U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

LLNL-operated diagnostics in support of NSTX-U Research Program

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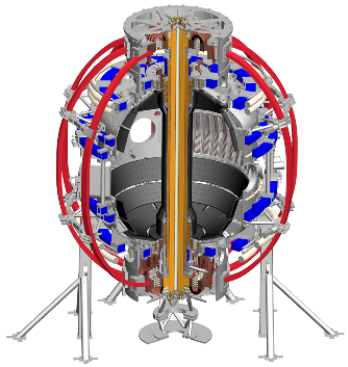
NSTX-U diagnostic collaborator research plan meeting

PPPL

17 May 2016

Lawrence Livermore National Laboratory

PPPL



LLNL Collaboration Research Focus Areas support NSTX-U priorities in FY2016-2018

1. **Scrape-off Layer and Divertor physics**
   - Snowflake divertor transport, turbulence and radiation
   - Radiative (detached) divertor and detachment front control
   - Experiment support for cryo-pump design
2. **Plasma-surface interactions and material migration**
   - Divertor and wall recycling with lithium
   - Divertor and wall material erosion and migration
   - Mixed-material interactions (Li, B, C, O, Mo, W)
3. **Core impurity studies**
   - Low and high-Z impurity transport
   - Laser blow-off impurity injector for impurity transport experiments
   - Impurity spectroscopy and Atomic physics
4. **Coaxial helicity injection (CHI) modeling**
   - NIMROD modeling of MHD effects on CHI

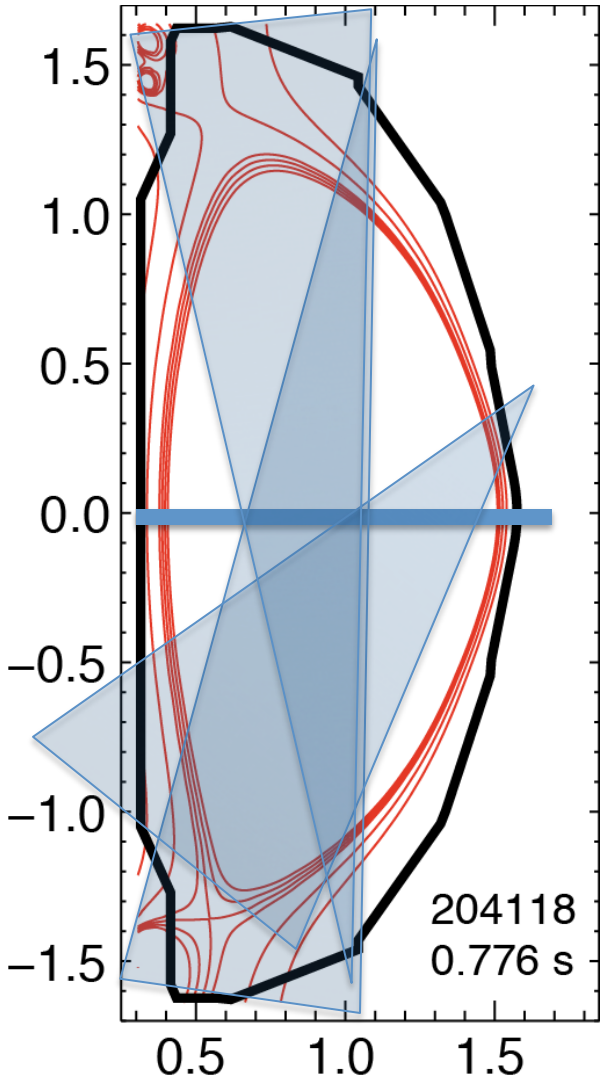
LLNL leads experiments, diagnostic development and operation, and edge modeling in these areas on NSTX-U

LLNL collaboration supports a number of edge and core diagnostics on NSTX-U to enable divertor, plasma-surface interaction and impurity transport studies

Diagnostic
1. EIES (Edge Impurity Emission Spectroscopy, aka Filterscopes)
2. LADA (Lower divertor radiometer AXUV diode array)
3. 1D CCD arrays (Lower divertor, Upper divertor, Center Stack)
4. Divertor SPRED (VUV spectrometer)
5. UV-VIS survey spectrometer VIPS2
6. UV-VIS imaging divertor spectrometer DIMS
7. Divertor Control Spectrometer DIBS (Lower divertor)
8. NIRS (Near-Infrared Spectrometer, 800 – 2200 nm)
9. Divertor imaging cameras (three Phantom, Lower divertor and Upper divertor)
10. Divertor Turbulence and Control Camera (Phantom, lower divertor)
11. Duo-chromatic divertor imaging radiation-hardened cameras TWICE (two CIDTEC cameras)
12. ENDD (Edge Neutral Density Diagnostic) camera
13. Optical Penning Gauge
14. EUV spectrometer (MonaLisa, 60-220 Å region)
15. EUV spectrometer (LoWEUS, 220 - 400 Å region)
16. EUV spectrometer (XEUS, 5 - 60 Å region)
17. Laser Blow-Off system

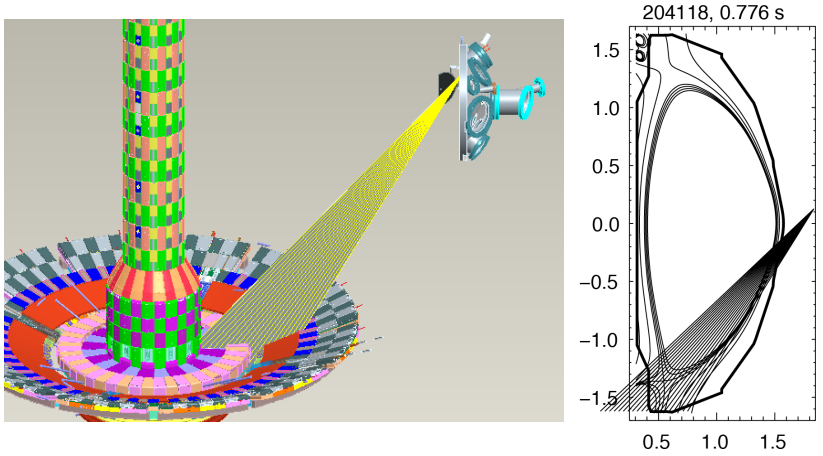
1. EIES (aka filterscopes): monitoring of edge recycling and impurity emissions for operations and protection

