U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Impurity Monitoring on NSTX-U with Three New Extreme Ultraviolet Spectrometers

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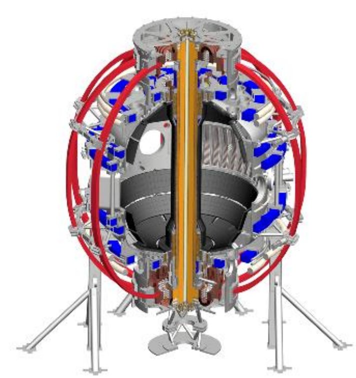

Abstract

The National Spherical Torus Experiment – Upgrade (NSTX-U) is a significant advancement from NSTX offering increased toroidal field, plasma current, and neutral beam injector input power. Due to these improvements generating more intense plasma conditions, impurities penetrating into the core could also be enhanced, despite efforts to improve wall conditioning (bake out, boronization, and lithium evaporation). To monitor and study these impurities, three extreme ultraviolet (EUV) spectrometers have been implemented on NSTX-U. All three are flat field grazing incident spectrometers capable of capturing time-resolved data to about 5.0 ms. Two of the spectrometers, the X-ray and Extreme Ultraviolet Spectrometer (**XEUS**, 5 – 65 Å) the Long-Wavelength and Extreme Ultraviolet Spectrometer (**LoWEUS**, 190 – 440 Å) were previously implemented on NSTX. The third has been dubbed the Metal Monitor and Lithium Spectrometer Assembly (**MonaLisa**, 50 – 220 Å). A new laser blow-off (LBO) system has also been developed in conjuncture with the spectrometers to introduce low and high-Z elements to study core impurity transport. The three spectrometers, along with the new LBO system, provide a unique opportunity to attain highly resolved spectra of impurities from 5 – 440 Å with time-resolution.

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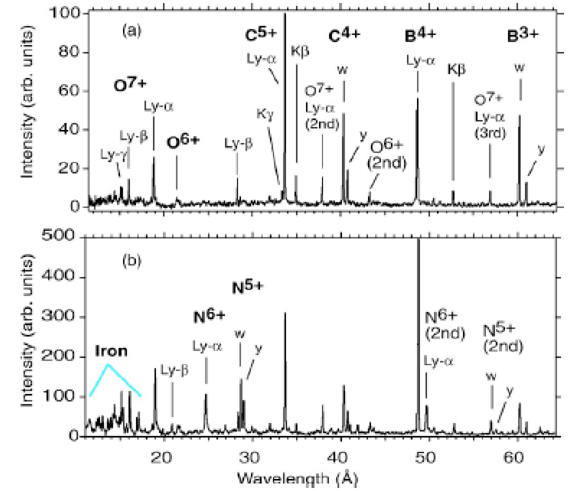
Brief History of EUV Spectroscopy on NSTX

- **XEUS** first introduced in 2004 on NSTX to study spectral line ratios useful as plasma diagnostics for astrophysics and for impurity monitoring with 50 ms time resolution (P. Beiersdorfer 2006).

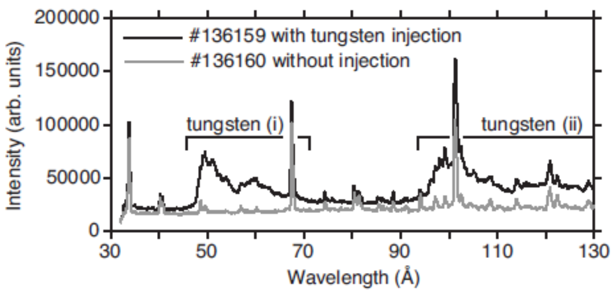
- In 2007 **XEUS** was modified with a new detector which resulted in a time-resolution down to 25 ms (P. Beiersdorfer 2008).

- **LoWEUS** was added to NSTX in 2008 to cover longer wavelengths (J. Clementson 2010).

- For NSTX-U there is a need to simultaneously cover all wavelengths between 5 – 440 Å with high time-resolution to study impurities from the core.



XEUS data from P. Beiersdorfer 2008

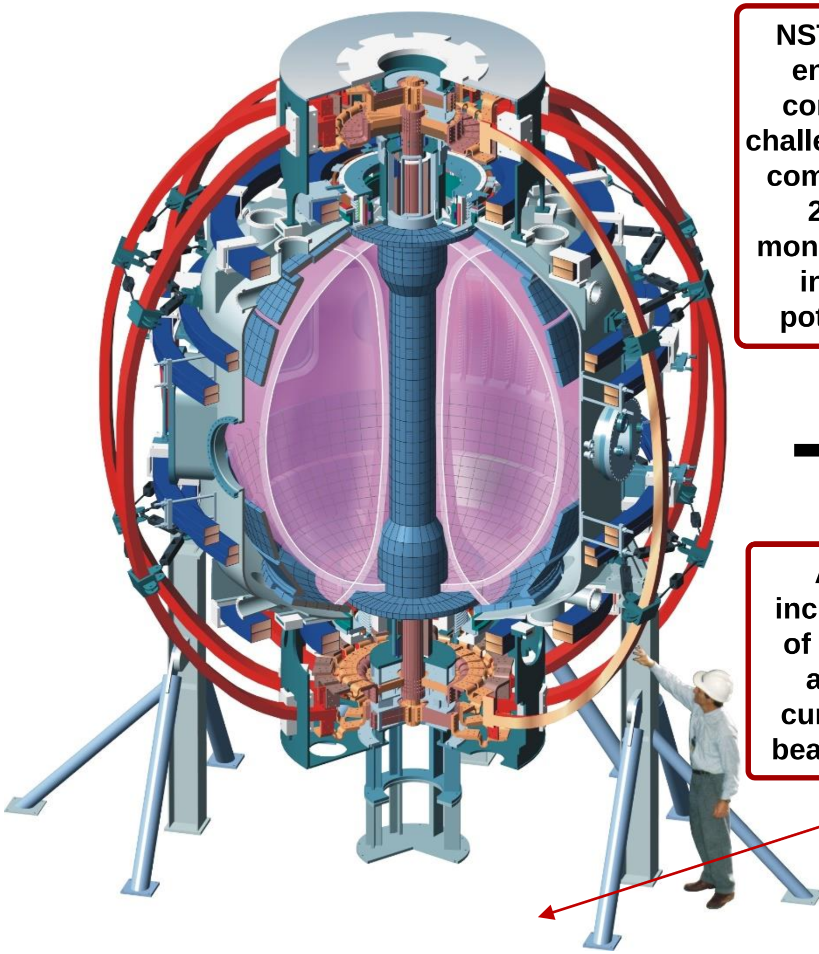


LoWEUS data from J. Clementson 2010

NSTX-U is a Major Advancement from NSTX and Will be a Challenge to PFCs

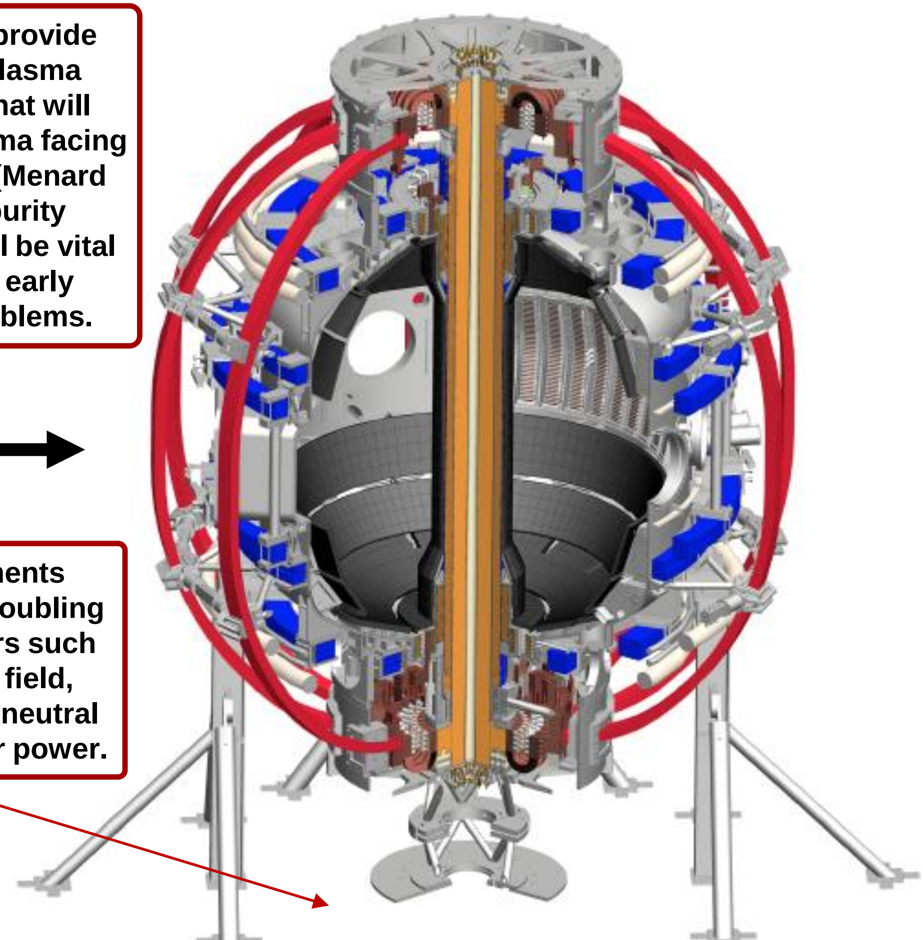
NSTX (1999 - 2011)

NSTX-U (2015 →)



NSTX-U will provide enhanced plasma conditions that will challenge plasma facing components (Menard 2012). Impurity monitoring will be vital in catching early potential problems.

