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# Thomson scattering upgrades on Alcator C-Mod

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## Abstract

The Thomson scattering (TS) diagnostics set [Rev. Sci. Instrum. **70**, 759 (1999); Rev. Sci. Instrum. **72**, 1107 (2001)] on the Alcator C-Mod tokamak [Phys. Plasmas **1**, 1511 (1994)] has been upgraded to deliver measurements of electron temperature ( $T_e$ ) and density ( $n_e$ ) with improved temporal and spatial resolution. Two 30 Hz, 1.3 J Nd-doped yttrium aluminum garnet (Nd:YAG) lasers share a vertical beam path through the tokamak plasma and are fired in alternating fashion, allowing collection of scattered light with a 60 Hz rep rate. Also, plasma variation occurring on faster time scales ( $10^{-5} \lesssim \tau(\text{s}) \lesssim 10^{-2}$ ) can be studied by closely spacing the pulses from either laser for operation in 30 Hz burst mode. Eight compact polychromators [Rev. Sci. Instrum. **61**, 2858 (1990)] have been added to the system, better than doubling the spatial resolution of core plasma TS measurements and allowing better diagnosis of core  $n_e$  and  $T_e$  gradients. Up to 14 fiber bundles view the core plasma, and a linear array of up to 22 single fibers of 1 mm diameter observes the plasma edge. Each fiber holder has been upgraded to incorporate a cam key and follower, so that the holders can be mounted to a cammed plate that automatically orients each holder to the correct viewing angle as its height is adjusted. This allows the fiber bundles to be repositioned easily between tokamak discharges, making it possible to concentrate core measurements in regions of particular interest, such as the vicinity of an internal transport barrier, with spatial resolution of  $\sim 1$  cm. The newly designed mount can be positioned with sub-millimeter precision, and its alignment with respect to the Nd-YAG beam can be adjusted between discharges using remotely controlled stepper motors. This capacity for correcting misalignment increases the reliability of density measurements. Cross-calibration of TS  $n_e$  measurements with electron cyclotron emission (ECE) diagnostics is performed using dynamic ramps of both plasma density and magnetic field to force ECE signal cutoffs at known values of  $n_e$ . This technique, which can be performed on any given day of an experimental campaign, supplements an absolute calibration based on Raman scattering in hydrogen and deuterium gas, which normally can not be done during a campaign.

## I. INTRODUCTION

On the Alcator C-Mod tokamak<sup>1</sup> (major and minor radius  $R = 68$  cm,  $a = 22$  cm), profiles of electron temperature ( $T_e$ ) and density ( $n_e$ ) are obtained in both the core and the edge plasma with a set of Thomson scattering (TS) diagnostics.<sup>2,3</sup> These diagnostics employ a pulsed laser beam, directed along a vertical chord of the plasma, from which photons undergo TS off free electrons. The spectrum of scattered light from a given location conveys information about the local electron velocity distribution function, and thus gives a snapshot of local  $T_e$ ,  $n_e$ .

Though clear profiles may be obtained over a wide range of temperatures and densities, the technique has as a limitation the relatively low repetition rate of a high power, Q-switched laser, which leads to low time resolution. In addition, the number of spatial points obtained with the C-Mod core TS system has been limited to six, due in part to the relatively large size of the spectrometers used.<sup>4</sup> To improve both the temporal and spatial resolution of the TS diagnostic set, as well as the accuracy of its measurements, several hardware upgrades have been undertaken recently.

First, an additional Q-switched Nd-doped yttrium aluminum garnet (Nd:YAG) laser, identical to the original, was added to the system. The lasers share a beam path through the tokamak plasma, increasing the number of  $T_e$ ,  $n_e$  measurements that can be made at a given spatial location. To improve spatial resolution, eight compact polychromators<sup>5</sup> have been added to the core TS system, bringing the number of potential spatial channels to 14. This enhanced profile coverage is expected to yield better diagnosis of core  $n_e$  and  $T_e$  gradients. The collection fiber tips for the new polychromators can be spaced as closely as 1.4 cm, which results in a spatial resolution of similar scale in tokamak midplane coordinates. All the core fiber holders, as well as the holder containing the linear array of edge TS fibers, are mounted to a cammed plate and can be easily moved to view various plasma scattering locations with the correct viewing angle. The angle of this plate with respect to the Nd:YAG beam can be adjusted using two stepper motors. The design of this optical assembly thus allows for both rapid repositioning of collection fibers and remote correction of misalignment of the beam with respect to collection optics.

