Design and Operation of a Frequency Doubled Nd:YAG Thomson Scattering System with Transmission Grating ICCD Spectrometer

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Novel Thomson scattering system deployed on the Pegasus Toroidal Experiment

- Scattering via a 7 ns, 2 J frequency doubled Nd:YAG laser at 532 nm
  - Laser focuses to 3 mm diameter within the plasma via a 7 m beam-line.
  - Cameras and remotely adjustable mirrors allow for shot-to-shot alignment.

- A custom multi-element lens collects scattered photons from $15 \text{ cm} < R_{maj} < 85 \text{ cm}$ with 1.2 cm radial resolution
  - 8 fiber optic bundles provide spatial points for sampling
  - Each set of 8 channels is measured in a single spectrometer

- The spectrometer utilizes a high efficiency (80%) volume phase holographic grating and a high quantum efficiency (> 40%) image intensified CCD (ICCD) camera
  - Two interchangeable gratings to cover 10 – 1000 eV
  - Optimized for $n_e$ from mid-$10^{18}$ to mid-$10^{19}$ m$^{-3}$

- Work supported by US DOE Grant DE-FG02-96ER54375 and the American Recovery and Reinvestment Act
Pegasus is a compact ultralow-A ST

Equilibrium Field Coils
High-stress Ohmic heating solenoid
Vacuum Vessel
Toroidal Field Coils
Ohmic Trim Coils
New Divertor Coils
Point-Source Helicity Injectors

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>$\leq$ 0.21</td>
<td>$\leq$ 0.30</td>
</tr>
<tr>
<td>$I_N$ (MA/m-T)</td>
<td>6 – 12</td>
<td>6 – 20</td>
</tr>
<tr>
<td>$R_B$ (T-m)</td>
<td>$\leq$ 0.06</td>
<td>$\leq$ 0.1</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>1.4 – 3.7</td>
<td>1.4 – 3.7</td>
</tr>
<tr>
<td>$\tau_{\text{shot}}$ (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>$P_{\text{HHFW}}$ (MW)</td>
<td>0.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Major research thrusts include:

- Non-inductive startup and growth
- Tokamak physics in small aspect ratio:
  - High-$I_N$, high-$\beta$ stability limits
  - ELM-relevant edge MHD activity

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Laser System Integrated into Pegasus Test Cell

Turning mirror enclosure with monitor camera

0.5m

2.7m

3.37m

Enclosed optical table layout

Beam dump enclosure with monitor camera

Nd:YAG laser

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- New Gen III image intensified CCD cameras provide quantum efficiency (QE) >40% through the visible region

- Improved efficiency with VPH gratings over conventional ruled reflective gratings

- Nd:YAG laser operates in the visible (532nm) through frequency doubling

- Estimates of ~35,000 photons scattered into viewing optics per spatial point for \( n_e = 1 \times 10^{19} \text{ m}^{-3} \)
  - Given component efficiencies, an estimated 6,390 photoelectrons per spatial channel reach the micro-channel plate for multiplication
  - See Dave Schlossberg for more details
“Turn-key” 2J Laser Optimized for Operation on Pegasus

- Continuum Powerlite DLS 9000 Nd:YAG laser
- Frequency doubled to provide 2J at 532 nm

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
<th>Determining factors</th>
</tr>
</thead>
<tbody>
<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>~7 ns FWHM</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>Polarization ratio</td>
<td>≥ 90%</td>
<td>Scattering dependence</td>
</tr>
</tbody>
</table>
Laser Meets Specifications and Provides Reliable Operation

- Flash lamps pulsed at 10 Hz in between shots to keep the system stable
- Delay generator triggers laser with picosecond resolution
- Verified laser stability (pointing stability, power, & pulse shape) on 5 minute shot-cycle

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Steering Mirrors and Cameras Enable Between Shot Alignment

- 2 actuated mirrors available for remote control of laser alignment
  - 1 mirror at exit of laser hutch
  - 1 mirror turns beam to enter vacuum vessel

