Prototype high resolution multi-energy soft X-ray array for NSTX

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Abstract

Previous work has shown the utility of 'multi-energy' filtered soft X-ray (SXR) data for the determination of electron temperature (T_e) profiles in a tokamak plasma [L. Delgado-Aparicio, Plasma Phys. Contr. Fus., **49**, 1245 (2007)]. A novel diagnostic design presently under development seeks to enhance the capability of multi-energy SXR detection by using an image intensifier to amplify the signals from a set of filtered X-ray profiles. The increased number of profiles along with a simplified detection system provides a compact diagnostic device with the capability of measuring T_e in addition to contributions from impurities. A prototype system has been implemented on NSTX which is comprised of a filtered X-ray pinhole camera which converts the X-rays to visible light using a CsI:Tl phosphor. The phosphor is mounted on an image intensifier, which is coupled to a high-speed CMOS camera using a fiber optic image bundle. SXR profiles have been measured in high performance plasmas at frame rates up to 10kHz, and comparisons to the toroidally displaced tangential multi-energy SXR will be made. *Work supported by DOE contract no. DE-AC02-09CH11466*

A prototype high-resolution Soft X-ray array has been tested on NSTX revealing dynamics of the plasma profiles near the edge.

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NSTX

An upgraded Multi-Energy SXR system will enhance fast electron temperature measurements

- Present ‘3 energy’ tangential system (TOSXR) measures fast T_e in core (r/a < 0.8) of ‘clean’ NSTX plasmas
- Additional energy bands will improve impurity estimates, expand range of fast T_e measurement
- Improved spatial resolution (<= 1cm) desired to resolve profiles near pedestal region
- Toroidally displaced arrays important to discriminate rotating structures from global profile changes
  (crucial for pedestal studies & non-magnetic control w/ SXR sensors)
- Prototype high-spatial resolution, single energy system tested on NSTX

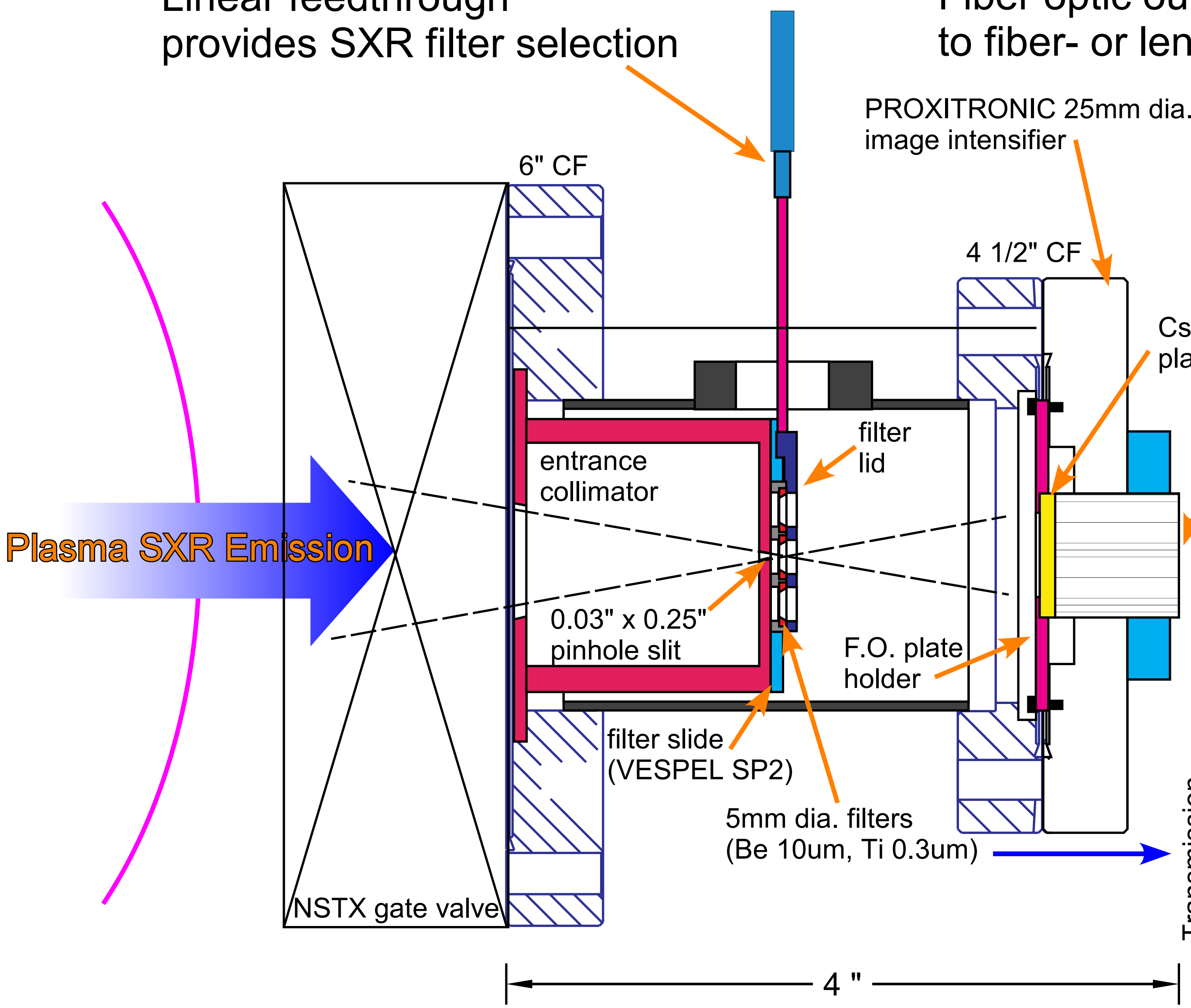
Outline

- Prototype hardware and layout
- Data readout and processing
- Signal sensitivities and characterizations
- Profile and impurity dynamics in NSTX edge plasma
- Next step Multi-Energy SXR system and physics mission

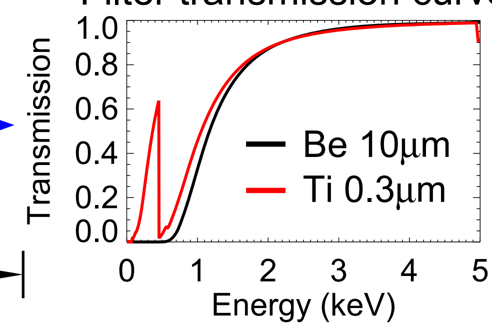
Compact prototype SXR array uses optical design