Raman scattering in hydrogen or deuterium gas, supplemented by Rayleigh scattering in argon, is the preferred method of absolutely calibrating the spatial channels of the C-Mod TS diagnostics. In cases where this calibration in gas yields poor results, or cannot be performed at all, cross-calibration with other diagnostics has proven successful. We commonly cross-calibrate TS  $n_e$  measurements with electron cyclotron emission (ECE) cutoffs. Both plasma density and magnetic field can be ramped dynamically to force the cutoff of ECE signal at known values of  $n_e$ . This technique yields reasonable results for the core TS system and can be performed on any given day of an experimental campaign.

## II. HARDWARE DESCRIPTION

The TS diagnostics are controlled with a variety of hardware and software tools. Operation of the laser is accomplished with a PC containing a National Instruments data acquisition board and running Labview data acquisition software. CAMAC standard hardware is used to control high voltage (HV) supplies to system detectors, to set up laser pulse timing, and to acquire measured TS signal from detector electronics. CAMAC hardware is driven by MDS-Plus data acquisition software<sup>6</sup>, which can now be run under both OpenVMS and Linux operating systems. Laser beam steering, system temperature control, and real time system monitoring is accomplished with programmable logic controller (PLC) modules, with which the user interacts through computers running Paragon control software.

### A. Beams

Two identical Q-switched Nd:YAG lasers<sup>7</sup> ( $\lambda_0 = 1064.0$  nm) make up the source of TS photons on C-Mod. Either laser has a fixed pulse rate of 30 Hz, with a nominal 1.3 J, 8 ns

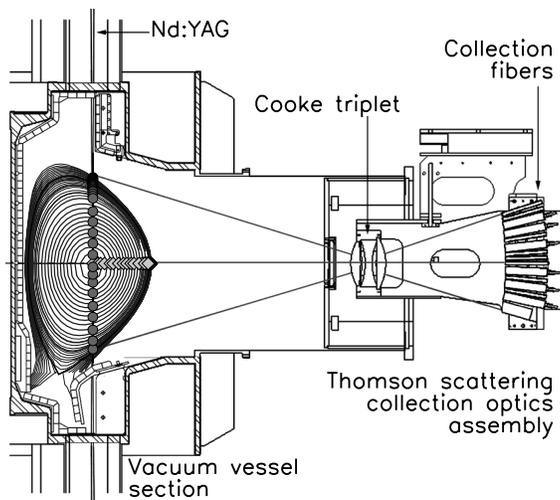


Figure 1: Cross section of Alcator C-Mod vacuum vessel with contours of constant poloidal flux for a sample plasma discharge. Thomson scattering (TS) collection optics are mounted such that a Nd-doped yttrium aluminum garnet (Nd:YAG) laser beam passing along a vertical chord through the plasma is imaged onto a set of optical fibers. Circles along the beam path represent real scattering volumes. Diamonds at the outer tokamak midplane show the locations of scattering when mapped along surfaces of constant flux to the midplane

pulse. Each Nd:YAG beam is coaligned with a CW He-Ne laser to assist in visual position control. The two beam paths are made close to parallel ( $d\theta \sim 5$  mrad) and directed along a beam path of greater than 10 m to a vertical port positioned over the tokamak vessel. A pair of steering mirrors on the laser optical bench is used to make fine adjustments to one or both of the beam positions atop the machine. Each mirror stage tilts in response to two actuators driven by DC motors, which can be controlled remotely from PLC hardware. Thus the position of the He-Ne beams can be adjusted remotely and in real time between plasma discharges, correcting for any drifts that occur.

From the top of the tokamak, the beams are directed vertically through a focusing doublet with a focal length of 3 m and into the tokamak, entering and exiting through windows placed at the Brewster angle allowing almost complete transmission of the linearly polarized Nd:YAG beams. The Nd:YAG beams are focused such that the nominal beam width is less than 2 mm across the length of the vertical chord passing through a typical C-Mod plasma. The tokamak poloidal cross section in Fig. 1 shows the beam path through the vessel. Also shown are contours of constant poloidal flux obtained from the magnetics reconstruction code EFIT<sup>8</sup>. The beam paths are nearly collinear throughout the plasma, and scattering from a given vertical location can be assumed to occur at the same radius for either laser. The angle of the beams with respect to the plane of the figure can be adjusted by a piezoelectric actuator, driven via PLC, attached to a steering mirror atop the machine. By observing the He-Ne footprints above and below the machine through video cameras, one can remotely make gross corrections to the beam alignment using the steering mirror

actuators. Finer corrections are determined by examining the TS signal collected in special alignment channels of the edge TS system, as described in Ref. 3.

