Plasma-wall interaction on the SLiC spherical tokamak device with large-area, dynamic liquid lithium free surface

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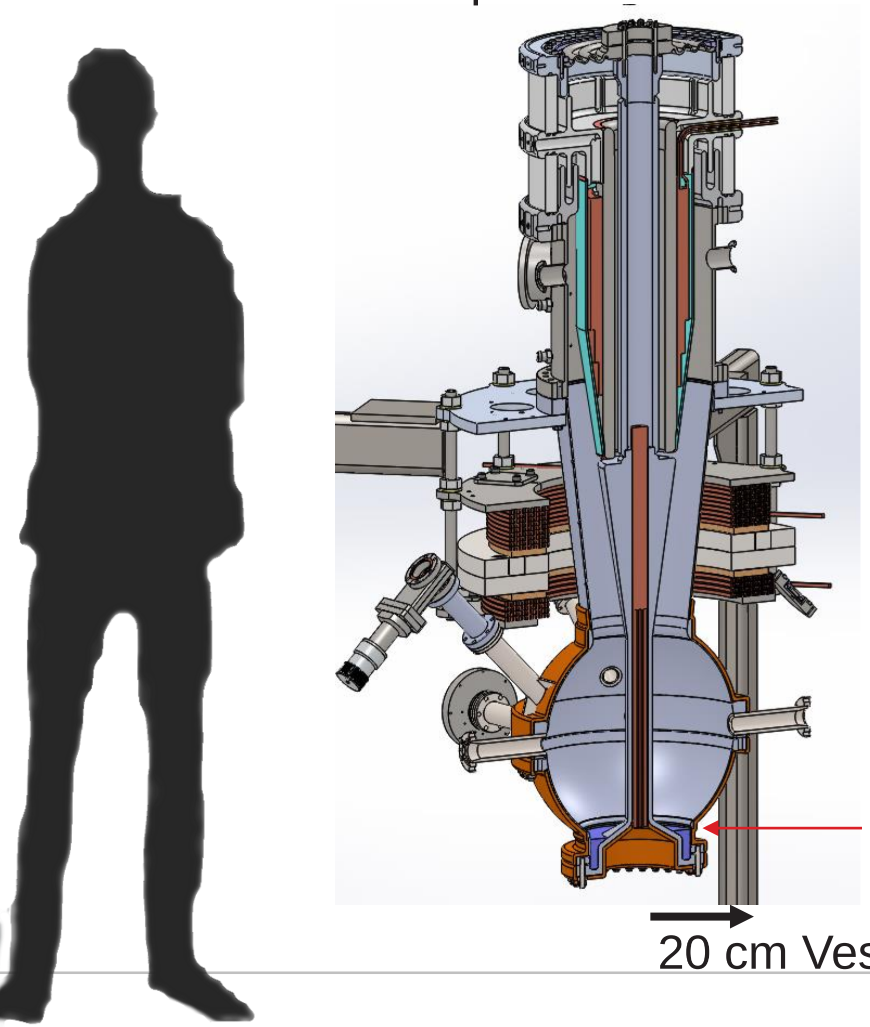
CHI onto Liquid Metal: De-Risking For MTF

SLiC (Spector Lithium Configuration)

Forms Spherical Tokamak plasmas onto Free Surface of Liquid Lithium



Lithium Puddle

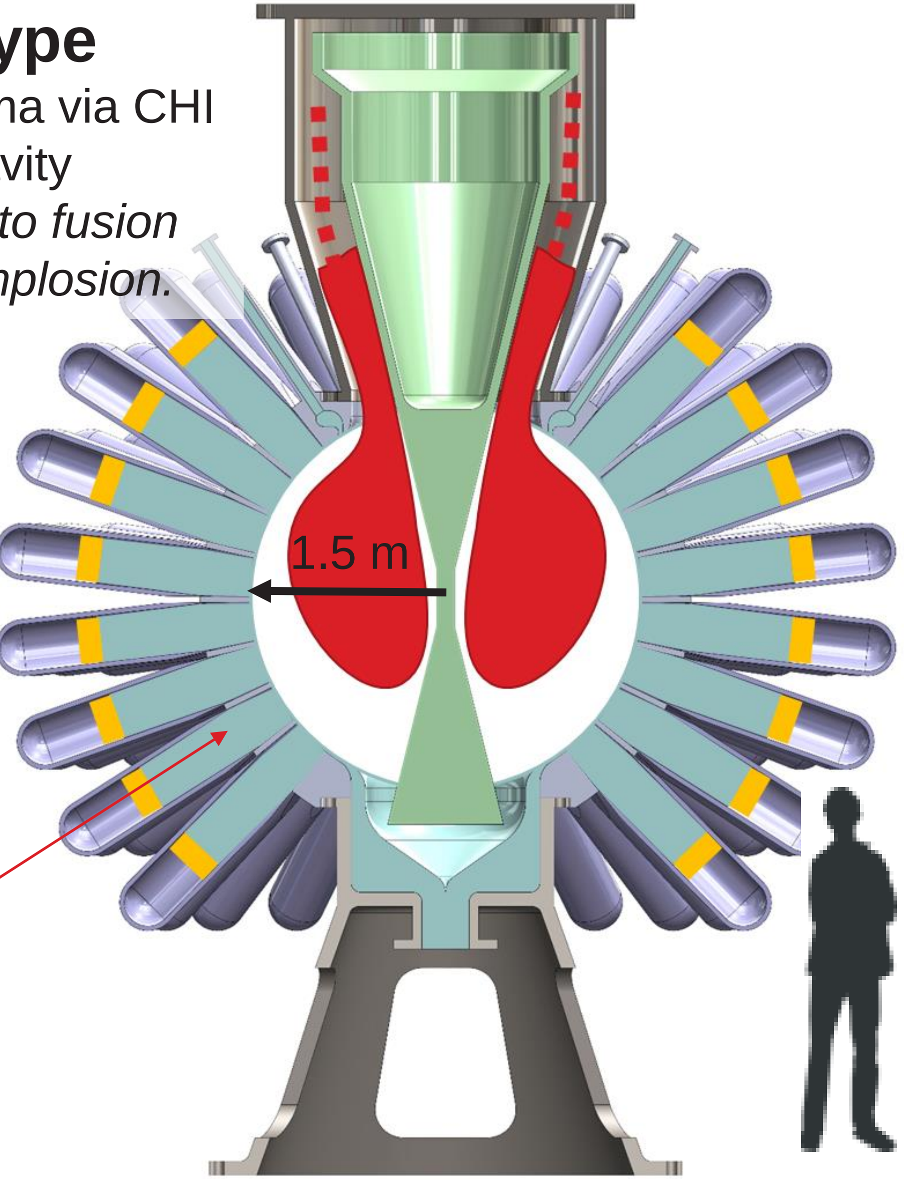
20 cm Vessel radius

MTF Integrated Prototype

Forms Spherical Tokamak plasma via CHI Into Liquid Lithium Spherical Cavity

And then compress the plasma to fusion conditions with Liquid Lithium implosion.

How does forming an ST on Liquid Li affect plasma performance?

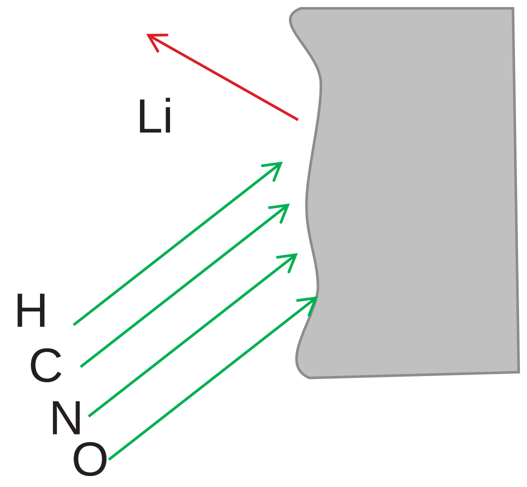


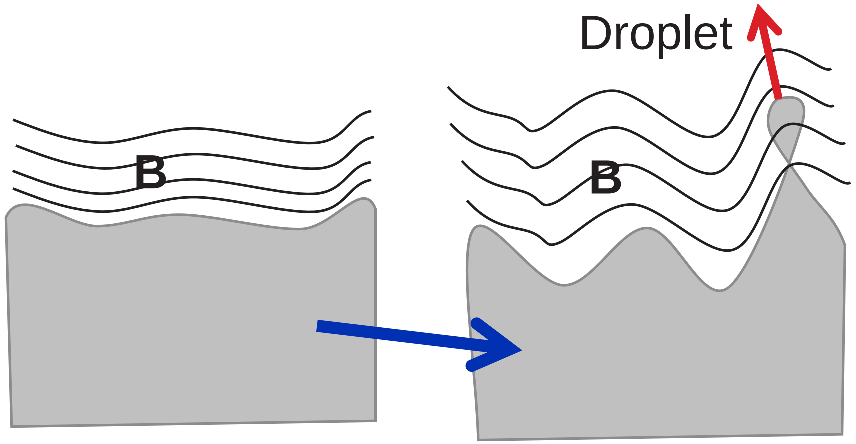
Lithium

Types of Plasma-Lithium interactions on SLiC

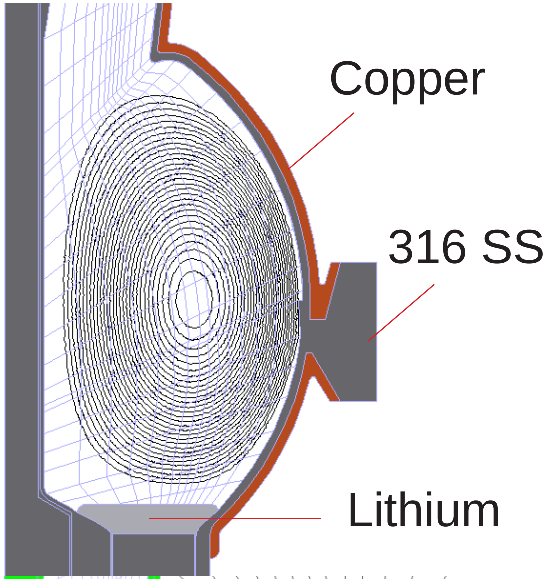
- Li absorbs incident particle flux, getters H, C, N, O.
- Li can evaporate and sputter, source of edge cooling.
- Magnetic forces will cause surface motion of liquid.

