Local Helicity Injection Studies at Increasing B_T on Pegasus-III

M.W. Aslin, M.W. Bongard, S.J. Diem, J.A. Goetz, M.D. Nornberg, J.K. Peery, S. Redd, J.A. Reusch, C.Rodriguez Sanchez, C.E. Schaefer, A.C. Sontag, T.N. Tierney, J.D. Weberski

Department of Nuclear Engineering & Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

66th Annual Meeting of the APS Division of Plasma Physics, Atlanta, GA, Presentation JP12.00066, 8 October 2024

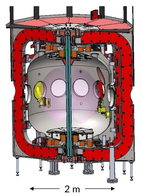
Work Supported by US DOE Grant DE-SC0019008

Pegasus-III Experiment

Pegasus-III: Exploring Solenoid-Free Startup

- Recent upgrade to Pegasus-III enables solenoid-free startup using helicity injection (HI)
- B_T capability increased 4x to $B_T = 0.6\ T$
- Helicity injection (HI) plasmas at higher B_T scale to higher plasma performance
- Increased B_T allows for HI studies that can scale to larger devices and fusion energy systems

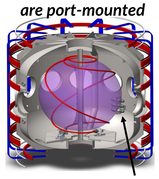
Pegasus-III



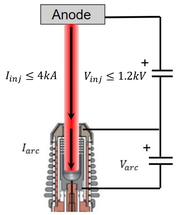
Helicity Injection Enables Non-Solenoidal Startup

- Helicity injection (HI) introduces DC helicity to plasma
  - Local helicity injection (LHI)
    - Small-area sources
  - Coaxial helicity injection (CHI) (JP12.70)
    - Large coaxial electrodes
- LHI: injected current streams reconnect, relax into a tokamak-like plasma
- Streams must have enough pitch angle to clear opposite injectors [1]
  - B_{pol} must increase with B_T to maintain pitch

Small, modular injectors are port-mounted

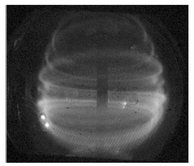


LHI injectors are compact, high-power plasma sources



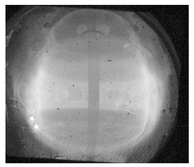
- Increased B_{pol} makes relaxation difficult
  - $B_{pol} \to 0$ ("field null") necessary for current streams to reconnect and relax [1,2]
- Global I_p limits [2,3]:
  - Taylor relaxation: $I_p \leq I_{TL} \sim \sqrt{B_T I_{inj}/w_{inj}}$
  - Helicity conservation: $V_{LHI} \approx \frac{V_{inj} B_{inj} A_{inj}}{\Psi}$
- Power balance: $I_p[V_{IND} + V_{LHI} - V_{diss}] = 0$
- Injector design sets plasma parameters:
  - I_{inj} and w_{inj} set I_{TL}
  - $N_{inj} A_{inj} V_{inj}$ attain/sustain I_p

Current Injection



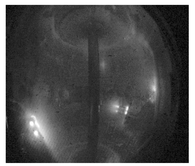
$I_p \sim N_{turns}\, I_{inj}$

Relaxation



$I_p \gtrsim N_{turns}\, I_{inj}$

Driven Tokamak



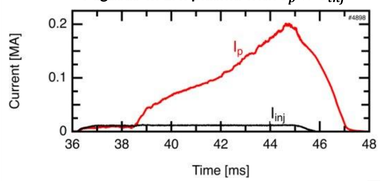
$I_p \gg N_{turns}\, I_{inj}$

[1]Tierney et al., JP12.00070

Taylor Limit Scaling Observed for $B_T \leq 0.3T$

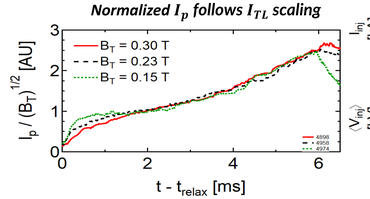
- Initial LHI studies on Pegasus-III use an injector array of 4x4 cm^2 circular injectors with $B_T \leq 0.3\ T$
- Upgrade to facility optimizes I_{TL} through increased B_T, I_{inj}
- High performing 4-injector plasmas reach $I_p \geq 0.2\ MA$

