IMPROVED CCD DETECTORS FOR HIGH SPEED, CHARGE EXCHANGE SPECTROSCOPY STUDIES ON THE DIII–D TOKAMAK

by

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GENERAL ATOMICS

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INTRODUCTION

- The ultimate goal of fusion research is to establish a burning plasma where the energy needed to sustain the plasma comes from its own fusion reactions
- From the standpoint of a spectroscopist, the tokamak plasmas utilized in magnetic fusion research provide a wonderful light source
  - Ion temperatures up to 27 keV and electron temperatures up to 10 keV are routinely available for several seconds in the DIII–D tokamak
  - Electron densities are typically in the 1–10 $\times 10^{19}$ m^{-3} range
- Spectroscopic measurements of Doppler broadening, Doppler shift and intensity of radiation from highly ionized atoms allows us to determine
  - Ion temperature T_i
  - Poloidal and toroidal rotation speeds V_θ, V_ϕ
  - Density n of a given ion
  - Radial electric field E_r (via radial force balance equation)
- By utilizing charge exchange excitation from the 80 keV D^0 neutral beams used to heat the plasma, we can perform spatially localized measurements
  - To date, we have used various H-like and Li-like ions: D I, He II, C IV, C VI, O VIII, F IX, Ne X, Ar XVI, Ar XVIII, Ca XXVIII, and Ca XX
  - D, He, C, and O are naturally present in the plasma; F, Ne, Ar, and Ca have been injected to study particle transport
  - Measurements are made at 40 spatial points using fiber optics to couple light to the spectrometers

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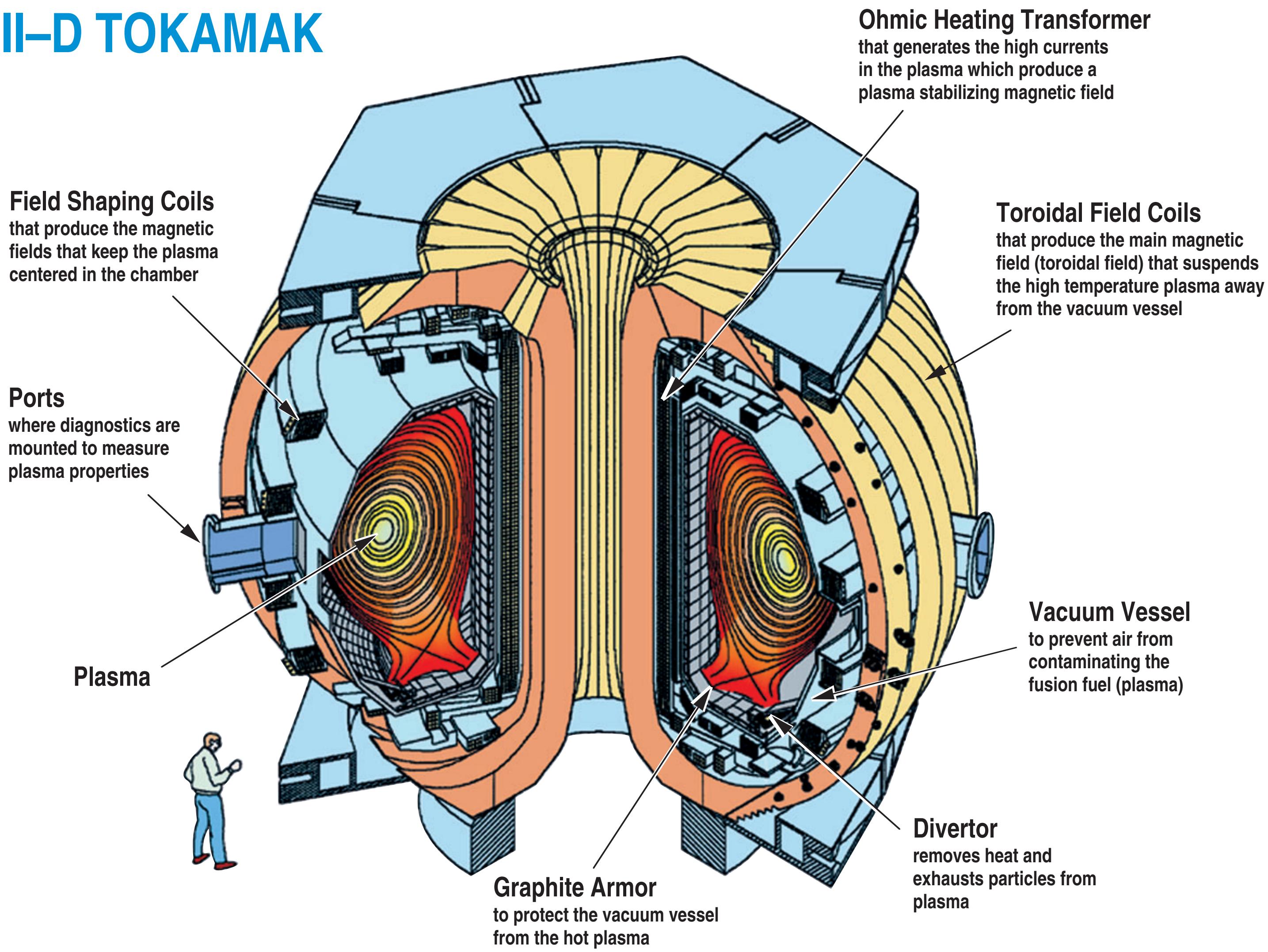
SUMMARY

