New spectrometer for SOL and divertor measurements on NSTX*

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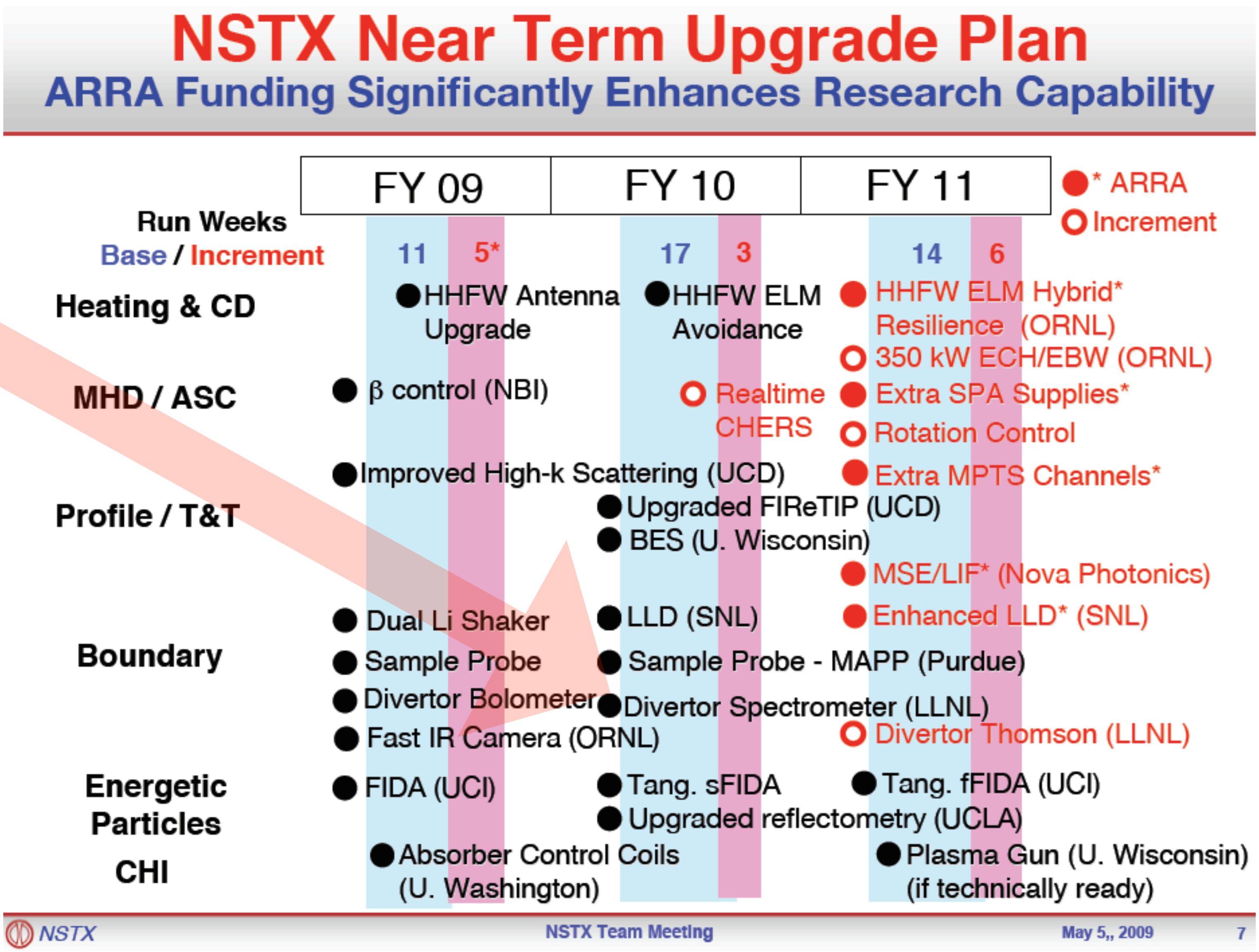
Acknowledgements: R. Bell, R. Kaita, A. L. Roquemore (PPPL)

NSTX Review, 22 May 2009, Princeton, NJ

NSTX Project has approved plans for a new divertor spectrometer for improved LLD diagnosis



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

- Divertor ion source characterization
  - Atomic D, Li, C influx **profile measurements in divertor**
  - Molecular sources (D_2, LiD, BD, CD_4, …)
- 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
- Various applications
  - Divertor and edge measurements in HHFW-heated plasmas
  - Near-infrared spectroscopy for ITER
  - Possibly, SOL flow measurements and helium line ratios
  - Possibly, LTX impurity profile measurements

VIPS 2 spectrometer is used for multi-point divertor and SOL measurements

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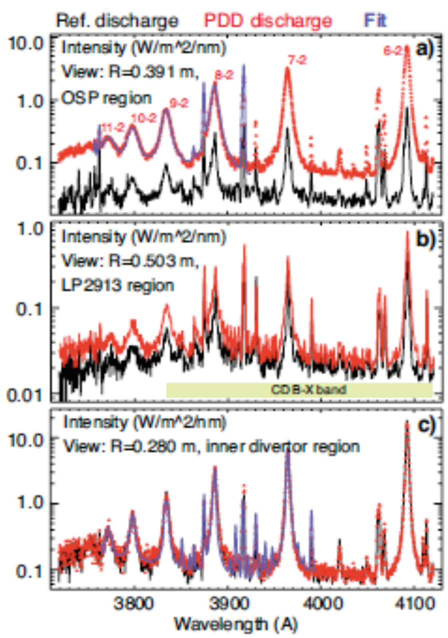


FIG. 9. (Color online) Divertor deuterium Balmer spectra recorded at three lines of sight shown in Fig. 1 in the reference 1.0 MA, 6 MW NBI discharge and the discharge with a partially detached OSP.

