Recent Progress in the Plasma Injector 3 Spherical Tokamak Program

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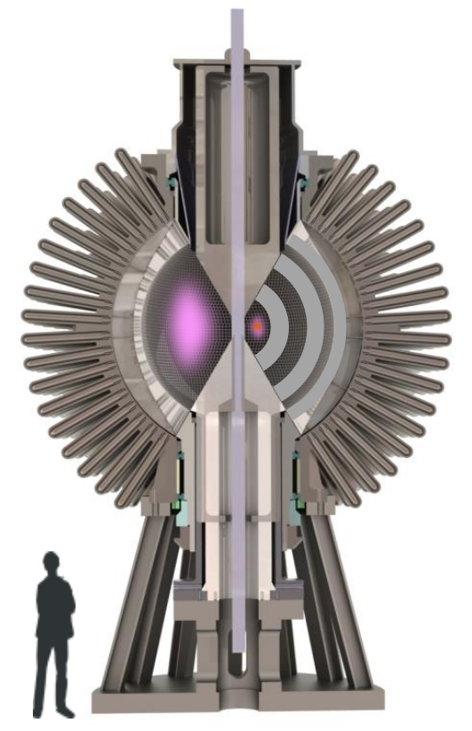
INTRODUCTION

Plasma Injector 3 (PI3) is the 3rd in a sequence of reactor-scale experiments at General Fusion studying the physics and engineering needed to produce self-confined plasmas suitable for use as an MTF target plasma.

- **PI1 and 2** explored high density (10^{22} m^{-3}), medium temperature (100 eV), and fast compression ($R_0/R = 4$, $\Delta t = 30$ μs) of a spheromak plasma using a 2-stage coaxial Marshall gun/railgun system. The accelerating railgun electrodes were conically converging to achieve the 4x radial compression to bridge the gap between the densities achievable with Marshall gun formation, and what was required for the initial state of a proposed MTF compression scenario.
- **PI3** is a single-stage coaxial Marshall gun for directly forming a spherical tokamak (ST) plasma target. This is a single-pulse fast CHI formation with no additional heating or current drive. Magnetic confinement is provided entirely by internal plasma currents and free-wheeling currents in the flux-conserving metal wall. PI3 will explore the plasma physics related to a slower MTF compression scenario where better thermal confinement times allow for lower densities, lower peak compression ratios and slower wall velocities. The PI3 device itself will not actually compress the plasma, but rather study basic physics objectives that are a prerequisite to building a large scale plasma compression experiment.
- **SPECTOR 1-5** devices are the latest in the PCS sequence of experiments, which are sub-scale (1/5th PI3 by radius) experiments to enable rapid development and testing of methods of plasma formation and compression by a moving metal wall. SPECTOR 1 is a lab-only device with an extensive set of diagnostics, SPECTOR 2-5 have been field mobile compression experiments, (see talk **NO6.00012**).

STEPPING STONE TO MTF DEMONSTRATION



Plasma Injector 3 is part of an risk reduction program needed to bridge the gap between existing subscale tests and a large scale plasma that has sufficiently good thermal confinement yet is produced by MTF-compatible methods. The vacuum vessel is complete and the machine and diagnostics are being tested at low power. The machine is currently scheduled to be in operation a full power in Q1 2019.

The program objectives are:

- Explore the physics of MTF reactor-scale self-confined plasmas.
- Demonstrate a >10x increase in on total inventory, magnetic flux, and energy confinement time from previous MTF experiments completed by GF.
- Remove technical risks for building a full-scale prototype of repetitively operated non-destructive compression device.

Plasma performance goals required to achieve net energy gain with a Magnetized Target Fusion (MTF) (nearly invariant among different possible schemes)

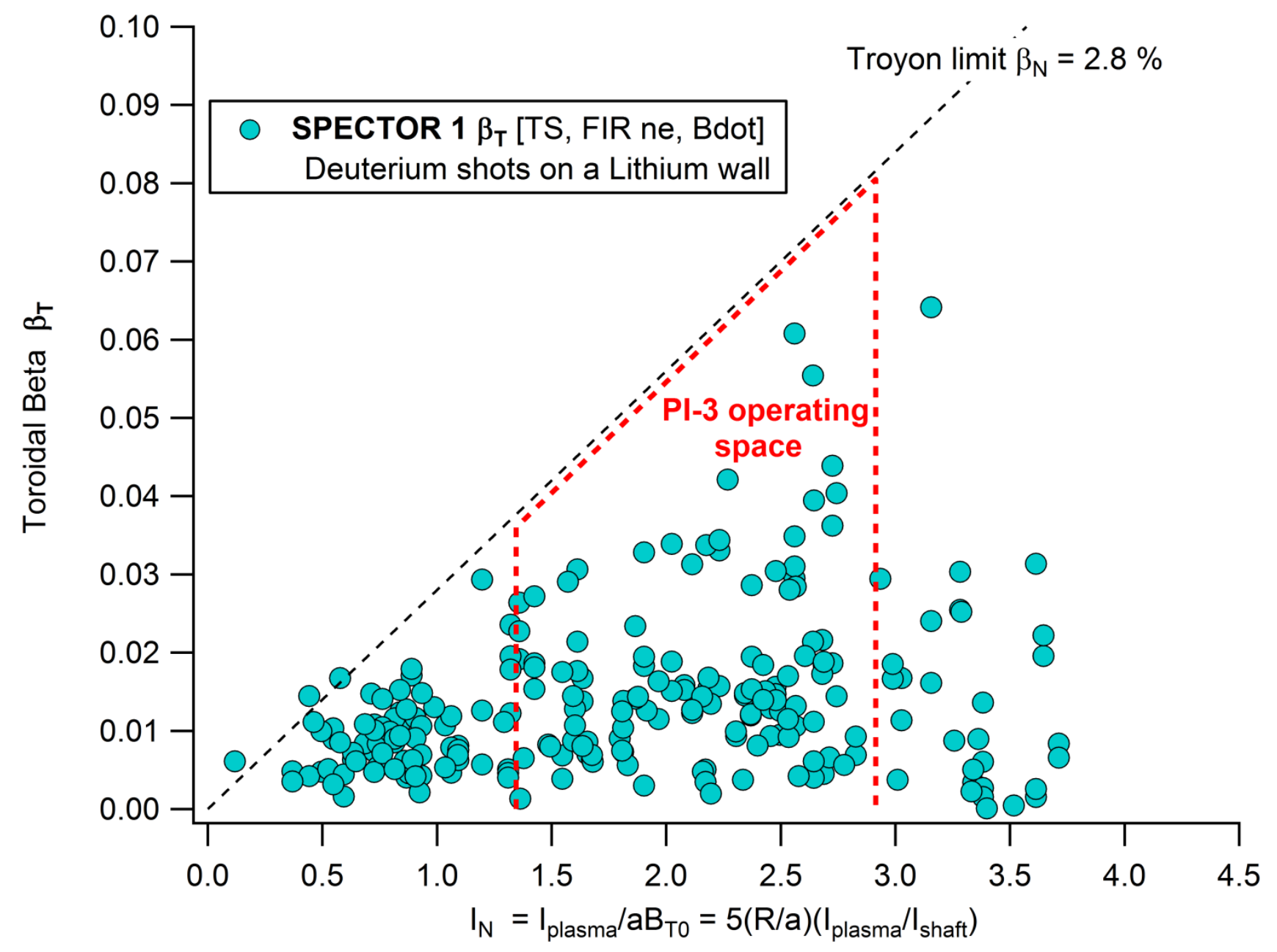
- Total particle inventory (~10^{21} ions),
- Sufficient magnetic flux (~0.25 Wb) to confine the plasma inventory without becoming MHD unstable,
- Initial thermal energy confinement time several times longer than the compression time.

