Development of a High Resolution X-Ray Imaging Crystal Spectrometer for Measurement of Ion-Temperature and Rotation-Velocity Profiles in Fusion Energy Research Plasmas

NSTX

K. W. Hill, M. L. Bitter, S.D. Scott

Princeton Plasma Physics Laboratory, Princeton, NJ

S. G. Lee

NFRC, Korea Basic Science Institute, Daejeon, Korea

A. Ince-Cushman, J. E. Rice

MIT Plasma Science and Fusion Center, Cambridge, MA

Ch. Broennimann, E. F. Eikenberry

SLS, Paul Scherrer Institute, Villigen, Switzerland

R. Barnsley

Queen's University Belfast and EFDA/JET

Visiting researcher at ITER International Team, Cadarache, France

Presented at the 12th Meeting of the ITPA Topical Group on Diagnostics, Princeton, NJ, 26 March, 2007

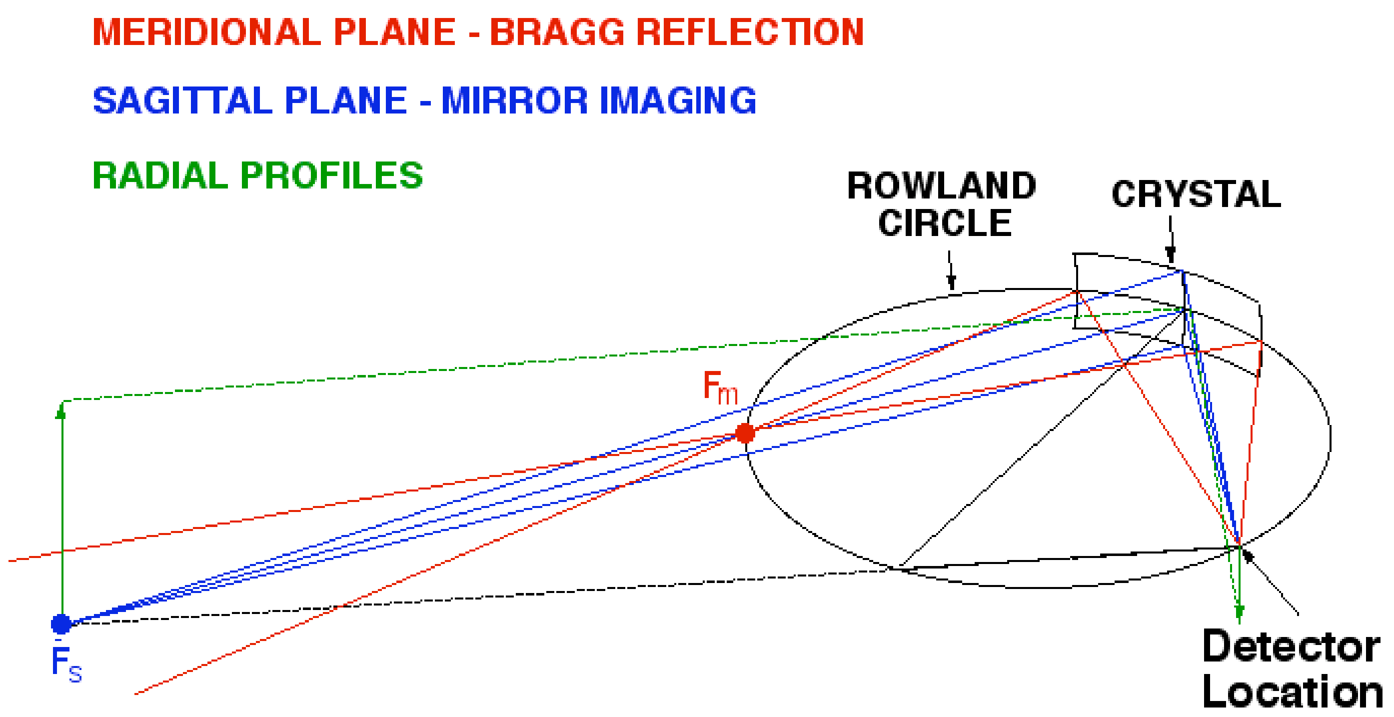
Motivation

- Ion-temperature and rotation-velocity profiles important for understanding intrinsic rotation and transport in ITER
- Charge exchange recombination spectroscopy requires a NB; NB intensity will be low in center of ITER
- Conventional x-ray crystal spectrometers (XCS) have poor spatial resolution
  - Few single-chord views
  - Separate instrumentation for each chord
- Imaging XCS provides continuous profile data with single instrument
  - Spherical crystal + 2D x-ray detector
  - Suitable for all heating methods

Main Points

- Proof-of-Principle of new imaging x-ray crystal spectrometer (XCS) for T_i- and rotation-profile (v_ϕ) measurement previously demonstrated
  - on NSTX, Alcator C-Mod, and TEXTOR;
  - temporal and spectral resolution limited by the available 2d x-ray detector (<400 kHz)
- New pixelated silicon detector with better spatial resolution and 100,000 times higher count-rate capability removes limitations
  - Highly tolerant of background radiation noise
- New detector tested on existing C-Mod spectrometer
- Imaging XCS adopted for ITER
- Imaging XCS being installed on Alcator C-Mod to measure full radial profiles of T_i and v_ϕ on - prototypical of ITER XCS
- Calculations of uncertainty in T_i and v_ϕ measurements predict performance of C-Mod and ITER spectrometers

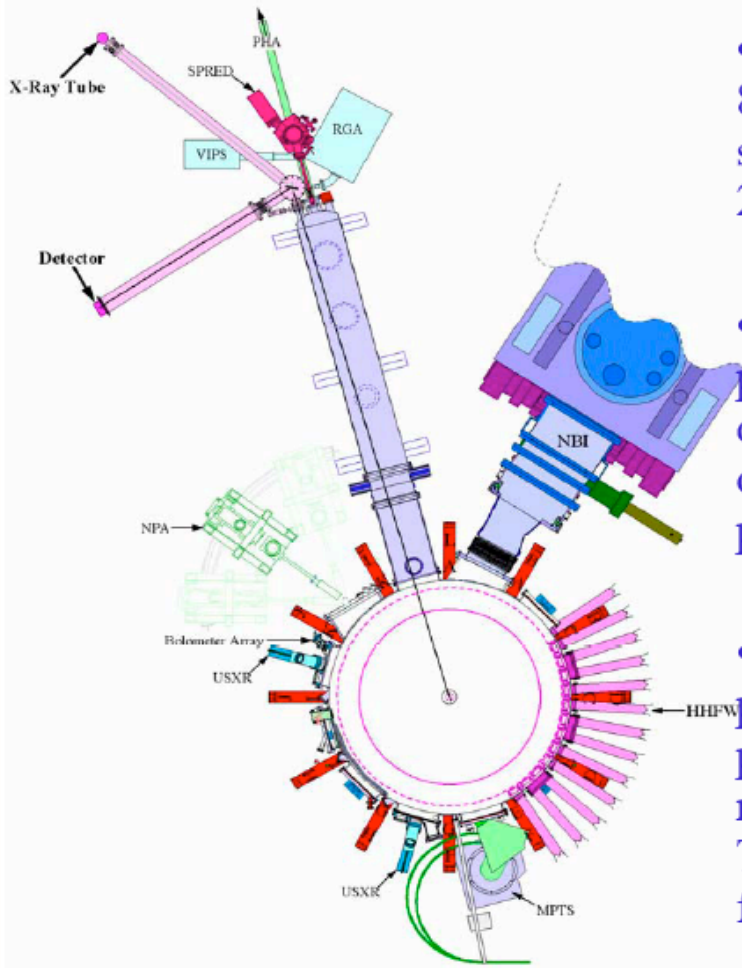
Spherical crystal images spectra in vertical direction



- Excellent spatial resolution can be obtained .
- Demagnifies plasma source to smaller detector.