- NSTX and NSTX-U system summary at http://nstx.pppl.gov/DragNDrop/Operations/Diagnostics_&_Support_Sys/EIES/
- EIES - about 32 channels, each includes
  - TFTR-age high voltage power supply
  - TFTR-age PMT in shielded housing
  - New 1” narrow band-pass interference filter
  - 2 kHz amplifiers
- One tunable EIES channel
  - 0.3 m monochromator with accurate wavelength calibration and PMT detector
  - Can be tuned to any line 400-700 nm, any sightline
- Fast EIES – 5 channels (20 kHz) for IGI
  - B II, B III, Li I, Li III, C II, CIII ,C IV filters to monitor granule penetration
- ORNL fast (<50 kHz?) filterscopes for ELM detection
  - 4-channel module being installed
- Main sightlines
  - Bay D top, viewing entire lower divertor
  - Bay E bottom, viewing entire upper divertor
  - Bay I midplane, viewing CS (spot 2 cm diameter)
  - Bay G tangential midplane, VB monitor view
  - Bay L midplane (CHERS fiber mount), edge views

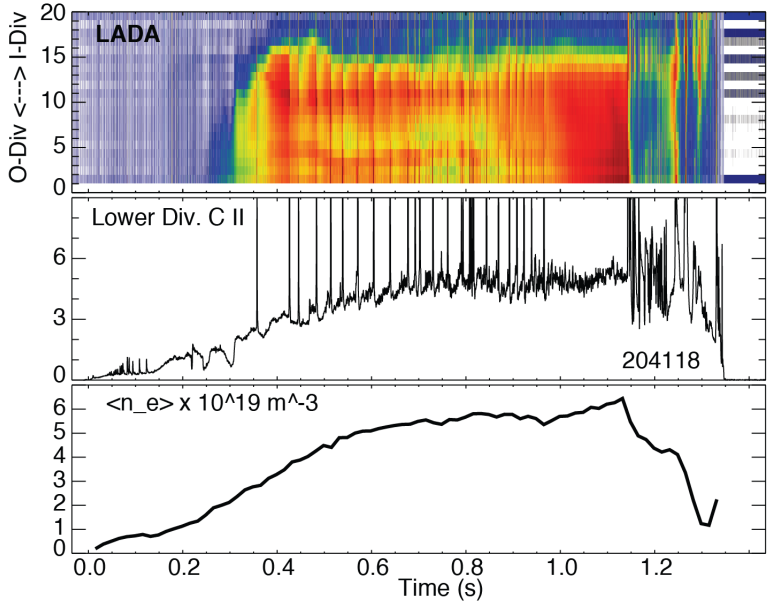


2. LADA: Lyman-α AXUV diode array is used as divertor radiometer in NSTX-U

- Described in V. A. Soukhanovskii, RSI 81, 10D723 (2010)
- LADA – Lyman Alpha (Ly_α) Diode Array
  - Operated without Ly-alpha filter (2016)
  - 20-channel AXUV-20EL diode array from IRD
  - 20-channel 10 kHz trans-impedance amplifier from Clear-Pulse, Inc.
  - D-tacq data acquisition module
  - cm-scale resolution in lower divertor

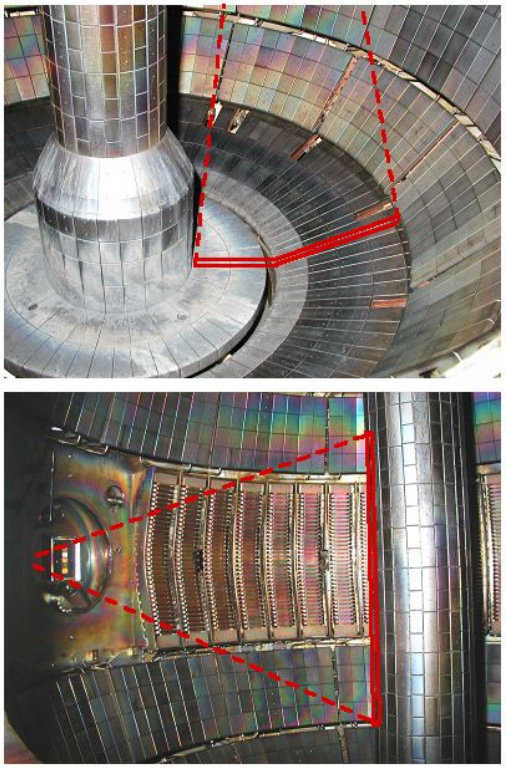


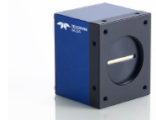
LADA placement on NSTX (and NSTX-U).



3. 1D CCD arrays: high spatial and temporal resolution recycling and impurity emission profiles for physics analysis

