Development of Sustained Spheromaks with Steady, Inductive Helicity Injection (SIHI)

Derek A. Sutherland, Ph.D.[1] and the HIT-SIU Team[2]

[1]CTFusion, Inc. and [2]University of Washington

dsutherland@ctfusion.net I twitter:@ctfusion_inc

Fusion Power Associates 42nd Annual Meeting

December 15 – 16, 2021

Outline

- Sustained spheromaks overview
- High-power HIT-SI3 campaign results
- Next HIT-SIU experiment (first plasma!)
- Summary and next steps

Outline

- Sustained spheromaks overview
- High-power HIT-SI3 campaign results
- Next HIT-SIU experiment (first plasma!)
- Summary and next steps

Spheromaks are compact, toroidal magnetized plasmas in the compact torus (CT) family of configurations

- Spheromaks are compact, toroidal magnetized plasmas contained in a simply-connected confinement volume
- Both (B_T) and poloidal (B_p) plasma-generated magnetic fields are present, but no externally applied B_T
- Safety factor $1 > q > 0$, which is generally higher than a reversed-field pinch (RFP) ($q < 0$ in edge) but lower than in a tokamak ($q > 1$)
- Large plasma currents require efficient sustainment while maintaining good energy confinement for a favorable scaling towards fusion conditions

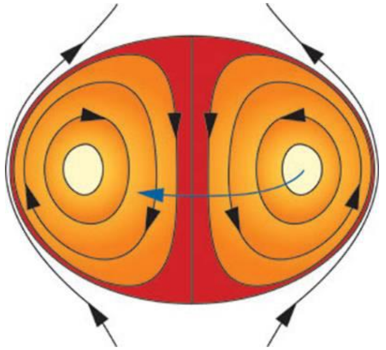
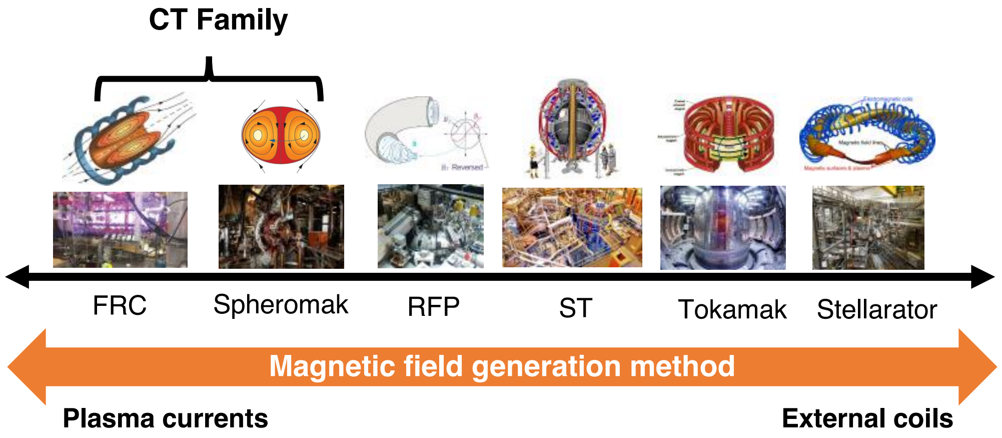


Figure: UW A&A Department, https://www.aa.washington.edu/research/HITsi/research/spheromak



Sustained spheromaks pursue an intermediate-β regime in scaling towards reactor relevant β/χ

- ”Traditional” spheromaks have low Mercier β-limits due low magnetic shear [1]
- Usage of concave flux conservers can provide access to higher β equilibria [2]
- Observed β in excess of Mercier seen in sustained spheromak experiments at times at low temperatures [3]
- Must establish the experimental confinement scaling towards reactor-relevant β/χ in the keV-regime

[1] M.N. Rosenbluth and M.N. Bussac, *Nucl. Fus.* **19**, 489 (1979), https://doi.org/10.1088/0029-5515/19/4/007
[2] U. Shumlak and T.R. Jarboe, *Phys. Plasmas* **7**, 2959 (2000), https://doi.org/10.1063/1.874147
[3] B.S. Victor, et al., *Phys. Plasmas* **21**, 082504 (2014), https://doi.org/10.1063/1.4892261

