Development of Soft X-ray Array Diagnostic System for KSTAR

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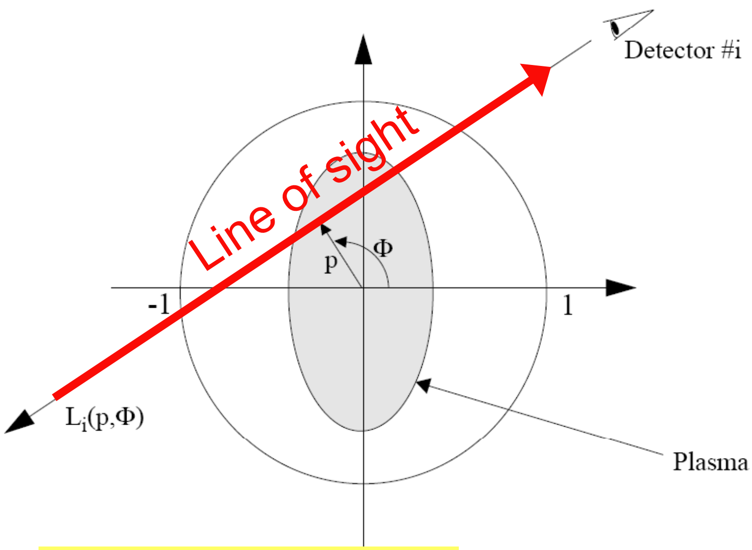
Tomography

A non-invasive imaging tool for observing the inner structure of the plasmas



$$f(L) = \int_L g(x, y)\,dl \quad \rightarrow \quad \mathbf{f} = \mathbf{W} \cdot \mathbf{g}$$

Solving inverse problem
(*ill-posed* problem)

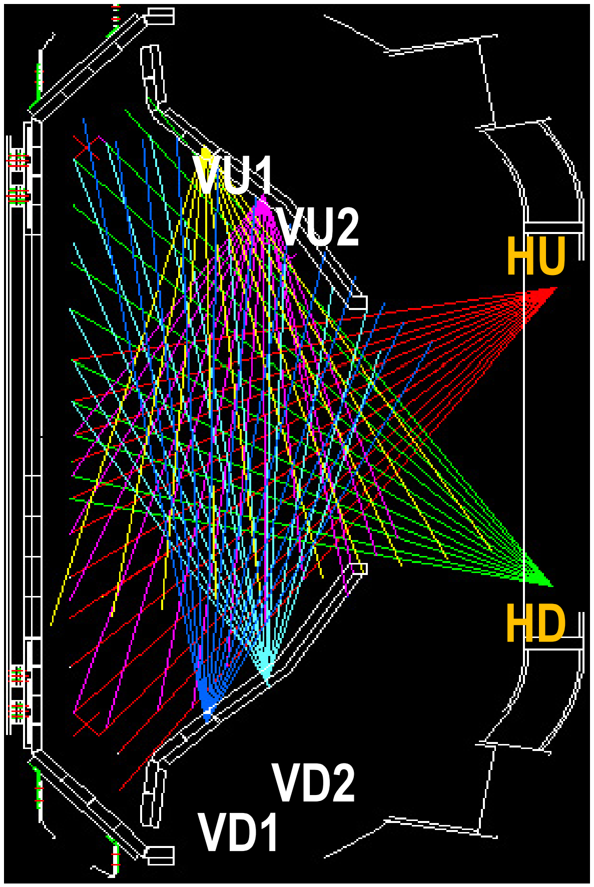
$$f(L) = \int_L g(x, y)\,dl$$

Measured ($f(L)$) Reconstructed ($g(x, y)$)

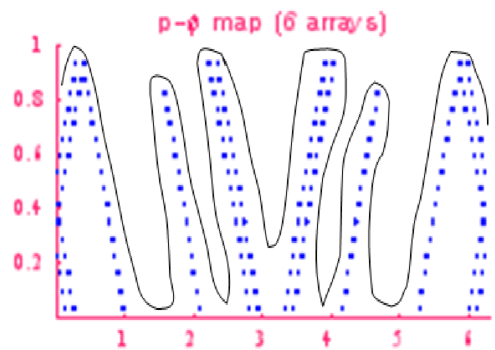
Reconstruction of 2-D local emissivity ($g(x, y)$)

- **Tomography problem : a matrix equation with the geometrical weight matrix and the measured values**
- **Ill-posed noisy problem → inversion requires regularization**
- **Various regularization approaches : e.g. whether to use statistical or physical information**

Optimized SXR arrays for KSTAR



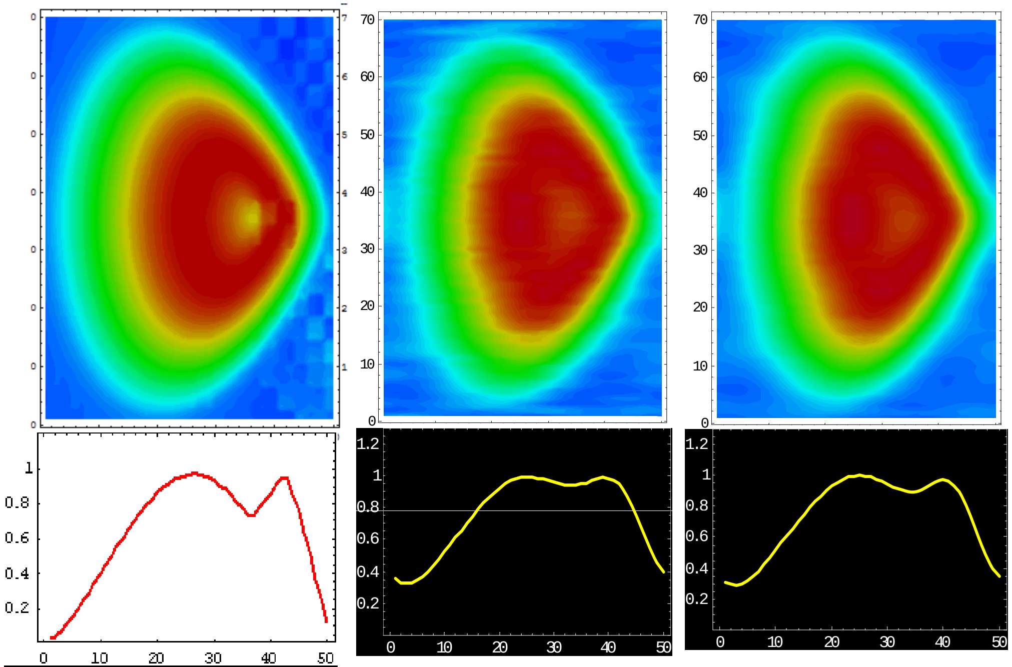
- 6-array system (240 ch)
- Spatial resolution = 2 cm
- Calculated coverage value (6-array : 0.57)
- T_e range : 1 keV - 10 keV (depending on filter)