- Position is monitored using a camera as beam-finder
  - Turning mirror acts as beam splitter
  - Ethernet based camera triggered to operate during Pegasus shot
Beam Dump Provides 2\textsuperscript{nd} Monitor for Laser Alignment through Vacuum Vessel

- Camera at beam dump acts as second beam-finder for laser alignment
  - Mirror acts as beam splitter
  - Neutral density filters reduce the signal to prevent camera saturation

- A beam dump (CVI 48-10) is used for the \~1.8J that reach the beam dump
Laser Diameter in Viewing Area is ~1mm

<table>
<thead>
<tr>
<th>Location</th>
<th>Beam diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Dump</td>
<td>10.50 mm</td>
</tr>
<tr>
<td>Plasma Core</td>
<td>2.26 mm</td>
</tr>
<tr>
<td>Plasma Edge</td>
<td>0.04 mm</td>
</tr>
<tr>
<td>Laser Exit</td>
<td>10.00 mm</td>
</tr>
</tbody>
</table>
• Each spatial channel is 2.5 mm tall (across the laser) by 12 mm along the laser in the plasma

• Fibers will be moved between shots as needed
  - Initially movement is manual with plans to automate in the future
  - Each spectrometer allows for 8 fiber bundles, 3 spectrometers will be deployed
Collection Lens Designed to Collect Full Field of View

- **Design Criteria:**
  - Collect 80 cm flat field of view 72 cm from lens
  - Resolution sufficient to collect a scattering area ~1.3 cm x 0.3 cm

- **Curved image plane with open locations for fiber placement**
  - F# 2.1
  - 20.2 cm focal length

- **Resolution:** 100um in the plasma

- **Magnification** ~1/3

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Custom Designed Louvers Shield Window from Getters

- Carbon painted stainless steel louvers angled to prevent rays of getter light from reaching the vacuum window
- Reduces system efficiency slightly to maintain window integrity
- Efficiency >90%

Getter Source

57.1cm

185.3cm

Louver and Vacuum Window

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Compact Spectrometer Uses VPH Gratings and ICCD Cameras

Light shield not shown for clarity

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8 Bundles Combined
Fiber Bundle at Collection Lens
Fiber Optic Bundle Repackaged at Spectrometer to Fit 8 Spatial Channels through System

• 8 individual ends provide flexibility in selecting viewing locations

• A slit composed of 8 individual bundles with a 2mm width allows all 8 channels to fit on a single CCD

• 3 spectrometers will provide a total of up to 24 spatial channels
  – A minimum of 12 of these channels will be used for viewing scattered laser light
  – The remaining channels will be either be used to collect background signal or as additional laser viewing channels

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VPH Grating Designed for High Efficiency in 2 Temperature Regimes

- Two gratings
  - 2971 lines/mm for low temperatures ($kT_e \sim 10\text{eV}-100\text{eV}$)
  - 2072 lines/mm for high temperatures ($kT_e \sim 100\text{eV}-1000\text{eV}$)

- Dispersion selected to utilize the full 13.3 mm width of the CCD

RCWA Theoretical Performance
Unpolarized input at 54.4 degrees

![Graph showing diffraction efficiency vs wavelength]

~ 80%
~ 70%

Wavelength (nm)  | Diffraction Efficiency (%)  
525  | 530  | 535  | 540  | 545  | 550  | 555  | 560  | 565  | 570  |
---|---|---|---|---|---|---|---|---|---|---|
10  | 20  | 30  | 40  | 50  | 60  | 70  | 80  | 90  | 100 |

J. Arns KOSI

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ICCD Detectors Chosen for High Gain & Low Noise Qualities