Linear feedthrough provides SXR filter selection

Fiber optic output window couples to fiber- or lens-based detector

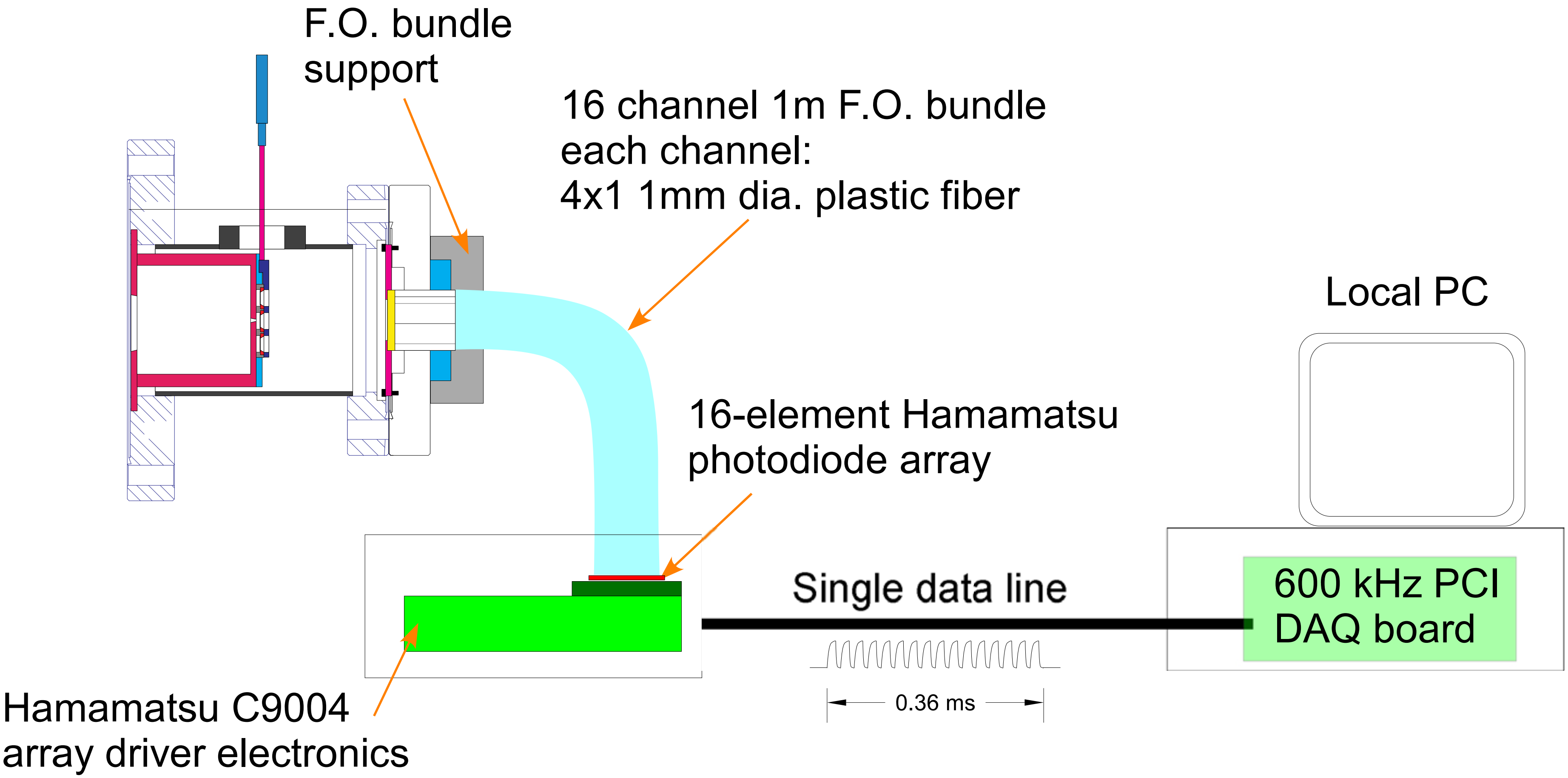


Filter transmission curves



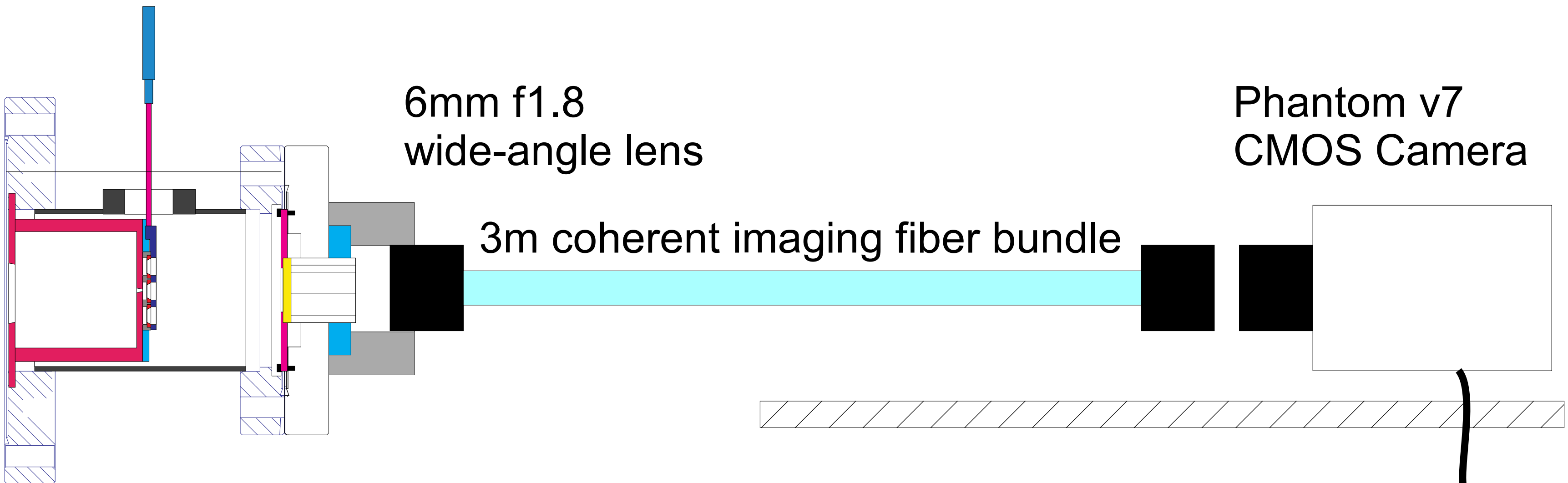
Compact size for versatile installation

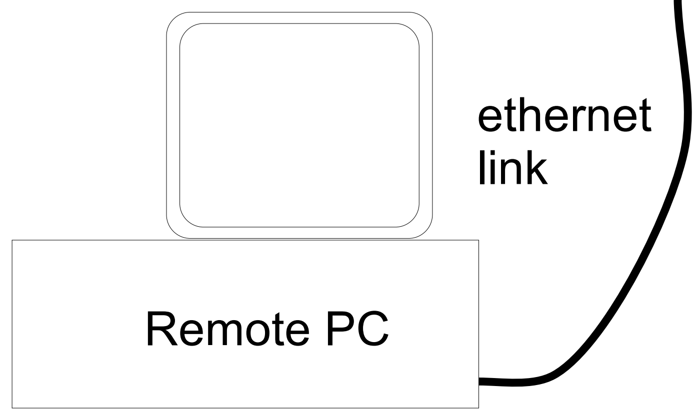
Detection method 1: fiber-coupled linear diode array



Multiplexed driver electronics provides 16 output signals on single data line at ~ 3kHz

Detection method 2: lens-coupled fast CMOS camera





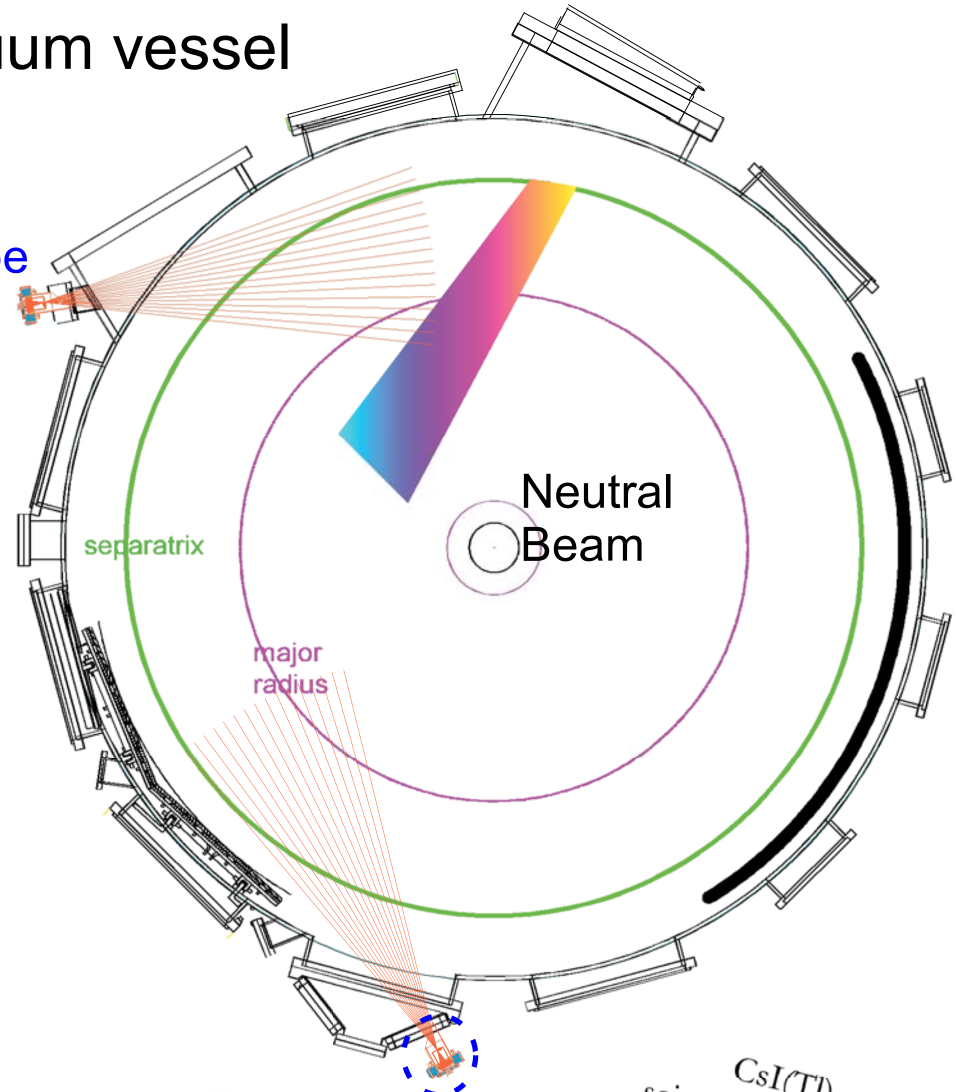
Fast camera allows SXR imaging frame rates up to 100kHz (2-10kHz typical)

Optimization of optics will boost SNR by factor of 2-4

Prototype has tangential view from core to plasma edge

Top-down view of NSTX vacuum vessel

Protototype
ME-SXR

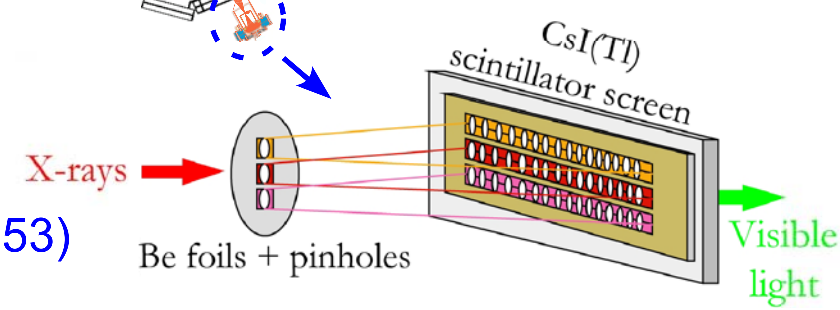


Prototype views beam-excited SXR emission

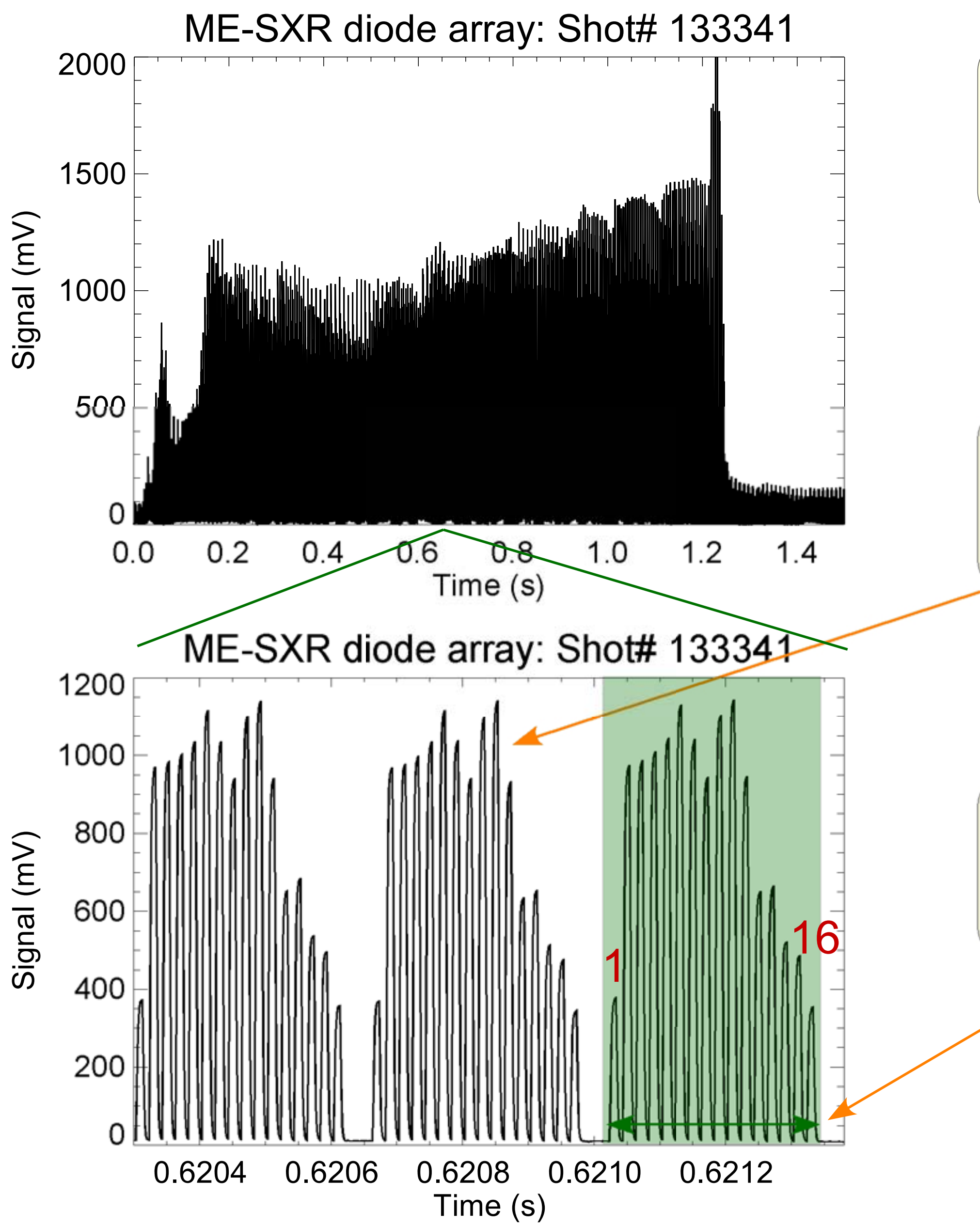
Comparison with present TOSXR system provides toroidially displaced measurements

