Measurements of recycling on liquid lithium divertor module in NSTX*

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Acknowledgements: R. Kaita, H. W. Kugel, A. L. Roquemore (PPPL), K. Tritz (JHU)

NSTX Review, 13 February 2009, Princeton, NJ

Recycling measurements will be important for LLD performance characterization

- Need to *measure* local recycling from LLD
- Define recycling as $R_{local} = \Gamma_i^{out} / \Gamma_i^{in}$
  - Ion flux into LLD Γ_i^{in} is measured by Langmuir Probes (combined PPPL / UIUC effort)
  - Ion outflux Γ_i^{out} into SOL plasma can be estimated from measured D flux and S/XB (ionizations/photon) coefficient from ADAS
    - Need absolutely calibrated D photon flux
    - Need molecular emission measurements to include contributions from molecules (outside of this talk)
- Recycling measurements are useful for UEDGE / Degas 2 modeling
  - calculation constraints
  - infer a global picture of LLD performance (pumping, etc)

Existing divertor Balmer line measurements will be difficult to interpret due to reflections from LLD

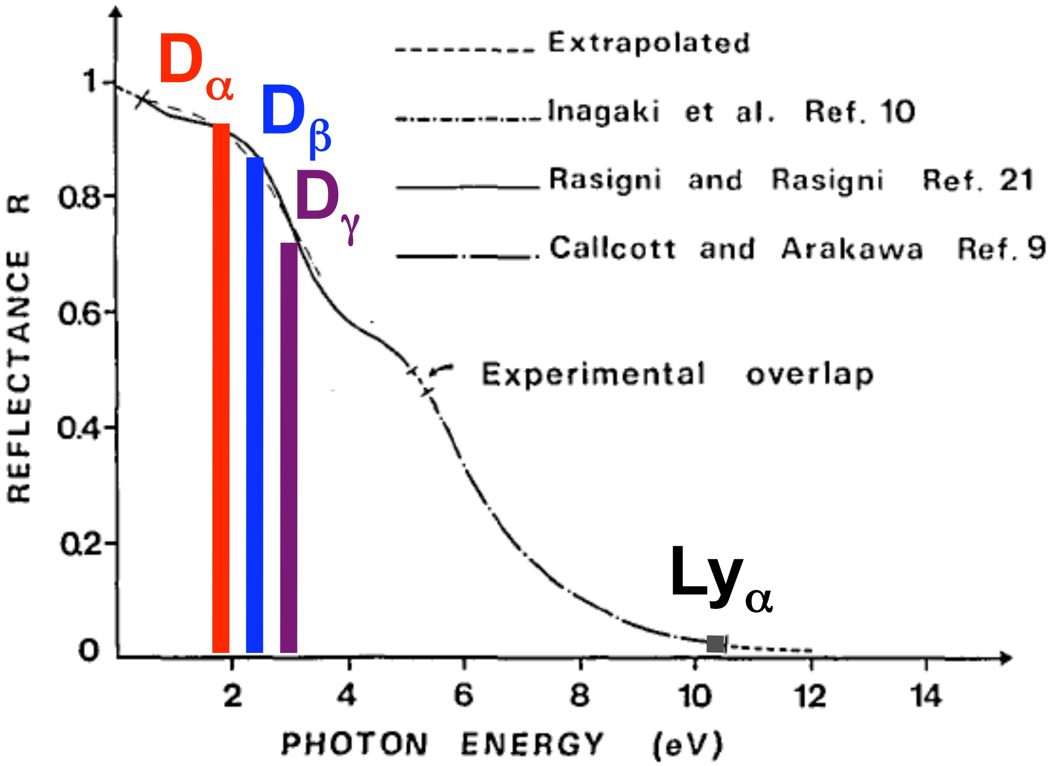
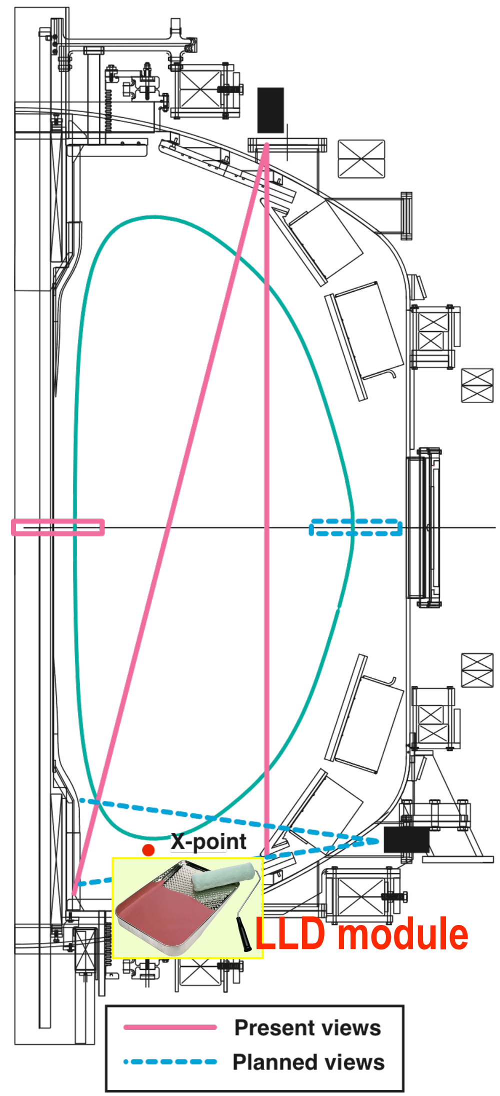


FIG. 1. Normal incidence reflectance data of lithium.

- 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



Existing D_α, D_β camera views

Ly$_\alpha$ diagnostic requirements

- Absolute calibration – need to convert the number of photons to ionizations
- Spatial coverage – lower divertor, with several chords on LLD
- Time response – need 1 kHz for steady-state, > 10 kHz for ELM-resolved measurements
- Data serving on a shot-to-shot basis
- Flexibility with spectral coverage desirable – e.g., Ly$_\alpha$, bolometry, Li II, C IV

Lyman-α diagnostic: wavelength selection elements and detectors

- Wavelength selection in far UV
  - Dispersive elements (e.g., diffraction gratings, prisms)
  - Narrow bandpass filters

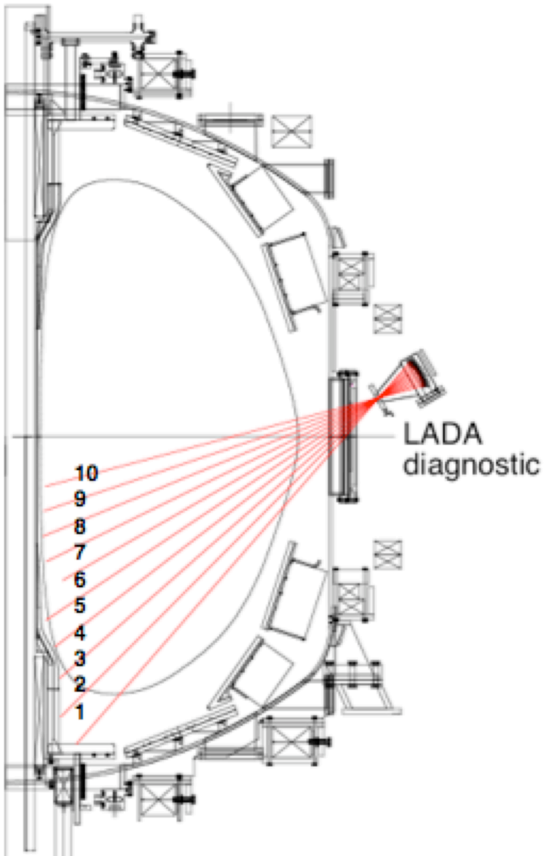
- Photon-efficient far UV detectors
  - Micro-channel plates + scintillators + CCD cameras
  - FUV scintillators + visible detectors (cameras, PMTs)
  - Photo-diodes

Main requirement: need for absolute calibration

=> Only option: filter + AXUV diode

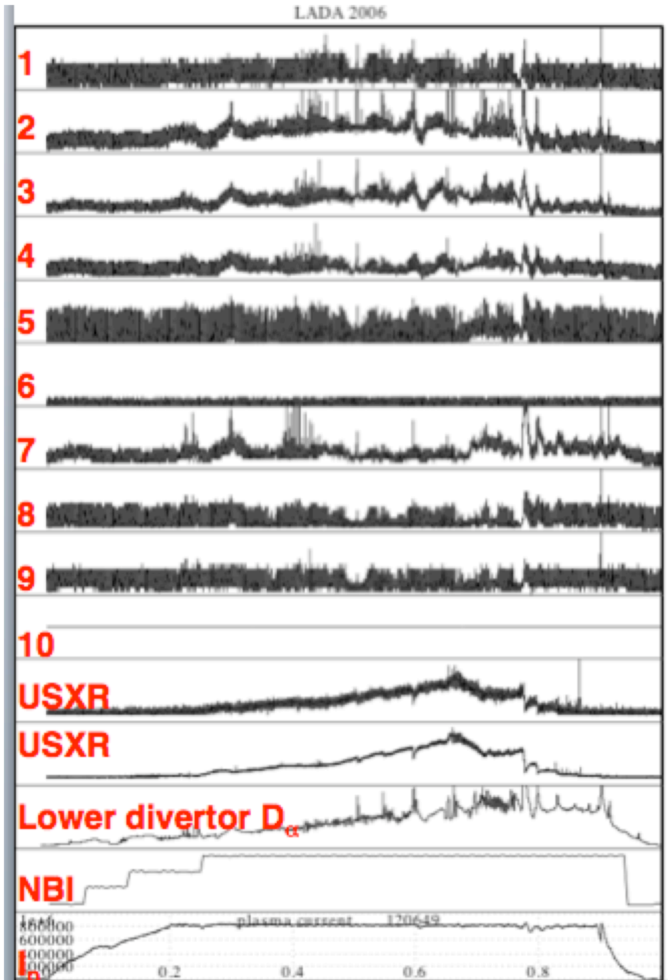
Positive first experience with Ly_{α} measurements obtained in NSTX in 2006

LADA diagnostic on NSTX monitored recycling from lower inner wall and inner divertor regions