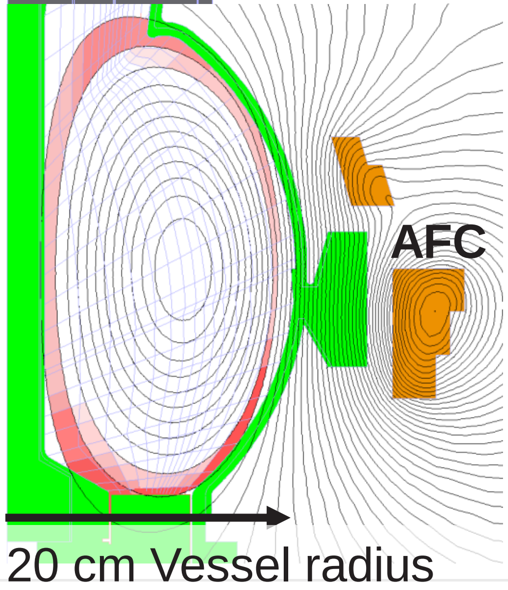
  - ➢ Surface ripples could feedback into plasma edge modes.
  - ➢ Ejected droplets could penetrate plasma edge and cool the core (if they reach it).
  - ➢ Droplets can land on diagnostic windows, requiring vessel openings to clean.





Operational Capabilities of the SLiC device





- Stainless steel inner shell with Copper outer layer as a passive flux conserver.
- Vessel heating allows temperature from 20 C (Solid Li) to 500 C (Hot Liquid).
- Maximum Lithium inventory 2.5 Liters (upgrading fill tank to 26 Liters).
  - Li puddle depth can range from 0 to 3cm.
- Range of compact ST plasma configurations possible ($0.5 < q_{min} < 2$).
  - Peak plasma current typically ~300 kA.
  - Total poloidal flux ~ 15-20 mWb.
  - Plasma density range ~ 5×10^{13} cm^{-3} to 2×10^{15} cm^{-3}
  - Peak $T_e \sim T_i \sim$ 75eV to 150 eV
- Comprehensive set of magnetic and optical diagnostics.

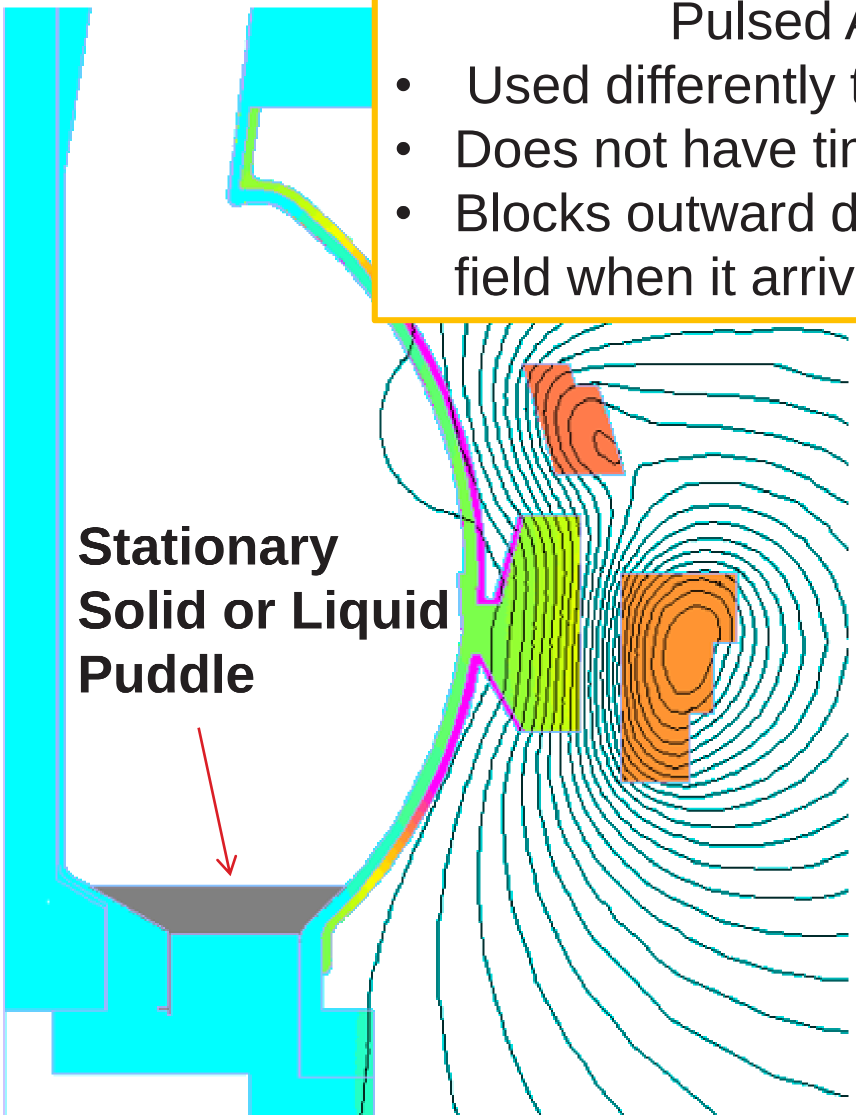
- Can push Li up the wall with MHD tsunami wave via 200kA Kicker circuit.
  - Transient coverage of lower hemisphere is almost stationary on plasma timescale of ~ 2 ms, but dynamic interaction does occur.

- Can control rate of outward soak of plasma B into wall with pulsed external coil (Active Flux Conserver coil, AFC). [See talk **JO09.6** today at 2pm CST]
  - Can increases plasma lifetime up to a factor 2.6x with AFC optimized.
  - Can control location of limiter point (outboard equator or puddle).

Possible initial states prior to CHI formation

Pulsed AFC field

- Used differently than tokamak PFC
- Does not have time to fill chamber
- Blocks outward diffusion of plasma field when it arrives



