NSTX

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Spectroscopic Diagnostics for Liquid Lithium Divertor Studies on NSTX

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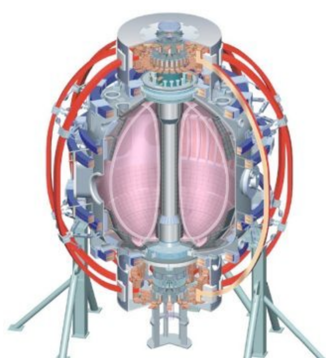
Poster F48

18TH TOPICAL CONFERENCE

HIGH-TEMPERATURE PLASMA DIAGNOSTICS

Wildwood, New Jersey

May 16-20, 2010



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Abstract and Acknowledgements

The NSTX device has been investigating the impact of lithium coatings on graphite plasma facing components for plasma density control. A recently installed liquid lithium divertor (LLD) module has a porous molybdenum surface, separated by a stainless steel liner from a heated copper substrate. Lithium will be deposited on the LLD from two evaporators. Two new spectroscopic diagnostics are installed to study the plasma surface interactions on the LLD: 1) a **AXUV diode array for divertor recycling rate measurements** in the highly-reflective LLD environment, and 2) an **UV-VIS-NIR imaging spectrometer** for D I, Li I-III, C I-V, Mo I, D_2, LiD, CD_4 emission and temperature profile measurements on and around the LLD module. The 20-channel diode array is equipped with a 6-nm bandpass filter centered at 121.6 nm (the Lyman-α transition). The spectrometer system includes a divertor viewing achromatic lens, a 50-fiber relay bundle, a *R*=0.67 m commercial Czerny-Turner spectrograph with 1800, 2400, and 3600 line/mm gratings, and a 512*x*512 pixel electron-multiplying CCD detector. The use of photometrically calibrated measurements together with atomic physics factors enables studies of recycling and impurity particle fluxes as functions of LLD temperature, ion flux, and divertor geometry.

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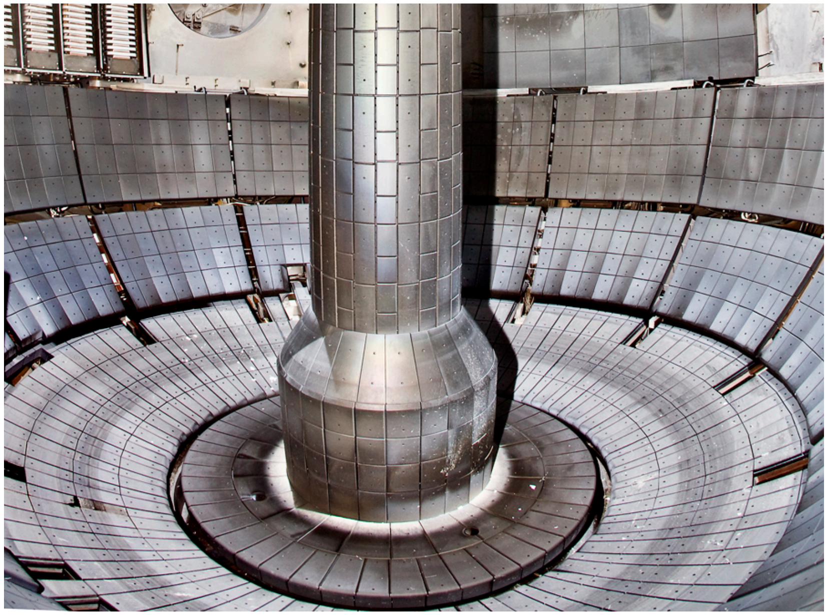
Lithium research program on NSTX focuses on solid and liquid lithium plasma facing components

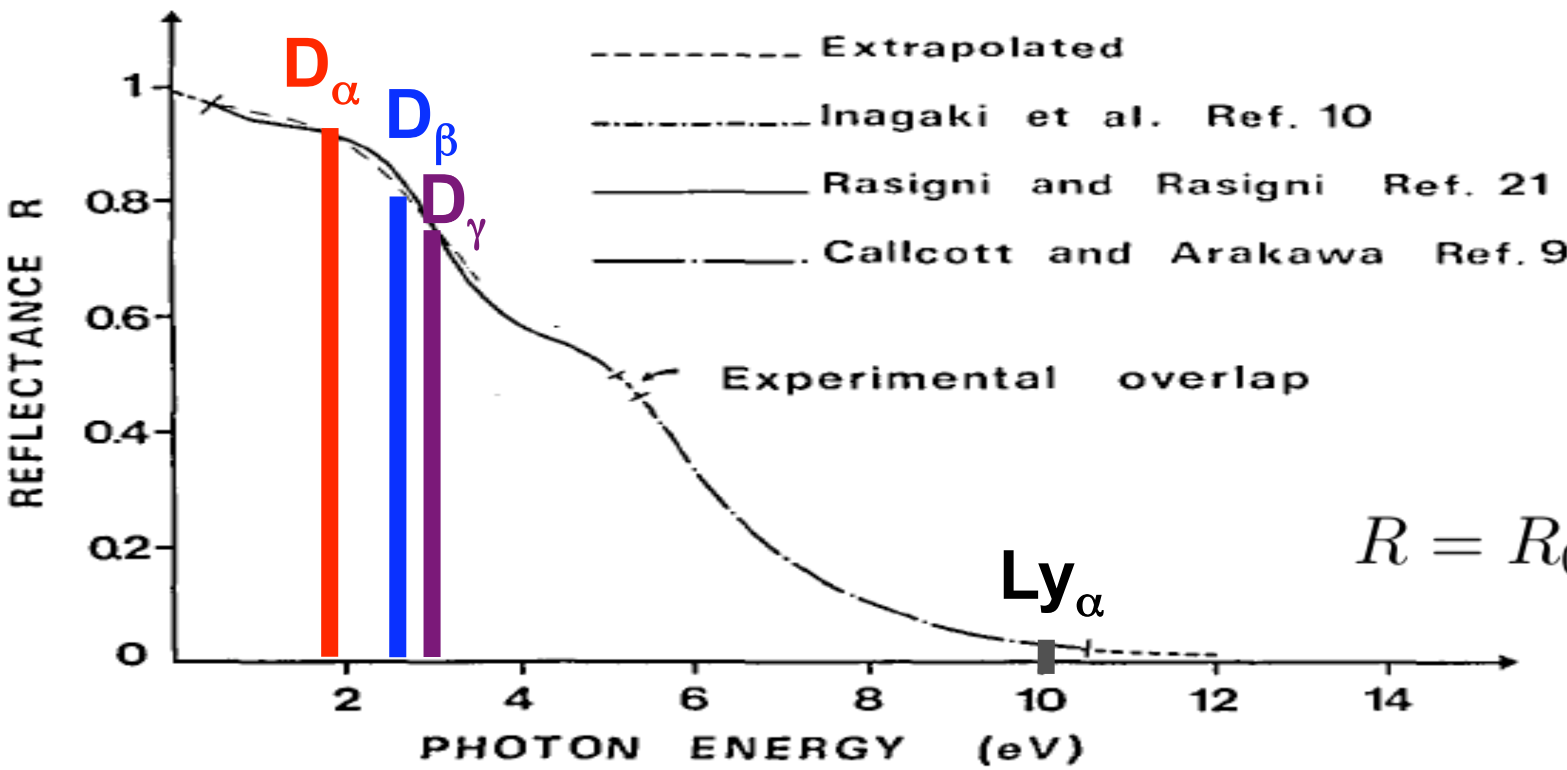
- **NSTX plasma facing components**
  - ATJ and CFC graphite tiles
  - Typical divertor tile temperature in 1 s pulses $T < 500$ C ($q_{peak} \leq 10$ MW/m^2)
- **Liquid Lithium Divertor**
  - 0.165 mm Mo plasma sprayed with 45% porosity, 0.25 mm 316-SS liner, brazed to 2.22 cm Cu substrate
  - LLD filling method – lithium evaporators
- **Lithium pumping**
  - Through formation of LiD
  - Coating can bind D with a full 200-400 nm thickness



Lithium coatings can affect diagnostic measurements and their interpretation

- Degradation of window transmission and mirror reflectivity
  - Examples: VIS and NIR measurements
- Exposed diagnostic parts
  - Examples: Langmuir probes, foil filters, windowless detectors
- Change in dynamic range of measured quantities
  - Examples: neutral pressure, density, recycling
- Effect due to measurement interpretation
  - Impact of reflectivity of LLD or Li-coated surfaces on IR thermography, visible spectroscopy

Deuterium Balmer line measurements may be difficult to interpret due to reflections from LLD

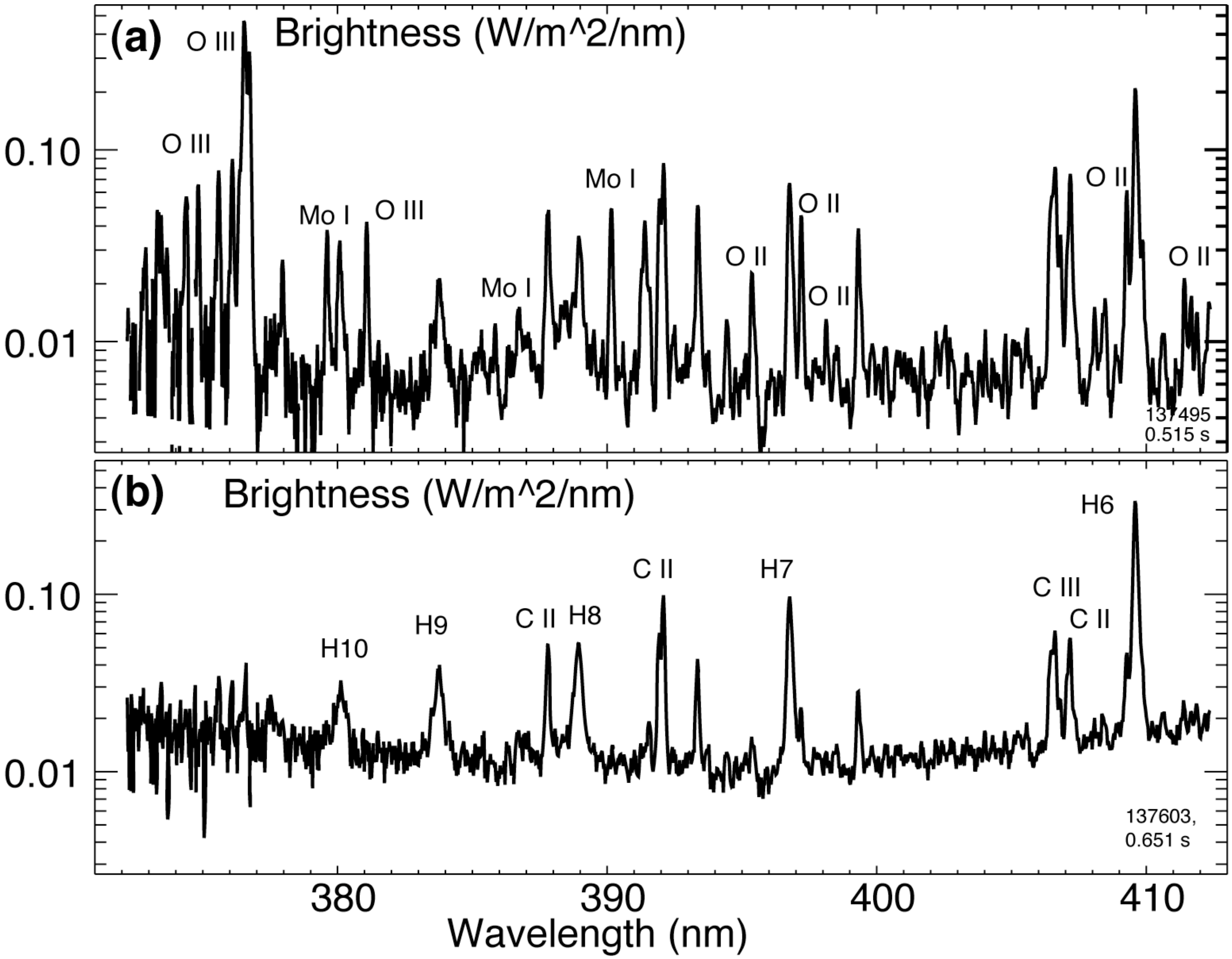


$$R = R_0 e^{-\frac{(4\pi d)^2}{\lambda^2}}$$

FIG. 1. Normal incidence reflectance data of lithium.

