# SXR to VUV imaging diagnostics for NSTX Upgrade

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**A suite of transport and MHD oriented SXR to VUV imaging diagnostics is being designed for NSTX-Upgrade. Two toroidally displaced tangential Multi-Energy SXR (ME-SXR) arrays will image the edge and core plasma with 1 cm and 3 cm resolution respectively, for measurements of perturbative impurity and electron transport ,fast $T_e$ and $n_z$ profiles, and non-magnetic MHD mode identification. The system is complemented by a tangential Transmission Grating Imaging Spectrometer measuring the spatial distribution of XUV impurity emission from the edge to the core and by a repetitive laser-blow off system aimed at multiple transport measurements during a discharge. For the divertor we design a dual grating Imaging Radiometer measuring with high space and time resolution the radiated power in multiple XUV and VUV spectral bins and aimed at assisting the divertor experimental and modeling studies planned at NSTX-U. Lastly, an ultrafast (4 MHz) dual-energy SXR imaging system is being studied for diagnostic of *AE modes and the associated $T_e$ perturbations.**

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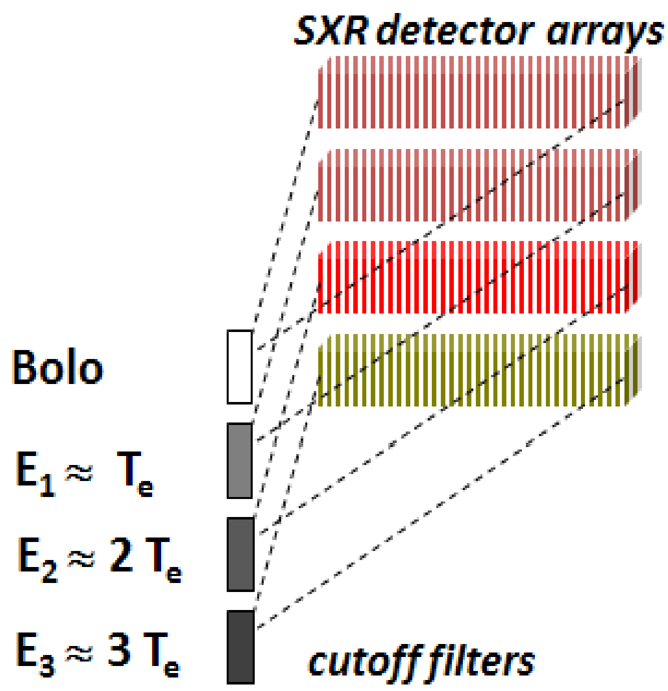
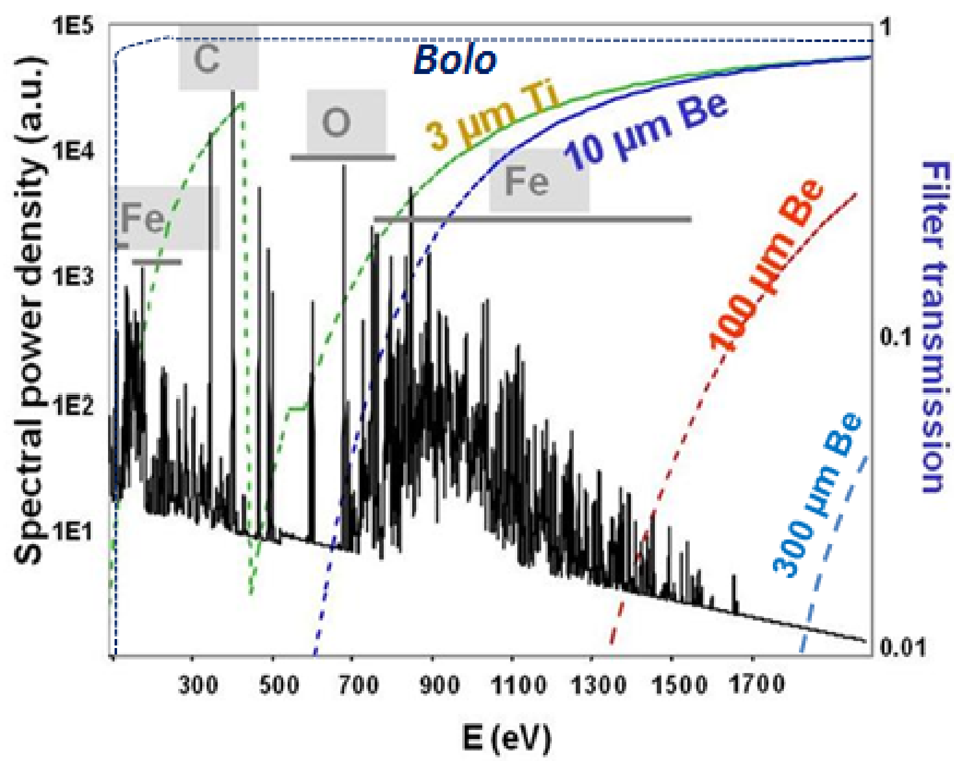
# Multi-energy SXR diagnostic (ME-SXR)



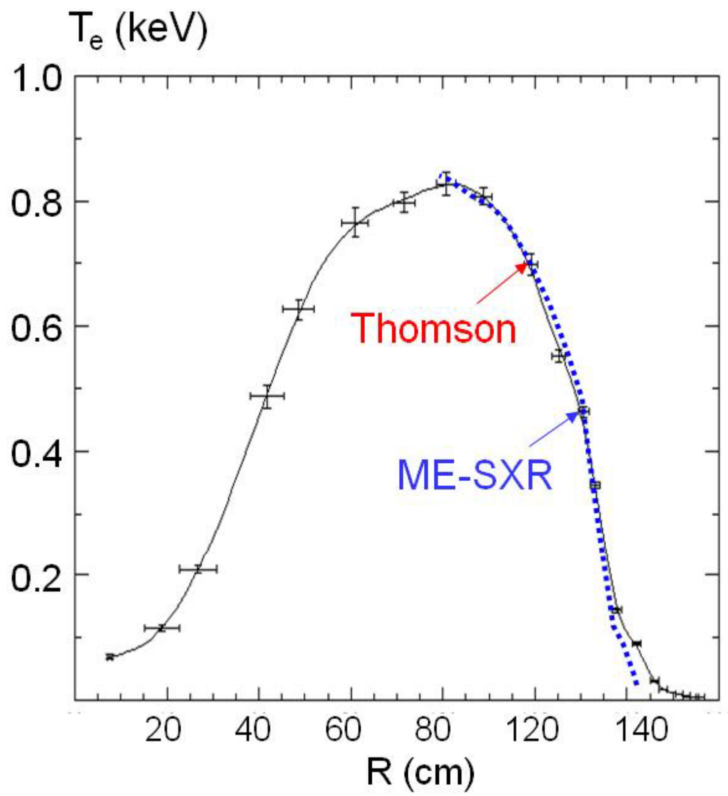




- **Same plasma volume simultaneously imaged in several energy bands**
- **Fast and simple measurement of plasma $T_e$, $n_z$, perturbative transport, MHD**
- **Five energy bands optimal for NSTX edge, four for the core:**

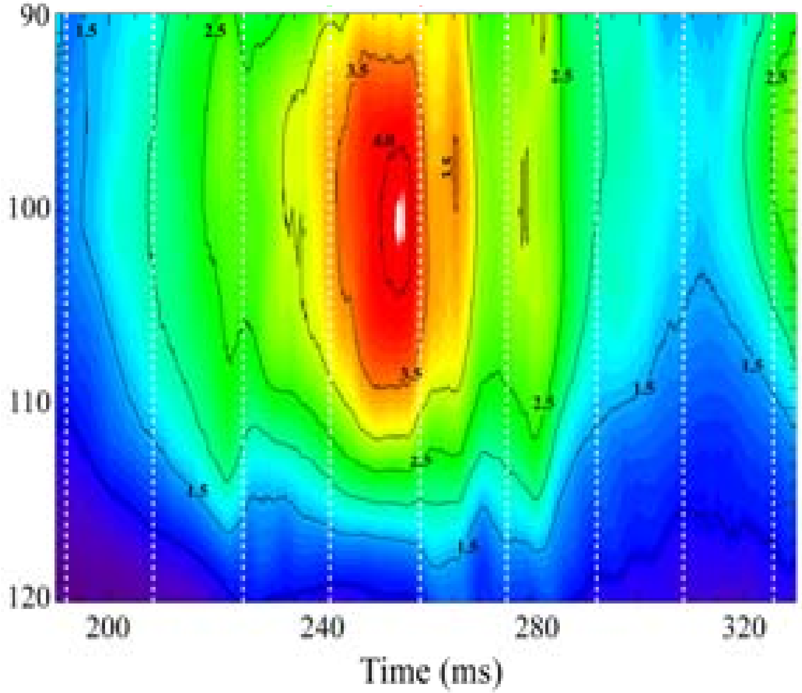
**Bolo($P_{rad}$) + Ti 3 μm (C lines) + three Be filters (C continuum + high-Z lines)**