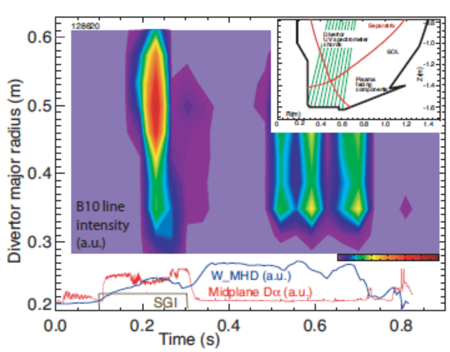


Figure 4: Spectroscopic evidence of X-point MARFE formation during SGI-U gas pulse.

Divertor Heat Flux Mitigation in NSTX High-Performance H-mode discharges 14

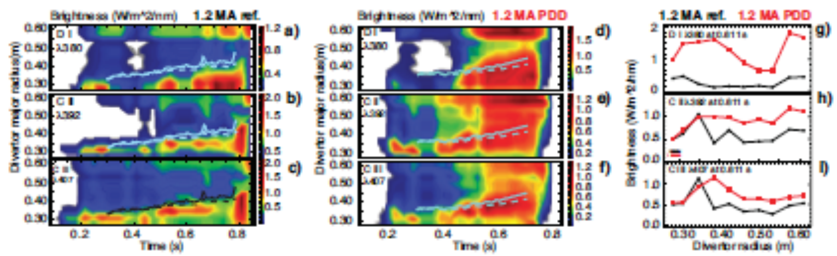


Figure 9. *Time histories of divertor line brightnesses and divertor emission profiles. In the 1.2 MA reference discharge: (a) - Deuterium λ380 nm B10 line, (b) - CII λ = 392 nm line, (c) - C III λ = 407 nm line; In the 1.2 MA PDD discharge: (d) - Deuterium λ380 nm B10 line, (e) - CII λ = 392 nm line, (f) - C III λ = 407 nm line. Panels (g), (h), (i) - Brightness profiles of B10, C II and C III emission in the reference and PDD discharges at 0.611 s. Solid lines show time histories of the OSP major radius. Dashed lines show a projection of the X-point major radius on the divertor along the spectrometer viewing chords.*

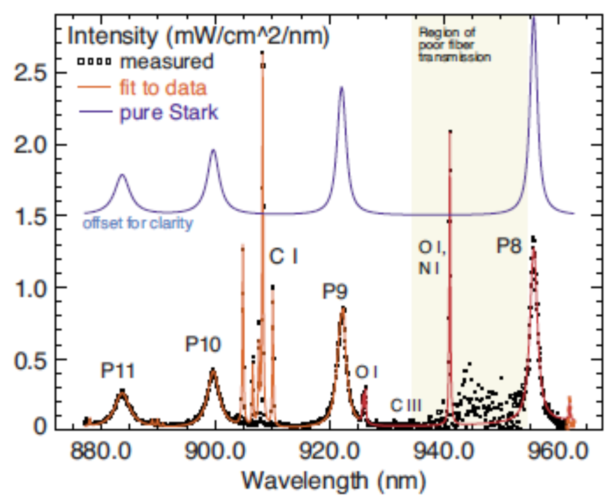


FIG. 3. (Color online) Stark broadening of P8–P11 Paschen series lines in the recombining (detached) divertor.

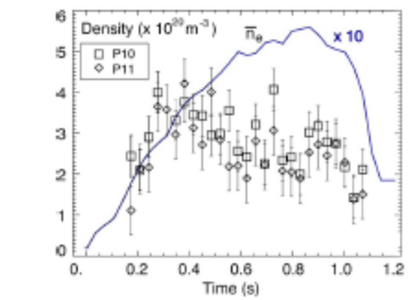


FIG. 5. Comparison of the detached divertor density inferred from the P10 and P11 lines.