- Figure from M. Rosigni et al., JOSA 67, 54 (1977)
- Shows that reflections for the Balmer lines (α, β, γ) in the visible range are much higher than for the Lyman line λ=121.6 nm (Ly_α) in the far UV range

UV spectroscopy to monitor plasma-LLD surface interactions



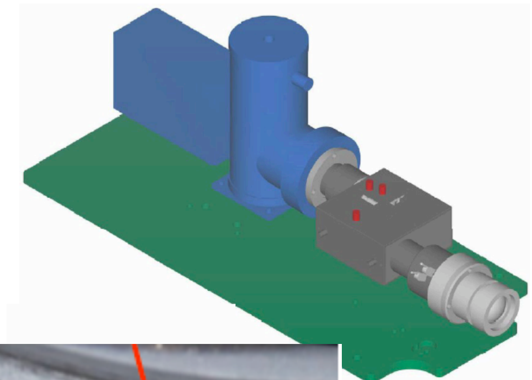
- LLD at room temperature,
- 3 MW NBI discharge,
- Mo I lines observed due to large plasma event hitting LLD

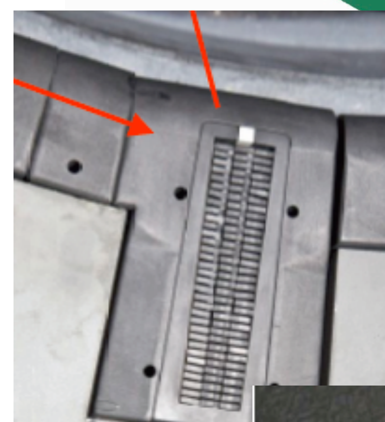
- LLD at 320 C,
- 3 MW NBI discharge,
- LiD, O II, O III line intensity reduced, no moly influx

Data from existing UV spectrometer

Experiments with lithium require special diagnostics

- New LLD diagnostics:
  - Two-color IR thermography (A. G. McLean, Poster N32)
  - Divertor Langmuir probe array (M. A. Jaworski, Poster J39; J. Kallman, Poster J40)
  - Material Analysis and Particle Probe
  - Lyman-α diode array (this poster)
  - Divertor UV-VIS-NIR imaging spectrometer (this poster)

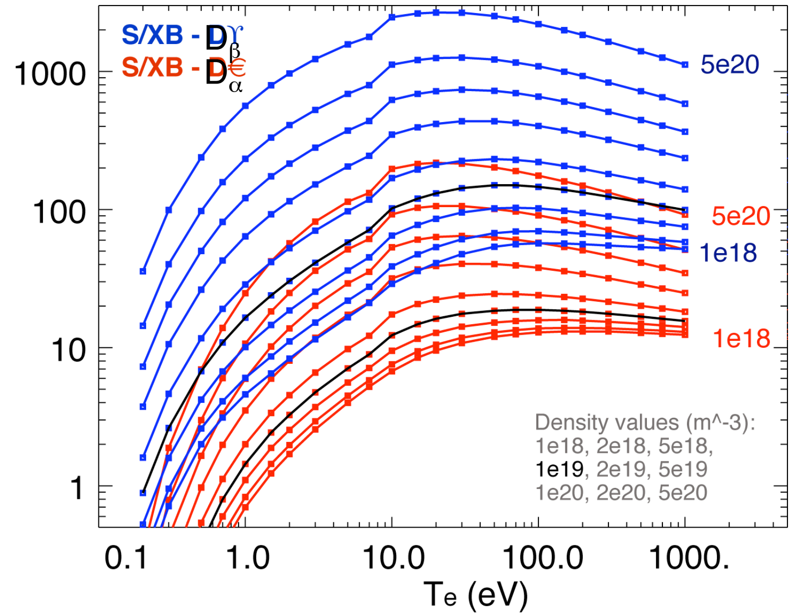




The relationship between lithiated surface conditions and edge and core plasma is studied in NSTX

- Study D retention as a function of LLD surface conditions (Li coverage, temperature), divertor T_e and n_e, strike-point location, and flux expansion
- Relate the LLD surface temperature to the measured influx of lithium and hydrogenic species
  - Using deuterium recycling measurements
  - Assessing D, Li, and C sources from the divertor and Li transport from the plasma edge to the core

- Define recycling as $R_{local}=\Gamma_i^{out} / \Gamma_i^{in}$
  - Ion flux into LLD Γ_i^{in} measured by Langmuir Probes
  - Ion outflux Γ_i^{out} estimated from measured D line intensity and S/XB (ionizations/photon) coefficient



S/XB technique is used to estimate particle influx from spectroscopic measurements

$$\Gamma_{ph} = \int_{x_1}^{x_2} n_i \, n_e \, X \, B \, dx$$

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial x}(v_i \, n_i) = S^{i-1} \, n_e \, n_{i-1} - S^i \, n_e \, n_i$$

$$\Gamma_{ph} = -\frac{X \, B}{S^i} \left(v_i \, n_i|_{x_1}^{x_2} - \int_{x_1}^{x_2} S^{i-1} n_{i-1} \, n_e \, dx + \int_{x_1}^{x_2} \frac{\partial n_i}{\partial t} \, dx \right)$$

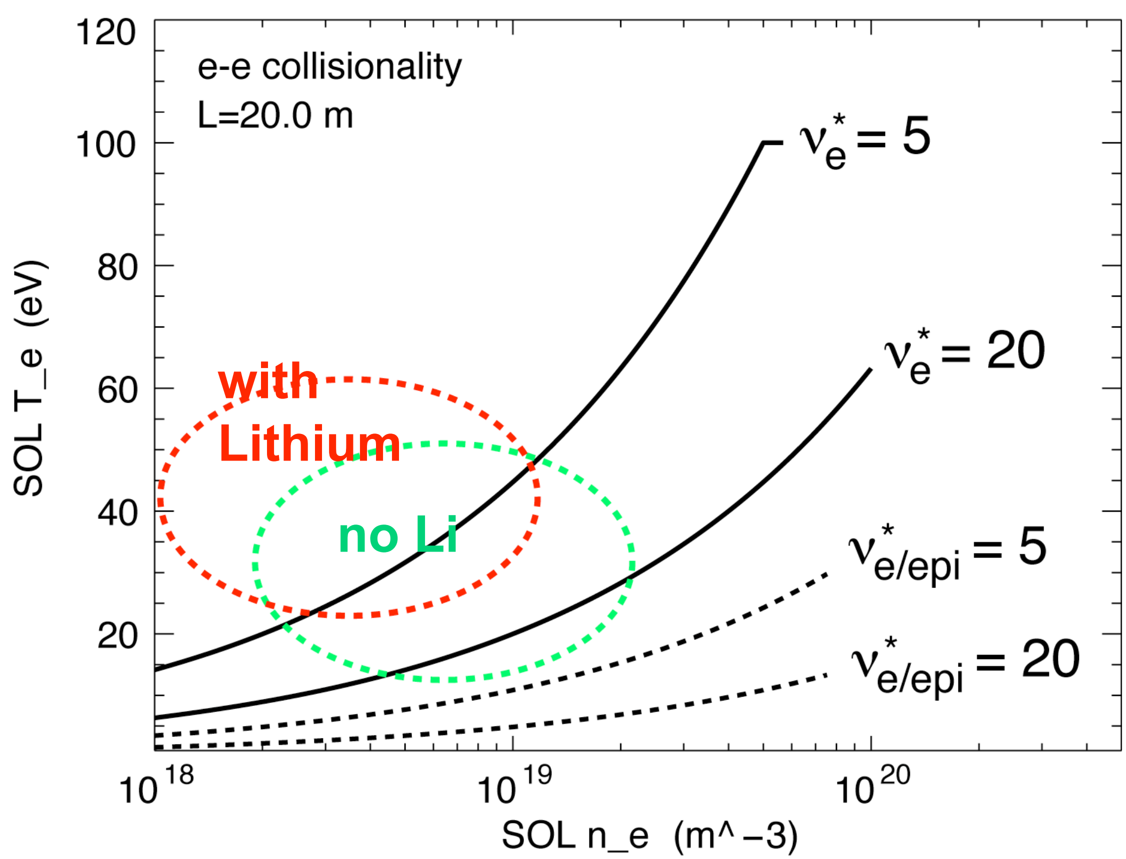
- Technique originally developed by L. C. Johnson & E. Hinnov, K. Behringer, A. Kallenbach
- Used for deuterium and impurities

$$\Gamma_i = -v_i \, n_i|_{x_1}^{x_2} + \int_{x_1}^{x_2} S^{i-1} n_{i-1} \, n_e \, dx$$

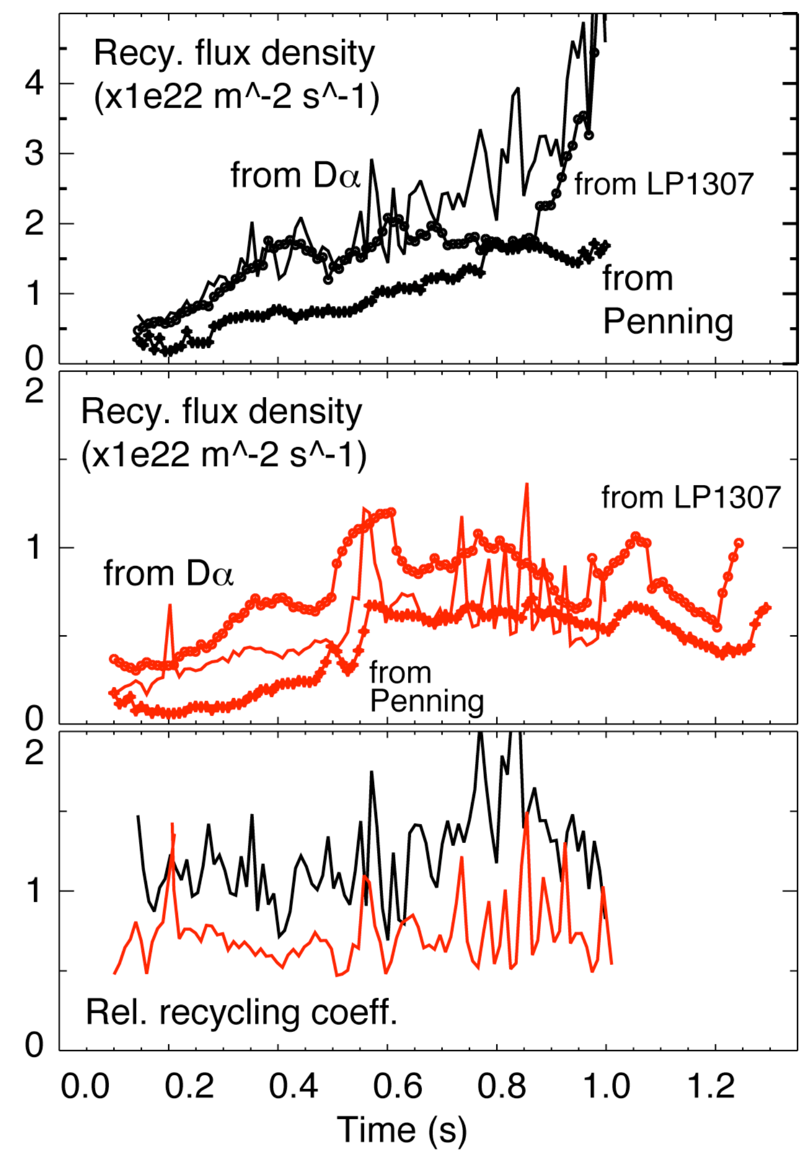
$$\Gamma_i = \frac{S}{X \, B} \Gamma_{ph}$$