NSTX X-Ray Imaging Crystal Spectrometer

NSTX



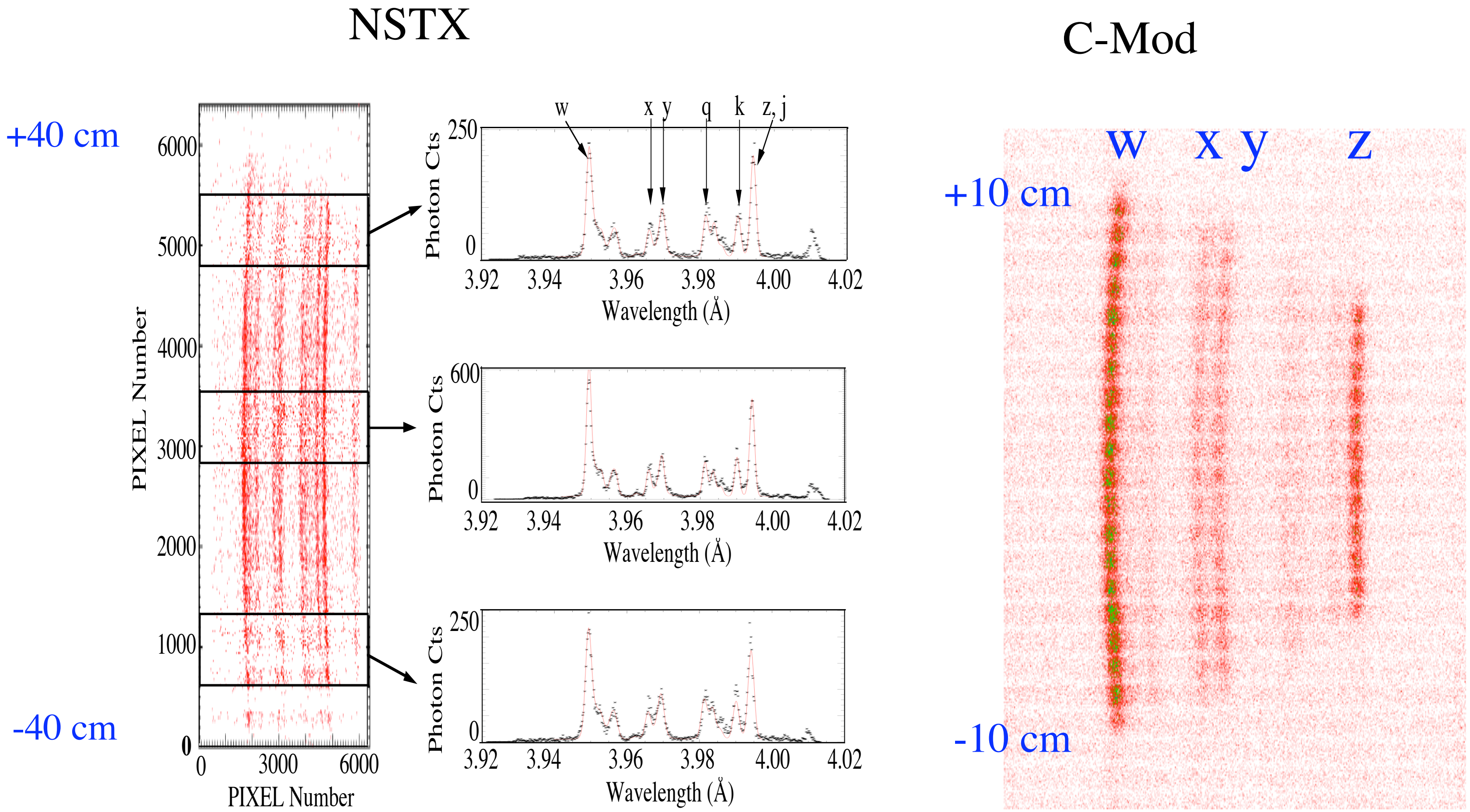
- X-ray spectra from multiple sightlines through an 80 cm high cross-section of the plasma are simultaneously recorded on a 10 cm x 30 cm large 2D position-sensitive detector.

- The spatial resolution in the plasma is 2.5 cm perpendicular to the NSTX mid-plane. It is determined by the height of the crystal, its radius of curvature, Bragg angle, and distance from the plasma.

- The spectrometer was proposed in 1998 and patented in 2001. First experiments were performed on Alcator C-Mod 2003. More recent results were obtained on TEXTOR and NSTX. The development of the spectrometer is being funded by the US Department of Energy.

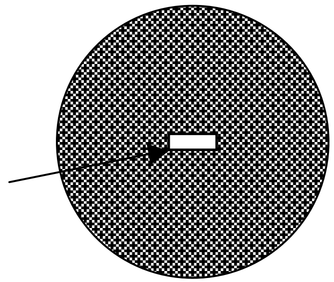
KBSI KAERI Alcator C-Mod

Spectral profiles were measured on NSTX and C-Mod good spectral resolution

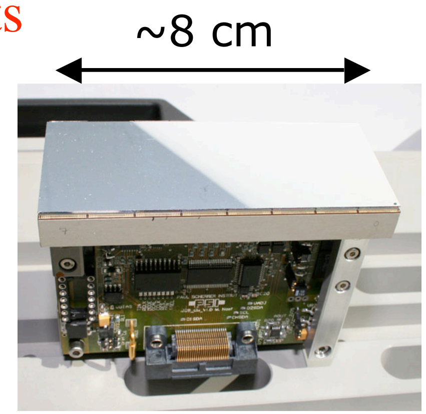


PILATUS detector solves count-rate and resolution issues

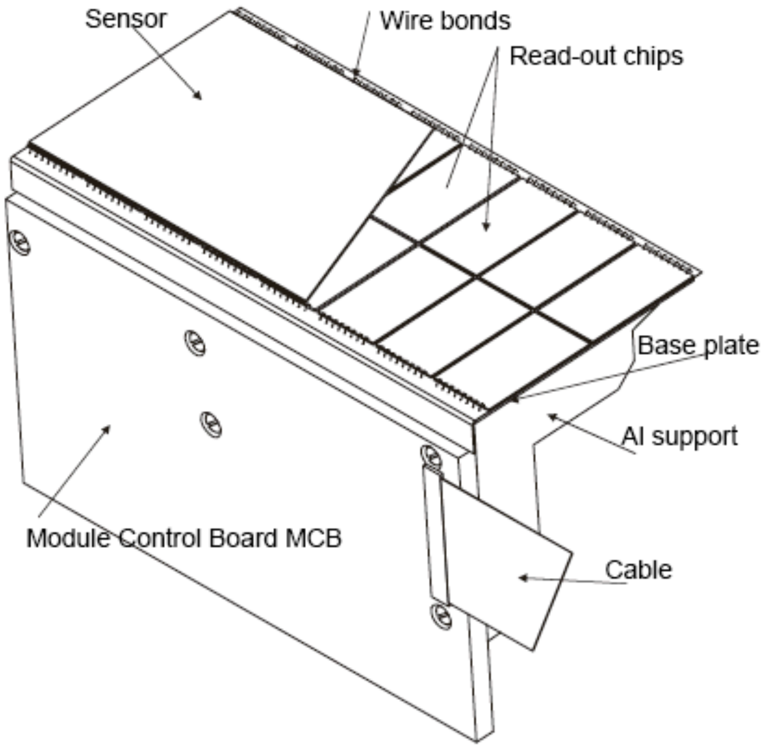
- MWPC rate limit (400 kHz) limited time resolution to > 100 ms
  - Delay-line readout; serial processing of x-ray signals
  - Pileup rejection in TDC and interface latency
  - Less than 0.5% of available Ar line intensity used on C-Mod
    - 8-cm diameter crystal masked down to 6 mm x 2 mm aperture
    - Mylar foils reduced x-ray transmission by factor 1/8
  - Background radiation on NB-heated tokamaks can saturate electronics

