Formation Efficiency Studies on the PI3 Spherical Tokamak Plasma

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General Fusion Inc., Vancouver, British Columbia, Canada

65th Annual Meeting of the APS Division of Plasma Physics, Denver, Colorado, October 29-Nov 3, 2023 YP11.00070

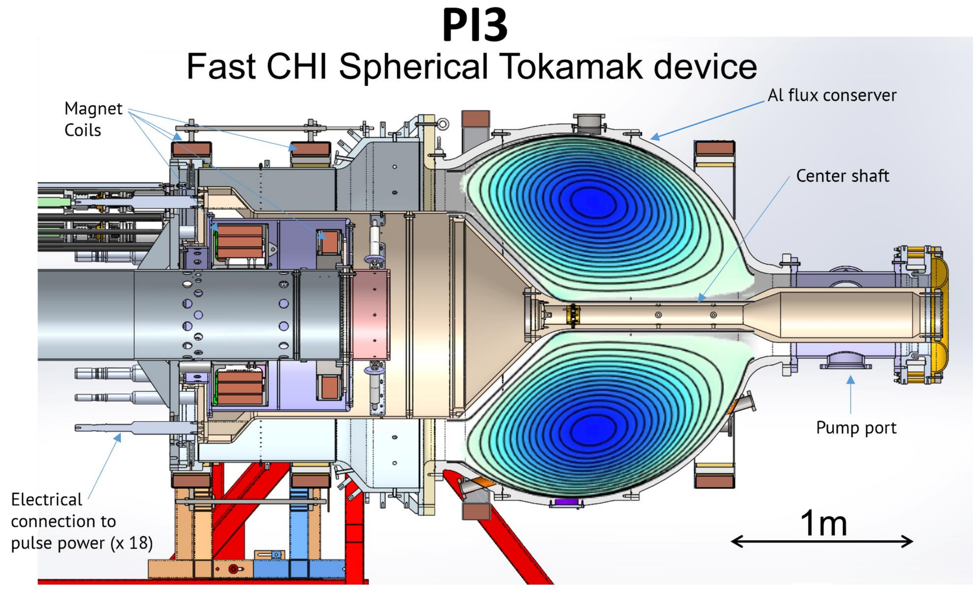
INTRODUCTION

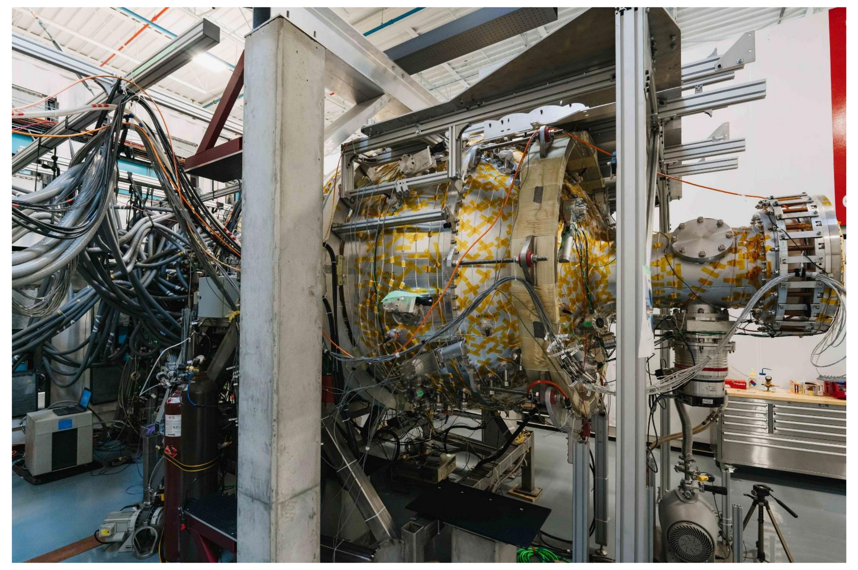
Abstract

Optimizing Marshall gun CHI (coaxial helicity injection) energy efficiency is an important factor in optimizing overall performance of the Magnetized Target Fusion approach being pursued by General Fusion. By maximizing the initial temperature, density and thermal confinement time of the self-organized spherical tokamak (ST) configuration, we enable fusion-relevant peak conditions via compressional heating of the plasma by a Li liner and maximize overall fusion yield. To find this optimum on the PI3 device we are embarking on a sequence of experiments and upgrades to the pulsed power and diagnostic capabilities. This poster will provide an update on latest results and methods, in the experiment and corresponding simulation studies.

