SUMMARY

- Charge exchange spectroscopy is one of the key profile diagnostics on the DIII–D tokamak, measuring ion temperature, poloidal and toroidal rotation speeds, impurity densities, and radial electric field

- For the 2000 campaign, we replaced the intensified photodiode array detectors on the 16 edge chords with advanced CCD detectors mounted on faster (f/4.7) Czerny-Turner spectrometers equipped with toroidal mirrors

- Photoelectron signal has increased by a factor of 20 and signal to noise by a factor of 2 to 8
  - S/N improvement depends on signal level and on CCD readout mode

- Major portion of signal level improvement comes from increased quantum efficiency of the back-illuminated, thinned CCD
  - 70% to 85% efficiency for CCD versus 10% for intensifier
  - Improved spectrometers account for the rest of signal increase

- Minimum integration time is 0.33 ms while archiving to PC memory and 0.15 ms using temporary on chip storage (254 spectra)
  - To date, tokamak data has been taken at integration times as low as 0.33 ms

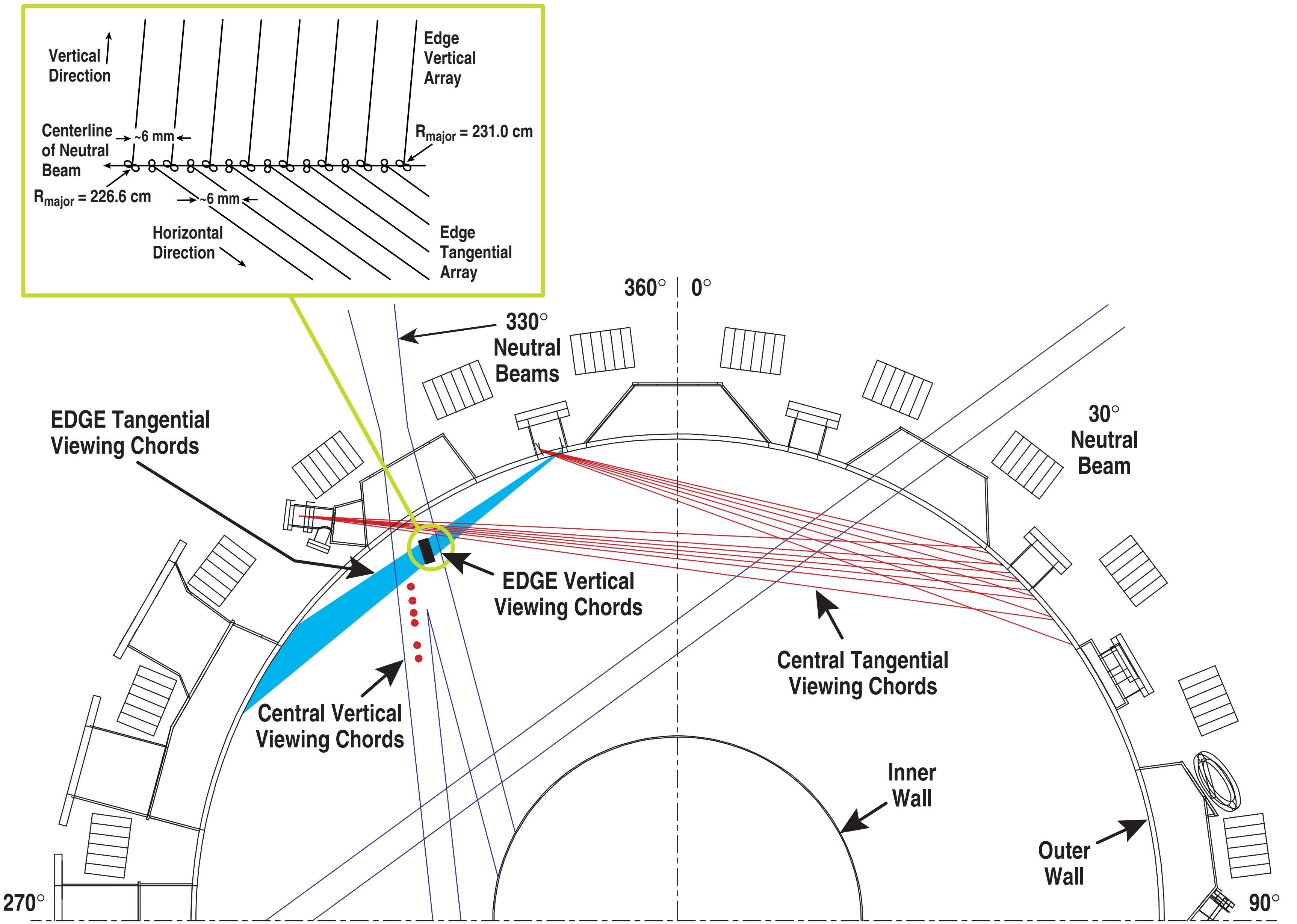
INTRODUCTION

- Charge exchange recombination (CER) spectroscopy is a standard technique on present-day fusion experiments
- By measuring the Doppler broadening, Doppler shift and intensity of a spectral line, we can determine
  - Ion temperature T_i
  - Poloidal / toroidal rotation speeds V_θ and V_ϕ of that ion
  - Density n of that ion
  - Radial electric field E_r (via radial force balance equation)
- The detectors on the edge CER system on DIII–D were based on image intensifiers fiberoptically coupled to linear silicon diode arrays
  - We had pushed this technology to its limits, achieving 0.52 ms readout time in our General Atomics FOMA cameras

INTRODUCTION (CONTINUED)

- Improvements in signal and signal to noise and reduction in minimum integration time are needed to meet the experimental objectives on DIII–D
  - Improved signal to noise will help speed data analysis, which was a major bottleneck
  - Improved signal and reduced integration time will allow study of rapid events (e.g. E_r evolution across L to H transitions)
- CCD technology has finally developed to the point where it is superior to intensifier-linear diode array combinations, even under conditions where sub-milisecond integration times are needed
- This paper describes details on the development and implementation of high time resolution CCD detectors for the 16 spatial chords which view the edge of DIII–D plamas