Pegasus-III LHI plasma with $I_p \gg I_{inj}$

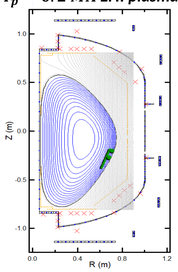


- Taylor limit studies show robust $I_{TL} \propto B_T, I_{inj}, w_{inj}$ scaling (GI03.05)

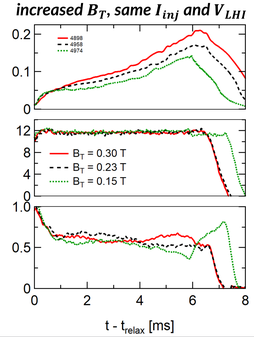
Normalized I_p follows I_{TL} scaling



Sample equilibrium for $B_T = 0.3\ T$, $I_p = 0.2\ MA$ LHI plasma



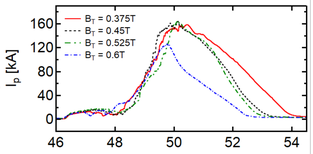
I_p follows I_{TL} scaling with increased B_T, same I_{inj} and V_{LHI}



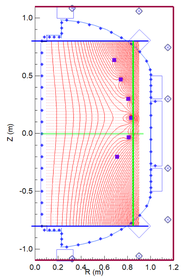
Scenario Development at $B_T \geq 0.3\ T$ is Ongoing

- $B_T \leq 0.6\ T$ capabilities have been commissioned on Pegasus-III
- While achieving relaxation at increased B_{inj} is a known challenge, relaxation is attainable at $B_T \geq 0.3\ T$
- LHI pulses at $B_T \geq 0.3\ T$ have attained $I_p \geq 0.1\ MA$

First LHI plasmas at $B_T \geq 0.3\ T$

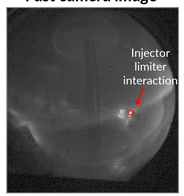


Null finder code models I_{inj}, B_{pol} to find field null



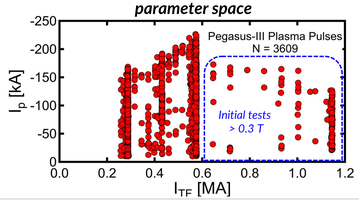
- Null finder code will aid in further scenario development by modeling where, when field null occurs [1]
- Pitch angle clearance at increased B_T leads to difficulty achieving relaxation
  - Interaction with limiter causes PMI (JP12.68)

Fast camera image



- Future experiments at high B_T will study handoff to electron Bernstein wave (EBW) heating systems (JP12.72, JP12.73)

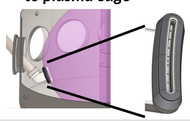
Pegasus-III plasma pulses across expanded parameter space



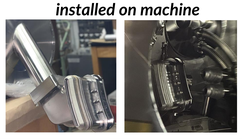
LHI-nc Expected To Provide Engineering, Physics Advantages for LHI

- LHI using a noncircular injector (LHI-nc) has been installed on vessel
- I_{TL} optimized through injector aperture design
  - w_{inj} minimized, conforms to plasma shape
- Increasing I_{TL} at the beginning of the pulse is known to be more effective in increasing I_p than increasing V_{LHI} [3]

LHI-nc aperture conforms to plasma edge

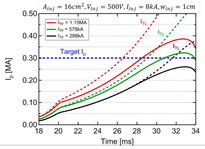


LHI-nc is port mounted and has been installed on machine

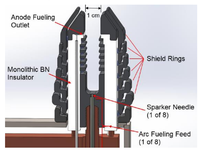


- LHI-nc designed to operate at $V_{inj} \leq 0.5kV$
  - Significant decrease in V_{inj} compared to 4x4 cm^2 may shorten conditioning time and extend injector lifetime
- High A_{inj} maintains sufficient V_{LHI} for operation
  - Comparable total A_{inj} to 4x4 cm^2 array