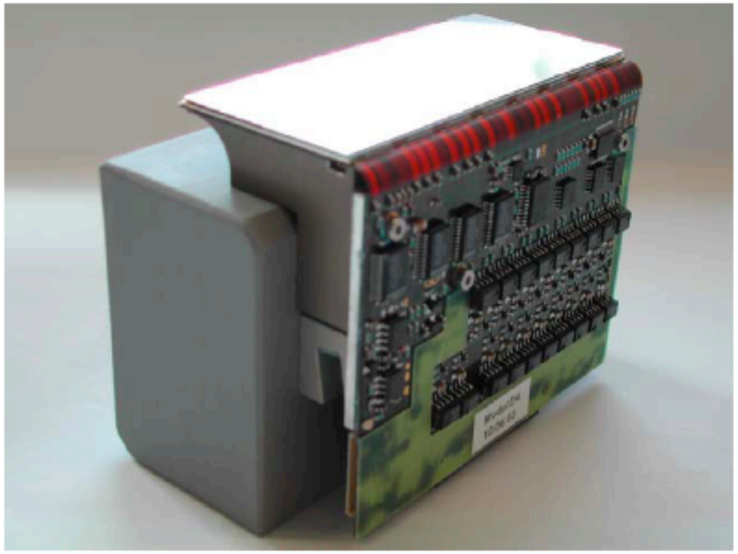


- PILATUS detector should enable 10-ms measurements
  - 487 x 195 pixels, each 0.172 x 0.172 mm^2
  - Analog and counting electronics for each pixel
  - Capable of count rates up to 1 MHz PER PIXEL - parallel processing
  - Can use full intensity available from C-Mod
    - 30 spatial channels
    - ~ 1 MHz per channel



PILATUS Module Typ II (readout electronics bended)





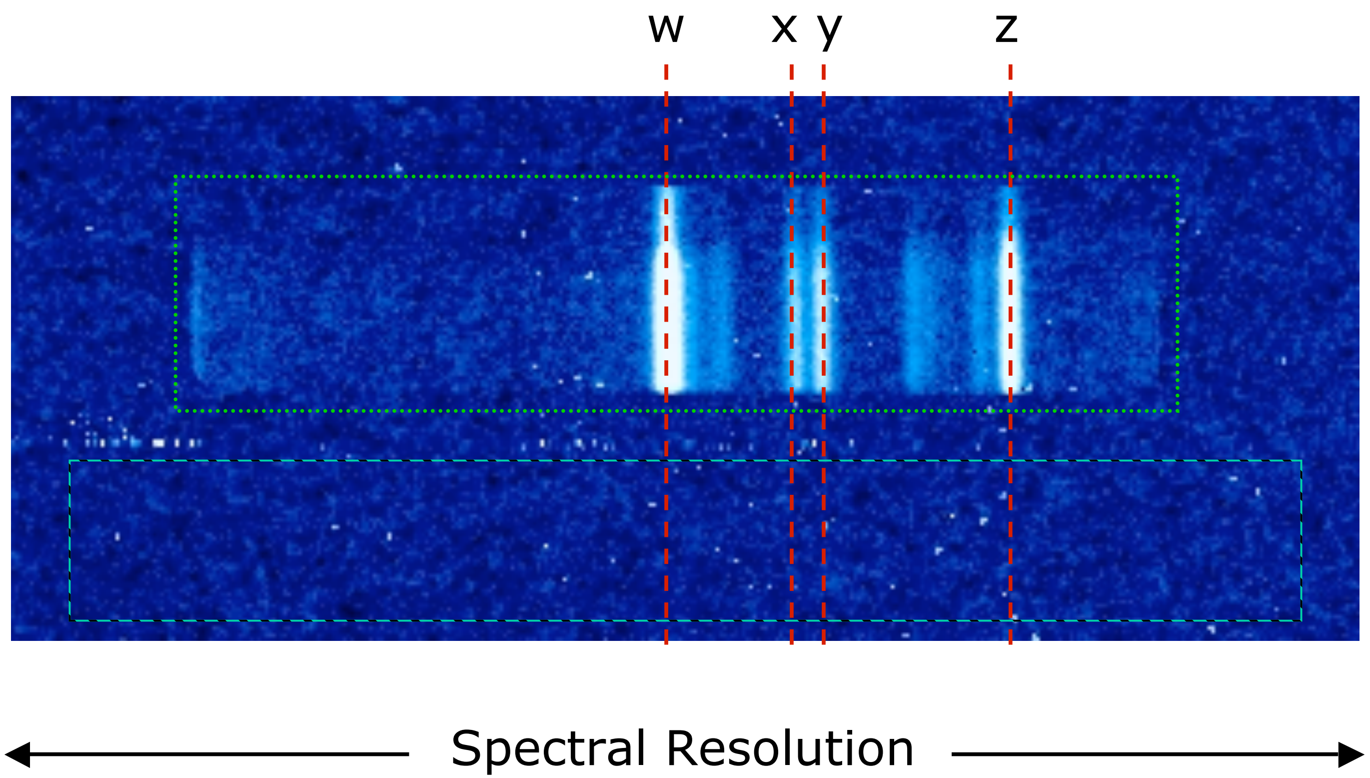
- Flexprint 6/2 from Dyconex
- Modules can be overlapped
- 80 x 35 mm^2 continuous sensitive area
- 2 x 8 readout chips
- Power consumption: 7V/1.5 A -> 10.5 W
- Fabrication of 21 Modules: Mai 03- Sept 03

Pilatus detector has several attractive features

- 487 x 195 pixels
- Size 0.172 x 0.172 mm^2 , ~ 2.5 times smaller then for MWPC
- Analog and counting electronics for each pixel
- Count rates up to 1 MHz per pixel
- Modular (5 x 12 array used on SLS)
- Readout time 2.54 ms => 10-ms resolution with full crystal
- Radiation hard (10^{14} n/cm^2)
- Can tolerate high n/γ background radiation noise levels
  - Each pixel receives 1/100,000 background rate of full detector
- Worked well in the electrically noisy C-Mod environment

Pilatus was proven to work at 3.1-keV He-like Ar energy at C-Mod

- A Pilatus detector was installed on one of the poloidally viewing Hirex spectrometers on C-Mod.
- Typically used at 8 - 12 keV for protein crystallography experiments