Advancements include the doubling of parameters such as toroidal field, current, and neutral beam injector power.



0.5 T, 1 MA, R_0 ~ 0.85 m, A ≥ 1.28, NBI_{max} = 7 MW

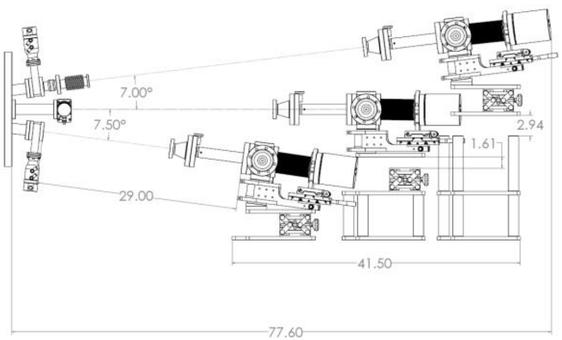
1.0 T, 2 MA, R_0 ~ 0.90m, A ≥ 1.5, NBI_{max} = 14 MW

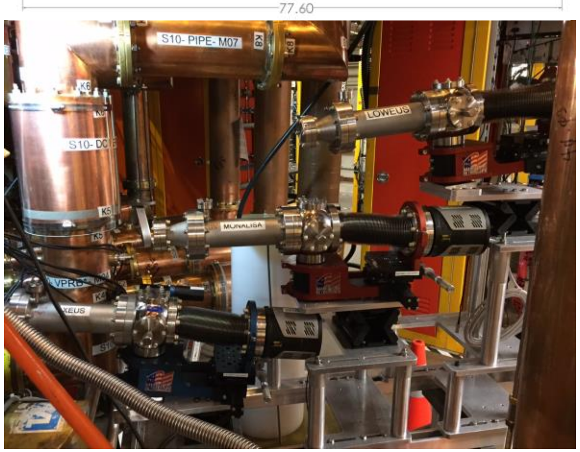
PFCs Will be Conditioned to Reduce Impurities in the Plasma

- Carbon is the PFC material on NSTX-U in the form of graphite tiles.
  - Low-Z element which minimizes radiative cooling compared to high-Z materials.
- Other impurities on NSTX-U include iron, copper, nickel, titanium, and molybdenum.
  - These metal impurities mainly compose stainless steel and RF antenna.
- Conditioning techniques to reduce sputtering from PFCs include:
  - **Bake out**: Heating the vacuum chamber to ~350 °C to remove water.
  - **Lithium evaporation**: Li has strong chemical affinity to hydrogen and deuterium, thereby suppressing recycling, which reduces impurities.
  - **Glow discharge cleaning**: With D_2 or He, effective in reducing oxygen impurities
    - **Boronization**: glow discharge cleaning with deuterated trimethyl boron.
- EUV spectroscopy can detect and monitor impurities.

XEUS, MonaLisa, and LoWEUS Settings and Location on NSTX-U

Spectrometer	Wavelength Range (Å)	Hitachi Grating (ℓ/mm)	Focal Distance (cm)	Angle of Incidence (°)	Slit (µm)	FWHM (Å)	Resolution (Å/ΔÅ)
XEUS	5 - 65	2400	23	1.3	100	0.1	50 - 650
MonaLisa	50 - 220	1200	23	3.0	100	0.3	170 - 730
LoWEUS	190 - 440	1200	23	3.0	100	0.3	630 - 1470

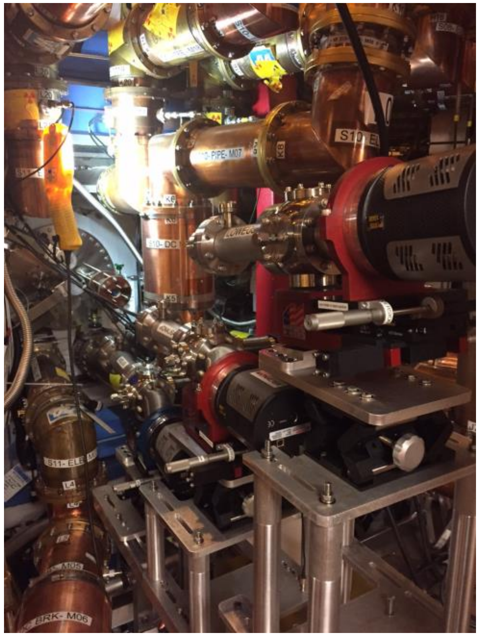




Spectrometers Mounted on NSTX-U

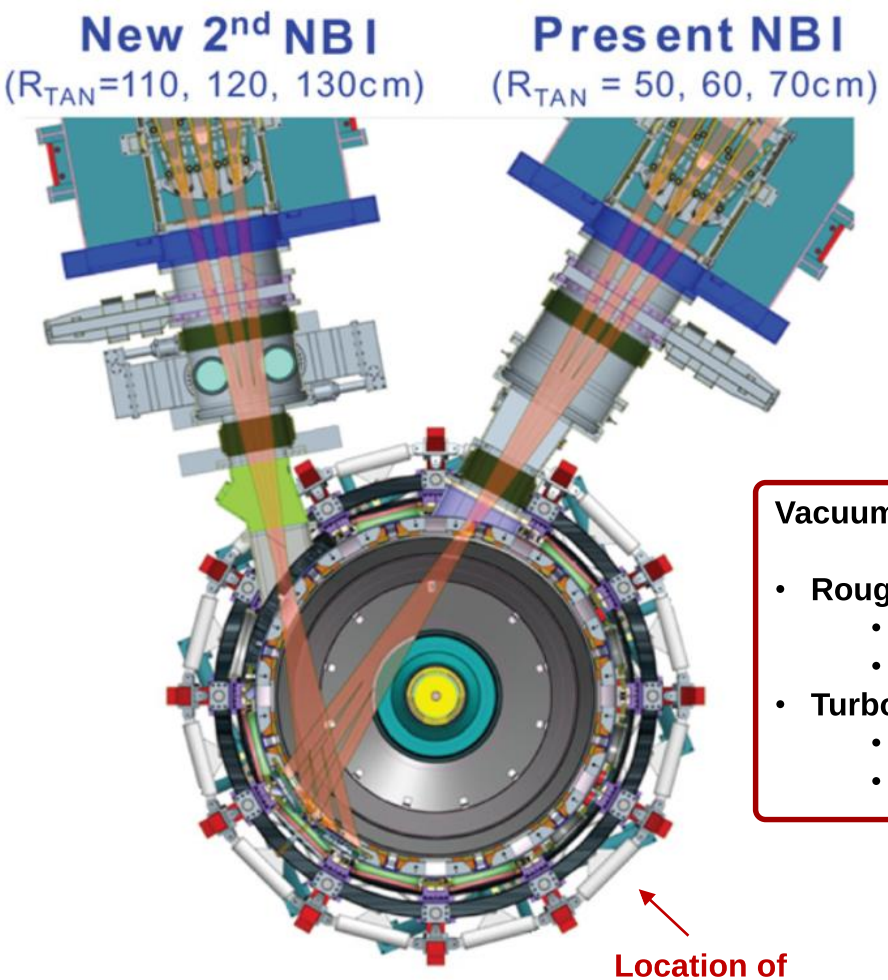
XEUS, MonaLisa, and LoWEUS are flat-field grazing incidence spectrometers (Nakano 1984) which provide high resolution in the EUV range.

