Advances in Steady Inductive Helicity Injection for Plasma Startup and Toroidal Current Drive

Brian Victor

on behalf of the HIT-SI team

September 27, 2011

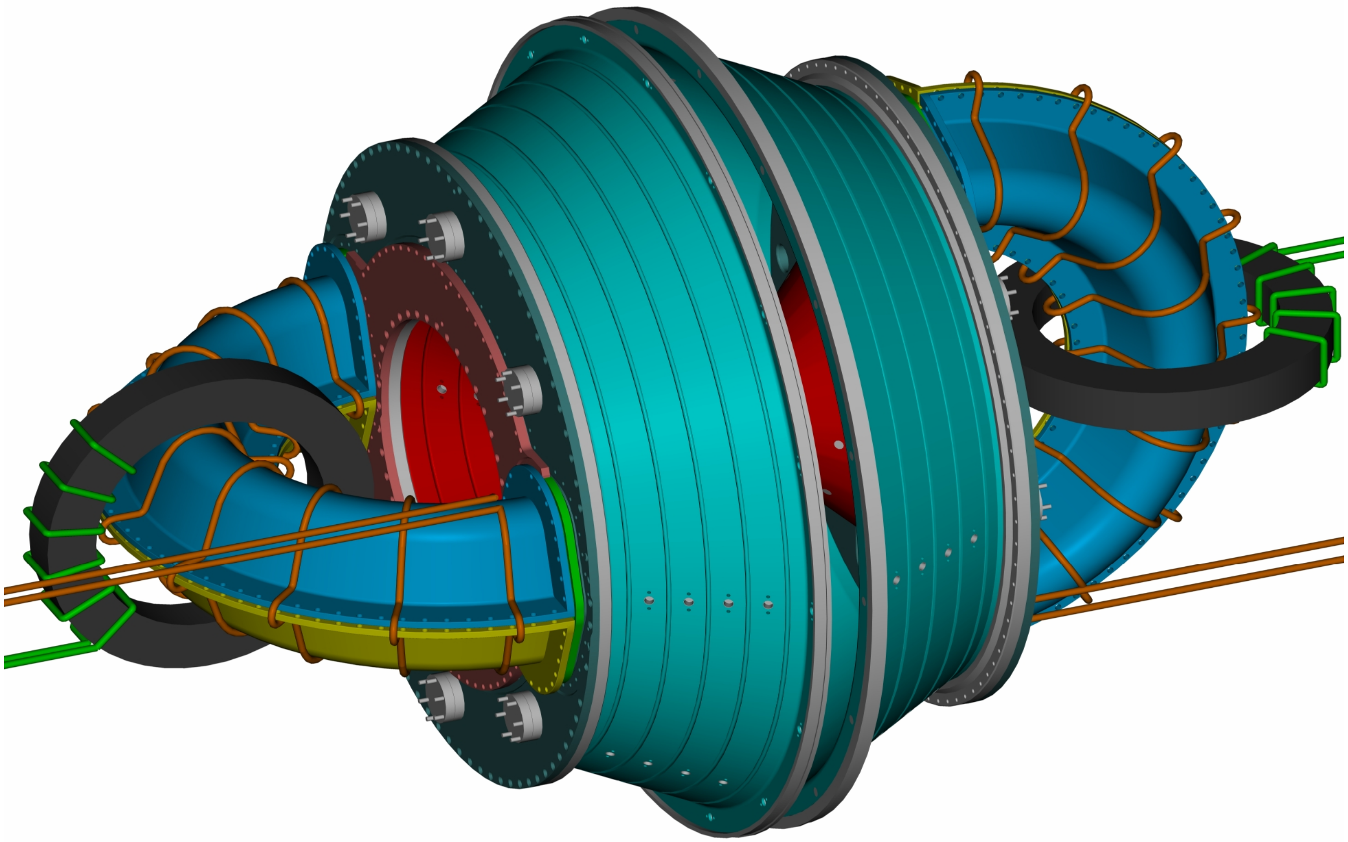
HIT-SI has achieved a major advance in current drive with deuterium operations

- Toroidal currents over 50 kA
- Separatrix current—current not linking the helicity injectors—sustained near 40 kA
- Current amplifications (I_{tor}/I_{inj}) of up to 3
- Toroidal current persistence of up to 0.65 ms after injector shutoff

Outline

- Description of the Helicity Injected Torus-Steady Inductive (HIT-SI)
- Results of deuterium experiments
  - Increase in the ratio of current density to electron density (j/n) led to improved performance
- High current ratio (I_{tor}/I_{inj}) deuterium shots have different characteristics than past helium shots
  - Decrease in the n = 1 toroidal mode at higher current amplifications indicates more quiescent, direct toroidal current drive
  - Lower magnitude internal magnetic fields with respect to Taylor equilibrium characteristic of plasma pressure

HIT-SI device



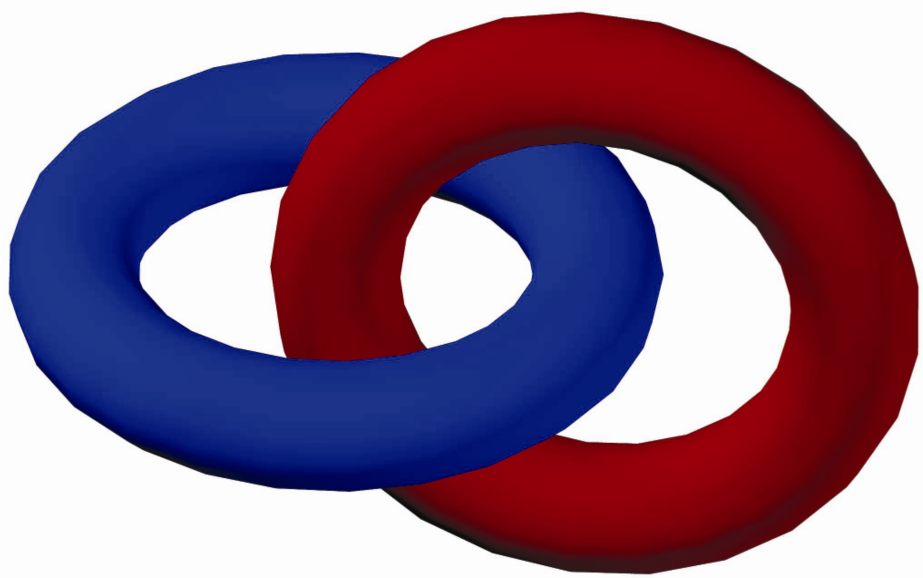
HIT-SI uses air-core transformers

Solid transformers shown for clarity

Voltage coils
Flux coils

AC injector drive generates DC toroidal current

HIT-SI injects helicity to form toroidal current in the confinement volume



$$\mathbf{K} \equiv \int \mathbf{A} \cdot \mathbf{B} \, dV = 2\phi\psi$$

- Magnetic helicity, K, is the self-linkage of magnetic flux
- Toroidal current is formed through the relaxation to a minimum energy, or Taylor, state under the constraint of helicity conservation

