Beam Emission Spectroscopy Diagnostics for W7X

Notes from 2015

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Modelling
Approx systems performance
Initial design

W7X CXRS Summary

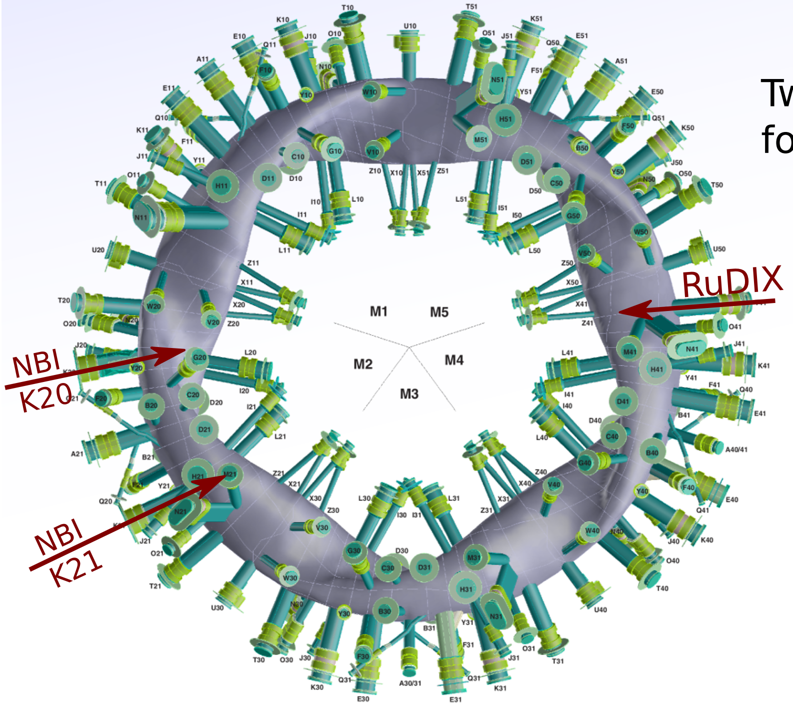
CXRS observes line emission from impurity species after charge exchange with a beam neutral.

Intensity --> n_i
Width (Doppler Broadening) --> T_i
Shift (Doppler Shift) --> V_φ/V_θ, V_θ --> E_r

Requirements for E_r:
Generally we think we'll be looking at $|Er| < 50$kV/m and wanting to see details down to preferably: $\delta Er \sim 2$kV/m,
At the very least: $\delta Er \sim 10$kV/m.

$B_\varphi \sim 2.5$T so E_r=2kV/m --> $v_\theta \sim 800$m/s.

Expect small values in very core, with most detail in $\rho_N > 0.5$.



Two neutral beam systems foreseen for W7X:

Diagnostic Beam (RuDIX):

(Module 4)
Can run effectively continuously (pulsed at low duty cycle)
Low-current (less perturbative)

Heating Beams (NBI):

(Module 2)
Max 10 seconds per box (7.5 for H, 10 for D)
Very perturbative (>1MW)

n_i, T_i can be provided by either, but v_φ / v_θ depends on the viewing geometry.
For W7X v_φ expected to be small, so E_r principally determined by v_θ.

Other diagnostics:
XICS: n_i, T_i, v_θ - line integrated, limited local information in the centre. Available only with Ar puff.
(Probably higher accuracy v_θ measurement (low stat noise) compared to CXRS.)
Edge Passive Spectroscopy: T_i, n_i, v_θ/E_r up to $T_e \sim$ few x100eV.
Doppler Reflectometry: Very edge E_r.

We will have very limited localised Er measurements in core to mid-radius from other diagnostics.

W7X NBI Active Spectroscopy Systems

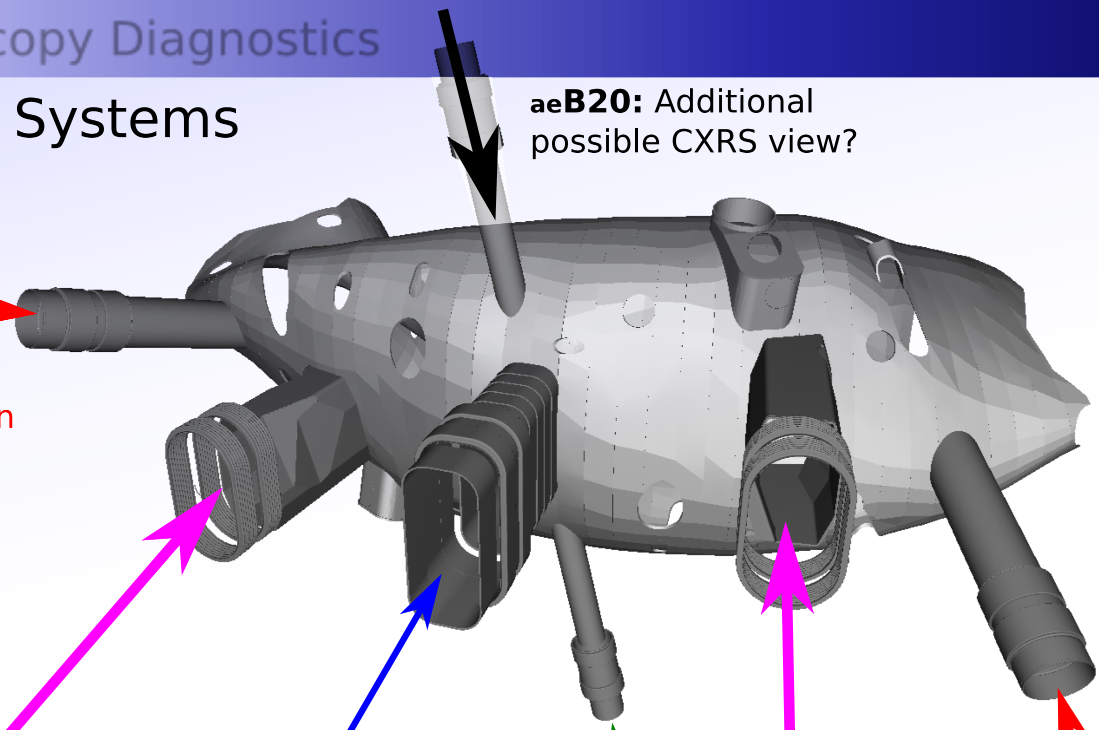
Neutral Beams on W7X:
RuDIX
Heating NBI

Diagnostics:

Beam Emission Spectroscopy (BES):
Record intensity of Doppler Shifter excited neutral beam particles.
Gives particle and energy deposition over radius.

Charge Exchange Recombination Spectroscopy (CXRS):
Record intensity, wavelength and width of impurity ion lines from states populated by charge exchange with beam neutrals.
Gives T_e, v and n_i information.

Motional Stark Effect (MSE):
Measure polarisation/splitting of Doppler shifted emission from beam neutrals.
Gives information on field/current.
Very challenging measurement on W7X.



aeB20: Additional possible CXRS view?

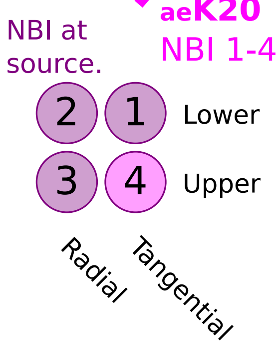
aeT20
Simple BES
Fibre system
~10cm resolution
~5 channels

aeA21
Primary NBI CXRS/MSE
2 ports
+(I/S)MSE
Optical relay system
with flexble back-end.

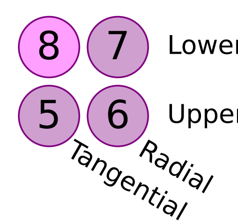
aeB21:
Additional
CXRS?

aeT21
Simple BES
Fibre system
~10cm resolution

aeK20
NBI 1-4

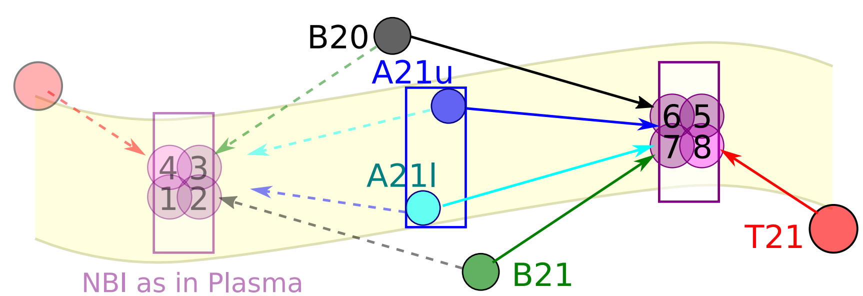


aeK21
NBI 5-8

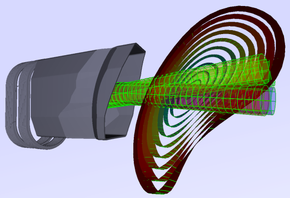


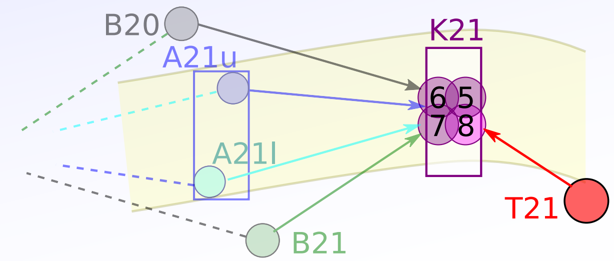
4,8 will be our 'favorite' beams:
- 3,4,7,8 comissioned first in OP1.2
- Tangential beams produce less fast-ion losses
- 4,8 have He capability.

Schematic:



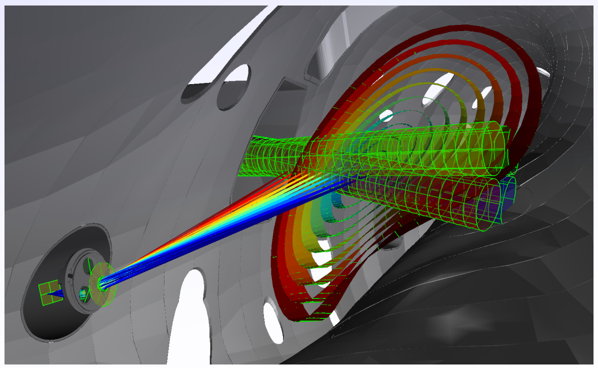
NBI Active Spectroscopy Systems





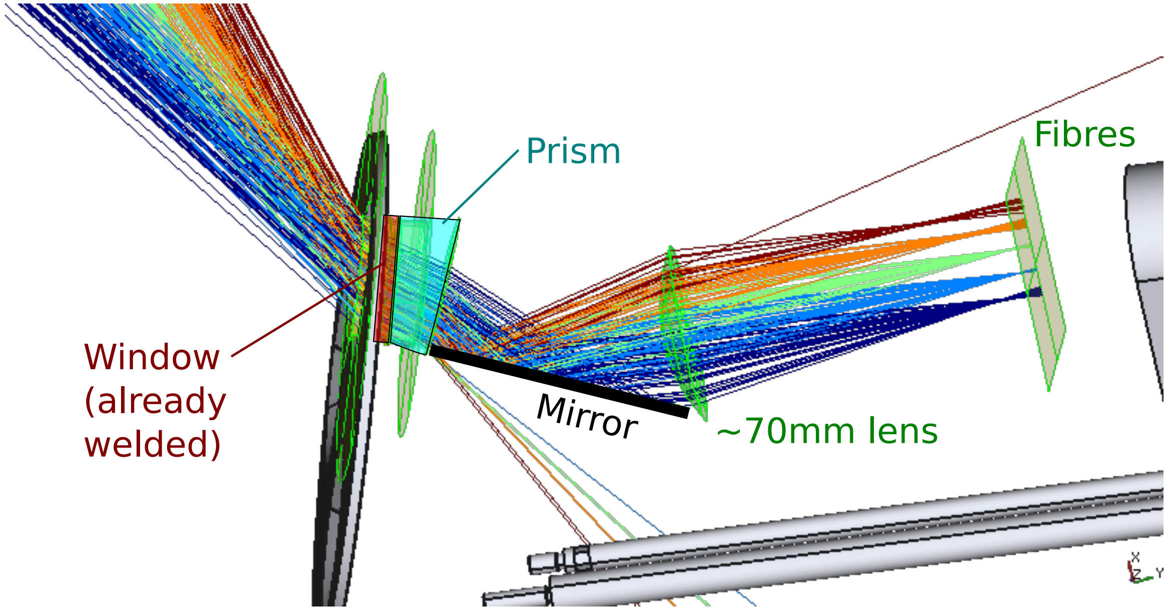
NBI:

- >1MW beams, so strong CX signal.
- Good spatial resolution for T_i, n_i.
- Limit on NBI usability - e.g. max duration.

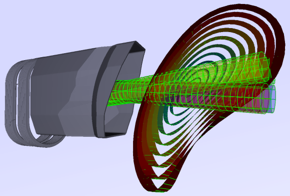


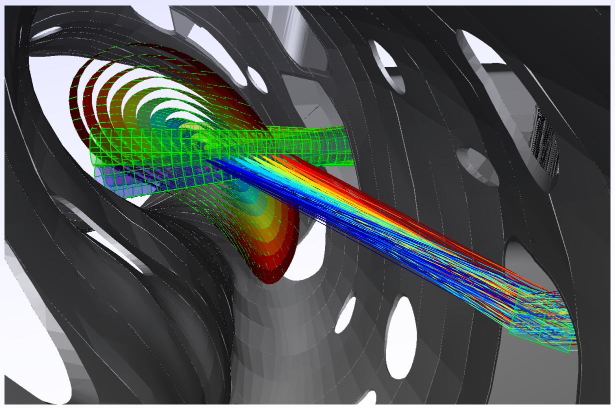
aeT21: Single small window in port shared with HST (Heat Shield Thermography).

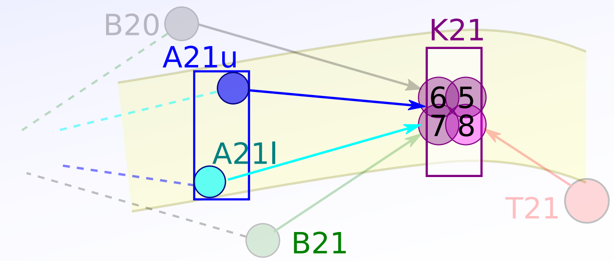
- Poor spatial resolution: 6-10cm
- Can be realised with prism instead of flip-out mirror.
  (prism pressed behind the already-welded window is sufficient)
- Forseen primarily for BES to measure beam deposition profiles.
- Low cost (€ + labour) to build optics: Prism + lens + ~ 5 fibres.



NBI Active Spectroscopy Systems





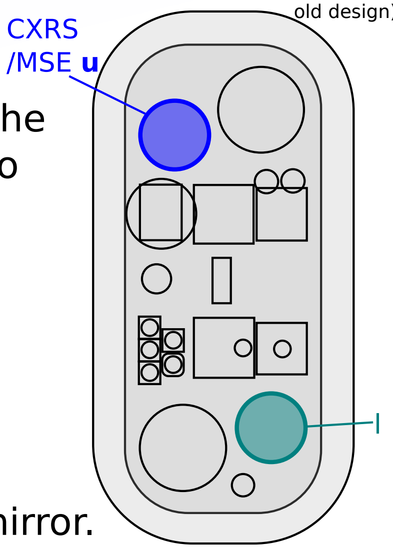


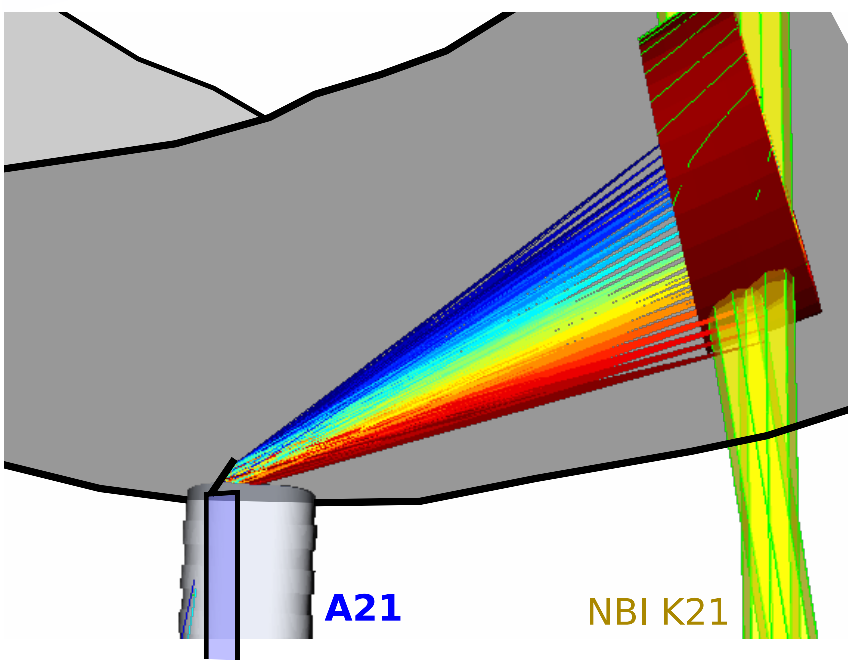
NBI:
- >1MW beams, so strong CX signal.
- Good spatial resolution for T_i, n_i.
- Limit on NBI usability - e.g. max duration.

aeA21: Two 150mm ports reserved, various possibilities:
- One system viewing each beam box K20/K21?
- One CXRS, one MSE?

