Abstract

• Use Thomson scattering to diagnose point-source helicity-driven plasmas on the PEGASUS Toroidal Experiment:
  – Characterize dominant particle transport mechanisms
  – Quantify helicity dissipation sources
  – Expect $<T_e> = 50 – 500$ eV, $n_e > 10^{18}$ m$^{-3}$

• Design, test, and deploy a novel diagnostic system:
  – 2 J, 8 ns Nd:YAG laser operating in the visible, focused to $\leq 3$ mm dia.
  – Custom collection optics views $>70\%$ of plasma radius, 1.4 cm resolution
  – High quantum efficiency, fast-gated CCD cameras detect signal

D.J. Schlossberg, APS-DPP 2011 Meeting, Salt Lake City, UT
PEGASUS is a compact ultralow-A ST

Major research thrusts include:
- Non-inductive startup and sustainment
- Tokamak physics in small aspect ratio:
  - High-$I_N$, high-$\beta$ operating regimes
  - ELM-like edge MHD activity

Experimental Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Achieved</th>
<th>Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>1.15 – 1.3</td>
<td>1.12 – 1.3</td>
</tr>
<tr>
<td>$R(m)$</td>
<td>0.2 – 0.45</td>
<td>0.2 – 0.45</td>
</tr>
<tr>
<td>$I_p$ (MA)</td>
<td>$\leq$ .21</td>
<td>$\leq$ 0.30</td>
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<tr>
<td>$I_N$ (MA/m-T)</td>
<td>6 – 12</td>
<td>6 – 20</td>
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<tr>
<td>$R_{B_t}$ (T-m)</td>
<td>$\leq$ 0.06</td>
<td>$\leq$ 0.1</td>
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<tr>
<td>$\kappa$</td>
<td>1.4 – 3.7</td>
<td>1.4 – 3.7</td>
</tr>
<tr>
<td>$\tau_{shot}$ (s)</td>
<td>$\leq$ 0.025</td>
<td>$\leq$ 0.05</td>
</tr>
<tr>
<td>$\beta_t$ (%)</td>
<td>$\leq$ 25</td>
<td>$&gt; 40$</td>
</tr>
<tr>
<td>$P_{HHFW}$ (MW)</td>
<td>0.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

D.J. Schlossberg, APS-DPP 2011 Meeting, Salt Lake City, UT
Thomson scattering will aid estimation of resistive helicity dissipation

Total helicity in a tokamak geometry: \( K = \int_V (A + A_{vac}) \cdot (B - B_{vac}) \, d^3x \)

\[
\frac{dK}{dt} = -2 \int_V \eta J \cdot B \, d^3x - 2 \frac{\partial \psi}{\partial t} \Psi - 2 \int_A \Phi B \cdot ds
\]

- **Resistive Helicity Dissipation**
  - \( E = \eta J \rightarrow \eta \approx \frac{\pi e^2 m^{1/2}}{(4\pi \epsilon_0)^2 (kT_e)^{3/2}} \ln(12\pi n\lambda_D^3) \) (Spitzer)
  - Use Thomson scattering to quantify \( T_e \) and \( n_e \)

- **These low-density non-solenoidal plasmas present the most challenging conditions for measuring Thomson scattering**

  - **AC Helicity Injection:** \( \dot{K}_{AC} = -2 \frac{\partial \psi}{\partial t} \Psi = 2V_{\text{loop}} \Psi \)
  - **DC Helicity Injection:** \( \dot{K}_{DC} = -2 \int_A \Phi B \cdot ds = 2V_{\text{inj}} B_{\perp} A_{\text{inj}} \)

D.J. Schlossberg, APS-DPP 2011 Meeting, Salt Lake City, UT
High-$\beta$, high $I_p/I_{TF}$ scenarios will be characterized with MPTS

- Using helicity startup, Pegasus can access $I_N > 5$ at $I_p \sim 0.2$ MA
- As facilities are upgraded, expect to challenge the Troyon limit
- Explore confinement and temperature distributions in these regimes unique to Pegasus
Thomson scattering occurs when incident EM radiation excites free electrons

- "Thomson scattering" = scattering of EM radiation from free electrons
  - assumes $h\nu \ll mc^2$
  - here, assume incoherent scattering ($k_{\text{inc}} \lambda_D \gg 1$)

- Small scattering cross-section necessitates high-energy incident light (i.e. laser)
  \[
  \frac{dP}{d\Omega} = r_e^2 \sin^2 \phi c \varepsilon_0 |E_i|^2
  \]