Conventional tokamaks use a central solenoid coil to inject helicity

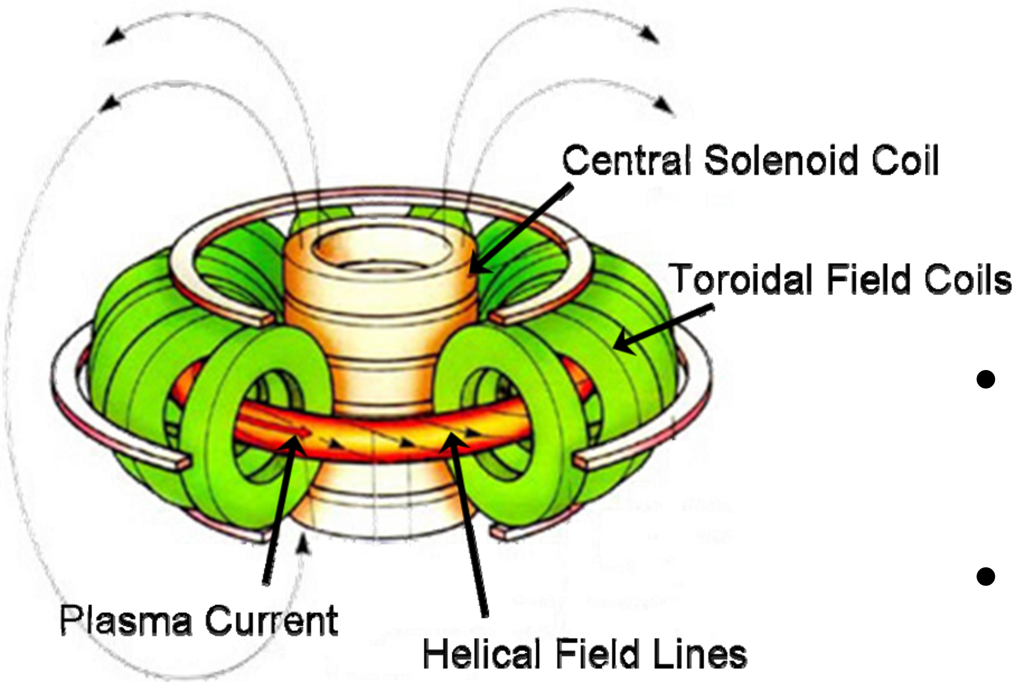
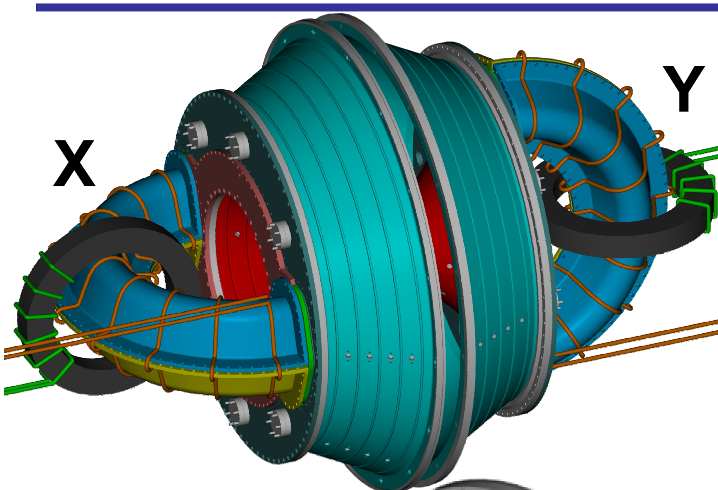


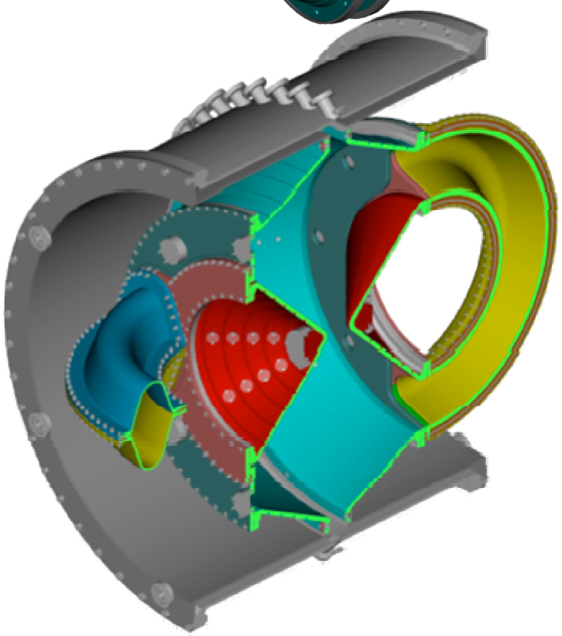
Image courtesy of
http://www.euronuclear.org

$$\dot{K} = 2V\Psi$$

- Loop voltage, V, from the central solenoid coil
- Toroidal flux, Ψ, from the toroidal field coils

Steady Inductive Helicity Injection (SIHI)





$$\dot{K} = 2V_{inj}\Psi_{inj}$$

$$V_{inj} = V_{max}\sin\omega t$$

$$\Psi_{inj} = \Psi_{max}\sin\omega t$$

The injectors operate 90 degrees out of phase, giving

$$\dot{K} = 2V_{max}\Psi_{max}(\cos^2\omega t + \sin^2\omega t)$$
$$= 2V_{max}\Psi_{max}$$

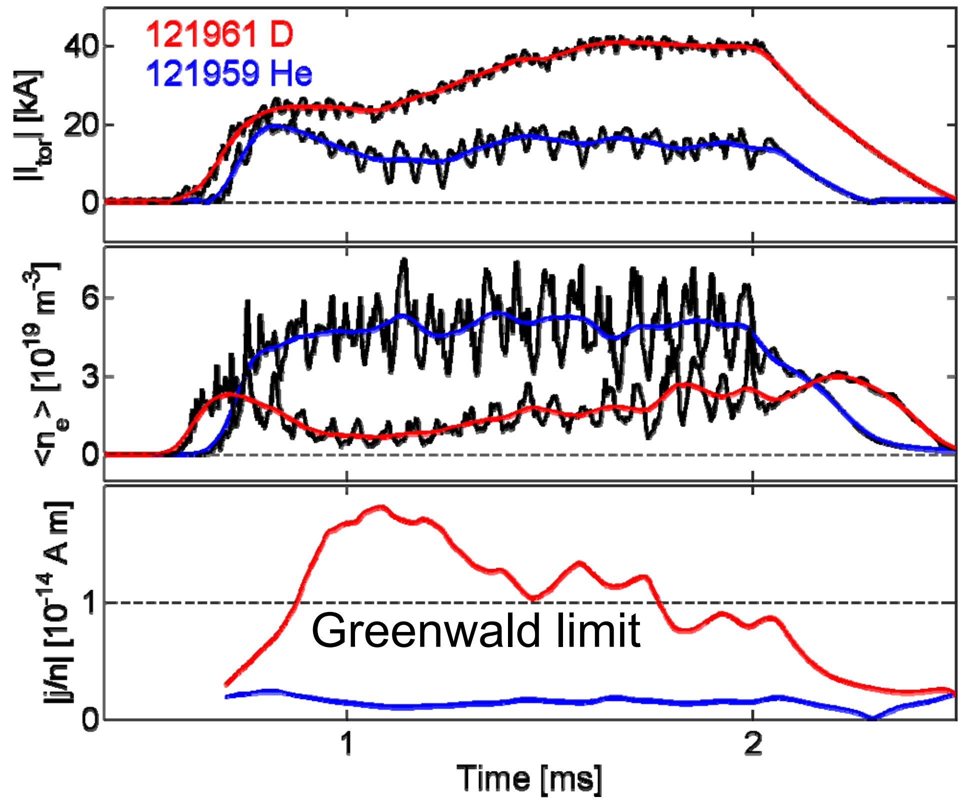
HIT-SI design features and parameters

Parameter	Range	D Values
R_0	0.33 m	0.33 m
axial length	0.57 m	0.57 m
f_{inj}	5.8, 15 kHz	~ 15 kHz (67 μs)
I_{inj}	≤ 30 kA	~ 15 kA
V_{inj}	200 – 600 V	~ 500 V
Ψ_{inj}	≤ 1.7 mWb	~ 1.2 mWb
P_{inj}	≤ 10 MW	~ 10 MW
n_e	1 – 5 x10^{19} m^{-3}	2 x 10^{19} m^{-3}
I_{tor}	≤ 58 kA	~ 50 kA