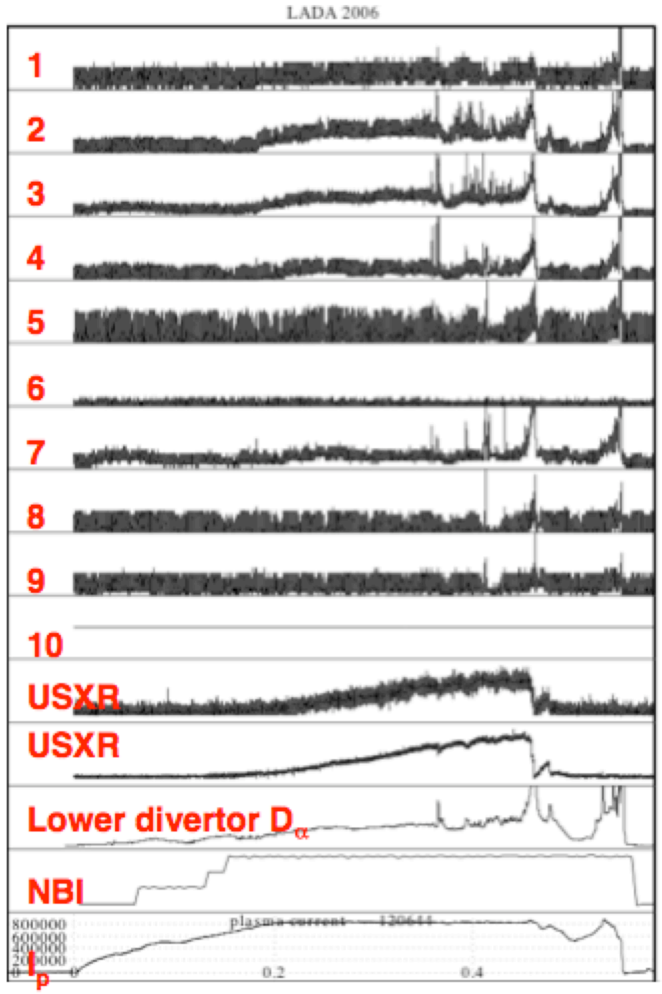


- Installed on Bay J midplane port in mid-May 2006
- Operated for about one month
- Used ten CAMAC differential amplifiers provided by CDX-U
- Used ten channel PC-based DAQ system provided by JHU
- Channel 1 was vignetted by in-vessel hardware
- Otherwise collected good data (examples on next page)

Positive first experience with Ly_α measurements obtained in NSTX in 2006



Ly_α filter mode



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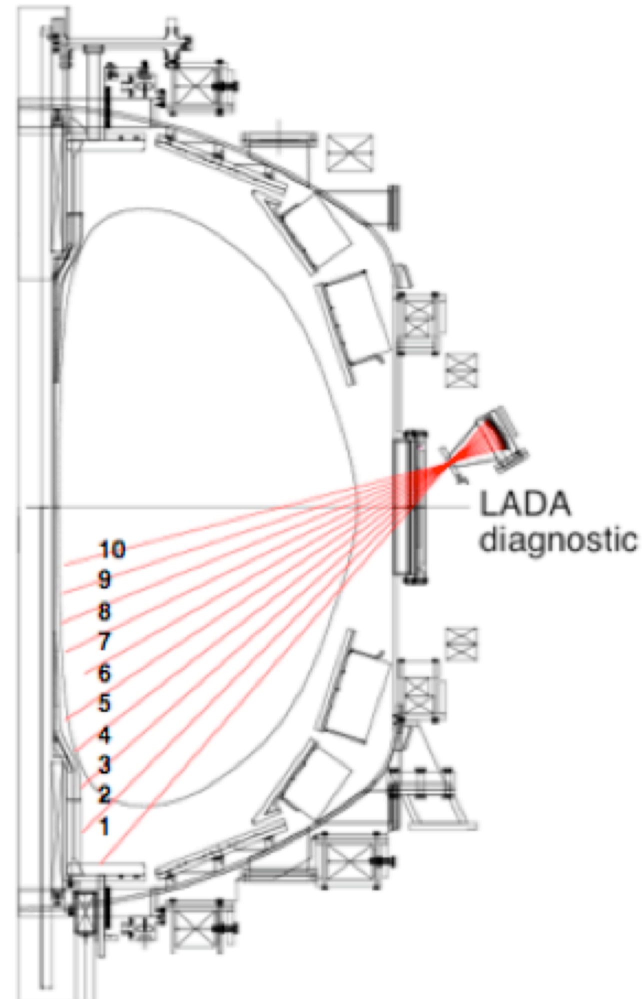
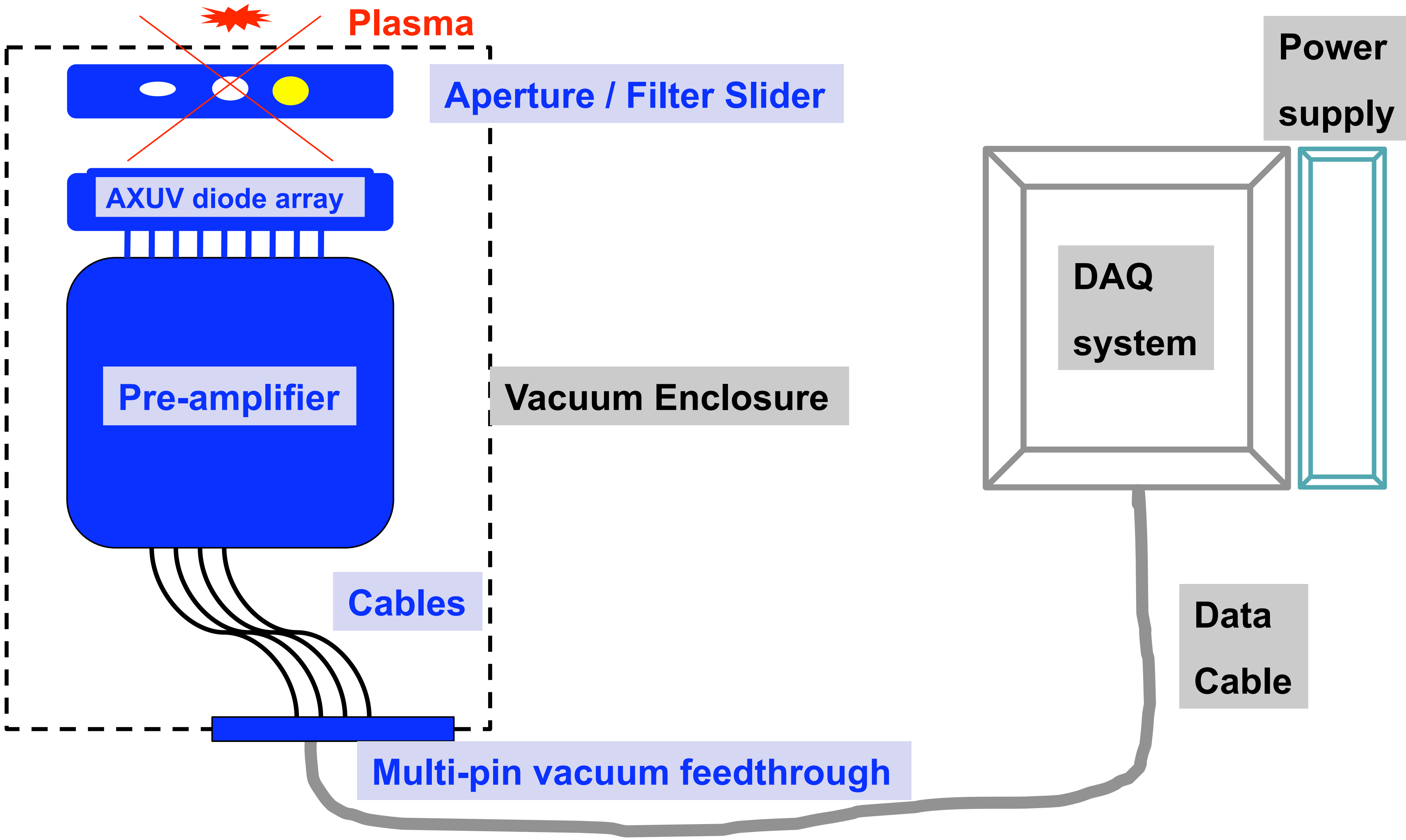
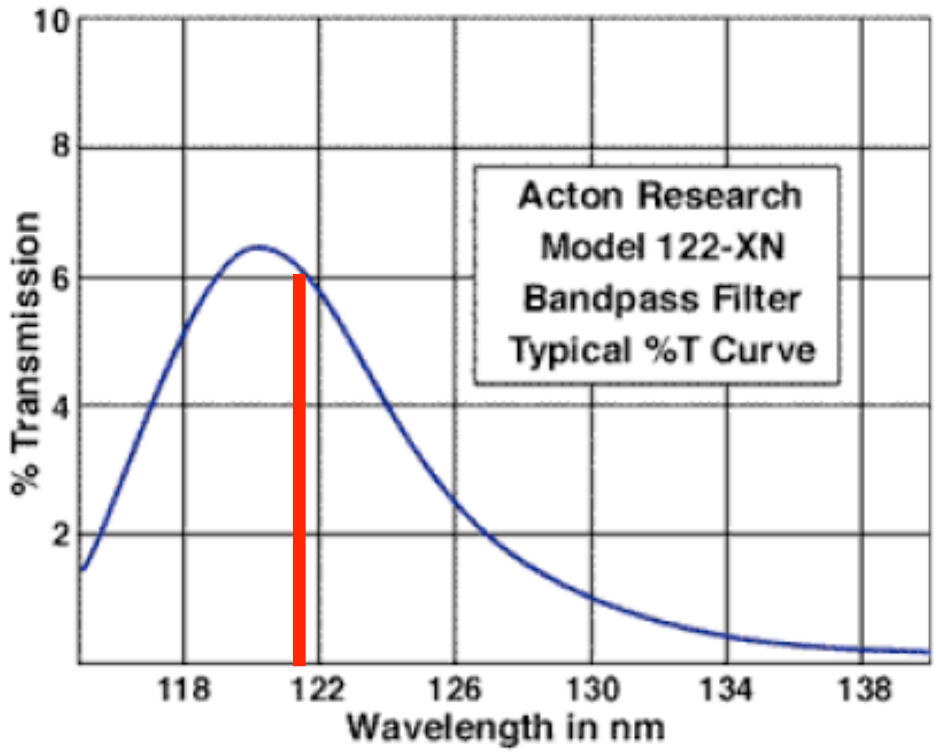
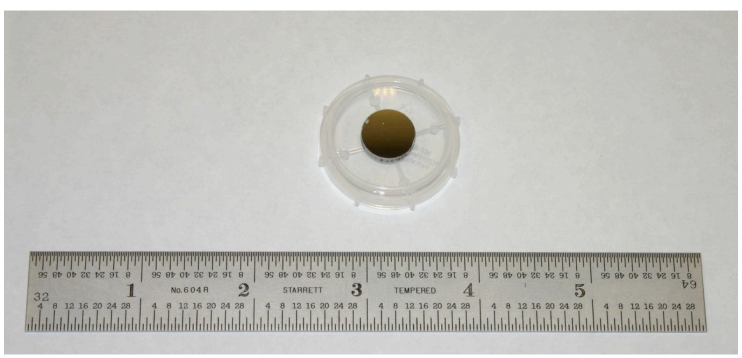


