Characterizing the Thomson Scattering System on the PEGASUS-III Experiment

T. N. Tierney[1], S. J. Diem[1], R. Raman[2], J. A. Reusch[1], C. Rodriguez Sanchez[1]

[1]*University of Wisconsin-Madison,* [2]*University of Washington-Seattle*

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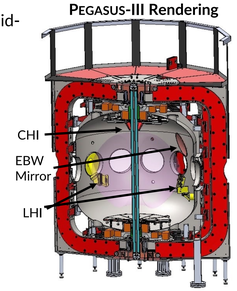
PEGASUS-III Experiment

Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

PEGASUS-III: Exploring Solenoid-Free Startup

- Future spherical tokamaks (ST) call for solenoid-free operation due to shielding and cost
- Removing solenoid simplifies ST design
  - Potential cost reduction
  - More space for shielding/blanket
  - Reduce PF system requirements
  - Lower electromechanical stress
- Solenoid-free startup may offer tools for modifying $J(R)$

PEGASUS-III Rendering



PEGASUS TF Bundle Test Fit



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

See also J. A. Goetz CP11.00041 , M. W. Bongard CP11.00040

Helicity Injection Enables Solenoid-Free Startup

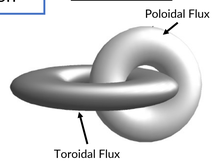
- Current drive increases the amount of poloidal flux linked with the toroidal flux created by external coils (magnetic helicity)

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

AC Helicity Injection | DC Helicity Injection | Helicity Dissipation

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

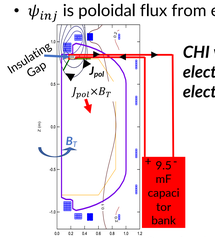
$$V_{HI} = \frac{\oint_S \Phi\,\vec{B}\cdot d\hat{s}}{\Psi} = \frac{V_{inj}A_{inj}B_{inj}}{\Psi}$$



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

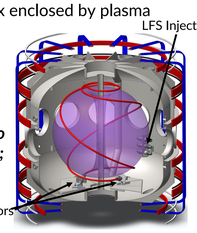
$$\lambda \equiv \frac{\vec{J}\cdot\vec{B}}{B^2} \qquad \bar{\lambda}_{plasma} \le \bar{\lambda}_{edge} \quad \rightarrow \quad I_p \le I_{inj}\frac{\Psi_t}{\psi_{inj}}$$

- ψ_{inj} is poloidal flux from electrodes, Ψ_t toroidal flux enclosed by plasma



CHI via biased, electrically isolated, electrodes

LHI streams undergo magnetic relaxation; form tokamak-like plasma

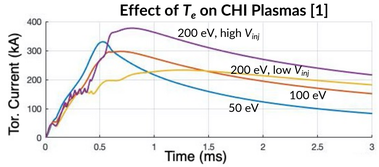


See also J. A. Reusch CP11.00044, A. C. Sontag CP11.00045

Multi-Point Thomson Scattering Measurements Crucial for Helicity Injection Investigations

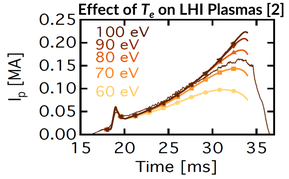
- CHI modeling shows strong dependence of current on electron temperature
  - Increasing T_e improves the persistent current
  - Lower plasma resistivity at the same V_{inj} improves the persistent current

Effect of T_e on CHI Plasmas [1]



- LHI modeling shows similar changes in plasma current
  - Higher T_e lowers the resistivity of the plasma
  - Lower resistivity improves plasma current

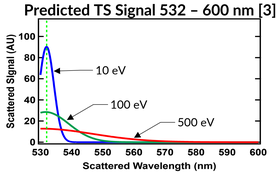
Effect of T_e on LHI Plasmas [2]