Mounted on the mid-plane of NSTX-U (Bay E) to capture radiation from the core of the plasma.



Spectrometers Mounted on NSTX-U

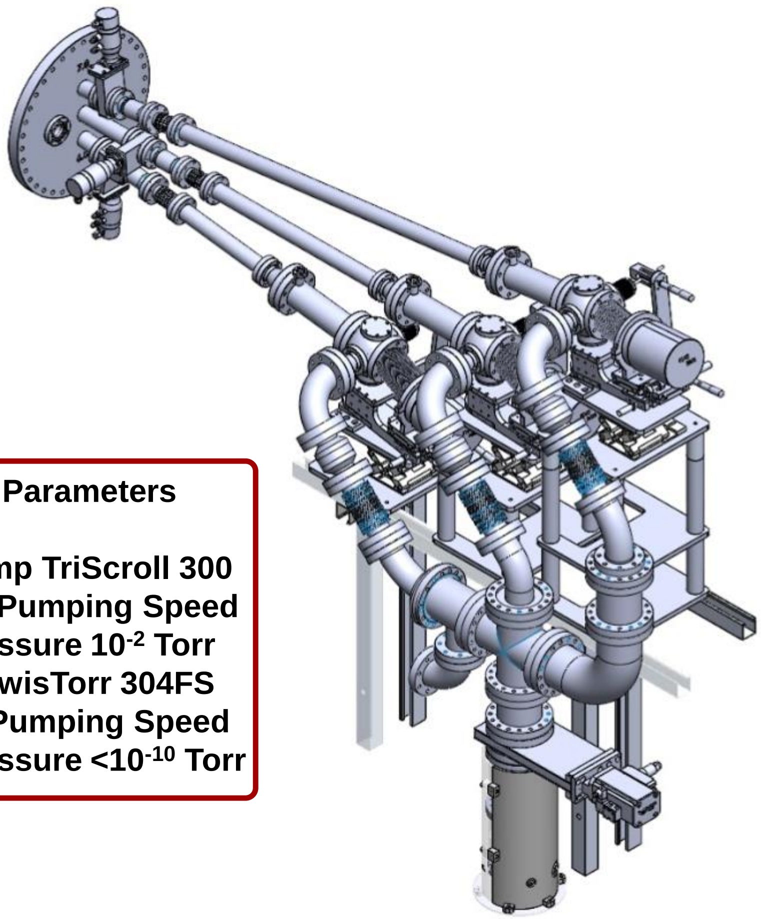
XEUS, MonaLisa, and LoWEUS Position on NSTX-U and Vacuum System Design



Location of Spectrometers Relative to NBI

Vacuum System Parameters

- Roughing Pump TriScroll 300
  - 4.17 l/s Pumping Speed
  - Min Pressure 10^{-2} Torr
- Turbo Pump TwisTorr 304FS
  - 250 l/s Pumping Speed
  - Min Pressure $<10^{-10}$ Torr



Highlighting Vacuum System

The Princeton Instruments PIXIS-XO 100B Detector is Suitable for Capturing EUV Spectra

- 1340 x 100 pixels, 20 x 20 µm pixel size
- 2 Mhz, 16-bit readout
- Back-illuminated CCD for sensitivity between ~ 30 eV to 10 keV
- Thermoelectric cooling with multi-stage Peltier Cooling
- WinSpec software for Windows 7
- Flexible user-selectable binning

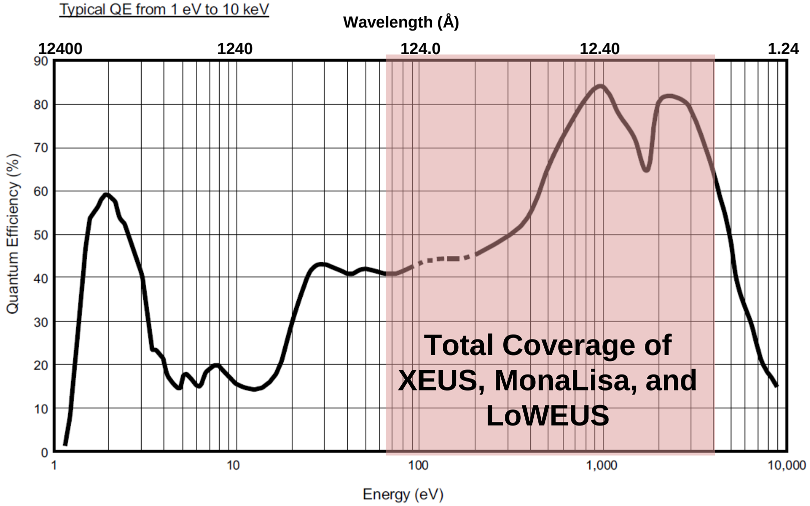
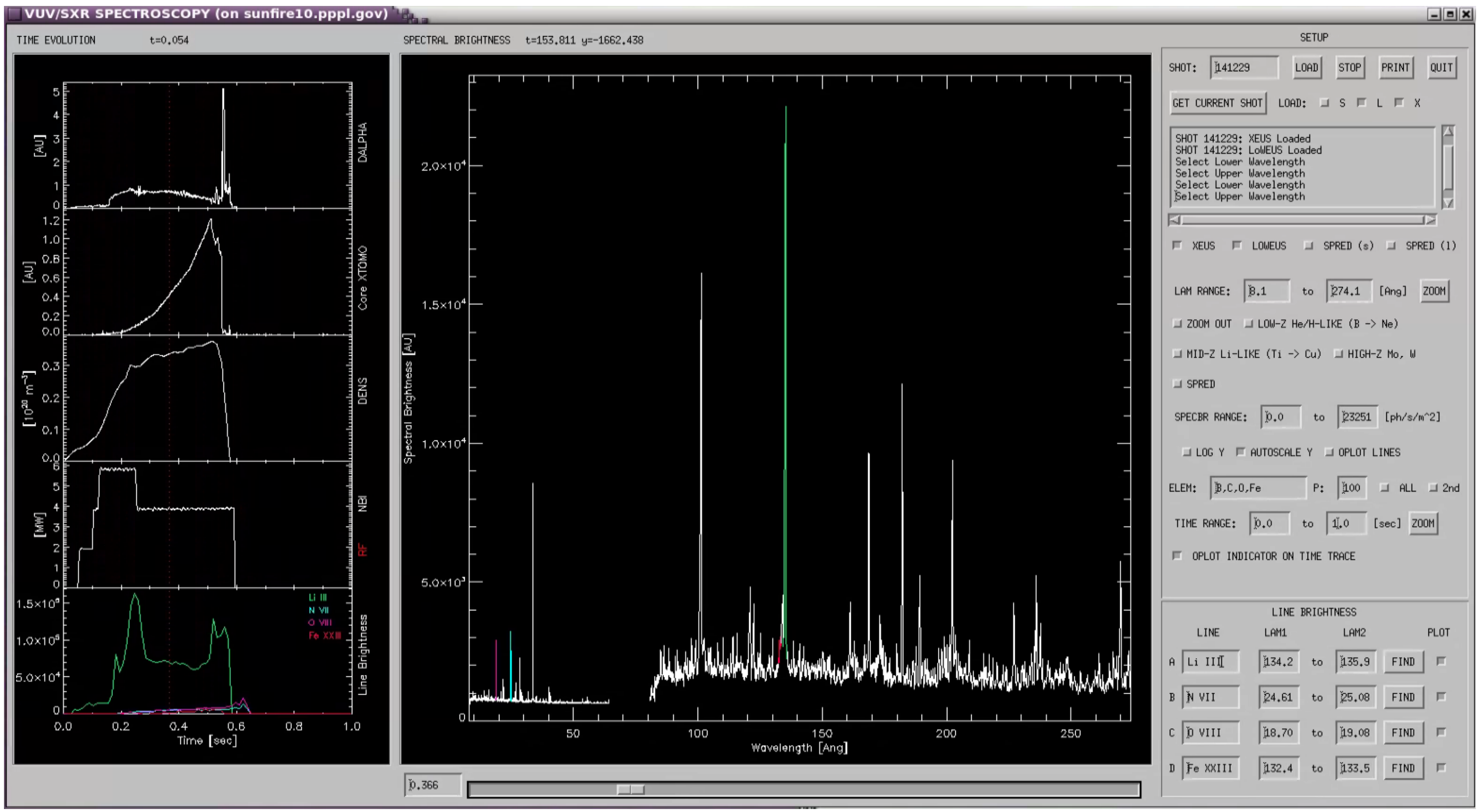


Figure taken from Princeton Instruments PIXIS-XO Manual (2014)

Existing Spectral Analysis Tools Imported, Ready for First Plasma Operations

- Developed on Alcator C-Mod for use with XEUS and LoWEUS spectrometers (Reinke 2010).
- Visualization widgets for manual intershot inspection.
- IDL routines automated by MDSPlus events for intershot line-fitting.
- W_SPEC widget and IMPSPEC line analysis part of GENIE toolset: https://github.com/mlreinke/GENIE.

