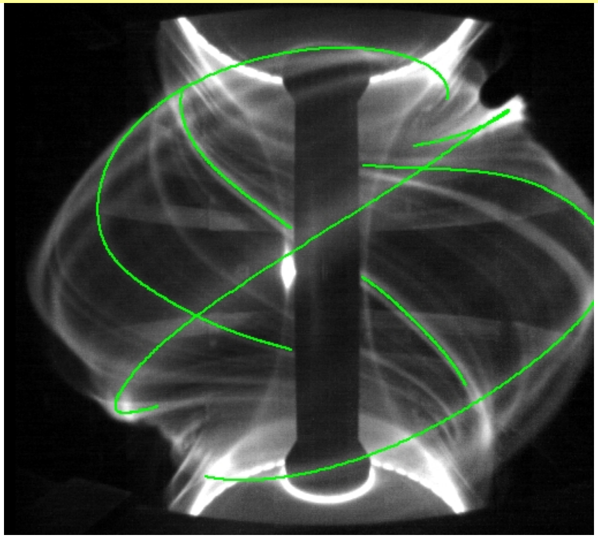
CXR and MSE on MAST



Presented by Paddy Carolan

Team(s) members:-

Neil Conway Nick Hawkes

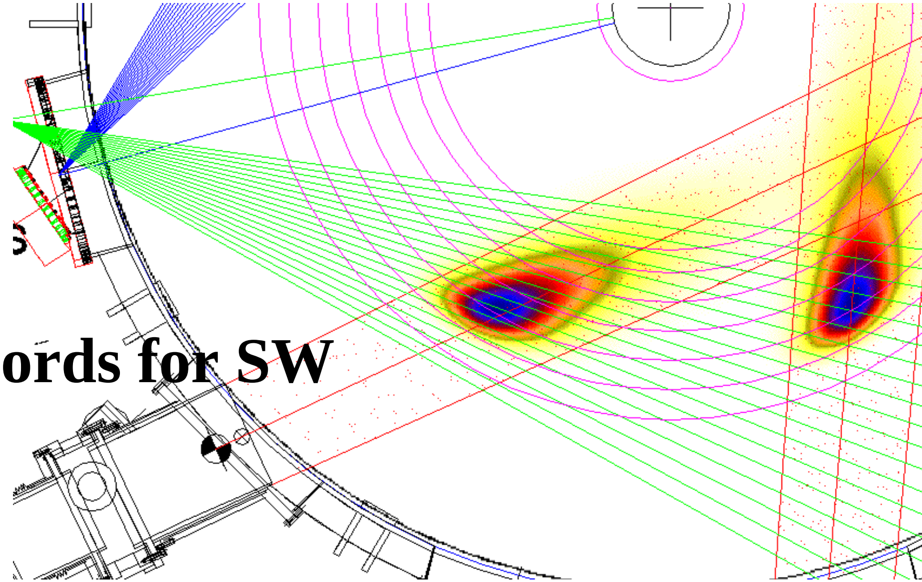
Mattias Kuldkepp Elisabeth Rachlew

Mikhail Turnyianski Mike Walsh

Marco Wisse

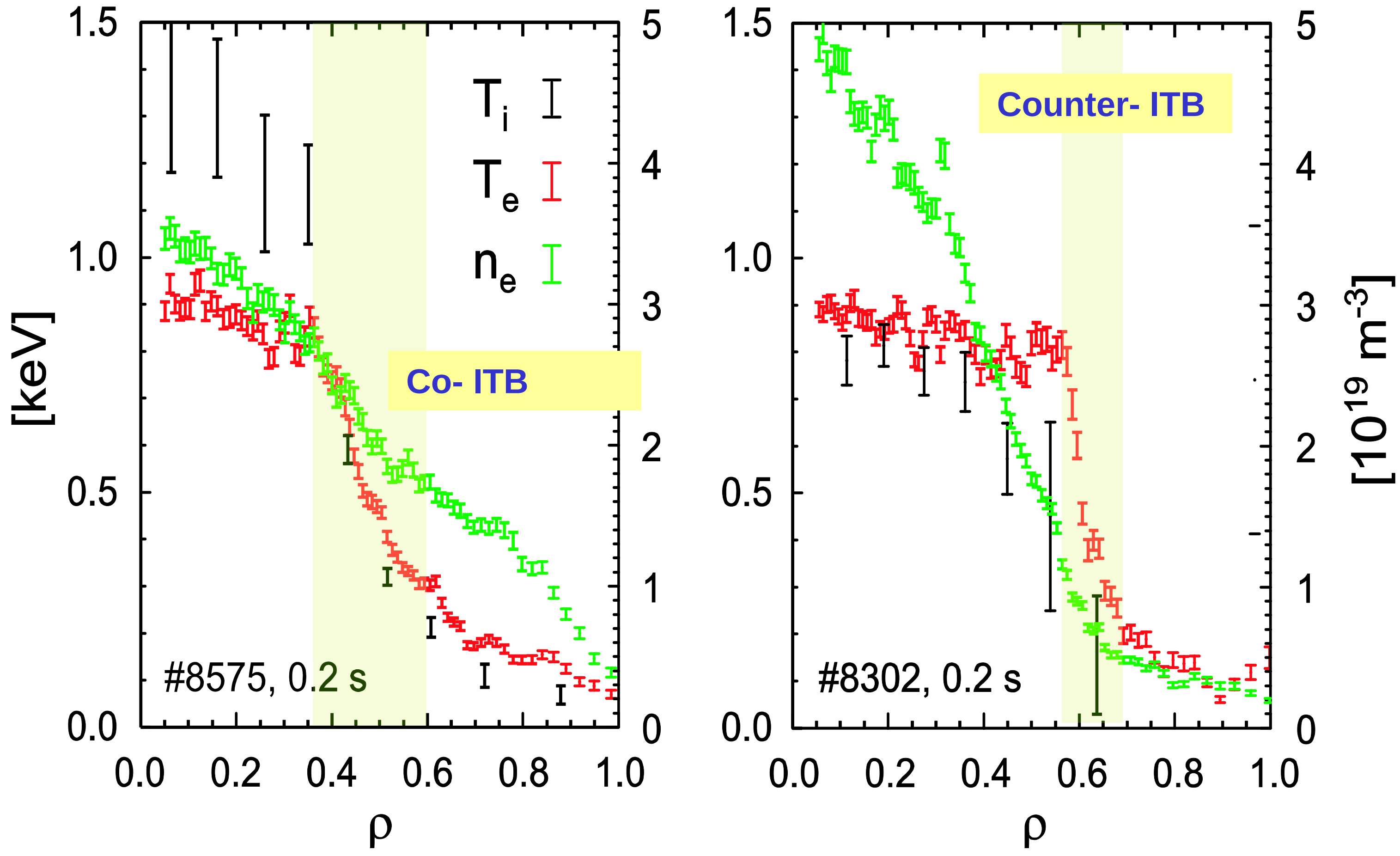
UKAEA Fusion Working in Europe

Previous CXR System - problems



- Sees both beams - edge emission from South (S) NBI spoils core chords for SW
- Spatial resolution poor
- Transmission and throughput poor (largely due to sacrifices made for UV)
- Insufficient bandwidth - spectral overlap
- No shuttering - inter-chord smearing
- No notching of beam
- Limited time slices - max. 72

Detailed electron and ion temperature and density distributions in edge and internal transport barriers