- For the 2000 experimental campaign, we replaced the intensified linear photodiode detectors on the 16 edge views with advanced CCD detectors mounted on faster (f/4.7) Czerny-Turner spectrometers equipped with toroidal mirrors
  - PixelVision Pluto cameras based on SITe O-18A chip were used
- Photoelectron signal has increased by a factor of 20 and signal to noise by a factor of 2 to 8, depending on signal level and CCD readout mode
  - Major portion of signal level improvement comes from increased quantum efficiency (70% to 85% versus 10% for intensifier)
  - Improved spectrometers account for the rest of the signal increase
- Minimum integration time is 0.32 ms while archiving to PC memory and 0.15 ms using temporary on-chip storage of spectra
- We are now in the process of upgrading another 16 views of the spectroscopic system to CCD detectors
  - This upgrade will use PixelVision cameras with SITe O-18B chip

DIII–D TOKAMAK



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DIII-D TOKAMAK PARAMETERS

Major Parameters

Plasma Major Radius R	1.67 m
Plasma Minor Radius a	0.67 m
Maximum Plasma Height	2.8 m
Elongation κ	1-2.5
Magnetic Field B_T	2.1 T
Fuel Gas	D, H, He

Heating Power to Plasma

Neutral Beam	16 MW
Electron Cyclotron Wave	3 MW
Ion Cyclotron Wave	4 MW

Operating Mode

Pulsed, Every	12 min.
Pulse Duration	5–10 s

DIII-D PLASMA PARAMETERS

Parameter		Simultaneous	Maximum
Electron Temperature	T_e	7.5 keV	16 keV
Ion Temperature	T_i	18 keV	27 keV
Density	n_e	1.0×10^{20} m^{-3}	1.7×10^{20} m^{-3}
Confinement Time	τ_E	0.4 s	0.5 s
Plasma Current	I_P	2.25 MA	3.0 MA
Stored Energy	W	4.2 MJ	4.2 MJ
Beta	β	6.7%	13%
Normalized Beta	β_N	3.9	6.0
Fusion Product	$n\tau T_i$	7×10^{20} keV s m^{-3}	7×10^{20} keV s m^{-3}