# Fast $T_e$ measurements

**ME-SXR vs. Thomson $T_e$**



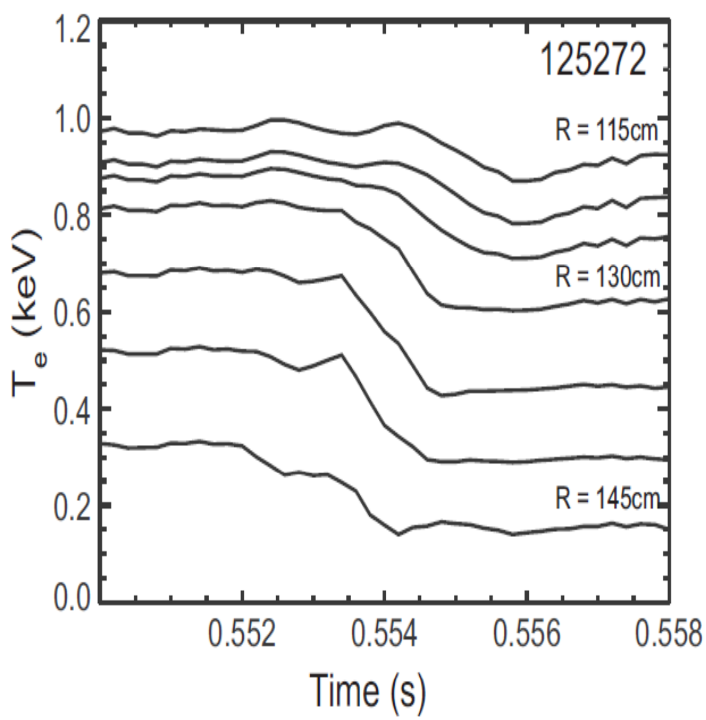

**ME-SXR $T_e$ during RF heating in NSTX (Delgado et al PPCF 2008)**



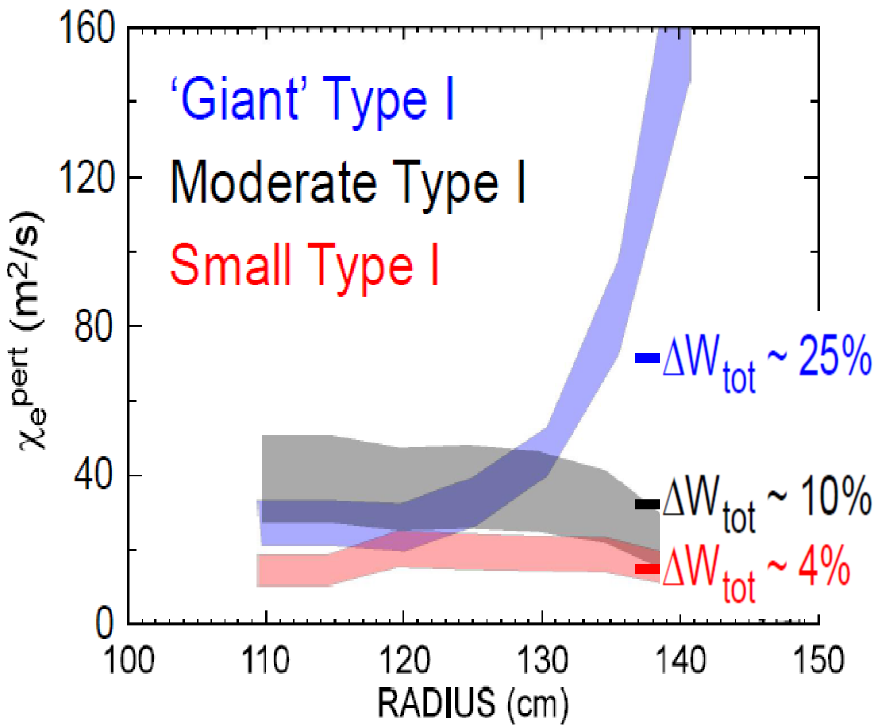

- **Intermittent normalization to Thomson scattering profiles improves accuracy**
- **Effective increase in the time/space resolution of the Thomson diagnostic**

# Perturbative electron transport measurements

**ME-SXR $T_e$ following giant Type-I ELM in NSTX**

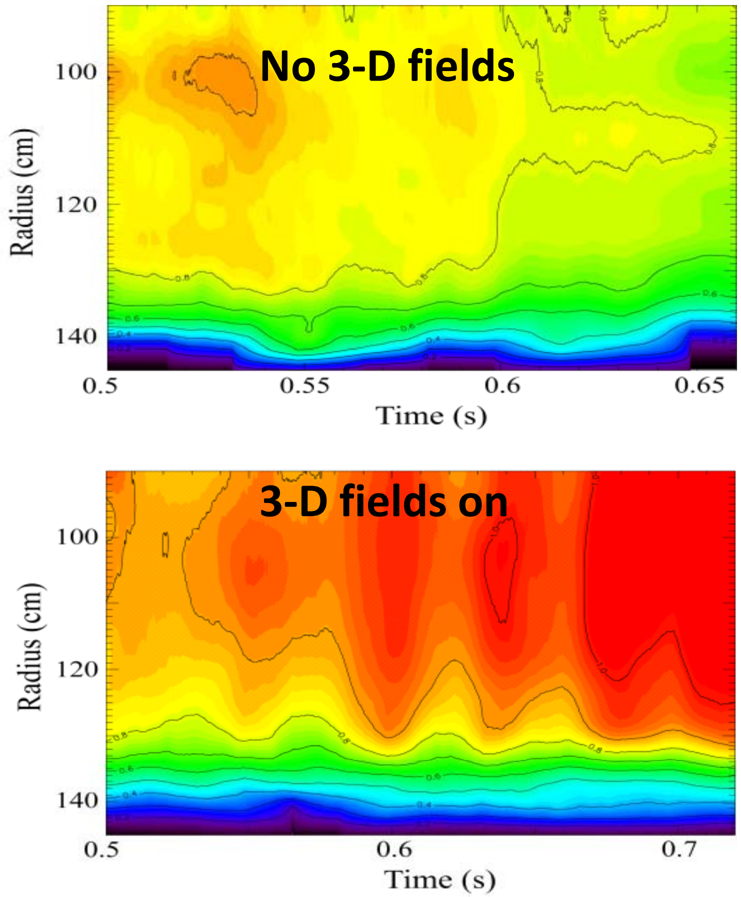



**$\chi_e^{pert}$ correlation with ELM severity (Tritz et al PoP 2008)**

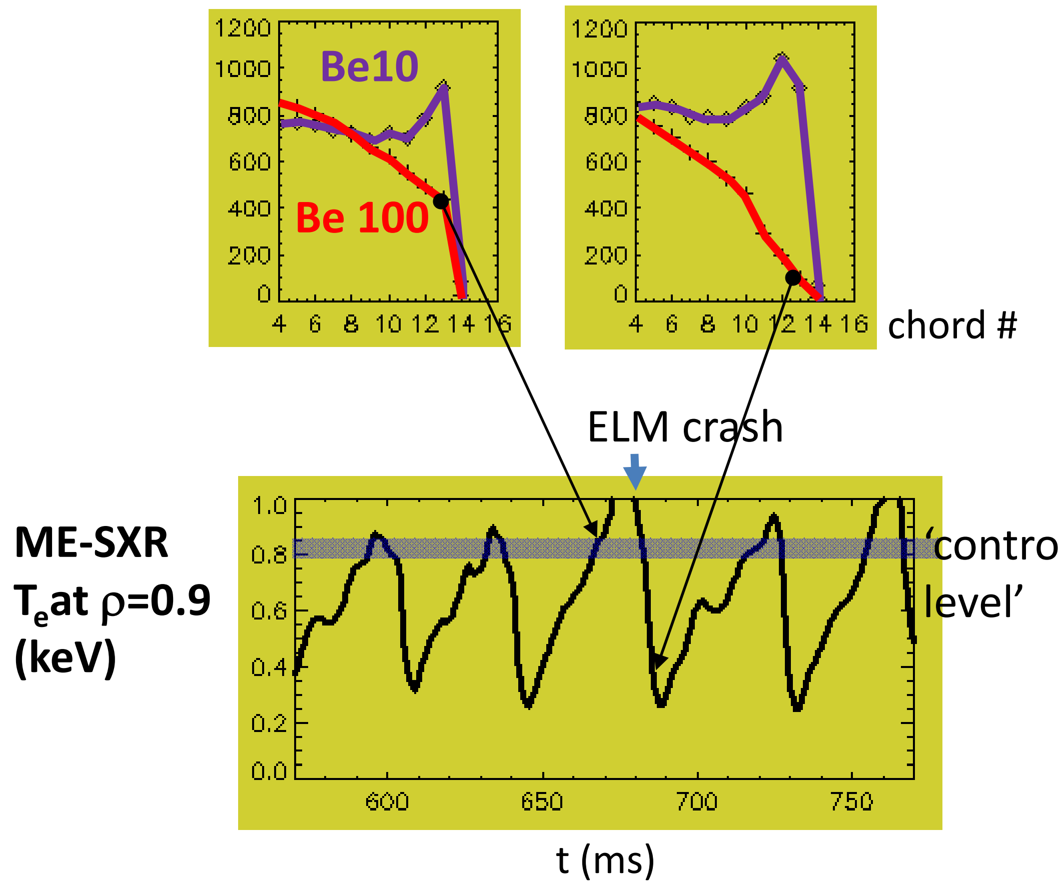


# Effects of 3-D fields, ELMs, potential for plasma control

## ME-SXR $T_e$ during RWM stabilization (Delgado et al PPCF 2011)

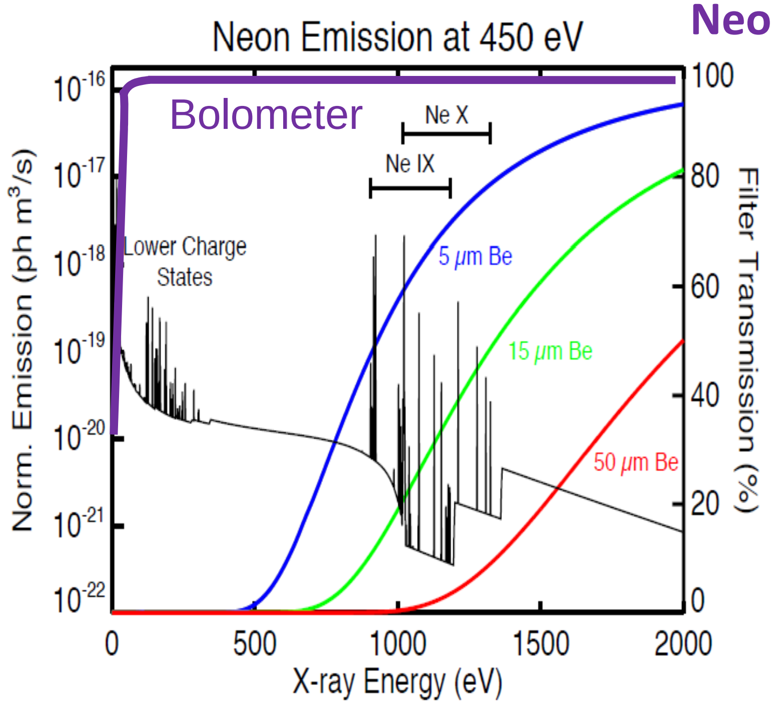



## ME-SXR $T_e$ during ELM cycle

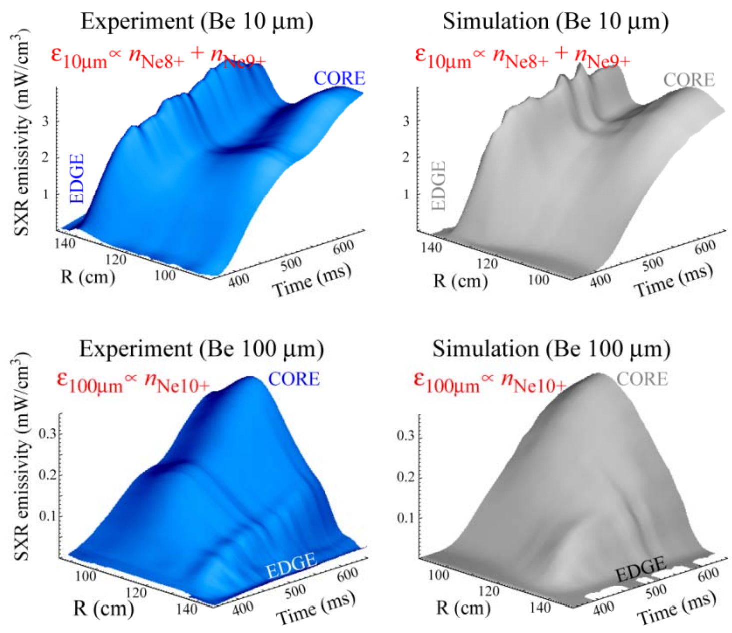



- Acting on the RWM with 3-D fields leads to $T_e$ modulations deep in the core
- ME-SXR '$T_e$' sensitive indicator of approaching ELM
- Toroidally displaced arrays for n>0 (MHD) and n=0 (equilibrium) profile changes