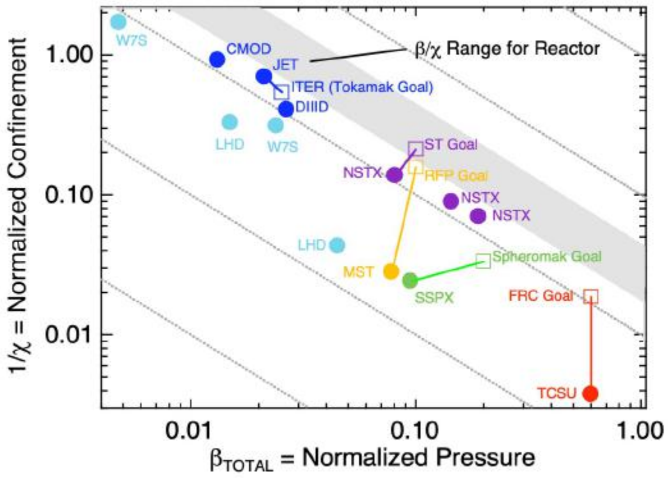
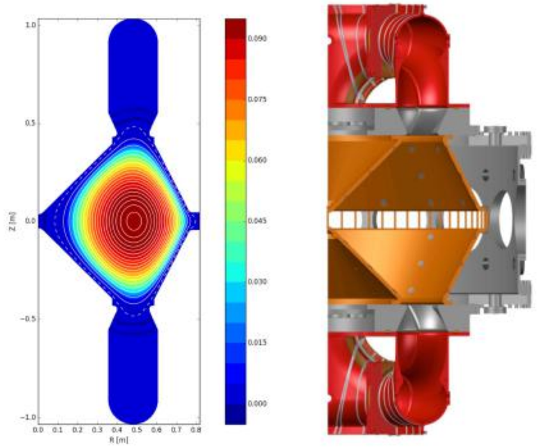


Figure from “Report of the FESAC Toroidal Alternates Panel,” (2008).



Spheromak in concave flux conserver with $\beta_{local} > 9\%$

Best absolute plasma performance to date was seen in the SSPX experiment at LLNL using Coaxial Helicity Injection (CHI) [1]

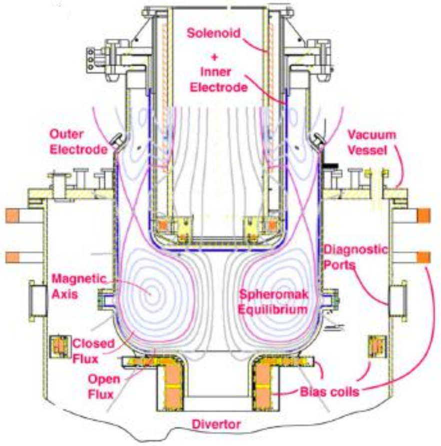
- SSPX used coaxial magnetic helicity injection (CHI) to form and sustain spheromak configurations in a cylindrical flux conserver

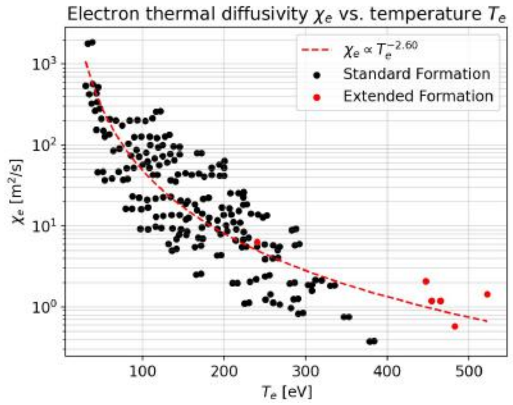
$$\dot{K} = 2\int \vec{E}_v \cdot \vec{B}_v \, dV = 2V_{inj}\psi_{inj}$$

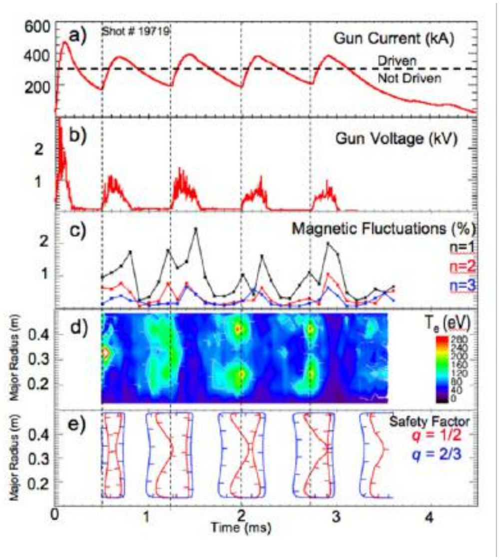
- During extended formation discharges, electron temperatures $T_e \sim 500$ eV and core thermal diffusivity $\chi_e \sim 1$ m²/s [1]

- However, during sustainment phases, a degradation of confinement quality was observed due to excitation current-driven instabilities

- Additionally, low observed current gain $G = I_{tor}/I_{inj} \sim 2$ accentuates need to increase gain for a favorable scaling towards fusion-relevant plasmas with reasonable I_{inj} from electrodes