Helium operations are used to condition the walls for high-performance deuterium shots

- The plasma facing surface in HIT-SI is made of alumina
  - When the surface is clean the alumina pumps deuterium
- To condition the machine, several (~ 30) low power helium shots are taken
  - The magnitude of hydroxide and deuterium line radiation indicates the cleanliness of the machine

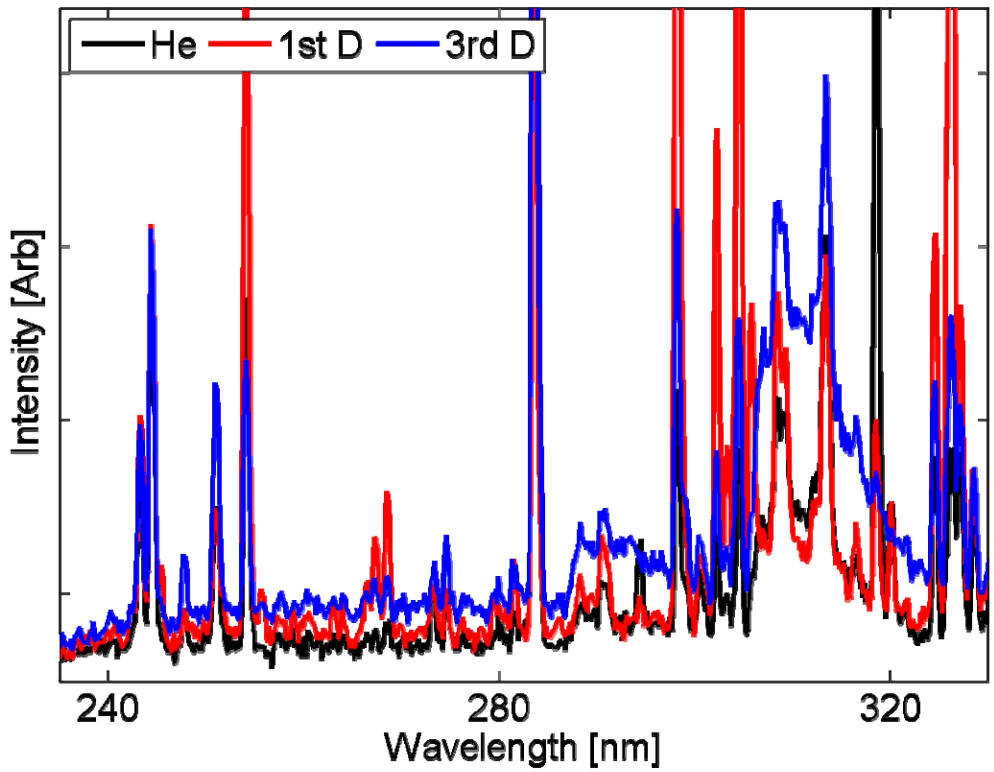
Improved toroidal current growth is a result of better density control



$$\frac{j}{n} \equiv \frac{\left|\overline{I_{tor}}\right|}{A\langle \overline{n}_e \rangle}$$

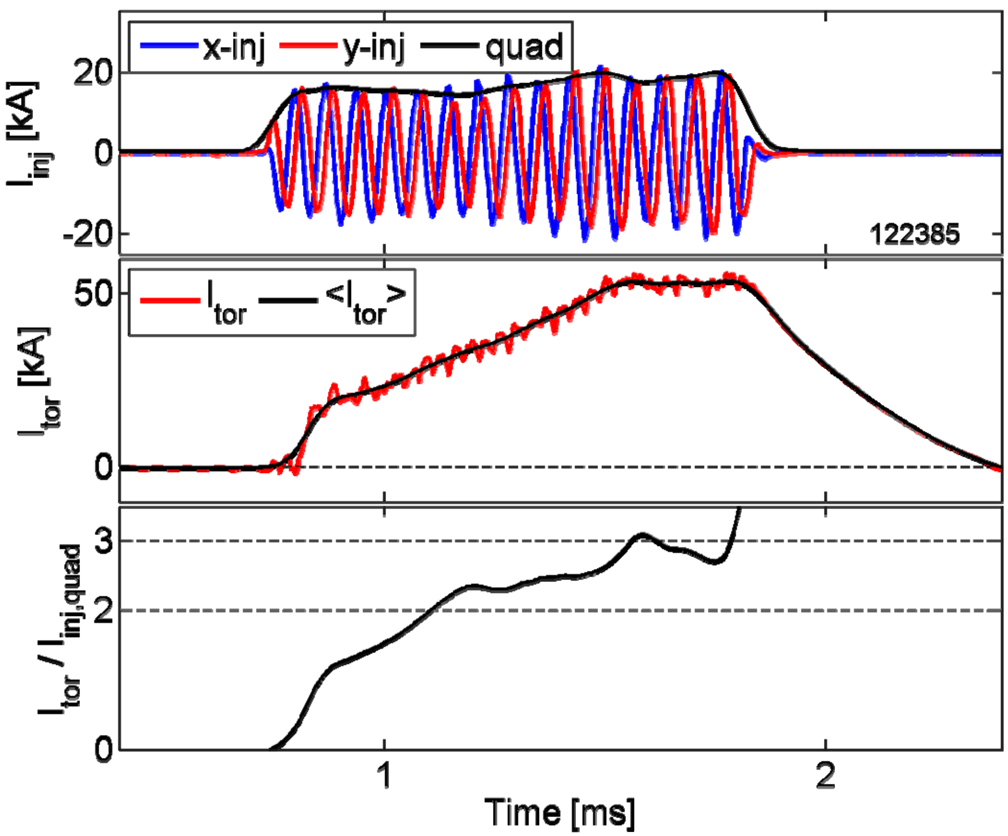
- **The key is to fuel the injectors without over fueling the confinement volume**
  - At too low of fueling rates the injectors become starved
  - Deuterium operations achieve lower density in the confinement volume with higher fueling rates