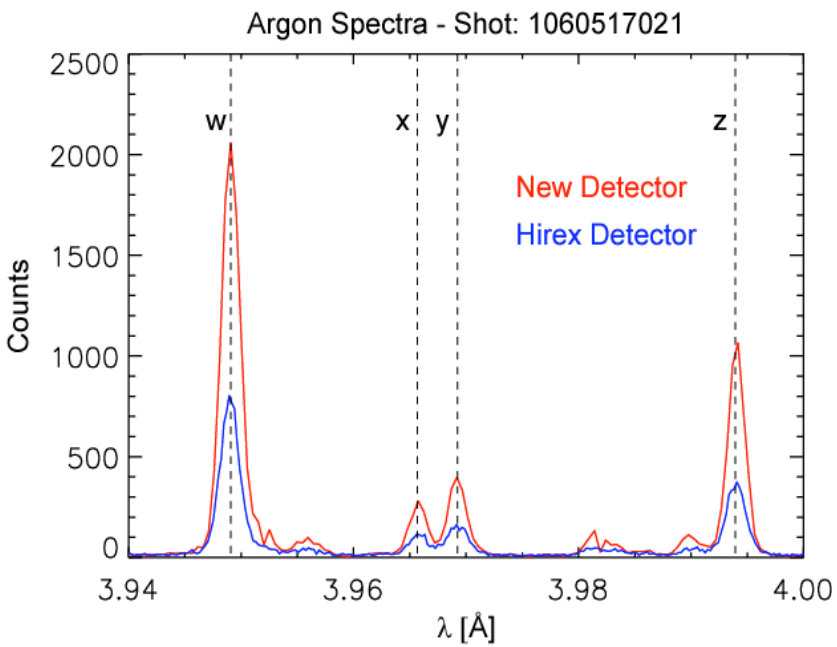


w	3.949Å
x	3.966Å
y	3.969Å
z	3.994Å

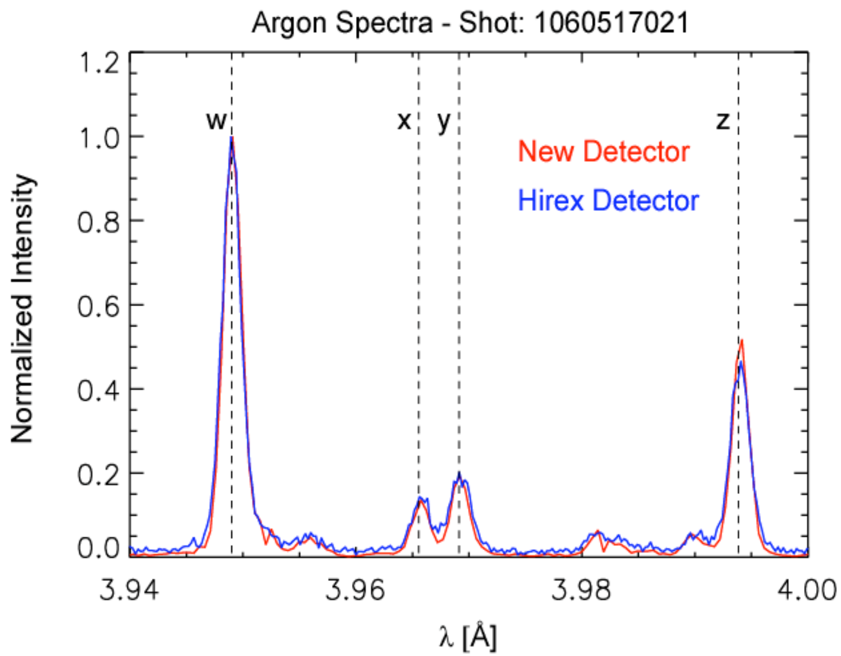
PILATUS II spectra similar to HIREX spectra

- Spectra are for the same discharge but with slightly different views
- No indication of problems in the electrically noisy C-Mod environment

Raw Spectra

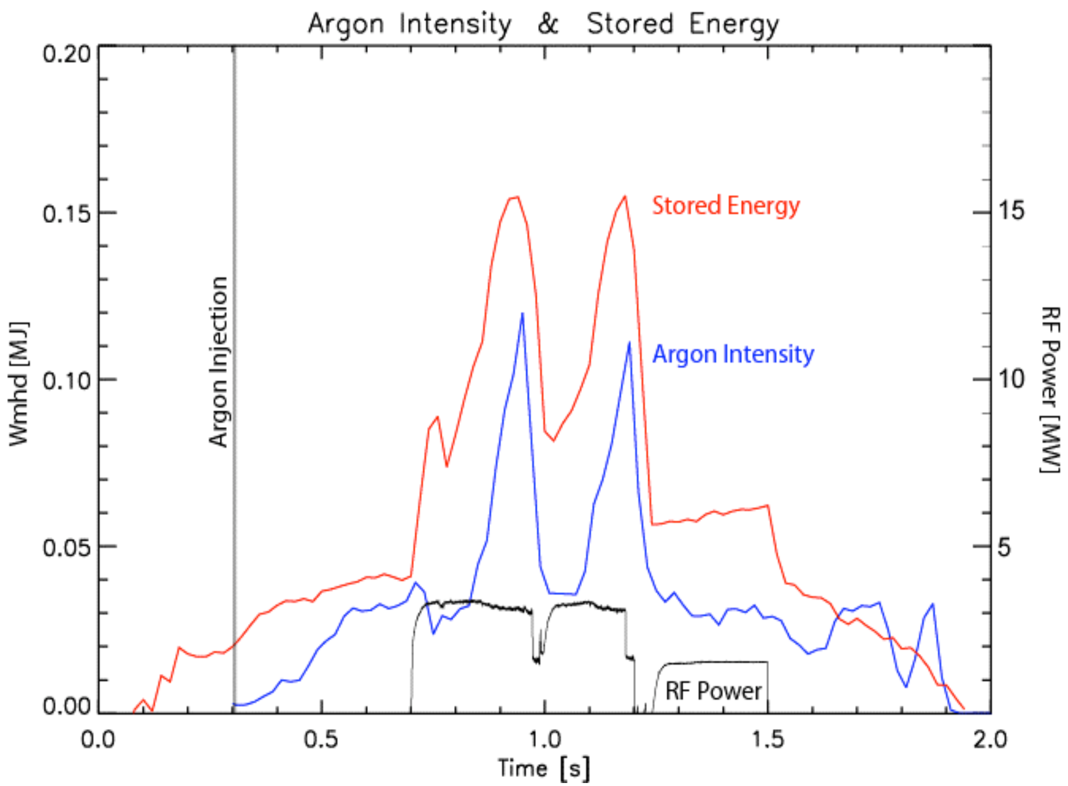


Normalized Spectra



PILATUS II Ar line time history similar to stored energy

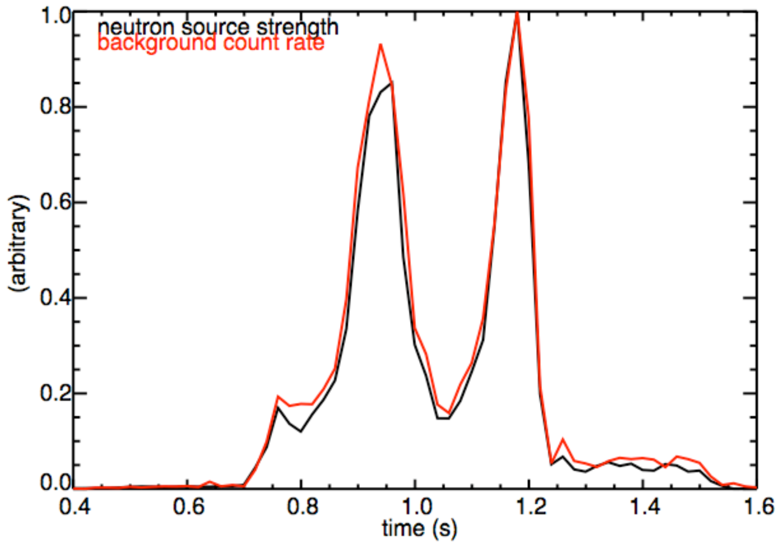
- Measured with 20 ms time resolution
- PILATUS readout time now down to 2.54 ms
- Ar XVII resonance line, w, measured by PILATUS II detector



Background rate low for unshielded PILATUS detector

NSTX

- Peak background count rate = 19 counts/pixel/s
- Peak x-ray rate ~ 900 counts/pixel/s
- Peak neutron rate = 5.8E13 n/s
- Counts per source neutron ~ 5x expected from radiation measurements (assuming 1-MeV neutrons at detector)



Imaging XCS configuration selected for C-Mod and ITER

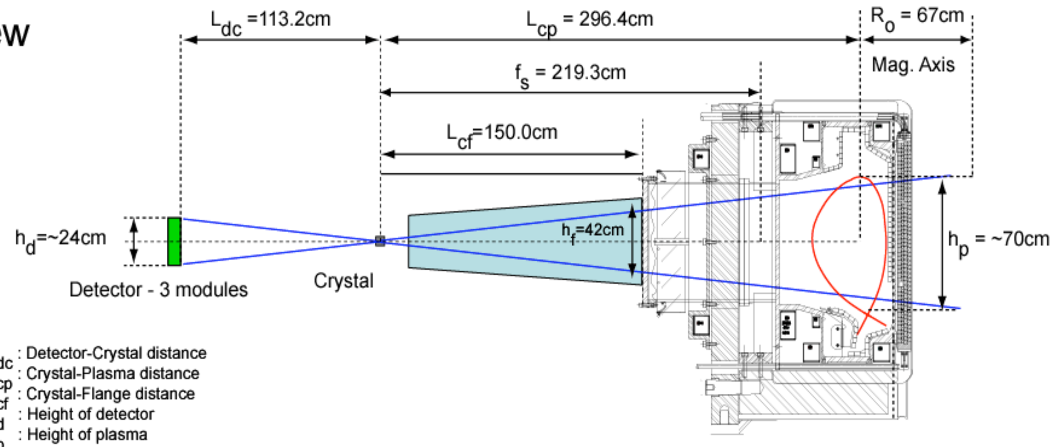
- An imaging XCS is being designed to measure full profiles of T_i and v_ϕ on C-Mod
  - successful demonstration of concept
  - successful operation of PILATUS detector at 3.1 keV
  - available intensity should enable 10-ms operation