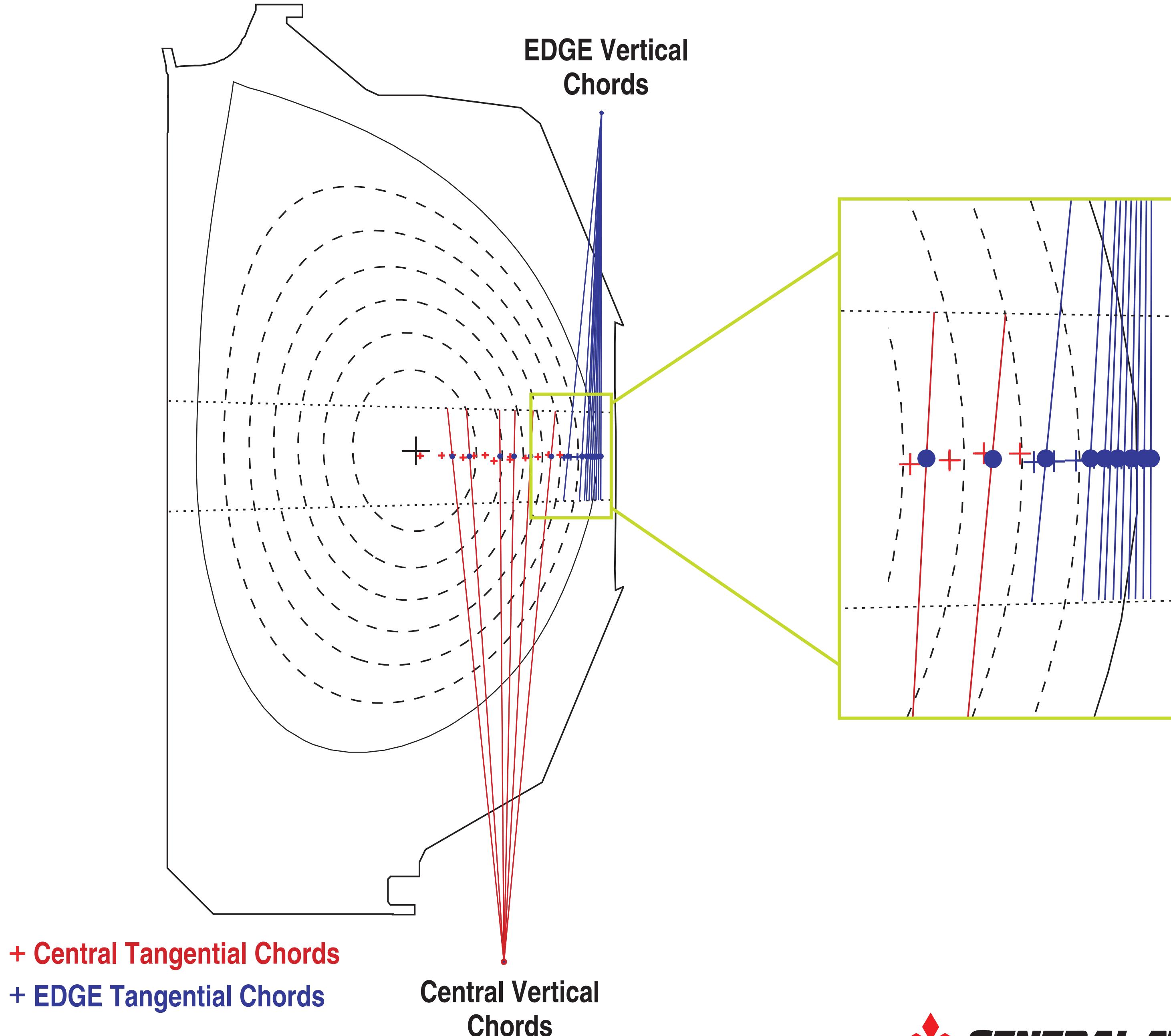
PLAN VIEW OF CER CHORDS



133-00/jy

GENERAL ATOMICS

VERTICAL VIEW OF CER CHORDS



133-00/jy

GENERAL ATOMICS

DESIGN PHILOSOPHY

- Detector performance must exceed that of the previous intensifier-linear diode array system by a large margin to make the development effort worthwhile
  - Signal and signal to noise should be well above those achieved in the previous system
  - Quantum efficiency should be well above the 10% available with standard image intensifiers
  - Minimum integration time should be well below 0.52 ms
- Design for highest possible light throughput and highest possible quantum efficiency
  - Requires a back illuminated, thinned CCD chip
  - Use as low an f/number spectrometer as commercially available
- Continue to use commercial Czerny-Turner spectrometer for ease of setting wavelength
  - Lines used in DIII–D experiments: D I 656.2 nm, He II 468.6 nm, B V 494.47 nm C VI 343.37 nm, C VI 529.05 nm, C VI 771.68 nm, Ne X 524.90 nm Ar XVI 346.3 nm, Ar XVIII 344.9 nm

CHOICE OF NEW CCD CAMERA

- In spite of an extensive development effort on our part, we could not reduce the readout noise of our Sarnoff VCCD512 cameras below about 75 electrons
  - Specifications were 35 to 45 electrons
  - Readout noise is too high for highest speed operation
  - S/N improvement depends on signal level and on CCD readout mode
- Found new CCD camera from PixelVision based on SITe 652 x 488 CCD chip
  - Back-illuminated, thinned for high quantum efficiency
  - Split frame transfer architecture with four readout nodes
  - Built into complete system including PCI computer interface, control electronics and 14 bit digitizers
  - Fiber optic data transfer to PC from camera
  - Readout noise of 15 to 30 electrons, depending on readout mode
  - Integrated TEC cooler to control chip temperature ($T \geq 220$ K); water cooling loop to hold output of TEC to 10°C
  - Minimum parallel row transfer time of chip is 0.4 microseconds; present electronics limits this to 0.6 microseconds

CCD HAS MULTIPLE READOUT MODES

- **PixelVision CCD camera is controlled with a flexible digital signal processing system which allows various software selectable readout modes**

