Charge Exchange Recombination(CER) Spectroscopy and Impurity Investigations via Visible Diagnostics on KSTAR

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Technology Collaborations with the KSTAR Project

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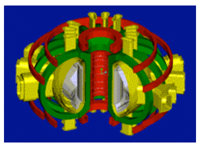


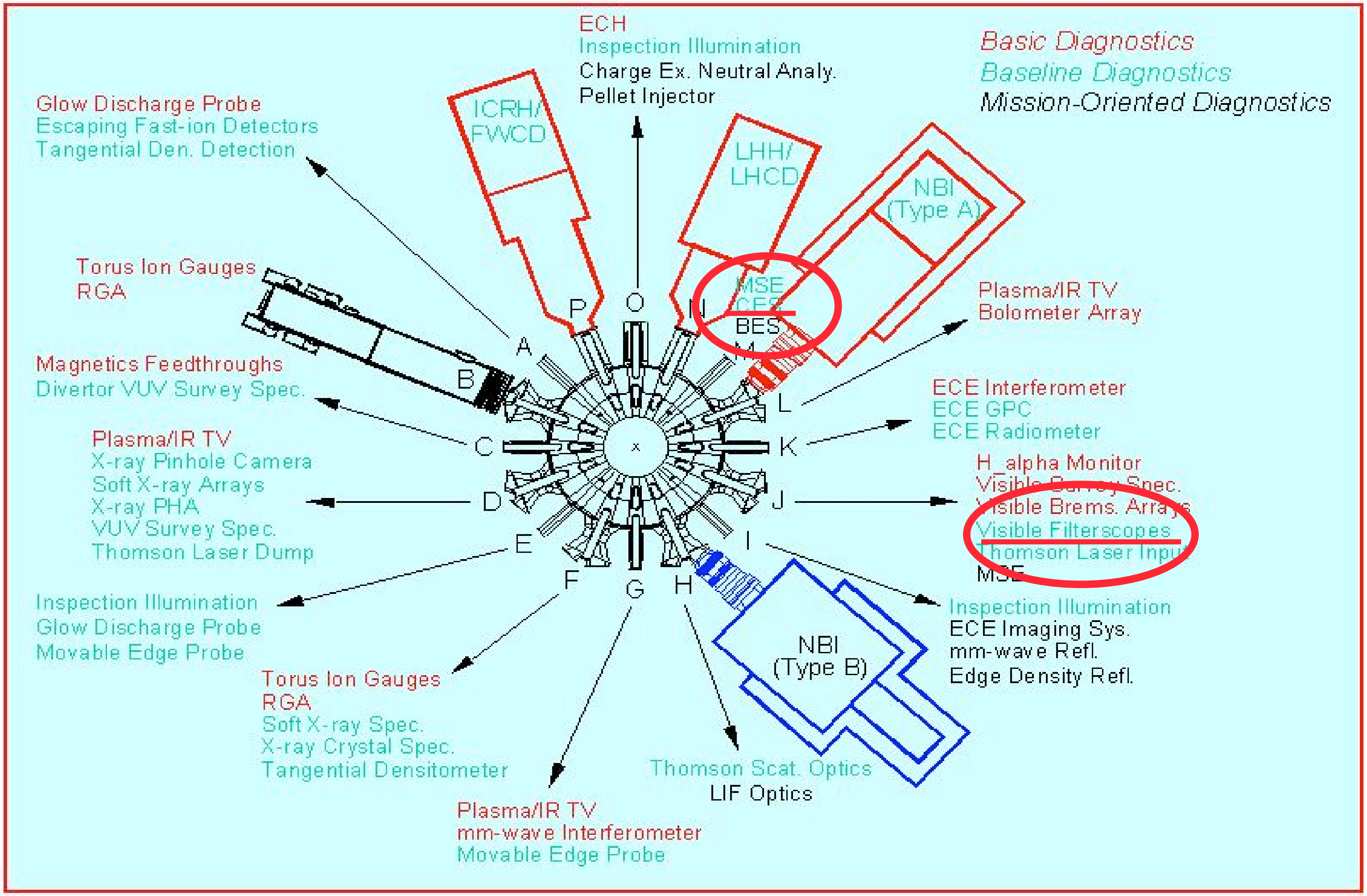
UT-BATTELLE

Abstract

The proposed CER diagnostic for KSTAR (Bay M) would use charge-exchange recombination spectroscopy via the 5290 Å $Carbon^{6+}$ line, in conjunction with the neutral heating beams to measure the ion temperature, toroidal rotation, and impurity density of Carbon and other impurities in KSTAR at ~20 radial locations (≈ 6 cm resolution) across the plasma cross-section. The visible light from the plasma would be collected via a periscope assembly with f/2.0 light collection optics and image the light onto twenty 1 mm quartz fibers. The light is then transferred to a low radiation area where the spectrometers are located. The CER diagnostic utilizes a very high throughput short focal length Kaiser Optical spectrometer with f/1.8 input optics, two entrance slits, a holographic transmission grating, and refractive optics. The detector is a thinned back-illuminated charge coupled device (CCD) that has a high quantum efficiency of ≈90%, a 10 MHz readout speed, and provides a time resolution of ~5 ms. This CER diagnostic package is currently being installed on JET, as a joint ORNL-PPPL- JET collaboration, to upgrade JET's previous CER diagnostic. Experience from the JET design can be directly applied to the KSTAR diagnostic package.

Another possible area of diagnostic collaboration is in the area of monitoring visible light emission via a filterscope. The filterscope is a diagnostic for monitoring visible light emission ($H_{\square}$, or impurity emission - C, He, Ne etc) from plasmas. Light from the plasma is conducted to the filterscope via optical fibers. This light is then split into multiple paths, which contain optical bandpass filters that provide very fast absolutely calibrated measurements of $D_{\square}$, $D_{\square}$, He, C, and various other impurities. The filterscope units are packaged with 5 photomultipliers in a single compact unit which digitizes and stores the data. Because of the large number of data channels employed, the filters and electronics are designed to be compact. Signals can be digitized at rates up to 100 kHz, thus permitting the study of ELMs , SOL turbulence, and recycling sources. The visible filterscopes are presently employed on DIII-D and NSTX and are presently envisioned on Bay J of KSTAR.