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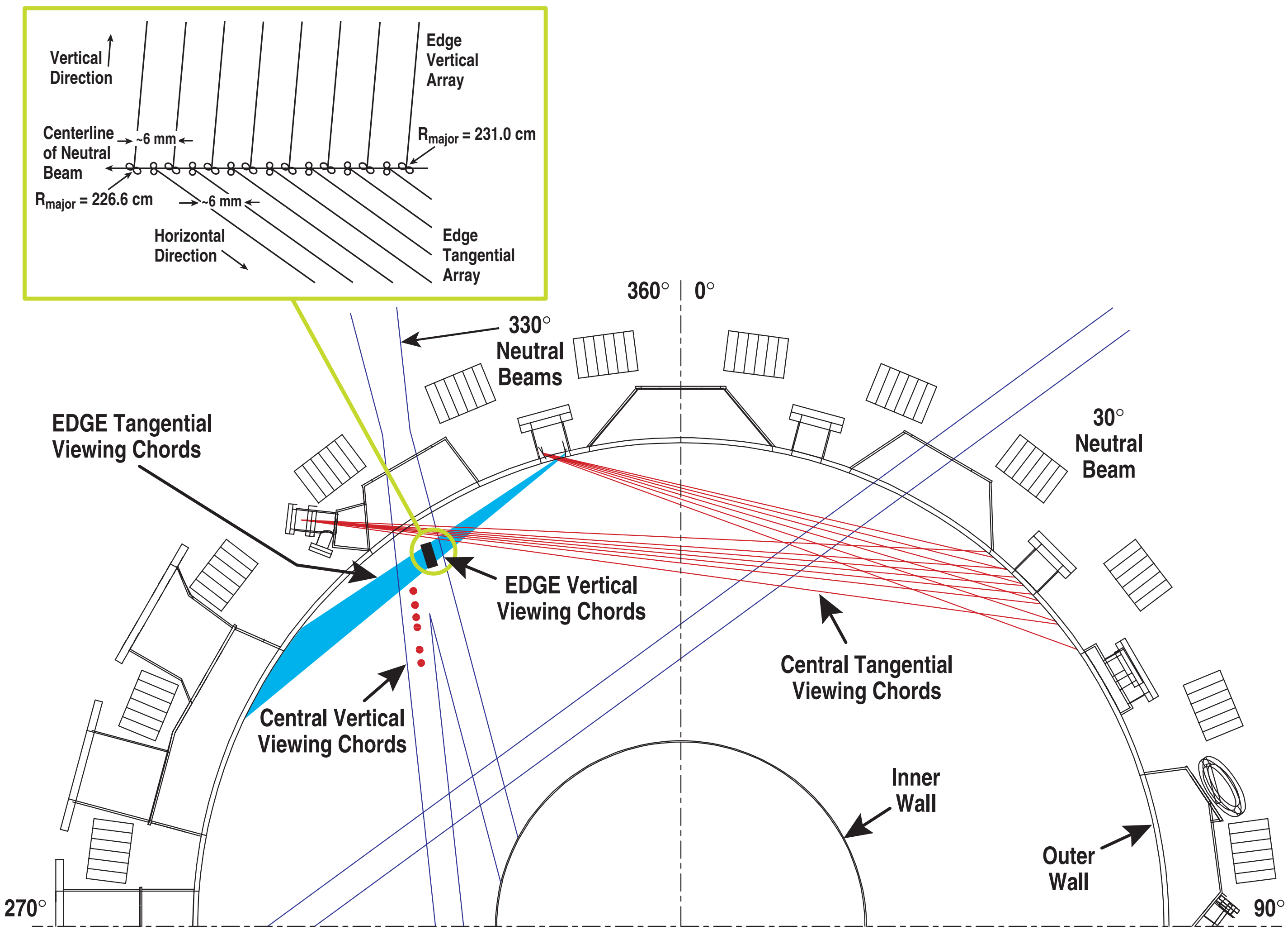
PLAN VIEW OF CER CHORDS



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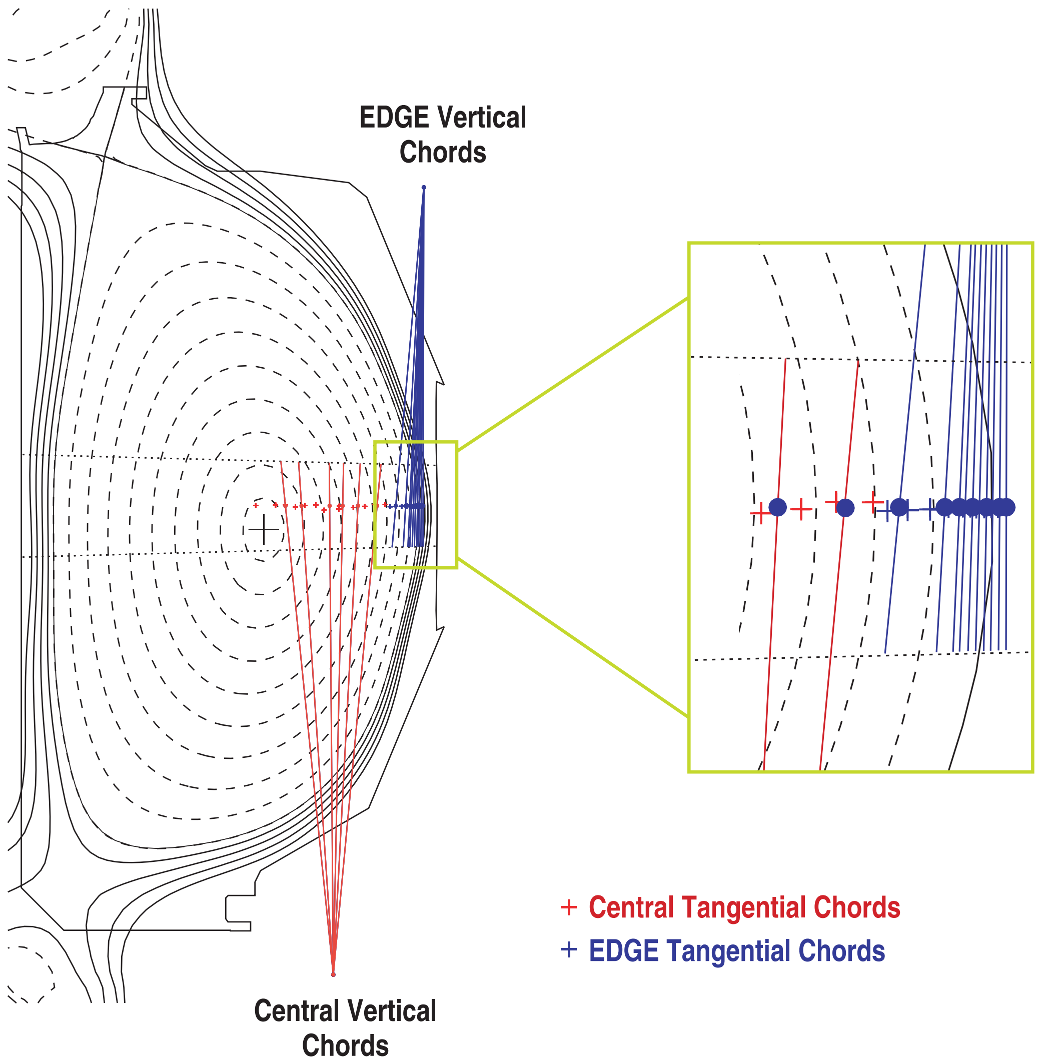
VERTICAL VIEW OF CER CHORDS