120° displacement from TOSXR, measures toroidal modes

TOSXR multicolor system
(see L. Delgado-Aparicio PP8.00053)



ME-SXR diode array readout provides serial readout of 16 channels with ~3kHz time resolution

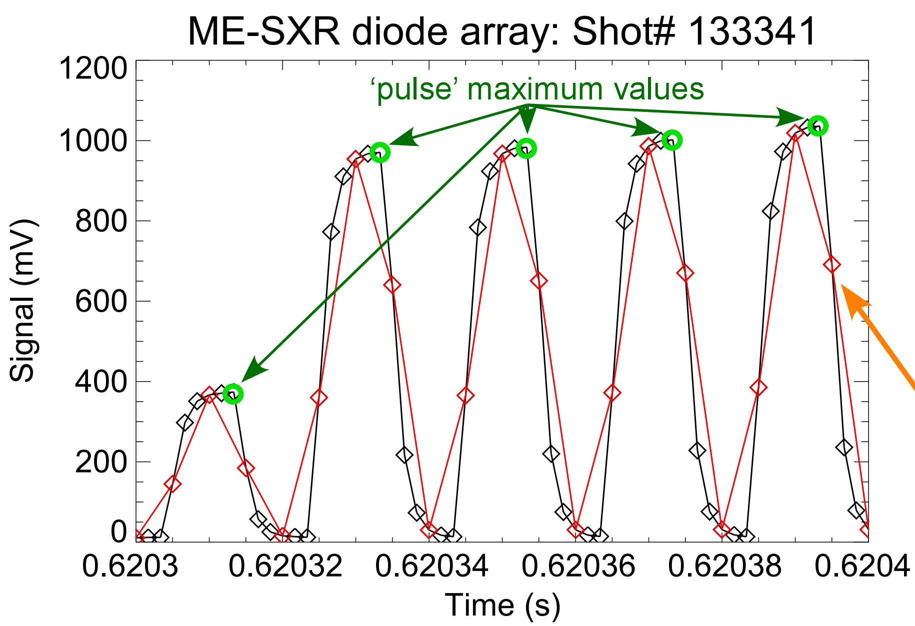


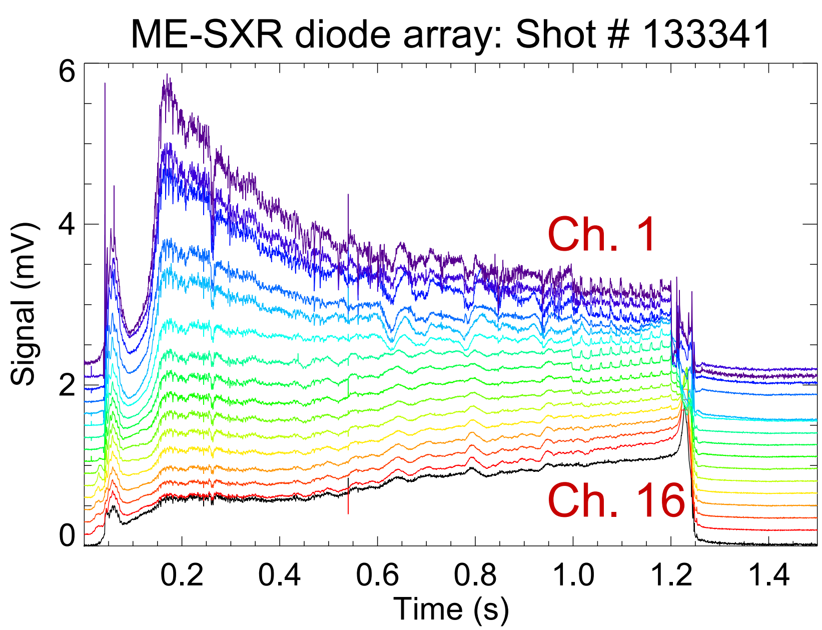
Datel DAQ board digitizes single channel from array at 600kHz

Signal processing first identifies every channel 'pulse'

Pulse timing analyzed to identify pulse 'groups' and 'channels'

ME-SXR diode array ‘pulses’ assembled into chord data: profile vs. time





Identification of pulse ‘maximum’ provides robust measurement

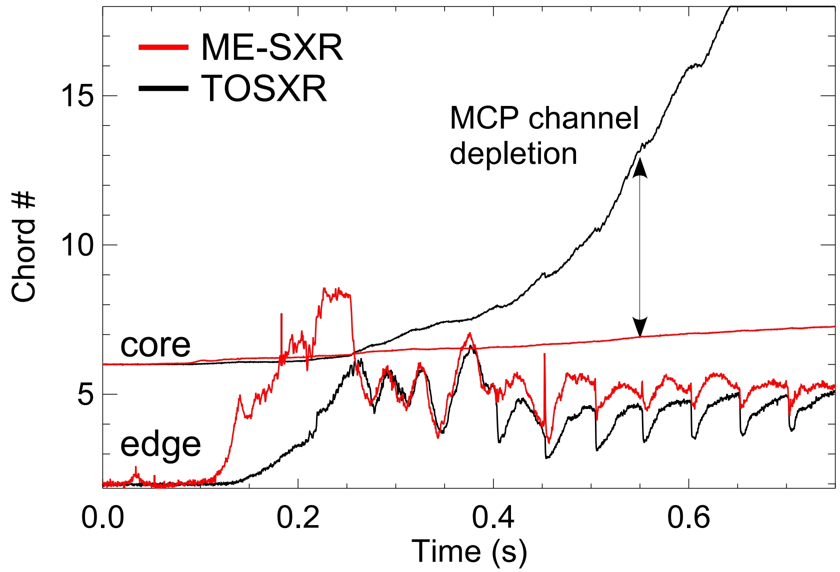
Slower digitization rate (200kHz - red) undersamples waveform

need ~500-600kHz minimum sampling for multiplexed data

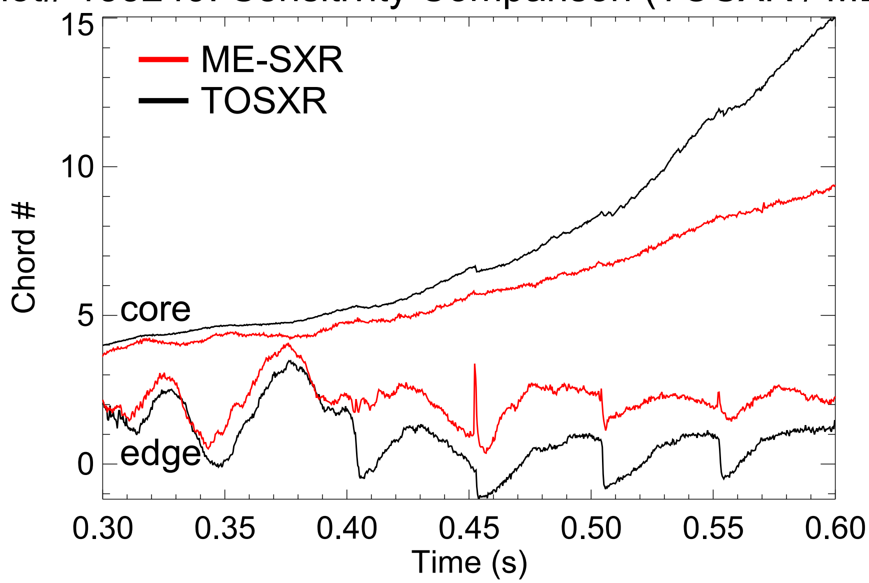
Assembled chordal data shows good SNR ratio

ME-SXR diode readout shows comparable SNR to present TOSXR system

Shot# 133249: Sensitivity Comparison (TOSXR / MESXR)



Shot# 133249: Sensitivity Comparison (TOSXR / MESXR)



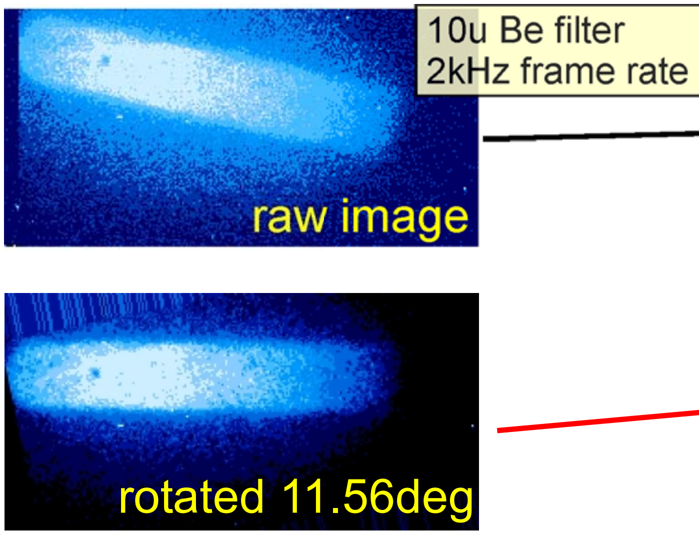
Good SNR allows high resolution (2cm) measurements of edge and core plasmas

Non-linear gain of image intensifier limits response at high signal levels (core plasma)
- not an issue for future intensifier

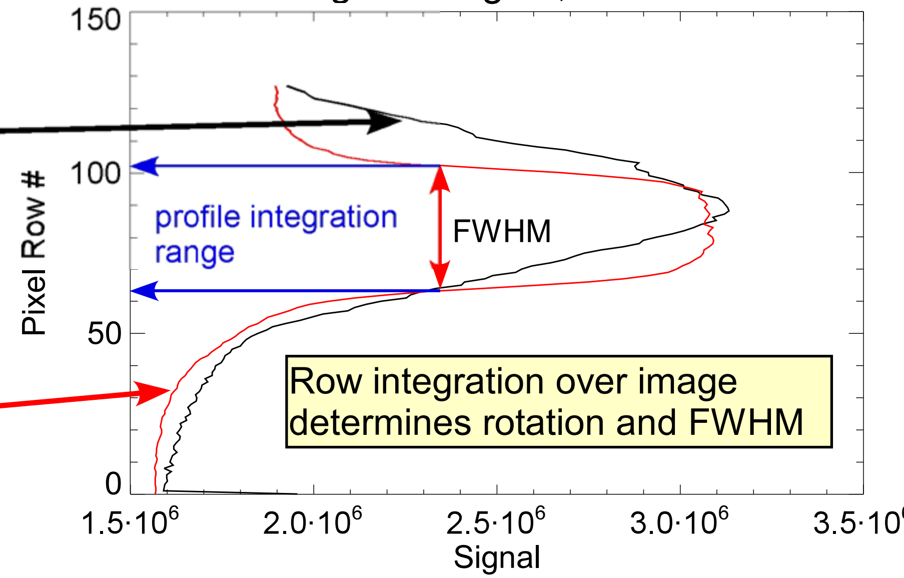
Simultaneous diode readout would improve SNR by x8 for same time/spatial resolution

