Installation of the Multi-Point Thomson Scattering System for the Pegasus-III Experiment

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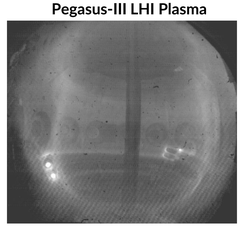
Pegasus-III Experiment

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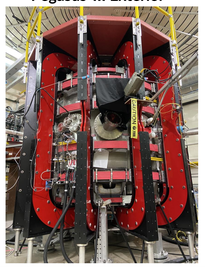
Pegasus-III: Exploring Solenoid-Free Startup

- Solenoid-free startup critical for spherical tokamaks (ST); beneficial to tokamaks in general
- 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
  - 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. Reusch YP11.00029 , J. A. Goetz YP11.00030

Helicity Injection Enables Solenoid-Free Startup

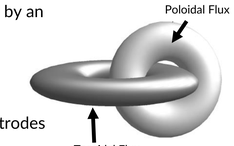
- Current drive increases the amount of poloidal flux linked with the toroidal flux created by external coils (magnetic helicity)[2]

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

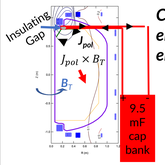
AC Helicity Injection | DC Helicity Injection | Helicity Dissipation

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

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

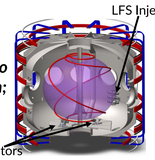


- CHI: Large area (A_{inj}) biased (V_{inj}) coaxial electrodes drive open field line current (I_{inj})
- LHI: Small area (A_{inj}) plasma guns biased (V_{inj}) against a vacuum vessel anode drive plasma streams (I_{inj})



CHI via biased, electrically isolated, electrodes

LHI streams undergo magnetic relaxation; form tokamak-like plasma

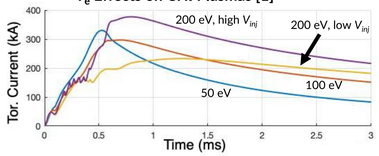


See also: A. C. Sontag YP11.00032

T_e Measurements from Thomson Scattering Crucial for Investigating Helicity Dissipation

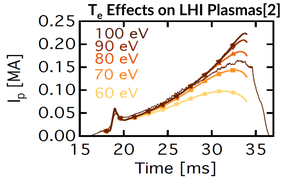
- CHI modeling shows strong dependence of current on electron temperature
  - Increasing T_e improves the persistent current
  - Lower plasma resistivity at the same V_{inj} improves the persistent current

T_e Effects 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

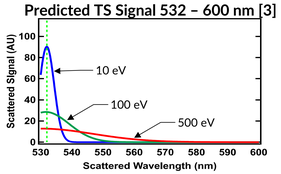
T_e Effects on LHI Plasmas[2]



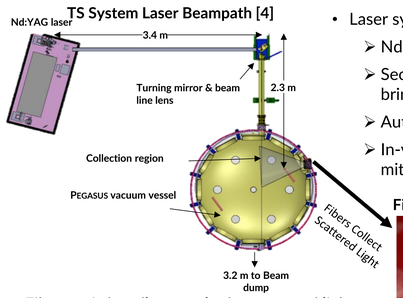
The Multi-Point Thomson Scattering System

- 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]

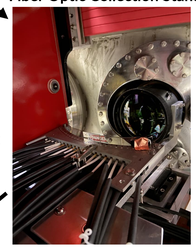


TS System Laser Beampath [4]



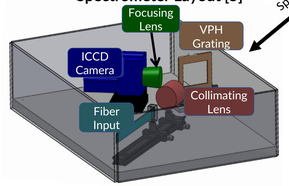
- Laser system features:
  - Nd:YAG laser at 1064 nm
  - Second harmonic amplifier to bring it to 532 nm
  - Automated mirror alignment
  - In-vessel baffle system to mitigate stray light

Fiber Optic Collection Stand



- Fiber optic bundles couple the scattered light to the spectrometer
- New TF coils forced modifications to fiber mount and supporting stand
  - Mount now has 65 cm of radial range

Spectrometer Layout [5]