PI3 will explore:

- How thermal confinement time scales with key plasma parameters; this is a major input to reactor simulations, and would determine size and structure of future devices.
- How edge physics and wall interactions scale with magnetic field strength, density, temperature, and size. This will be used as inputs to guide simulation.

COMPARISON TO SPECTOR PARAMETER SPACE

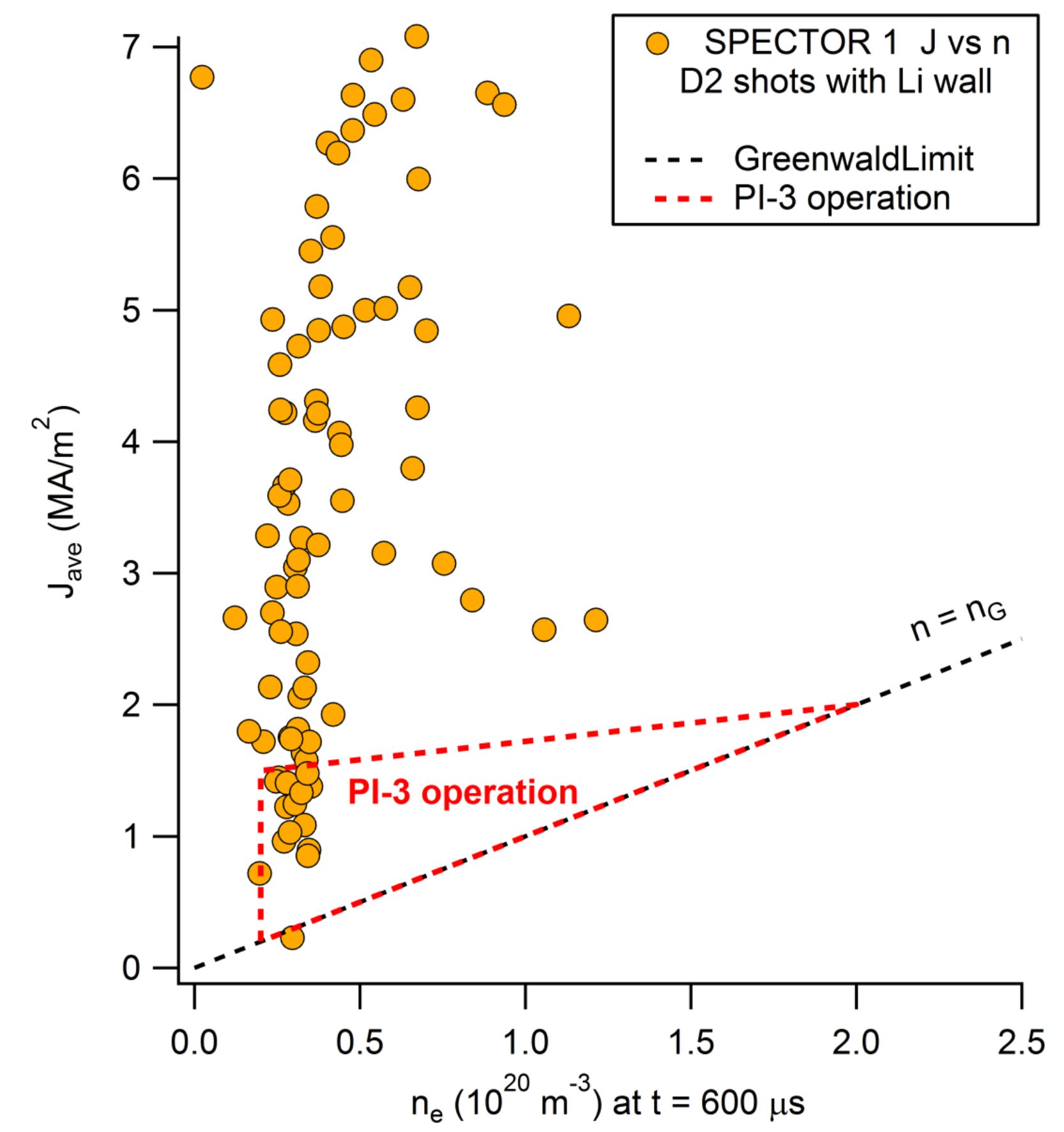
Plasma beta β vs normalized plasma current I_N



SPECTOR achieved its best performance in terms of temperature, overall magnetic lifetime, and plasma stability at a relatively low-β range, 1- 5% , bounded by the empirical Troyon limit for Ohmically heated tokamaks, which is reasonable considering SPECTOR's lack of additional heating.

PI3 is expected to operate in a similar range of β values. This should be acceptable tor an MTF target plasma, the initial state before compression needs to be at moderately low β to prevent crossing a β-limit as the compression yields $\beta \sim R_0/R$ for the perfect adiabatic spherical case. This would convert initial $\beta_0 = 5\%$, into a peak value of $\beta_{Final} = 50\%$ in a 10:1 radial compression scenario.

