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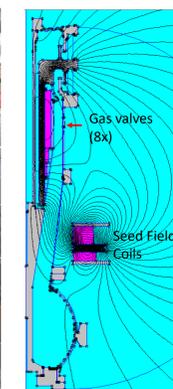
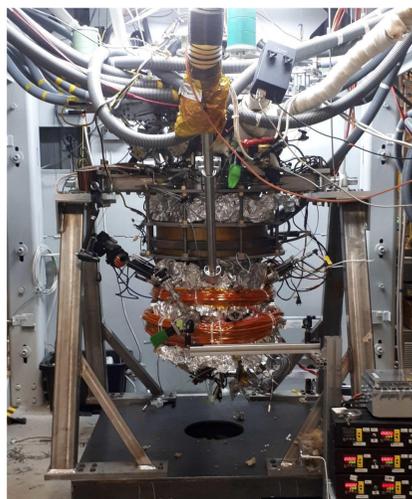
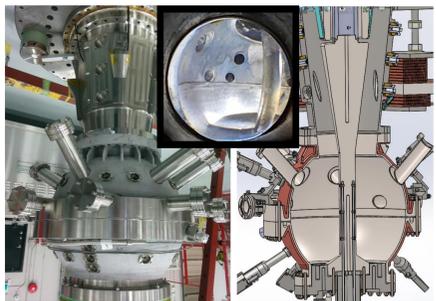
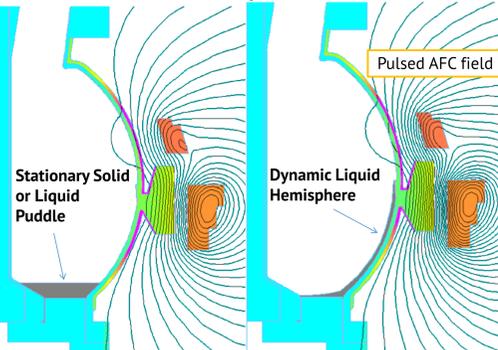
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INTRODUCTION TO THE SLiC EXPERIMENT

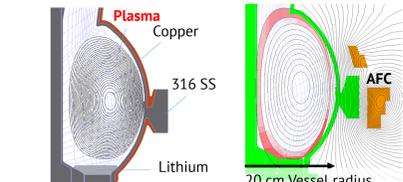
Operational Capabilities of the SLiC device

- Stainless steel inner shell with Cu outer layer as a passive flux conserver.
- Vessel heating allows 20 C (Solid Li) to 450 C (Hot Liquid).
- Maximum Lithium inventory 26 Liters
 - Typical 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 ~400 kA.
 - Total poloidal flux ~ 15-20 mWb.
 - Plasma density range ~ $5 \times 10^{13} \text{ cm}^{-3}$ to $2 \times 10^{15} \text{ cm}^{-3}$
 - Peak $T_e \sim T_i \sim 75\text{eV}$ to 300 eV
- Comprehensive set of magnetic and optical diagnostics.
- Can push Li up the wall with MHD tsunami wave via 200kA Kicker circuit or 2 kA Spin-Drive 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).
- Can increase 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