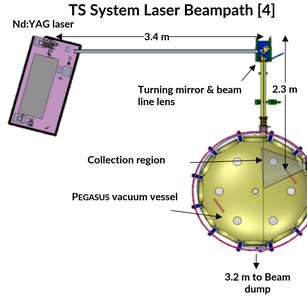
PEGASUS has Implemented a MPTS System

- Thomson scattering (TS) is the low-energy limit of Compton scattering
  - T_e is related to distribution of scattered wavelengths
  - n_e is found by combining spectrum with absolute calibration

Predicted TS Signal 532 – 600 nm [3]

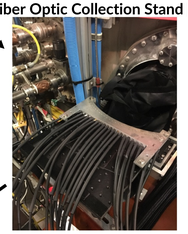


TS System Laser Beampath [4]



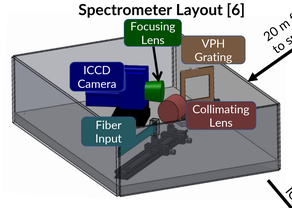
- Laser system features:
  - Nd:YAG laser at 1064 nm
  - Second harmonic amplifier to bring it to 532 nm
  - Automated mirror alignment
  - In-vessel baffle system to mitigate stray light

Fiber Optic Collection Stand [5]



- Fiber optic bundles couple the scattered light to the spectrometer
- New system will have ~60–65 cm of radial range
  - Will have 21 on-laser points and 3 off-laser points

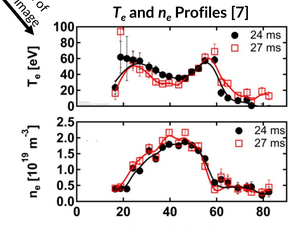
Spectrometer Layout [6]



- Fiber bundles couple light to fast shutters and holographic gratings
  - 2 grating types: low temperature and high temperature
    - Gives range of 10–250 eV
- Light diffracts off grating onto image-intensified CCD camera
- Data is corrected for dark current and background counts
- Data averaged over multiple shots
  - Typically 5–7 shots
- Wavelength mapping done using Hg, Kr, and 532 nm lamps
- Data fitted with Selden's formula to find electron temperature [8]
- Rayleigh Scattering into Ar gives absolute calibration to determine n_e
  - Measures $n_e > 2\times10^{18}$ m^{-3}

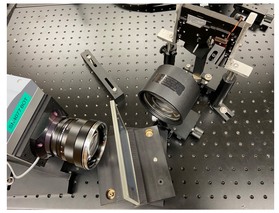
Analysis of ICCD image

T_e and n_e Profiles [7]



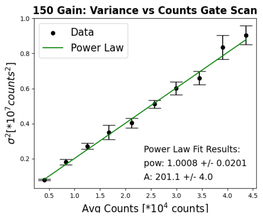
MPTS Spectrometers Ready for Day 1 Operation

Spectrometer Ready for Use

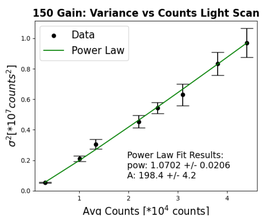


- Main shutter system tested and operational
  - One shutter found to be malfunctioning and replaced
  - Looking to upgrade shutters to include open/close state info

150 Gain: Variance vs Counts Gate Scan



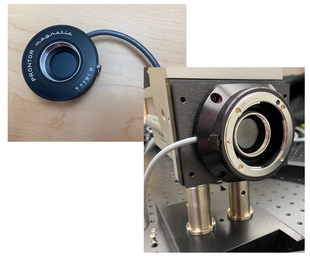
150 Gain: Variance vs Counts Light Scan



- Absolute gain was also tested using a calibrated light source
  - Gain found for each superpixel and averaged over the entire camera
  - Shows slight drop from factory values
    - Most likely from aging of 10 year old cameras

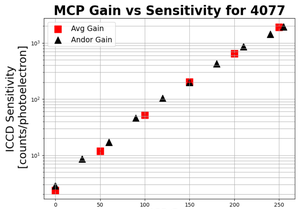
- For day 1 operations, main concern is current state of equipment
- Must check:
  - Main shutters to ensure they still open and protect from outside light
  - Ensure cameras still operate as expected