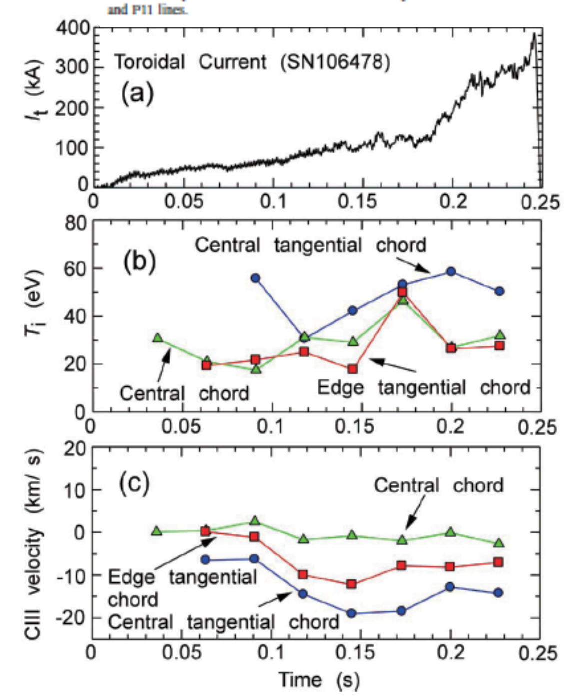


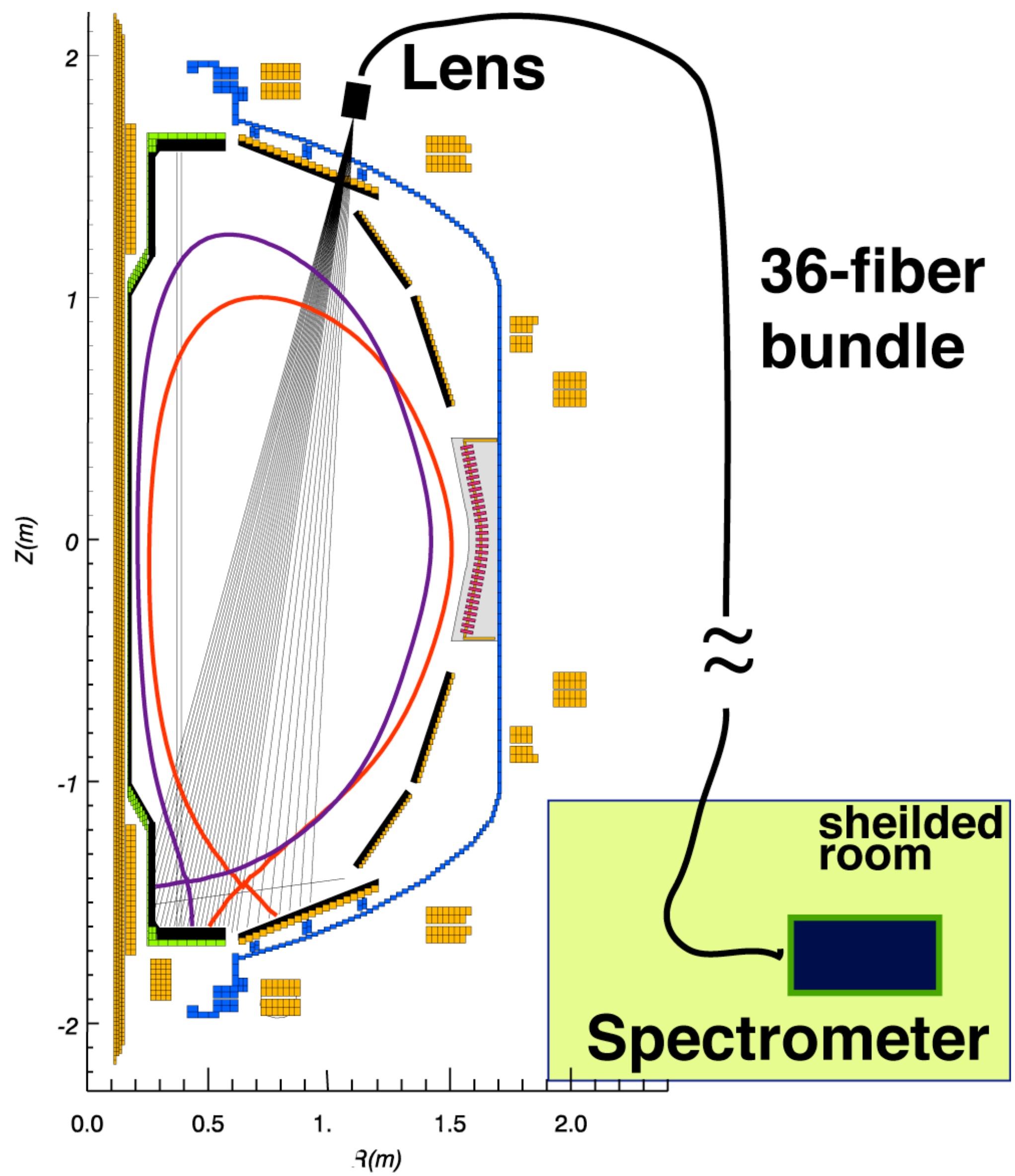
Fig. 3 Time evolution of the toroidal current I_t (a), Doppler ion temperature $T_{i,D}$ (b) and CIII ion flow velocity (c).

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

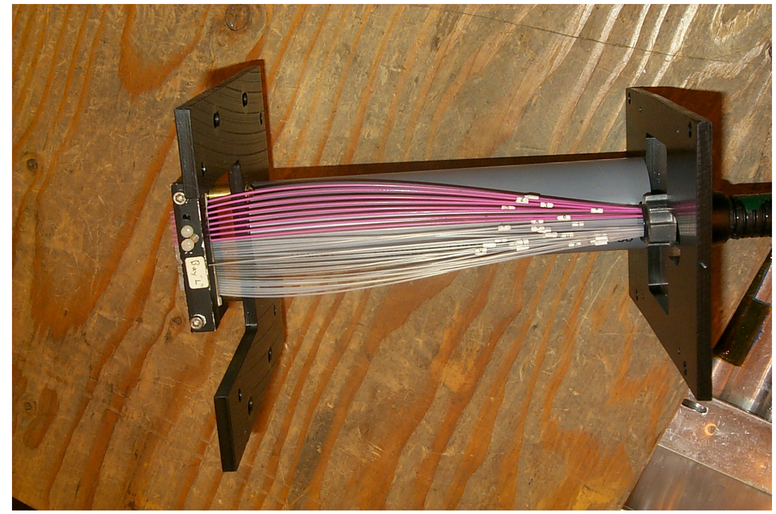
System layout and Components

- Imaging lens
- 30 m fiber bundle
- Spectrometer input optics
- Spectrograph and gratings
- CCD detector