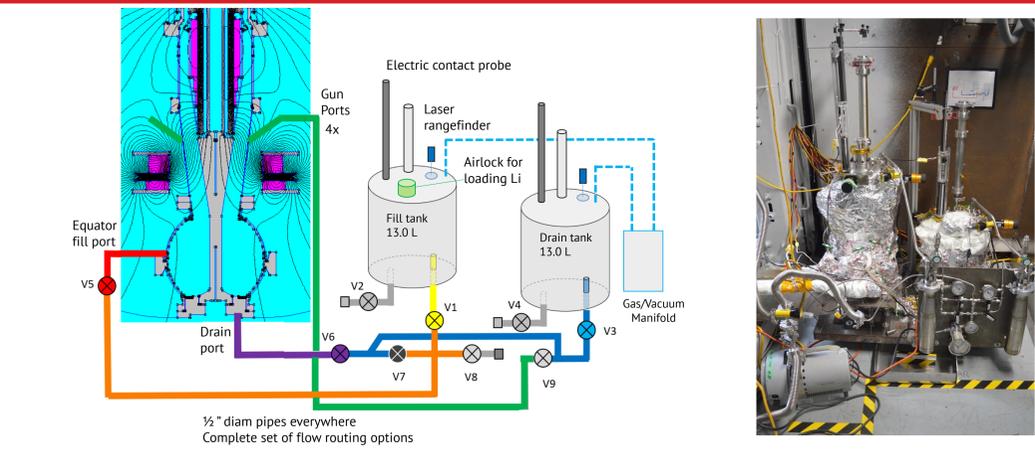
Design of Marshall gun for fast-CHI formation. This plot shows a typical initial poloidal field in the gun, which is displaced downward by coaxial railgun discharge across the plasma that breaks down near the gas valves. Axial current runs down the central shaft to control $q(\psi)$.



The flux conserver/vacuum vessel in which a spherical tokamak plasma is formed is made from a composite of 316 stainless steel with an outer layer of spray-coated copper. In addition to the passive metallic flux conserver we also have an active coil dynamically opposes outward resistive flux soak through the wall.

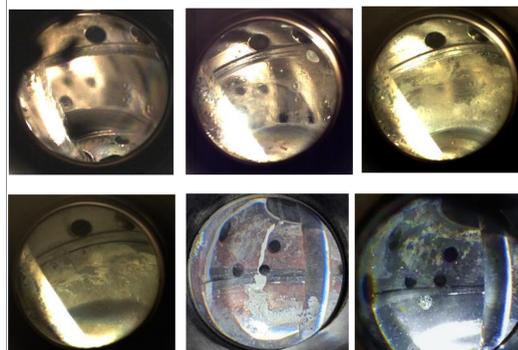
The purpose of SLiC is to explore the novel engineering and physics issues that may arise when working with liquid Li as a plasma facing surface. This is central to General Fusion's plan to reach fusion conditions by rapidly compressing a plasma with liquid metal. SLiC is a small step towards the Fusion Demonstration Program (FDP).

RECIRCULATING LITHIUM SYSTEM



CHALLENGES OF 250° C GUN WITH LI

Accumulation of slag layer



At elevated temperatures liquid Li reacts with background impurity gases, forming nitrides, oxides, carbonates as well as hydrides from with the H, D in the main plasma. This slag slowly accumulate over time and mostly float on the surface and stick to the vessel as a persistent residue.

Air leaks from thermal cycling

Thermal cycling combined with the mechanical shock of pulsed power can loosen bolts that clamp vacuum seals. If a leak opens while the system is hot then exposed Li can become contaminated. Normal maintenance to prevent bolt-loosening and fix a leaking seal are complicated by the bolts being inaccessible under thick thermal insulation. Even when cold, the presence of Li significantly impedes attempts to open a vessel to replace a metal gasket without allowing even more contamination to occur. Elaborate argon shrouds become required.

Air leaks from lithium attacking copper seals

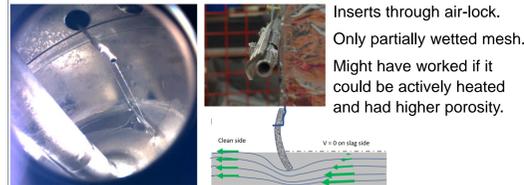
Once wetted onto the stainless vessel, Li can wick up into unexpected places where it can dissolve copper gaskets. Annealed stainless gaskets can be used in these locations instead, if anticipated.