PI3

Fast CHI Spherical Tokamak device



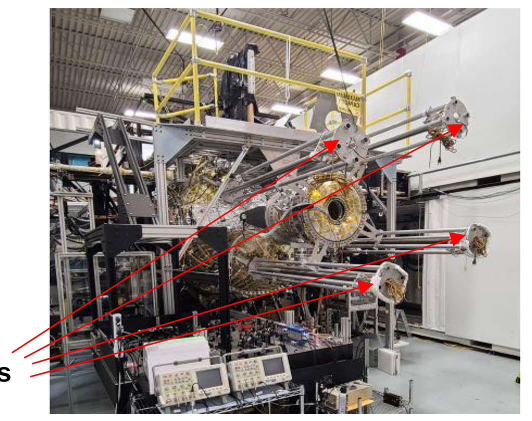


Diagnostics

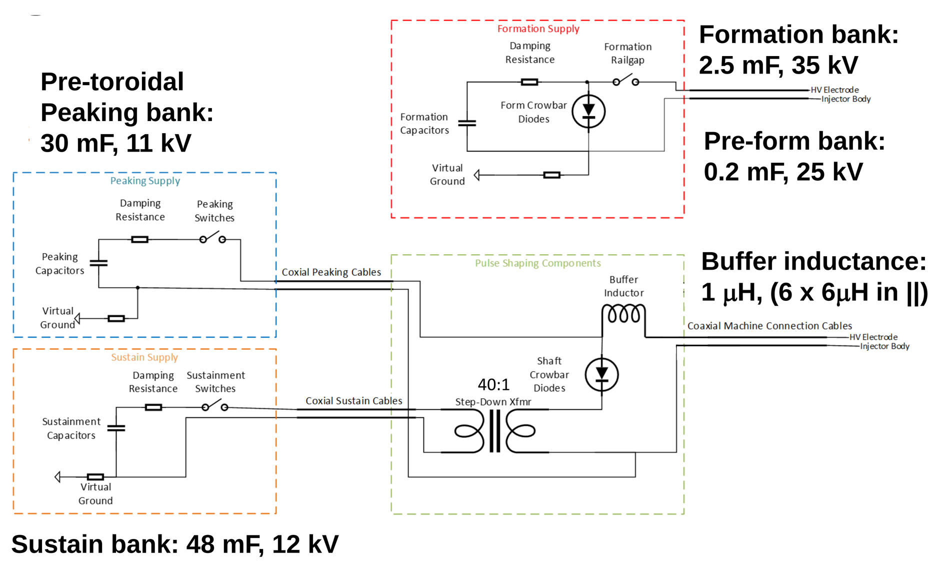
- 32 Mirnov probes for surface poloidal and toroidal B
- Visible imaging (Phantom/Photron fast camera)
- Visible survey spectrometers
- Line averaged ion Doppler spectroscopy
- Time resolved visible bandpass filtered photodiodes
- 4 chords for CO2 interferometers
- 2 pairs of filtered AXUV photodiode sensors
- 2 radial fans of unfiltered AXUV each with 16 channels
- Up to 5 points of Thomson scattering (1064nm)

Evaporative Lithium Coating

The inner surface of the vacuum vessel is coated with evaporatively deposited lithium up to 5 µm thick using 4 large retractable coating probes in the main chamber, and 6 smaller probes in the Marshall gun region. Lithium coating significantly improves plasma lifetime and temperature, while decreasing n_e.