More CXR points needed for transport barrier investigations

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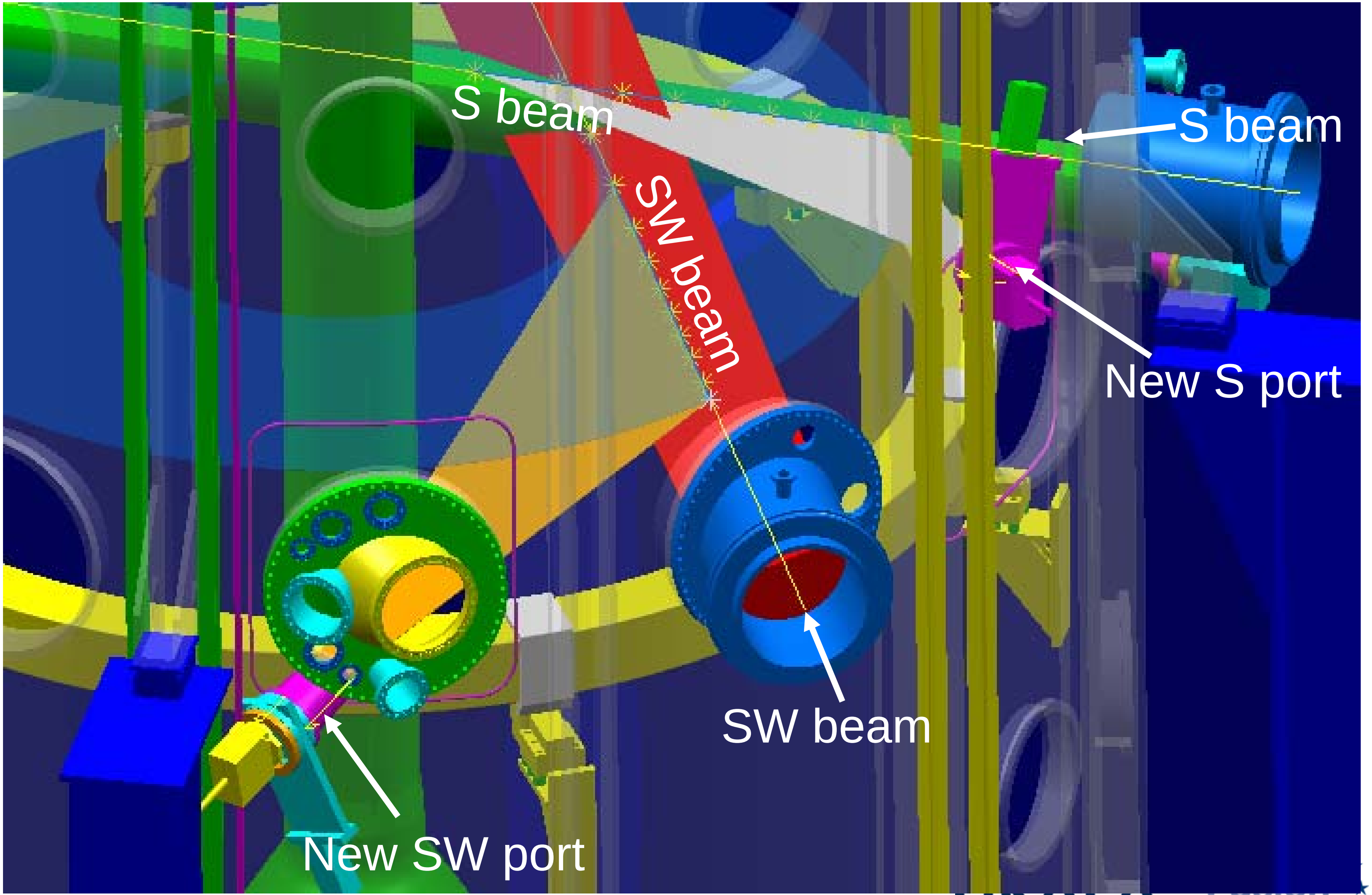
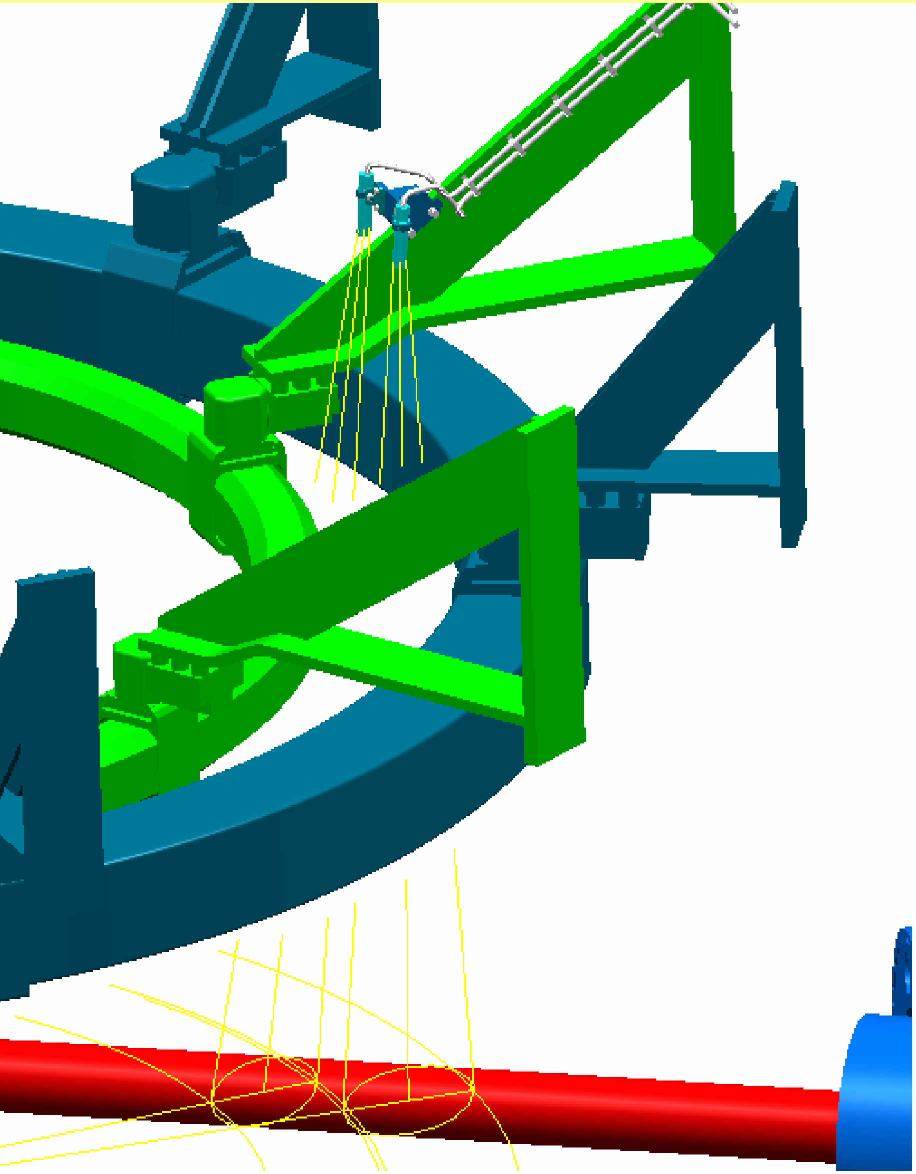
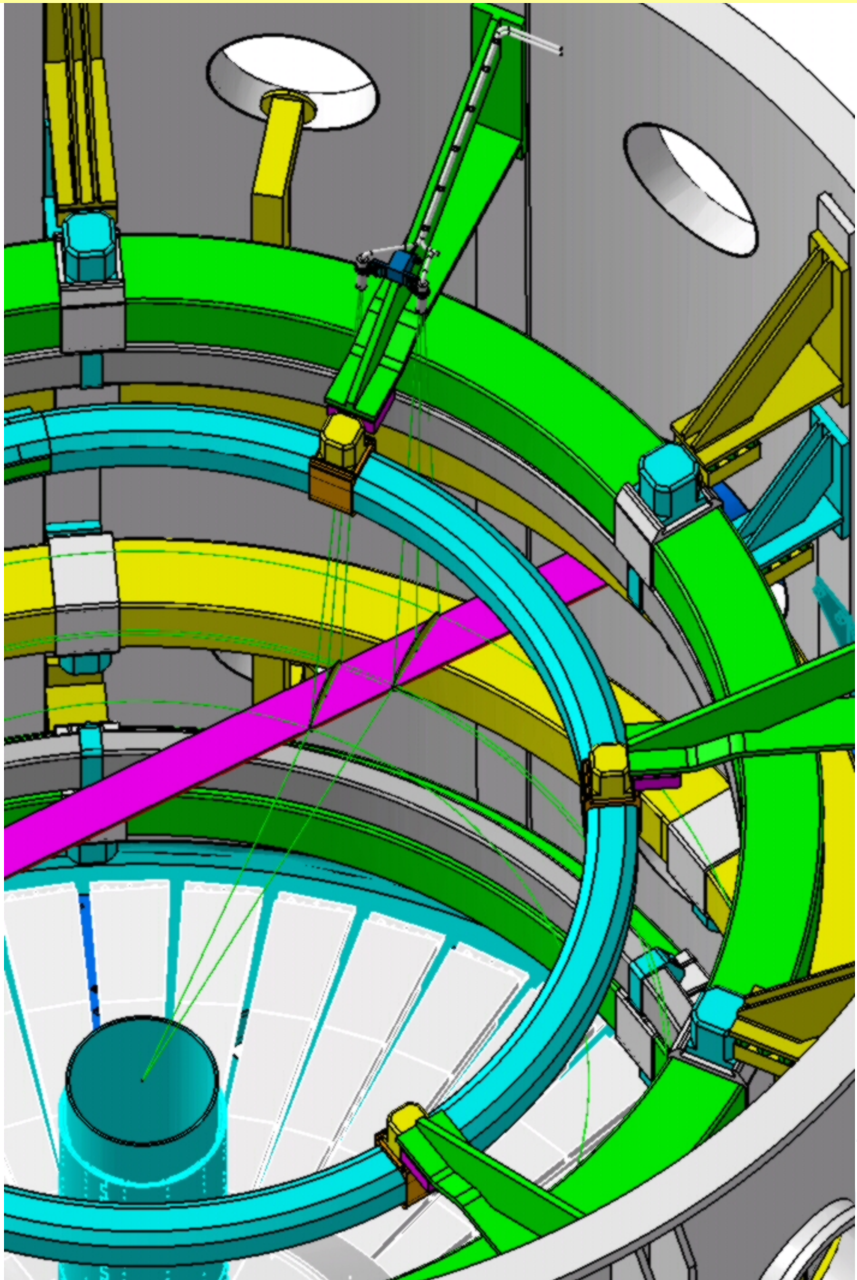
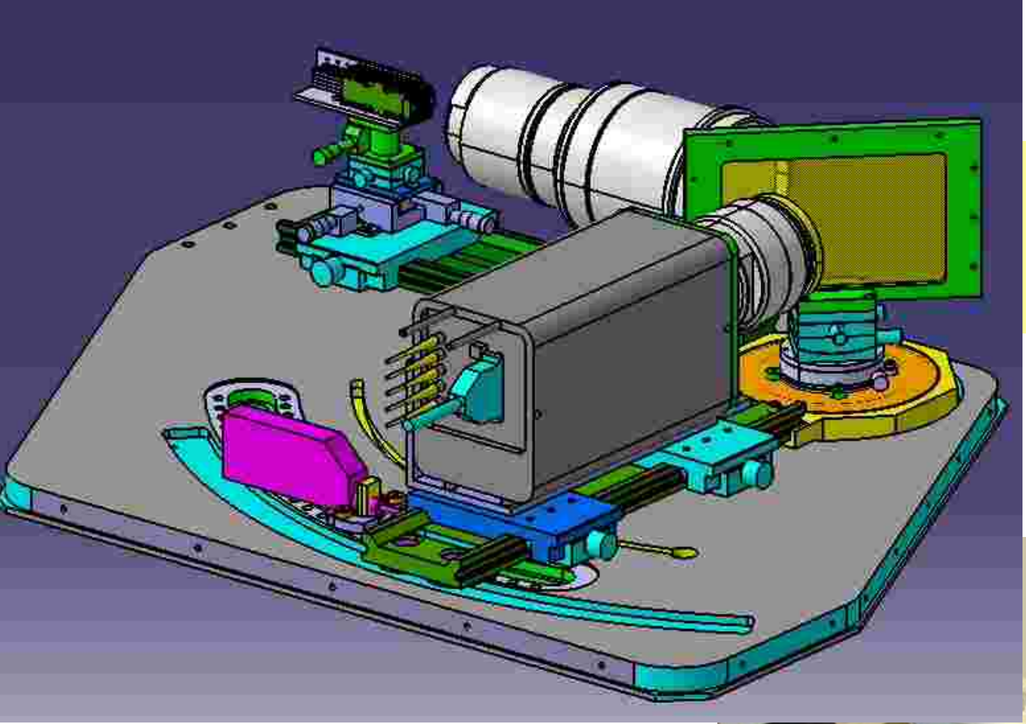
New ports required