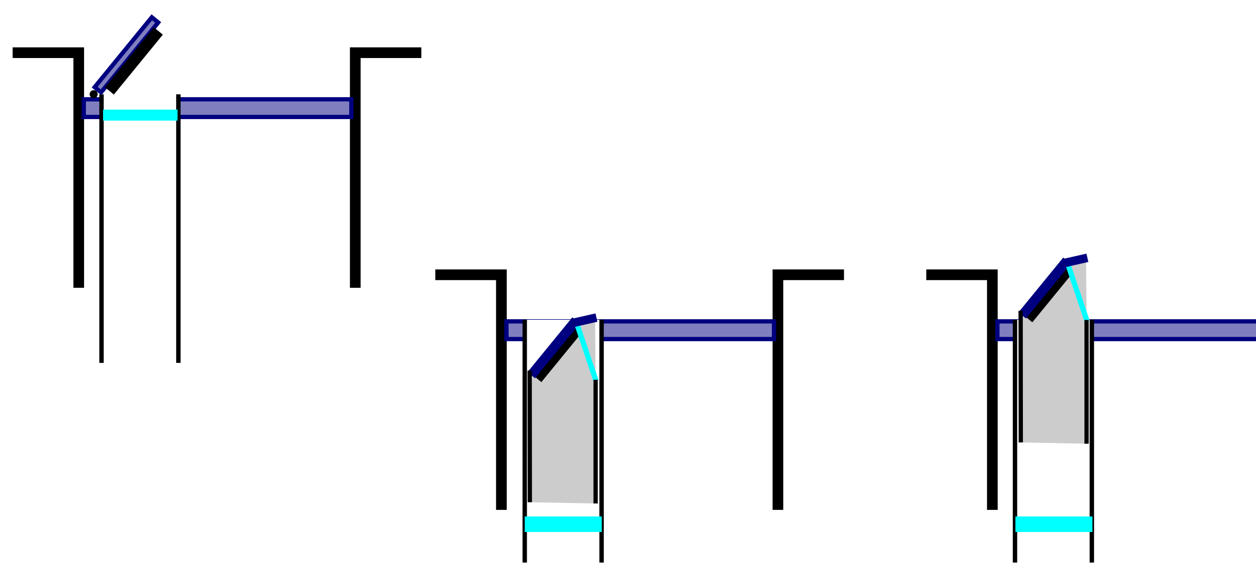
- MSE requirements are much more demanding and need the full image relayed to outside of vessel and cryostat, so probably leave until at least OP1.2b.

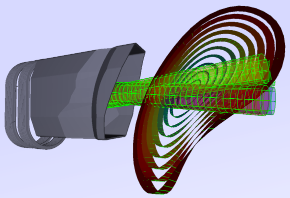
Is it possible to split light spectrally and share each port between CXRS and (I)MSE?



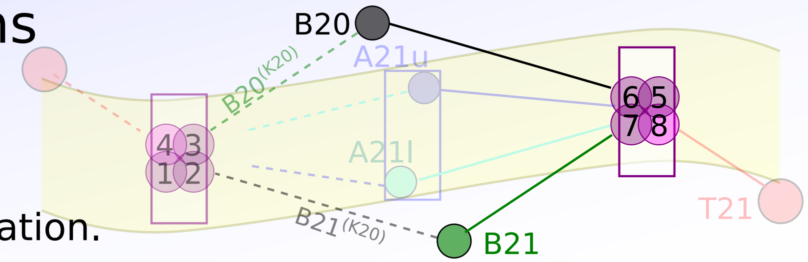


- Either system will require a fold or push-out mirror.

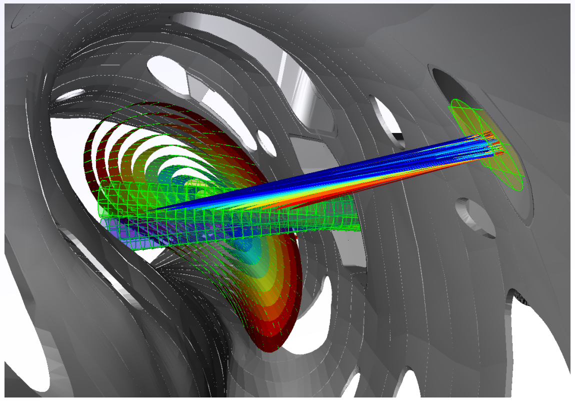




NBI Active Spectroscopy Systems



NBI:
- >1MW beams, so strong CX signal.
- Good spatial resolution for T_i, n_i.
- Limit on NBI usability - e.g. max duration.

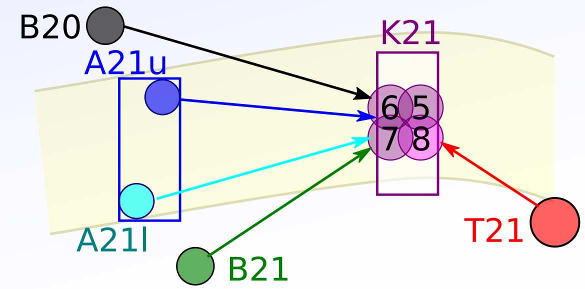


aeB20/B21: Other possibilities in ports shared with others.
B20 offers good spatial resolution with ~40% contribution of V_{perp} for possible assist to RuDIX in Er measurement?

Port Reservation (12/11/2015):

B21:
- QSI: Lithium Beam (OP2+)
- CBD20: 'Sniffer Probes'
- ???

B20:
- QSI: Lithium Beam (OP2+)
- QSC: Edge Passive Spectroscopy (OP1.2)
- QSS: 'Edge Visible Spectropscopy'

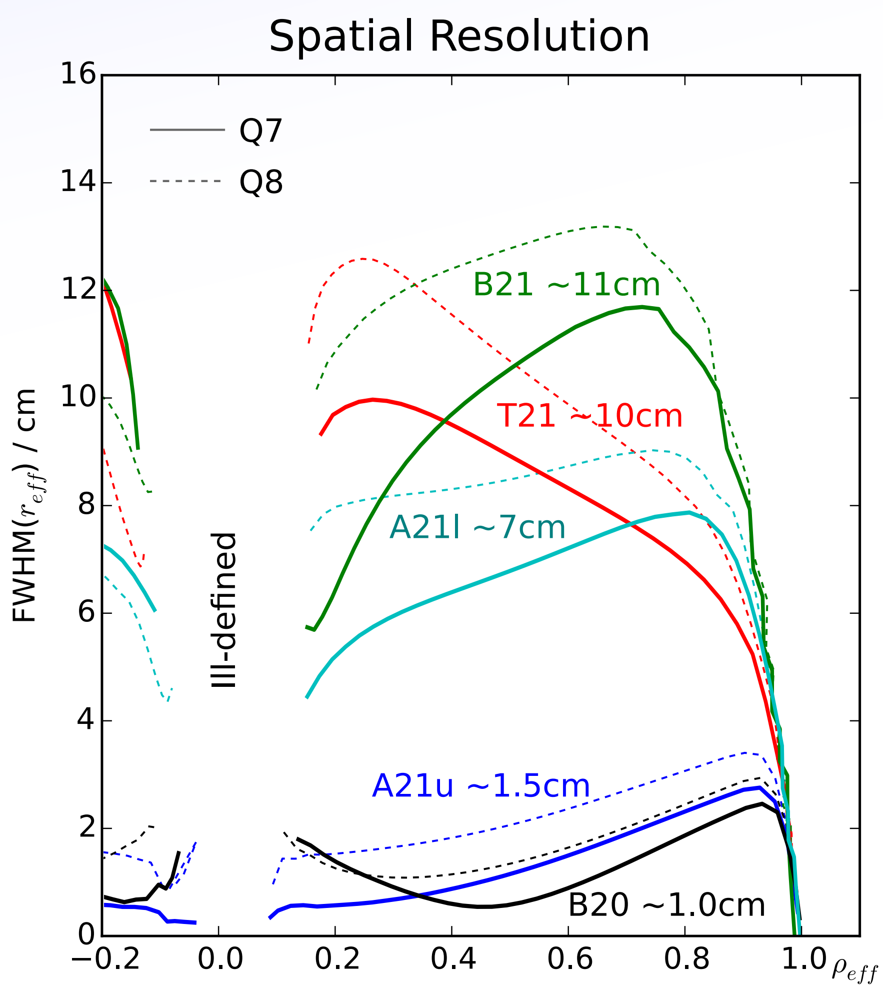


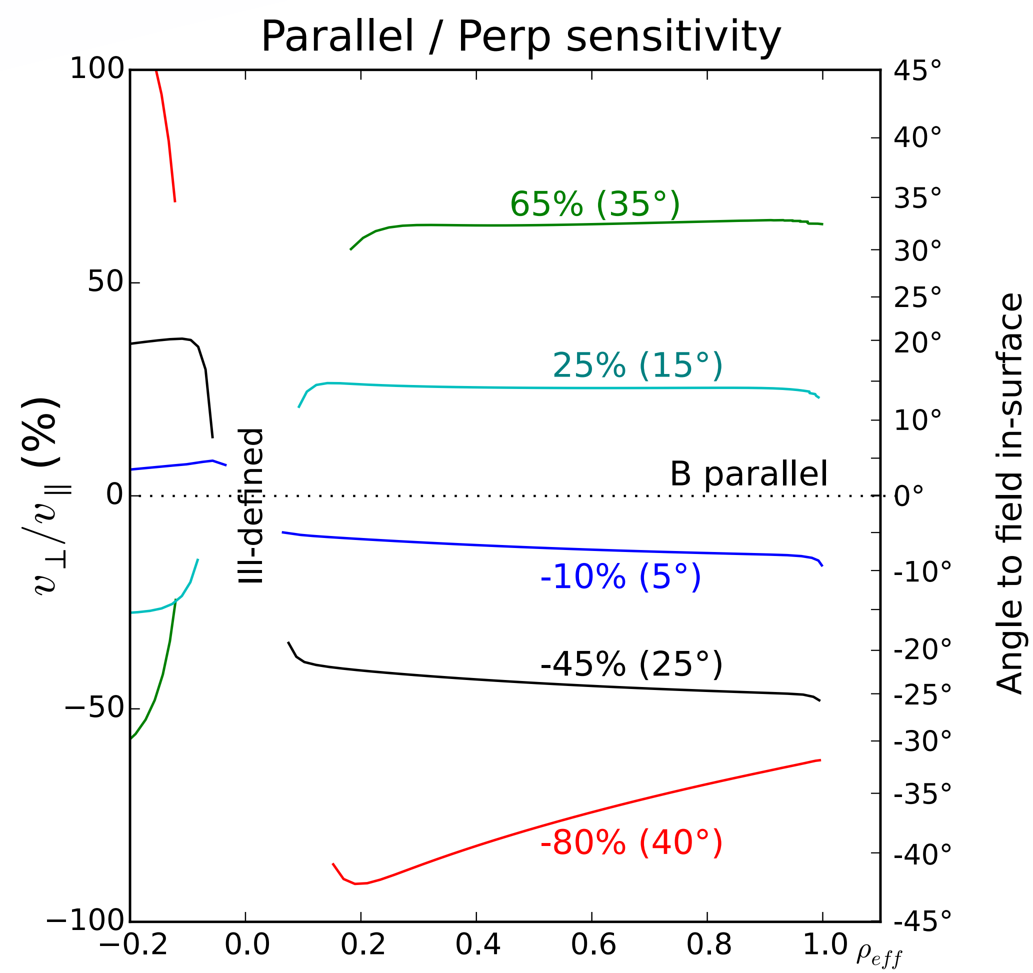
Resolution of each system is calculated by taking moments of ρ_{eff} or r_{eff} along lines of sight with the beam intensity (is the CX intensity proportional??).

Average ρ_{eff}: $$< \rho > = \int I(l)\ \rho(l) dl\ \ /\ \ \int I(l) dl$$

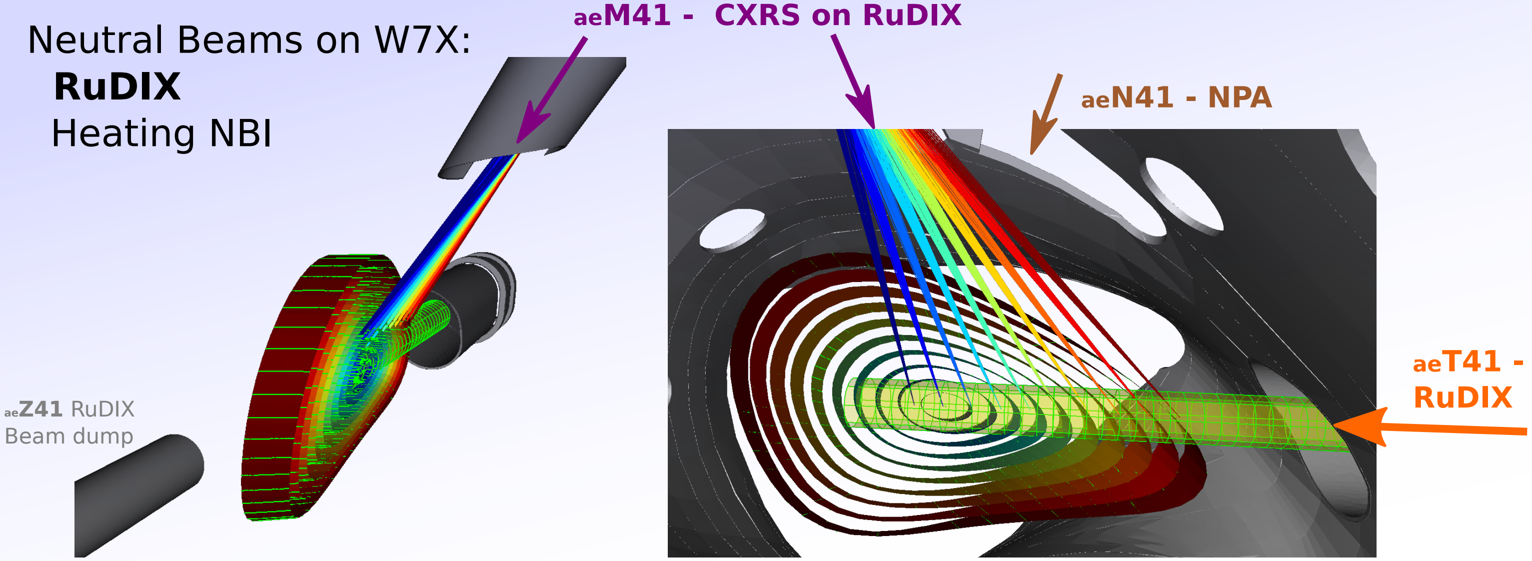
FWHM $r_{eff} = 2.35\sigma_r$ $$\sigma_r^2 = \int I(l)\ [r(l) - < r >]^2\, dl\ \ /\ \ \int I(l) dl$$

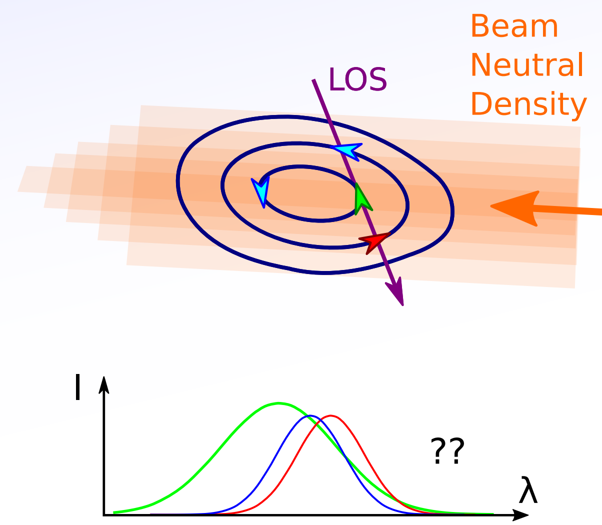
Projection $v_\perp / v_\parallel$: $$< v_\perp > = \int I(l)\ (b_\perp(l) \cdot l) dl\ \ /\ \ \int I(l) dl$$