Conceptual layout of pin-hole Ly-α camera



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 (Li, C, O) emission lines within bandpass (e.g. Boivin et. al. RSI 72 (2001) 961

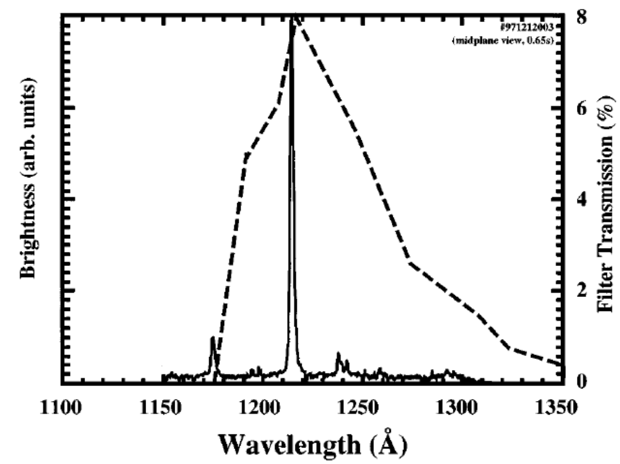
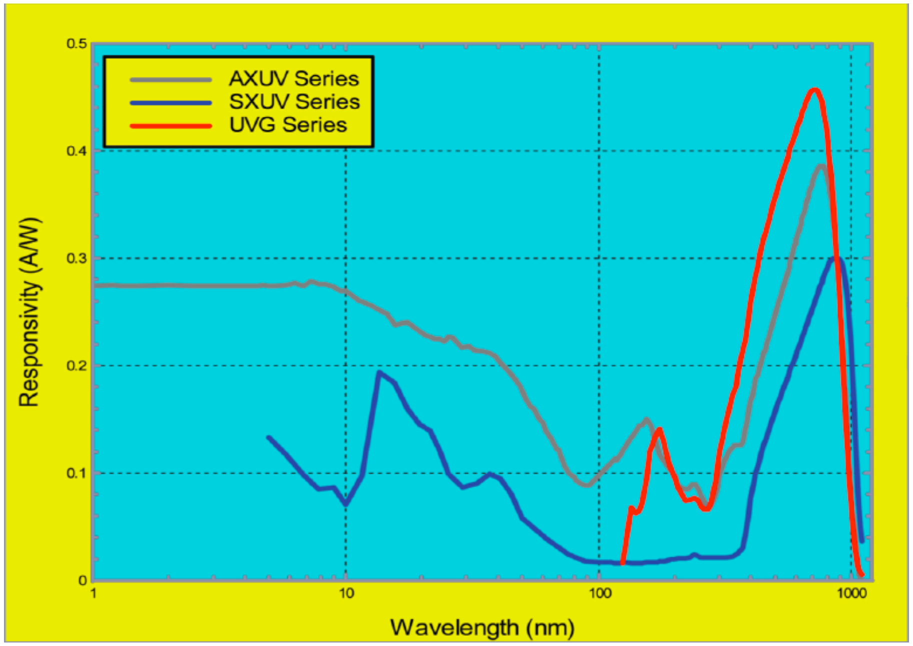


FIG. 3. Measured plasma emission in the UV region using a McPherson (VUV) spectrometer. Overlaid is the measured filter response.

AXUV diode arrays from IRD



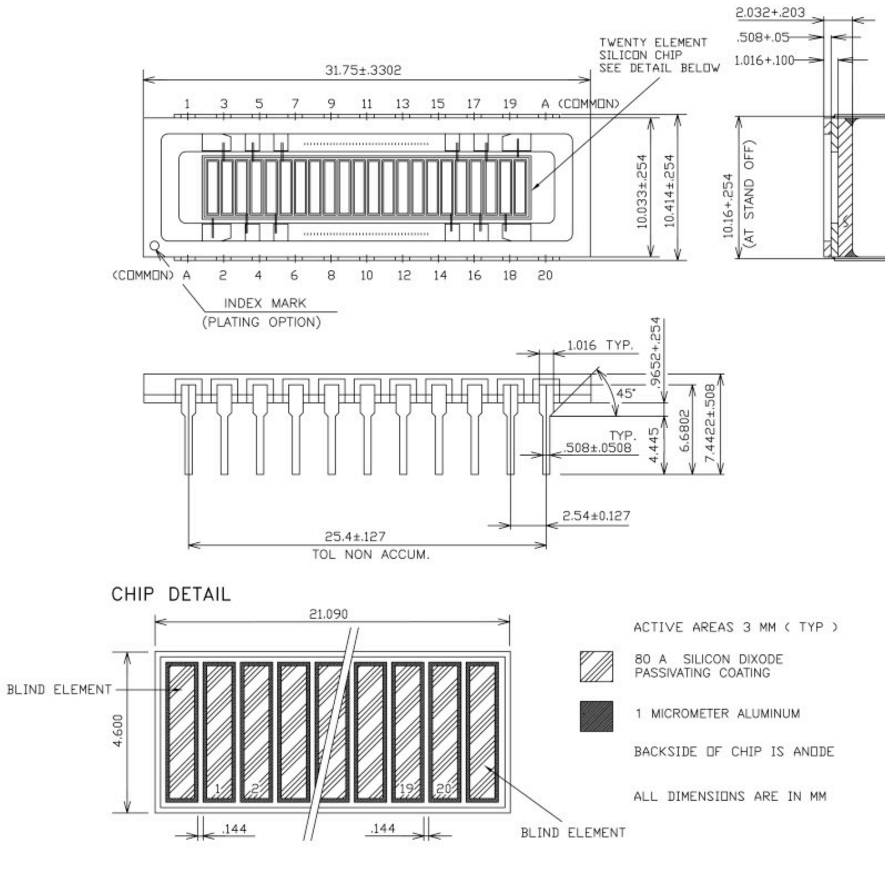
Propose to buy two AXUV arrays:

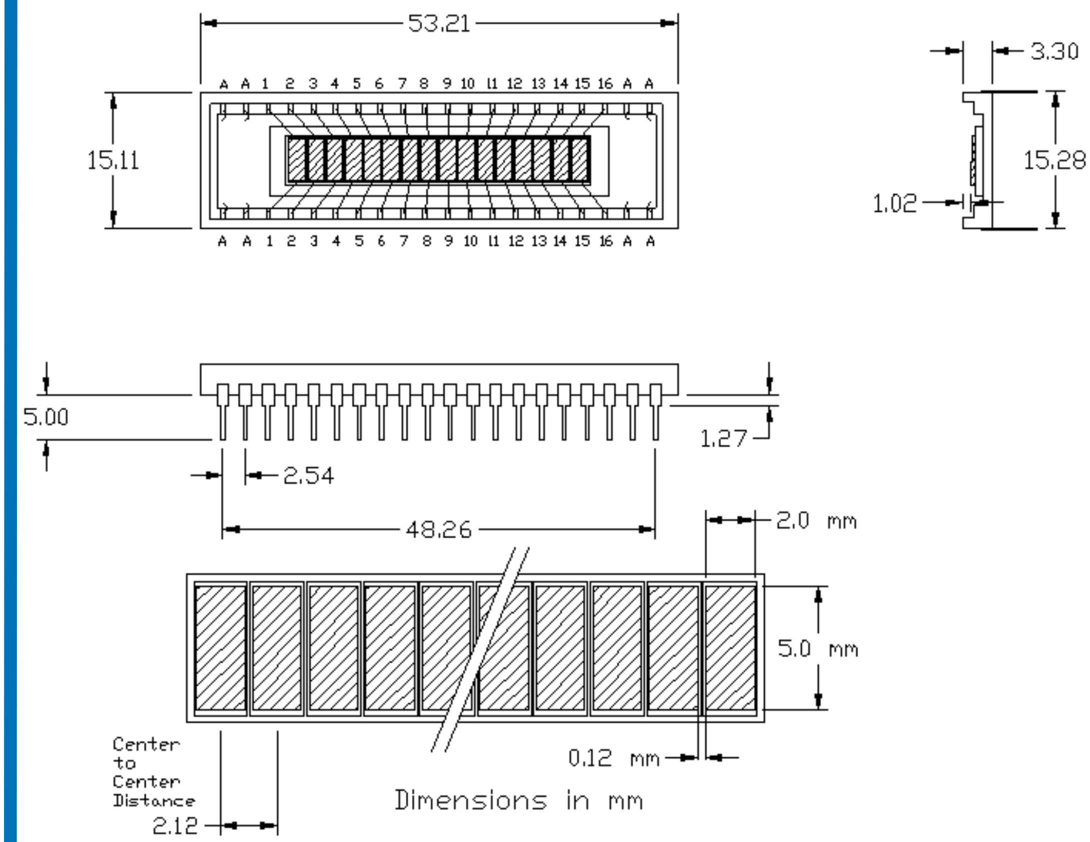
- AXUV20EL (workhorse)
- AXUV16EL (backup)