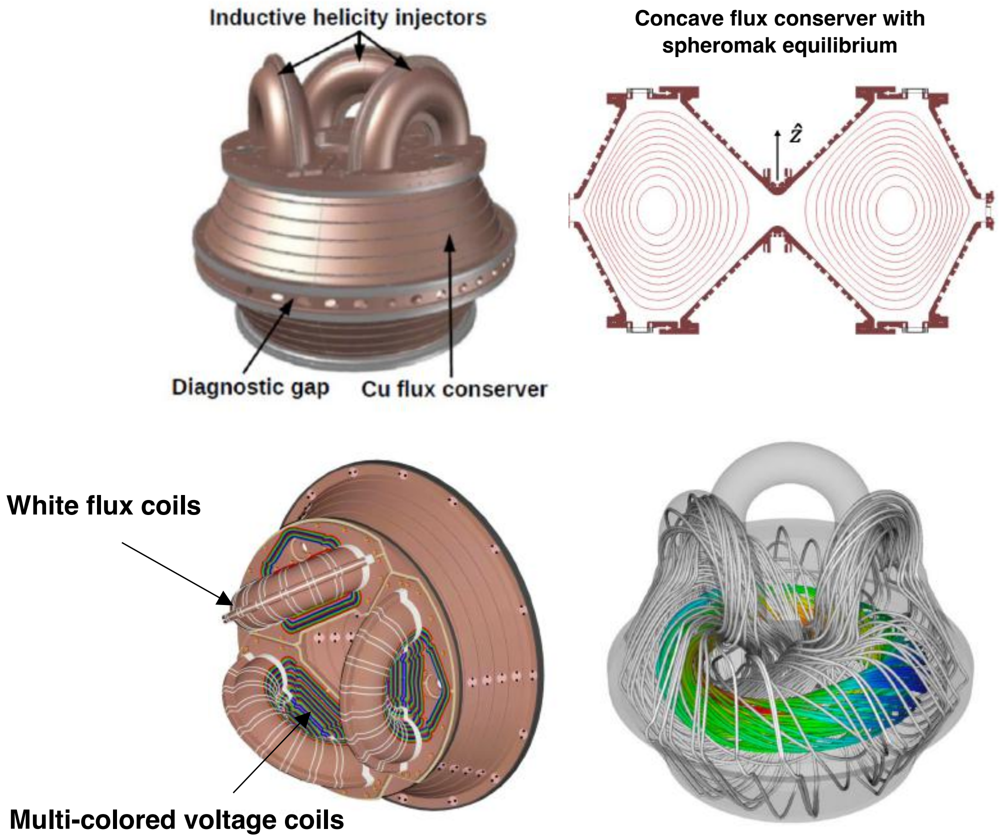


[1] B. Hudson, et al., *Phys. Plasmas* **15**, 056112 (2008), https://doi.org/10.1063/1.2890121.

Spheromaks sustained with steady, inductive helicity injection (SIHI) aim to overcome these challenges with key technical differences

- Steady, Inductive Helicity Injection (SIHI) is used to form and sustain spheromak configurations
- Fully inductive operation provides a more attractive scaling of engineering requirements than a CHI-driven system
- Individual helicity injectors operate AC in kHz range and are driven with a resonant RLC circuit
- Temporal phasing with multiple injectors allows for the continuous injection of magnetic helicity
- The previous HIT-SI3 experiment has two injector phasings (60^o & 120^o) that provides steady, inductive helicity injection.

Previous HIT-SI3 Experiment



Figures courtesy of John Rogers and Dr. Chris Hansen, University of Washington

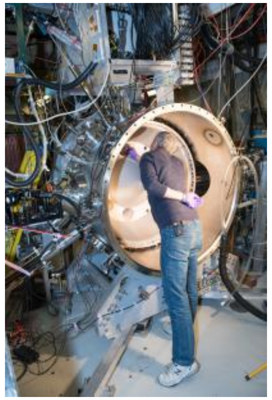
Outline

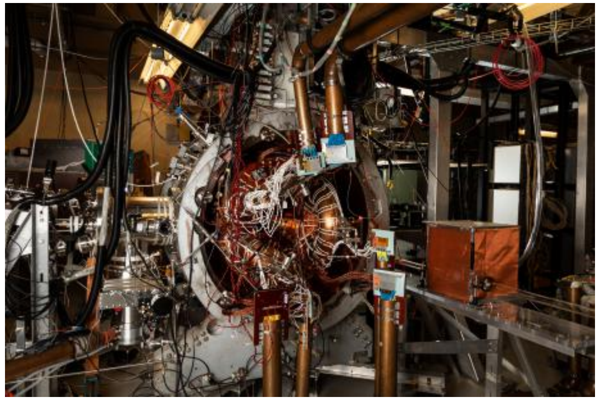
- Sustained spheromaks overview
- High-power HIT-SI3 campaign results
- Next HIT-SIU experiment (first plasma!)
- Summary and next steps

HIT-SI3 power supplies were upgraded, and new diagnostic and control systems were built and installed for a high-power HIT-SI3 campaign*