The triggers for flash lamp and Q switch pulses are provided by CAMAC hardware. Though the Nd:YAG rep rate is fixed at 30 Hz, there is considerable freedom in the relative delay between triggers delivered to the two lasers. Setting the delay equal to 16.667 ms results in an evenly spaced Nd:YAG pulse train and subsequent measurement of TS profiles at 60 Hz. The minimum length of the delay is limited by detector electronics and the maximum digitization frequency of digitizers. The current edge TS system uses sample-and-hold circuitry combined with multiplexing of signals prior to digitization, and the minimum time between measurements for edge profiles is 4 ms. The core TS system, however, can digitize measurements as little as 30  $\mu$ s apart. The upgraded TS system can therefore operate to some degree in 30 Hz burst mode, capturing  $T_e$ ,  $n_e$  profile evolution on somewhat shorter time scales than was previously possible.

## B. Collection Optics

Shown also in Fig. 1 are the TS collection optics and sample ray traces. Thomson scattered light leaves the vessel through a vacuum window at a horizontal port, and is collected by an air-spaced Cooke triplet lens at  $F/7$ . This lens, described in detail in Ref. 4, has a focal length of 30.8 cm and 1:2 demagnification, with minimal aberration. The collection fibers of the TS set lie at the focus of the lens, and their positions, together with the radial location of the Nd:YAG beams, determine the vertical location of the scattering volumes. The height of each scattering volume is roughly twice the vertical dimension of its corresponding collection fiber, and it is typically this dimension that determines the spatial resolution of a given TS channel.

Twenty-two polymer clad single strand quartz fibers with a 1 mm active diameter make up the edge TS collection fiber array. These fibers are mounted closely together near the bottom of the focal surface and view the upper edge of C-Mod plasmas, as discussed in Ref. 3. The remainder of plasma is viewed by core TS collection fibers bundles, the older version of which<sup>4</sup> employ as light concentrators glass prisms with approximately 1 cm of extent along the focal surface. As part of the TS upgrade, these six collectors are supplemented with eight fiber bundles, 0.4 cm in lateral extent. The smaller size allows both improved spatial resolution in a given TS channel and closer spacing between fibers. Figure 1 indicates the locations of scattering volumes for a typical arrangement of collection fibers. Also shown are the mappings of these volumes along surfaces of constant flux to the outboard tokamak midplane. Such mappings are obtained from the equilibrium output by EFIT, and radial profiles are typically plotted in terms of midplane radius, under the usually valid assumption of constant  $T_e$ ,  $n_e$  on a flux surface. A typical mean spacing of 1.5 cm in midplane radius is the result for the upgraded core TS system, an improvement over the previous mean spacing of approximately 4 cm.

The ability to easily change the positions of core TS collection fibers is highly desirable, in order that spatial regions of interest may be diagnosed more effectively. For example, improved spatial resolution in the core plasma profiles about  $r/a \sim 0.5$  is particularly useful in the diagnosis of internal transport barriers (ITBs), phenomena characterized by locally enhanced core  $n_e$ ,  $T_e$  gradients. The upgraded TS system uses a collection optics assembly that allows easy adjustment of fiber position. The assembly is shown in profile in Fig. 1.

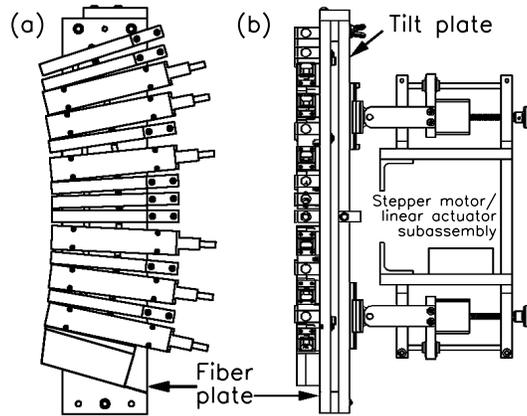


Figure 2: Fiber mount subassembly, consisting primarily of a fiber plate and tilt plate. Onto the face of the fiber plate (a) are mounted the edge TS fiber array holder (bottom), six light collector holders from the older core TS system, and eight thinner holders for core upgrade fibers. The fiber plate mounts to the tilt plate (b), which can be moved laterally and tilted using linear actuators driven by stepper motors.

