Performance Simulation of the ITER MSE Diagnostic

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Outline

- MSE measurement requirements
- Baseline plan for MSE polarimetry on ITER
- Modifications to the perf code
- Spectral overlap from HNB 4 and 5
- Spatial resolution
- Effect of vertical angular spread of beams
- Uncertainty in pitch angle measurement
  - Noise due to visible Bremsstrahlung
  - Sensitivity to beam voltage, plasma density, viewing geometry, VB subtraction.

MSE measurement requirements

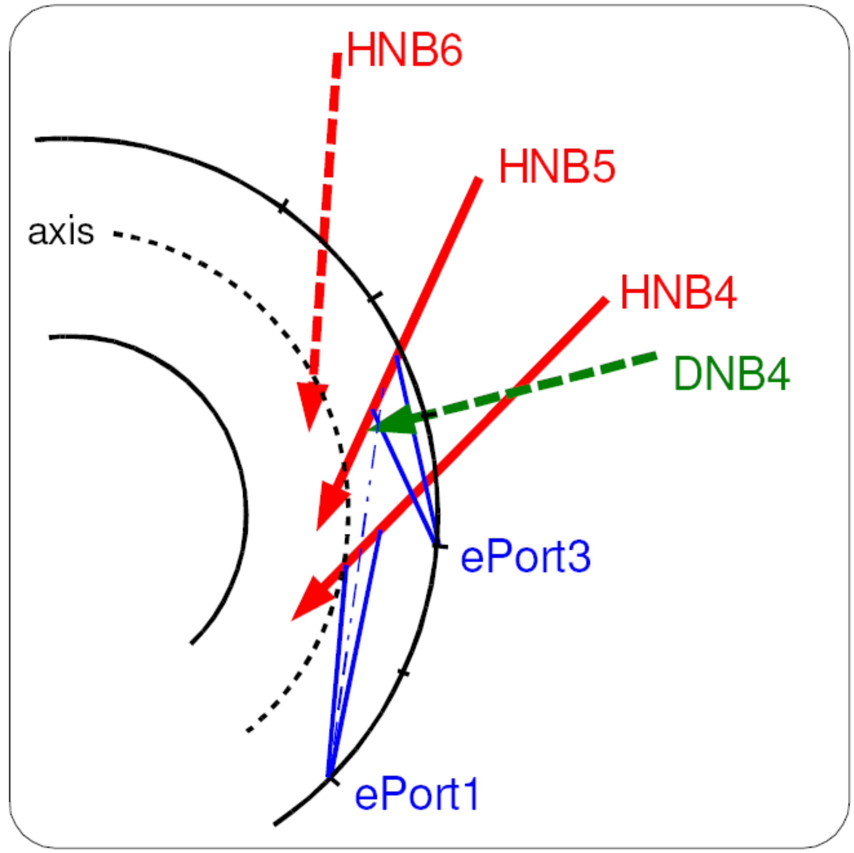
- From "Reference Level 1-ITPA Diagnostic Group Approved Specifications", March 2005:

MEASUREMENT	PARAMETER	CONDITION	RANGE or COVERAGE	RESOLUTION		ACCURACY
				Time or Freq.	Spatial or Wave No.	
25. Current Profile	q(r)	Physics study	0.5 – 5	10 ms	a/20	10 %
			5 – TBD	10 ms	a/20	0.5
	r(q=1.5,2)/a	NTM feedback	0.3 – 0.9	10 ms	–	50 mm/a
	$r(q_{min})/a$	Reverse shear control	0.3 – 0.7	1 s	–	50 mm/a

- a=2.0 m → a/20=0.10 m
- Other requirements:
  - Diagnostic must be able to follow three beam aiming scenarios with Z at tangency: -0.131 m (reference), 0.156 m (on-axis), and -0.417 (off-axis)
  - Diagnostics must be able to function with beam energies in 0.4-1.0 MeV range

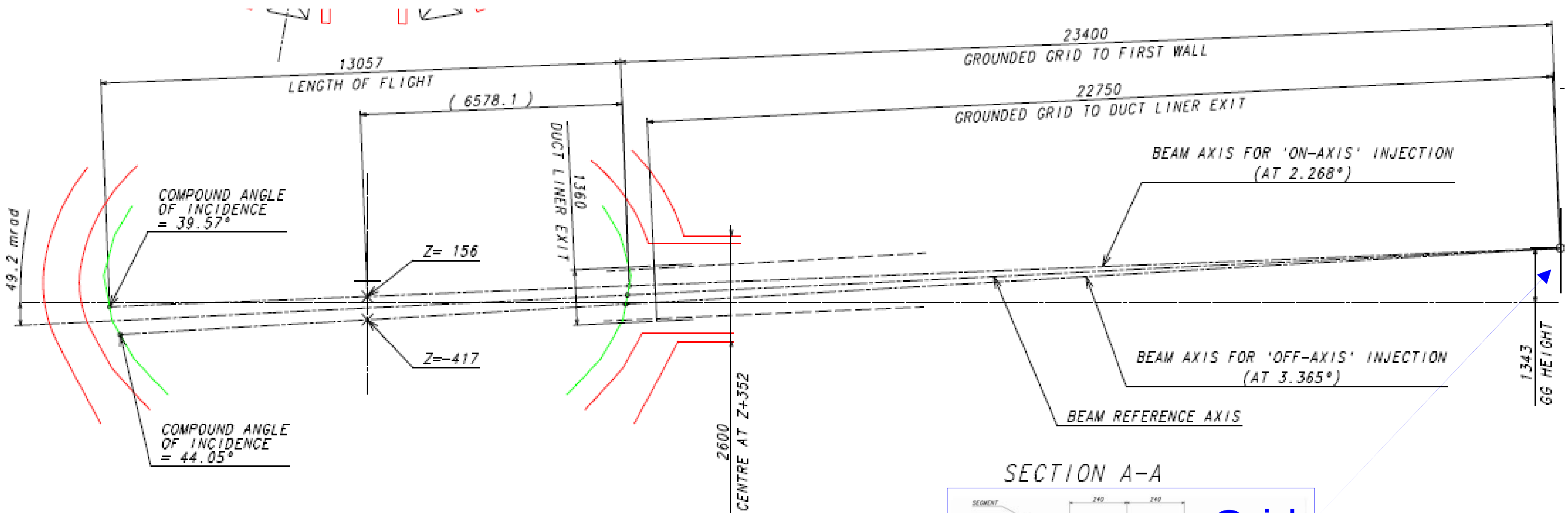
Baseline MSE diagnostic design

- Design study done by EU group (Hawkes, Lottle, Malaquias, Kuldkepp, and Rachlew) used to develop baseline design
- System views heating neutral beams (1 MeV) to give measurable signal in core
- Two views needed to achieve good spatial resolution (Z=elevation of viewing optics above machine midplane):
  - Core: ePort 1 view of HNB4 (Z=1.278 m – above port plug midplane)
  - Edge: ePort 3 view of HNB5 (Z=0.67 m – on port plug midplane)

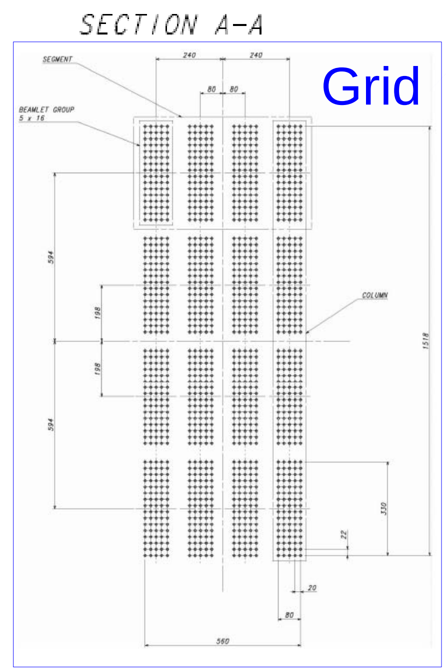


N. Hawkes

ITER beam geometry



- Grid consists of 16 groups of apertures (80 in each) in a 4 X 4 arrangement
- Three beam aiming scenarios with Z at tangency: -0.131 m (reference), 0.156 m (on-axis), and -0.417 (off-axis)



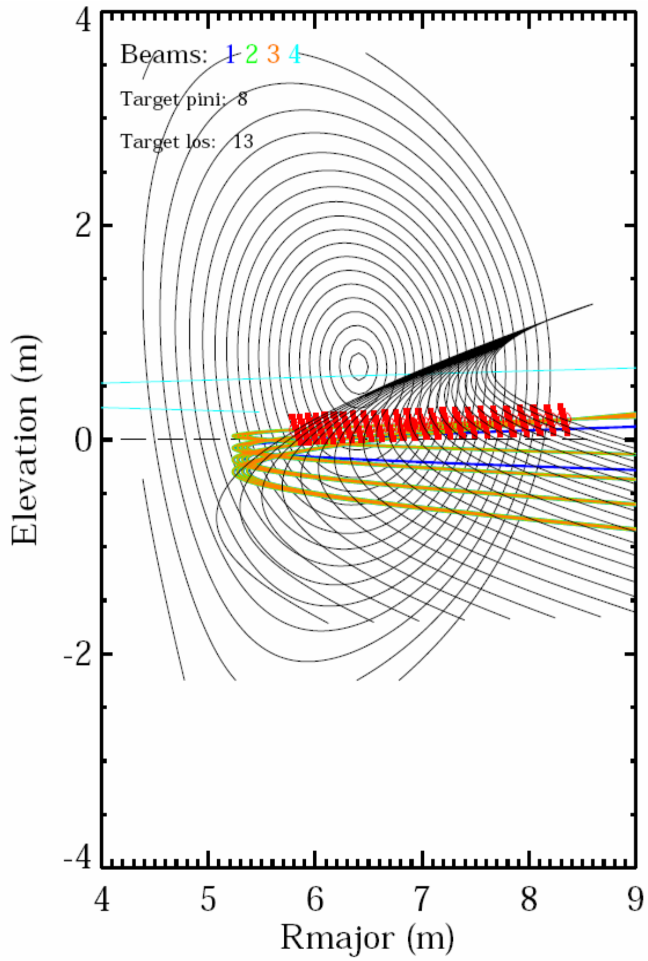
PERF code modifications

- Modified *PERF* code developed by N. Hawkes (UKAEA-Culham) to model MSE diagnostic performance on JET and ITER
- Output written to netCDF file for easy input to other codes and plotting via IDL or Java.
- Code reads EFIT equilibria
- Heating beam treated as 16 beamlets
  - Correct vertical elongation and divergence for each segment.
  - Beam neutral density represented as cut-off Gaussian for each segment.
  - Beam attenuation model does not include multi-step ionization processes.
- Visible Bremsstrahlung
  - Integrated thru plasma, specular reflection at torus wall.
  - Polarization at reflection computed from Fresnel equations.
  - Compute Stokes vector components just as for MSE signal.