- **Targeted upgrades of the HIT-SI3 experiment provided:**
  - Access higher injector power, voltage, and energy storage (peak $P_{inj} > 20$ MW, $V_{inj} > 600$ V, $\tau_{pulse} \sim$ 2-5 ms)
  - Built a new, two-color multi-chord interferometry system for density profile measurements
  - Use a low-latency GPU-based feedback control for improved helicity injector phase control
  - Improved density control by optimizing gas puff timing and fueling

arpa·e awardee OPEN **2018**

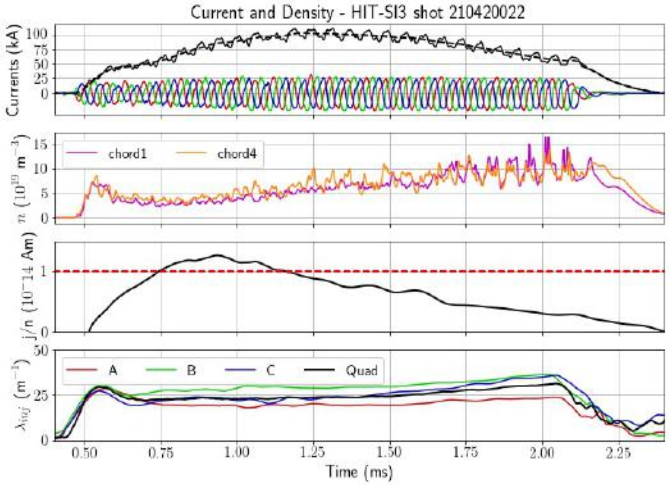


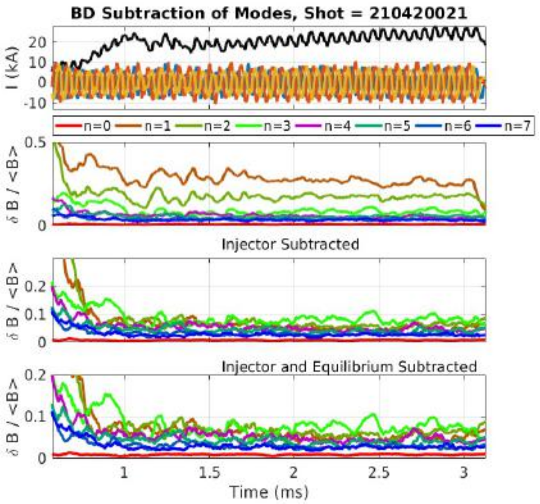


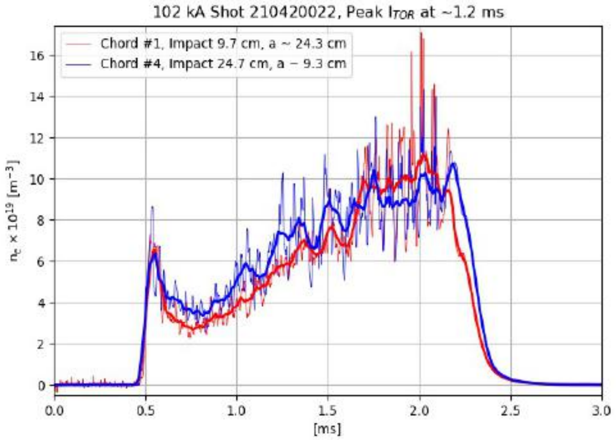
*Publication in the works

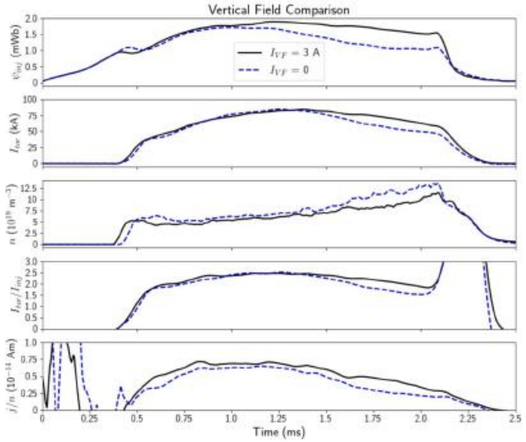
Highest toroidal current SIHI-driven spheromaks produced during high-power HIT-SI3 campaign in Spring 2021

- Higher power injection provides access to $j/n > 1\times10^{-14}$ A-m early in time, which is followed period with $I_{tor} \geq 100$ kA
- Biorthogonal decomposition suggests majority of non-axisymmetric fields are from injectors, like previous campaigns
- Multi-chord interferometer provides density profile information for the first time
- Application of small vertical field ($< 10\%\ B_p(a)$) provides improved density control late in time