# Impurity transport measurements




**Neon injection in NSTX H-mode (Delgado et al NF 2007)**




• Same principle of discriminating groups of charge states using coarse spectral resolution applies to impurity transport measurements using injected impurities (e.g. Neon):

- Be channels measure K-shell and fully stripped charge states
- Bolometer channel measures L-shell charge states (source for K-shell states)

• Much improved constraint for fitting transport coefficients compared to conventional, single energy SXR imaging

# ME-SXR can provide also $n_{z,}$ $n_e$ profiles

• Assume two-component plasma, e.g. H and C with total densities $n_H$ and $n_C$
• Assume coronal equilibrium for the fractional abundances, $f_i(T)=n_i(T)/n_C$, with $n_i(T)$ the density of charge state 'i' at electron temperature T
• The emissivity at an electron temperature T and for a photon energy E:

$$\varepsilon(E;n_H,n_C,T)=n_H\cdot n_e\cdot H(E;T) + n_e\cdot n_C\, C(E;T)$$

with H(E;T) the line and continuum radiative emission coefficient for H and $C(E;T)= \sum f_i(T)C_i(E;T)$ the radiative coefficient for C

• $n_e=n_H+n_C\cdot\sum Z_i f_i(T)=n_H+n_C\cdot F(T)$
• The functions H, C and F have theoretically well known dependence on T and E
• The emissivity can be then written:

$$\varepsilon(E;n_H,n_C,T)=n_H^2\cdot H(E;T)+n_C^2\cdot F(T)\cdot C(E;T)+n_H\cdot n_C\cdot[C(E;T)+F(T)\cdot H(E;T)]$$

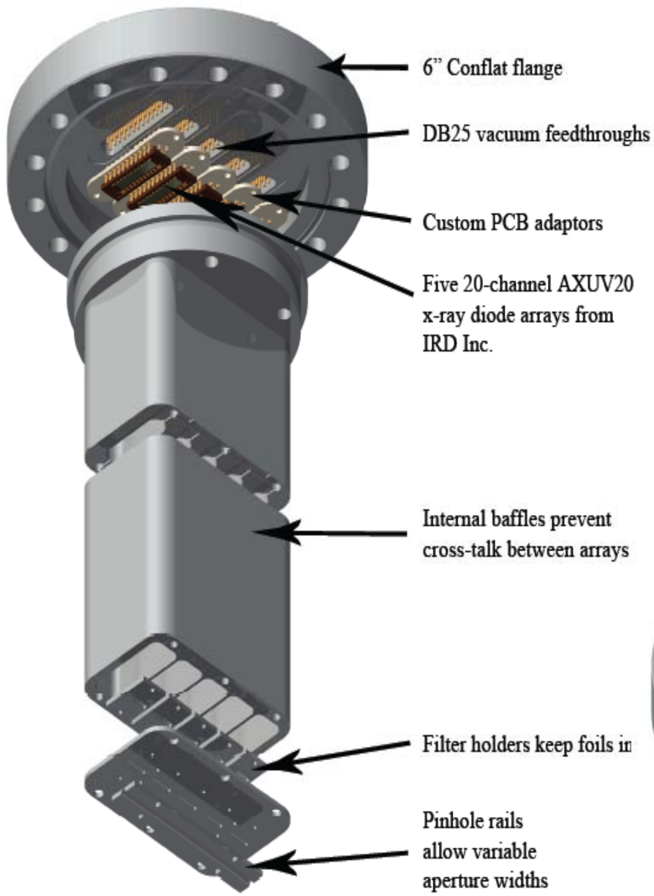
• Emissivity measurements at multiple energies $E_1$, $E_2$, $E_3$,…$E_n$ can thus provide a sufficient set of constraints to determine $n_H$, $n_C$, $T_e$, $n_e$

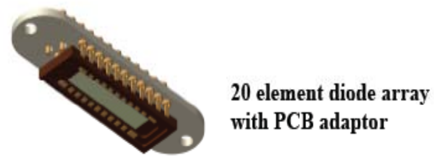
• Transport can be determined from time dependent emissivity of injected impurity

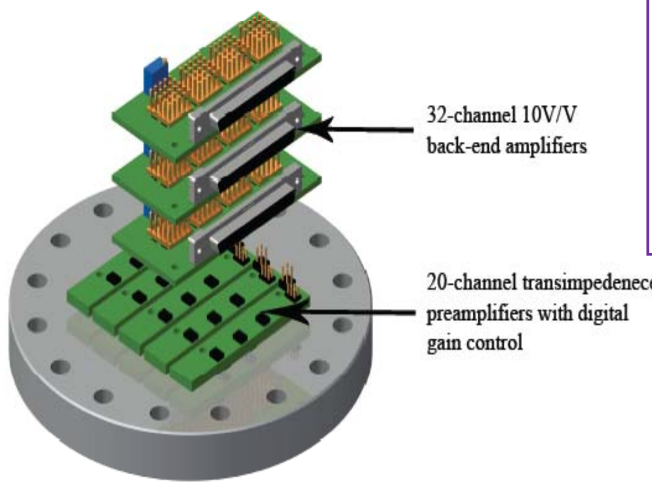
• An external $n_e$ measurement such as the Thomson profile or the line integrated interferometric density can also be used to constrain the $n_z$ calculation
(K Tritz et al, this conference)

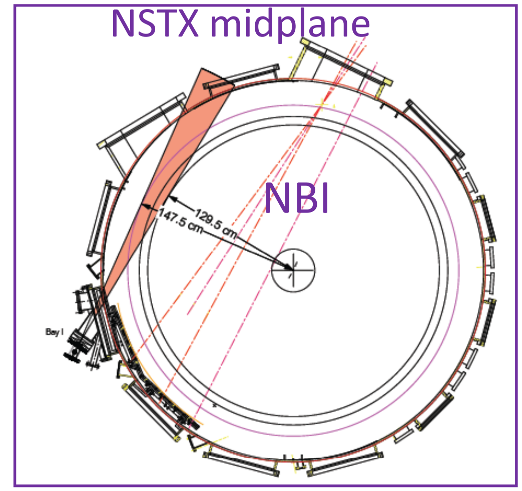
# High resolution ME-SXR arrays developed for NSTX edge

## Absolute diode based ME-SXR array (K Tritz et al RSI 2010)



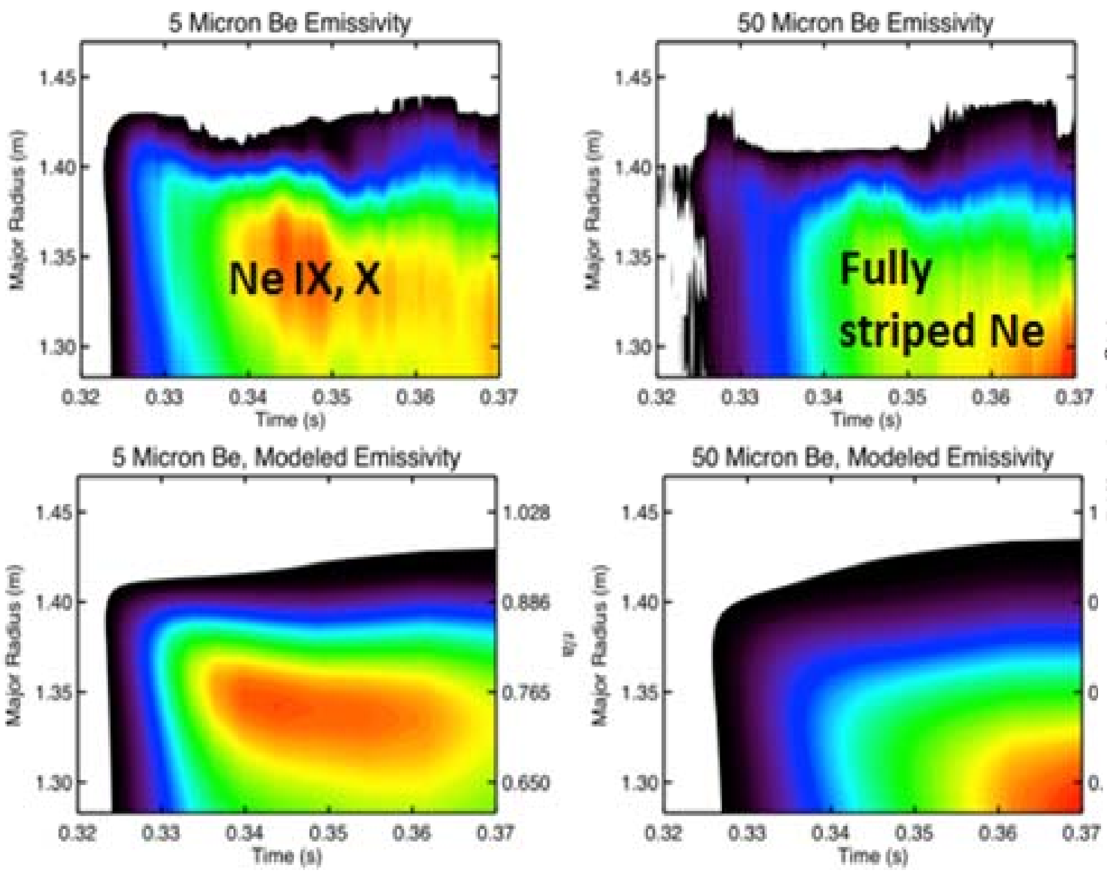

- Five energy bands from 0.01 to 10 keV, 1 cm spatial resolution, ≤100 kHz speed
- High resolution 'optical' ME-SXR arrays also demonstrated

# Edge transport measurements with improved accuracy

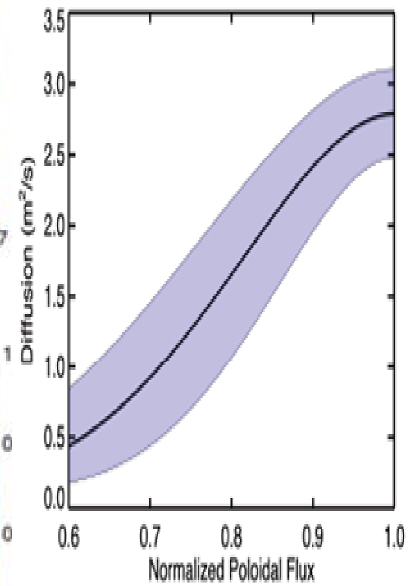
**Ne injection in NSTX H-mode edge (D Clayton et al this conference)**