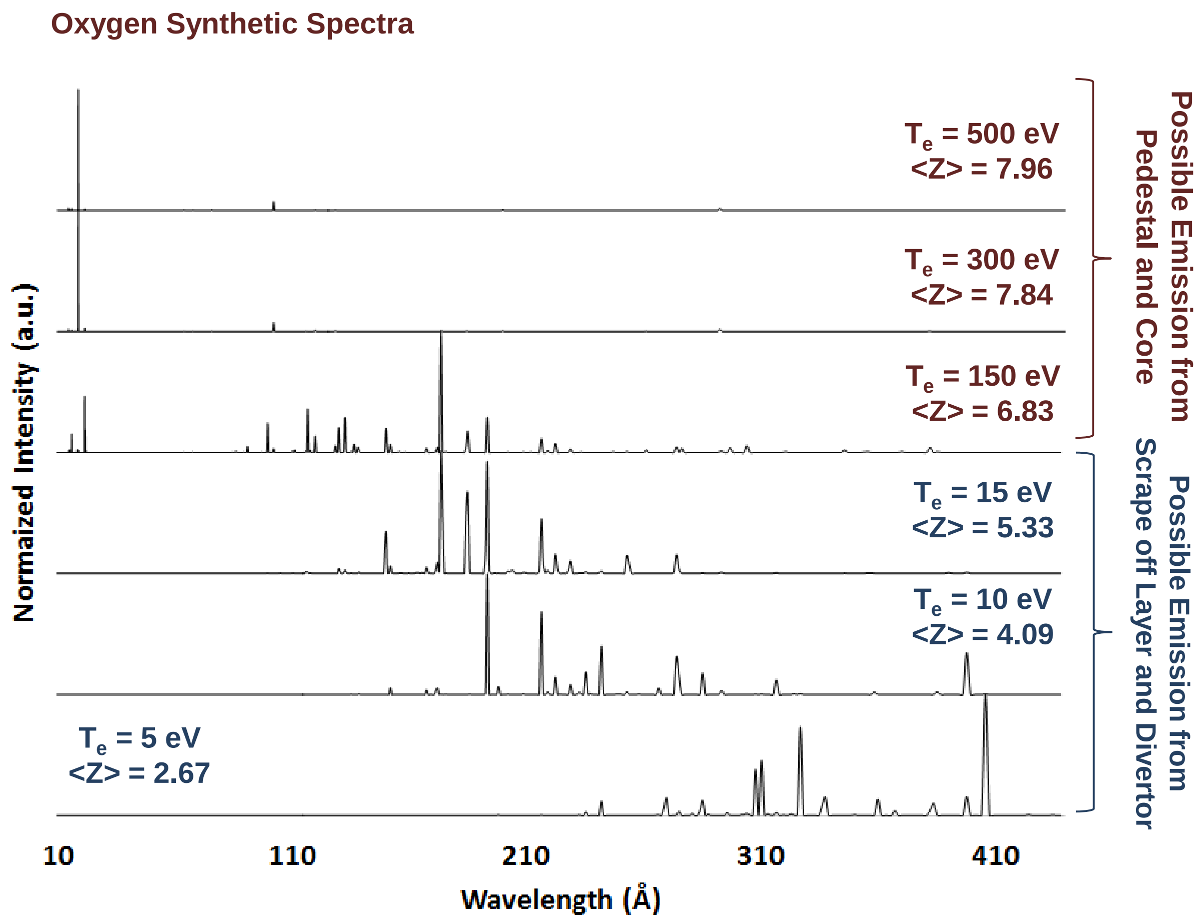


A Collisional Radiative Model SCRAM using FAC Data Will be Used for Modeling

- Theoretical models are needed to help with spectral analysis.
- The Spectroscopic Collisional-Radiative Atomic Model (SCRAM) was developed at the University of Nevada, Reno to diagnose plasma parameters for various experimental conditions (Hansen 2003).
- The Flexible Atomic Code (FAC, Gu 2008) is used to produce atomic data which is then input into SCRAM.
- The atomic data includes the ground states from the bare to neutral atoms and the details from H-like to Al-like ions including singly (up to n = 6) and doubly (up to n = 4) excited states.
- Models include: Li, C, N, O, Mg, Al, Ar, Ti, Fe, Cu, Zn, Kr, Mo, and Ag. For more information see references (Yilmaz 2009, Wilcox 2008, Ouart 2010, Weller 2014).
- Cu model, for example, used to help diagnose NSTX data (Safronova 2010).
- Future work will include models other impurities that may be present in NSTX-U, including M-shell models for high-Z materials such as Mo and W.

Example of Theoretical Model to be Used - Oxygen

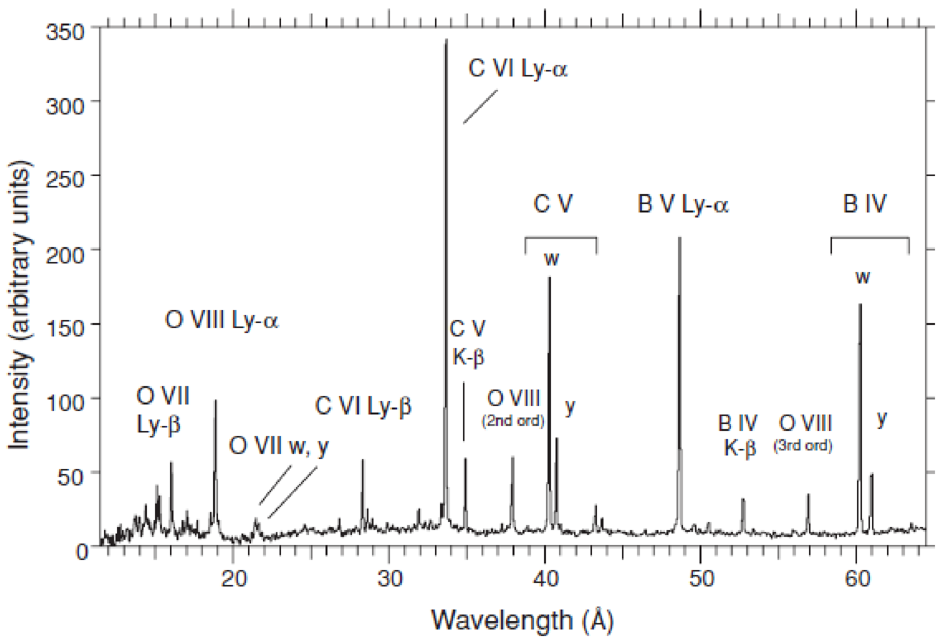
- To illustrate the amount of lines that radiate between 8 and 440 Å, an O model was utilized.
- The electron density used was 5 x 10^{13} cm^{-3} and the electron temperature ranged from 5 and 500 eV.
- Average charge balance calculated is shown.
- Dozens of diagnostically important O lines are seen within a vast temperature range, which cover emission from the scrape off layer to the core.