- MHD activities
- Transport
- Te (two color)
- Plasma position
- Radiated power
- Impurity etc

High-resolution tomography

Fast MEM   Fast MEM



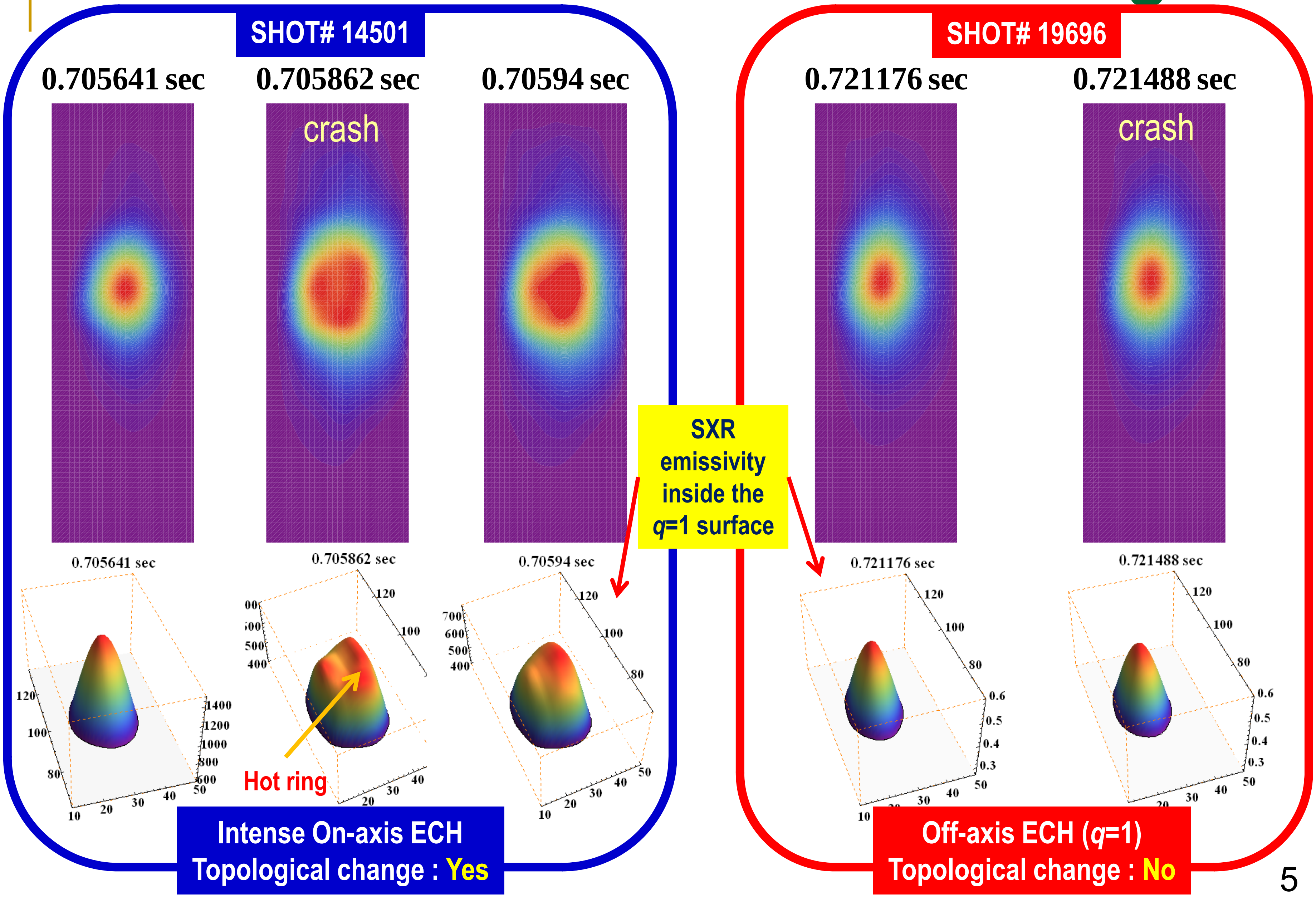
Source Phantom   Low Resolution   High Resolution

- High-resolution (50x70=3500 pixels) tomography shows more reliable reconstruction result despite the increased ill-posedness.
- PTM is the most accurate in both low and high resolution.
- Fast MEM gives the fastest calculation (//el computation by 4 cpu's).