**Expt.**

**STRAHL+ ADAS**

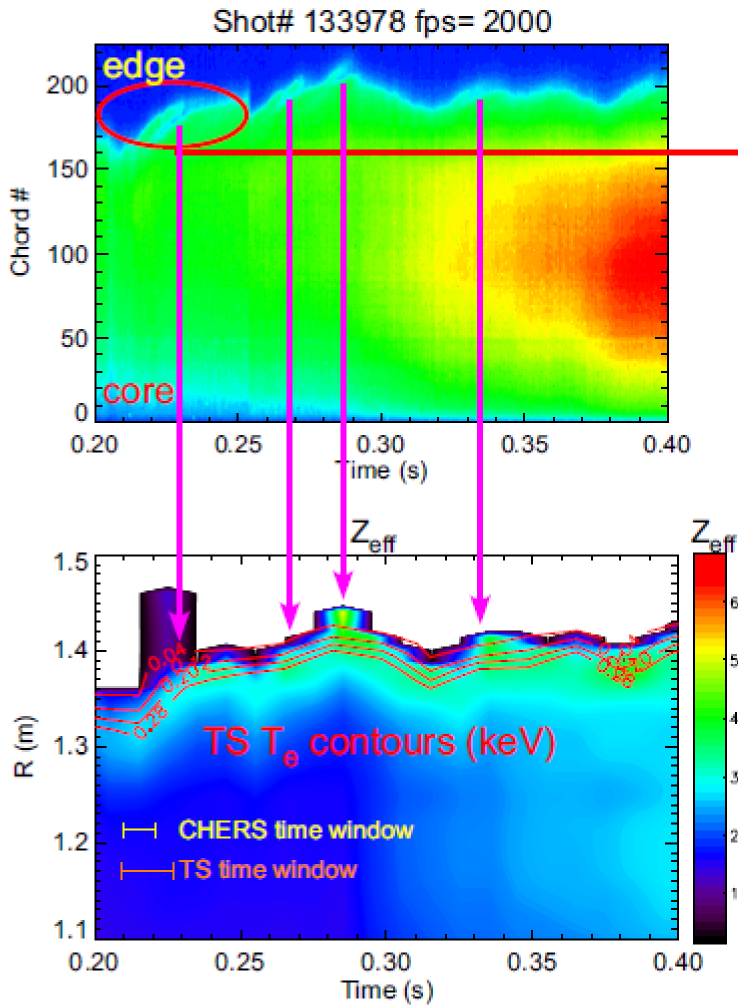


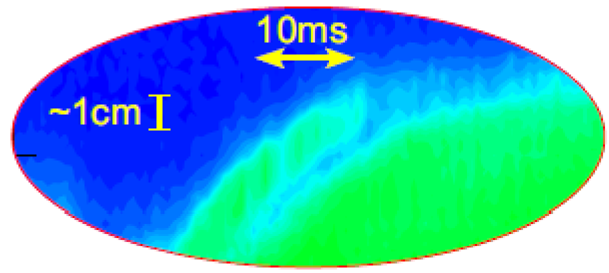

**Neon diffusivity**




- **Multiple energies and high spatial resolution strongly constrain D fit**
- **Core + edge ME-SXR measurement, non-recycling impurity source for accurate V**
- **Two toroidally displaced arrays can account for boundary movements**

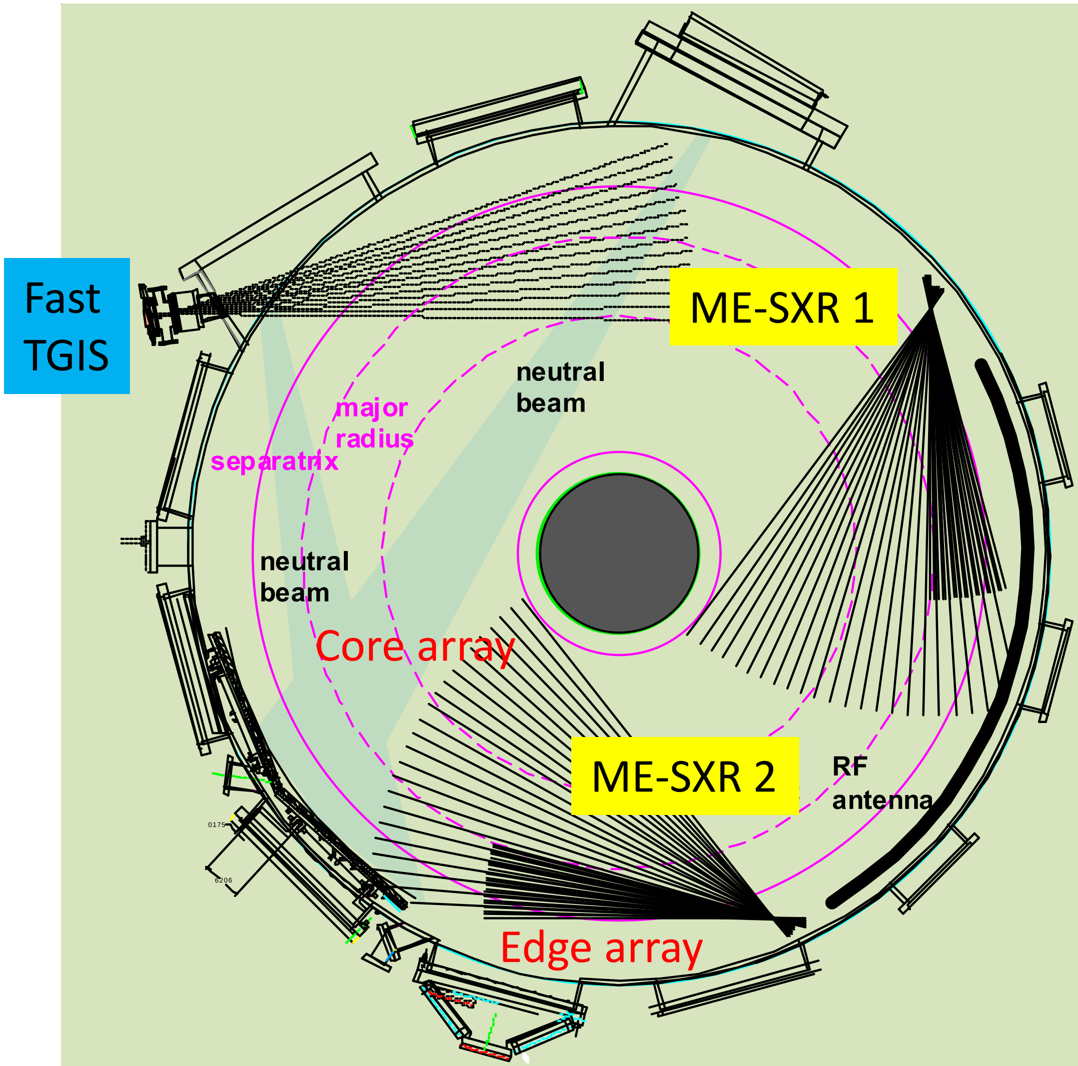
# High resolution ME-SXR reveals also new edge phenomena



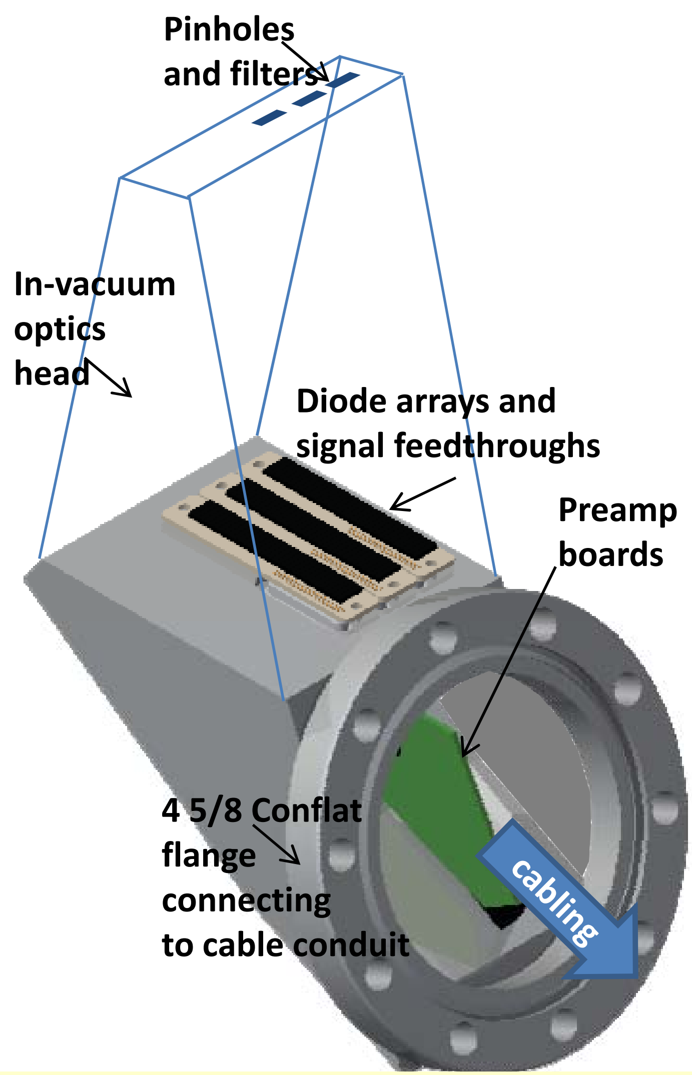




- **Slow, quasi-periodic boundary modulations and impurity rich filaments not explained by MHD**
- **Apparent also in Thomson $T_e$ and CHERS $Z_{eff}$ profiles**
- **Toroidally displaced ME-SXR arrays can ascertain whether these are equilibrium or MHD effects**