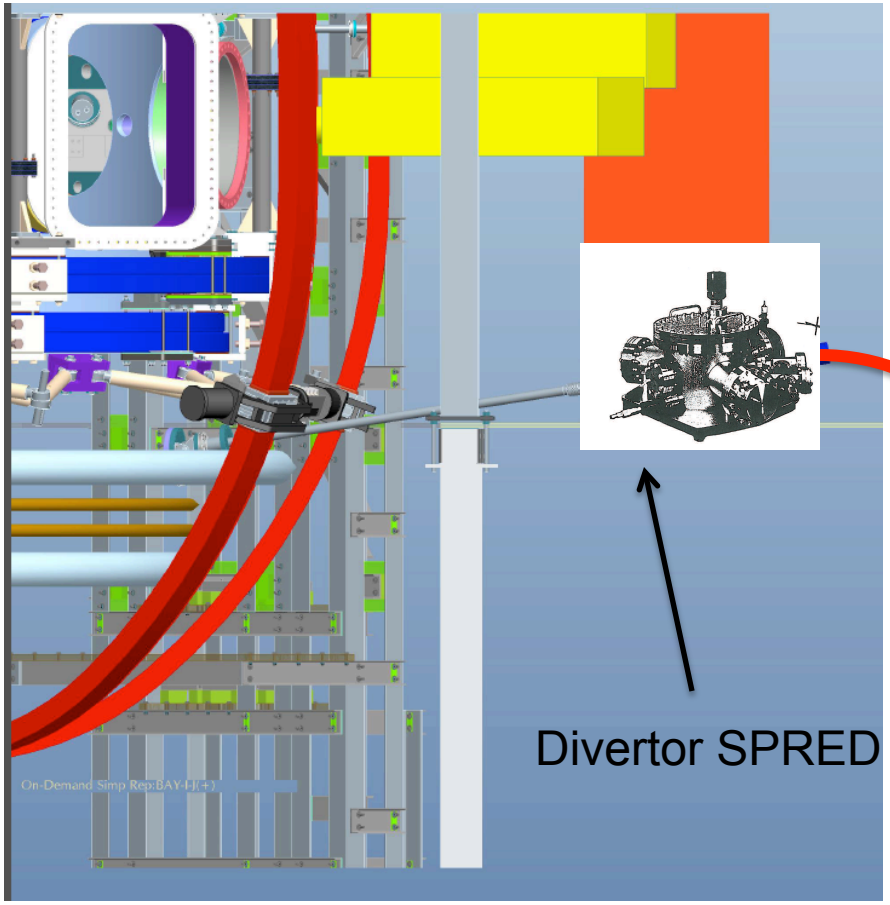
- Described in V. A. Soukhanovskii, RSI 74, 2093 (2003)
  - New DALSA Spider 3 SG-14 cameras (36 kHz, 1024 pixels, GigE)
  - Primary data for edge transport code comparisons
  - Used for recycling, ELM, impurity analysis
- NSTX-U system includes 3 views at 3 wavelengths
  - Bay D top, viewing lower divertor (3 cameras)
  - Bay E bottom, viewing upper divertor (3 cameras)
  - Bay B midplane, viewing CS (3 cameras)
- Redesigned optics and detector system
  - Imaging lens on port
  - Schott 15 ft fiberoptic bundle
  - Detector box with image splitter, lenses, filters and 3 cameras
  - Candidate filters D_β, C II, and Li I, possible filter wheel
- Need to develop data acquisition system
  - Looking into options, 1 PC per three cameras
  - Considering Linux and Python based solution





1D CCD views.
A DALSA Spider 3 camera.

4. Divertor SPRED VUV spectrometer for impurity emission measurement in outer divertor leg, real-time T_e



- Steady-state and transient divertor impurity measurements
  - Li II-III, C II-IV, N II-V, Ne, Ar, Mo, W line emission
  - Radiative divertor control via T_e analysis

12.5' fiberoptic imaging bundle

Shielded CCD detector

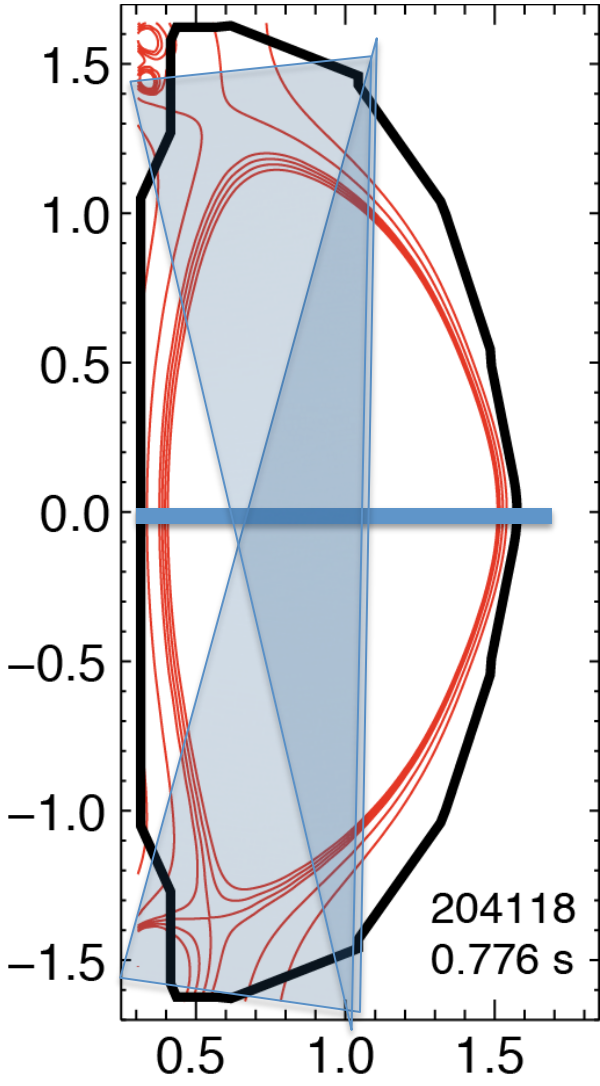
- Divertor SPRED spectrometer
  - McPherson Model 251 flat-field 0.3 m spectrograph (Weight: 250 lb)
  - Two-grating turret with Au-coated gratings 290 and 2105 l/mm
  - MCP-based detector with CsI-coated photocathode and P46 phosphor
  - Ion pump with controller
  - Schott 12 ft imaging bundle 25x4 mm
  - Princeton Instruments Pro-EM 1600x200 camera

- Described in V. A. Soukhanovskii, APS DPP 2015; HTPD 2016 poster, RSI paper to be submitted

5. UV-VIS spectrometer VIPS2: general purpose surveys for wall conditioning studies

- Described in V. A. Soukhanovskii, RSI 77, 10F127 (2006)
- Applications on NSTX-U
  - H/D ratio monitoring
  - Survey of impurity emissions
  - Penning, GDC emission studies