KSTAR Diagnostic Layout



KBSI

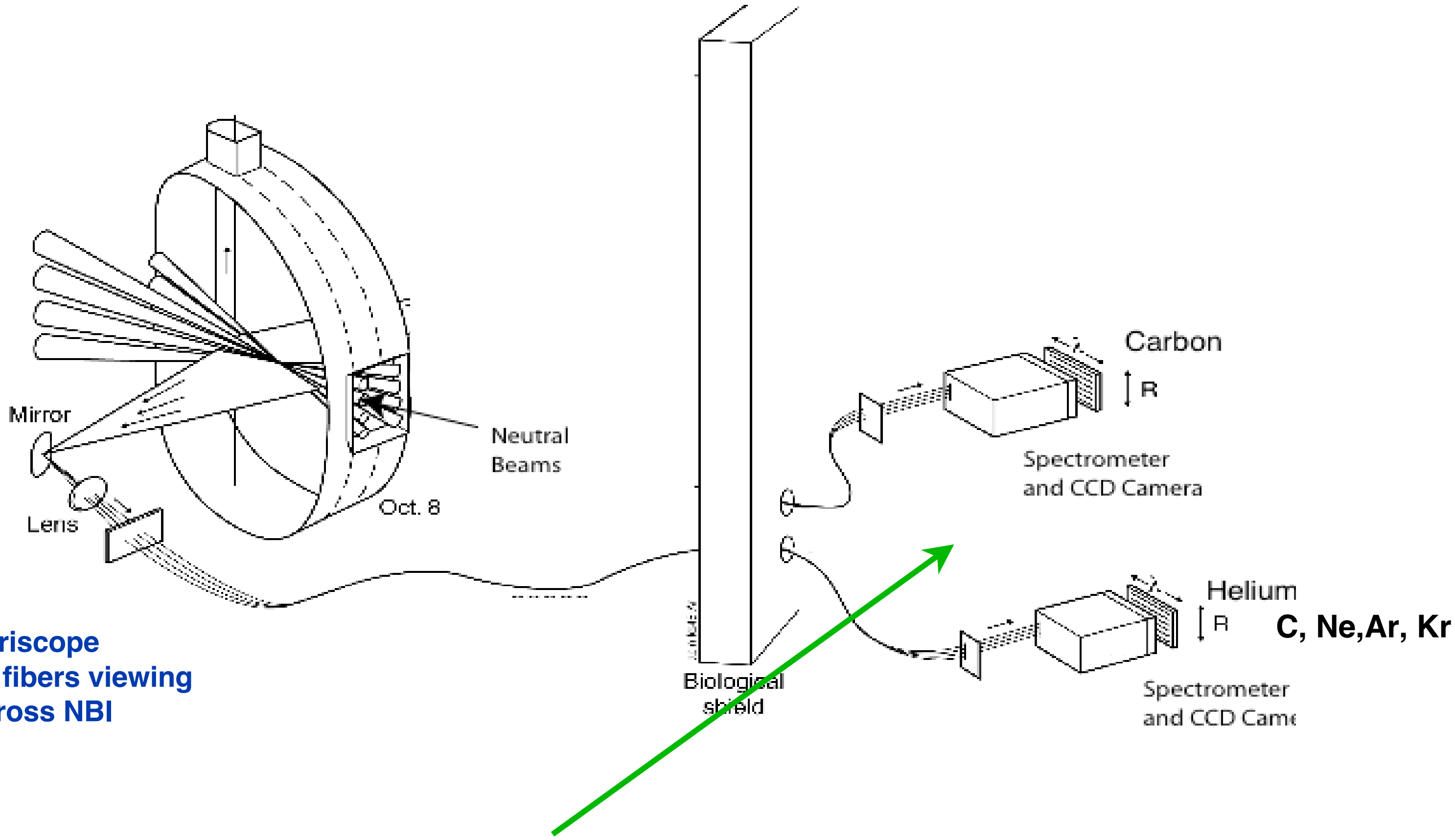
CER Diagnostic for KSTAR

- US proposes a CER diagnostic for KSTAR.
  - Similar to system that ORNL & PPPL are currently preparing for JET
  - and is also in use at PPPL on NSTX.
- KSTAR CER diagnostic should have high photon collection capability, excellent spatial resolution, and sufficient radial channels to investigate edge pedestal region and internal transport barriers near the plasma edge.
- CER system would be mainly dedicated to ion temperature profiles, carbon and impurity density profiles, and toroidal rotation measurements.
  - Assuming Carbon to be the main impurity ion C^{6+} (5290 Å), then routine measurements of ion temperature and toroidal rotation would be with 5290 Å Carbon line.

CER Helium Ash Diagnostic for KSTAR

- Excellent spatial resolution (70 radial locations) across plasma cross section for investigating Internal Transport Barriers(ITB) and edge pedestals.
  - 50 spatial chords across beam for CER measurements
  - 20 spatial chords of background views (not looking across beam)
- Good time resolution
  - Radial profile every 5ms throughout KSTAR discharge
- Primary use of this diagnostic would be to provide:
  - ion temperature, Carbon density, and toroidal rotation profile measurements for all KSTAR discharges
  - would also provide CER measurements of other impurity lines (C, Be, Ne, Ar, Kr, etc.) during radiative divertor, or impurity transport experiments.

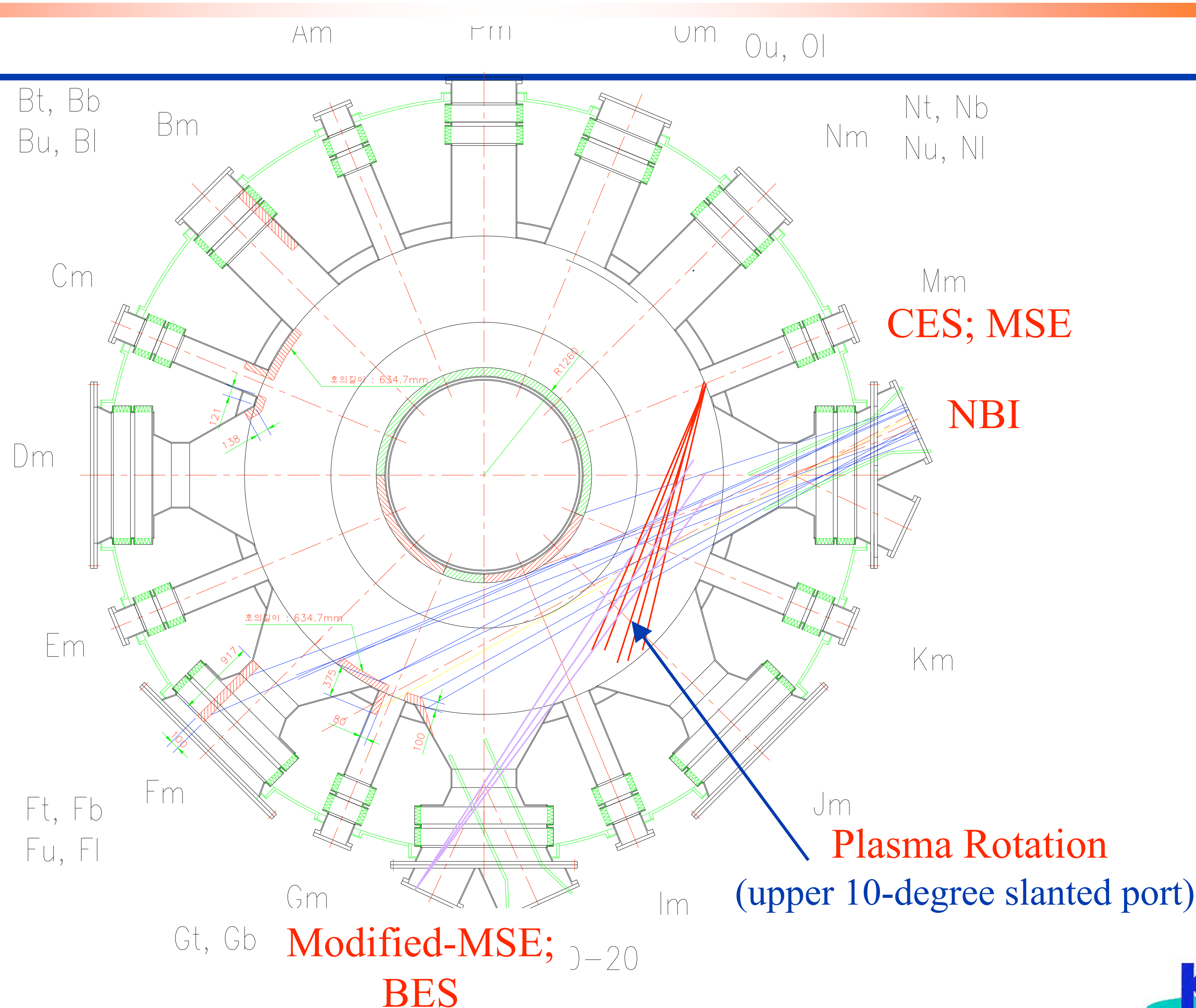
KSTAR CER System



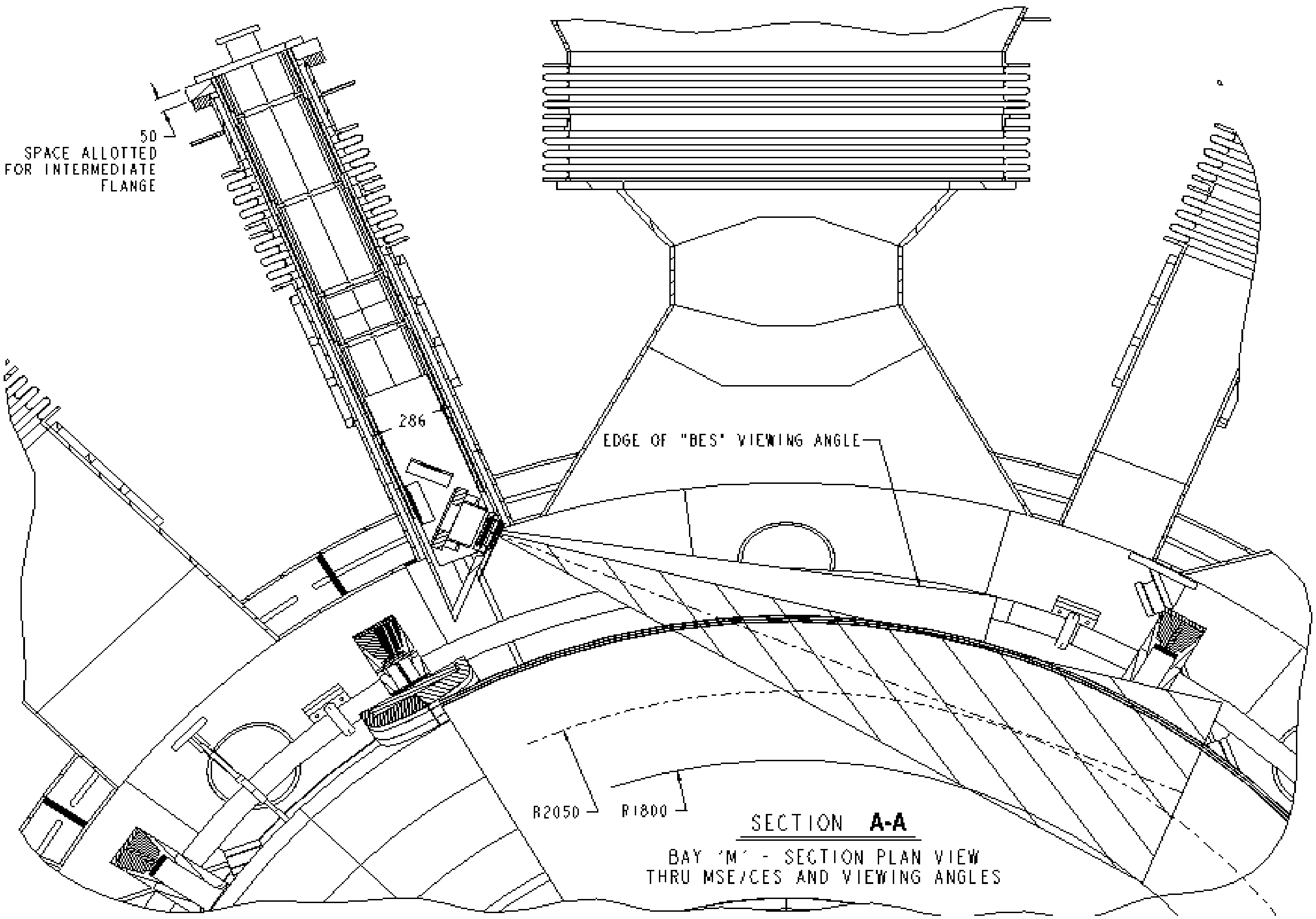
Periscope
50 fibers viewing
across NBI

- one 0.5 m Czerny-Turner Spectrometers with variable wavelength (10 fibers)
- 3 high photon throughput Kaiser Optical spectrometers with Holographic Gratings fast (5 ms) CCD Detectors, fixed wavelength (5290 Å) (20 fibers each)

