# First Results from the Thomson Scattering Diagnostic on Proto-MPEX[a)]

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(Presented XXXXX; received XXXXX; accepted XXXXX; published online XXXXX)
(Dates appearing above are provided by the Editorial Office)

A Thomson scattering diagnostic has been successfully implemented on the prototype Material Plasma Exposure eXperiment (Proto-MPEX) at Oak Ridge National Laboratory. The diagnostic collects the light scattered by plasma electrons and spectroscopically resolves the Doppler shift imparted to the light by the velocity of the electrons. The spread in velocities is proportional to the electron temperature, while the total number of photons is proportional to the electron density. Thomson scattering is a technique used on many devices to measure the electron temperature ($T_e$) and electron density ($n_e$) of the plasma. A challenging aspect of the technique is to discriminate the small number of Thomson scattered photons against the large peak of background photons from the high-power laser used to probe the plasma. A variety of methods are used to mitigate the background photons in Proto-MPEX, including Brewster angled windows, viewing dumps, and light baffles. With these methods, first results were measured from Argon plasmas in Proto-MPEX, indicating $T_e \sim 2$ eV and $n_e \sim 1\times10^{19}$ m$^{-3}$. The configuration of the Proto-MPEX Thomson scattering diagnostic will be described and plans for improvement will be given.



## I. INTRODUCTION

The design of the Thomson scattering (TS) system[1] for Proto-MPEX[2] has previously been reported elsewhere. As the design was implemented, a number of changes had to be incorporated in order to facilitate the successful measurement of TS spectra from Proto-MPEX plasmas. In particular, as with all TS diagnostics, great care must be taken to reduce and eliminate unwanted "background" photons that might be present in the collection optics.[3-6] These stray photons arise from errant ray trajectories introduced by inherent laser beam divergence, scattering centers on the optics and mirrors, and reflections at air-to-vacuum interfaces. Since the number of TS "signal" photons is linearly proportional to plasma electron density, it is helpful to commission the diagnostic in electron dense plasmas. For these purposes Argon plasmas were produced in Proto-MPEX, due to favorable electron density, as compared to Helium, Hydrogen, or Deuterium. Effecting "low background" and "high signal" contributes to the successful operation of a TS diagnostic, including the optimization of the collection optics.

This paper will outline the Proto-MPEX Thomson scattering laser system in Section II, particularly those changes that were incorporated during implementation and differ from the published design. The mitigation techniques to effect low background photons will be discussed in Section III. And the first diagnostic results from Argon plasmas will be shown in Section IV. Potential improvements and future work will be included in the summary, Section V.

## II. THOMSON LASER IMPLEMENTATION

The TS photons are originally generated by a Q-switched Spectra Physics Quanta Ray Pro-350 Nd:YAG laser, operating frequency doubled, to produce up to 1.4 J/pulse of 532 nm light in 8 ns pulses at 10 Hz.[7] The beam emerges from the laser with a 13 mm diameter, established by the diameter of the amplifying laser rod. While the beam divergence is low (at full power), after traversing the ~ 20 m of enclosed beam line from the laser room to the device, the beam diameter is ~27 mm at the last turning mirror, prior to entering Proto-MPEX vacuum, if no additional focusing measures are applied. At this diameter, the beam could not be made to fit on the reflecting surface of a 25 mm mirrored prism. Significant amounts of light are scattered from the mirror mounting hardware and result in intolerable stray light in the Proto-MPEX chamber. Moreover, that light which is successfully redirected by the mirror still has a diameter near to the ~35 mm inner diameter of the standard 2.75 inch conflat-flanged vacuum pipe that constitutes the diagnostic "flight tube," making beam steering though the device exceedingly difficult.