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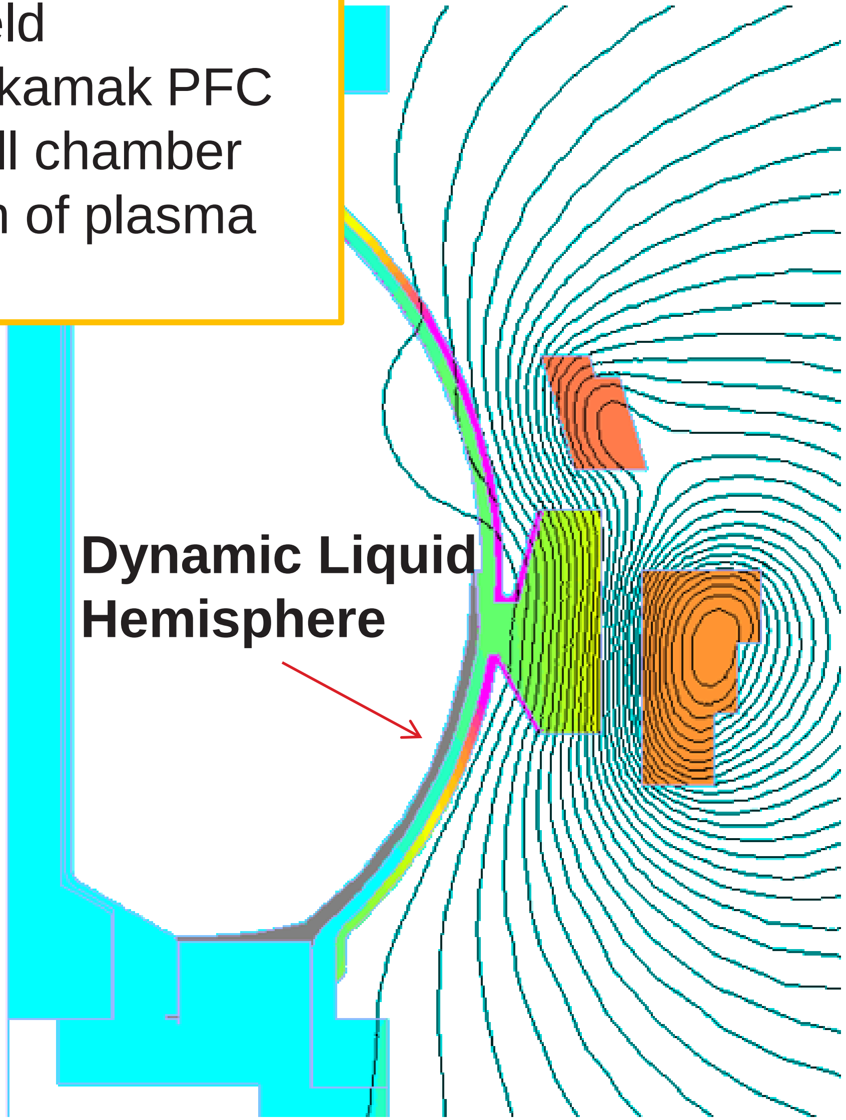
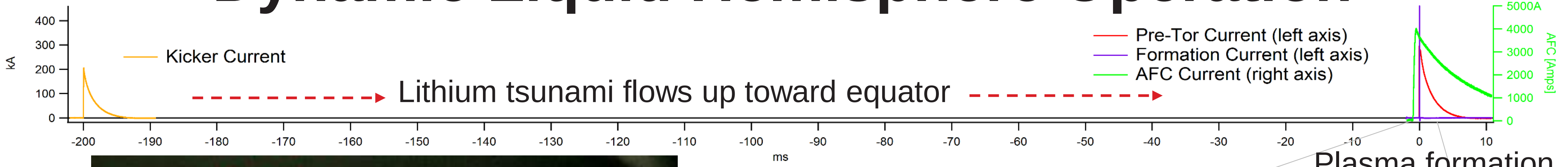
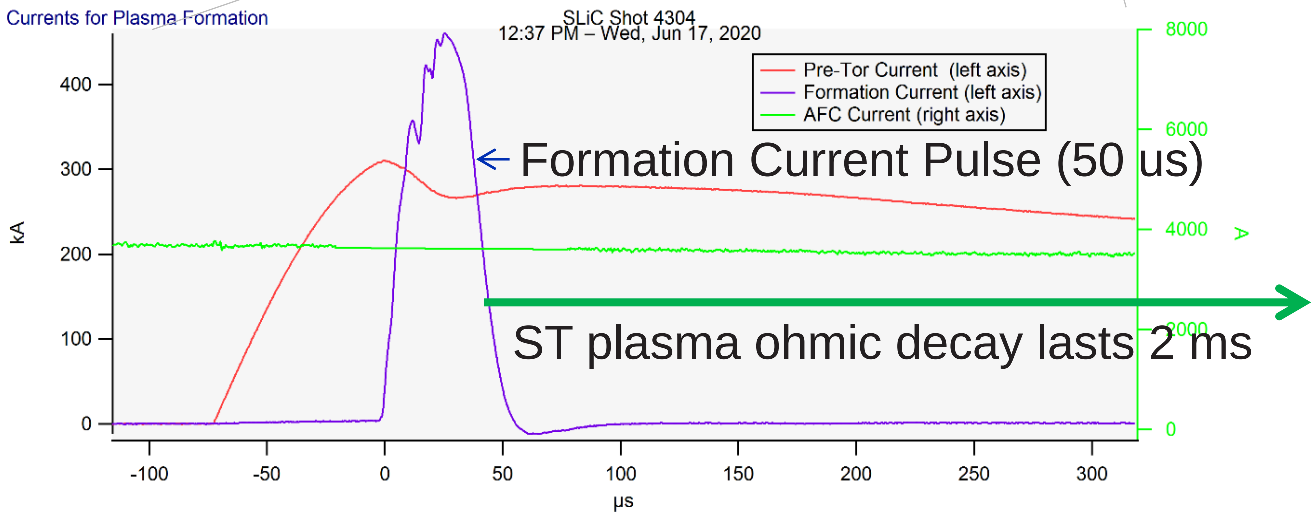