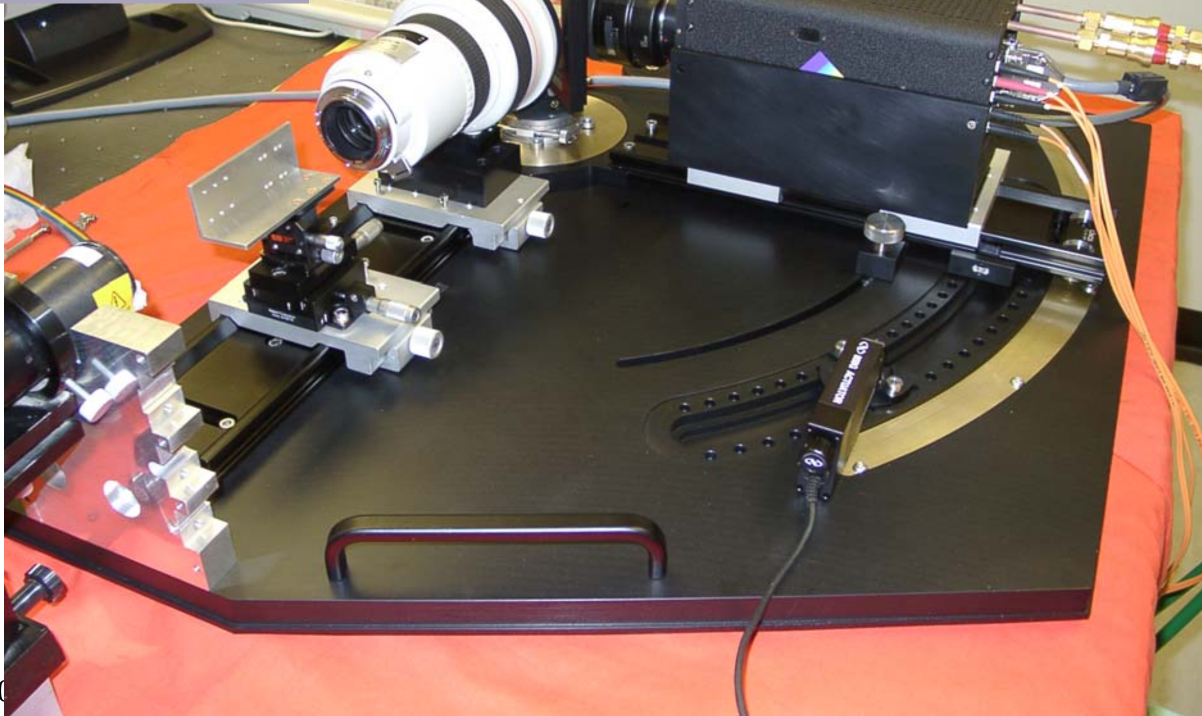
Poloidal views







New 200+ chord CXR spectrometer



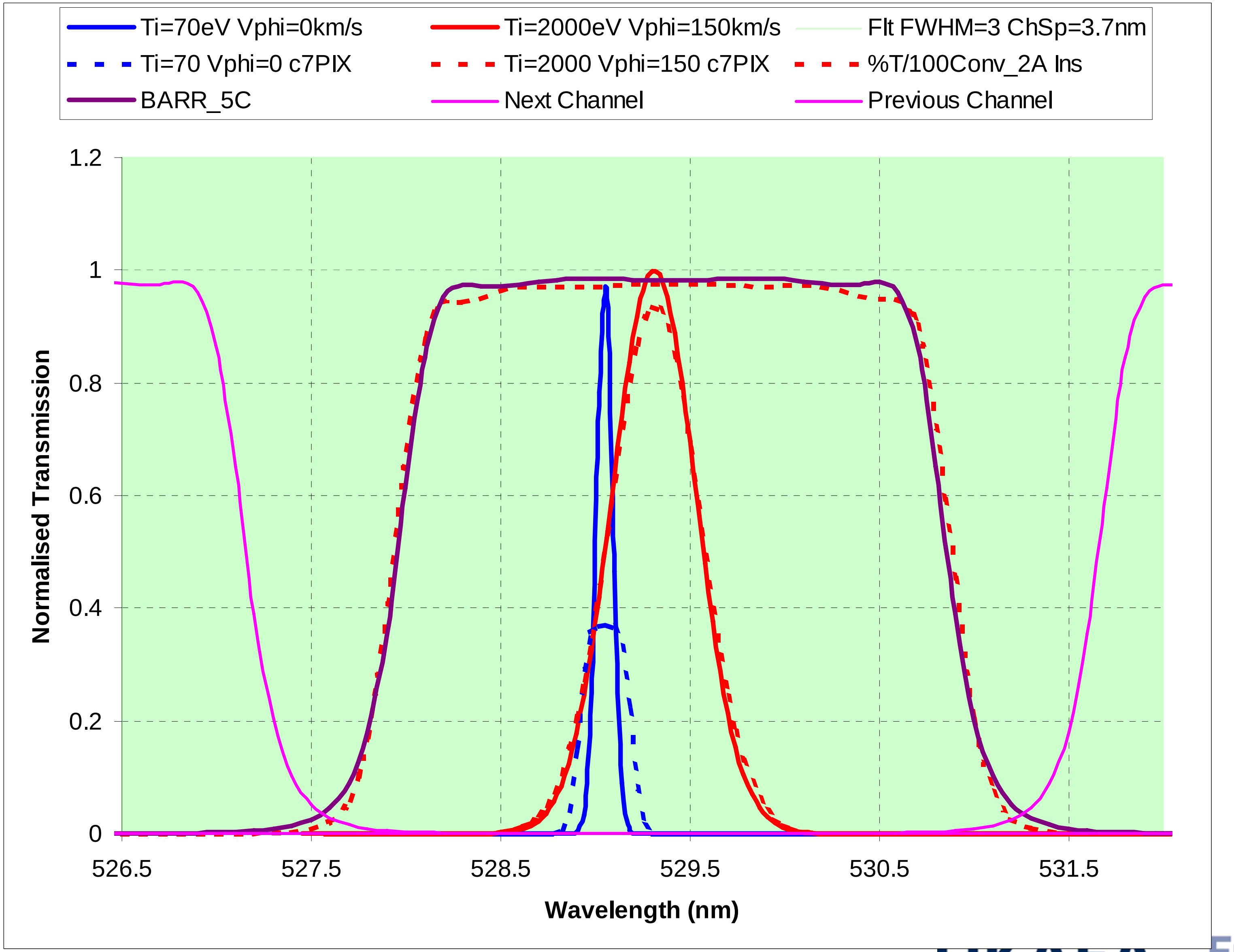
Outline specifications

- 64-80 continuous channels per view
  - (80 means ~1cm resolution at edge)
  - viewable 720-1500mm
  - f/2 lens, 75mm focal length
  - Use 400/424um fibres
  - Get 224 views
  - Manufacture in bunches of 8
  - Make them side and top stackable so can add more ‘viewers’ to ports
- multiple views
  - look at both beams
  - 24 passive channels
  - 64 poloidal channels (incl. passive)
  - 1 to 2 radial channels
- CCD - Pixelvision BioXight
  - 652 x 488 x 12um pixels
  - Fast Readout (4 taps @ 2.2Mhz each)
    - bin 32 rows: clock-down time + shutter close/open time + digitisation time
    - 14-bit ADC
    - Achievable frame rate ~ 300Hz
  - Pixel width corresponds to ~0.4A
  - Filter BW ~3nm
  - Channel spacing 3.7nm
- Use tuned FLC (ferroelectric liquid crystal) shutter (response time ~100us)

Spectrometer details

- **Equal incidence and diffraction angles - no anamorphic distortion**
- **Large grating (transmission; refractive index modulated)**
- **Off-the-shelf SLR lenses (as “fast” as possible)**
- **Demagnification ~2.3**
- **Good lens to lens coupling assisted by use of “over-fast” input lens.**
- **Extract light from fibres at ~f/3 - very credible NA, keeps collection lens reasonably straightforward**
- **f/# coupled onto the CCD camera is about f/1.2 - f/1.3…**
- **Design allows variable wavelength**
- **Design decisions:**
  - **Single spectrometer for all chords (224: 64 toroidal, 32 poloidal for each beam; remaining chords for background and radial views)**
  - **system will work best for Ti < 3keV, vi < 300km/s**
  - **system will work fairly well for Ti < 5keV, vi < 500km/s**
  - **nominal required bandwidth = 2.3nm**

Bandpass filter and spectra



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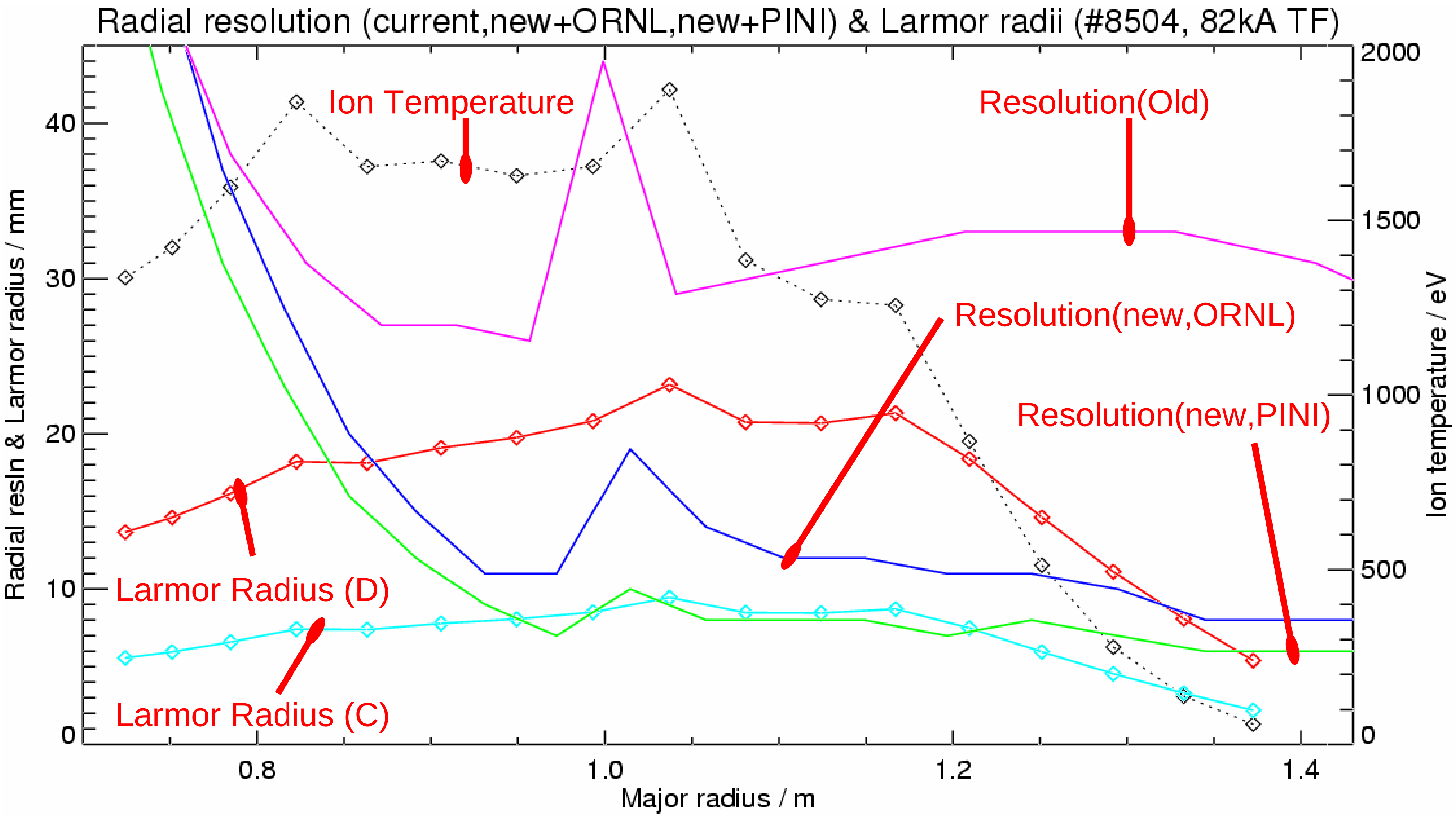
Radial Resolution for new ports



