PHYSICS OBJECTIVES OF PI3 SPHERICAL TOKAMAK PROGRAM

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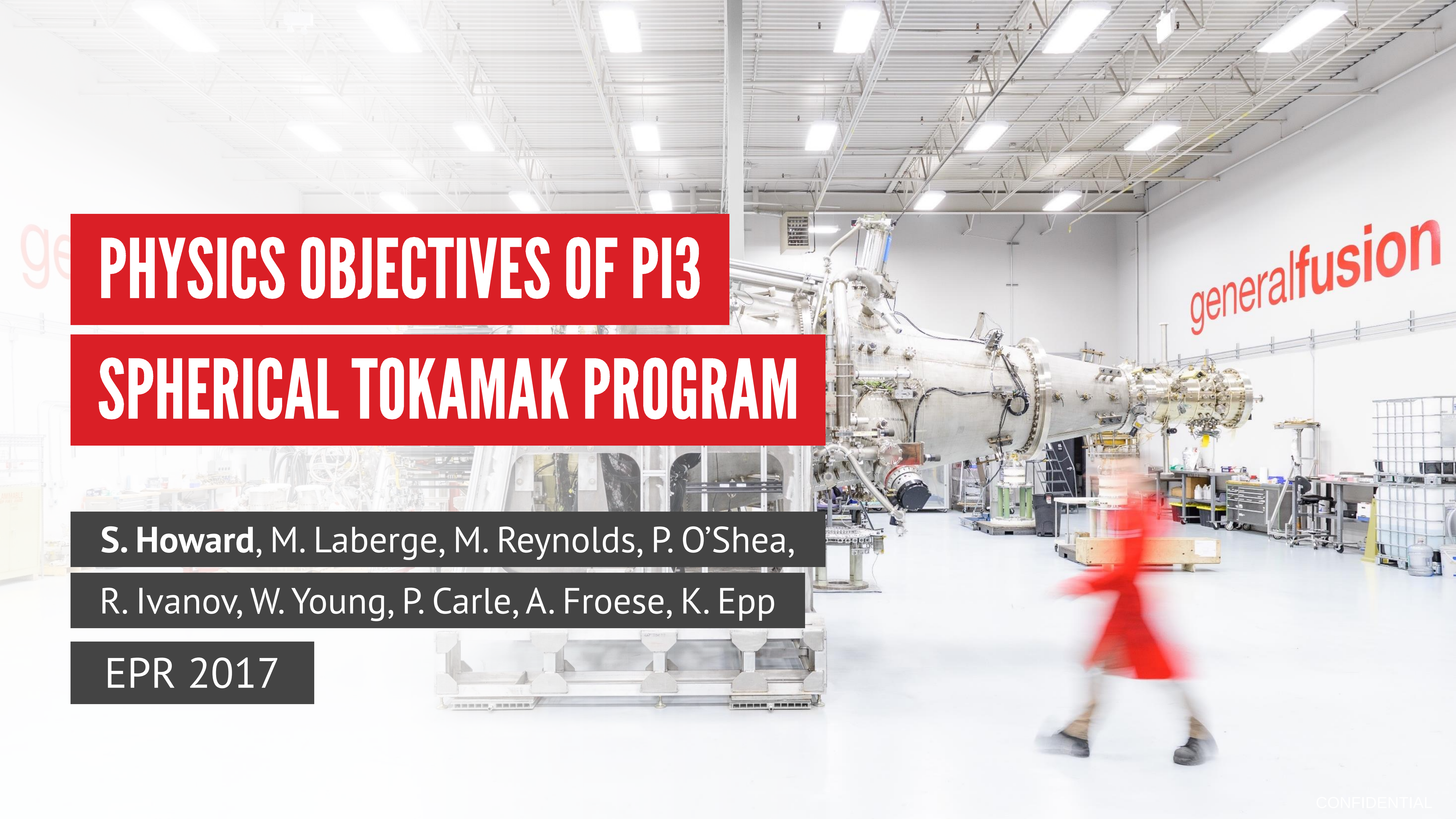
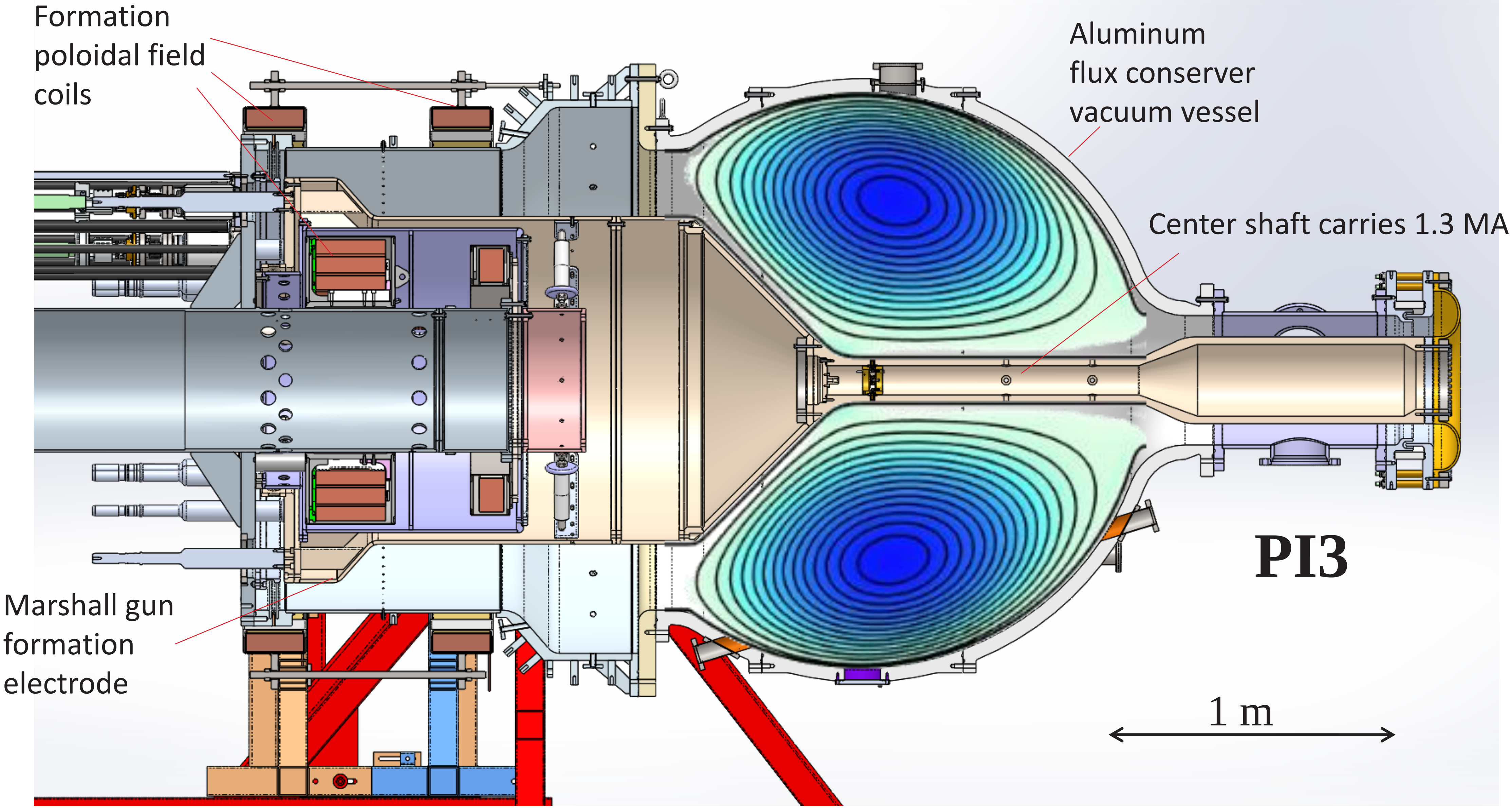
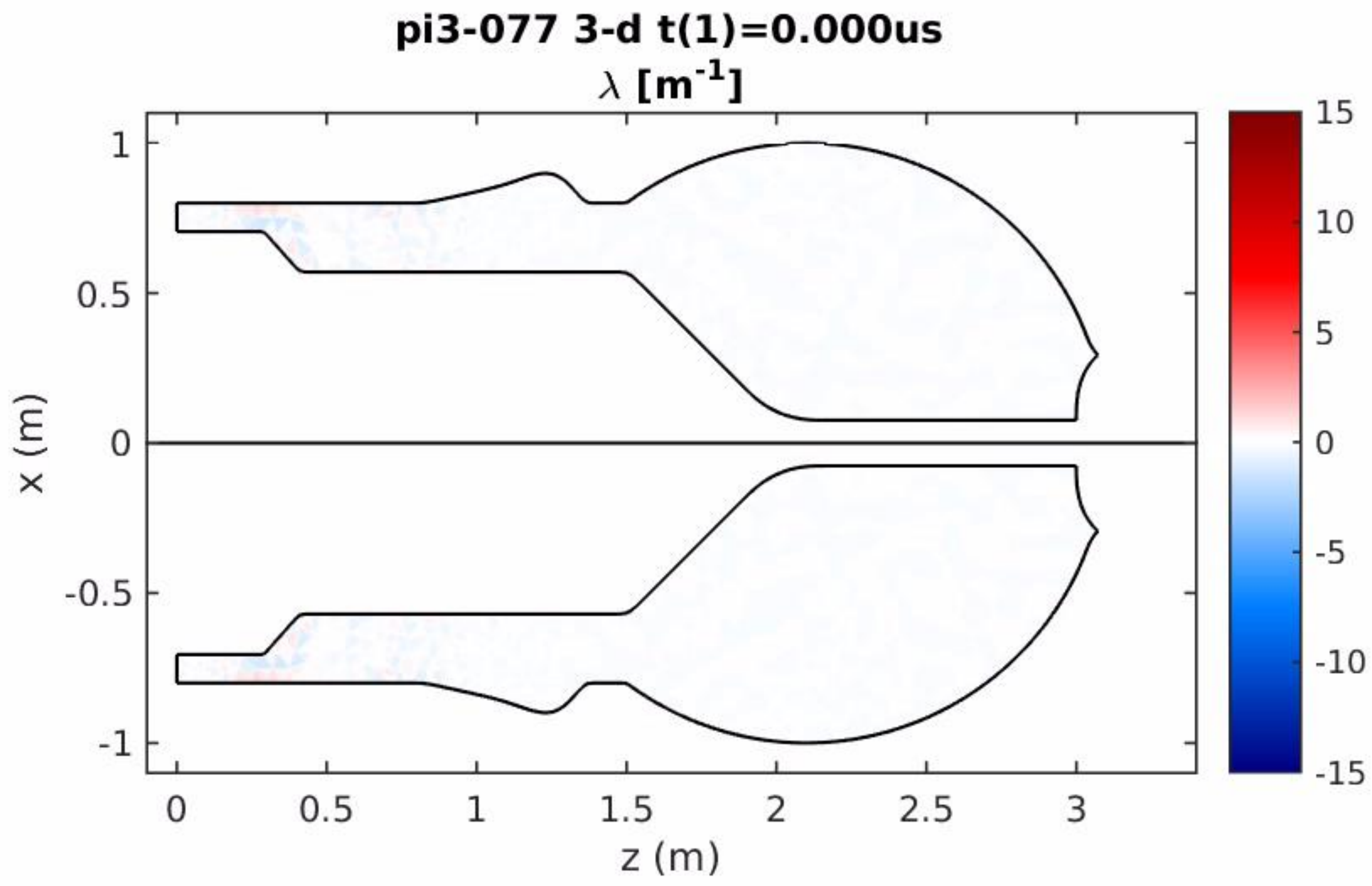