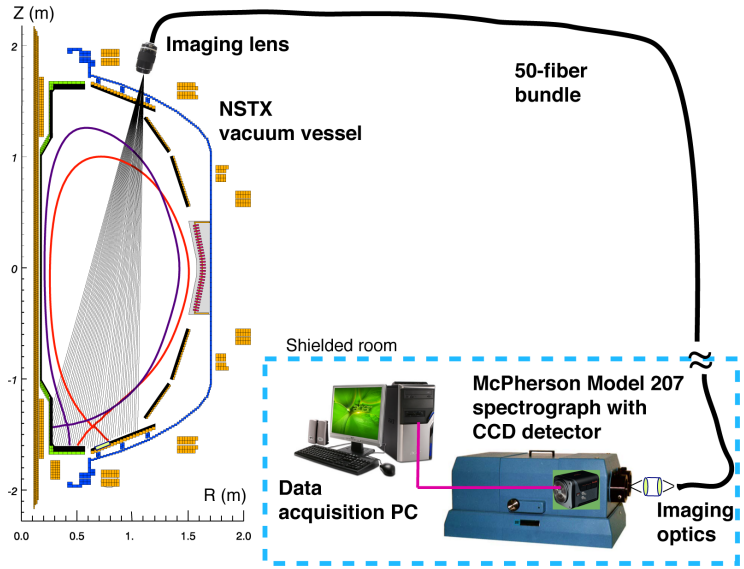
- VIPS 2 spectrometer
  - Acton Research SpectraPro 500i, 0.5 m, *f* / 6.5 Czerny-Turner scheme
  - Three gratings: 600, 1200, 2400 l/mm
  - CCD detector - 1340 x 100 pixel Princeton Instruments Model Spec-10:100B
  - 4-fiber input interface
  - Presently connected to Bay D Lower divertor, Bay E upper divertor, Bay B midplane EIES sightlines



VIPS2 divertor lines of sight

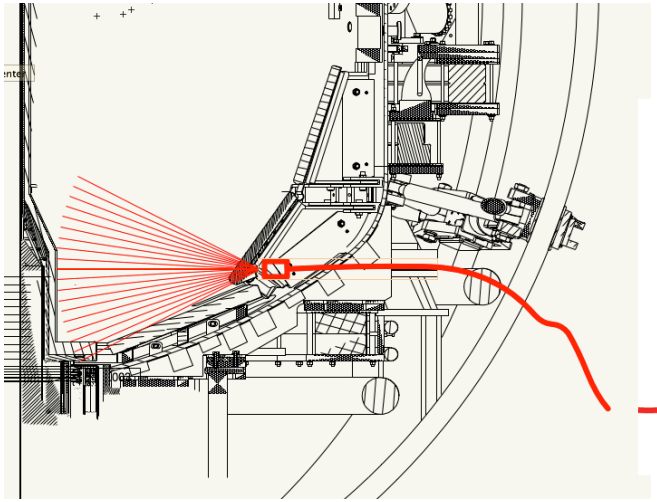
6. UV-VIS-NIR DIMS divertor imaging spectrometer designed for impurity profile and T_i measurements

- Described in V. A. Soukhanovskii, RSI 81, 10D723 (2010)
- DIMS – Divertor Imaging Spectrometer
  - high-resolution imaging spectroscopy from 250 nm to 1100 nm
  - 18-chord divertor profiles with 1 cm spatial resolution, 1-10 ms time resolution
  - Tochigi Nikon UV 105mm f/4.5 imaging lens
  - 50-fiber optical relay bundle, 400-um FBP400 broadband fibers from Polymicro, Inc.
  - McPherson Model 207 R=0.67 m f/4.7 spectrograph
  - Three gratings (3600, 2400, 1800 lines/mm) for ultraviolet, visible, and near-infrared line spectra
  - Princeton Instruments Pro EM 512 CCD camera



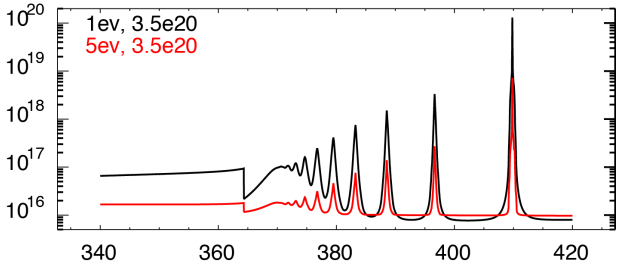
DIMS lines of sight and layout

7. Divertor Imaging Balmer Spectrometer (DIBS) enables fast line and continua meas'ts for radiative divertor control



- 26-fiber bundle (Radiation resistant Molex FVP 200 um)
- 10-fiber bundle (Molex FBP 200 um)
- 30 m length
- Kogaku 8 or 12 mm imaging UV lens
- Fiber projection spot size 2-6 mm
- SCT 320 Czerny-Turner-Schmitt spectrograph
  - 600, 1200, 1800 gr/mm UV-VIS 68 mm gratings
- CCD camera PI ProEM 1600x400
- Real-time DAQ via WinSpec32 (pvcam)

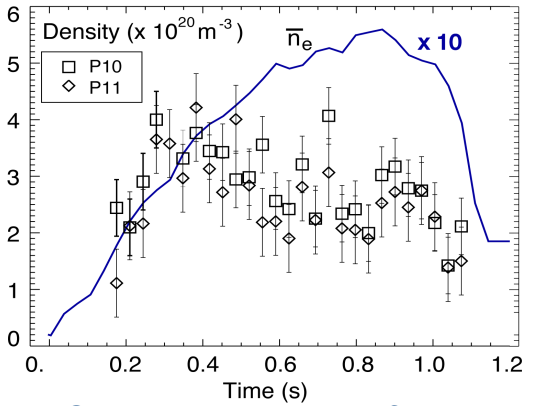
- Described in V. A. Soukhanovskii, APS DPP 2015; HTPD 2016 poster, RSI paper to be submitted
- Multi-chordal deuterium and impurity measurements for
  1. Radiative divertor control via T_e
  2. Recombination front studies
  3. Divertor C, N, Ar, Mo, .. distribution