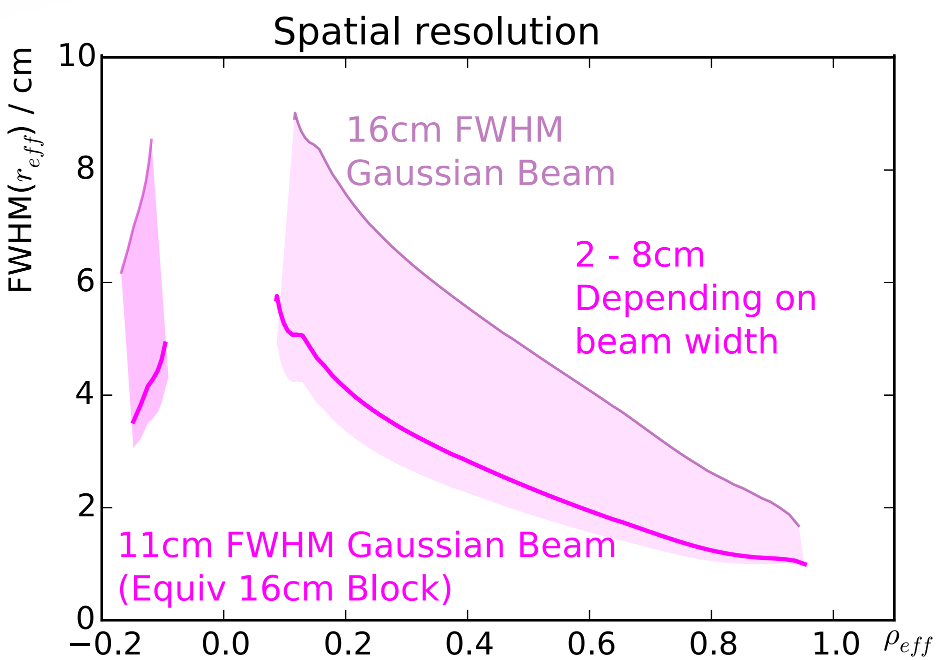


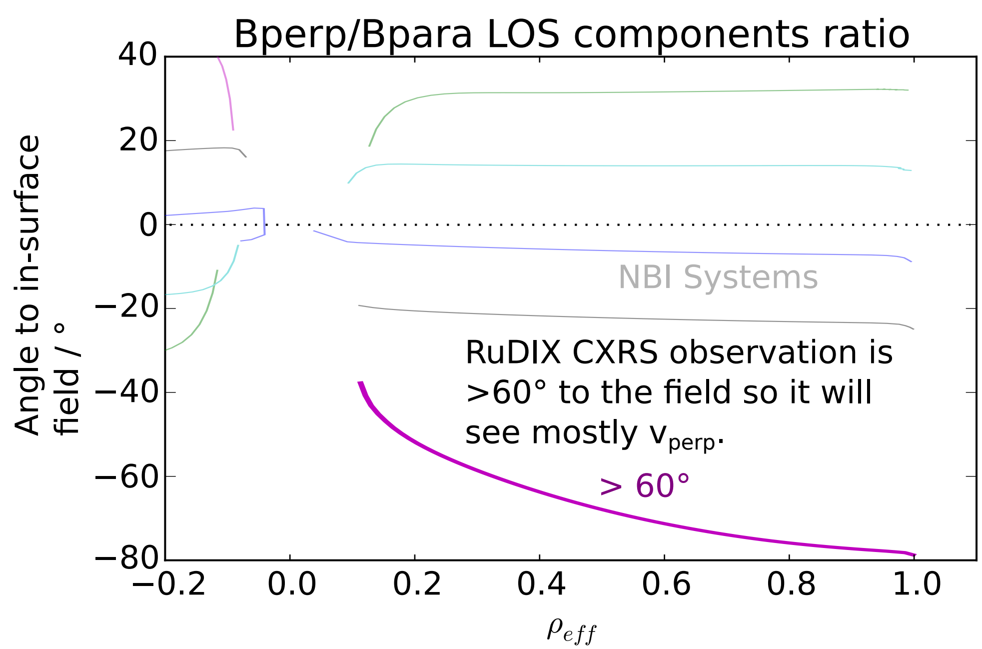
W7X Beam Emission Spectroscopy Diagnostics



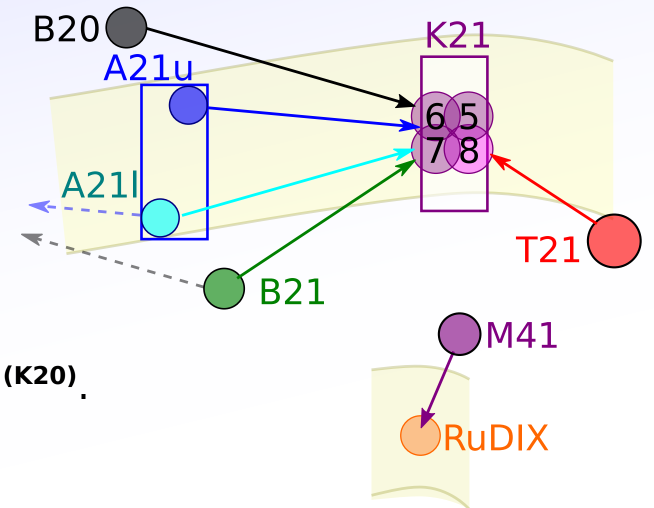


Good resolution at edge, very good V_{perp} sensitivity.
Near triangular plane, central surfaces have low elongation giving low spatial resolution for n_i, T_i near core.
With velocity, calculation is more complex as LOS flow projection varies strongly across beam.
Needs forward-modelling to interpret in core (at least for $\rho < 0.3$), apart from the core most channel, which should see only T_i.





NBI CXRS: Summary



NBI:

➤ **A21u:** Very good resolution, $v_{//}$ only. Primary core T_i, n_i system.
Complex design due to mirro/shutter.

~~A21l~~: Poor resolution, some v_{perp}. Better used for K20 beams.

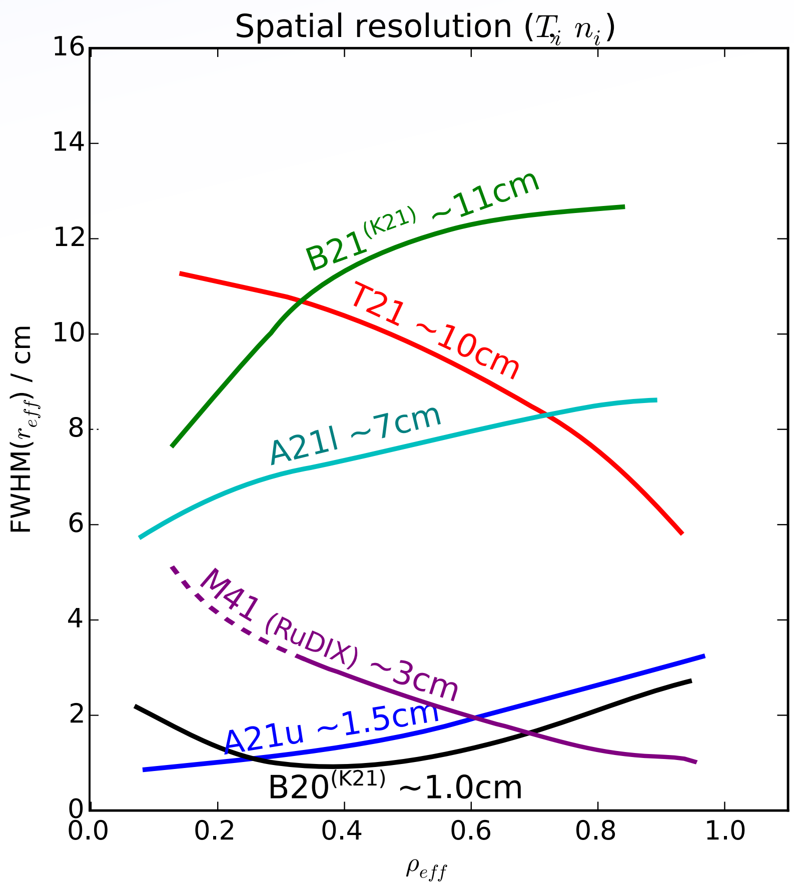
T21: Good v_{perp}, very poor resolution. Probably used for BES. Simple build.

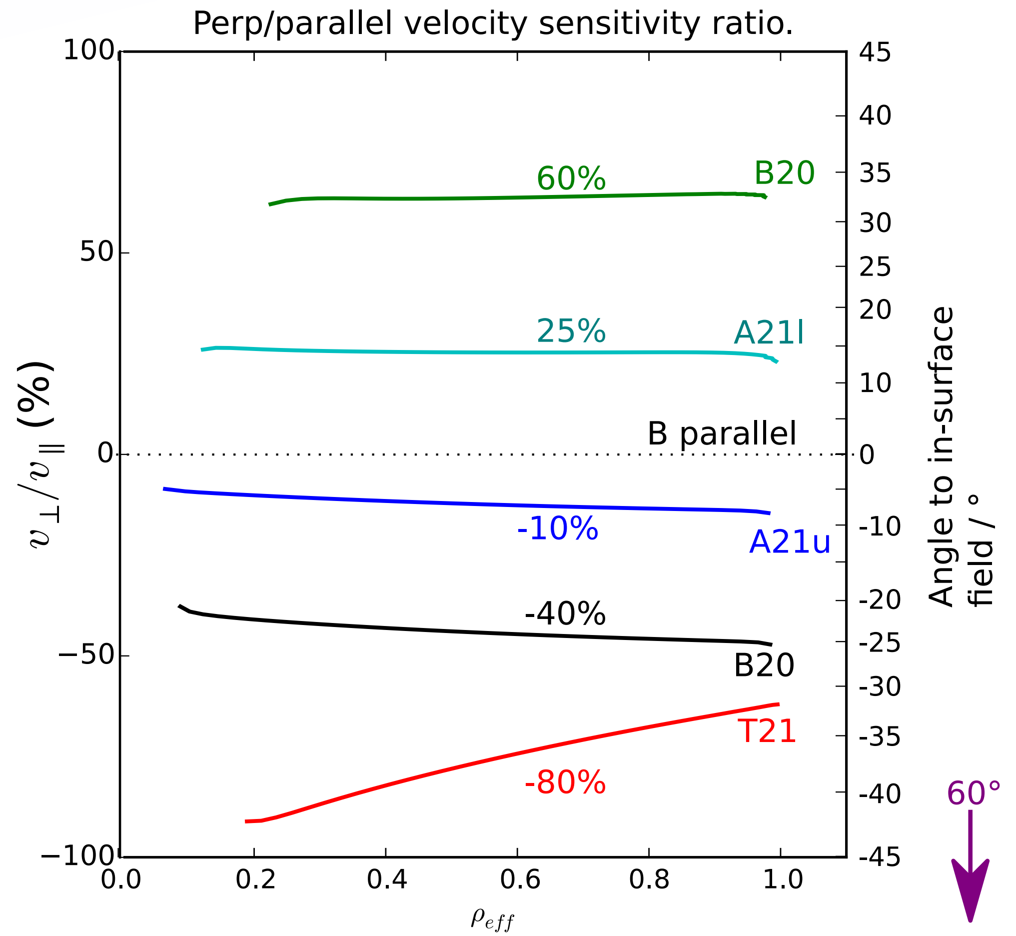
?➤ **B20$^{(K21)}$:** Very good resolution, some v_{perp}. Is a window free?

~~B21~~$^{(K21)}$: Good v_{perp}, very poor resolution. Better used for K20 beams as **B21$^{(K20)}$**.

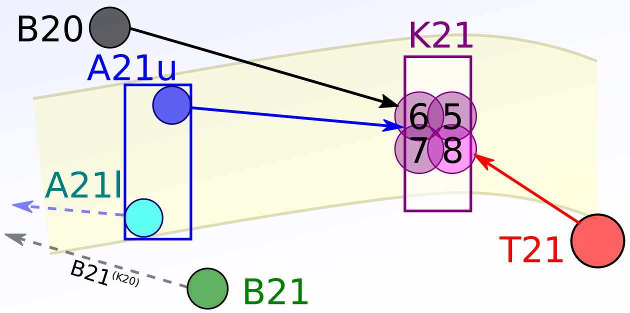
RuDIX:

➤ **M41:** Good edge resolution. Excellent v_{perp} sensitivity.





CXRS: Todo



Modelling:

- Parameterisation of flow (ExB + Pfirsch-Schlüter + Bulk toroidal) into Minerva. (Also, for XICS - A. Alonso is helping).
- Generic backend model (spectrometer etc) - see what we are likely to measure with each system. (S/N, etc)

A21u: (Primary Core CXRS)

- Update project specification.
- Mirror/shutter conceptual design - This will be the biggest part, particularly if it will be OP2 ready.
- Optical design.
- Lens + fibres.

...

T21: (Beam Emission Spec)

- Complete optical design.
- Check port design progress.
- Purchase lens + fibres.
- Consider spectrometer to use etc.

B20$^{(K21)}$ or **B21** $^{(K20)}$: (Supplementary CXRS)

- Check current design of B21, see if there's a window free.
- Basic optics design - is view too oblique?

M41: (RuDIX CXRS):

- Complete optical optimisation.
- Modify optic head design.

NBI CXRS: More ports

NBI:

A21u: Very good resolution, $v_{//}$ only. Primary core T_i, n_i system.
Complex design due to mirro/shutter.

A21l: Poor resolution, some v_{perp}. Better used for K20 beams.

T21: Good v_{perp}, very poor resolution. Probably used for BES. Simple build.

B20$^{(K21)}$: Very good resolution, some v_{perp}.

B21$^{(K21)}$: Good v_{perp}, very poor resolution. Better used for K20 beams as **B21$^{(K20)}$**.

RuDIX M41: Good edge resolution. Excellent v_{perp} sensitivity.