2.67 GHz, Win XP

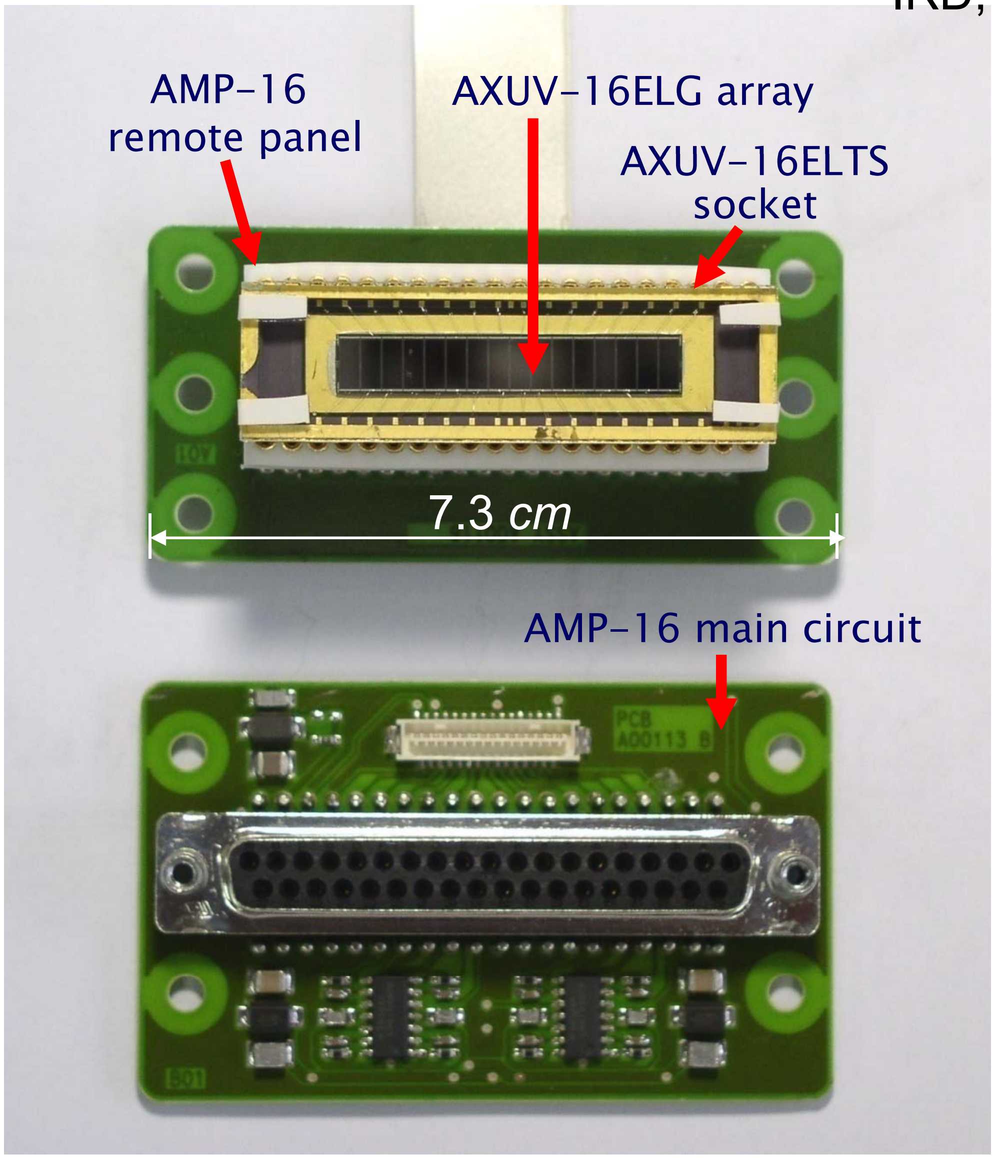
Methods	MFI (TCV code)		Fast MEM		PTM	
Relative error / calculation time	σ (%)	Time (s)	σ (%)	Time (s)	σ (%)	Time (s)
Low Resolution	7.1	1.7	7.2	1.3 (0.08)	6.2	2.7
High Resolution	5.7	3.6	5.3	2.5 (0.19)	5.0	5.6

On-axis vs. Off-axis ECH in the high-κ

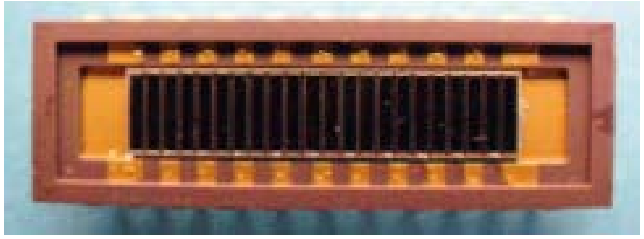


AXUV Photodiode array and preamplifier

IRD, Inc.