- Collection lens & fiber bundles provide spatially resolved measurements

- Frequency bandwidth of the scattered light is proportional to $T_e$
  - Dispersion grating used to measure $\Delta\nu = c/\Delta\lambda$

- Small signal levels dictate high-sensitivity, fast detection electronics (ex. fast-gated image-intensified CCD)

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Scattered intensities $\sim \mu$Watt for low-density non-solenoidal plasmas

- Preliminary calculations yield scattered intensities of $\sim 4 \times 10^3$ total photons
  - Assumes incoherent, non-relativistic scattering
  - Assumes 2J, 7 ns Nd:YAG laser pulse
  - Assumes solid angle of $\sim 0.01$ ster per channel

- Since plasma durations in PEGASUS are $\sim 30$ ms, will only be able to measure one laser pulse

\[
I_{\text{det}} = \frac{E_{\text{laser}} \sigma n_e l \xi}{E_{\text{photon}} 4\pi} \\
= E_{\text{laser}} \left( \frac{\lambda_{\text{laser}}}{hc} \right) \sigma n_e l \frac{\xi}{4\pi} \\
\approx 2.66 \times 10^{11} \text{s}^2/\text{kg} \left( E_{\text{laser}} \cdot \lambda_{\text{laser}} \cdot n_e \cdot l \cdot \xi \right)
\]

**Symbol:**

**Inputs:**

- $E_{\text{laser}}$: Laser output energy (J)
- $\lambda_i$: Incident laser wavelength, $\lambda_m$ (m)
- $n_e$: Electron density ($m^{-3}$)
- $l$: Length of beam for one channel (m)
- $\xi$: Solid angle subtended by optics (ster)
- Pulse duration (s)

**Output:**

- $I_{\text{laser}}$: Number of laser photons incident/pulse
- $I_{\text{det}}$: Number of photons scattered/pulse
- Joules incident at primary wavelength
- Watts at primary wavelength

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Spectral range 532 – 592 nm for PEGASUS operating scenarios

- PEGASUS plasmas typically $10 \text{ eV} < T_e < 500 \text{ eV}$

- Use high dispersion VPH grating for low temperatures:
  - $532 \text{ nm} < \lambda_{\text{inc}} < 562 \text{ nm}$

- Use low dispersion VPH grating for high temperatures:
  - $532 \text{ nm} < \lambda_{\text{inc}} < 592 \text{ nm}$

- Signal levels will likely dictate $\Delta \lambda_{\text{inc}} \approx 4 \text{ nm}$ and $8 \text{ nm}$ in the low and high temperature cases, respectively

- Predictions assume $90^\circ$ average scattering angle with $\sim 10^{-2}$ solid angle
  - Relativistic effects evident in shift of central wavelength at $T_e = 1 \text{ keV}$

*Based on: J. Sheffield, Plasma Phys., Vol 14, 783-791 (1972)*

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Design method divides entire system into strongly coupled subassemblies

Subassemblies include:

1) Laser & enclosure
2) Beamline
3) Beam Dump
4) Collection Optics
5) Fiber Optics
6) Spectrometers
7) Control Code & SCRAM systems interface
8) Safety Overall
Multiple locations and methods used to reduce stray light

- Baffling along laser entrance tube
- Enclosed beam dump with baffles
- Sharp cut-on filter at spectrometer
- Grating alignment such that laser wavelength not incident on detector

Transmission through Spectrometer Entrance Filter

- Detection Active Area
- 532 nm spectral component
- To spectrometer

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New Technology Reduces Cost & Complexity, Increases Performance

- **Image-Intensified CCD** chosen over APDs & fast digitizers
  - Significantly lower cost/channel
  - More compact form factor

- **Volume Phase Holographic (VPH) grating** chosen over bandpass filters
  - Dynamic spectral binning (with CCD)
  - Multiple channels per single grating

- **Frequency-doubled ND:YAG laser** chosen over Ruby laser
  - >2J at 532 nm possible
  - Visible light eases alignment
  - Excellent pointing stability allows tighter viewing volume

- **Beamline** optimized for simplicity and performance
  - Remotely actuated turning mirrors
  - Short beamline (<7 m)

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Novel spectrometer system employed – see Schoenbeck PP9.00007

- Custom achromat entrance lens
- Custom Volume Phase Holographic (VPH) diffraction gratings
- Image Intensified CCD (ICCD) detector
  - High quantum efficiency Gen 3 Intensifier
  - Fast gating capability down to 1.2 ns