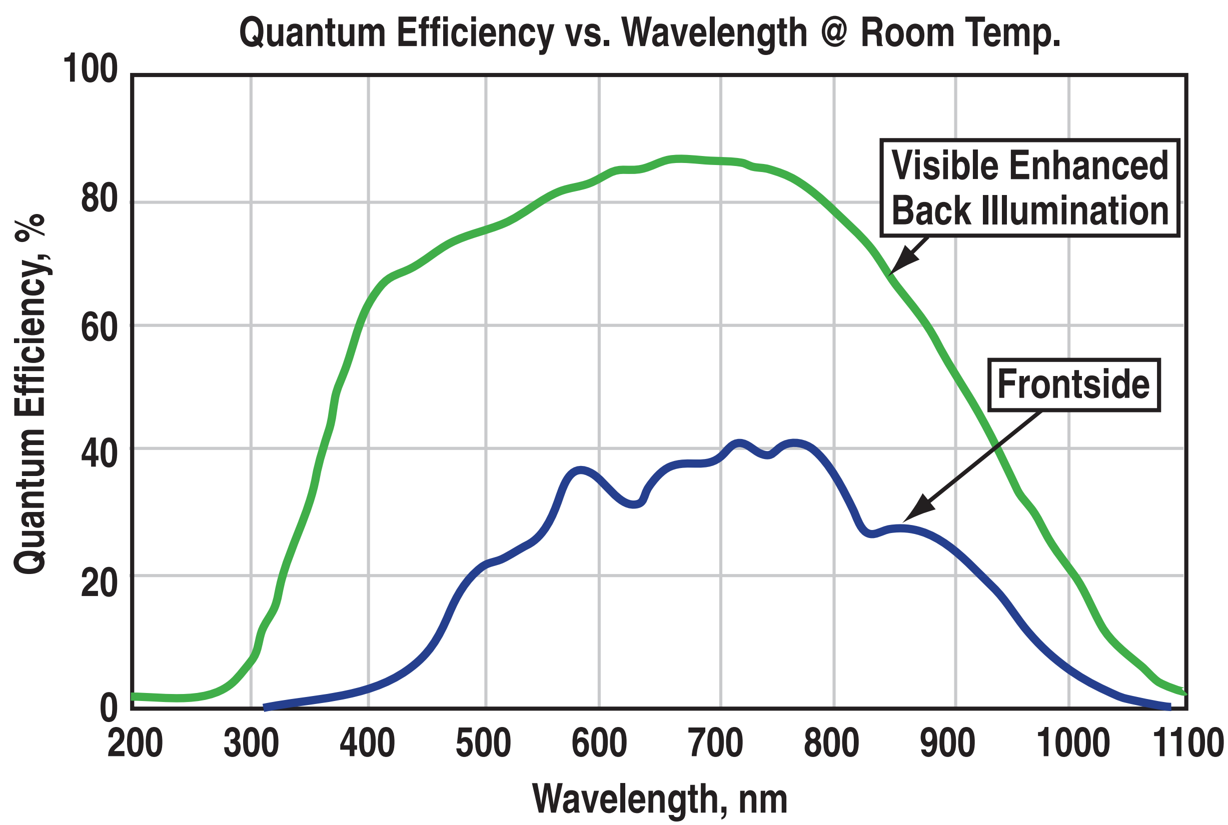
- **Image mode allows readout as a standard 2-D imager**
  - Very convenient for aligning camera to spectrometer
  - Used with PixelVision-provided software on PC
  - Much too slow for tokamak spectroscopy

- **TDI mode: standard tokamak spectroscopic mode**
  - When external trigger occurs, charge in exposure area on chip is clocked to the storage areas
  - Two storage areas, one for upper and one for lower half of chip
  - At the same time, all 251 pixels in each column of each storage area are binned on to the serial readout register
  - Serial register is then read out at 2.2 MHz digitizing rate; left and right halves of both registers are digitized separately (4 output channels total)
  - Data is archived to PC memory; number of spectra limited only by PC memory
  - 0.33 ms minimum integration time
  - 30 electrons readout noise

CCD HAS MULTIPLE READOUT MODES (Continued)

- **Sample mode**
  - When external trigger occurs, charge in exposure area is binned onto the first row of the storage area
  - Storage area is clocked once to move charge to next row
  - Cycle repeats until storage area is full
  - Storage area is then read out one row at a time at 0.5 MHz digitizing rate
  - Only 254 spectra can be stored in storage area
  - 0.15 ms minimum integration time
  - 15 electrons readout noise