Fast camera-based readout system provides improved spatial and time resolution

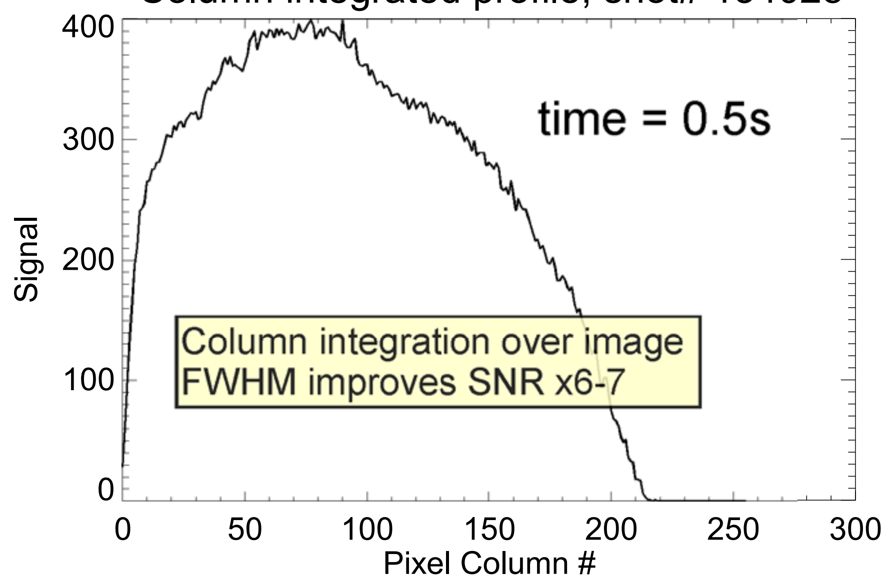
Integrated Phantom camera image, shot# 134028