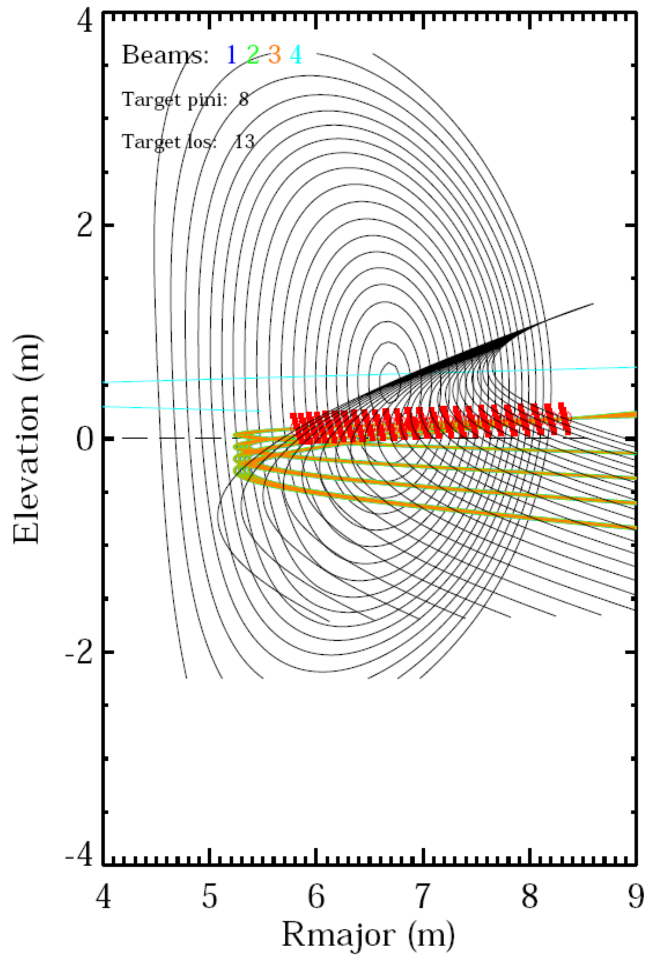
ITER beam footprint calculation

- Divides beam source accel grid into many small beamlets, each with a specified divergence.
- Follows individual beam trajectories through the ITER beamline, scraping off power where beams hit an aperture.
- Computes:
  - 2-D (horizontal and vertical) power distribution for each of 16 beam segments at 6 specified 'targets' along the beam trajectory
  - Full-width 1/e beam size in horizontal and vertical directions for each of the 16 beam segments and for the sum of the 16 segments
  - 'Total' beam size in horizontal and vertical directions, taken to be the size where the beam intensity drops to 2% of the maximum value
- Reasonable agreement with previously published ITER calcs.

EFIT equilibria read into *PERF*

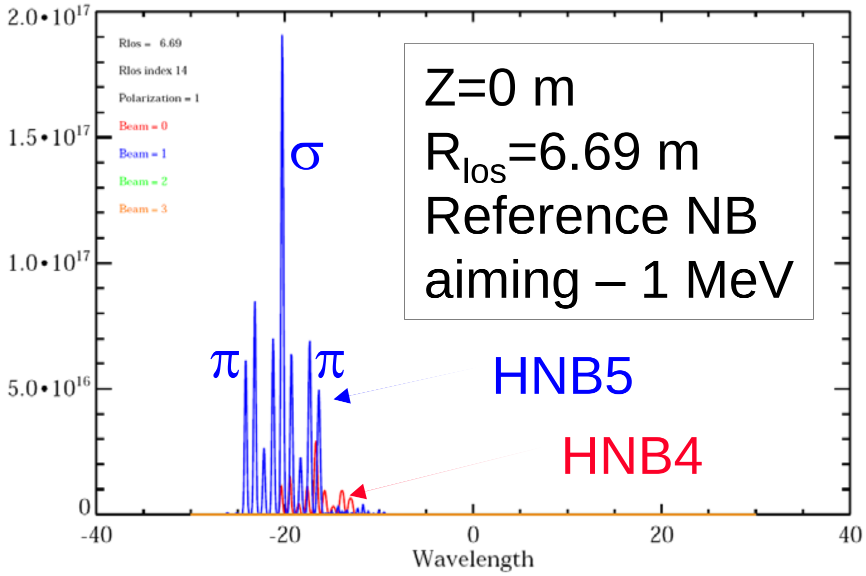


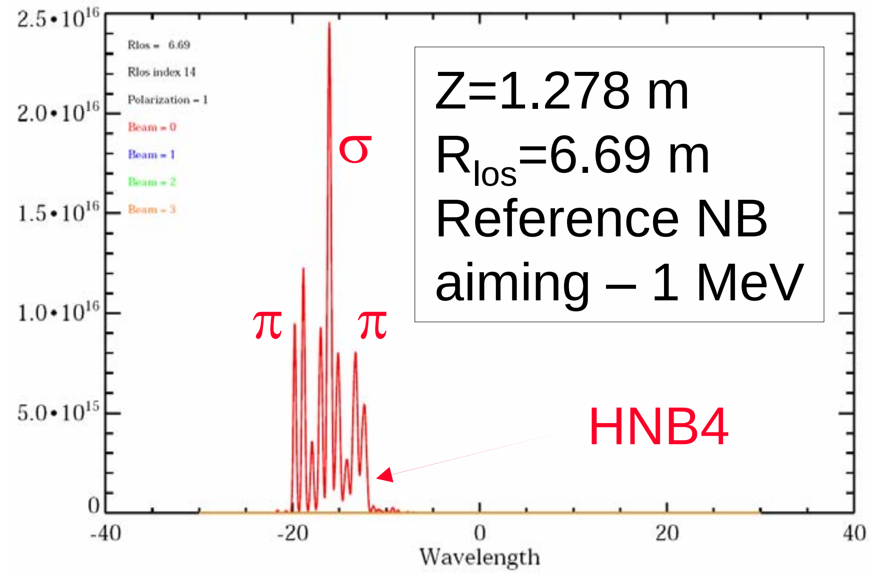
Scenario 2: 15 MA, Q=10, 400 s plasma



Scenario 4: 9 MA, Q=5, 3000 s plasma; β_N=2.57 case

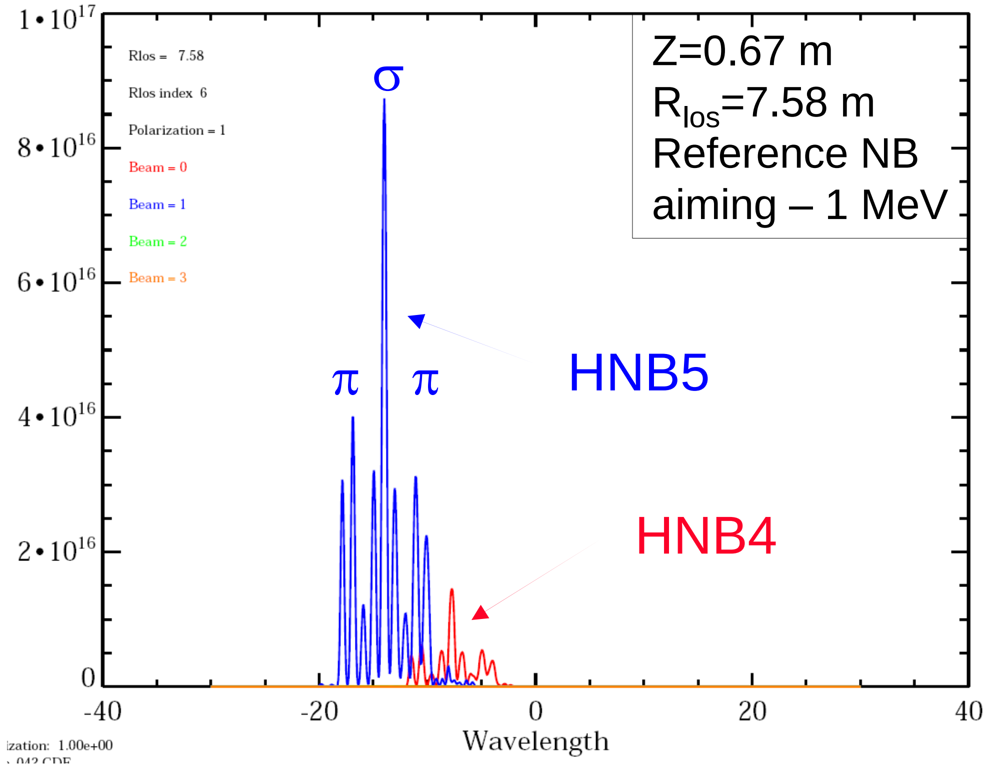
Off-midplane ePort 1 core view avoids spectral overlap