Expected Impurity Lines - XEUS

Expected Impurities (5 – 65 Å)

Lines	Transition	λ (Å)
O VIII Ly-β	$3p\ ^2P_{1/2,3/2} \rightarrow 1s\ ^2S_{1/2}$	16.00
O VIII Ly-α	$2p\ ^2P_{1/2,3/2} \rightarrow 1s\ ^2S_{1/2}$	18.97
O VII ω	$1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$	21.60
O VII y	$1s2p\ ^3P_1 \rightarrow 1s^2\ ^1S_0$	21.80
C VI Ly-β	$3p\ ^2P_{1/2,3/2} \rightarrow 1s\ ^2S_{1/2}$	28.46
C VI Ly-α	$2p\ ^2P_{1/2,3/2} \rightarrow 1s\ ^2S_{1/2}$	33.73
C V ω	$1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$	40.26
C V y	$1s2p\ ^3P_1 \rightarrow 1s^2\ ^1S_0$	40.72
B V Ly-β	$3p\ ^2P_{1/2,3/2} \rightarrow 1s\ ^2S_{1/2}$	40.99
B V Ly-α	$2p\ ^2P_{1/2,3/2} \rightarrow 1s\ ^2S_{1/2}$	48.58
B IV ω	$1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$	60.31
B IV y	$1s2p\ ^3P_1 \rightarrow 1s^2\ ^1S_0$	61.09



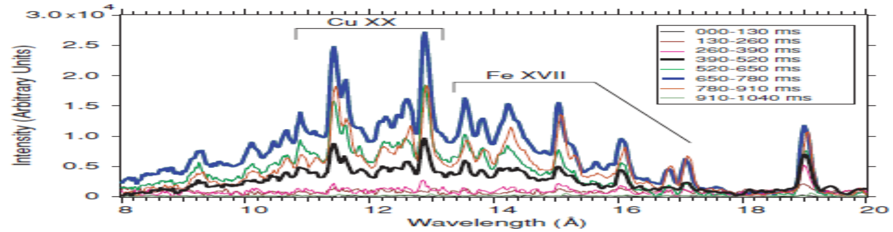
Spectra from NSTX taken with XEUS. Figure from Lepson 2010

K-shell O, C, and B radiate within the XEUS range.

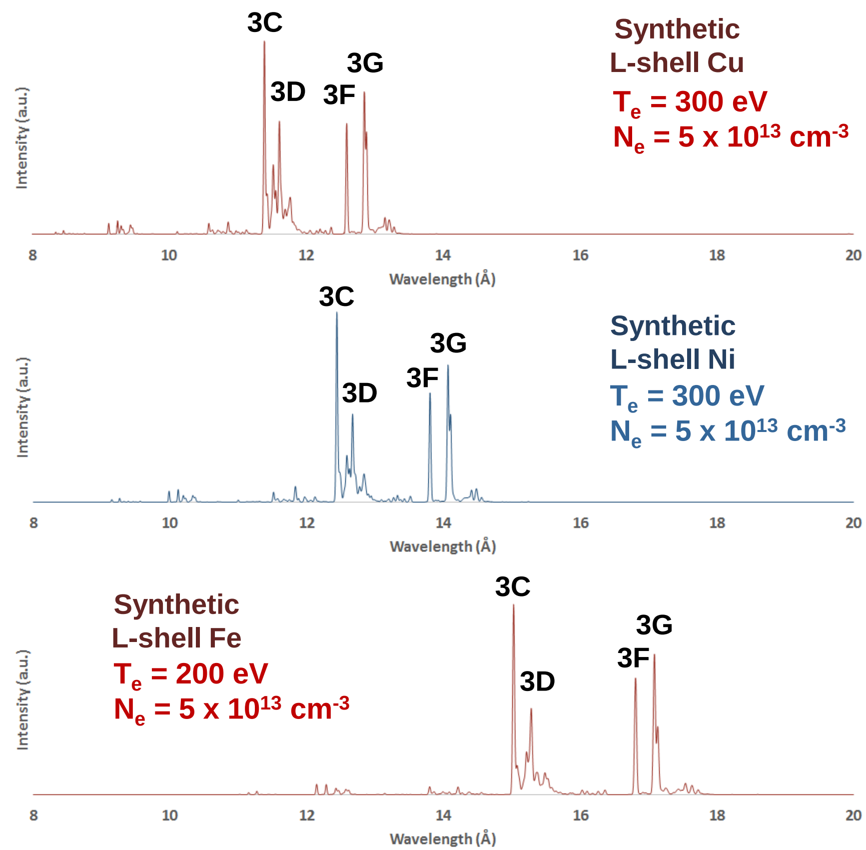
Possible Impurity Lines – XEUS

Possible Impurities (5 – 65 Å)

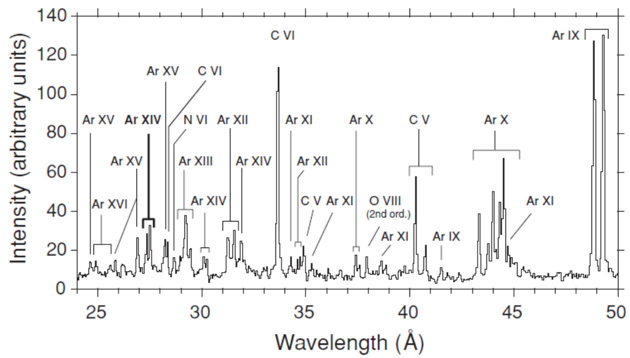
Lines	Transition	λ (Å)
Cu XX 3C	$2p^5 3d\ ^1P_1 \rightarrow 2p^6\ ^1S_0$	11.39
Cu XX 3D	$2p^5 3d\ ^3D_1 \rightarrow 2p^6\ ^1S_0$	11.61
Cu XX 3F	$2p^5 3s\ ^1P_1 \rightarrow 2p^6\ ^1S_0$	12.59
Cu XX 3G	$2p^5 3s\ ^3P_1 \rightarrow 2p^6\ ^1S_0$	12.85
Ni XIX 3C	$2p^5 3d\ ^1P_1 \rightarrow 2p^6\ ^1S_0$	12.44
Ni XIX 3D	$2p^5 3d\ ^3D_1 \rightarrow 2p^6\ ^1S_0$	12.67
Ni XIX 3F	$2p^5 3s\ ^1P_1 \rightarrow 2p^6\ ^1S_0$	13.80
Ni XIX 3G	$2p^5 3s\ ^3P_1 \rightarrow 2p^6\ ^1S_0$	14.06
Fe XVII 3C	$2p^5 3d\ ^1P_1 \rightarrow 2p^6\ ^1S_0$	15.02
Fe XVII 3D	$2p^5 3d\ ^3D_1 \rightarrow 2p^6\ ^1S_0$	15.28
Fe XVII 3F	$2p^5 3s\ ^1P_1 \rightarrow 2p^6\ ^1S_0$	16.81
Fe XVII 3G	$2p^5 3s\ ^3P_1 \rightarrow 2p^6\ ^1S_0$	17.08



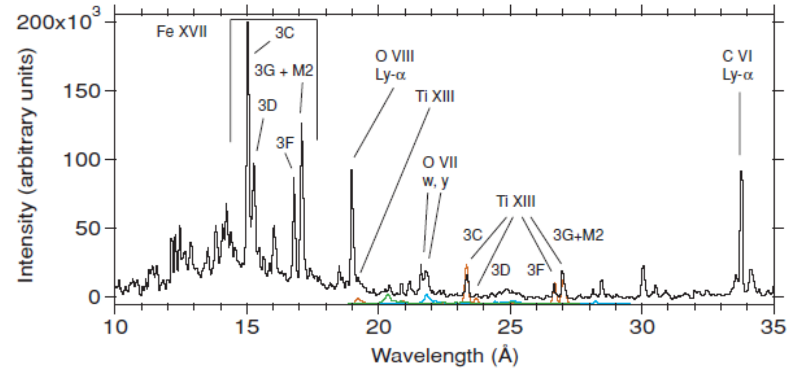
Cu and Fe on NSTX from XEUS. Taken from Lepson 2010



Possible Impurity Lines – XEUS



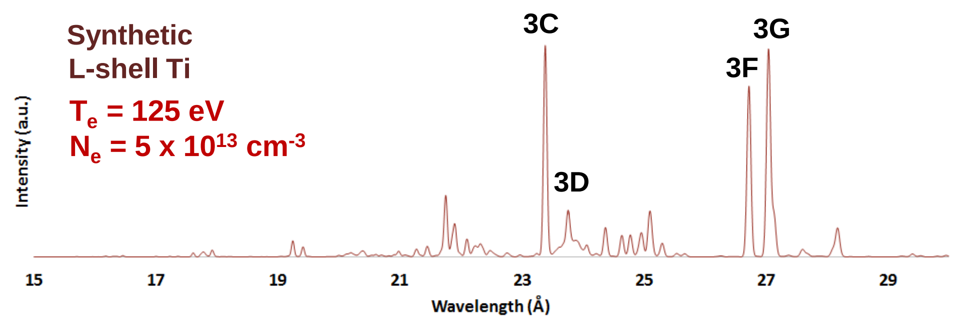
Example of Ar spectra from NSTX. Taken from Lepson 2010.