Dynamic Liquid Hemisphere Operation

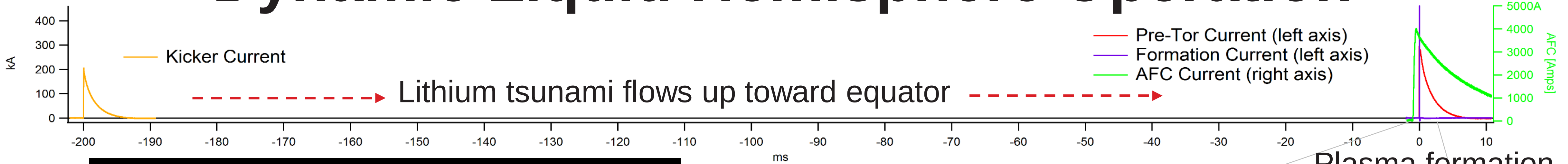


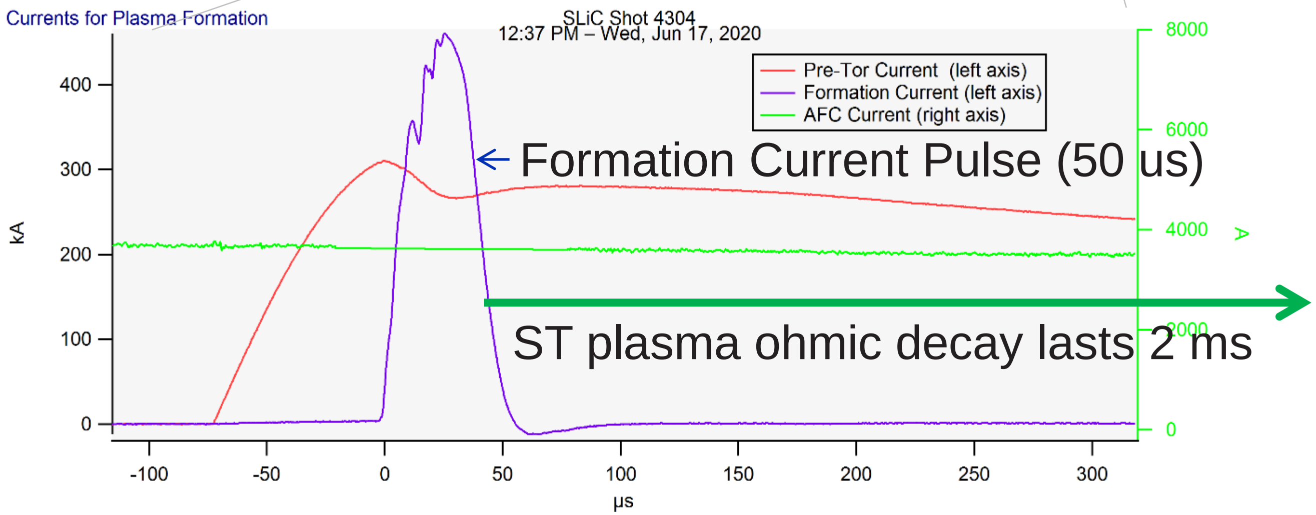
Plasma formation

zoom in



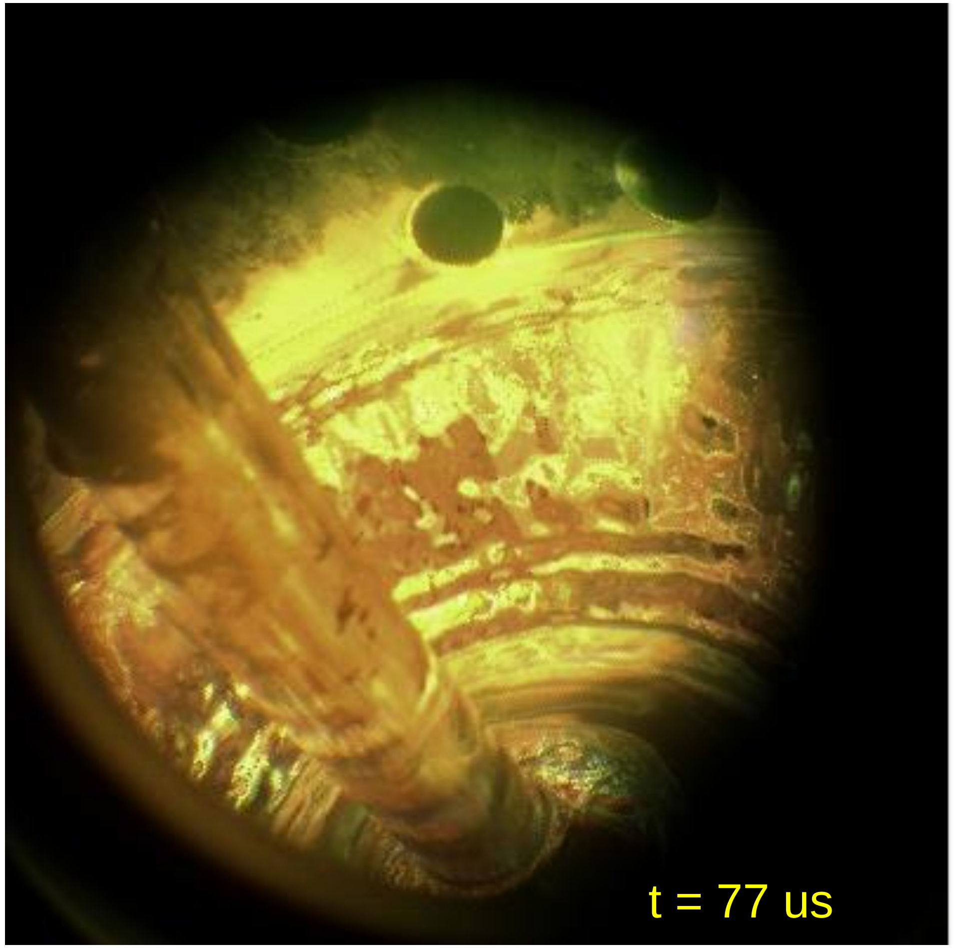
Dynamic Liquid Hemisphere Operation

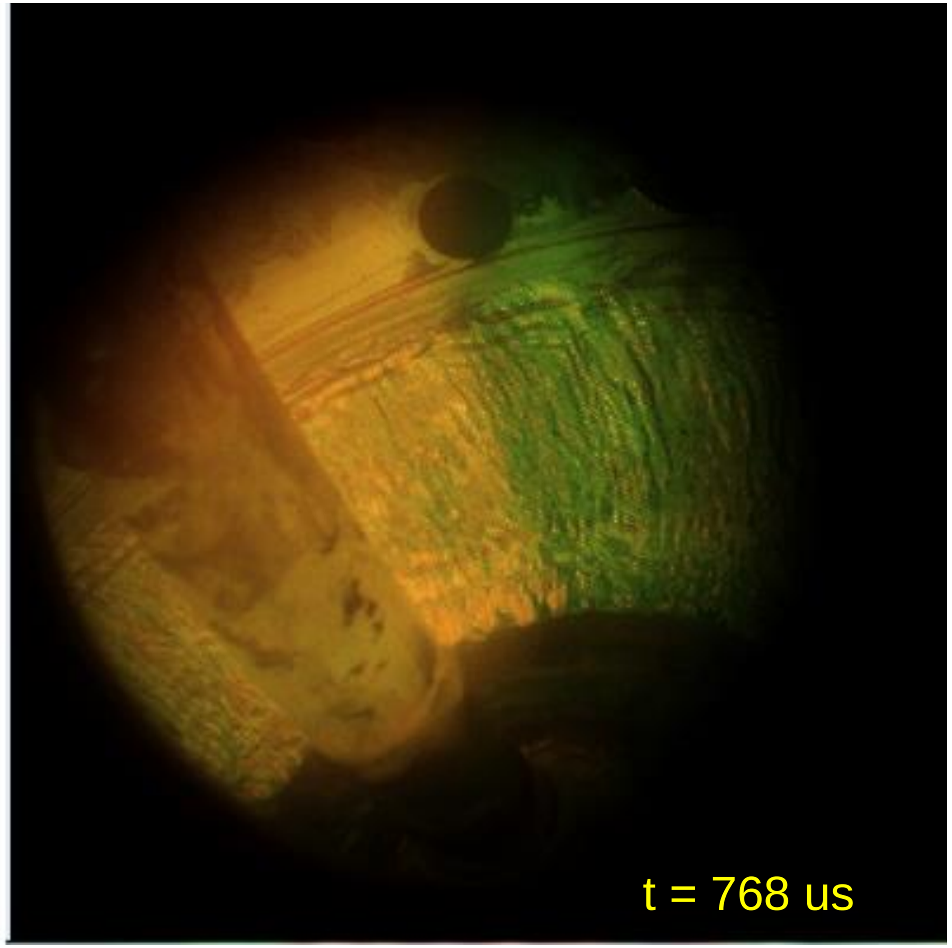




ST Plasma magnetic field perturbs free surface of Li

Short wavelength (~ 5 mm) ripples grow in amplitude during 1.5 ms plasma lifetime