Simulated DIBS Balmer series spectra

8. Near-Infrared Spectrometer (NIRS) to be used for divertor impurity and detachment studies

- Described in
  - V. A. Soukhanovskii et. al. Rev. Sci. Instrum. 77, 10127 (2006)
  - V. A. Soukhanovskii, Rev. Sci. Instrum. 79, 10539 (2008)
  - V. A. Soukhanovskii, RSI 85, 11E418 (2014)
  - ICAPiP 2016 Invited Talk
- Measurement goals
  - Evaluate NIR spectroscopy application for ITER
  - Paschen series and Brackett series lines in DIII-D divertor for T_e and n_e

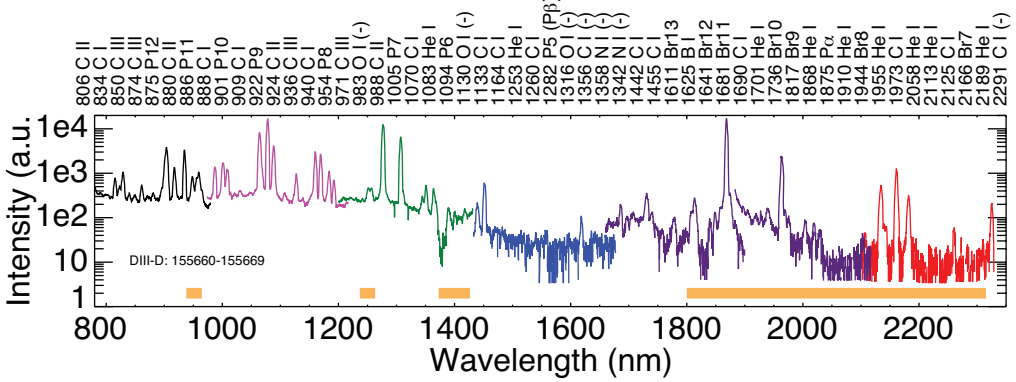


NSTX divertor density from Paschen line Stark broadening

- NIRS is currently operating at DIII-D

- NIRS includes
  - Princeton Instruments OMA V 1024-2.2 detector (LLNL)
  - Acton SP2500 spectrometer (previously SP300i)
    - Focal length 500 mm
    - Three NIR-blazed gratings on a turret

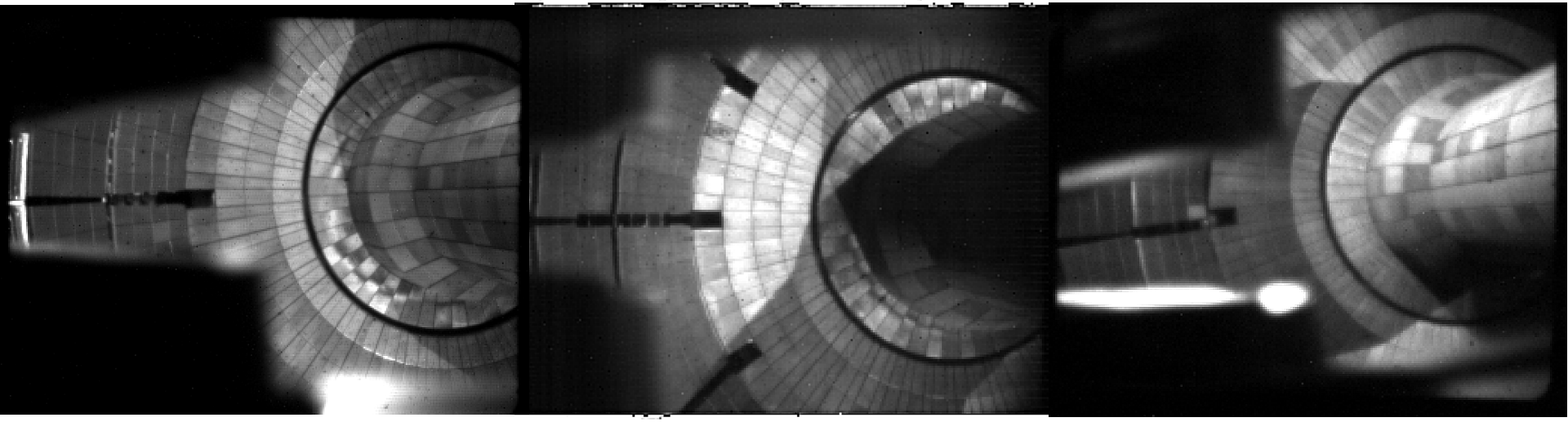
DIII-D divertor spectrum



9. Photometrically-calibrated, fast cameras with wide angle view provide full toroidal divertor imaging

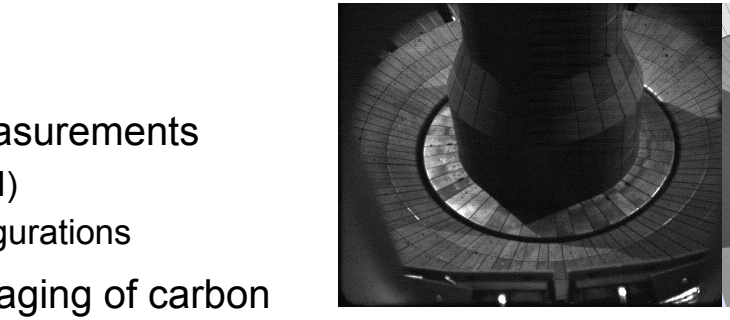
- Described in F. Scotti, RSI 83, 10E532 (2012)
- Cameras Phantom v710, Phantom v7.3, Miro 4
- Spatial resolution better than 1cm/pixel, framing 10-100kHz w/o cropping
- Fast optics and narrow bandpass filters allow studies of impurity emission, non-axisymmetric effects, turbulence
- Available filters: C I, C II, C III, C IV, B III, Li I, Li II, D-α, D-γ, Gero band (CD), O II on remotely controlled filter wheels

Lower divertor view (Bay E) Lower divertor view (Bay J) Upper divertor view (Bay H)



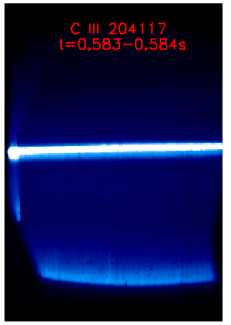
10. New LLNL Phantom camera dedicated to divertor turbulence, divertor control, LGI imaging

