Evaluation of ITER Upper Visible/IR Camera Design and Performance

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Outline

Lasnier:

- Tasks in Statement of Work
- Specifications

Seppala:

- Required field of view
- Optical design and performance

Morris:

- Physical Layout

Lasnier

- Needed R&D
- Next steps
- Discussion of specifications

Statement of Work contains clear objectives

- 3. **WORK DESCRIPTION (from SOW#531-20060608)**
    - 3.1. Review functional specifications for upper visible/IR cameras and recommend changes to optimize physics productivity for these systems.
    - 3.2.a. Assess the performance of the reference design relative to these requirements and
    - 3.2.b. evaluate limitations on image frame rate for narrowband imaging of recycling and impurities and for temperature maps of the divertor.
    - 3.3. Travel to the EU and confer with experts on ITER endoscope design and identify opportunities for collaboration.
    - 3.4. Obtain optical design parameters for the reference endoscope and the CEA group design and incorporate into optical model using a commercial optical design package.

Statement of Work tasks

- 3.5. Modify design to be compatible with 'central tube' implementation in upper plugs.
- 3.6. Identify minimum tube outer diameter (likely determined by size of viewing head) and inner diameter (likely determined by optical relay aperture) consistent with satisfying the endoscope performance parameters.
- 3.7. Export optical designs in CAD-compatible format (approved by PPPL) to facilitate integration into central tube and upper port plug and subsequent neutronics analysis. (integration and neutronics analysis are not covered in this SOW)
- 3.8. Identify high priority R&D issues related to the upper camera optical system.

Statement of Work tasks

- 3.9. a. Write report contrasting the features of both designs and, for the central tube implementation,
- 3.9. b. illustrating the dependence on tube diameter.

- 3.10. Present summary of findings at a workshop or topical meeting and provide electronic file copy of presentation.

Specifications were conveyed from the ITER organization

- Complete as possible IR coverage of the outer target plate
- Surface temperature: 200-2500°C (IR)
- Time resolution: 20 μs IR, 10 ms visible
- Spatial resolution: 3 mm (IR)
- No lenses in the port plug (radiation damage)
- Two vacuum windows must be used for tritium safety

MEASUREMENT	PARAMETER	CONDITION	RANGE or COVERAGE	RESOLUTION		ACCURACY
				Time or Freq.	Spatial or Wave No.	
17. First Wall (FW) Visible Image & Wall Temperature	FW image		TBD	100 ms	TBD	–
	FW surface temperature		200 – 1500°C	10 ms	TBD	20°C
38. Heat Loading Profile in Divertor	Surface temperature		200 – 1000°C	2 ms	3 mm	10 %
			1000 – 2500°C	20×10^{-6} s	3 mm	10 %
	Power load	Default	TBD – 25 MW/m^2	2 ms	3 mm	10 %
		Disruption	TBD – 5 GW/m^2	0.1 ms	TBD	20 %

Cameras monitor high temperatures and extreme heat load

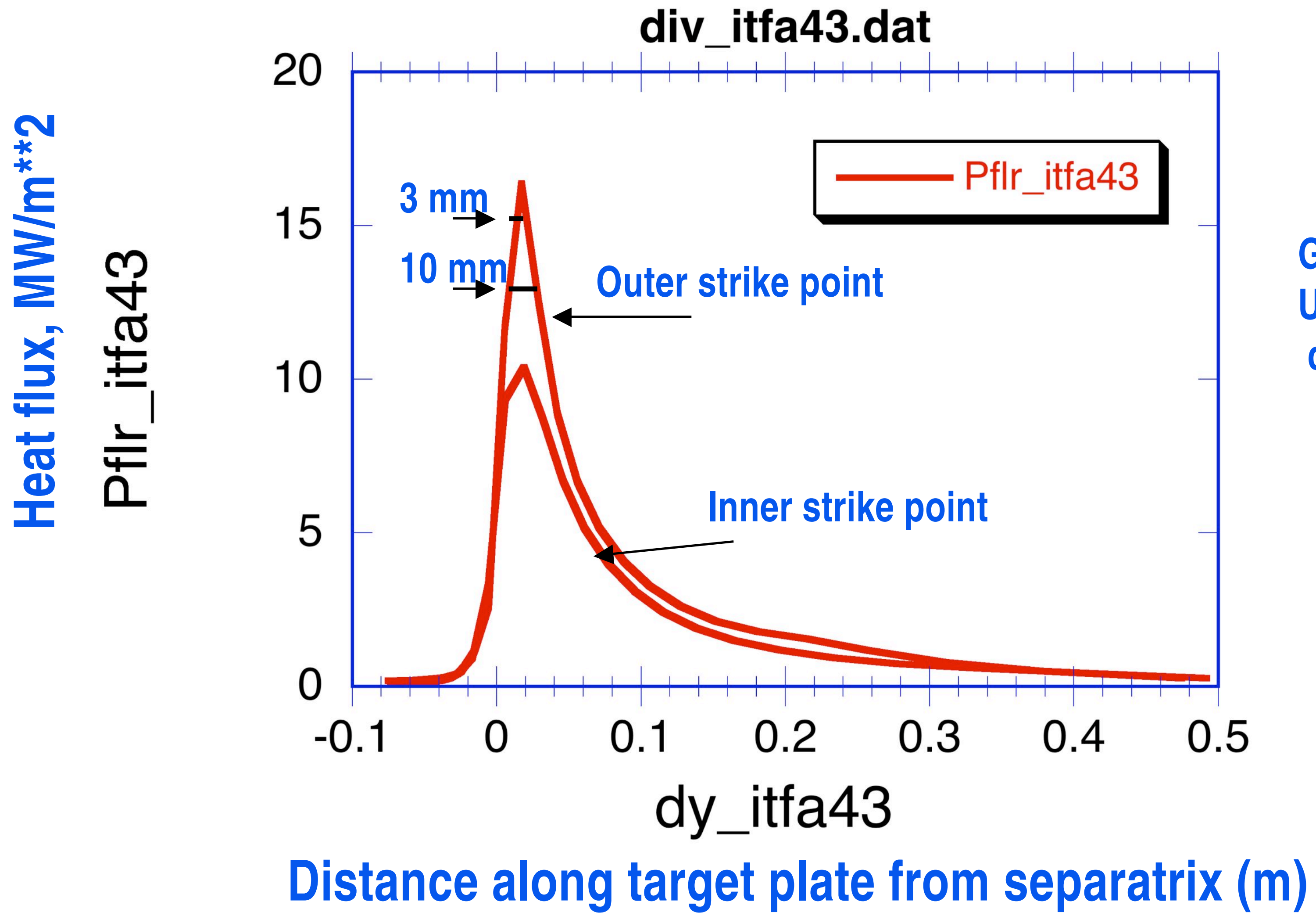
- IR cameras will be used to see as much of the divertor as possible to watch for overheating of components, and to align the plasma shape with the walls.
- Visible cameras will watch for tile damage, MARFE location.
- Cameras will also be used for physics measurements.

Evaluation of specifications

- Plenty of IR signal for 20 μs time resolution
- 10 ms visible time resolution is enough for vessel protection but not for ELM physics- same 20 μs desirable. However, the light levels may not permit this short exposure.
- 3mm spatial resolution over the whole divertor sounds small, but there is a good reason for 3mm when compared with the width of the heat flux profile peak.

3mm Spatial resolution is tough to meet , but there is a reason

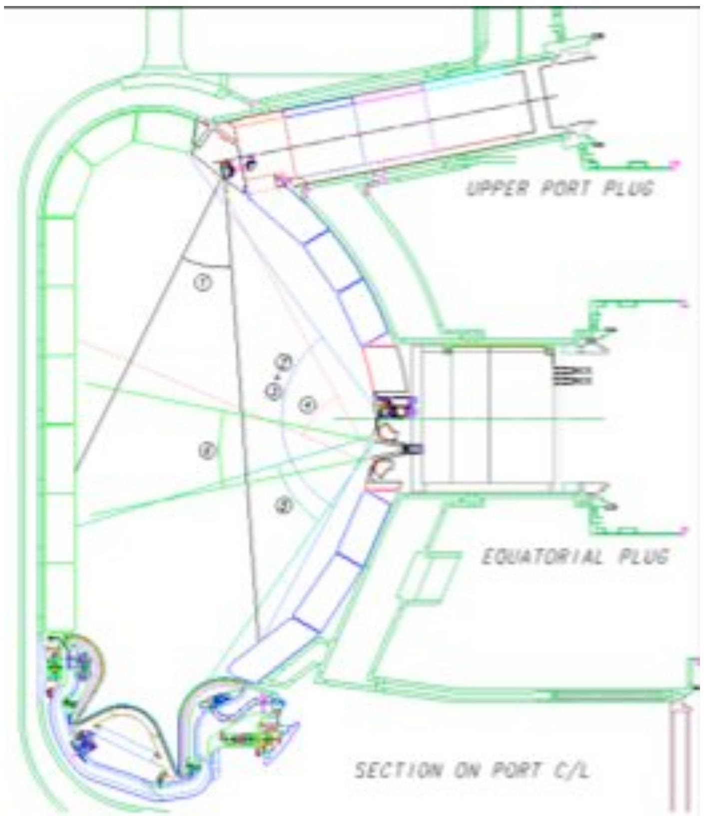
- Heat flux on the target plate is predicted to be sharply peaked



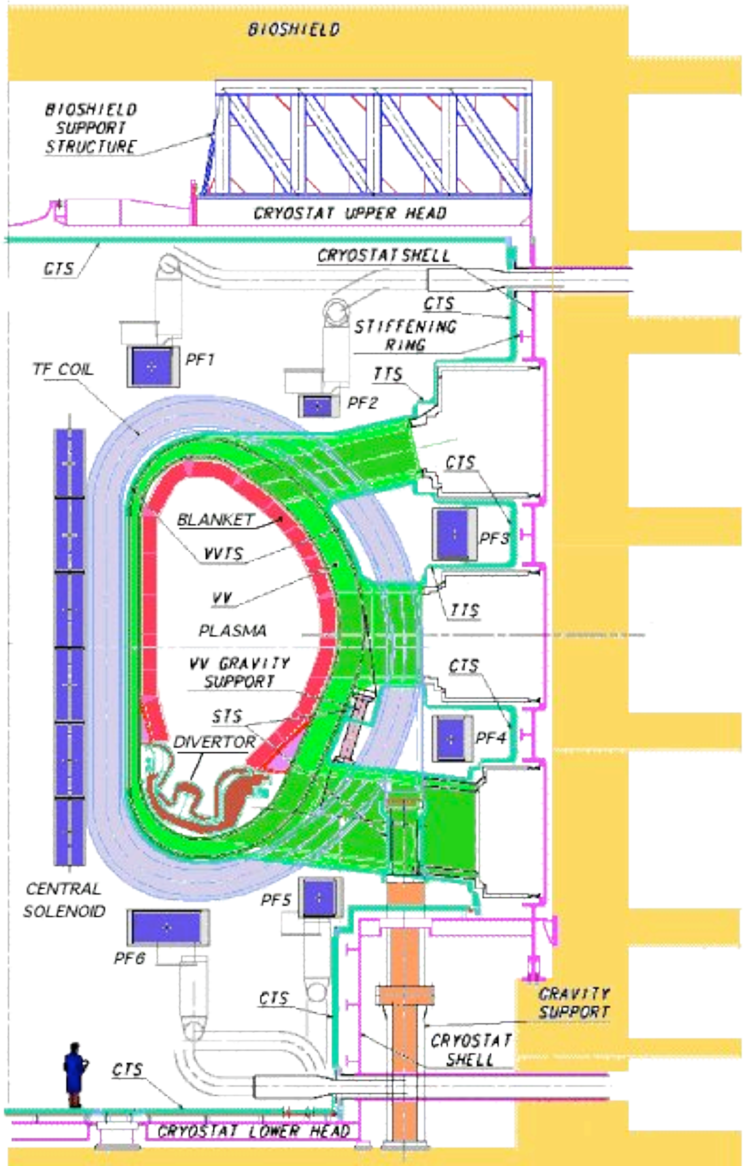
Gary Porter
UEDGE
calculation

A wide-angle view is planned

- We have 6 upper ports
- We need to view as much of the outer target as possible
- So, each camera needs to see about 60 degrees of the torus
- The view must be tilted toroidally to see the outer target