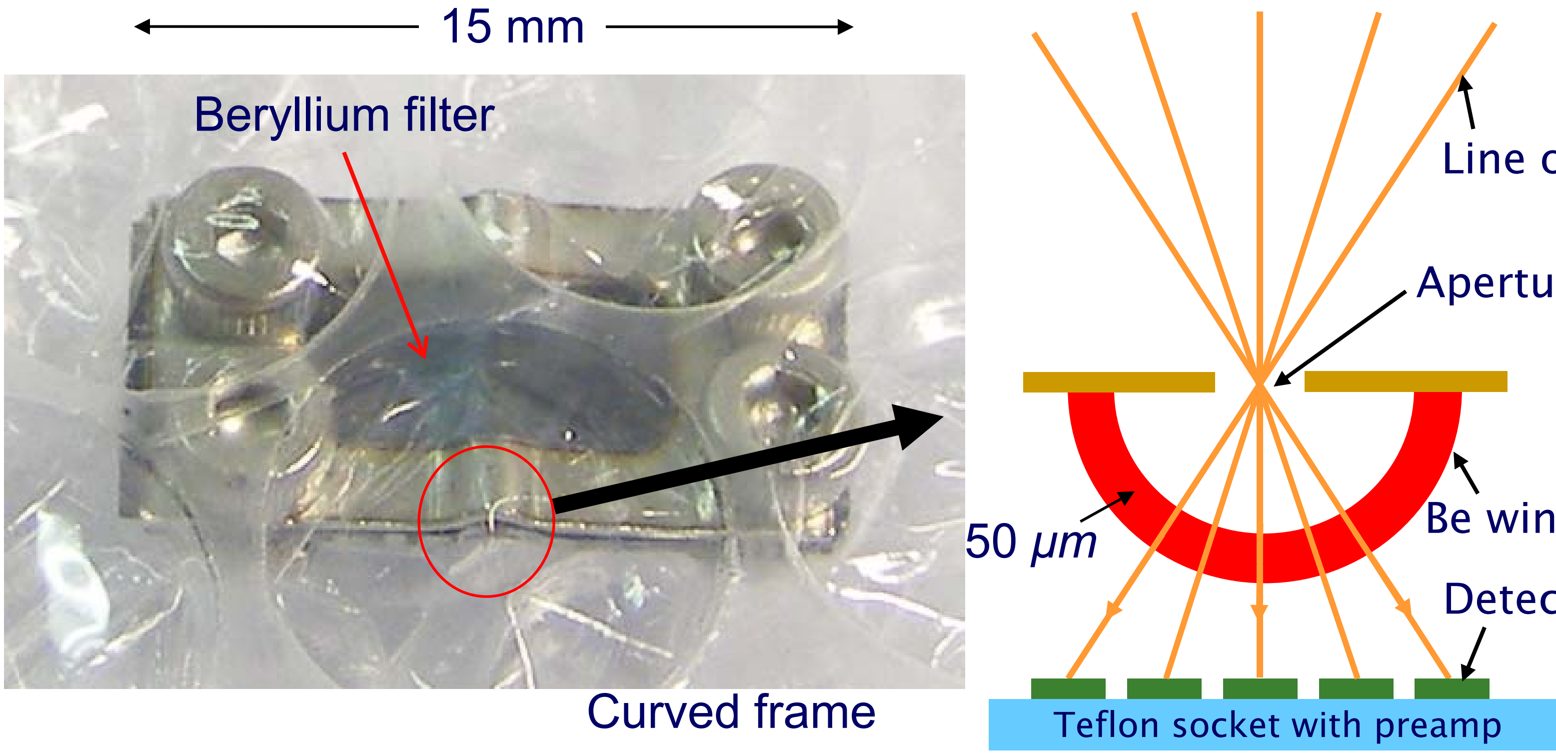


AXUV-20ELG array



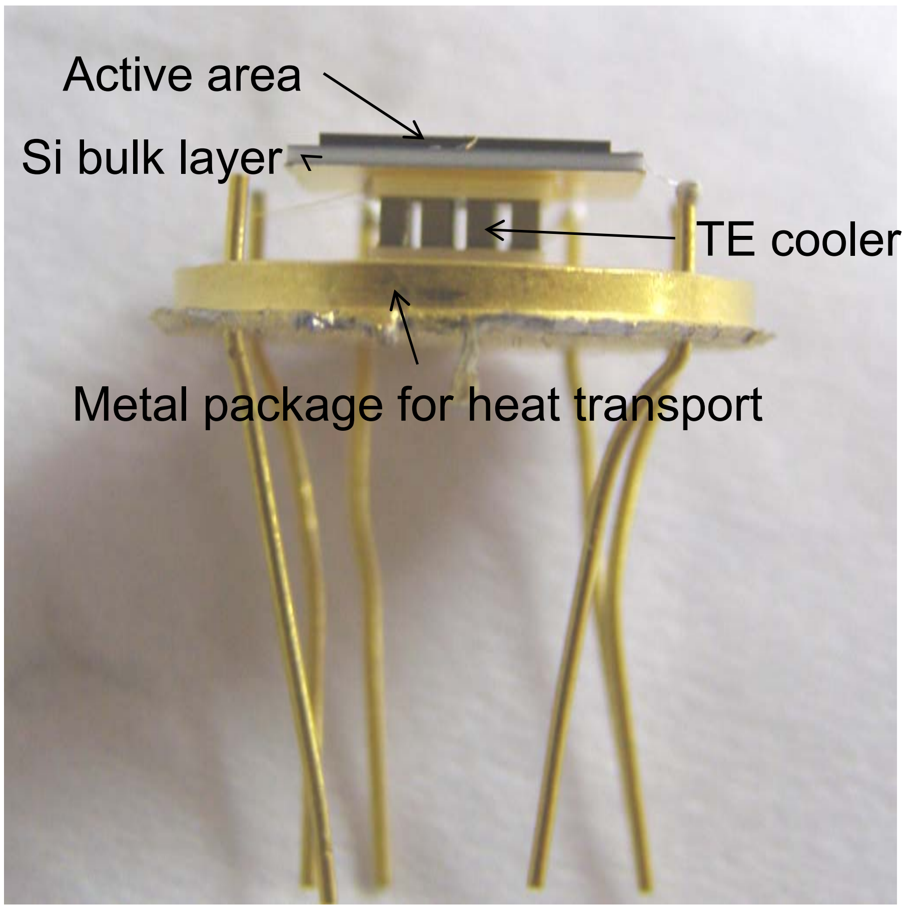
- AMP-16 :
  In-vacuum preamplifier developed for KSTAR SXR array
- Modified version for separate preamp
- Transimpedance gain : 10^4 - 10^5
- Bandwidth : ~600 kHz (be able to observe the fast MHD activities)
- AXUV-20ELG array (high spatial resolution)

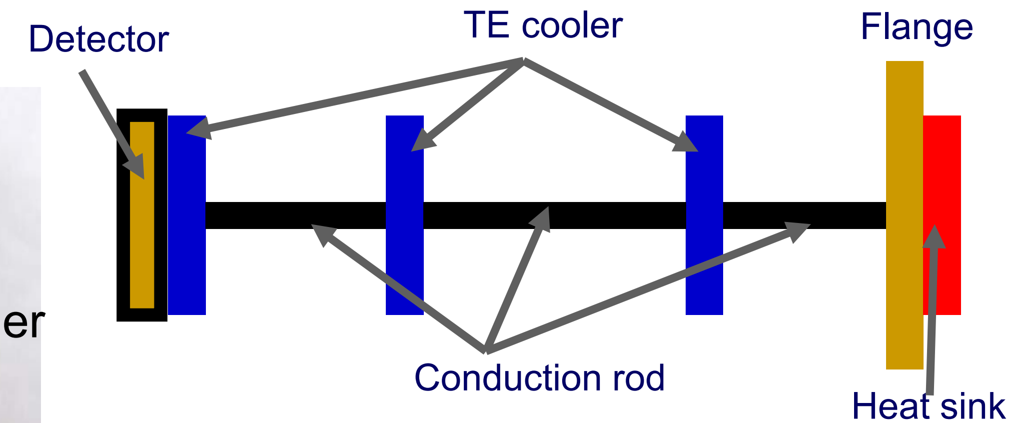
Curved Beryllium Filter



- Thickness : 50 μm for KSTAR
- T_e range : 1 - 10 keV (1 - 0.1 nm, AXUV array)
- Low cut-off energy of photons penetrating the Be window along chords is same.
- Only relative calibration among detector elements is required.

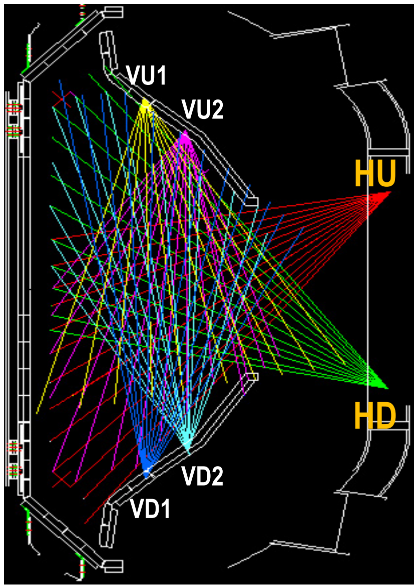
Thermo-electric cooling system





- Conduction rod for heat transfer between the detector and the heat sink
- Multi-stage TE coolers (TE-cooling system only)
- External temperature controller

Plan for KSTAR SXR array



- 6 arrays, max. 240 ch (total system)
- Bandwidth of preamp: 500 kHz (for fast MHD such as TAE)
- T_e range: 1-10 keV
- Inter-shot and post-shot analysis
- Developed tomographic reconstruction codes will be used.
- MHD phenomena and thermal heat transport will be studied.
- FY2009 : HU and HD will be installed (AXUV array).
- FY2010 : VU and VD will be installed (Optical array).
- FY2011 : HU and HD will be replaced by Optical array.