PI-3 Device Overview



Fast CHI Formation into Pre-Existing Toroidal Field



3D MHD simulation (VAC) of ST formation process.

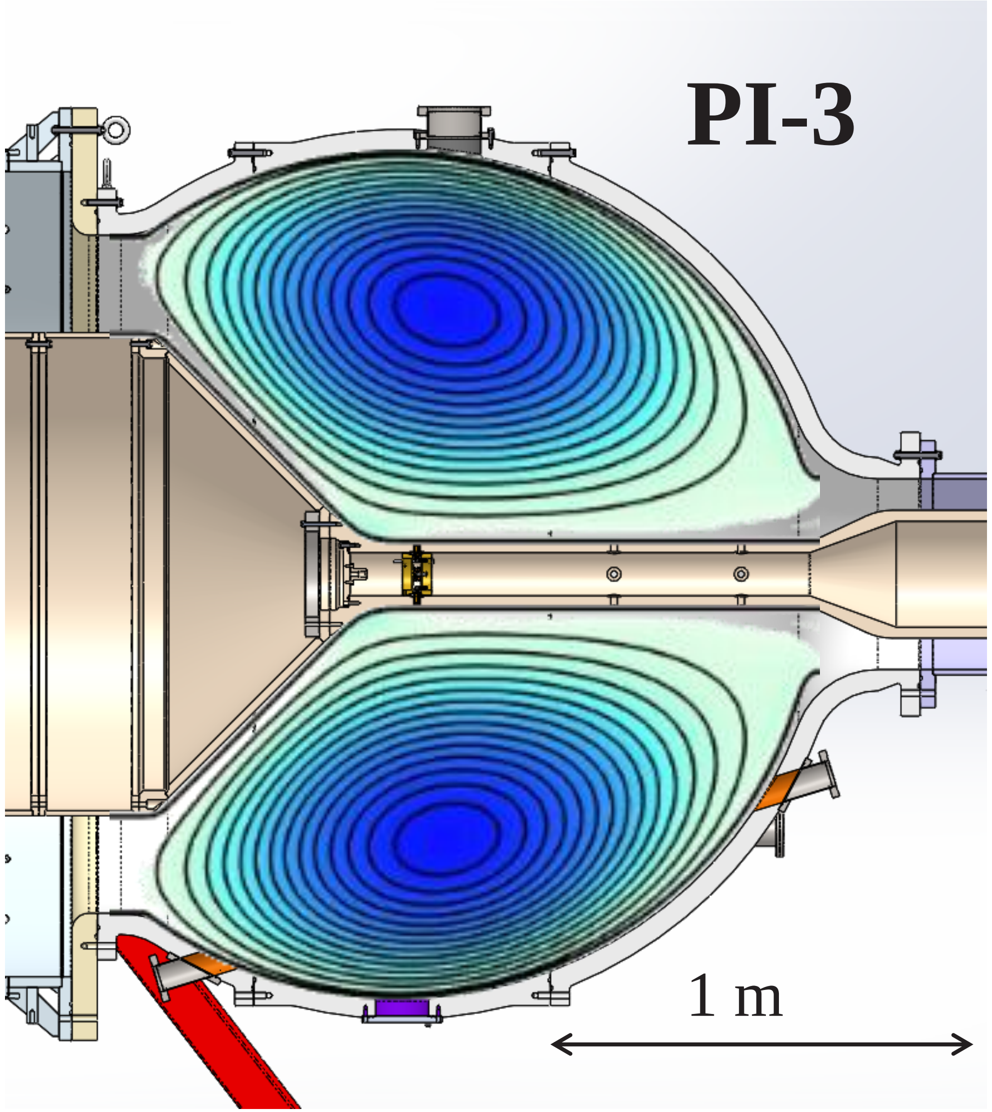
Shows evolution of $\lambda = \mu_0 J_{||}/B$.

Shaft current of 1.2 MA rising to 1.3 MA. Plasma current of 750 kA falling to 500 kA

Negative λ regions (blue) exist in this simulation that causes plasma to stay small.

Steep gradients go unstable and it reorganizes into a larger object with less hollow profiles, q becomes >1.