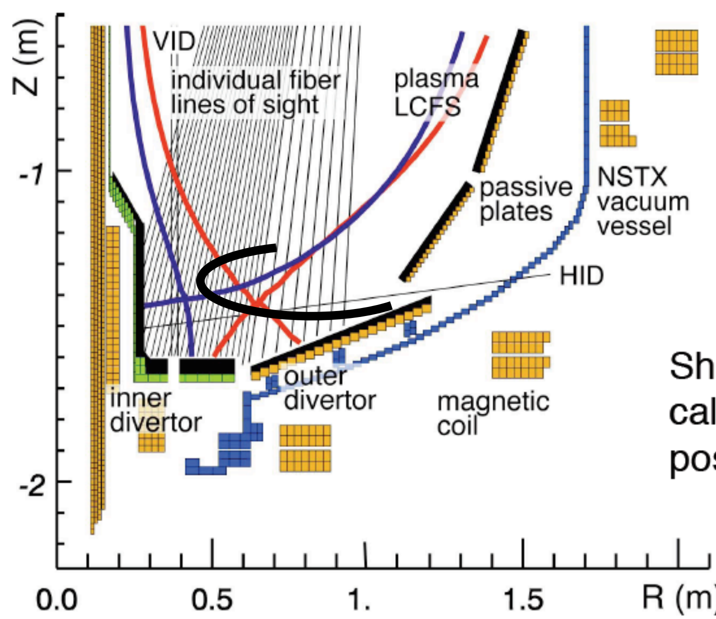


NSTX machine interface and proposed views

- Top divertor view from Bay C top port – existing window with lens and fiber bundle mount (VIPS 2)



- Tangential divertor view from Bay B horizontal divertor port (to share with camera FOB)



Shown are actual calibrated view chord positions

Imaging lens

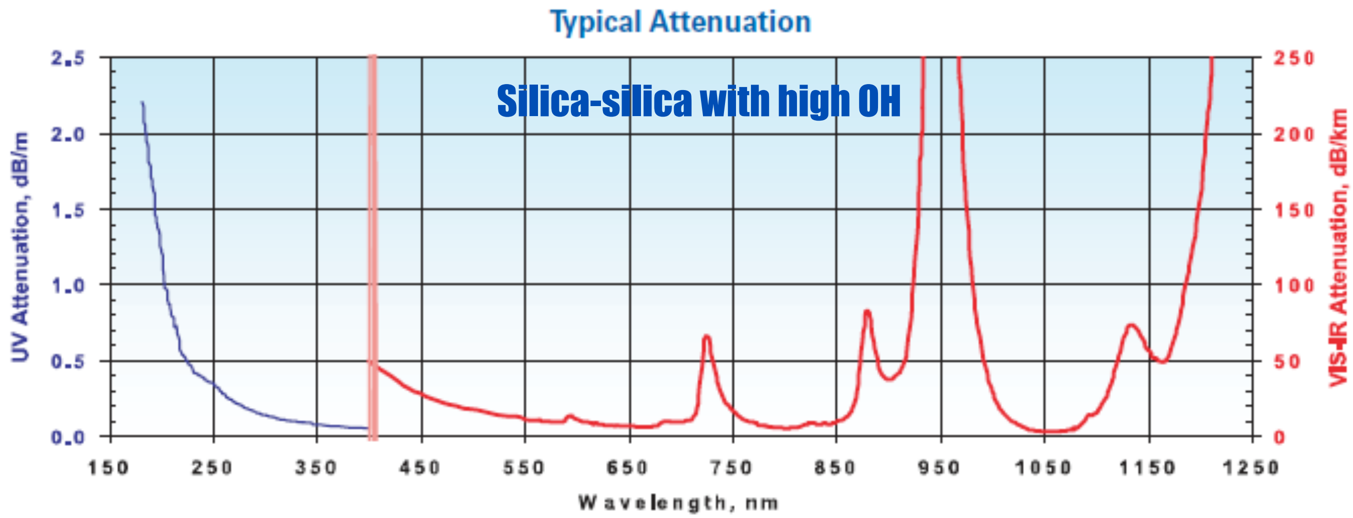
- Present lens –
  Nikon model Nikkor NIK18028DAF, f=180 mm, f/# 2.8
- In initial phase, propose to use this lens
- Eventually will use lens with improved UV transmission

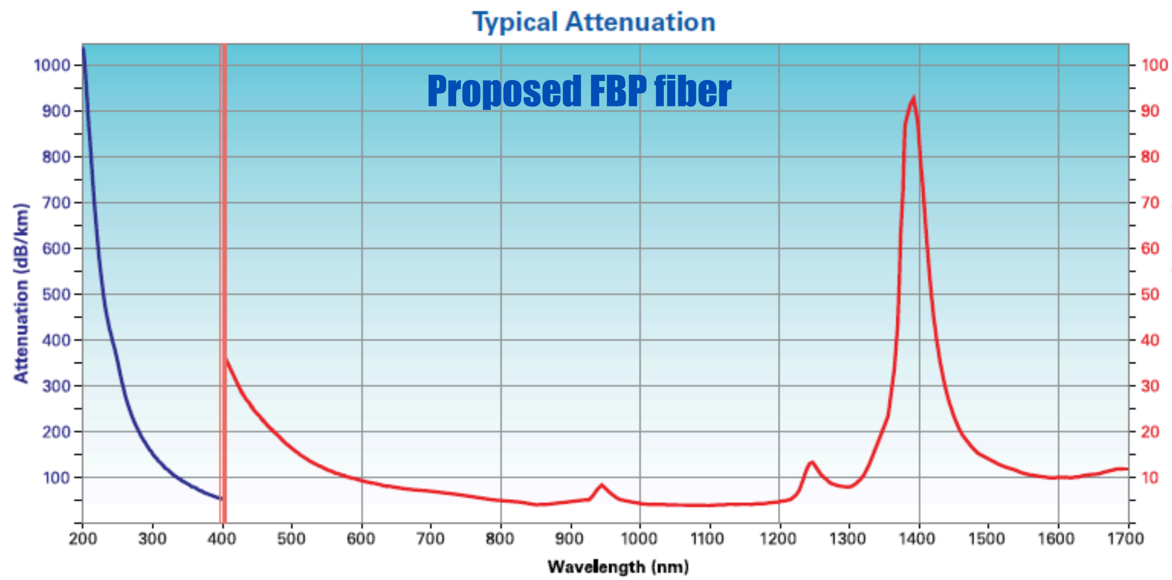
NIK18028DAF

Example of UV-VIS lens

Fibers

- Typical choice – silica-silica with high OH
- Propose new Polymicro FBP broadband fiber
- NA=0.22 (f/#=2.27)



