Electron Heating Studies of Helicity Injection Plasmas on the Pegasus-III Experiment

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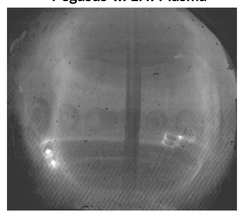
Pegasus-III Experiment

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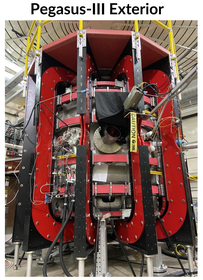
Pegasus-III: Exploring Solenoid-Free Startup

- Solenoid-free startup critical for spherical tokamaks (ST); beneficial to tokamaks
- Removing solenoid simplifies ST design
  - Potential cost reduction
  - More space for shielding/blanket
  - Reduce PF system requirements
  - Lower electromechanical stress

Pegasus-III LHI Plasma



Pegasus-III Exterior



- Provides facility to compare/contrast solenoid-free startup techniques
  - Local helicity injection
  - Coaxial helicity injection
  - Microwave heating and sustainment
- **Goal: Use diagnostic systems to validate physics and technology basis for extrapolation to MA-class non-inductive startup**

See also: M. W. Bongard JP12.00065

Helicity Injection Enables Solenoid-Free Startup

- Current drive increases the amount of poloidal flux linked with the toroidal flux created by external coils (magnetic helicity)[2]

$$K = \int_V \boldsymbol{B}\cdot\boldsymbol{A}\,dV\,;\quad \frac{dK}{dt} = -2\frac{\partial\psi}{\partial t}\Psi - 2\int_S \Phi B\cdot dS - 2\int_V \eta \boldsymbol{J}\cdot\boldsymbol{B}dV$$

AC Helicity Injection | DC Helicity Injection | Helicity Dissipation

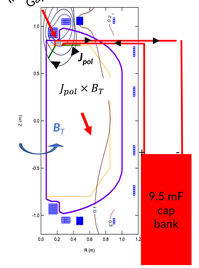
- DC helicity injection (HI) can be represented by an effective loop voltage:

$$V_{HI} = \frac{\oint_S \Phi\,\vec{B}\cdot d\hat{s}}{\Psi} = \frac{V_{inj}N_{inj}A_{inj}B_{inj}}{\Psi}$$

- Taylor Relaxation sets one upper bound on I_P:

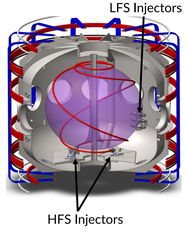
$$I_P \le I_{TL} = I_{inj}\frac{\Psi}{\Phi_{inj}}$$

CHI Sketch



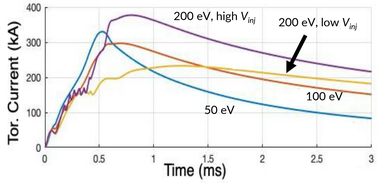
- CHI: Large area (A_{inj}) biased (V_{inj}) coaxial electrodes drive open field line current (I_{inj})
- LHI: Small area (A_{inj}) plasma guns biased (V_{inj}) against a vacuum vessel anode drive plasma streams (I_{inj})

LHI Model



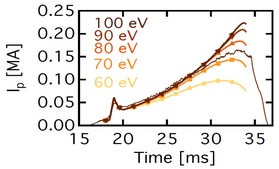
Helicity Dissipation Dependent on T_e

T_e Effects on CHI Plasmas [1]



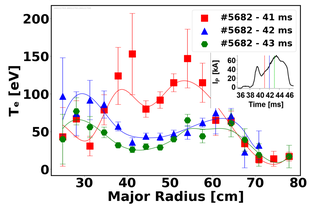
- HI modeling shows strong dependence of current on electron temperature, T_e
  - Increasing T_e improves the plasma current after injector shut-off
  - Lower plasma resistivity at the same V_{inj} increases current
- Having high T_e is crucial for developing helicity injection systems:
  - Increasing T_e decreases plasma resistivity, slowing helicity dissipation and increasing I_P
  - Higher T_e leads to burn through of low Z impurities and lower radiated power

T_e Effects on LHI Plasmas[2]



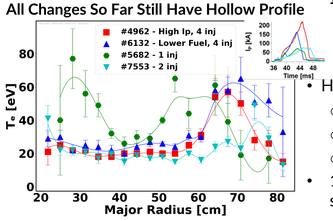
T_e Evolution of LHI Plasmas

T_e Profiles Start Peaked and Hollow Out



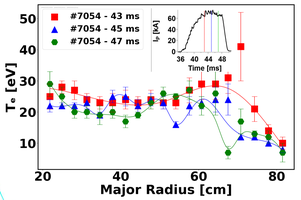
- Late in the discharge, the electron temperature profiles stay hollow
- Even when held at a flattop for several confinement times, T_e does not increase in the core

All Changes So Far Still Have Hollow Profile



- Current LHI plasmas tend to start with peaked T_e profiles shortly after relaxation
- Within a few milliseconds, these peaked profiles always hollow out