PULSED POWER CIRCUIT & SPECS

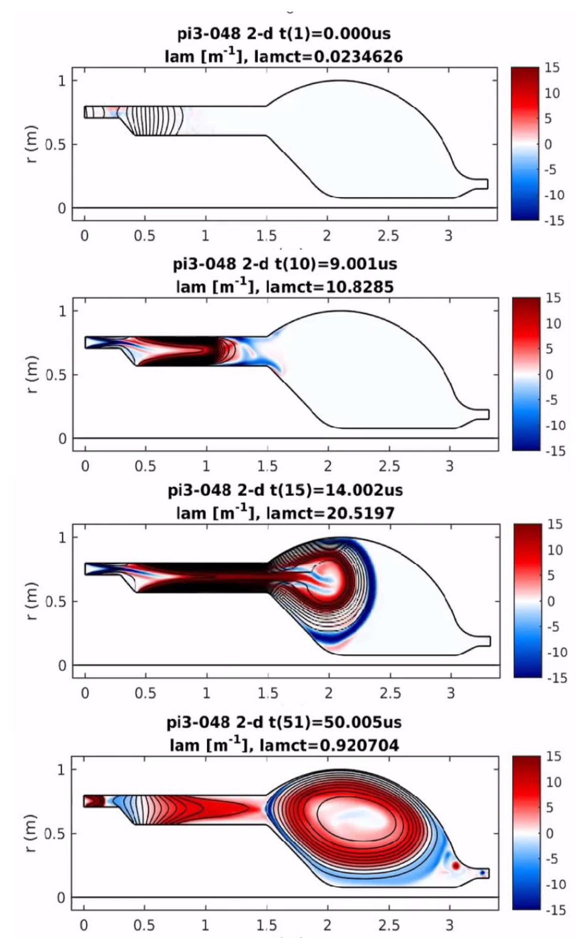


Parameter		Value range
Vessel inner radius	D/2	1 m
Major radius	R	0.6 – 0.7 m
Minor radius	a	0.3 – 0.4 m
Elongation	κ	1.0 – 1.6
Triangularity	δ	-0.15 – +0.1
Poloidal flux	Ψ_{CT}	0.15 – 0.25 Wb
Plasma current	I_p	0.3 – 0.6 MA
Shaft current	I_s	1.0 – 1.2 MA
Plasma density	n_e	$1x10^{19}$ – $4x10^{19}$ m^{-3}
Temperature	$T_e \sim T_i$	100 – 300 eV
Thermal confinement time	τ_E	5 – 15 ms

MHD SIMULATION

Fast CHI Formation Simulations

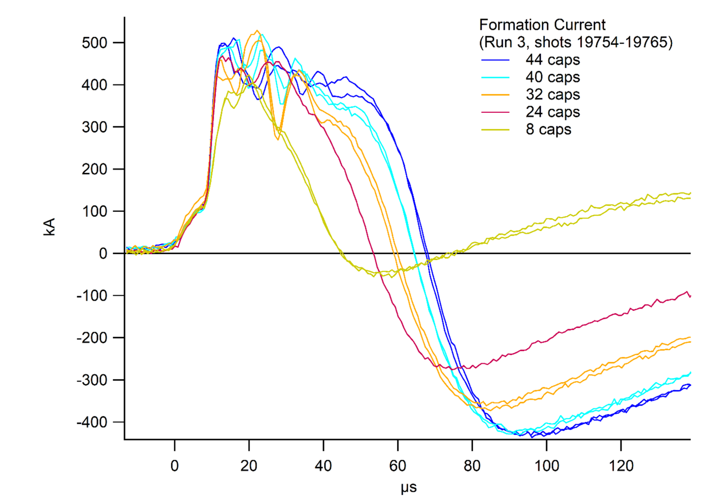
We use VAC (Versatile Advection Code) to conduct 2D and 3D MHD simulations of the fast CHI formation of a spherical tokamak plasma configuration. Black contours show poloidal flux surfaces, which are initially created by DC Coils in the Marshall gun as open field lines. Color scale is plasma lambda = $\mu_0 J_{||}/B$ [units of m^{-1}].