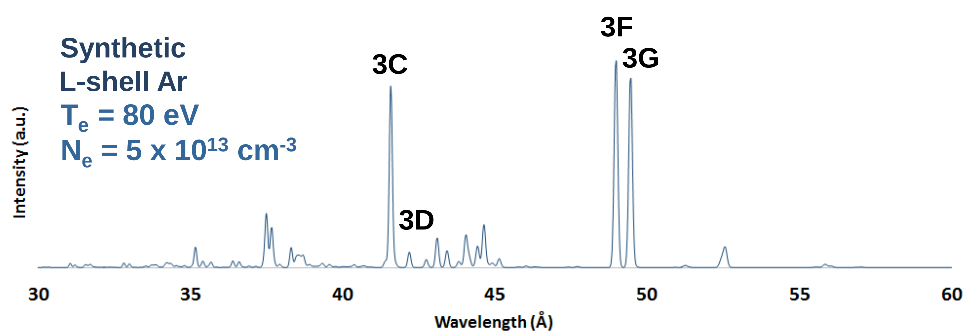


Example of Ti spectra from NSTX. Taken from Lepson 2010.

Possible Impurities (5 – 65 Å)

Lines	Transition	λ (Å)
Ti XIII 3C	$2p^5 3d\ ^1P_1 \rightarrow 2p^6\ ^1S_0$	23.36
Ti XIII 3D	$2p^5 3d\ ^3D_1 \rightarrow 2p^6\ ^1S_0$	23.70
Ti XIII 3F	$2p^5 3s\ ^1P_1 \rightarrow 2p^6\ ^1S_0$	26.64
Ti XIII 3G	$2p^5 3s\ ^3P_1 \rightarrow 2p^6\ ^1S_0$	27.04
Ar IX 3C	$2p^5 3d\ ^1P_1 \rightarrow 2p^6\ ^1S_0$	41.48
Ar IX 3D	$2p^5 3d\ ^3D_1 \rightarrow 2p^6\ ^1S_0$	42.52
Ar IX 3F	$2p^5 3s\ ^1P_1 \rightarrow 2p^6\ ^1S_0$	48.73
Ar IX 3G	$2p^5 3s\ ^3P_1 \rightarrow 2p^6\ ^1S_0$	49.18



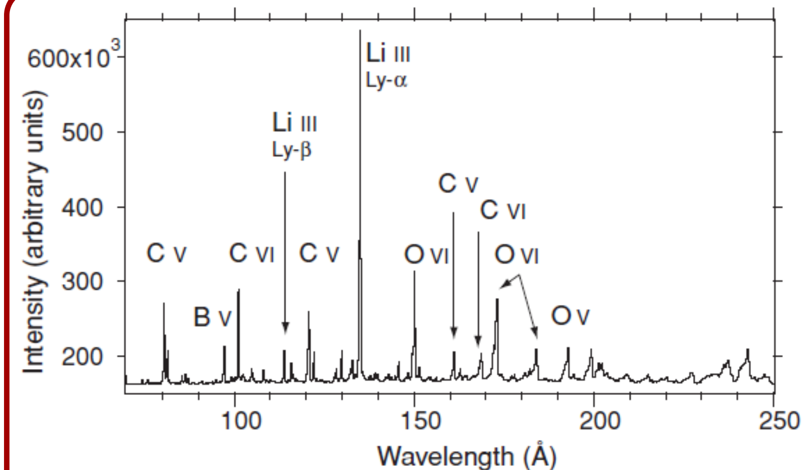


Expected Impurity Lines - MonaLisa

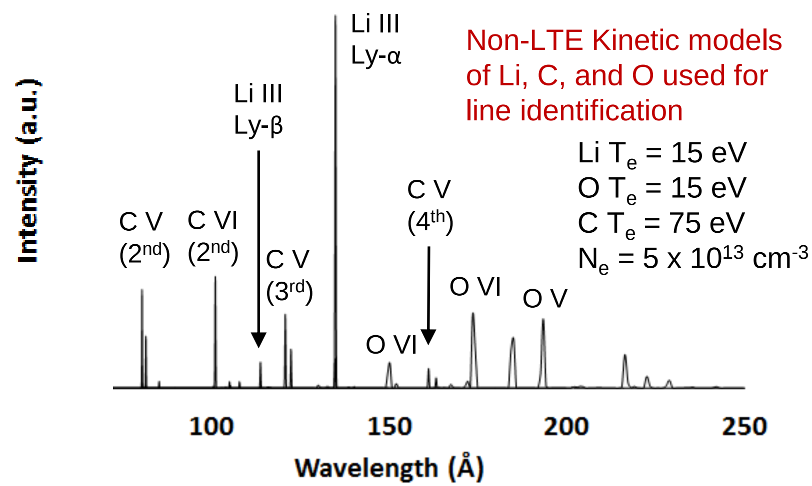
Expected Impurities (60 – 220 Å)

Lines	Transition	λ (Å)
Li III Ly-β	$3p\ ^2P_{1/2,3/2} \rightarrow 1s\ ^2S_{1/2}$	113.90
Li III Ly-α	$2p\ ^2P_{1/2,3/2} \rightarrow 1s\ ^2S_{1/2}$	134.94
Li II ω	$1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$	199.28
Li II y	$1s2p\ ^3P_1 \rightarrow 1s^2\ ^1S_0$	202.32
O VI	$1s^2 3p\ ^2P_{1/2,3/2} \rightarrow 1s^2 2s\ ^2S_{1/2}$	150.08
O VI	$1s^2 3d\ ^2D_{3/2,5/2} \rightarrow 1s^2 2p\ ^2P_{1/2,3/2}$	173.08
O VI	$1s^2 3s\ ^2S_{1/2} \rightarrow 1s^2 2p\ ^2P_{1/2,3/2}$	184.12

One purpose of MonaLisa is to measure Li impurity lines.



Impurities on NSTX in MonaLisa range. Taken from Lepson 2010

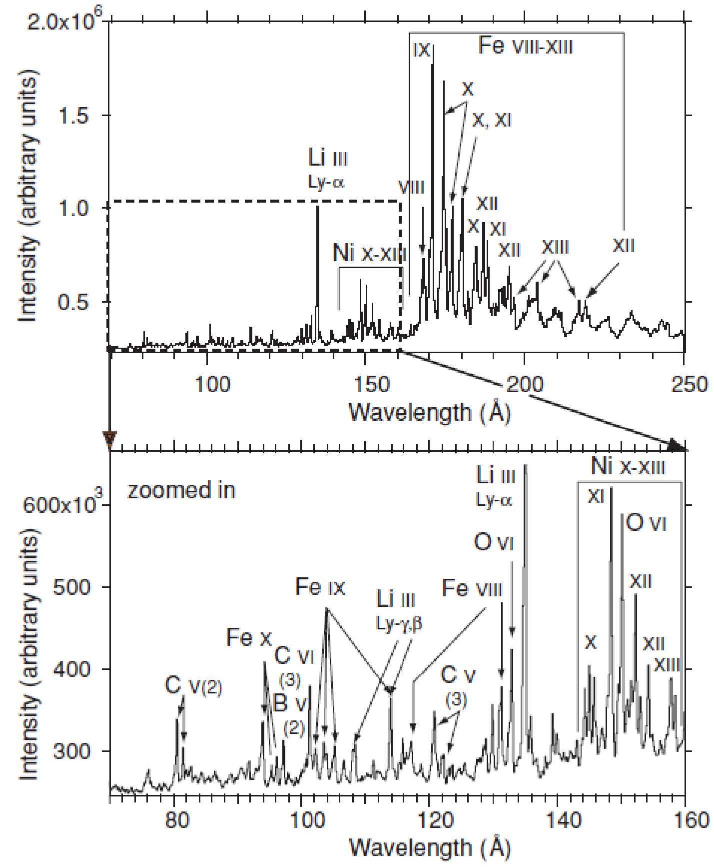


Possible Impurity Lines - MonaLisa

Possible Impurities Expected (60 – 220 Å)

Lines	Transition	λ (Å)
W XLIV	$4s4p^2\ ^2D_{3/2} \rightarrow 4s^24p\ ^2P_{1/2}$	61.33
Mo XXV	$3p^53d\ ^1P_1 \rightarrow 3p^6\ ^1S_0$	74.17
Fe XXII	$2s2p^2\ ^2P_{3/2} \rightarrow 2s^22p\ ^2P_{3/2}$	114.41
Fe XXII	$2s2p^2\ ^2P_{1/2} \rightarrow 2s^22p\ ^2P_{1/2}$	117.14
W XLV	$4s4p\ ^3P_1 \rightarrow 4s^2\ ^1S_0$	132.88
Ni XI	$3p^53d\ ^1P_1 \rightarrow 3p^6\ ^1S_0$	148.38
Fe IX	$3p^53d\ ^1P_1 \rightarrow 3p^6\ ^1S_0$	171.07

Radiation from mid to high-Z metals will also radiate in MonaLisa range.