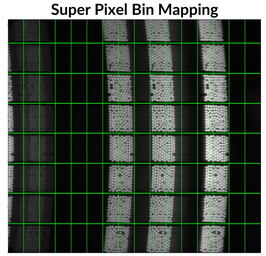


- Fiber bundles couple light to fast shutters and holographic gratings
  - 2 grating types: low temperature and high temperature
    - Gives range of 10-250 eV
- Light diffracts off grating onto image-intensified CCD camera

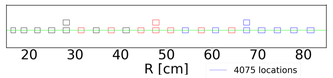
Thomson System Calibrated and Operating

- Once spectrometers installed, cameras focused on the fibers
- Fiber mounts strengthened to improve system focus
  - Corrected a slight rotation seen in full frame image of fibers
- Full 1024x1024 image binned to 8x16 "super pixels"
- Super pixel height set based on fiber focusing; width is 64 pixels

Super Pixel Bin Mapping

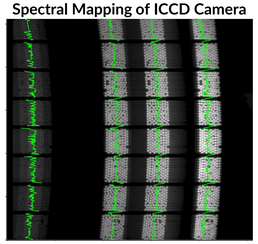


Fiber Viewing Locations



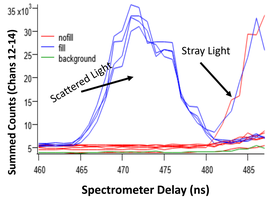
- In-vessel radial alignment of fibers allows calculating scattered angle
- Available viewing locations from R= 16.5 cm to R=81.5 cm

Spectral Mapping of ICCD Camera

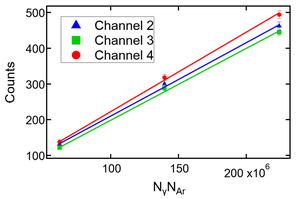


- Spectral map brings camera's counts into wavelength space for fitting
- Calibration uses 532 nm laser, Hg, Kr, and Ne pen lamps shown on detector
- Linear fit and pixel binning give mapping for each super pixel

Timing Set to Capture Only Scattered Light

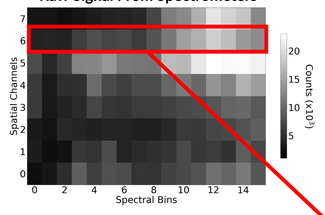


Rayleigh Scattering Calibration Gives Density Coefficient



First T_e and n_e Profiles Acquired

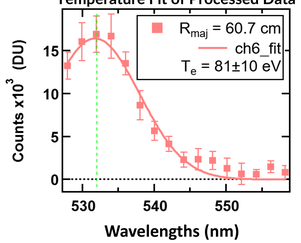
Raw Signal From Spectrometers



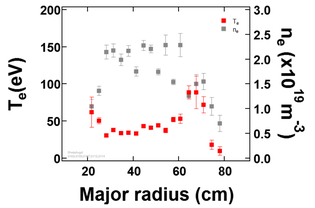
- Spectrometers collect raw data signal
- 3-5 raw images averaged together to make a data set
- Data is background subtracted and flat field corrected
- Processed data is handed over to fitting routine

- Data set fit with Selden's formula to get electron temperature[6]
- Rayleigh scattering calibration gains used to determine density
- Temperature and density fit for every viewing location
- Higher I_P LHI plasmas (~140 kA) show hollow temperature profiles
- Lower I_P LHI plasmas (~60 kA) show peaked temperature profile

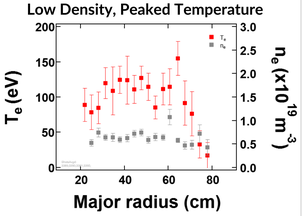
Temperature Fit of Processed Data



High Density, Hollow Temperature



Low Density, Peaked Temperature



Summary and Future Work

- The MPTS system on Pegasus-III will be a vital diagnostic tool in researching helicity injection plasmas
- The system has been installed and calibrated to the upgraded Pegasus-III experiment
- The system has taken the first temperature and density profiles for LHI plasmas
- Going forward, the system will be used to look at temperature and density evolution in LHI and CHI plasmas
- Future updates to the system will include single shot fitting functionality using off laser views as background

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] N. L. Schoenbeck *et al.*, Rev. Sci. Instrum. 83, 10E330 (2012) , [6] A. C. Selden, Physics Letters, Vol. 79 A (1980),

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