ITER cross-section shows ports, first wall, and biosheild



The Port Plugs contain diagnostics and neutron shielding

Additional constraints

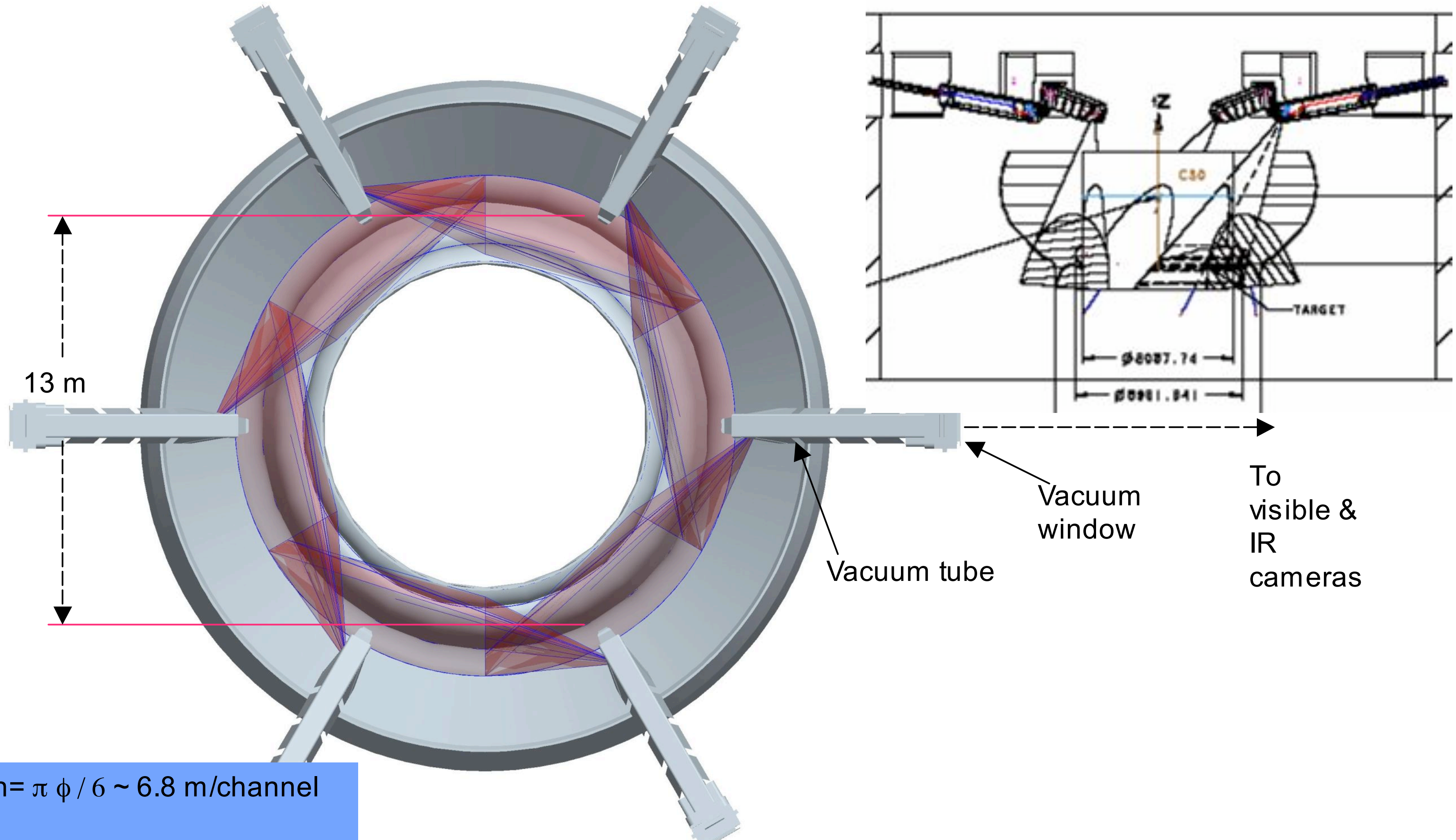
- Hot mirrors/lenses/windows, background if unbaffled, add IR
- Two-color or multi-color IR may be necessary for low-emissivity surfaces (e.g. tungsten)

ITER visible & IR optical designs

Lynn Seppala

February 6,2007

IRTV system uses 6 locations to provide 360 degrees coverage on ITER divertor

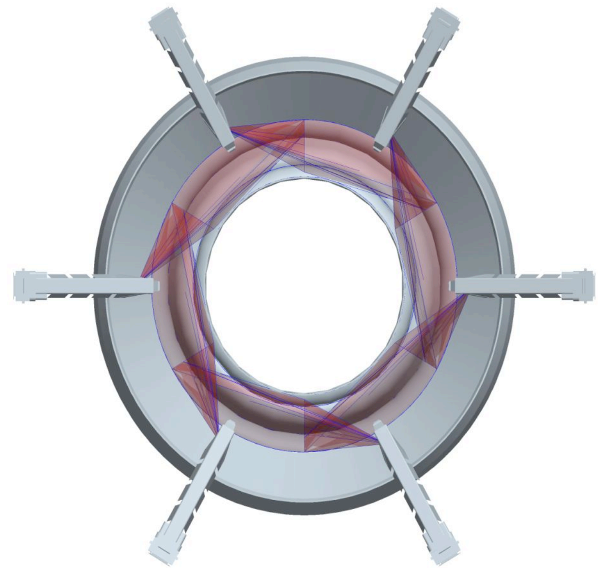


Object length= $\pi \phi / 6$ ~ 6.8 m/channel

System is side-looking to allow view of divertor trough

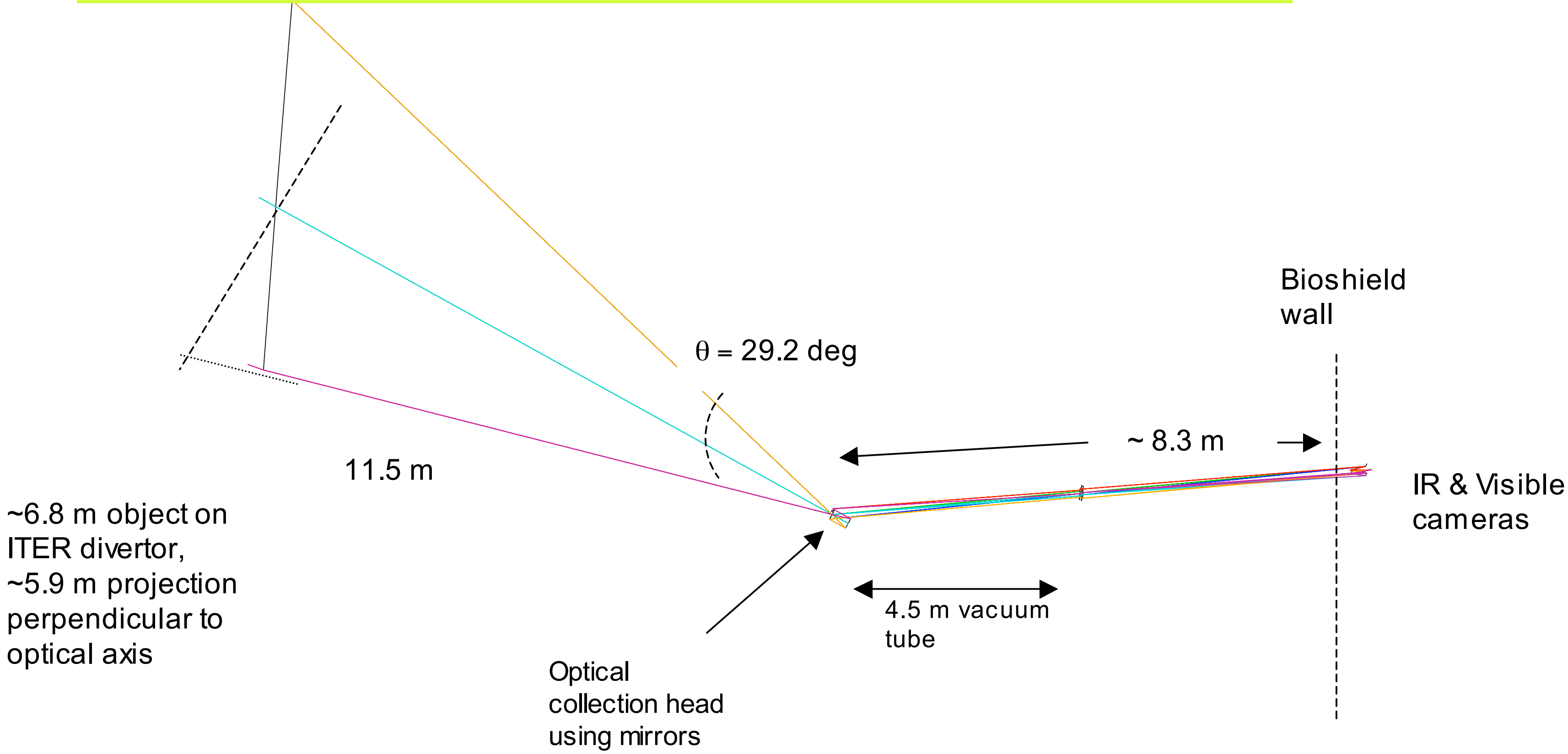
Optical design requirements

- Operating wavelengths
  - IR 3.0 to 5.0 μm,
  - Visible 400 to 700 nm
- Resolution at ITER divertor
  - IR ~ 3 mm or ***best possible***; Visible should be equal or better
- No focusing elements in 4.3 m-long vacuum space between collector head and vacuum window
- All components must be enclosed within a 36 cm tube
  - Limited tube diameter conflicts with desired resolution



Optical schematic for IRTV

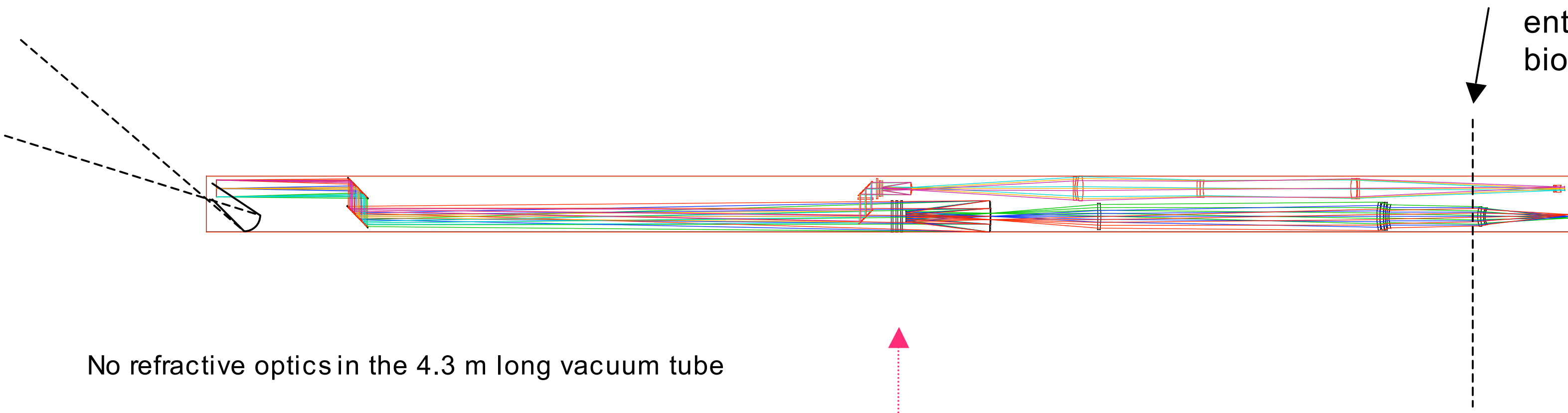
Proposed optical design is enclosed in a 36 cm diameter beam tube



Visible (top) and IR (bottom) relay optical designs must share the 36 cm tube

Tube is 8.93 m long x 0.36 m in diameter

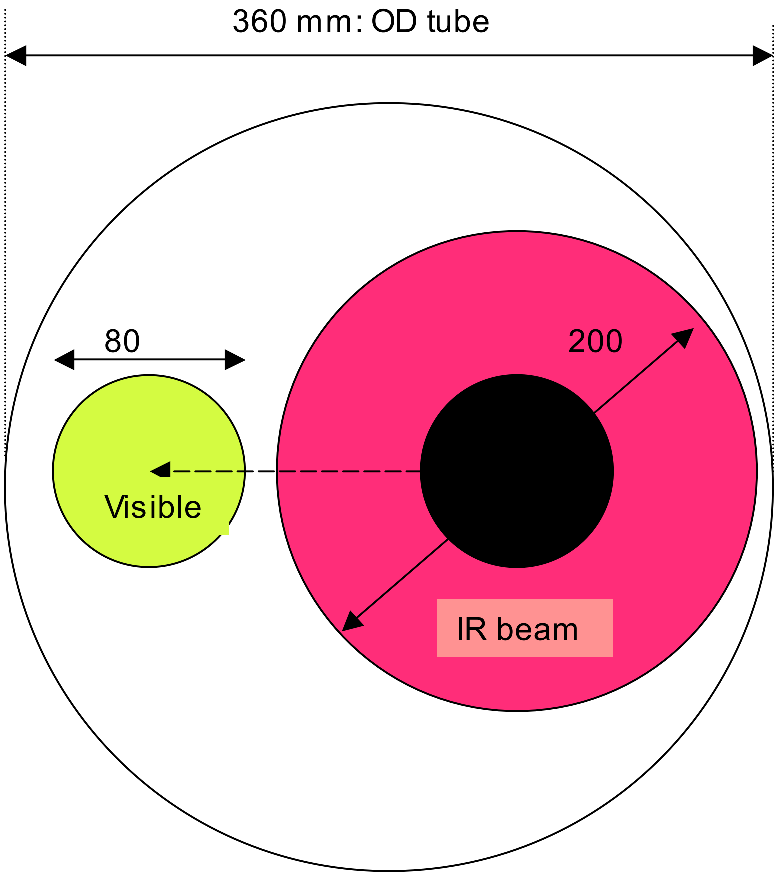
~8.2 m from entrance hole to bioshield:



No refractive optics in the 4.3 m long vacuum tube

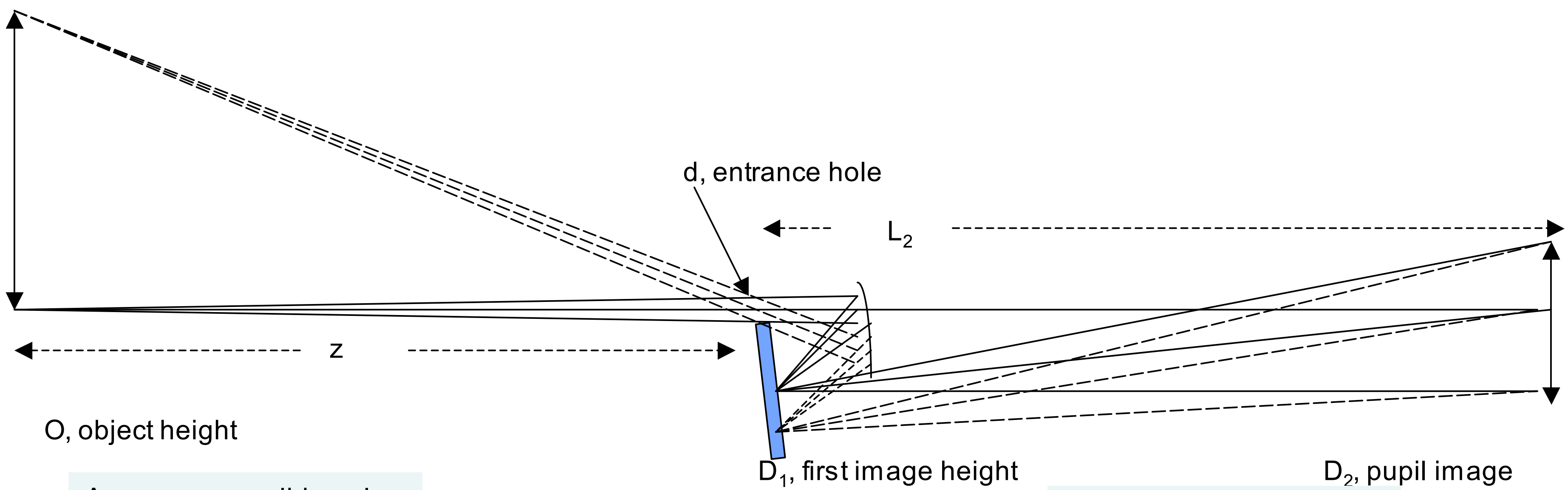
Collecting optics and dual imaging systems must be enclosed in a 36 cm diameter tube

Beam footprints at pupil plane outside of Vacuum window: Inner area of beam is used for the Visible channel



IR beam size is limited to just over 50% of the tube diameter to make room for the visible beam

Etendue ($\delta A\ \delta\omega$) is constant throughout the system: Entrance hole diameter <u>d</u> depends on beam sizes in the tube



Area x solid angle

$(\pi O^2/4)\ (\pi d^2/4)\ /\ z^2$

=

Area x solid angle

$(\pi D_1^2/4)(\pi D_2^2/4)/\ L_2^2$

Setting $D_1 = 0.5\ D_2$ yields: **$d=0.5z\ D_2^2/(O\ L_2)$** **For $O=5900$, $z=11500$, $L_2= 4300$**

(necessary for collector geometry) **$d \sim (D_2\ /\ 66.4)^2$**

Aperture hole size is limited by tube size

$d \sim 9.1$ mm for $D_2=200$ mm

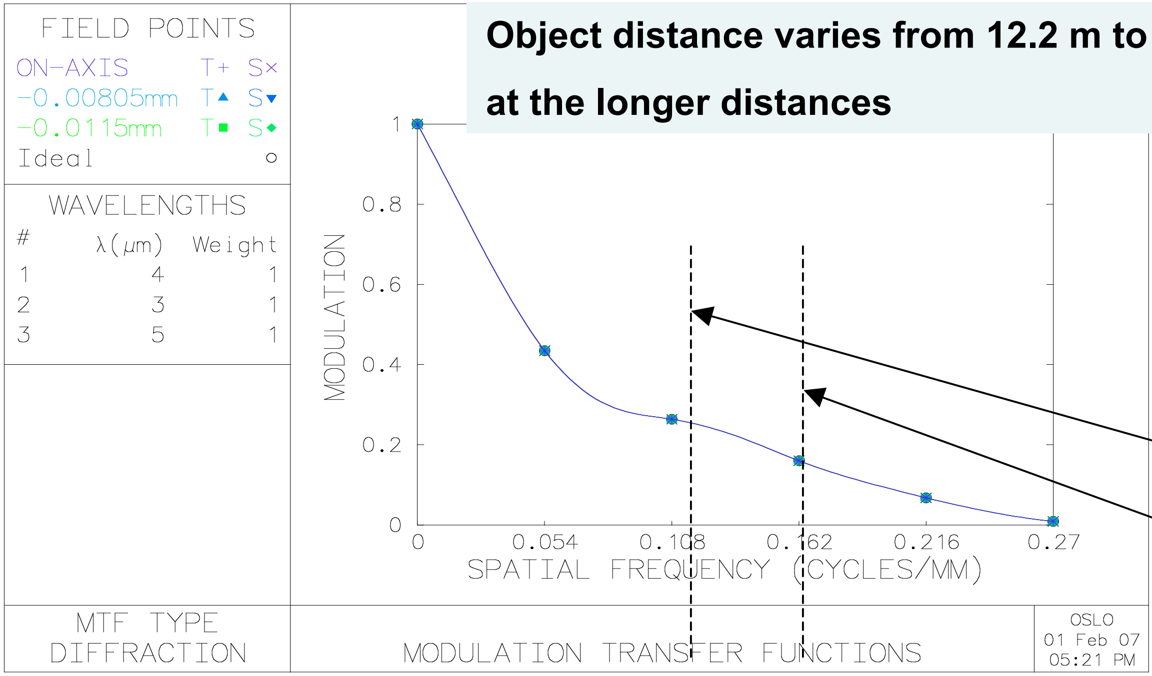
Actual optical design uses 10 mm hole

Entrance hole size of 10 mm limits IR resolution

Object distance varies from 12.2 m to 8.7 m; best views of divertor are at the longer distances

Dist to divertor	Viewing aperture size	λ	Object feature at which the MTF goes to zero contrast ($\lambda f_{\#}$)	Estimate of resolved feature ($1.5 \lambda f\#$)	+/- Depth of focus
(m)	(mm)	(microns)	(mm)	(mm)	(m)
11.5	10	5.0	**5.8**	8.6	13
11.5	10	3.0	**3.5**	5.2	8
11.5	4.15	0.7	**1.9**	2.9	11
11.5	4.15	0.4	**1.1**	1.7	6

Entrance hole size of 10 mm limits IR resolution



Object distance varies from 12.2 m to 8.7 m; best views of divertor are at the longer distances

Perfect polychromatic IR optical system (3 to 5 μm) MTF for object located 11.5 m from a 10 mm entrance hole, with 41.5% obscuration.

Feature size:

9.0 mm

6.0 mm

Dist to divertor	**Viewing aperture size**	**λ**	**Object feature at which the MTF goes to zero contrast (λ $f_{\#}$)**	**Estimate of resolved feature (1.5 λ f#)**	**+/- Depth of focus**
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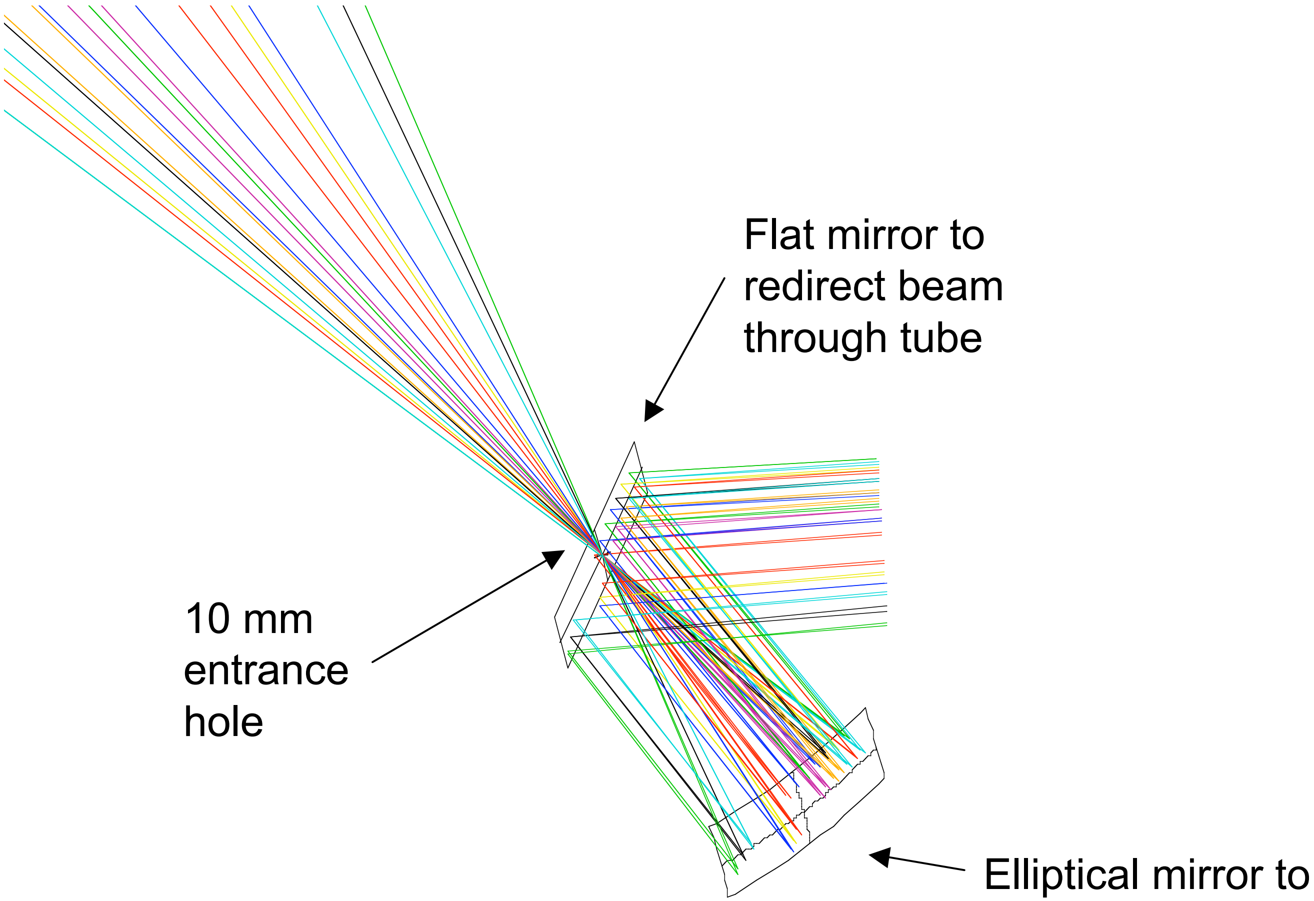
Resolution requirements drive pixel count across the detector

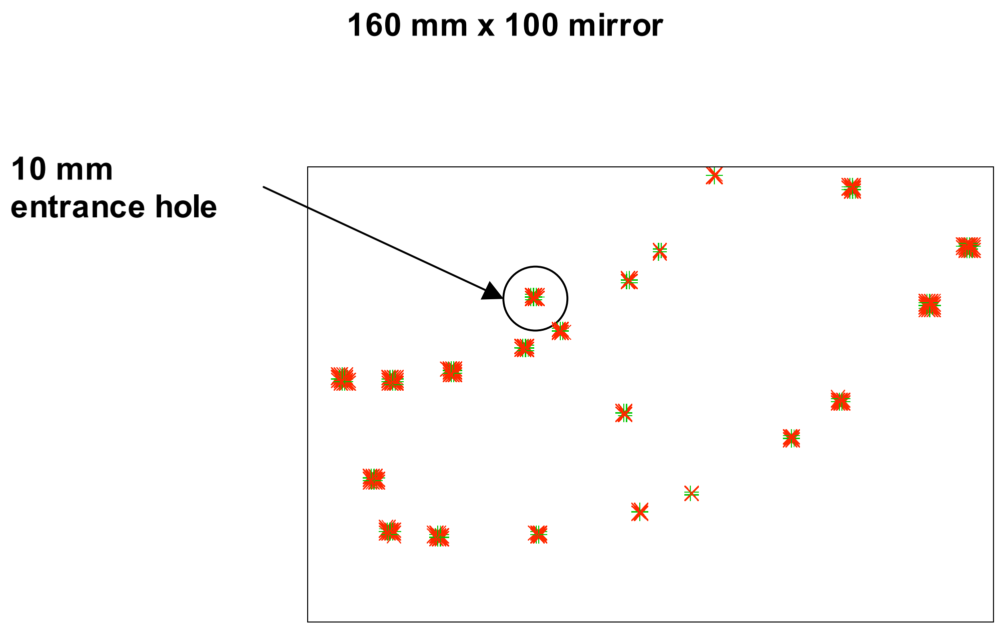
Divertor length (mm)	Resolved feature at divertor (mm)	Pixels per resolved feature	Total number of pixels/row
5700.0	3.0	2	3800
5700.0	5.2	2	2190
5700.0	8.5	2	1344
5700.0	12.0	2	951
5700.0	17.0	2	672