If the laser power is reduced the situation becomes even worse. The laser collimation/focusing is optimized at the manufacturer (at a distance of 3 m) and relies on thermal equilibration between the heat generation of the flash lamps at full power and the heat removal of the water cooling system. Reducing the energy of the flash lamps results in subtle changes to the thermal lensing characteristics of the laser rods, and consequently a degradation in laser pointing stability and divergence, that becomes apparent at large distances (>10 m). The laser quality (at full power) was verified by the vendor-supplied technician during laser installation, but beam profile was not guaranteed at distances >10 m. In fact, laser vendor anecdotes[8] of drifting mode purity and the development of "hot spots" for large distances were confirmed at Proto-MPEX by significant damage inflicted to high-damage threshold (8 J/cm$^2$) steering-mirrors at ~20 m, when the laser was operated at full power. Consequently, the laser energy was typically operated at reduced capability (<0.9 J/pulse) to avoid damaging the last turning mirror, though effectively making the laser beam diameter "too wide" to thread through Proto-MPEX, without additional focusing elements.

To recover system functionality, a laser beam expanding telescope (BET) was installed ~ 1 m from the laser housing, within the enclosure of the first turning mirror. The laser beam entering the enclosure is 13 mm in diameter, with vertical

[a)]Contributed paper published as part of the Proceedings of the 21st Topical Conference on High-Temperature Plasma Diagnostics, Madison, Wisconsin, June, 2016.
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polarization. The beam encounters a laser λ/2 waveplate with axis at 45 degrees to vertical, in order to rotate the polarization to the horizontal orientation. (This is done to ensure the laser electric field is oriented transverse to the collection optics viewing direction after Thomson scattering from plasma electrons.) The beam then enters a 2x Galilean BET with lenses of -100 mm and +200 mm, separated by 100 mm, emerging with 26 mm diameter.[9] A property of beam expanding telescopes is that the emerging 2x beam has ½ the divergence. To accommodate the larger diameter beam all 3 steering mirrored prisms (25 mm) were replaced with 2 inch (54 mm) diameter round mirrors. The BET serves 2 purposes, 1) it reduces the energy density on the optics, and 2) it reduces the beam divergence resultant from operating the laser at reduced energy. For the Proto-MPEX TS system this is sufficient to deliver a reasonably collimated beam at 20 m, without damaging optically coated surfaces.

Prior to the last turning mirror a long focal length (1500 mm) converging lens (anti-reflection coated) is inserted into the laser path. The focusing lens is ~20 m from the BET, and the rays are essentially parallel to each other. The lens is placed such that the Proto-MPEX magnetic axis is ~1.5 m "downstream" from the lens along the optical path. The intention is to create a narrow waist in the laser beam in the plasma, to effect a high axial spatial resolution (~<1 mm) of the measurement in the plasma, as well as to increase the density of photons for TS measurements. After this waist the laser beam is expanding as it leaves Proto-MPEX and is dumped. From the focusing lens, the beam is converging. The beam diameter on the focusing lens is ~30 mm. The last turning mirror is roughly 50 cm from the focusing lens, and the beam diameter is roughly 20 mm at this location. The air-to-vacuum window is ~10 cm below the turning mirror, and the beam diameter on the window is ~17 mm. The inner diameter of the vacuum flight tube is ~35 mm, and the beam is still converging from this point to the axis of the machine, ~90 cm from the Brewster window. Hence, beam steering through Proto-MPEX is made significantly easier with the addition of these elements. The diverging beam exits Proto-MPEX in much the same (reverse) sequence. The vacuum-to-air window is ~50 cm from the magnetic axis, and the beam diameter is ~13 mm. The beam is again turned within the dump box, and impacts the laser dump surface at an inclined angle to spread the beam energy over a large area (outside of the direct line of sight of the exit window) and thereby minimize back reflection of stray light into the Proto-MPEX chamber from the dump surface. A small flaw (introduced) in the dump turning mirror allows a fraction of laser light through, which falls on a laser energy monitor. In this way, the laser energy of each pulse is measured and recorded.

## III. STRAY LIGHT MITIGATION

The injection of ~1 J/pulse of 532 nm laser light implies ~$2.7\times10^{18}$ photons/pulse. A small fraction of these are Thomson scattered into the collection optics from plasma electrons. This small fraction must be discriminated from any stray photons, which have arrived in the collection optics for whatever reason. A number of measures are used to mitigate stray photons and thereby improve signal-to-noise.

