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** See annex of F. Romanelli et al, "Overview of JET Results", (Proc. 22[nd] IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).*

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ABSTRACT.
Since 1994 JET has had a mirror-link spectroscopy system with a poloidal view of 150mm of the outer divertor split into 3 ranges: near-UV (~300-450nm), visible (450-750nm) and near-IR (750-1200nm). The system consists of 3 Czerny-Turner/CCD pairs: 1-meter focal length for the near-UV, imaging 0.75m for the visible, and imaging 0.5m for the near-IR. All were aligned along the same optical path to the divertor. As part of the JET ITER-like wall enhancements, the diagnostic system will be upgraded in 5 areas: 1) Frame-rate, 2) QE, 3) Radial coverage, 4) Optical throughput, and 5) for the near-UV, Spectral resolution and survey capability. New CCD's for the near-UV and visible will have increased QE and allow 3X's frame rate. The near-UV will benefit from a 0.75m imaging spectrometer with 3 gratings. The optics have been redesigned to allow ~360mm view and >2X throughput. The paper will look at the design and implementation as well as the new diagnostic capabilities of the system.

1. INTRODUCTION/OLD SYSTEM

The system was original designed to vertically view neutral beams for active phase (i.e. tritium operation) CXRS where the mirror-link allows observation of the 343.4nm C VI CXS line1. However, with the advent of the JET divertor the system was redesigned to provide spatially resolved spectroscopic views of the outer divertor. The system is shown schematically in figure 1 minus the near-IR system. The optical design dates from circa 1993-94, and at the time full 3D design was not possible with the packages available at JET. The optics consist of a long focal length plano-convex lens (A) which places an intermediate image of a 150mm portion of the divertor onto a 150mm x 50mm toroidal mirror (B) which acts as a field element. The toroidal mirror ensures all light going through the lens goes through the biological penetration by imaging the lens into the penetration. A flat mirror at the end of the tube folds the path into the horizontal plane of the spectrometer lab. Due to the non-orthogonal geometry of the system, a rotation of the image on the toroidal mirror is introduced which was then partially compensated for by adding another mirror in the spectrometer room at the appropriate angle/position to reverse the rotation. The light from the field mirror, after folding back into a horizontal plane, intercepts two edge/notch filters. The first reflects the near-UV (230-370nm ~90%) and transmits the visible; the second reflects the visible (430-880nm ~90%) and the remaining near-IR is transmitted. The intermediate image was brought to a focus on the spectrometer slits using either Newtonian telescopes (near-UV and visible) or an IR achromatic doublet (near-IR). The total optical path length from divertor floor to spectrometer slit is ~30 meters.

Starting with two 1-Meter Czerny-Turners without astigmatism correction, several incremental upgrades were made resulting in the following set of instruments in use from 1998 onwards:

A. Near-UV: 1-meter Czerny-Turner (CT) with 1200l/mm grating and in-house astigmatism correction
B. Visible: 0.75-meter Imaging CT with a triple grating turret.
C. Near-IR: 0.5-meter Imaging CT with triple grating. turret.

Tables I and II show specifications for the three systems; table I details the CCD's used up to the end of 2009, and table II shows the spectral capabilities including wavelength range, and wavelength coverage (per grating).

The mirror-link allows great flexibility in wavelength coverage from the near-UV to the near-IR. The system has been used successfully for many divertor spectroscopy experiments.

2. NEW SYSTEM

In preparation for the ITER-like wall project at JET [2], we looked to modify several aspects of the system to improve outer divertor spectroscopy especially regarding the near-UV tungsten and beryllium lines:

A. **Increased divertor coverage** which would allow one fixed optical alignment. With the old 150mm view mirror-A needed to be moved remotely to appropriate positions to view the outer strike point. In addition, during strike point sweeps not all of a sweep could be seen. The question was how much of the divertor could be seen given the torus port limitations with respect to geometry?

B. **Reduce/eliminate the image rotation** at the field optic. This rotation caused vignetting at the field optic for the edges of the image which resulted to sensitivity to alignment for those edge views.

C. **Increase flexibility of the near-UV system.** The old single grating system with a wavelength coverage of ~14nm meant that some survey measurements were limited; specifically, the Balmer series could only be measured from the series limit to n-n'=11-2.

D. **Increase optical throughput.** This could be addressed in three areas:
   a. Newly coated clean optics to improve throughput. On the newly built system in 1995-97, these measurements could easily reach 227nm (C V); but as the years passed anything below 300nm became problematic.
   b. Increase diameter of limiting apertures in the system
   c. Improve QE of the CCD's. The near-UV system would especially benefit moving from a front-illuminated CCD to a back-illuminated CCD with UV-phosphor.

E. **Increase the frame rate.** The old system could only run at ~10 frames per second for 14 tracks. The addition of new faster CCD means that frame rates increase by about a factor of 3-5 for the same number of tracks on the CCD.