QUANTUM EFFICIENCIES OF BACK ILLUMINATED AND FRONT ILLUMINATED CCD CHIPS



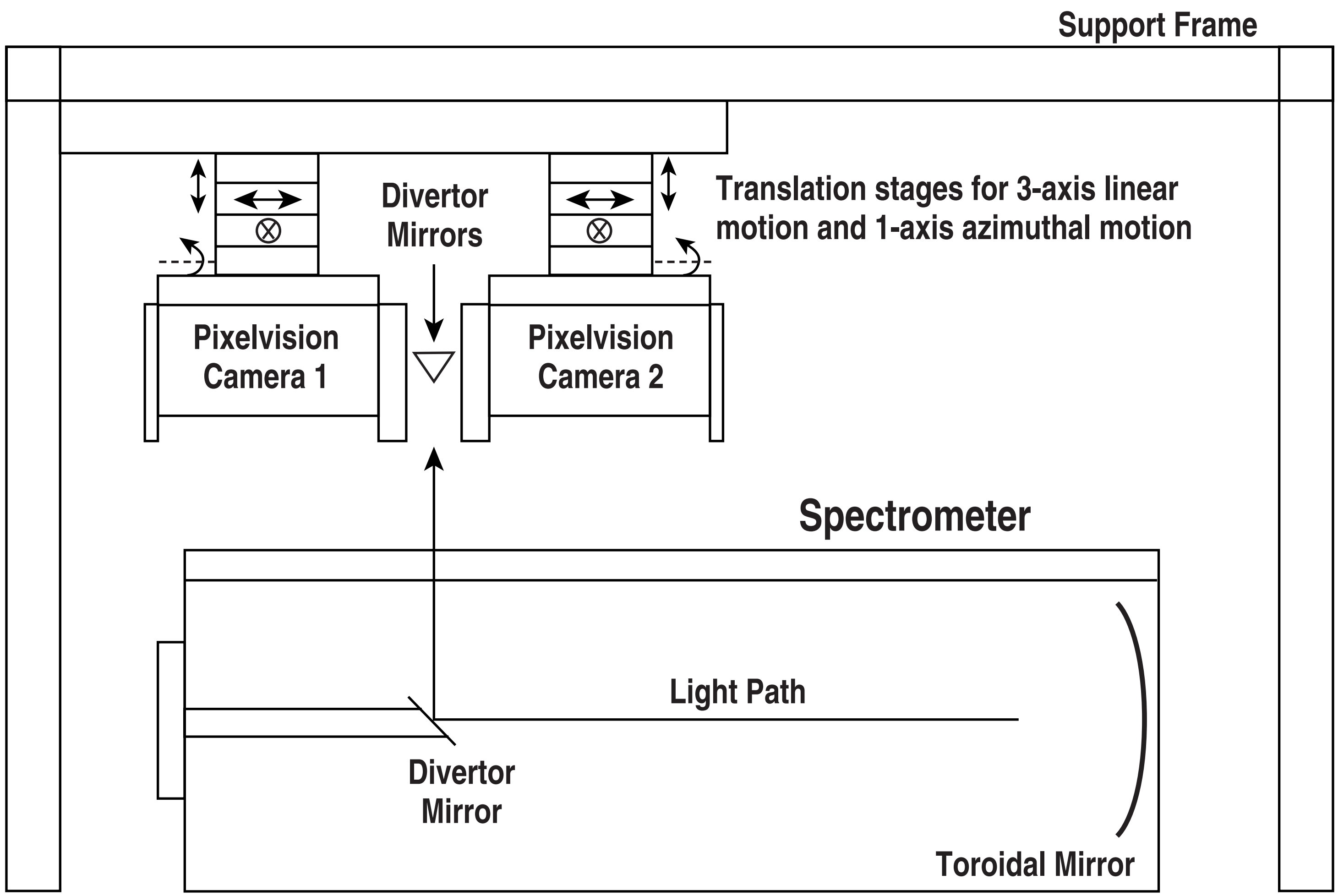
133-00/jy

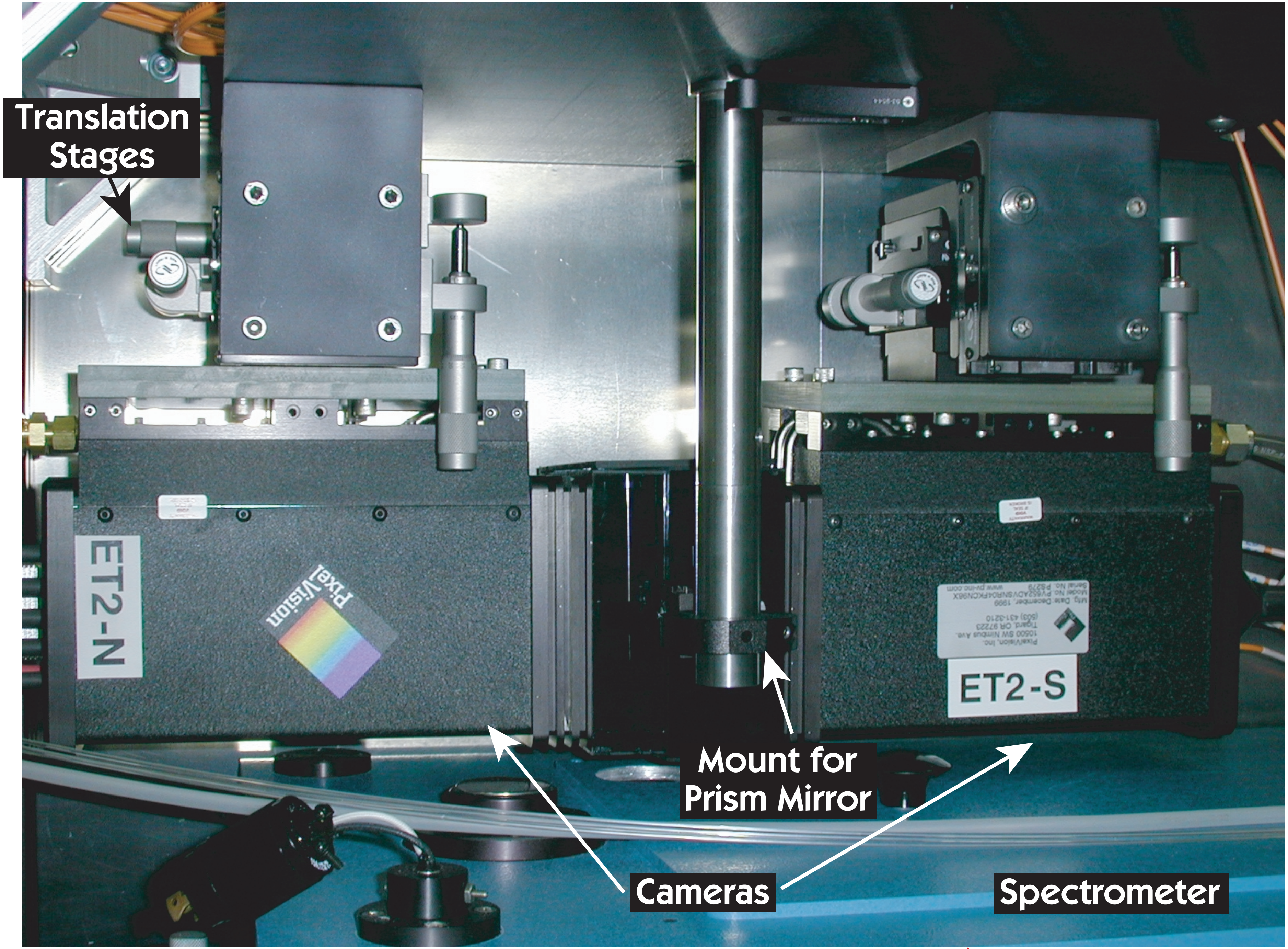
GENERAL ATOMICS

COUPLING CCD CAMERAS TO SPECTROMETERS

- Initial desire was to use a 1024 x 1024 Pluto chip
  - Large enough to take four spectra
  - Would require one camera per spectrometer
  - Even after waiting almost two years, chip is still not available in commercial quantities and it may never be available
- 652 x 488 chip has been available for several years, but only has one third the area of the 1024 x 1024 chip
- Because of broad wavelength range needed in our system (300 to 800 nm), optics to couple the output of the spectrometer to the smaller chip would have been complicated and expensive
  - It was significantly cheaper to buy more cameras to get the necessary area
- Planar mirror coupling arrangement shown below is simple, robust and works over the required wavelength range
  - This design required boring hole in spectrometer's removable hatch
  - In principle, this coupling scheme could be done with one mirror
  - One mirror design would require milling a 120 mm wide slot in the body of the spectrometer to accommodate the bodies of the CCD cameras