Hydroxide radiation increases with repeated deuterium shots



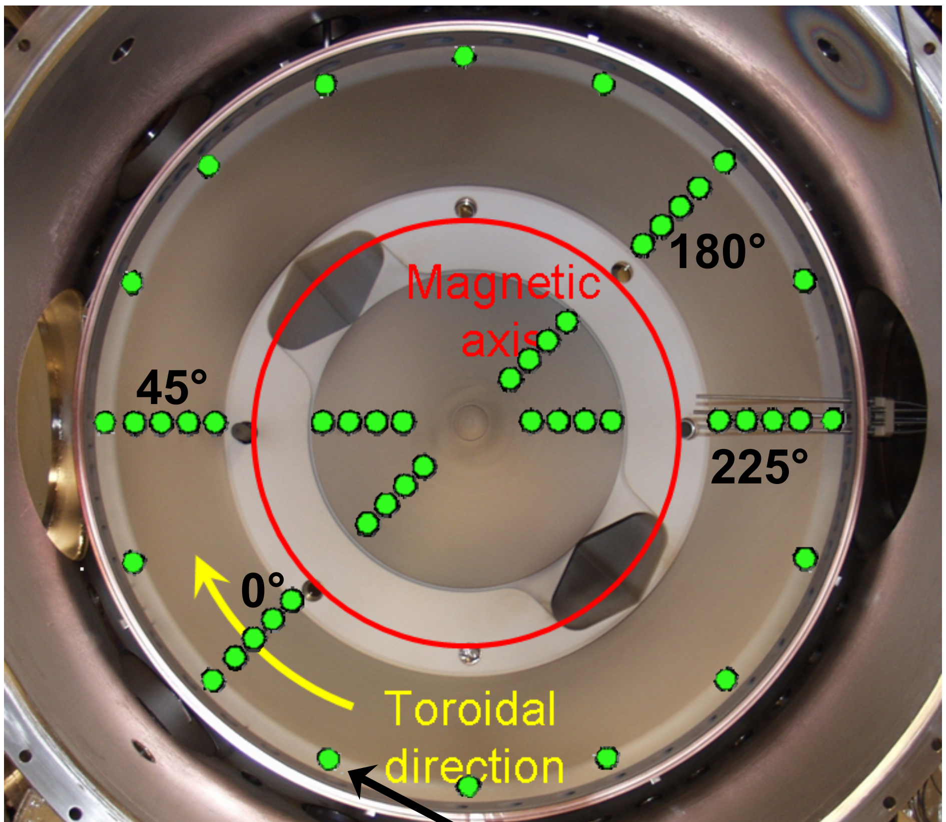
- A large, broadband increase in hydroxide radiation occurs after repeated deuterium shots with the buildup of deuterium in the walls

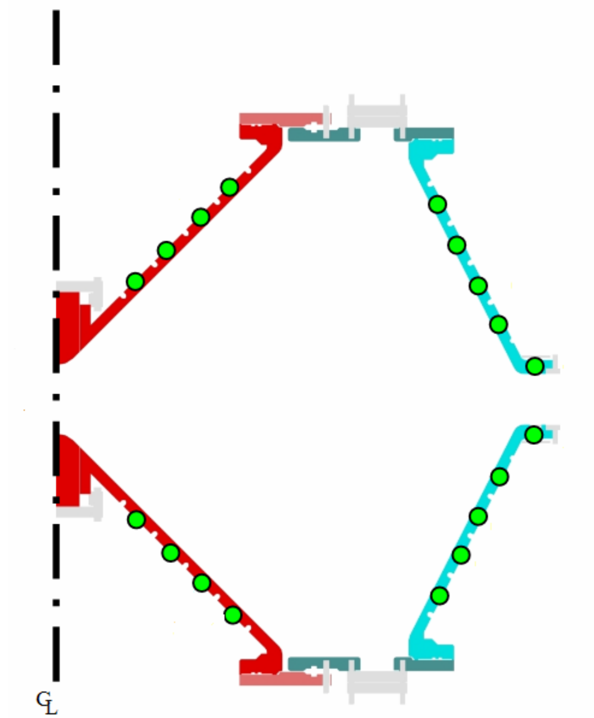
Current amplification of 3 is a spheromak record



- The injector currents are added in quadrature and smoothed over an injector cycle
- The toroidal current is smoothed over an injector cycle
- Shows a sustained current amplification greater than 2 with a peak value of 3
- Up to 0.65 ms toroidal current persistence