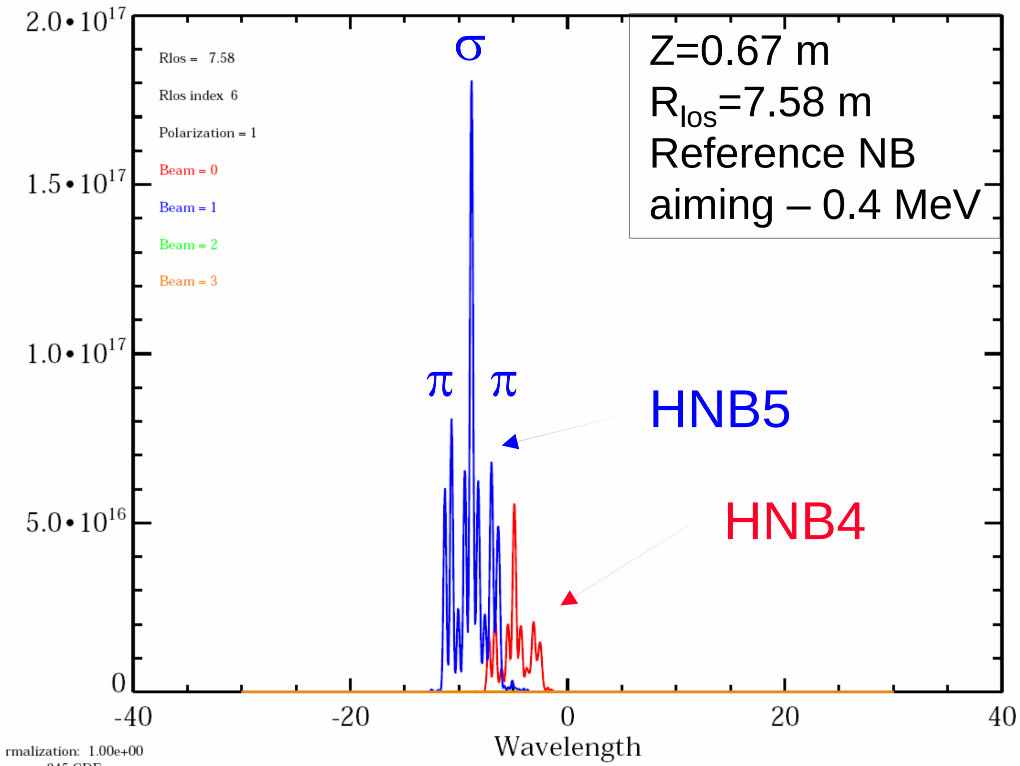
- Z=1.278 m ePort 1 view of HNB4 avoids spectral overlap of σ lines with HNB5 signal seen with Z=0 m view for R<7.0 m
- OK for reference, on-axis, and off-axis beam aiming
- Wavelength in units of Stark splitting (~1.5 nm) relative to unshifted D_{α} wavelength (656 nm)

Spectral overlap not a problem for ePort 3 edge view



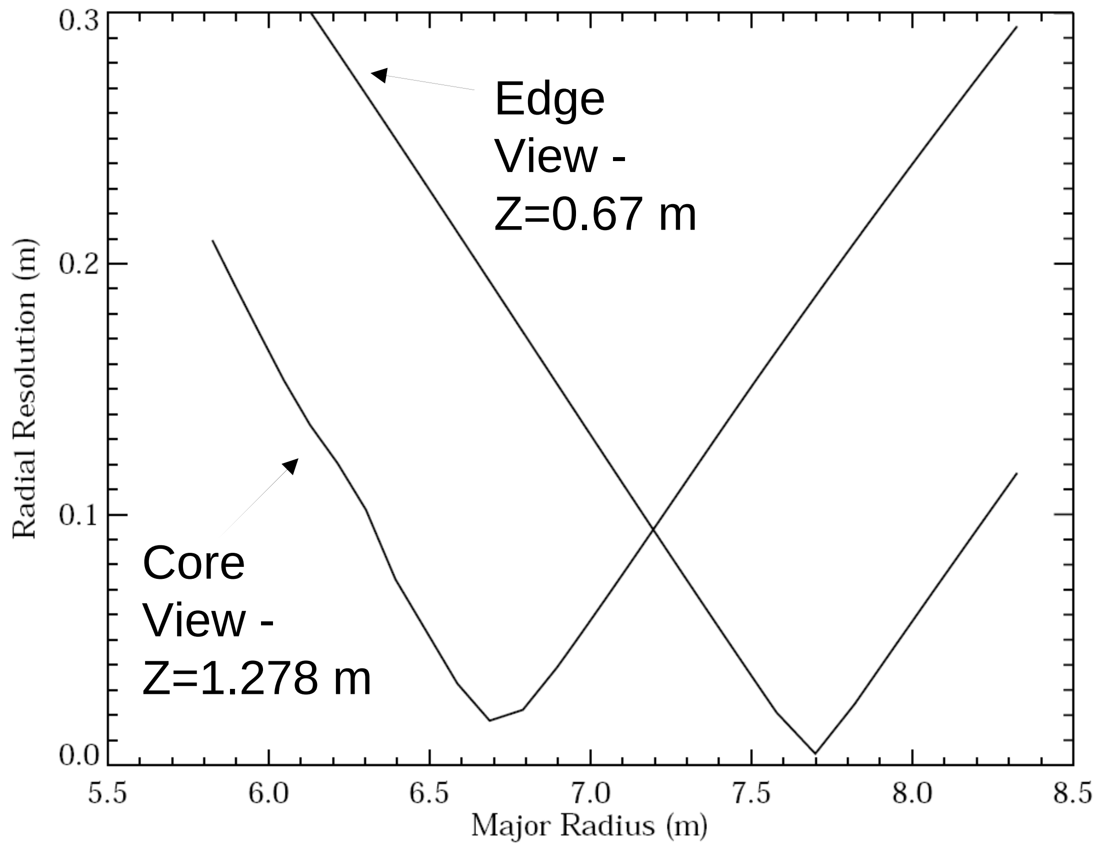
- Z=0.67 m ePort 3 view of HNB5 avoids spectral overlap with HNB4 signal
- OK for reference, on-axis, and off-axis beam aiming

Lower beam energy not a problem for ePort 3 view



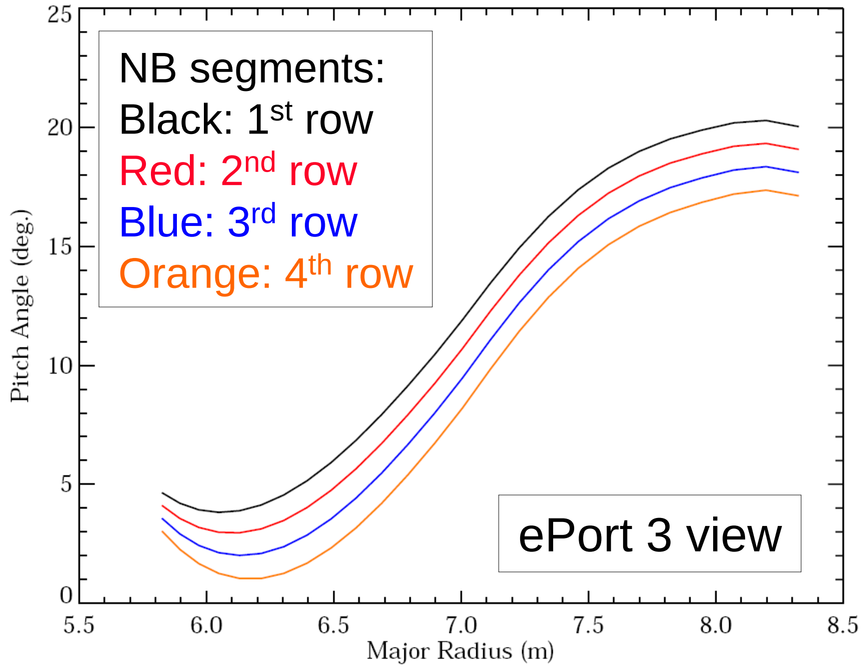
- No overlap of HNB5 σ lines with HNB4 emission with both beams at 0.4 MeV
- Lower beam energy also not a problem for ePort 1view.
- There will be problems if beams operate at significantly different voltages.

Good spatial resolution for core and edge views



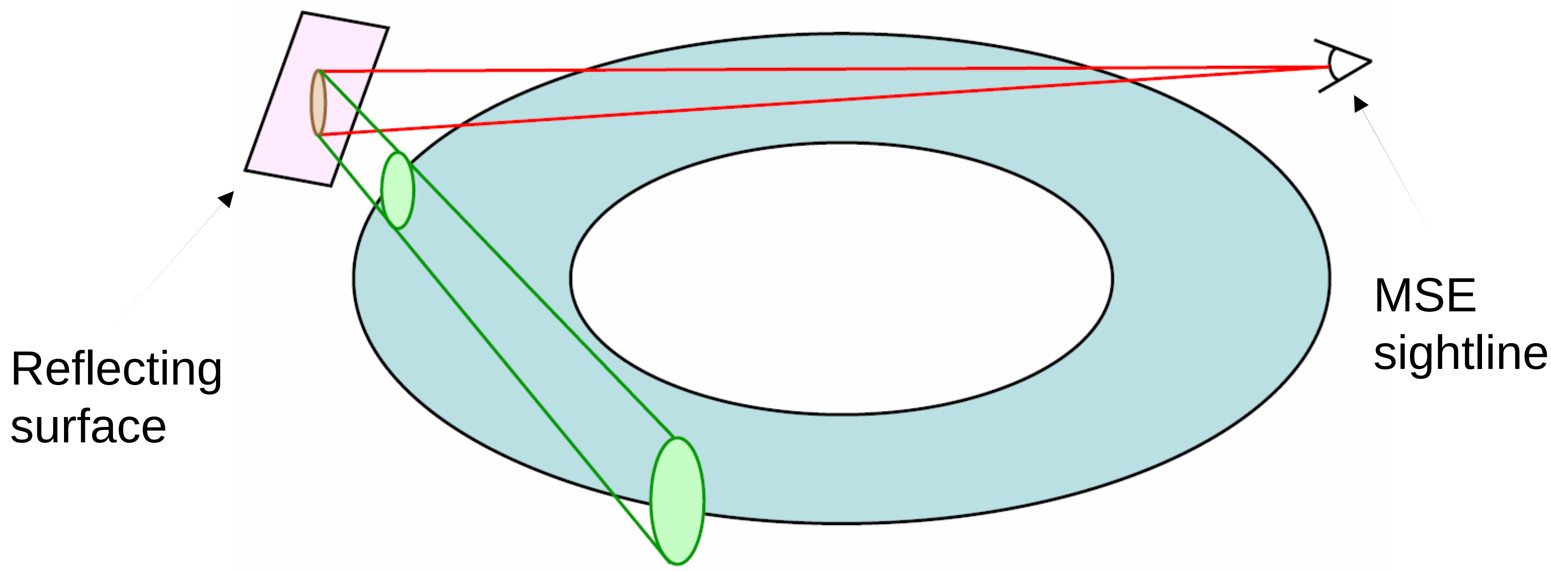
- Radial resolution ≤ 0.1 m for 6.3 m ≤ R ≤ 8.2 m meets measurement requirement.