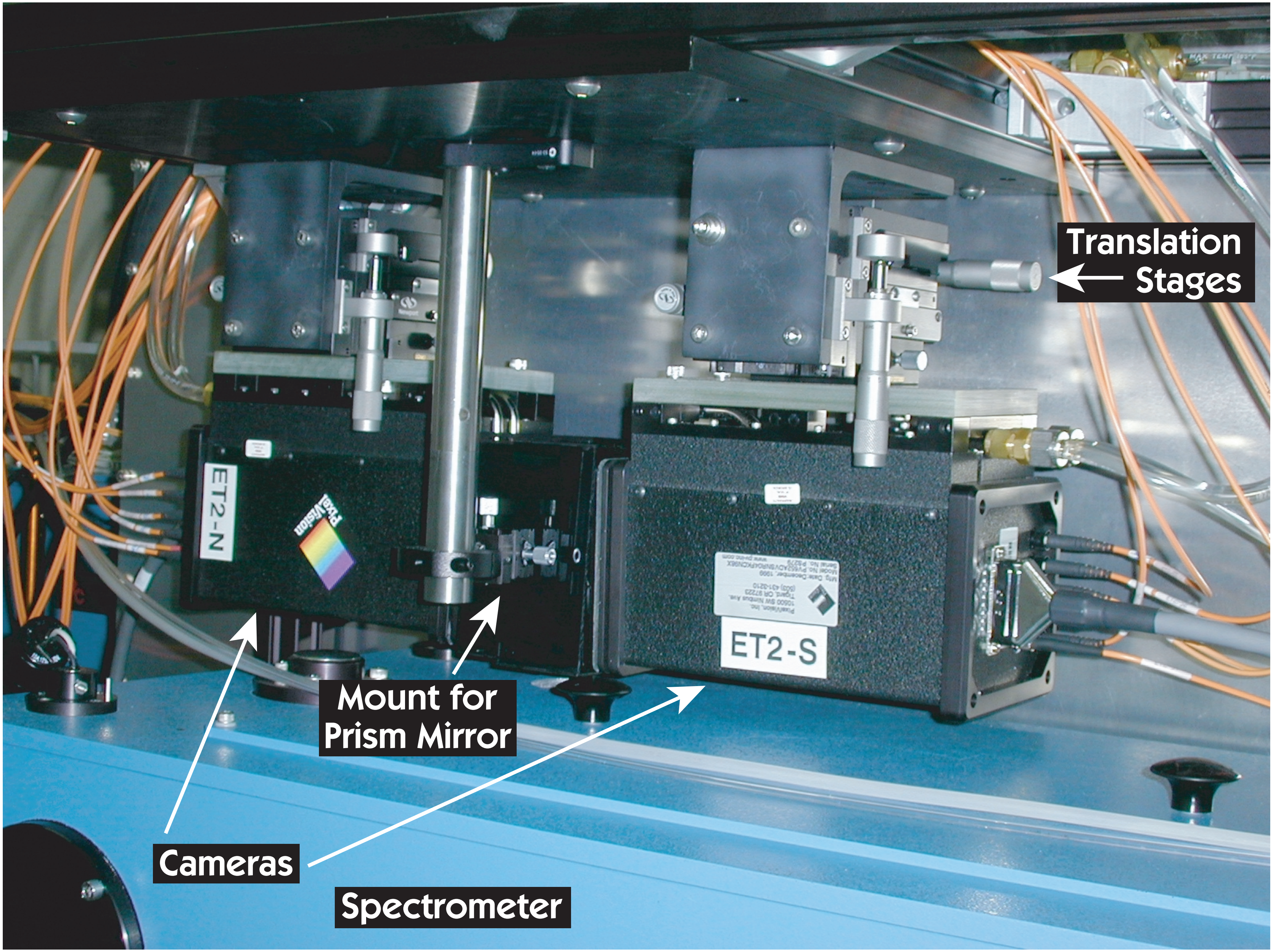
SIDE VIEW OF SPECTROMETER, DIVERTOR MIRRORS AND CCD CAMERAS





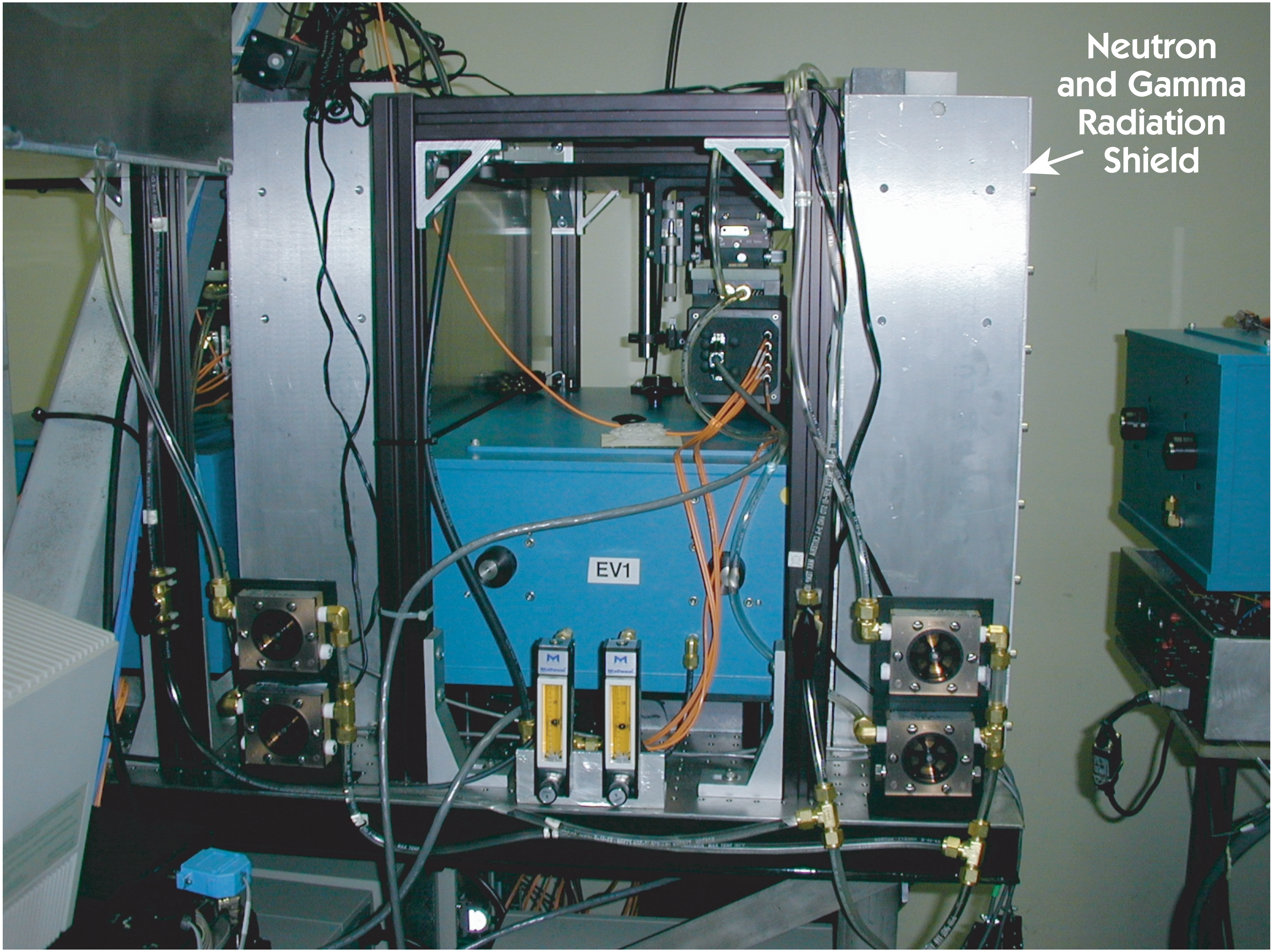
133-00/jy

GENERAL ATOMICS



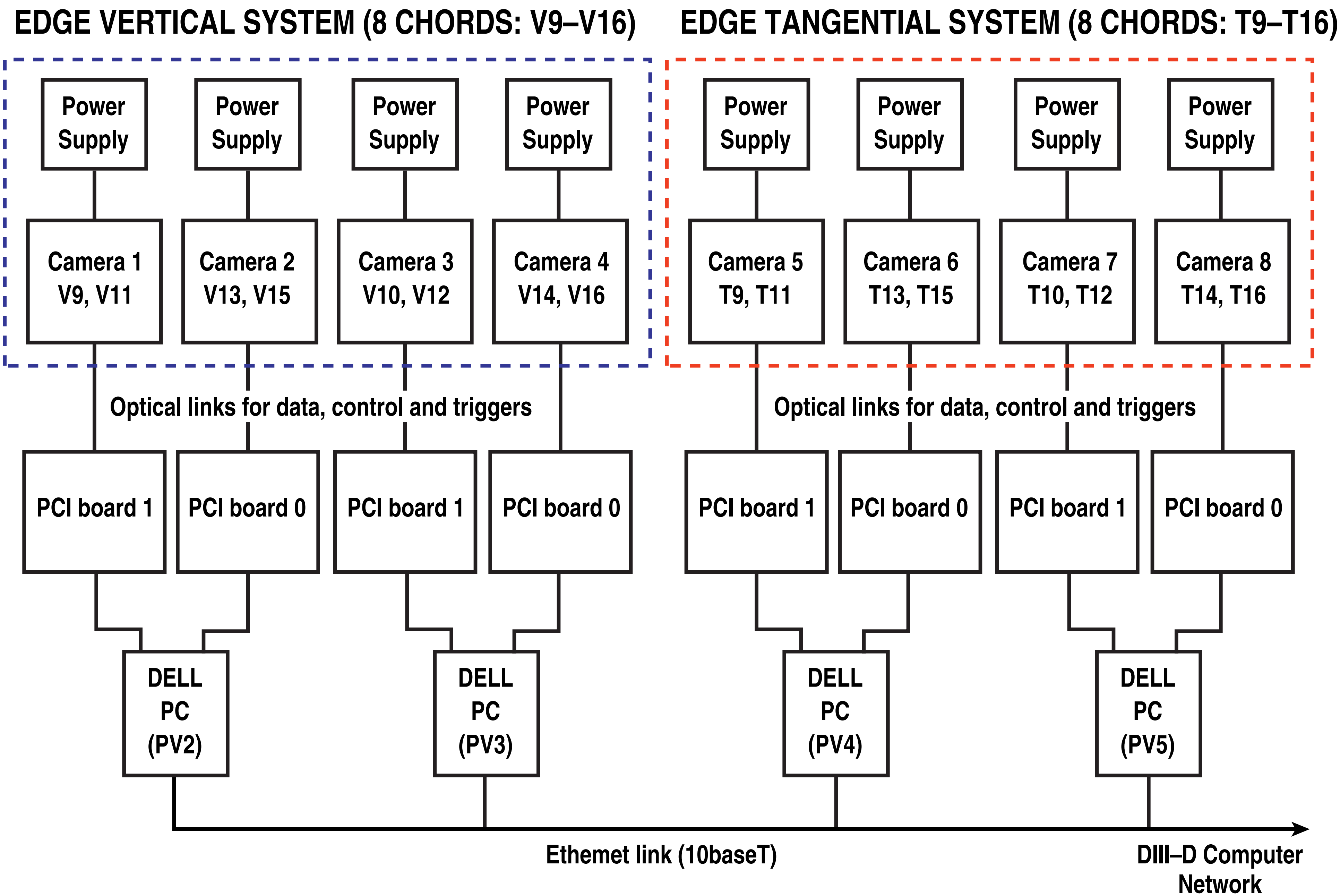
133-00/jy

GENERAL ATOMICS



GENERAL ATOMICS

SCHEMATIC DIAGRAM OF PIXELVISION CAMERAS AND COMPUTERS LAYOUT



133-00/jy

GENERAL ATOMICS

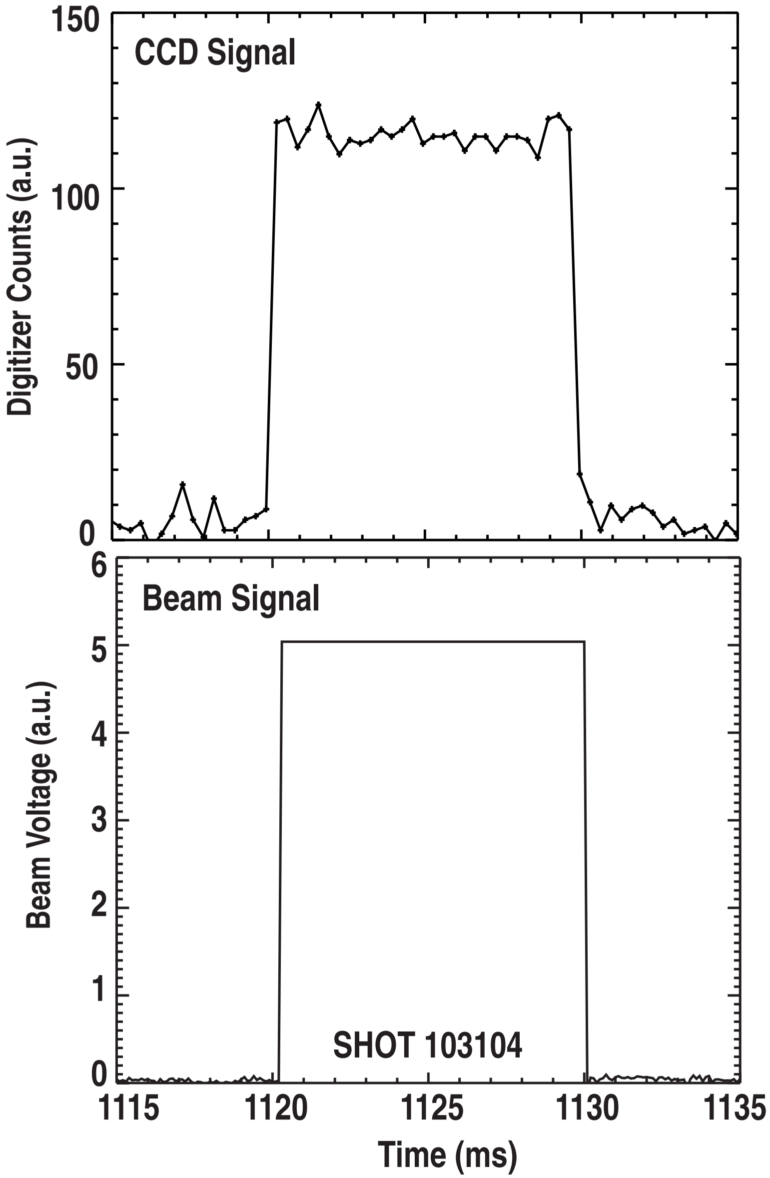
TOROIDAL MIRROR FOR ACTON SPECTROMETER

- Standard Czerny-Turner spectrometers use spherical mirrors; this leads to astigmatism with tangential (wavelength-direction) and sagittal (vertical) focal planes being different
  - Offset by 12 mm at center of exit plane
  - Tilted about 1 degree
- Vertical blurring at best wavelength focus reduces number of spatial chords which can be imaged on a given detector without cross talk
  - Techniques used previously to reduce this blurring cost signal
- Toroidal mirror for first (collimating) mirror in spectrometer can reduce astigmatism
  - Focal planes meet along a line of middle of exit planes
  - Focal planes are still tilted, but this produces very small blurring over 7.8 mm width of detector