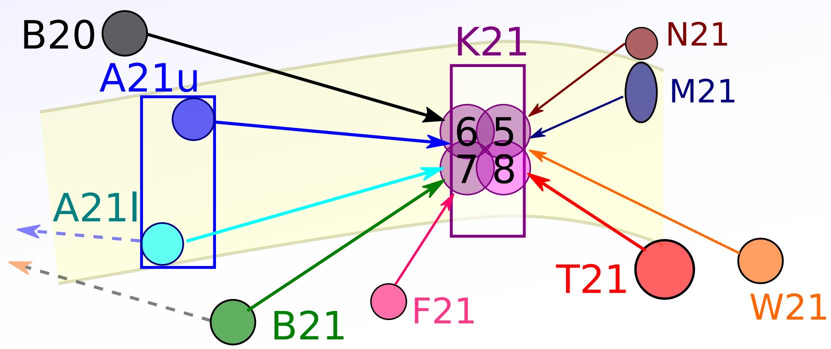
N21: Poor resolution [SX Multi-foil / visible bulk spec]

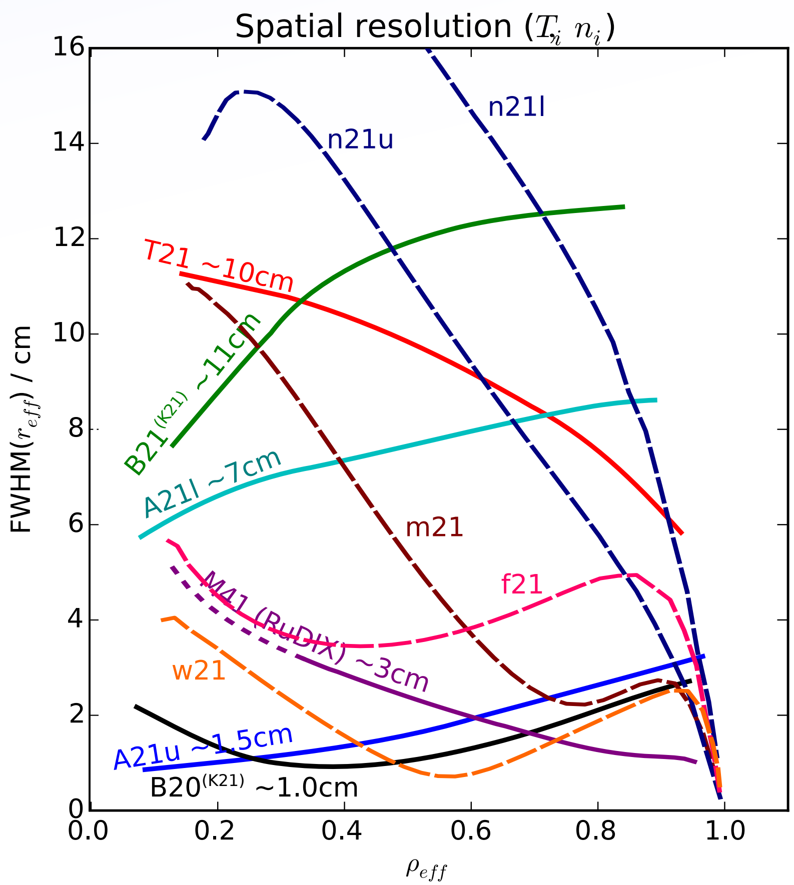
M21: Ok resolution only at edge. Good Er. [SX Flexible cam / visible bulk spec]

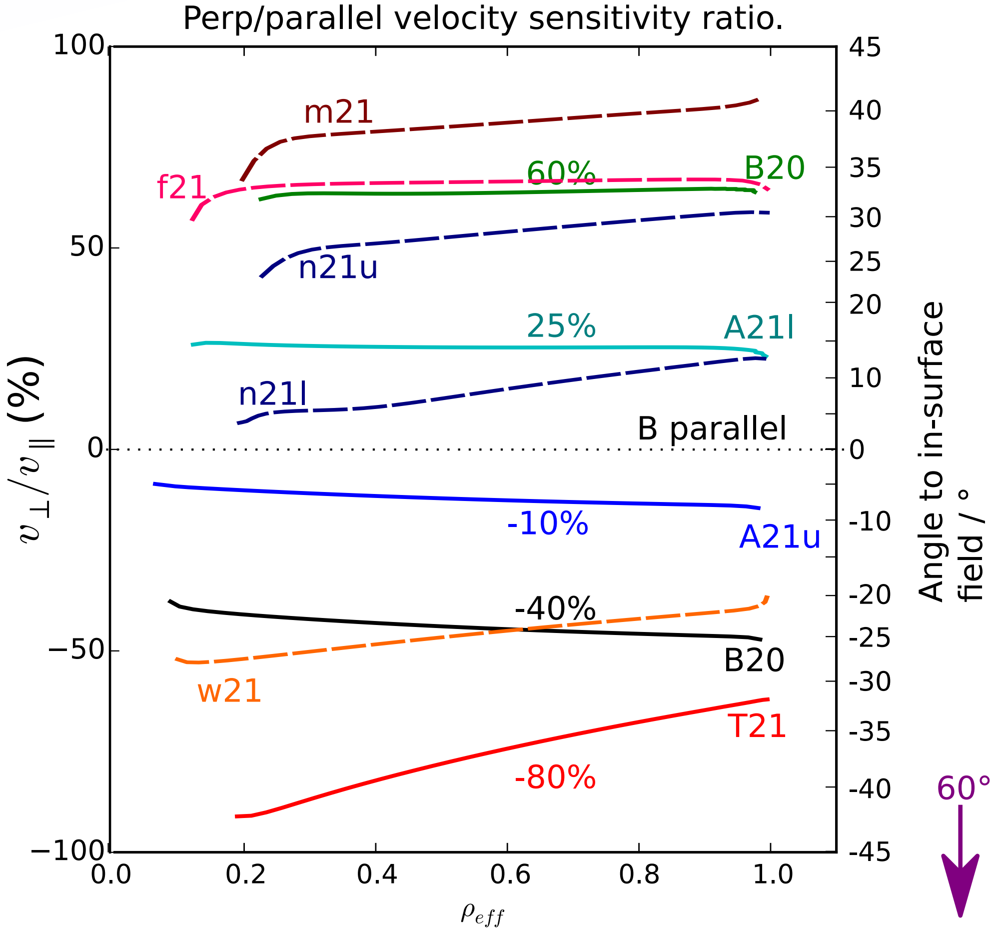
F21: Not great resolution, Good Er. [Lots of E4 diagnostics]

W21: Good/OK resolution, same Er as B20 [XMCTS / Bolometry]

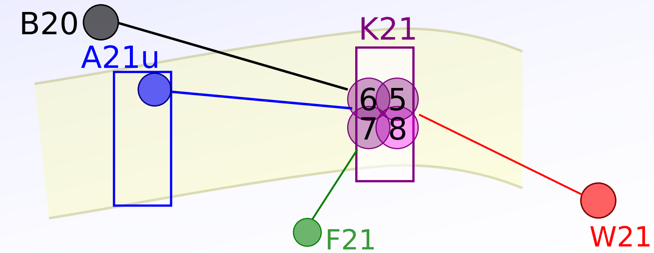
So, B20$^{(K21)}$ / B21$^{(K20)}$ is still the best choice. W20/21 is the 2nd best choice.





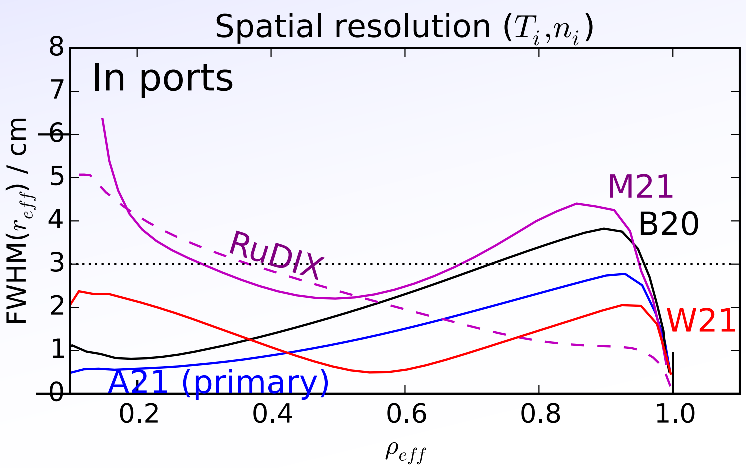


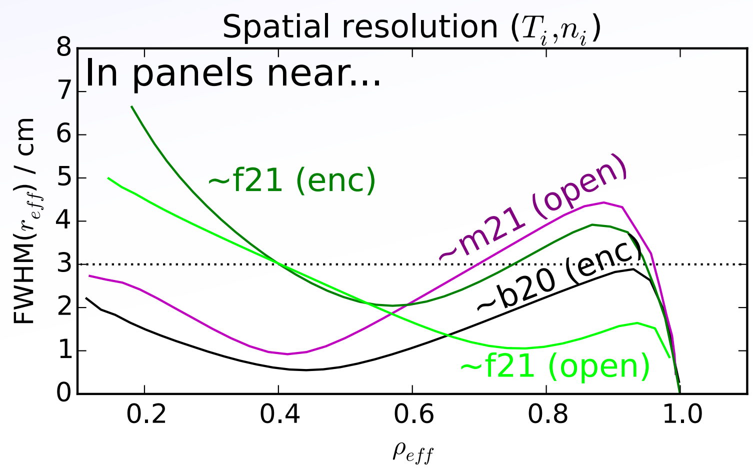
NBI CXRS: Best options

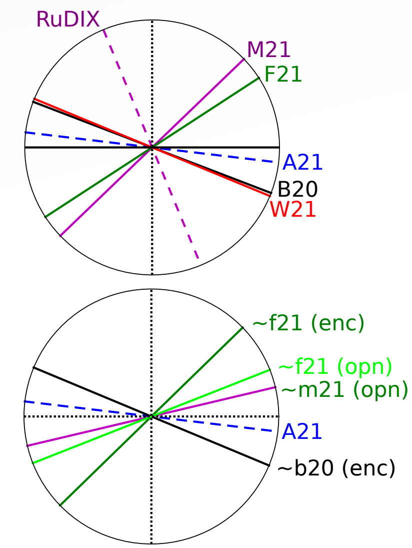


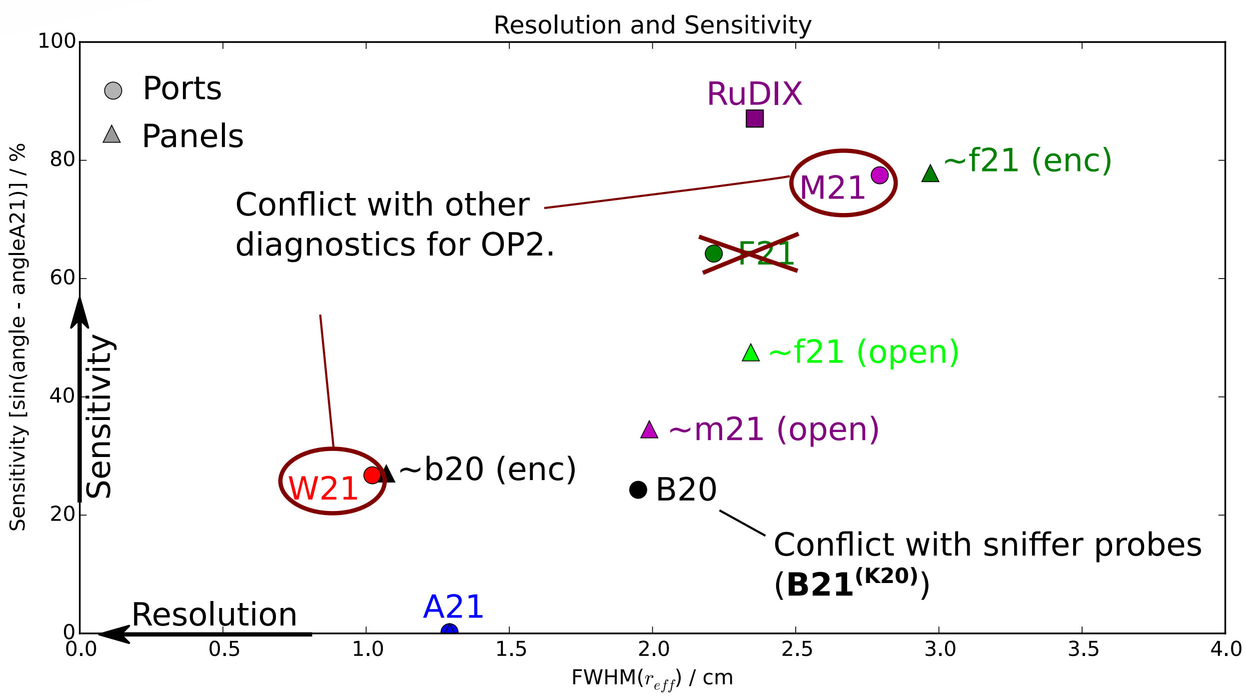
Closer look at highest resolution options:
The A21 system will be the primary NBI CXRS system for ni, Ti, and measures at ~ -7° to the field, so mostly parallel flow.

Looking for a port to isolate the other component:









Poor sensitivity is possible to overcome later with better spectrometers / longer integration etc, but spatial resolution isn't so easy.

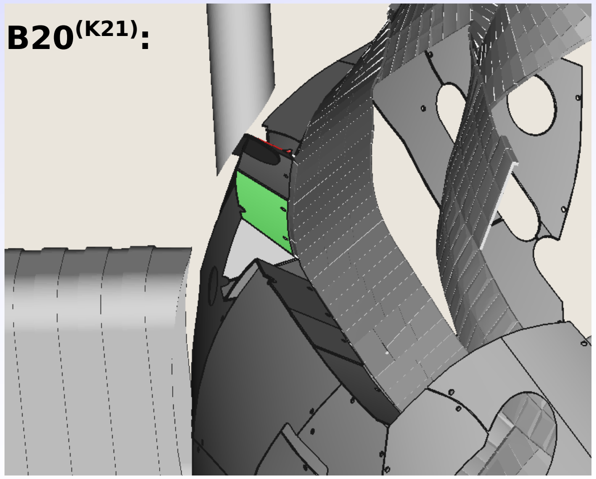
CXRS brings the spatial resolution which XICS can't provide, particularly towards the core.

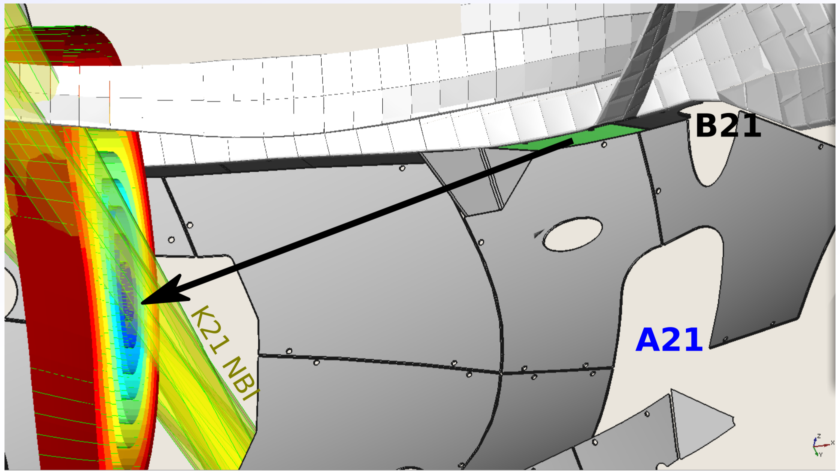
Port occupancy:

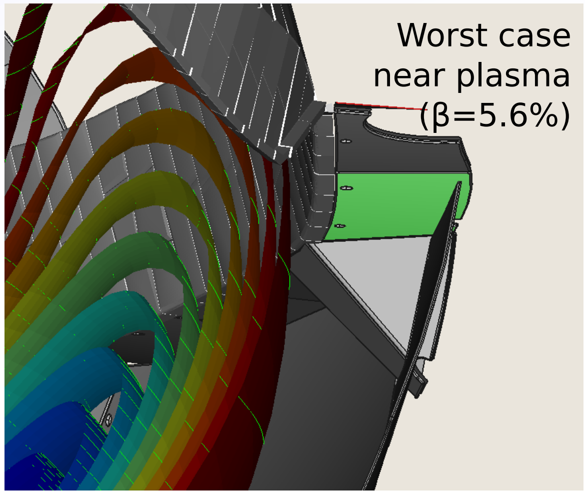
- **A21:** Primary core T_i, n_i system.
- **B21$^{(K20)}$:** Sniffer probes
- **M21:** Visible bulk spec, **M20:** SX Flexible camera
- **F21, F20:** Video diagnostics - no space.
- **W21:** Bolometry, **W20:** XMCTS

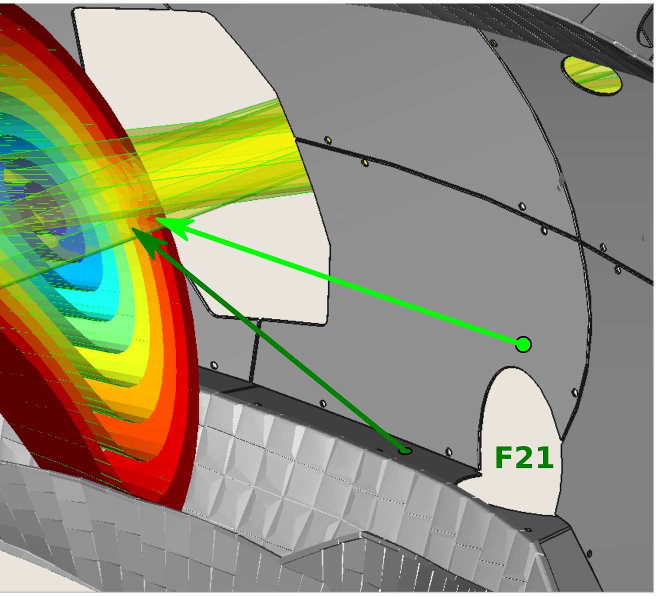
NBI CXRS: Panel options

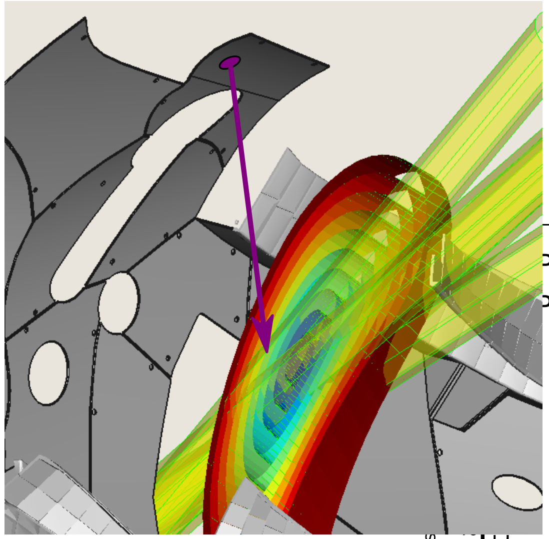
Complicated option of mounting heads in panels.