Basic Parameters

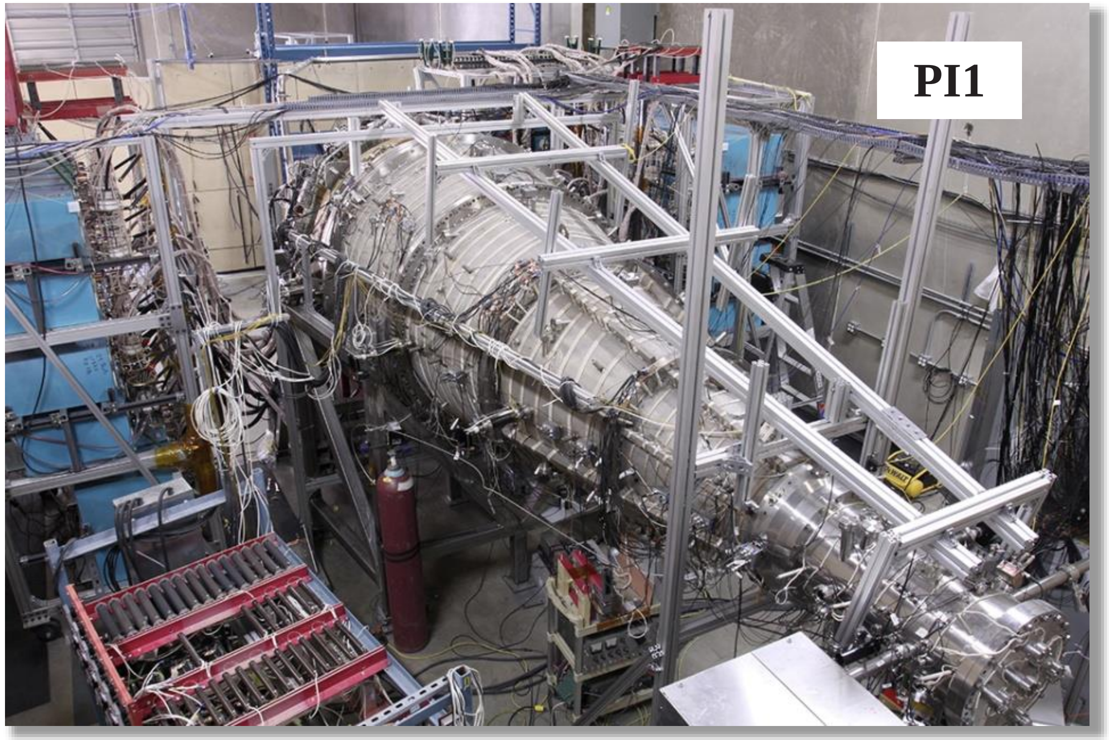


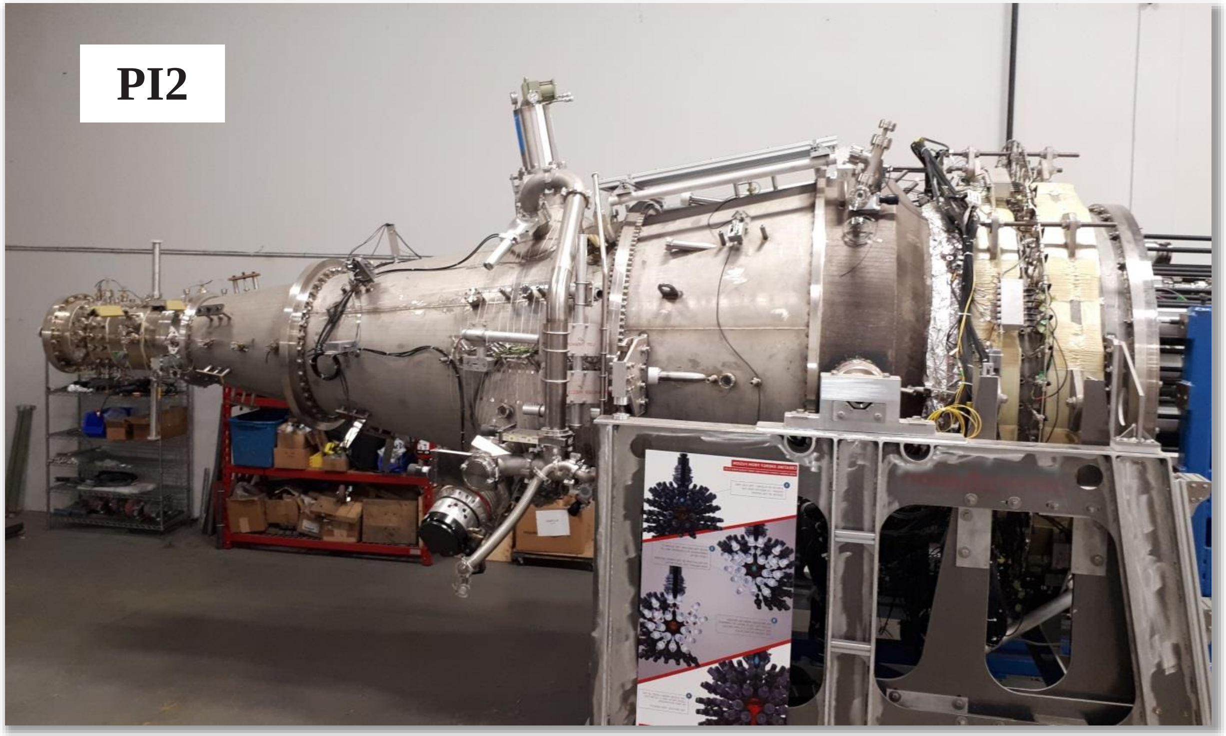
Parameter	Value range
Vessel inner radius	1 m
Major radius R	0.6 – 0.7 m
Minor radius a	0.3 – 0.4 m
Elongation κ	1 – 1.6
Triangularity δ	-0.15 – +0.1
Poloidal flux Ψ_{CT}	0.15 – 0.3 Wb
Plasma current I_p	0.3 – 0.6 MA
Shaft current I_s	1.0 – 1.3 MA
Plasma density n_e	2×10^{19} – 2×10^{20} m^{-3}
Temperature $T_e \sim T_i$	100 – 500 eV
Beta β	2% - 8 %

Plasma Injectors 1 and 2

PI-1 and PI-2 were 2-stage coaxial Marshall gun/railgun accelerator systems producing spheromak plasmas. They explored:

- high density (10^{22} m^{-3})
- medium initial temperature (100 eV)
- fast compression ($R_0/R = 4$, $\Delta t =$ 30 μs)

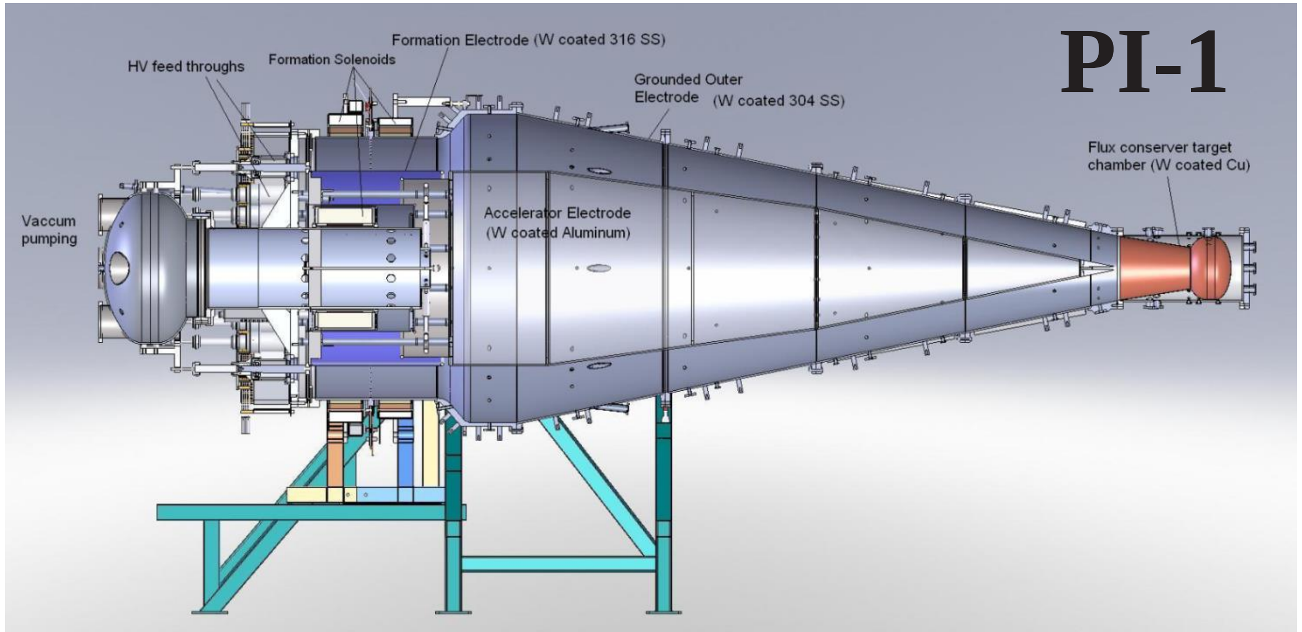


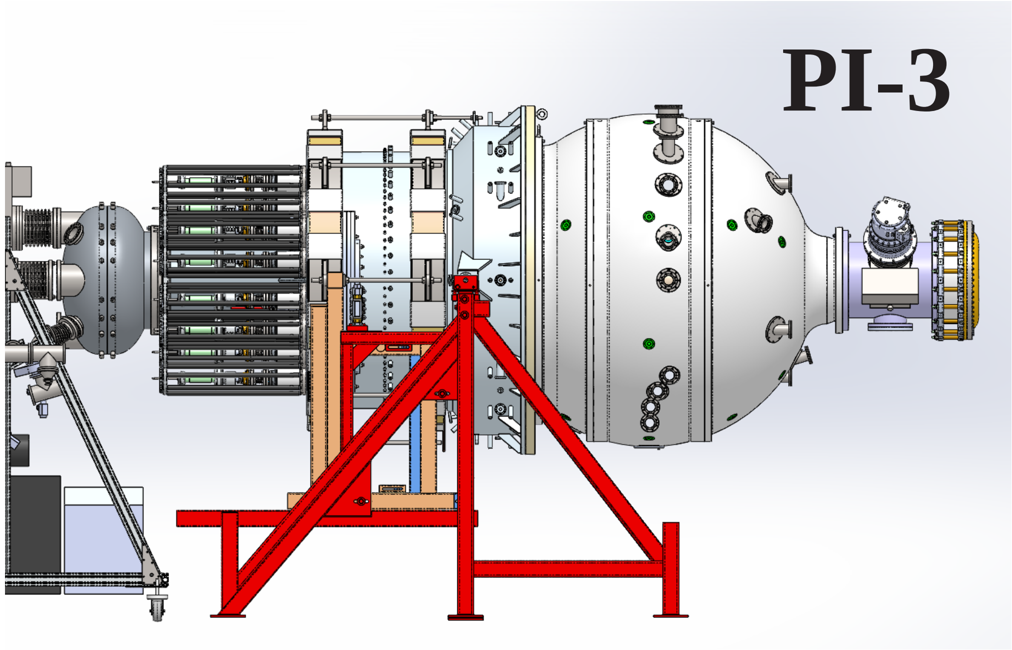


The accelerating railgun electrodes were conically converging to achieve the 4x radial compression to bridge the gap between the densities achievable with Marshall gun formation, and what was required for the initial state of the proposed MTF compression scenario.