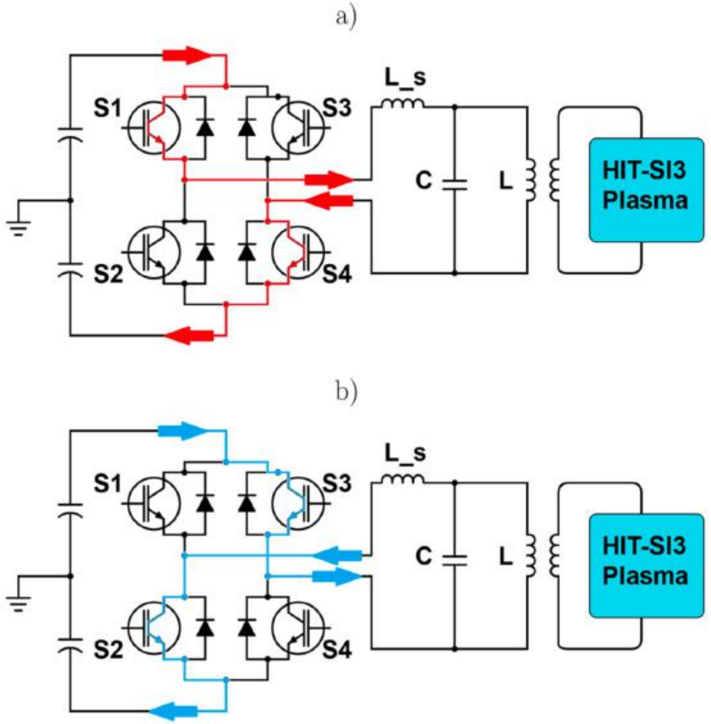




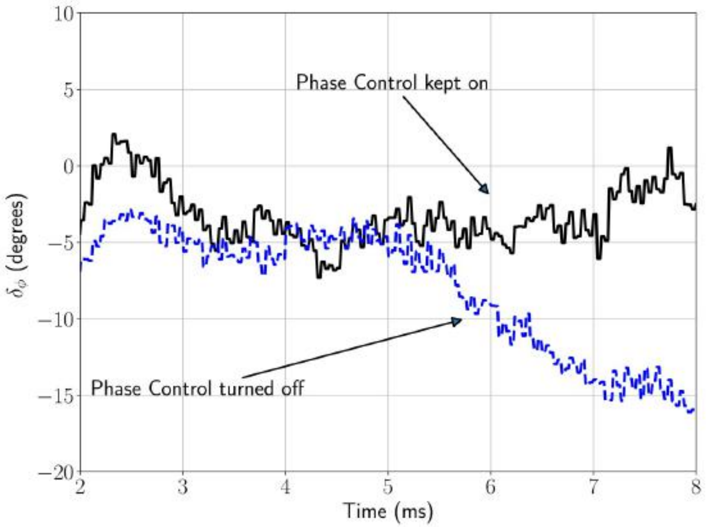


Demonstrated operation with GPU-based feedback control system and ability to change injector phasing during a shot while maintaining spheromak current [1]

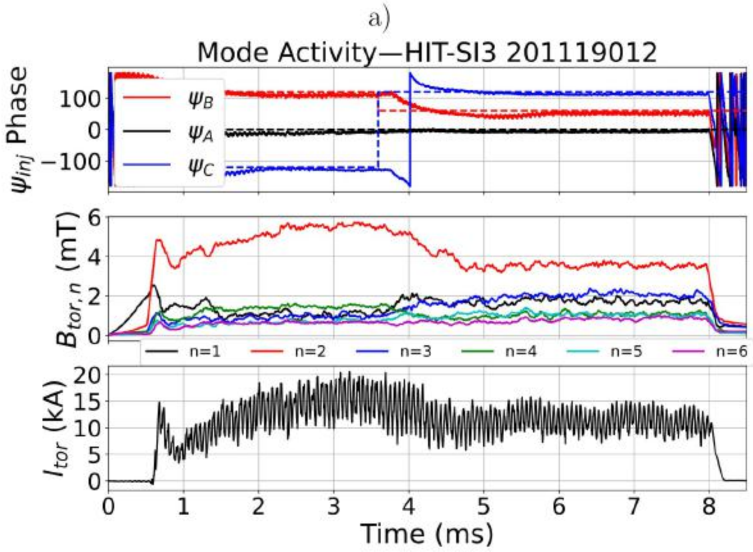
SIHI circuits with positive (red) and negative (blue) pulses



Improved phase control of helicity injector circuits



Demonstrated ability to change phasing during a shot while maintaining spheromak I_{tor}



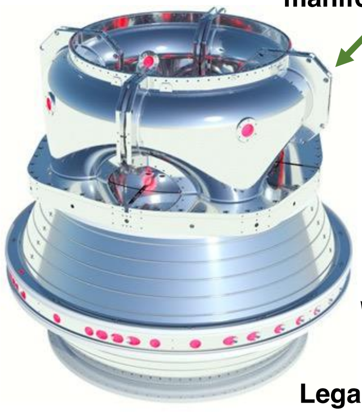
[1] K.D. Morgan, et al., *Rev. Sci. Instrum.* **92**, 053530 (2021), https://doi.org/10.1063/5.0044805

