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

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Pegasus-III Experiment

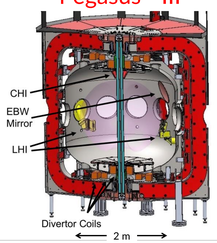
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PEGASUS-III Studies Non-Solenoidal Startup

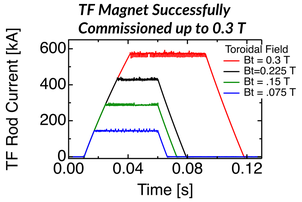
- Non-solenoidal startup is critical to any ST path to fusion [1,2]
- Tokamaks presently rely on inductive current drive via a central solenoid
  - ITER solenoid is largest & most powerful pulsed superconducting electromagnet ever built – with associated costs and power supply
  - Uses volume more desirable 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
  - multiple techniques tested on same device
    - higher power LHI system than PEGASUS
    - CHI & RF added in planned upgrades
    - will compare/contrast & combine
  - see Reusch *et al.*, *YP11.00029*

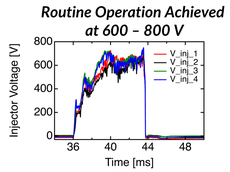


Upgrade Complete & Systems Commissioned

- Significant upgrades completed (see Goetz *et al.*, *YP11.00030*):
  - Solenoid removed from system
  - Upgraded/expanded TF power supply and new stored energy
  - Upgraded TF magnet assembly capable of >4x higher field
  - Upgraded LHI power supplies and new stored energy
  - New vacuum wall, upgraded magnetics, new PFCs







LHI Allows Fully Non-Solenoidal Operation

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

$$K = \int_V \boldsymbol{B}\cdot\boldsymbol{A}\,dV\,; \quad \frac{dK}{dt} = -2\frac{\partial\psi_p}{\partial t}\Psi_T \;(\text{AC Helicity Injection}) \; - 2\int_S \Phi B\cdot dS \;(\text{DC Helicity Injection}) \; - 2\int_V \eta \boldsymbol{J}\cdot\boldsymbol{B}dV \;(\text{Helicity Dissipation})$$

- 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

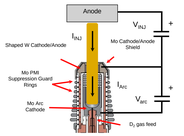
$$I_p = \frac{A_p V_{LHI}}{2\pi R_0\langle\eta\rangle} \approx \frac{V_{inj}A_{inj}}{2\pi R_0\langle\eta\rangle}\left(\frac{B_{inj}}{B_0}\right)$$

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

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

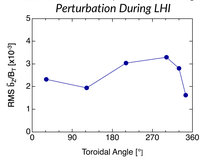
- LHI injectors use internal arc discharge as electron source for extracted electron beam
  - injector parallel to vacuum helical B field
- Electron beam is extracted by biasing arc anode with respect to an external anode
  - vacuum vessel used for Pegasus-III anode
  - arc ions pulled into arc cathode cup

LHI Injector Schematic

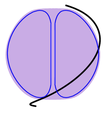


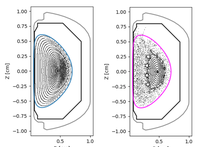
- LHI Open-Field Currents Affect B-field Structure
  - simple model of I_{inj} on helical vacuum field gives basic perturbation
  - measured toroidal variation of perturbed field confirms
- Basic field line following (no plasma response) shows significant effects
  - See talk BO08.00005 by C.E. Schaefer for more detail
- Effects of open-field currents must be included in MHD equilibrium reconstruction also
  - See YP11.00036 by J.D. Weberski in this session for more detail

Measured Toroidal Dependence of Magnetic Perturbation During LHI



$$\boldsymbol{B}_{total} = \boldsymbol{B}_{equil} + \boldsymbol{B}_{pert,vacuum} + \boldsymbol{B}_{response}\,(\to 0)$$

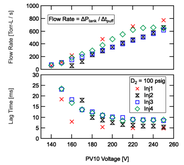




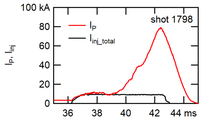
Initial Operations Characterize & Condition