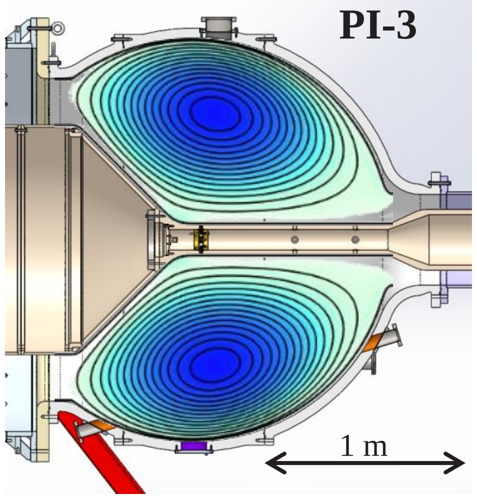
Comparison between PI-1 and PI-3

- Same outer vessel formation section, HV feedthroughs, gas puff array.
- New inner formation coils (PI-1 could reach 120 mWb, PI-3 can reach 300 mWb).
- PI-3 has new large spherical flux conserver.
- Repurpose existing hardware, infrastructure from PI-1, 2 devices as practical way to save cost.
- PI-1 explored an MTF scenario relying on high density, fast compression, small physical size.
- PI-3 is exploring the plasma physics pre-requisites of a slower, lower-density MTF scenario.
- This shift is motivated in part by the improved thermal confinement of spherical tokamaks over spheromaks.





Power Supply for PI-3



PI-3 will use a total of **10MJ** stored capacitor energy

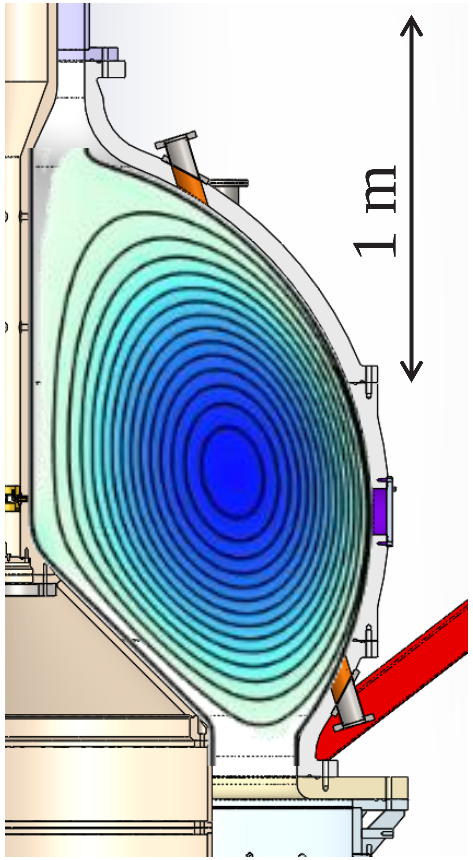
The capacitor bank is divided up into:

- CHI formation of **1.5 MJ** (2.5 mF, 35 kV),
- Two-stage circuit to fill and sustain the vessel with sufficient toroidal flux for q(Ψ) > 1
  - the first stage rises in 500 μs to peak current (1.3 MA) using **2 MJ** (40 mF, 10 kV),
  - followed by a second, active crowbar stage of **6.4 MJ** (128 mF, 10 kV) that maintains the current against resistive losses in the conductors. Flat-top of 7 ms.

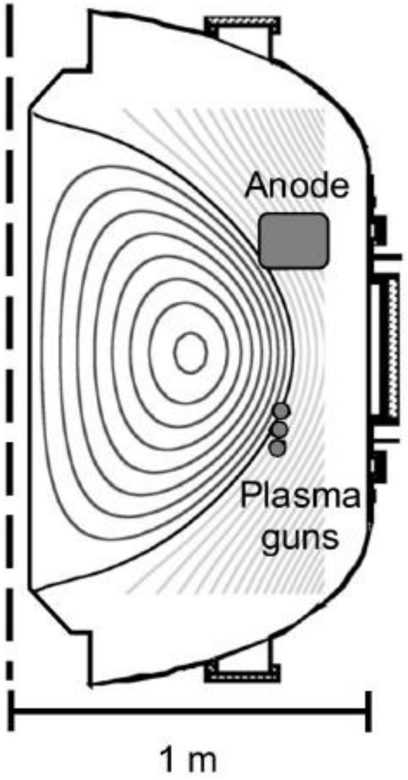
- Formation poloidal field bias coils are powered by a bank of lead-acid batteries.

- For comparison, CHI bank energy of NSTX = 25-100 kJ, SPECTOR = 200-375 kJ

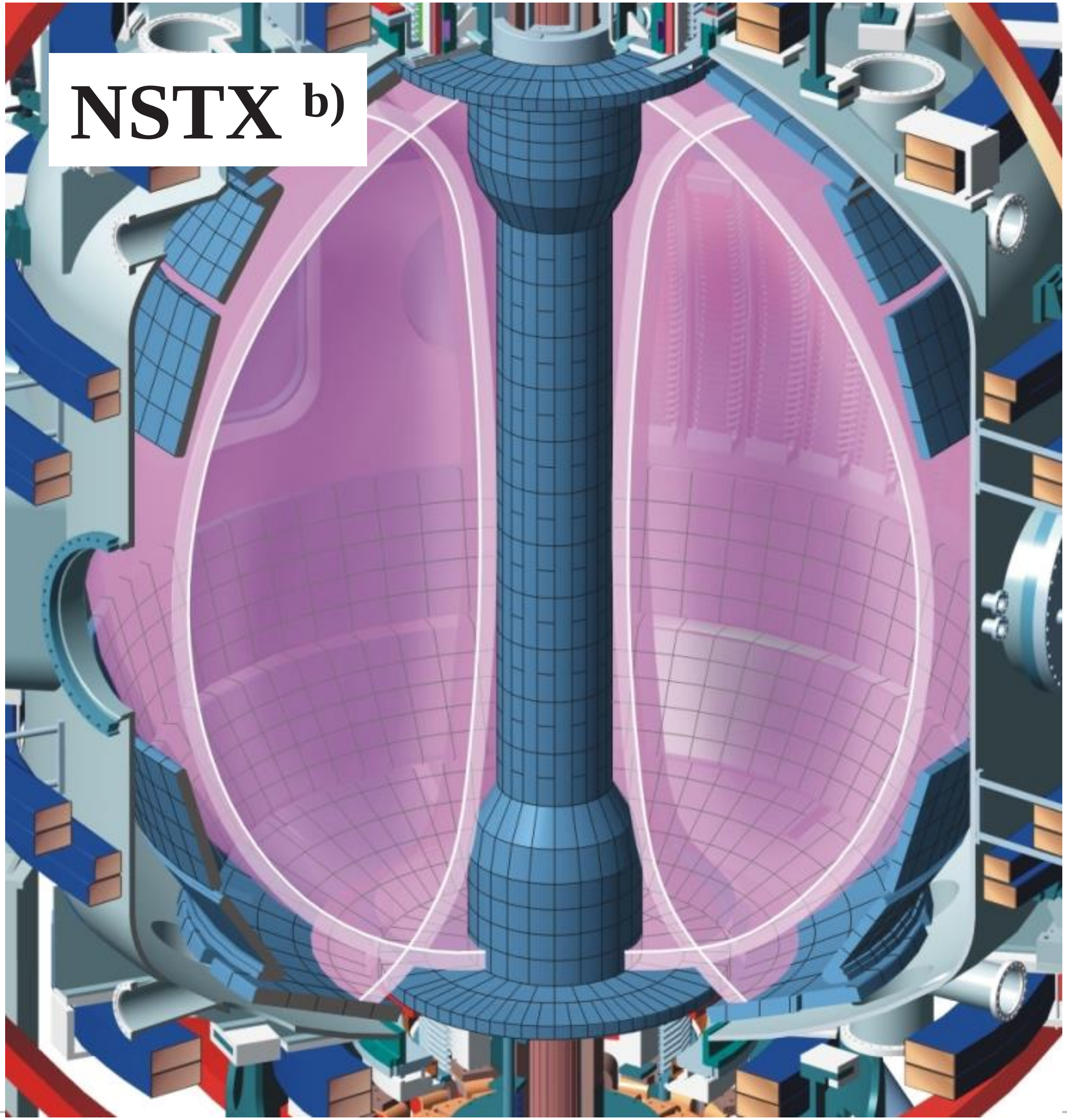
PI-3



Pegasus a)