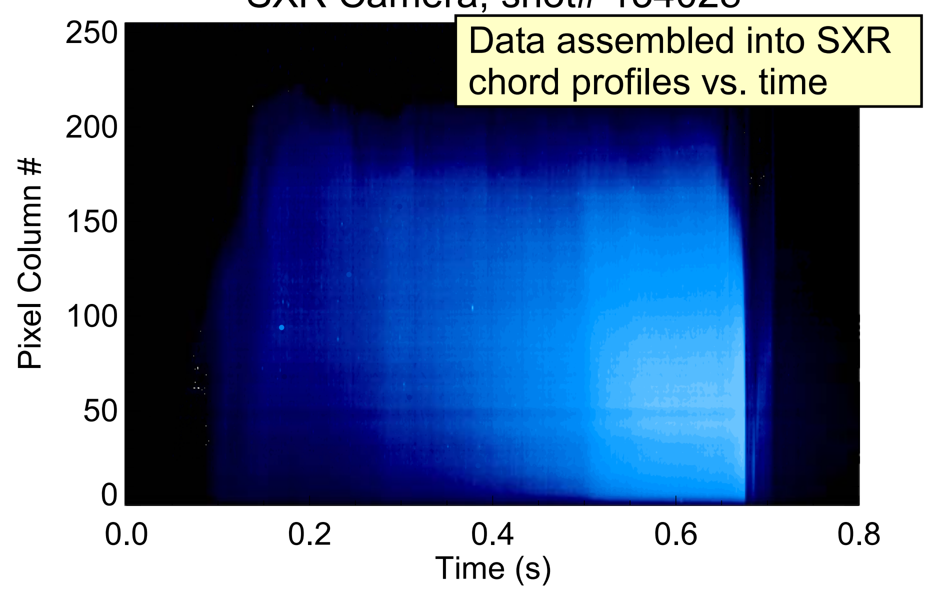
Row integrated signal, shot# 134028



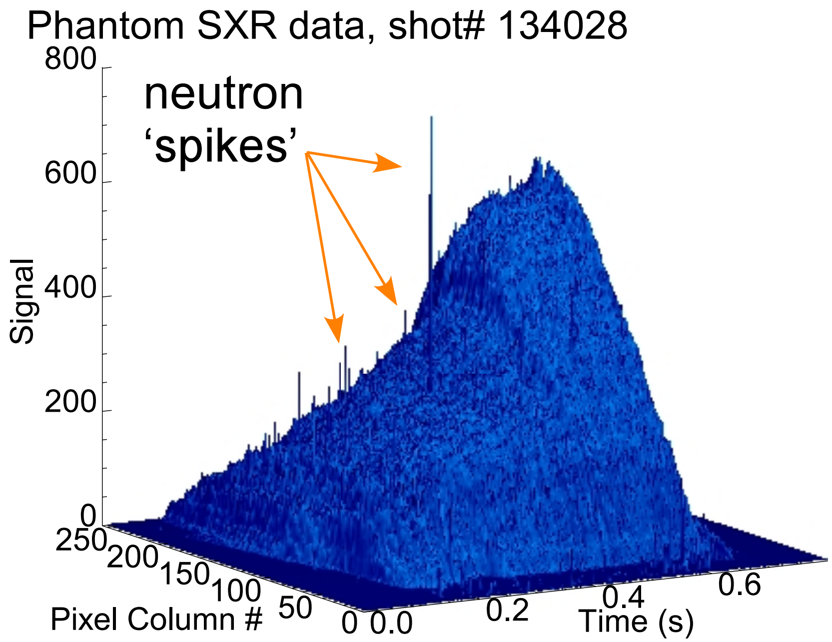
Column integrated profile, shot# 134028

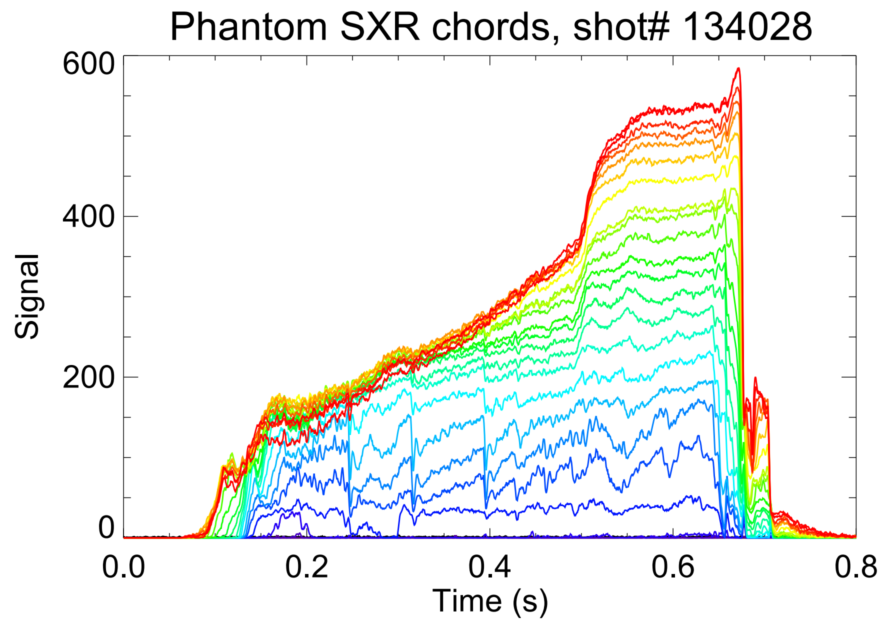


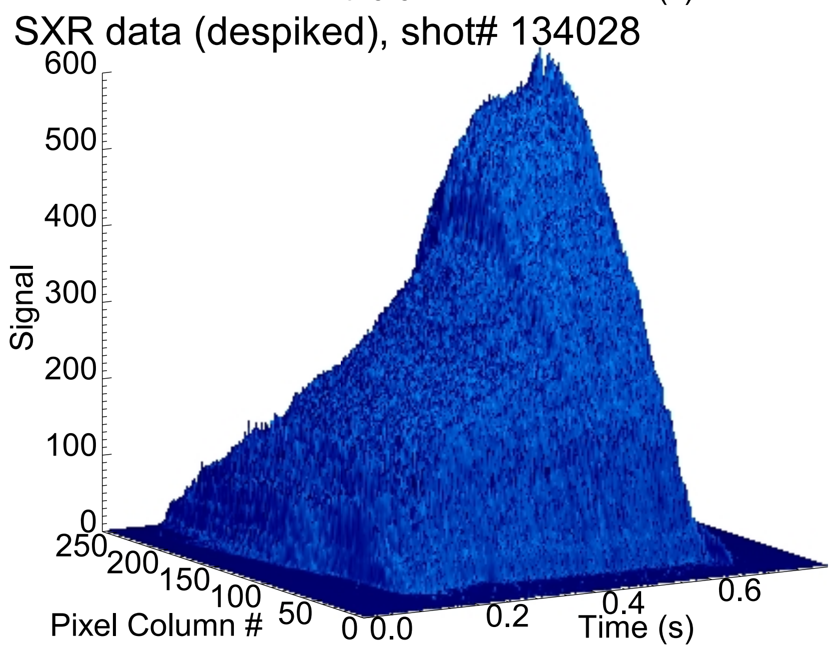
SXR Camera, shot# 134028



Fast camera SXR data assembled into high-spatial resolution profile time series





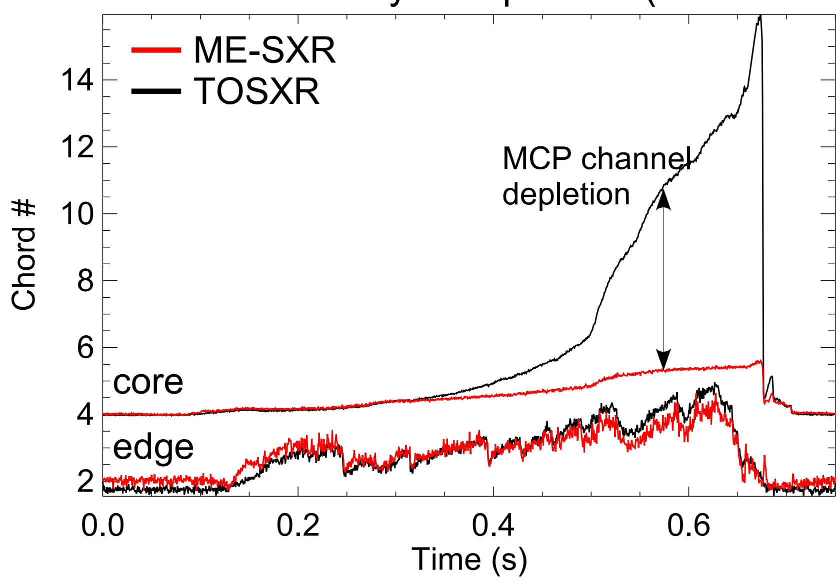


Camera-based profile has 256 chords with ~1.5cm resolution

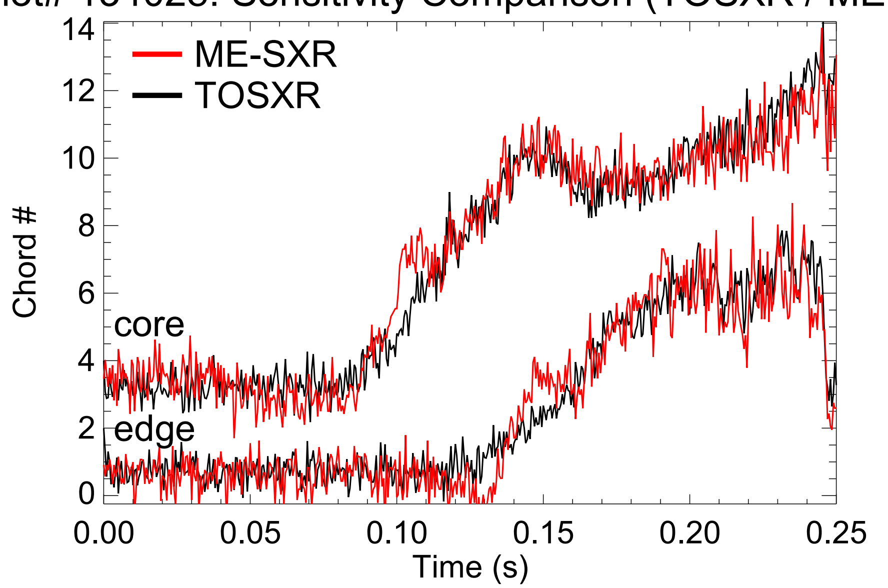
De-spiking algorithm removes neutron 'spikes' in data

Using single channel from camera ME-SXR readout gives lower SNR than present TOSXR system

Shot# 134028: Sensitivity Comparison (TOSXR / MESXR)



Shot# 134028: Sensitivity Comparison (TOSXR / MESXR)



Lower sensitivity result of:

smaller effective detector size
.02mm x 1mm (ME-SXR)
4mm dia. (TOSXR)

higher radial spatial resolution
~1.5cm (ME-SXR)
~4-5cm (TOSXR)

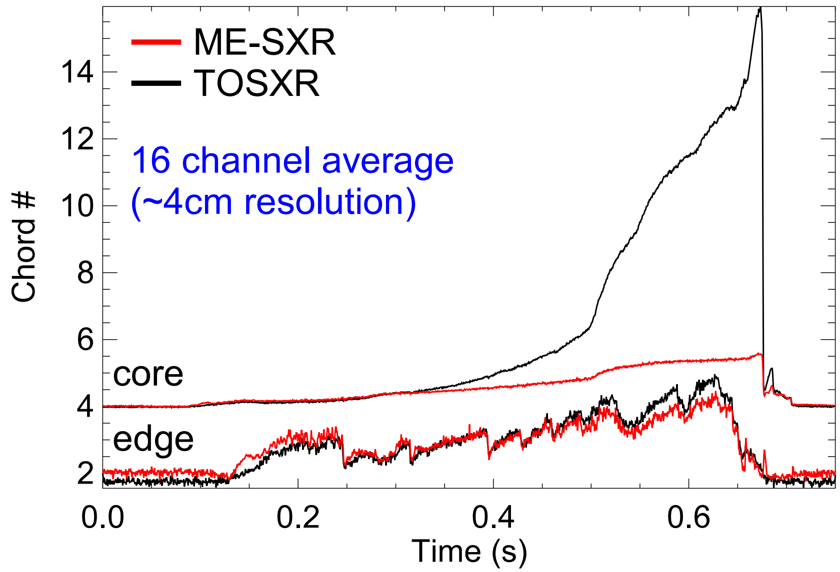
un-optimized camera optics

nonlinear intensifier response at high signal levels

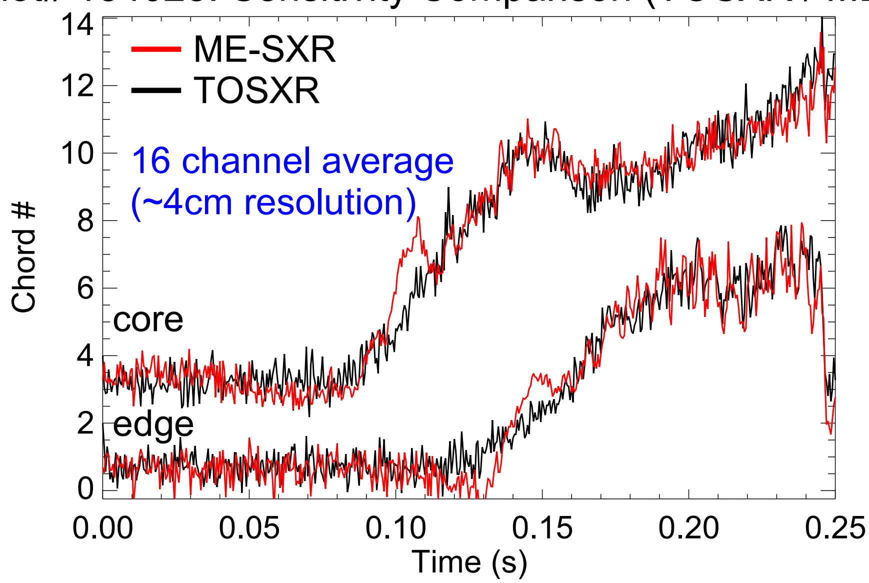
$SNR_{ME\text{-}SXR} \sim 0.5 * SNR_{TOSXR}$

Spatial averaging of camera-based SXR profile significantly boosts $SNR_{ME\text{-}SXR}$

Shot# 134028: Sensitivity Comparison (TOSXR / MESXR)



Shot# 134028: Sensitivity Comparison (TOSXR / MESXR)



256 channel profile spatially oversamples ~ 5-6x

4 channel spatial average: maintain ~1.5cm resolution

$SNR_{ME\text{-}SXR} \sim SNR_{TOSXR}$

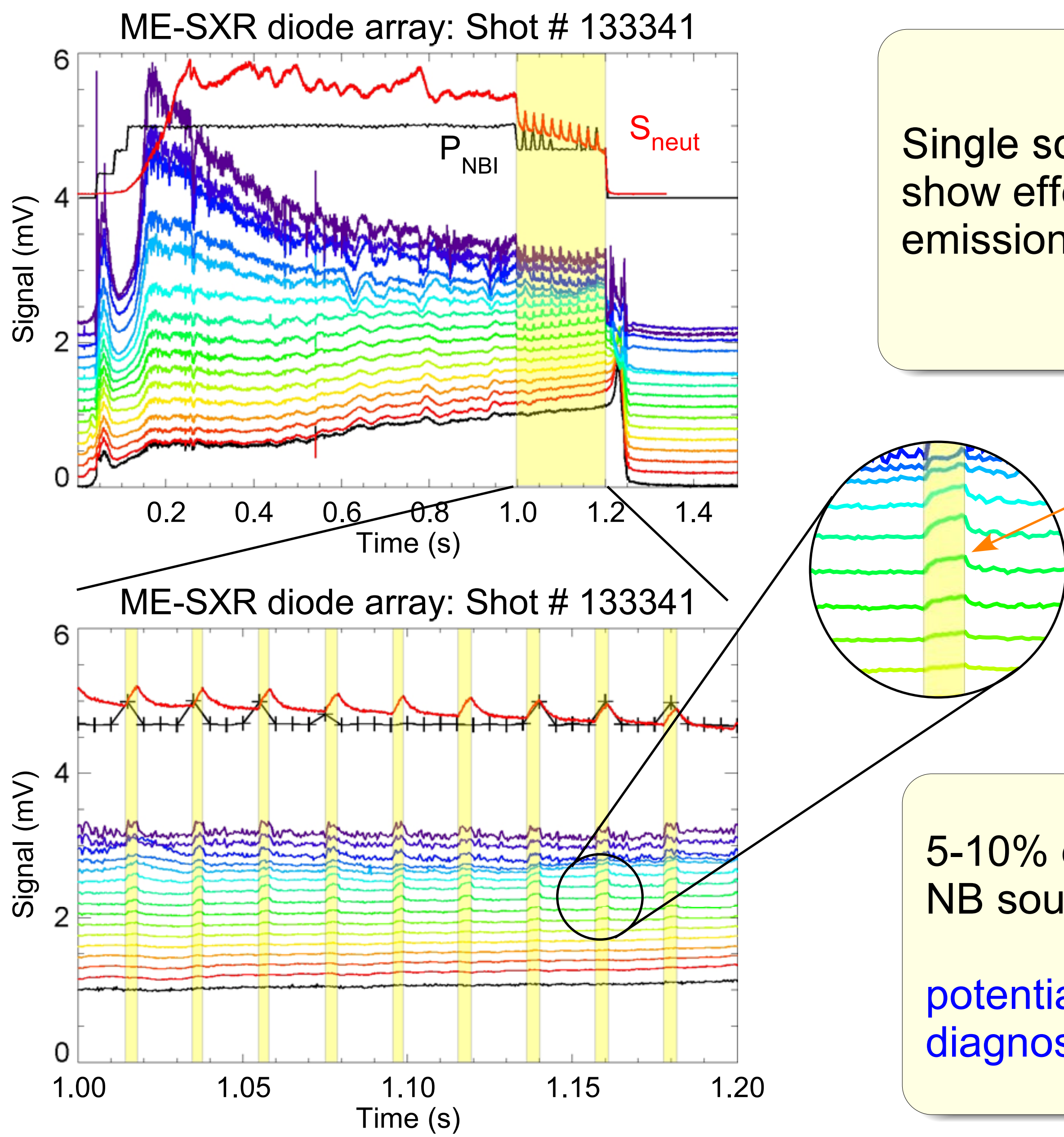
16 channel spatial average: match TOSXR ~4cm resolution

$SNR_{ME\text{-}SXR} \sim 2 * SNR_{TOSXR}$

Fully optimized camera-based ME-SXR system should obtain spatial resolution ~1-1.5cm with:

$SNR_{ME\text{-}SXR} \sim 2\text{-}4 * SNR_{TOSXR}$

Prototype ME-SXR system observes NB SXR emission



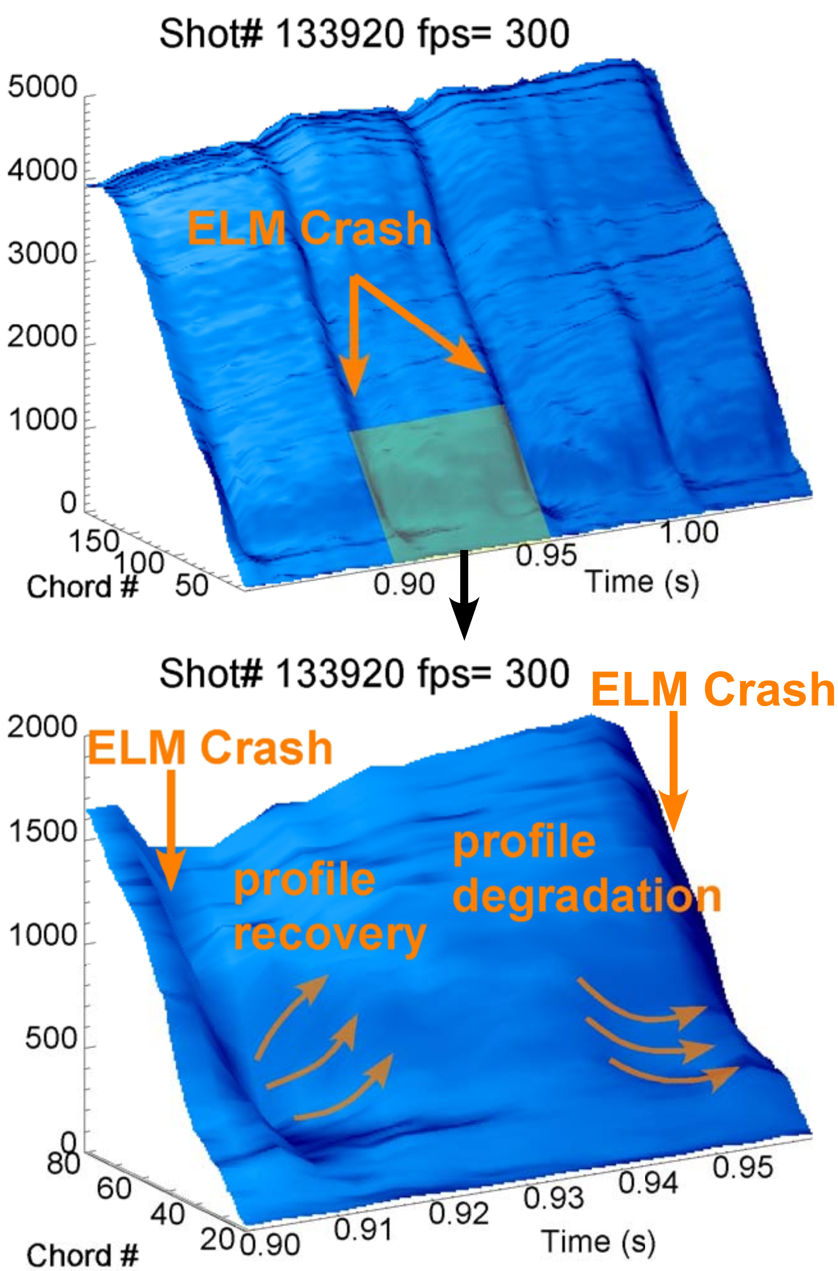
Single source NB dropout + ‘blips’ show effect of SXR beam emission on measurement

+ 5-10% modulations on SXR signal

5-10% enhancement from single NB source (x3 = 15-30%)

potentially useful for SXR BES diagnostics

Increased spatial resolution reveals unexpected profile dynamics during Type I ELM cycle



ELM cycle consists of:

Fast ‘crash’ of edge profile (<1ms)

Slow recovery of edge (~10s ms)

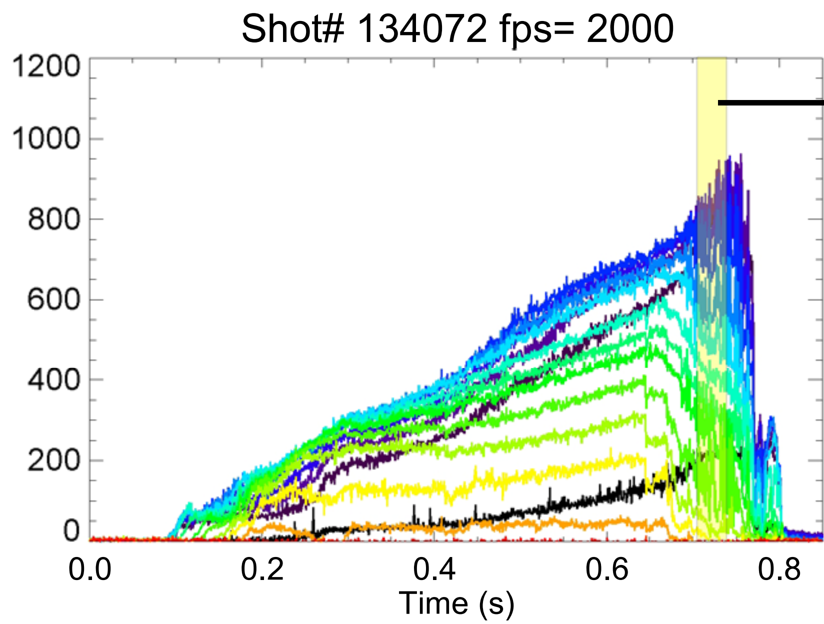
High spatial resolution reveals:

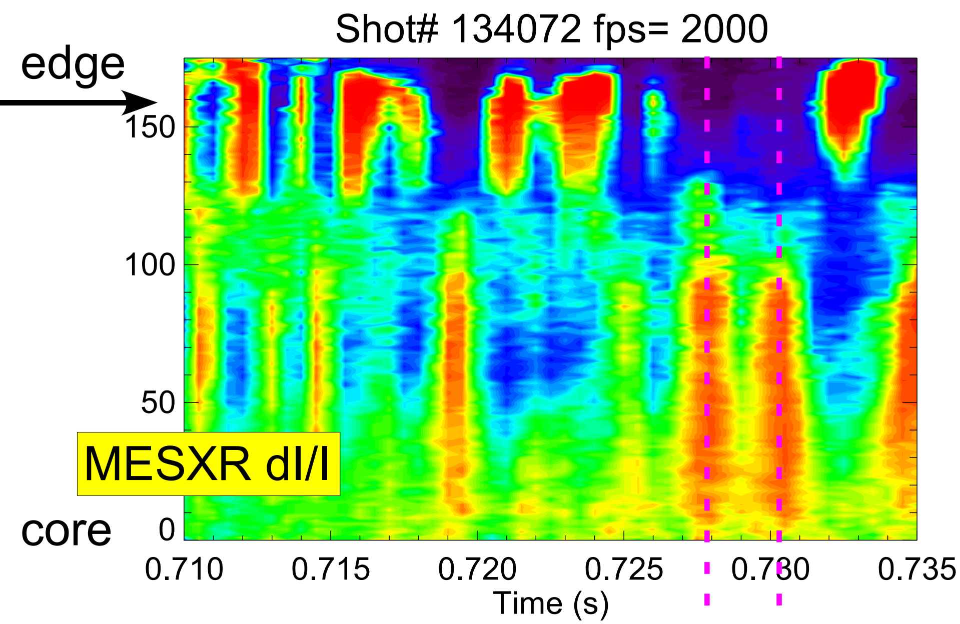
degradation of edge profile ~10ms before ELM crash

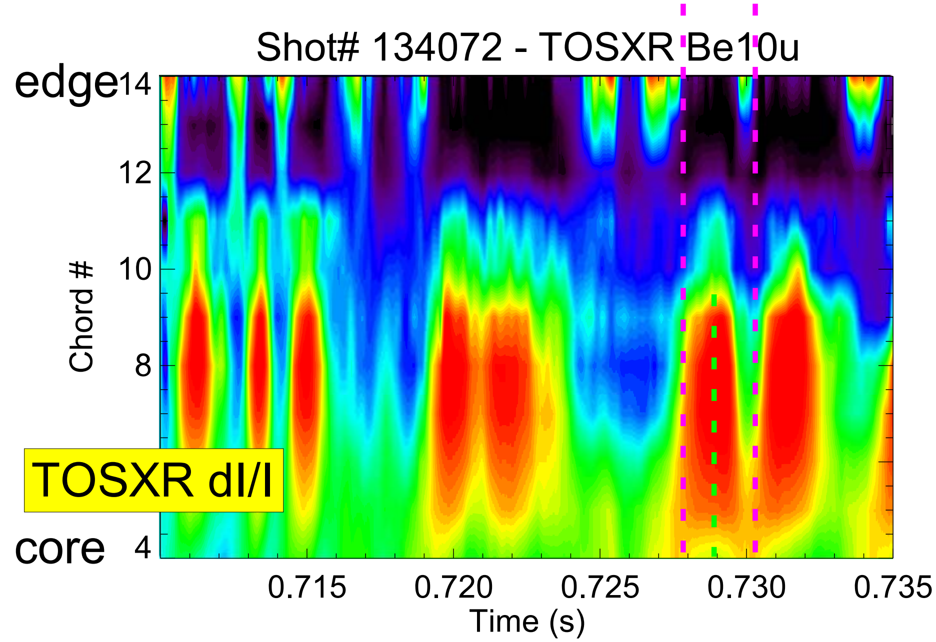
Time resolution too coarse to follow fast dynamics during crash

No observed toroidal component to crash, need ≳10kHz to verify (diode-based ME-SXR)

Toroidally displaced arrays important for measuring helical modes and activity





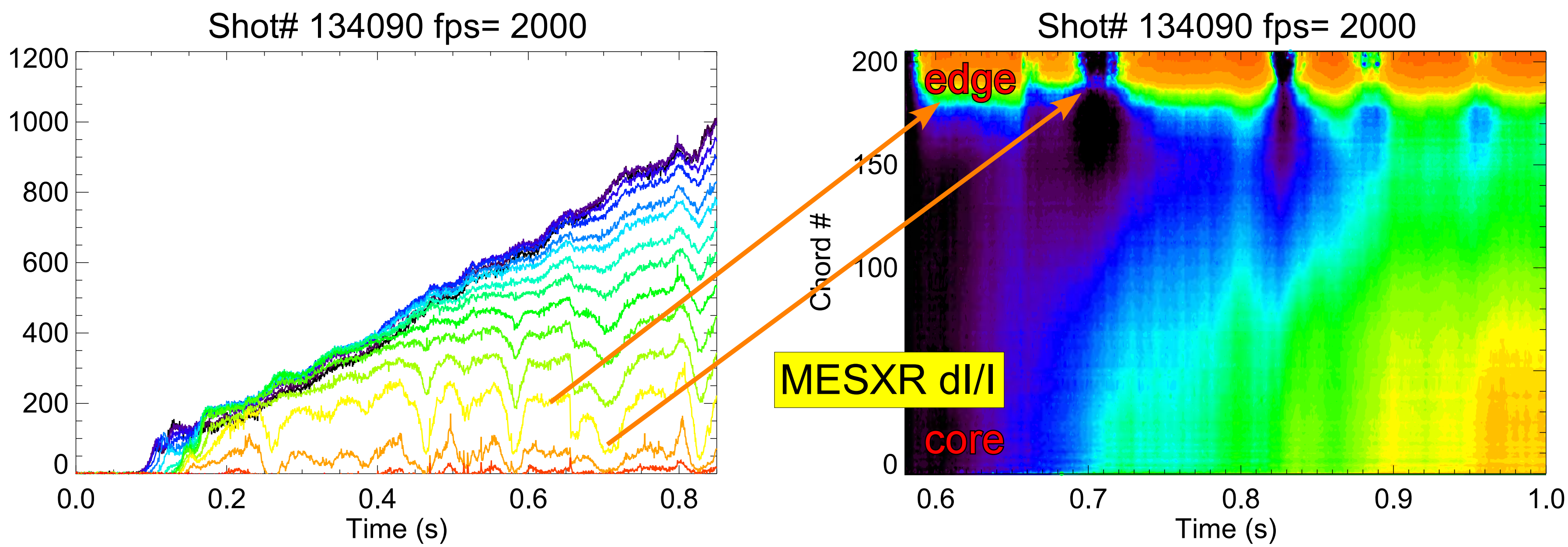


ME-SXR displaced 120° toroidally from TOSXR

Expect ~ 2/3π phase shift for 1/1 mode (1/3 of τ_{MHD})