Plasma current density J vs line averaged density n_e

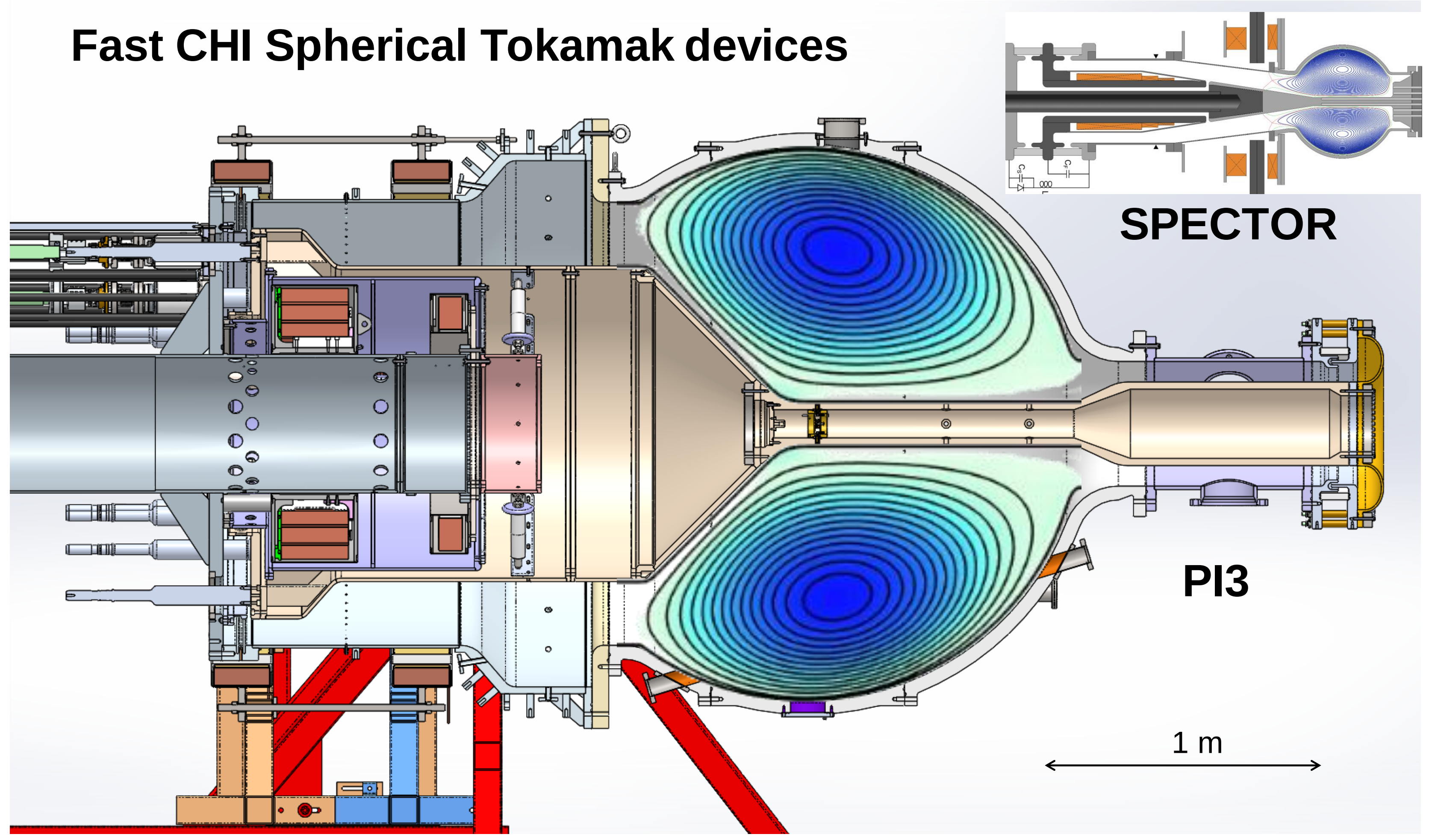


SPECTOR typically operated in the low-density edge of parameter space, just at the boundary of the run-way limit, confirmed by the detection of hard X-ray emission from a significant population of run-away electrons. High performance shots routinely achieved high temperature operation over a wide range of total plasma current.