- Imaging XCS design selected for ITER
  - Uncertainty in μ and σ increased by n/γ radiation
  - Careful neutronics calculations and shielding important

Full plasma radial view and toroidal component planned for C-Mod

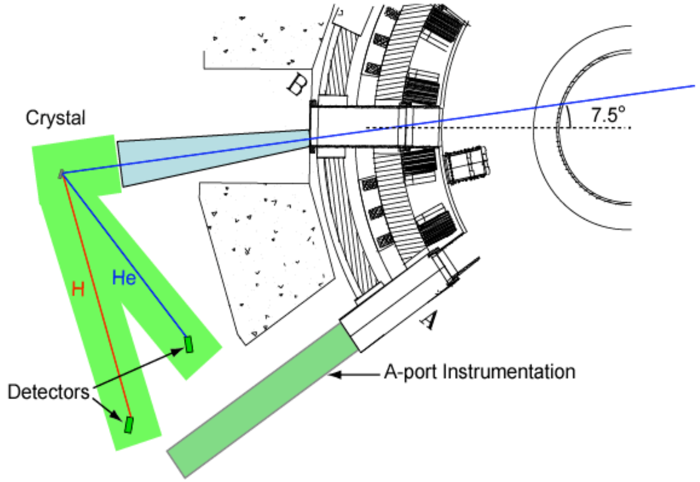
NSTX

Side View



L_{dc} : Detector-Crystal distance
L_{cp} : Crystal-Plasma distance
L_{cf} : Crystal-Flange distance
h_d : Height of detector
h_p : Height of plasma
h_f : Height of spectrometer flange
L_f : Length of spectrometer flange
f_s : Focal length of sagittal rays

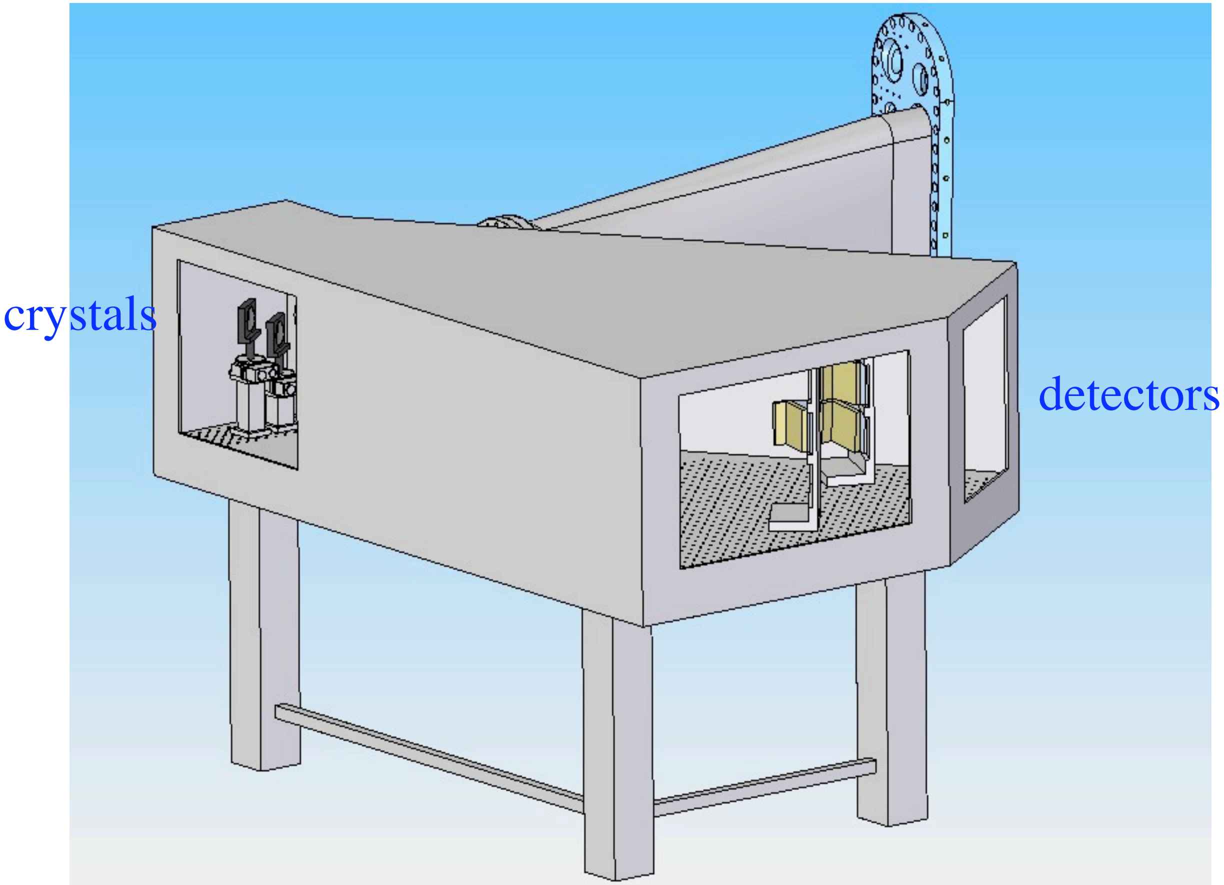
Top View



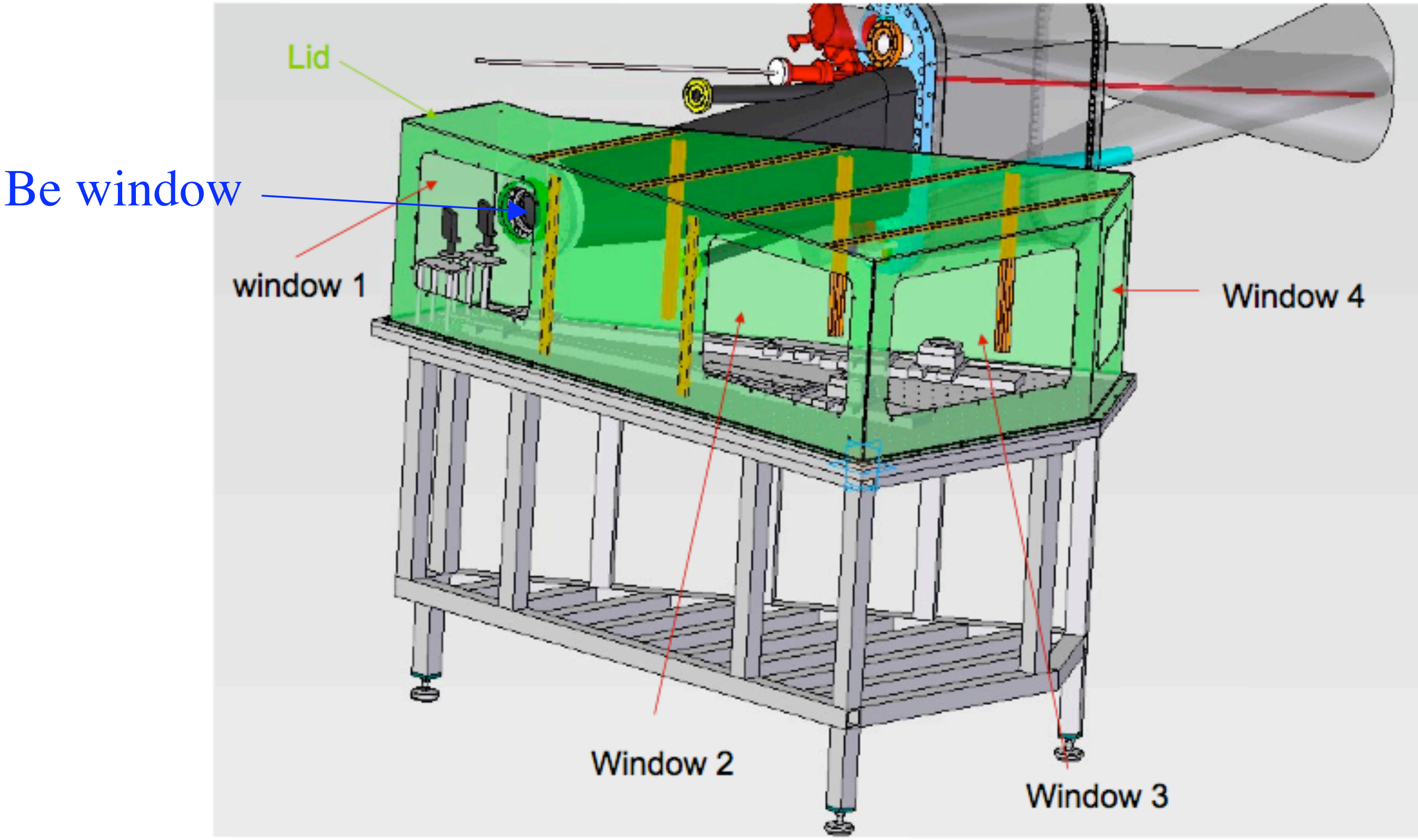
He		H	
Rad Curv	: 1300	Rad Curv	: 1800
2d Spacing	: 4.562	2d Spacing	: 4.913
Brag Angle	: 60.53	Brag Angle	: 49.46
Res. power	: 9600	Res. power	: 7800
Sag Focus	: 219.3cm	Sag Focus	: 881.6cm
Magnif	: 0.42	Magnif	: 0.513
Spec wid	: 22.69mm	Spec wid	: 2.3 mm