Surface probes are used to construct Amperian loops at 4 toroidal angles

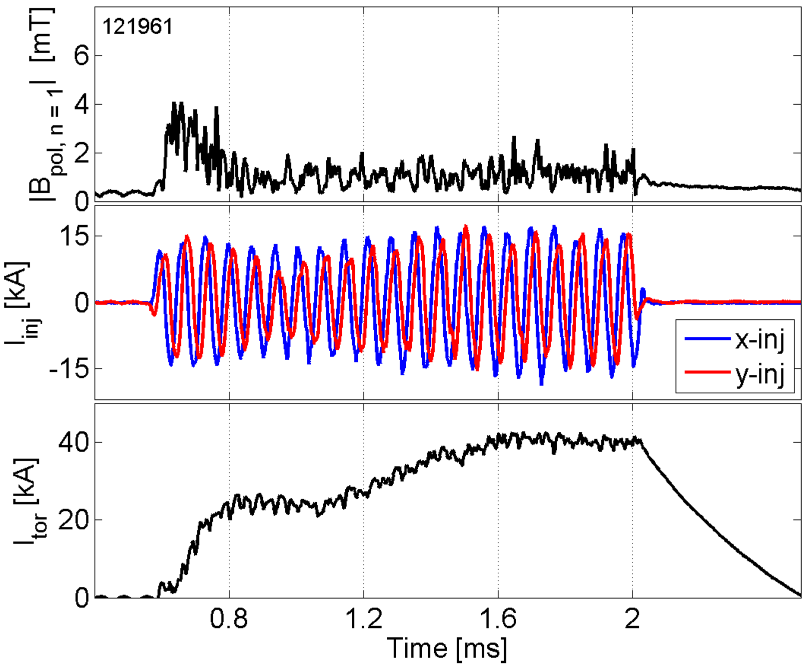


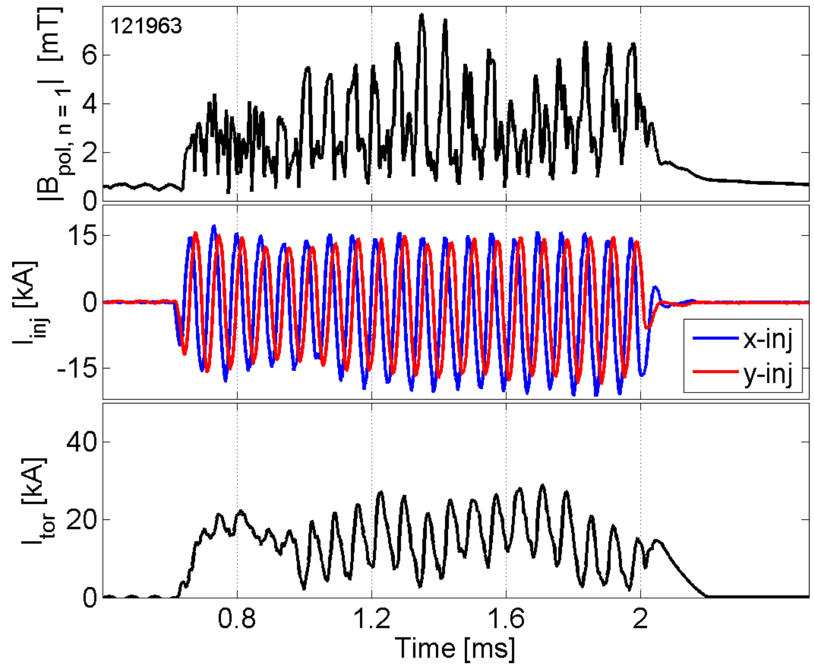


Poloidal cross section

Additional probes used for Fourier mode decomposition

n = 1 toroidal mode decreases at higher toroidal currents

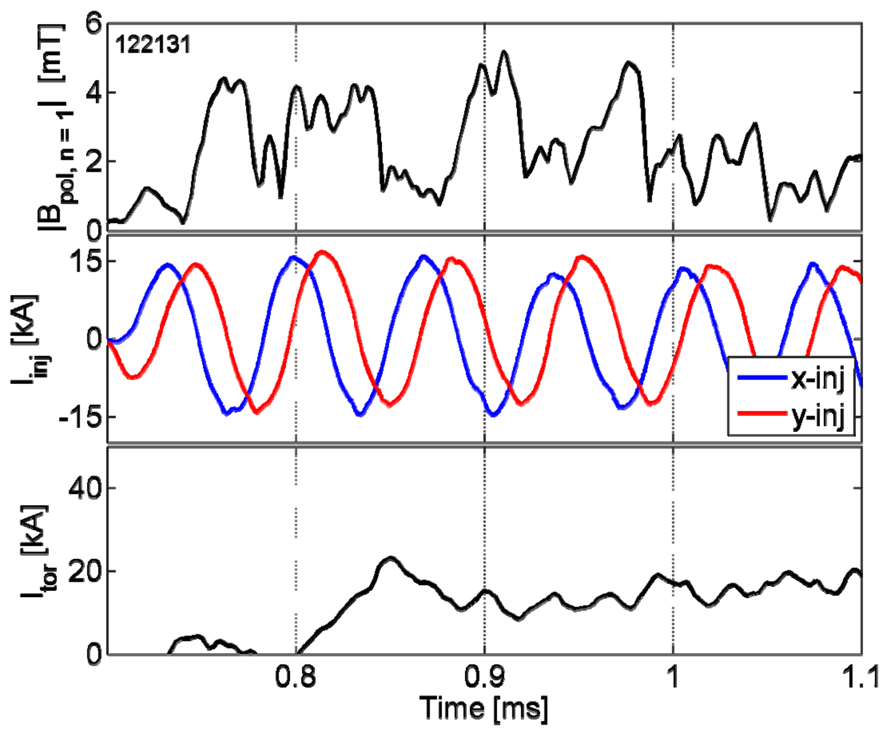




- Calculated using Fourier analysis of the poloidal magnetic fields measured by the surface probes

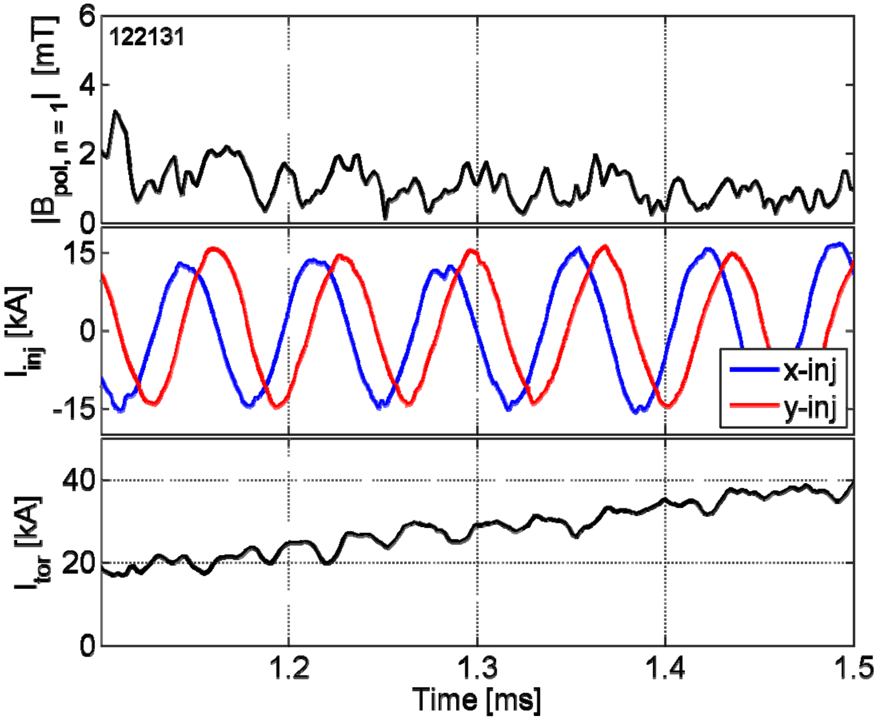
- Poor performing shot has significantly higher n = 1 activity despite similar injector currents

Initially the injectors couple to the n = 1 eigenstate of the confinement volume



- Increased n = 1 mode activity is measured before toroidal current is measured
- Note: the Fourier analysis of the surface probes cannot distinguish between the injectors and the n = 1 eigenstate

As the toroidal current grows the injector currents flow in the same toroidal direction as the n = 0 eigenstate

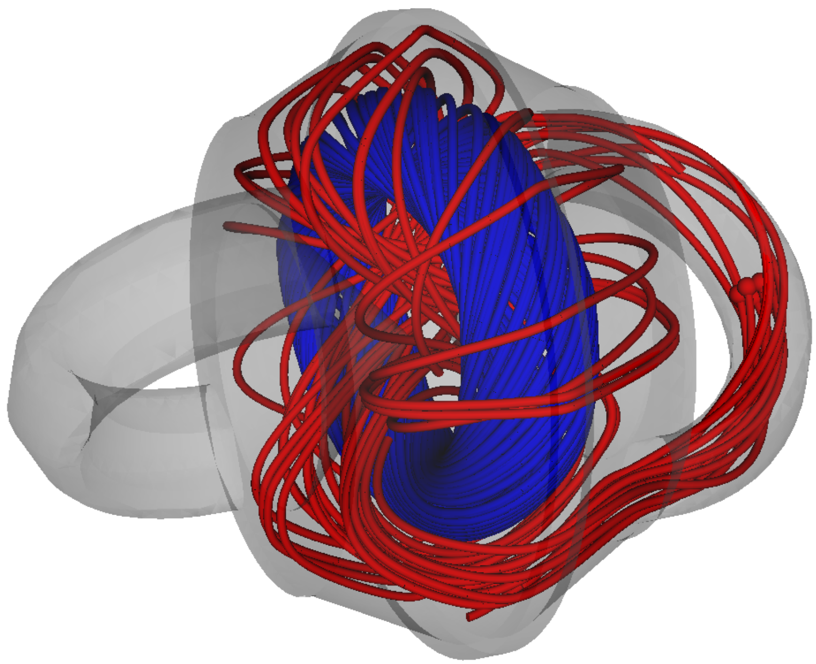


- The n = 0 eigenstate is the lowest energy eigenstate of the confinement volume
- Injectors begin to couple directly to the n = 0 eigenstate
- More quiescent current drive mechanism an indication of direct coupling between the injectors and n = 0 eigenstate

