports
HIT-SI Dimensions

- 59 cm
- 33 cm
- 7.7 cm
- 24 cm
- 15 cm
- 58 cm
- 5.6 cm
Equilibrium Region Diagnostics

- 20 flux loops
- 96 three-axis surface magnetic field probes

Shaded field of view:
- $H_\alpha$ line radiation sensors
- Digital camera
- Ion Doppler Spectrometer

Internal magnetic field probe

Other diagnostics:
- Far-Infrared Interferometer
- Multi-Point Thomson Scattering
- Langmuir Probe Array
- VUV Spectroscopy
Steady Inductive Helicity Injection (SIHI)

With a spheromak equilibrium present, the edge fields are mostly poloidal (across the diagnostic gap)

Relaxation will form a spheromak equilibrium that links the injector flux, if it can be driven faster than:
• resistive decay
• helicity loss to open field lines
There is no vacuum $E_z$ at the geometric axis, so SIHI is compatible with bow-tie shape.

These toroidal fields are not enclosed within a current sheet, but they have a 5 kHz rotating $n=1$ structure.

The vacuum flux intersects the spheromak region, so the “bubble burst” criterion is not required.

The injector is a segment of a RFP, driven by a transformer.
3-D Finite Element Calculation of the n=0 Taylor State

First eigenvalue ($\lambda = 10.47/m$), plots of radial magnetic field

The computational domain includes the midplane gap and outer vessel, but not the injectors

The n=0 equilibrium state has little radial field in the midplane gap (approx. 5% of maximum radial field)
3-D Finite Element Calculation of the n=1 Taylor State

Second eigenvalue ($\lambda = 12.04/m$), plots of radial magnetic field
3-D Finite Element Calculation of the n=1 Taylor State
Second eigenvalue ($\lambda = 12.04/m$), plots of radial magnetic field

The n=1 equilibrium state has significant radial field in the midplane gap (>10% of maximum radial field)
Extending the Boundary Simulates Field Soak-Through in the Resistive Outer Tank

Second eigenvalue ($\lambda = 11.48/m$), plots of radial magnetic field
Outer boundary moved from $R=61.6$ cm To $R=85.6$ cm
The Resistive Outer Tank Allows More Open Field

Second eigenvalue ($\lambda=11.48/m$), plots of radial magnetic field

The extended domain does not greatly change the equilibrium region structure...

…but it allows a great deal more field out the midplane gap (>35% of the maximum radial field)
Radial Fields Have Been Observed In the Diagnostic Gap

A strong n=1 structure was observed in the diagnostic gap. The total magnetic flux out the gap was comparable to the injector flux.
A copper strap is installed to provide a low-resistance, low-inductance current path across the gap. This reduces the flux leaving the equilibrium region.
The Strap Reduces the Open Flux Through the Diagnostic Gap

This discharge has comparable parameters to the discharge previously shown. A considerable reduction in the midplane gap open flux is observed.

Shot 103774, t=1.525 ms, radial and toroidal fields averaged over 10 µs
HIT-SI uses a passive flux conserver. The L/R time of the shell (~ 45 ms) is much longer than the pulse length (6 ms) so the rate of flux soaking past a flux loop is a measure of the n=0 component of $B_{pol}$ at low frequencies.

To determine the spheromak current, the poloidal fields are fit to the Bessel function $J_0$, where the argument of the Bessel function is simply $\lambda R$, in which R is the major radius.
Observations of Spheromak Current

Significant spheromak currents have been observed for the first time in HIT-SI. To date, the spheromak current is as much as 90% of the amplitude of the injector currents.
The following factors may have contributed to the favorable results:

• Aggressive discharge cleaning campaigns

• Baking the vacuum vessel above 100°C

• Installation of the copper strap

• Recent change from series to parallel resonant driving circuit on each injector

• RF pre-ionization

• Helium working gas
Discharges with significant spheromak current usually adhere to the following pattern

A. An interval having little toroidal current

B. A period of fluctuations in the bolometer signal

C. The spheromak current rises, bolometer fluctuations decrease, and visible light emissions from the injector become more smooth.
Conclusions

As originally constructed, the HIT-SI midplane diagnostic gap allowed open field lines to depart the equilibrium region. These open fields were predicted in Taylor-state equilibrium calculations and were observed in the experiment.

Open field lines dissipate magnetic helicity, so a copper strap was installed across the diagnostic gap as a flux-conserving boundary. The strap has proven to be an effective means of reducing open flux in the diagnostic gap. Future experimental plans include replacing the strap with current-carrying bridges to improve diagnostic access and vacuum pumping speed.

Significant toroidal plasma currents (comparable to the injector current amplitudes) have been observed in HIT-SI, suggesting spheromak formation.