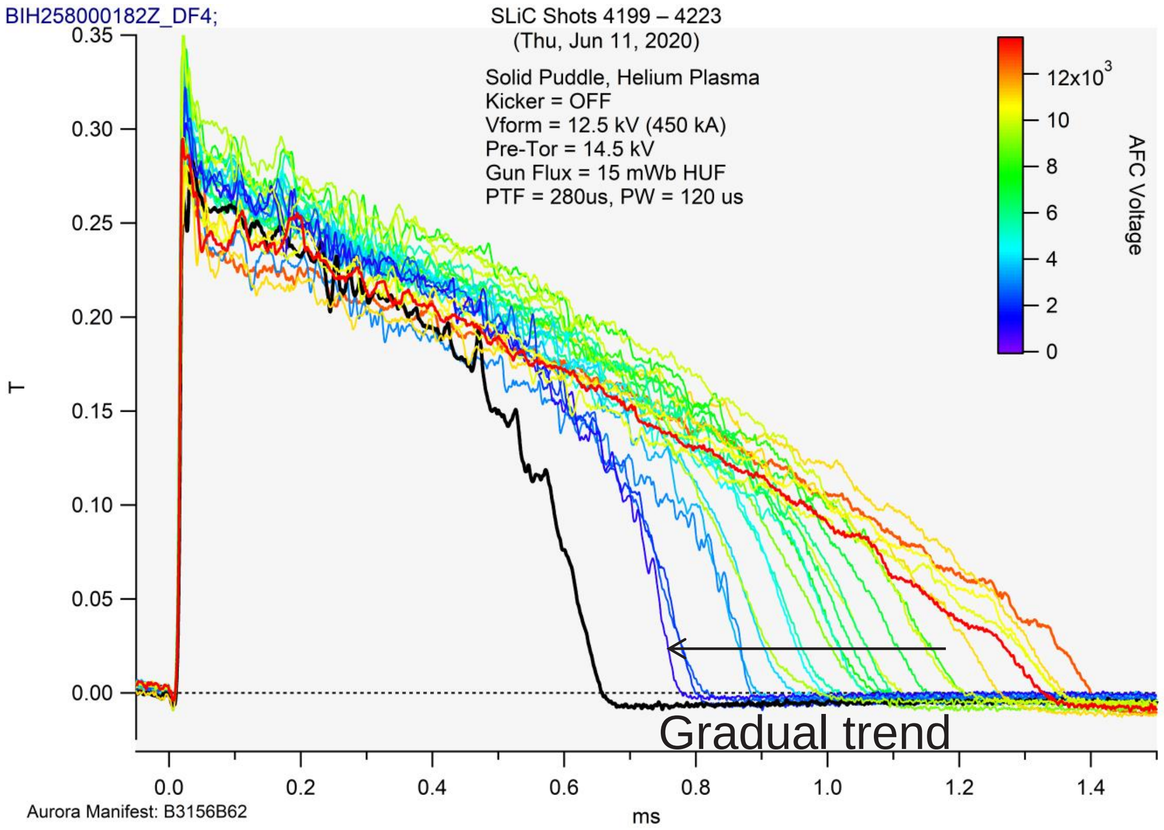


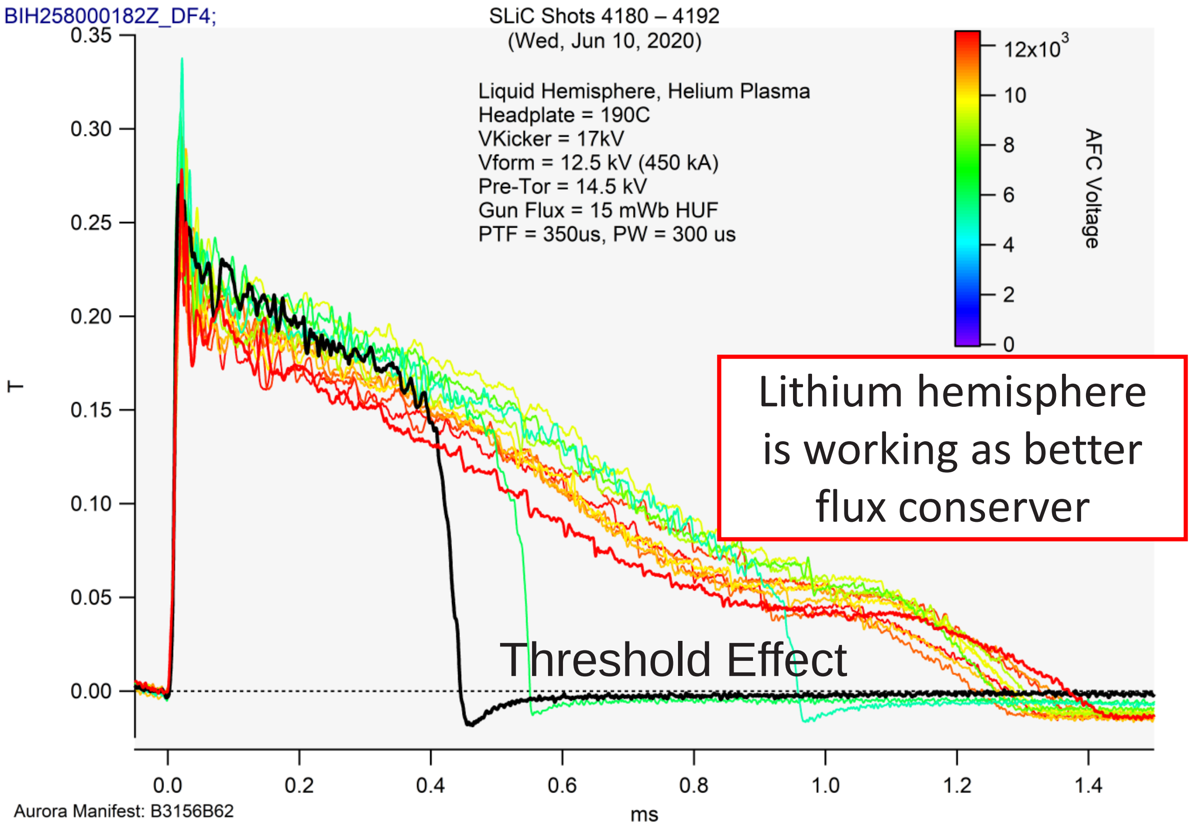


Wall interaction is modified by Liquid hemisphere

Liquid Li Hemisphere changed Poloidal field decay and allows less required AFC field

Solid Puddle Effect on **BPol** during AFC Scan **Liquid Hemisphere**



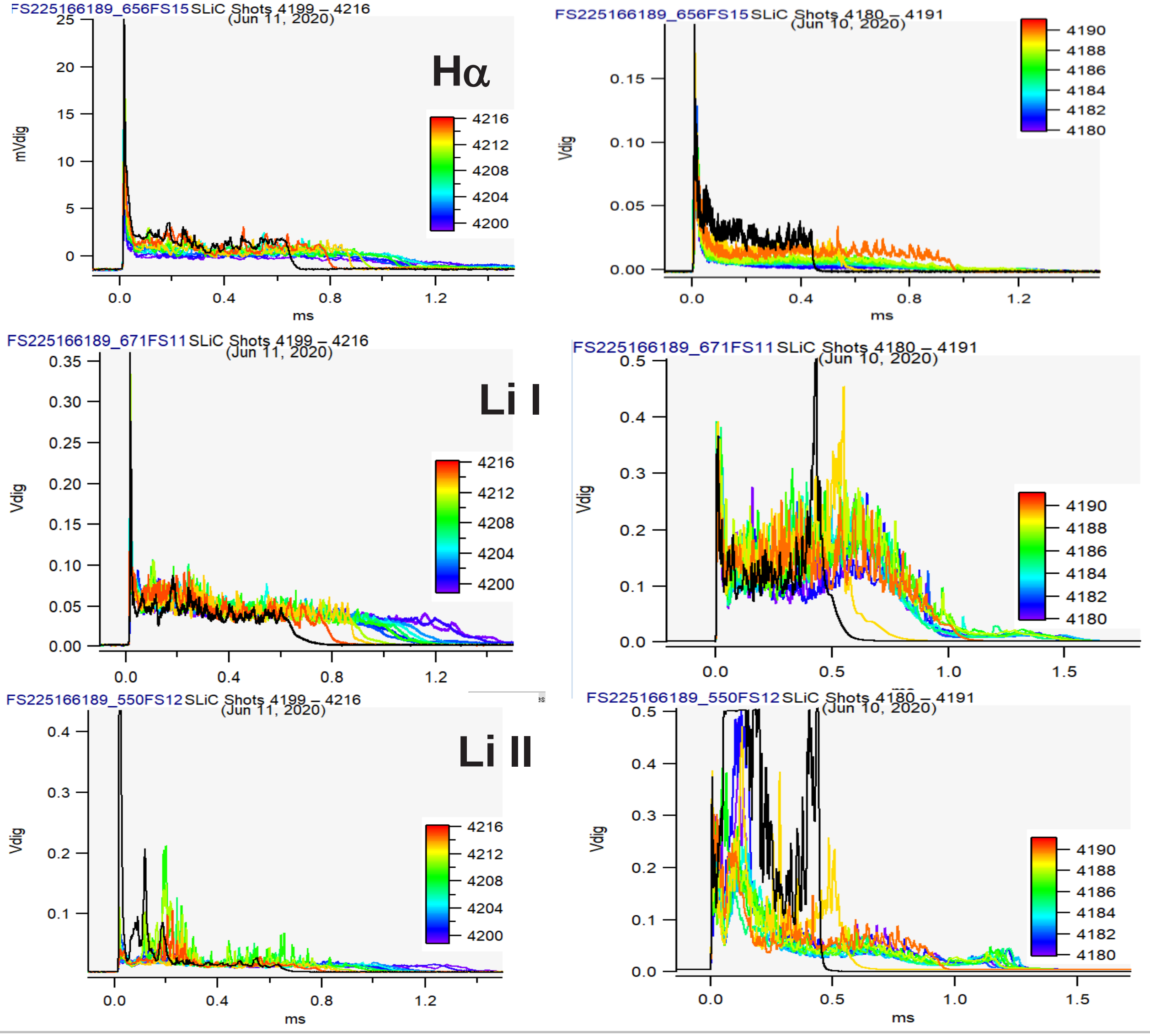


Lithium hemisphere is working as better flux conserver

Liquid hemisphere increases visible light emission

- Hα, He I (656nm), and Hβ (486nm) increase 10x
- Neutral Li (671nm) increases ~ 2 to 3x
- Singly ionized Li II (548 nm) increases ~ 3 to 10x
- Singly ionized O II (280nm) increases ~ 2 to 10x