Effect of vertical angular spread of beams



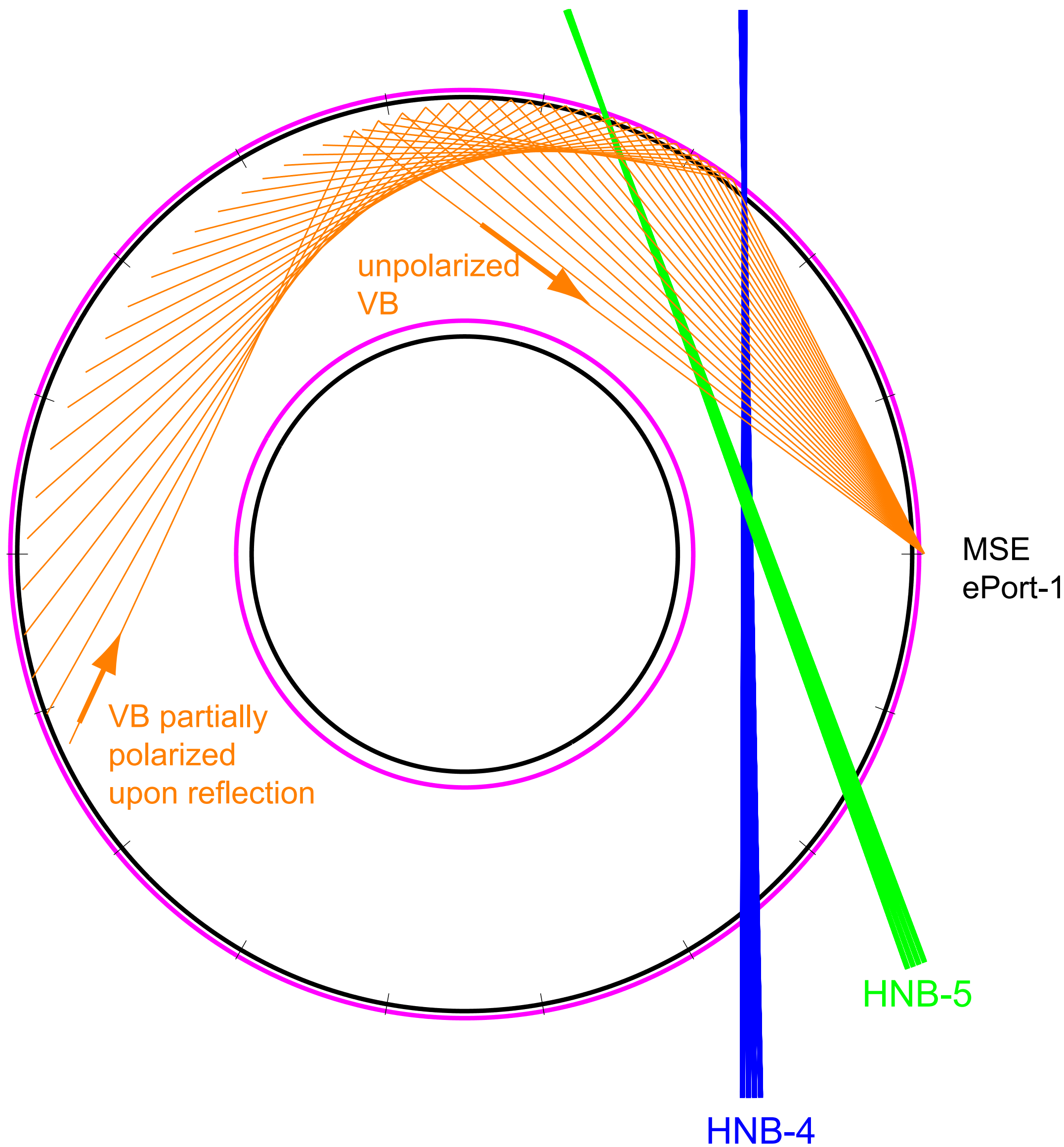
- Problem identified by N. Hawkes
- 4 rows of beam segments have vertical angular spread of 3°
- Leads to 2.8° spread in measured polarization angles
- MSE measurement very sensitive to stability of segments
- Individual segments can not be independently powered
- How to calibrate relative contribution of segments to signal?

Effect of bremsstrahlung on MSE measurement

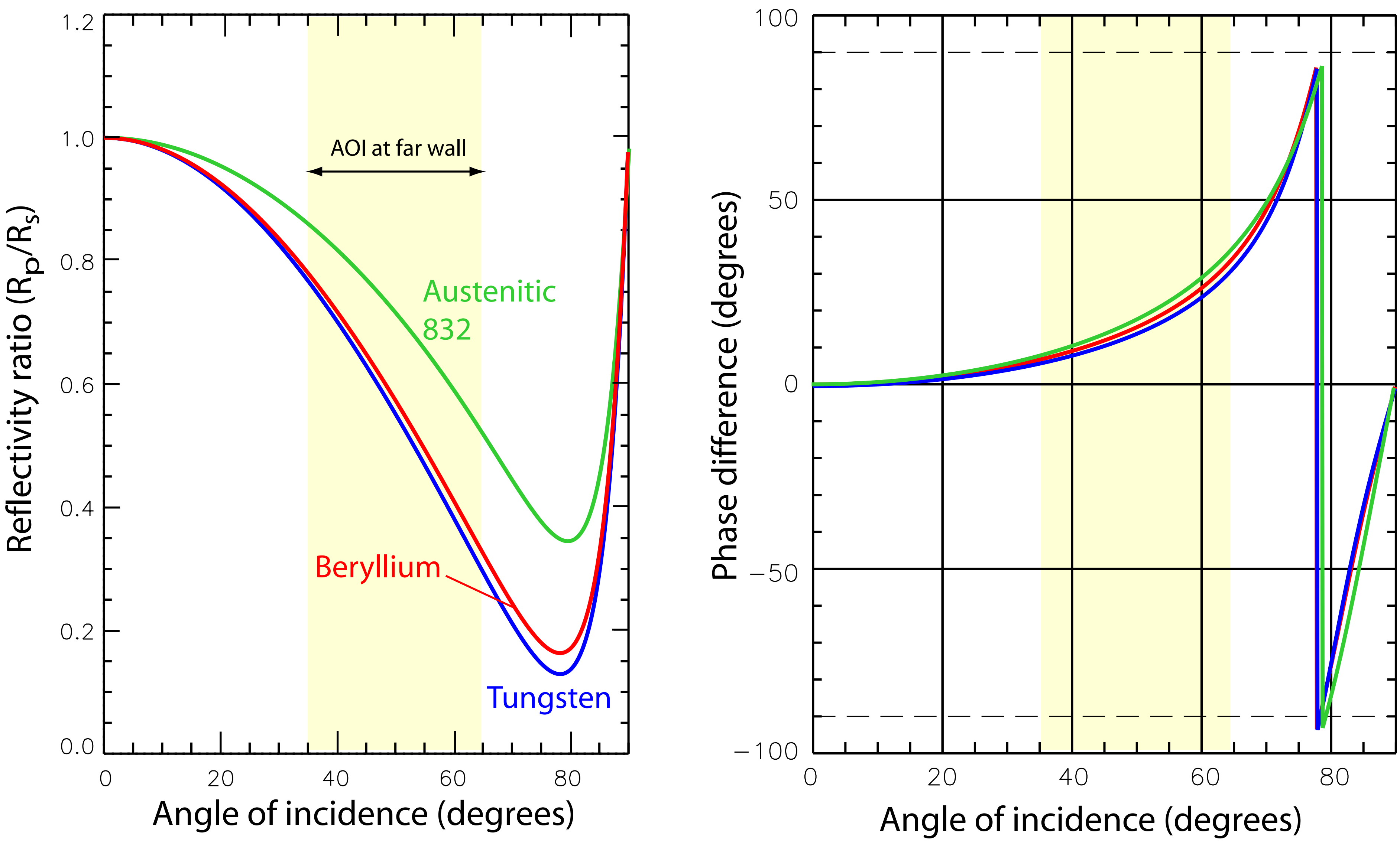


- Visible bremsstrahlung emission from ITER will be intense
- VB should not affect measured pitch angle but will contribute to noise on signal
- If partially-polarized due to reflections, VB will affect pitch angle measurement
- This effect has been seen in existing MSE systems
- These effects are being incorporated into code

Geometry of the visible Bremsstrahlung calculation



Optical properties of first wall materials are similar



Accurate subtraction of the visible Bremsstrahlung needed for accurate pitch angle measurements