F. **Improve the robustness** of the optical mounts.

2.1. INCREASED DIVERTOR COVERAGE

The torus port window is only 80mm in diameter and at the end of a 85mm-long tube which is welded to the port flange which is 1270mm from the top of the vacuum vessel. The port flange is wedge shaped which limits the innermost ray. The limits of the view can be seen by drawing the rays connecting the window aperture to the bottom of the port tube aperture. This gives the absolute maximum size that could fit. Figure 2 shows this "ray" tracing. The limit of this fan is about 360 mm. Of course to provide imaging resolution and light gathering actual ray tracing in an optical design package had to be done.

2.2. OPTICAL THROUGHPUT

By replacing old optics with newly coated optics it is hoped to increase the lower limit of the near-UV measurement. In addition, the near-UV system would get a new back-illuminated CCD with UV-phosphor, whereas, the old CCD was front illuminated with UV coating. This back illuminated CCD will give about a factor of 2 improvement in QE from 200-400nm. The visible system gets a new back-illuminated CCD (no UV phosphor) so it's QE will increase by ~50% over the older CCD. Also, during the optical design phase, it was found that if the collection area of the imaging lens was increased from a diameter of ~1cm to ~2cm that 4x's the light throughput could be achieved. However, this required the diameter of the biological penetration tube to be increased from 95mm to 130mm to allow this extra light into the spectrometer lab.

3. OPTICAL DESIGN PROCESS

Before the optical design was started the components in the torus hall were photogrammetrically surveyed to determine the location of the existing optics. These coordinates and pertinent aperture information were then fed into the machine configuration drawings so that a final record of the old design as on the machine was made and to facilitate future design work. Next the unfolded optical path distances along with aperture information were input into the optical design program Zemax [3]. This was done to simplify the initial optical design question: how much more of the divertor floor could we see? First stage optical analysis resulted in an increased radial viewing width to 360mm confirming the geometrical port constraints (see figure 2).

Next the 3D-model including the folds was input into Zemax and work on the port optics was performed to attempt elimination of the image rotation. The rotation is induced from our non-orthogonal geometry which is due to port and machine constraints. Let's call the port or last mirror before the torus-window, mirror-A. Experimentation with configurations in Zemax showed that to remove the rotation and keep the image vertical on the limb mirror, two extra mirrors were needed [4]: one along the radial line of the first mirror/port (mirror-B) and another at tangential to the port mirror but displaced toroidally (mirror-C). In addition, it was found that the mirror-B needed to be displaced vertically from mirror-A and mirror-C which are at the same height. The image can be adjusted for verticality at mirror-D by rotating the plane of mirrors ABC about the line AC. This also means that no translating movement of mirror-C is needed.

Several iterations between the Zemax 3D model and the 3D machine model were made to obtain optimum mirror A-C geometry. Figure 3 shows the folded layout in overview and figure 4 shows a close up on the port optics configuration (mirror-A, mirror-B, lens-A and mirror-C).

The nominal physical parameters of the torus hall optics are listed in table 3. Mirrors D and E are retangular. Note also the field mirror D has been simplified to a simple concave mirror over the old systems more expensive toroidal mirror.

4. PHYSICAL DESIGN

Our philosophy was to use off the shelf mounts where possible. For the mirror mounting this worked remarkably well. Mirrors A and C utilize Newport SL8A gimbal mounts. Mirror B uses a Newport Ultima series 50.8mm gimbal mount. The lens-A is enclosed in a simple lens cell. For the two large mirrors (field optic mirror-D and flat mirror mirror-E) gimbals were still ideal, but finding off-the shelf gimbals for such large rectangular mirrors that also met the space constraints proved impossible. We came up with the idea of using two orthogonal goniometers (Newport) with the addition of extra locking plates to ensure stability. All optical mounts were modified with the addition of indexing pin holes so that positioning accuracy could be ensured. Figure 5 is side overview of the torus hall components. Figure 6 shows a close up of the port mirror box (mirrors A-C and lens-A) and figure 7 shows the boxes for mirrors-D and mirrors-E.

SUMMARY OF THE CAPABILITIES OF THE NEW SYSTEM

Spatially, going to 360mm coverage from 150mm means the difference between seeing full sweeps and not; in addition, for some plasmas the separatrix can be viewed as well as the private flux regions. Figure 2 shows just how much more the new system sees compared to the old. The increased frame rates (30msec from 100msec) means some ELM induced behaviour might be seen/resolved. Tables IV and V show the enhancements CCD and spectroscopic capabilities for comparison to the old system (tables I and II). The near-IR system remains unchanged as the old large format CCD is ideal for the survey work; it would have been better to have a modern fast CCD, but large frame-transfer CCD's are out of vogue in the push to ever smaller pixels size for the commercial markets. The visible system suffers a little in wavelength band covered per grating, but for at least the 1200l/mm setting the old system band was wider than necessary (typically observing D-delta, C II 426.7nm and D-gamma). However, the near-UV gets big improvements for the Balmer series observations the 44.1nm will allow coverage of the series limit to n−n'= 6-2. For tungsten the near-UV system should be able to view the two W I lines at 268.1nm and 255.1nm for one setting and the three W I lines at 430.2, 429.4 and 400.8nm at another wavelength setting [5].

Ultimately, the most important question is what kind of physics can we now do? With the re-extension into the near-UV (<300nm) we can observe beryllium and tungsten lines that no other diagnostic at JET can; with these observations influx and recycling measurements can be improved.