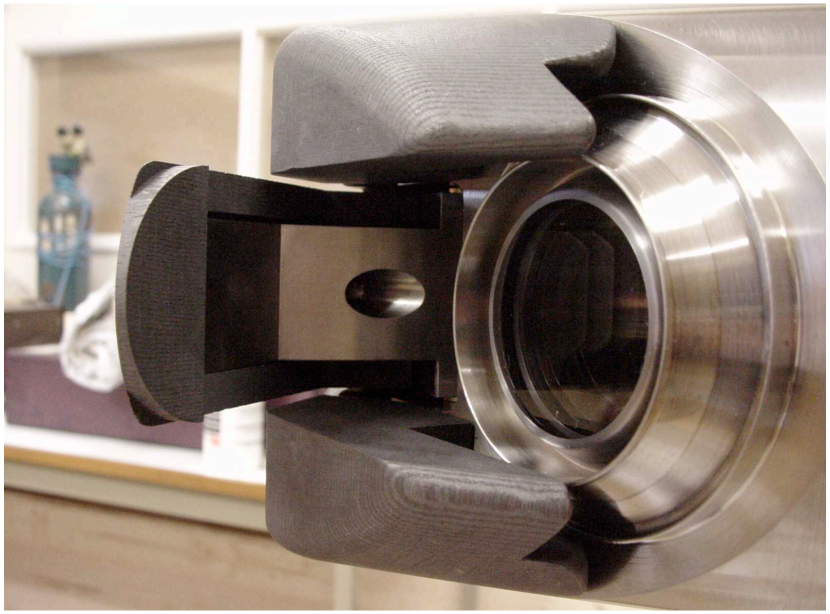
Optical System Layout

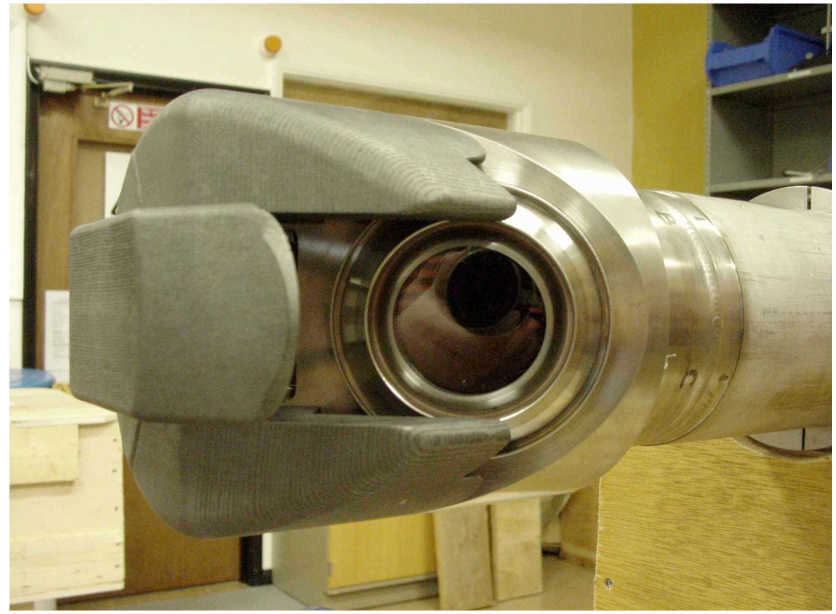


KSTAR Periscope
- Plasma Viewing Optics -



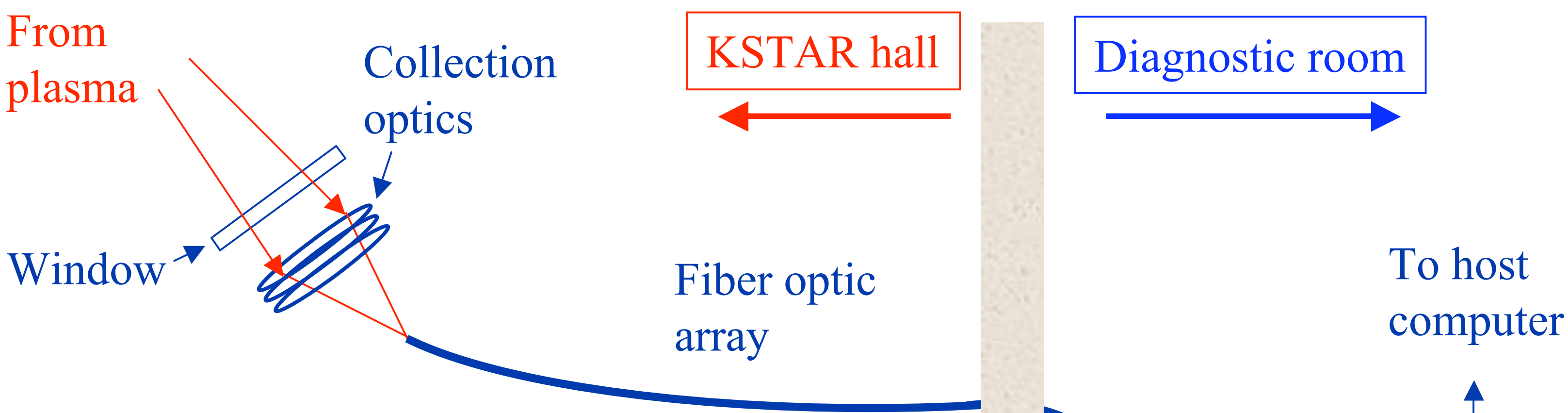
The JET Periscopes

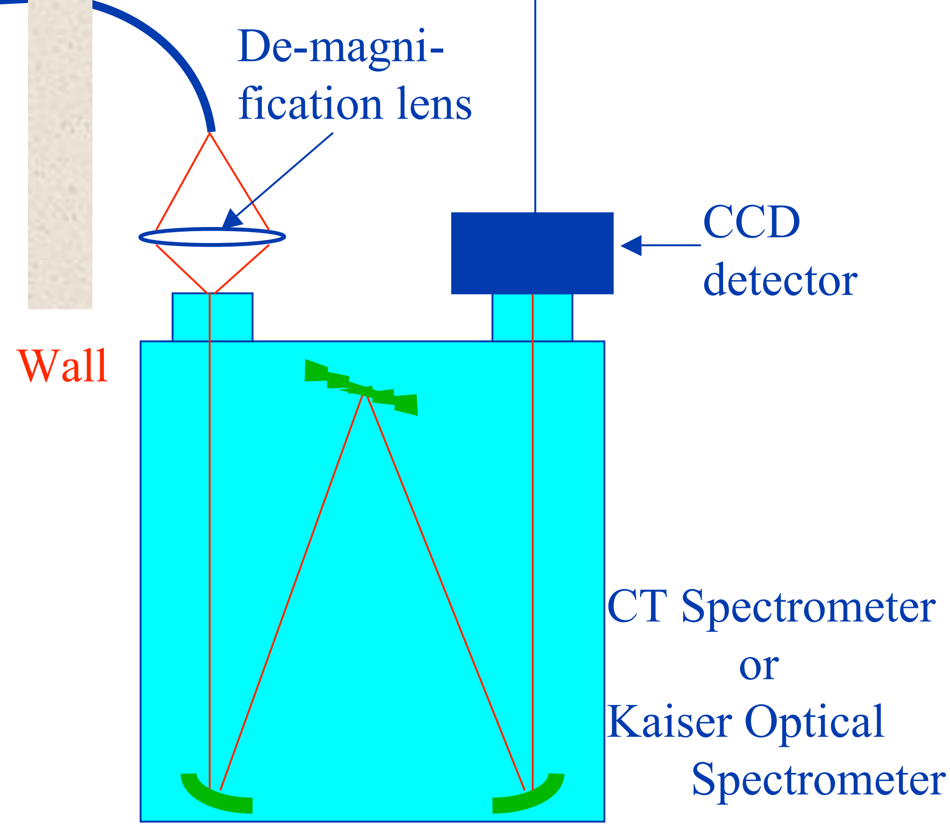




- **Optical heads of periscopes consist of a short focal length quartz multiplet (F = 50 mm, f/2.0)**
- **Images visible light from plasma onto fiber bundle located inside the periscope**