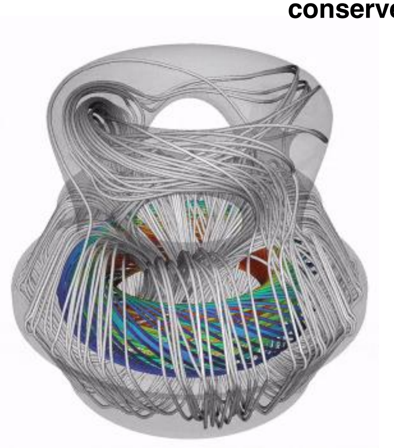
Outline

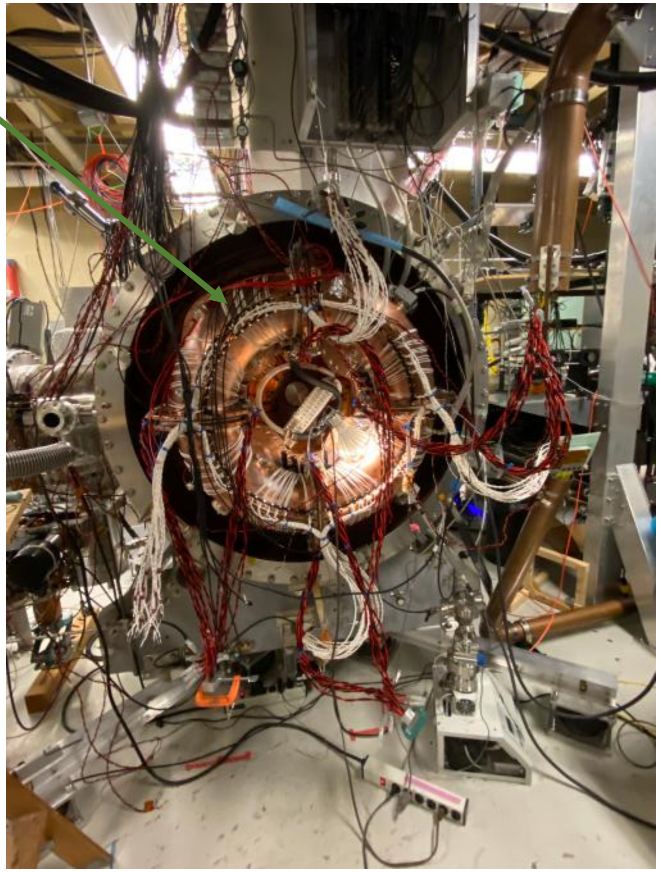
- Sustained spheromaks overview
- High-power HIT-SI3 campaign results
- Next HIT-SIU experiment (first plasma!)
- Summary and next steps

HIT-SIU uses the legacy flux conserver from HIT-SI3 but a new SIHI system geared towards higher current gain spheromaks

- Usage of helicity injection manifold for improved helicity injection and density control
- Low-density breakdown in “tokamak-mode” and transition to ”spheromak-mode” during a shot
- Direct helicon pre-ionization system of helicity injection manifold for the first time
- Test sample inserts for evaluating different insulating PMI coatings in manifold
- Same power, control, and diagnostic systems as high-power HIT-SI3 campaign