Manufacturer’s Specifications: Andor iStar 734

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Active Area (mm)</td>
<td>13.3 x 13.3</td>
</tr>
<tr>
<td>Effective Pixel Size (um)</td>
<td>19.5 x 19.5</td>
</tr>
<tr>
<td>Read Noise</td>
<td>As low as 2.9 e-</td>
</tr>
<tr>
<td>Active Pixels</td>
<td>1024 x 1024</td>
</tr>
<tr>
<td>Spectral Range (nm)</td>
<td>120 - 1090</td>
</tr>
<tr>
<td>Photocathode QE (max)</td>
<td>Up to 45%</td>
</tr>
<tr>
<td>Minimum Optical Gate Width</td>
<td>As low as 1.2ns</td>
</tr>
<tr>
<td>Image Intensifier Gain</td>
<td>&gt;200</td>
</tr>
</tbody>
</table>

From Andor iStar 734 Manual

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Efficiencies Collection Optics and Spectrometer
Predict 5000 Photons Reach the MCP

- 34 000 red-shifted photons scattered into viewing optics for plasmas with $n_e = 1 \times 10^{19} \text{ m}^{-3}$

- Variable gain with a maximum gain setting of 300

- Predicted efficiency:
  - Fiber optics, spectrometer and camera sub-system efficiency of $>25\%$ predicted
  - $>19\%$ for the full system, including the collection lens and louvers

<table>
<thead>
<tr>
<th>Component</th>
<th>Efficiency</th>
<th>Photons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scattered photons*</td>
<td>n/a</td>
<td>34 000</td>
</tr>
<tr>
<td>Louvers</td>
<td>90%</td>
<td>25 704</td>
</tr>
<tr>
<td>Collection Lens</td>
<td>84%</td>
<td>29 376</td>
</tr>
<tr>
<td>Fiber Optics</td>
<td>65%</td>
<td>16 708</td>
</tr>
<tr>
<td>VPH Grating</td>
<td>&gt;85%</td>
<td>14 201</td>
</tr>
<tr>
<td>Camera QE</td>
<td>45%</td>
<td>6 390</td>
</tr>
<tr>
<td>A/D conversion</td>
<td>2 photoelectrons per count</td>
<td>3 195 Counts**</td>
</tr>
</tbody>
</table>

*Red-shifted scattered photons into collection volume per laser viewing spatial channel
**Counts calculated is the minimum, assuming unity gain factor in the MCP

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Fiber Optics and Spectrometer Efficiency Matches Estimates Well

• Fiber optics, spectrometer and camera efficiency determined by absolutely calibrated integrating sphere.

• Low dispersion, high Te grating system approaches predicted efficiency of >25%

• High dispersion, low Te grating setup leads to high vignetting and walkoff
  – Approaches theoretical efficiency from ~532 to ~542
  – Walkoff a significant effect at upper range of interest
Dark Noise Testing Indicates Camera is Read Noise Dominated

- CCD dark noise $\sim \sqrt{N_{\text{Read}}^2 + N_{\text{Dark Current}}^2}$
  - Dark noise dominated by read noise without on-chip binning
  - Read noise without on-chip binning is $\sim 7$ counts per pixel

- On-chip binning
  - RMS noise in a super-pixel of 128 vertical pixels x 51 horizontal pixels is $<12$ counts
  - Equivalently, a 128x51 pixel super-pixel contains 0.03 RMS noise counts per single pixel

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Key components of the Pegasus Thomson scattering system include:

- 2J Nd:YAG laser operating at 532nm
- Remotely actuated mirrors and cameras for between shot alignment
- Fiber bundles designed to maximize use of CCD camera
- Volume phase holographic gratings with efficiencies >80%
- ICCD cameras for simplified data acquisition

A single 8-channel spectrometer currently deployed with plans to expand to 3 spectrometers (24 total channels) late 2012 and into early 2013

Laser system and 1st spectrometer being fine-tuned:

- Alignment of viewing optics and laser beam
- Fine-tuning laser path to maximize signal
Ohmic plasmas are low impurity and dominated by Bremsstrahlung radiation

- May be able to eliminate or reduce background channels

In helicity Injection plasmas impurity line emissions \(\approx 10\) times the background

Background signal will need to be evaluated to determine if the bremsstrahlung and impurities are a significant effect on the nanosecond timescale
Stray Light Reduction Techniques Employed

532 nm focused off detector active area to spectrometer

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