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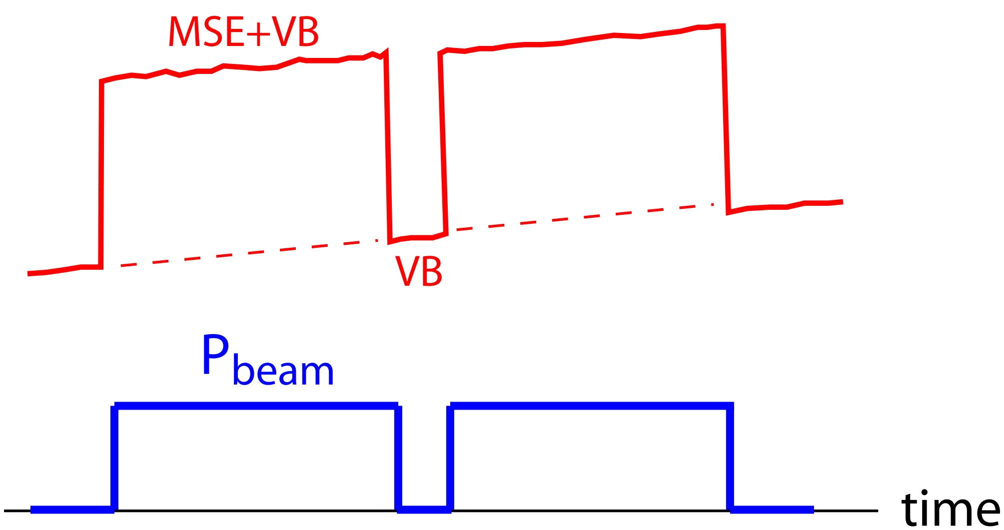
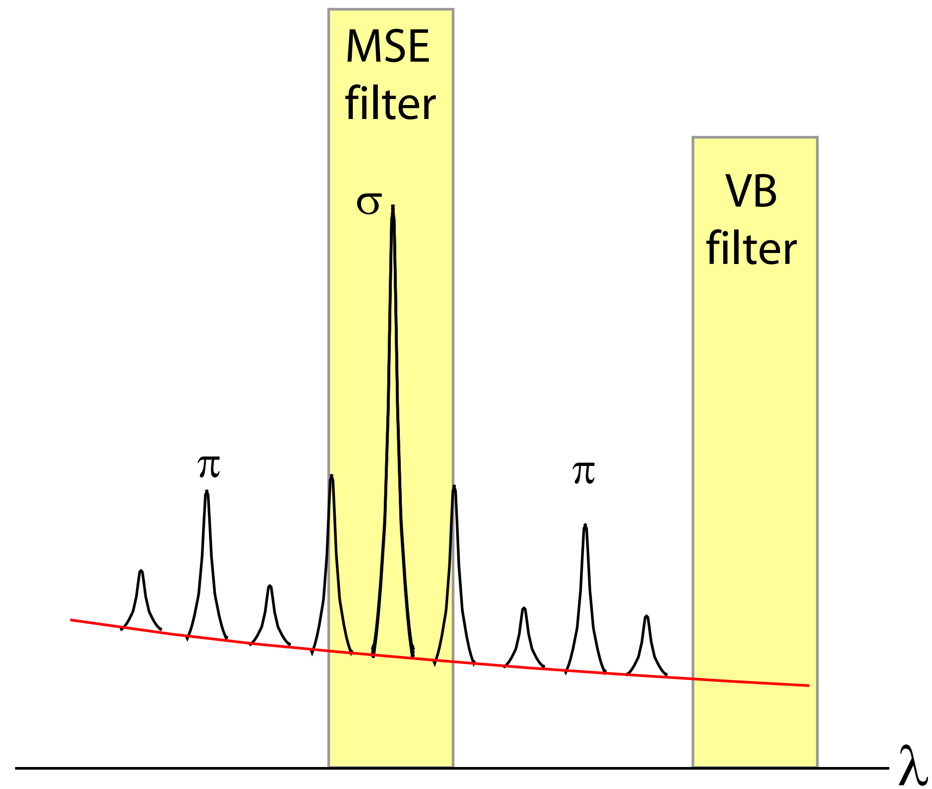
Beam modulation,
single filter



Dual filters,
simultaneous measurement



R_{VB} = ratio of actual VB intensity during MSE measurement to interpolated value.

Angle uncertainty in presence of partially polarized VB

$$I^{tot} \equiv I^{MSE} + I^{VB}. \tag{1}$$

The projected pitch angle γ is given by

$$\tan(2\gamma) = \frac{I_2^{MSE}}{I_1^{MSE}} = \frac{I_2^{tot} - I_2^{VB}}{I_1^{tot} - I_1^{VB}} \equiv R \tag{2}$$

where the subscripts 1,2 refer to the measured intensities at the second harmonic of the two PEM frequencies. The uncertainty in the angle, σ_γ, is

$$\begin{aligned}
\sigma_\gamma &= \frac{\sigma_R}{2(1+R^2)}. \\
\Delta R &= \frac{\Delta x}{y} - \frac{x\Delta y}{y^2} \\
\sigma_R &= R\left(\frac{\sigma_x}{x} + \frac{\sigma_y}{y}\right)
\end{aligned} \tag{3}$$

In this case,

$$\begin{aligned}
x &= I_2^{tot} - I_2^{VB} = \left(\frac{J_2(A_2)}{\sqrt{2}}\right)\left(S_2^{tot} - S_2^{VB}\right) \\
\sigma_x^2 &= I_2^{tot} + I_2^{VB}
\end{aligned} \tag{4}$$

so

$$\begin{aligned}
\frac{\sigma_x}{x} &= \left(\frac{\sqrt{2}}{J_2(A_2)}\right)^{1/2} \frac{(S_2^{tot} + S_2^{VB})^{\frac{1}{2}})}{S_2^{tot} - S_2^{VB}} = \left(\frac{\sqrt{2}}{J_2(A_2)}\right)^{1/2} \frac{(S_2^{MSE} + 2S_2^{VB})^{\frac{1}{2}}}{S_2^{MSE}} \\
\frac{\sigma_y}{y} &= \left(\frac{\sqrt{2}}{J_2(A_1)}\right)^{1/2} \frac{(S_1^{tot} + S_1^{VB})^{\frac{1}{2}})}{S_1^{tot} - S_1^{VB}} = \left(\frac{\sqrt{2}}{J_2(A_1)}\right)^{1/2} \frac{(S_1^{MSE} + 2S_1^{VB})^{\frac{1}{2}}}{S_1^{MSE}} \qquad (5)
\end{aligned}$$

The expression implemented in the MSE simulation code is then:

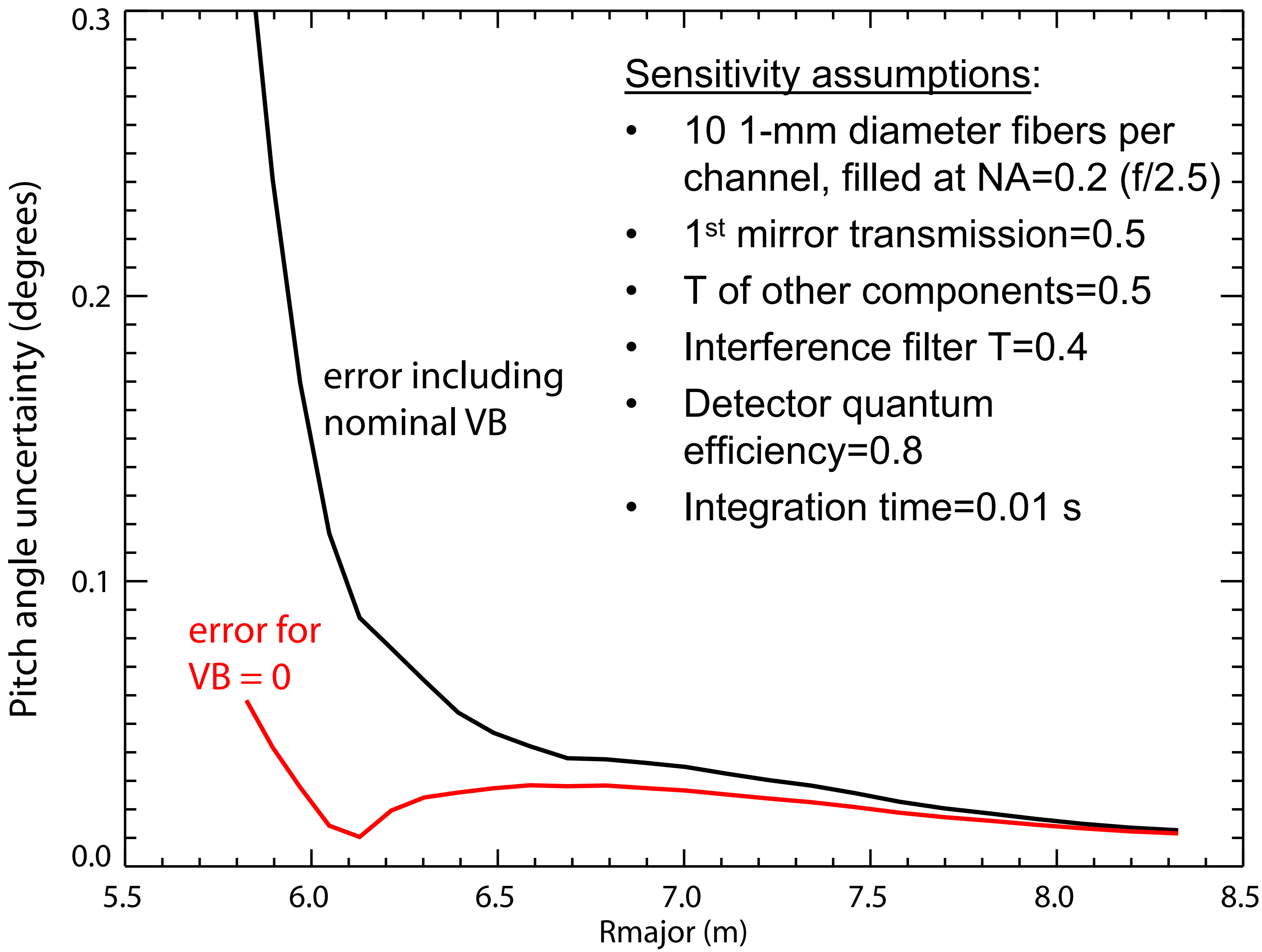
$$\sigma_\gamma = \frac{R}{1+R^2}\left(\frac{\sigma_x}{x} + \frac{\sigma_y}{y}\right) \qquad (6)$$

with σ_x/x and σ_y/y given by Eq. 5. *Does not include noise at* $2\Omega_1$ *and* $2\Omega_2$ *from unpolarized* VB.