- Injector gas feed characterization revels low conductance
  - overswaged PEEK capillaries
  - low flow & delayed response
- Hardware conditioning is required prior to high-power plasma operations
  - injector bias voltage (v_{LHI}) proportional to LHI drive
  - ~ 1 week of operations time required to achieve conditions sufficient for plasma relaxation

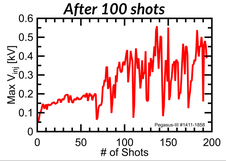
Injector Gas Valve Characterization



Initial Relaxation



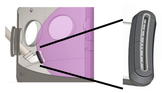
Conditioning Progress Evident After 100 shots



Injector Systems Development Ongoing

- New injector geometries being explored
  - minimize injector width while maximizing area
  - plasma coupling
  - arc / extracted current uniformity
- Injector hardware must survive extreme conditions
  - > 1 MW/m² surface loading inside arc chamber
  - cathode spots on shield components
- Cathode spot detection/mitigation being implemented
  - see YP11.00035 by M.D. Nornberg
- Neutral fueling must be controlled
  - see YP11.00034 by A.L. Ferris

Advanced Non-circular Injector in PEGASUS-III

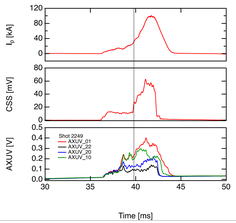


Port mounted injector assembly completed



Detection of cathode spot

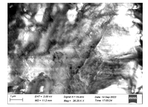




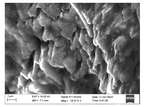
- Affects of materials choices on component lifetimes being studied
  - cathode spot damage
  - cracking causes
  - see YP11.00033 by A.S. Rajendra

Mo Frustum Shield

Before Use



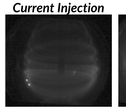
After Use



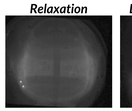
Initial Plasmas Being Diagnosed

- Determining initial operating point & limits to operational space
  - high n_e, low T_e
    - gas control inhibiting performance
    - will repair next vent!

Current Injection — $I_p \sim N_{turns}\, I_{inj}$



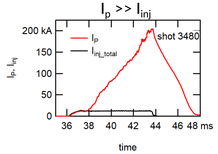
Relaxation — $I_p \gtrsim N_{turns}\, I_{inj}$



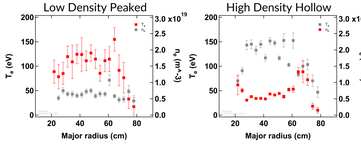
Driven Tokamak — $I_p \gg N_{turns}\, I_{inj}$



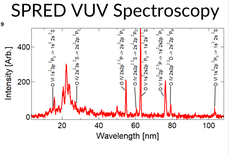
Pegasus III plasma $I_p >> I_{inj}$



First Thomson Scattering Profiles from Pegasus-III

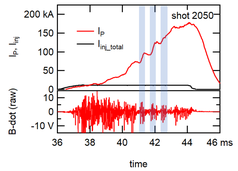


SPRED VUV Spectroscopy



- Thomson Scattering to study profile evolution
  - Do initially hollow T_e profiles fill in?
  - see YP11.00040 by T.N. Tierney
- MHD connection to current drive
  - n=1 bursts
  - turbulence and current diffusion
  - see YP11.00038 by R. Sassella
- Impurity content & transport under study
  - SPRED survey VUV spectrometer
  - AXUV diode array for bolometry
  - VB for Zeff
  - see BO08.00006 by C. Rodriguez-Sanchez

MHD During Ip Ramp on Pegasus III



Pegasus-III Facility Beginning Physics Analysis of LHI Plasmas at Increased B_T

- Pegasus-III has begun physics operations at 2x (presently and 4x soon) maximum toroidal field of previous Pegasus operations
  - also increased LHI injection capability
  - new record I_p for LFS LHI achieved
  - developed LHI sustained discharges at I_p > 100 kA
- Initial performance limited by gas load
  - will be remedied with injector disassembly during next vessel entry
- Diagnostic commissioning allowing initial physics studies to begin
  - currently restoring previous Pegasus diagnostics with some upgrades
  - beam diagnostics for more profile data planned

References: [1] J.E. Menard *et al.*, Nucl. Fusion **56**, 106023 (2016); [2] J.E. Menard, Phil. Trans. R. Soc. A **377**, 20170440 (2019)

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