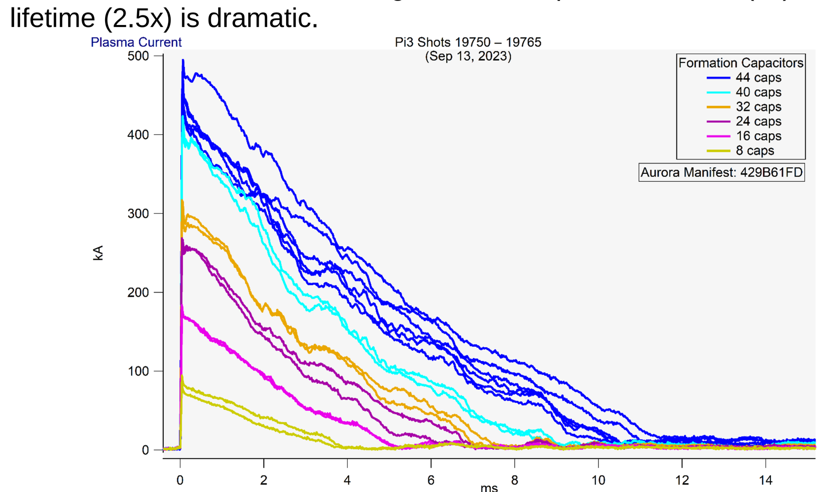
CHI FORMATION PULSE LENGTH

Longer formation pulse length improves efficiency

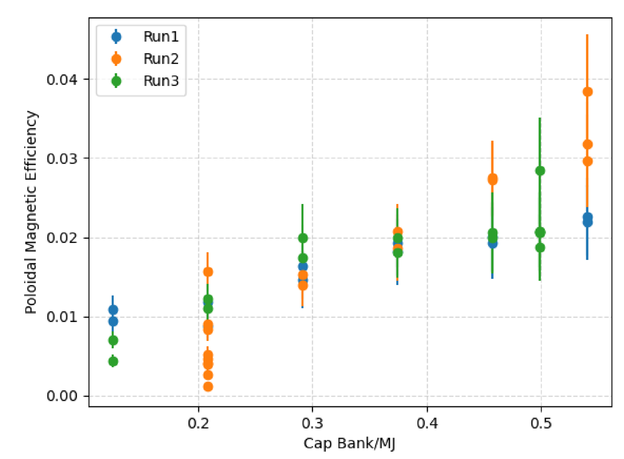
Efficient conversion of capacitor energy to magnetic energy of the CHI-formed ST plasma becomes important for reducing costs as capacitor banks are scaled up to reactor size. We have found that increasing the duration of the dynamic CHI current pulse induces more plasma current and increases formation efficiency as a nearly-linear function of bank energy. Here is the result of a scan over number of caps discharged.



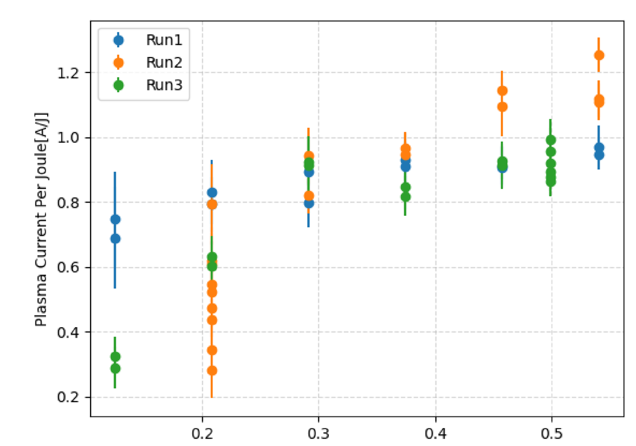
The peak of formation current is similar for all cases, and enough to always pass the ideal bubble-out threshold, however the pulse width almost doubles and the resulting increase in plasma current (5x) and total lifetime (2.5x) is dramatic.



As the formation bank energy U_{form} is increased by adding caps at constant voltage, the poloidal magnetic energy efficiency U_{pol}/U_{form} increases nearly linearly with bank energy in a favorable scaling for larger machines. These scans were repeated over 3 runs with differing amounts of initial toroidal field: Run 1, 3 at V_{peak} = 7 kV, Run 2 at V_{peak} = 4 kV, while Run 3 also had the shaft sustain circuit on at V_{sus} = 7 kV.



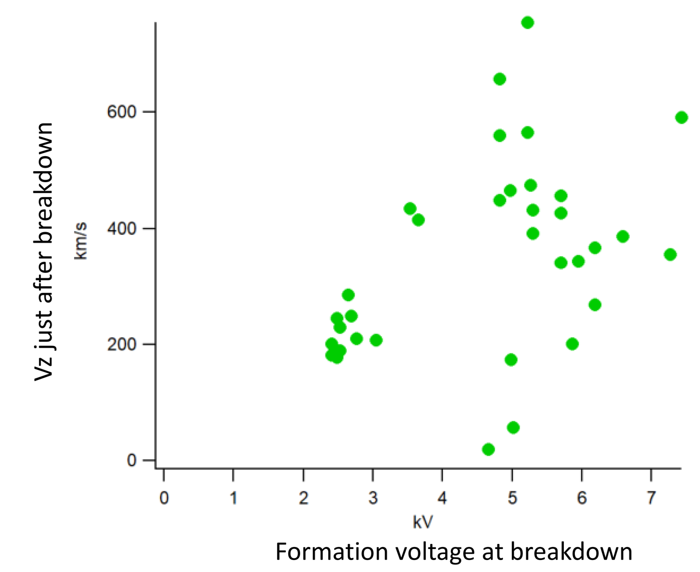
We also see that the plasma current per Joule of U_{form} increases with pulse length (and U_{form}) such that we could go from 0.5 MA (present average) up to 1 MA of plasma current if U_{form} increased from 540 kJ up to 870 kJ. At 20 kV this would be an increase from 48 to 77 caps.