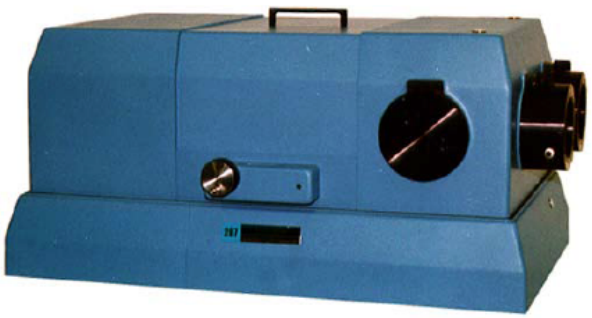


Spectrograph

- Commercial Czerny-Turner mount to minimize development
- McPherson Czerny-Turner spectrographs have highest f/#'s for given focal length in industry (cf Acton Research Corp., HORIBA / Jobin Yvon, Chromex)
- McPherson offers cylindrical correcting mirror for high quality imaging applications
- McPherson offers a variety of large size high groove density holographic gratings

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

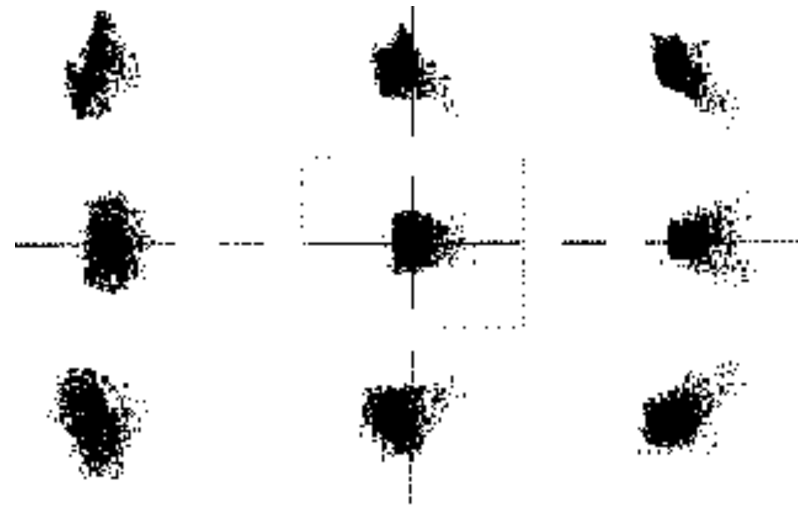


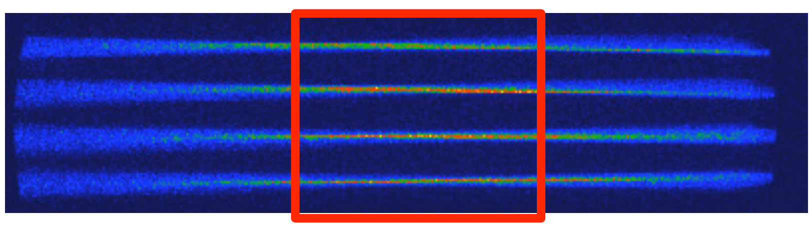
Grating Groove Density (g/mm)	3600	2400	1800	1200	600	300	150	75
Resolution** (nm)	0.012	0.018	0.02	0.03	0.06	0.12	0.24	0.48
Dispersion (nm/mm)	0.43	0.62	0.83	1.24	2.48	4.96	9.92	19.84
Wavelength Range	185 - 430 nm	185 - 650 nm	185 - 860 nm	185 - 1300 nm	185 - 2600 nm	185 nm 5.2 um	185 nm 10.4 um	185 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

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





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 and 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

QUANTUM EFFICIENCY

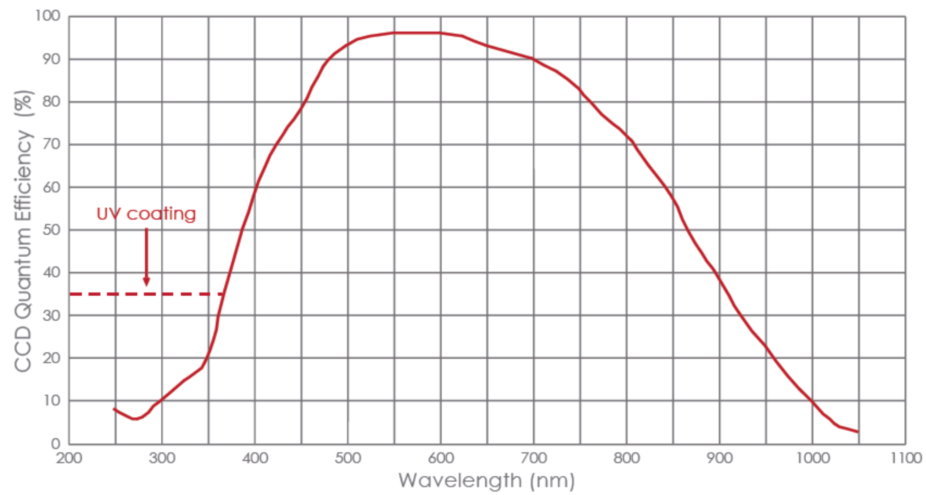


Image sensor	e2v CCD97; back-illuminated, frame-transfer EMCCD	
CCD format	512 x 512 imaging pixels 16 x 16 µm pixels 8.2 x 8.2 mm imaging area (optically centered)	
	EM mode	Normal CCD mode
Read noise (typical)	25 e- rms @ 5 MHz 50 e- rms @ 10 MHz Read noise effectively reduced to <1 e- rms with on-chip 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 33msec exposure time and ~1000x multiplication gain	
Electron multiplication (EM) gain	1 to 1000x, controlled in linear, absolute steps	
Digitization	16 bits @ 10 MHz, 5 MHz, 1 MHz and 100kHz	
Vertical shift rate	300 nsec/row - 5 µsec/row (variable)	
Binning	Flexible binning in vertical and 2x to 32x in horizontal	
Operating systems supported	Windows XP/Vista	
I/O signals	Exposure, Readout, Trigger In	
Operating environment	0 to 30°C ambient, 0 to 80% relative humidity, non-condensing	