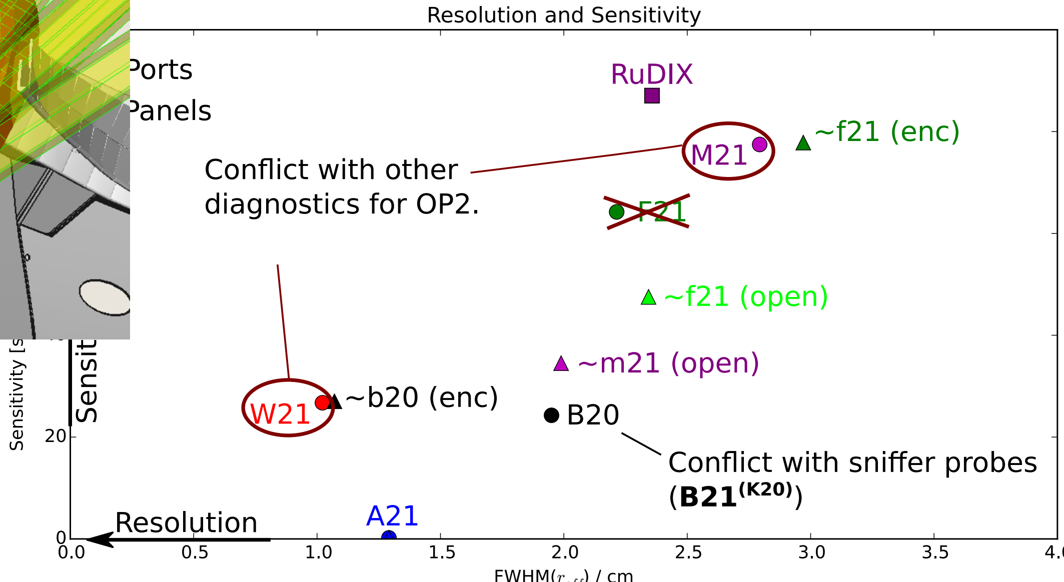






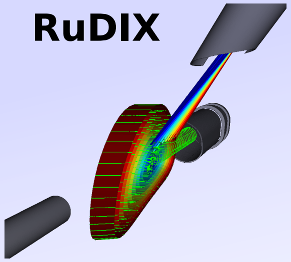




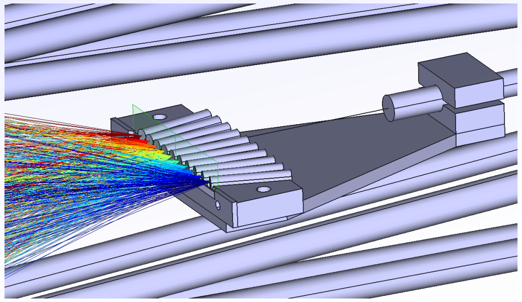


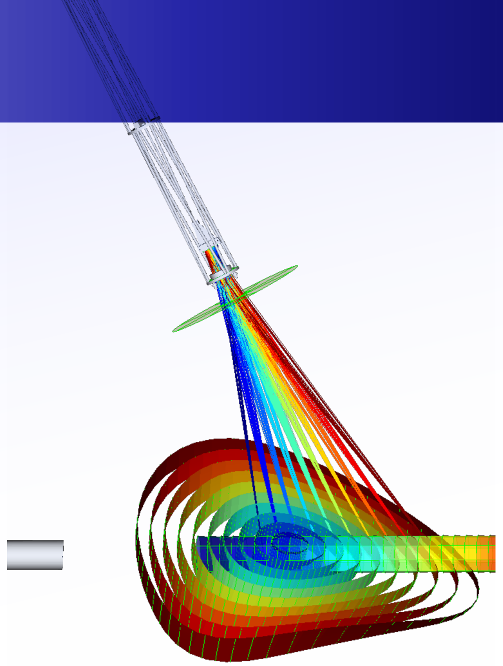
RuDIX CXRS Mech

RuDIX



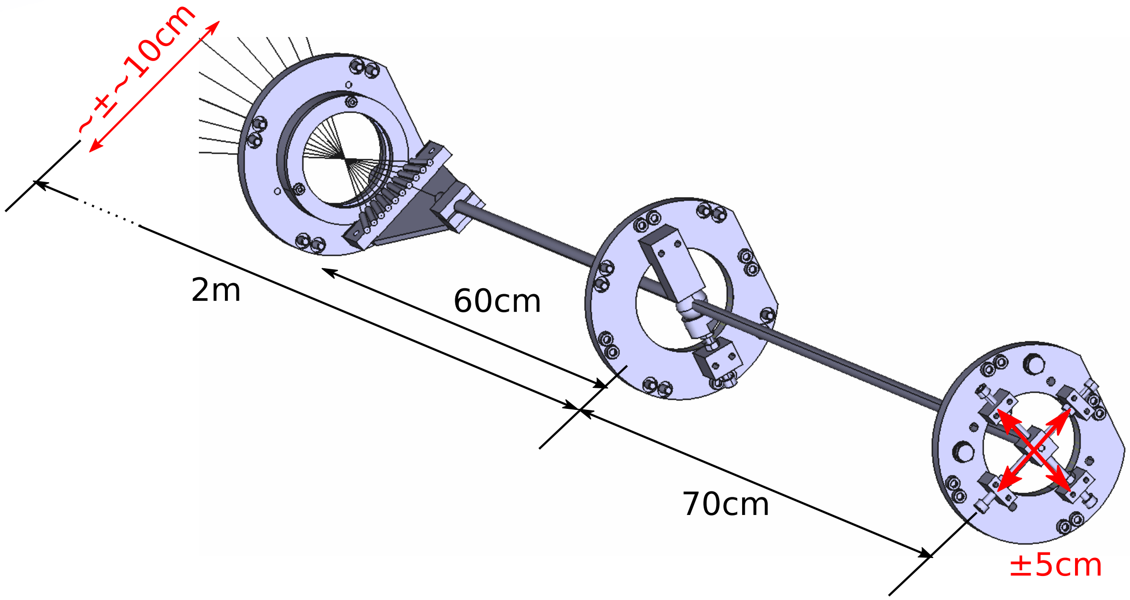
10 Fibres/Channels. Tracing CAD gives:
Good coverage edge - core + 1channel.





Optical head tiltable by many degrees when optics are out of imersion tube.
Fine positioning in-place from steering mechanism.

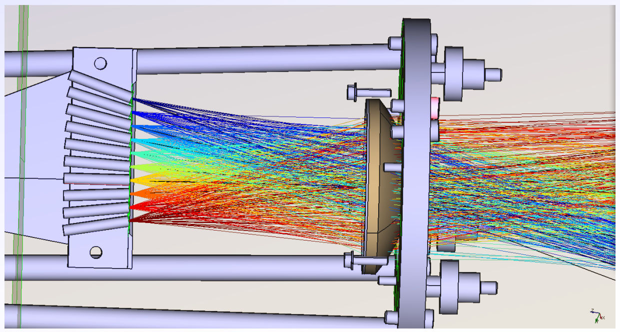
Immersion tube designed OP2 ready and thoroughly tested.



RuDIX CXRS - Fibre Focus Optimisation

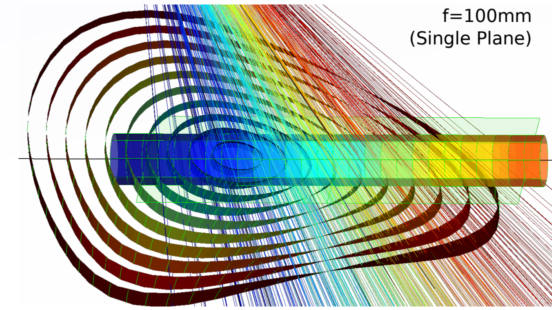
Fibres are 10x Bundles of 54x 100µm (125µm jacket), ~1mm end diameter, Length = 30m, NA=0.28
Lens is Planar Convex BK7 f=100mm d=80mm (f/1.25).
Both already purchased + delivered.

With current design (06/11/2015) and current lens (although head can be moved):

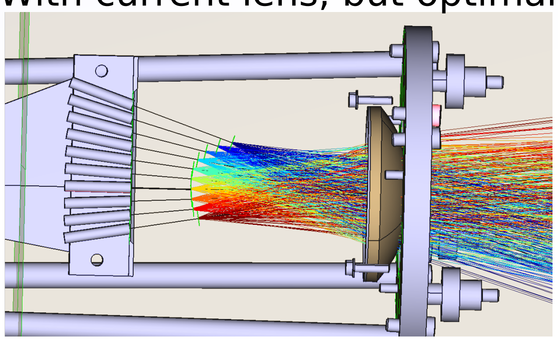


Very poor resolution: 13 - 20cm
Core:13cm Edge:18cm FWHM

a=130mm, NA=0.31, 85% capture

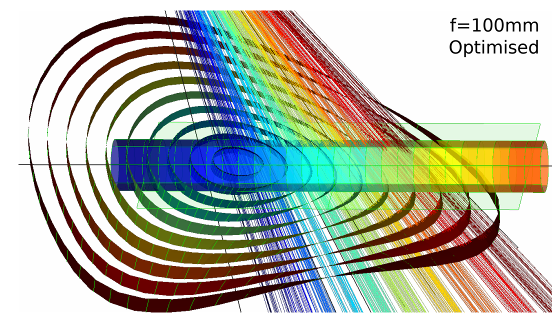


With current lens, but optimal fibre positions:

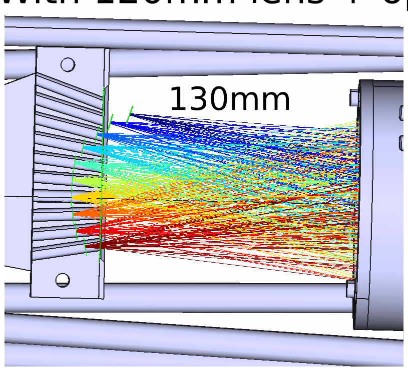


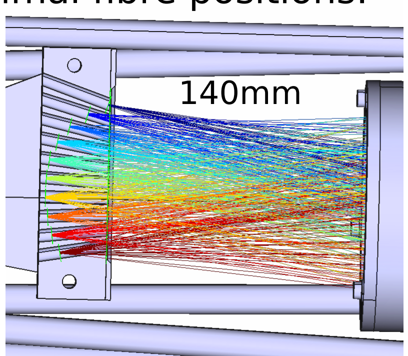
Better resolution: 3.5 < ΔR < 4.6cm

a=100mm, NA=0.40, 50% capture



With 120mm lens + optimal fibre positions:

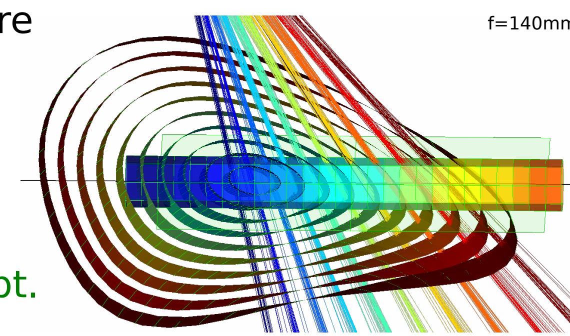




120mm: 1.5 < ΔR < 2.0cm,
a=130mm, NA = 0.31, 85% capture

130mm: 1.4 < ΔR < 2.0cm
a=140mm, NA = 0.29, 96% capt.

140mm: 1.2 < ΔR < 2.0cm, *
a=153mm, NA = 0.26, 100%+ capt.

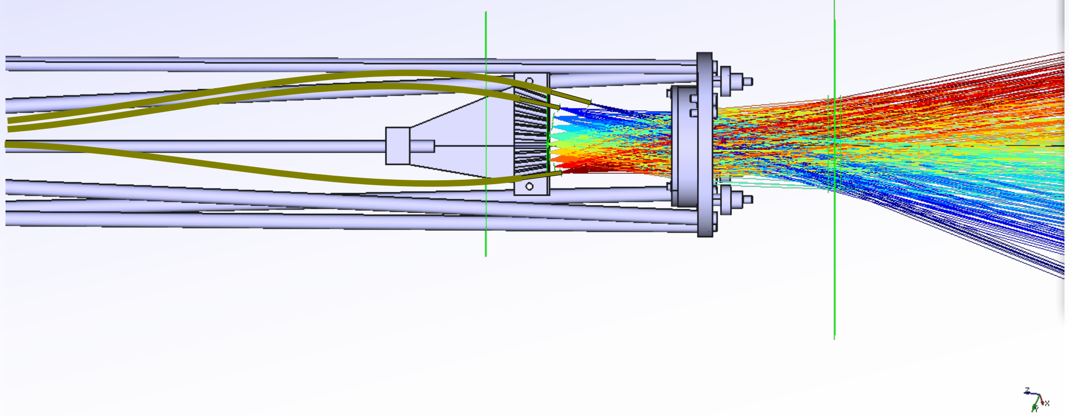


*Need to optimise the fibres to the light cone axes too (due to vignetting). *Spectrometers are f/6 (NA=0.08)

RuDIX CXRS - Fibre Focus Optimisation

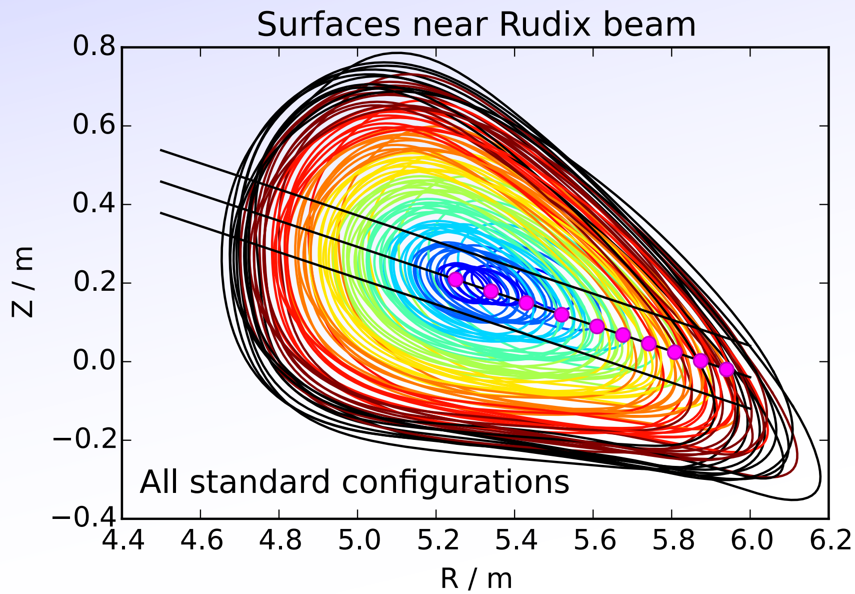
Other considerations:

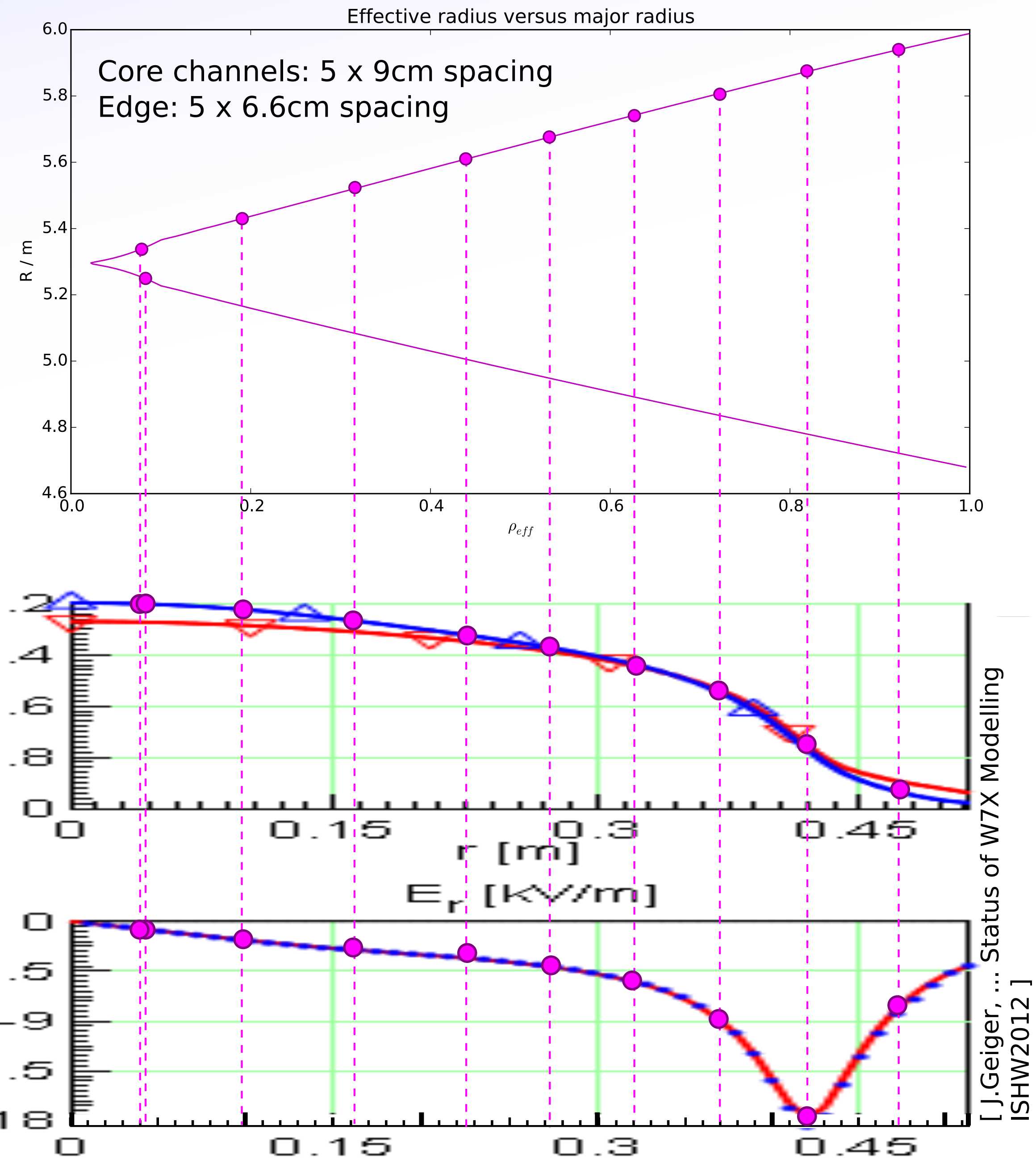
- Channel spacing: Where exactly do we want to look at?
- Fibre bending: Is angle to light cone too tight to bend the fibre bundle to it?



CXRS Requirements

Current design for RuDIX CXRS has 10 equally spaced fibres.

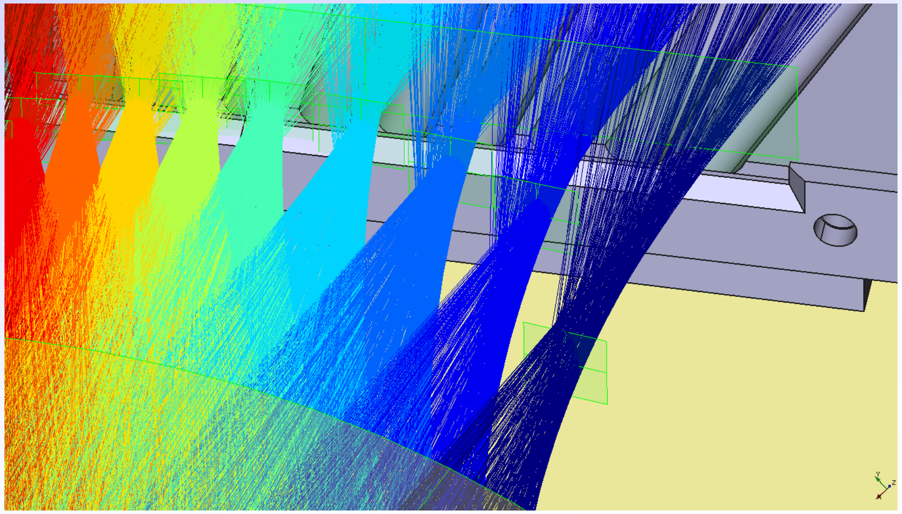




10 channels split into 2 groups:
Core: 5x 9cm spacing.
Edge: 5x 6.6cm spacing.

2 central channels straddle core for β=0%
and for finite β will move towards 2nd.

CXRS Rudix Optimisation

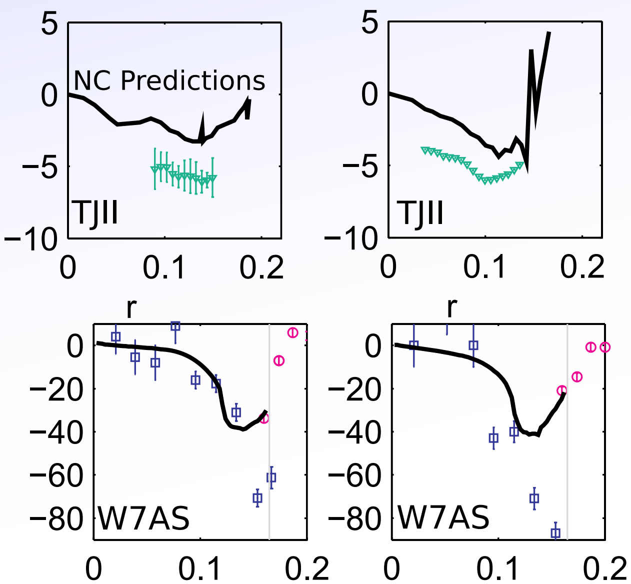


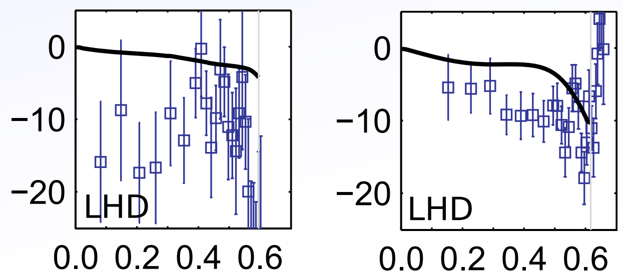
Reoptimised focus to find best only in δR (ignoring δφ width)
Now:
δR = 1.8 - 3.5cm at NA=0.28 (fibres)
δR = 1.0 - 1.7cm at NA=0.125 (f/4 spectrometer)

CXRS Requirements

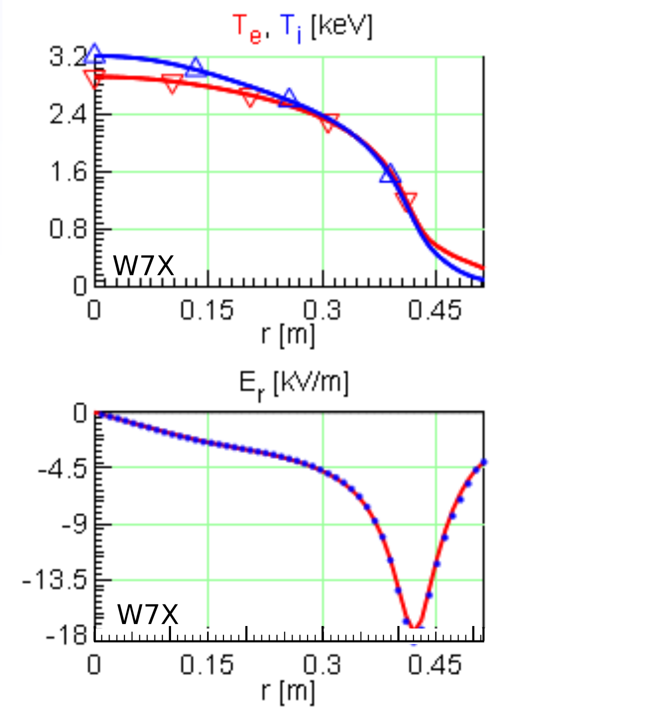
Primary requirements are accurate, well resolved measurements of T_i, n_i, E_r, V_φ.

What do we need to resolve?
Some predictions and measurements from elsewhere:





[A.Dinklage ...
Nucl Fus 53 2013]



[J.Geiger, ... Status of W7X Modelling
ISHW2012]

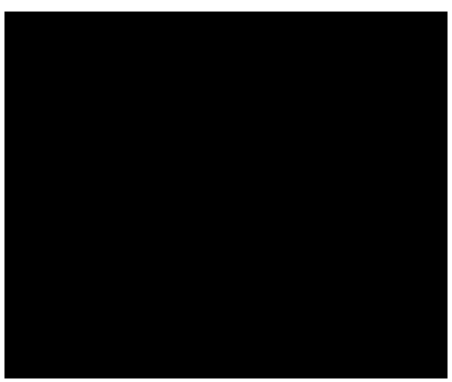


FIG. 3. Spectroscopically measured ion temperature prof le dots together with a f t of a generalized Gaussian function solid line to the measurement.

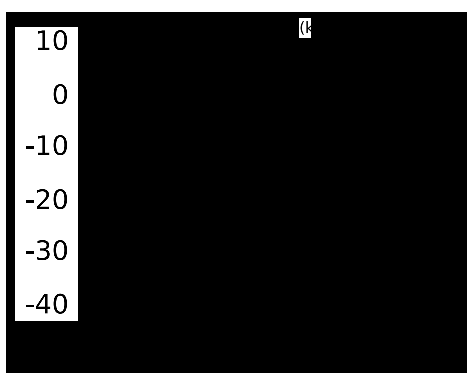


FIG. 4. Spectroscopically measured radial electric f eld dots , and Langmuir probe measurement squares . The solid line shows the result of the neoclassical DKES calculation.

[J.Baldzuhn, ...]

So, for Er, generally suspect that we'll be looking at |Er| < 50kV/m and wanting to see details down to:
Preferably: δEr ~ 1kV/m, At the very least: δEr ~ 5kV/m.

B_φ ~ 2.5T so E_r=1kV/m --> v_θ ~ 400m/s.
At λ~500nm (HeII/CVII), --> Δλ ~ 0.7pm!!

Expect small / uninteresting values in core, with more detail in the last ~5cm.

For Ti - also expect more interesting edge.

CXRS Capabilities (AUG)

AUG Edge CXRS: f/4 Lens-based Czerny-Turner, f=280/180mm
2400 grooves/mm
512x512 16µm ProEM back-illuminated frame tranfer CCD
13.1nm wide @494.5nm
50µm entrance slit --> 32 - 46pm
Lens ???mm - ~ 1m from beam
25x LOS
ΔR = 3mm!!, **Δt = 2.7ms, δv = ±<1km/s** (1.65pm)

Core CXRS 1: (NBI1, CER)
91x 400µm fibres (3 rows (BES+CXRS+FIDA), 30x fibres / row, 1.6cm vert. sep. at beam)
Optical head: Nikon f/1.8 Obj + AR coated Al mirror, 2.5cm optical resolution
f/4 Czerny-Turner 2400 g/mm
512x512 16µm ProEM back-illuminated frame tranfer CCD
13.1nm wide @494.5nm
0-400µm entrance slit. @100µm --> 67 - 75pm instrument function.
Lens ???mm - 2.5m from beam
usual B after Boronisation, can switch to C, N etc
ΔR = 2.5cm, **Δt = 3.5ms - 10ms, δv=±10km/s core**, 1km/s edge

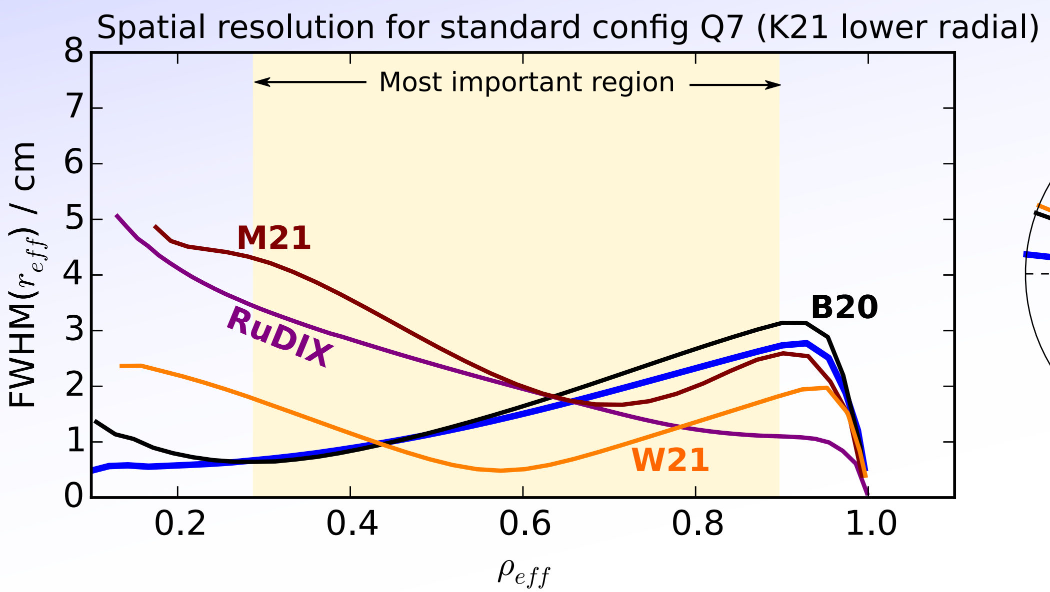
Core CXRS 2: (NBI2, COR/CUR)
Optical head ?,
10x LOS, 5-6cm resoltion
400µm fibres
f/6.5 Czerny-Turner 2400g/mm f=500mm,
Typically 100µm slit --> 38 - 58pm instrument function
Lens ???mm - 1.8m from beam
usual B after Boronisation, can switch to C, N etc
ΔR = 5cm, **Δt = 7.5 - 20ms, δv ~ ± 10km/s,** 1km/s edge, δTi ~ -±30ev - ±100ev

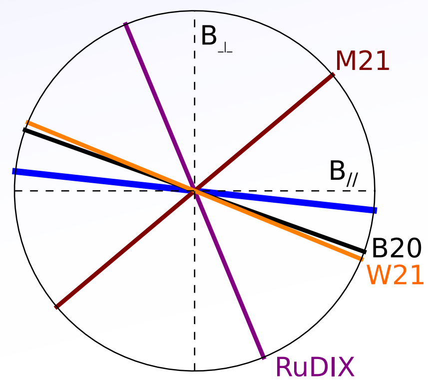
AUG Parameters comparative:
AUG: ne 5 - 10x1019,
W7X: 10 - 20x1019

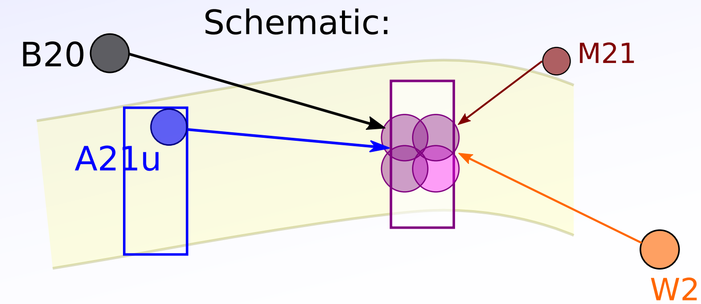
Same NBI.
Core-Edge distance ~the same.
AUG: W wall; so much less C
AUG uses B from Boronisation, not sure how that will work for W7X.

NBI CXRS: BMW Options

Looking more closely at B20, M21, W21 ports..