FORMATION VOLTAGE

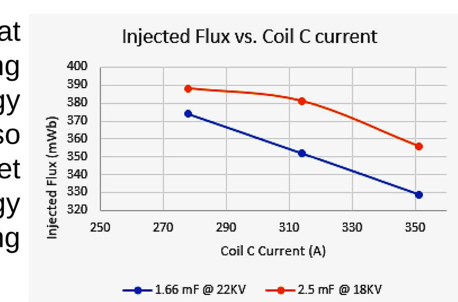
Higher formation voltage increases ion velocity

This experiment was designed to scan formation voltage while adjusting number of caps discharged in a way that either approximately conserved total charge in the bank, or total energy. To directly measure the ion velocity, we installed an ion Doppler collection fiber on a port on the back flange, looking forward in the +z direction, which can measure plasma velocity Vz during the breakdown and bubble out by looking at He II ions at 468.5 nm.



Increasing the plasma velocity during bubble-out corresponds to a higher initial ion kinetic energy, which will then thermalize over time to yield a higher ion temperature. It is desirable to begin the MTF compression with as high of ion temperature as possible, since the temperature gain factor is challenging to increase.

However, there is evidence that increasing voltage while keeping fixed the formation bank energy (by decreasing its capacitance so CV^2 = constant) results in a net decrease of magnetic energy efficiency. Loss of Ohmic heating may outweigh the gain of Ti.



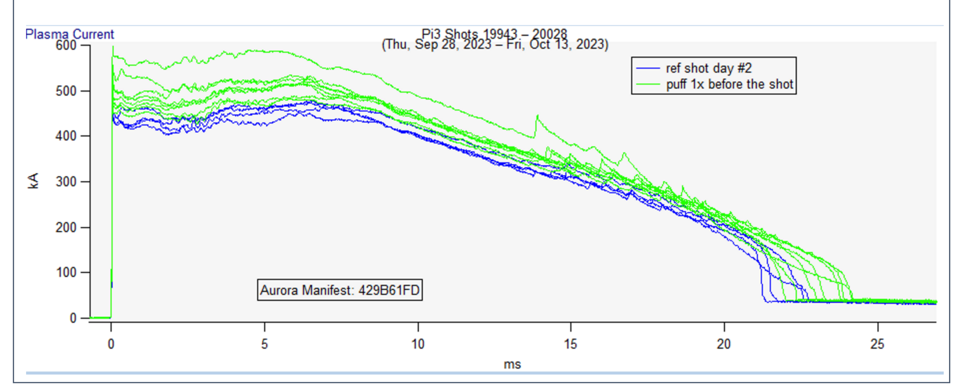
GAS PUFF PRELOADING

We have found that pre-loading the walls of vessel with gas (D2) approximately one minute before the plasma discharge results in better repeatability, significantly higher plasma current (20-50%) as well as higher plasma density (30-60%) in comparison to shots where we only intentionally add gas from the main gas puff promptly before applying formation voltage to initiate breakdown.

This was discovered after exploring the root cause of always having the maximum plasma current on the first shot of the day, followed by a steady decay of achievable plasma current for the same settings throughout the day (noticeable over a span of 10 shots).

Typically, for the first shot of the day it was standard practice to exercise the formation puff valves to verify they were functioning correctly. We found that repeating this pre-puff followed by pumping back to the normal base pressure (~ 1 min) allowed us to regain or exceed 1st shot plasma current values. The total gas emitted by the puff valves is estimated to range between $2x10^{20}$ to $6x10^{20}$ atoms of D per shot.

