**CCD DIRECT DETECTION ON A SPRED SPECTROMETER**

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**Abstract**

This paper presents the installation and performance of a direct UV photon charge-coupled device (CCD) device on the SPRED spectroscopy system of the TCV tokamak. The legacy SPRED detector, based on a micro-channel plate (MCP) UV conversion design, had limitations related to sensitivity to electromagnetic fields, as well as susceptibility to damage from arcing. To address these issues, a solid-state, thinned back-illuminated CCD detector was selected. A novel alignment methodology, with He-Ne 632.8nm lasers, precisely aligned the gratings resulting in unrotated dispersed spectral images. The CCD detector demonstrated improved performance over the legacy system with a reduced full width half maximum (FWHM) and reliable operation for over 20,000 pulses, providing valuable insights into plasma composition and assisting long-term machine conditioning studies.

1. INTRODUCTION

Spectroscopic measurements are crucial for tokamak research as they provide valuable information on plasma composition, power loss channels and plasma-wall interactions. Coupled with modelling tools, these measurements can also be used to infer ion transport rates, elemental ionisation balance and spatial distributions. In particular, the vacuum ultraviolet (VUV) spectral range measures plasma emission in the 10-130 eV range from incompletely ionised elements in the core and divertor. These are typically made using a “survey, poor resolution, extended domain” (SPRED) spectrometer. The TCV tokamak employs such a SPRED system with a vertical line of sight that integrates emission from the core and divertor, as shown in Figure 1.

Figure 1 - SPRED line of sight on the TCV tokamak (magenta). Standard plasma configuration overlaid (blue).

1. SPRED SPECTROMETER AND DETECTOR

TCV’s SPRED system is a McPherson 251 grazing incidence spectrometer with a focal length of 0.2 m and an F-number of 14. Its grating mount supports two externally selectable gratings: 450 g/mm and 2105 g/mm. The system is designed to operate under ultra-high vacuum system with a windowless view of the TCV plasma to remove absorption of VUV photons.

* 1. Legacy detector design

The legacy SPRED detector employed a photocathode on a micro-channel plate (MCP) to convert photons to primary electrons. A high voltage across MCP amplifies this signal, as an image, with a near exponential gain response. The exiting electrons impinge upon a green phosphor deposited on a coherent fibreoptic bundle. The fibreoptic array had a tapered design to reduce the final width of the spectra, allowing for a larger spectral range to be recorded by the Reticon array. These components of the detector are presented in Figure 2.

The shortcomings of this design were primarily related to the MCP. Specifically, the MCP is sensitive to electromagnetic fields from the tokamak, which can be exacerbated by a plasma disruption that can result in data loss or require a detector reset. Additionally, increases in neutral pressure within the TCV vessel from impurity seeding working gas plasma fuelling often led to a pressure rise at the MCP followed by arcing and consequent damage, altering system sensitivity over time. Furthermore, the alignment and calibration that could be achieved was limited as this system could only be aligned under vacuum and only integrated the image in the vertical direction (1D detector with 2.5mm high pixels).

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Figure 2 - Legacy SPRED detector design with front end (left), tapered fibreoptic array (middle) and Reticon array with acquisition (right)

* 1. New Detector Selection

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Description automatically generatedTo overcome the limitations of the MCP in the hostile tokamak environment and increase system reliability, a direct photon detection approach, via a thinned back-illuminated solid-state sensor, was selected. The electrodes on a front-illuminated charge-coupled device (CCD) would stop VUV photons. In the last decade, back-illuminated chips with a thinned silicon substrate have become more common, making them accessible for low-light level and short-wavelength applications. The detector selected was a Greateyes™ full-frame back-illuminated CCD, consisting of 2048 x 512 pixels of size 13.5 µm x 13.5 µm. A full-frame CCD was preferred as 2D images allow for precise alignment and calibration. The downside of this design has low temporal resolution (~10x ms) due to slow readout speeds.

The CCD is mounted onto a vacuum flange in the standard camera design and this was not compatible with the detector mounting assembly on the spectrometer. The sensor chip was mounted with an offset on the flange so that it was in the spectrometer’s focal plane, Figure 3. A Peltier cooler on a cooling copper block was used to ensure CCD cooling in vacuum. An electromagnetic shield was installed to reduce pickup on the exposed cables. A slit in the front of the shield reduced the effective active CCD area, to reduce stray radiation in the spectrometer reaching the detector.

Figure 3 - Offset sensor with Peltier cooler and copper heatsink

1. NOVEL ALIGNMENT METHODOLOGY AND CALIBRATION

The system is operated under high vacuum to allow VUV transmission, requiring repeated pumping and venting during alignment, together with cycling the calibration source. A novel methodology was developed with visible light from 632.8nm HeNe lasers. To increase the precision of the process, the laser was aligned over long paths with apertures placed in the beam path. Coarse adjustment of the grating position and angle (α) was achieved by placing one laser at the grating normal and another at the entrance slit. The intersection of the two is the required grating position. The incident angle could then be set by ensuring that the laser normal to the grating was reflected directly back to its source and the 0th and 2nd order reflections of the laser incident on the slit reached calculated locations, marked on the ports, Figure 4a. This approach gave an accuracy in α of 0.5° and 2.3° for the 450g/mm and 2105g/mm gratings respectively. Final fine alignment was performed using the 0th order (reflection) of a fluorescent lamp captured by offsetting the CCD on the detector flange. A laser was not used here to prevent damage to the CCD. The two-dimensional imaging of the detector allowed for any image rotation due to grating tilt to be taken out of the system, as shown in Figure 4b. The final accuracy in α achieved was estimated at 0.1° for both gratings.