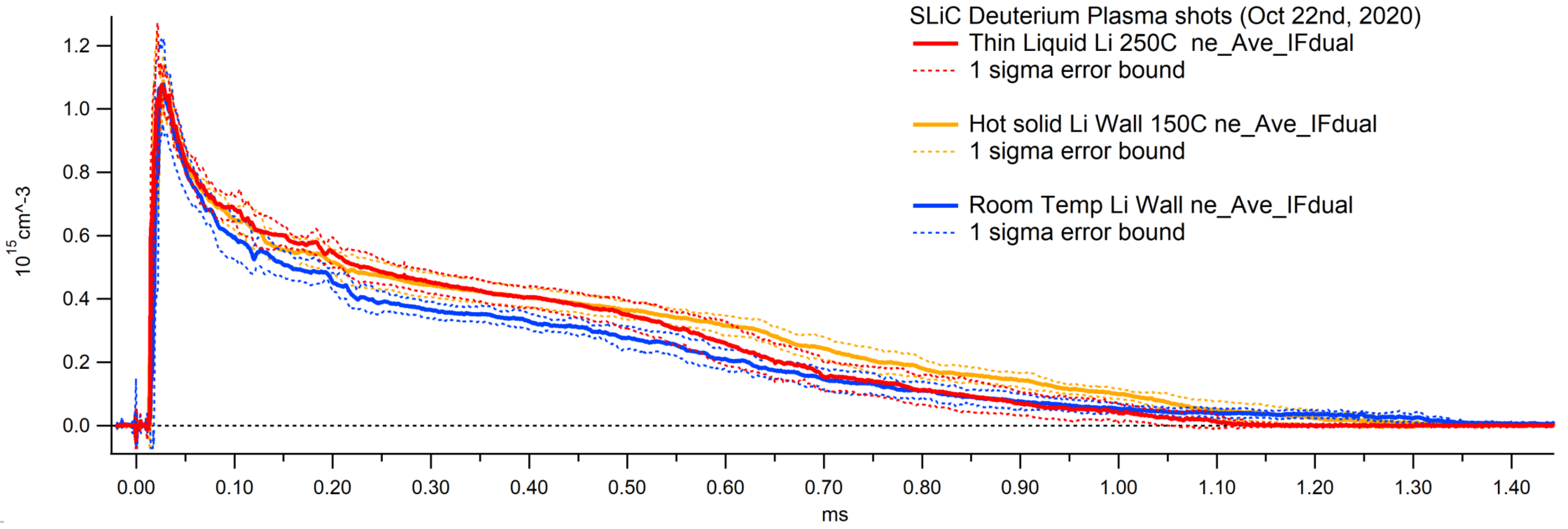
Solid Puddle **Liquid Hemisphere**



Vessel temperature scan with a Thin Li Layer

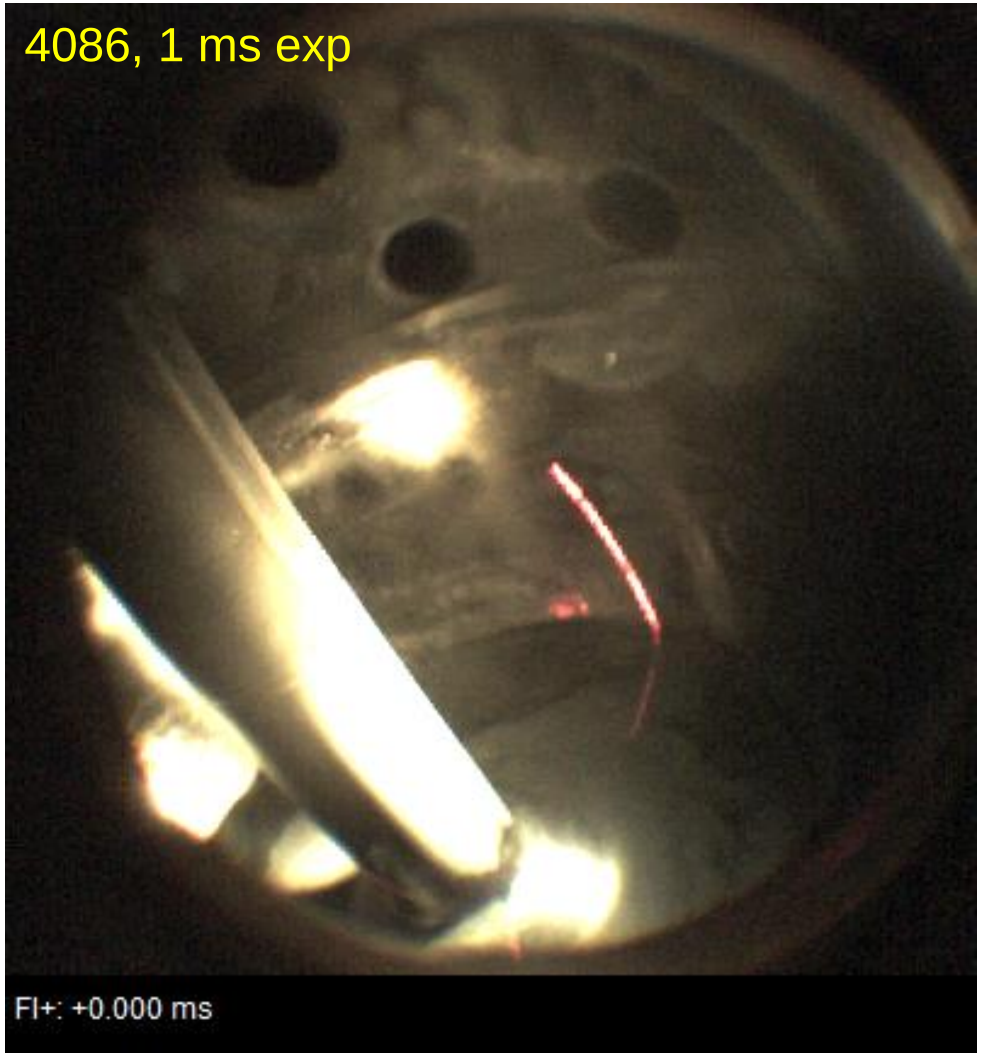
For a thin 1 mm layer of Li it was possible to scan the temperature from **30 , 150, 250 C** , but without the Kicker (less vibration on IF) to see if density was different when wall was hot or cold.

Density **did not** significantly change due to increase of wall temperature

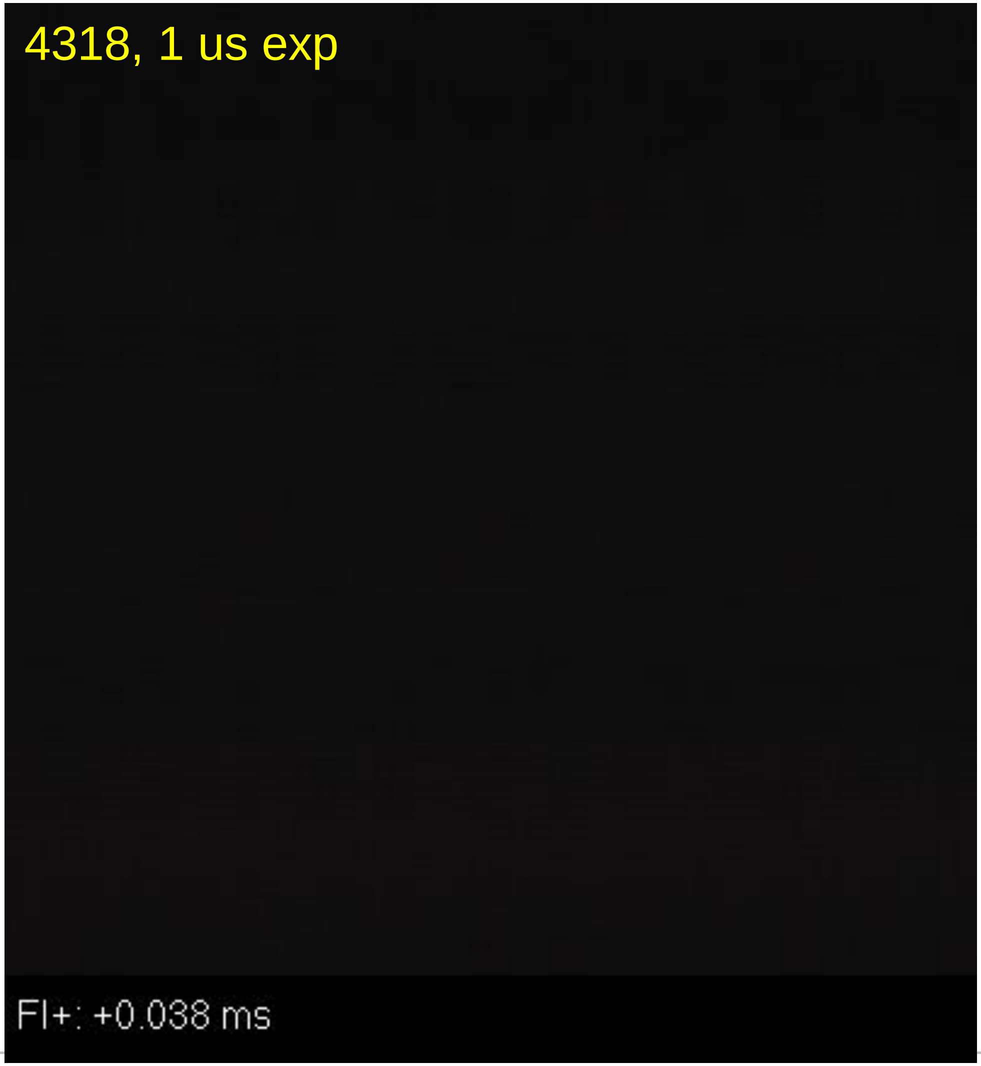


Droplets ⇨ Comets (green 548nm = Li II)

Kicker current launches surface droplets



Some droplets may still be aloft when plasma forms



Conclusions

- We are able to form a spherical tokamak plasma via fast-CHI onto a large area (dynamic hemisphere) of liquid Li without significant problems; we get similar plasma lifetime, density and temperature to previous ST experiments in the same geometry (Spector devices).
- Lithium in any form (thick, thin, hot, cold) has positive benefits for plasma lifetime (compared to bare stainless steel walls).
- Liquid Lithium increases edge brightness, especially when droplets enter the plasma.
- Plasma magnetic fields push on the Lithium and can set in motion droplet formation after the plasma is gone.
- Oxide layers and tungsten dust may cause early droplets, but this does not have a noticeable effect on plasma lifetime unless droplets enter the plasma.

General Fusion Talks and Posters

- Mon, 2-5pm: Paria Makaremi-Esfariani, Peter de Vietien
  CP19.21 ***Coupled CFD/MHD Simulations of Plasma Compression by Resistive Liquid Metal***
- Mon, 2-5pm: Aaron Froese, D. Brennan, S. Barsky, M. Reynolds, Z. Wang, M. Laberge
  CP19.22 ***Effects on Stable MHD Region of a Magnetized Target Plasma Compression***
- Tues, 9:30-12:30: Stephen Howard, A. Mossman, W. Zawalski, D. Froese
  GO13.8 ***Plasma-wall interaction on the SLiC spherical tokamak device with large-area, dynamic liquid lithium free surface***
- Tues, 2-5pm Meritt Reynolds
  JO09.6 ***Consequences of Flux Diffusion in a Liner Compression Fusion Reactor***
- Tues, 2-5pm: Cody Moynihan, S. Stemmley, A. de Castro, J. Zimmermann, D. Ruzic
  JP19.11 ***Design and Initial Results from the Dynamic Lithium Corrosion Test Bed***
- Wed, 2-5pm: Ivan Khalzov, Ryan Zindler, Michel Laberge
  PP12.15 ***2D Lagrangian Code for Resistive Evolution of Plasma Equilibrium and Its application to MTF Studies at General Fusion***
- Fri, 9:30-12:30: Kelly Epp, B. Rablah, S. Howard, M. Laberge, M. Reynolds, R. Ivanov, P. Carle, W. Young, A. Froese, C. Gutjahr, K. Bell, S. Bolanos, A. Rohollahi, R. Corfu, A. Wong, C. Eyrich, S. Barsky, C. Ribeiro
  ZP07.11 ***Confinement Physics on Plasma Injector 3***