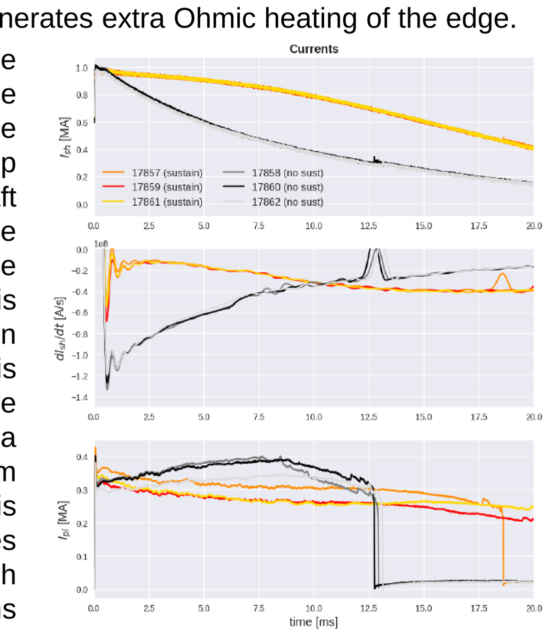
The leading theory for why we increase plasma current when we add neutrals to the walls is based on the possibility that a source of abundant charge carriers at the wall during Paschen ionization cascade improves the conductivity of the initial plasma in the first few microseconds just after breakdown. More conductive plasma will capture more of the gun flux during CHI bubble-out resulting in higher plasma current.



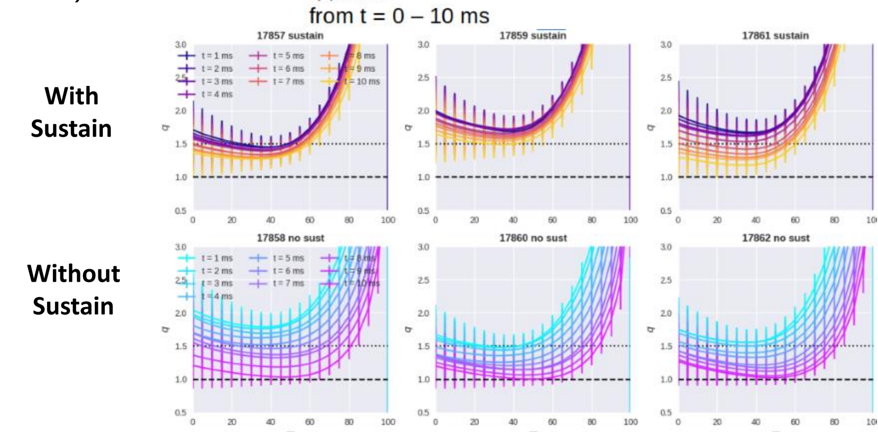
SHAFT CURRENT DECAY RATE

We have a separate power supply (called the sustain circuit) that applies a slow pulse of voltage (~100 V) via transformers to the electrode to sustain the current in the center shaft, compensating for resistive decay. Without the sustain bank firing, we get a decay time of 8.3 ms for shaft current at t = 5 ms, and this can be slowed to a decay time of 45 ms when we apply the sustain voltage. Because the decay rate without sustain is comparable to the L/R time of the plasma, conservation of toroidal flux causes a large induced current at the outer region of the plasma that generates extra Ohmic heating of the edge.

Yellow-red traces show the cases *with sustain*, while black-grey traces show the case of *without sustain*. Top graph shows the shaft current in both cases. Middle graph shows the inductive drive term dI_{shaft}/dt, which is smaller in magnitude when Sustain is on than when it is turned off. This inductive drive increases the plasma current with time (bottom graph, black) when sustain is off. Falling shaft current does affect the q-profile which decreases with time (graphs below).