More complicated image processing using multiple exposures may reduce to pixel row-count by 50%

Collector head uses an elliptical mirror to focus light and a flat mirror to redirect light



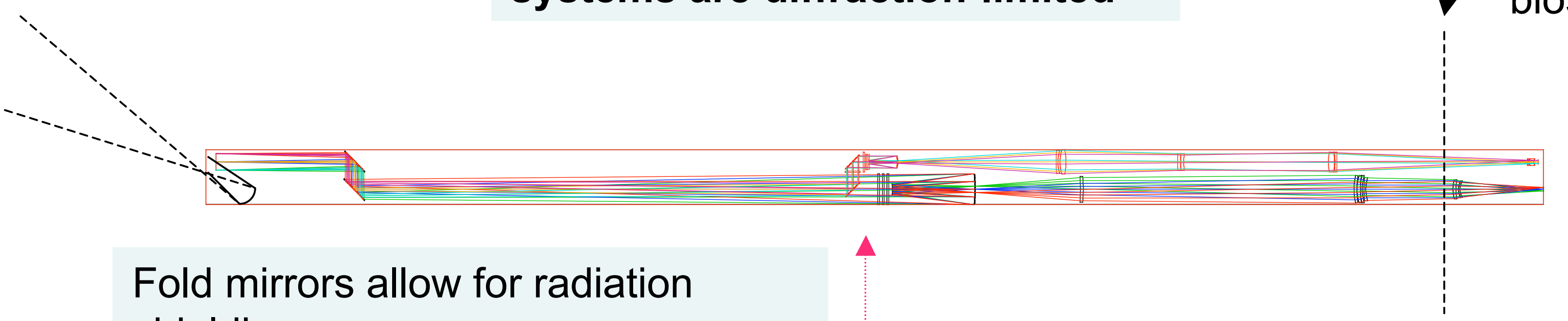
First image plane is near flat fold mirror of collector head; entrance hole is on edge of the image



Visible (top) and IR (bottom) relay optical designs must share the 36 cm tube

Visible and IR systems are split off near the vacuum window: **both systems are diffraction-limited**

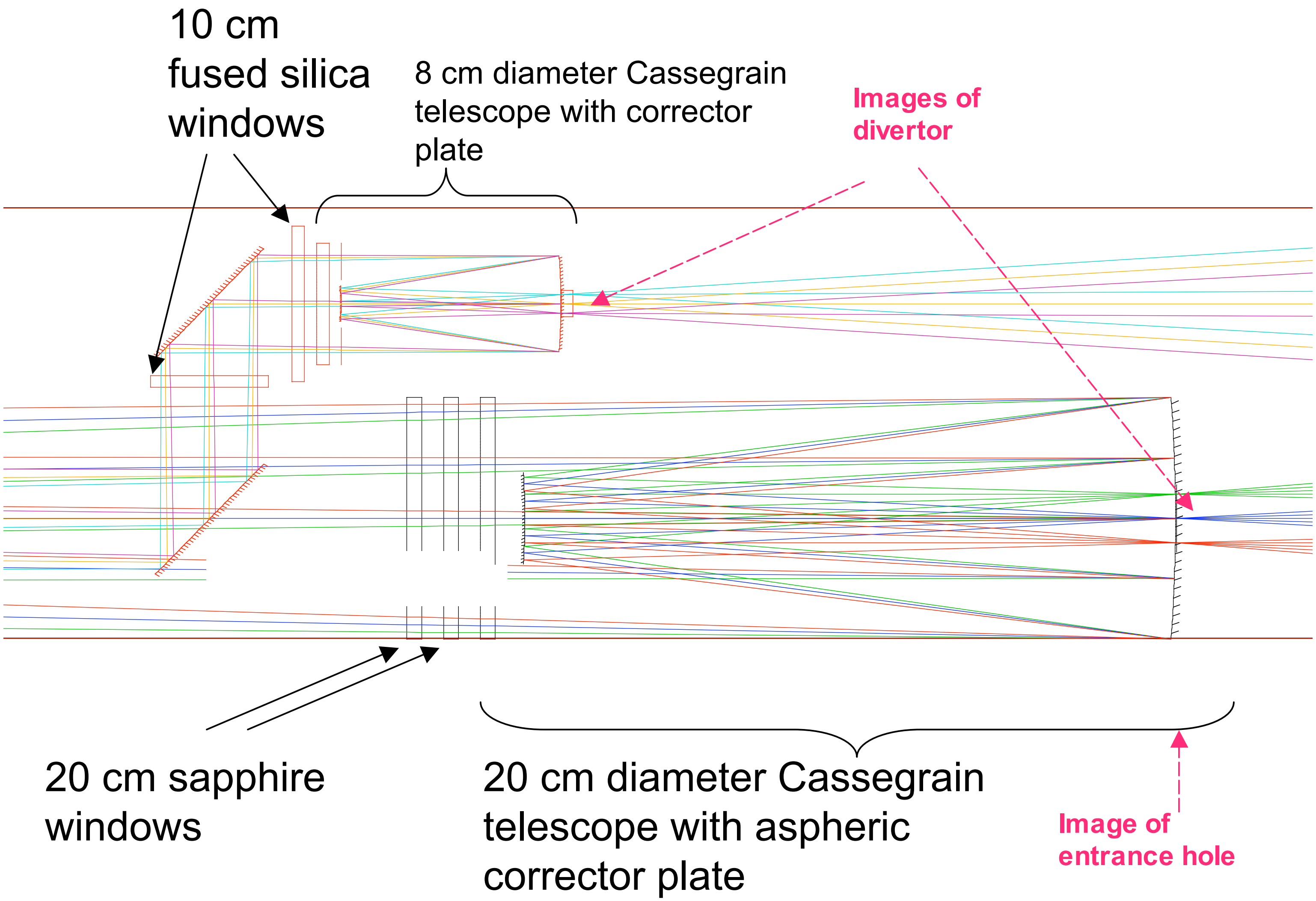
~8.2 m from entrance hole to bioshield:



Fold mirrors allow for radiation shielding

Each vacuum window material and coating can be optimized for either Visible or IR bands

Visible (top) and IR (bottom) designs



Visible (top) and IR (bottom) designs

16 cm diameter fused silica/ CaFl doublet

11 cm radiation hardened Schott SF8G07 doublet

13 cm diameter fused silica/ CaFl doublet

4.5 cm diameter fused silica doublet

17 cm ZnSe lens

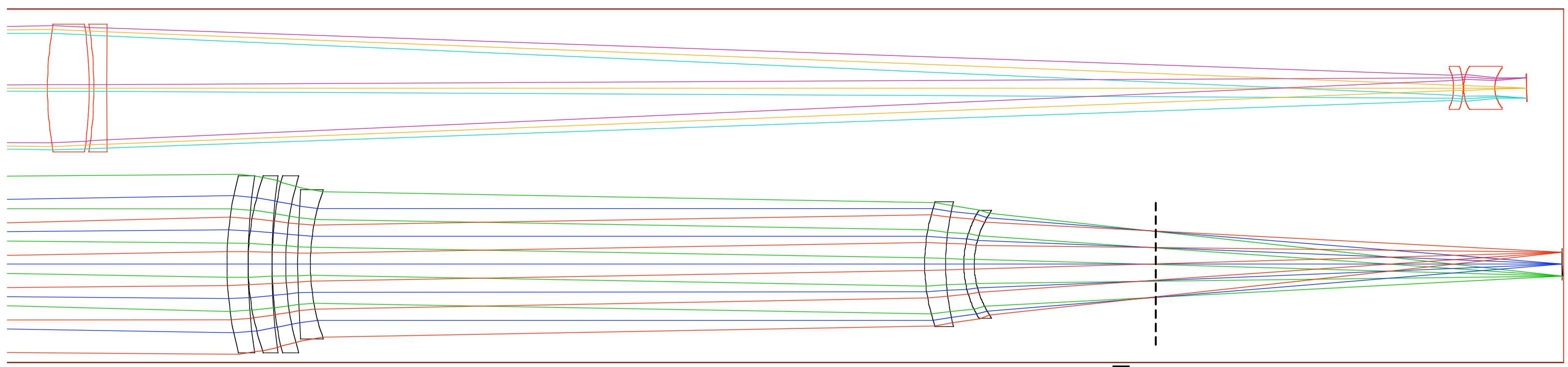
18 cm diameter: Two ZnSe, one Germanium & one ZnS lenses

13 cm diameter ZnSe/ZnS doublet

Visible (top) and IR (bottom) designs

13 cm diameter
fused silica/ CaFl
doublet

4.5 cm
diameter
fused silica
doublet



2.7 x 1.3 cm
detector:
(6.7μm
pixels x4K)

3.1 x 1.5 cm
detector:
(20μm
pixels x1.55K)

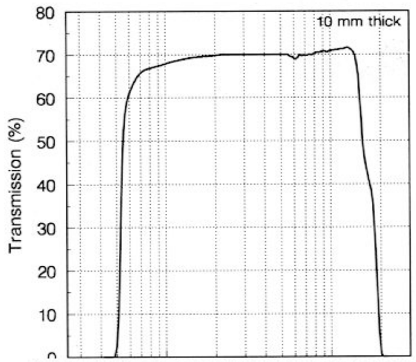
18 cm diameter:
Two ZnSe, one
Germanium & one
ZnS lenses