KSTAR CER system layout

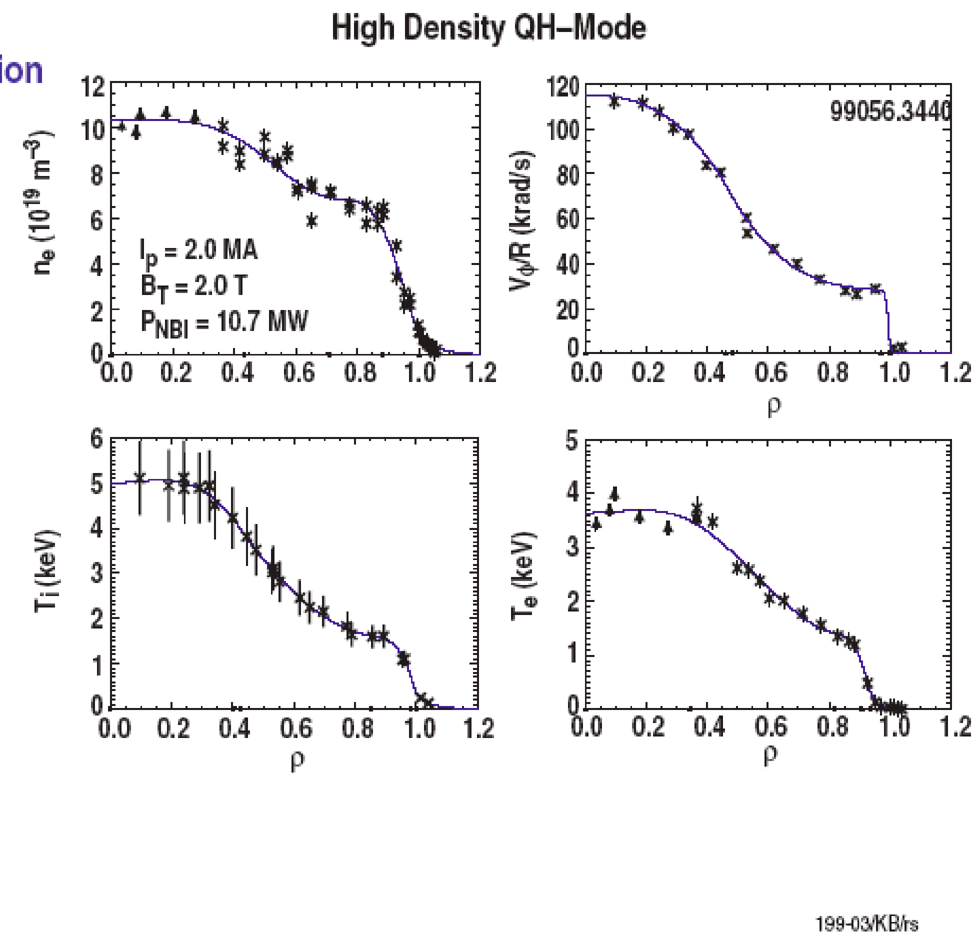




Component	Specifications	Remarks
Window	Fused Silica, Dia.100 mm	
Collection lens set	Fused Silica, Dia. 150 mm, Magnification factor: 1: 10	
Fiber Optic Array	50 ch., Dia.1 mm, (view NBI) 20 ch., Dia. 1 mm (background) Length: 50 m	
De-magnification lens	Fused silica, Dia. 100 mm De-magnification factor: 10:1	
Spectrometer	1 Czerny-Turner type, F=0.5 m 3 Kaiser Optical f/1.8	

To understand the physics of edge transport barriers and pedestals requires very detailed CER spatial profile measurements

- Requires neutral beam injection counter to I_p direction plus divertor cryopumping
- QH–mode seen to date for
  - $3.4 \leq q_{95} \leq 5.8$
  - $1.0 \leq I_p$ (MA) ≤ 2.0
  - $1.8 \leq B_T$ (T) ≤ 2.1
  - $1.0 \leq n_e^{ped}$ (10^{19} m^{-3}) ≤ 6.5
- Low field example at B_T = 0.95 T, I_p = 0.67 MA and $n_e^{ped} = 1.1\times10^{19}$ m^{-3}



- **Approximately 50 spatial channels needed for KSTAR**

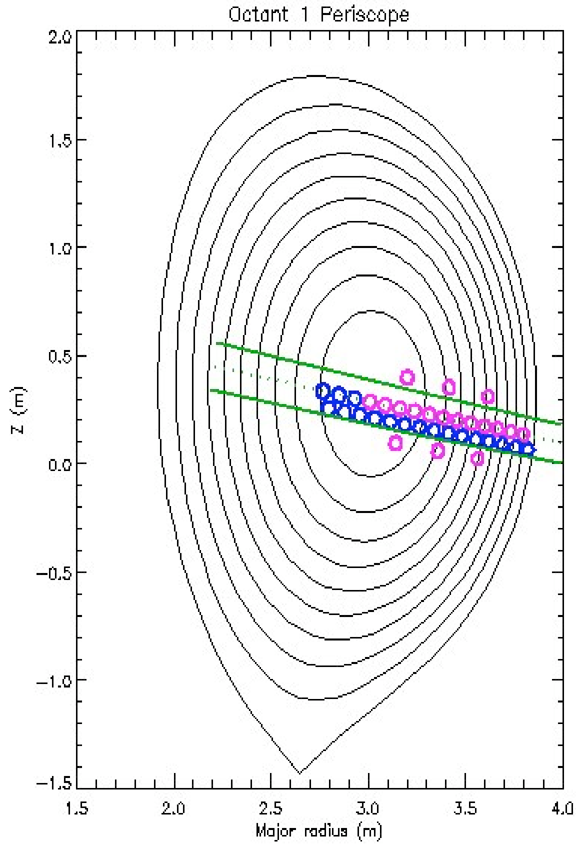
General Fiber Views for KSTAR

70 spatial locations

KSTAR

- Fibers are 1mm fused silica quartz with 25 micron cladding
  - N_{AP} fiber at plasma side is = .22 (or f/2.27)
- radial coverage (viewing lines) 175 cm to 230 cm
  - 50 chords across beam
  - 20 chords (not across beam) - background view
  - radial resolution 5mm near center to 7 mm near edge

JET



Measurement Strategy and Viewing Geometry

Three Kaiser Optical Spectrometers with Holographic Transmission Gratings are used:

- Twenty (20) sight lines are possible on each spectrometer via 2 curved entrance slits (10 fibers on each entrance slit).
  - High photon efficiency (f/1.8), but fixed wavelength (5290 Å)
  - Spectrometer will view CVI CXRS 5290 Å line for fast T_i, toroidal rotation, and Carbon density measurements (every 5-10 ms) throughout the plasma discharge.
- The viewing geometry is optimized to provide high spatial resolution □ sightlines tangent to flux surfaces where they intersect beam.
- Dedicated background views (20) [which do not see the beam] are used to separately measure the cold background component of the lines arising from the intrinsic emission shell at the plasma edge.
- CCD Camera is optimized for light collection at 5290 Å (QE ≈ 92%)
- Kaiser Optical about 10 times more efficient than conventional CER Czerny-Turner Spectrometer systems

One Czerny-Turner Spectrometer with a tunable wavelength

- Provides routine measurements, but can be easily tuned to other CER impurity lines for transport studies, such as N, Ne, Ar, Kr, etc.

Kaiser Optical Spectrometer

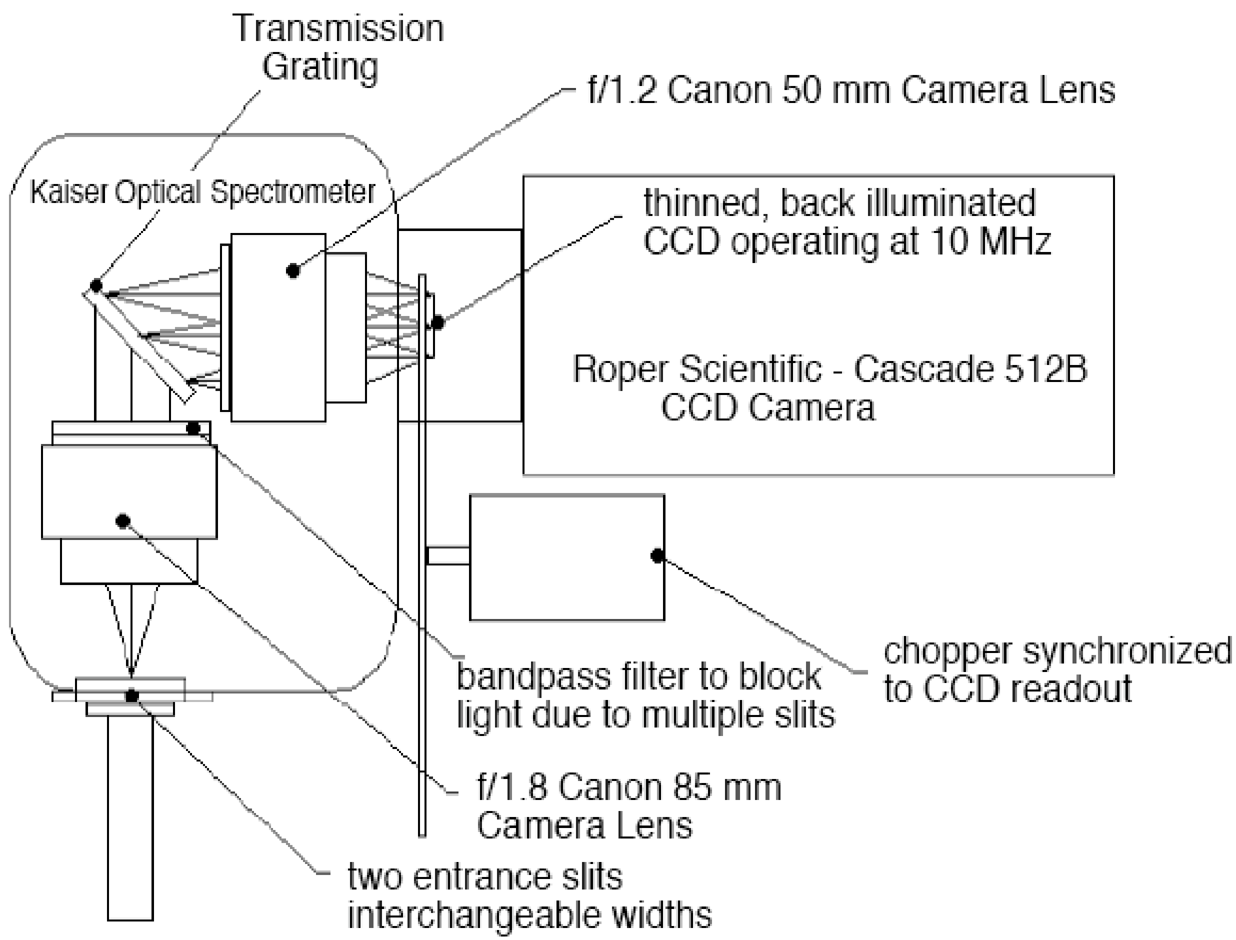
- **Holospec f/1.8**
  - Input optics: 85 mm focal length to collect at f/1.8
  - Output optics: 50 mm lens f/1.2