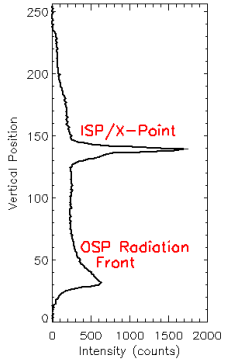
- Described in F. Scotti, APS 2015
- Physics goals
  - Support divertor turbulent filaments measurements
    - Cross correlation with midplane blobs (GPI)
    - Churning mode studies in snowflake configurations
  - Support radiative divertor control via imaging of carbon radiation front
  - LGI granule emission imaging
- Two setups will be used for turbulence studies and radiative divertor control
  - Midplane port (6” flange) on Bay J port cover
  - Radial divertor port (2” window) on Bay B lower dome
- New Vision Research Phantom v1211 camera
  - Coherent fiber bundle 1000x800 10 μm fibers, 15’ long
  - 1:1 imaging on detector
  - Resolution: 360x288 pixels (crop 360x100)
  - Max fps: 76.6kHz (crop 182.7kHz),
  - Max. recording time: 2s



Lower divertor from Bay J mid

Lower divertor from Bay B H.Div.



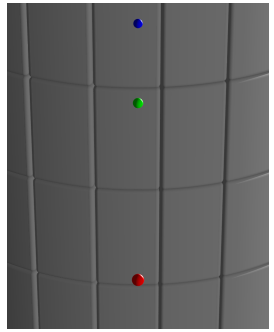


3 granules:

Ψ_N=0.6

Separatrix

Limiter

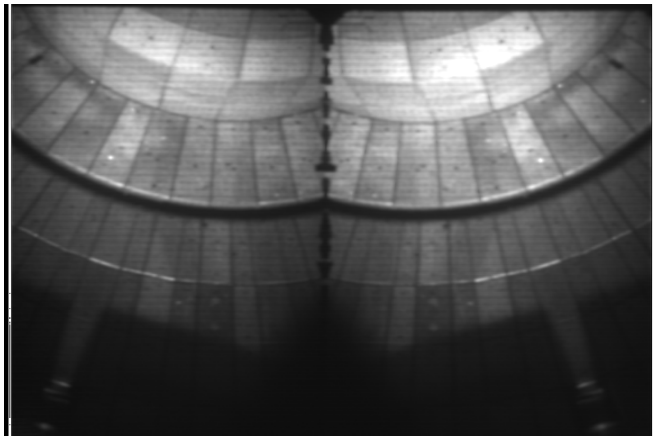


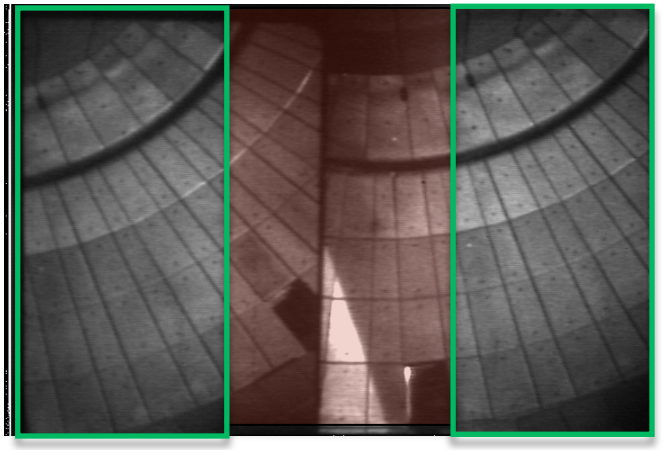
Rendered field of view (POV-Ray) with imaging bundle and 50 mm lens

11. Duo-chromatic intensified camera systems (TWICE-1,2) for mixed material plasma surface interaction studies

- Described in F. Scotti, RSI 86, 123103 (2015);
  - Single filtered cameras described in
    - M. E. Fenstermacher,W. H. Meyer, R. D.Wood, D. G. Nilson, R. Ellis, and N. H. Brooks, Rev. Sci. Instrum. 68, 974 (1997)
    - A. James et.al.,, Plasma Phys. Control. Fusion 55, 125010 (2013)
- Duo-chromatic imaging with rad-hardened intensified cameras
  - ThermoScientific CIDTEC cameras CID8710, CID 3710
  - VGA resolution (720x480) – 8 bit, 30 Hz interlaced
- TWICE-I
  - Beam splitter for simultaneous 2-color imaging on same detector
  - Four filter wheels (2 for bandpass filters, 2 for neutral density filters)
  - B I, B II, Li I, D-γ, CD, O-II
- TWICE-II
  - 2.5x higher light throughput, 2 orders of magnitude higher intensifier
  - Fixed filters, currently dedicated to CD/D γ

TWICE-I (Bay J)

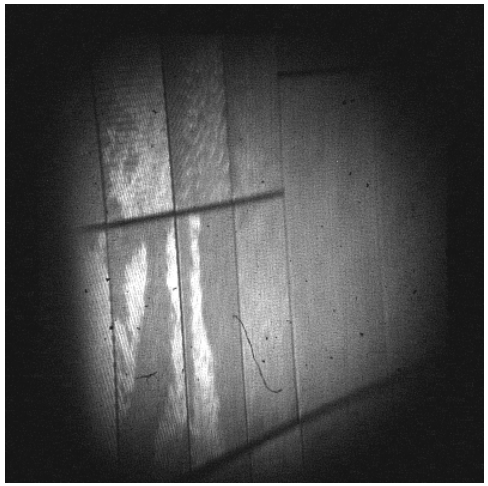


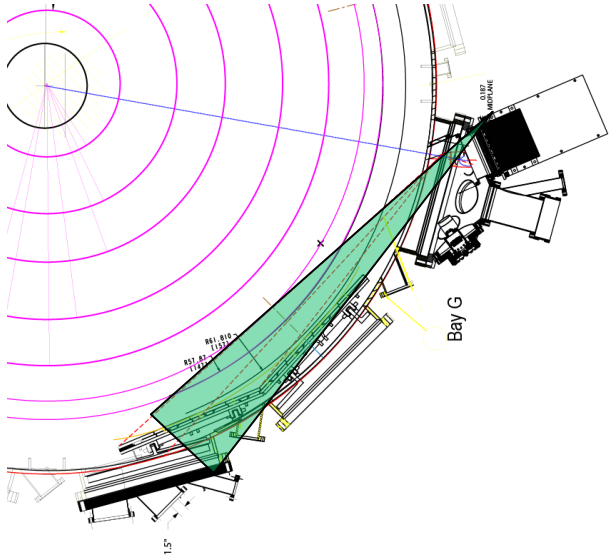


TWICE-II (Bay I)