- 2:1 imaging
- R halved rel. to prototype
- 3 PILATUS detectors
- ~30% toroidal fraction

He-filled chamber houses crystals and detectors

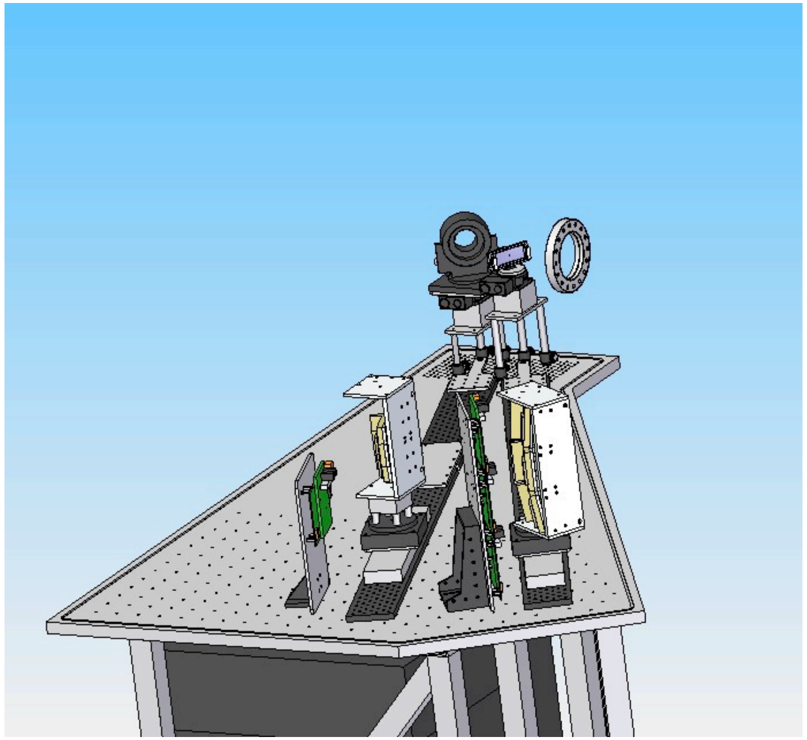


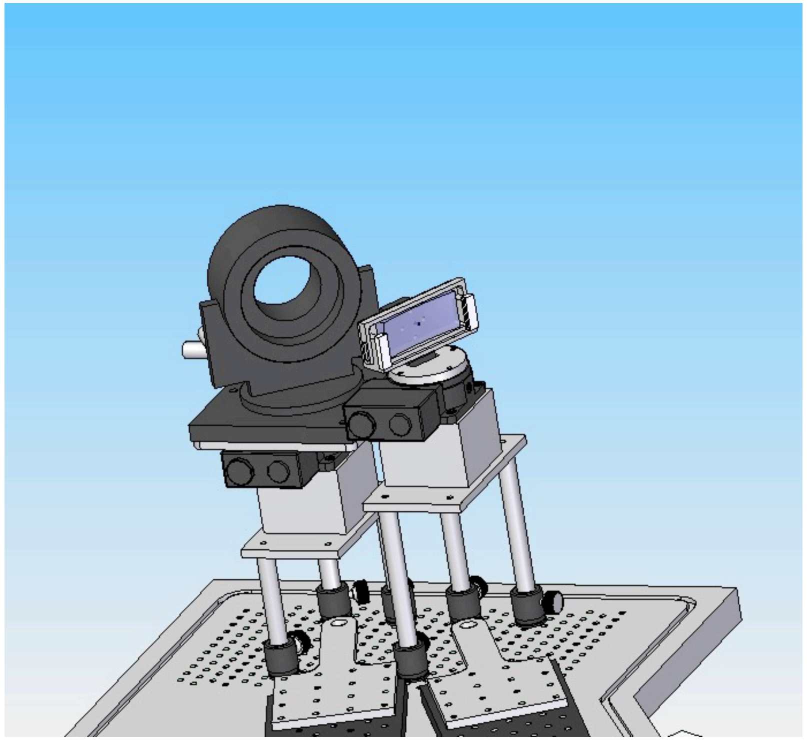
Windows allow observation and access



Concept for XCS-component layout is in advanced stages

NSTX





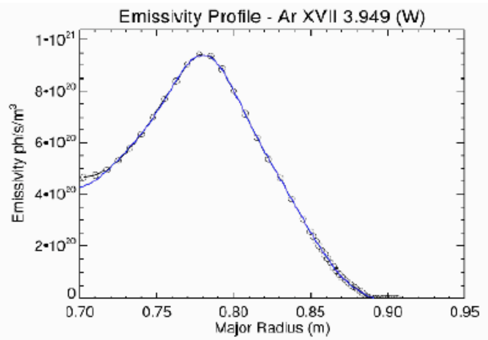
- Detectors, electronics, and crystal holders on XCS table

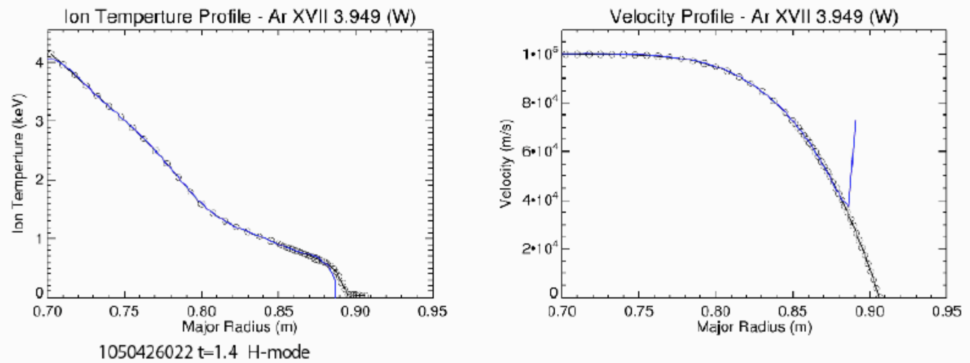
Mounts for crystals for He-like and H-like Ar

