Electron Temperature Diagnostics on the Pegasus Toroidal Experiment

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A soft X-ray (SXR) Pulse Height Analysis (PHA) system has been implemented to measure the electron temperature on the Pegasus Toroidal Experiment. The detector is a silicon drift diode (SDD) mounted on a bellows. The SDD detector is well suited for high resolution (139 eV at 5.9 keV), high count rate (10^6 cps) X-ray spectroscopy and therefore is able to obtain time-resolved temperature measurements on the order of a millisecond. The detector is radially scannable which permits profile measurements on a shot-to-shot basis with a spatial resolution as low as a few centimeters. Temperatures in the range of 300 eV - 1 keV should be measurable with the PHA system. Temperatures below 300 eV can be measured using oxygen and carbon line ratios with SXR Ross filter spectroscopy. A Thomson-Scattering system is also being designed for future implementation. The first generation of the diagnostic will include a 10 J, 40 ns Q-switched ruby laser (λ = 694.3 nm) and a single-spatial-channel avalanche photodiode detector/spectrometer system.

**Work supported by U.S. D.O.E. Grant DE-FG02-96ER54375**

*This research was performed under appointment to the Fusion Energy Sciences Fellowship Program administered by Oak Ridge Institute for Science and Education under a contract between the U.S. Department of Energy and the Oak Ridge Associated Universities.*
Motivation

• $T_e$ is a figure of merit for plasma performance and confinement properties

• $T_e$ measurements support equilibrium reconstruction and stability analysis
  – Important for q-profile and current drive modeling

• Deployment strategy must match available resources
**T_e Measurements on Pegasus**

First generation T_e diagnostics

- SXR Ross Filter spectroscopy (70 eV - 300 eV)
  - Spectral line intensity ratio of impurities provides crude measurement of T_e
  - Temporally resolved measurements
- SXR Pulse Height Analysis (200 eV - 1 keV)
  - SXR continuum spectrum depends strongly on T_e
  - Temporally and spatially resolved measurements
  - SXR emission code developed to model Pegasus system

Second generation T_e diagnostic

- Thomson Scattering (20 eV - 1 keV)
  - Ruby laser TS system from MST
  - Collection optics from MST and Phaedrus-T
# Pegasus Diagnostic Suite

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<td>$T_{\phi}(t)$</td>
<td>Planned</td>
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Pegasus Diagnostic Layout

First generation $T_e$ diagnostics
SXR Ross Filters

Central chord temperature measurement based on H-like and He-like impurity line intensity ratios for carbon and oxygen

MIST calculations of line ratios for both species considering different temperature profiles and diffusion coefficients (D)

Line Intensity Ratios (CV/CVI)

- ParaT D=5.0
- SharpT D=5.0
- FlatNe D=5.0
- ParaT D=1.0
- SharpT D=1.0
- FlatNe D=1.0

CV - CVI Range 70 - 150 eV

Line Intensity Ratios (OVII/OVIII)

- Para T
- Sharp T

OVII - OVIII Range 150 - 400 eV

Ross filter system can provide a crude estimate of temperature since line ratios depend on temperature profile and electron diffusion rate.

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Four diode pairs (8 total channels)
- 10 x 10 mm diode size
- AXUV-10 International Radiation Detectors Inc.

Filters:
- C\textsubscript{V} (4.0268 nm)
- C\textsubscript{VI} (3.3736 nm)
- O\textsubscript{VII} (2.1602 nm)
- O\textsubscript{VIII} (1.897 nm)

Temporal resolution \sim 0.1 ms

The Ross Filter diode array has been implemented on the machine and noise suppression work is in progress
SXRF Pulse Height Analysis (PHA)

Scannable midplane temperature measurement based on SXR continuum spectrum

- For $h\nu \geq T_e$, the emission spectrum has an exponential dependence on $T_e$
- Oxygen recombination line radiation can dominate SXR spectrum
- Be filter is added to the system to attenuate emission below 1 keV

Model results for Pegasus-like plasma and current PHA design

- SXR Emission Spectrum
  - Oxygen conc = 0%, $n_e = 5 \times 10^{19} \text{ m}^{-3}$

- SXR Emission Spectrum
  - $T_e = 200 \text{ eV}$, $n_e = 5 \times 10^{19} \text{ m}^{-3}$

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SXR Emission Model for Pegasus

**Temperature Profile**
- Density Profile
- Carbon & Oxygen content \( \frac{n_z}{n_e} \)

**Program Inputs**
- FORTRAN SXR emission spectrum calculation
- Be filter thickness
- Pinhole size
- Calculate etendue of pinhole system
- Compute number of photons reaching diode
- Calculate intensity spectrum after Be filter
- Compute spectrum emissivity and chordal integrated intensity

**Design parameters influenced by SXR emission model**

- Pinhole aperture: chosen so expected operating regime yields detector count rate of \( 10^5 - 10^6 \) cps

- Be filter: chosen so oxygen line radiation about equal to level of non-recombination radiation

*Based on code written by Ryan Schoof*

*D.J. Battaglia, APS-DPP, Denver, CO, October 2005*
PHA Well Suited for $T_e > 200$ eV in Pegasus

SXR emission code is used to model PHA performance for different plasma parameters.

