Maintaining, Upgrading, and Expanding the Role of Thomson scattering on DIII-D

D. Eldon¹*, A.G. McLean², T.N. Carlstrom³, C. Liu³, M. Watkins³, B.D. Bray³, E. Kolemen⁴, R.J. Groebner³, T.H. Osborne³, P.B. Snyder³, R.L. Boivin³, G.R. Tynan¹

¹University of California–San Diego, San Diego, CA 92093, USA; ²Lawrence Livermore National Laboratory, Livermore, CA 94550, USA; ³General Atomics, San Diego, CA 92121, USA; ⁴Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA
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Outline

• Introduction
• Recent Major Upgrades
• Results
• Further Improvements
• Closing
Thomson Scattering is a Key Tokamak Diagnostic

- Instantaneous* measurement of electron temperature and density at many spatial locations
- Always available
  - No restrictions based on magnetic field, neutral beam injection, etc., unlike ECE, CER BES, MSE, DBS, reflectometer, ...
  - Range of measurable temperatures and densities covers all typical plasma set-ups.
  - Non-perturbative: no reason not to use Thomson scattering.
- Easy to interpret
  - Each datum fixed to a known location in space and time: straightforward mapping.
  - Reported measurement is simply $T_e$ and $n_e$ with uncertainty at each point, no tomography or de-convolution.

*8ns laser pulse
DIII-D’s Thomson Scattering Diagnostic Covers a Wide Range of Parameters

- \( n_e \gtrsim 0.2 \times 10^{19}/m^3 \)
- \( 1\text{eV} \leq T_e \leq 10\text{keV} \)
- Spatial Resolution \( \geq 6\text{mm} \)
  - Maps to even higher resolution @ midplane
- Scattering length \( \geq 4\text{mm} \)
- Typical \( \delta T_e \leq 10\% \)
System Layout

- 54 view-chords through three ports
- Three laser paths:
  - Core + edge @ 230Hz
  - Divertor @ 50Hz
  - Tangential @ 40Hz
- Nd:YAG lasers @ 1064.3nm
Scattered Light Fed into Polychromators

Scattered Spectrum @ 1keV

Filter Transmission Functions

Background Light

Input Fiber

Optical Path

APD Detectors

Signals @ 1keV

Detector Dark Noise

Fit to model

Measurement & uncertainty

Eidon / Thomson scattering @ DIII-D / LAPD 2013
Major Upgrades were Performed during 2010 Long Vent

Outline

• Introduction

• Recent Major Upgrades
  – Motivation
  – Spatial Resolution
  – Temporal Resolution
  – Electronics

• Results

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High Resolution Thomson Scattering Upgrade Needed for Understanding Pedestal Physics

- Fusion power $\sim P^{2}_{e,ped}$
- Pedestal limited by MHD stability
- Pressure & current profiles required for calculation
  - Current influenced by pressure (bootstrap current)
- EPED model formulates in terms of limits on pedestal height and width.
  - Very good measurement of pedestal height and width needed!
    - Also must measure small changes in width

Very good measurement of pedestal height and width needed!
  Also must measure small changes in width

Previous TS system could only set upper bound on pedestal width in many cases.
Increase Resolution by Shortening Scattering Length, Packing in More Chords. But How Many?

Plasma physics relevant position coordinate:
For small view chord height, the laser diameter will begin to dominate span across flux surfaces: diminishing returns for short scattering lengths.
Fitting Simulated Pedestals with Various Spot Sizes Shows Best Value at Half Previous Value

Narrowest Pedestal Resolved:
- 15mm: Pre-upgrade
- 10mm: 2x shorter scattering length
- 10mm: 3x shorter scattering length

- Laser spot = 3.0 mm, view height = 8.6 mm
- Laser spot = 3.0 mm, view height = 4.3 mm
- Laser spot = 3.0 mm, view height = 3.0 mm
Spatial Resolution Upgrade: Twice as Many Chords
3mm → 2x 1.5mm

Close up of Fiber terminators

Unmodified fiber terminators:
3.0x1.5mm bundles of 104 fibers

Silica / Silica fibers

High resolution fiber terminators:
Two 1.5x1.5mm bundles each

Eldon / Thomson scattering @ DIII-D / LAPD 2013
Upgraded Thomson System Resolves Pedestal

- 12→6mm chord-chord
- 9→5mm scattering length
- 10 new chords→20 in high resolution band

Measurement region
Maps to ~3mm chord-chord at midplane (where many diagnostics are located)

Before

142000@4985ms
Not enough points to resolve pedestal!