Effect of uncertainty in subtracting beam-off noise ($R_{VB} \approx 1$):

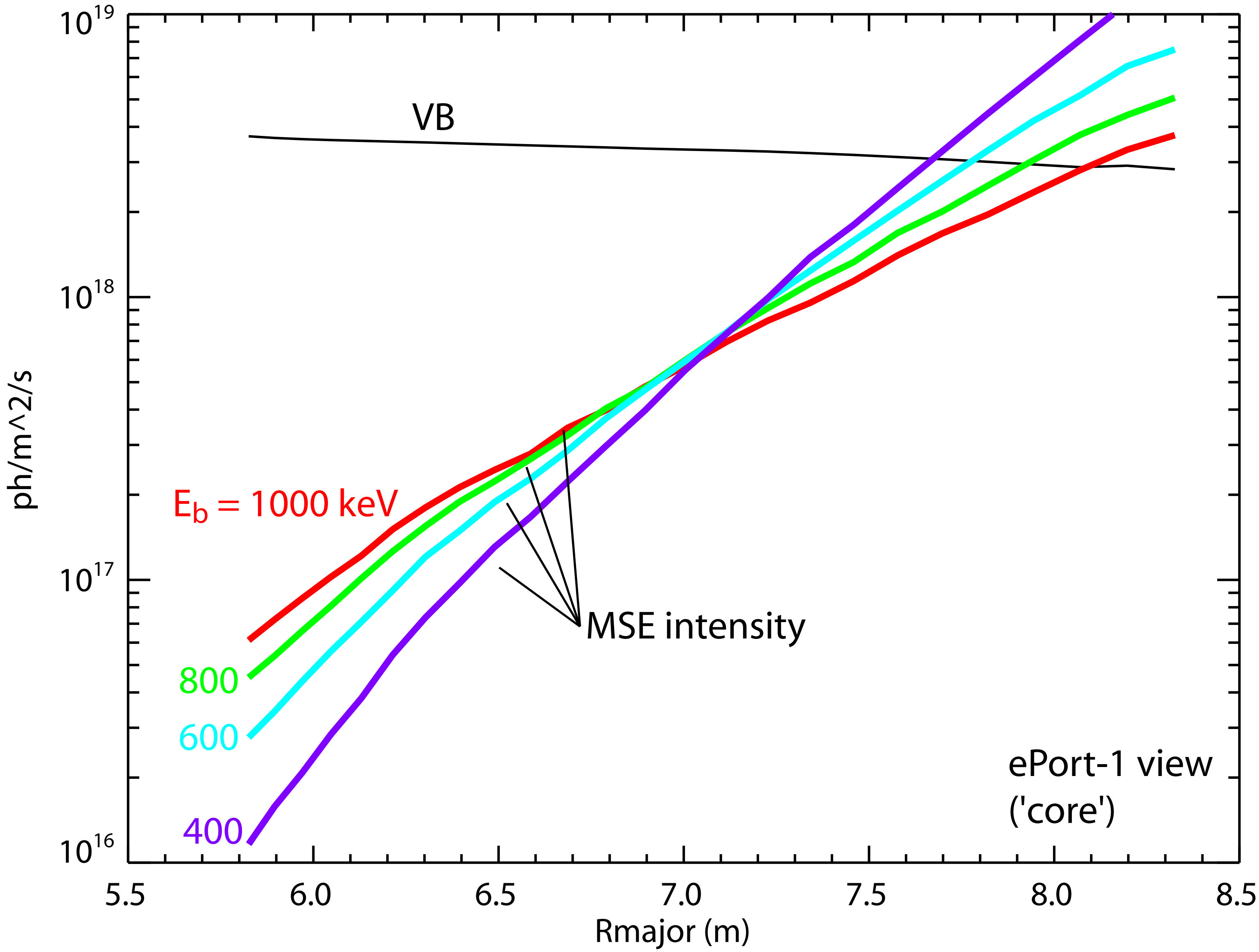
$$\begin{aligned}
\tan(2\gamma_{upper}) &= = \frac{I_2^{tot} - R_{VB} I_2^{VB}}{I_1^{tot} - R_{VB} I_1^{VB}} \\
\tan(2\gamma_{lower}) &= = \frac{I_2^{tot} - I_2^{VB}/R_{VB}}{I_1^{tot} - I_1^{VB}/R_{VB}} \\
\sigma_\gamma &\equiv abs(\gamma_{upper} - \gamma_{lower})/2 \qquad (7)
\end{aligned}$$

Visible Bremsstrahlung significantly increases error bars on measured angle in the plasma core