- $R = 30$ cm  $a = 27$ cm
- Peaked $n_e$ and $T_e$ profiles
- 3 mil Be filter
- 2% Oxygen content
- 5 cm spatial resolution

10^5-10^6 cps

Typical operation space for Pegasus Experiments

It is possible to optimize the system for other operating spaces by changing the spatial resolution of the pinhole system.
Silicon Drift Diode Detector for SXR PHA

KETEK AXAS (Analog X-ray Acquisition System)
- Windowless
- Single channel
- Peltier cooling allows for room temperature operation with no external cooling
- 5 mm² silicon drift diode (SDD)
- Energy resolution $\leq 200$ eV @ 5.9 keV
- Maximum count rates nearing $10^6$ cps

Shaping electronics incorporated within detector
- Shaping time of 150 ns
- Allows operation at maximum count rate of detector with minimal pulse pile-up
- Aided by pulse pile-up correction software

Accurate temperature measurements require $\sim 1000$ pulses per spectrum. Thus, at $10^6$ counts per second, the temporal resolution is $\sim 1$ ms.
Tangency radii can be changed on a shot-to-shot basis
Pulse Fitting Reduces Pile-up Effects

- Pulse pile-up inevitable at high count rates

- PHA uses pulse fitting routines instead of an MCA
  - Pulse fitting routines are less sensitive to pile-up effects at high count rates than a traditional MCA
  - Increases useable count rate by about a factor of five

Data path of present PHA system does not use an MCA to find SXR spectrum

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Fitting the Pulse Train

Functional form of pulse:

\[ E = \frac{E_0}{n^n \exp(-n)} \left( \frac{2(t-t_0)}{\tau} \right)^n \exp\left( \frac{-2(t-t_0)}{\tau} \right) \]

\( n = 8 \) and \( \tau = 150 \ \mu s \)

Example pulse from shot 27590 fit with pulse model

Simulated pulse train deconstructed by pulse train fitting routine
Status of the SXR PHA

- Energy resolution measured
- PHA system built and integrated into operations
- Electronic noise has an RMS of < 50 eV, well below the measured energy resolution of 200 eV.

Fe - 55 energy spectrum measured with SDD

5.895 keV K\textsubscript{\alpha} FWHM: 200 eV
6.490 keV K\textsubscript{\beta} FWHM: 230 eV

PHA data taken during a gun + ohmic discharge

Shot 27581

Shot 27590

Improved electrostatic shielding
Thomson Scattering System

Single and multi-point Thomson scattering system being developed with MST and Phaedrus-T hardware

Ruby laser from MST
- Wavelength: 694.3 nm
- Q-switched (Pockels cell)
- Linear flash-lamped pumped
- Multimode (not spatially filtered)
- Maximum output energy: 10 J
- Output beam diameter: 16 mm
- Pulse duration (FWHM): 40 ns
- Polarization: Horizontal
- Beam divergence: 90% within 1.2 mrad

Spectrometers and detectors
First generation
- Single spatial point, multi-spectral point APD system from MST

Second generation
- Multi-spatial point (ten radial points), multi-spectral point MCP system from Phaedrus-T and S1

Optics
- Holographic edge filter from MST
- 8” collection lens from Phaedrus
Thomson Scattering System on MST

System routinely used with MST plasmas
$T_e \sim 200$ eV and $n_e \sim 1 \times 10^{19}$ m$^{-3}$

T.M. Biewer, D.J. Den Hartog, D.J. Holly, M.R. Stoneking. 


*D.J. Battaglia, APS-DPP, Denver, CO, October 2005*
The ruby laser and collection optics are now in house

The system will be constructed and calibrated off-line

A small laser room will be built to minimize dust and control the ambient temperature of the optics environment

The TS system will be integrated into Pegasus operations in approximately two years
Summary

• Accurate and reliable $T_e$ measurements are important to Pegasus experiments

• $T_e$ diagnostics deployed for present experiments
  – SXR Ross Filters: Compares impurity line ratios for crude measurements at low $T_e$
  – SXR PHA: Spatially and temporally resolved SXR spectrum measurements at higher $T_e$

• Thomson Scattering system will be integrated into Pegasus operations in the future
Acknowledgements

The author would like to thank the following:
Matt Reinke, Ryan Schoof, and Charles Ostrander for their contributions to the SXR diagnostics
Daniel J. Den Hartog, Mike Borchardt and the MST team for their assistance with the Thomson scattering system
Ben Ford, Ben Lewicki, Greg Winz and the Pegasus Undergraduate team for their efforts
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