- **Gratings:**
  - 5290 Å 1.74 nm/mm Coverage 5258Å - 5336Å (78Å)
  - 5290 Å 4.3 nm/mm Coverage 5099Å - 5466Å
- **Slits & input fiber mounts**
  - 2 curved entrance slits(250μm)
  - ten 1-mm fibers on each entrance slit

CCD Cameras - Cascade 512B

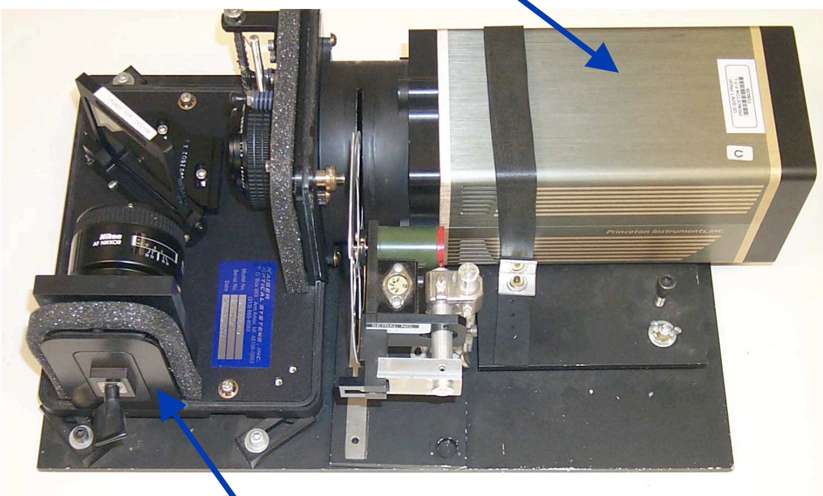
- 512x512 pixel array (16μ x 16μ pixels)
  - E2V CCD87, back illuminated with on-chip multiplication gain(up to gain 1000)
  - 8.2 x 8.2 mm imaging area (optically centered)
  - Single pixel well = 200ke- ; output node 800ke-
- Frame transfer CCD - thermoelectrically cooled (-30º C)
- Readout: 16-bit, dynamic range @10MHz, 5MHz, and 1MHz
- Two port readout: port1 - 1MHz or 5MHz without on chip gain
  - port2 - 5MHz or 10 MHz with on chip amplification
    on chip gain (1-1000)
- Parallel (vertical shift rate) 2.0 μsec/row
- Binning (any number vertical)
- Readout noise: 15 e-rms @ 5MHz ; and < 1 e-rms @10 MHz with on chip-gain enabled.
- Readout time for entire chip : 34 ms @ 10 MHz
- Readout time for 10 rows (50 pixel bins) (ie, 10 fibers on entrance slit)
  - 10 MHz 1.3 ms

Schematic of Kaiser Optical Spectrometer



High Throughput CER Spectrometer/Detector System

Cascade 512B CCD
10 MHz, 16 bit

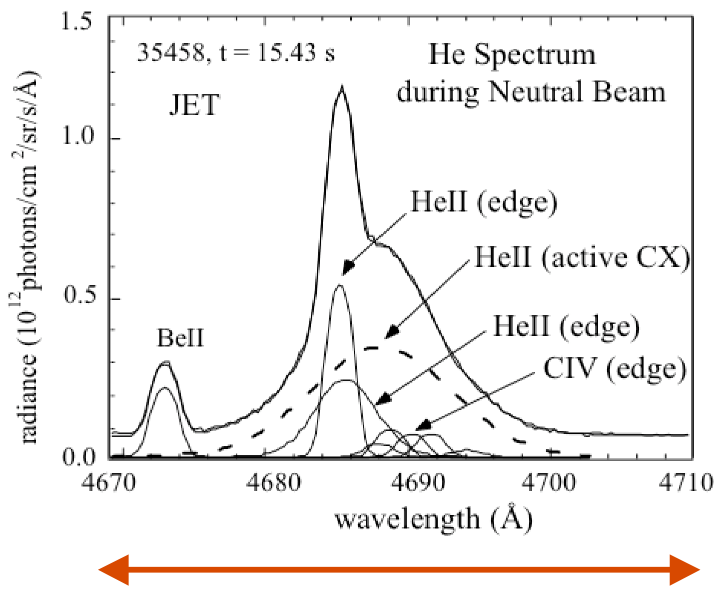


Kaiser Optical Spectrometer

- A high throughput spectrometer/detector system is used. Similar Design used at PPPL by R. Bell, *et al*., RSI, **70**, 821 (1999).
- In each system, light is dispersed with a f/1.8 **Kaiser Holospec Imaging Spectrometer**, which utilizes a holographic transmission grating .
- Multiple slits (10 fibers/slit) are used, permitting a large number of spectra to be simultaneously recorded.
- The detector is a Roper Scientific **Cascade 512B Camera**, utilizing a thinned, back illuminated CCD, operating a 10, 5, and 1 MHz. The CCD is cooled thermo-electrically to -30° C. The CCD has 512x512 16mm square pixels.
- A chopper wheel is used to blank the CCD during fast readout(5 or 10 ms integration times) to avoid image smearing. The CCD readout is synchronized to the chopper.
- The frame time is variable from 5 ms to 500 ms. Generally it is expected that the CER spectrometer system will operate at 10 ms for normal operation.
- Data from each CCD is digitized at 16 bits, under the control of a dedicated PC which is linked to the central JET data archival system.

Typical JET Helium Spectra from He gas puffing with Kaiser Optical Spectrometers (not DT)

He core concentration ≈ 5% (shown below) in gas puffing



Region of Helium Spectra measured with new Spectrometer
He (4665Å - 4710Å)

KSTAR Budget and Schedule for CER diagnostic

CER System (possible division of effort)	DESIGN ($k) FY05 (work to-date not included)		FABRICATE / PROCURE ($K) FY06		INSTALL / COMMISSION ($K) FY07		Possible US participants
	US	KO	US	KO	US	KO	
Bay M cassette							
cassette body optimize	50			75		20	PPPL
viewing windows, weldments	4			10		8	PPPL
window covers, mounts	20			5		2	PPPL
shutters & actuators	30			20		15	PPPL
optics rail supports	10			5		5	PPPL
temperature control	5	5		5		5	PPPL
reviews and travel	15						PPPL
Collection optics Bay M (50 ch integr. with MSE)							
optics carriage, rails, adjustments	25		60		10	10	PPPL
optimize optical design	40						PPPL/ORNL
collection lens assembly	10		20				PPPL
lens mounts	10		10				PPPL
fiber optic input holder	20		25				PPPL
fiber optics (50x50 m)	8		25	15			PPPL
assemble and test optics					20	20	PPPL/ORNL
reviews and travel	20	5	20	5			PPPL/ORNL
Collection optics background view (20 ch)							
optics carriage, rails, adjustments	25		60		10	10	PPPL
optimize optical design	25						PPPL/ORNL
collection lens assembly	10		20				PPPL
lens mounts	10		10				PPPL
fiber optic input holder	20		25				PPPL
fiber optics (20x50 m)	8		25	10			PPPL
assemble and test optics					20	20	PPPL/ORNL

KSTAR Budget and Schedule for CER diagnostic (continued)