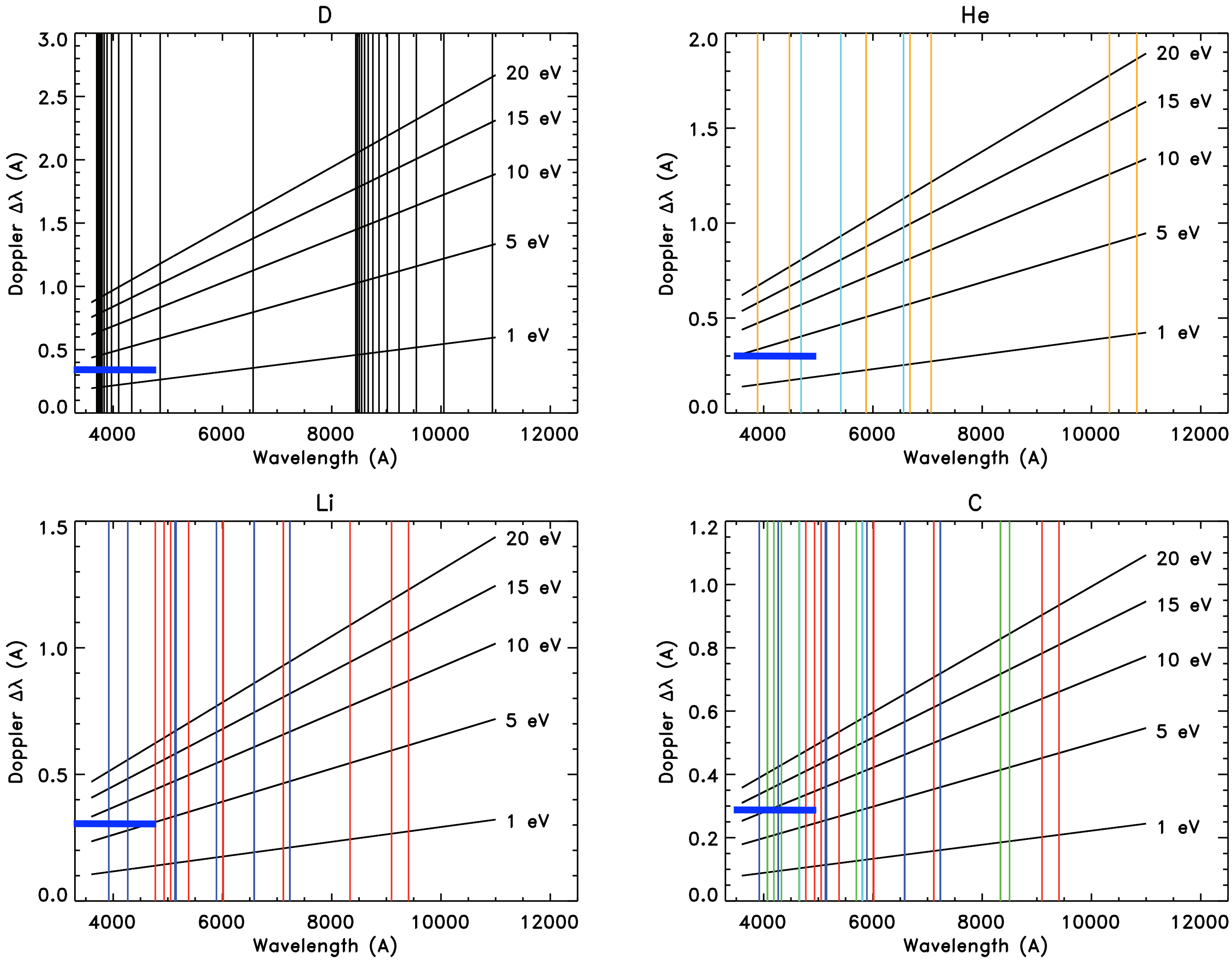
Doppler spectroscopy

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

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

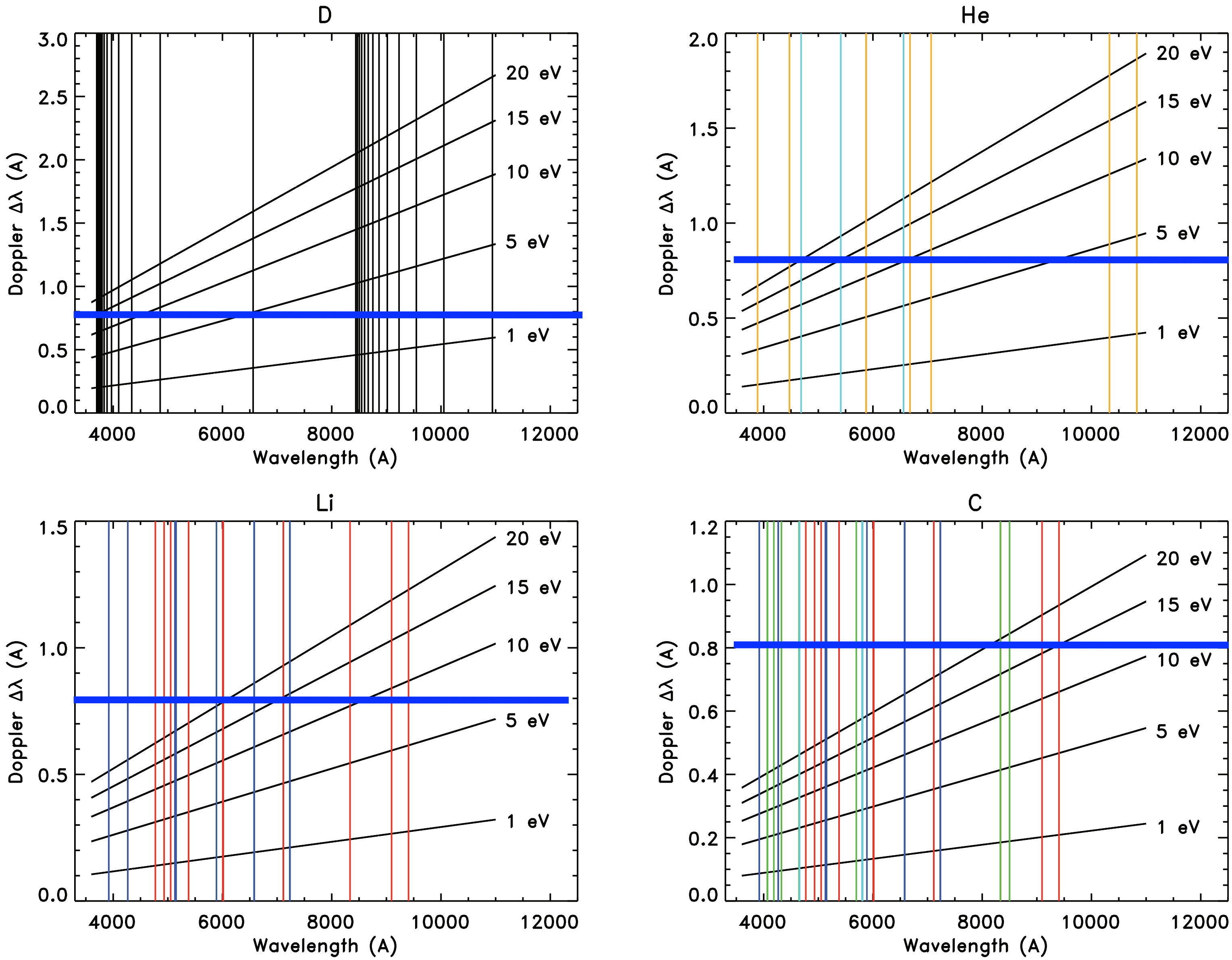
- When ions charge-exchange with neutrals (e.g. D), neutral temperature is close to ion temperature
- Large variety of D, He, Li neutral and ion lines in UV, VIS, and NIR