0-D power balance model predicts $I_p \geq 0.3\ MA$ using LHI-nc



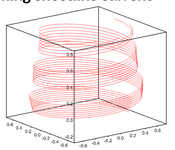
LHI-nc designed to ensure uniform I_{inj}



- Designed to produce uniform current sheet
  - Sparker needles designed to facilitate breakdown across injector channel
  - Eight gas apertures designed to provide even fueling
- New anode fueling feature may aid in arc reliability and reduce fluctuations in V_{inj}

- Future experiments will examine the shape of injected current streams
  - Will facilitate study of role of stream shape in stability and CD

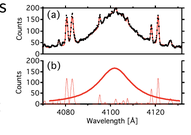
LHI-nc current stream achieves pitch angle condition assuming sheetlike current



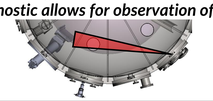
n_{arc} Studies Are Planned for LHI-nc Arcs

- Experiments to determine the relationship between n_{arc}, I_{arc}, and fueling are planned for LHI-nc
  - Past studies have found a linear relationship between n_{arc} and I_{arc} using circular injectors
- Projections for LHI-nc performance have assumed a uniform J_{inj}
  - n_{arc} studies can help inform future refinements to models with updated current stream geometries

Representative spectrum illustrating Lorentzian fit to D-δ line [6]



Planned sightline for Stark broadening diagnostic allows for observation of n_{arc}

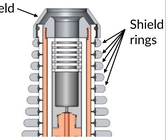


- Stark broadening diagnostic will be used to observe n_{arc} for LHI-nc [5]
  - Diagnostic line of sight will observe LHI-nc arc channel

LHI-nc Design Features May Mitigate Cathode Spots

- Cathode spots occur at high $E_{inj} \sim {}^{V_{inj}}/_{\lambda_D}$
- Frustum shield lowers plasma density near injector to increase λ_D, decrease E_{inj}
- Floating shield rings prevent flashback arcing [7]
- Reduced w_{inj} from LHI-nc is projected to maintain high I_{TL} with lower V_{inj}, reducing risk of cathode spotting

Like previous injector arrays, LHI-nc is designed to mitigate destructive cathode spots [7]



Summary and Future Work

- The Pegasus-III B_T system has been upgraded to have $B_T \leq 0.6\ T$ capabilities, a 4x increase in toroidal field capability
- Initial LHI studies on Pegasus-III using LFS injector array with $B_T \leq 0.3\ T$ confirm $I_p \leq I_{TL} \propto \sqrt{B_T}$ scaling
- Expanded operating space through increased B_T allows for future experiments to study EBW heating and sustainment
- LHI-nc installed, expected to achieve higher I_{TL} with reduced input power compared to circular array
  - $I_p < I_{TL}$ increased through geometric scaling
  - V_{inj}, I_{inj} necessary for high I_p decreased
- Installation of Stark broadening diagnostic is planned to study relationship between n_{arc}, I_{arc}, and fueling for scenario development
- LHI-nc design offers potential of mitigating cathode spots

References: J.M. Perry *et al* 2018 *Nucl. Fusion* **58** 096002. [2] D.J. Battaglia et al 2011 Nucl. Fusion 51 073029. [3] J.L. Barr *et al* 2018 *Nucl. Fusion* **58** 076011. [4] A.T. Rhodes, Preliminary Exam, 2020. [5] Hutchinson, *Principles of Plasma Diagnostics*, 2nd ed. (Cambridge, 2002). [6] E. T. Hinson et al., Phys. Plasmas 23, (2016). [7] M. W. Bongard et al., Nucl. Fusion 59, (2019).

Reprints available at https://pegasus.ep.wisc.edu/technical-reports.