13 cm
diameter
ZnSe/ZnS
doublet

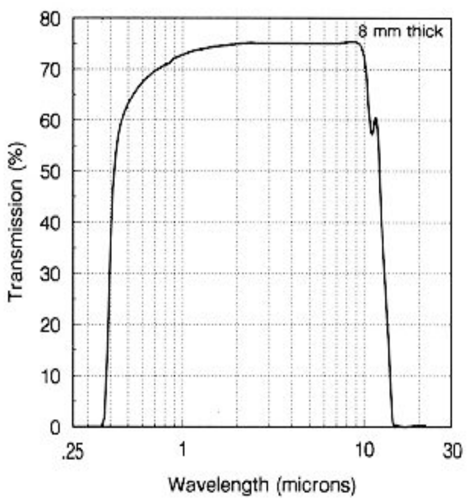
7 cm
diameter
cold stop

Baseline design has adequate IR transmission for the 3-5 micron band

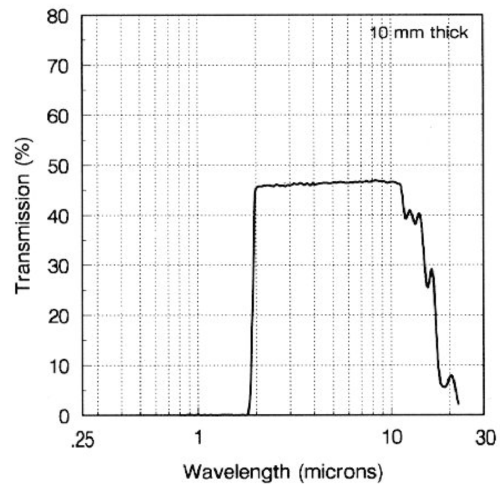
ZnSe Transmission Spectrum



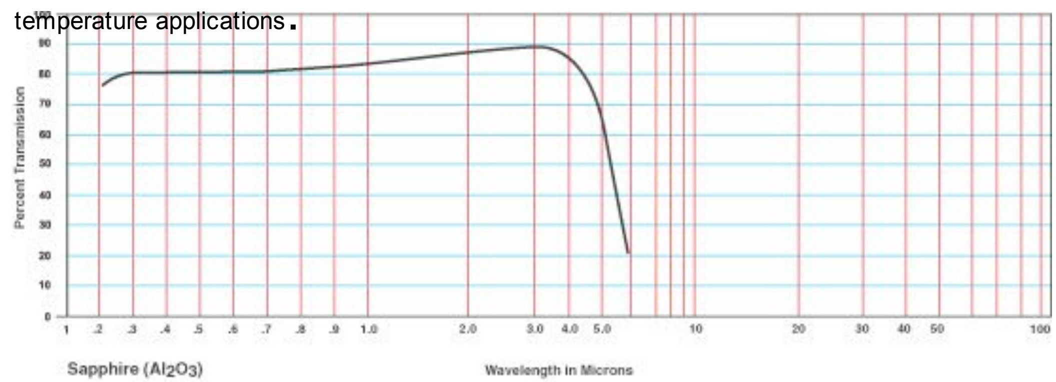
ZnS MultiSpectral Transmission Spectrum



Germanium Transmission Spectrum



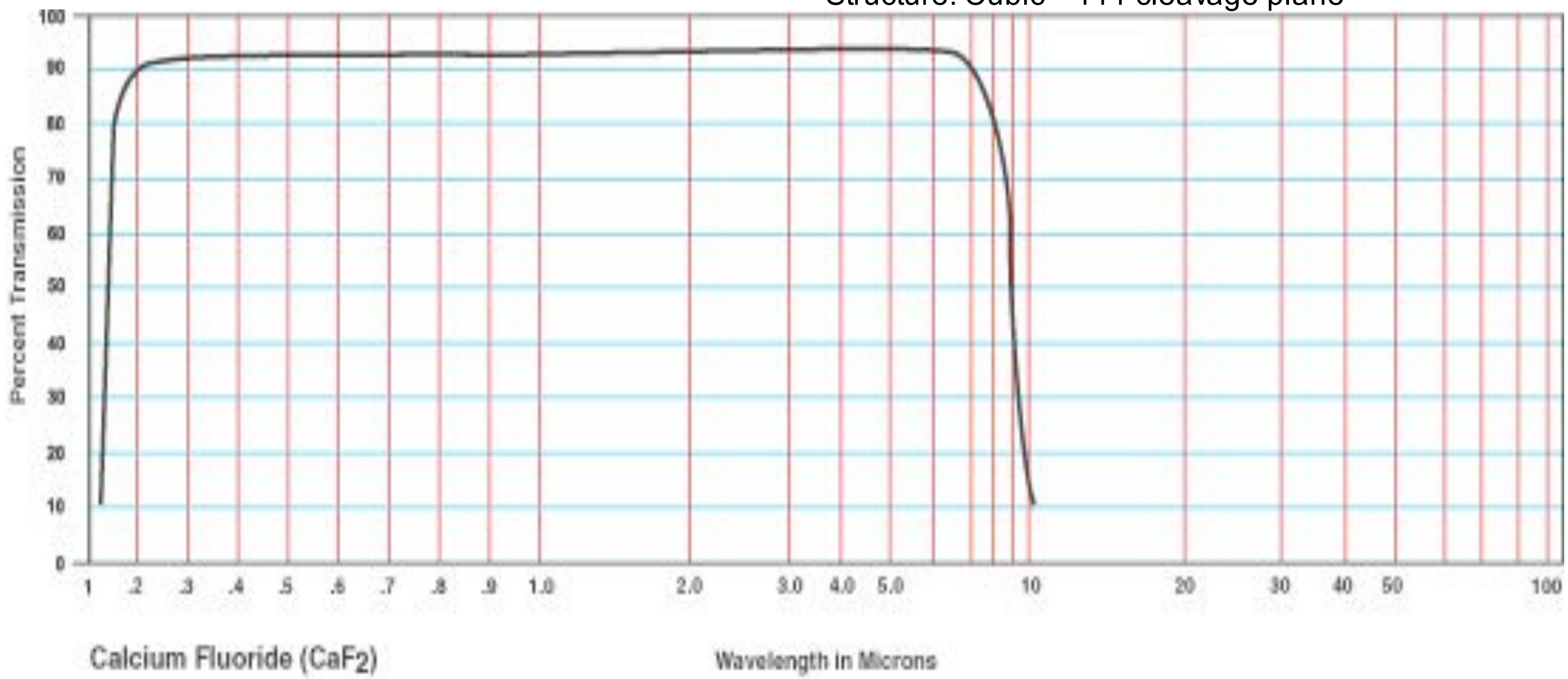
Sapphire (Al2O3) is an extremely hard material which is useful for UV, NIR and IR applications through 5 microns. It is particularly useful for high pressure and high temperature applications.



Using CaF_2 for vacuum windows allows extended IR wavelengths

Optical Properties - Calcium Fluoride (CaF2) Optical Crystals
Transmission Range: 130nm to 9µm
Refractive Index: 1.40 @ 5µm
Reflection Loss: 5.4% @ 5µm (2 surfaces)

Physical Properties - Calcium Fluoride (CaF2) Optical Crystals
Melting Point: 1360° C
Hardness (Knoop): 158 psi
Young's Modulus: 75.8 GPa
Modulus of Rupture: 5300 psi
Structure: Cubic---111 cleavage plane