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

AXUV-20EL and AXUV16EL arrays



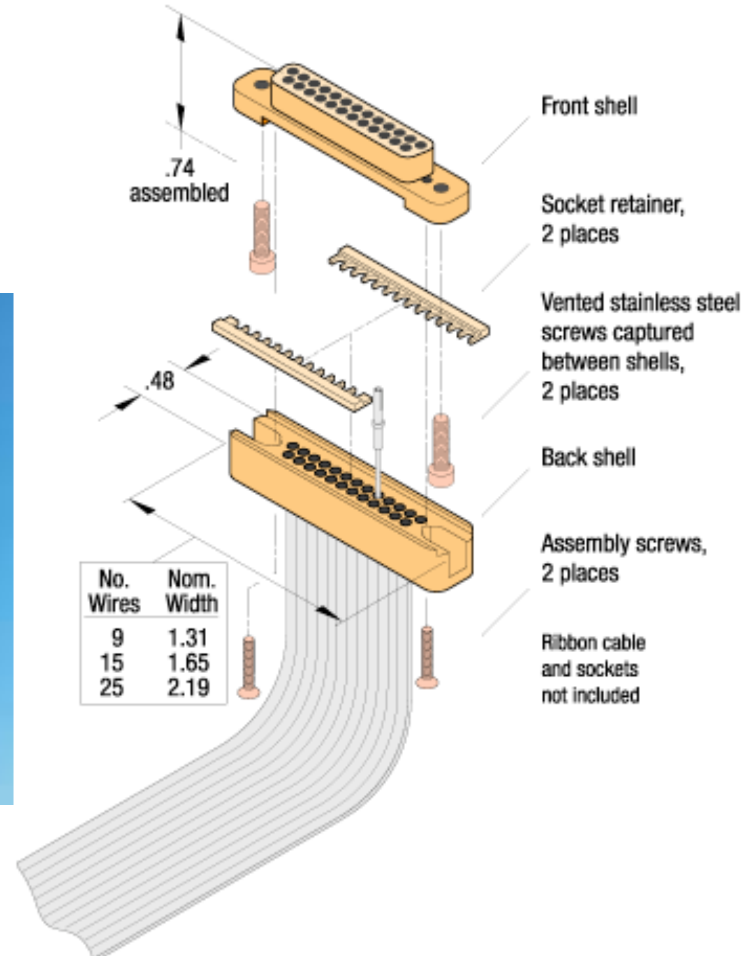


UHV-compatible pre-amplifier

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

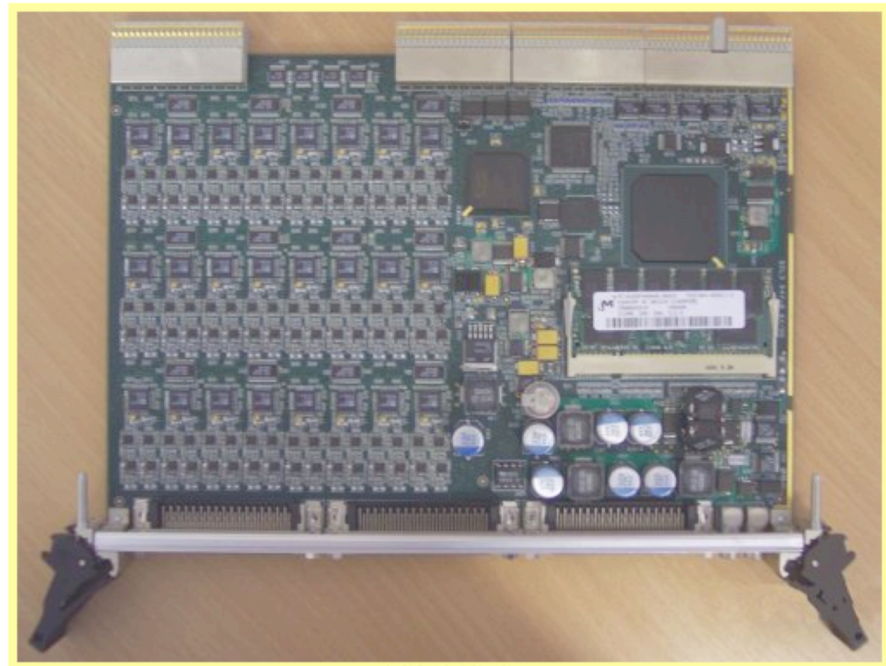
Cables, connectors, feedthroughs

- 50 pin 2-3/4" flange feedthrough
  - UHV compatable materials
  - 250°C bakeout temperature
  - Kapton® insulated wire
- UHV-compatible connectors



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

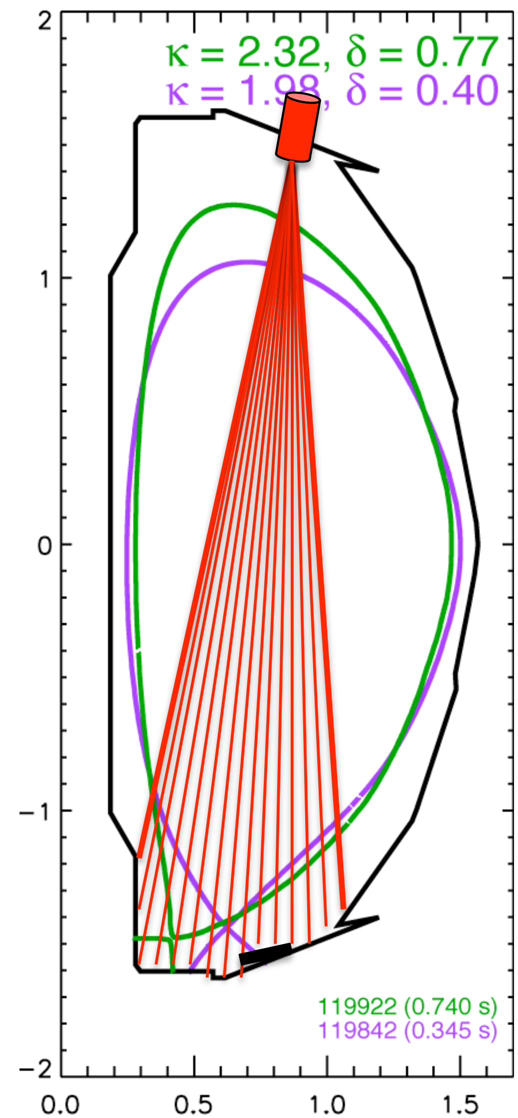


ACQ196CPCI

Plan for installation and operation on NSTX

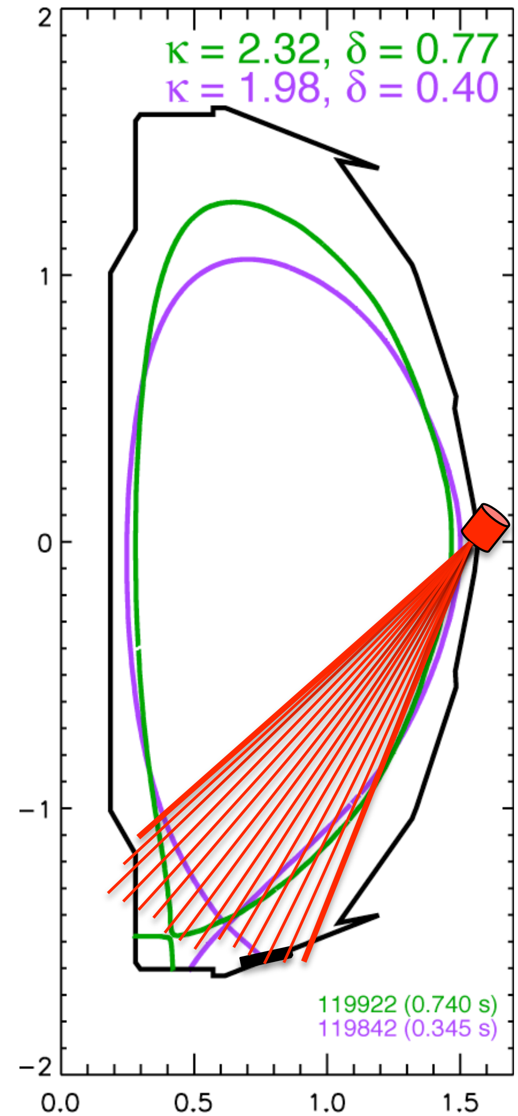
- **Phase 1 -** initial FY 2009 operation
  - Install at Bay G top port with TIV
  - No cooling required
  - Goal is to test the design and all aspects of operation before LLD installation
  - Rack for DAQ module identified
  - Install by late summer 2009

- Geometry calculations
  - Lower divertor spatial coverage requirement – 0.80 m, spread angle – 13.8°
  - Magnification: ~ 33, Pinhole-AXUV array distance – 0.10 m
  - For 2 mm spacing between diode elements, 33 X 2 mm = 66 mm spacing on divertor



Plan for installation and operation on NSTX

- **Phase 2** – LLD operation
  - In-vessel installation at candidate port
    - on the wall in pump duct, or
    - on flange at Bay G midplane
  - Cables will be taken out through 2-3/4” flange
  - Will need in-vessel air or water cooling – package temperature not to exceed 70^{o} C during bakeout and operation
  - Remotely controlled filter and aperture slider



Signal estimates

- Input parameters
  - AXUV diode efficiency at Ly_{α} wavelength - 0.11 A W^{-1}
  - Ly_{α} filter transmission - 0.06 (or 6%)
  - Pre-amp gain - 10^6 V A^{-1}
  - Diode area - $3x10^{-6}$ m^{-2} (AXUV-20EL) or 10^{-5} m^{-2} (AXUV-16EL)
  - Etendue - $3x10^{-4}$ x A_0 sr m^2 or 10^{-3} x A_0 sr m^2
  - Ly_{α} brightness - 10^3-10^5 W m^{-2} sr^{-2}
  - Variable parameters: pinhole aperture e.g., A_0=10 mm^2
- Signals – lower bound ~ 0.02 V, upper bound 5 V

Cost estimates

- **M&S – total about 20 K** with DAQ
  - AXUV diode array from IRD, Inc. - $ 1.25-1.6 K
  - Ly$_\alpha$ Filter from ARC - $ 1 K
  - Pre-amplifier from Clear-Pulse, Inc. – $ 5 K
  - Vacuum feedthrough from ISI - $ 1 K
  - Cables – $ …
  - Data acquisition module from D-TACQ - $ 10,600.00
- Labor
  - Need to design and make housing and holder for Phase 1
  - Need technician to make cables and connections
  - Computer system integration
  - Need to design housing and cooling for Phase 2

Future directions

- More arrays with better spatial coverage
- Routine operation in Recycling / Radiated power / Li modes
- Can measure C IV 155.0 line with bandpass filter from ARC (similar to Ly_{α} filter)
- Can measure Li II 19.9 nm line with multilayer foil filter (e.g., Al/Nb/C with bandpass 17-21 nm) or a multilayer mirror

Appendix – previous presentations

- Presentation on Ly_{α} array for NSTX LLD measurements – LLD diagnostics FDR 07/2008
- Presentation to CDX-U / LTX group on Ly_{α} measurements – 08/2006

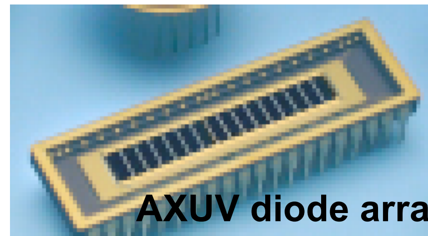
Lyman-α arrays to be used for recycling rate measurements from highly reflective LLD

Mirror-like lithium surface will complicate interpretation of visible (400-750 nm) spectroscopic diagnostics

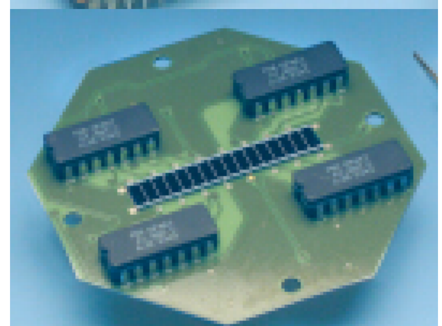
AXUV diode arrays with bandpass filters measure Ly-α n=1-2 H/D transition at 121.6 nm, where reflections are negligible