- Based on PI ProEM CCD, 4 pixels 16 um each, FWHM of one instrumental line takes 64 um, or 0.064 mm
- With given McPherson 207 spectrograph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

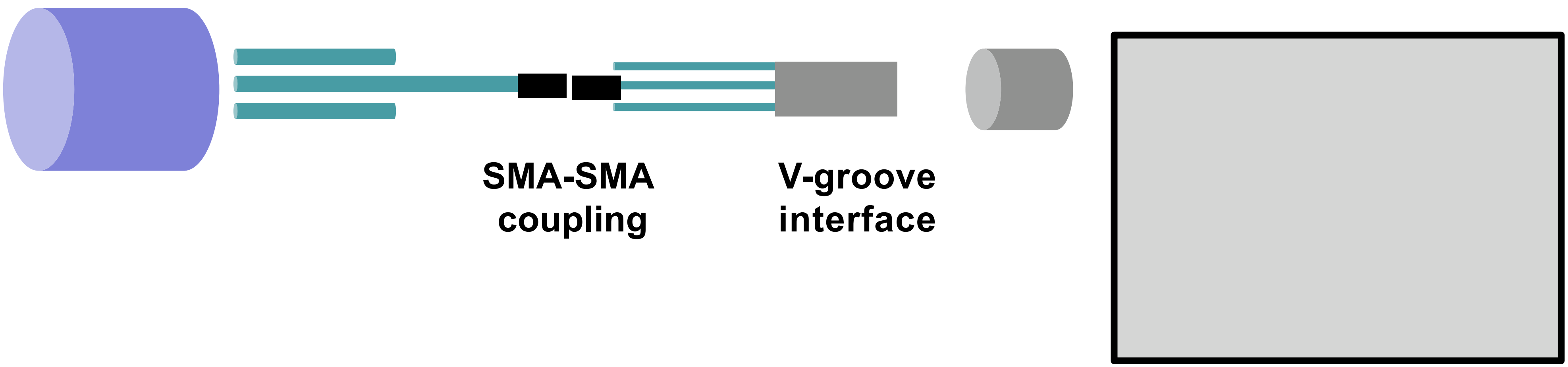


100 A on CCD chip

Conjugation of optical components

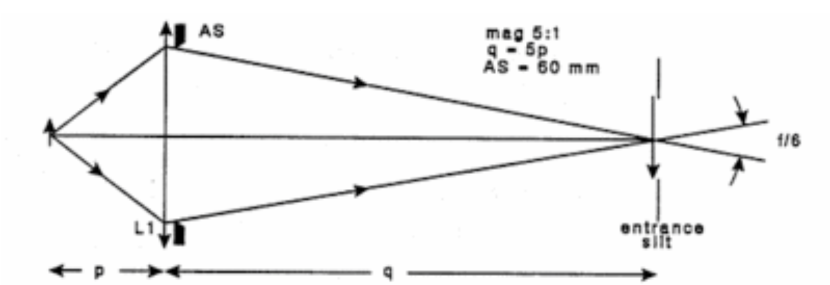
- Matching F numbers:

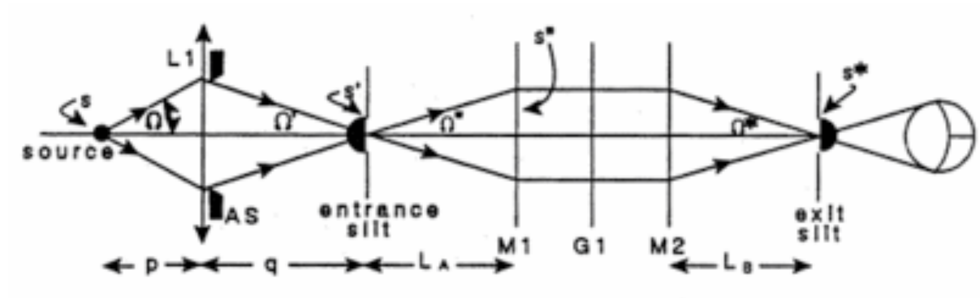
Lens: 2.8 - Fiber: 2.3 - Matching optics: from 2.8 to 4.7 - Spectrograph: 4.7



- Magnifications:

Lens: 1./16.7 - Fiber: 1 - Matching optics: 1.68 - Spectrograph: 1





Summary

- Lens ($ 4 K)
- New fibers ($ 20 K)
- Fiber matching optics ($ 5 K)
- McPherson spectrograph ($ 35-45 K)
- Princeton Instruments CCD camera ($ 38 K)
- New PC ($ 1 K)
- Misc. small parts ($ 2 K)
- Total M&S: $ 105-115 K
- Minimal technical labor
  - Need technician to put fibers in core-lock
  - Need machinist to make front-end fiber holder
  - Need programmer to adopt existing software for CCD

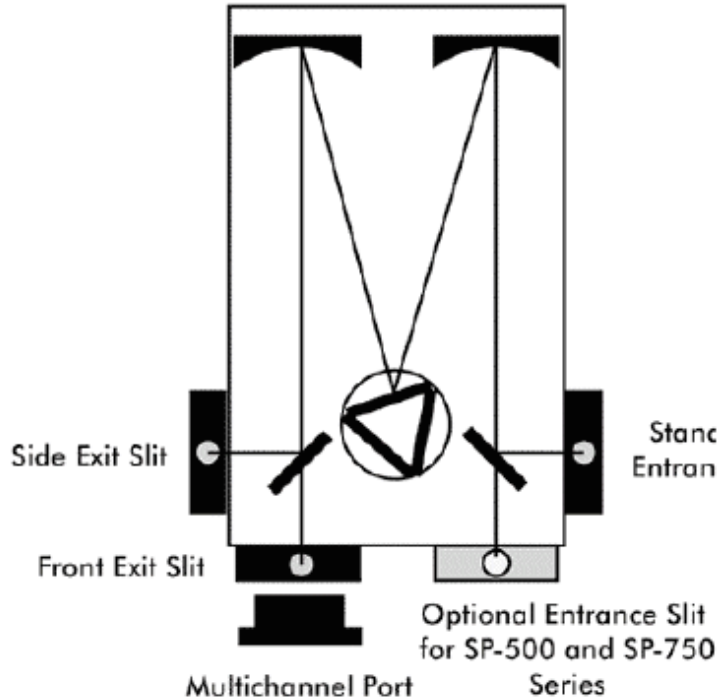
Schedule

- June 2009
  - Order McPherson spectrograph (delivery 2-3 months)
  - Order CCD detector (delivery 4-7 weeks)
  - Finalize design of input optics and order components, including fibers (delivery 4-6 weeks)
- September – December 2009
  - Mount new fiber holder at Bay C top port
  - Run fibers from NTC
  - Put together spectrometer components
  - Develop DAQ
  - System tests with full system

Reference: VIPS 2

- Acton Research SpectraPro 500i
- 0.5 m. *f* / 6.5 Czerny-Turner scheme
- **Ten** input fibers with *f*-matching optics
- Three gratings: 600, 1200, 2400 l/mm
- CCD detector - 1340 x 100 pixel Princeton Instruments Model Spec-10:100B
- CCD operated in binned mode
- Typical readout times 15-50 ms / chip

- Spectrometer and imaging system photometrically calibrated with URS-600 LabSphere radiation standard *in-situ* on NSTX



Model	150 g/mm	300 g/mm	600 g/mm	1200 g/mm	1800 g/mm	2400 g/mm	3600 g/mm
SP-150	40 nm/mm 1000 nm	19 nm/mm 483 nm	9 nm/mm 229 nm	4 nm/mm 100 nm	2.2 nm/mm 56 nm	1.2 nm/mm 30 nm	1.1 nm/mm 28 nm
SP-300i	21 nm/mm 533 nm	11 nm/mm 279 nm	5 nm/mm 127 nm	2.3 nm/mm 58 nm	1.4 nm/mm 36 nm	0.85 nm/mm 22 nm	0.7 nm/mm 18 nm
SP-500i	13 nm/mm 330 nm	6.5 nm/mm 165 nm	3.2 nm/mm 81 nm	1.5 nm/mm 38 nm	0.9 nm/mm 23 nm	0.6 nm/mm 15 nm	0.45 nm/mm 11.5 nm
SP-750	8.8 nm/mm 224 nm	4.4 nm/mm 112 nm	2.2 nm/mm 56 nm	1 nm/mm 25 nm	0.6 nm/mm 15.2 nm	0.4 nm/mm 10 nm	0.3 nm/mm 7.6 nm