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**RCWA Theoretical VPH Grating Efficiency, 2971 l/mm**

- ~80%
- ~70%

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**Quantum Efficiency Curves for Gen 3 Image Intensifiers**

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Initial System Designed for Expandability

- Individual channels correspond to close-packed fiber bundles
  - 1.5 cm radial resolution

- Initially, 4 data channels and 4 background monitors
  - Evaluate performance & plasma conditions and reconfigure as needed
  - Upon successful implementation, immediately begin expanding to 16 additional channels

- Scan array radially from shot-to-shot
  - Initially manual positioning
  - Expand to automated positioning across curved collection optics focal plane

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Laser specifications balanced between commercial availability and physics needs

- Identify tolerable limits due to physics needs and layout constraints
- Reliable, “turn-key” operation of laser desired
  - Nd:YAG used extensively for MPTS in plasmas
  - Operate flash lamps at steady 10 Hz to obtain maximum stability
- Implement design with consideration for possible future upgrades:
  - Additional spatial points
  - Multiple laser passes
  - Multiple time points per shot

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
<th>Determining factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Energy</td>
<td>≥ 2000 mJ</td>
<td>Scattered intensity fraction</td>
</tr>
<tr>
<td>Divergence</td>
<td>≤ 0.5 mrad</td>
<td>Desired spatial resolution, component damage thresholds</td>
</tr>
<tr>
<td>Pointing stability</td>
<td>≤ 50 µrad</td>
<td>Beam line</td>
</tr>
<tr>
<td>Pulse length</td>
<td>≥ 10 ns</td>
<td>Availability at desired power</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>≥ 10 Hz</td>
<td>Shot duration; availability</td>
</tr>
<tr>
<td>Jitter</td>
<td>≤ 500 ps</td>
<td>Time resolution</td>
</tr>
<tr>
<td>Beam diameter</td>
<td>8 – 15 mm</td>
<td>Availability</td>
</tr>
<tr>
<td>Polarization ratio</td>
<td>≥ 90%</td>
<td>Scattering dependence</td>
</tr>
<tr>
<td>Energy stability</td>
<td>± 2 %</td>
<td>Availability; repeatability; Intensity resolution</td>
</tr>
</tbody>
</table>
Beam energy and temporal pulse shape satisfy design requirements

- In-house calibration to ensure actual performance matches requirements
  - Test key laser properties (energy, pulse duration, pointing stability)
- Tests designed to mimic Pegasus shot cycle times and typical laser use
  - Single laser pulse every ~5 minutes


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Beam pointing stability and focusing will provide well-defined viewing volume

- Beam focused over ~9m path length onto a fast-framing CCD camera
  - Single plano-convex lens
  - 5.6 µm pixel size, 640x480 pixels
  - Attenuation > $10^{-6}$ needed to avoid camera saturation

- Pointing stability within 3 mm viewing area defined by collection optics

- Focused beam diameter within expected range

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Full-power beam diameter matches design specification

- Burn paper used to measure beam diameter at or near full-power
  - As beam is focused, unattenuated energy density becomes too large for burn paper
  - Use OD(1) high-power dielectric attenuator to reduce energy
- Unfocused beam diameter \( \sim 10 \) mm
- Diameter varies by <25\% over expected plasma radius
- Long-focal length lens allows convenient fine-tuning on optical table

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Several calibration methods under consideration

• Typical calibration methods span orders of magnitude in cross-section:
  – $\sigma_{\text{Rayleigh}} \approx 10^{-28}$ cm$^2$/sr
  – $\sigma_{\text{Raman}} \approx 10^{-31}$ cm$^2$/sr
  – $\sigma_{\text{Thomson}} \approx 10^{-33}$ cm$^2$/sr

• Alternate methods include:
  – Comparison with existing PEGASUS diagnostics (ex. $\mu$wave interferometer)
  – Calibration source during machine vents (requiring vessel entrance)
  – Vacuum-compatible calibrated source, actuated to move along beamline (ex. MST mini integrating sphere)

NSTX Raman Calibration

Raman spectrum
Polychromator spectral bins
1048
1058
1064

$\lambda$ (nm)

Rayleigh (a.u.)