16-20 channel diagnostic can be assembled from off the shelf components for 10 K, plus 10-15 K for DAQ system

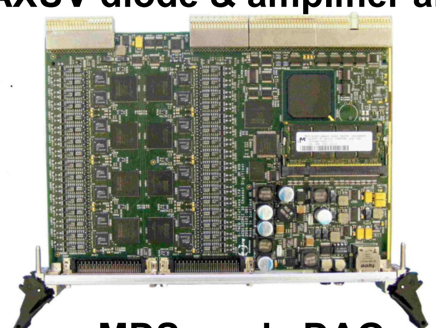
One array will be fielded in FY09 at Bay G upper divertor port



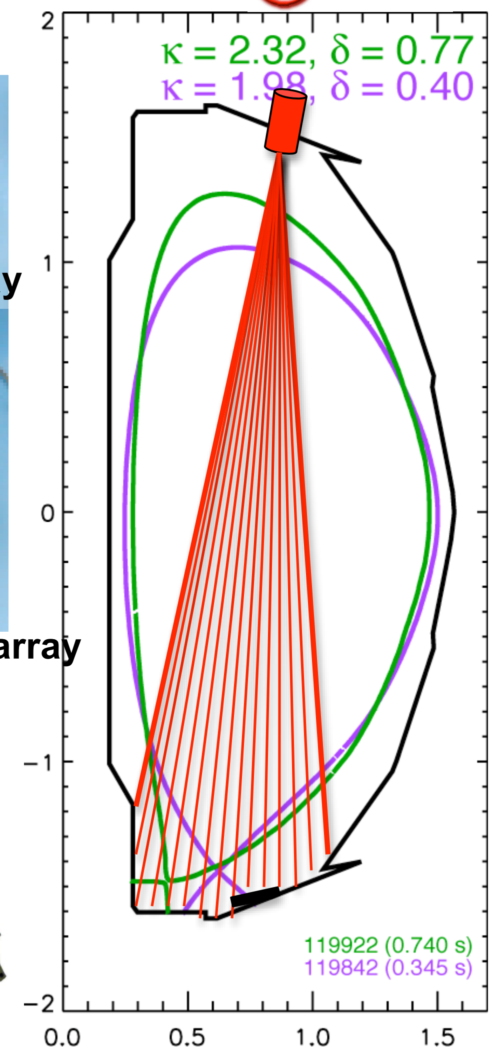
AXUV diode array



AXUV diode & amplifier array



MDS-ready DAQ



V. Soukhanovskii, LLNL

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Recycling measurements using hydrogen (deuterium) Lyman Alpha line and AXUV diodes

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Acknowledgements:

R. Kaita[a], A. L. Roquemore[a], K. Tritz[b]

[a]Princeton Plasma Physics Laboratory, Princeton, NJ
[b]The Johns Hopkins University, Baltimore, MD

LTX Meeting
Princeton, NJ
15 August 2006

Recycling measurements background

- Recycling is the dominant (*) source of fueling in present day plasma fusion devices (* with some exceptions)
- Recycling is usually measured spectroscopically using atomic H (D) line emission
- Simple measurements - can be done with
  - spectrometers
  - detectors with narrow bandpass interference filters
- Since recycling is localized to the surface plasma layer, line integrated measurements are usually not contaminated by main plasma emission
- However, **if the surface is reflecting, measurements are hard to interpret**

Spectroscopic background

- Balmer alpha line H_α (D_α) (3-2) is most commonly used
  - λ=656.3 nm (656.1 nm) - it's in the visible range
  - …where many optical detectors (CCDs, PMTs, silicon diodes, APDs, …) have high efficiency
  - However, PFC surface reflections are a problem (very high!)

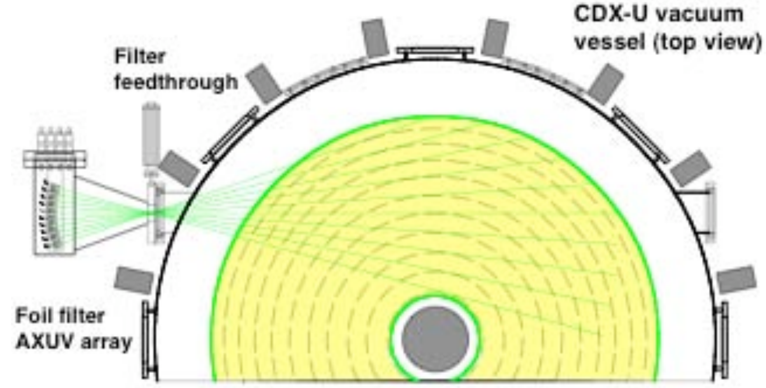
- Balmer beta line H_β (D_β) (4-2) is a good choice
  - λ=486.1 nm (486.0 nm) - it's also in the visible range
  - …where many optical detectors have *fairly high* efficiency
  - but: about x10 less intensity than H_α (D_α) intensity
  - and PFC reflections are still (but less of) a problem

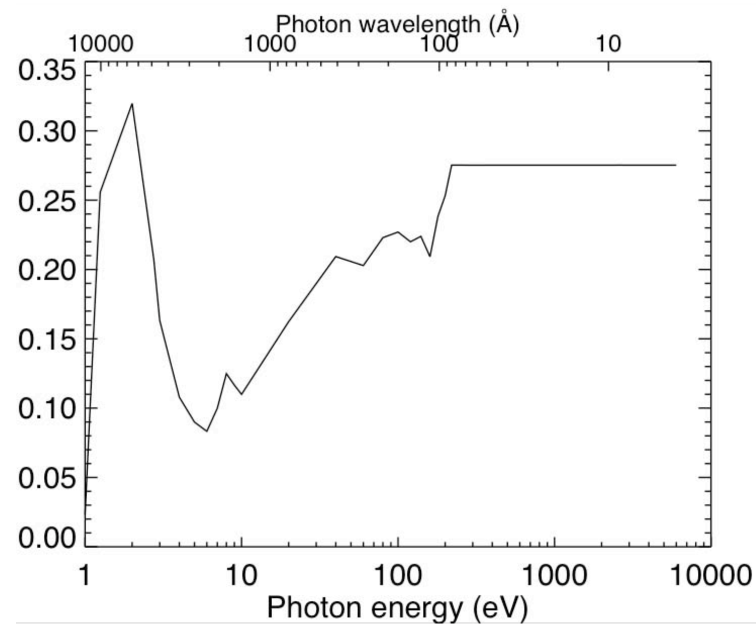
- Higher level transitions (5-2, 4-3) are weak but can be considered

- Lyman alpha line Ly_α $(2-1)$ is also a good choice
  - λ=121.6 nm - in the Vacuum Ultraviolet (VUV) wavelength region
  - very bright - resonant transition!
  - but: need special VUV detectors , filters and windows
  - normal reflections are weak from common PFC materials (graphite, CFC, blackened SS, etc)

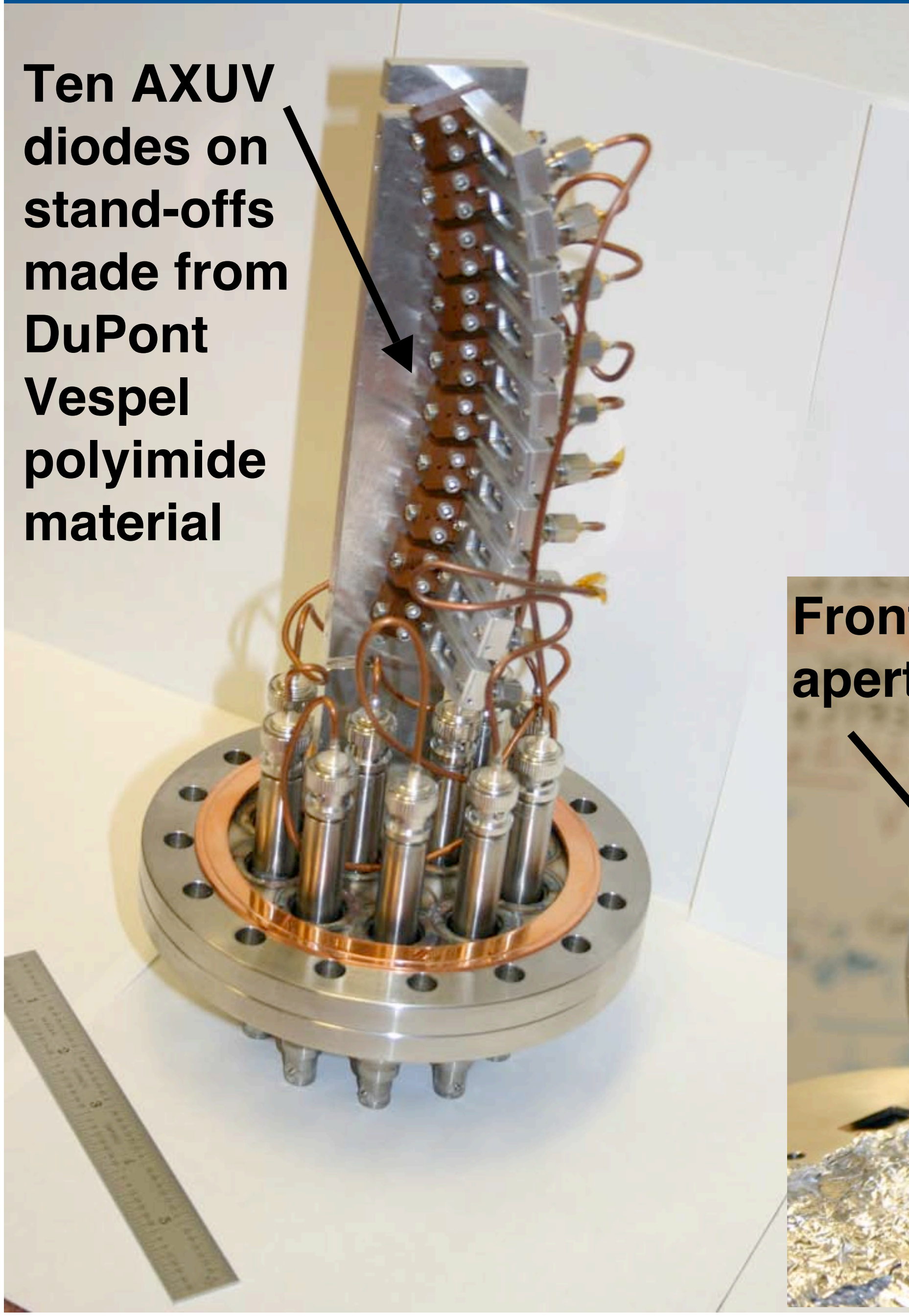
AXUV diode array diagnostic on CDX-U

- AXUV diode is an ***absolute*** radiometric reference if properly used. Manufactured by International Radiation Detectors http://www.ird-inc.com/
- AXUV arrays developed by JHU Plasma Spectroscopy Group in collaboration with PPPL for CDX-U and NSTX spherical tori
  - CDX-U: RSI 72 (2001) 737; PPCF 44 (2002) 2339; RSI 72 (2001) 915
  - NSTX: RSI 70 (1999) 572
- AXUV radiometer array operated on CDX-U from 1999 to 2006
  - Used for radiated power measurements
  - Used for plasma position and equilibrium estimates
  - Used for midplane impurity profile measurements in 1999-2000 with NSTX amplifiers and Ti / Be filters
- Many other plasma devices have built and used AXUV diode arrays (Alcator C-Mod, DIII-D, TCV, CHS, T-10, T-11M, LHD - ask me for the references)