Example of possible impurities NSTX. Figure taken from Lepson 2010

Expected and Possible Impurity Lines - LoWEUS

Probable Impurities Expected (190 – 440 Å)

Lines	Transition	λ (Å)
C IV	4p $^2P_{1/2,3/2} \rightarrow$ 2s $^2S_{1/2}$	244.90
He II Ly-β	3p $^2P_{1/2,3/2} \rightarrow$ 1s $^2S_{1/2}$	256.31
B V	3p $^2P_{1/2,3/2} \rightarrow$ 2s $^2S_{1/2}$	262.40
C IV	4d $^2D_{3/2,5/2} \rightarrow$ 2p $^2P_{1/2,3/2}$	289.23
O VIII	4d $^2D_{5/2} \rightarrow$ 3p $^2P_{3/2}$	292.77
He II Ly-α	2p $^2P_{1/2,3/2} \rightarrow$ 1s $^2S_{1/2}$	303.78
C IV	3p $^2P_{1/2,3/2} \rightarrow$ 2s $^2S_{1/2}$	312.42
C IV	3s $^2S_{1/2} \rightarrow$ 2p $^2P_{1/2,3/2}$	384.18
C IV	3s $^2S_{1/2} \rightarrow$ 2p $^2P_{1/2,3/2}$	419.92

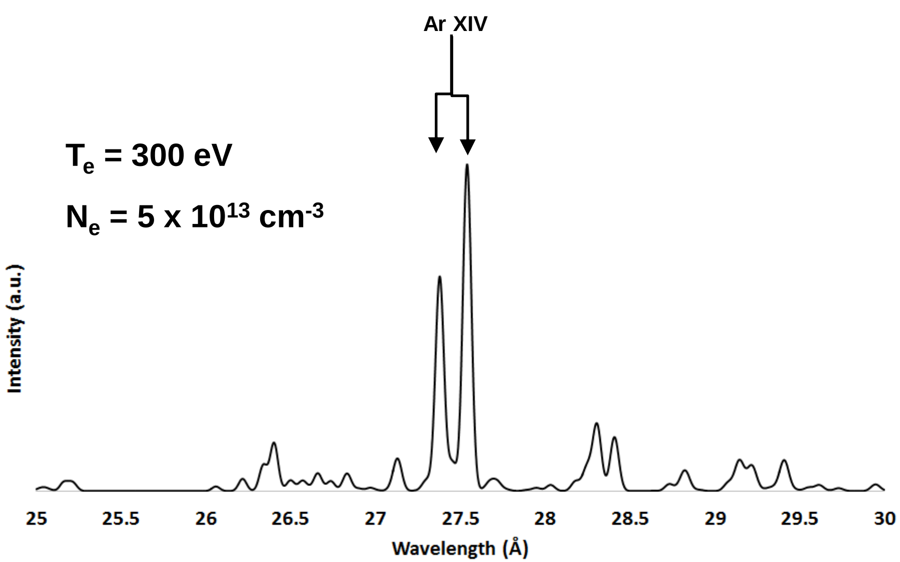
Possible Impurities Expected (190 – 440 Å)

Lines	Transition	λ (Å)
Cl XIV	2s2p $^1P_1 \rightarrow$ 2s^2 $^1S_0$	233.30
Ni XVII	3s3p $^1P_1 \rightarrow$ 3s^2 $^1S_0$	249.19
Cu XIX	3p $^2P_{3/2} \rightarrow$ 3s $^2S_{1/2}$	273.35
Ni XVIII	3p $^2P_{3/2} \rightarrow$ 3s $^2S_{1/2}$	291.99
Cu XIX	3p $^2P_{1/2} \rightarrow$ 3s $^2S_{1/2}$	303.55
Fe XVI	3p $^2P_{3/2} \rightarrow$ 3s $^2S_{1/2}$	335.41
Fe XVI	3p $^2P_{1/2} \rightarrow$ 3s $^2S_{1/2}$	360.76
Cl XV	2p $^2P_{3/2} \rightarrow$ 2s $^2S_{1/2}$	380.63
Cl XV	2p $^2P_{1/2} \rightarrow$ 2s $^2S_{1/2}$	411.29

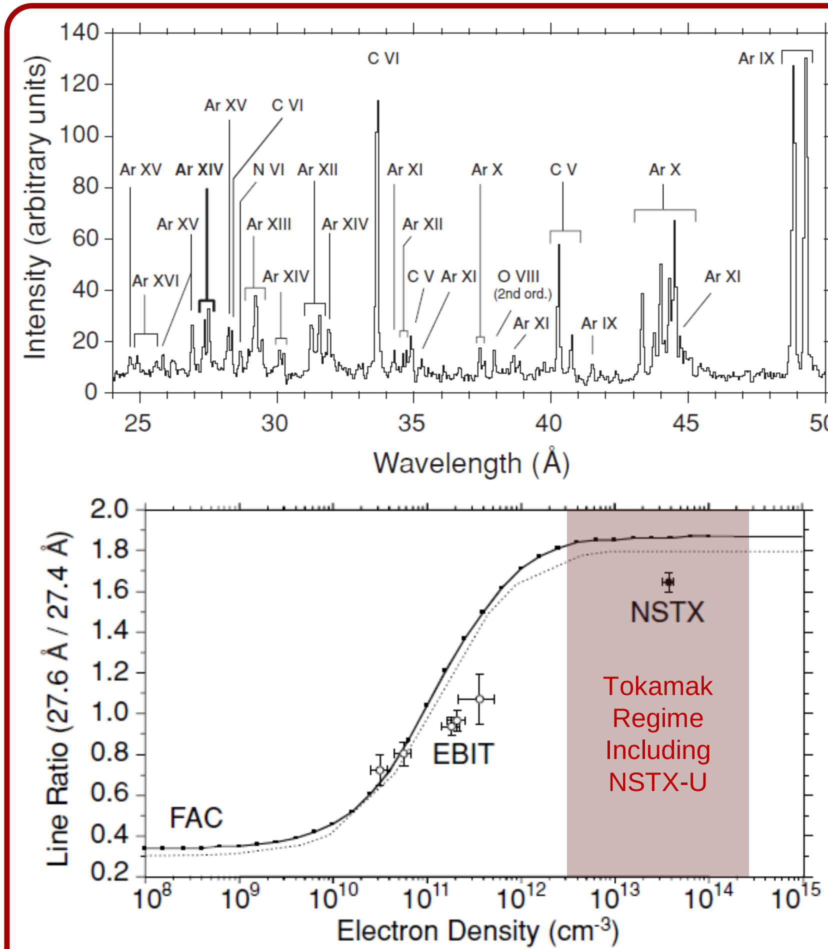
Brief listing of expected and possible impurity lines to be measured by LoWEUS. There are hundreds of lines from various high and low-Z materials that will radiate within the LoWEUS range.

Line Ratios Can Give Information of Plasma Conditions

- Certain line ratios may be used for plasma condition determination.
- For example in boron-like Ar XIV at 27.4 and 27.6 Å is sensitive to electron density between 10^9 and 10^{14} cm^{-3}, which is within NSTX-U operation.
- Laboratory measurements in NSTX-U combined with Thompson scattering can be used to benchmark theoretical atomic models, such as FAC.



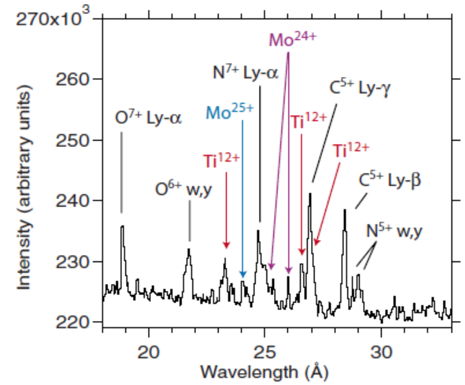
Synthetic spectra of Ar XIV calculated with SCRAM using FAC data.