It is built mostly of G10 components and is mounted to the concrete structure, known as the igloo, that surrounds the C-Mod cryostat. No contact is made with the machine inside the igloo, ensuring vibrational isolation from the tokamak vessel. The assembly supports both the Cooke triplet and the fiber mount subassembly, which positions the fibers on the focal surface. During installation two hard stops attached to the assembly abut the vacuum vessel flange, so that the optics assembly can be secured at the correct radial position. The stops are then withdrawn and a height adjustment is performed using a vertical jack screw, in order to align the optical axis with the tokamak midplane.

Figure 2 shows more detail of the fiber mount subassembly. It consists of a fiber plate mated with a tilt plate, which is manipulated by two linear actuators. The plan view of the fiber plate is shown in Fig. 2(a). Flush to this plate are mounted the edge TS fiber array (bottom), six core TS prism holders with fiber bundles attached to their backs, and eight smaller fiber bundle holders used in the core TS upgrade. The fiber plate has two slots cut out that form arcs; these act as cam slots, orienting the fiber holders at the correct scattering angle as they are slid vertically along the fiber plate. Figure 3(a) gives a clearer view of the cam slots, from the opposite side of the fiber plate. Each fiber holder contains a cam key and follower, which are inserted into the rear and forward cam slots, respectively. The cam key and followers are shown in magnified views for the older core holder [Fig. 3(b)], for the core upgrade holder [3(c)], and for the edge TS fiber holder [3(d)]. In all cases, the cam key is free to slide along the length of the fiber holder and forces its holder to be oriented normal to the rear cam slot, while the fixed cam follower causes the collecting tip of each holder to lie on the focal surface of the lens. A millimeter scale on the front of the fiber plate allows precise placement of the fiber holders, after which the holders are secured to the plate with screws, and the fiber plate is mounted to the tilt plate.

Attachment to the tilt plate is shown from the rear view (looking into the tokamak) of

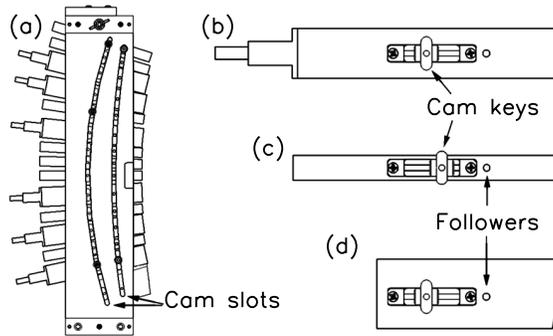


Figure 3: (a) Reverse of fiber plate shown in Fig. 2(a). Into the cam slots are inserted cam keys and followers, which are incorporated into the backs of the older core TS collector holders (b), the core upgrade fiber holders (c), and the edge TS fiber holder (d). A cam key is free to slide along the length of its holder, and followers are fixed. As a holder is moved along the cam slots, the cam key positions the holder normal to the rear slot, while the follower in the forward slot maintains the placement of the holder tip at the focus of the collection lens.

Fig. 2(b). The tilt plate incorporates tooling balls that act as pickups for repeatable and precise reattachment of the fiber plate. With the two linear actuators shown, the tilt plate lateral position can be adjusted across a distance of more than 2 cm, and the angle of the plate can be varied up to  $10^\circ$ , when the fiber mount subassembly is free of obstruction. In practice, the freedom of motion in the C-Mod port is more limited, due to the presence of other components, but enough freedom remains to precisely align the tilt plate with respect to the Nd:YAG beam image. Stepper motors driving the actuators can be operated remotely with PLC, allowing for alignment corrections between plasma discharges. This capability, combined with the beam steering capacity described above, allows for consistent and accurate collection of TS signal, and thus reliable  $n_e$  measurements.