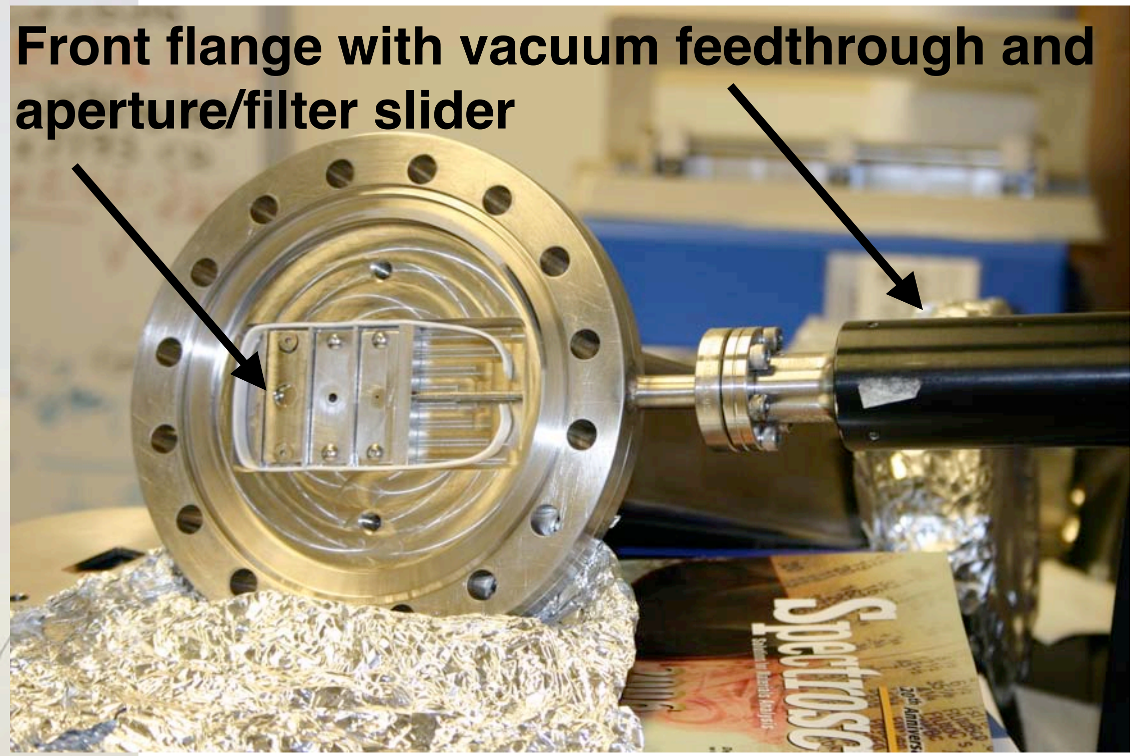




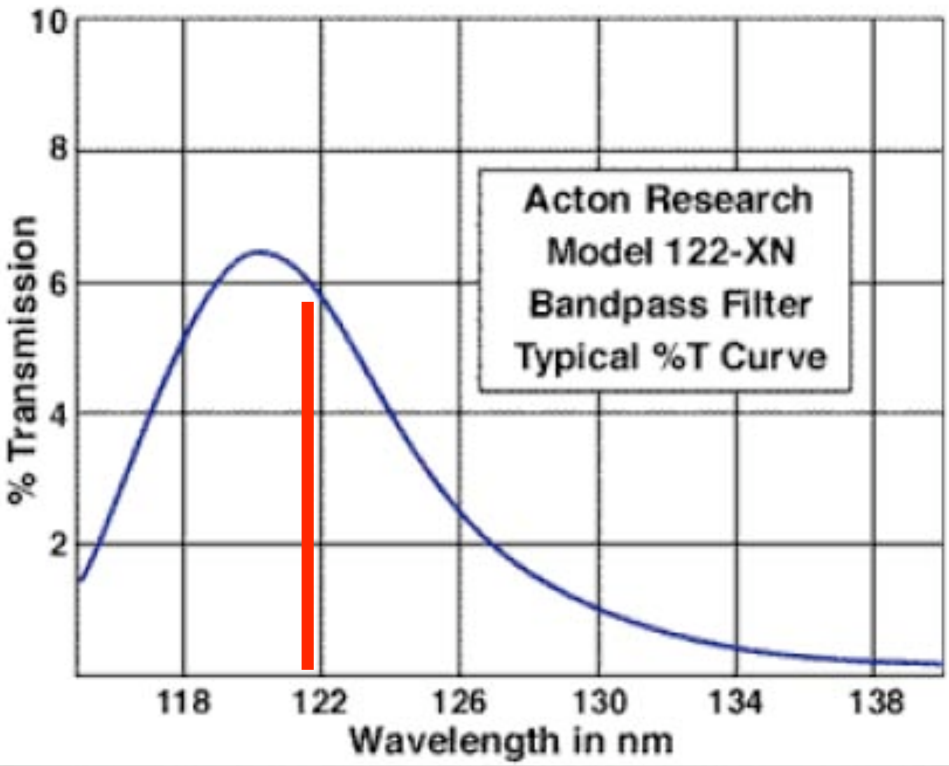
LADA diagnostic used on NSTX in 2006

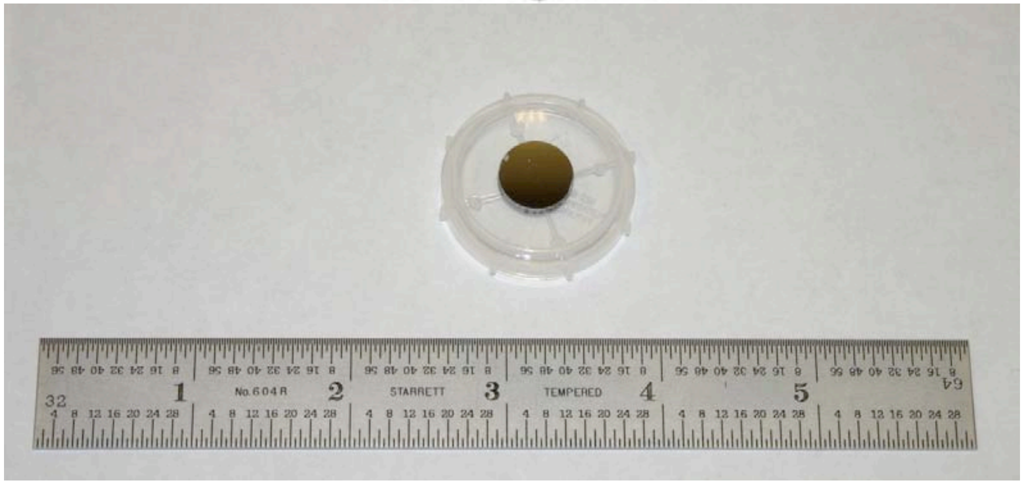


- LADA means Lyman Alpha Diode Array
- Upgraded CDX-U AXUV array to all UHV-compatible materials
- Replaced pinhole apertures
- Mounted ARC Ly_α 1/2” diameter filter purchased by LLNL
- Three apertures: one small and one large for radiometry, Ly_α filter for recycling measurements



ARC (Acton Research Corp.) bandpass filter enables VUV Ly_α emission filtering





- Open-faced multilayer transmission filter mounted on MgF_2 substrate
- Bandpass is narrow enough to transmit only Ly_α light
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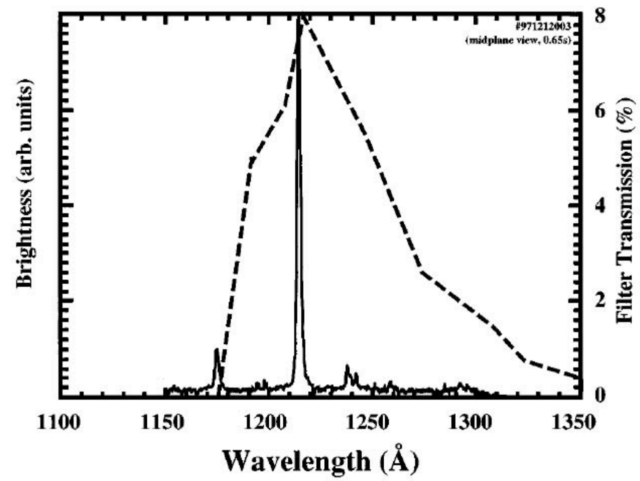
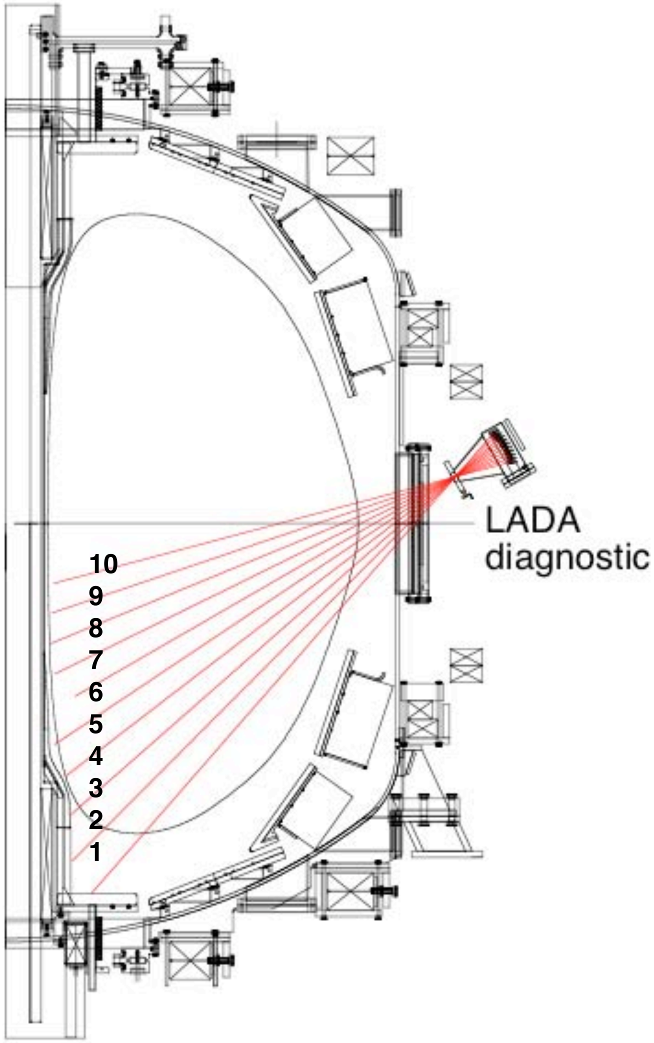


FIG. 3. Measured plasma emission in the UV region using a McPherson (VUV) spectrometer. Overlaid is the measured filter response.

