Plasma Initiation by Local Helicity Injection (LHI) on PEGASUS-III

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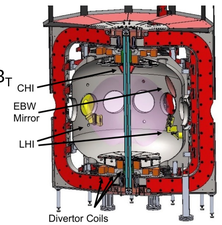
64th Annual Meeting of the APS Division of Plasma Physics, Spokane, WA, Presentation CP11.00045, 17 October 2022

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PEGASUS-III Experiment

PEGASUS-III Studies Non-Solenoidal Startup

- Tokamaks presently rely on inductive current drive via a central solenoid
  - ITER solenoid is largest & most powerful pulsed superconducting electromagnet ever built – with associated costs and power supply
  - Uses volume more desirable for blankets/shielding
- PEGASUS-III is dedicated to solenoid-free startup/operation
  - Increase B_T to >0.4T
    - Overlap with larger experiments
    - Upgraded centerstack has no solenoid
    - Determine critical physics scalings with B_T
  - Multiple techniques tested on same device
    - Higher power LHI system than PEGASUS
    - CHI & RF added in planned upgrades
    - Will compare/contrast & combine
  - See Bongard *et al.*, *CP11.00040*



PEGASUS-III Upgrades Nearly Complete

- Significant upgrades underway (see Goetz *et al.*, *CP11.00041*):
  - Solenoid removed from system
  - Upgraded/expanded TF power supply and new stored energy
  - Upgraded TF magnet assembly capable of >4× higher field
  - Upgraded LHI power supplies and new stored energy
  - New vacuum wall, upgraded magnetics, new PFCs

Parameter	PEGASUS	PEGASUS-III
I_{TF}	0.288 MA	1.15 MA
N_{TF}	12	24
ψ_{sol} (mWb)	40	0
R_{inner} [cm]	5.5	7.0
TF Conductor Area [cm²]	13.2	72
$B_{T,max}$ [T] at R_0~0.4 m	0.15	0.58
B_T Flattop [ms]	25	50-100
A	1.15	1.18

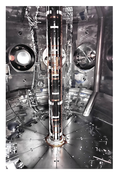
TF Magnet Assembly



Power Supplies



Internal Hardware

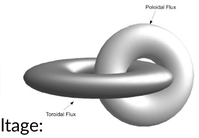


Local Helicity Injection can Initiate and Drive Tokamak Plasmas with Localized Electrodes

- Current drive increases poloidal flux ψ_p linked with toroidal flux Ψ_T from external coils (magnetic helicity K)

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

AC Helicity Injection | DC Helicity Injection | Helicity Dissipation



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

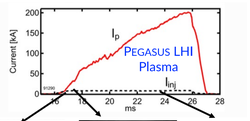
$$V_{HI} = \frac{\oint_S \Phi\,\vec{B}\cdot d\hat{s}}{\Psi_T} = \frac{V_{inj}A_{inj}B_{inj}}{\Psi_T}$$

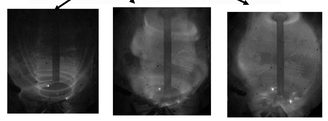
- LHI: Plasma current scales with injector voltage, area, and location

$$I_p = \frac{A_p V_{LHI}}{2\pi R_0\langle\eta\rangle} \approx \frac{V_{inj}A_{inj}}{2\pi R_0\langle\eta\rangle}\left(\frac{B_{inj}}{B_0}\right)$$

- Taylor relaxation limits I_p to lowest energy state that conserves K

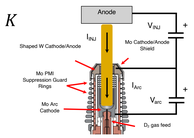
$$\lambda \equiv \frac{\vec{j}\cdot\vec{B}}{B^2} \qquad \bar{\lambda}_{plasma} \le \bar{\lambda}_{edge} \quad \rightarrow \quad \boxed{I_p \le I_{inj}\frac{\Psi_T}{\psi_{inj}}}$$



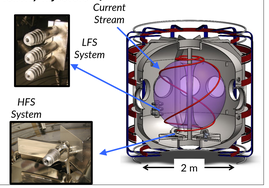


$I_p \approx N_{turns}\, I_{inj}$ $\quad I_p \gtrsim N_{turns}\, I_{inj}$ $\quad I_p \gg N_{turns}\, I_{inj}$