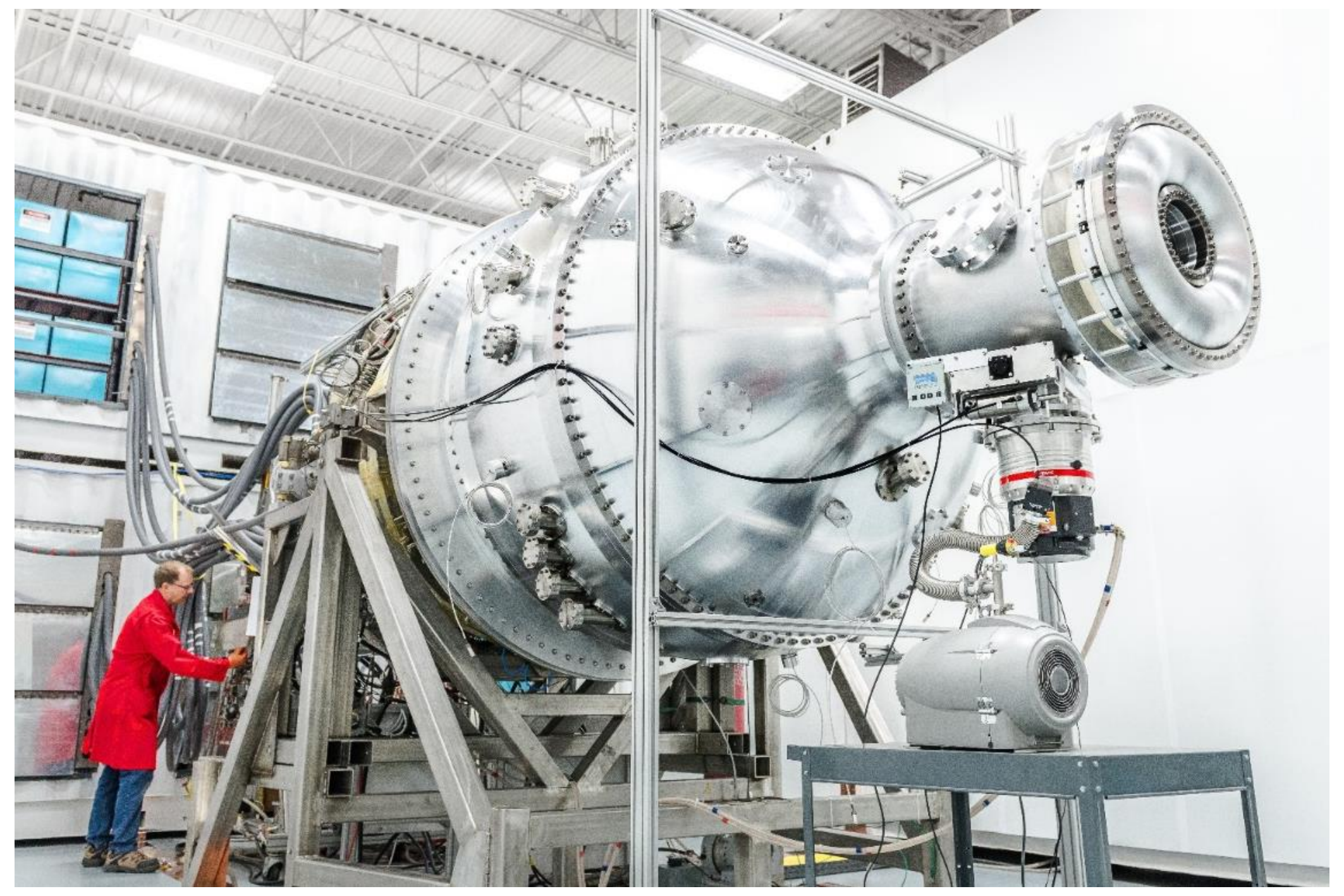
PI3 will operate in the lower range of plasma current density J, and will instead work to explore higher density conditions near the Greenwald limit.

PLASMA INJECTOR 3 DESIGN

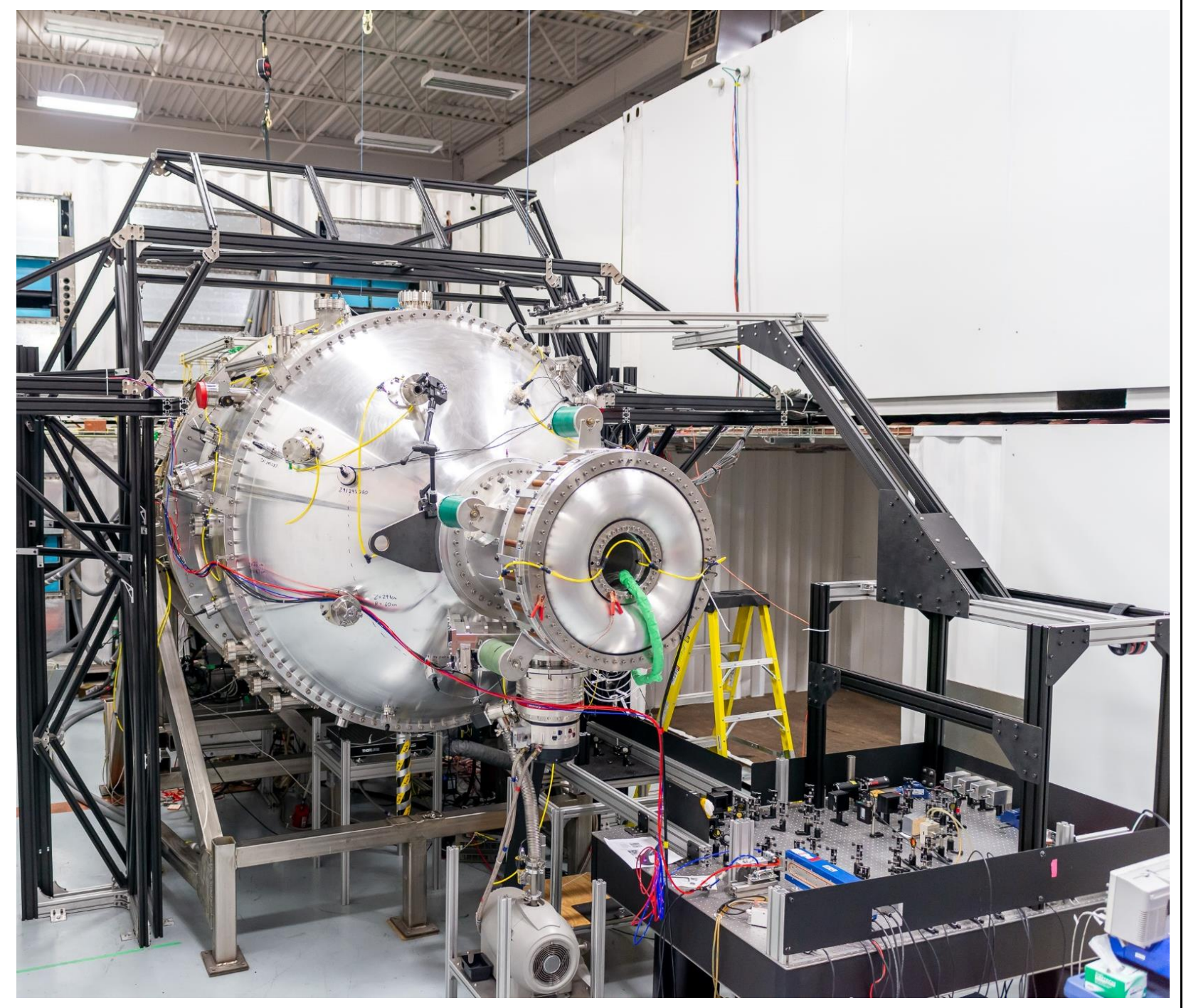
Fast CHI Spherical Tokamak devices



Mechanical drawing of PI3 vessel with overlay of magnetic equilibrium (poloidal flux surfaces). Shown at same scale is the SPECTOR device for comparison. This cross section view shows location of internal and external poloidal bias coils, central electrode structure with HV feedthroughs, load bearing support frame, primary vacuum pumping duct (center left), secondary pumping duct (center right).