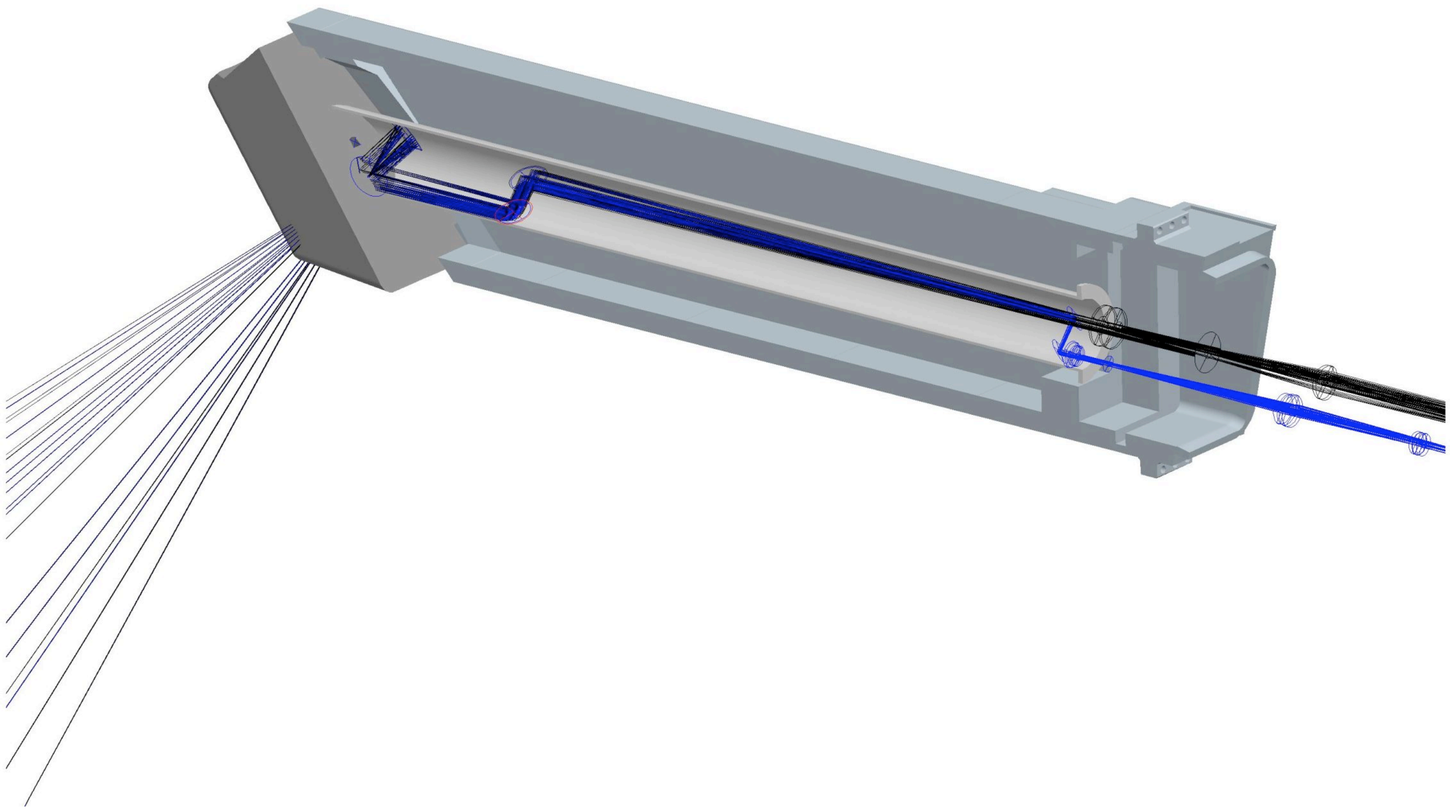


Physical Layout

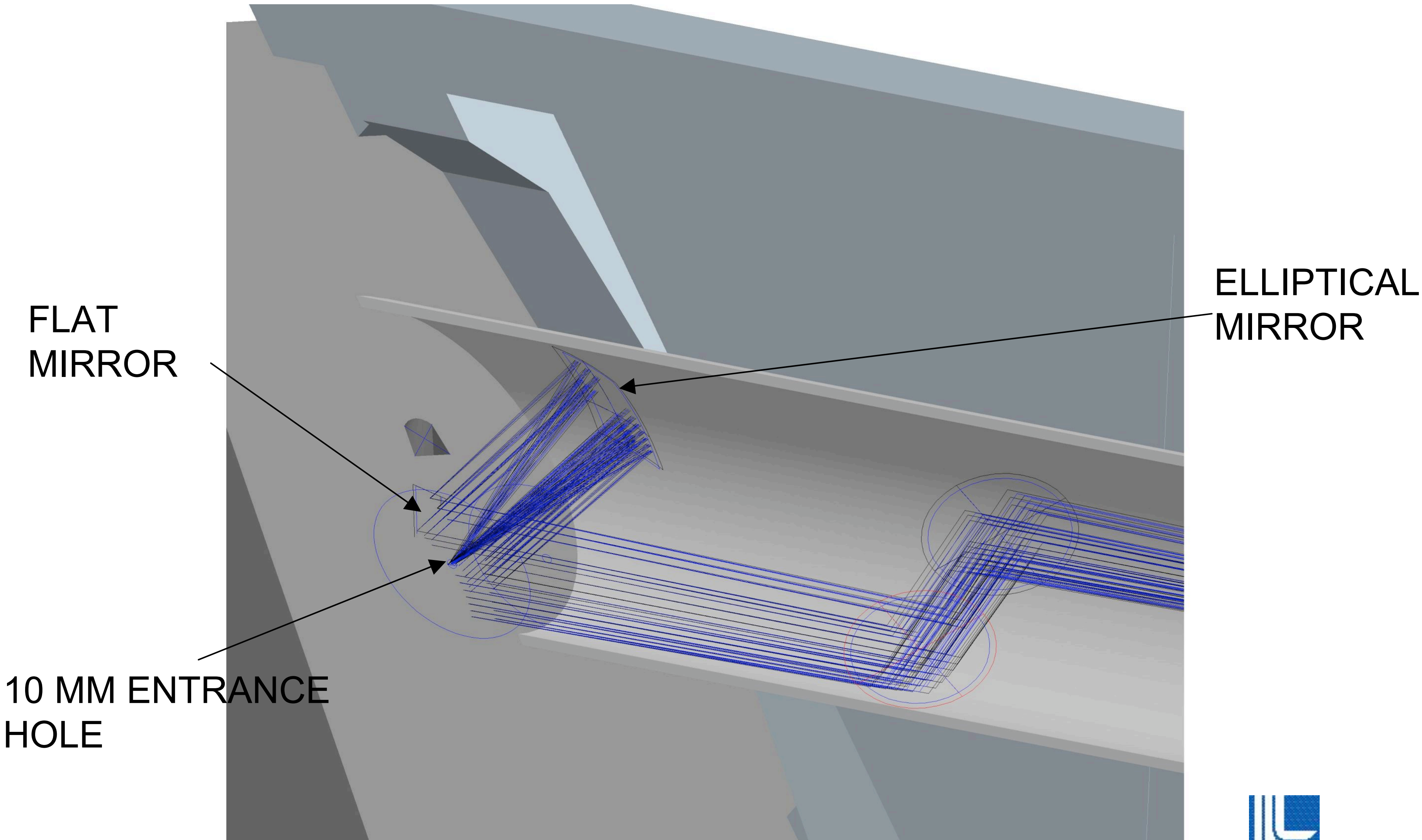
Kevin Morris

February 6,2007

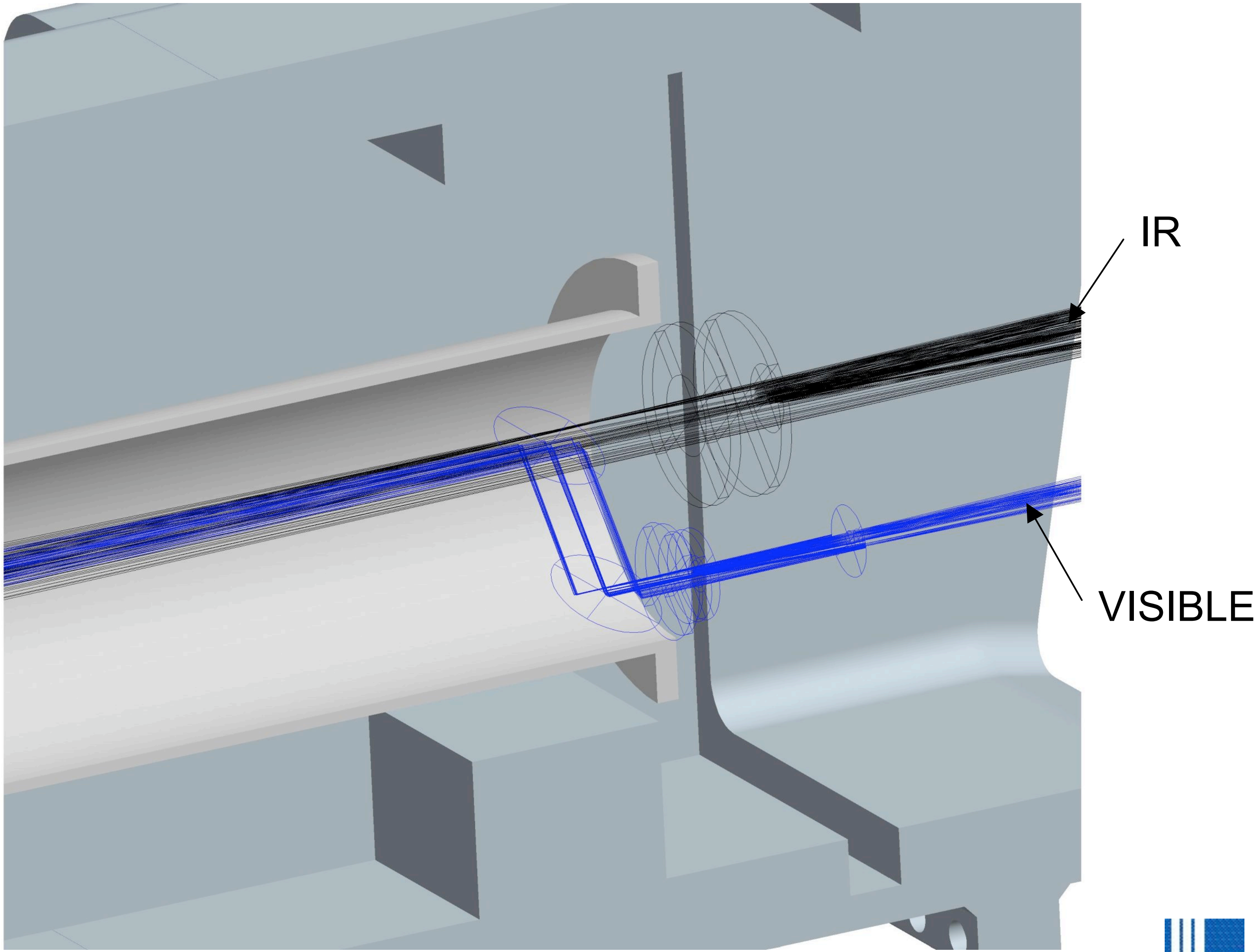
ITER VISIBLE and IR
UPPER PORT



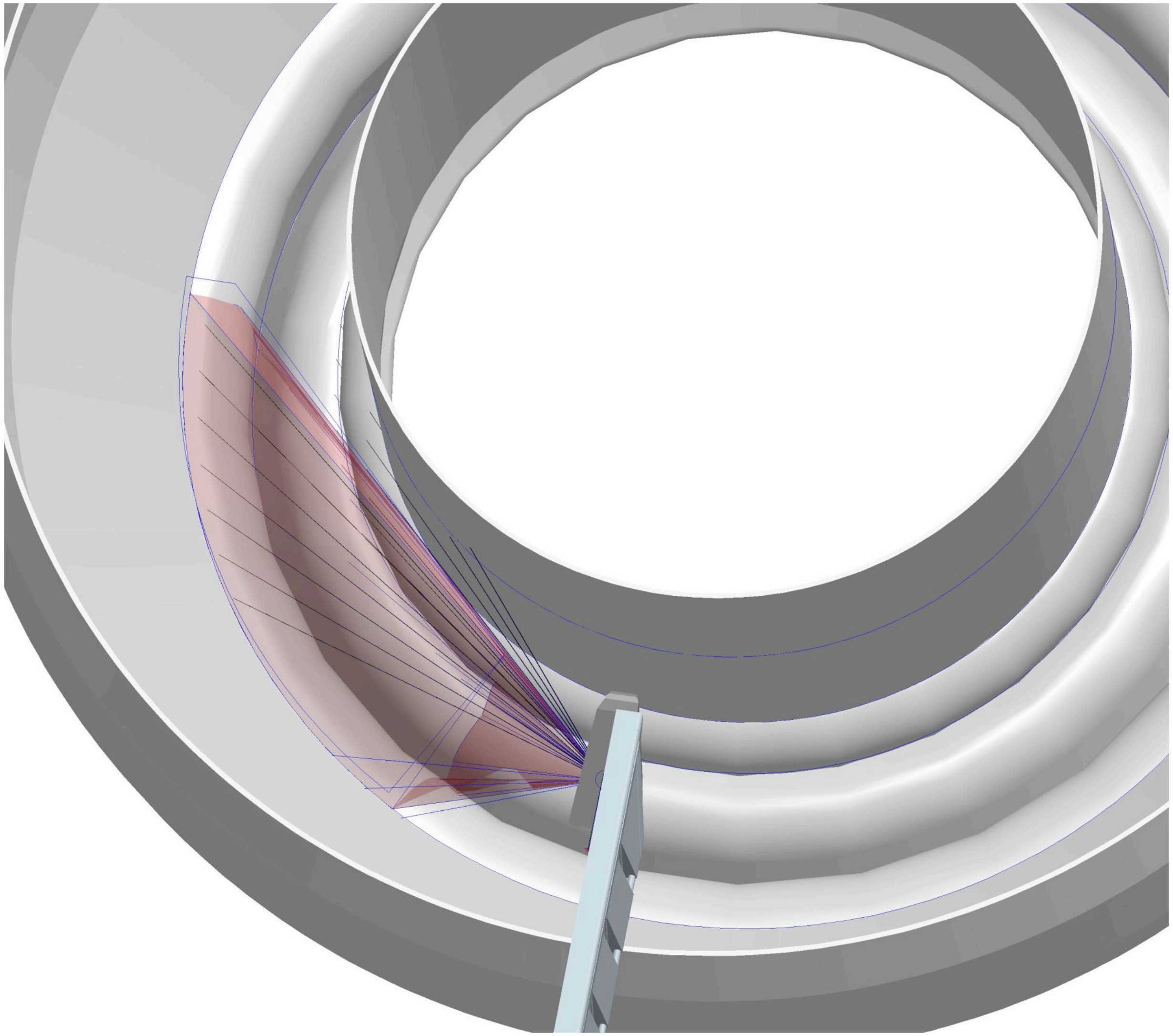
COLLECTOR HEAD

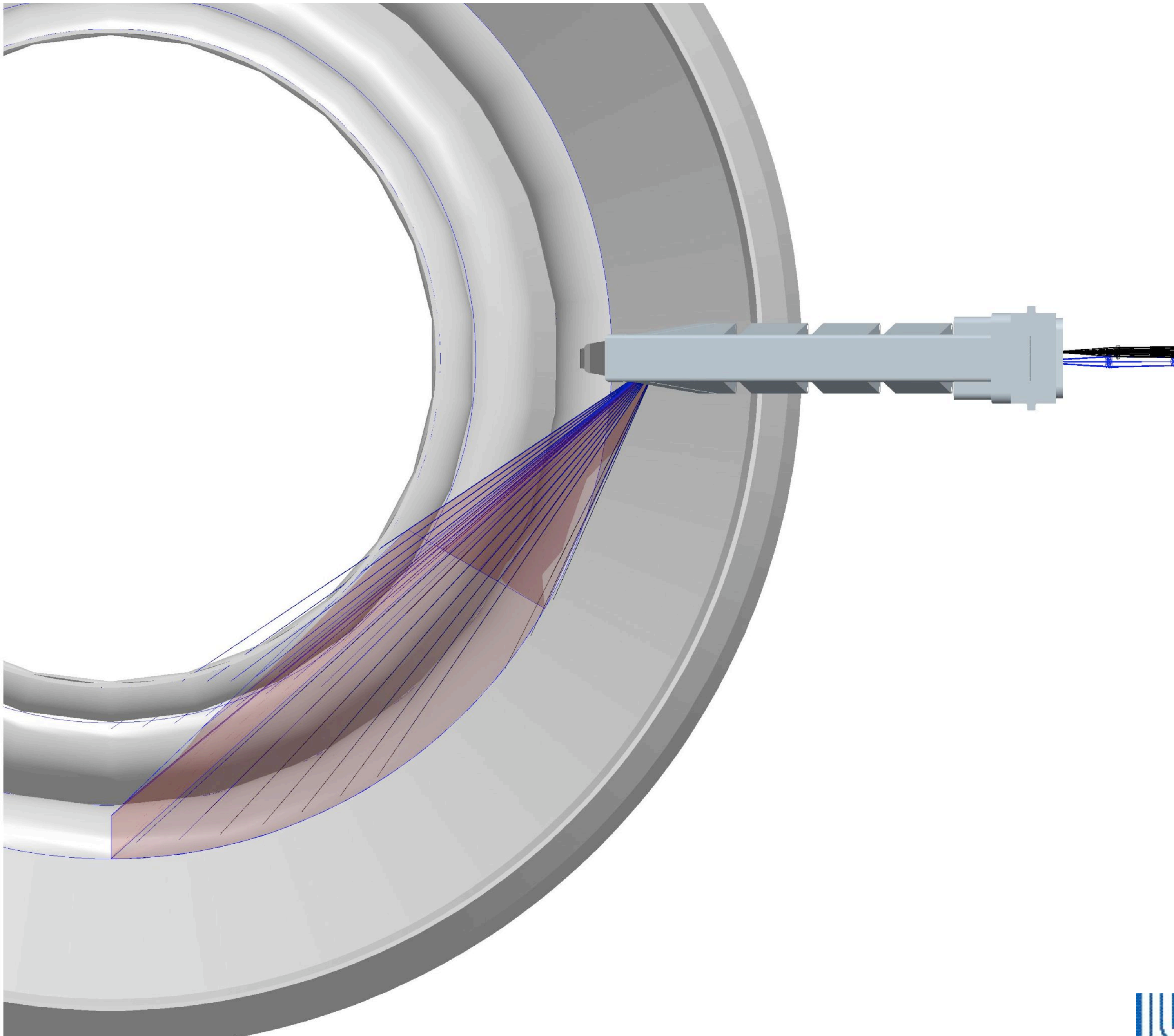


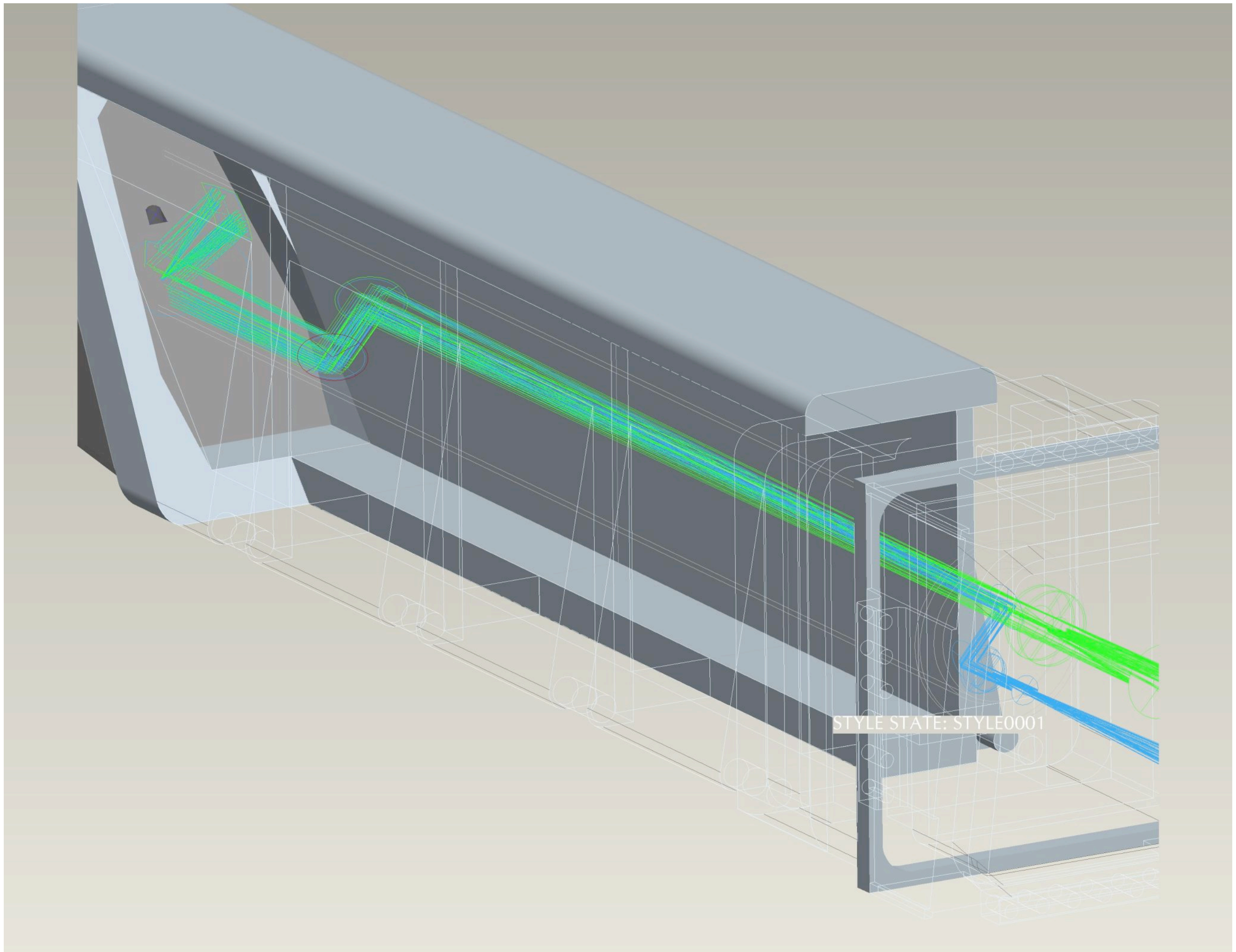
VACUUM WINDOWS



COVERAGE OF ONE PORT



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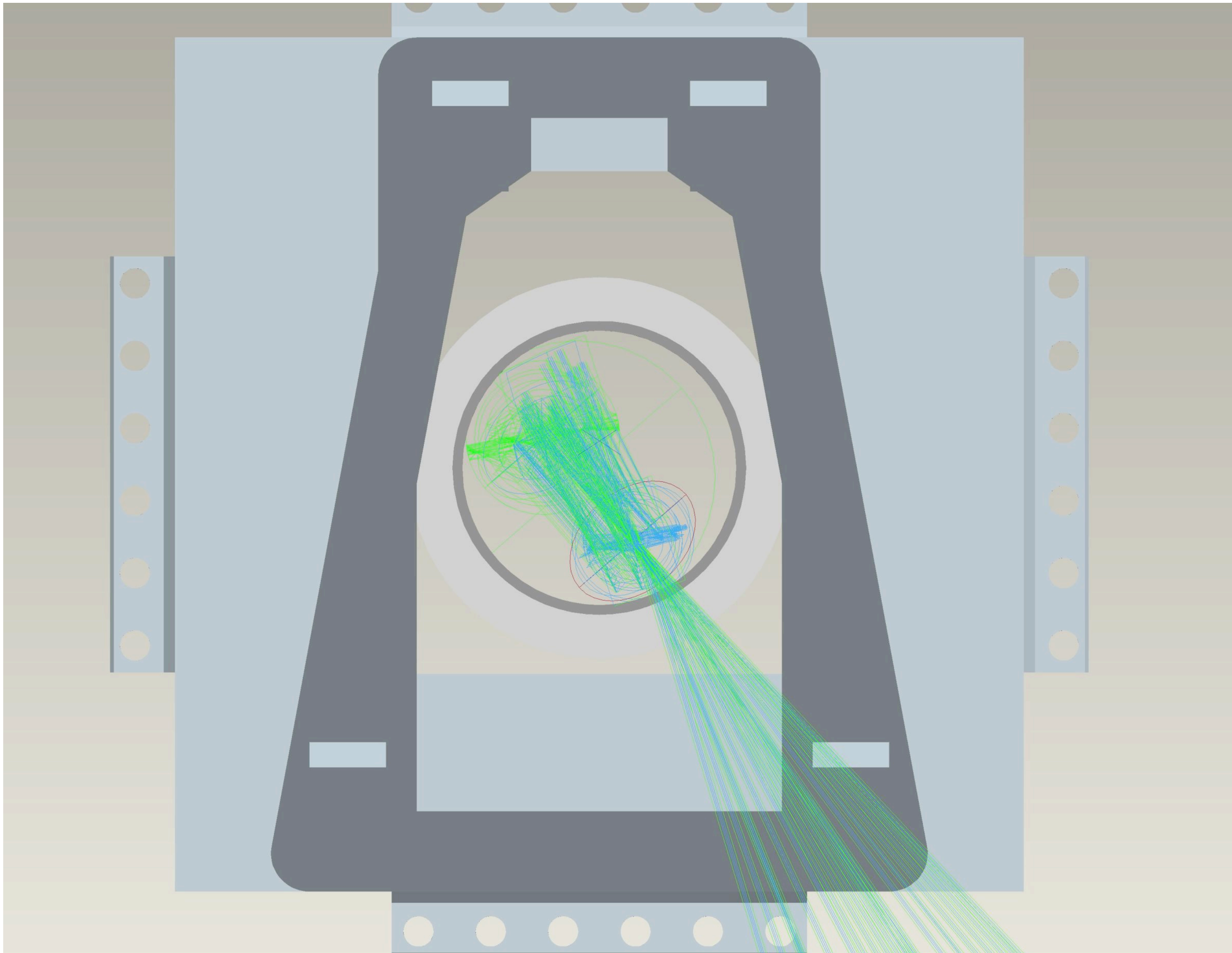


Follow-up

- Needed R&D
- Next steps

Specs imply big optics

- Small 10 mm aperture means low resolution
- Larger aperture + wide angle = large optics
- Optics for 20 mm aperture take up most of the port plug

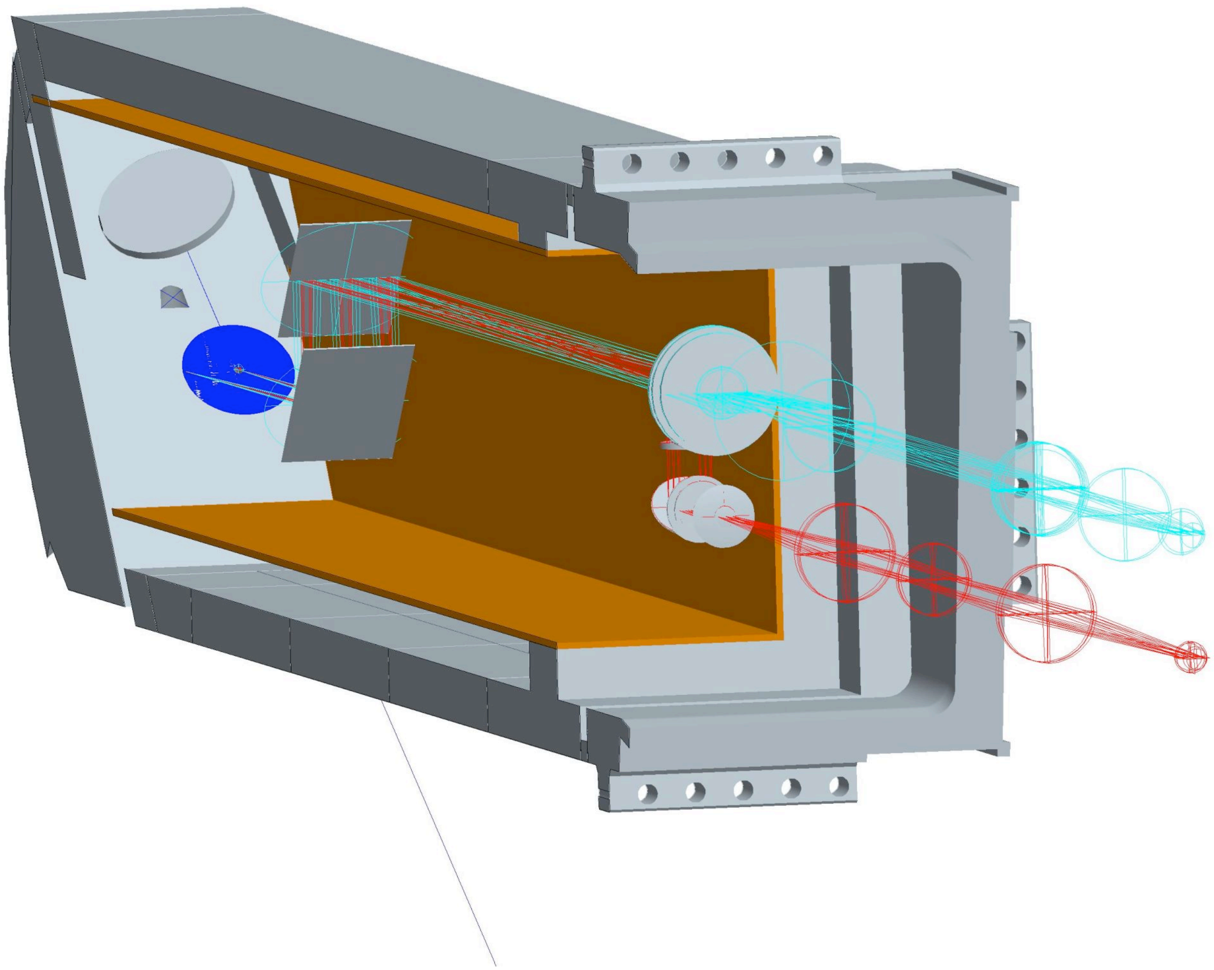
- Reduction in field of view would allow higher resolution

Outstanding issues requiring research/decision/attention

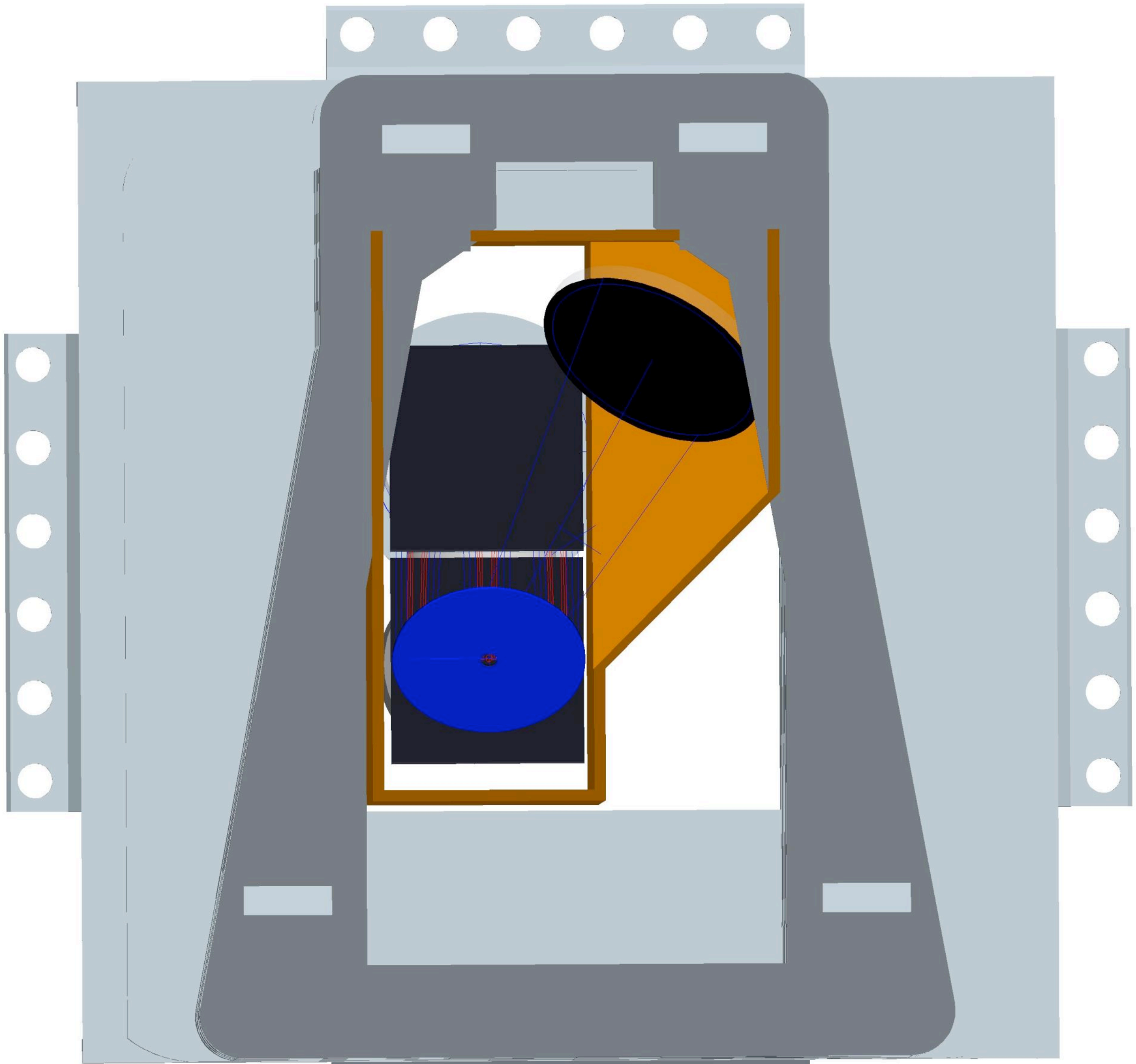
- **A. Large detector for IR, up to 3000-4000 pixels wide, 18-20 μm pixels**
- **B. Large visible detector, 3300 pixels, 4cm long**
- **C. Rejection of microwave power from gyrotrons**
- **D. Acquisition, processing, and storage, and analysis of huge data sets**
- **E. Durability of rhodium-coated mirrors under ion bombardment**
- **F. Durability of visible and IR anti-reflection coatings in high neutron environments**
- **G. Dependence of IR transmission on neutron fluence for ZnSe and Ge**
- **H. Estimate fluorescent emission from optics**
- **I. Develop scheme for calibration of the visible system (if needed)**
- **J. Decide to give up spatial coverage, spatial resolution, or some of both- possibly one system with localized high-resolution coverage- decide on an optical design**
- **K. test/develop reliable vacuum sealing for large ZnSe windows**
- **Items in red before construction of visible/IR camera diagnostic**
- **Items I, J, possibly K before mechanical design**