- Signal improved about a factor of two over system without toroidal mirror

PIXELVISION CAMERA's SIGNAL TO NOISE IS SIGNIFICANTLY BETTER THAN INTENSIFIED DIODE ARRAY's

- Signal proportional to DQ/f^2
  - D is dispersion (pm/pixel) (CCD system 15.6; intensifier system 11.62)
  - Q is quantum efficiency (CCD system 0.75; intensifier system 0.1)
  - f is spectrometer f/number (CCD system 4.7; intensifier system 6.8)
  - Binned serial output on CCD system to produce 326 pixels with 15.6 pm/pixel dispersion
  - Result is factor 20 improvement for new CCD system over intensified diode system
- New system noise estimate
  - $(S_e + r_e^2)^{1/2}$
  - S_e is signal in photoelectrons
  - r_e is read noise in electrons
- Intensifier system noise estimate
  - $(3.24\ S_e + r_e^2)^{1/2}$
  - Factor $3.24 = 1.8^2$ is due to amplification in intensifier
- Signal to noise ratio improvement
  - For small signal levels: 2 for TDI mode and 4 for sample mode
  - For large signal levels: 8 for both readout modes

OBSERVATION OF DOPPLER-SHIFTED D_α FROM BEAM NEUTRALS SHOWS EXCELLENT TIME RESPONSE OF PIXELVISION CCD DETECTOR AT 0.33 ms INTEGRATION TIME