Hollow emissivity profiles can be inverted

Inversion Simulation: He-like 'w' line

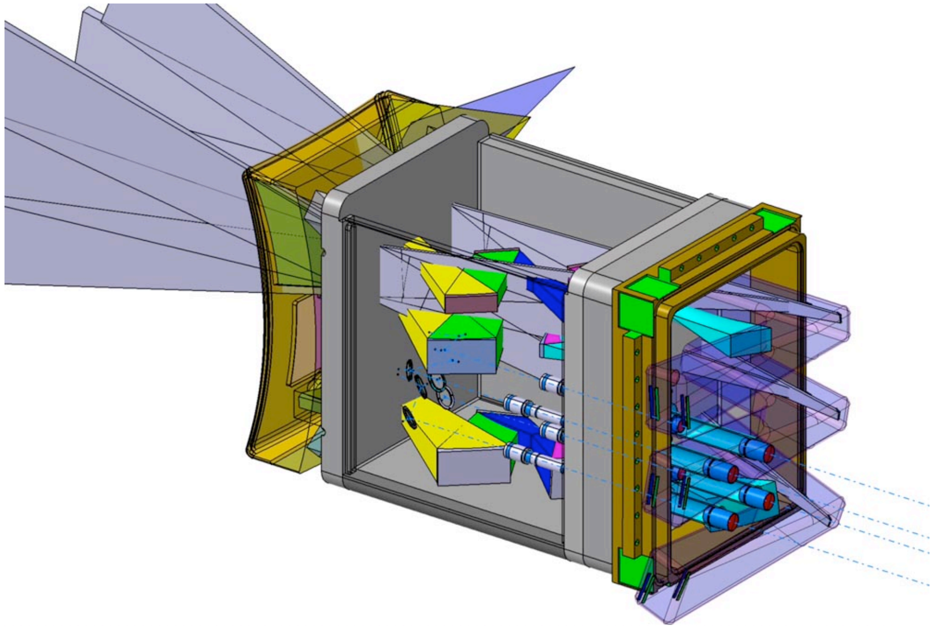
- Black w/ circles indicate inputs
- Blue line is reconstruction
- All three profiles can be accurately reconstructed





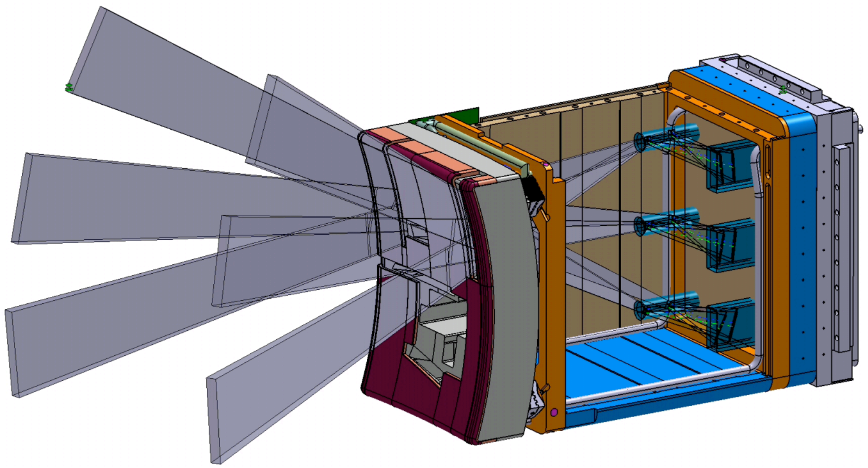
24

ITER imaging x-ray spectrometer



Design options for spectrometer location

- Ex-port
    - Better access
    - Better shielding
- In-port
    - Wider view of plasma



Choice will be based on:

- Neutronics modelling
- **Detector radiation hardness**
- **Detector background rejection**

Neutronics calculations indicate Pilatus detector survivable near back of port plug

NSTX

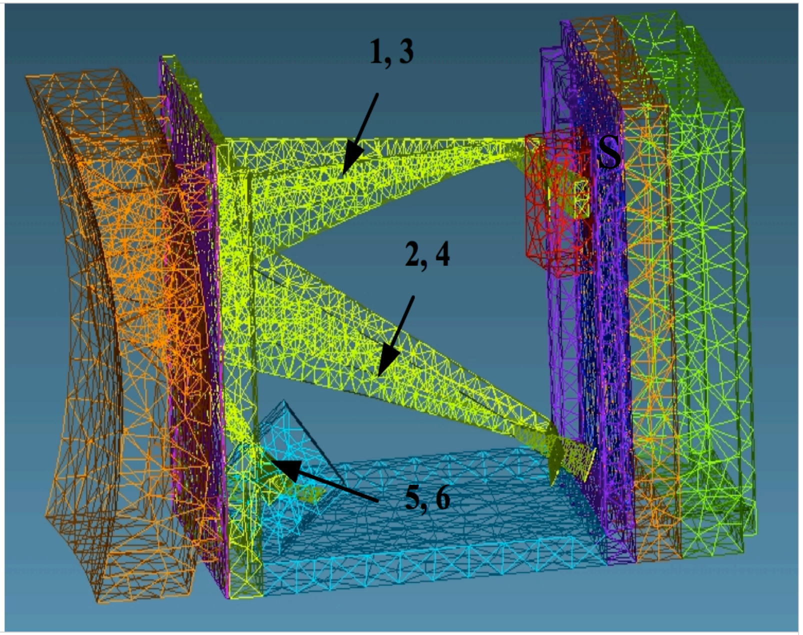


Table 7: Estimates of detector lifetimes due to neutron damage. 10^7s: ITER lifetime. 10^6s: maintainable			
Detector location	Flux >100 keV ($n/cm^2.s$)	Time for fluence of 10^{14} $/cm^2$ (s)	Time for fluence of $10^{16}/cm^2$ (s)
1	$3.3 .10^6$	**$3 . 10^7$**	$3 . 10^9$
2	$2.9 .10^3$	**$3.4 . 10^{10}$**	$3.4 . 10^{12}$
3	$5.8 . 10^6$	**$1.7. 10^7$**	$1.7. 10^9$
4	$2.0 . 10^4$	**$5 . 10^9$**	$5 . 10^{11}$
5	$2.0 . 10^{11}$	**500**	**$5 .10^4$**
6	$4.9 . 10^9$	**$2 . 10^4$**	$2 . 10^6$

S. Davis, R. Barnsley, R. Pampin

Estimates of performance of C-Mod and ITER spectrometers

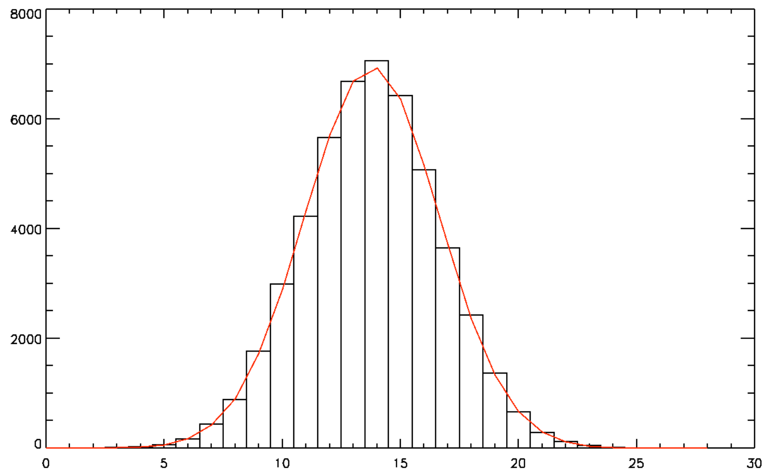
NSTX

- Estimates of uncertainty in T_i measurement and minimum resolvable toroidal rotation velocity were made for C-Mod imaging spectrometer.
- On ITER, both x-ray continuum and fusion-neutron background will increase uncertainties in measurement of T_i and v_{tor}.
  - Numerical and analytic statistical analyses were made to quantify these increased uncertainties.
  - Based on Equations from I. H. Hutchinson, "Statistical Uncertainty in Line Shift and Width Interpretation"

$$\sigma_\mu = \frac{\sigma_I}{\sqrt{N_I}}\sqrt{1+\frac{\sigma_B{}^2 N_B}{\sigma_I{}^2 N_I}}$$ Position

$$\sigma_S = \frac{\sigma_I}{\sqrt{2N_I}}\sqrt{1+\frac{\sigma_B{}^4 N_B}{\sigma_I{}^4 N_I}}$$ Width