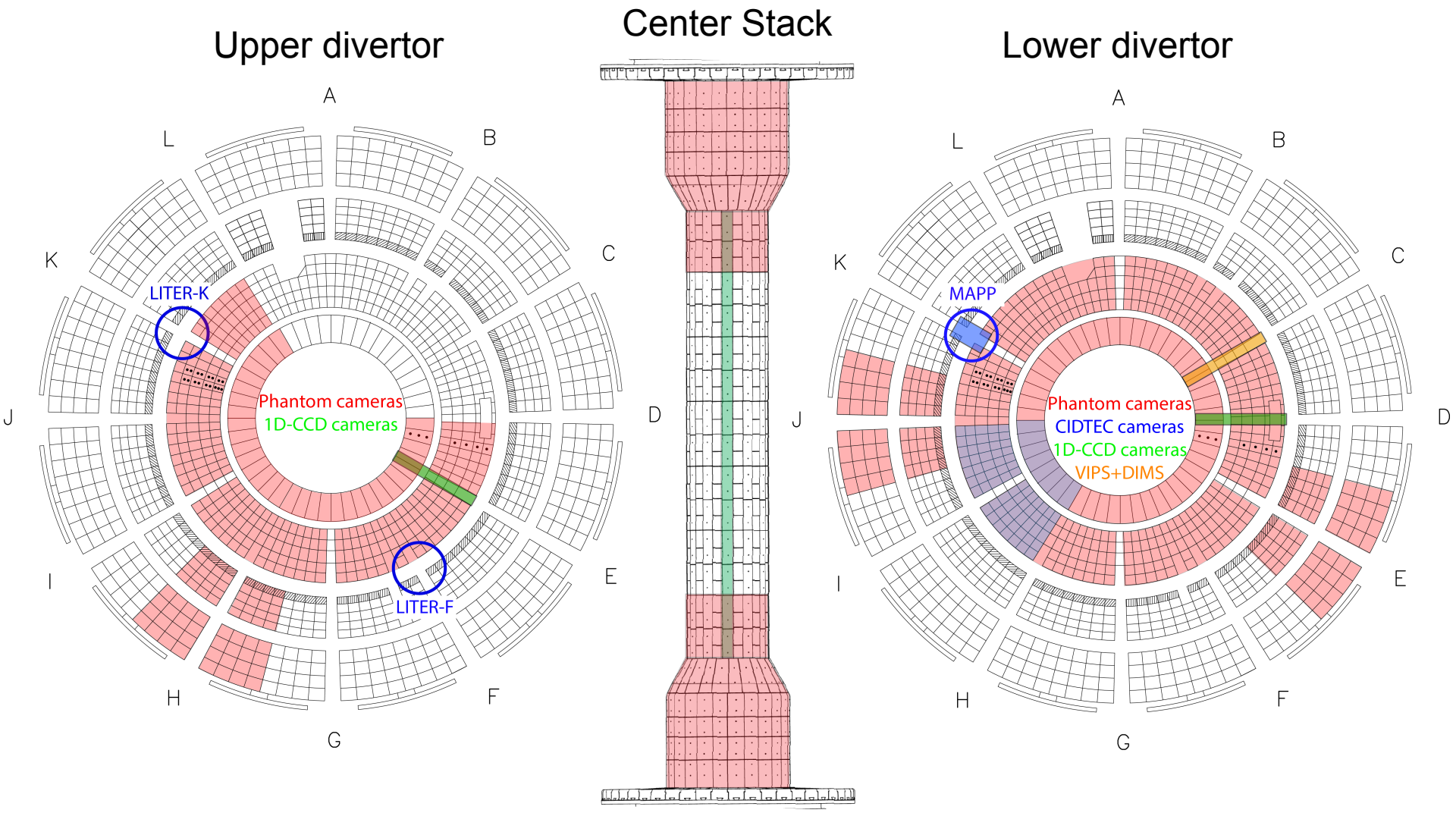
12. ENDD diagnostic updated with imaging bundle and new view aimed at NBI dump

- Described in D. Stotler, F. Scotti, R. Bell, A. Diallo, B. LeBlanc, M. Podesta, A. Roquemore, and P. Ross, Phys. Plasmas 22, 082506 (2015).
- Dedicated to carbon sources monitoring and edge neutral density studies via DEGAS2
- DALSA D256T camera
  - 128x128 pixels, up to 250 Hz
  - Schott imaging bundle, 4 ft 1000x800 fibers





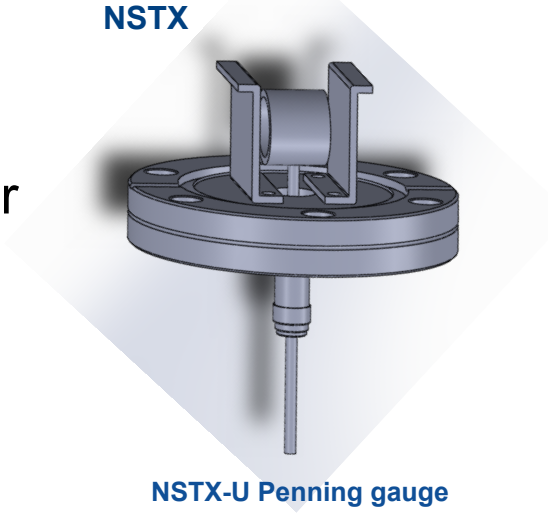
LLNL diagnostics provide full poloidal and toroidal coverage of SOL and divertor impurity emission at multiple wavelengths