Photograph of PI3 during low power commissioning phase.



PI3 with diagnostic support frame and interferometer.

PI3 uses a total of 7.6 MJ in stored capacitor energy to create an ST configuration within an aluminum flux conserver. There are 4 separate formation poloidal field bias coils which are powered by a bank of lead-acid batteries. The capacitor bank is divided up into CHI formation of 1.5 MJ (2.5 mF, 35 kV), and then a 2-stage circuit to fill and sustain the vessel with sufficient toroidal flux for q-profile to be in the ST range, the first stage rapidly reaches peak current (1.2 MA) using 1.3 MJ (27 mF, 10 kV), followed by a second active crowbar stage of 4.8 MJ (96 mF, 10 kV) that sustains the shaft current to less than 15% drop over 7ms.

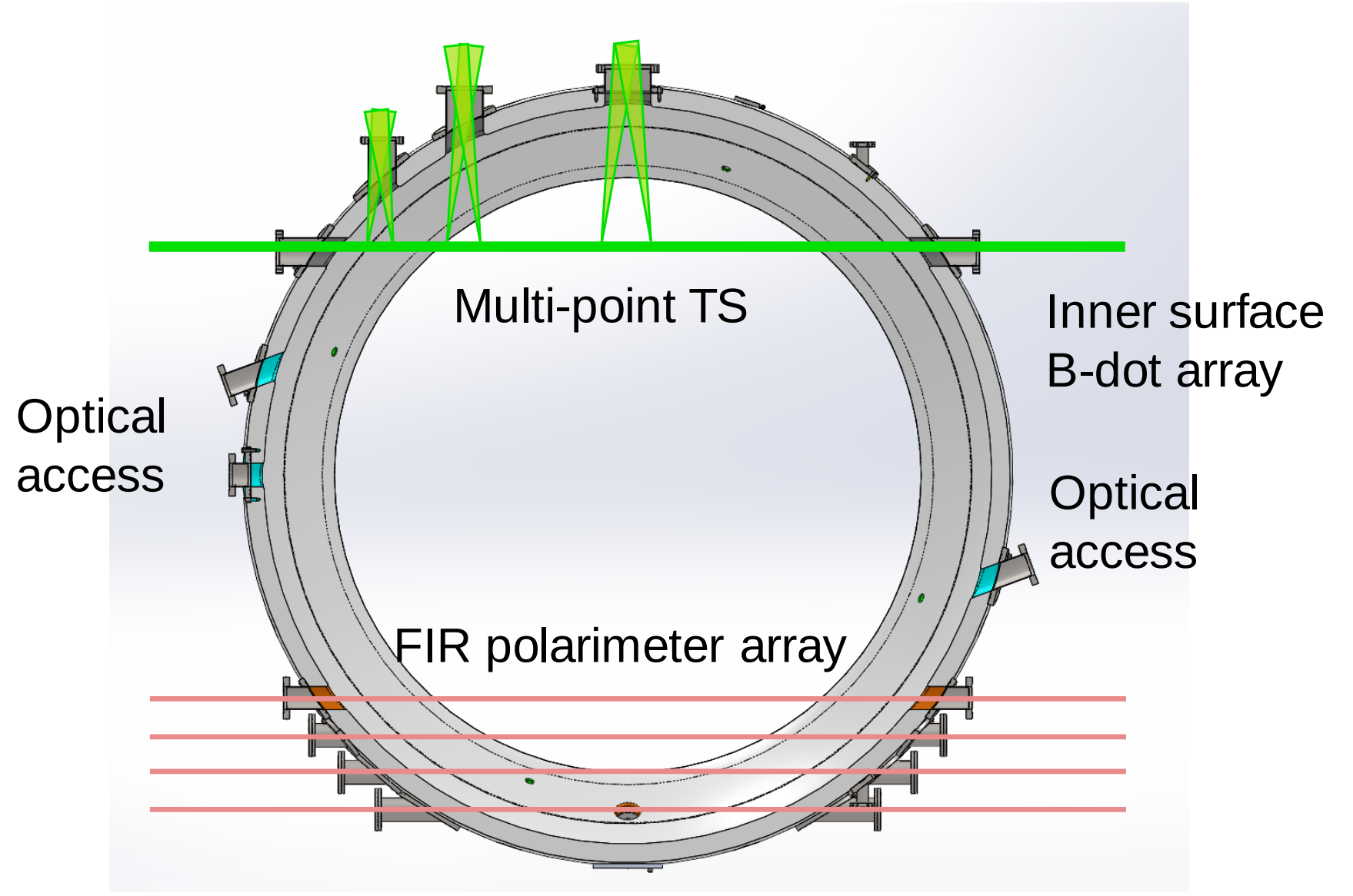
The key plasma properties will be measured during the 7 ms "flat-top" interval in order to determine the stability and thermal confinement of the target plasma in its initial, non-compressed state. In addition to verifying that the thermal confinement time is suitable for compression, the testing will explore other physics questions important to the design of the full compression system.

Fast CHI formation of an ST plasma has many advantages for an MTF application, it requires no auxiliary heating (no RF or neutral beam) to obtain sufficient pre-compression temperature, and it does not require a central solenoid or toroidal field coils, instead using current down a shaft in a manner compatible with a liquid metal compression system.