The main culprits for stray light are errant photons from imperfections or "dust" on the last turning mirror, as well as misdirected rays from the air-to-vacuum interface. These can be intercepted by installing light "baffles" in the vacuum flight tube between the window and the Proto-MPEX plasma chamber. This is accomplished by taking advantage of the fact that the vacuum flight tubes consist of various segments: a windowed flange tube, a vibration mitigating bellows (to reduce mechanical vibration between the machine and the TS structure), an extension tube, and an insulating ceramic break (to electrically isolate the TS structure from the machine.) Where each of these elements are joined (and to the Proto-MPEX main flange), there is a copper vacuum gasket. Standard gaskets are typically a thin annulus, with an inner diameter that is larger than the inner diameter of the flight tube. "Blind" gasket blanks were purchased, and then machined to have an inner diameter that was considerably more narrow, i.e. ~2x the laser beam width at each location, as it converges towards the axis of Proto-MPEX. In each section the inner surface of the vacuum segment is covered with a sleeve of vacuum-compatible Acktar Spectral Black foil[10] to absorb the back scattered photons in that segment. In this way, errant rays are stripped off the converging beam and prohibited from entering the plasma region, reducing the stray light in the chamber. A similar sequence of vacuum-gasket light-baffles and black, absorbing foils are inserted in the exit flight tube. As the diverging, un-used laser beam is exiting Proto-MPEX light can back reflect from the vacuum-to-air window, or can enter the flight tube at oblique angles after incomplete absorption and multiple reflections in the dump box.

Since the laser light is polarized, the stray light entering the collection optics can be further reduced. The collimated, usable laser light arriving at the entrance window should be polarized along a unique axis. Any rays that do not have this polarization are likely to have been affected by imperfections in/on the preceding optics, and hence are likely to contribute to background photons and not TS photons. By replacing the "flat" air-to-vacuum window with a "Brewster angled" window at the correct orientation, then the correctly polarized rays are permitted to cross the interface, while the incorrectly polarized rays are dominantly reflected (into the turning mirror enclosure.)[11] By lining the enclosure with black felt, or painting appropriate surfaces black, these errant photons are absorbed before they reach the vacuum flight tube. A similar approach is applied to the vacuum-to-air Brewster exit window in the dump box.

The incident laser beam thus traverses the plasma vertically with a horizontal (along the Proto-MPEX axis) polarization. TS photons from plasma electrons should then be horizontally polarized. Any back-scattered or stray photons, reflecting from bare metal surfaces in the plasma chamber, along with plasma bremsstrahlung light, should be randomly polarized. By placing a linearly polarized horizontal sheet in front of the ex-vessel collection optics any remaining stray background light photons should be reduced by another factor of 2. As a final measure to reduce stray light reflected into the collection optics, a viewing dump of Spectral Black foil is placed in the Proto-MPEX port that is opposite the TS collection optics.

## IV. RESULTS FROM ARGON PLASMA

The production of light-ion (Hydrogen, Deuterium, Helium) plasma discharges with high electron density is an area of active research for Proto-MPEX.[12] Helicon antenna plasma sources are used routinely to produce high density plasmas using heavy ions, particularly Argon. While Proto-MPEX has since overcome the intermittency issues of producing light-ion, high density plasmas, at the time of these experiments Argon was used to produce consistently, relatively-high electron density plasmas specifically to benchmark the TS diagnostic. These plasmas were produced in the so-called "standard" magnetic field configuration of Proto-MPEX, with an on-axis main coil field of ~0.7 T. The magnetic field in the helicon antenna region was ~0.05 T. The pre-fill vacuum pressure was ~5.3 mTorr of Argon. The plasma was produced by simultaneous input of ~8 kW of 18 GHz μ-waves and ~100 kW of 13.56 MHz helicon rf waves. A Langmuir probe was used (at the same location, but not simultaneous with TS) to measure an electron density of 1 +/- 0.2 x$10^{19}$ $m^{-3}$ and an electron temperature of 3 +/- 0.6 eV, with modest time variation during the 150 ms plasma pulse, as shown in Figure 1.