- 1D viewing geometry
- x1- recycling / erosion boundary, x2 - detector location
- Recombination neglected
- Excitation and ionization occur in the same volume
- Steady-state condition

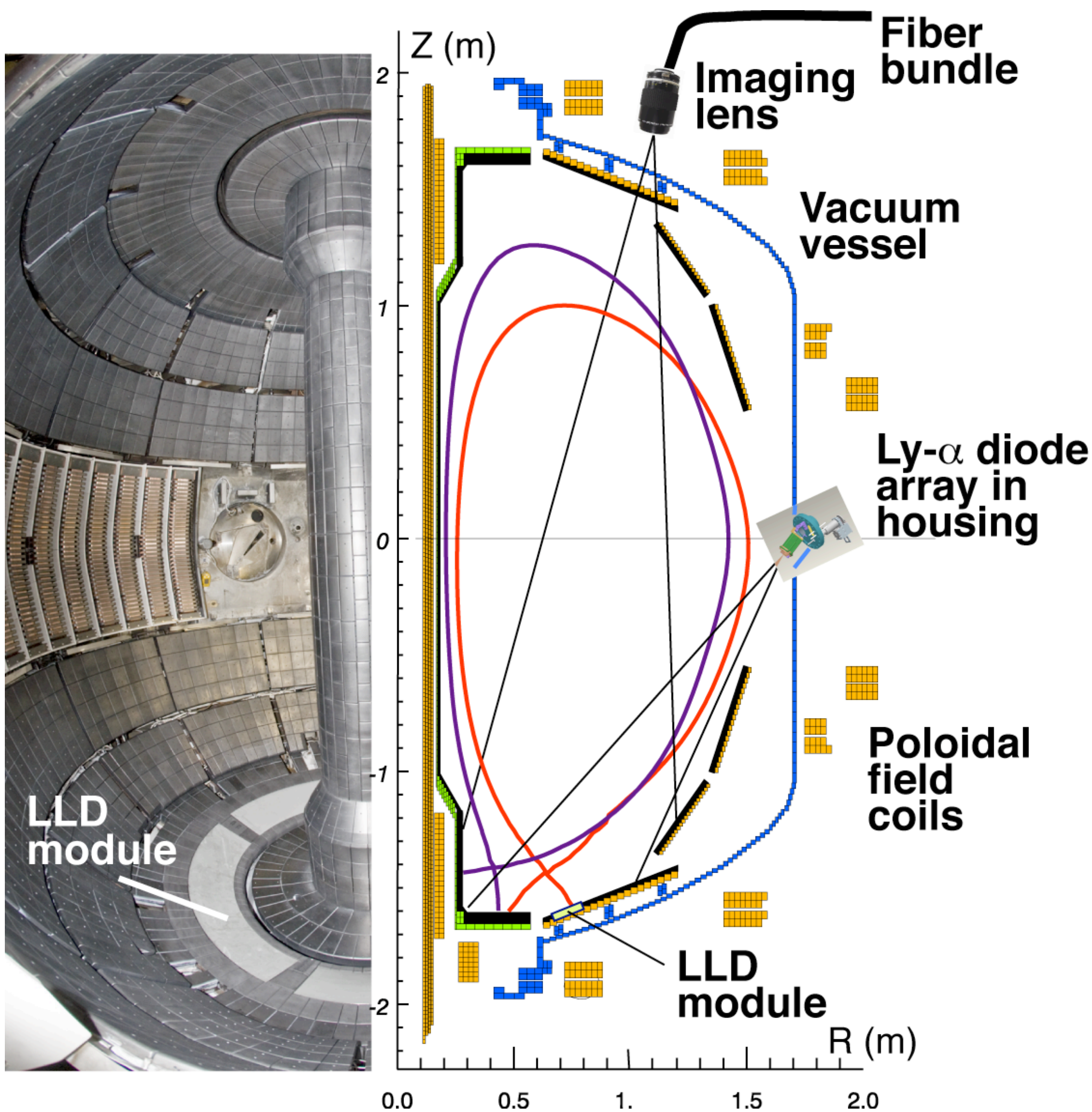
Divertor recycling and SOL collisionality decreased in discharges with lithium coatings



Transition from conduction-limited (high recycling) regime to low-recycling (sheath-limited)



New diagnostics LADA and DIMS are installed on NSTX to enhance spectroscopic studies of LLD

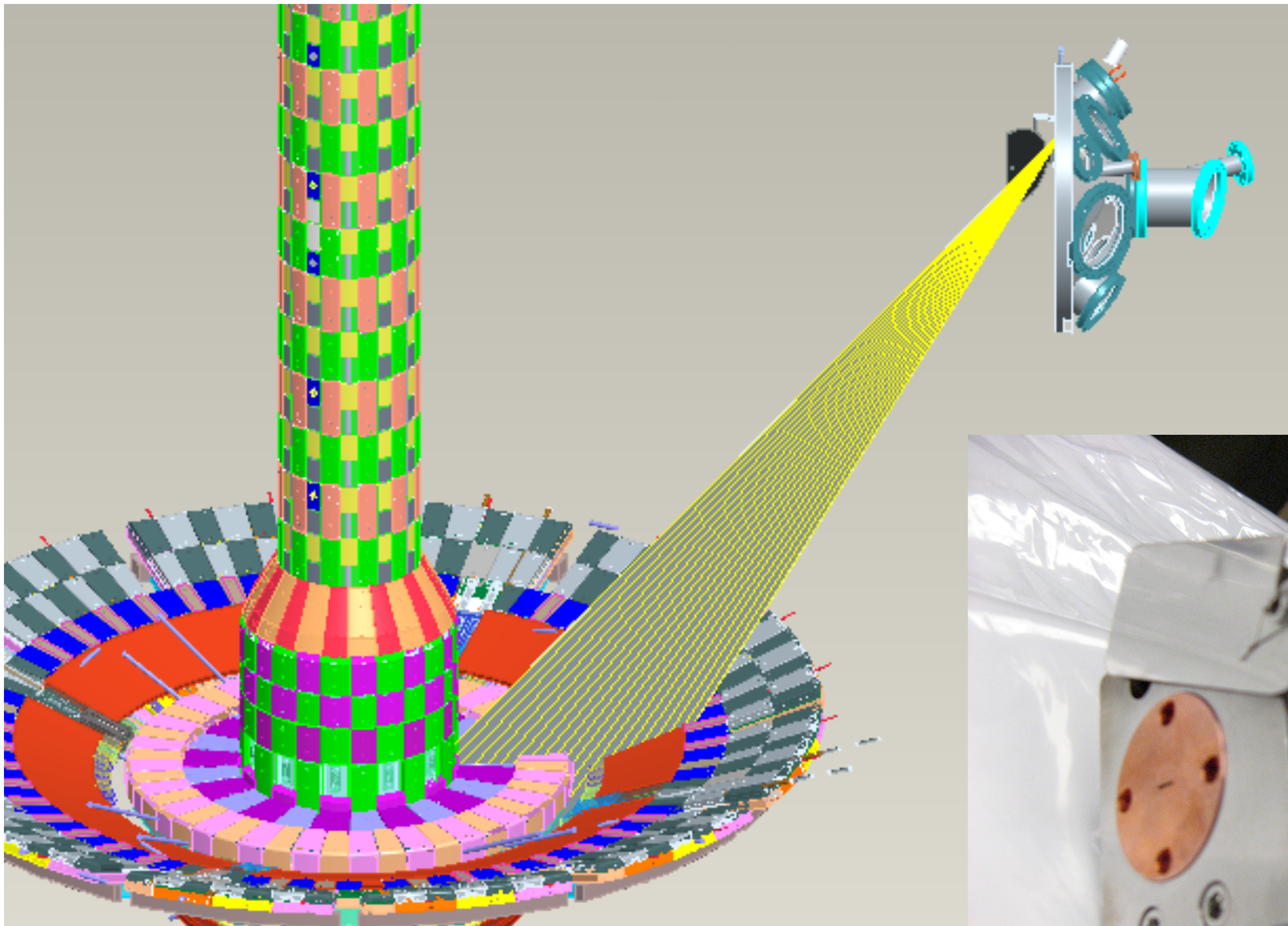


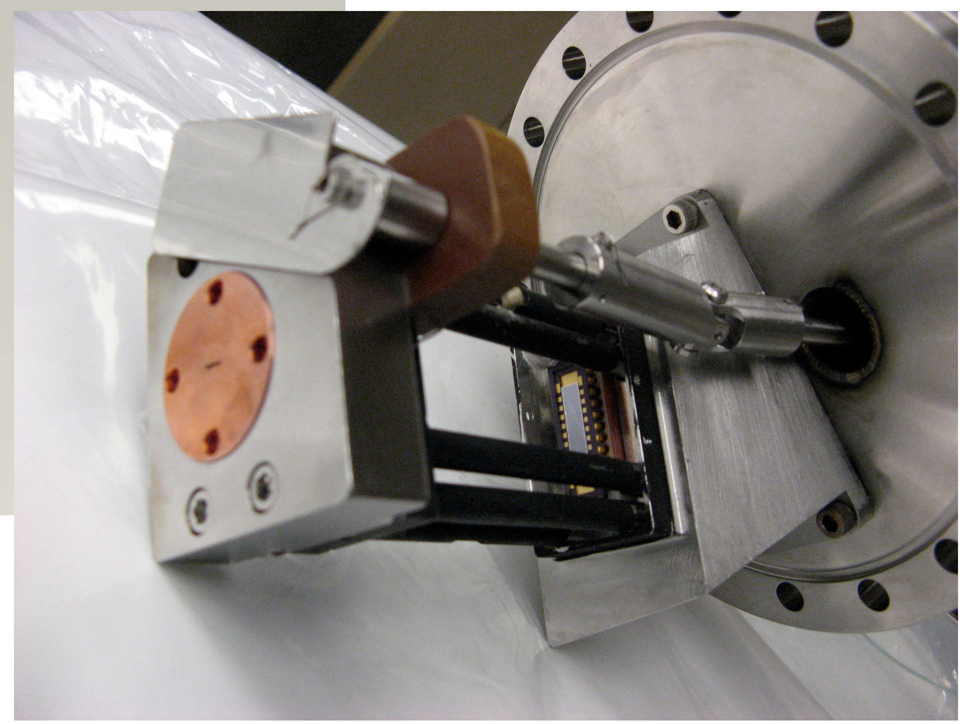
- LADA –
  Lyman Alpha (Ly_{α}) Diode Array
- DIMS –
  Divertor Imaging Spectrometer