$\Delta t_{MESXR/TOSXR}$ ~ 1ms
τ_{MHD} ~ 2.7ms

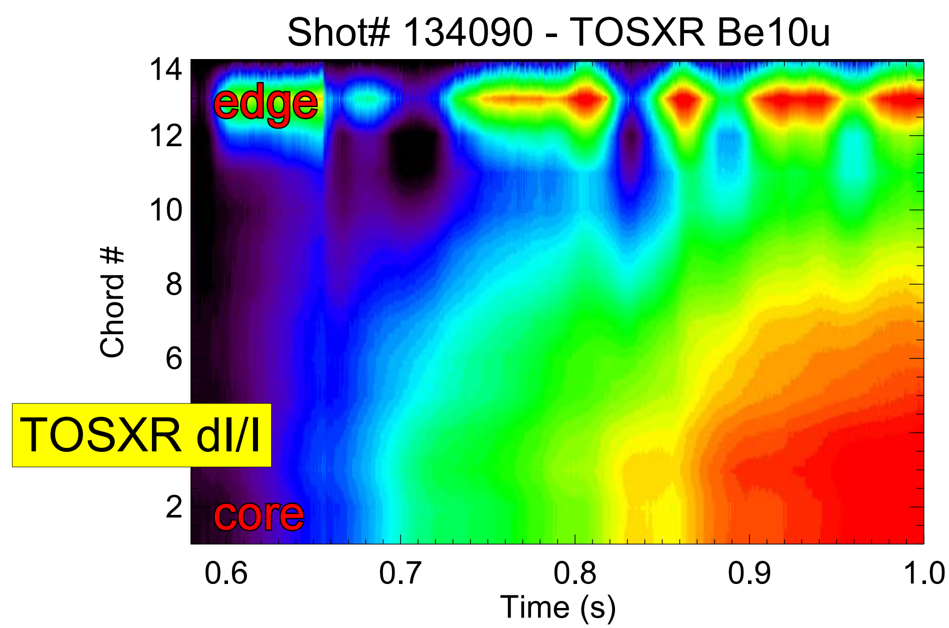
Large, slow edge modulations observed during LITER ELM-free operation on NSTX



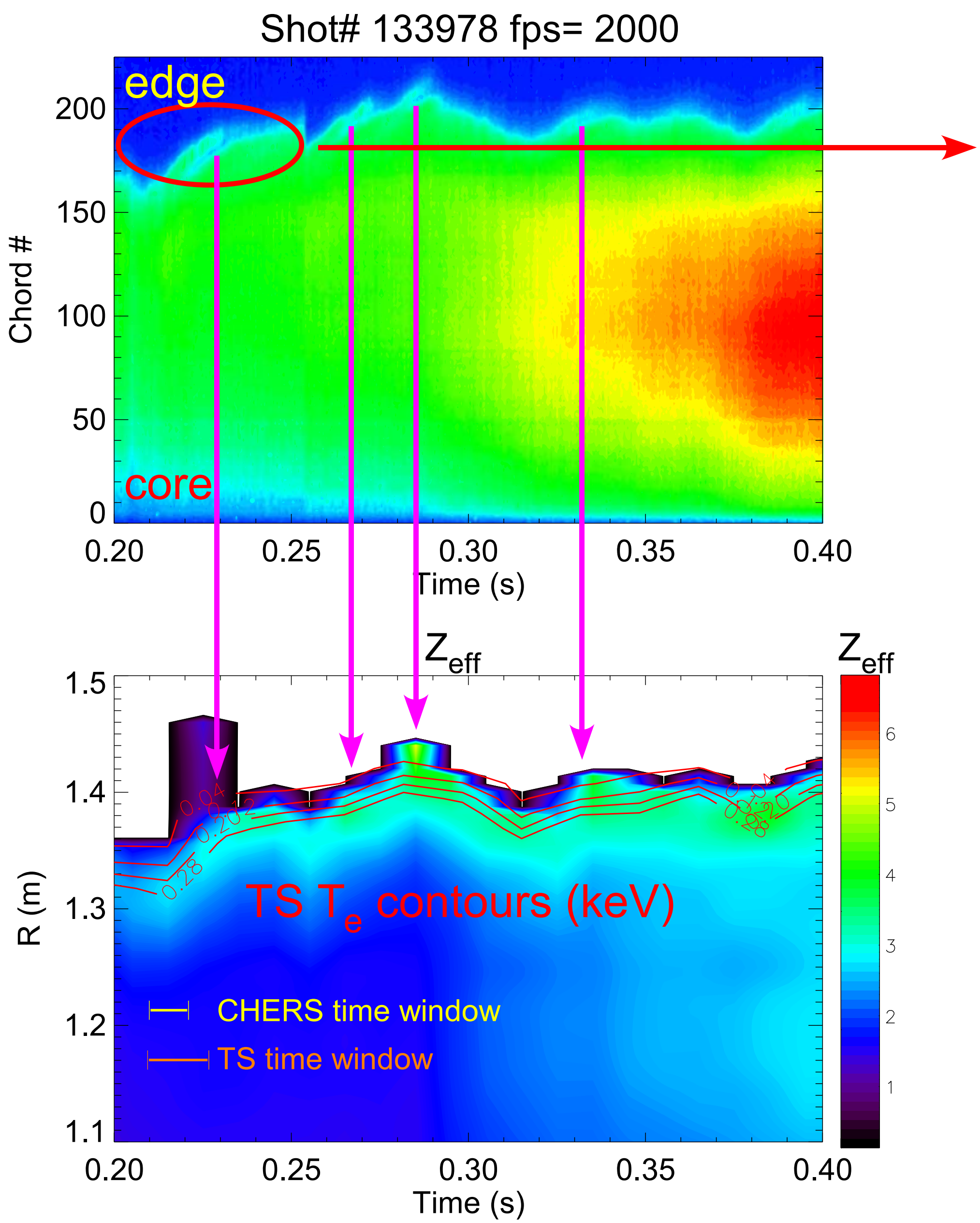
Quasi-periodic modulations have time scales ~30-60ms

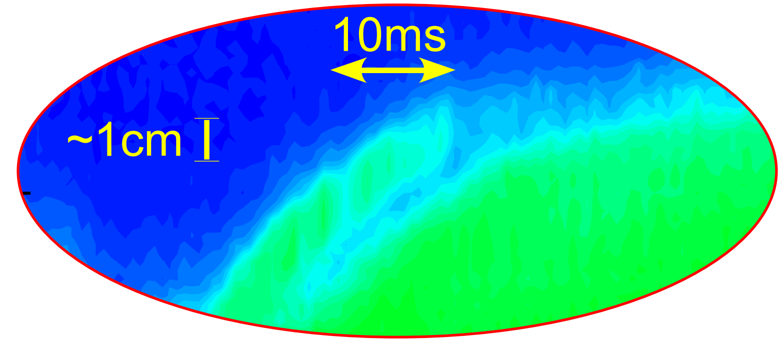
Show strongly in edge SXR measurements

Lack of toroidal component indicates global profile/equilibrium changes



High spatial resolution reveals 'filaments' are associated with slow edge modulations





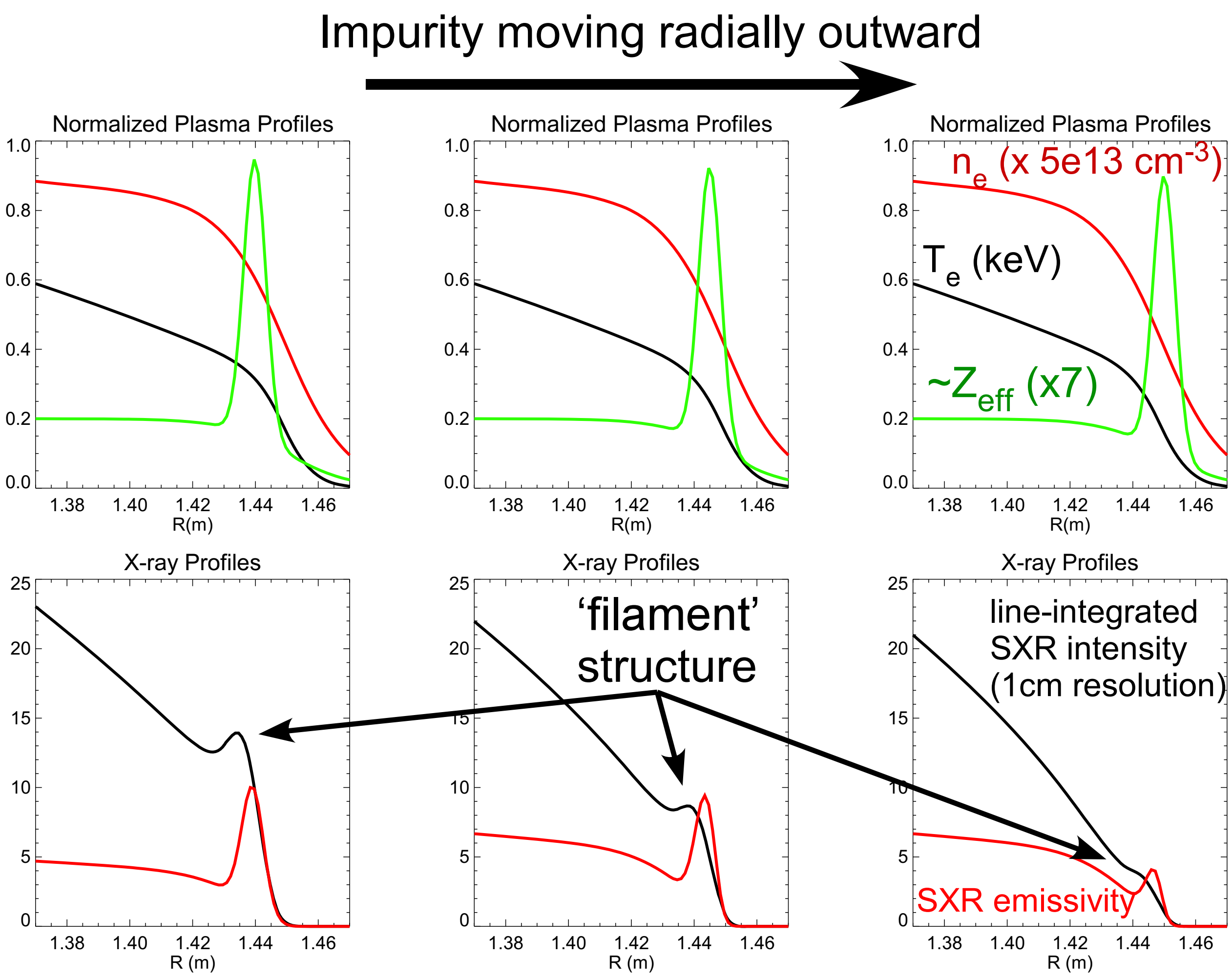
Slow edge modulation appears correlated with movement of boundary and/or Z_{eff} peak