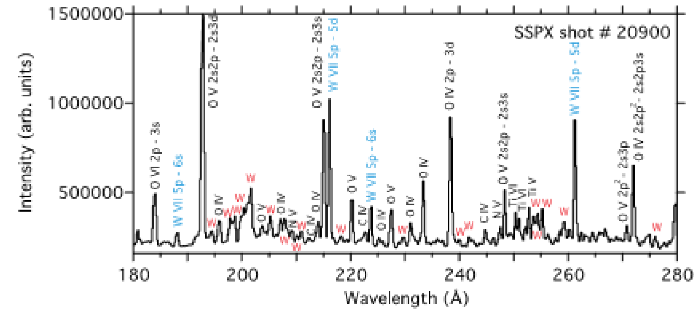
Argon spectra from XEUS (top) and Argon line ratios (bottom) taken from Lepson 2010.

Will Measure Future PFC High-Z Impurities from Mo and W

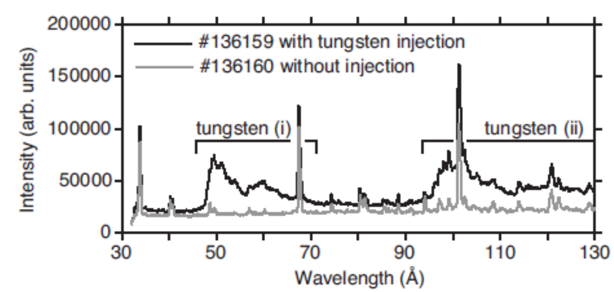
- Future plans for PFC on NSTX-U include introducing high-Z materials.
- For example the molybdenum alloy titanium-zirconium-molybdenum is planned to be used in the divertor.
- Tungsten is a leading PFC candidate for future fusion devices, such as ITER and will be used in NSTX-U experiments.
- XEUS, MonaLisa, and LoWEUS will have capability to measure many lines from different ionization stages of both Mo and W.



Mo data on NSTX from Beiersdorfer 2008



W data on SSPX from Clementson 2008



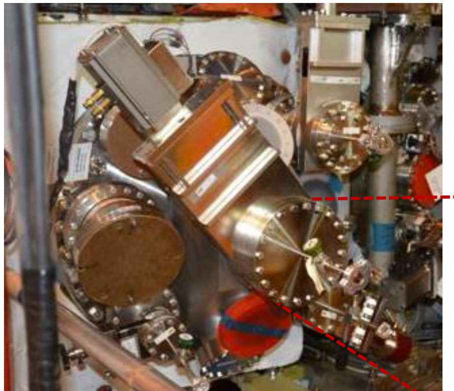
W data on NSTX from Clementson 2010

A New Laser Blow-Off System Will Be Introduced into NSTX-U

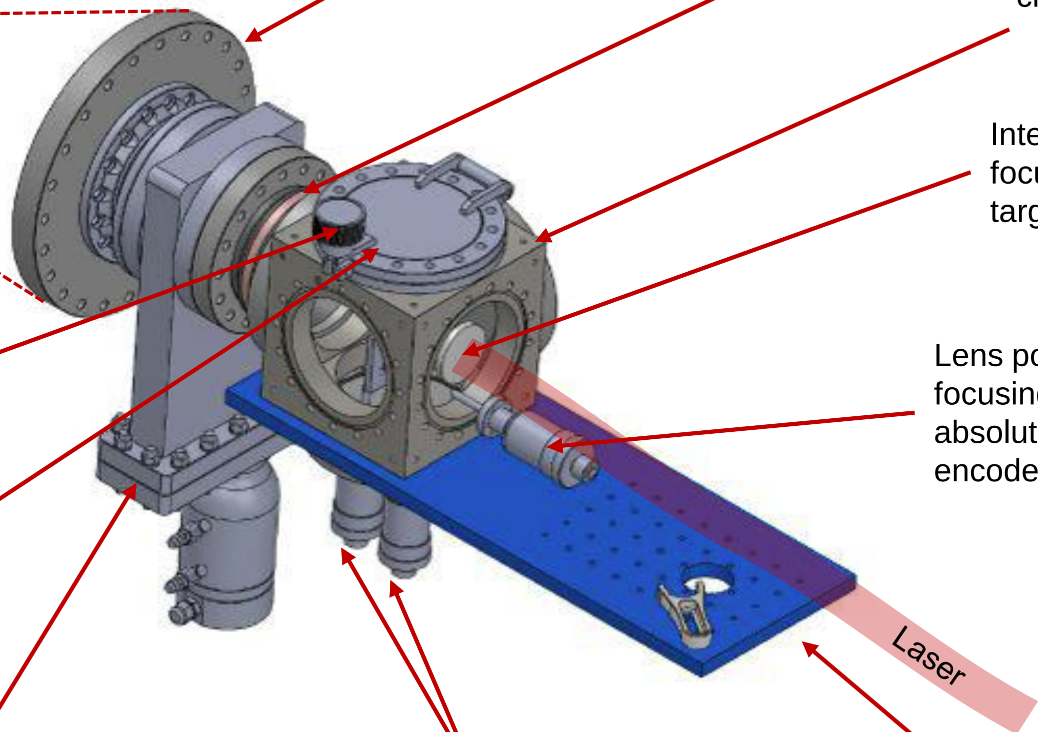
- Laser Blow-Off physics goals:
  - Study edge and core ion transport in NSTX-U
  - Edge Transport-code development and testing
  - Atomic physics studies for astrophysics
  - Benchmarking atomic physics models
- Will be a User Facility that is available for anyone needing the controlled injection of solid material for NSTX-U physics studies
  - Injection material is evaporated from glass slide
  - Injection amount per shot is variable
  - 10 Hz laser, allowing single and multiple injections at $\Delta t \geq 100$ ms between injections
- 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 Laser and Optic System

The LBO Target Chamber

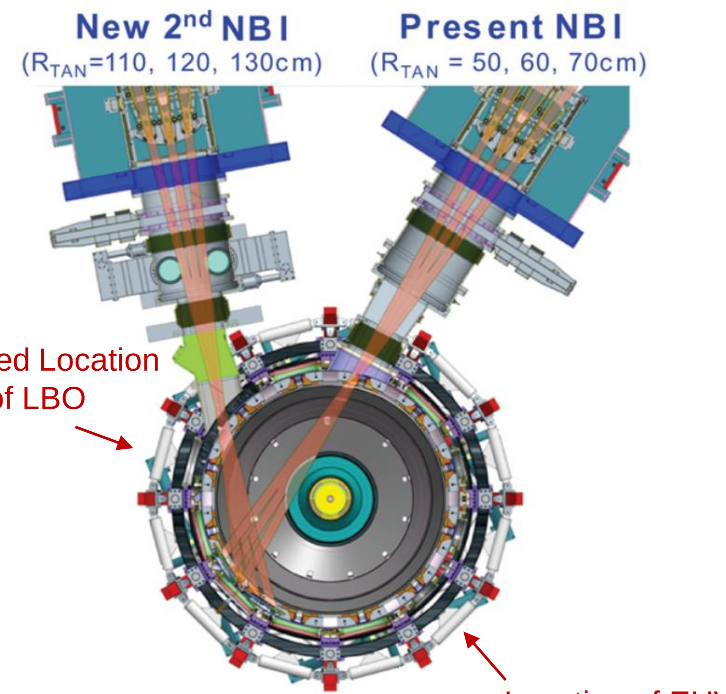


Bay J Port



LBO Will be Used for Impurity Transport Studies

- The combination of a new LBO system and high-resolution EUV spectrometers make for ideal diagnostics to study impurity transport in the plasma.
- Will be able to inject a very controlled amount of atoms of a specific element into the plasma at a given time.
- The location and timing of the injection will be known. XEUS, MonaLisa, and LoWEUS covers a range of temperatures that radiate from the scrape off layer to the core of the plasma.
- Will be able to study impurity diffusivity and convective pinch velocity from the measurements.
- With future plans for high-Z metal impurities, NSTX-U will have unique capability to address high-Z impurity transport in low collisionality and high-β regime.



Conclusions

- Impurity monitoring from three high resolution grating spectrometers covering 8 – 440 Å will be implemented on NSTX-U.
  - Will be an early detector of any potential problems that could develop.
- The three spectrometers will have a resolution between 0.1 and 0.3 with time resolution down to 5 ms.
  - Will have fast analysis of data between experiments.
- Hundreds of spectral lines will be covered including: oxygen, carbon, boron, lithium, iron, nickel, copper, argon, krypton, molybdenum, and tungsten.
  - Have theoretical models to help identify and analyze lines.
- A new Laser Blow-Off system will be implemented on NSTX-U.
  - Different materials will be ablated into NSTX-U with precise control.
  - Will be able to study impurity transport in the core.

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