LADA diagnostic summary

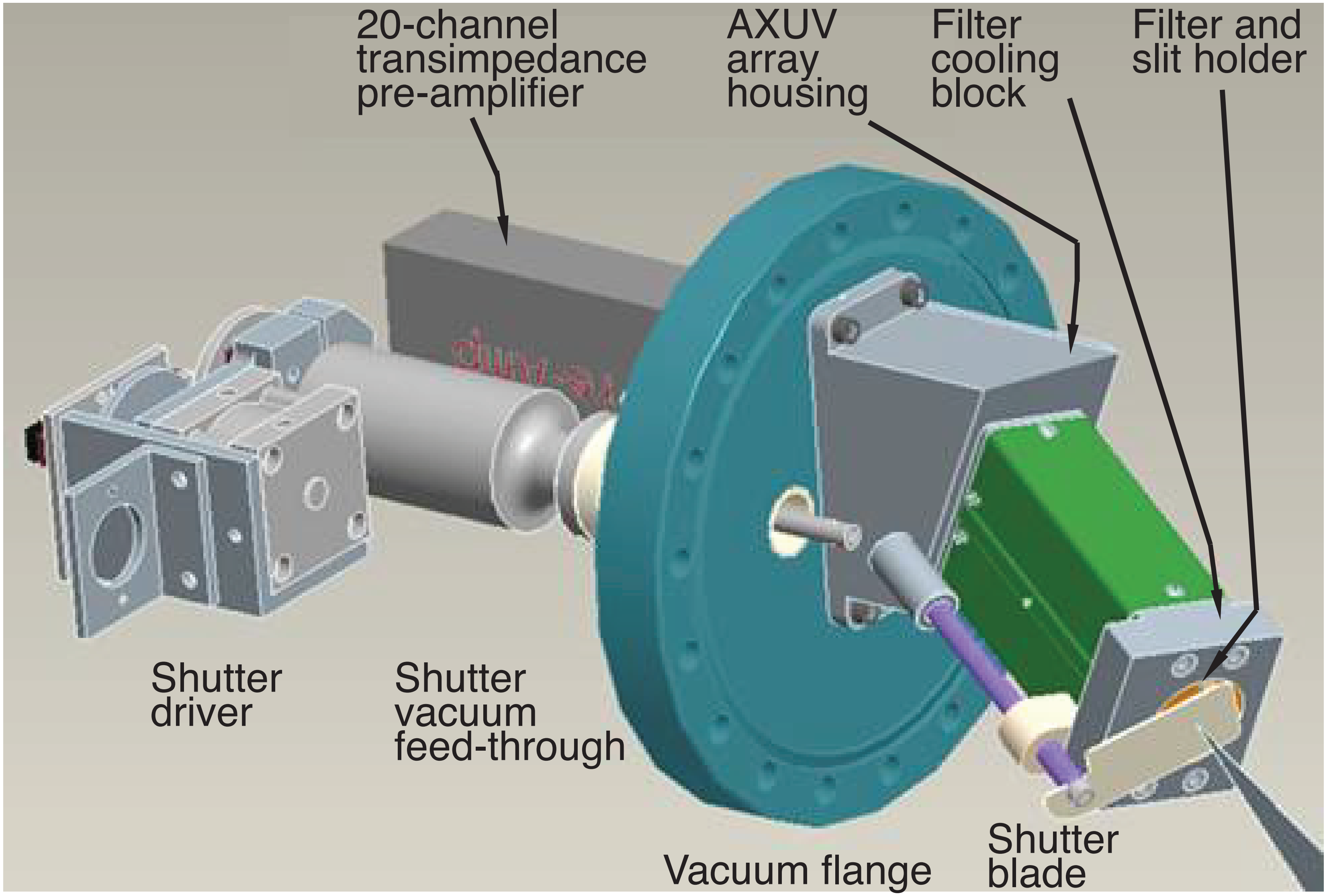
- LADA – Lyman Alpha (Ly_{α}) Diode Array
  - 20-channel AXUV-20EL diode array from IRD Inc.
  - Narrow bandpass filter with central wavelength at λ=121.6 nm from Acton Research Corp.
  - 20-channel trans-impedance amplifier from Clear-Pulse, Inc.
  - D-tacq data acquisition module transfers data directly to MDS Plus data server after every shot
  - cm-scale resolution in lower divertor, 3-5 channels on LLD
  - 10-20 kHz time response
  - In-vessel installation is required to avoid absorption of vacuum ultraviolet (VUV) emission by air
  - Active water cooling of in-vessel filter holder to avoid permanent filter transmission loss occurring at T > 60-70^{O} C

LADA provides 20-chord imaging of lower divertor with 5-6 chords on LLD for recy measurements



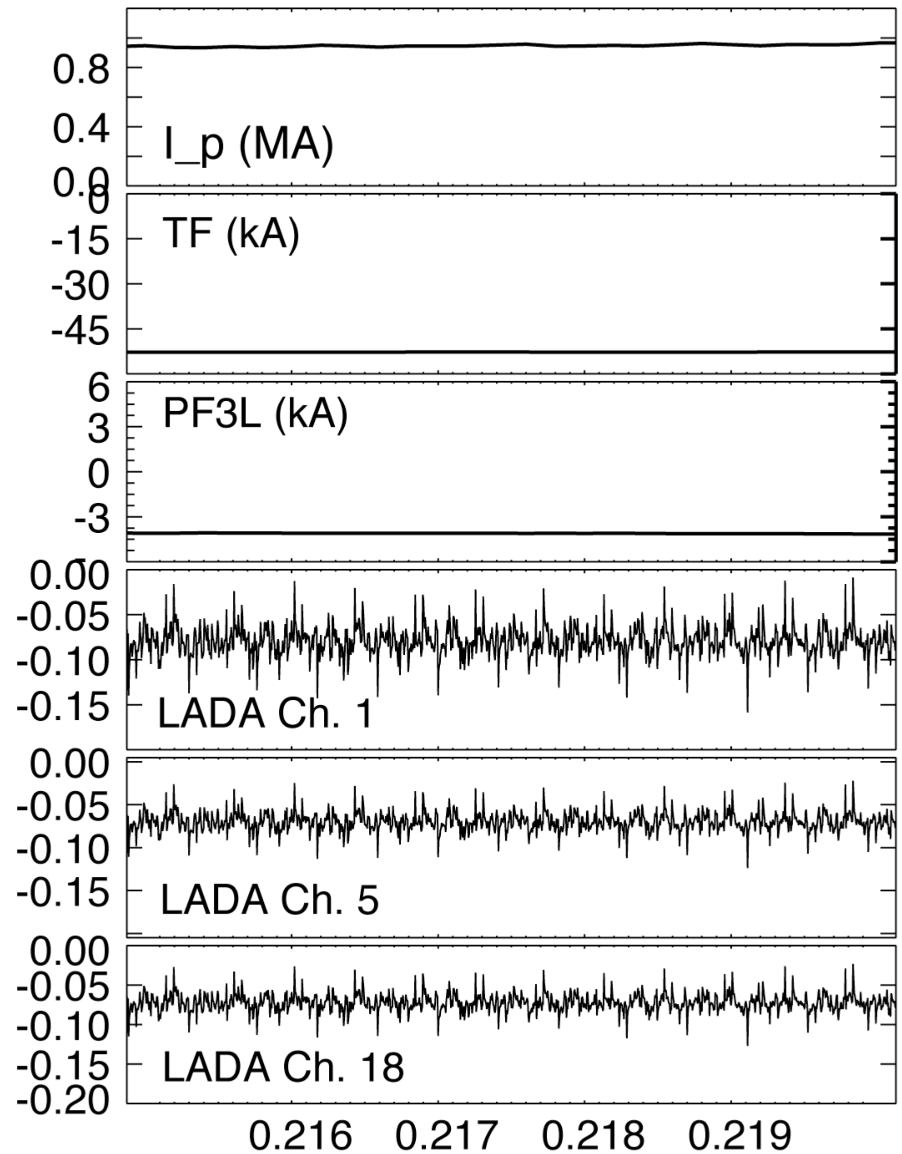


LADA is a filtered pin-hole camera and comprises of mostly in-vessel hardware

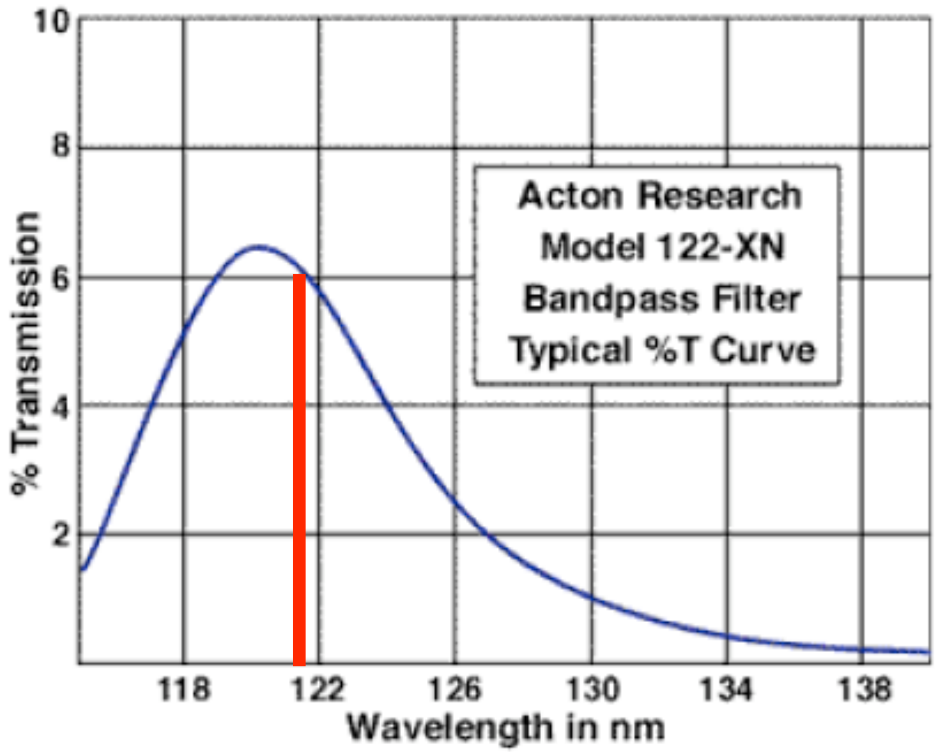


Encouraging background noise data has been collected during initial NSTX operation in 2010