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DETECTOR HISTORY

- When we developed the charge exchange spectroscopy system originally in 1985, we obtained the speed we needed using detectors based on image intensifiers fiber optically coupled to linear silicon diode arrays
  - We pushed this technology to its limits, obtaining 0.52 ms readout times of 1024 diode Reticon linear arrays
- In the mid-1990's, CCD technology finally developed to the point where it was superior to intensifier-linear diode array combinations, even under conditions where sub-millisecond integration times are needed
  - We developed a detector system based on the Sarnoff VCCD512 chip
  - Minimum integration time was 0.38 ms using a 1 MHz readout of the serial register
  - However, in spite of several years development effort, system read noise was about 75 electrons, much worse than the 35–45 electrons promised in the specifications
  - Basic board set was from Sarnoff; General Atomics did system integration
- In the late 1990's, complete commercial scientific CCD camera systems became available
  - System integration performed by vendor
  - Complete camera cost the same as Sarnoff board sets
  - Data acquisition to inexpensive PC instead of expensive CAMAC digitizers and Unix workstation

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
  - Some of the 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, F IX 479.4 nm, F IX 342.9 nm, Ne X 524.90 nm, Ar XVI 346.3 nm, Ar XVIII 344.9 nm, Ca XVIII 344.9 nm, Ca XX 346.3 nm

CCD HAS MULTIPLE READOUT MODES

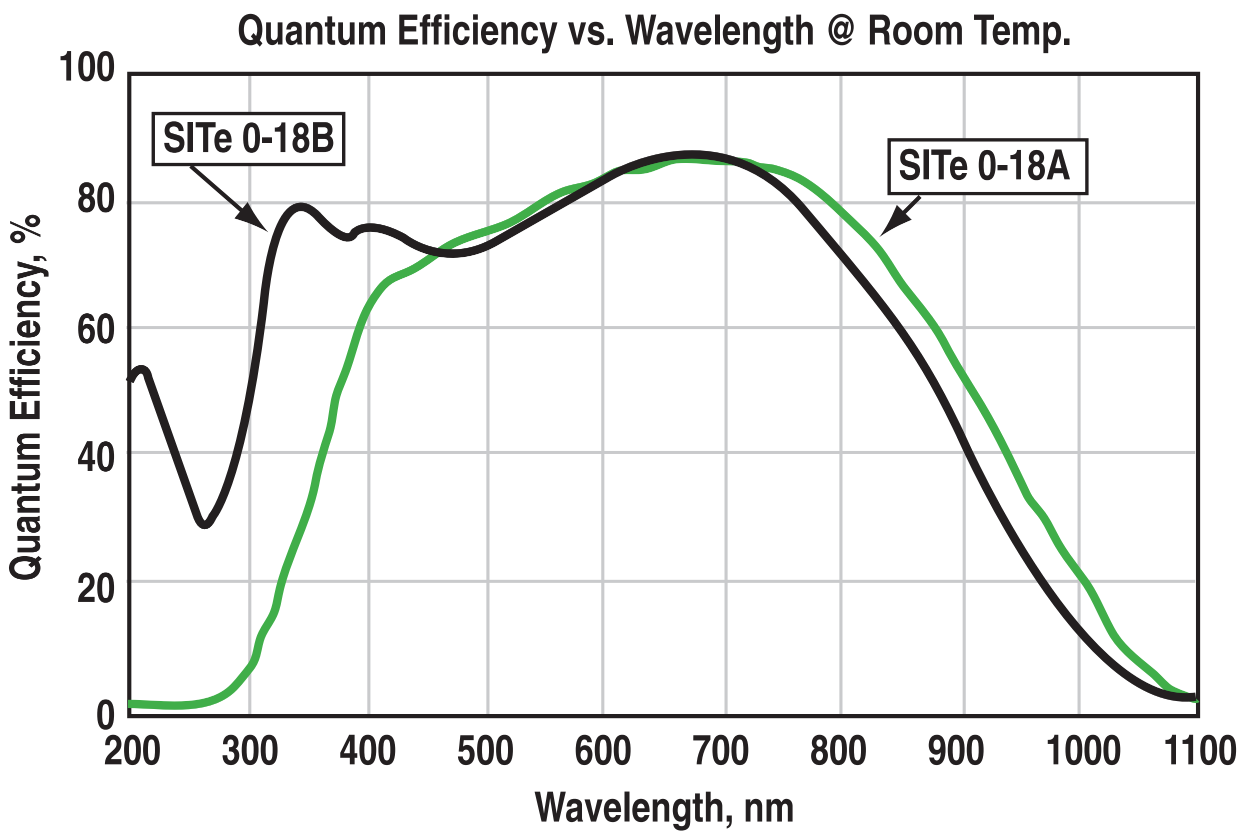
- PixelVision CCD camera is controlled with a flexible digital signal processing system which allows various software selectable readout modes