(incl. image of fiber, ~1cm)

CCD camera

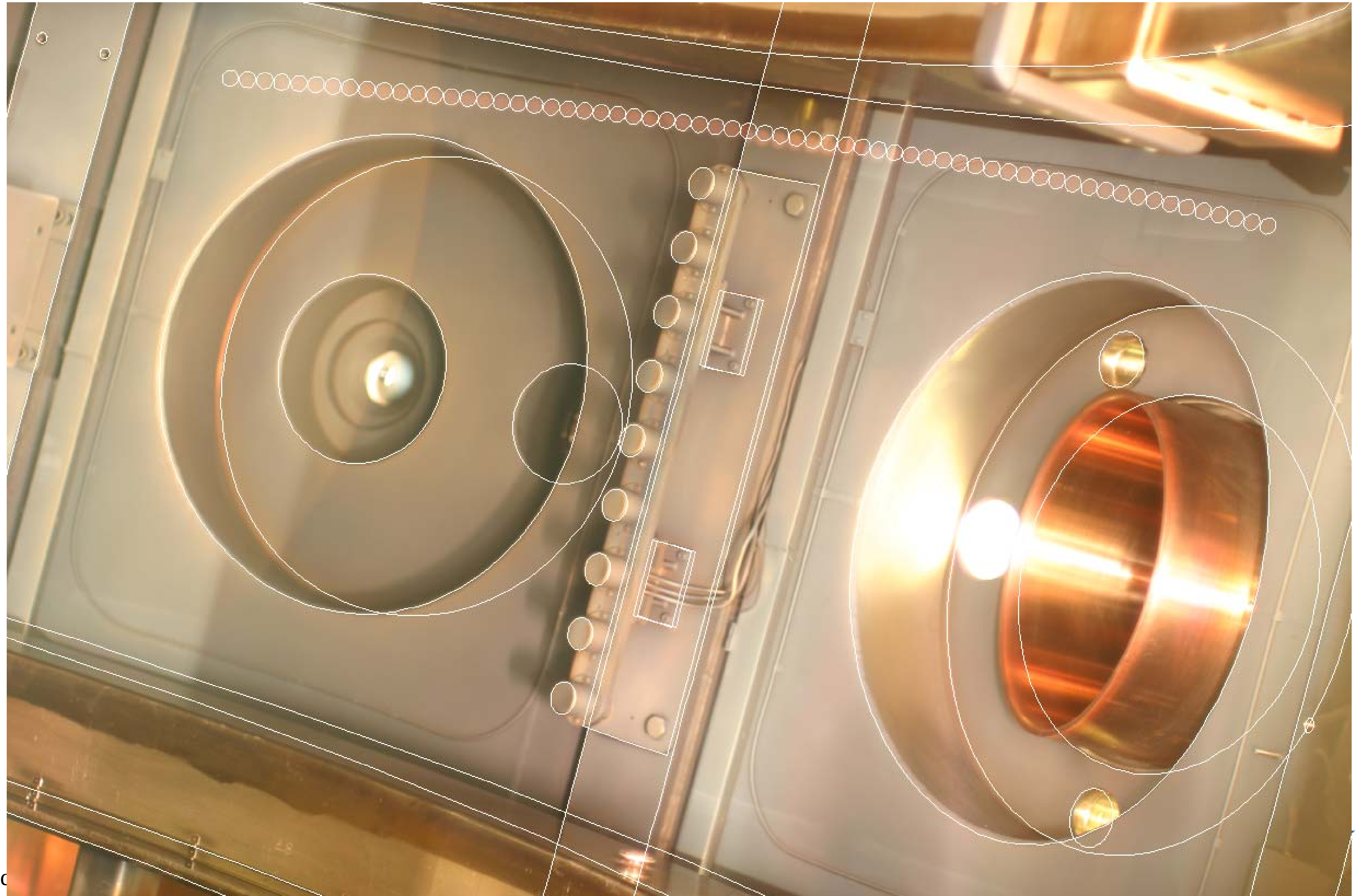
Key component - underpins many design parameters

- many aspects not easy to control
  - pixel size, sensor dimensions, readout speed are often driven by large markets, so we have to make do with best match to our needs
- want good QE, fast digitisation, fast row-transfers, low readout noise…

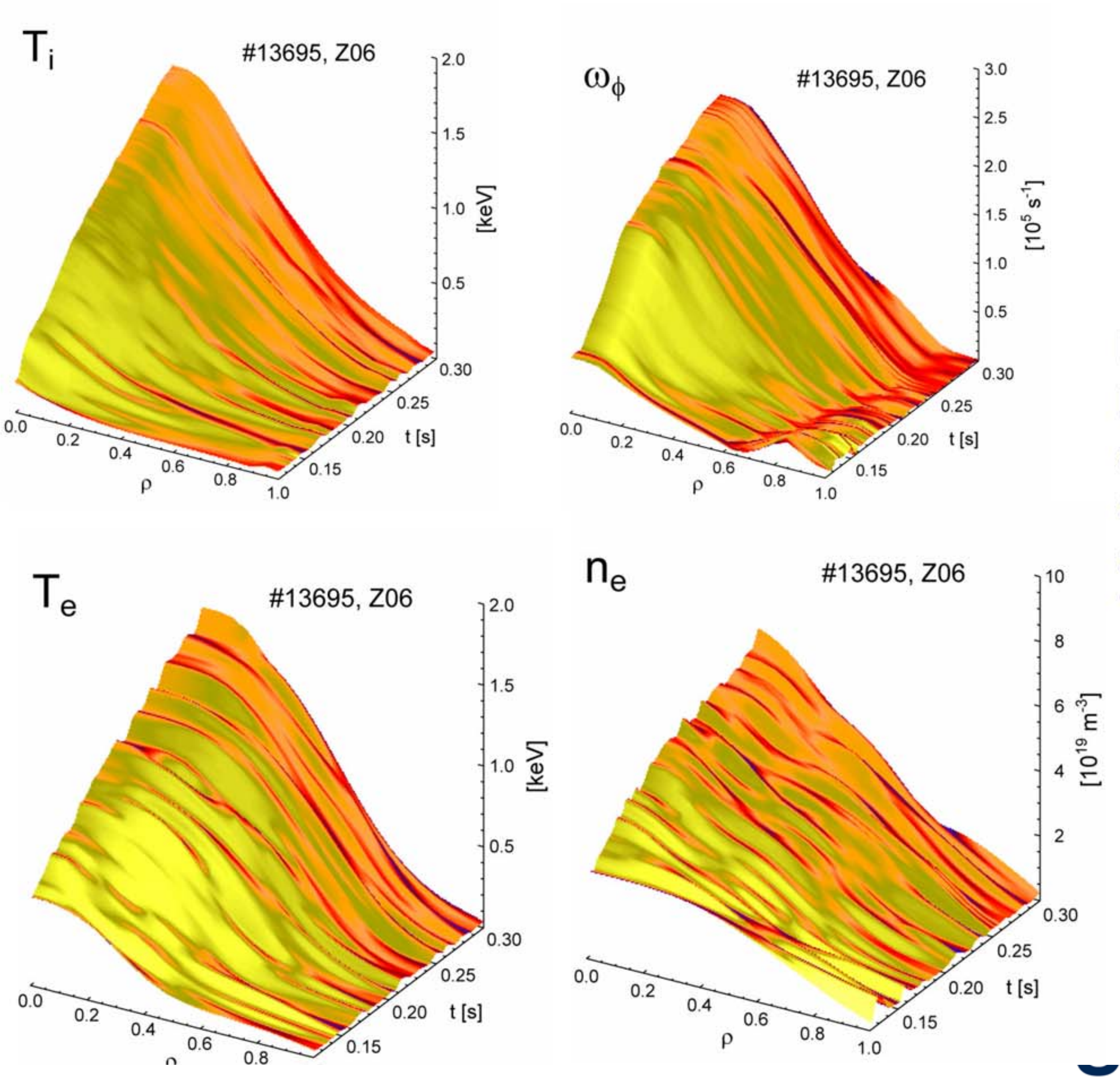
At the time of commencing the redesign of the diagnostic, we already possessed one high-end camera from PixelVision, with 4-tap readout @ 2.2MHz per tap, 14-bit ADC, ~30 electron RMS readout noise…

As the design took shape, it became clear that this camera was ideal, particularly in enabling the large number (224) of spatial channels.

CXRS sector 9 fibres on wall, plus overlay of various objects…



High resolution kinetic measurements



High resolution time-resolved (5ms) CXRS and Thomson scattering allow detailed transport analysis e.g. using TRANSP

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Transport analysis

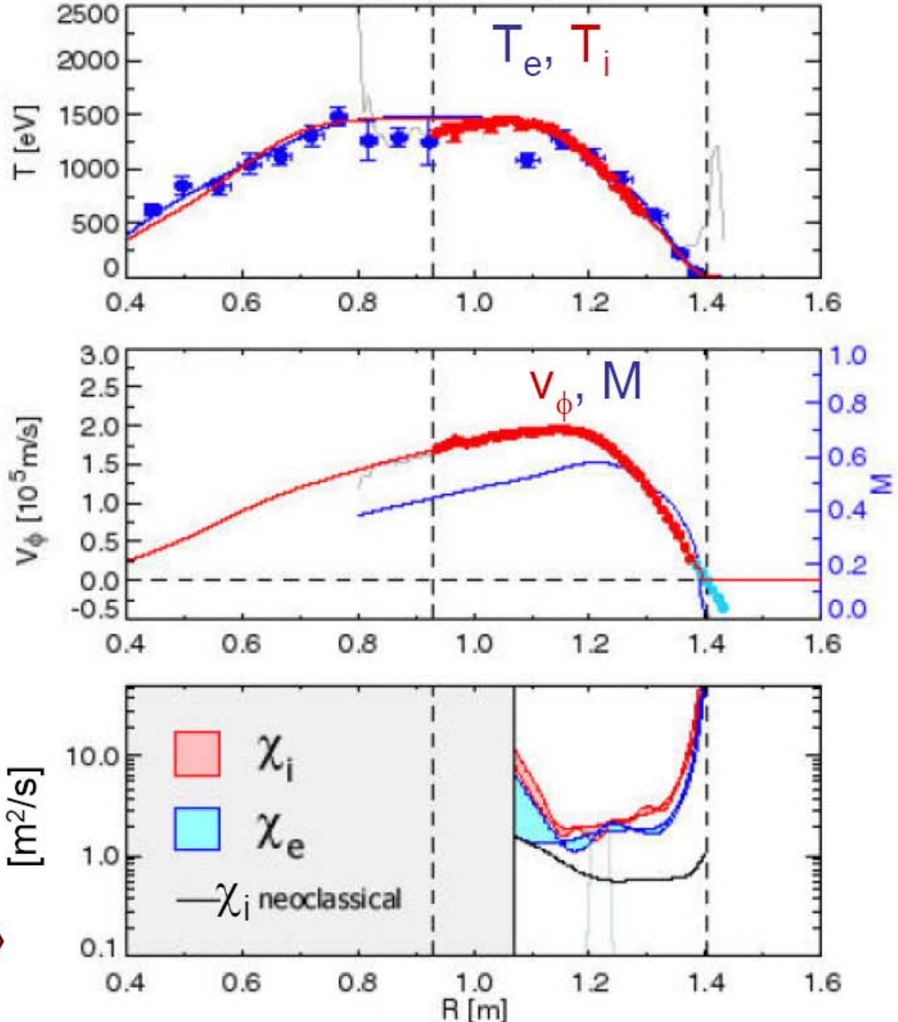
High ExB flow shear in MAST

- ❑ ITBs readily formed in both electron and ion channel

- ❑ χ_e, χ_i can approach χ_i^{neo} at ITB and in H-mode

- ❑ For both co- and counter-NBI, barriers form in the core initially then broaden substantially and weaken