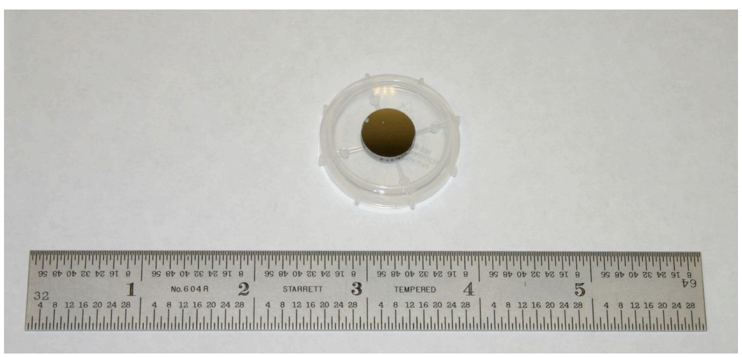
- Input parameters
  - AXUV diode efficiency at Ly_α wavelength - 0.11 A W^{-1}
  - Ly_α filter transmission - 0.055
  - Pre-amp gain - 10^6 V A^{-1}
  - Diode area - $3x10^{-6}$ m^{-2} (AXUV-20EL)
  - Aperture (slit) area – $2x10^{-6}$ m^{-2}
  - Etendue - $6x10^{-10}$ sr m^2
  - Ly_α brightness - 10^3-10^5 W m^{-2} sr
- Signal estimates
  - From Ly-α – lower bound ~ 0.01 V, upper bound 1-2 V
  - Johnson (thermal) noise ~ uV level



Narrow-bandpass multilayer FUV filter from ARC



- Open-faced multilayer transmission filter mounted on MgF_2 substrate
- Bandpass is narrow enough to transmit only Ly_{α} light
- Practically no impurity (C, O) emission lines within bandpass (e.g. Boivin et. al. RSI 72 (2001) 961



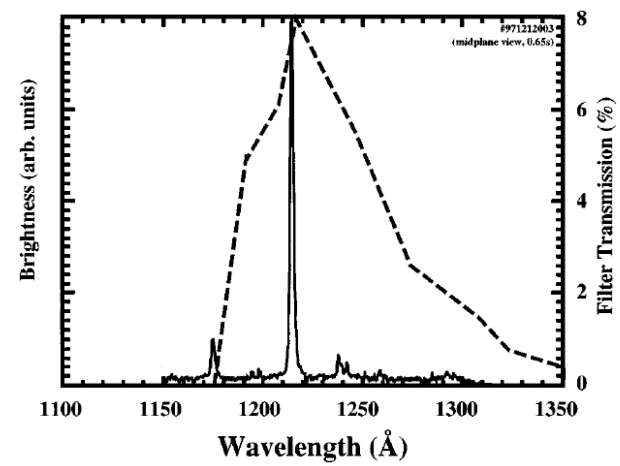
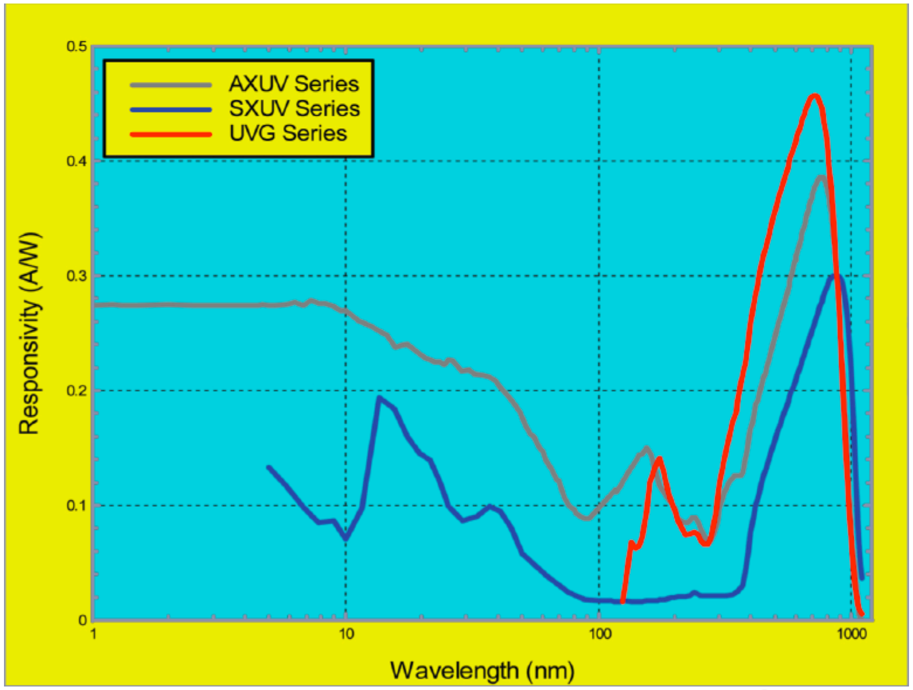


FIG. 3. Measured plasma emission in the UV region using a McPherson (VUV) spectrometer. Overlaid is the measured filter response.

AXUV20EL array



AXUV Arrays

Model no.	Sensitive Area (mm^2)	Size (mm)	Shunt Resistance (MΩ)**	Capacitance @ 0V (pF)**	Risetime (10-90%) (nSec)**	Package/ Page no.
AXUV3ELA#	1 (X3)	1 X 1 (X3)	1000	40	1	C3EL/21
AXUV10EL#	1 (X10)	1 X 1 (X10)	1000	40	1	C10EL/21
AXUV16ELO/G	10 (X16)	2 X 5 (X16)	100	2000	500	C16ELO/21
AXUV16EL	10 (X16)	2 X 5 (X16)	100	2000	500	C16EL/22
AXUV20EL	3 (X20)	0.75 X 4 (X20)	300	1000	200	C20EL/22
AXUV22EL	4 (X22)	1.0 X 4.0 (X20)	200	1000	200	C22EL/22

DC-coupled 20-channel pre-amplifier

- Clear-Pulse Inc. (Japan)
- Model 8986A Pre-amplifier
  - 20 ch
  - Teflon or ceramic sockets
  - 40 cm Kapton cable
  - Gain: 10^6
  - 10 kHz time response

Data acquisition: MDS Plus ready D-TACQ module

- Module ACQ196CPCI-96-250
  - 96 channels
  - 250 kSPS Simultaneous Digitizer
  - 16 bit ADC per channel for true simultaneous analog input
  - True differential input to each channel
  - Plant cable interface to front panel - 3 x SCSI 68 connectors on front panel
  - Standalone networked mode
  - External clock, trigger, internal clock
  - Direct TCP/IP connection to network / to MDS server

ACQ196CPCI

DIMS diagnostic summary

- DIMS – Divertor Imaging Spectrometer
  - Optimized for ultraviolet, visible, and near-infrared high-resolution imaging spectroscopy from 250 nm to 1100 nm
  - Tochigi Nikon UV 105mm f/4.5 imaging lens
  - 50-fiber optical relay bundle, 400-um FBP400 broadband fibers from Polymicro, Inc.
  - Two achromatic triplet lenses as input optics
  - McPherson Model 207 R=0.67 m f/4.7 spectrograph with aberration-corrected imaging optics
  - Three gratings (3600, 2400, 1800 lines/mm) for ultraviolet, visible, and near-infrared line spectra
  - Princeton Instruments Pro EM 512 CCD camera
  - Expect 18-point divertor profiles with 1 cm spatial resolution, 1-10 ms time resolution

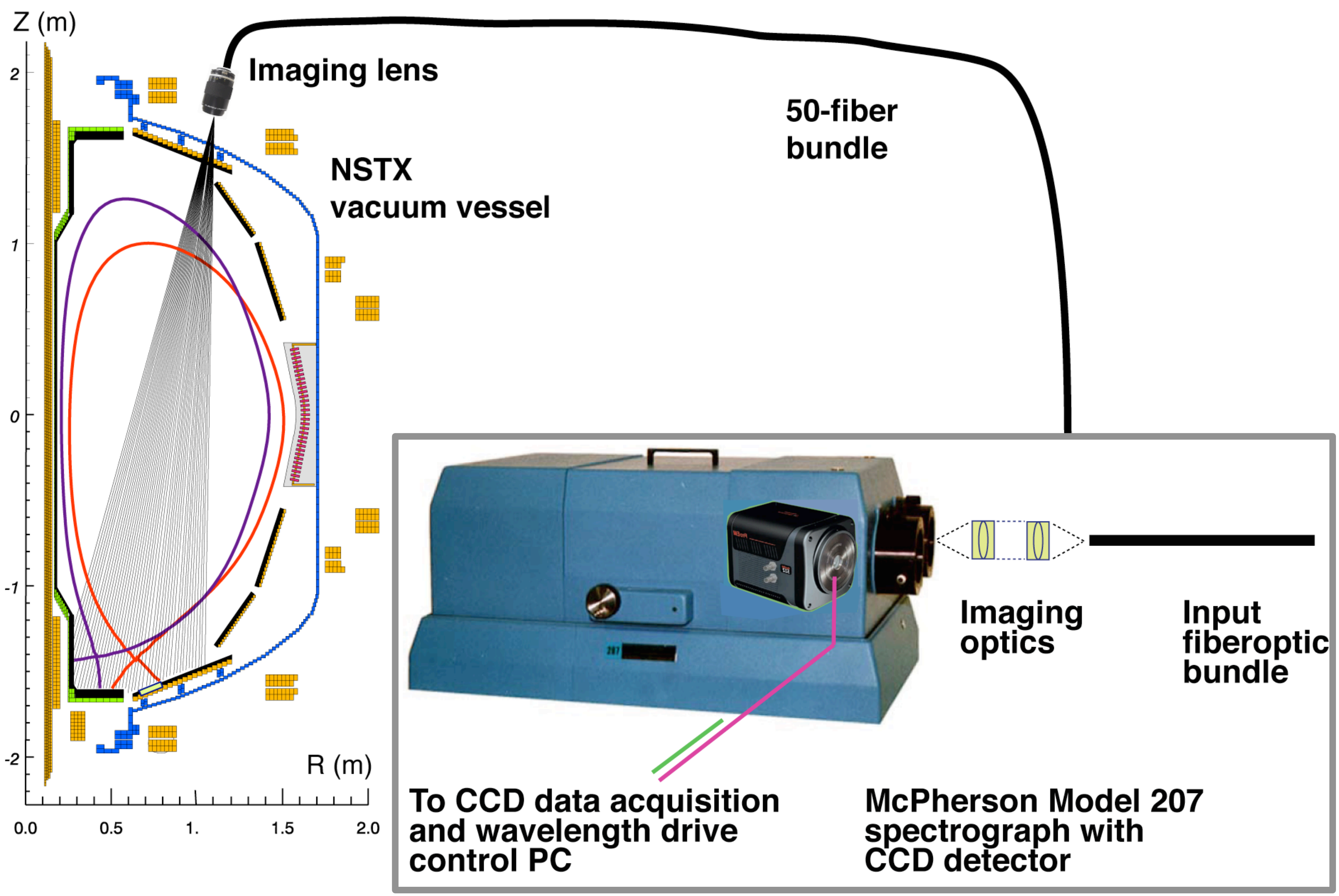
New spectrometer will address high-priority goals in NSTX Boundary Physics research

- Divertor source characterization
  - Atomic D, Li, C influx **profile measurements in divertor**
  - Molecular sources (D_2, LiD, BD, CD_4, …)
  - Atomic Mo, Fe sources for LLD protection

- Divertor ion sink characterization
  - Electron-ion recombination patterns in divertor (D, He, Li)
  - High-*n* Balmer (and Paschen) series lines for n_e, T_e estimates

- Ion temperature measurements in divertor (based on Doppler broadening) for ion heat transport analysis