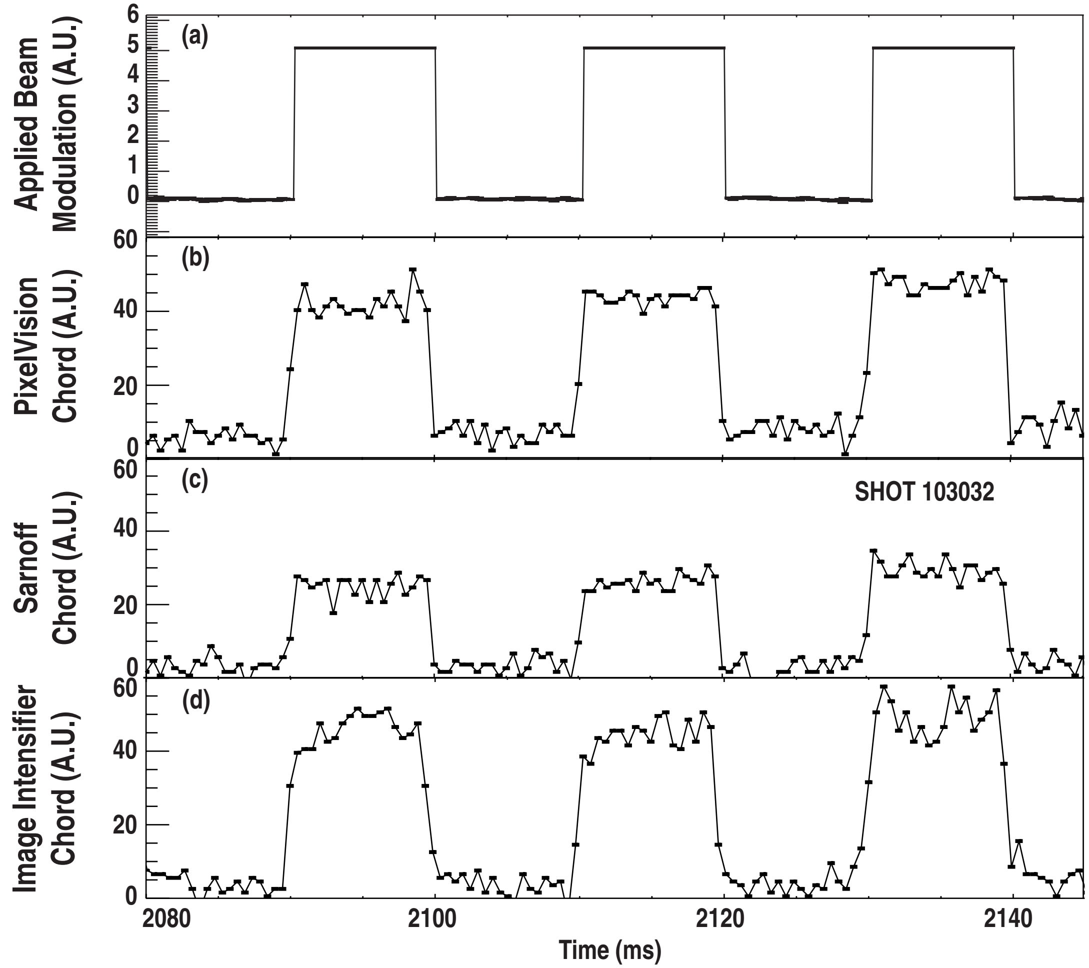


- Beam signal digitized at 0.1 ms

133-00/jy

GENERAL ATOMICS

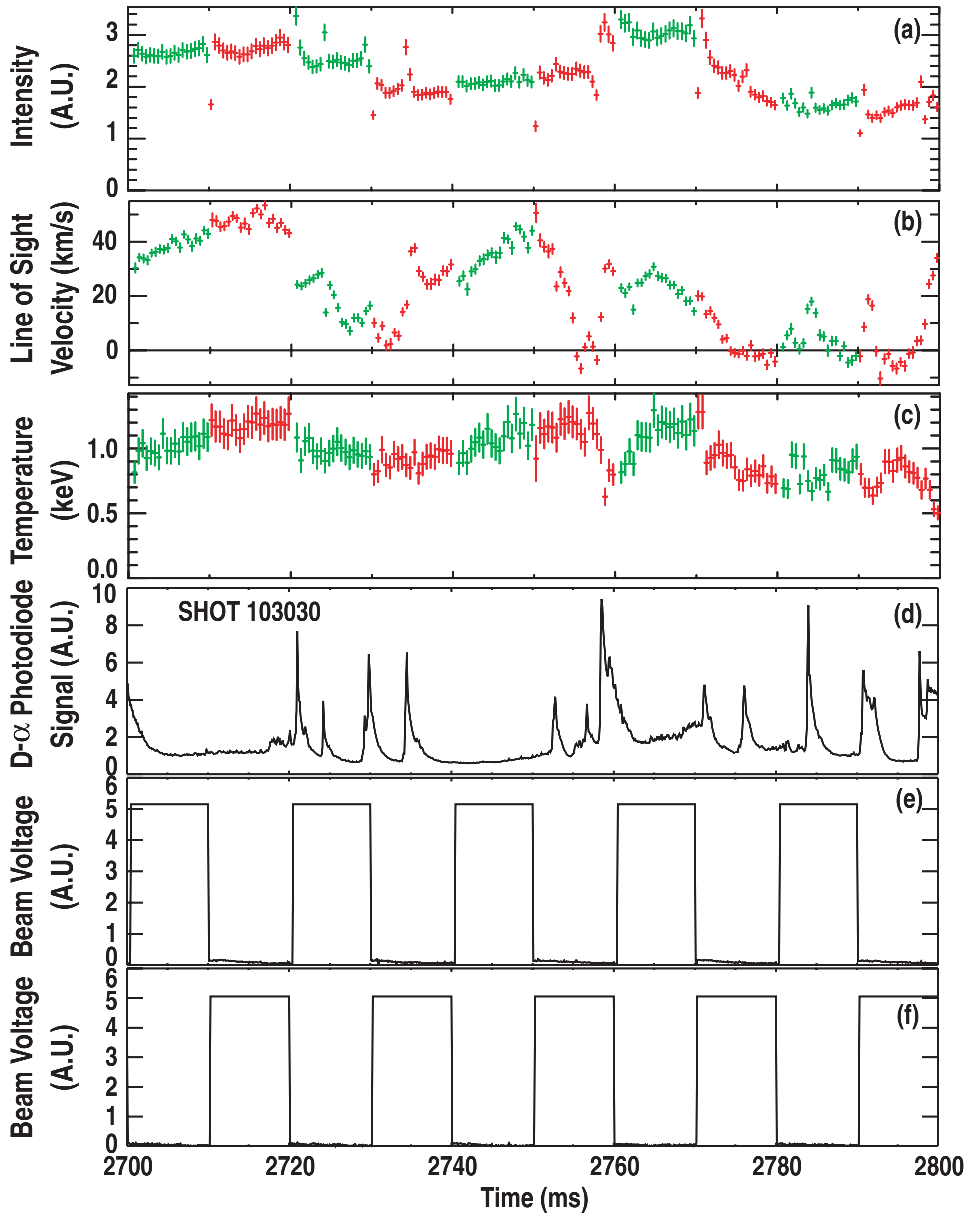
CCD SYSTEMS SHOW BETTER TIME RESPONSE AND LOWER NOISE THAN INTENSIFIER – BASED SYSTEM



- Time response of C VI 529.05 nm signals from three chords on different detector systems observing nearly the same location in the plasma during beam modulation: (a) beam timing (b) chord on PixelVision CCD camera, (c) chord on Sarnoff CCD camera, (d) chord on intensified diode array detector. Plot is single pixel on each detector.

GENERAL ATOMICS

CHANGES IN CARBON SIGNAL INTENSITY, TOROIDAL ROTATION SPEED AND ION TEMPERATURE ASSOCIATED WITH ELMs AT THE PLASMA EDGE



- Integration time of CCD camera is 0.5 ms

BACKGROUND LEVEL DRIFT AND REFRESH CIRCUITRY

- The dark current and dc offset contributions must be subtracted from the total digitized value to obtain the signal due to photoelectrons
- The dark current and dc levels showed unexpected changes when the external triggers start or when the interval between the triggers changes
  - This can amount to 10's of digitizer counts
  - Level can take several seconds to stabilize when external triggers first start
  - Level change stabilizes in a fraction of a second when the interval between triggers changes (e.g. from 10 ms to 1 ms)
- With Sarnoff system, background level changed only due to change in dark current with integration time
  - Recording 9 frames at shortest and 9 frames at longest integration time was sufficient to provide proper background subtraction
  - Background to be subtracted could be interpolated between shortest and longest integration values

BACKGROUND LEVEL DRIFT AND REFRESH CIRCUITRY
(Continued)

- To minimize background level change on PixelVision camera, we implemented control electronics which repetitively trigger the cameras at 10 ms intervals between tokamak shots
  - Tokamak synchronous triggers take over during shot