CER Task	Design (K$) FY05		Fabricate-Procure (K$) FY06		Install/ Commission (K$) FY07		US partners
Detection system							
temperature controlled room with services		10		50			
3 Kaiser transmission grating spectrometers	15		70				ORNL
0.5 m Czerny-Turner spectrometer	8		29				ORNL
4 CCD cameras & control electronics	15		227				ORNL
choppers and synchronization	36		38				PPPL/ORNL
fiber output and slit assemblies	38		37				PPPL/ORNL
data acquisition	30		50		18		ORNL
data analysis software			20		60		PPPL/ORNL
calilbration hardware & software	15		25		28		ORNL
on-site integration			10	10	20	20	PPPL/ORNL
initial calibrations					30	20	PPPL/ORNL
initial data analysis					85	85	PPPL/ORNL
reviews and travel			20	5	45		PPPL/ORNL
totals	522	20	806	210	346	240	

Summary	US	KO	
Design	522	20	
Procure or Fabricate	806	210	
Install and Commission	346	240	
Subtotal	1674	470	**2144**
Escalation 8%	134	38	
Contingency 20%	362	102	
Total	**2170**	**609**	**2779**

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Total Cost of KSTAR CER Diagnostic

Summary			US	KO	
	Design		522	20	
	Procure or Fabricate		806	210	
	Install and Commission		346	240	
		Subtotal	1674	470	**2144**
	Escalation 8%		134	38	
	Contingency 20%		362	102	
		Total	**2170**	**609**	**2779**

- **Total Cost to US: $2170K**
- **Total Cost to KSTAR: $609K**
- **Total Cost of CER: $2779K**

Note: ~ 3 Year program for design, fabricate, install, commission

Conclusions

- The US could provide a new high throughput CER Diagnostic system to KSTAR for :
  - Total Cost to US: $2170K
  - Total Cost to KSTAR: $609K
  - Total Cost of CER: $2779K
- 3 year program which could begin in FY05
  - FY05 - complete design
  - FY06 - purchase hardware and construct
  - FY07 - install and commission
- Light collection should be ~ 10 times greater than existing Czerny-Turner Spectrometer systems now used on most devices for CER
- New High Throughput Spectrometer System provides better photon collection capability, excellent spatial resolution, excellent time resolution, and 70 radial viewing lines

In support of ITER and future burning plasma experiments

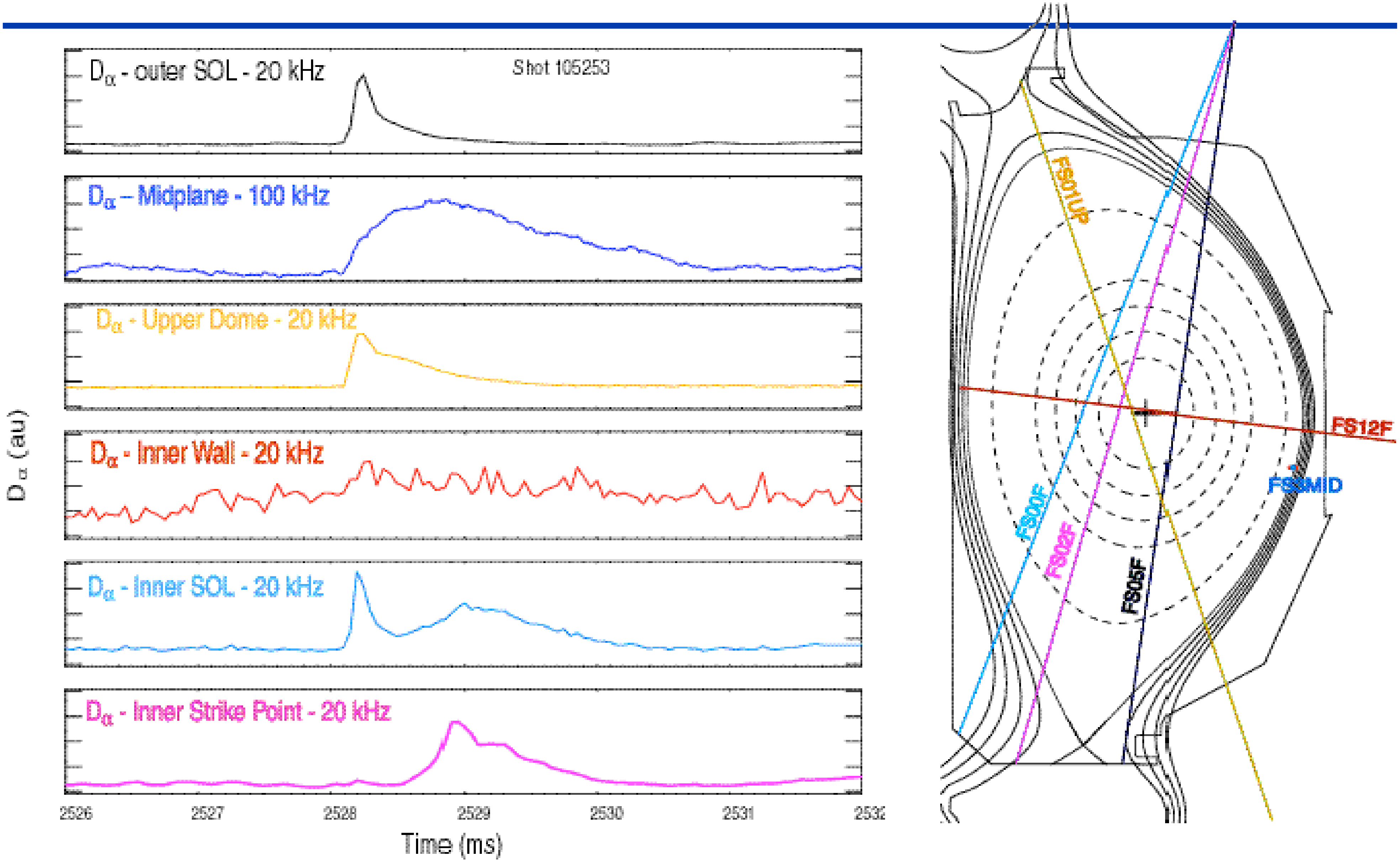
- Provides detailed spatial profiles of Ti, impurity density, and toroidal rotation versus time for plasmas with transport barriers and plasmas with edge pedestals.
- Further develops a diagnostic capability which is useful for future burning plasma experiments.

ORNL Filterscope Development

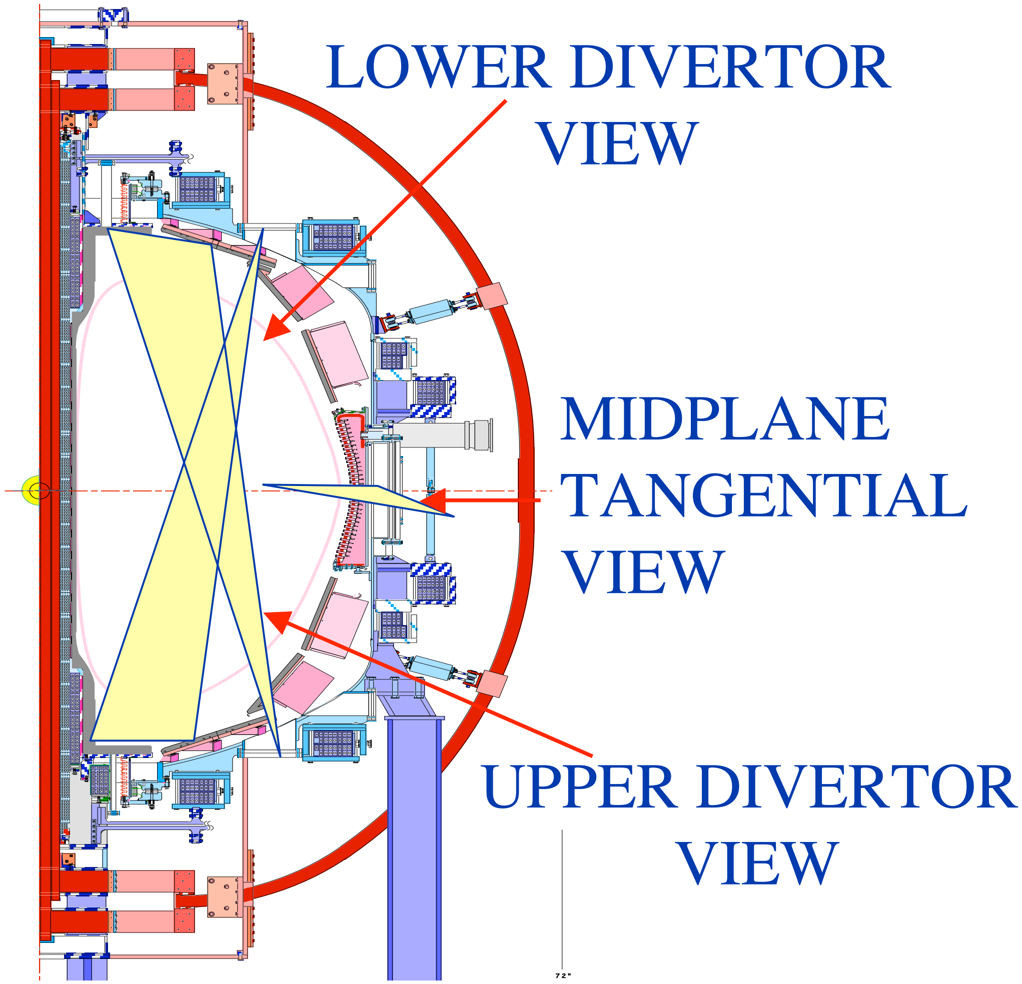
Fast Time Response H-alpha and Impurity Monitoring via ORNL Filterscopes