LADA diagnostic on NSTX monitored recycling from lower inner wall and inner divertor regions



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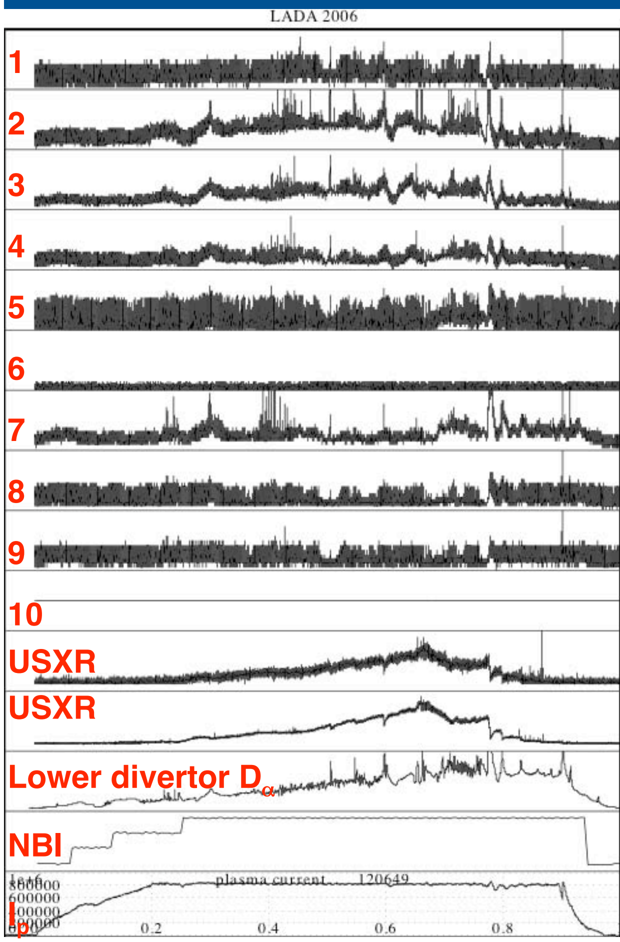
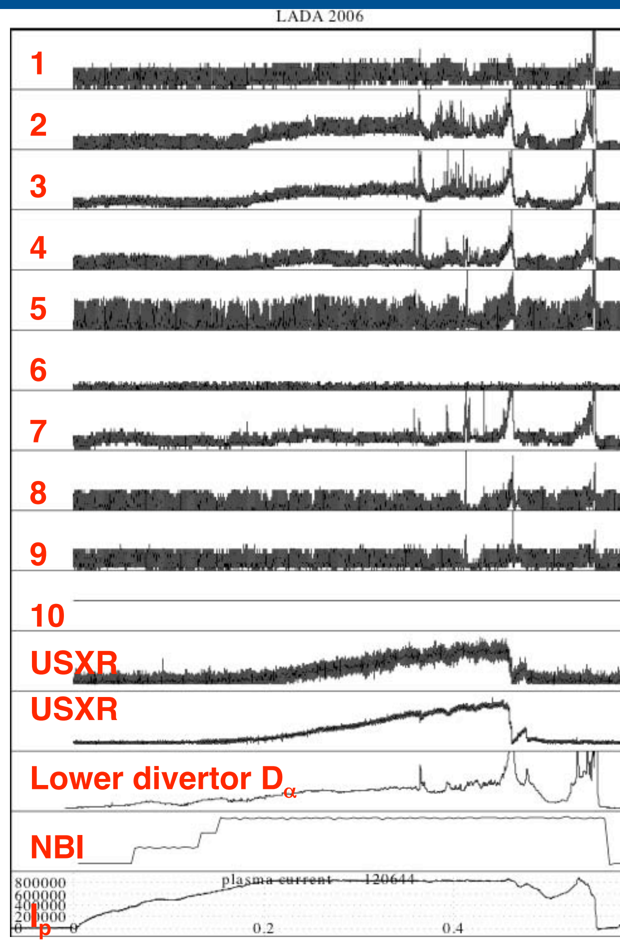
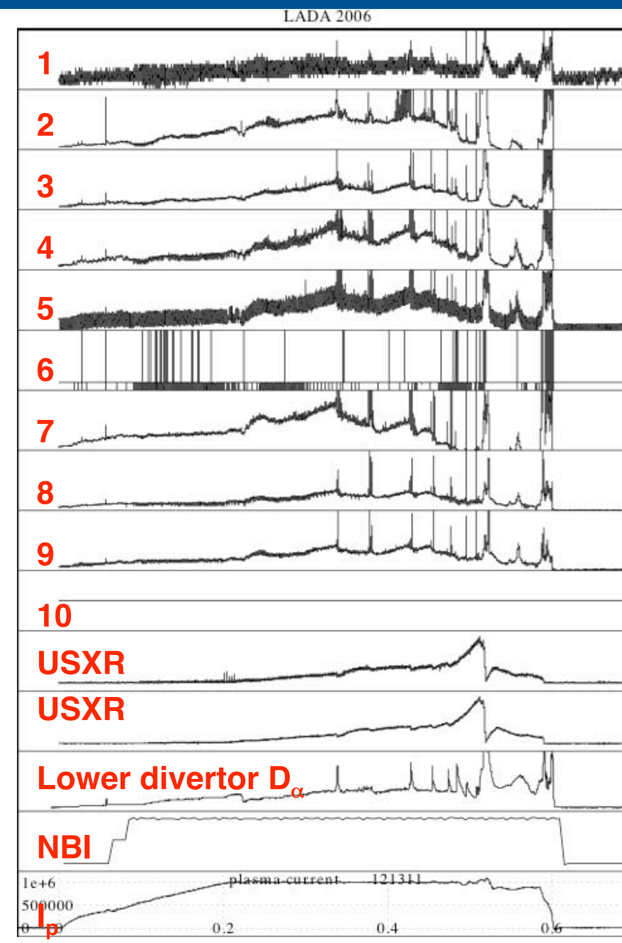
- Channel 1 was vigneted by in-vessel hardware
- Otherwise collected good data (examples on next page)

LADA diagnostic on NSTX operated in Ly$_\alpha$ and radiometer mode







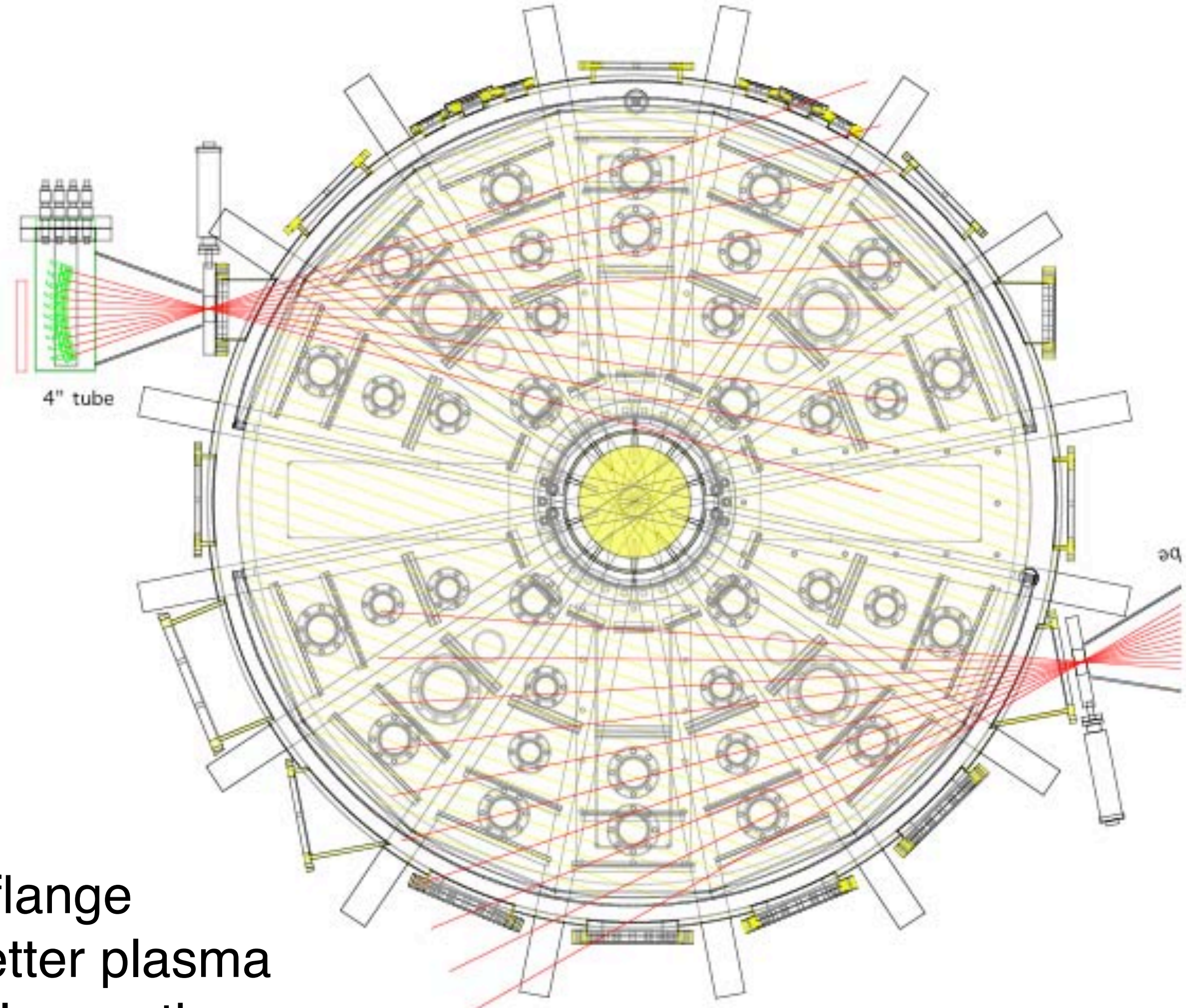
Ly$_\alpha$ filter mode

Ly$_\alpha$ filter mode

Radiometer mode (no filter)