### C. Photon Detection

Collected TS photons are transmitted to an assortment of instruments designed to detect scattered light falling into distinct spectral bands near the Nd:YAG laser line. All use temperature-stabilized Si avalanche photodiodes (APDs) for detection, and the response of each APD is digitized with CAMAC hardware. The timing for this pulsed data acquisition is provided by a portion of Nd:YAG light that leaks through steering mirrors as the beam is directed to the tokamak. The edge TS polychromator and the previous core TS spectrometers have been described in Refs. 3 and 4. These components remain largely the same in the current upgrade. The eight added core TS channels employ compact polychromators<sup>5</sup> fabricated by General Atomics, modified to accept a input fiber bundle at  $F/3.5$ . The polychromators have four spectral channels covering a wavelength range of 710–1060 nm. The spectral configuration, shown in the following section, is expected to provide a wide dynamic range in  $T_e$  measurement, and the detectors are expected to provide acceptable signal-to-noise at all reasonable densities on C-Mod.

### III. CALIBRATIONS

The shape of the TS spectrum observed from a given scattering location is a known function of  $T_e$  and scattering angle  $\theta$ , while the amplitude of the spectrum is proportional to both the laser pulse energy  $E_0$  and the local  $n_e$ . Analytical forms of the TS form factor  $S(\lambda, T_e, \theta)$  are readily found in the literature.<sup>9,10</sup> To obtain expected signals from a TS detectors as a function of  $T_e$ , we convolve the fully relativistic form factor with the detector spectral instrument response function  $f_i(\lambda)$ . To obtain a spectral calibration for a given TS detector, we fill the input fiber at  $F/3.5$  with the output of a calibrated scannable Czerny-Turner monochromator. The wavelength dispersion of the monochromator is 1–2 nm at typical input aperture widths, which is sufficiently small to accurately measure the bandpasses, all several nm wide or wider. The relative amplitudes of the  $f_i(\lambda)$  are verified by illuminating fibers with the output of a spatially uniform integrating sphere, also with a calibrated spectral intensity. Typical spectral responses for the core upgrade TS detectors, the older core TS detectors, and the edge TS detectors are compared in Fig. 4(a–c). Figure 4(d) gives a sample set of TS form factors at various  $T_e$ . Increasing  $T_e$  leads to larger signal in spectral channels far from the laser line and less signal in the closer channels. The variation of signal with  $T_e$  in each spectral channel is demonstrated in Fig. 5 for each TS subsystem. The range in  $T_e$  over which useful signal is obtained is a good indication of the dynamic range of each system. The effective  $T_e$  range of the core upgrade polychromators is at least as large as that of the older core spectrometers, while requiring fewer spectral channels per measurement. We expect reasonable measurements from 20 eV to 20 keV, which spans the core  $T_e$  of C-Mod plasmas. The expected dynamic range in density is  $0.05 \lesssim n_e (10^{20} \text{ m}^{-3}) \lesssim 5$ .

To obtain plasma  $n_e$ ,  $T_e$ , a non-linear least squares fit on these two parameters must be performed on the real signals measured from each scattering location. It is necessary beforehand to obtain calibration coefficients that account for the throughput and gain of each spatial channel. This is normally done by backfilling the tokamak with several hundred torr of gas and measuring laser scattering signal. Known cross sections<sup>11</sup> for Rayleigh scattering in Ar and for Raman scattering in D<sub>2</sub> and H<sub>2</sub> can be used to relate measured signal to gas density, and thus relate measured TS signal to  $n_e$ . Gas scattering is a reliable technique for determining absolute calibration coefficients, but the necessary gas fill is typically reserved for the earliest part of a run campaign, or delayed until the end of the campaign. To calibrate the TS densities without the benefit of gas scattering calibrations, we take advantage of cutoffs in electron cyclotron emission (ECE) that occur under certain plasma conditions.

The ECE diagnostic on C-Mod measures second-harmonic electron cyclotron emission in the extraordinary mode. These signals are cut off when the second harmonic electron cyclotron frequency ( $\omega = 2\omega_{ce} = 2eB/m_e$ ) is less than the right hand cutoff frequency of the plasma:

$$2\omega_{ce} < \omega_R = \frac{1}{2}[\omega_{ce} + (\omega_{ce}^2 + 4\omega_{pe}^2)^{1/2}] \quad (1)$$

or after simplification,

$$2\omega_{ce}^2 < \omega_{pe}^2 \quad (2)$$

where the plasma frequency  $\omega_{pe}$  is equal to  $(e^2 n_e / \epsilon_0 m_e)^{1/2}$ . This condition simplifies to  $n_e > n_{ec}$ , where the cutoff density  $n_{ec}$  is proportional to  $B^2$ , the square of the magnetic field. As  $n_e$  between the ECE antenna and the measurement location rises above the cutoff density, an