13. Optical Penning Gauge to be used for divertor and wall conditioning studies

- Potential applications
  - Divertor seeding gas pressure
  - HeGDC product analysis
  - Gaseous molecular impurity analysis
- Project started on NSTX as collaboration between PPPL, LLNL and U Washington (R. Raman)
- Potential for collaboration with U Wisconsin (Prof. O. Schmitz)
- One Optical Penning gauge installed on NSTX-U at Bay H lower divertor
- EIES or spectrometers (VIPS2, DIMS) to be used for emission monitoring and analysis

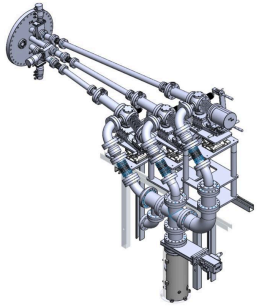
Color-camera image of Penning gauge operated during helium glow discharge cleaning on NSTX



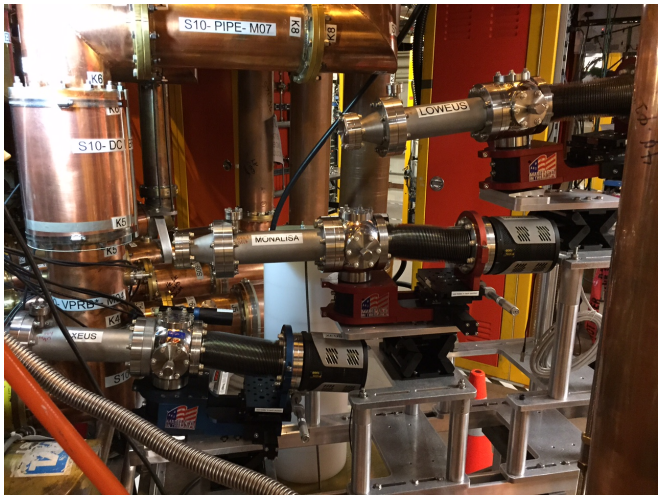
NSTX-U Penning gauge

13-15. Three EUV spectrometers provide simultaneous measurements of all low Z, medium-Z, and high-Z impurities

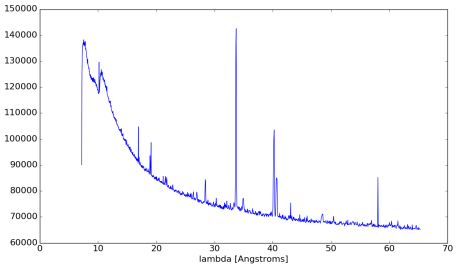
- Described in
  - J. K. Lepson, J. Phys. B: At. Mol. Opt. Phys. 43, 144018 (2010)
  - J. Clementson, RSI 81, 10E326 (2010)
  - J. K. Lepson, RSI 83, 10D520 (2012)
  - M. Weller, APS 2015, HTPD 2016, to be submitted to RSI



- Midplane sightlines
- Two upgraded NSTX spectrometers
  - XEUS, 5 to 60 Å region, 2400 gr/mm grating
  - LoWEUS, 200 to 400 Å region, 1200 l/mm grating
  - Princeton Instruments PIXIS XO 100B CCD detector
- New MonaLisa (Metal Monitor and Lithium Spectrometer Assembly) spectrometer, 60 to 220 Å
  - 0.23 m, 1200 l/mm grating
  - Princeton Instruments PIXIS XO 100B CCD detector

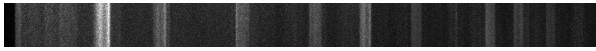


LLNL EUV Spectrometers Mounted on NSTX-U



First Xeus spectrum

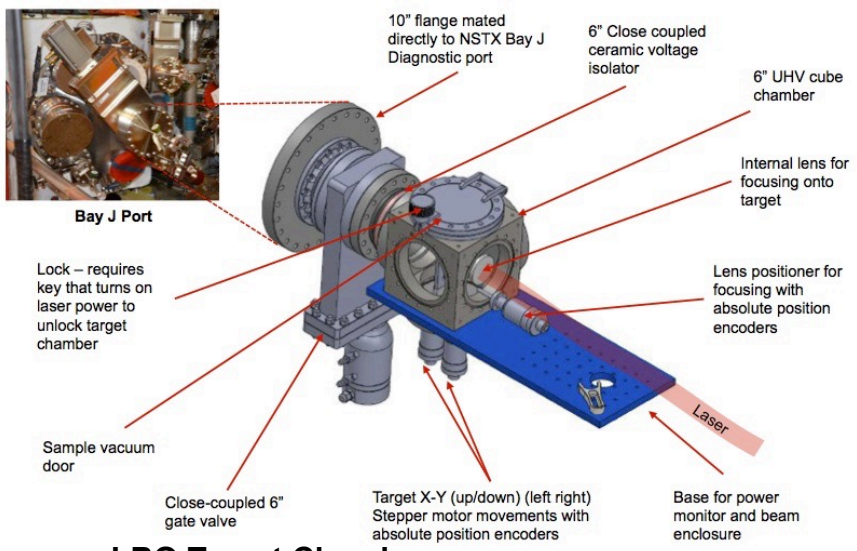
First Loweus spectrum



First MonaLisa spectrum

16. New Laser Blow-Off System for impurity transport and atomic spectroscopy studies

- Laser Blow-Off physics goals:
  - Study edge and core impurity transport
  - Transport and turbulence code development and benchmarking
  - Time-dependent ionization studies for astrophysics
- NSTX-U User Facility
- Injection material is evaporated from glass slide
- Injection amount per shot is variable
- 10 Hz laser, allowing single and multiple injections at Δt 100 ms between injections
- LLNL Q-switched Nd-YAG laser Continuum model NY82-10
  - Infrared beam at 1064 μm
  - 16 ns pulse duration
  - 12 mm beam diameter
  - Linearly polarized
  - 1.4 J output energy
  - Previously used as LBO system on LLNL EBIT (Niles 2006)



LBO Target Chamber

LBO Laser and Optic System