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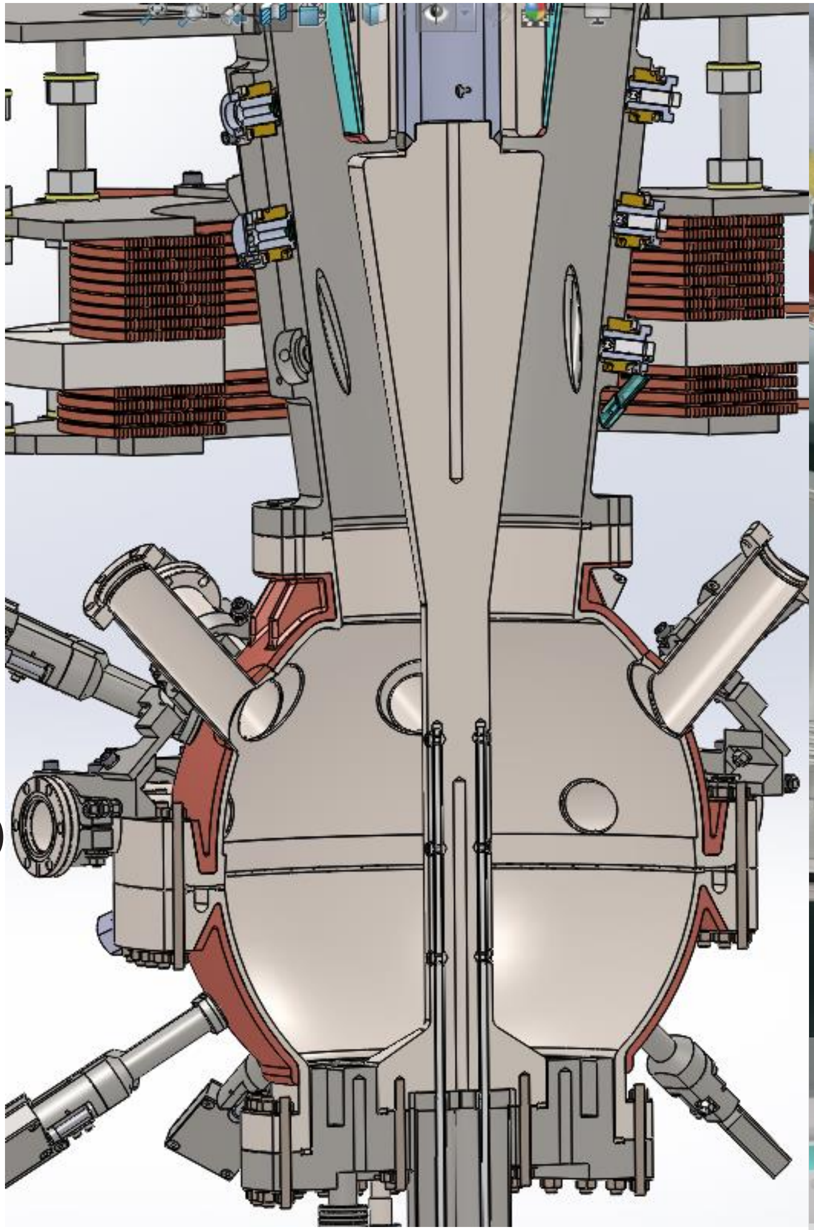
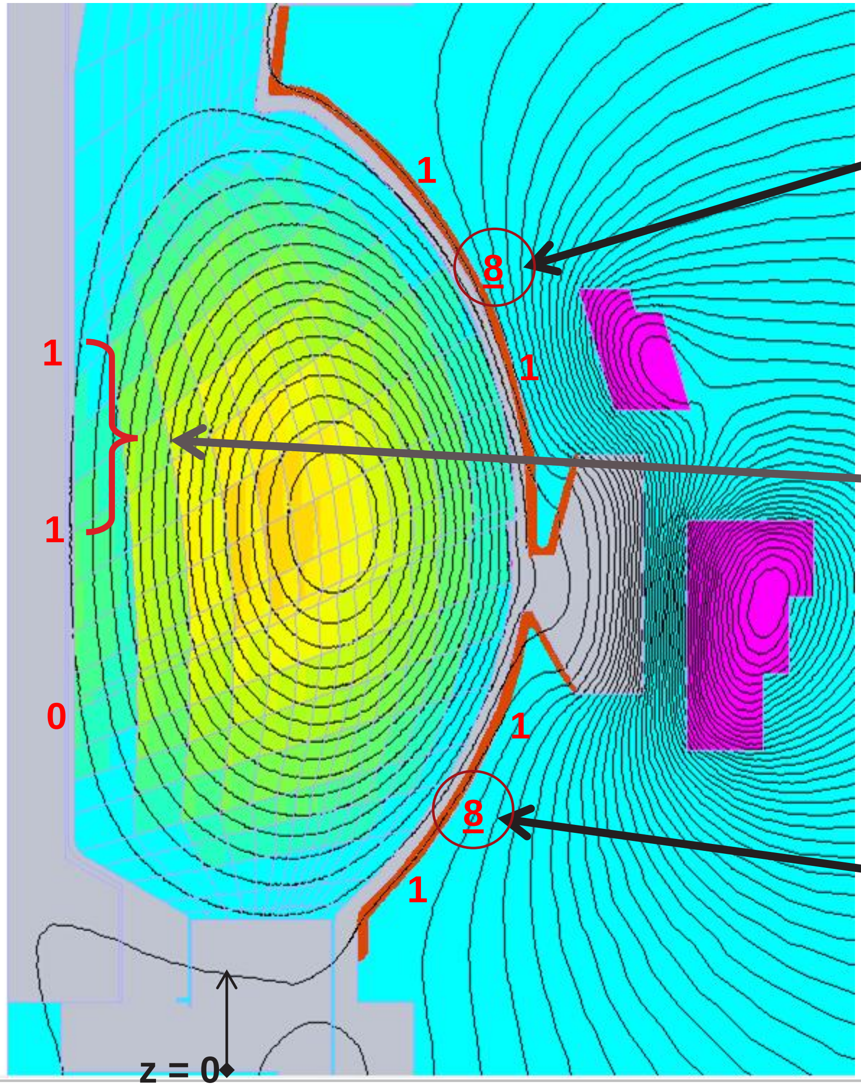
SLiC Design

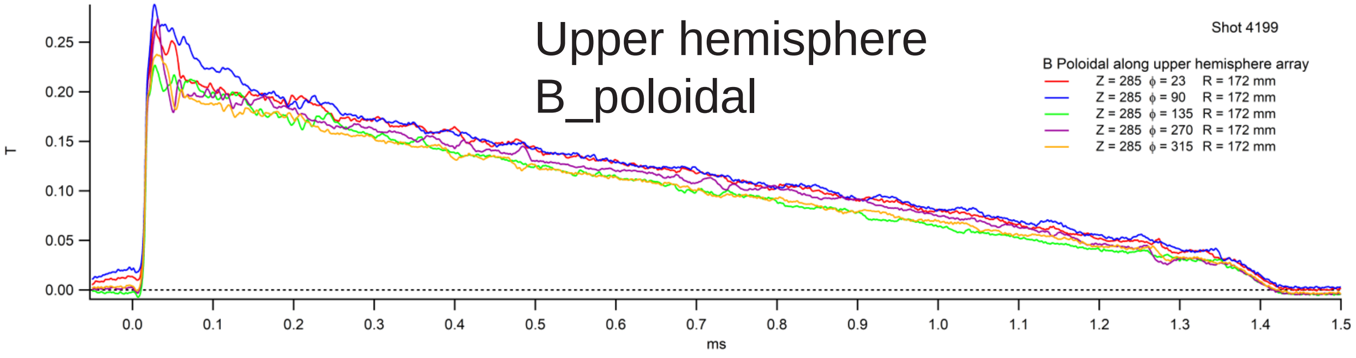
- Composite flux conserver vacuum vessel composed of 316 stainless with outer Cu spray coat (4.5 mm) and then a thin Al spray overcoat to protect Cu from oxidizing.
- 8 independent heater circuits for controlling temperature gradients
- Max temp of 500 C for lower section, 200 C max for formation electrode (with internal coil).
- Pulsed power cap banks (18 kV)
  - ➢ Formation: 1.32 mF (213 kJ)
  - ➢ Toroidal Field:1.35 mF (219 kJ)
  - ➢ Kicker Circuit: 636 uF (103 kJ)
- Diagnostic ports on upper section need protection from Li tsunami wave/droplets
  - ➢ Control MHD drive to prevent
  - ➢ Flow deflection features on surface (ski jumps)