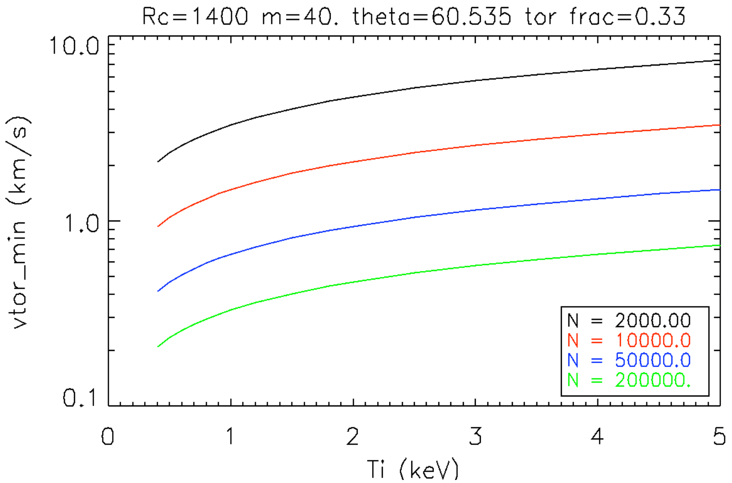
Numerical line position and width agree with equations

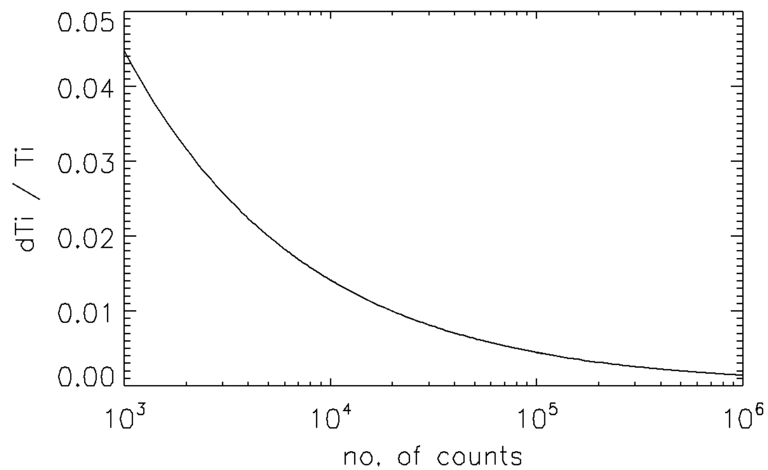


- Generate normal dist with RANDOMN
- Bin onto detector pixels with HIST
- Fit Gaussian with GAUSSFIT
- Record line position and width
- Do "experiment" "Nexp" times
- Calculate moments for μ and σ

- N = 50000 counts in Gaussian
- N_{exp} = 5000
- No background
- $\langle\mu\rangle$ = 13.78556 pixels
- $\langle\sigma_I\rangle$ = 2.86904 pixels
- s_μ = .0128111 pixels
- σ_I / sqrt(N) = .0128307 pixels
- s_σ = 0.009171 pixels
- σ_I / sqrt(2N) = 0.0090727 pixels

Statistical contributions to v_{tor} and T_i error can be small





- C-Mod spectrometer
- 2000 to 10000 counts in 10 ms
- Background not included
- 1-3 km/s resolvable

$$\Delta\left(\frac{v}{c}\right) = \frac{\Delta\lambda}{\lambda} = \cot\theta \frac{\Delta x}{R}$$

$$\Delta x = \frac{\sigma_I}{\sqrt{N}}$$

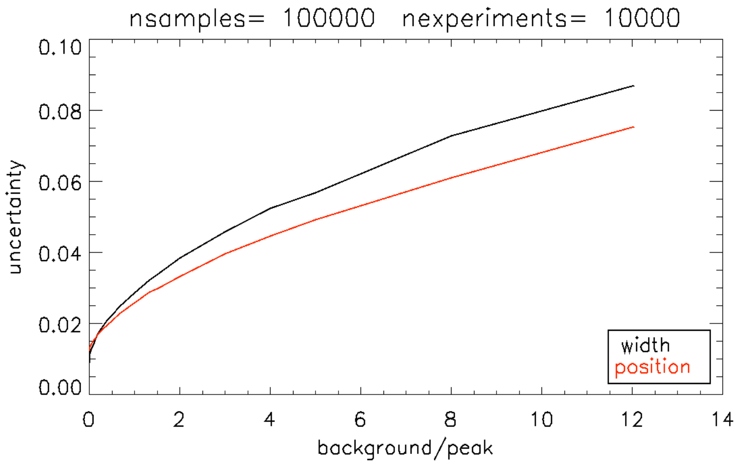
$$T_i \propto \sigma_I^{\,2}$$

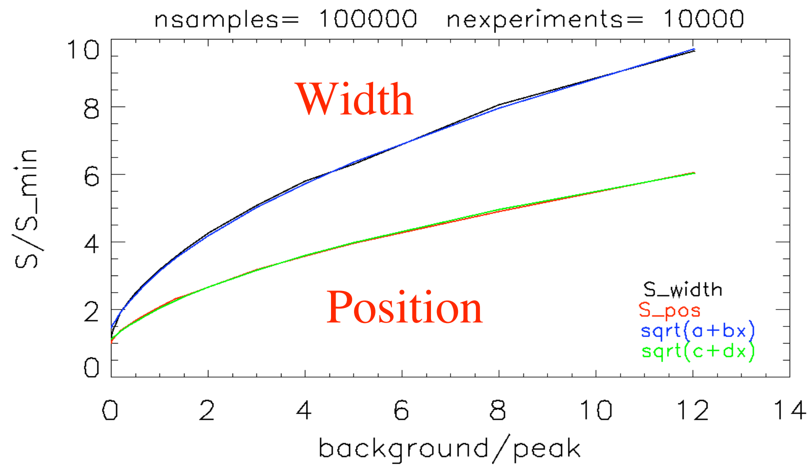
$$\frac{\Delta T_i}{T_i} = \frac{2\Delta\sigma_I}{\sigma_I} = \sqrt{\frac{2}{N}}$$

- 1 - 3% error in T_i

Position and width uncertainties increase with background approximately as expected

Normalized to no-background case





- Uncertainty for P/B=1 increases
  - 2x for position
  - 3x for width
- Simulated Gaussian plus background
- a=2.13, b=7.67, c=1.24, d=2.92

$$\sigma_\mu = \frac{\sigma_I}{\sqrt{N_I}}\sqrt{1+\frac{\sigma_B^{\,2} N_B}{\sigma_I^{\,2} N_I}}$$ Position

$$\sigma_S = \frac{\sigma_I}{\sqrt{2N_I}}\sqrt{1+\frac{\sigma_B^{\,4} N_B}{\sigma_I^{\,4} N_I}}$$ Width

Conclusions

- New imaging x-ray spectrometer developed for T_i -, T_e - and rotation-profile measurement on tokamaks.
- Imaging concept PoP verified on C-Mod, NSTX, and TEXTOR.
- Very small crystal area provided high count rates from C-Mod
  - Suggests small area crystals suitable for ITER
- Detector count-rate limit and position-resolution issues solved by PILATUS II detector. Radiation-background issue greatly alleviated
- Numerical and statistical analyses provide basis for estimating performance of imaging XCS on C-Mod and on ITER with neutron background.
- Imaging spectrometer being installed on C-Mod.
  - Detectors on track to be shipped this week
  - Testing of spectrometer with x-ray tube in laboratory next week
  - Addition of detectors and installation in C-Mod test cell following week

Future work

- Further detector development, segmented MWPC, GEM…
- Gain experience with C-Mod spectrometer using Ar
- Study use of Mo L lines for T_i, v measurements
- Possible imaging XCS on DIII-D
  - Te > 10 keV with RF heating
  - Use Kr and W spectral for T_i, v measurements
- More complete neutronics calculations including streaming through neighboring diagnostic ducts