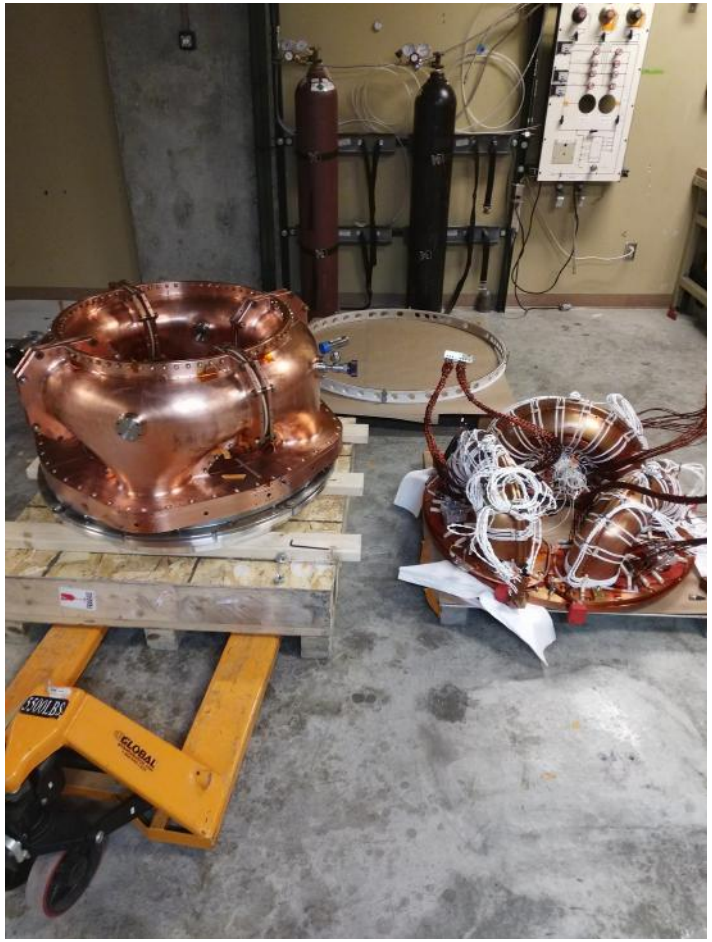


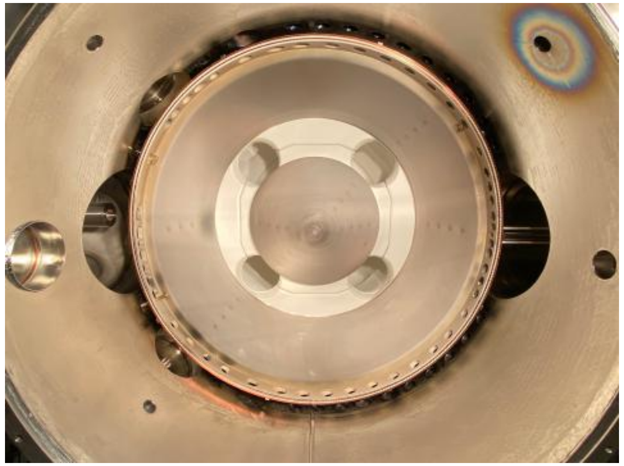


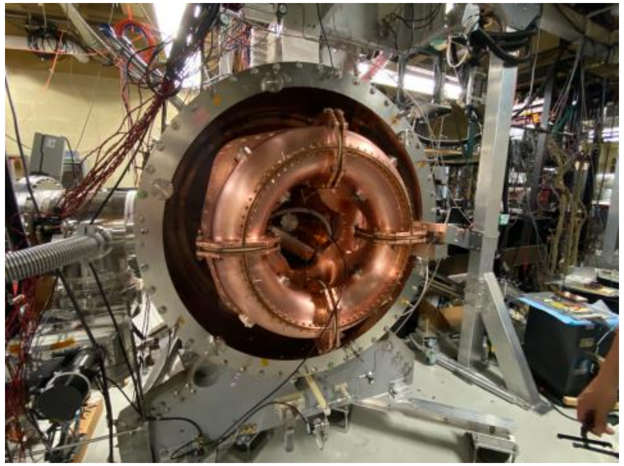


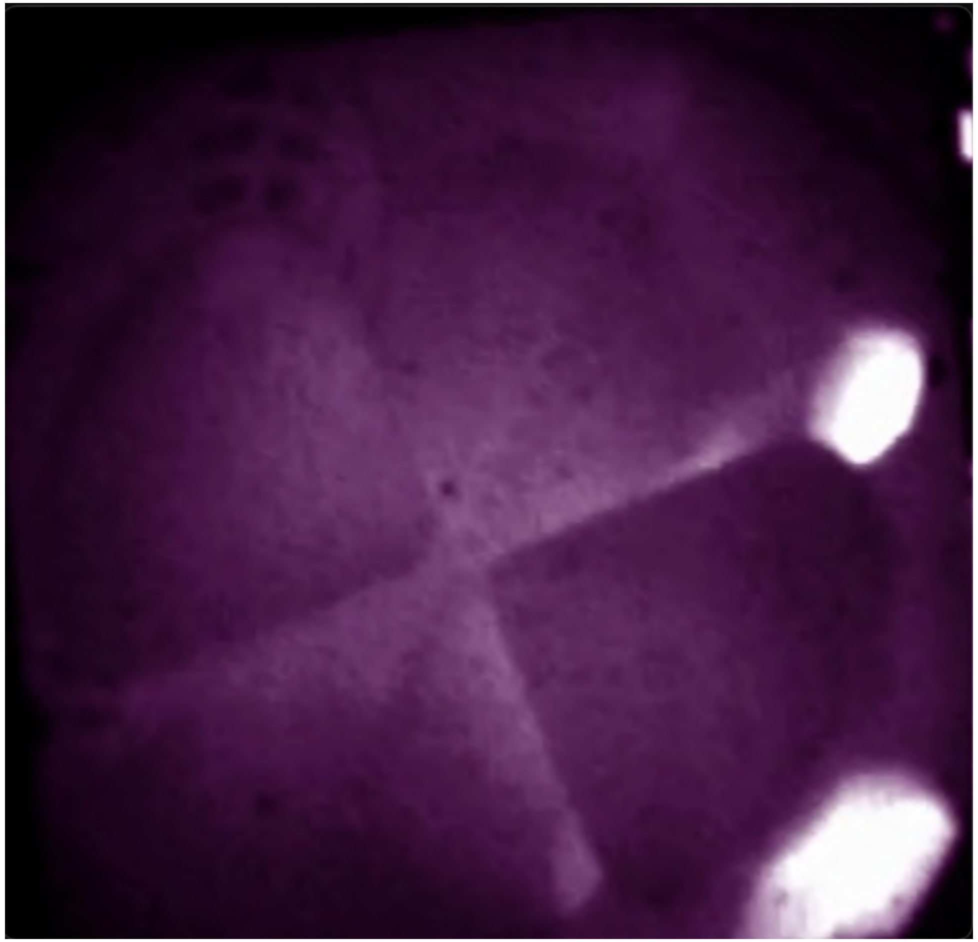
arpa·e awardee OPEN 2018 BETHE

HIT-SIU first plasma achieved in Fall 2021!



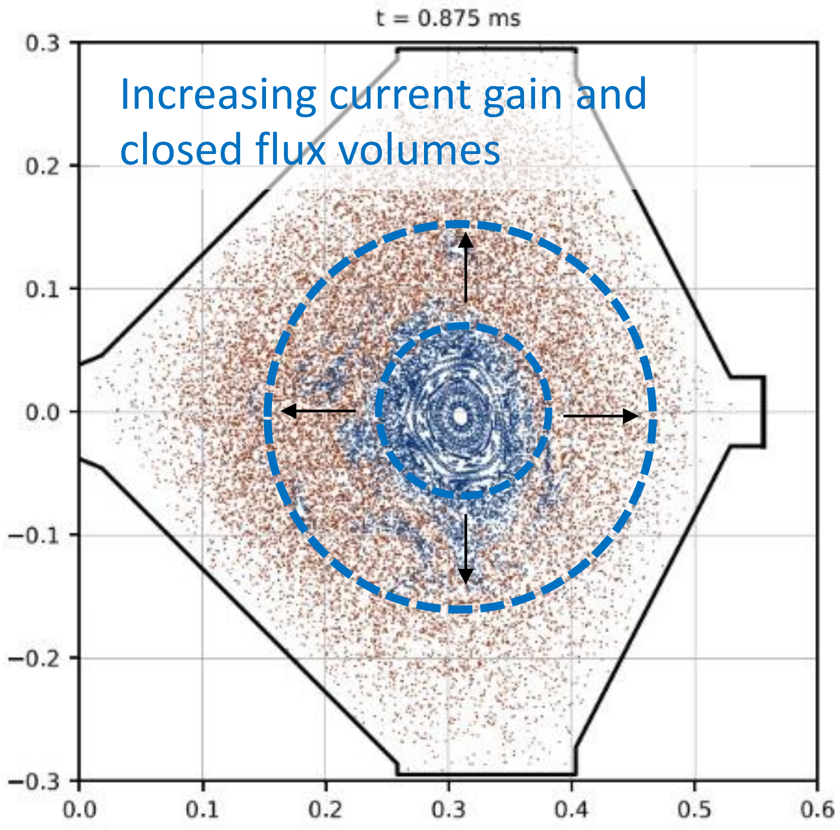






Currently working towards highest performance SIHI-driven spheromaks in HIT-SIU in Spring 2022

- High-j/n operation for majority of shot to access higher current gain $G > 5$
- Extended-MHD simulations suggest threshold for formation of closed-flux volumes $G \sim 5$[1]
- Higher current gain should provide access to $T_i, T_e > 100$ eV with $I_{tor} > 100$ kA in HIT-SIU
- Next-generation device to provide first size scaleup of concept to access G > 10 and a corresponding increase in T_i, T_e towards keV-regime in an Ohmically heated plasma



[1] A.A. Kaptanoglu, et al., *Phys. Plasmas* **27**, 072505 (2020), https://doi.org/10.1063/5.0006311

Outline

- Sustained spheromaks overview
- High-power HIT-SI3 campaign results
- Next HIT-SIU experiment (first plasma!)
- Summary and next steps

Summary and next steps

- Spheromaks are compact, toroidal magnetized plasmas with plasma-generated toroidal and poloidal magnetic fields, but no externally applied toroidal magnetic field

- SIHI is being developed to overcome limitations of CHI-driven spheromaks to provide a more attractive pathway towards fusion-relevant plasma conditions

- Targeted upgrades of the previous HIT-SI3 system has enabled the highest performance SIHI-driven spheromaks to date in Spring 2021

- HIT-SIU has produced first plasma and should provide access to even higher performance SIHI-driven spheromaks than HIT-SI3 with improved density control, opening access to higher-j/n and current gain

- Next-generation device to follow HIT-SIU will provide needed size scaling to confirm access to $G > 10$ and a corresponding significant improvement in plasma performance towards Ohmically heated, keV-class plasmas