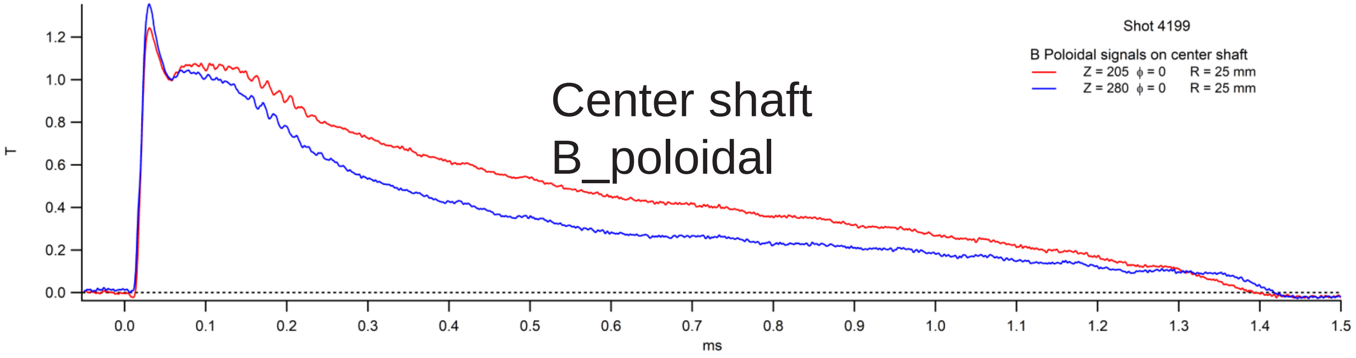


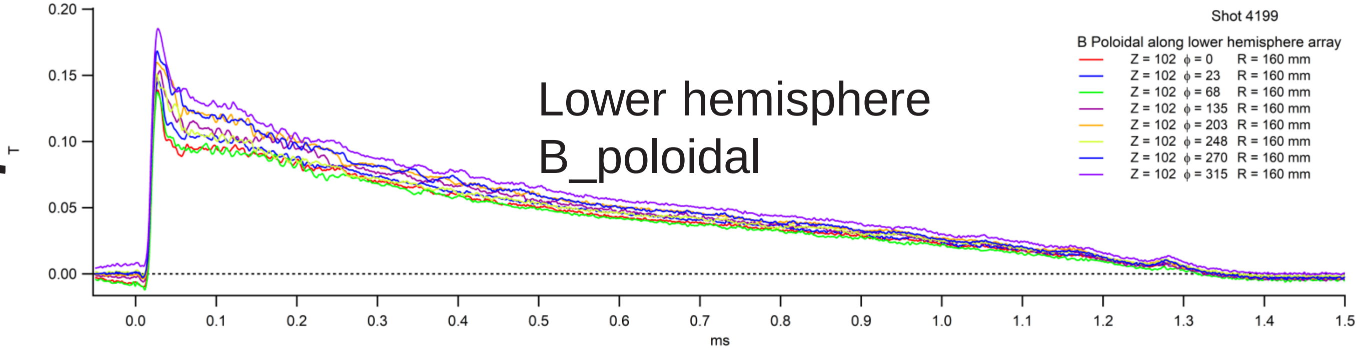
Surface Mirnov Probes (poloidal, toroidal components)

Magnetic Probe positions (number active)

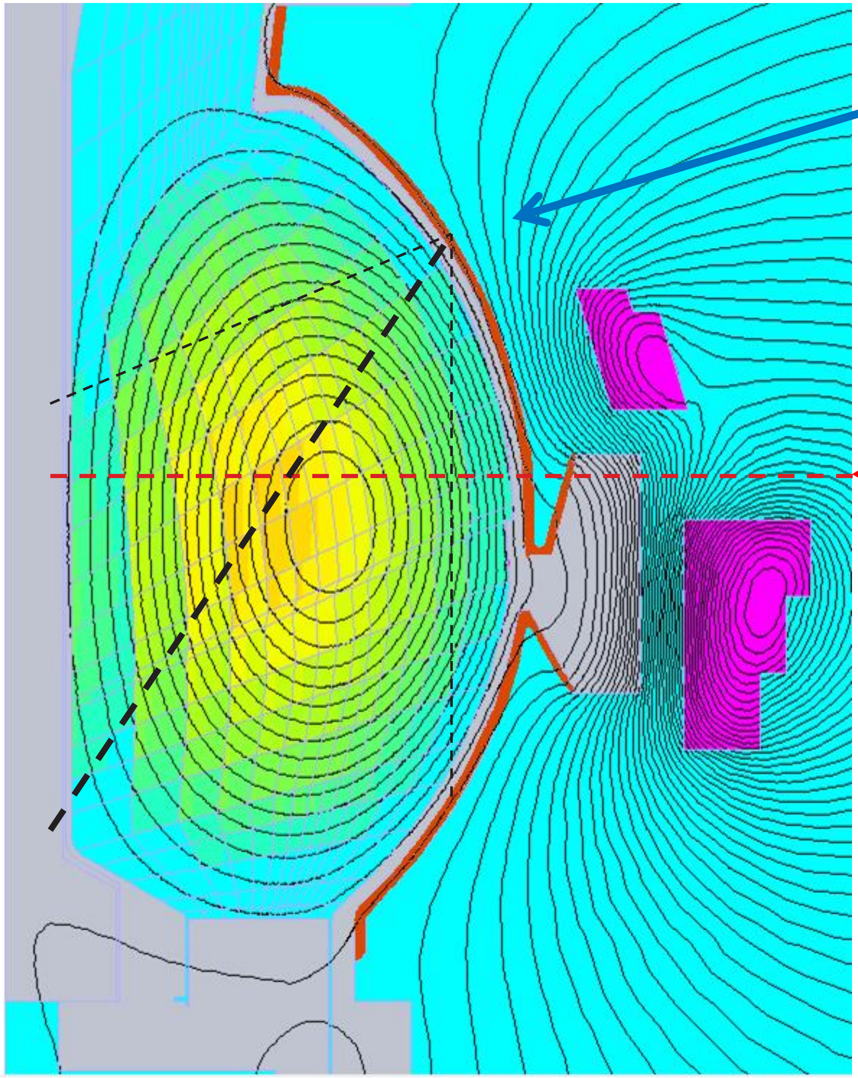








Optical Diagnostic Coverage



45 degree downward-angled chords
- Color Phantom Camera (with LED illumination)
- Red Laser line for puddle surface profile

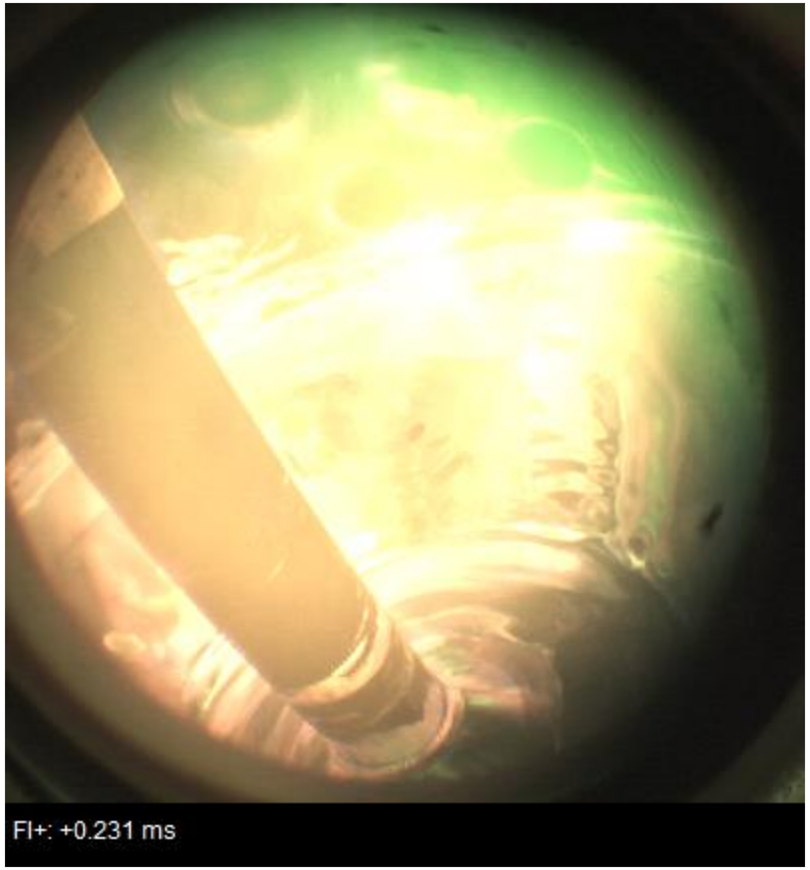
Equatorial plane
- CO2-HeNe Dual interferometer chord
- 1 Ion Doppler (has observed He II and Li II)
- 6 Visible light survey spectrometers (time staggered)
- 8 Filtered photodiodes (various visible lines)
- 2 Total visible emission signals (300-700nm)
- 4 Filtered AXUV channels ($E_\gamma > 1$ keV)

Deuterium highlights separatrix dynamics near shaft

Phantom watching fast plasma action

Separatrix near shaft can be seen as plasma shrinks as it dies

Liquid Hemisphere (4290)



Liquid Hemisphere (4291)

Liquid Hemisphere (4262)

Record lifetime was with thin Evap Li layer

Evaporative coated Li gettering layer gave really good performance on SLiC b runs in April 2020

- Record SLiC lifetime of 1.9 – 2 ms
- AFC was at 12 kV , Vform = 12 to 14 kV, VPT =14 kV, GunFlux ~ 12 to 16 mWb, PTF/PTW =(260-280)/100