- 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 either 0.5 MHz or 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
  - 0.32 ms minimum integration time at 2.2 MHz, 0.82 ms at 0.5 MHz
  - 30 electrons readout noise at 2.2 MHz, 15–20 electrons at 0.5 MHz

- 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
  - 15–20 electrons readout noise

QUANTUM EFFICIENCIES OF BACK ILLUMINATED CCD CHIPS



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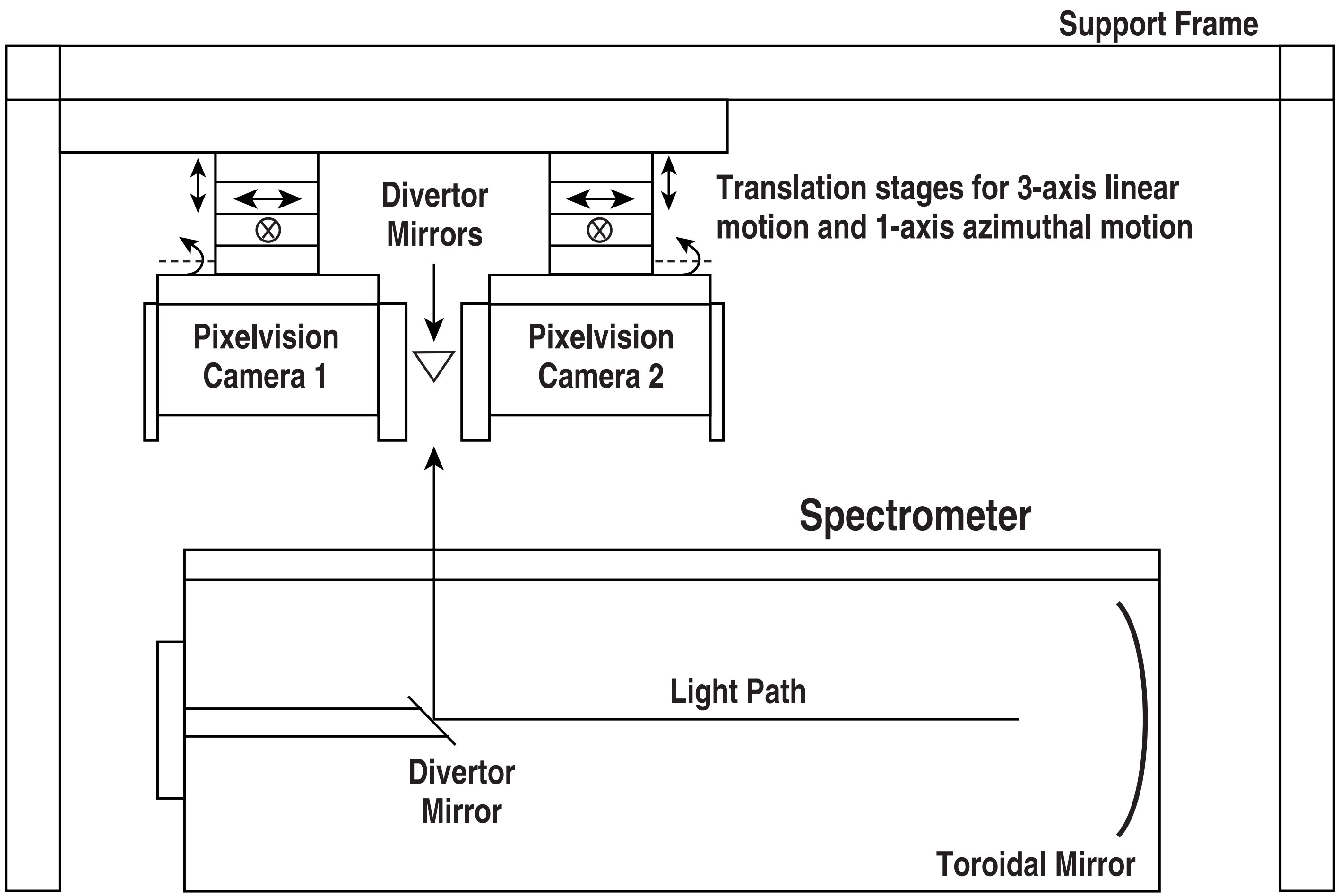
COUPLING CCD CAMERAS TO SPECTROMETERS