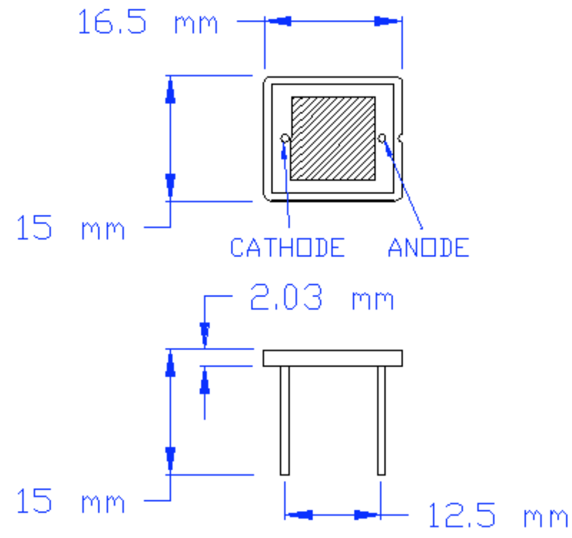
LARDA diagnostic for LTX

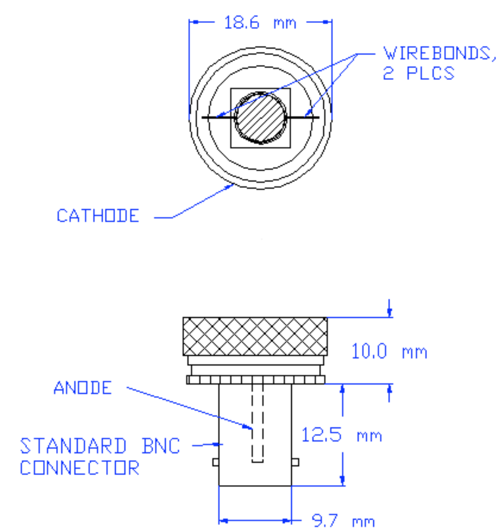
- LARDA now means Lyman Alpha and *Radiometer* Diode Array
- Three positions in the filter slider:
  one for radiometer aperture, one for 1/2” Ly_{α} filter, one vacant (can use for other filter or different size radiometer aperture)
- The horizontal rectangular flange mounting provides much better plasma coverage in LTX (vs CDX-U mounting on 4” midplane flange)



Options for single AXUV diode channel

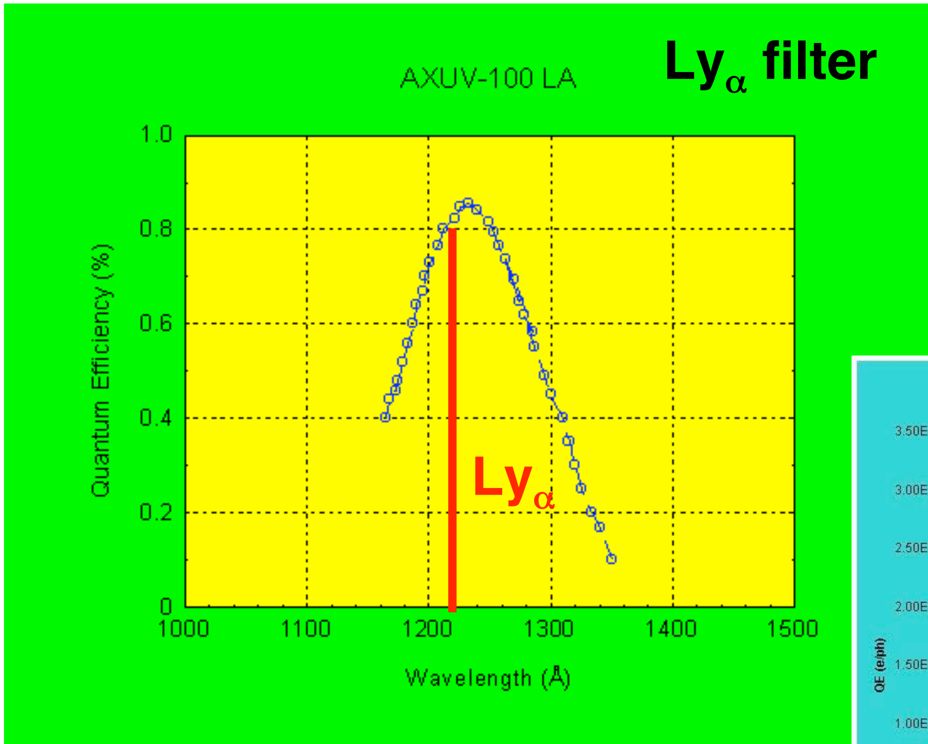
- AXUV diodes come in various packaging:
  - No package - need to design own mount
  - BNC package - can be conveniently mounted in-vacuum on a BNC feedthrough
- AXUV diodes can be coated with multilayer transmission filters by IRD (see next page):
  - Ly_{α} filter available
  - Li III filter for λ = 13.5 nm
  - Li II filter for λ =19.9 nm
- Another option is to go with ARC transmission filter as on NSTX LADA for Ly_{α} measurements
- IRD also sells trans-impedance variable gain amplifiers for AXUV diodes

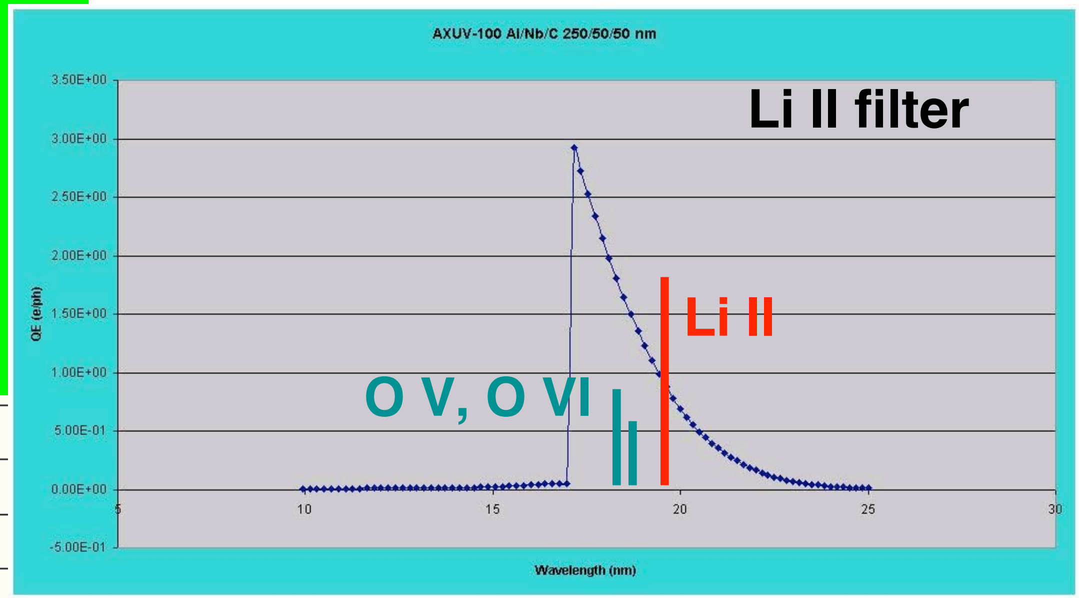


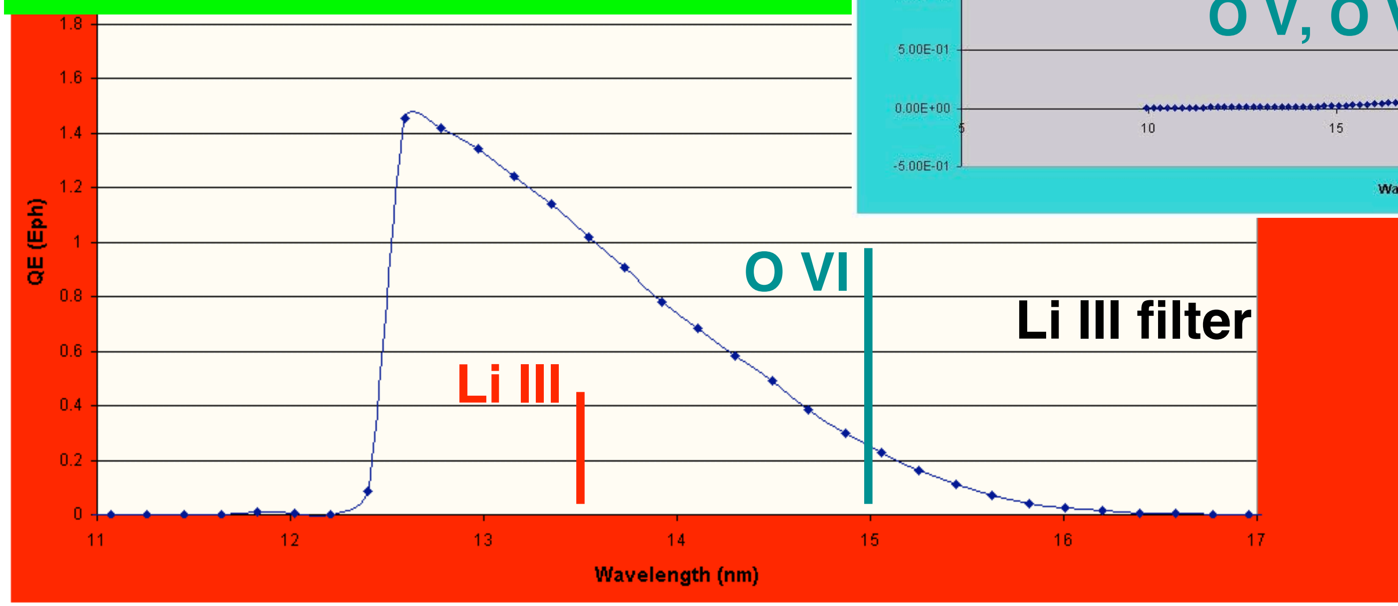


Options for LTX single AXUV diode channel

Shown are transmission curves of foil filters optionally deposited on AXUV diode by IRD







Figures courtesy of IRD Inc.

Summary

- LADA diagnostic worked well on NSTX in 2006
- In radiometric mode collected good data on ELM propagation along inner wall
- In filtered Ly_{α} mode the LADA diagnostic could only detect very bright emission from the inner detached divertor leg region (aperture was too small)
- LADA array is a good candidate for recycling measurements on LTX providing
    - Aperture sizes and mounting geometry properly arranged
    - We understand VUV light reflection from lithium-coated metal surfaces
- Useful links
    - International Radiation Detectors: www.ird-inc.com
    - Acton Research Corporation: www.acton-research.com