<table>
<tr><th>~ 2009. 1st q.</th><th>~ 2nd q.</th><th>~ 3rd q.</th><th>~ 4th q.</th><th>~ 2010. 1st q.</th><th>~ 2nd q.</th><th>~ 3rd q.</th><th>~ 4th q.</th><th>~ 2011. 1st q.</th><th>~ 2nd q.</th><th>~ 3rd q.</th><th>~ 4th q.</th></tr>
<tr><td colspan="2">Procurement</td><td></td><td colspan="2">Procurement</td><td></td><td colspan="2" rowspan="5">Maintenance & Repair</td><td colspan="2">Procurement</td><td></td><td></td></tr>
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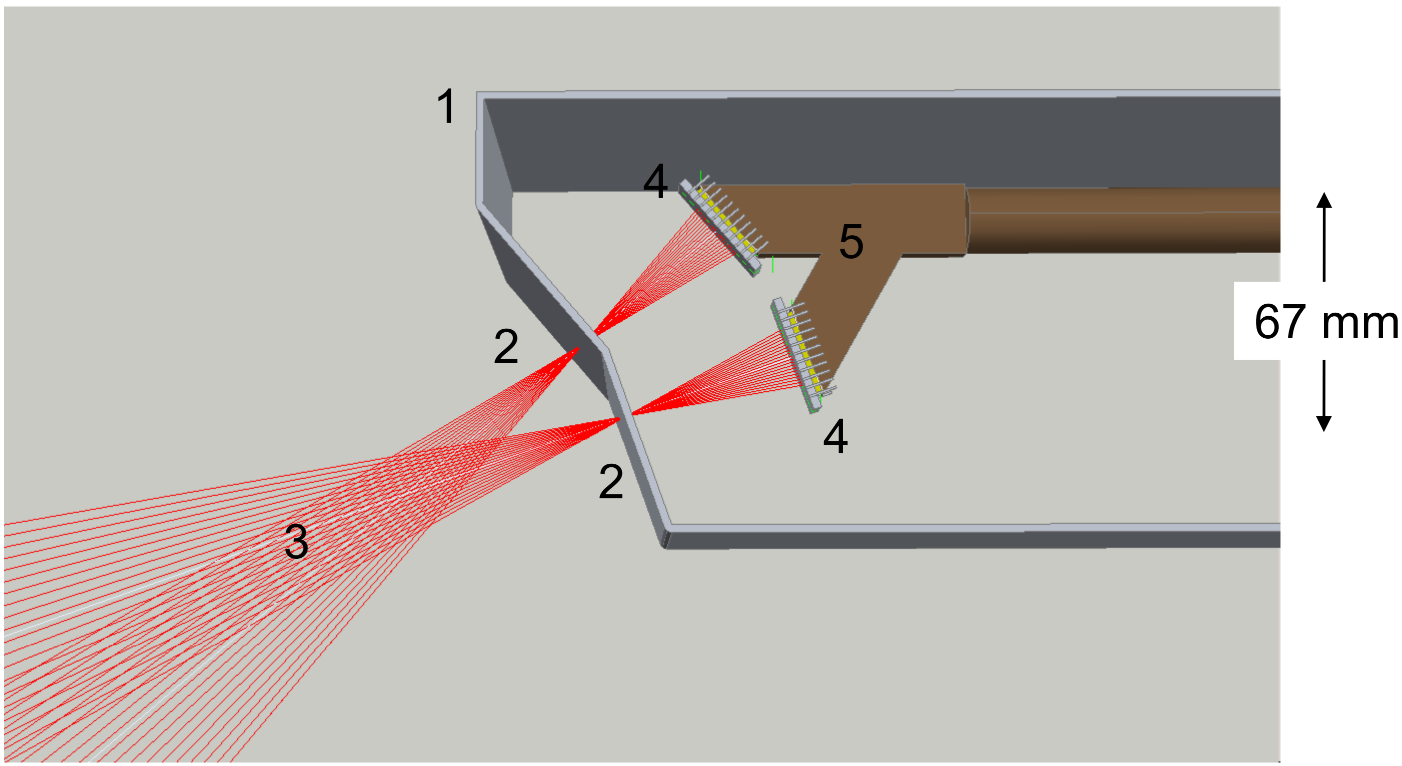
Circular Ohmic

Double Null

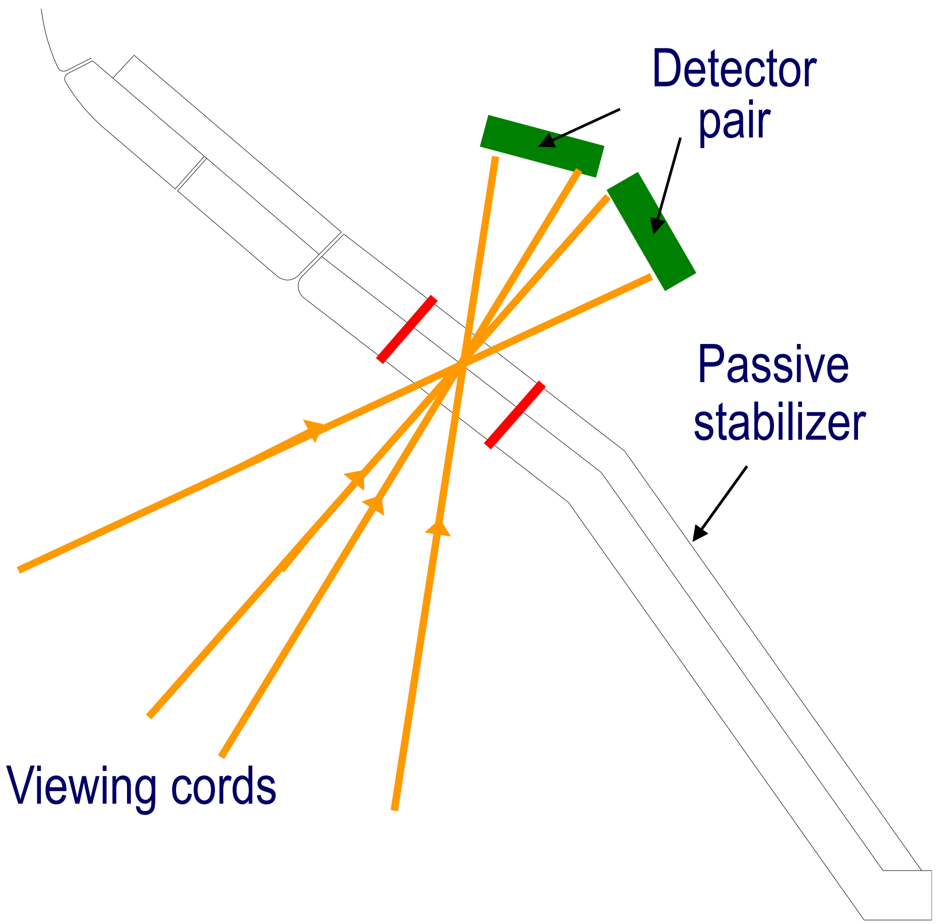
Single & Double

SXR Array System (1 sets (HU or HD))