# Toroidally displaced edge/core ME-SXR arrays for NSTX-U

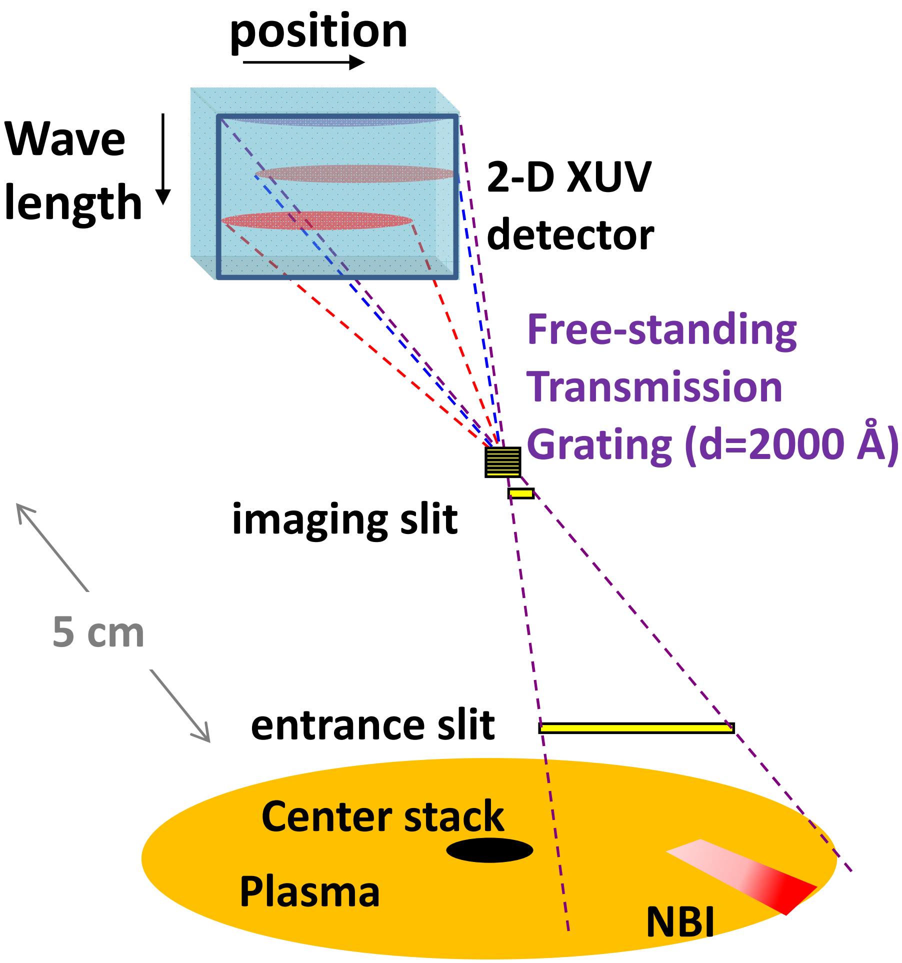



In-vessel ME-SXR array design

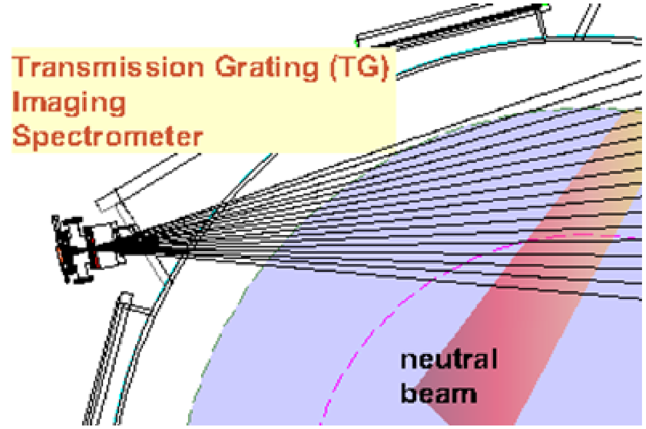


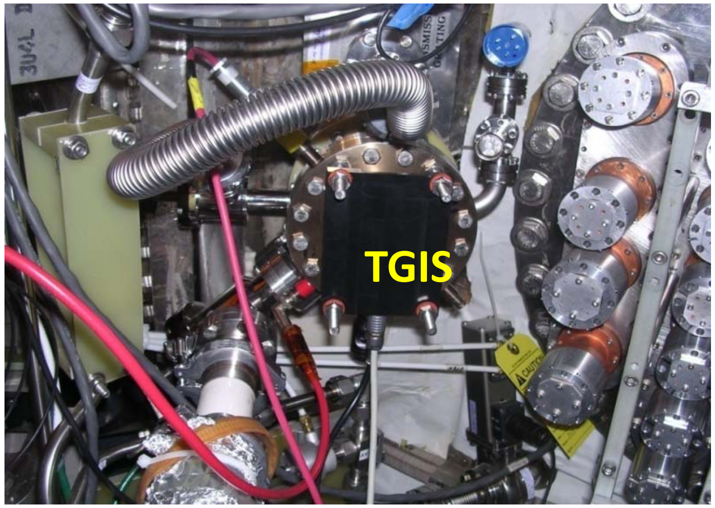

- 5 energy x 20 chord edge array + 4 energy x 25 chord core array
- Re-entrant in-vessel design using atmospheric pressure signal conduit

# Transmission Grating Imaging Spectrometer diagnostic (TGIS)




TGIS on NSTX (D. Kumar et al RSI 2010)

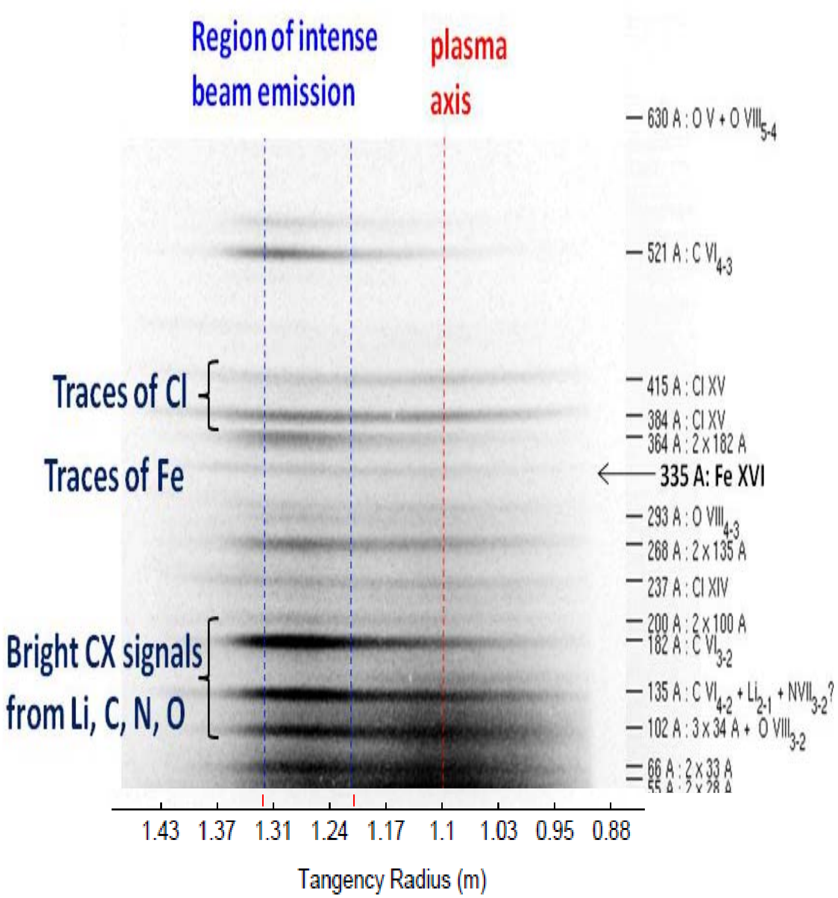


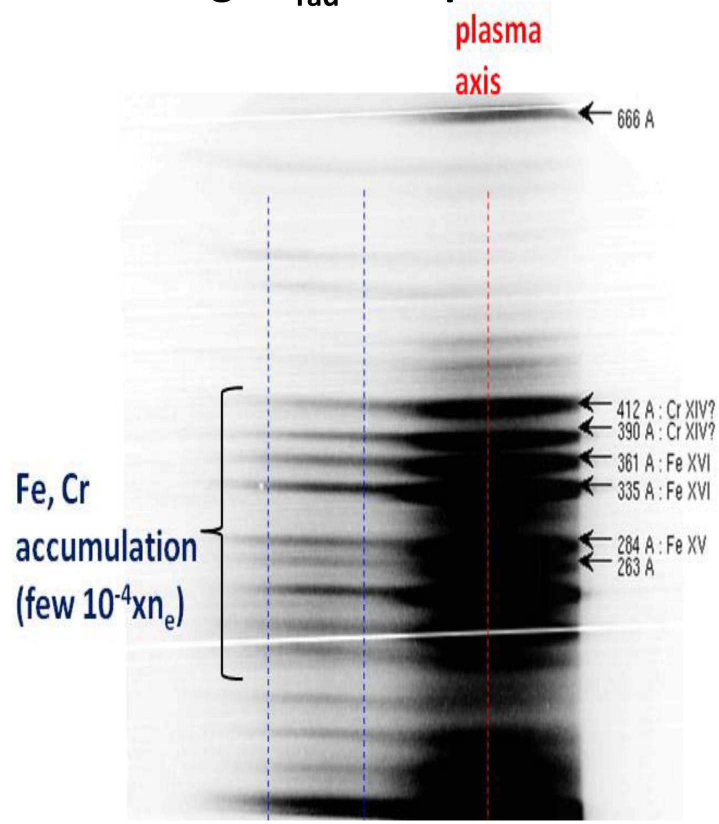

- Space resolved EUV impurity spectra for ME-SXR modeling, impurity monitoring
- Up to 2 cm/few ms resolution, scalable from SXR to VUV, simple and compact
- Little affected by proximity to plasma (multiple Li campaigns in NSTX)