- ❑ Broad rotation profile with counter-NBI gives $\chi_e \sim \chi_i \sim 2m^2/s$ over a wide region



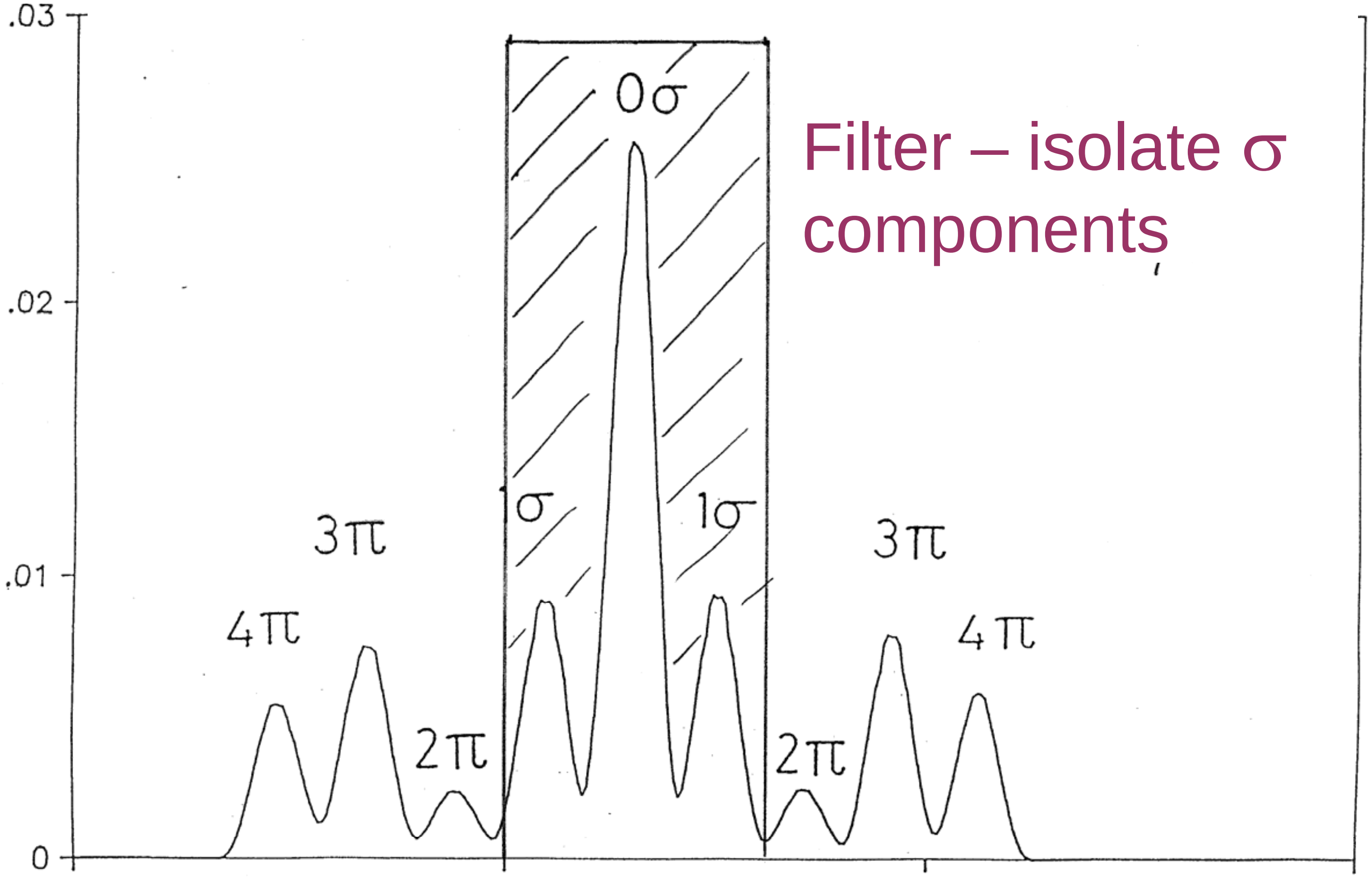
MSE Implementation on MAST

Different options available for spectral selection. We opted for narrow-band interference filters.

- Use ~1Å interference filters
- This is very narrow and small tilt angles will broaden bandwidth considerably.
- => no angular adjustment to filter
- Select filters according to Doppler shift (viewing angle and beam voltage).
- Optically share with CXR ports.
- For the initial 2 channel pilot experiment use spare CXR lens and have sole access during first testing period (now completed).

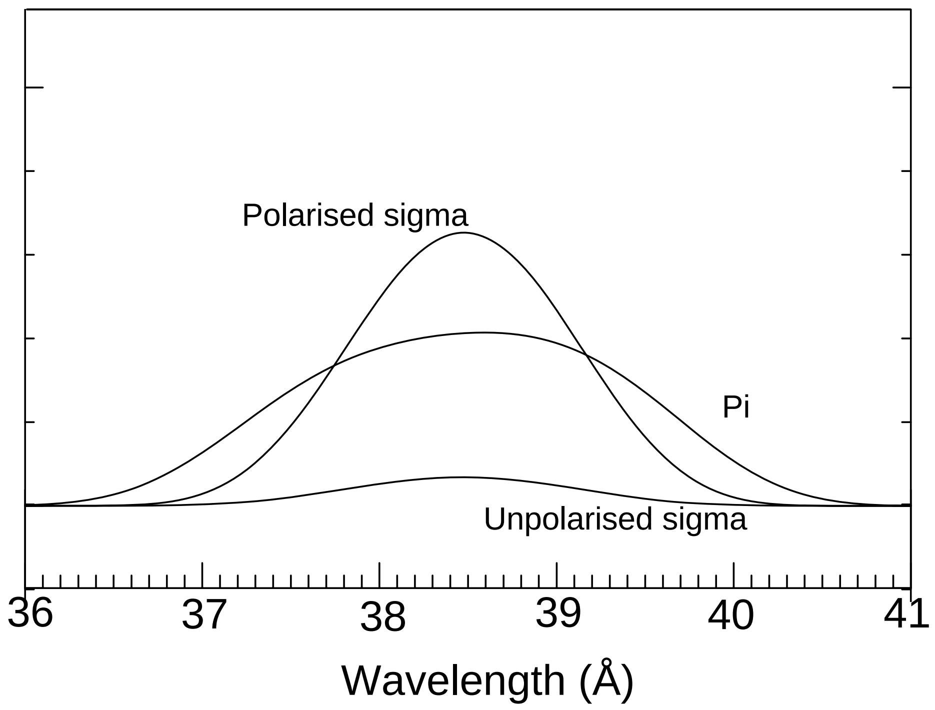
MSE and CXRS mounted on same port

Selection of polarised components



Filter – isolate σ components

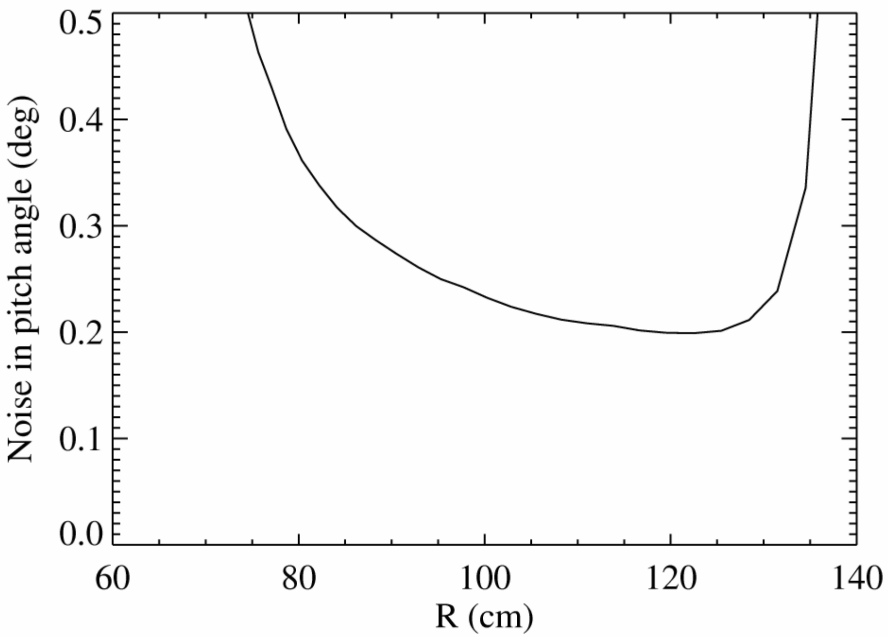
Calculated *(ab initio)* spectra (R=0.84m)



- 1.0 Å filter gaussian(FWHM)
- B_T=0.5 T
- 4 cm dia. finite beam volume
- 60 keV beam
- Use a filter to select out the part of the spectrum that maxmises the polarisation difference
- Total of 1.4-1.5 Å broadening (FWHM), included depth of beam