DIMS is places in a remote room shielded from radiation

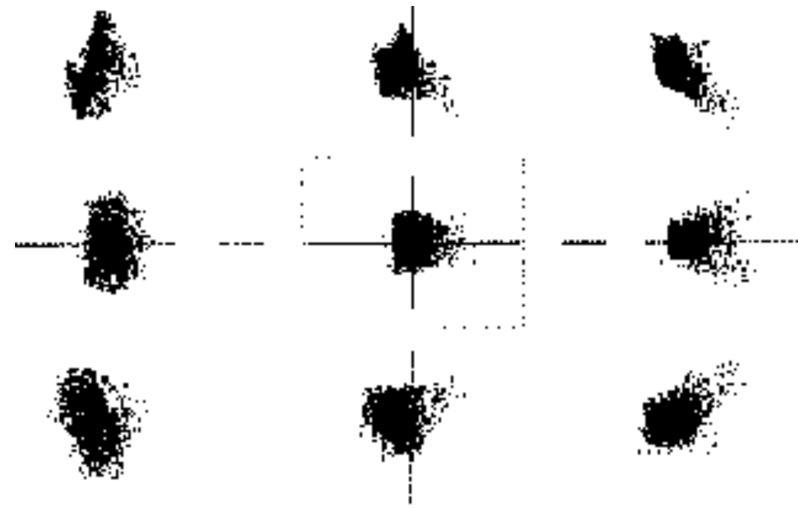


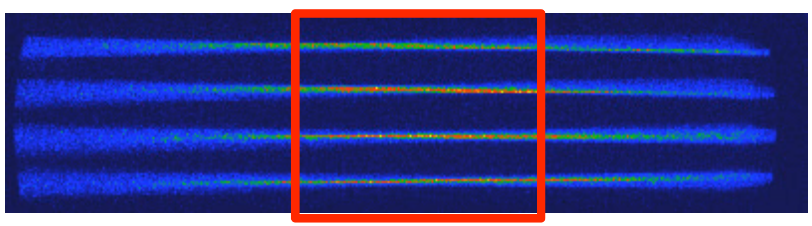
Conceptual requirements to new spectrometer

Diagnostic requirement	Input optics, including fibers	Spectrograph	CCD camera detector
Full divertor coverage with 1 cm resolution	Long FL imaging lens; Small diameter fibers	Stigmatic, aberration-free imaging of input slit of < 1 cm height	CCD chip height
Broadband spectral coverage 350-1200 (1900) nm	Low attenuation in range	Several gratings	Broadband sensitivity
Temporal resolution 1- 50 ms	Optimized throughput	Largest f/# for given size	Fast readout
High spectral resolution > 0.01 nm	Optimized throughput, imaging of divertor on entrance slit	Large size; 2400-3600 gr/mm gratings	Small pixel size (10-15 um)
High imaging quality	Stigmatic, aberration-free imaging	Stigmatic, aberration-free imaging	Square chip

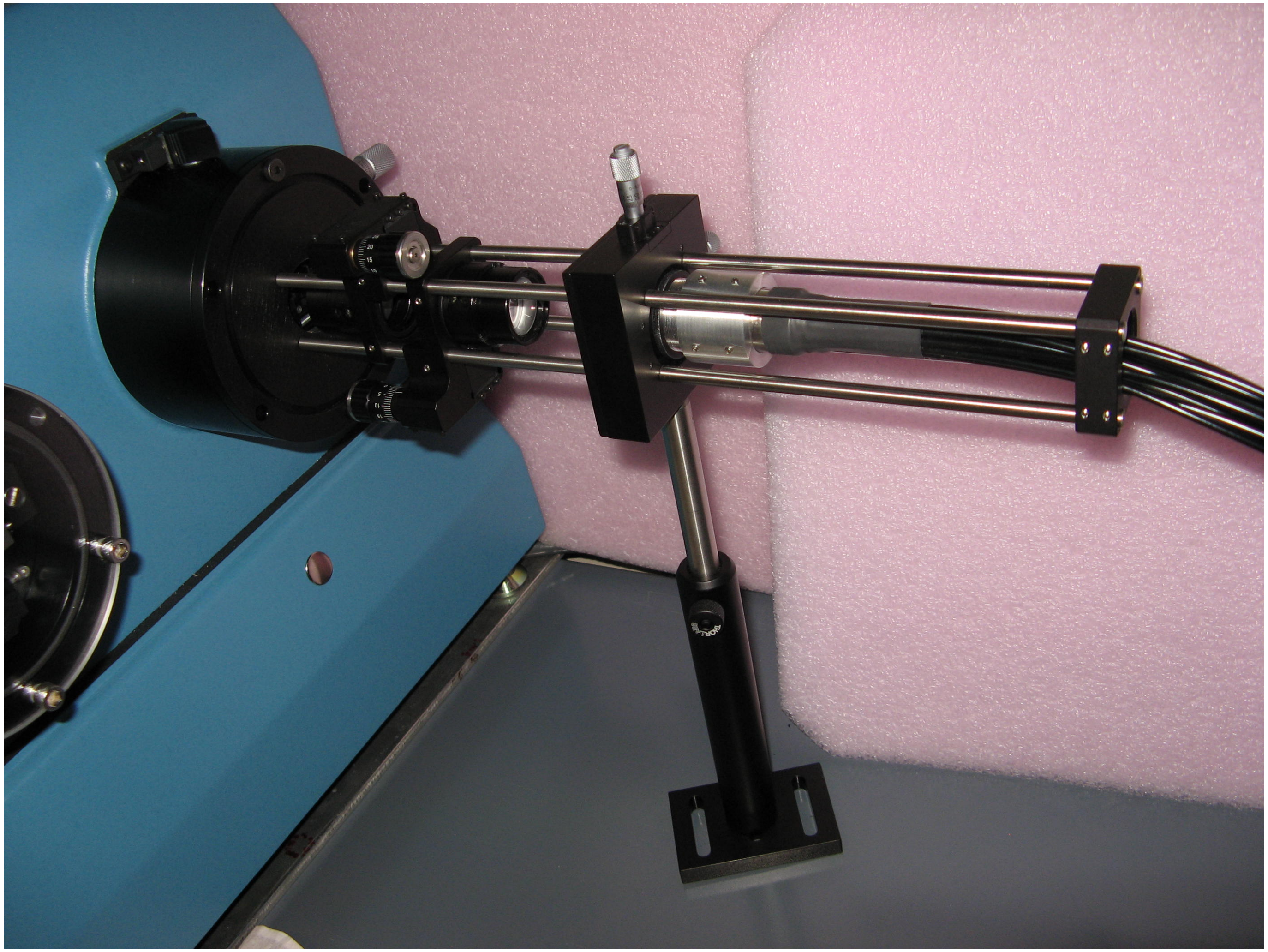
Imaging with McPherson spectrographs

- Imaging aberrations: spherical aberration, astigmatism, coma, line curvature
- Correcting spherical aberration and astigmatism is self-exclusive
- McPherson: introduce a master cylinder correction mirror at one of the side port mirror positions
- Ray-tracing: 9 spots at ± 10 mm spatially, ± 13 mm on the dispersion axis, 100 um diameter
- Since high quality imaging region is limited, CCD detector can be square, not extended along dispersion axis





DIMS etendue is optimized by matching F/#'s of all optical components

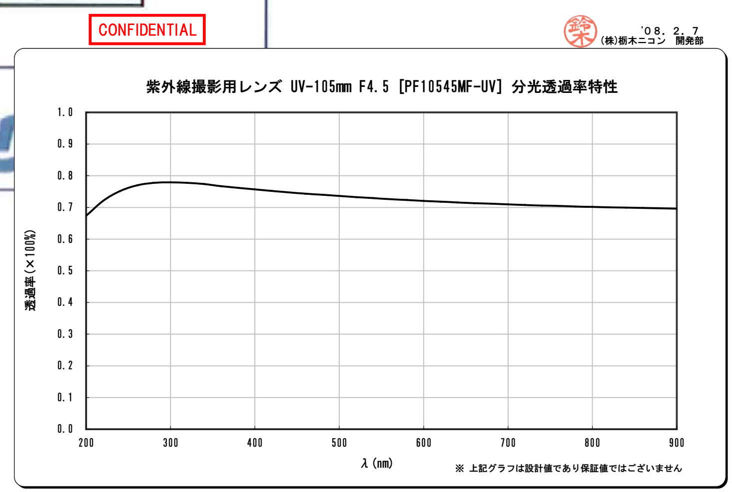


Lens: F/#2.8 - Fiber: F/#2.3 - Matching optics: F/#2.0 - Spectrograph: F/#4.7

Divertor imaging lens provides achromatic imaging in a broad UV-VI-NIR range

Focus Distance	105mm
Maximum Diameter Ratio	1:4.5
Lens Construction	6-set 6-piece
Color Correction Range	220nm ~ 900nm
Angle Of View	23°20'
Distance Range	∞ ~ 0.48m 1.57ft
Magnification Ratio Range	1:10 ~ 1:2
Aperture Range	4.5 ~ 32
Mount	Nikon F mount
Attachment Size	M52 (P=0.75)
External Dimension	Φ68.5
Length	116.5mm (108mm from the mount base surface) = 4.6"
Weight	515g = 1.14lbs

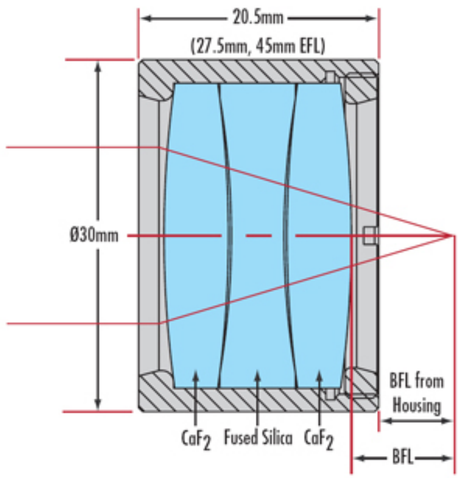
Daitron Inc.
http://www.daitron.com



Tochigi Nikon 105mm, f/# 4.5

Spectrometer front-end focusing optics comprises two infinity-conjugated achromatic lenses

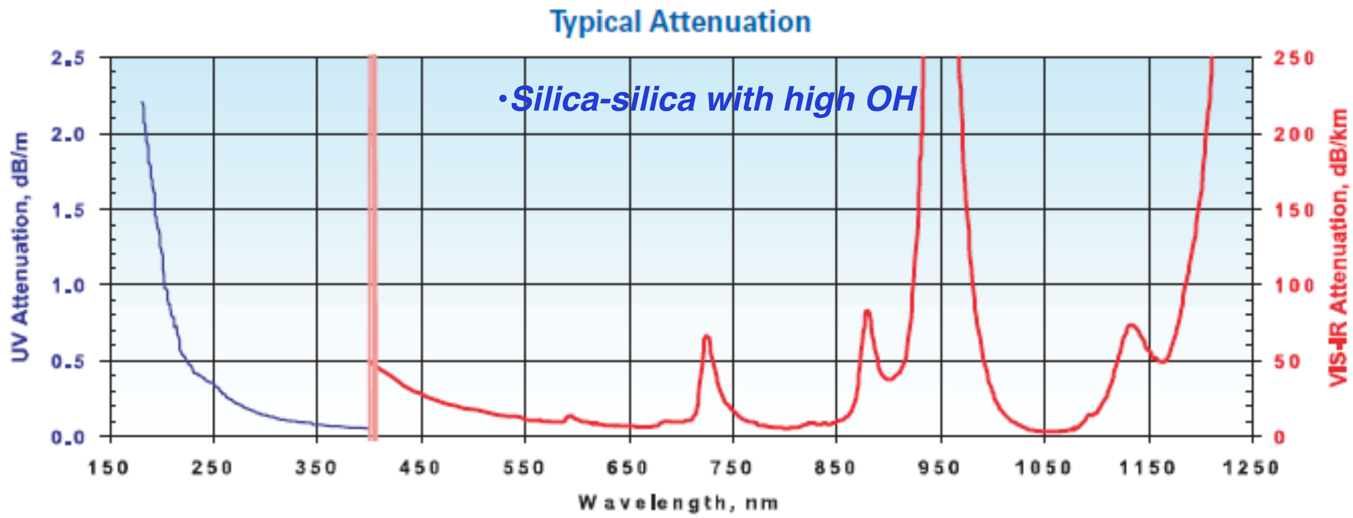
- f=90mm EFL UV-to-NIR Corrected Triplet, Uncoated, Edmunds Optics, Model NT47-311