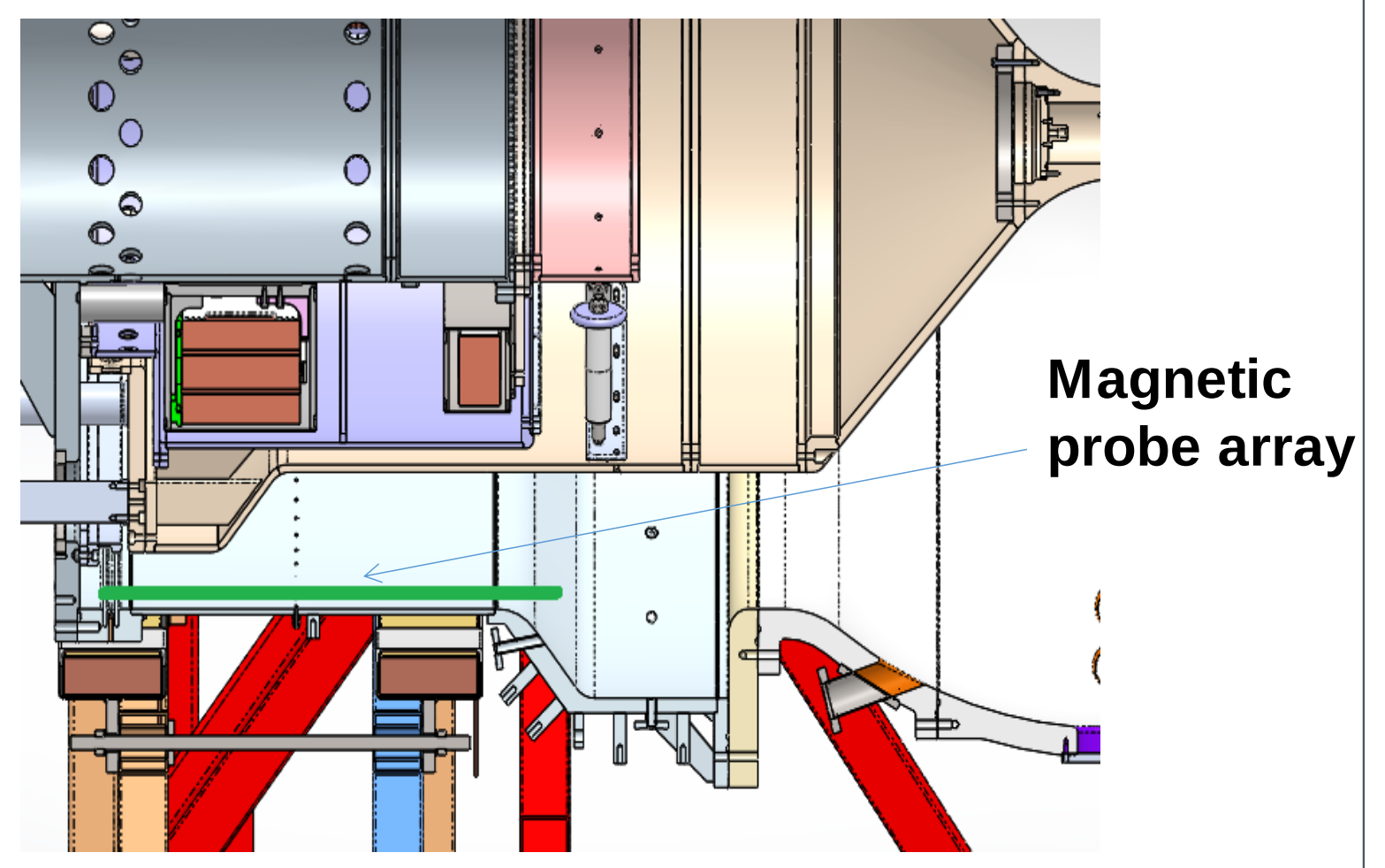
Parameter	Value range
Vessel inner radius	1 m
Major radius R	0.6 – 0.7 m
Minor radius a	0.3 – 0.4 m
Elongation κ	1 – 1.6
Triangularity δ	-0.15 – +0.1
Poloidal flux Ψ_{CT}	0.15 – 0.25 Wb
Plasma current I_p	0.3 – 0.5 MA
Shaft current I_s	1.0 – 1.2 MA
Plasma density n_e	2×10^{19} – 2×10^{20} m^{-3}
Temperature $T_e \sim T_i$	100 – 500 eV
Beta β	2% - 8 %

DIAGNOSTICS

Equatorial diagnostic plane



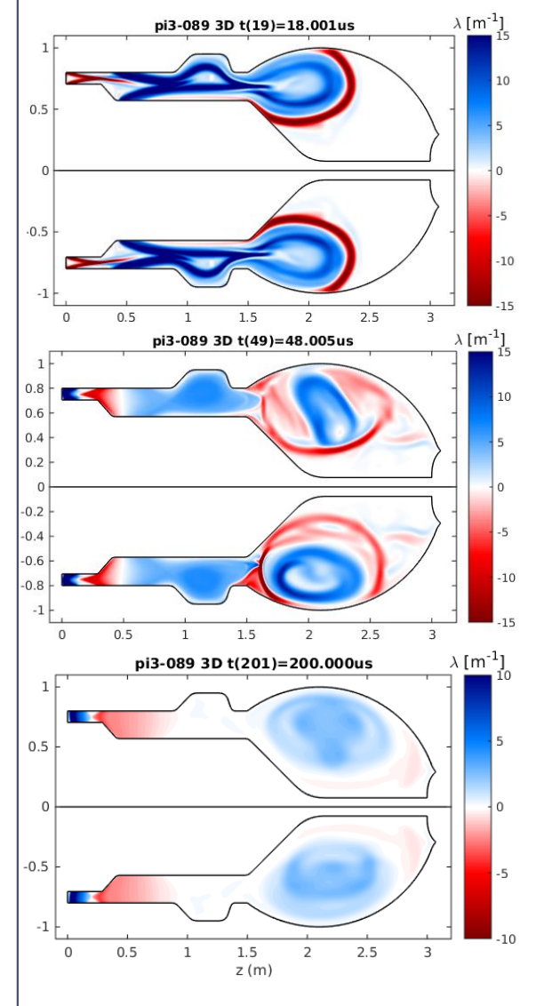
Plasma temperature will be measured using multi-point Thomson scattering, ion Doppler spectroscopy, and soft X-ray radiometry. Magnetic structure will be determined from a synthesis of surface magnetic probe array data and reconstructions from the multi-chord FIR polarimeter array. Impurity composition will be assessed through time-resolved visible and VUV spectroscopy.



The current density J_r into the vessel wall will be measured using an array of magnetic probes in a closed ceramic tube in the gun region. The data will be compared with similar measurements on Spector to determine gun wall current density scaling.