Demonstrates strength of SXR for **fast measurement/feedback of plasma boundary position**

Filament time scale too slow for ELM or similar MHD phenomenon

Filaments appear correlated with modulation of peak Z_{eff} amplitude

SXR modeling shows filaments consistent with impurity 'blob' leaving plasma



SXR profiles generated from CHIANTI X-ray modeling code

Simulated plasma profiles used with impurity concentrations: C ~ 4%, O ~ 6% peak Z_{eff} ~ 7

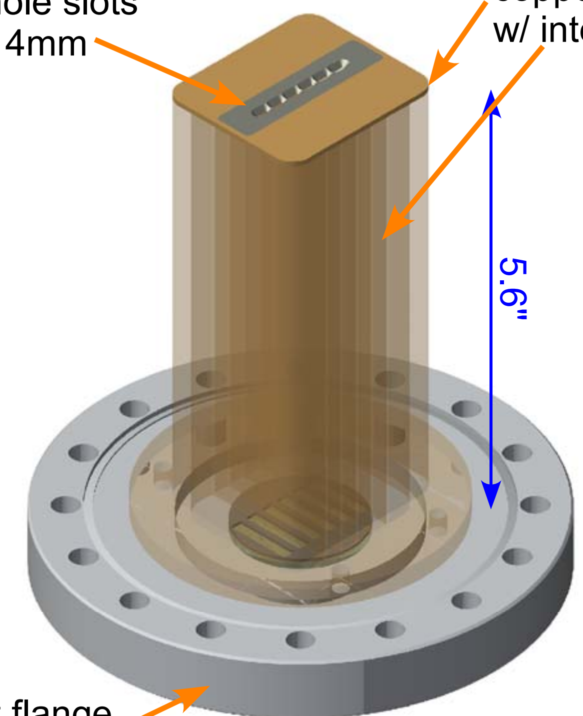
Local peaks in line-integrated intensity indicates **strong** localized emissivity

Impurity characterization and transport increasingly important for NSTX discharges with lithium

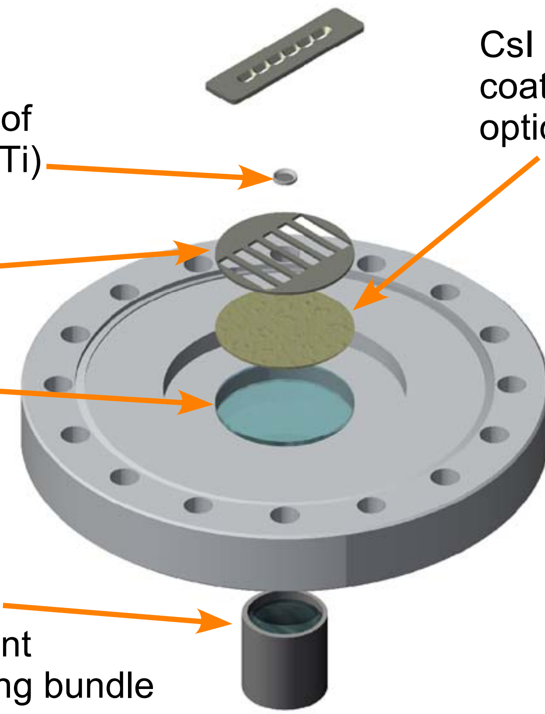
TOSXR sufficient for core impurity transport studies; high spatial resolution necessary to measure impurity transport in NSTX edge

Optical-based ME-SXR system under design & construction for NSTX 2010 run

5 energy optical system



Exploded view



Benefits of optical-based SXR:

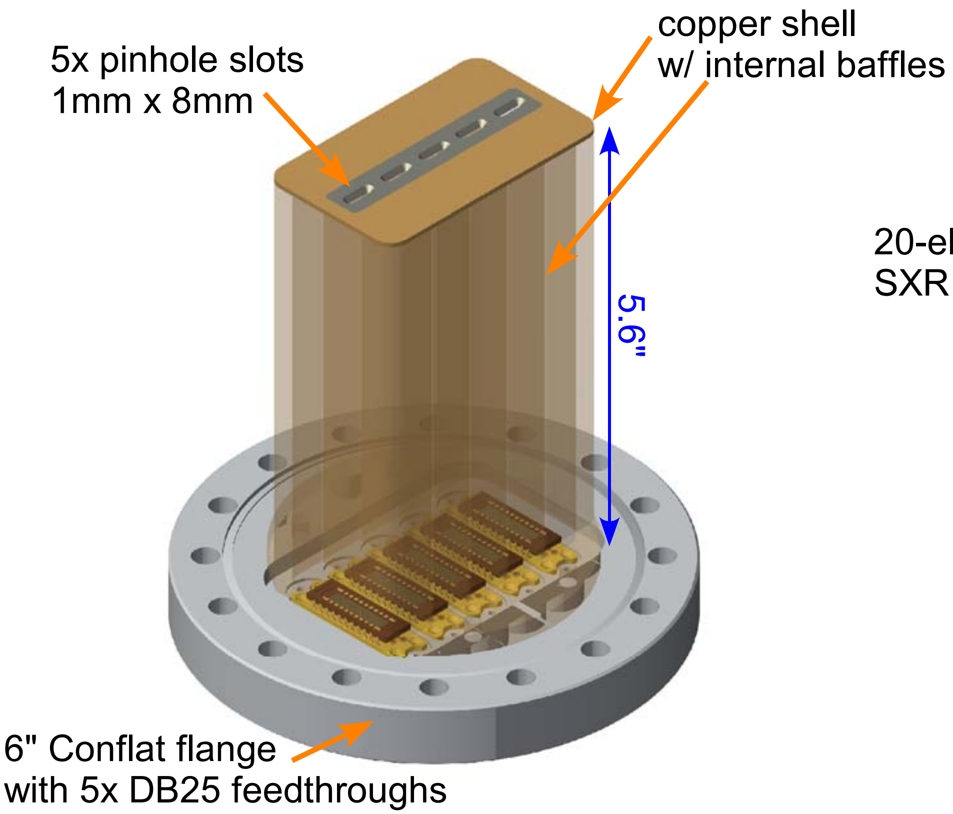
high spatial resolution with spatial oversampling
filter/energy band versatility
simple design and components

Image intensifier amplifies signal before optical detection chain

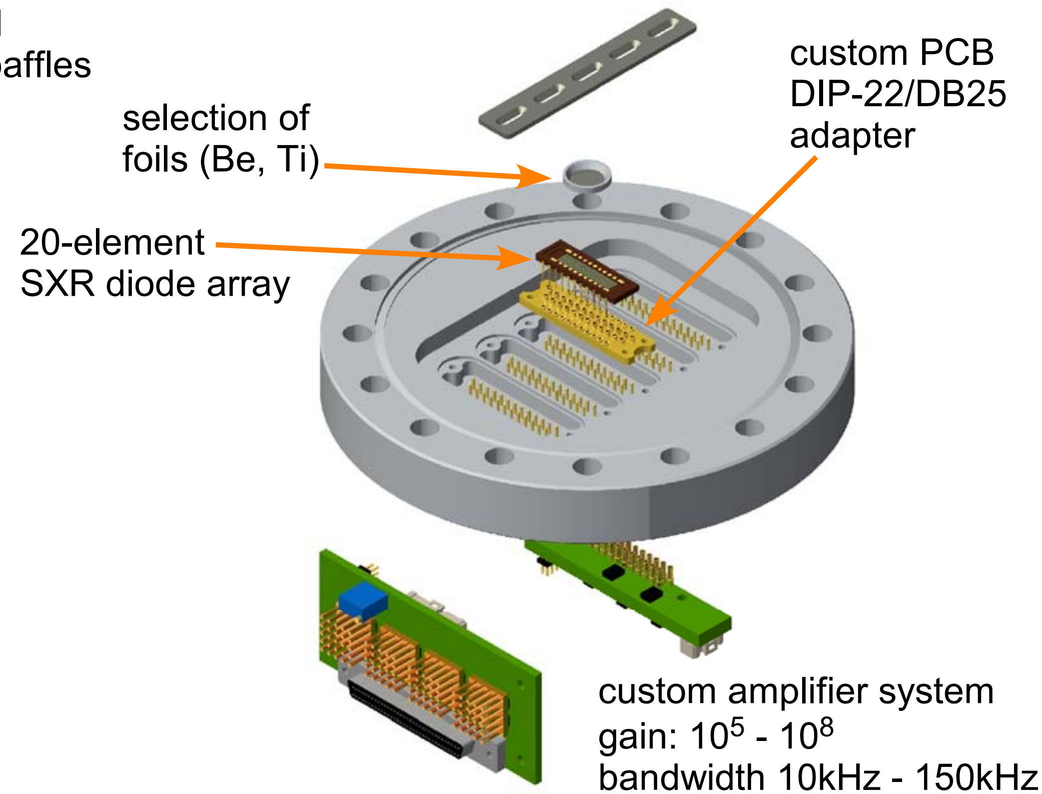
Detector flexibility (cameras, diode arrays) allows optimization of time, spatial resolution and SNR

Diode-based ME-SXR system also under development for possible fast system (> 10kHz)

5 energy diode system



Single energy - exploded view



Benefits of diode-based SXR:

high dynamic range
high bandwidth
modular components
compact detector and electronics

System has gain 10^5 - 10^8, compatible with direct connection to 96 channel DTacq acqusition

Single energy system currently under testing for LTX

High resolution ME-SXR system will provide important measurements for plasma periphery (r/a > 0.5)

- System will measure important NSTX edge phenomena
  - profile evolution before/after ELMs, and during crash (fast system)
  - RWMs/RFA modes (w/ additional toroidally displaced system) *(Delgado-Aparicio - PP8.00054)*
  - slow MHD modes, edge islands and kink activity
  - Impurity influx and transport increasingly important for lithium operation and during ELM cycle
- Additional energy bands improves fast T_e measument
  - increases sensitivity range for measurements of ΔT_e
  - allows for measurements of changing impurity concentrations
  - can provide fast measurements of n_e, T_e, and n_{imp} profiles
- Integration with transmission grating spectrometer
  - tangential TG provides spatial- and time-resolved spectra 30-300Å
  - measurements of impurity concentrations important to constrain and separate T_e, n_e, and n_{imp} for accurate fast profile modeling *(Stutman - CP8.00042)*