LHI Injector Schematic



Local Helicity Injectors — *Injected Current Stream*



LHI Predictive Models Need Data at Higher B_T for Scaling

- Predictive LHI model based on:
  - 0D power balance
  - Helicity injection limits
  - Plasma geometry evolution
    - Global I_p limits:
      - Taylor relaxation

$$\boxed{I_p \le I_{TL} \sim \sqrt{I_{TF} I_{inj}/w}}$$

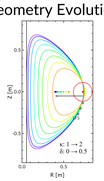
      - Helicity conservation

$$\boxed{V_{LHI} \approx A_{inj} B_{T,inj} V_{inj}/\Psi}$$

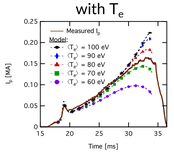
    - Predictive power balance: $I_p(t)$

$$\boxed{I_p[V_{LHI} + V_{IR} + V_{IND}] = 0; I_p \le I_{TL}}$$

LFS LHI Plasma Geometry Evolution

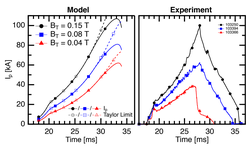


Model Variation with T_e



- Requires tuning to match experiment
  - Adjust resistivity to match I_p
  - Adjust confinement to match T_e
  - See Weberski *et al.*, *CP11.00049*
- Impurity content affects Z_{eff}
  - Model uses resistive dissipation
  - Impurity radiation may cause high core P_{rad} at low B_T
    - Initial work shows Z_{eff} ~ 1 (see Bodner et al., PoP 2021)
    - Should be reduced at higher B_T
  - Initial studies indicate high impurity transport during LHI
  - See Rodriguez Sanchez *et al.*, *CP11.00050*

LHI Variation with B_T

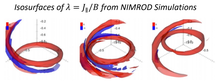


LHI Current Drive Mechanism Under Investigation

- Taylor relaxation requires redistribution of parallel current (λ)
  - No specific mechanism given
  - Need to determine if mechanism scales to higher B_T
- NIMROD modeling suggests merging flux rope rings provide toroidal current
  - Co-helicity streams merge/reconnect
  - Repeated process builds I_p
  - Associated with low-f MHD
  - Consistent with initial relaxation observations
- CD efficiency improvement with reduction of low-f MHD suggests high-f oscillations also related to current drive
  - LHI stream instabilities drive turbulent Alfven cascade
  - Determining relationship to current drive/redistribution
  - See Sassella et al., CP11.00048

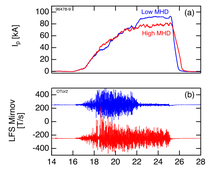
NIMROD Simulation of LHI

Isosurfaces of $\lambda = J_\parallel/B$ from NIMROD Simulations

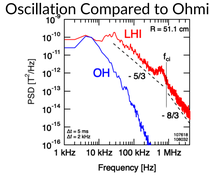


O'Bryan and Sovinec, Plasma Phys. Control. Fusion **56** *64005 (2014).*

LHI Driven Current Increases with Drop in Low-f Edge MHD



LHI Drives High Frequency Oscillation Compared to Ohmic

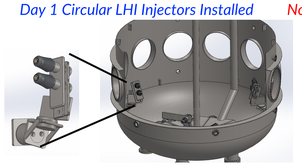


See Richner, et al., PRL **128** 105001 (2022).

LHI Studies at Higher B_T will Guide Hardware Scaling

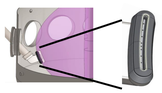
- Studies at higher field with upgraded LHI injectors will allow access to new operational regimes
- Hardware physics / materials issues to be studied:
  - Bias voltage control via double layer physics
  - Arc density, uniformity and impurity generation
  - Main-chamber fueling, charge exchange neutrals
  - Injector conditioning requirements
  - Cathode spot detection/mitigation
- Non-circular injector to optimize LHI configuration
  - Simultaneously addresses two LHI limits
    - Taylor limit wants minimum width
    - Helicity limit wants maximum area
  - To be installed after initial LHI run campaign

Day 1 Circular LHI Injectors Installed



Non-Circular Injector Will Be Tested

Advanced Non-circular Injector in PEGASUS-III



Port mounted injector assembly completed



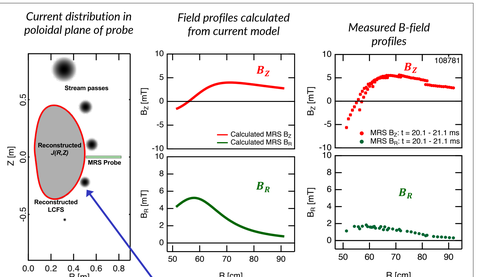
Two Arrays of 2× 4 cm² Circular Injectors (Twice Area on PEGASUS)



LHI Current Streams Affect Magnetic Field Structure

- Each stream has up to 4 kA of current
  - LHI $\frac{\tilde{b}_Z}{B_\varphi} \sim 10^{-2}$
  - Strong implications for core confinement and transport
- LHI streams modeled as helical current structure on open field lines
- Equilibrium I_p and helical stream qualitatively reproduce spatial B-field probe data
- GPEC calculations being performed to get first estimate of impact on field structure
- See Schaefer *et al.*, *CP11.00047*

Current distribution in poloidal plane of probe | *Field profiles calculated from current model* | *Measured B-field profiles*



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