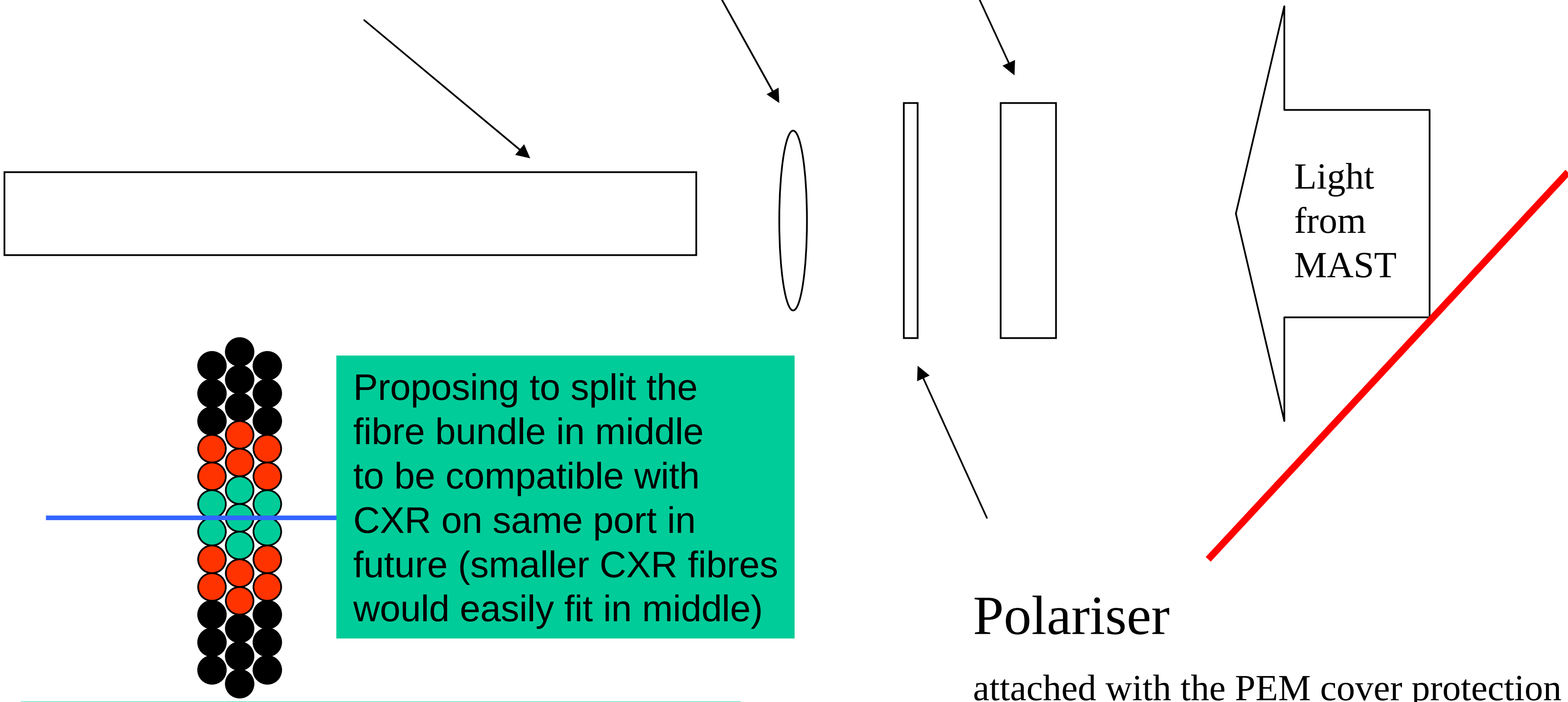
Signal to Noise

- Only shotnoise and dark current considered as noise sources
- 1 ms integration time
- 40% transmission in filter
- APD with 80% QE considered



- Beam emission from separate code, H-mode emission used.
- Noise in polarization angle close to what is commonly expected from other Tokamak experiments. This is surprising but in line with measurements by Levinton on NSTX.

Light Collection End



Lens

38 mm diameter
f=72 mm
M=1/25 at centre

PEMs

Fibre array

Light
from
MAST

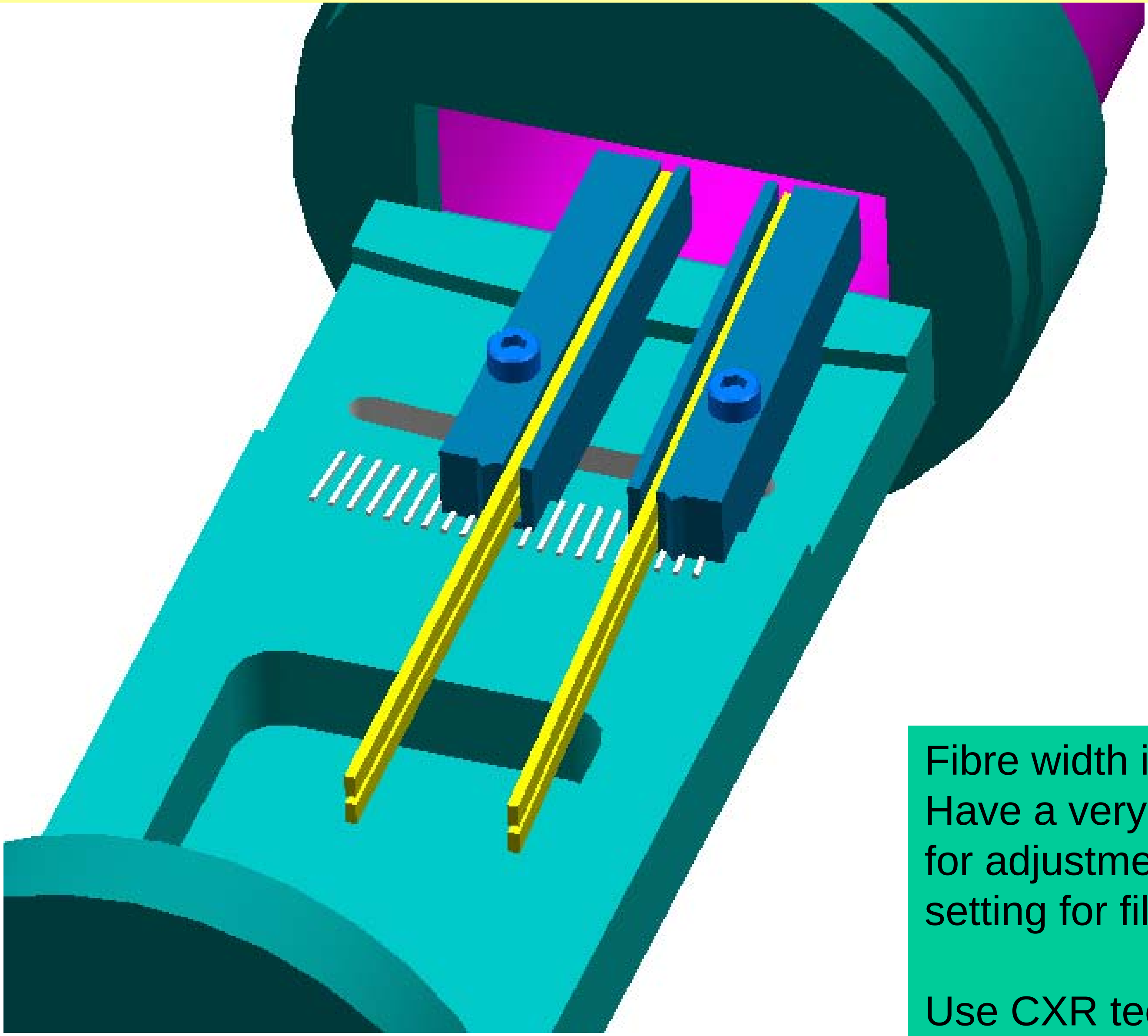
Proposing to split the fibre bundle in middle to be compatible with CXR on same port in future (smaller CXR fibres would easily fit in middle)

Polariser

attached with the PEM cover protection

37pc 0.4 mm core, 0.43 mm clad fibres
(5.16mmX1.2mm) Object size~130mmx30mm
(when projected, it goes up to 40mm wide approx)

View of collection lens back end and fibre holder

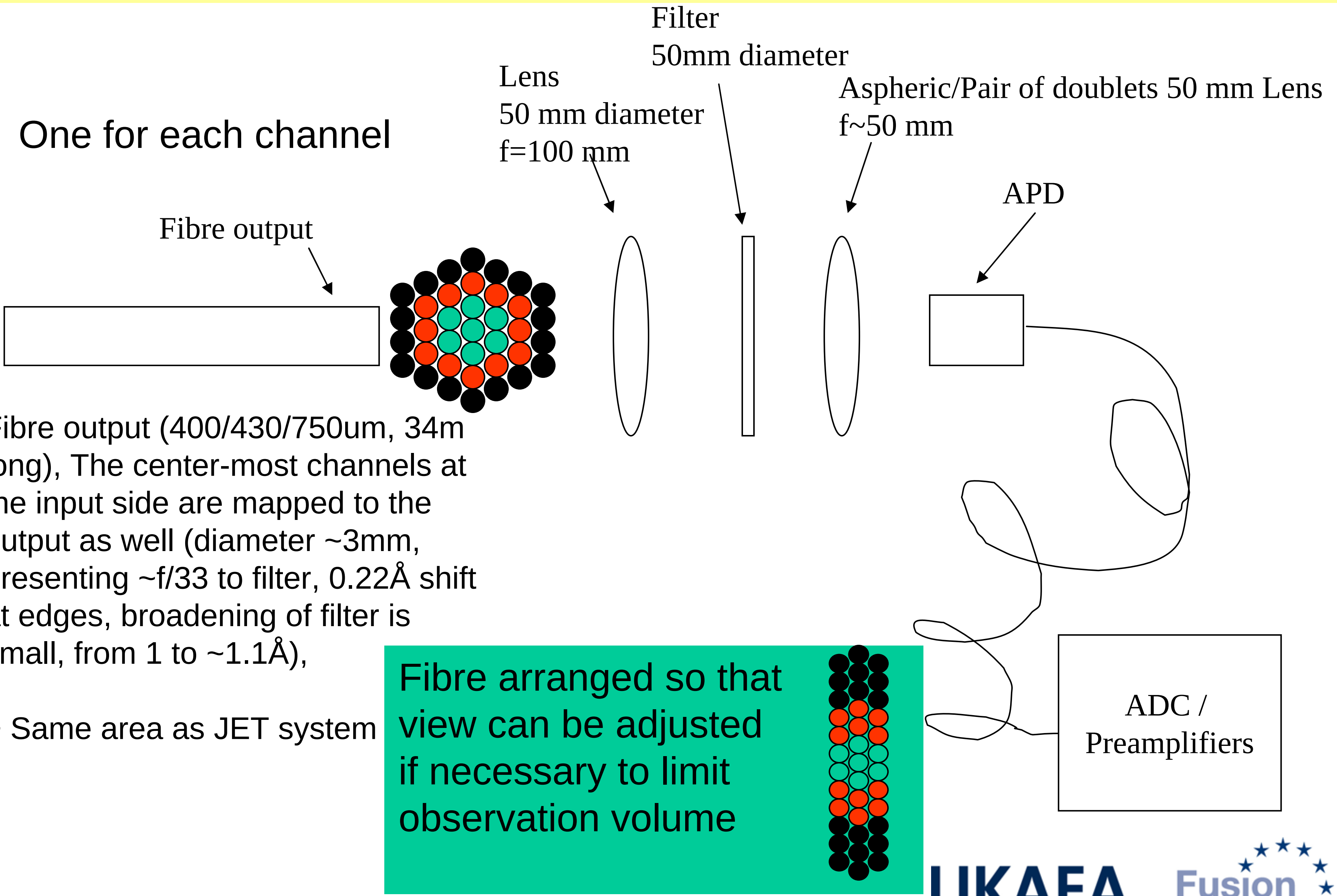


Fibre width is 1.2mm
Have a very simple facility
for adjustment to get zero order
setting for filters