Diagnostic challenges from Li splashes and vapor

The dynamic nature of free surfaces of liquid Li interacting with hot plasma and pulsed electromagnetic forces will often result in diagnostic windows become partially or fully coated with lithium, ranging from a few μm to 1 cm in thickness. Since this happens frequently the straightforward approach of removing the window under inert gas fill, then cleaning with H₂O bath is not optimal. We have explored methods of cleaning windows with pulsed lasers (4J Nd:YAG 20ns 1064nm), which has the advantage of no gas fill being needed, however it can etch the window surface, and in rare cases can cause a leak at the window's seal. Alternative methods to be explored include in-situ cleaning with inert gas jets, fast-closing shutters, and electromagnetic induction/repulsion. For thin vapor deposited layers, it may be simpler to track changes to transmission with a reflectance measurement and then adjust optical calibrations.

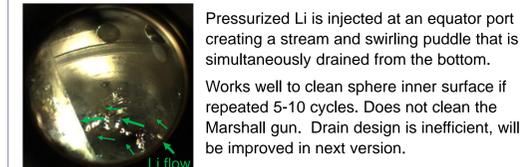
IN-SITU CLEANING METHODS

Mesh Skimmer



Inserts through air-lock. Only partially wetted mesh. Might have worked if it could be actively heated and had higher porosity.

Swirl and Drain



Pressurized Li is injected at an equator port creating a stream and swirling puddle that is simultaneously drained from the bottom. Works well to clean sphere inner surface if repeated 5-10 cycles. Does not clean the Marshall gun. Drain design is inefficient, will be improved in next version.

Heated Syphon Tool



Inserted via a long bellows, this heated tube can be dipped into the slag layer while the vessel is under argon fill and the drain tank connected to the tube is evacuated, causing Li to be drawn from near the surface. A prototype was successfully demonstrated, however it was challenging to heat well enough to entirely prevent freezing/clogs.

GUN WETTING

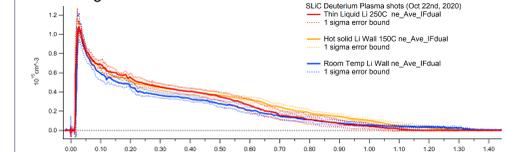


We want to test what happens to the performance of the fast-CHI formation when the gun has significant Li wetting the electrode surfaces because we know this will happen in the FDP device during an MTF compression shot. We have several ways to add a liquid Li layer to the gun electrodes, with various degrees of extent of coverage and control of outcome. These include:

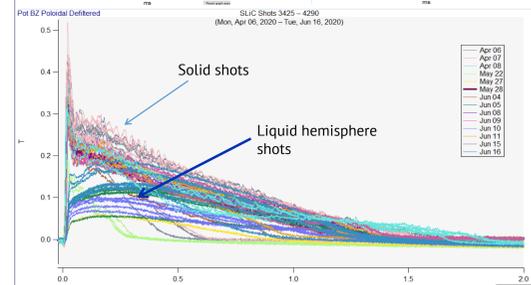
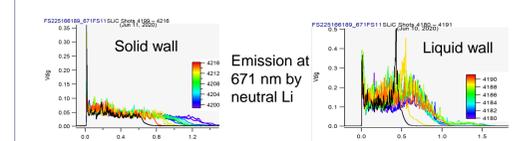
- Evaporative deposit from hot puddle $T > 400 \text{ C}$ (remove AFC 1st)
- Flow Li in through 4 ports in gun outer electrode, (Shown in figures above and to left)
- Moderate splash of Li upward from puddle using gas bubble (worked best when happened accidentally)
- Mega-splash using pulsed shaft current into deep fill. Wets up into gun and center shaft but also fills all of the diagnostic ports.