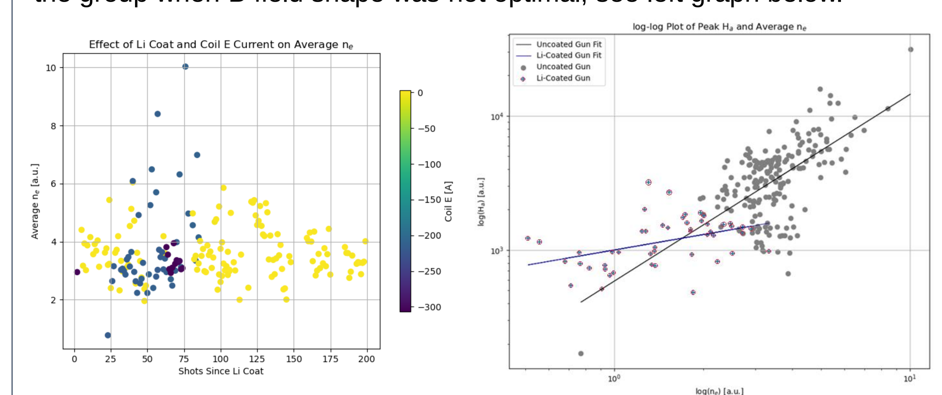


q-profiles from t = 0 – 10 ms

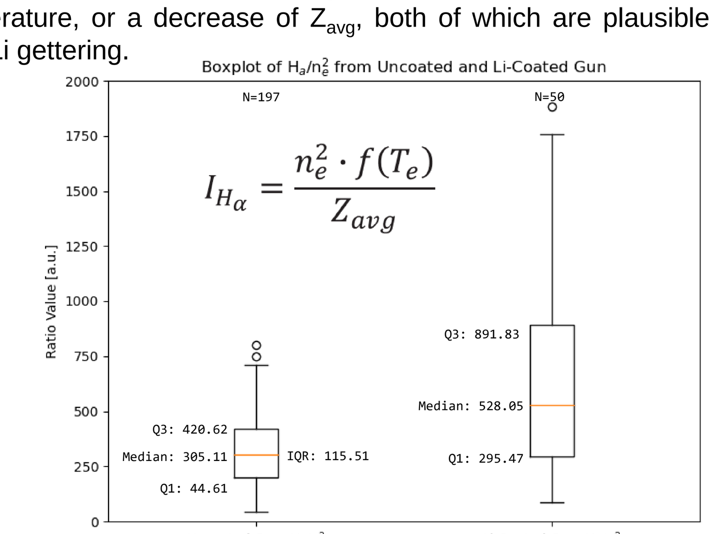


LITHIUM COATING OF GUN

Plasmas had lower densities after gun Li-coating. Median electron density decreased from $3.3x10^{19}\,m^{-3}$ to $1.5x10^{19}\,m^{-3}$ after gun Li-coating, see right graph below. Some Li-coated n_e-values exceeded the low average of the group when B field shape was not optimal, see left graph below.



We also see that H_α (656 nm) peak intensity decreases significantly after Li coating the gun, as observed with the survey spectrometer [a.u.]. However, the ratio of H_α/n_e^2 increases significantly due to Li coating (by >73%), this could be caused by either an increase of plasma edge temperature, or a decrease of Z_{avg}, both of which are plausible effects from Li gettering.



$$I_{H_\alpha} = \frac{n_e^2 \cdot f(T_e)}{Z_{avg}}$$

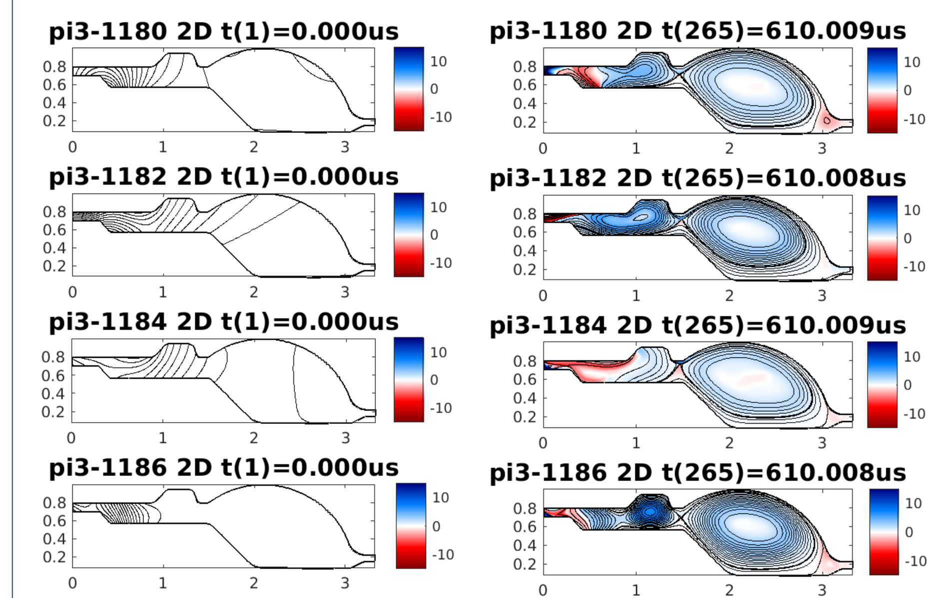
DC MAGNETIC GEOMETRY

There is a wide space of possible magnetic configurations that have differing axial variation of magnetic field strength, variation of location and volume of an electron Penning trap that enhances ionization, each with a different ratio of linked flux in the gun to open buffer flux in the flux conserver.