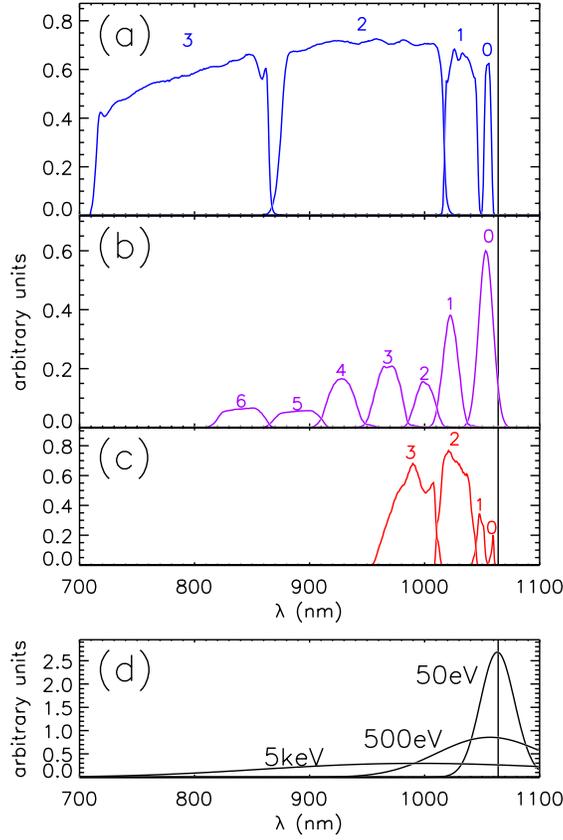


Figure 4: Typical spectral responses of the core TS upgrade polychromators (a), the older core spectrometers (b), and the edge TS polychromator (c). The vertical line at 1064 nm represents the Nd:YAG laser line. The indices associated with each spectral channel are referenced below in Fig. 5. (d) shows the Thomson scattering spectral distribution for a given electron density ( $n_e$ ) at three values of electron temperature ( $T_e$ ).

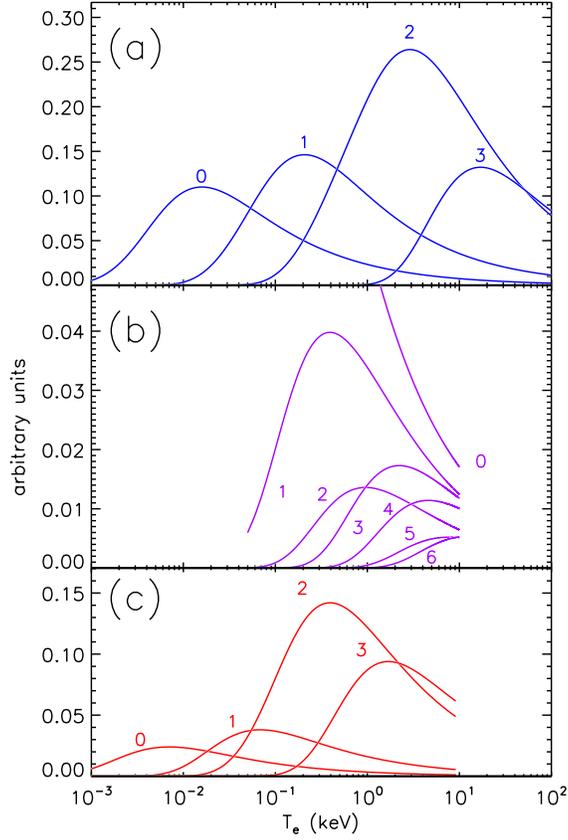


Figure 5: Responses at a given  $n_e$  as a function of  $T_e$  obtained by integrating the products of the curves in Fig. 4(a–c) and the TS spectral function. The core TS upgrade (a) has a quite large dynamic range in  $T_e$  and requires fewer spectral channels than the older system (b). The edge TS diagnostic (c) is suited for  $T_e$  under 1 keV. Indices correspond to those in Fig. 4.

abrupt loss of signal occurs. Thus, as long as  $dn_e/dR < 0$  between the measurement location and the plasma edge, a signal becoming cut off indicates that  $n_e$  at the ECE measurement location is passing through  $n_{ec}$ . The ECE diagnostic measures emission at up to 28 distinct frequencies, each corresponding to a particular magnetic field; since field falls with increasing major radius ( $B \propto 1/R$ ), cutoffs can be observed one by one across the entire outboard side of the plasma, provided the above conditions are achieved.