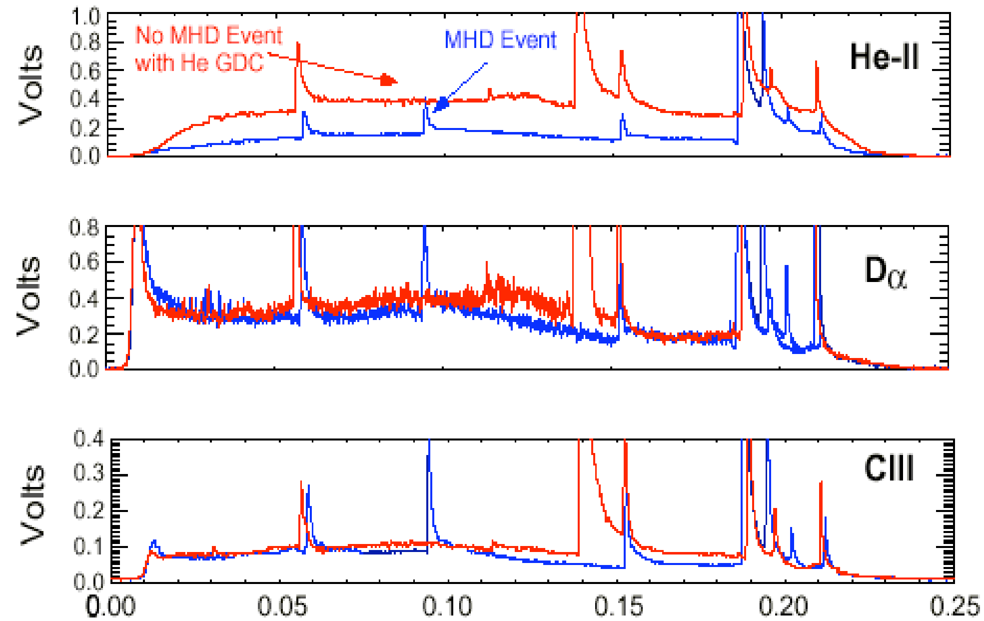
D.L. Hillis and R.J. Colchin

Detector D Response to a Type 1 ELM



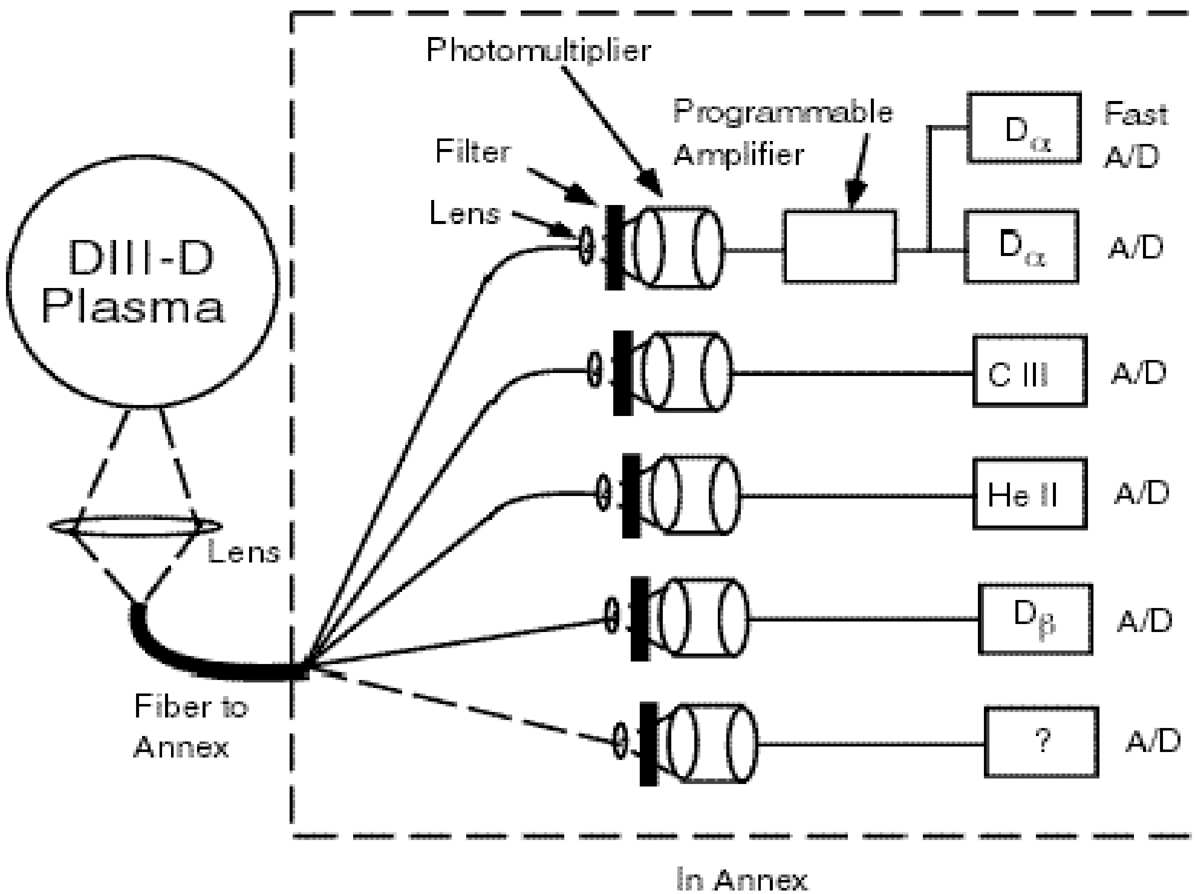
NSTX FILTERSCOPE CHANNELS VIEW LOWER DIVERTOR, UPPER DIVERTOR, AND MIDPLANE





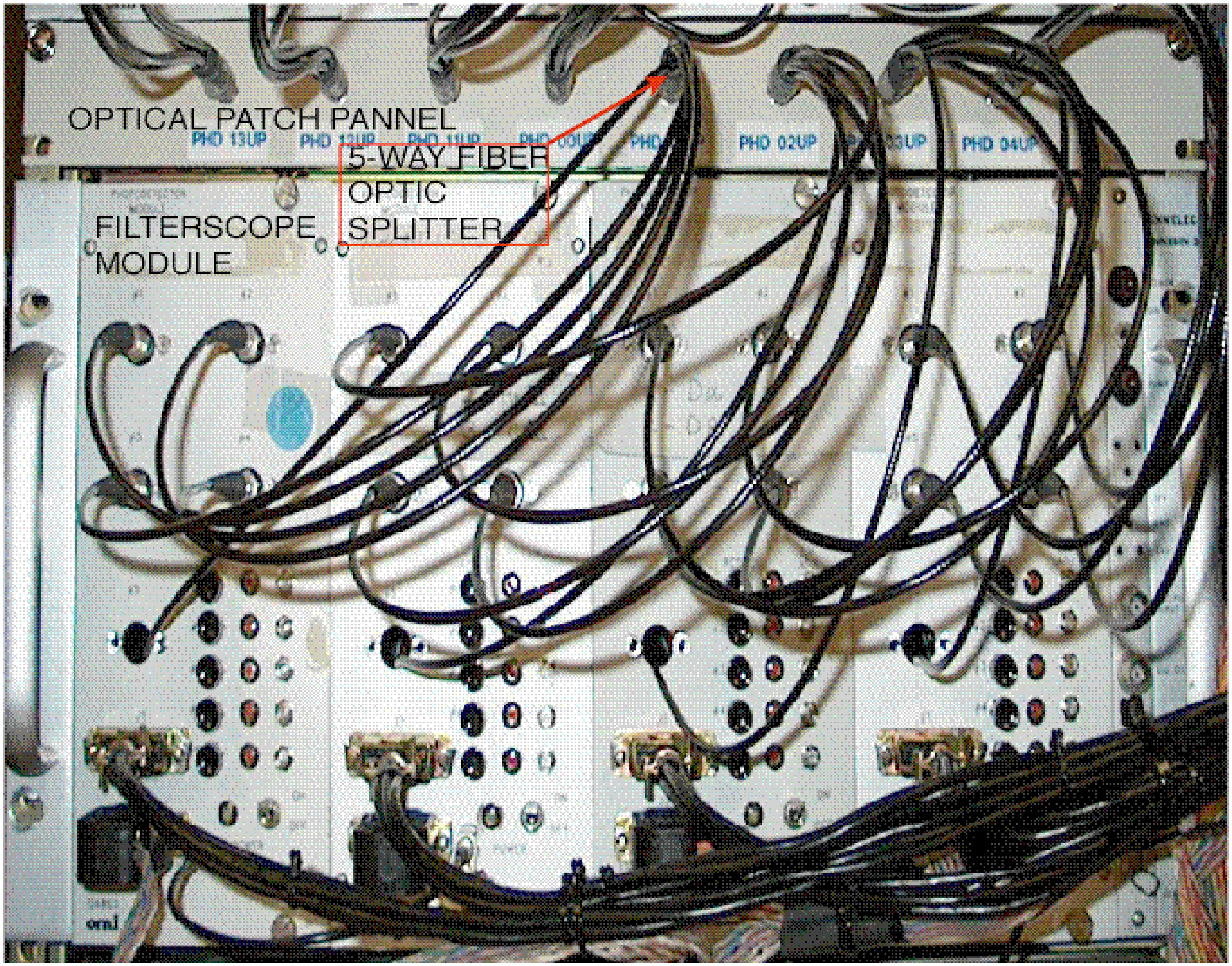
Filterscope Schematic

One View Chord

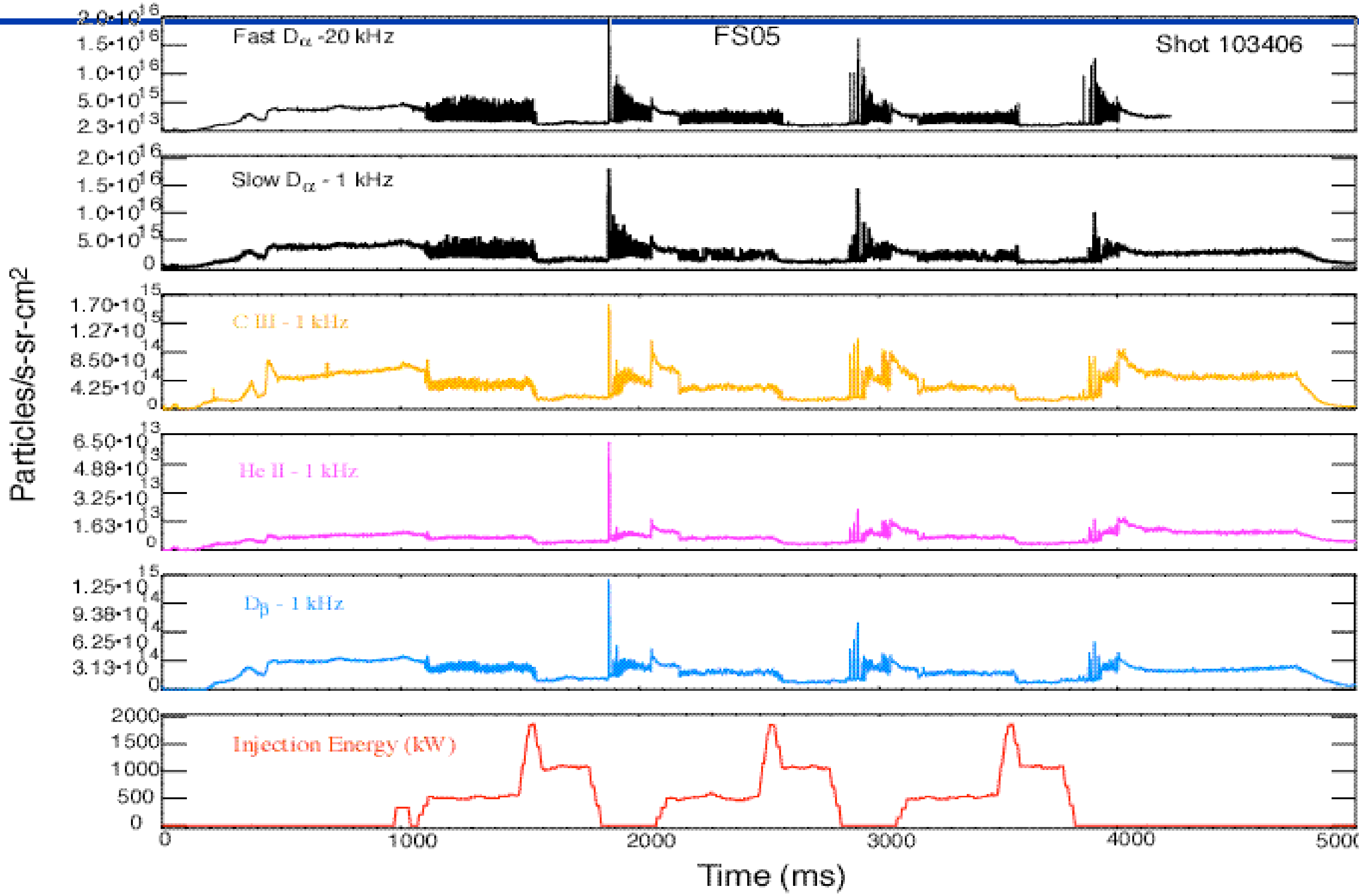


ORNL Filterscope Diagnostic

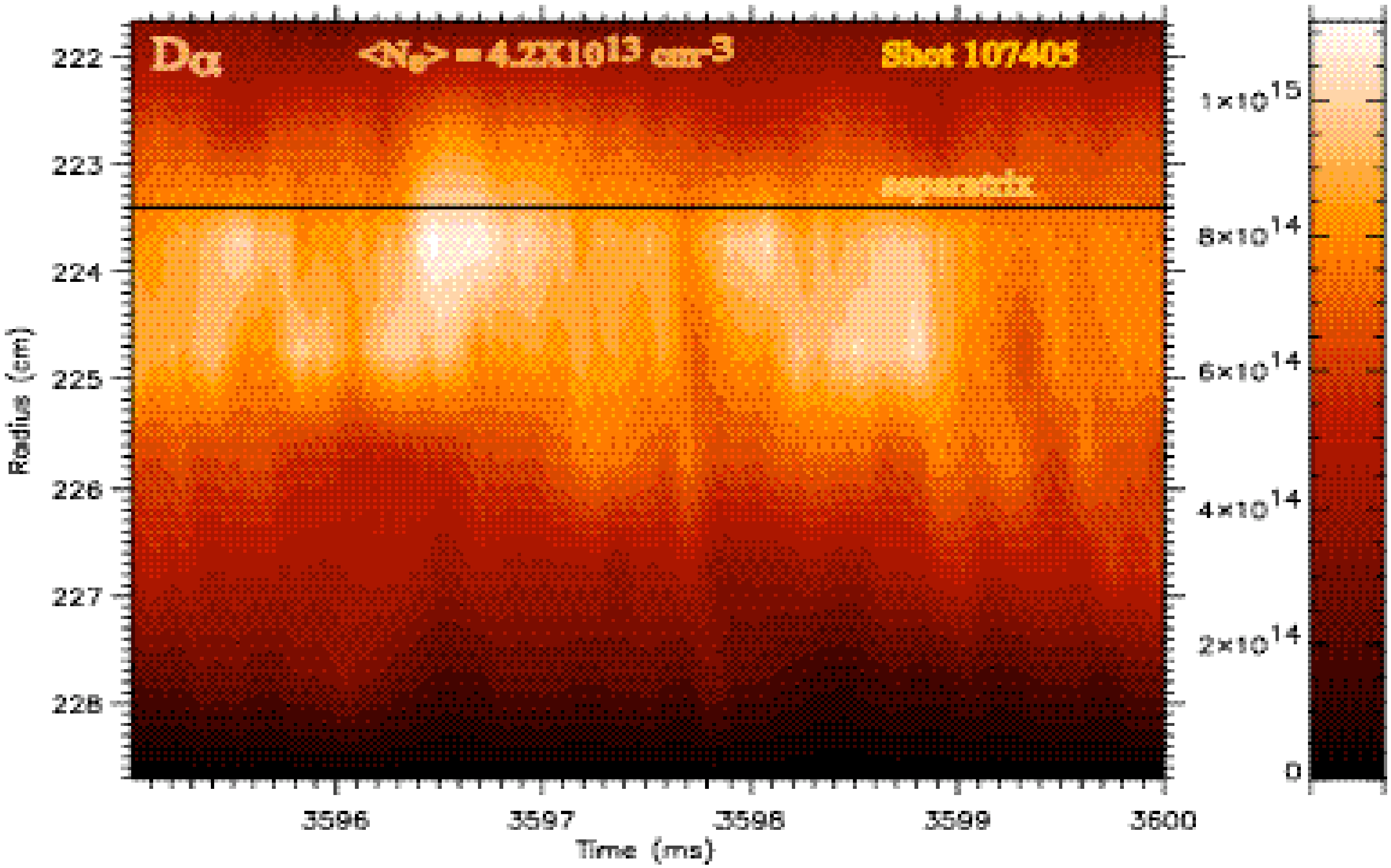
Four Filterscopes per Module



Divertor Filterscope Signals from a Single Viewing Chord



D_α Contour Plot
Edge Turbulence



Midplane Filterscopes - 100 kHz Digitization Rate
Inverted Data

SUMMARY

- Filterscopes provide a convenient, reliable, and compact diagnostic for monitoring visible line radiation.
- Filterscopes presently in use on the DIII-D & NSTX tokamaks record 105 signals per discharge.
- Filterscope signals are calibrated, allowing for long-term shot comparisons, quantification of plasma edge conditions, and comparison of recycling sources.
- Radial profiles of D_{α} light from inversion of chordal data has yielded contour plots of edge turbulence as well as profiles of ionization rates and neutral density.
- KSTAR expressed interest in this diagnostic and Dick Colchin of ORNL visited KSTAR in 2002.