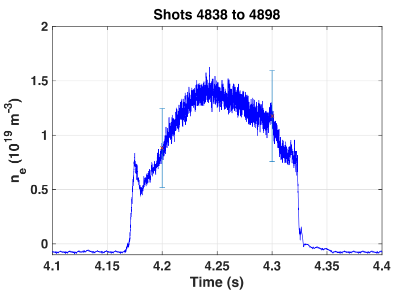


**Figure 1 (color online)** Langmuir probe measured central electron density evolution from Argon plasmas in Proto-MPEX.

While it was initially envisioned that single-laser pulse TS measurements would be possible in Proto-MPEX, in practice this was not actualized for these initial results. Despite the measures (as described in Section III) taken to reduce the level of the stray light background, the signal-to-noise of single-pulse measurements remained intolerably low. Stray laser light remained as the primary contaminant of the measurement, which made it difficult to discern the TS photons in the "wings" of the spectrum. However, the stray light was sufficiently reduced that the detector had enough dynamic range to remain not-saturated at the rest 532 nm laser wavelength. Hence, to overcome the limitations of the stray light a software mask was effected in the data analysis, which suppressed a region around the laser line, allowing the TS photons in the wings to be discerned. Multiple plasma discharges with two laser pulses per discharge were ensembled together to yield the first TS spectra fits. Figure 2 shows a ~40 shot ensemble (pulse numbers between 4826 and 4898) of discharges. In aggregate, the Thomson scattering measured electron density was 1.0 +/- 0.3 x$10^{19}$ $m^{-3}$ and the electron temperature was 1.9 +/- 0.6 eV, roughly consistent with Langmuir probe measurements.

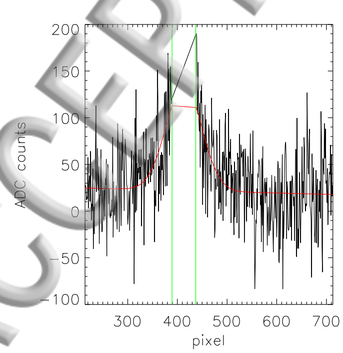


**Figure 2 (color online)** Typical Thomson scattering spectra from ~40 shot ensemble Argon plasmas in Proto-MPEX. The central (stray) laser peak is suppressed (between green vertical lines) in software to highlight the TS "wings," which are fit to a Gaussian distribution (red line). The fit parameters yield 1.1x$10^{19}$ $m^{-3}$ and 1.3 eV at 25 ms into the helicon discharge, and 0.9 x$10^{19}$ $m^{-3}$ and 2.5 eV at 125 ms.

## V. SUMMARY & FUTURE WORK

A Thomson scattering diagnostic has been implemented on the Proto-MPEX device and first results (in Argon) are shown in this paper. System modifications (from design parameters) were necessary to enable these measurements, and those modifications (as they relate to achieving first results) are described in this paper. The measurements still suffer from poor signal-to-noise and further improvements to reduce the background stray (laser) light are necessary to make TS a more routinely useful diagnostic on Proto-MPEX. At the moment, a multi-point Langmuir probe profile can be achieved (with superior temporal resolution) in ~1/10$^{th}$ the number of plasma discharges, and single-point measurements in ~1/50$^{th}$.

Since these first results were achieved, Proto-MPEX in an altered magnetic configuration has achieved high electron density plasmas during light-ion (Deuterium) operation[13]. These plasmas exceed the density conditions reported here for Argon and potentially provide a better candidate plasma for TS measurements. The TS system is currently being recommissioned to make measurements on these plasmas. Moreover, the TS diagnostic is being re-designed to make measurements on Proto-MPEX in the helicon antenna region, where preliminary measurements suggest that the density and temperature are each an additional order of magnitude higher (than at the target plate). Langmuir probes are routinely damaged in the helicon region after ~1 discharge due to the plasma conditions, and consequently do not produce reliable measurements, suggesting that TS would be a superior technique near the helicon.

## VI. ACKNOWLEDGEMENTS

The authors would like to gratefully recognize the work of the many support personnel at ORNL that contributed to the construction of this diagnostic system, and the operation of Proto-MPEX, especially J.B.O. Caughman and R. Goulding.