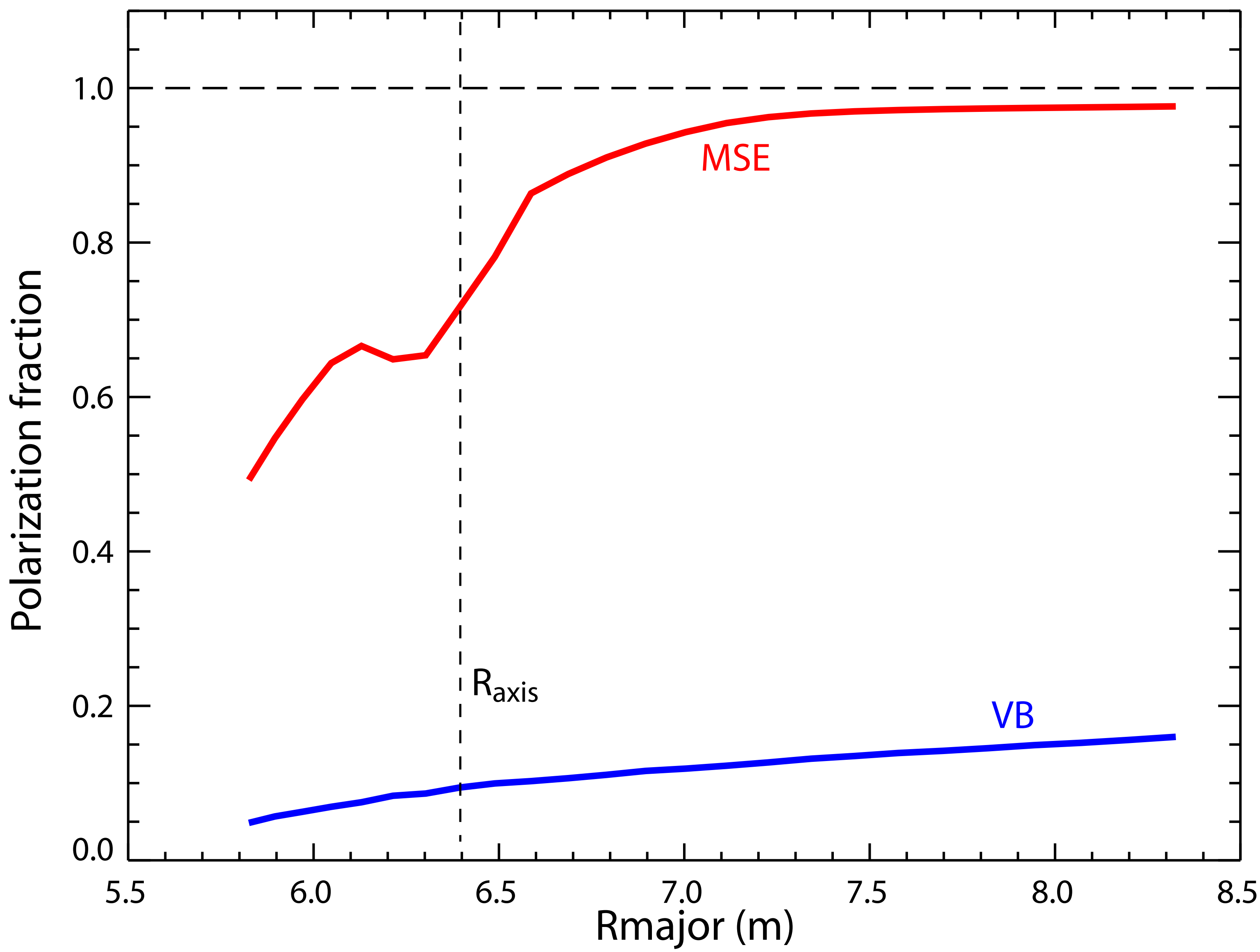


ePort-1 view

The total VB photon intensity greatly exceeds the MSE intensity in the core

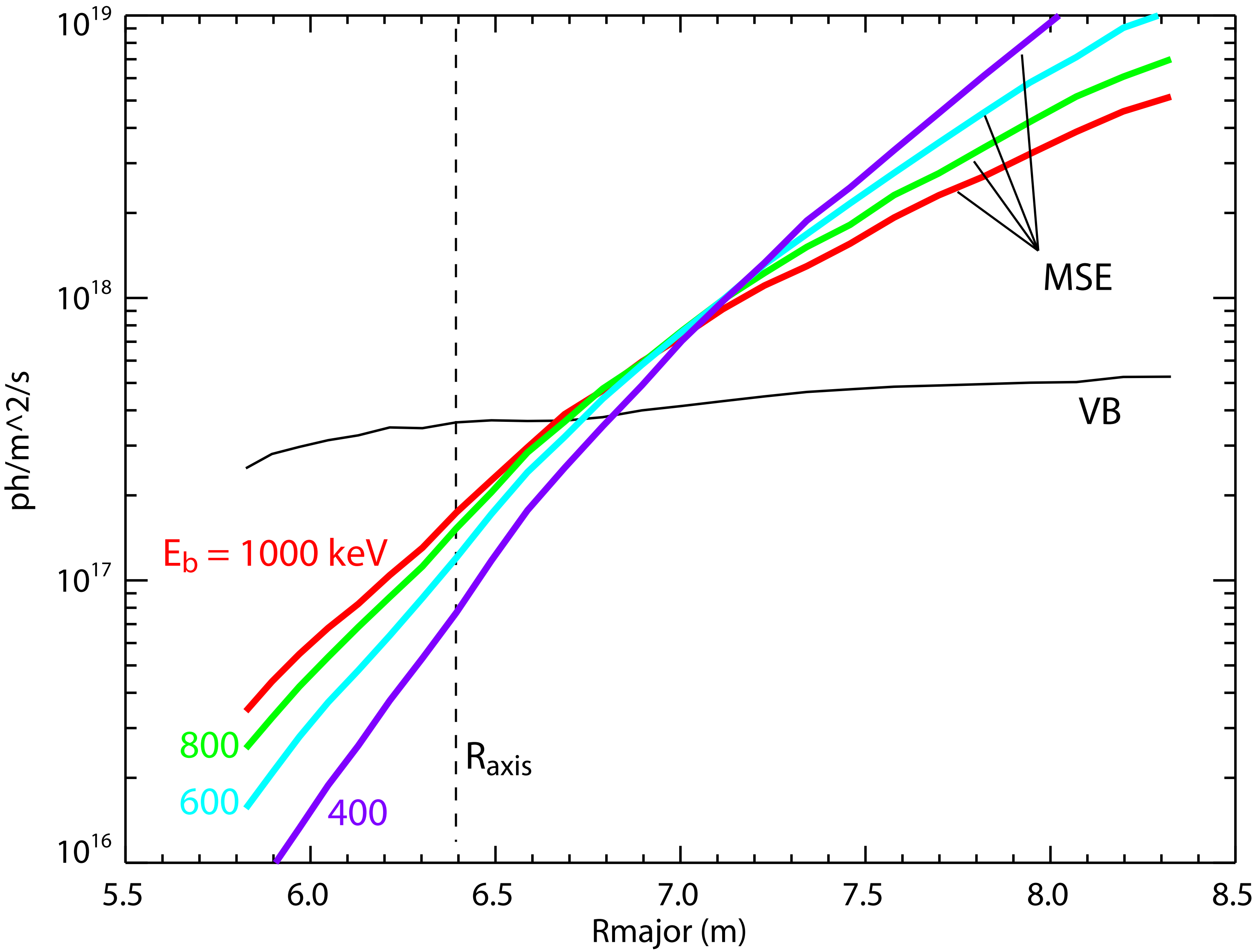


The visible Bremsstrahlung emission is only weakly polarized

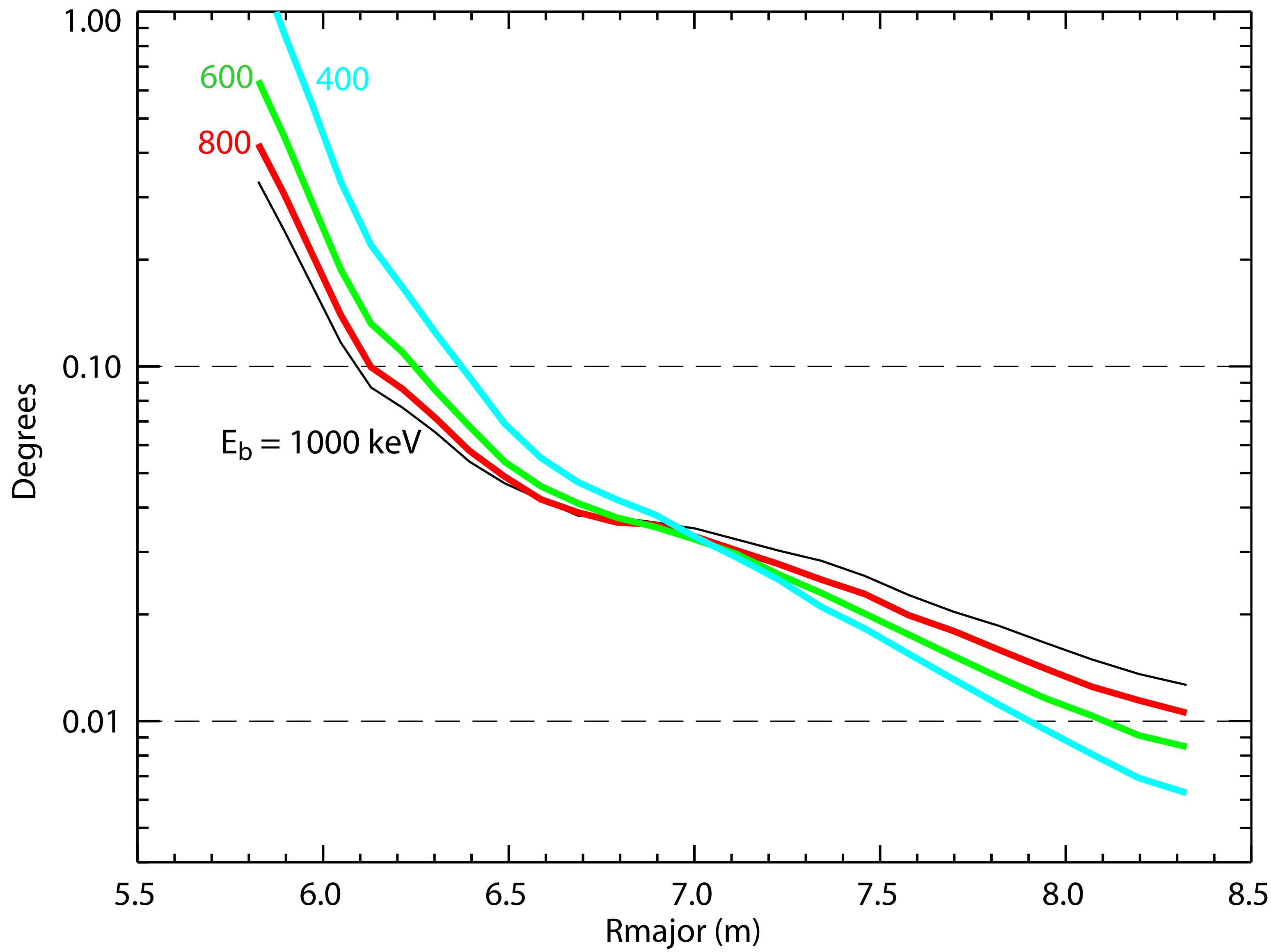


ePort-1 view
('core')

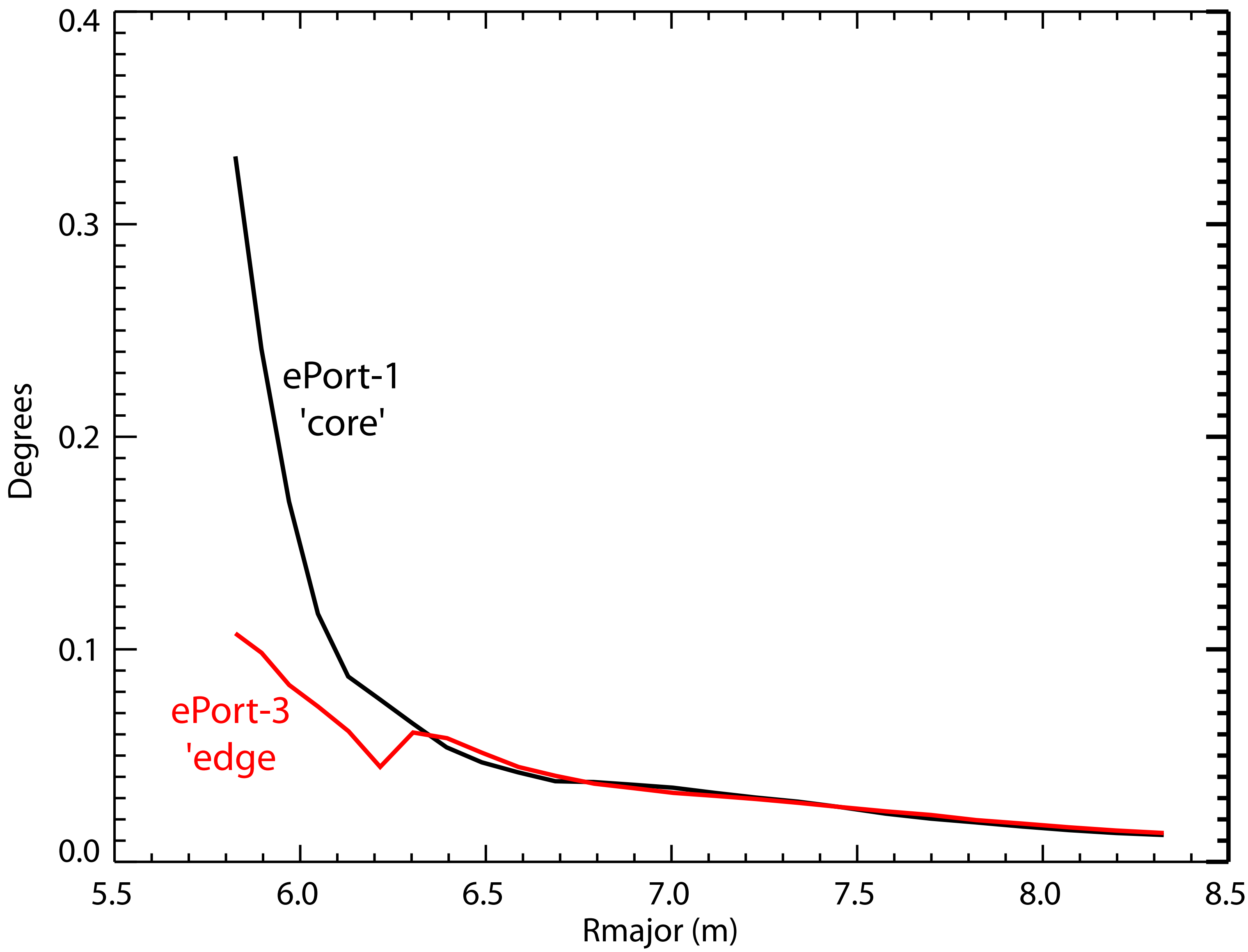
But the signal strength at $2\Omega_1$ and $2\Omega_2$ is still dominated by MSE because VB is only weakly polarized.