1. In-vacuum Housing (SUS)
2. Slit and Be window
3. Line of sights
4. SXR detector with TE cooler
5. Cu for cooling system



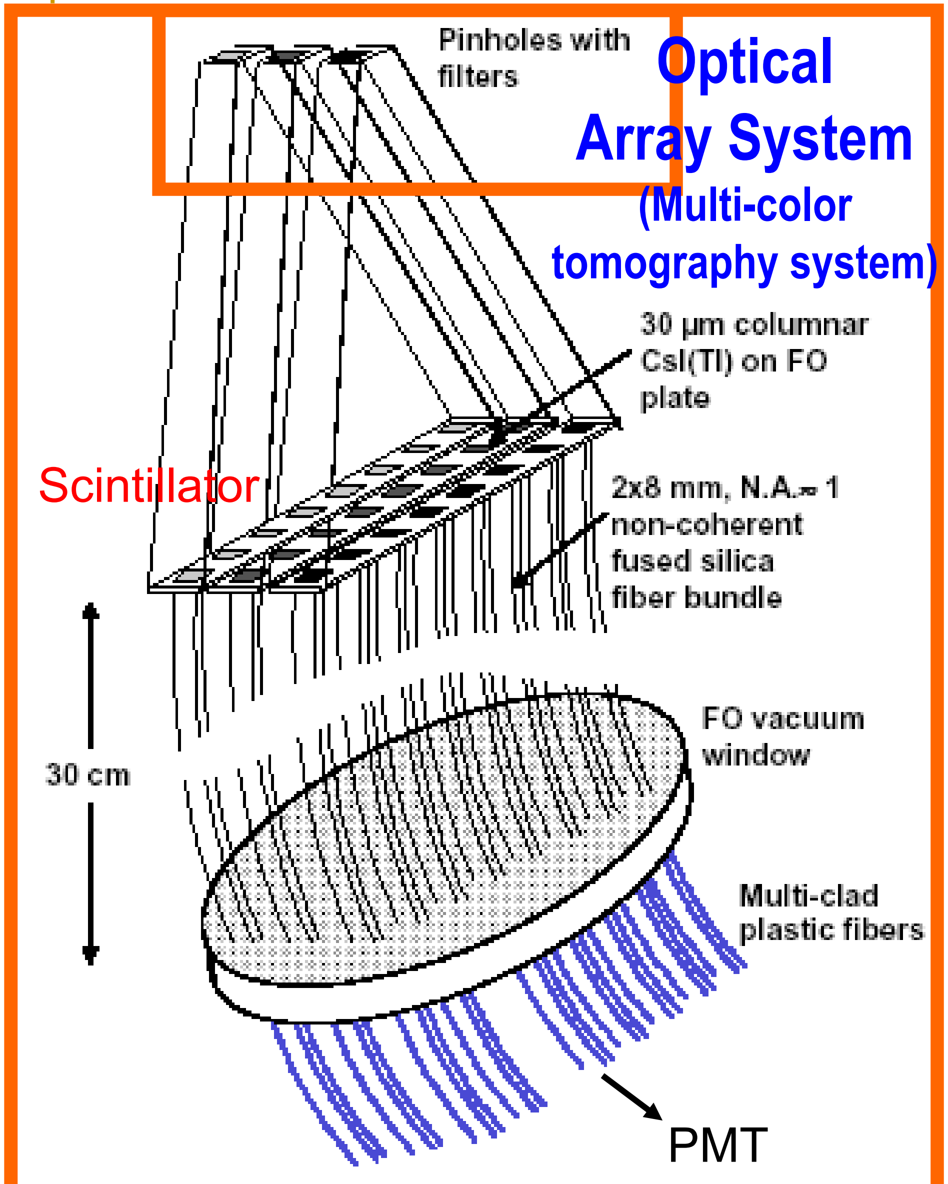
Vertical SXR Array (V-shaped)



- Incident angle of the V-shaped detector pair is smaller than the linear detector pair.
- V-shaped array (20ch-20ch)
  → signal difference between edge/center element ~ 1 %

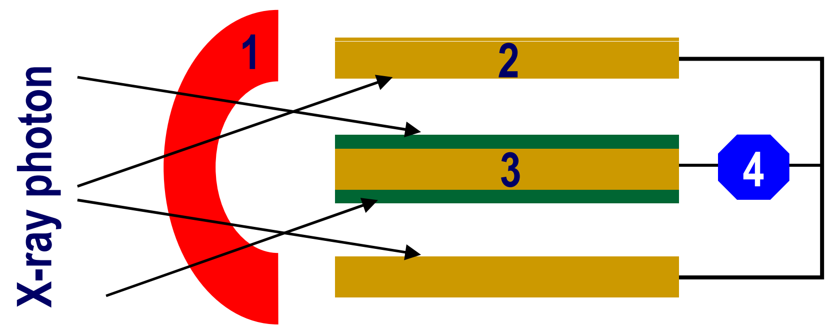
  cf) Linear arrangement of two detectors (40 ch) ~ 5 %
- Hole diameter in the passive stabilizer ~ 40 mm

2nd generation SXR array



Vacuum photodiode detector

- Conversion of SXR photon flux into current
- Insensitive to the neutron noise
- Detectable energy band is wider than the conventional photodiode.
- ITER-relevant soft x-ray array