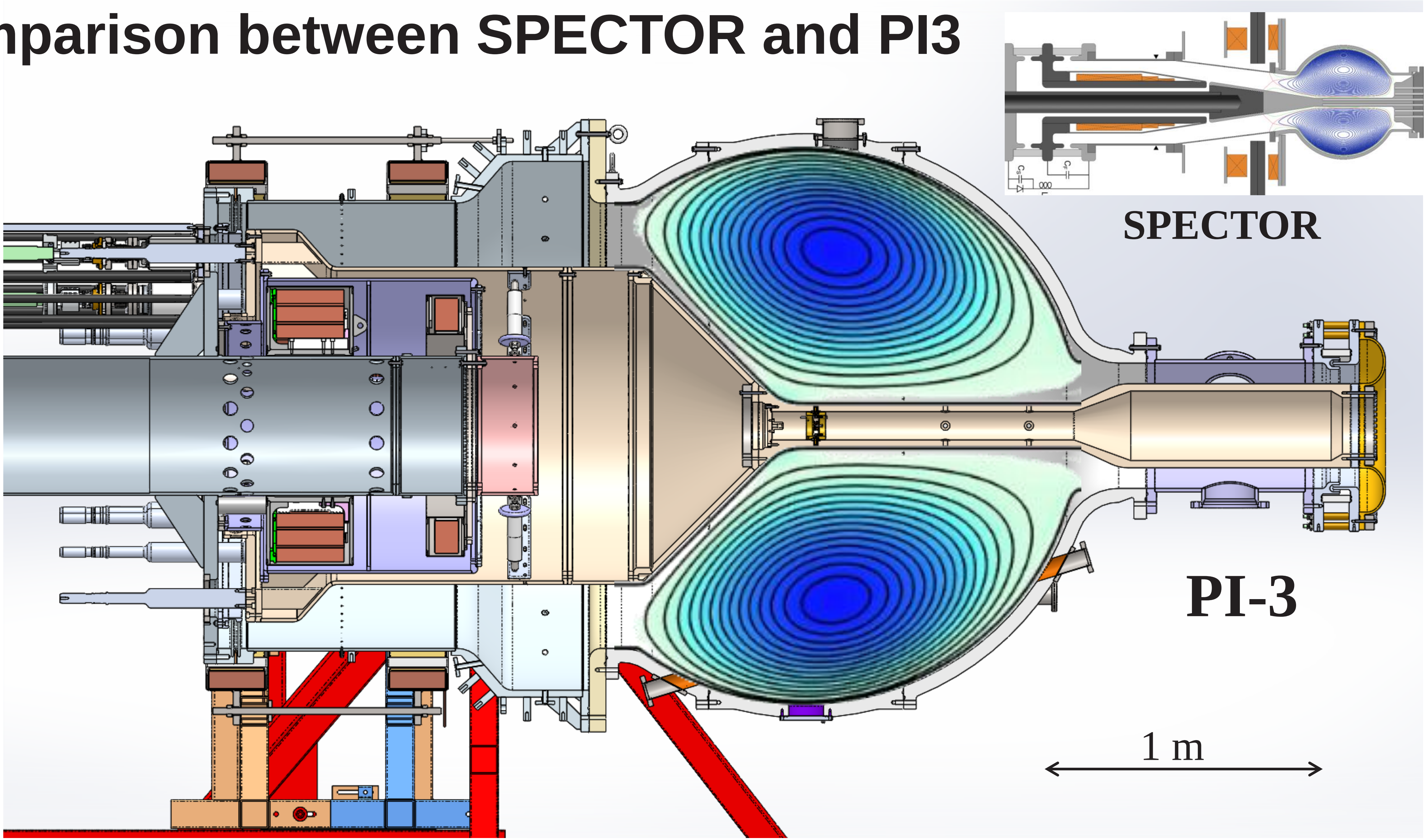


NSTX b)



a) D. J. Battaglia, et al, PRL 102, 225003 (2009)
b) http://nstx.pppl.gov (2017)

Comparison between SPECTOR and PI3

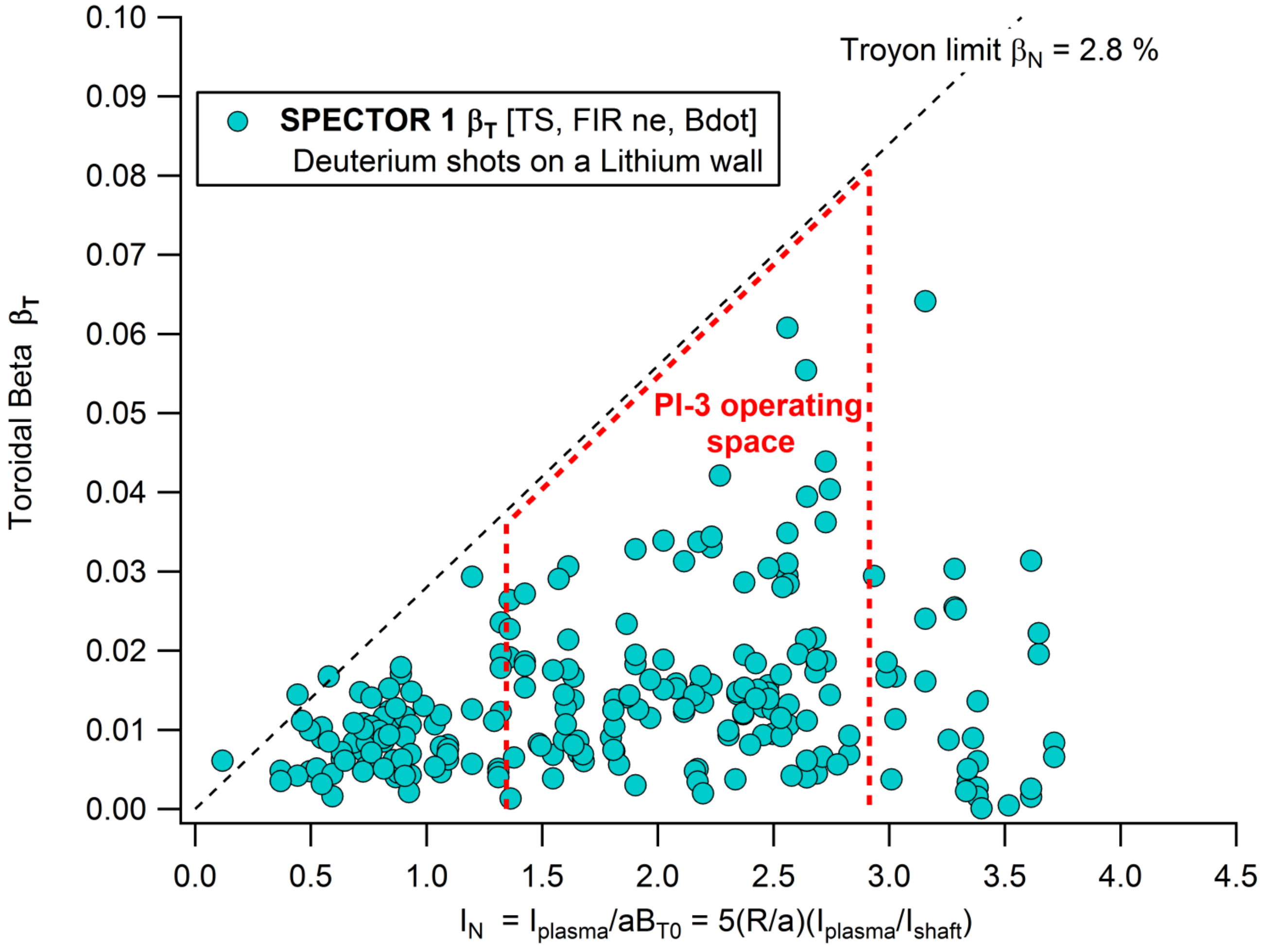


Comparison between SPECTOR and PI3

PI-3 is very similar to the SPECTOR sequence of devices in design and operation.

- Increasing device radial size by 5x is expected to yield magnetic lifetime increase of 25x. (Poloidal flux total lifetime of 2 ms → 50 ms, however PI-3 TF flattop is only 7 ms due to power supply limit, but sufficient to study 3ms MTF scenario)
- Maximum temperature of PI-3 is expected to be similar (400-500 eV).
- PI-3 has a factor of 20x increase in poloidal flux over SPECTOR
- 20x increase of total magnetic energy.
- 13x increase in terms of total cap bank energy.