T_e Profiles Stay Hollow Through Flattop



Hypotheses for low T_e tested so far:

- Not enough helicity drive
- Too high of a neutral load
- I_P too low

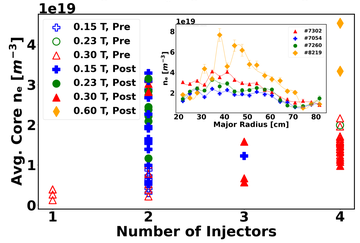
- 1 injector only yields higher edge T_e; suggests impurities are cooling core

Pegasus-III Easily Achieves High Core n_e

- Fueling system changed in March of 2024, improving gas throughput by factor of 2
  - Pre changes, n_e mostly at or below $1x10^{19}$ m^{-3}
  - Post changes, n_e reaches $2x10^{19}$ m^{-3} and higher
- Higher densities enable study of electron Bernstein wave heating

See also: J. K. Peery JP12.00072

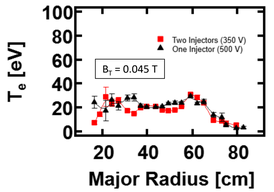
Average Core n_e Higher Post Fueling Fix



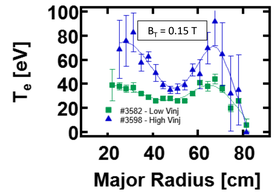
Next Steps to Increase Core T_e

Experiments Planned to Examine V_{inj}, V_{HI} Effect on T_e

Constant V_{HI}, Changing V_{inj} [3]



Changing V_{HI}, Changing V_{inj}



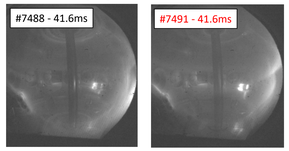
- Prior work suggested V_{inj} alone was not enough to increase the T_e profile [3]
- Recent Pegasus-III experiments have shown higher V_{HI} from increased V_{inj} raises core current density, which heats the core

See also: J. D. Weberski GI03.00005

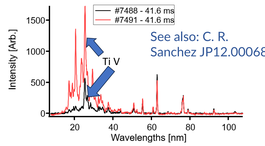
- Experiments looking to directly examine how increasing V_{HI} and V_{inj} affect T_e are planned alongside experiments to examine if P_{inj} can increase T_e

New Local Limiters Built to Reduce Impurities From PMI

Fast Imaging Camera Shows PMI



SPRED Data Shows Impurity Pickup



See also: C. R. Sanchez JP12.00068

- Strong evidence from fast imaging cameras and SPRED diagnostic shows plasma interaction with local limiter leading to Ti impurities
- New local limiters have been designed and fabricated to decrease this interaction

New Local Limiter Fabricated



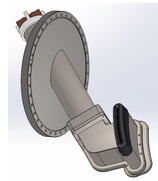
Pegasus-III Will Study Next Gen Injectors

- Two new DC helicity injection systems are soon to be installed to study increasing A_{inj}:
  - LHI using non-circular injectors (LHI-nc) to maximize the Taylor relaxation limit

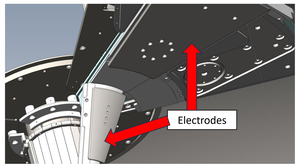
See also: M. W. Aslin JP12.00066

  - CHI using 2 large area electrodes electrically isolated from the vacuum vessel

CAD Model of LHI-nc Injector

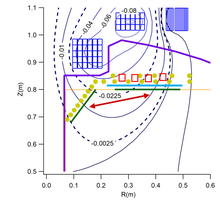


CAD Model of CHI System



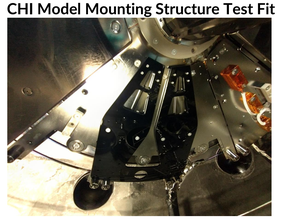
- Initial CHI tests will use transient CHI (T-CHI) with sustained CHI to follow
- T-CHI shortens injector pulse length as much as possible to limit impurities
- Shorter run time may also help lock-in early peak temperature profiles

Diagnostic Housing Incorporated in Design



- CHI electrode mounting structure designed with embedded diagnostics:
  - 16 Flux loops
  - 24 Windowpane coils
  - 4 B-dot Triplets

CHI Model Mounting Structure Test Fit



- Performed a preliminary test fit using an acrylic cutout of the mounting structure for CHI
- Test showed bolt pattern in structure design matches existing pattern in top of machine

Summary

- Pegasus-III electron temperature profiles have so far started out peaked following relaxation and very rapidly hollowed out, but core electron densities are peaked, giving a flat electron pressure across the plasma
- Near term experiments look to study increasing T_e by increasing V_{inj} and V_{HI}, changing the local limiter, developing new injectors, and increasing B_T
- New non-circular injectors set to be installed and novel CHI system featuring 2 floating electrodes is nearing a final design and has several initial tests successfully completed

References: [1] R. Raman *et al.*, Fusion Sci. Tech. (2022), [2] J.L. Barr *et al.*, Nucl. Fusion 58, 076011 (2018), [3] G. M. Bodner, PhD Thesis, UW-Madison (2020)

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