Final VUV alignment and calibration was conducted with a hollow cathode lamp directly coupled to the SPRED using differential pumping (Danzmann 1988). The lamp was placed on a mount with a vacuum bellows allowing it to be scanned across the entire etendue of the spectrometer. The adjustable detector assembly was then used to focus across the whole detector with example images shown in Figure 5. The final full width half maximum (FWHM) of the 30.4nm spectral line was less than half of that from the legacy detector and comparable to the original design paper albeit using an entrance slit width twice as large (Fonck 1982). Table 1 gives an overview of these values with a comparison to one of the original systems installed on JET.



Figure 5a - Schematic of laser alignment



Figure 5b - Images with twisted and level grating



Figure 6 - Image produce using the hollow cathode lamp (left). Spectral line produced as a function of binning height on the sensor (right)

**Table 1. Comparison of FWHM achieved on JET, the SPRED design paper, TCV legacy detector and the CCD detector established in this work**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| System | Slit Width (µm) | Image Height (mm) | FWHM (A) | Slit Width | | Image Height (mm) | FWHM (A) |
|  | 450 g/mm | | | | 2105 g/mm | | |
| JET | N/A | N/A | 5 | N/A | | N/A | 1.5 |
| Fonck 1988 | 25 | 1 | 2 | N/A | | N/A | N/A |
| TCV legacy | 50 | 4 | 5 | 50 | | 4 | 2 |
| TCV CCD | 50 | 2 | 2.5 | 50 | | 2 | 0.7 |

Operating the hollow cathode lamp with prescribed parameters enabled a sensitivity calibration of the detector at the wavelengths of known emission lines (Danzmann 1988). The inverse sensitivity of the two gratings is presented in Figure 7. The values from the JET system that uses an MCP detector, are superimposed for comparison (Lawson 2009). Both gratings show a decrease in inverse sensitivity at longer wavelengths, where the reflectivity of the grating increases. Surprisingly, the inverse sensitivity between 20-40nm is similar for the JET system with an MCP and the TCV system with a CCD. Conversely, the JET system shows an increase in inverse system sensitivity with increasing wavelength, attributed to the differences in the detector responses. It should be noted that the JET system sensitivity changes with MCP gain and the values reported here are taken for a fixed gain (Lawson 2009).



Figure 7 - System sensitivity and comparison with the JET SPRED system

1. RESULTS FROM TCV TOKAMAK

Measurements made during plasma operation yielded high resolution spectra with the full etendue of the spectrometer. Sample spectra are shown in Figure 8 for a standard Ohmic discharge (red), nitrogen seeded discharge (green) and with neutral beam injection that resulted in metal impurities being sputtered into the plasma (blue). The detector position was adapted for the beam injection discharge to capture spectral lines at shorter wavelengths. The large apparent FWHM at these shorter wavelengths is not due to system performance but to a high density of numerous metal impurity lines between 10-20nm.



Figure 8 - Sample spectra for a standard Ohmic discharge (red), nitrogen seeded discharge (green) and metal impurities injected into the plasma through sputtering of the neutral beam injection duct (blue).

The system has been now operating reliably for over 20,000 pulses since March 2017. The only system failure during this period was of the Peltier cooler that prevented on chip binning due to thermal leakage, leading to a reduction in temporal resolution to around 100ms. The reliability of the system has permitted long-term analyses of machine conditioning and impurity evolution in the plasma. An example of this is presented in Figure 9, where four spectral ranges were integrated at plasma breakdown for ~110 discharges. The first 20 discharges are in standard operation and low plasma emission is measured at wavelengths between 16-40nm. Between discharges #67832 and #67897, negative triangularity configurations were performed resulting in plasma contact with virgin surfaces on the low field (outer) side of the tokamak. During this period, the spectral emission between 16-40nm was significantly increased, indicating higher impurity content in the plasma. The increased impurity content is attributed to higher outgassing and sputtering of the virgin surfaces interacting with the plasma. Furthermore, a number of discharges have no spectral data due to failed breakdowns, again resulting from increased impurity content.



Figure 9 – Integrals of spectral regions at plasma breakdown during standard operation and negative triangularity shaped plasmas.

1. CONCLUSIONS

A direct detection CCD detector was installed on the SPRED spectrometer on TCV. A novel alignment method was applied to align the gratings to an α of ~0.1° and reduce image rotation. The FWHM achieved through this process was less than half that of the original detector. The sensitivity of the system was found to be comparable to the JET system with an MCP detector. The system has now performed reliably on TCV for over 20,000 pulses, providing information on plasma composition and aiding in long term machine conditioning studies. These results demonstrate the advantages of a CCD detector for SPRED systems on tokamaks.

1. ACKNOWLEDGMENTS

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