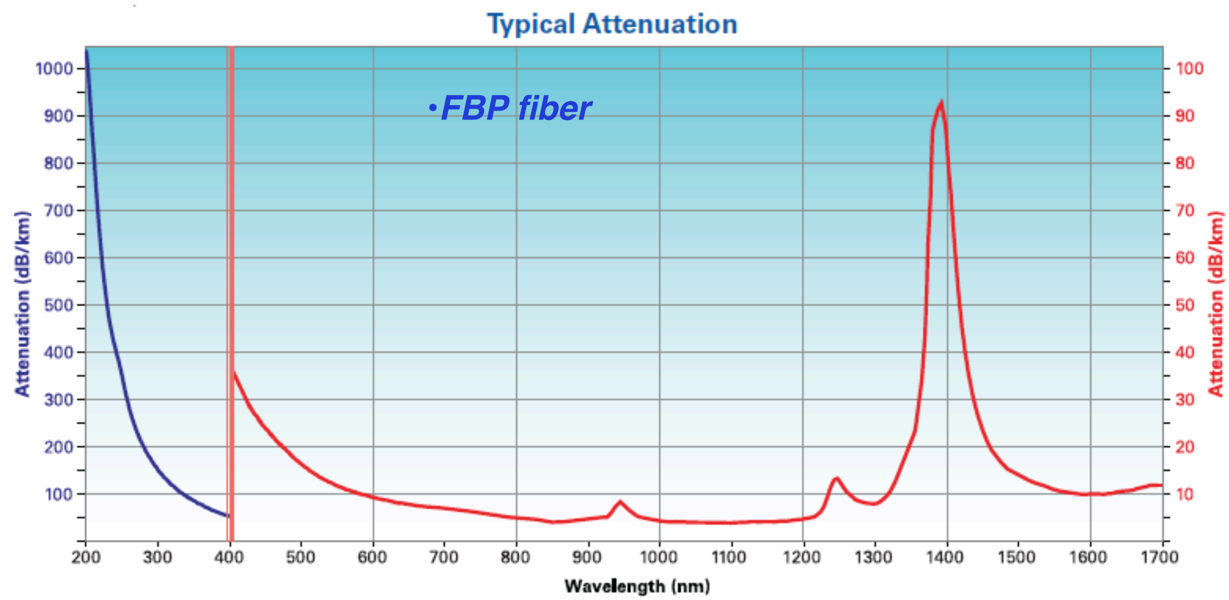


Effective Focal Length EFL	193 - 400nm		400 - 1000nm		193 - 1000nm	
	Chromatic Shift	RMS Spot Size	Chromatic Shift	RMS Spot Size	Chromatic Shift	RMS Spot Size
45mm	1.1mm	88.1µm	0.26mm	68.5µm	1.3mm	96.6µm
90mm	2.0mm	64.3µm	0.55mm	37.9µm	2.48mm	69.17µm
135mm	1.6mm	48.7µm	0.59mm	30.8µm	2.14mm	50.71µm
180mm	1.4mm	45.6µm	0.61mm	28.3µm	1.89mm	45.17µm

Light relay optical fibers have low attenuation over a broad UV-VIS-NIR range

- Polymicro FBP broadband fiber Type FBP400440480
- NA=0.22 (f/#=2.27)
- Diameter : 400 um core
- With Nikon imaging lens, estimated spots on divertor - 1 cm diameter





McPherson Model 207 Spectrograph

- Highest f/# 4.7 at R=0.67 m in industry
- Grating Size 120 x 140 mm
- Imaging Optics
- Automated wavelength scan
- Accuracy 0.05 nm (with 1200-g/mm grating)
- Reproducibility ±0.005 nm (with 1200-g/mm grating)
- Entrance slit height 2-20 mm, entrance slit width 5-4000 um

Grating Groove Density (g/mm)	3600	2400	1800	1200	600	300	150	75
Resolution** (nm)	0.012	0.018	0.02	0.03	0.06	0.12	0.24	0.48
Dispersion (nm/mm)	0.43	0.62	0.83	1.24	2.48	4.96	9.92	19.84
Wavelength Range	185 - 430 nm	185 - 650 nm	185 - 860 nm	185 - 1300 nm	185 - 2600 nm	185 nm 5.2 um	185 nm 10.4 um	185 nm 20.8 um
Available Grating Blazes (* Holographic gratings are available where noted.)	Holographic* 240	Holographic* 240 300	Holographic* 400 500	Holographic* 250 300 500 750 1 um	Holographic* 300 500 750 1 um 1.85 um	300 500 750 1 um 3 um 4 um	300 500 1.25 um 2.5 um 4 um 6 um 8 um	2 um 3 um 8 um 10 um 12 um

** Spectral resolution typically measured at 313.1 nm

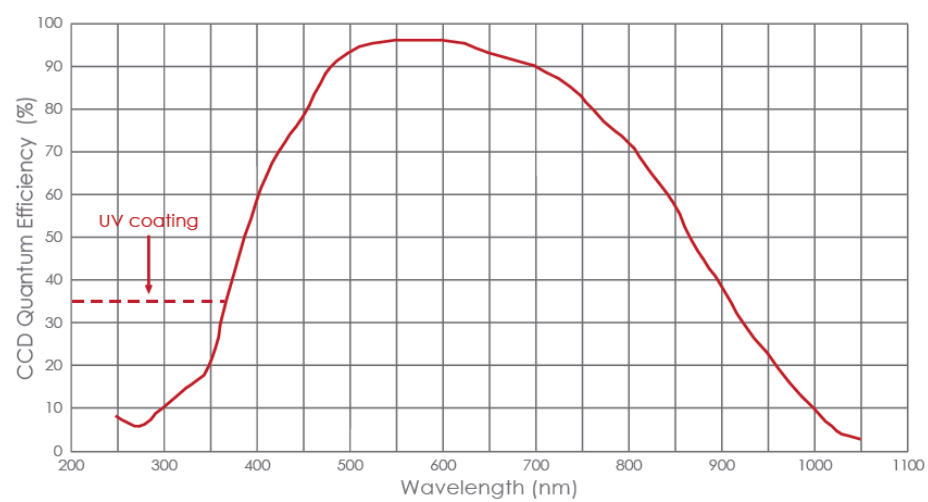
Princeton Instruments Pro EM 512 CCD camera

FEATURES	BENEFITS
Electron multiplication (EM) gain	Low-noise, impact-ionization process for single-photon sensitivity
OptiCAL ™	Linear, absolute EM gain calibration using built in precision light source EM and Non-EM modes for the lowest noise and the best linearity.
BASE ™	Baseline Active Stability Engine - stable bias for quantitative measurements
PINS ™	Princeton Instruments Noise Suppression technology. Independently optimized EM c for the lowest noise and the best linearity.
Back-illuminated CCD	>90% peak quantum efficiency for the highest available sensitivity
Frame-transfer architecture	Allows 100% duty cycle imaging for tracking applications
Deep cooling	Thermoelectric cooling below -80°C minimizes dark current and allows long exposure times Camera can be cooled with air or water, or a combination of both, and fan can be permanently turned off for vibration-sensitive environments
Single optical window	Vacuum window is the only optical surface between incident light and the CCD surface - No losses due to multiple optical surfaces
Built-in shutter	Conveniently capture dark reference frames and protect camera from dust when not in use
Dual amplifiers	Individually optimized signal chains for a true 2-in-1 camera configuration, for high speed (EM mode) or long integration (normal CCD mode) applications
16-bit digitization	Wide dynamic range to capture dim and bright signals in a single image
10- and 5-MHz readout	Video rates at full-frame resolution. Use ROI/binning for hundreds of frames per second
100-kHz readout	Noise performance of a slow scan camera for precise photometry applications
Kinetics readout mode	Powerful readout mode offers microsecond time resolution between sub-frames
Gigabit Ethernet (GigE)	Reliable data transmission over 50m for remote operation
Software interface	Universal interface for easy custom programming, real-time focus & image access via circular buffers
C-mount (Adjustable)	Easily attaches to microscopes, standard lenses, or other optical equipment

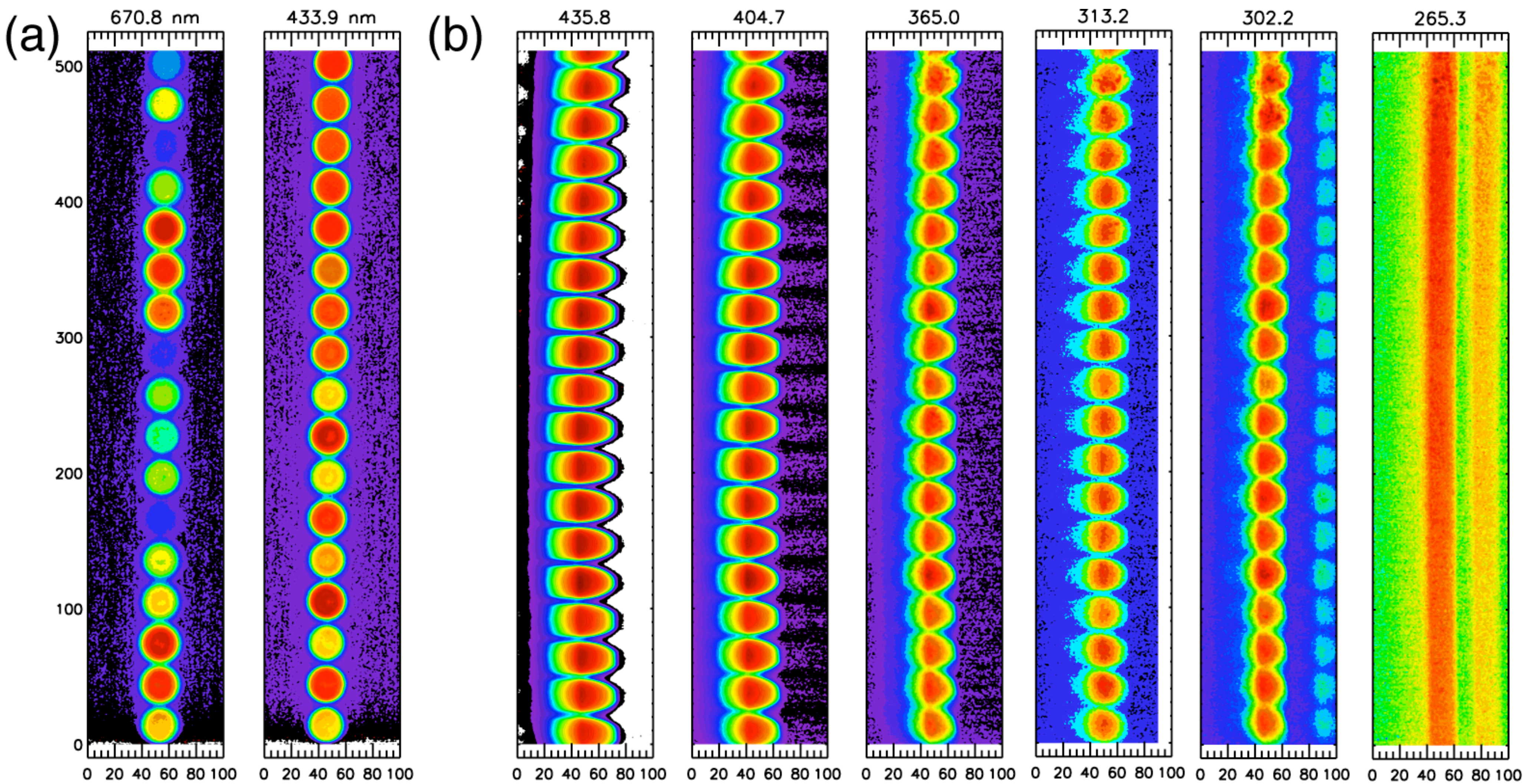
Princeton Instruments Pro EM 512 CCD camera