PHYSICS INVESTIGATIONS

Measurement and control of plasma profiles



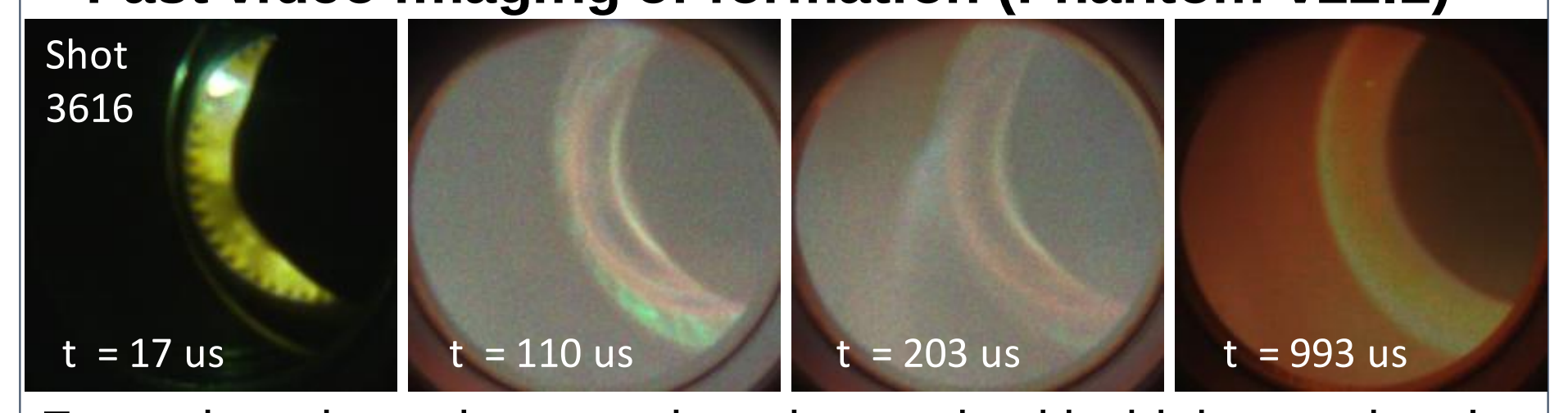
Lambda profile $\lambda(\psi) = \mu_0 J/B$ is critical for determining plasma volume, shape, Ohmic heating power and the magnetic L/R decay timescale. CHI formation relies on self-organization of plasma currents to converge on final equilibrium state. Evolution of safety factor $q(\psi)$ profile is determined by resistive MHD and choice of operational parameters for external circuit. MHD stability of the plasma as a whole is determined both by $q(\psi)$ and gradients in $\lambda(\psi)$. Temperature and density profiles will also be measured and combined with full set of diagnostic data to produce models of plasma structure and evolution.

Fluctuations and edge physics Analysis and modeling of fluctuation data, from magnetic probes, X-ray and optical radiometry, interferometry can provided constraints on plasma profiles and dynamic processes. Interaction with the wall and the physics within the edge region is critical to the work in MTF.

Transport and radiative losses The ultimate goal of this work is to demonstrate sufficiently low thermal losses such that significant heating can occur during MTF compression. Quantitative bounds on actual energy loss pathways are needed in order to better understand scaling laws for this class of self-organized ST plasma device.

PI3 INITIAL OPERATION

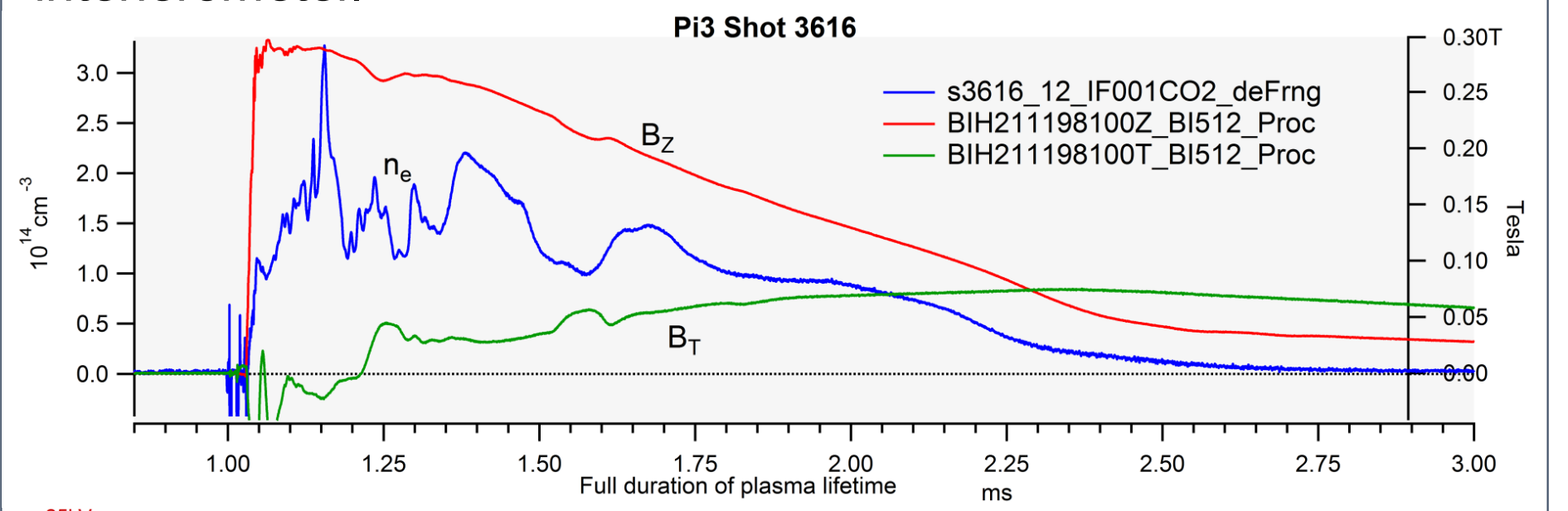
Fast video imaging of formation (Phantom v12.1)