This work was supported by the U.S. D.O.E contract DE-AC05-00OR22725. Research sponsored by the Laboratory Directed Research and Development Program of Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U. S. Department of Energy.

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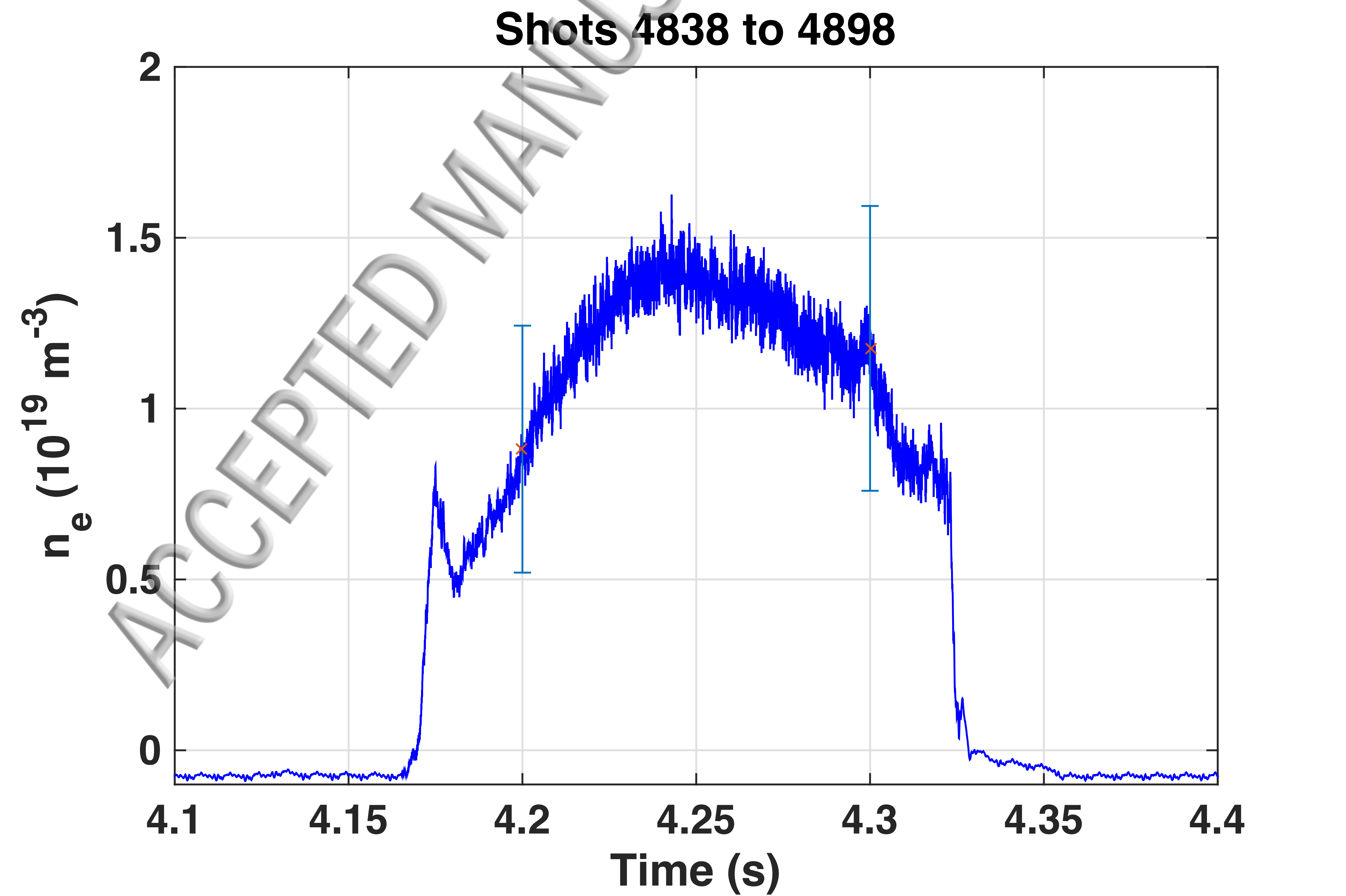