# TGIS spatial resolution enables discriminating low-Z/high-Z and CX/electron excited emission

**Low $P_{rad}$ NBI plasma**

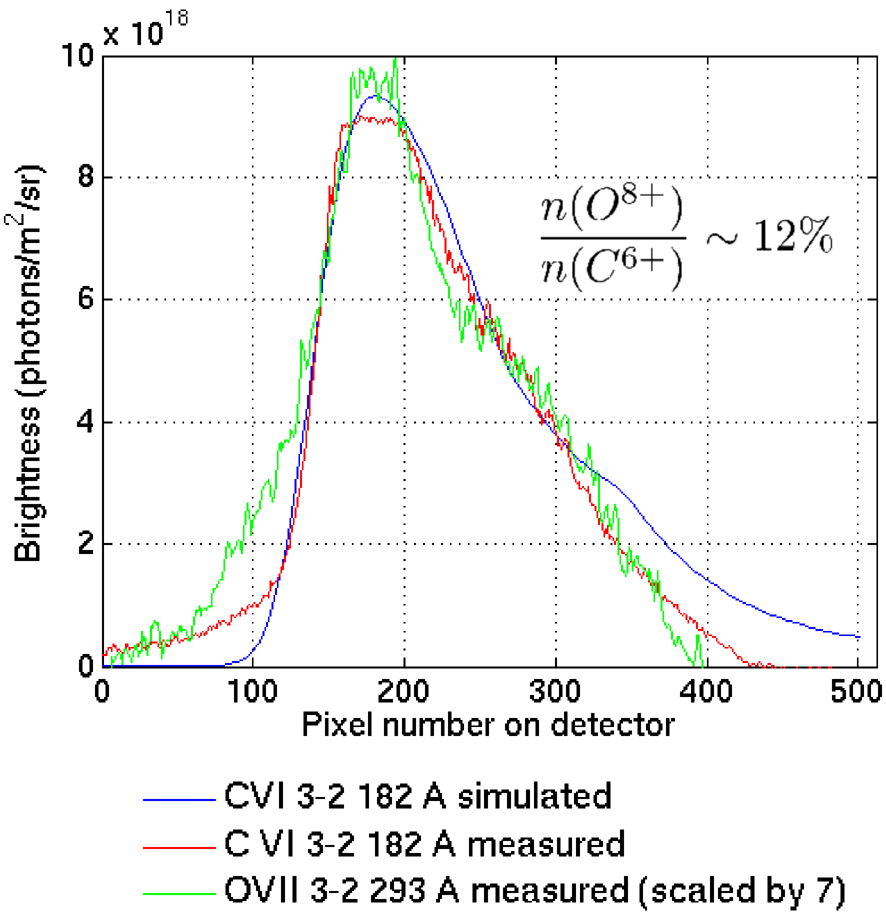



**High $P_{rad}$ NBI plasma**

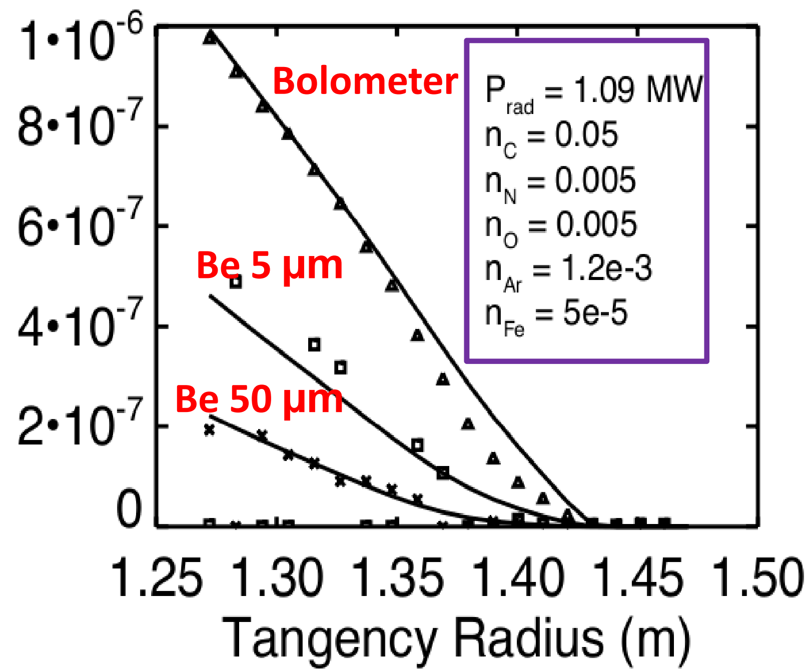


# Impurity content measurements together with ME-SXR

**Measured and computed TGIS profiles (D. Kumar et al submitted to PPCF)**

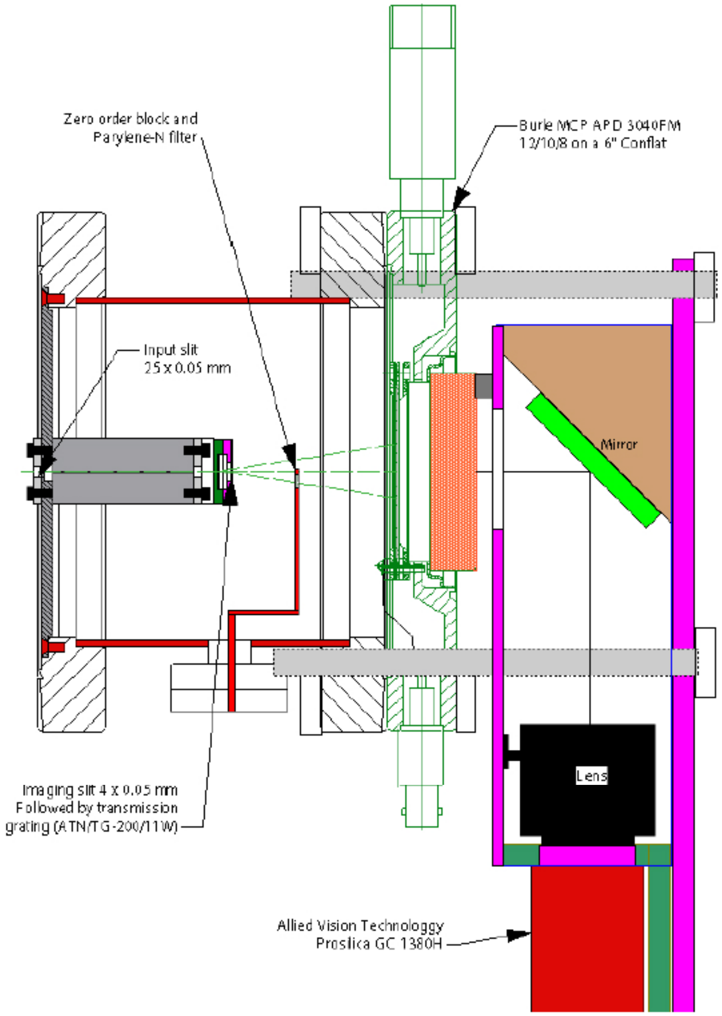



**Measured and computed ME-SXR profiles**

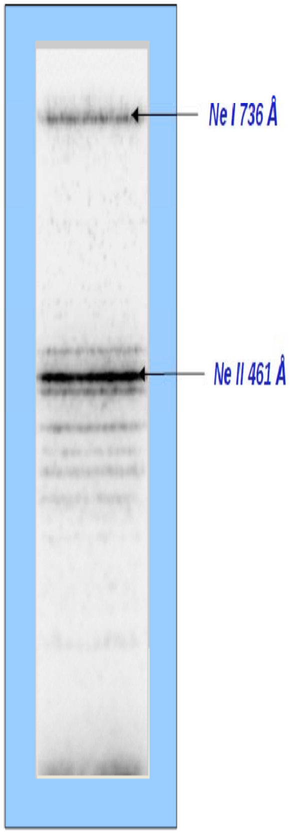


# Fast TGIS for NSTX-U

### Fast readout for TGIS

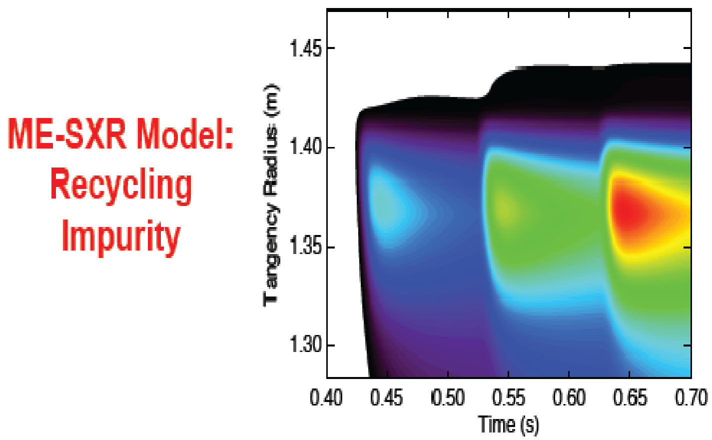


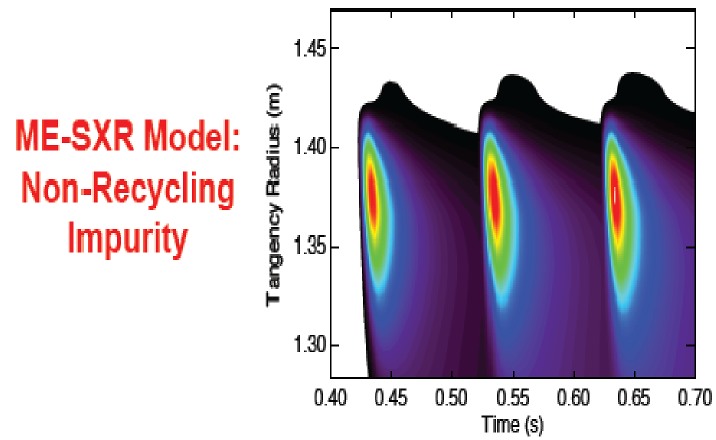

### 100 fps TGIS spectrum of Penning plasma (D. Kumar et al this conference)



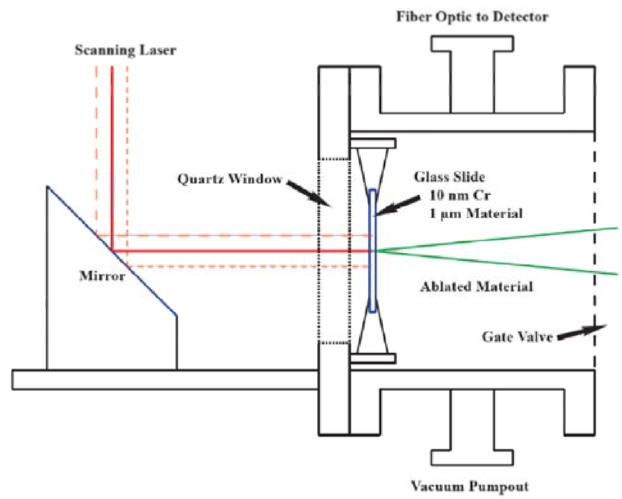

- 90% QE progressive scan CCD + f/0.9 objective
- CCD low cost enough to be periodically replaced if damaged by neutrons

# Repetitive laser blow-off (LBO) system for multiple transport measurements in a single discharge



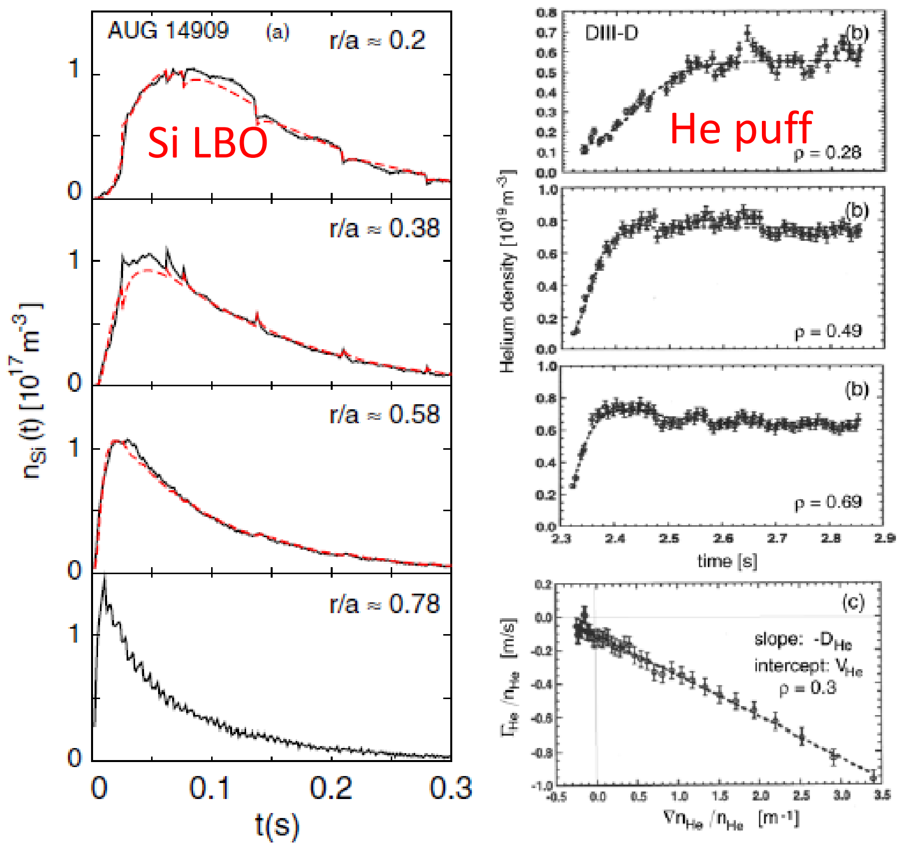

10 Hz, 600 mJ
Nd:YAG scanning
laser



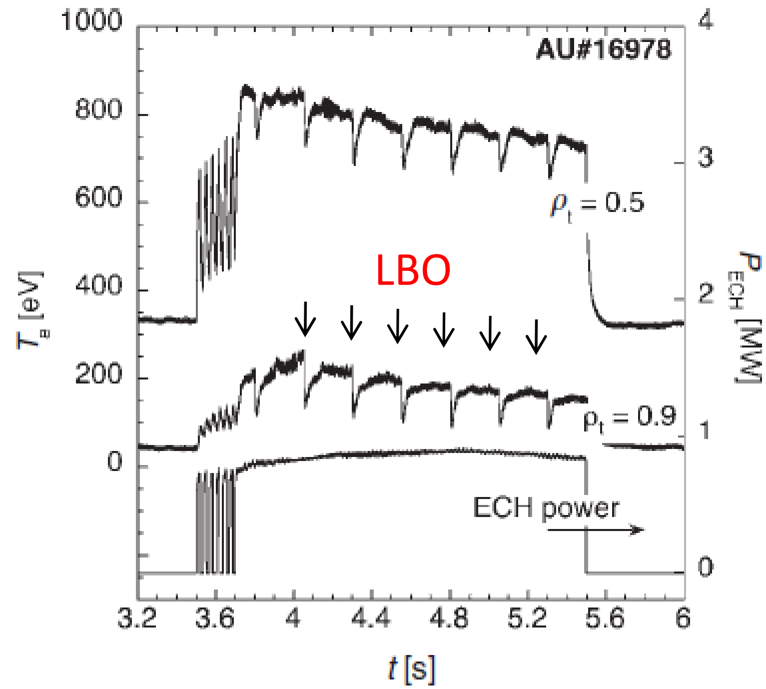

- **Precise source of low/high-Z non-recycling impurities for multiple ME-SXR measurements of impurity and electron transport in long pulse NSTX plasmas**
- **Design similar to C-mod multi-pulse system (N. Howard et al RSI 2011)**