Main Shutter Lens and Mount



- Photometric calibrations were done to check the state of the cameras
  - First test varied the MCP on-time over 10 time settings
  - Second test changed the light source's intensity over 8 counts
  - Both tests show a linear relationship between variance and mean counts
  - Linear relationship confirms cameras are photon noise dominated

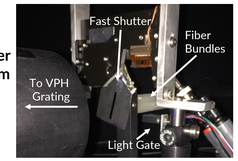
MCP Gain vs Sensitivity for 4077



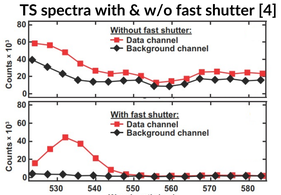
Fast Shutters Improve Signal-to-Noise

- ICCD cameras with just main shutters has 13 ms minimum exposure time
  - Allowed background light would leak through the MCP
- Solution: repurpose hard drive read-arm into fast shutters to improve SNR

Fast Shutter System [5]



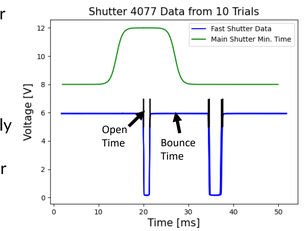
TS spectra with & w/o fast shutter [4]



- Fast shutters showed initial success in Phase-II implementation with LFS injectors
  - Decreased shots for average from 10–15 to 5–7
- Shutters removed for HFS runs
  - Open times became unreliable
  - HFS showed less background light
- With phase III utilizing LFS injectors, fast shutters are expected to be needed again

Remodeled Fast Shutters Show Reliability

- Two issues with previous fast shutter implementation:
  - Open times were unreliable
  - A bounce that re-exposed the camera to background light
- Bench tests showed shutters as highly reproducible
  - Added more light gates to further monitor shutter's position



	Shutter 4075	Shutter 4076	Shutter 4077
Open Time-Up Swing (ms)	1.71 +/- 0.006	3.16 +/- 0.02	1.38 +/- 0.01
Bounce Time-Up Swing(ms)	14.62 +/- 0.01	26.9 +/- 0.7	15.8 +/- 0.2
Open Time-Down Swing (ms)	1.63 +/- 0.004	2.67 +/- 0.01	2.53 +/- 0.01
Bounce Time-Down Swing (ms)	11.24 +/- 0.05	16 +/- 1	>40

- Bounce was seen in bench testing:
  - Cause was the force of shutter's swing
  - Solution was to find a material to eliminate bounce, or at least limit it
- Tested materials and 1 layer of 5 mm thick sorbothane was the best
  - Other Materials tested: No material, Teflon, thin rubber silicon, metal spring,
- Still bounces, but sorbothane increases the bounce time past the minimum exposure time
  - Black boxes show selected swings and their timing for each shutter

Summary and Future Directions

- **Goal: Use diagnostic systems to validate physics and technology basis for extrapolation to MA-class non-inductive startup**
- PEGASUS-III will use Thomson scattering to further investigate HI plasmas as a method of non-solenoidal startup
- The PEGASUS multi-point Thomson scattering spectrometers have been characterized by photometric calibrations and are ready for day 1 operation
- Fast shutters have been reintroduced to improve signal to noise on the MPTS system

References: [1] R. Raman *et al.*, Fusion Sci. Tech. (2022), [2] J.L. Barr *et al.*, Nucl. Fusion **58**, 076011 (2018), [3] D. J. Schlossberg, PhD Thesis, UW-Madison (2017), [4] D.J. Schlossberg *et al.*, Rev. Sci. Instrum. **87**, 11E403 (2016), [5] G. M. Bodner, PhD Thesis, UW-Madison (2020), [6] N. L. Schoenbeck *et al.*, Rev. Sci. Instrum. **83**, 10E330 (2012) , [7] G. M. Bodner *et al*, Phys. Plasma **28**, 102504 (2021), [8] A. C. Selden, Physics Letters A **79**, 405 (1980)

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