< Elementary VPD cell (1 channel) >

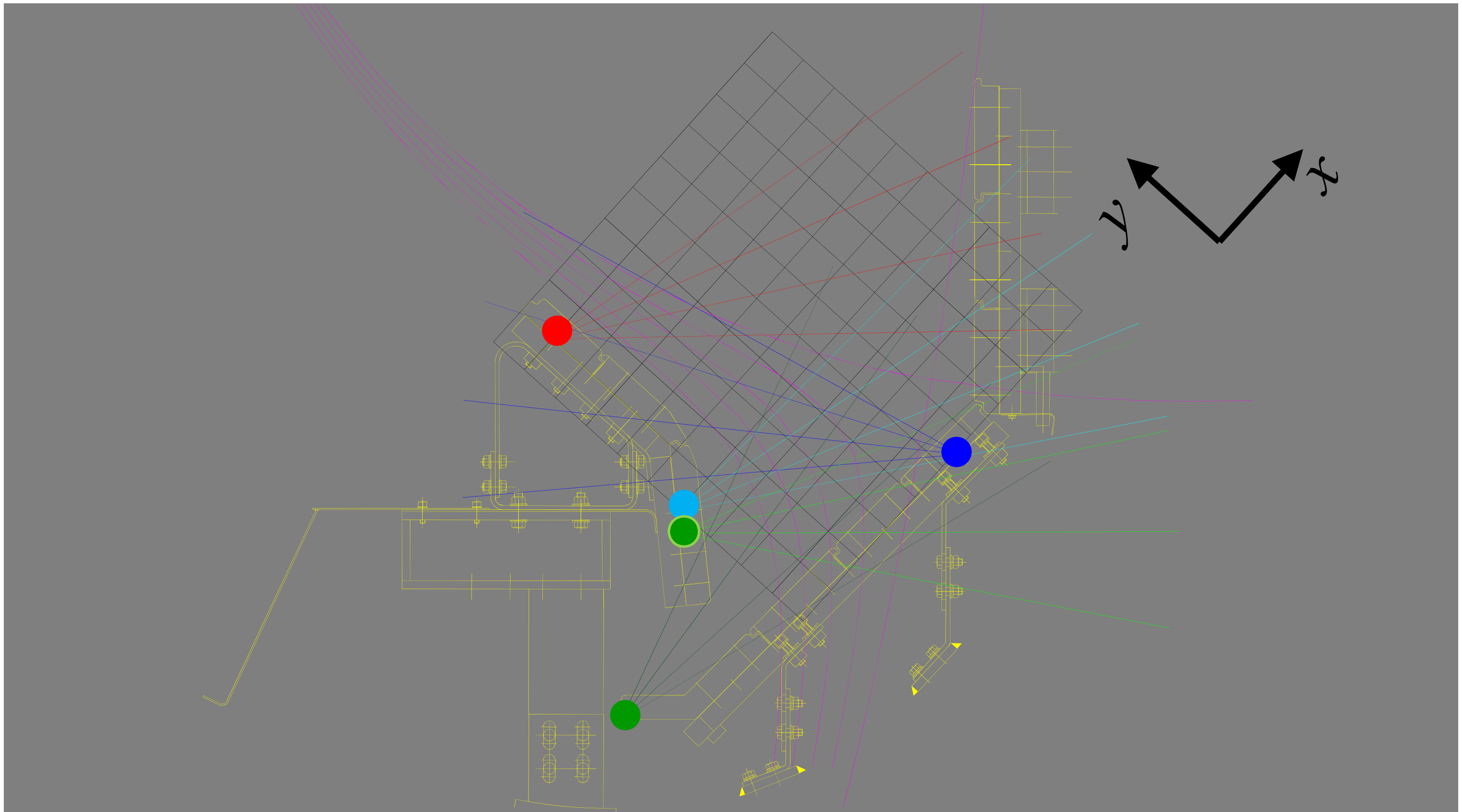
- 1 : Curved Be window
- 2 : Anode (Be)
- 3 : Ta deposited Be cathode
- 4 : Ammeter

Required Equipments

- **Preparable items in 3 months :** Detector head (AXUV array, Preamp (AMP16 or AMP20), TE-cooler), In-vacuum wire bundle, Low-speed DAQ (up to 100 kS/s/ch), Be-filter (50 μm), Power supply, Analysis software

- **Additional requirements :** Housing, Insulation (Kapton Tape & Ceramic Insulator), Electrical wire bundle (Tokamak flange → Diagnostic room), High-speed DAQ (200 ~ 500 kS/s/ch), Slit, Bay-D Cassette (Prepared by KSTAR), Additional Power Supply, Additional controller for TE-cooler, 19’’ rack

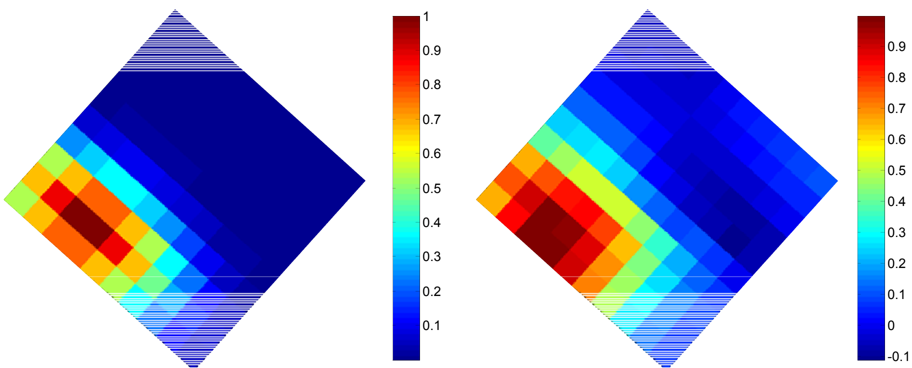
Divertor bolometer design



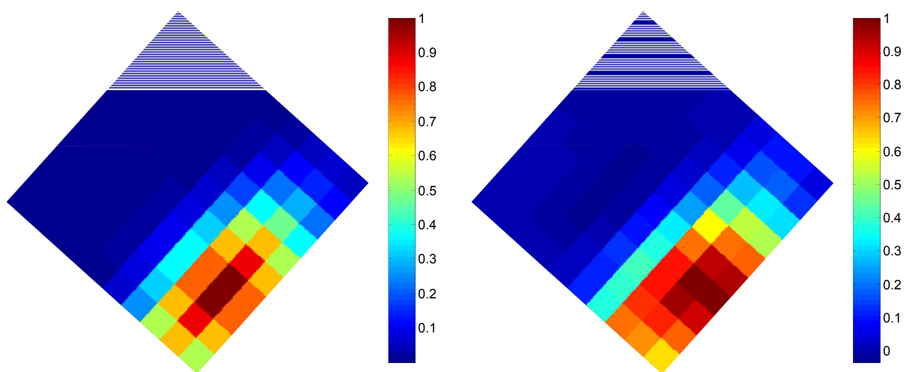
- Tomographic reconstruction area : 10×10 pixels
- Detector : 5 arrays x 4 ch/array = 20 ch