- Initial desire was to use a 1024 x 1024 Pluto chip
  - Large enough to take four spectra
  - Would require one camera per spectrometer
  - Chip was never available in commercial quantities
- 652 x 488 0–18 A chip was available in 1999, 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



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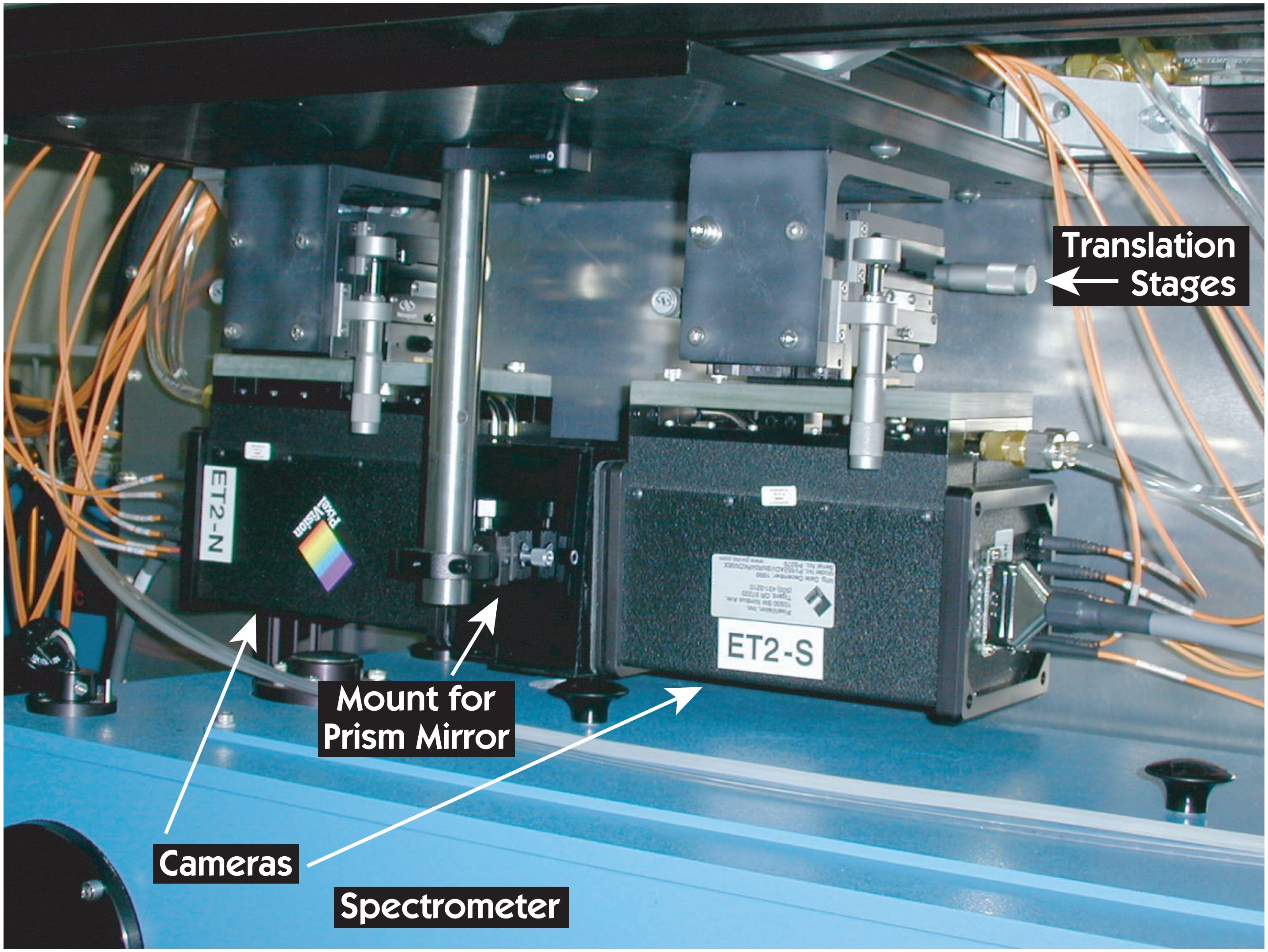