After

146439@2226ms
2x Resolution

Eidon / Thomson scattering @ DIII-D / LAPD 2013
A Concurrent Upgrade Increased Temporal Resolution by Adding More Lasers

- Nd:YAG
- λ=1064.3nm
- ~1J / 10ns pulse
- Previously: 8x 20Hz divided among subsystems:
  - Core: 80Hz
  - Divertor: 20Hz
  - Tangential: 60Hz
- New: 4x 50Hz + 6x 20Hz:
  - Core: 230Hz
  - Divertor: 50Hz
  - Tangential: 40Hz
Electronics Upgrade Increases SNR and Reliability

- Takes advantage of ~20 years of advances in semi-conductors
  - High speed, low noise electronics
  - Read noise / dark noise: 40 → 30 photo-electrons/pulse
  - Higher bandwidth preamplifier → circuit response: 200 → 25ns
- Better background subtraction
  - Integration gate: 65 → 30ns  (less background light accumulation)
  - Subtraction delay: 100 → 30ns  (subtracted background closer to current level)
- Replaced obsolete CAMAC system with D-TACQ
  - Better reliability
  - Allows additional chords
- SNR 2.5 to 6x better, depending on conditions.

Output Comparison

Filtered light from DIII-D

The Upgrade Came Online for the 2011 Campaign

- **Outline**
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- **Results**
  - Physics accomplishments: fulfillment of motivation
  - Data quality
- Further Improvements
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Upgraded Thomson Scattering Measurements Have Contributed to Model Validation

- **Improved testing of the EPED model\(^1,\,2\)**
  - More precise measurement of pedestal width $\rightarrow$ better test.
  - Higher time resolution $\rightarrow$ more profiles at important times, better statistics, better test.
  - This was part of the motivation for the upgrade.

- **Testing of critical gradient models for divertor heat flux width**
  - Important model for predicting head loads on ITER divertor target.
  - Needs gradient scale lengths on small ($<2\text{cm}$) spatial scales.

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\(^1\)P.B. Snyder, et al., Phys. Plasmas, 19, 056115 (2012)


Successful Startup After Upgrade, with Some Issues

- Horizontal stripes = systematic errors
- Not all new detectors survived burn-in
- Bad measurement from affected chords
  - Monitor, replace, recalibrate
  - New electronics include temp and voltage monitoring hardware

Shot 144794 on 2011-06-15
(start of 2011 campaign)
Detector Reliability Improved by the End of 2011

- Chord – chord systematic errors reduced.
- Still Some unexplained scatter.
- Room for more improvement.

Shot 147060 on 20111024 (end of 2011 campaign)

Temperature (keV)
0.0 1.0 2.0

Z (cm)
1 2 3

Time (s)
Once the System Basically Worked, Higher Order Corrections were Pursued

- **Outline**
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- **Further Improvements**
  - Spectral measurement of all optics
  - More accurate scattering angles from new CMM
  - Improved thermal stabilization of hardware
  - Filter set optimization and expansion
- Closing
Sign of Trouble: Neighboring Chords Through Different Optics Disagree

- Scattering angle and hardware change
- Lens transmission is calibrated regularly with Rayleigh scattering
  - At the laser wavelength only!
The Spectral Transmission Function of the Collection Optics Changed Significantly

Example Temperature Correction for midplane optics

Assumed to be \sim constant transmission vs. \lambda

New/Old

keV

0.8
1.0
1.2
1.4

0 1.0 2.0 3.0

Laser

Midplane Optics

Top of Machine Optics

0.5keV
1.0keV
2.5keV
5.0keV
10.0keV

\lambda (nm)

700 800 900 1000 1100
New Coordinate Measurement Machine Allows for Improved Measurement of Scattering Angles