Use CXR techniques for spatial
calibration

Light Detection End

One for each channel



Fibre output (400/430/750um, 34m long), The center-most channels at the input side are mapped to the output as well (diameter ~3mm, presenting ~f/33 to filter, 0.22Å shift at edges, broadening of filter is small, from 1 to ~1.1Å),

~ Same area as JET system

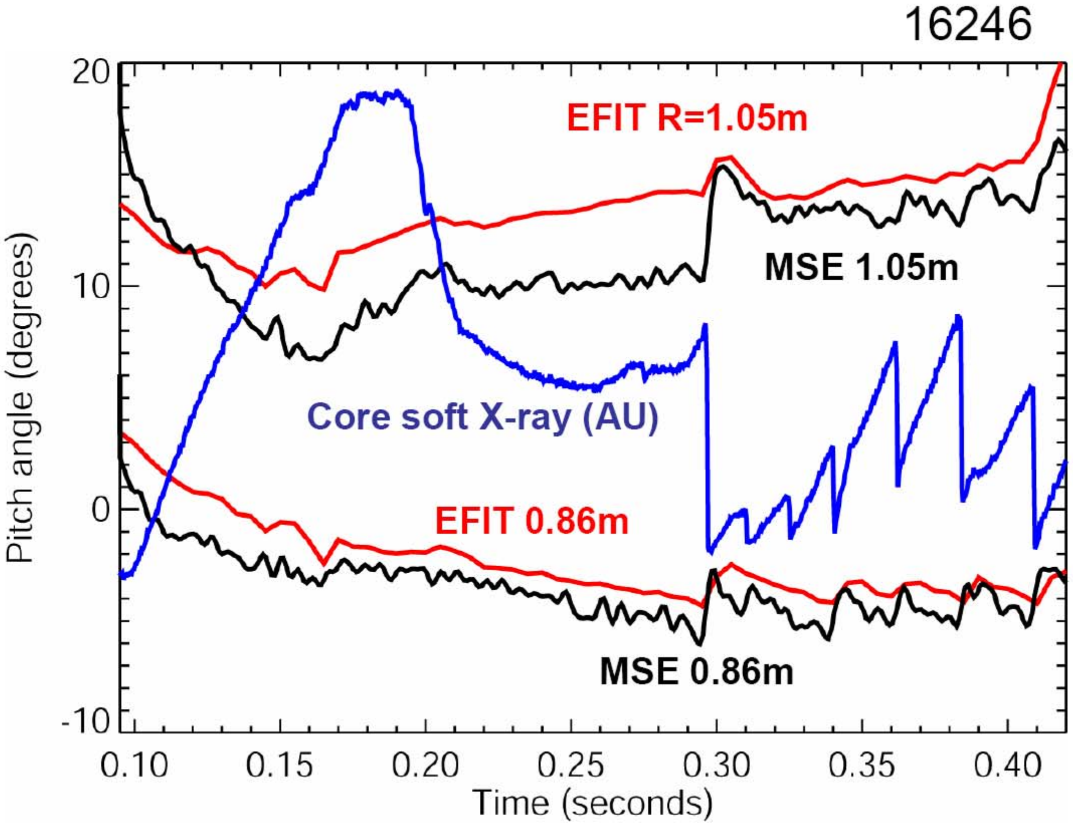
Fibre arranged so that view can be adjusted if necessary to limit observation volume

Comparison of different systems

System	Fibres mm^2	Collection Solid Angle(sr)	Effective efficiency	Triple Product
JET	6x1mmϕ (4.7)	0.15	1	0.71
NSTX	76x1mmϕ(60)	0.08	0.2	1
MAST	36x0.4mmϕ(4.5)	0.2	1	0.88

This assumes all systems see same polarisation fraction and light collection [NSTX lens is large but collects a thin slice of light 250mmx30mm thus dropping the collected solid angle and their chosen approach (Lyot filter) is narrow band but poor in transmission at the moment]

Pilot MSE measurements



Results from two-chord pilot system (in collaboration with KTH Sweden)

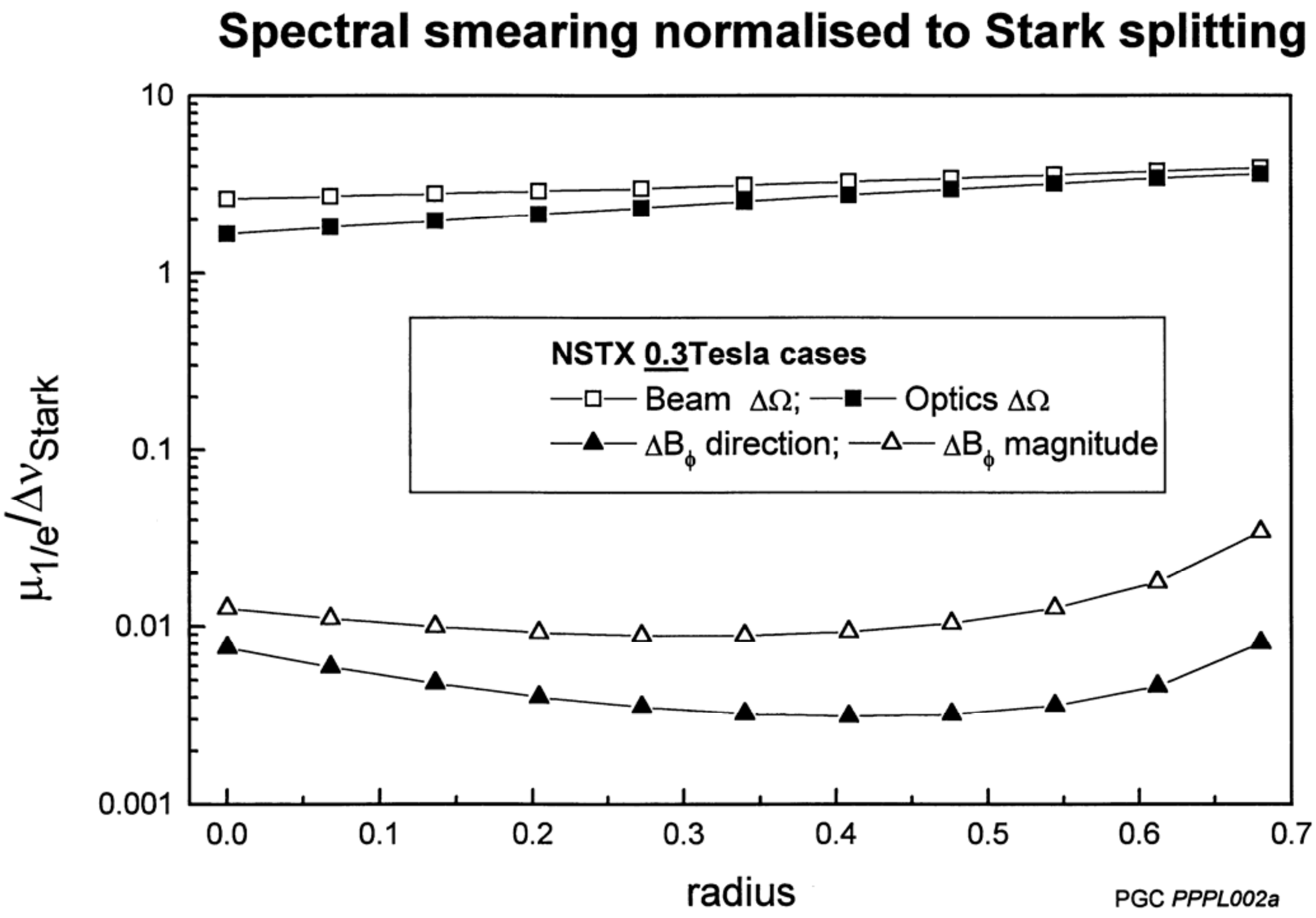
Readily expandable to multi-channel system for full q-profile.

5ms resolution

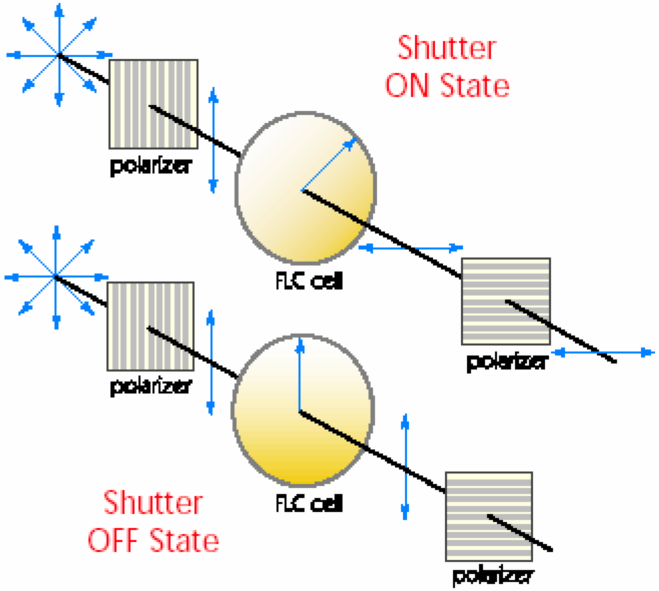
MSE – Future ambitions on MAST

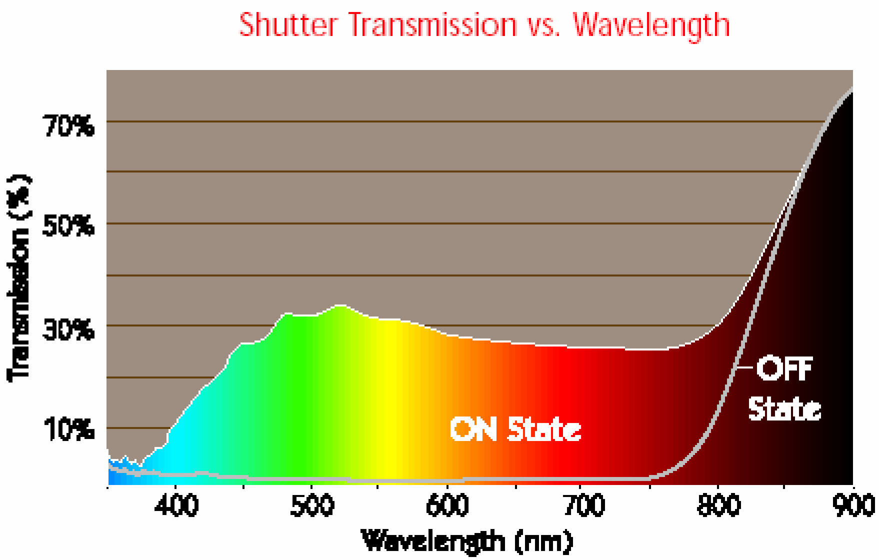
- Opt for simplicity in design to reduce costs and efforts, primarily by using fixed wavelength interference filters.
- Aim for ~25 chords per beam, phasing in first set ~Sept. 2007.
- Providing a second diagnosed beam (2008/9) will give greater beam implementation flexibity and reliability but also, with accurate alignment, allow ~ 50 diagnosed positions.
- Use CXR in determining Er contribution to total E.
- Continue to analyse present results e.g. Sources of depolarisations.
- Recruit/collaborate... ☺