Reconstruction test results

Phantom **Recontruction**



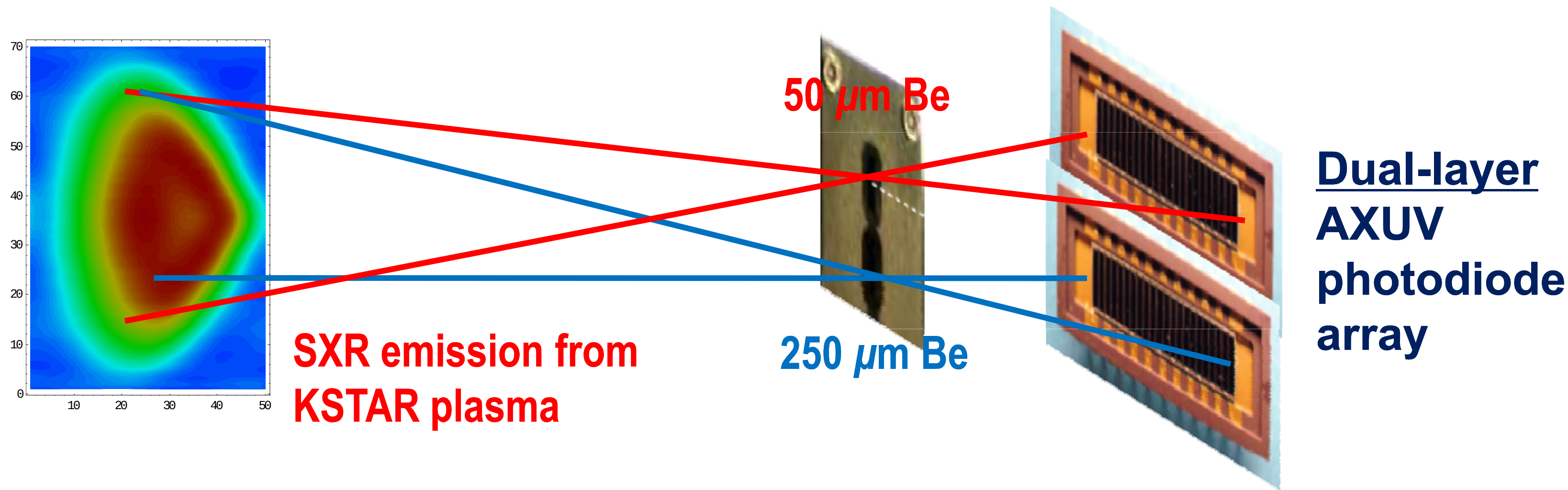
- **Large radiation toward the outer divertor plate**



- **Large radiation toward the inner divertor plate**

- Reconstruction shows reasonable results : < 4% error compared to the phantom
- Ghosts in the little radiation region
  → require more channels?

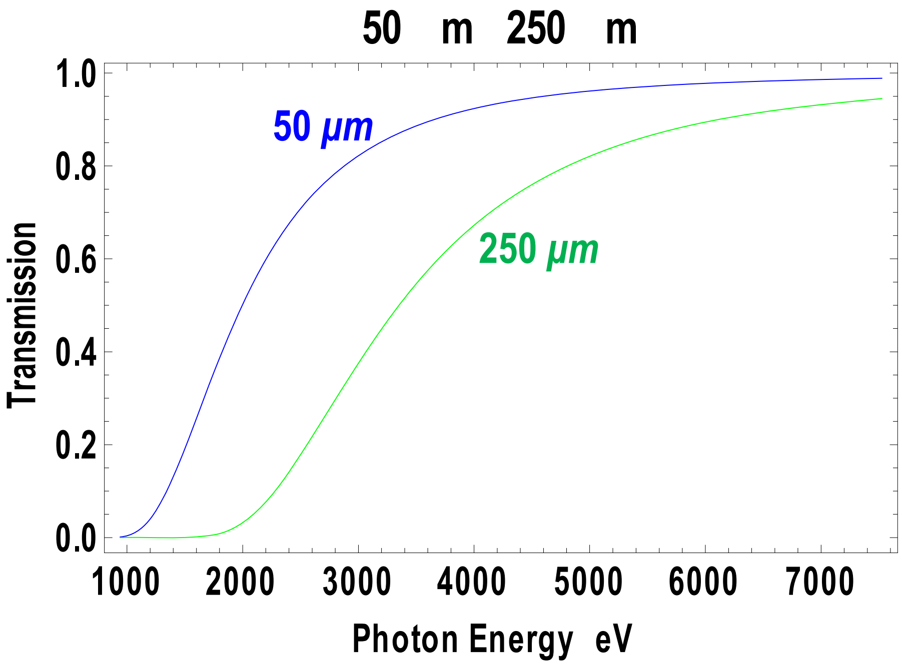
"Two-Color" SXR Array (Plan)

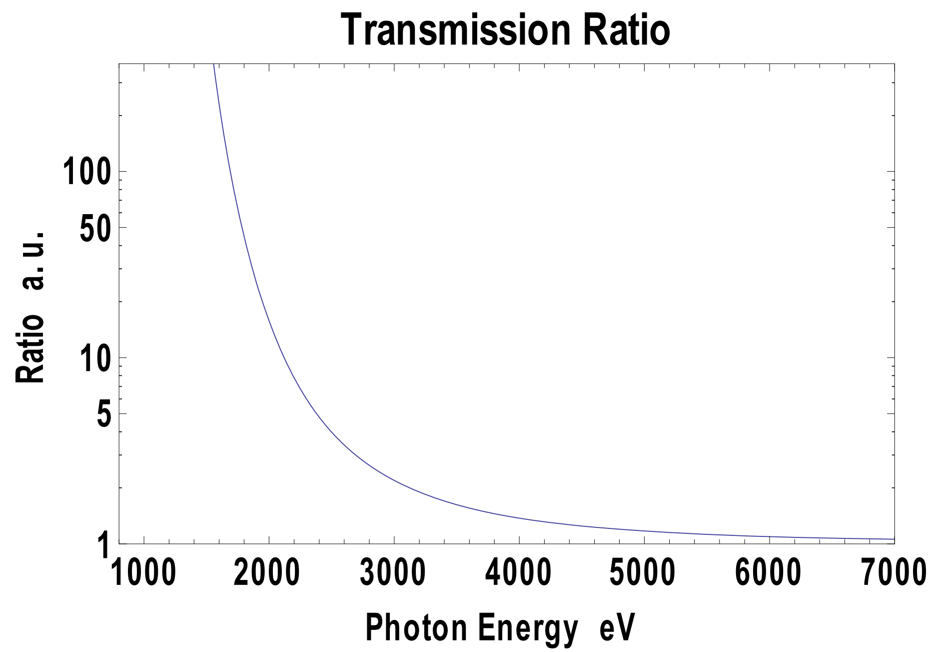


Multi-color technique ("double-foil" method) :

- This technique utilizes the multi-color principle, in which T_e is obtained by comparing the localized radiation intensities of the two energy ranges, rather than from the measured absolute intensity.
- This design approach naturally eliminates a number of factors that degrade the accuracy of the conventional single color SXR diagnostics for T_e measurements.

Proposed Be foils for KSTAR SXR array / Estimation of T_e





Lower limit : Lower cut of thicker Be filter ~ 1.5 keV

Upper limit : Tolerable minimum contrast at ~ 7.0 keV

Detectable range : 1.5 - 7.0 keV