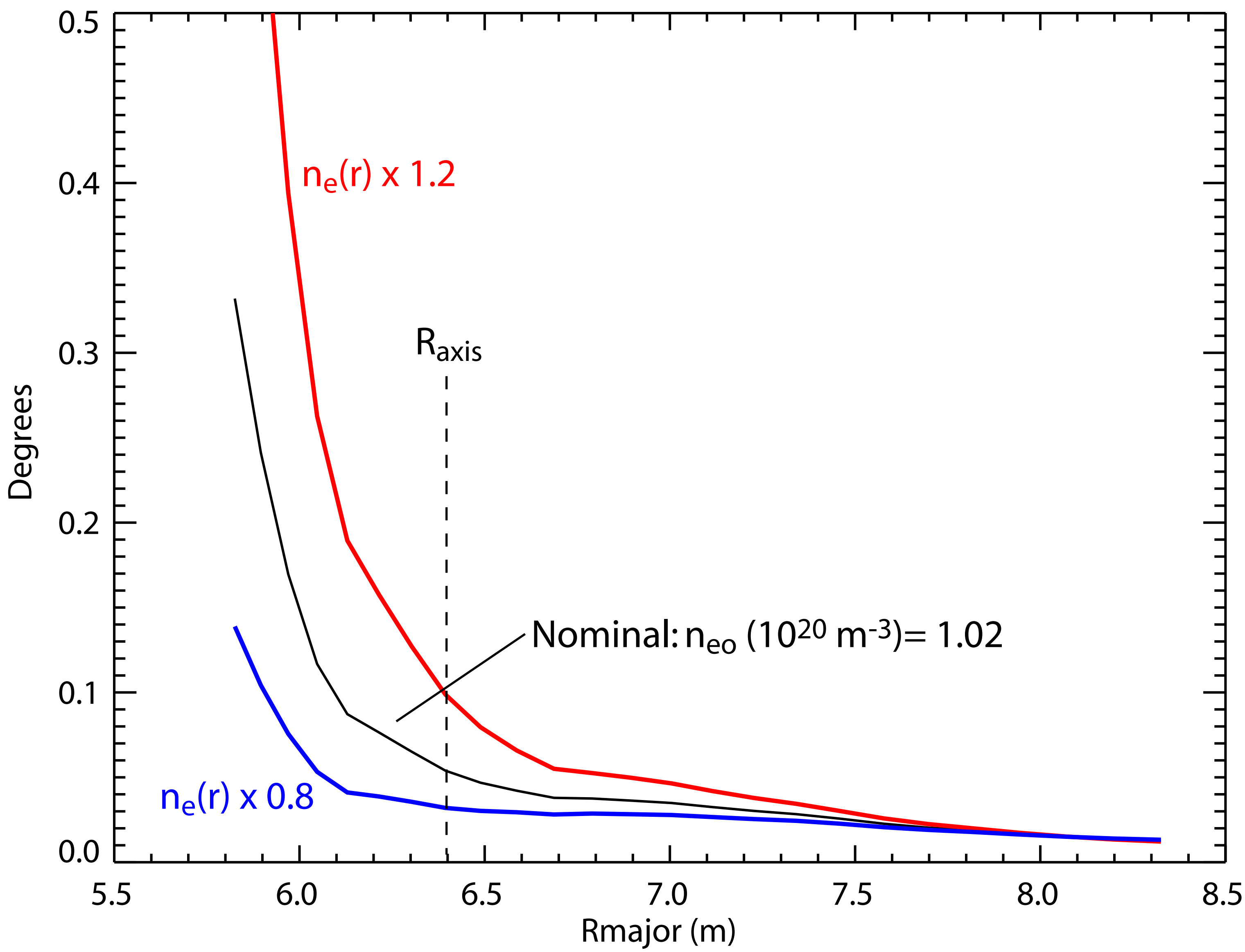
Pitch angle uncertainty in core increases as beam voltage is lowered, but remains acceptable (< 0.1o)



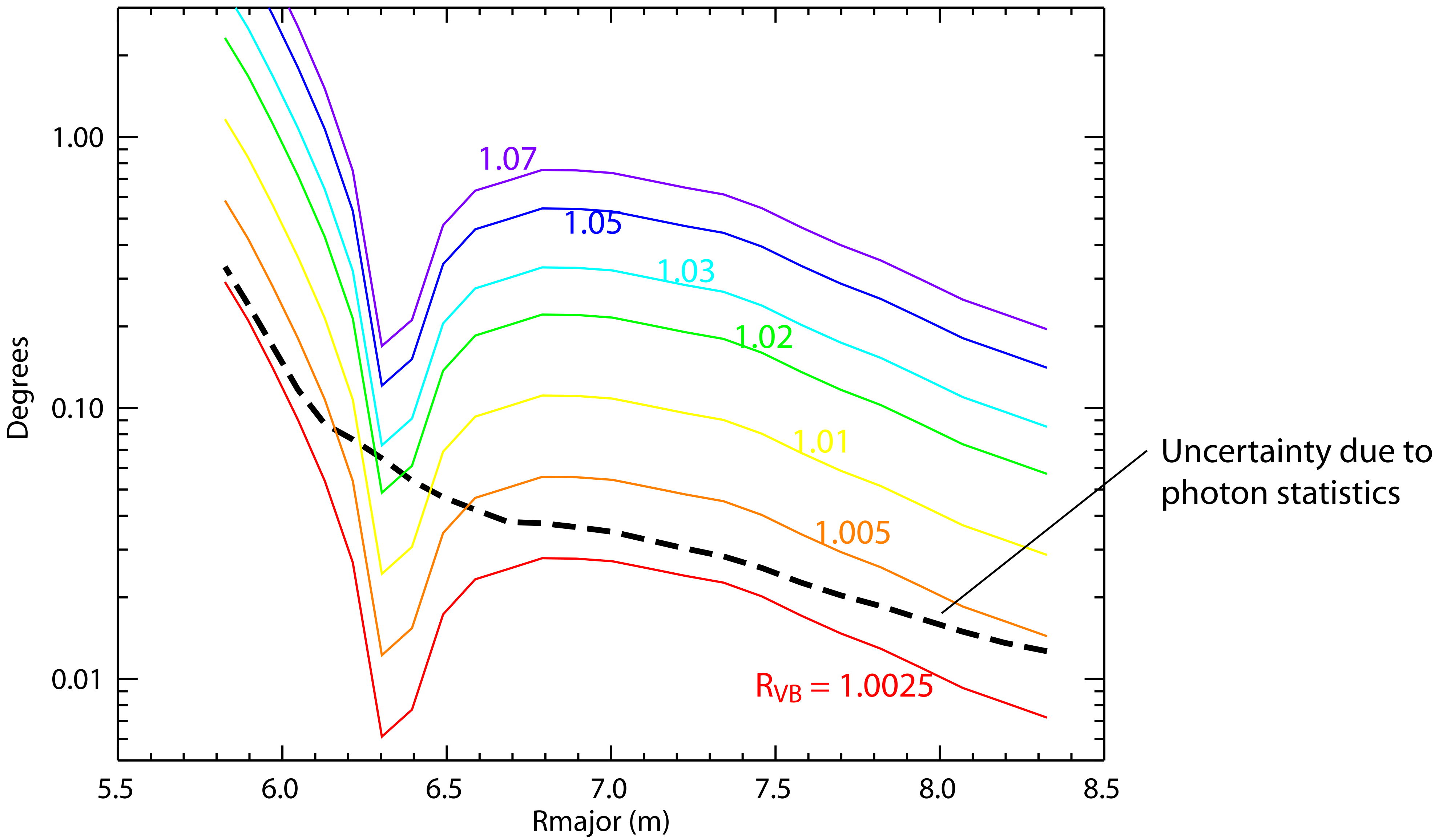
Pitch angle uncertainties are comparable for the edge and core MSE systems



Pitch angle uncertainty remains acceptable for modest variations in plasma density



Accuracy of interpolating VB noise must be better than ~0.5% to achieve the pitch-angle uncertainty due to photon statistics



Summary and plans

- Baseline MSE diagnostic:
  - σ lines free from interfering beam overlap for core and edge views.
  - Beam overlap not a problem for Eb= 0.4-1.0 MeV unless beams are of different voltage.
  - Good radial resolution.
  - ***Statistical uncertainty in pitch angle measurement is acceptable:***
    - But only if accuracy of VB interpolation (beam on – off) is ~0.5%
    - May need simultaneous VB measurement with dual filters or spectrometer.
    - Must consider futher polarization of VB by MSE mirrors themselves.

- Remaining work:
  - Assess effect of 5% beam voltage ripple.
  - Very absence of overlap with poorer beamlet divergence.
  - Calculate fraction of unpolarized VB that falls within passband at $2\Omega_1$, $2\Omega_2$.

Other issues – not part of this study

- Design of mirror labyrinth.
- Need for in-situ calibration and measurement of first mirror properties.

Acknowledgements

- *Thanks to N. Hawkes for sharing the perf code and for helpful discussions and to Fred Levinton for code to compute reflection propeties of metal surface.*
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