Injector n = 1 → n = 0 eigenstate

Taylor state reconstruction is compared to internally measured fields

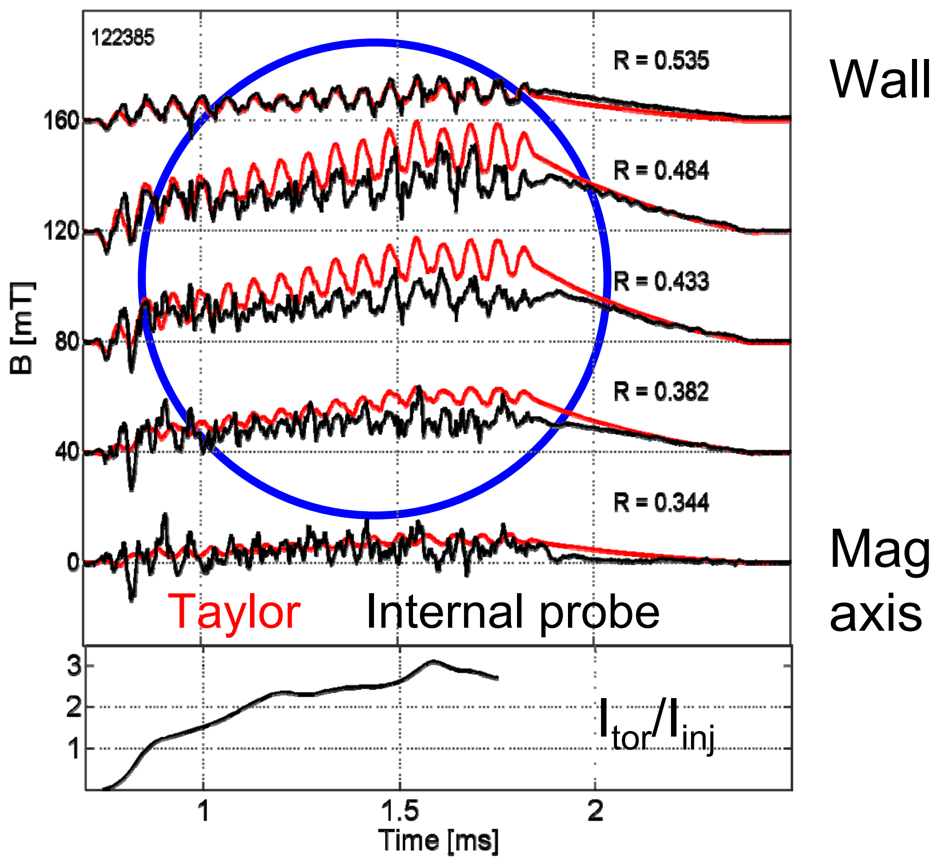
- DC field scaled by surface probe measurement of toroidal current
- Injector fields scaled by Rogowski measurement of injector currents
- Taylor state comparison gives information on differences between plasma conditions and zero pressure, constant lambda ($\lambda = 10.3\ m^{-1}$) equilibrium solution

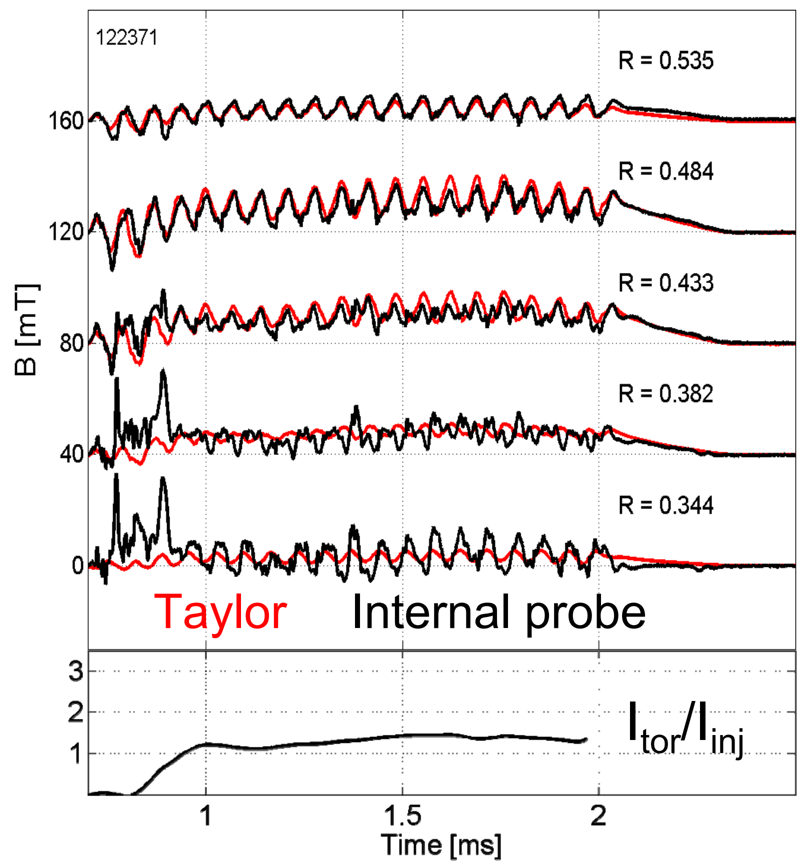


$$\nabla \times \vec{B} = \mu_0 \vec{j} = \lambda \vec{B}$$

Equilibrium model courtesy of C. Hansen

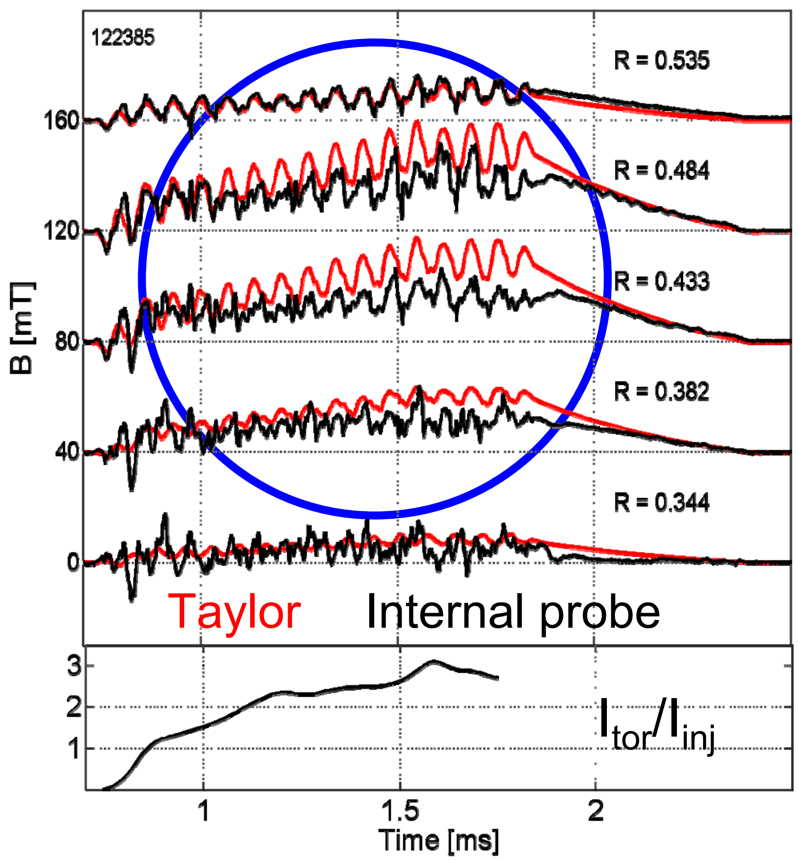
Internal poloidal field suppressed for high current ratio shots