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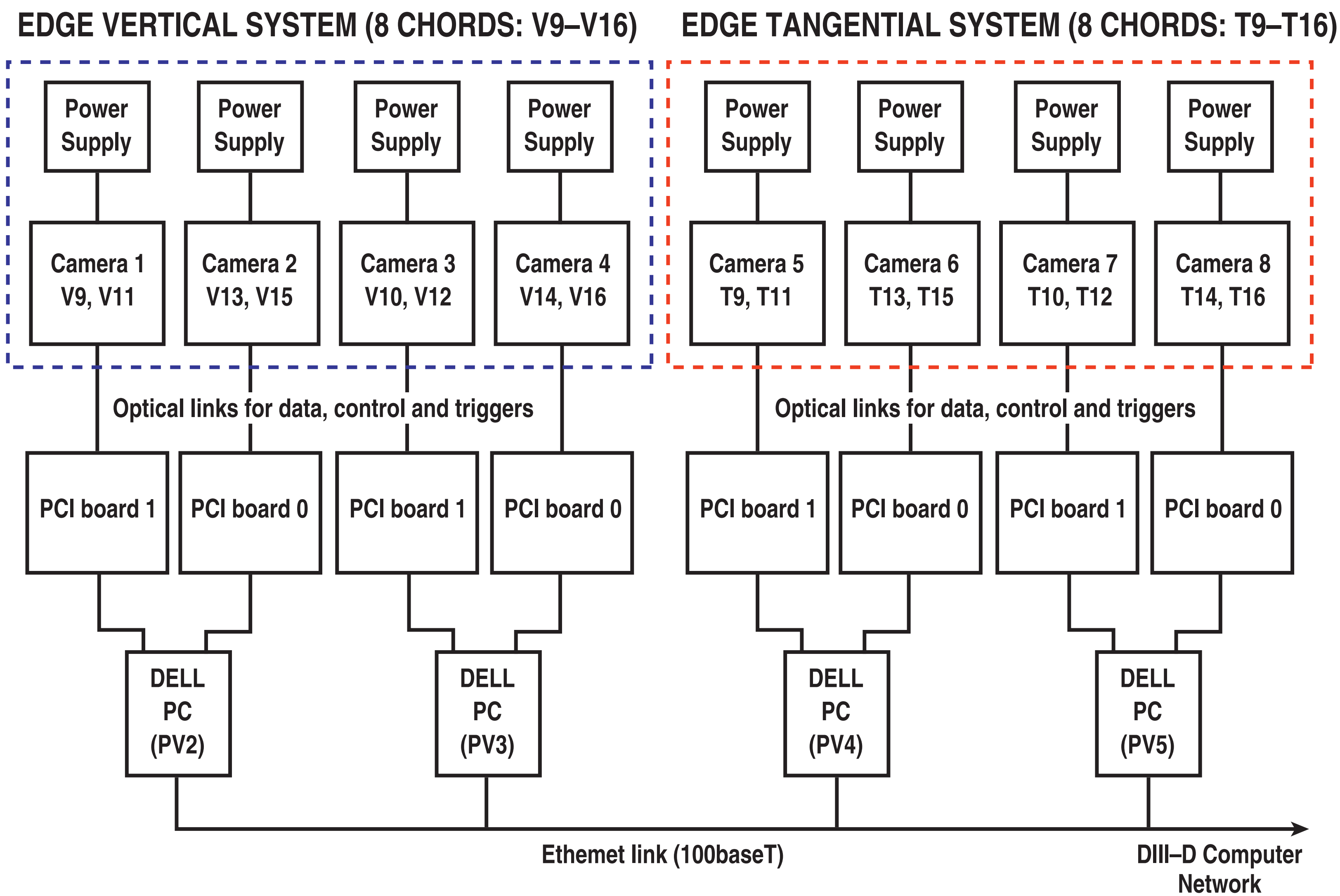
SCHEMATIC DIAGRAM OF PIXELVISION CAMERAS AND COMPUTERS LAYOUT



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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 in 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 2.2 MHz readout speed and 4 for 0.5 MHz
  - For large signal levels: 8 for both readout modes