Shots 4838 to 4898
$n_e$ ($10^{19}$ $m^{-3}$)
2
1.5
1
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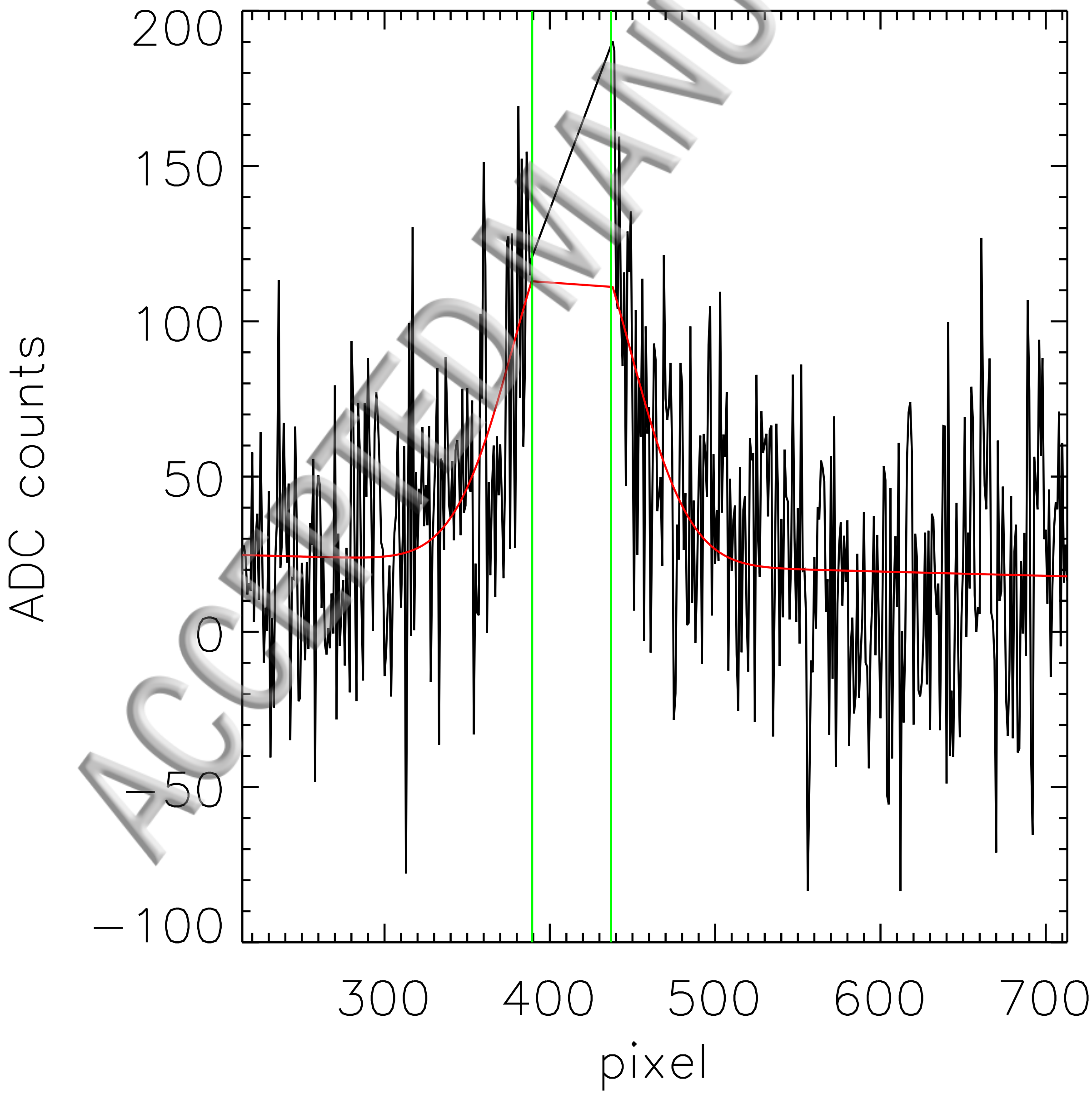
0
4.1
4.15
4.2
4.25
4.3
4.35
4.4
Time (s)


200
150
100
50
0
−50
−100
ADC counts
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