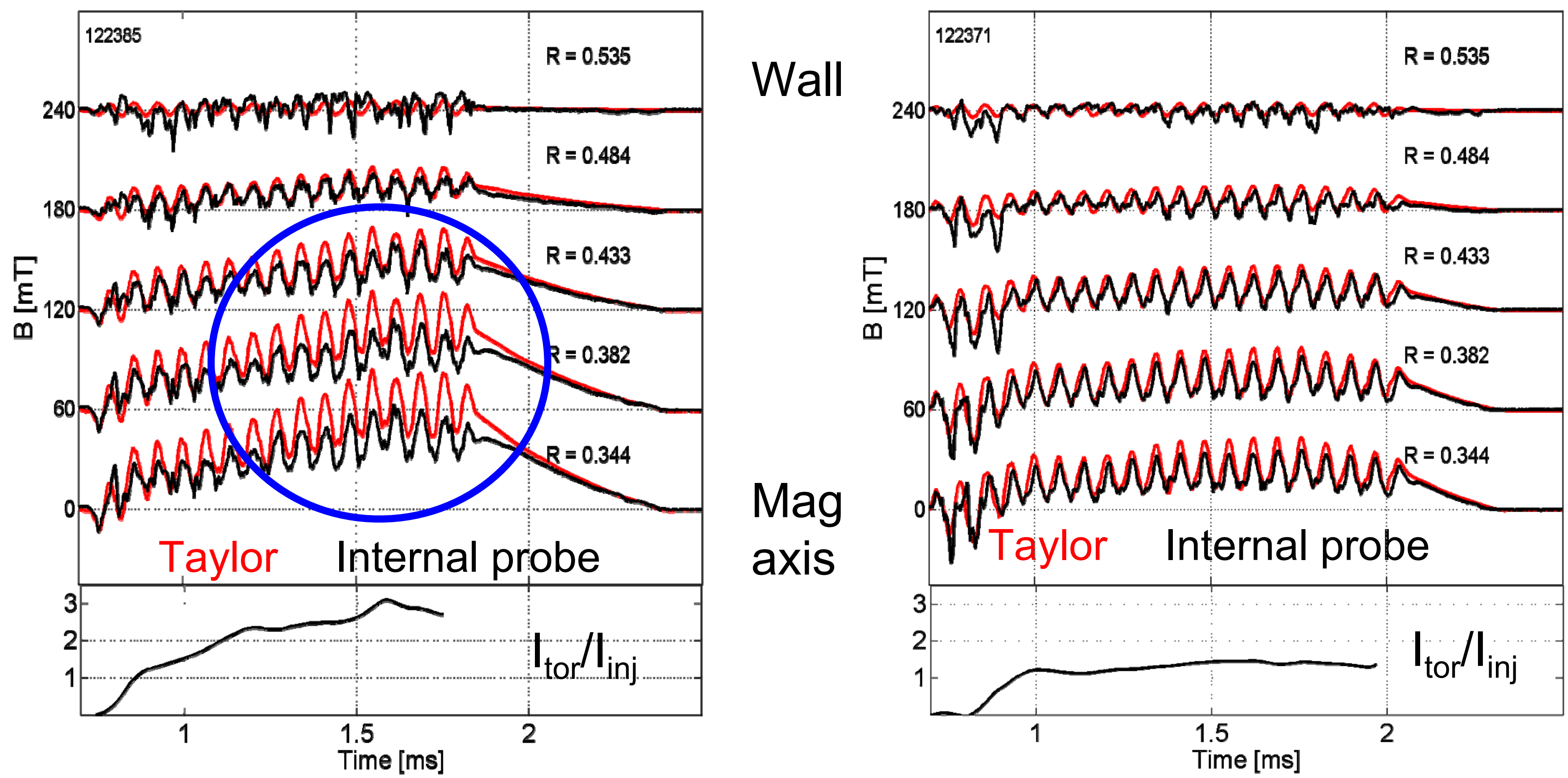
HIT - SI

Internal poloidal field suppressed for high current ratio shots

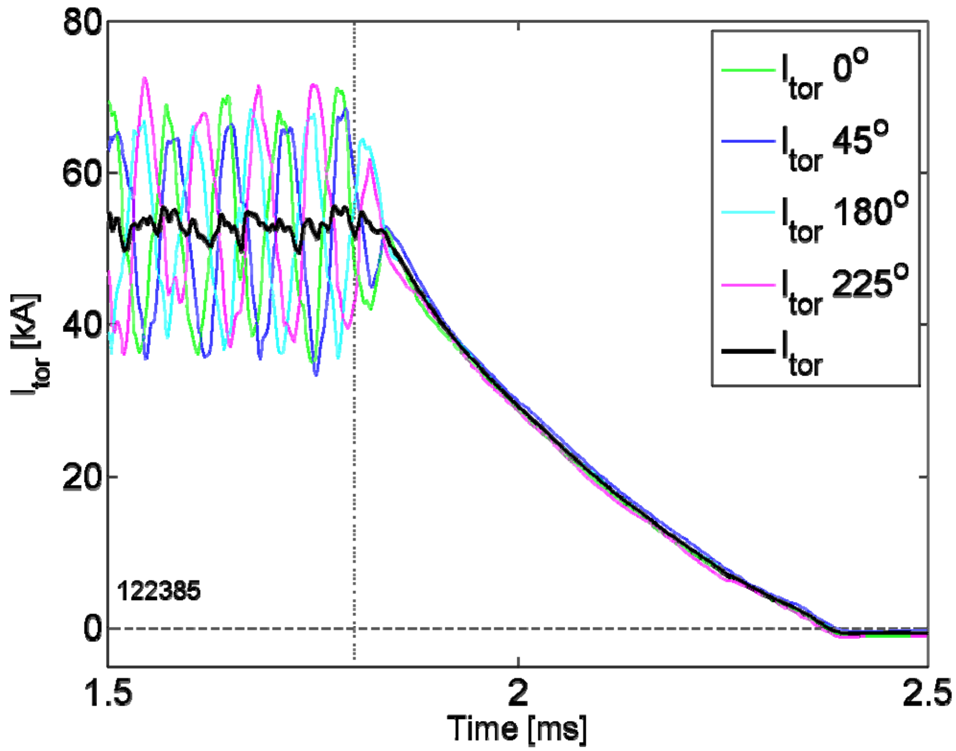


- Internal field near the wall consistent with the surface probes
- DC field away from the wall inconsistent with the Taylor state as predicted by surface probe measurements
- This diamagnetic effect is indicative of plasma pressure and a region of plasma separate from the injector flux