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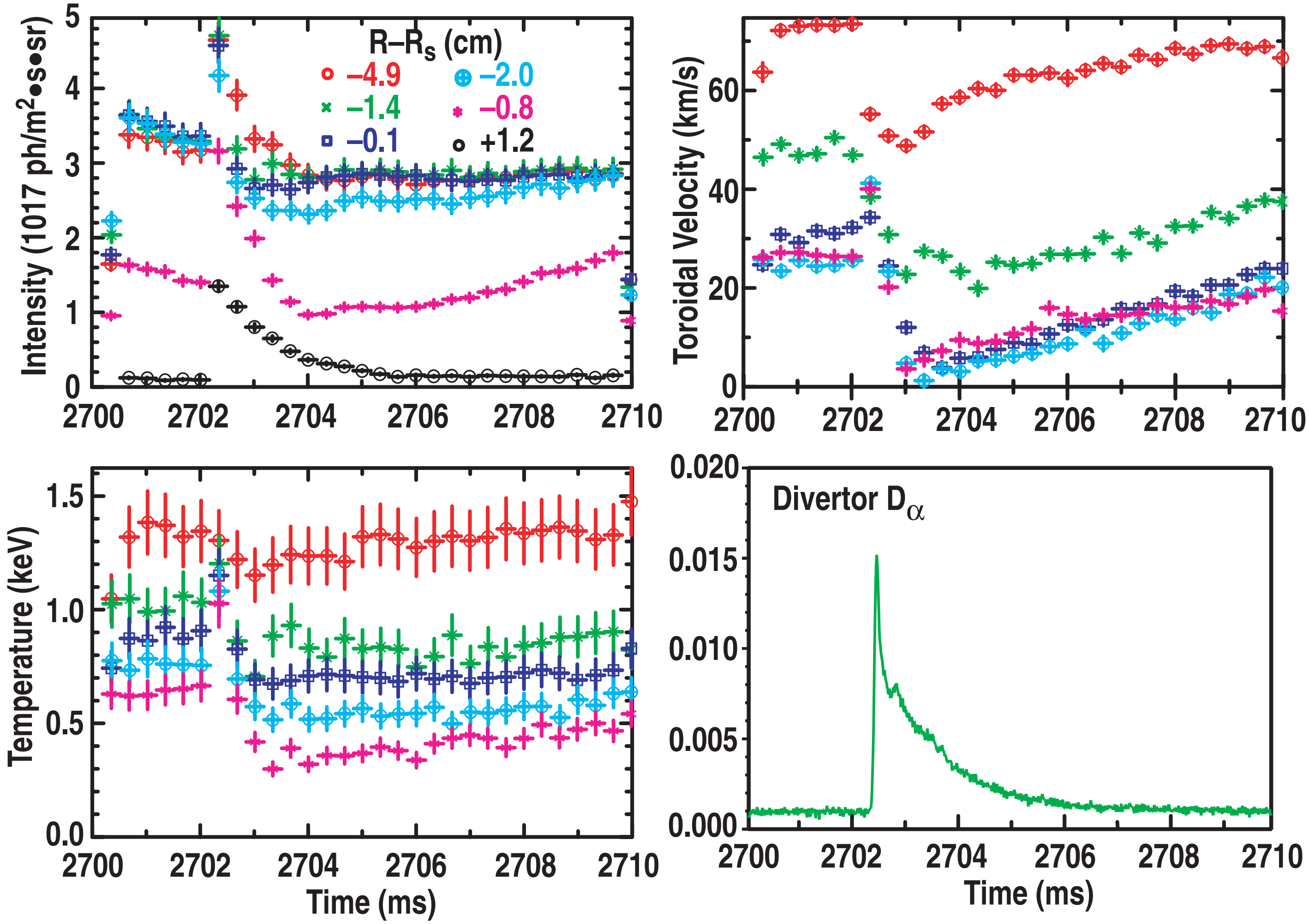
BACKGROUND LEVEL DRIFT AND REFRESH CIRCUITRY

- The dark current and dc offset contributions must be subtracted from the total digitized value to obtain the signal due to photo electrons
- 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 many 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)
- To minimize background level change, we implemented control electronics which repetitively trigger the cameras at 10 ms intervals between tokamak shots
  - Tokamak synchronous triggers take over during shot
- We have implemented software to record a complete set of background data with timing duplicating the tokamak timing
  - We fit an interpolation function to this and archive the parameters of the interpolation function
  - Initial functional form was simply linear
  - Working on a form which adds a decaying exponential to the linear fit

NEUTRON/GAMMA REJECTION

- Because of D-D fusion reactions in the DIII–D tokamak plasma, neutron and gamma radiation is present in our spectrometer room
  - Maximum neutron rate is up to 10^{16}/s next to tokamak
- Shielding has been installed to reduce the neutron/gamma hits on the CCD detectors
  - Enough has been installed to reduce the neutron/gamma hits on the detectors to a maximum rate of a few hits in 10 ms
  - This consists of the main shielding surrounding the whole tokamak plus local shielding for each spectrometer
  - Complete shielding would be expensive and make access to the equipment extremely difficult
- Software is used to identify pixels whose signals are polluted by neutron/gamma hits and these are ignored in the analysis which computes temperature and rotation
  - Neutron/gamma spikes are typically much more localized than the spectrometer instrumental response and have more rapid pixel to pixel variation
  - These differences are used as the basis for the software rejection algorithm

HIGH TIME RESOLUTION CER MEASUREMENTS SHOW DETAILED EFFECTS OF PULSED MHD INSTABILITY (ELM) ON EDGE PLASMA



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