0.0
0.2
0.4
0.6

Line integrated density ($10^{19}$ m$^{-3}$)

0
1
2
3
4

15
20
25
30

Time (ms)

Typical PEGASUS plasma density

MST Insertable Integrating Sphere
Minature Integrating Sphere
Insertable Probe
Pumping Duct
Stepper Motor

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Precision timing provided by tunable delays

- Sub-nanosecond synchronization necessary between components
  - User requests laser pulse at given time $t_0$ during shot
  - PEGASUS control code issues Timing Sequence Module (TSM) pulse at $(t_0 - t_{\text{flash lamps}} - t_{\text{Q-switch}})$
  - Variable Sync Output on laser supply triggers camera acquisition

- Tuned to account for laser propagation time through beamline and electronics calculation time internal to camera
Bremsstrahlung emission a tolerable fraction of scattered signal

- Predicted Bremsstrahlung emission shows ~photons/nm collected
  - Short collection time (8ns)
  - Moderate single channel viewing volume (231 cm$^3$)
- Actual Bremsstrahlung measured with scanning spectrometer
  - Small peaks within Thomson collection spectral range
- Choice of spectral collection region avoids D$_{\alpha}$ and N$_2$ lines

**Predicted Bremsstrahlung Emission**
per 8 ns pulse from 231 cm$^3$ scattering volume

*following Karzas and Latter, Astrophys. J. (Supplement) 61961, 167

**Measured Bremsstrahlung Spectrum**
Initial data analysis routines being created and evaluated

- After system completion, data image will contain 4 scattering channels & 4 background channels
- All rows for one spatial point will be binned
- Selectable spectral binning (columns) based on plasma conditions
- Several possible fitting functions being evaluated for temperature estimation:

**Selden:**

\[ S(e, \theta) = c(a)A^{-1}(e, \theta) \exp \left[ -2aB(e, \theta) \right] \]

where:

\[ A(e, \theta) = (1 + e)^3 \left[ 2(1 - \cos \theta)(1 + e) + e^2 \right]^{\frac{1}{2}} \]

\[ B(e, \theta) = \left( 1 + \frac{e^2}{2(1 - \cos \theta)(1 + e)} \right)^{\frac{1}{2}} - 1 \]

\[ c(a) = \left( \frac{\pi}{a} \right)^{\frac{1}{2}} \left( 1 - \frac{15}{16}a^{-1} + \frac{345}{512}a^{-2} + \ldots \right) \text{ when } a \gg 1 \]

and:

\[ 2a = \frac{m_ek^2}{kT_e}, \theta = \text{scattering angle}, c(a) = \text{normalizing constant} \]

\[ \epsilon \equiv \left( \frac{\lambda_{ls}}{\lambda_i} \right) - 1 \text{ measures relative wavelength shift} \]


**Sheffield:**

\[ P_{sc}(R, \lambda_s)d\lambda_s d\Omega = \frac{P_i r_0^2 d\Omega n_e Lc}{2\pi^2a_i \sin \left( \frac{\theta}{2} \right)} \]

\[ \left\{ 1 - \frac{7 \Delta \lambda}{2 \lambda_i} + \frac{c^2 \Delta \lambda^3}{4a^2 \lambda_i^3 \sin^2 \left( \frac{\theta}{2} \right)} \right\} \]

\[ \times \exp \left( -\frac{c^2 \Delta \lambda^2}{4a^2 \lambda_i^2 \sin^2 \left( \frac{\theta}{2} \right)} \right) \cdot d\lambda_s \]

where:

incident power \( P_i = \frac{cE_i^2}{8\pi} A \)

\[ r_0 = \frac{e^2}{mc_0^2} = 2.82 \times 10^{-13} \text{ cm} \]

\( \lambda_s = \lambda_i + \Delta \lambda \)

Summary

- A novel Thomson scattering diagnostic is being installed on the PEGASUS Toroidal Experiment
- Laser characterization shows promising performance
- Spectrometer assembly and characterization underway
- After installation and calibration, system will be used:
  - As a routine density and temperature diagnostic
  - To investigate dominant confinement mechanisms in point-source helicity-driven plasmas
  - To quantify sources of helicity dissipation
Future directions

- Finish characterizing collection lens and detector components
- Assemble spectrometers
- Install laser, collection optics, fiber optics, and spectrometer rack in experimental area
- Perform system-wide calibration
- Finish creating and evaluating analysis routines
- Investigate physical phenomena in both higher-density ($10^{19}$ m$^{-3}$) Ohmic plasmas and lower-density non-solenoidal plasmas
Please leave your name, affiliation, and e-mail address:

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