Internal toroidal field also suppressed for high current ratio shots

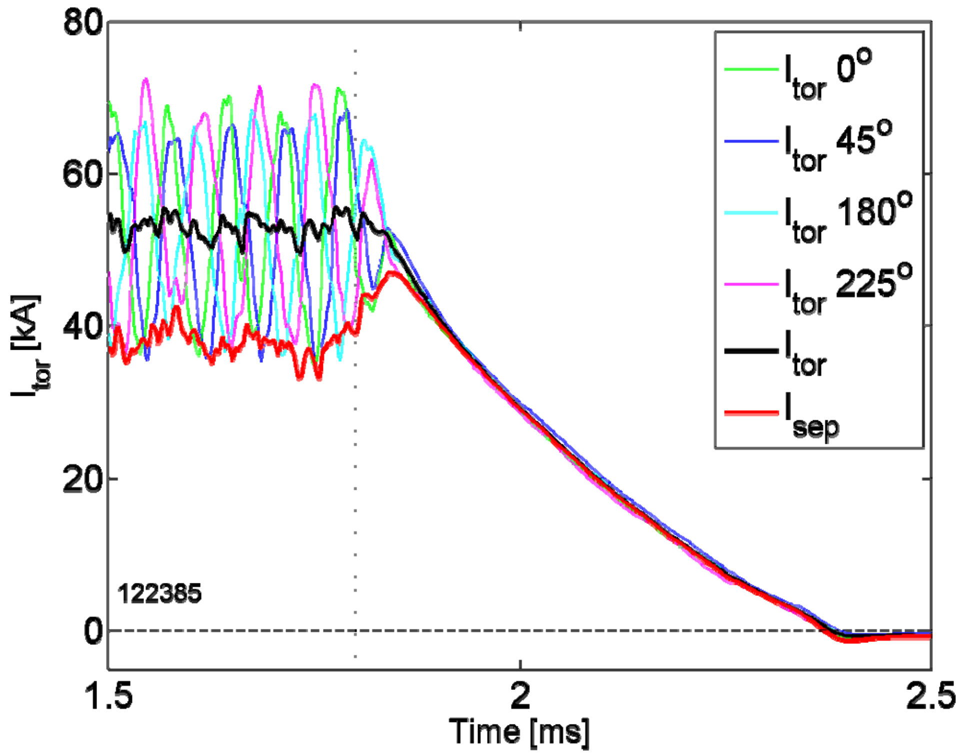


Minimum toroidal current near 40 kA seen at each toroidal angle



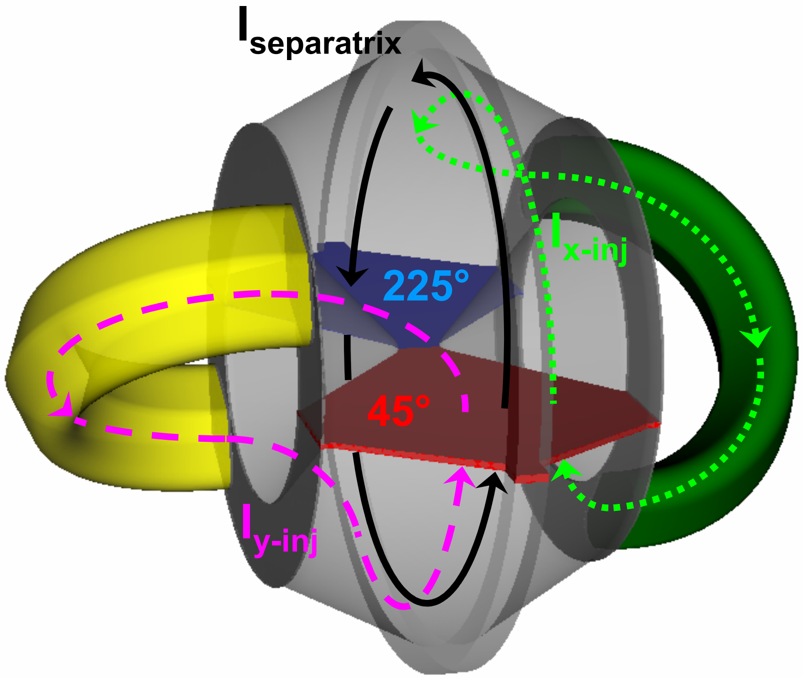
- Toroidal current is sustained through each Amperian loop for multiple injector cycles
- This is not an average current, but a minimum toroidal current in the confinement volume

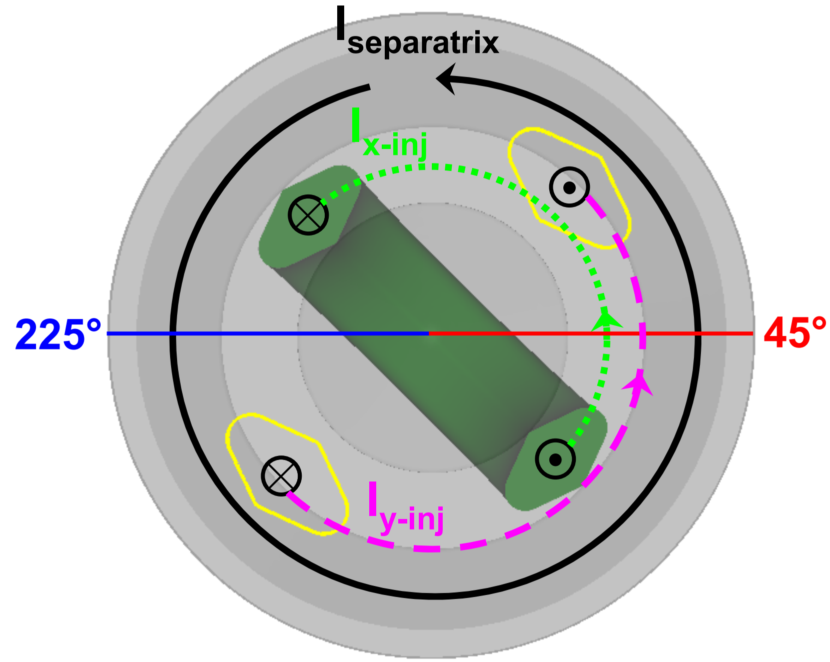
Minimum current bounds toroidal current not linking the injectors



- Separatrix current is current that does not link the injectors
- Up to 40 kA of separatrix current achieved during injector drive

Toroidal currents through Amperian loops are explained by a model with separatrix and injector currents





The key to the model is that the injector currents always flow in the direction of the separatrix current

Summary

- Large improvement in performance seen for deuterium operations
  - I_{tor} > 50 kA, I_{tor}/I_{inj} ~ 3, I_{tor} persistence ~ 0.65 ms
- Magnetic characteristics of high performance shots consistent with region of toroidal flux separate from injector flux
  - Change in mode activity at higher current ratios indicates more direct injector drive of toroidal current
  - Internal probe measurements indicate plasma pressure during injector drive
- Minimum toroidal current through each Amperian loop bounds separatrix current at 40 kA

Acknowledgements

Faculty and Staff

- Thomas Jarboe
- Brian Nelson
- David Ennis
- Roger Smith
- George Marklin
- Nathaniel Hicks
- Raymond Golingo
- John Rogers
- Jonathan Hayward
- Dzung Tran
- Dennis Peterson
- Luisa Pareja-Klemisch
- Susan Griffith

Graduate Students

- Cihan Akcay
- Chris Hansen
- Aaron Hossack
- Kyle Morgan

Undergraduates

- Briar Doty
- Matthew Kraske