# LBO enables precise tuning of perturbations in tokamaks

**Non-recycling laser vs. recycling gas puff impurity injection (Ryter et al PPCF 2010)**




**Perturbative electron transport dynamics using repetitive laser blow-off (Jacchia et al NF 2005)**



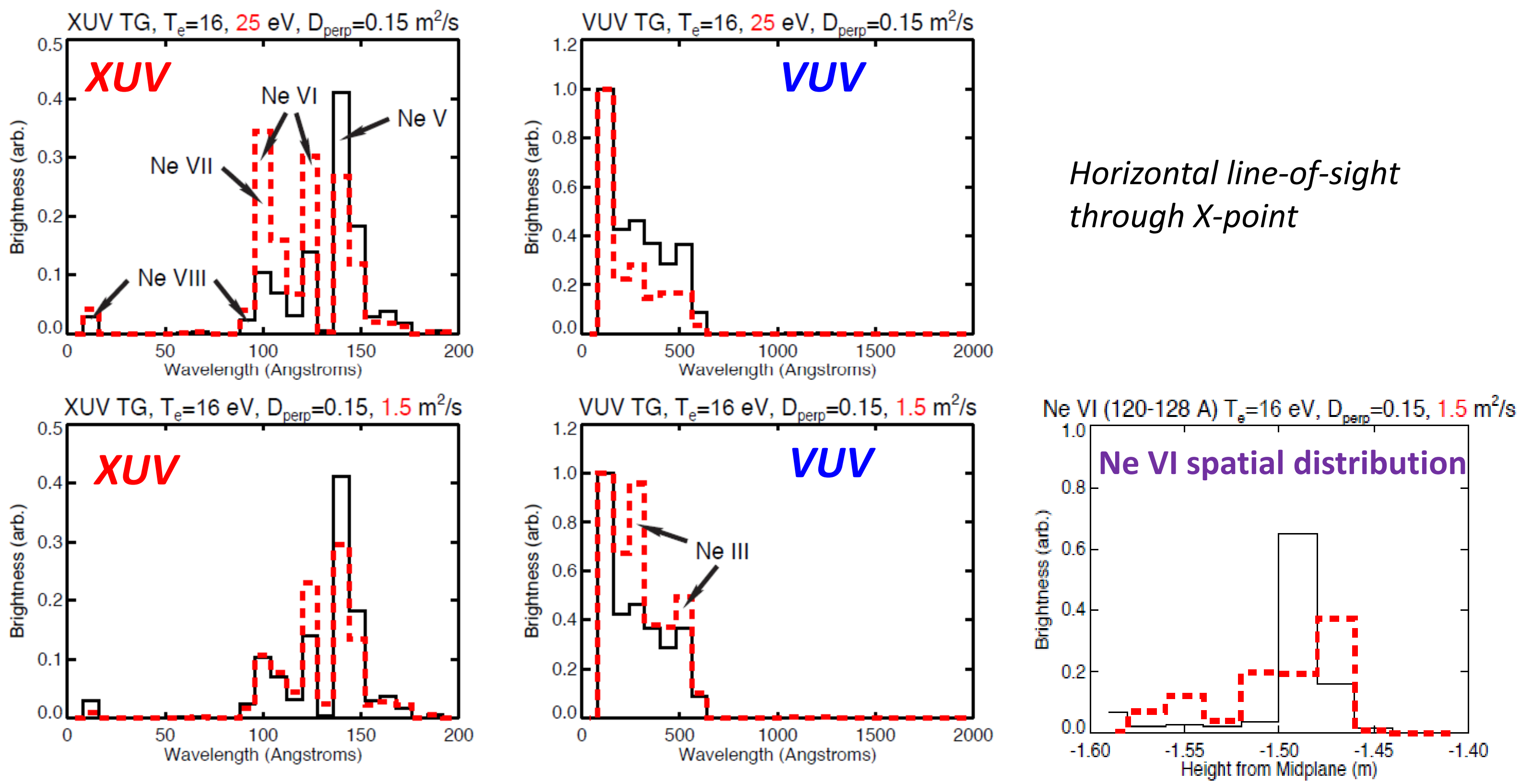

- **Low cost, simple and robust repetitive LBO systems nowadays possible**

# Divertor Imaging Radiometer (DIR)

## OEDGE computed spectra for Ne seeded NSTX divertor plasma (M. Jaworski, PPPL)

**$P_{rad}(\lambda,r)$ changes with $T_e$**

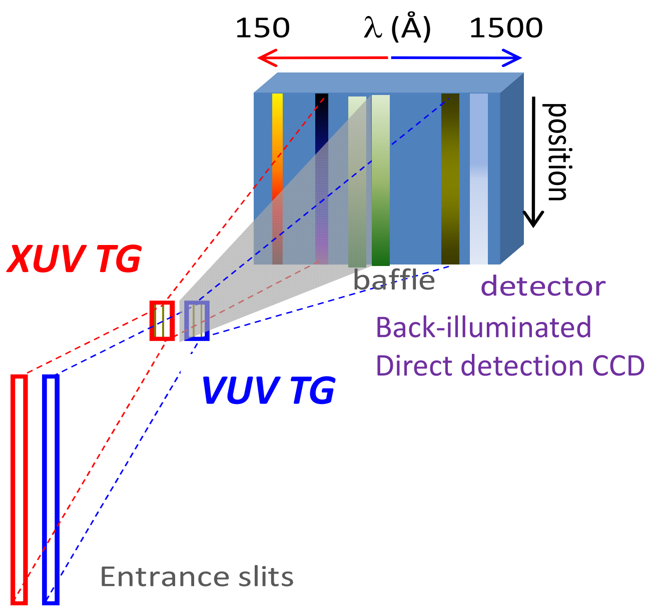
**$P_{rad}(\lambda,r)$ changes with $D_{perp}$**

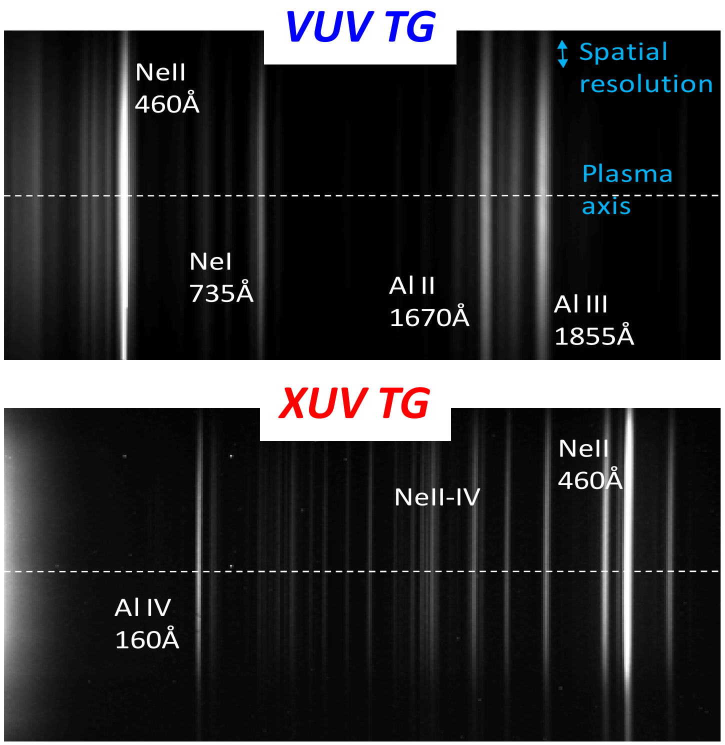



*Horizontal line-of-sight through X-point*

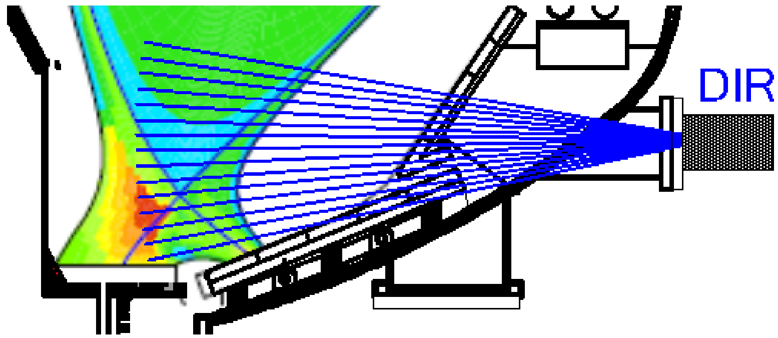
- **Divertor impurity density, radiation, power and particle balance critical in NSTX-U**
- **The multi-energy technique can be extended to divertor relevant temperatures using low resolution spectral bins in the XUV (0-200 Å) and VUV (0-2000 Å) ranges**
- **XUV/VUV $P_{rad}(\lambda,r)$ measurements could also provide approximate $T_e$ and $D_{perp}$**