Beta Scaling

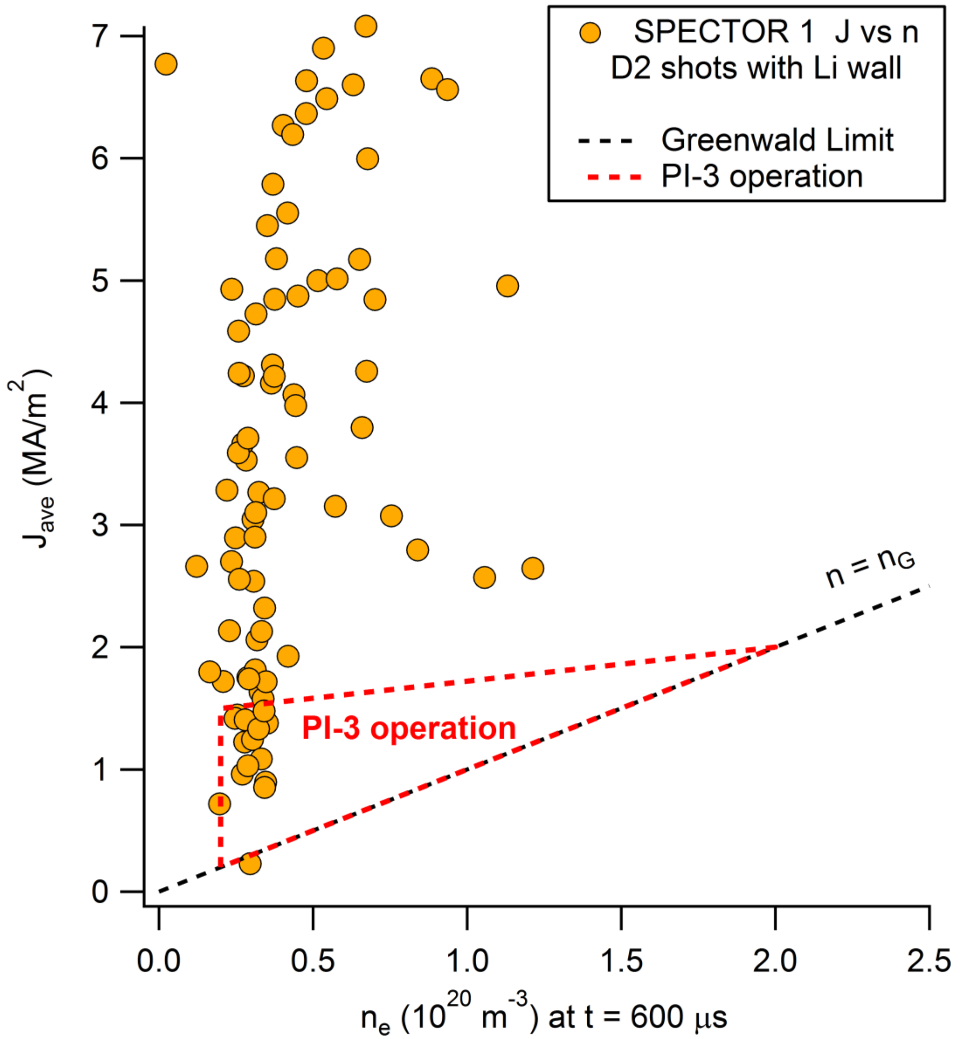


SPECTOR achieved its best performance in terms of temperature, overall magnetic lifetime, and plasma stability at a relatively low-β range, 1- 5% , bounded by the empirical Troyon limit for Ohmically heated tokamaks, which is reasonable considering SPECTOR's lack of additional heating.

PI-3 is expected to operate in a similar range of β values. This should be acceptable for an MTF target plasma:

- Initial pre-compression state needs to be low β to prevent crossing a β-limit as the compression increases beta ($\beta \sim R_0/R$ for the perfect adiabatic spherical case).
- This would convert intial β_0 = 5%, into a peak value of β_{Final} = 50% in a 10:1 radial compression scenario.

J/n parameter space



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.

PI-3 will operate in the lower range of plasma current density J, and will instead work to explore higher density conditions near the Greenwald limit.

Motivation: Stepping Stone to MTF Demonstration

Requirements of MTF target plasma

- ❑ Plasma formation method is compatible with compression by liquid metal flux conserver
  (No TF coils, but shaft is OK, No solenoid, No neutral beam heating) → Fast CHI formation
- ❑ Total inventory of confined particles is sufficient for Lawson criteria for a given compression trajectory
- ❑ Sufficient magnetic flux to confine plasma energy in a stable manner throughout compression
- ❑ High enough, but not too high, initial temperature, value dependent on compression trajectory
- ❑ Sufficient thermal confinement time, at least several times longer than compression time *

Plasma Injector 3 Objectives:

- Explore the physics of MTF reactor-scale plasmas
- Demonstrate performance goals on total inventory, magnetic flux, and energy confinement time. These goals are a >10x increase from previous MTF experiments completed by GF.
- Remove technical risks for building full-scale prototype of repetitively operated non-destructive compression device that is capable of reaching 10 keV temperature range.

- [ ] Sufficient thermal confinement time, at least several times longer than compression time *

Need to carefully consider thermal transport during compression

Analytic consideration is usually limited to the ideal adiabatic case, for spherical compression we have:

$$\frac{n(t)}{n_0} = C_R^3, \quad \frac{T(t)}{T_0} = C_R^2, \quad \frac{B(t)}{B_0} = C_R^2, \quad \frac{p(t)}{p_0} = C_R^5, \quad \frac{\beta(t)}{\beta_0} = C_R.$$

where $C_R(t) = R_0/R(t)$ is the radial compression factor. Typically, to include thermal losses a full numerical approach is taken. However much insight can be gained by looking at thermal diffusion within a periodic cylinder approximation of a torus (ρ = minor radius), compressed in a spherical scaling. A solution for the temperature evolution exists of the form:

$$T(\rho,t) = T_0\, C_R^2(t) \exp\left(-\frac{j_{01}^2}{a_0^2}\int_0^t \chi_E(t) C_R^2(t) dt\right) J_0\left(\frac{j_{01}}{a_0} C_R(t)\rho\right)$$

where j_{01}= 2.4048 is the first root of Bessel function $J_0(x)$, a_0 = initial minor radius of plasma, and χ_E is the global thermal diffusivity, which is possibly a function of time. The time-dependent part *T(t)* further simplifies for a class of compression trajectories with constant χ_E of the form:

$$C_R(t) = \left(1 - \frac{t}{\tau_{acc}}\right)^{-1/2} \longrightarrow T(t) = T_0\, C_R^{\epsilon}(t) \qquad \epsilon \le 2$$

- Sufficient thermal confinement time, at least several times longer than compression time *

$$C_R(t) = \left(1 - \frac{t}{\tau_{acc}}\right)^{-1/2} \longrightarrow T(t) = T_0\, C_R^{\epsilon}(t) \qquad \epsilon \leq 2$$

The values of χ_E, ε, and τ_{acc} are related through:

$$\chi_E = \frac{(2-\epsilon)}{2}\left(\frac{a_0}{j_{01}}\right)^2 \tau_{acc}^{-1}$$

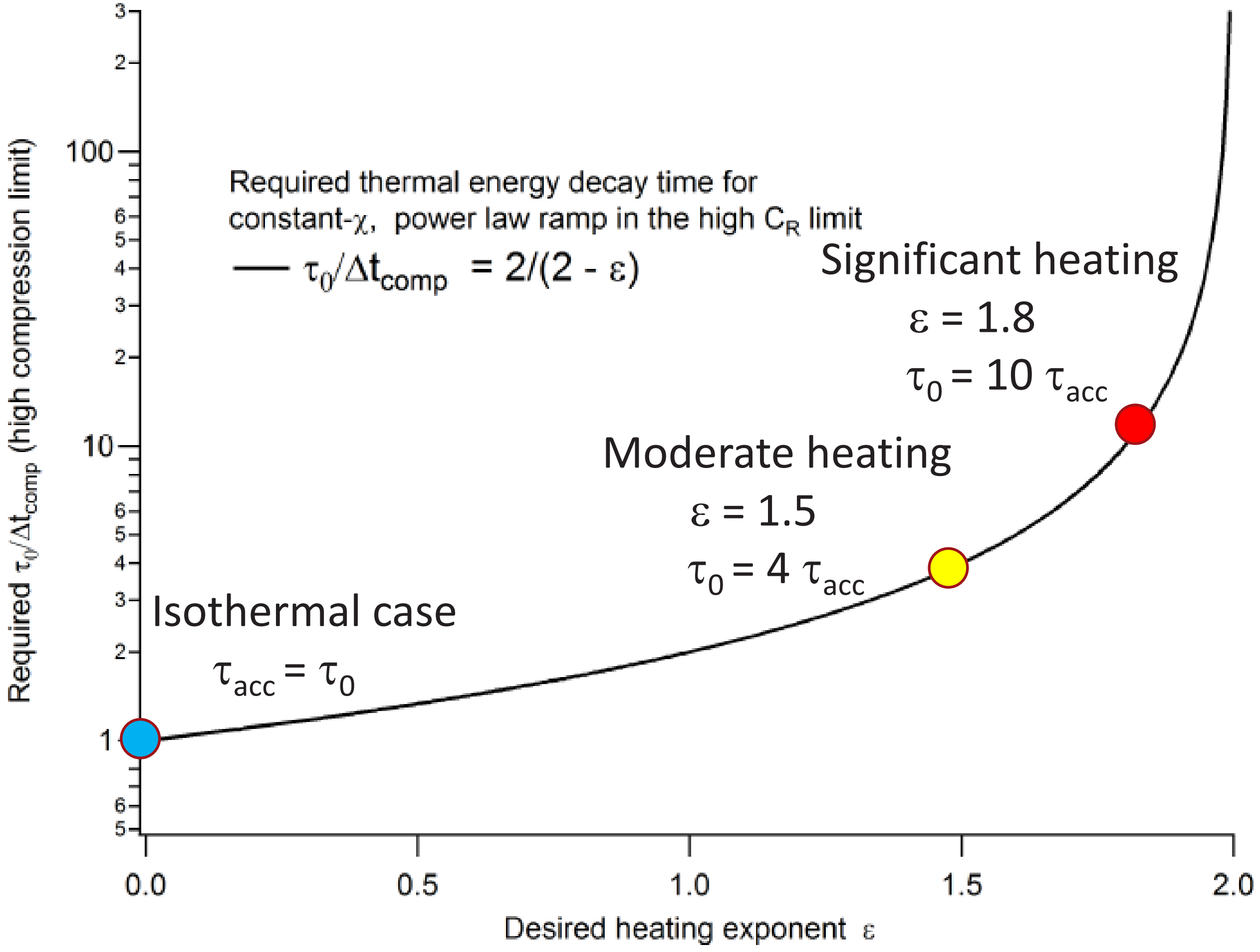
Thermal diffusivity χ_E is related to initial thermal confinement time τ_0 by:

$$\chi_E = (a_0/j_{01})^2/\tau_0$$

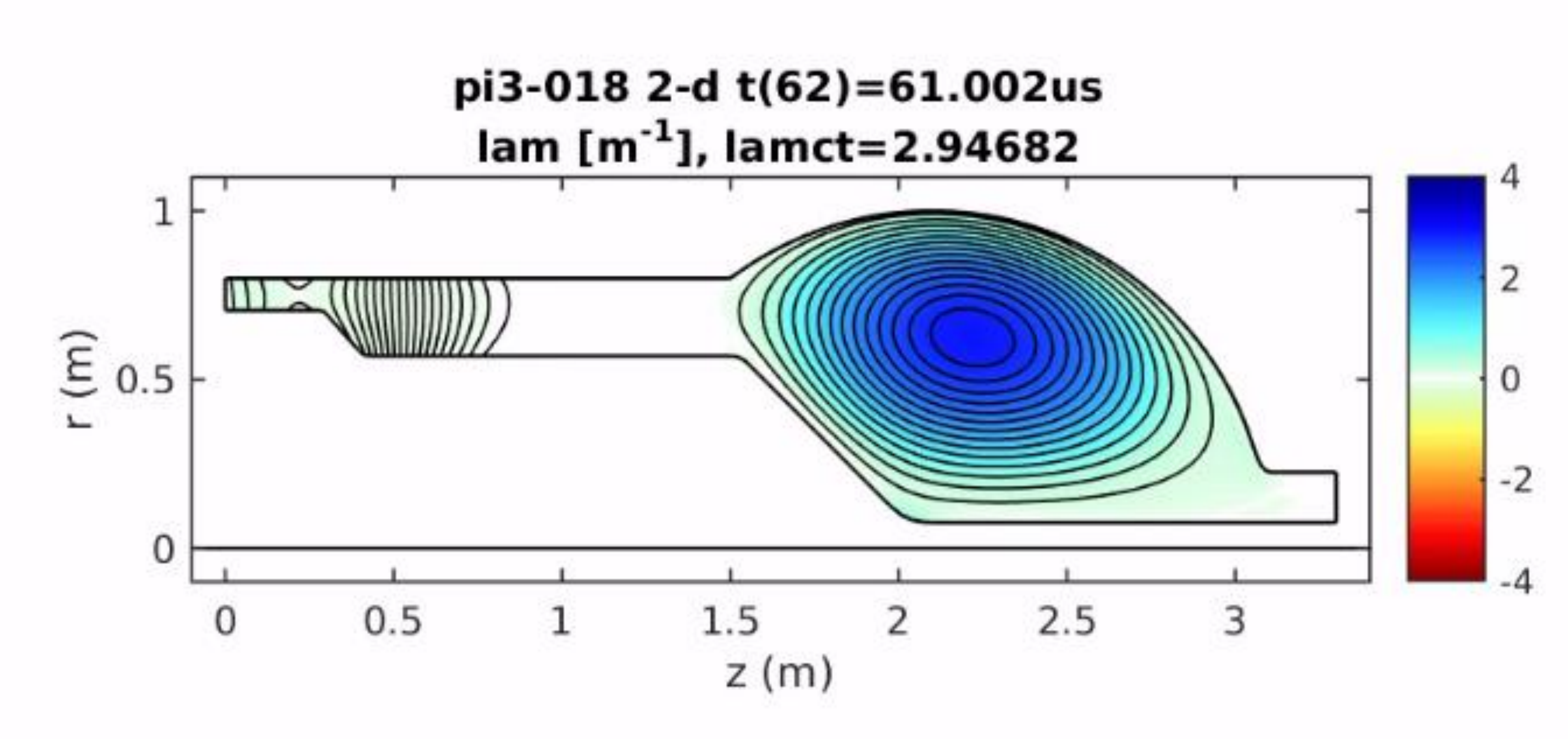
Slightly simpler to work with thermal τ_0 and total Compression time Δt_{comp}.

$$\tau_{acc} = \left(\frac{2-\epsilon}{2}\right)\tau_0 = \frac{\Delta t_{comp}}{1 - C_{max}^{-2}}$$

$$\frac{\tau_0}{\tau_{acc}} = \frac{2}{(2-\epsilon)} = \frac{2}{\left(2 - \frac{\ln(T/T_0)}{\ln(C_R)}\right)}$$

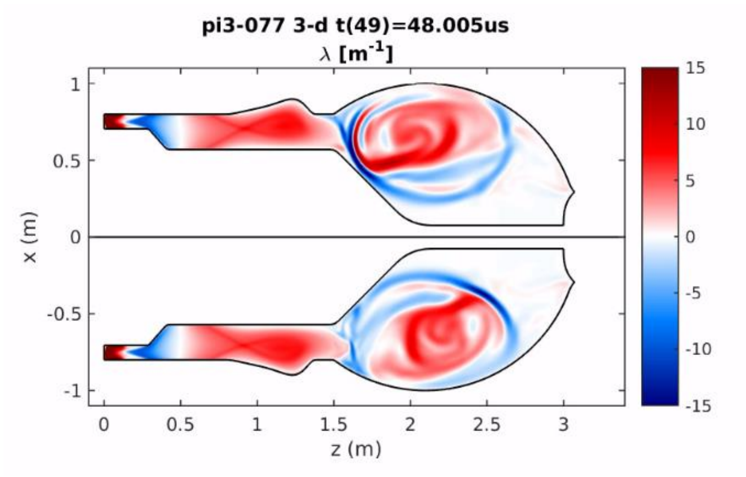


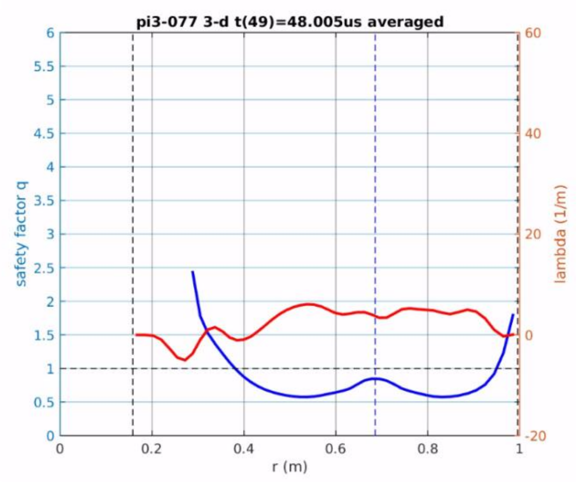
Need to measure thermal transport on PI-3

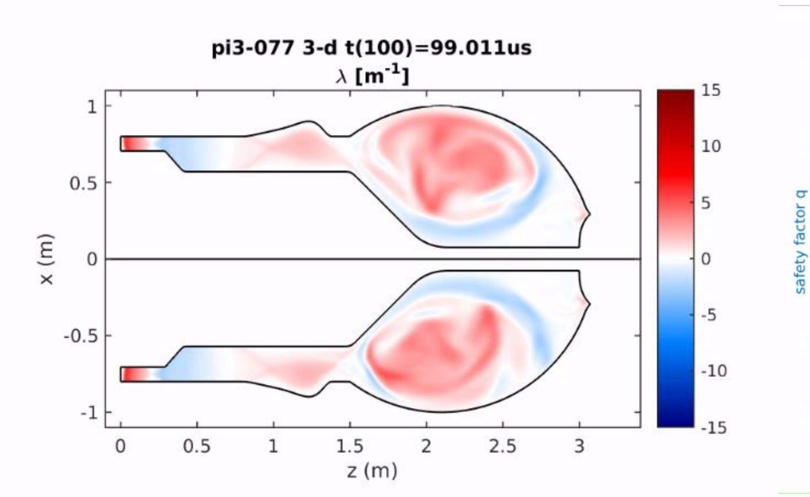


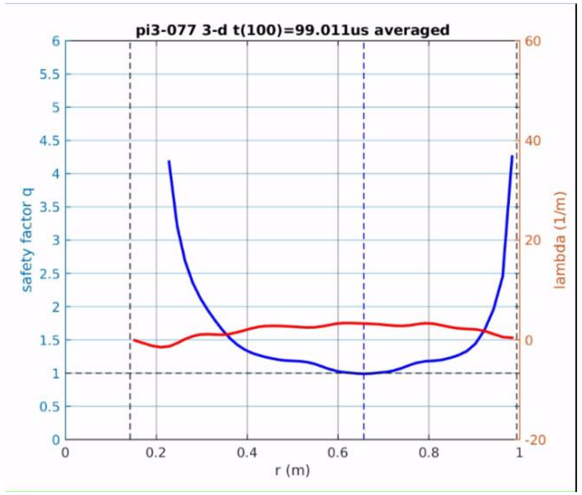
$$\chi_E = (a_0/j_{01})^2/\tau_0 \quad = ????$$