Image sensor	e2v CCD97; back-illuminated, frame-transfer EMCCD	
CCD format	512 x 512 imaging pixels 16 x 16 μm pixels 8.2 x 8.2 mm imaging area (optically centered)	
	EM mode	Normal CCD mode
Read noise (typical)	25 e- rms @ 5 MHz 50 e- rms @ 10 MHz Read noise effectively reduced to <1 e- rms with on-chip multiplication gain enabled	3 e- rms @ 100 kHz 7 e- rms @ 1 MHz 12 e- rms @ 5 MHz
Full well (typical)	800 ke- (output node)	200 ke- (single pixel)
Non-Linearity	<2%	<1%
Analog gain (typical)	12, 6, 3 e/ADU	3.2, 1.6, 0.8 e/ADU
Deepest cooling temperature (@ +20°C ambient)	-80°C +/- 0.05°C (typical) -70°C +/- 0.05°C (guaranteed)	
Dark current @ -70°C	0.005 e-/p/sec (typical) 0.02 e-/p/sec (maximum)	
Clock induced charge (CIC) (typical)	0.005 e-/pixel/frame measured with 33mse	
Electron multiplication (EM) gain	1 to 1000x, controlled in linear, absolute ste	
Digitization	16 bits @ 10 MHz, 5 MHz, 1 MHz and 100	
Vertical shift rate	300 nsec/row - 5 μsec/row (variable)	
Binning	Flexible binning in vertical and 2x to 32x in	
Operating systems supported	Windows XP/Vista	
I/O signals	Exposure, Readout, Trigger In	
Operating environment	0 to 30°C ambient, 0 to 80% relative humid	

QUANTUM EFFICIENCY



Initial laboratory tests show excellent imaging properties over broad spectral range



(a) Test of front optics at two λ, (b) Tests of Hg-lamp imaging with at six λ

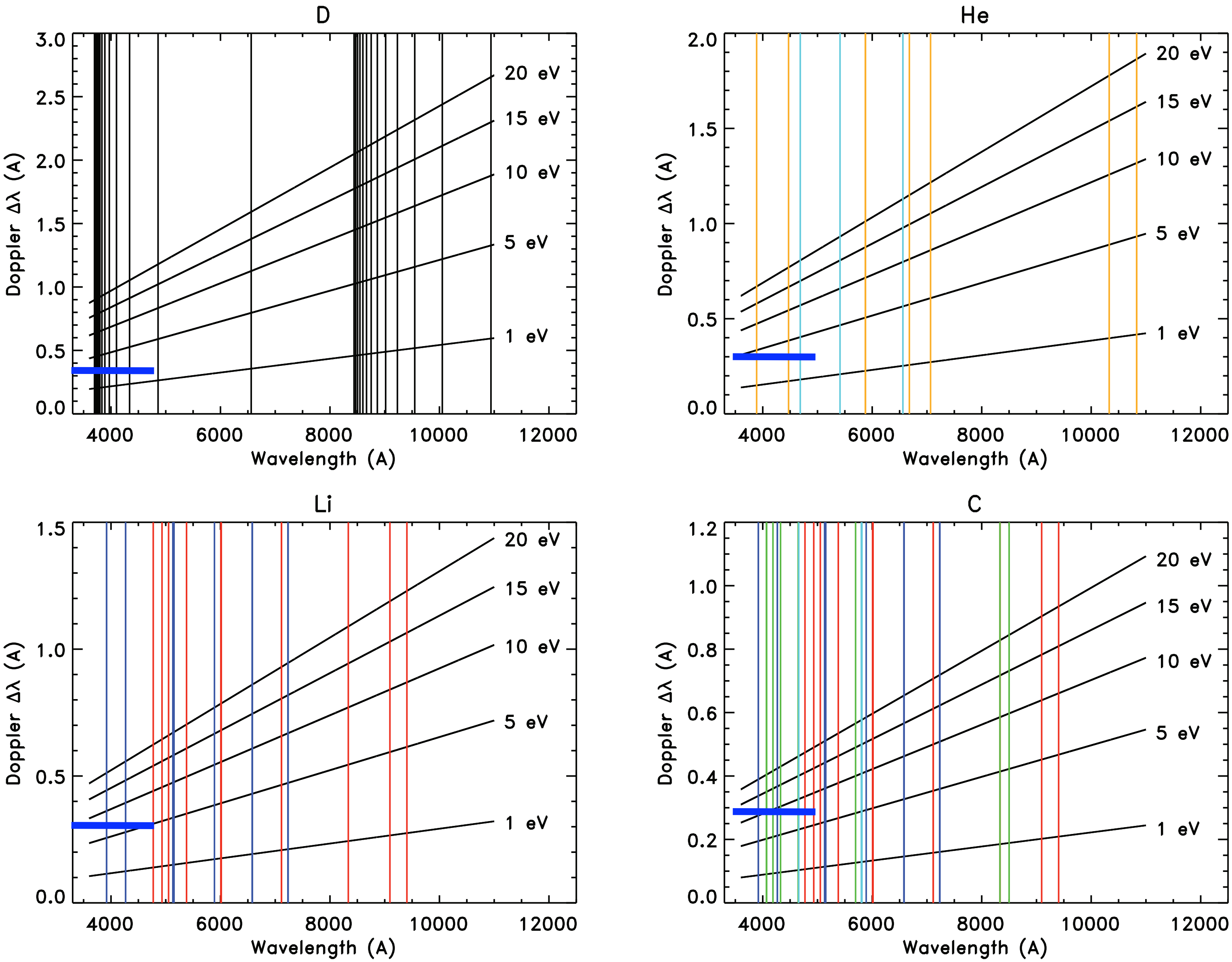
Doppler spectroscopy

- Maxwellian distribution of atom (ion) velocities lead to a Gaussian shape of projection on line of sight
- FWHM is related to temperature

$$\Delta\lambda_D = 7.16 \times 10^{-7} \lambda \sqrt{T/\mu}$$

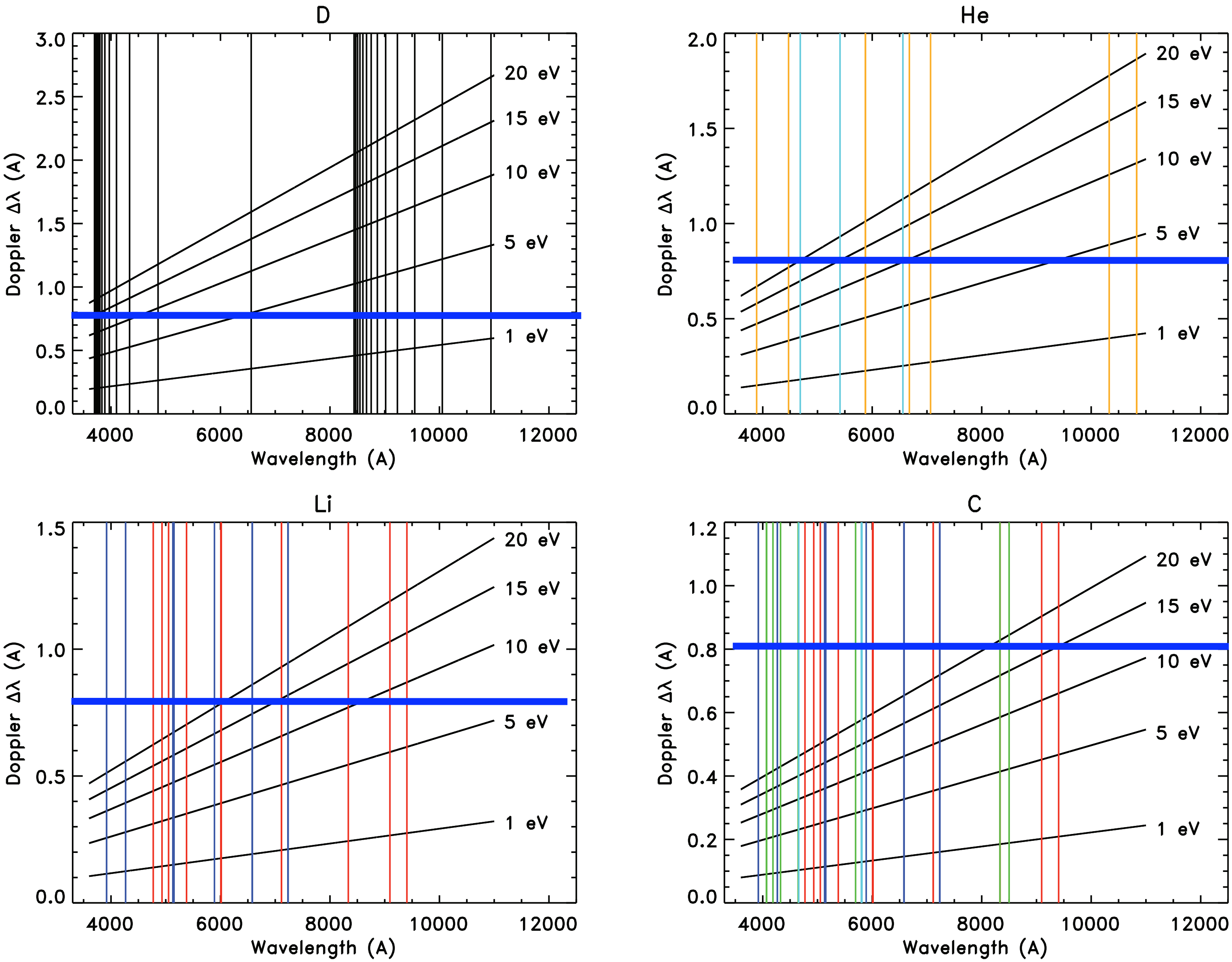
- When ions charge-exchange with neutrals (e.g. D), neutral temperature is close to ion temperature
- Large variety of D, He, Li neutral and ion lines in UV, VIS, and NIR
- Based on PI ProEM CCD, 4 pixels 16 um each, FWHM of one instrumental line takes 64 um, or 0.064 mm
- With given McPherson 207 spectrograph imaging quality and dispersion, FWHM of Doppler broadened line must exceed 0.064 mm on the detector

McPherson 207 with 3600 g/mm grating and Pro EM 512 CCD will have 0.027 nm instr. line



•*35 A on CCD chip*

McPherson 207 with 1200 g/mm grating and Pro EM 512 CCD will have 0.08 nm instr. line



•*100 A on CCD chip*