End

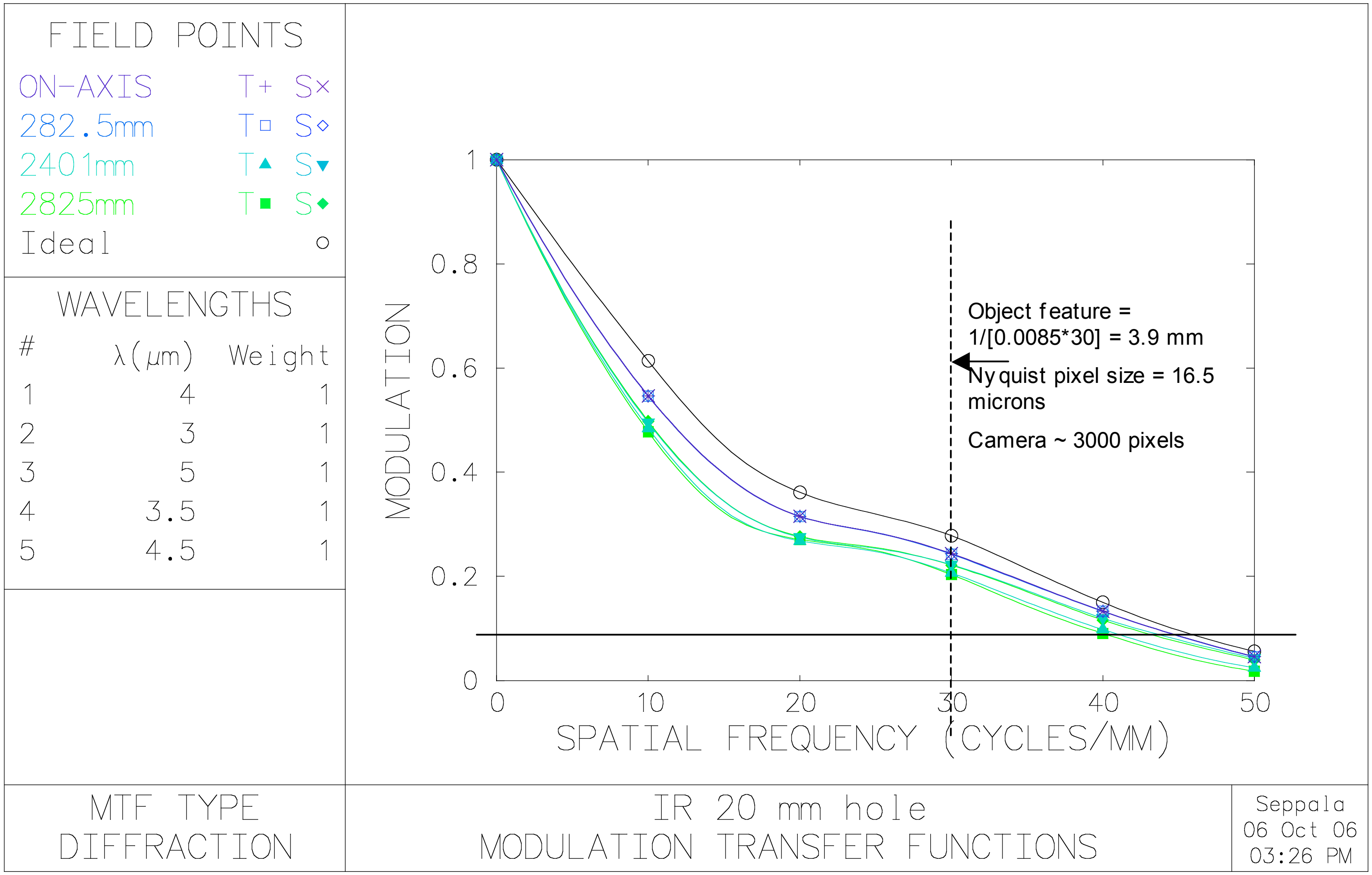
20 mm aperture design has large optics



20 mm aperture design takes up a lot of the port plug

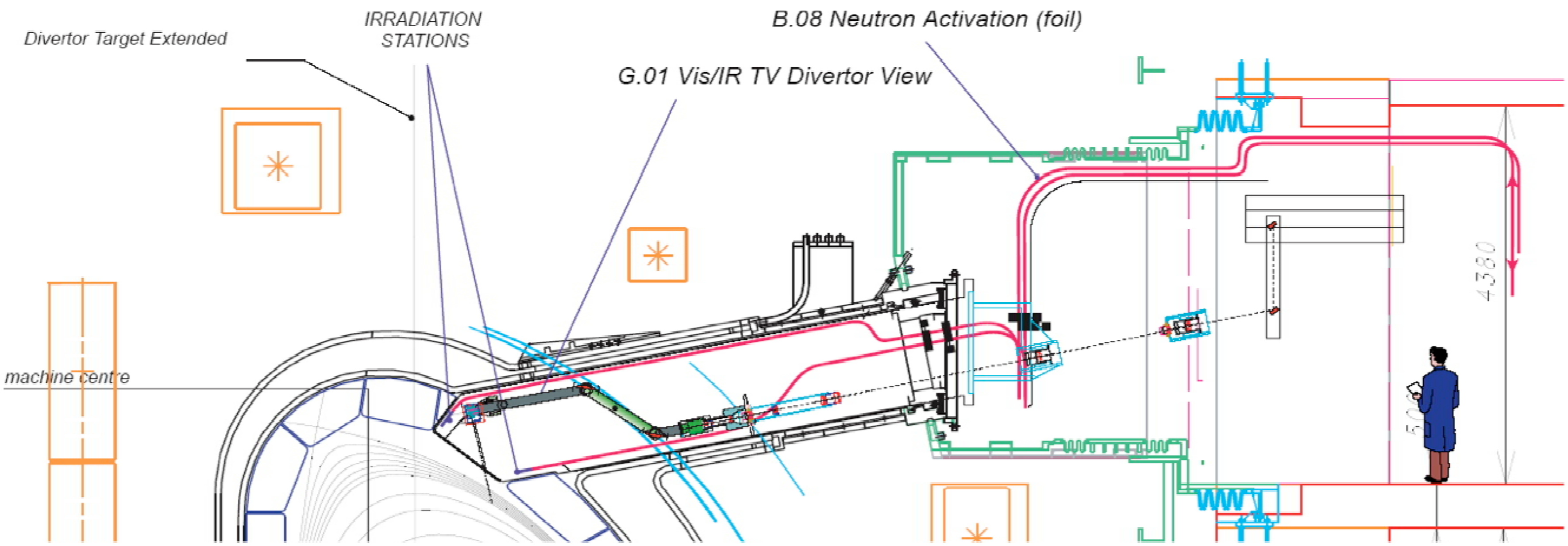


20mm aperture IR system magnification = 0.0085
Features 4 mm in size have MTF = 20%

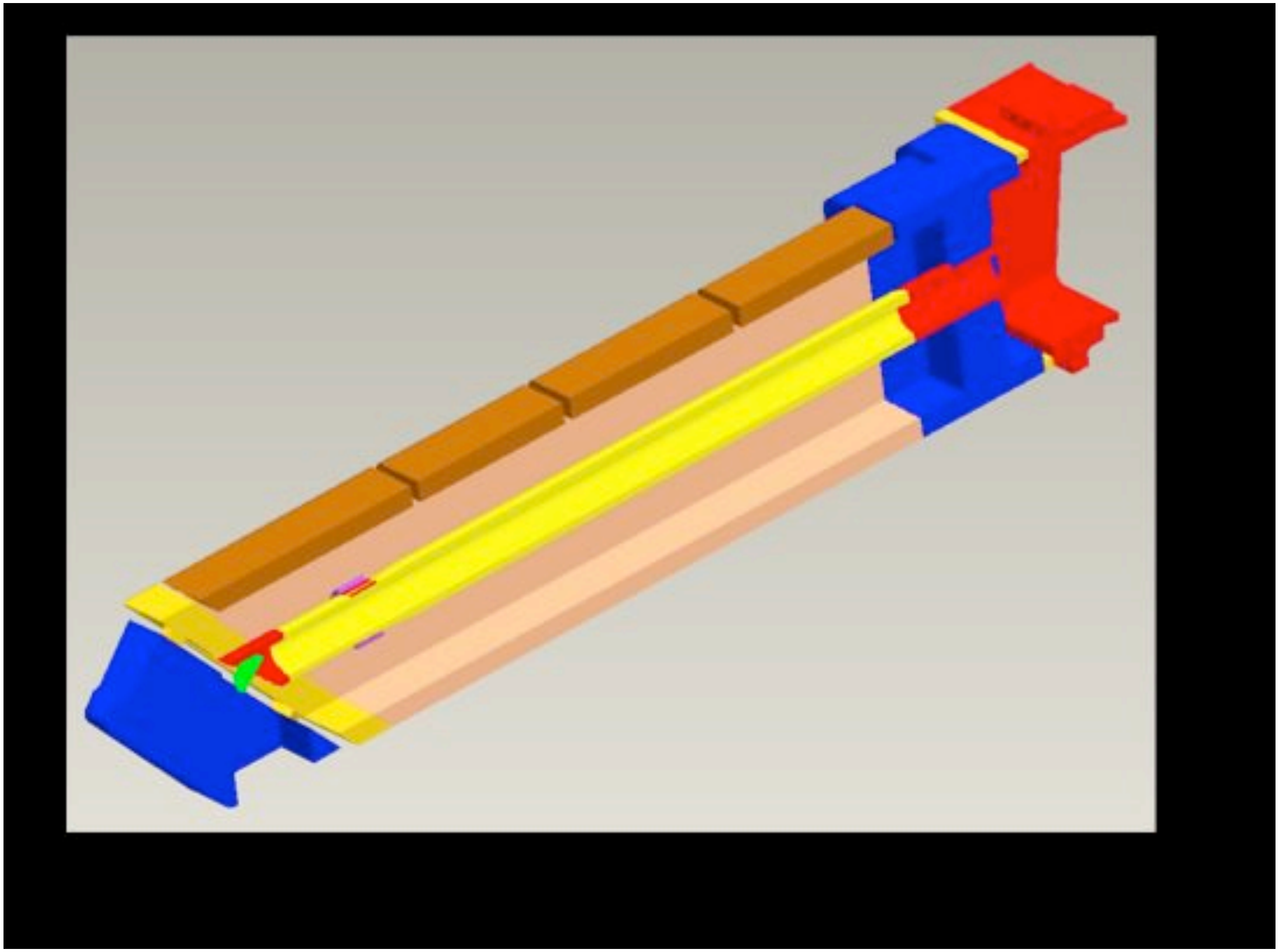


The reference design has doglegs to stop neutrons

- **From the Statement of Work**

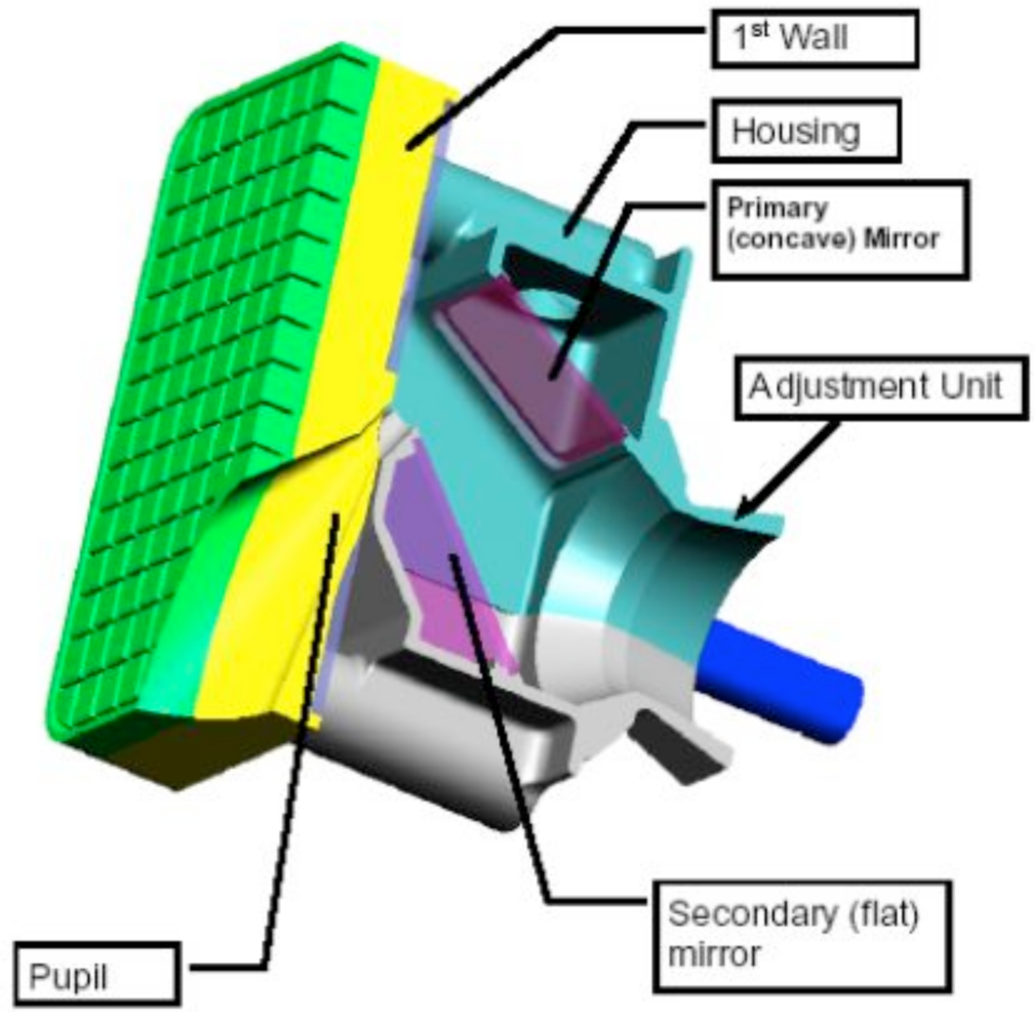


A Central Tube design would have no doglegs



To protect the mirrors, the hole in the wall is very small

- **5-20 mm pupil diameter!**
- **We need to examine the effect on the design of this hole size.**
- **No lenses are allowed in the port plug due to neutron damage.**
- **First two mirrors should be water-cooled**



CEA design

A Central Tube design has been built for JET and is now in use