Measurement and control of plasma profiles







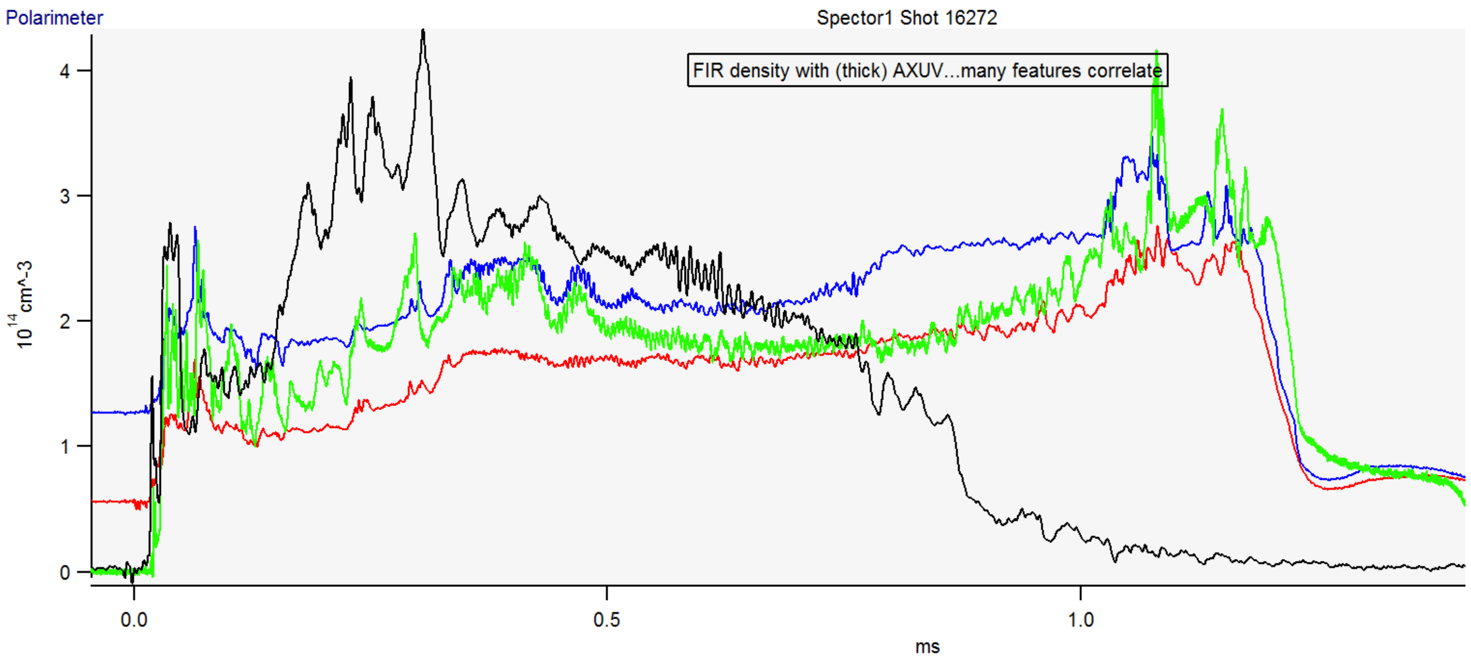


Lambda profile $\lambda(\psi) = \mu_0 J/B$ is critical for determining plasma volume, shape, Ohmic heating power and the magnetic L/R decay timescale. CHI formation relies on self-organization of plasma currents to converge on final equilibrium state.

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 forward 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 work in MTF.

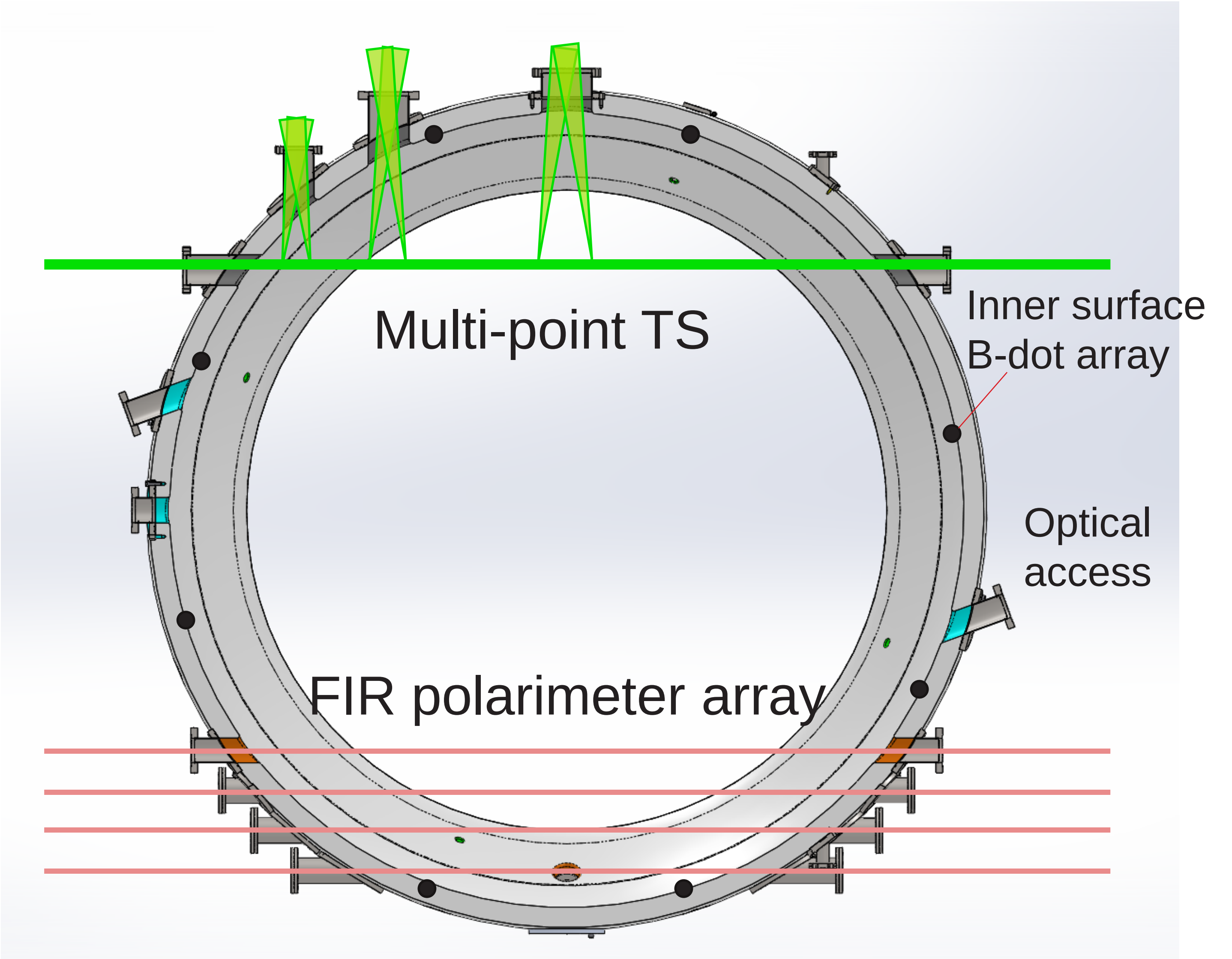
Diagnostic Plan

- Multi-point Thomson scattering.
- Ion Doppler spectroscopy.
- Soft X-ray radiometry.
- Extend the use of soft X-ray diagnostics to better constrain the position of the inversion radius during sawtooth oscillations.
- Soft X-ray and visible plasma imaging.

- Surface magnetic probe array data.
- Multi-chord FIR polarimeter array.

- Impurity composition will be assessed through time-resolved visible survey spectroscopy, VUV spectroscopy.
- High energy scintillators detect hard X-rays produced by run-away electrons, and neutrons produced during deuterium shots.

Equatorial diagnostic plane



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