By way of example, Fig. 6 shows density and ECE data from a 0.8 MA, 3.4 T ohmically heated plasma discharge. The average plasma density was ramped dynamically as shown in Fig. 6(a). As the core  $n_e$  profile rises, ECE signals get cut off, beginning with the outermost midplane radii and proceeding inward. A sampling of of ECE signals is shown in Fig. 6(a–e). By interpolating the observed cutoffs in time and radial dimensions to the measured core TS profiles, we can determine scalar correction coefficients for the TS channels, bringing them into agreement with the ECE cutoff results. After several shots with clear cutoffs, we can derive coefficients with 10% or less uncertainty, which is comparable with the uncertainty resulting from gas calibrations. Figure 6(f) shows that when the obtained corrections are applied to the TS channels (circles), the  $n_e$  profiles rise through the curve of  $n_{ec}$  vs.  $R$  (dashed line with diamonds) as expected.

#### IV. CONCLUSIONS

A number of hardware upgrades to the C-Mod TS system are being brought online, enabling greater spatial and temporal resolution than was previously obtained on this tokamak. Two lasers can now be fired into plasma, nearly collinear with one another, obtaining measurements with a temporal spacing limited only by detector electronics and data acquisition speeds. New polychromators with excellent dynamic range in both  $T_e$  and  $n_e$  are calibrated and in place, improving the core TS midplane resolution to better than 2 cm ( $dR/a < 0.1$ ). A retooled optical assembly allows for precise placement of focusing optics and light collection fibers. It is also designed for fast and easy adjustment of both fiber position and alignment with respect to Nd:YAG beams. Using ECE cutoffs in high density, low field discharges to supplement gas scattering calibrations has proved successful in a previous C-Mod run campaign, and the procedure likely will be repeated routinely in the future.

#### ACKNOWLEDGMENT

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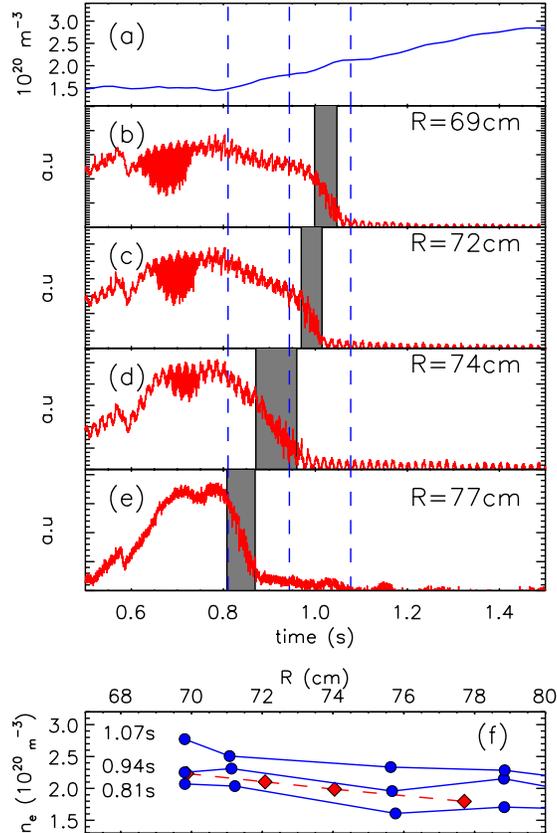


Figure 6: Density calibration data from a 0.8 MA, 3.4 T discharge in which the line-averaged density (a) was ramped. Electron cyclotron emission signals from four channels are plotted in (b–e). Signal is cut off as  $n_e$  rises above a known cutoff density that is proportional to the square of the local magnetic field. Cutoffs occur first at the outermost major radii and propagate inward. The vertical dashed lines correspond to three TS measurements: before, during, and after the progression of cutoff. Calibration coefficients derived from multiple shots of this type are used to produce the  $n_e$  measurements (circles) shown in (f), corresponding to the same time points. The dashed curve is the cutoff density as a function of radius, while the diamonds represent the position of the ECE measurements in (b–e).

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