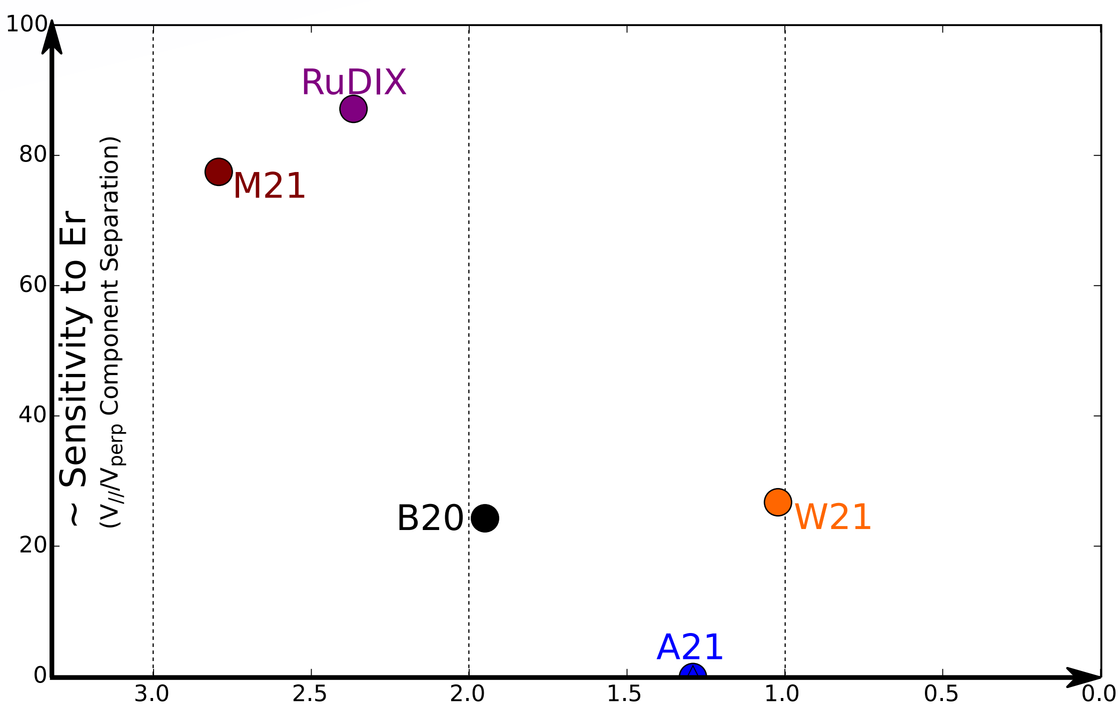






Port occupancy:

- **A21:** Primary core T_i, n_i system.
- **B21[(K20)] :** Sniffer probes
- **M21:** Visible bulk spec (OP2+)
- **W21:** Bolometry (OP2+)

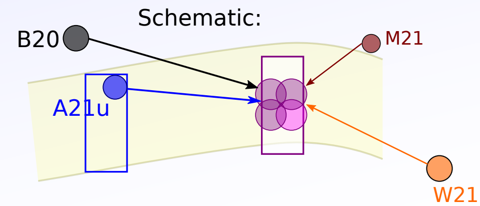


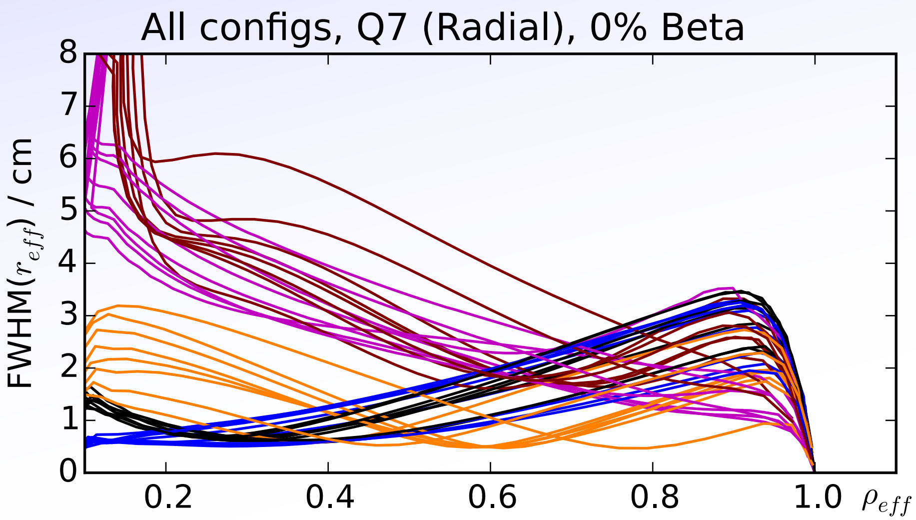
General summary:

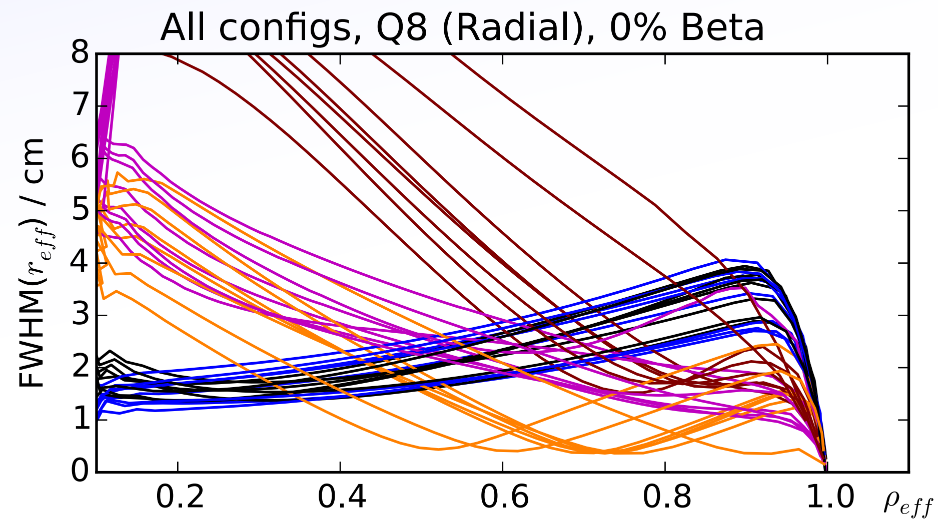
- **M21**: Good angle, OK resolution, port free until OP1.2, can probably keep it much longer if the CXRS is good. Plausible design, even for OP2.
- **B20**: OK resolution, v.good in core, E4 want the port for OP2+ (Li beam). Difficult to share for OP2.
- **W21**: Best resolution in important region. Difficult design, very hard for OP2. Reserved for bolometry (E5) for OP2+.

NBI CXRS: BMW Options

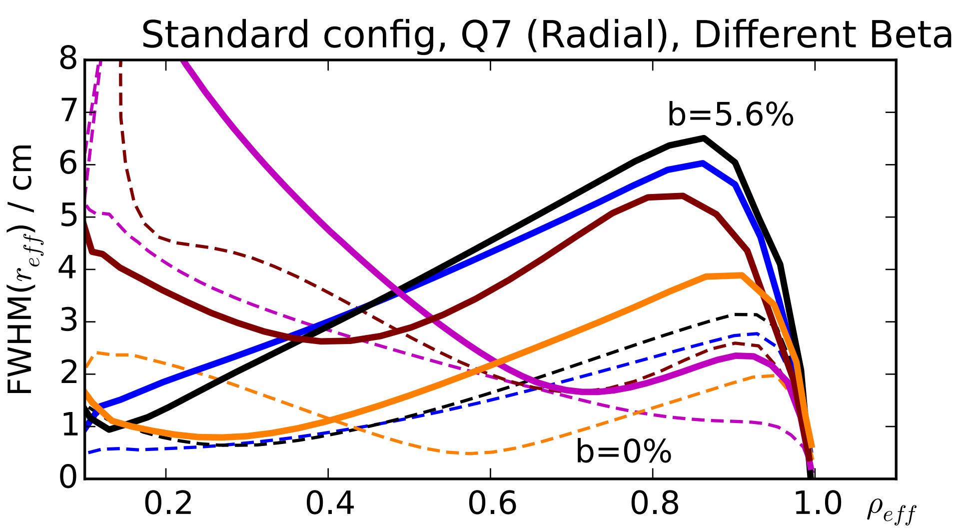
All systems resolution depends on choice of beam and magnetic config, mainly due to the outward shift. Q7 (Radial) gives better resolution, but Q8 ('Tangential') desired to reduce shinethrough/fast ion losses. **M21** particularly poor resolution in core for Q8.

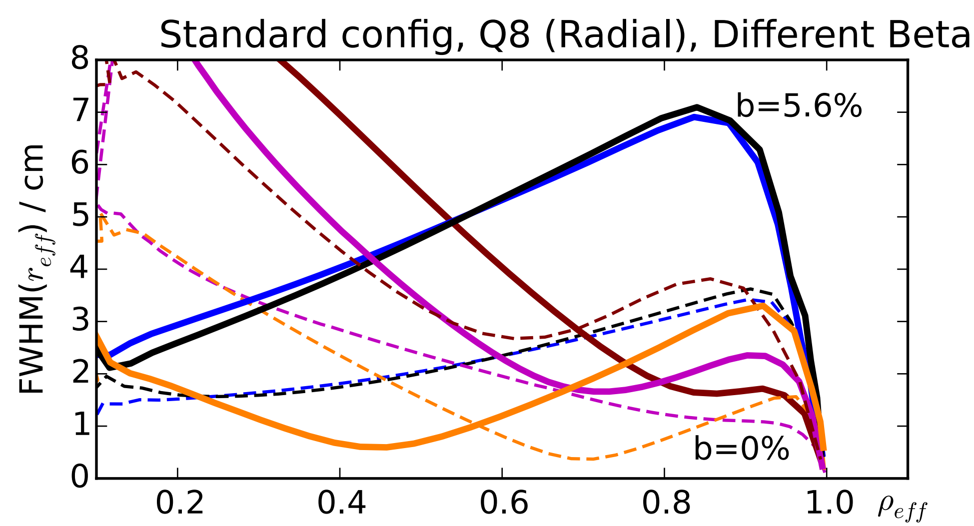




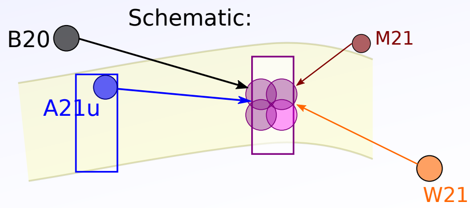


All NBI systems measure on outboard ~midplane of intermediate plane. Beta has large effect on the mapping to reff and so effective resolution is deminished at high beta. RuDIX CXRS would be less effected.

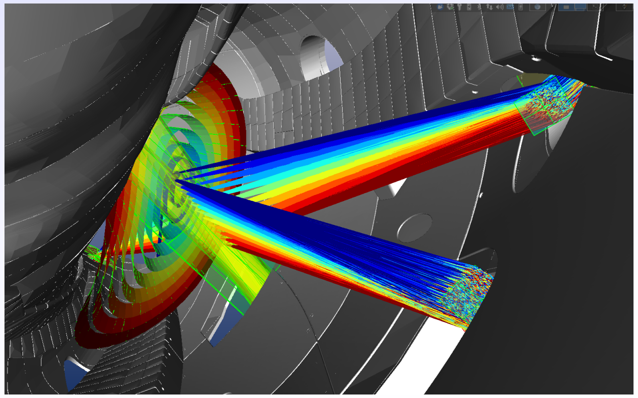


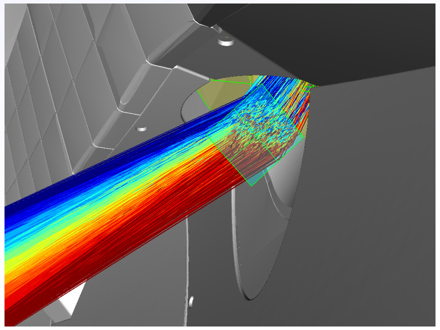


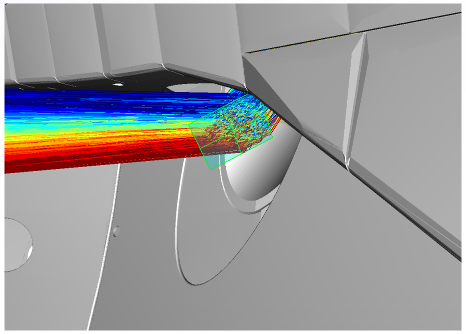
NBI CXRS: B20 Plausibility.

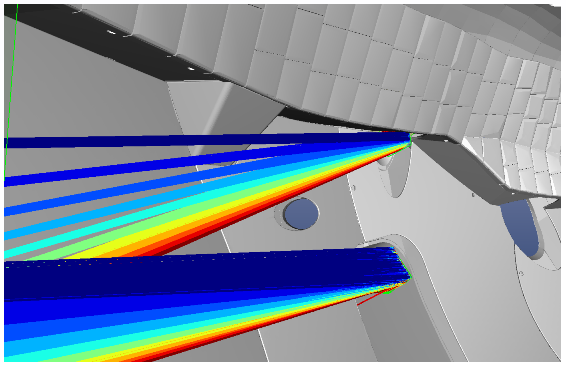


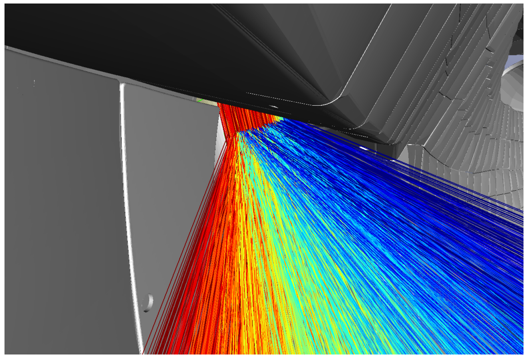
Looking at plausibility of ports, very rough model in ray tracer.
B-port

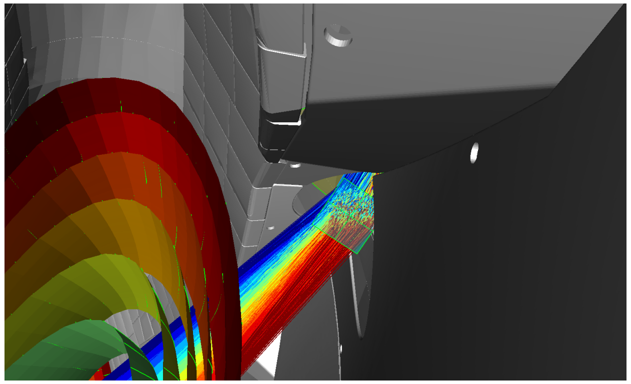


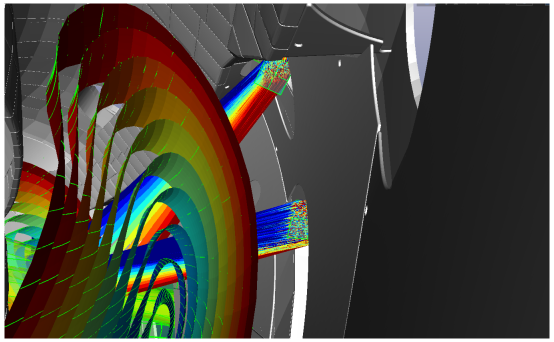




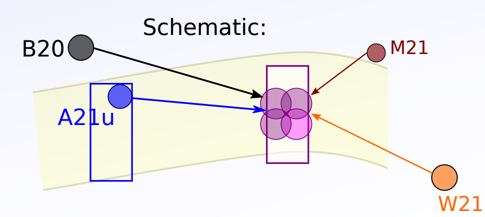




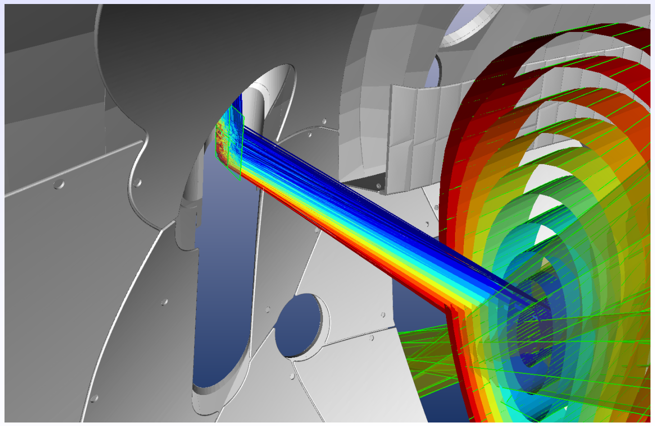


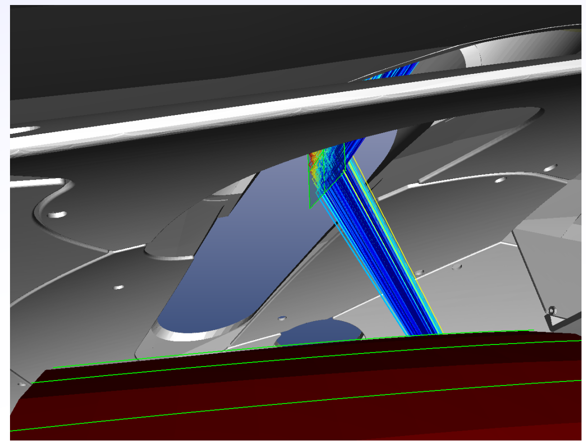


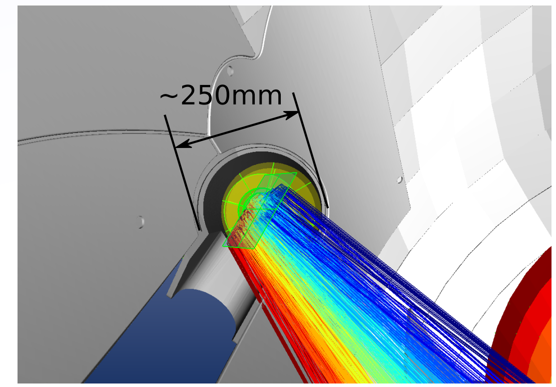
NBI CXRS: M21 Plausibility.