  - Drift reduced markedly, but still present
- We are implementing software to record a complete set of background data with timing duplicating the tokamak timing
  - We will fit an interpolation function to this and archive the parameters of the interpolation function

FUTURE PLANS

- **Near term**
  - Complete programming needed to archive full background data set under same timing conditions as tokamak shot
  - Complete programming needed to utilize sample mode
  - Complete programming needed for hardware binning on the serial readout register

- **FY2001**
  - Upgrade firmware in PixelVision CCD cameras to allow low speed readout (0.5 MHz digitizing rate) in TDI mode
    - ★ Will allow readout with 15 electrons read noise for integration time longer than 0.8 ms
  - Replace the intensified diode arrays on the rest of the CER system with PixelVision CCD cameras

SUMMARY

- Charge exchange spectroscopy is one of the key profile diagnostics on the DIII–D tokamak, measuring ion temperature, poloidal and toroidal rotation speeds, impurity densities, and radial electric field
- For the 2000 campaign, we replaced the intensified photodiode array detectors on the 16 edge chords with advanced CCD detectors mounted on faster (f/4.7) Czerny-Turner spectrometers equipped with toroidal mirrors
- Photoelectron signal has increased by a factor of 20 and signal to noise by a factor of 2 to 8
  - S/N improvement depends on signal level and on CCD readout mode
- Major portion of signal level improvement comes from increased quantum efficiency of the back-illuminated, thinned CCD
  - 70% to 85% efficiency for CCD versus 10% for intensifier
  - Improved spectrometers account for the rest of signal increase
- Minimum integration time is 0.33 ms while archiving to PC memory and 0.15 ms using temporary on chip storage (254 spectra)
  - To date, tokamak data has been taken at integration times as low as 0.33 ms