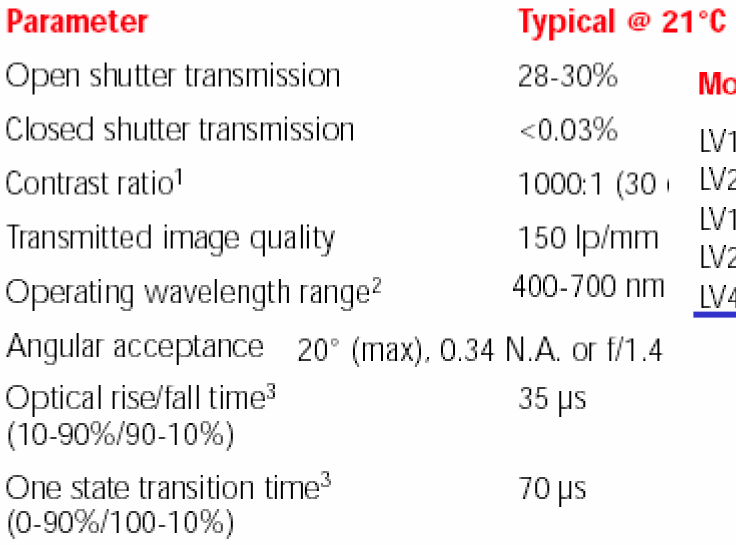
Beam divergence and optics dominate the smearing of the Stark splitting.



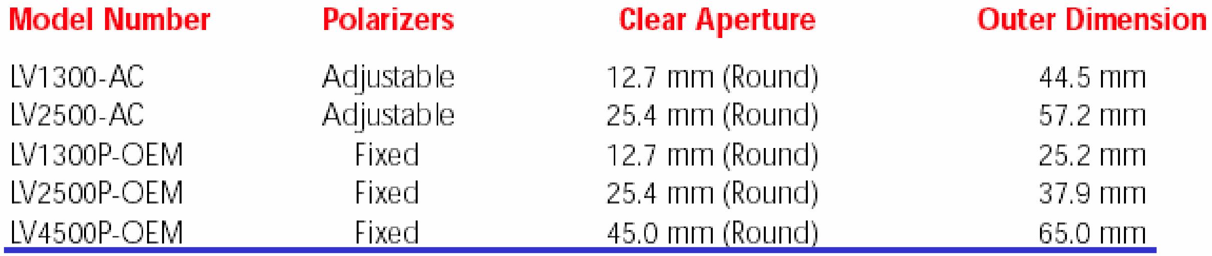
FLC shutter







Parameter	**Typical @ 21°C**
Open shutter transmission	28-30%
Closed shutter transmission	<0.03%
Contrast ratio[1]	1000:1 (30
Transmitted image quality	150 lp/mm
Operating wavelength range[2]	400-700 nm
Angular acceptance	20° (max), 0.34 N.A. or f/1.4
Optical rise/fall time[3] (10-90%/90-10%)	35 µs
One state transition time[3] (0-90%/100-10%)	70 µs



Model Number	**Polarizers**	**Clear Aperture**	**Outer Dimension**
LV1300-AC	Adjustable	12.7 mm (Round)	44.5 mm
LV2500-AC	Adjustable	25.4 mm (Round)	57.2 mm
LV1300P-OEM	Fixed	12.7 mm (Round)	25.2 mm
LV2500P-OEM	Fixed	25.4 mm (Round)	37.9 mm
LV4500P-OEM	Fixed	45.0 mm (Round)	65.0 mm

FLC = “Ferro-electric liquid crystal”

Stark shifts compared

Stark shift:-

$$\begin{array}{lllllll} \Delta\nu_S = & \pm & \alpha_{S_n} E & - & b_n E^2 & \pm & c_n E^3 \\ & & \text{linear} & & \text{quadratic} & & \text{cubic} \\ & & \text{dominant} & & \text{small} & & \text{negligible} \end{array}$$

Zeeman shift:-

$$\begin{array}{llll} \text{Zeeman} & \Delta\nu_Z & \propto & B \\ \text{Motional Stark} & \Delta\nu_S & \propto & v \times B \\ & \frac{\Delta\nu_S}{\Delta\nu_Z} & = & \frac{3}{\alpha}\frac{v \sin\Theta}{c} \\ & & = & 1.9 \times 10^{-2} \left(\frac{E(eV)}{AMU}\right)^{\frac{1}{2}} \sin\Theta \\ \text{H, 10keV and } \Theta = \frac{\pi}{2} & & \Rightarrow & \sim 2 \end{array}$$

Only the beam energy matters in relative magnitude of Motional Stark to Zeeman splitting.

Doppler:-

$$\begin{array}{llll} \text{Doppler} & \Delta\nu_D & = & \frac{v}{c}\nu_0 \cos\Theta_{Beam,View} \\ \text{Motional Stark} & \Delta\nu_S & = & \alpha_{S_n} v B \sin\Theta_{Beam,Bfield} \\ & \frac{\Delta\nu_S}{\Delta\nu_D} & = & B \frac{\alpha_{S_n} c}{\nu_0} \frac{\sin\Theta_{Beam,Bfield}}{\cos\Theta_{Beam,View}} \end{array}$$

Only the magnetic field strength matters in relative magnitude of Motional Stark to Doppler spectral shifts.

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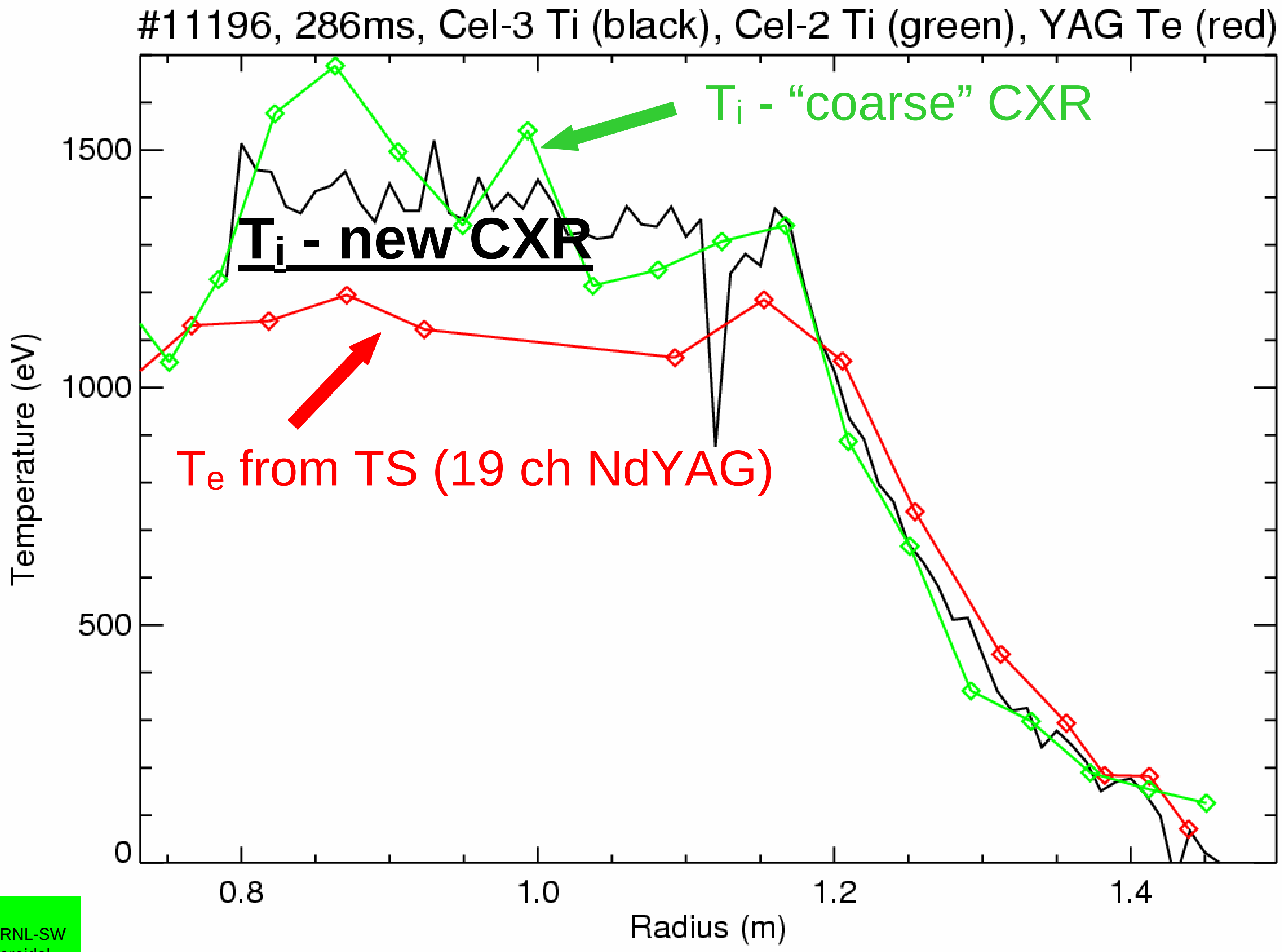
First Results from new CXR spectrometer



#11196, 286ms, Cel-3 Ti (black), Cel-2 Ti (green), YAG Te (red)

T_i - “coarse” CXR

T_i - new CXR

T_e from TS (19 ch NdYAG)

Shot no: 11196
Beam Viewed: ORNL-SW
Tor/Pol Profile: Toroidal

Neil Conway, Mike Walsh, Paddy Carolan *et al*