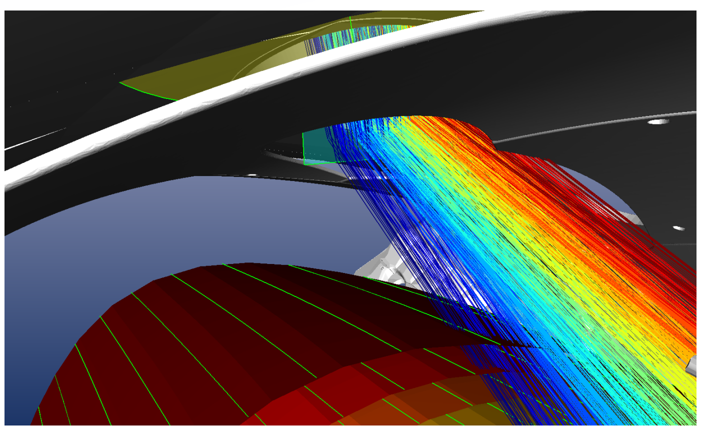


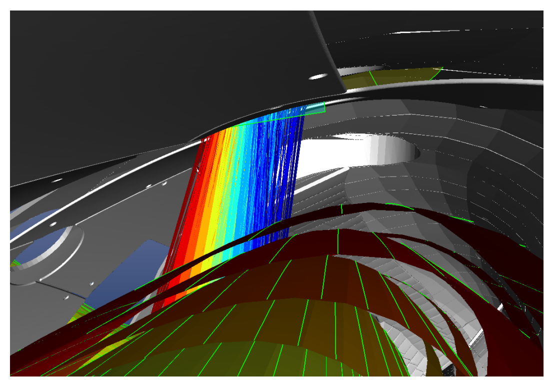
Looking at plausibility of ports, very rough model in ray tracer.
M-port

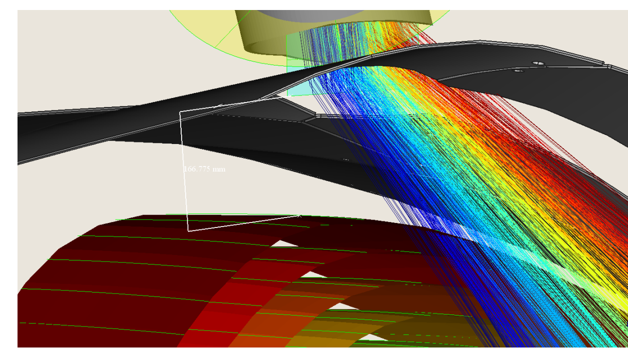




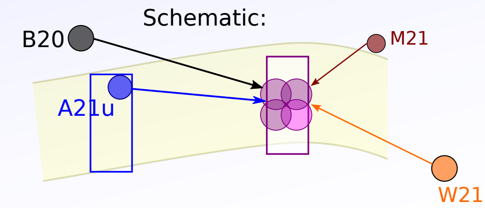




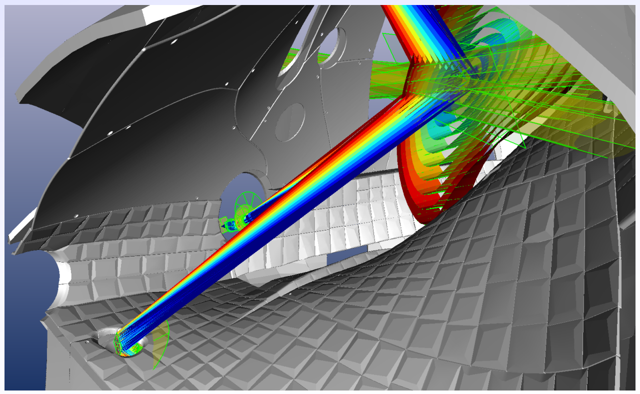


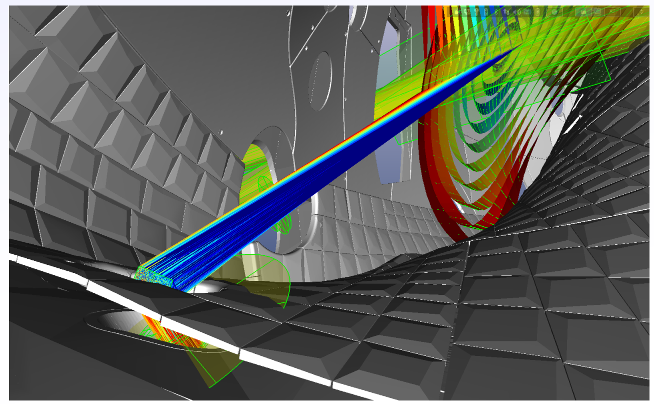


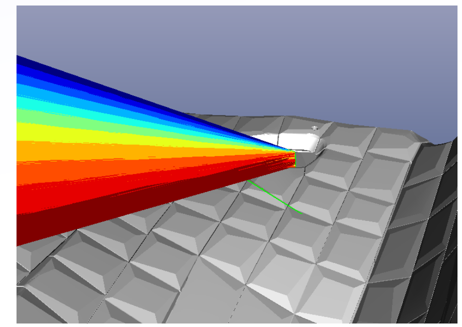
NBI CXRS: W21 Plausibility.

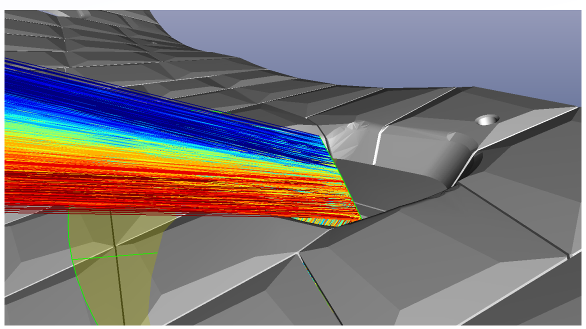


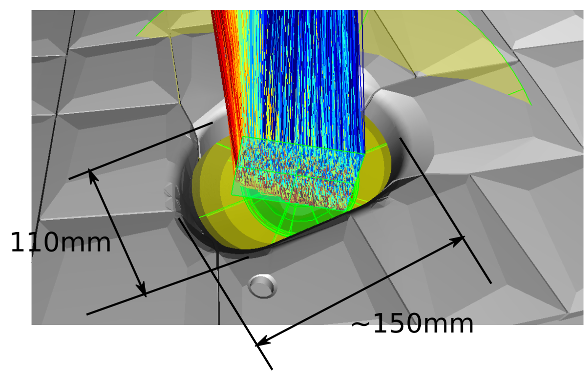
Looking at plausibility of ports, very rough model in ray tracer.
W21 port

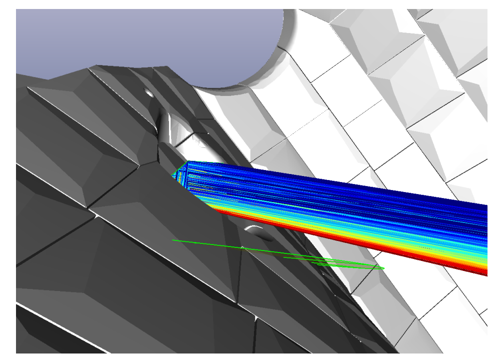


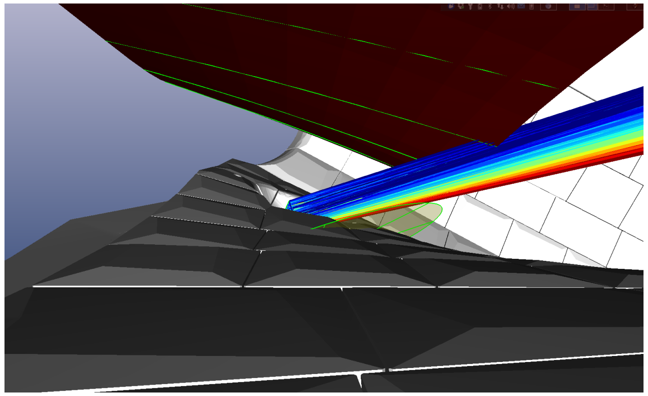


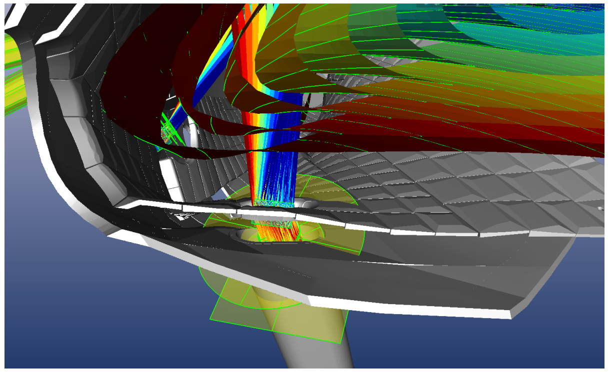






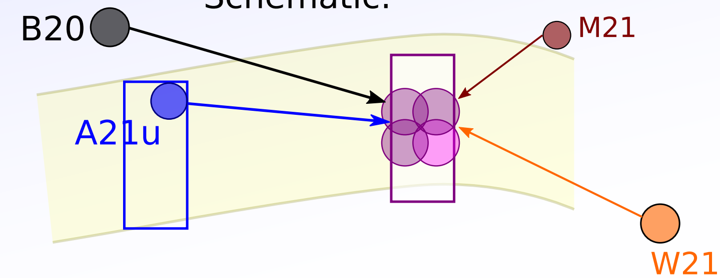






NBI CXRS: BMW Options

Looking more closely at B20, M21, W21 ports..

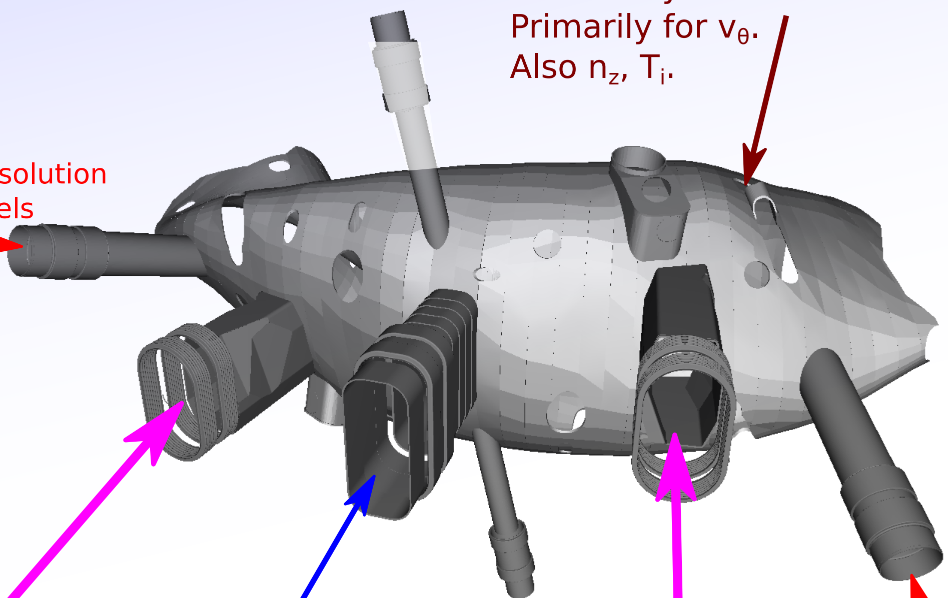


Port	Resolution Core	Resolution Edge	Er Sensitivity	OP1.2 Availabilty	OP1.2 Complexity	OP1.2 Availabilty	OP1.2 Complexity	
A21	1cm	3cm	N/A	Already Reserved	Easy (~ 1 Month)	Already Reserved	Possible	Primary system.
M21	5cm	3cm	80%	Free	Easy (~ 1 Month)	E4 (Baldzuhn) Bulk Spec	Possible	Should build.
B20	1cm	3cm	25%	E3 Sniffer Probes (exchange B20/B21)	Easy (~ 1 Month)	E4 Li Beam Bulk Spec	Possible	Could build, doesn't gain much.
W21	2cm	2cm	25%	Free	Hard Few months	~~E5 Bolometry~~	~~**Effectively Impossible**~~	Very difficult Low return.

CXRS on NBI: Optical heads

aeM21
Secondary NBI CXRS
Primarily for v_θ.
Also n_z, T_i.

aeT20
~10cm resolution
~5 channels



aeA21
Primary NBI CXRS
1 port for OP1.2
n_z, T_i, v_φ

aeT21
Additional
~10cm resolution
~5 channels

NBI at source.

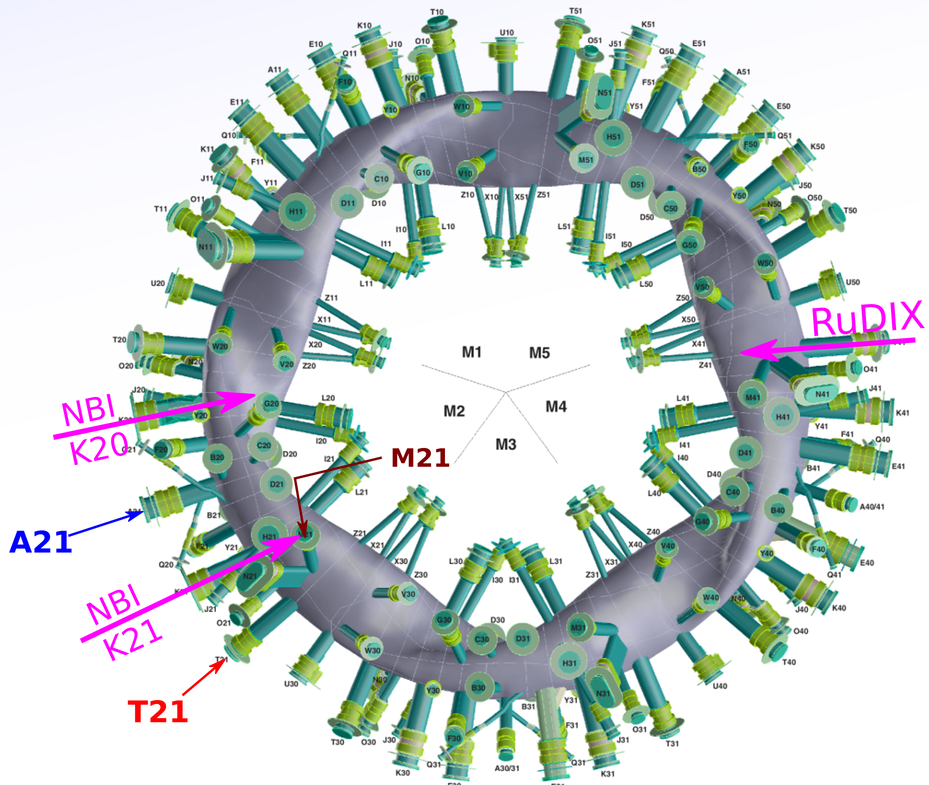
aeK20
NBI 1-4

2	1	Lower
3	4	Upper
Radial	Tangential	

aeK21
NBI 5-8

8	7	Lower
5	6	Upper
Tangential	Radial	

- 3,4,7,8 comissioned first in OP1.2
- Tangential beams produce less fast-ion losses
- 4,8 have He capability.



CXRS on NBI: Optical heads