Standard theory of Marshall gun operation predicts that the dominant behavior is determined simply by the ratio of total linked flux bridging radially across the electrodes (called the gun flux), and the total current that passes from one electrode to the other. However, we find that small changes in plasma breakdown conditions can have large effects on the resulting plasma performance. Adjusting the magnetic geometry in the gun is one way to modify the breakdown and the resulting bubble-out process with the goal of optimizing formation efficiency. Experimentally, most effort has been put exploring a small space near the initial estimate of optimum performance. However, we are now beginning to explore a wider range of geometries, guided partly by the results of MHD simulations (VAC).

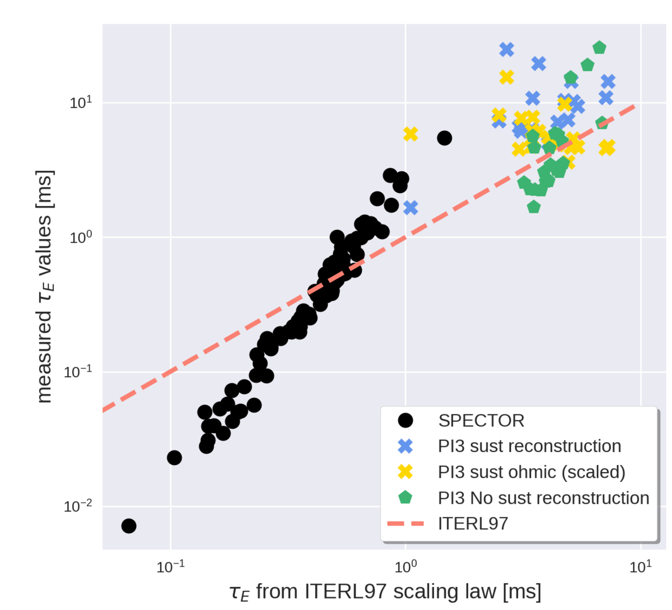
Various examples of initial DC magnetic geometries

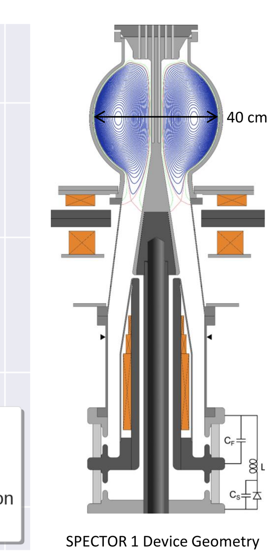
Resulting ST configurations after bubble out is complete



CONFINEMENT TIME SCALING

Energy confinement time for PI3 and SPECTOR





SPECTOR 1 Device Geometry

Original ITERL97 scaling law [S.M. Kaye *et al* 1997 *Nucl. Fusion* **37** 1303]

$$\tau_E^{IT97} = 0.023 \left(\frac{I_p}{1\,\mathrm{MA}}\right)^{0.96} \left(\frac{B_t}{1\,\mathrm{T}}\right)^{0.03} \left(\frac{R}{1\,\mathrm{m}}\right)^{1.83} \left(\frac{R}{a}\right)^{0.06} \kappa^{0.64} \left(\frac{\bar{n}_e}{10^{19}\,\mathrm{m}^{-3}}\right)^{0.40} M_{eff}^{0.20} \left(\frac{P_L}{1\,\mathrm{MW}}\right)^{-0.73}$$

SPECTOR:

- The bulk of SPECTOR data lie along the ITERL97 scaling law around τ~ 0.5-0.7 ms. Higher values of τ exceed the ITERL97 scaling law

PI3:

- Sustained ('sust') shots have slower decay of the shaft (poloidal) current and hence of the toroidal magnetic field
- Kinetic-Ohmic method (yellow crosses) calibrated against a known answer from MHD simulation. [C. Ribeiro **JP11.00103** APS DPP 2023]
- Good agreement between values of τ computed with different methods (comparison only available for sustained shots)