# Radiometer based on tested dual-TG design



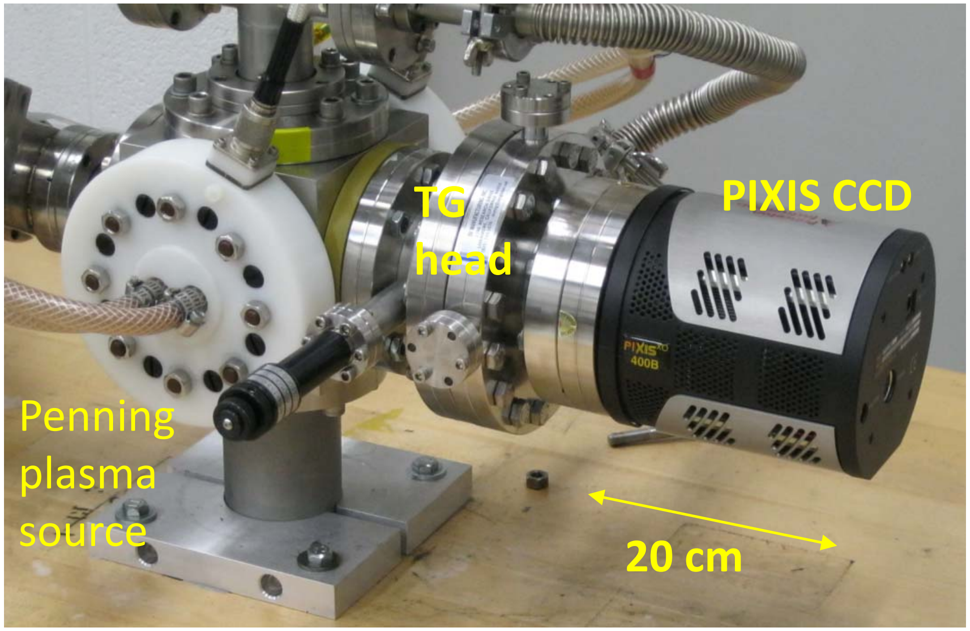

*Dual-TG Penning Plasma Spectra*



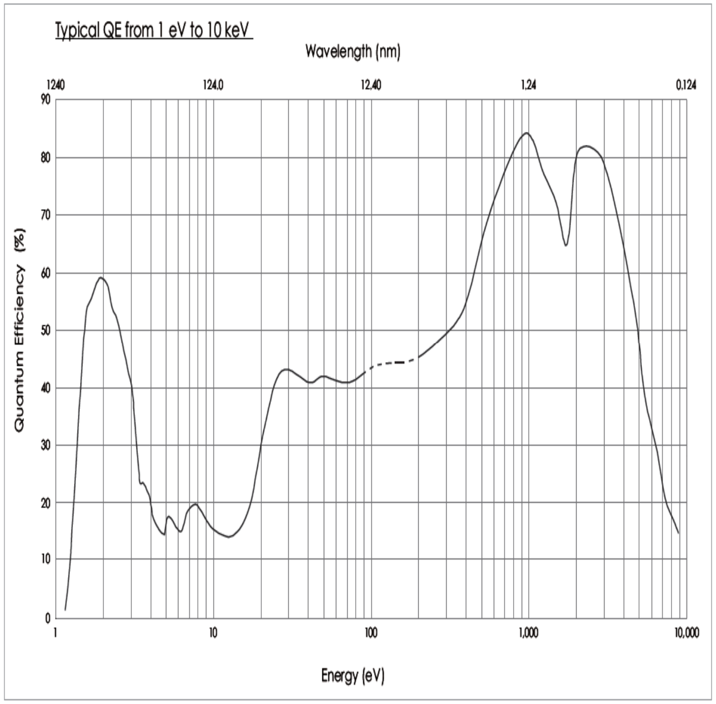

- $P_{rad}(\lambda,r)$ **diagnostic with 2 cm spatial resolution, ≥ 60 fps speed**

# Efficient, compact and radiation resistant diagnostic

**Test TG radiometer with direct detection CCD**

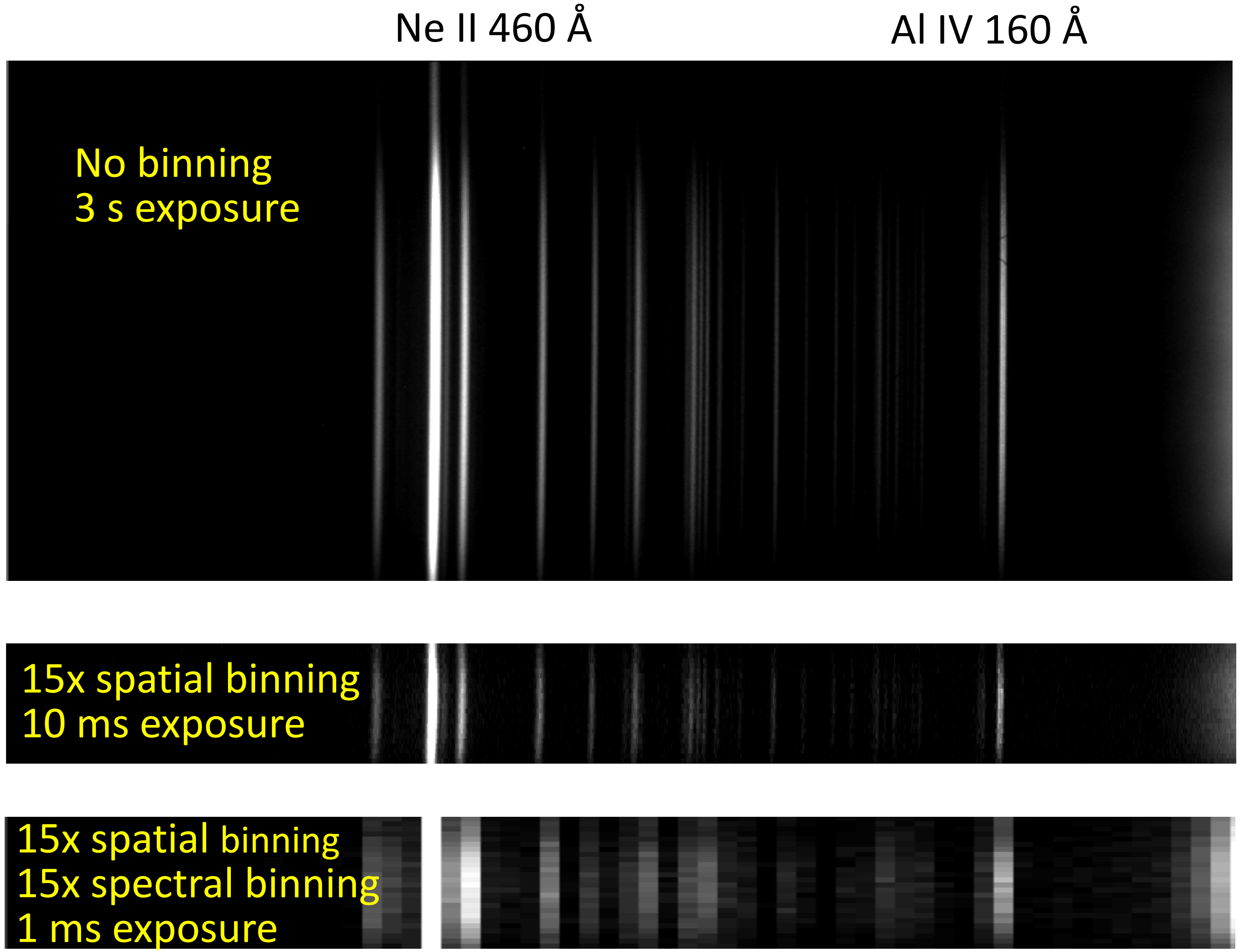



**CCD quantum efficiency**



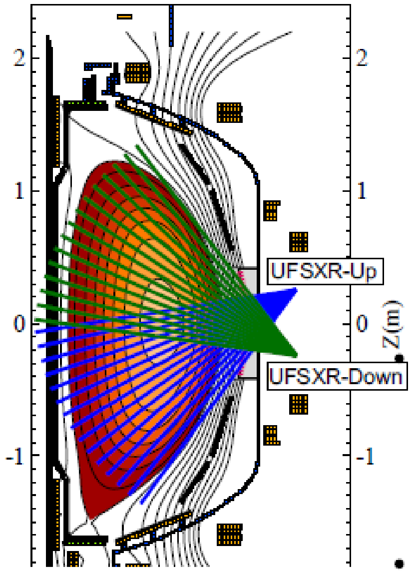

- **NSTX experience with direct detection CCDs (e.g. Princeton Instruments PIXIS-XO) suggests good n, $\gamma$ noise immunity and radiation resistance**
- **If needed, neutron shielding not too difficult due to device compactness**

# Spectral binning enables fast $P_{rad}(\lambda,r)$ measurements

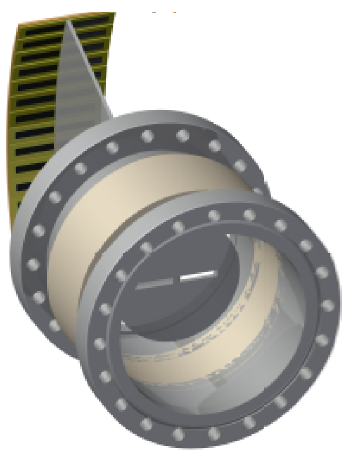



- **Few tens of spectral bins sufficient to characterize the low $T_e$ XUV /VUV emission from low to medium-Z plasmas**

# Ultrafast ME-SXR studied for *AE diagnostic




High-E Low-E



## Dual-energy, 4 MHz diode based system

- 2x16 channels viewing poloidally through two different filters ~2-3cm resolution
- at least 1 set of 16 channels will have a variable filter setting
- time resolution ~4MHz

**Upgraded system would replace current H-Up, H-Down USXR arrays**
- maintain spatial resolution
- significantly increase temporal resolution
- two-color capability should provides temperature/density discrimination $\Delta Te/Te \geq 0.5\%$

- **Projected physics capabilities for NSTX-U:**
  - Maintain/improve physics capabilities of present USXR system
  - Measure high-frequency *AE modes, including poloidal structure
  - Provide $T_e/n_e$ discrimination and phase measurement to distinguish CAE/GAE
  - Provide validation data for fast MHD simulations with good time/spatial resolution
  - *AE measurements in conjunction with transport measurements for $\chi_e$ studies

- **Supports NSTX-U research priorities:**
  - II-1: investigate *AE effects on electron thermal transport
  - IV-2: measure *AE modes for simulation validation, projection to FSNF
  - IV-3: investigate effects of *AE on RF heating of plasma using $T_e$ discrimination
  - VI-2: identification of high-frequency precursors to disruptions for mitigation/control

# Summary

Suite of transport and MHD diagnostics based on multi-energy imaging proposed for multiple measurement capabilities on NSTX-U:

- ***Multi-scale Transport***: electron thermal and impurity particle transport from the edge to the core, in L-mode and H-mode, for comparison with the advanced turbulence diagnostics and validation of transport simulations planned at NSTX
- ***Plasma Boundary***: Measurements of H-mode pedestal profiles with increased time and spatial resolution, effects of lithium, of ELMs and of 3-D fields on the pedestal electron thermal and impurity particle transport
- ***Divertor***: Impurity density and radiation, improved power and particle balance, approximate electron temperature and cross field transport, validation of advanced divertor models
- ***Macroscopic Stability:*** RWM mode structure and $T_e$ perturbation, plasma response to 3-D fields, effects of tearing modes on plasma profiles, disruption precursor, evolution and thermal quench, toroidal measurements of massive gas injection
- ***Non-inductive Plasma Start-up/Ramp-up***: Boundary evolution, temperature, impurity content and radiated power of solenoid-free plasmas, for optimization of formation, confinement and heating
- ***Advanced Operating Scenarios***: Real-time measurements of $T_e$ and $Z_{eff}$ profiles, detection of the onset of disruptions