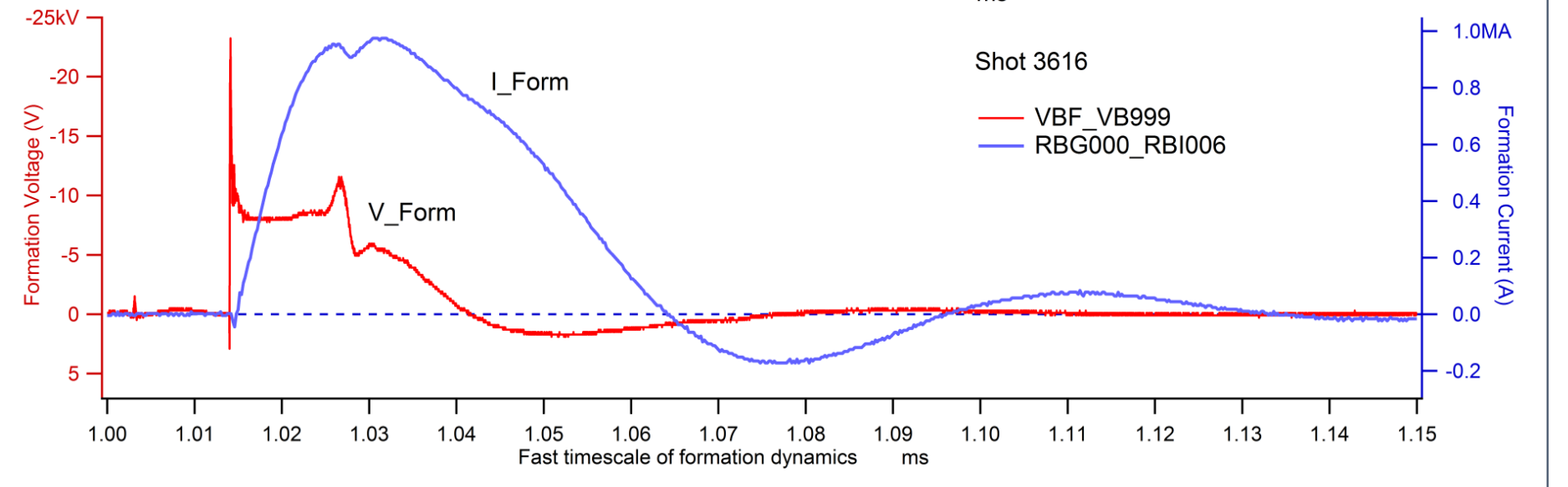


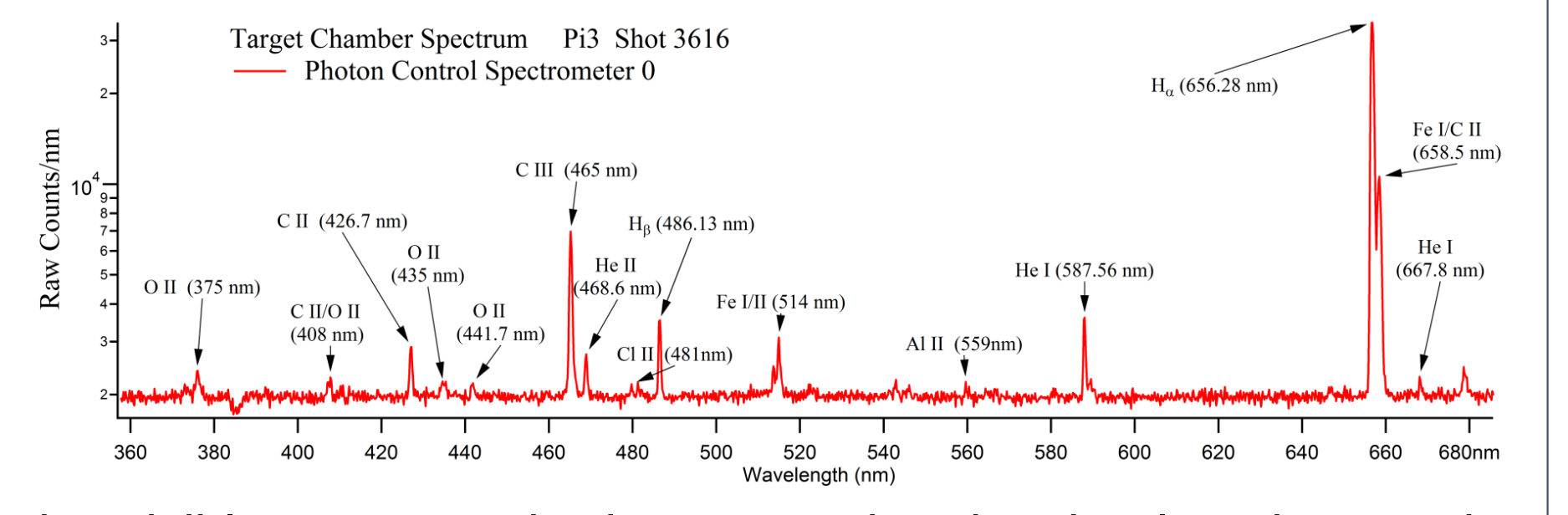
Formation dynamics can be observed with high-speed color videography (22 μs exp). Looking back into the gun it shows (left to right) breakdown of gas plumes from valves, emergence of ST into the chamber, having uniform glow and occasional helical structure, then decays to a reddish glow dominated by hydrogen.

The PI3 vacuum vessel was completed and low power plasma shots were started in December 2017. The capacitor bank power supplies are inside of the shipping containers which surround the main vacuum vessel. The 1.5 MJ formation power is being slowly being tested to higher current. The peak current at full power will be 3.5MA. The initial testing is being done without the 2 stage shaft power supply. The shaft power supply will be integrated into the system starting in November 2018 and reaching full power in March 2019. The formation capacitor bank containers (photo on the left) house 6 capacitor banks in each of the 2 containers. Each bank has 4 (52 uF, 44 kV) capacitors, one railgap switch, and crowbar diodes across the caps to limit the voltage reversal. The shaft power supply (not show) is housed in 6 containers. The first stage has 24 banks of 6 (185 uF, 11 kV) caps with an ignitron switch. The second stage has 6 banks of 8 (2 mF, 11 kV) caps with an ignitron switch. They go to 3 20:1 pulse transformers.

Data from a low power test shot is shown below. Peak formation current is 1 MA. The poloidal and toroidal B field traces at the outer wall of the flux conserver equator are shown along with the line average plasma density as measured by a CO2 laser interferometer.







The visible spectrum in the target chamber is also shown. The gas puff was helium, but the spectrum shows primarily hydrogen sourced from the unconditioned vessel walls. The relatively short life (2 ms) is expected at low power and without good wall conditioning. The expected lifetime at full power is > 25 ms.