- More accurate position of scattering volumes and port windows
  - (most were less severe)
- Some scattering angles changed by up to a degree
- $T_e$ changes by a few % in extreme cases

Adapted From, http://www.nikonmetrology.com/en_US/Products/Portable-Measuring/Articulated-Arms/MCA-II-6-Axis/

D.C. Pace, et al., CMM Usage, DIII-D Science Meeting, August 10, 2012
Detector Gain Varies with Temperature → Better Temperature Control was Implemented

- Gain varies with detector temperature and shows hysteresis
  - Room temperature varies by 1°C as air conditioner cycles
  - New electronics include thermistor next to APD, allowing this to be monitored.
  - ~5% variation in gain

- Improved chiller, thermal insulation, and monitoring.
  - Detectors now stable to 0.1°C
Divertor Filter Sets Re-Optimized for Better Performance

- Example: Divertor Polychromator (low temperature oriented)
- Before: $20 < T_e < 800 \text{eV}$
- After: $1 < T_e < 6000 \text{eV}$

After

Added higher temperature filter
Divertor Filter Sets Re-Optimized for Better Performance

Before

Added higher temperature filter

After

Filter Transmission

λ (nm)
Divertor Filter Sets Re-Optimized for Better Performance

Filter is sloped at laser line: small wavelength error = large transmission error!

Flatter peak on laser filter

Added filter to red side

1064.3 nm

Before

20 \leq T_e < 800 \text{eV}

After

1 < T_e < 6000 \text{eV}
Many Fixes and Improvements Contributed to Higher Data Quality

Data from 2011

Temperature (keV)

Data from 2013

Temperature (keV)
Many Fixes and Improvements Contributed to Higher Data Quality

- Polarization filters on collection optics
- Lens spectral measurement
- CMM scattering angles
- Thermal stabilization
- Filter set optimization and maintenance
For example, local temperature in divertor plasma can be controlled:
- Cool by puffing in more gas
- Feedback on real time electron temperature measurement from TS
We Have Some Exciting Ideas for the Future

• **Outline**
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• **Closing**
  – Future Plans
    • 2D divertor
    • In-situ calibration
    • Tangential laser and midplane port upgrades
  – Summary
Adjustable Position Divertor System

- Present divertor system measures above divertor shelf
- Move laser beam further inboard to access other divertor geometries
- Requires in-vessel laser mirrors and beam dumps
- Maybe even 2D imaging
In-Situ Measurement of All Optics Would Provide More Reliable Calibration with Less Work

- Include all components and couplings together
- Avoid taking things apart
- Scanning monochromatic light source
  - Pulsed instead of CW!
  - Currently, spectra measured with CW source and detector background channel
    - Have to translate to the pulsed channel
Reverse Tangential Laser Beam for Higher Temperature Support

- Retro-reflector on far wall
- More favorable scattering angle
- Higher maximum temperature 6\(\rightarrow\)30keV

![TOP VIEW OF MIDPLANE TS OPTICS](image)

**Thomson Scattering**

- Thomson Scattering at 150 degrees

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Scattered signal (AU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
<td>1keV</td>
</tr>
<tr>
<td>800</td>
<td>2keV</td>
</tr>
<tr>
<td>900</td>
<td>5keV</td>
</tr>
<tr>
<td>1000</td>
<td>10keV</td>
</tr>
<tr>
<td>1100</td>
<td>30keV</td>
</tr>
</tbody>
</table>

**Current**

- Current Thomson Scattering curves

**Planned**

- Planned Thomson Scattering curves
The Upgrade Worked

- The high resolution upgrade to the DIII-D Thomson scattering diagnostic contributed to validation of physics models
- Ongoing improvements have provided higher and higher quality data
- Further improvements are planned to expand the capabilities of the system

- We gratefully acknowledge the support of the DIII-D Team

Also supported by:
- The US Department of Energy under DE-FG02-07ER54917, DE-AC52-07NA27344, DE-FC02-04ER54698, DE-FG02-95ER54309 & DE-AC02-09CH11466
- The Oak Ridge Associated Universities Postdoctoral Research Program