HOT/COLD PERFORMANCE COMPARISON

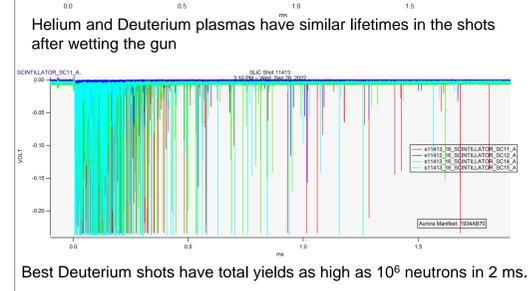
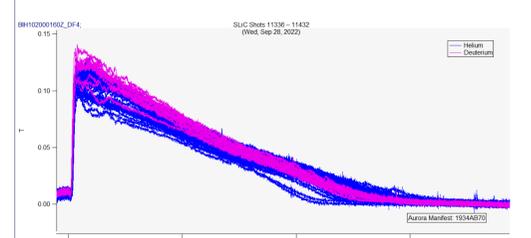
Overall, we get similar plasma performance on hot liquid Li, or cold solid lithium surfaces. Generally, we observe a noticeable increase in plasma repeatability when running with a liquid surface, especially a thick liquid surface. Plasma performance can worsen if liquid droplets are ejected deep into the plasma volume in advance of formation, or if dissolved gas is released.



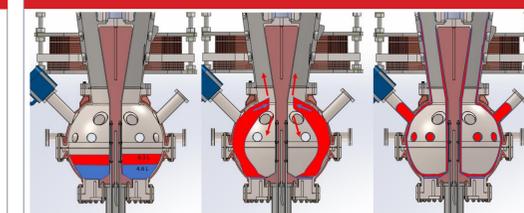
Electron density is very similar on different surface conditions. However visible line emission is much brighter on liquid walls than solid.



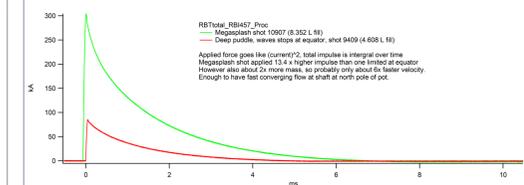
With the dynamic free surface of Li in the lower hemisphere, the thickness of the liquid is sufficient to filter out the highest frequency components of the plasma magnetic field, as measured by a probe in the lower hemisphere that is submerged. Upper hemisphere probe locations are not effected and show the same plasma evolution.



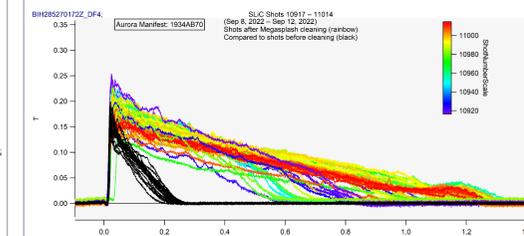
MEGASPLASH



After exhausting all conventional means to deal with a sequence of air contamination of Li in the gun, we chose to sacrifice most of optical access in favor of the chance of recovering plasma performance. With the vessel filled with 8.3 liters of lithium, we closed all port gate valves and then fired an axial current pulse of 300 kA while also firing the AFC at maximum power. This causes an enormous tsunami wave that splashes everywhere below the formation gas valves. To be sure it worked we did it twice in a row. Then we drained all the Li out of the vessel and went back to taking plasma shots.



As a result of the megasplash, we completely blocked the interferometer, AXUV, and fast camera ports. We had only 2 optical ports that we were able to shift Ion Doppler, survey spectrometers, and Filterscope light collection to. The sub-surface Mirnov probes were unaffected by a thin layer of clean Li and we could see the plasma magnetic lifetime radically increase once the wall was clean.



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 (Specter 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.
- Various mechanisms may cause droplets that enter the plasma edge, but this does not have a noticeable effect on plasma lifetime unless droplets enter the plasma core.
- Although it poses challenges for UHV vessel engineering when running with the Marshall gun electrodes at elevated temperatures and wetted with Lithium, we find the advantages in repeatability and increased maximum performance outweigh the complications. This is a reassuring result for going forward with the lithium-coated FDP formation design.