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[2]. G.F. Matthews et al Phys. Scr. 2007 137

[3]. ZEMAX Development Corporation, 3001 112th Avenue NE, Suite 202, Bellevue, WA 98004-8017 USA

[4]. One extra mirror would place the image horizontally at mirror-D which would then not clear the various machine obstructions.

[5]. A. Pospieszczyk et al, ADAS workshop proceedings at http://www.adas.ac.uk/talks2009.php

	H x V (pixels)	pixel sixe (_m)	Image plane CCD (mm2)	ADC (MHz)	Bit - range	Min Exp (msec) @ 14 tracks
A	770 x 576	22.5	17.3 x 12.9	0.2	15	70
B	1242 x 576	22.5	27.9 x 12.9	0.2	15	100
C	1242 x 576	22.5	27.9 x 12.9	0.2	15	100

JG10.39-8c

Table 1: Old system CCD specifications.

	Overall range (nm)	Spectrometer	Wavelength window (nm)
A	300 - 700	1-m CT with in-house correction: B&M	14.0 @ 12001/mm & 350nm
B	390 - 800	0.7-m Imaging CT: Action SP - 2758i	122.4 @ 3001/mm & 500nm 28.0 @ 12001/mm & 500nm 14.0 @ 24001/mm & 500nm
C	650 - 1300	0.5-m Imaging CT: Action SP - 500i	179.3 @ 3001/mm & 930nm 84.8 @ 6001/mm & 930nm 34.2 @ 12001/mm & 930nm

JG10.39-9c

Table 2: Old system spectrometer/ccd wavelength information.

Optic	Location	Size (mm)	Radius of curvature (mm)
Mirror-A	Port	80_	∞
Mirror-A	Port	50_	∞
Lens-A	Port	50_	1225
Mirror-C	Port	80_	∞
Mirror-D	Limb	360x360	7900
Mirror-E	Limb	550x60	∞

JG10.39-10c

Table 3: Torus hall optics.

	H x V (pixels)	pixel sixe (_m)	Image plane CCD (mm2)	ADC (MHz)	Bit - range	Min Exp (msec)@ 20 tracks with 16 bit & 1MHz clock
A	770 x 576	22.5	17.3 x 12.9	1 or 3/5/10	16 or 14	30
B	1242 x 576	22.5	27.9 x 12.9	0.2	16 or 14	30
C	1242 x 576	22.5	27.9 x 12.9	0.2	15/16	100 @ tracks

JG10.39-11c

Table 4. New System CCD.

	Overall range (nm)	Spectrometer	Wavelength window (nm)
A	200 - 700	0.75-M Imaging CT: Action SP - 2758i	44.1 @ 3001/mm & 350nm 11.0 @ 12001/mm & 350nm 5.5 @ 24001/mm & 350nm
B	390 - 800	0.7-M Imaging CT: Action SP - 2758i	58.3 @ 3001/mm & 500nm 13.5 @ 12001/mm & 500nm 6.7 @ 24001/mm & 500nm
C	650 - 1300	0.5-M Imaging CT: Action SP - 500i	179.3 @ 3001/mm & 930nm 84.8 @ 6001/mm & 930nm 34.2 @ 12001/mm & 930nm

JG10.39-12c

Table 5. New system spectrometer/ccd wavelength information.

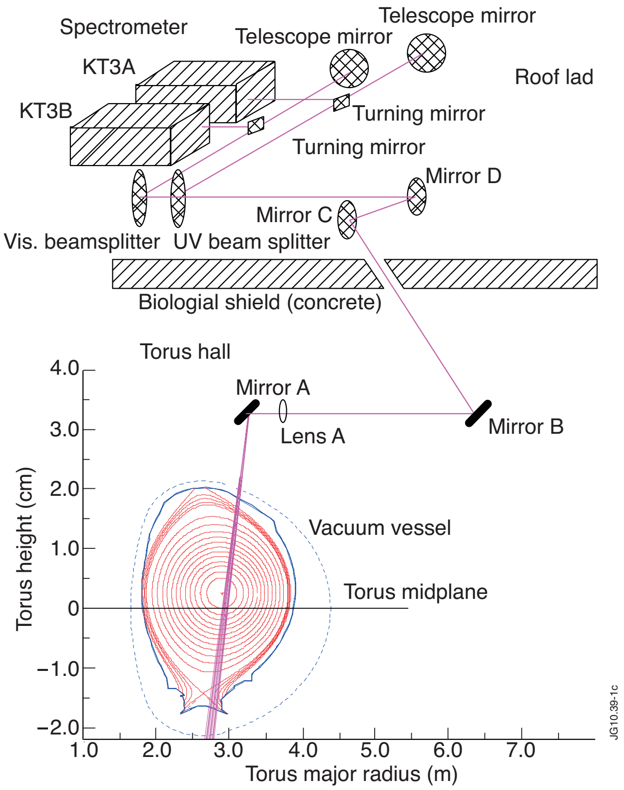

Figure 1: Schematic showing the old optical train including the near-UV and visible spectrometers but excluding the near-IR system.

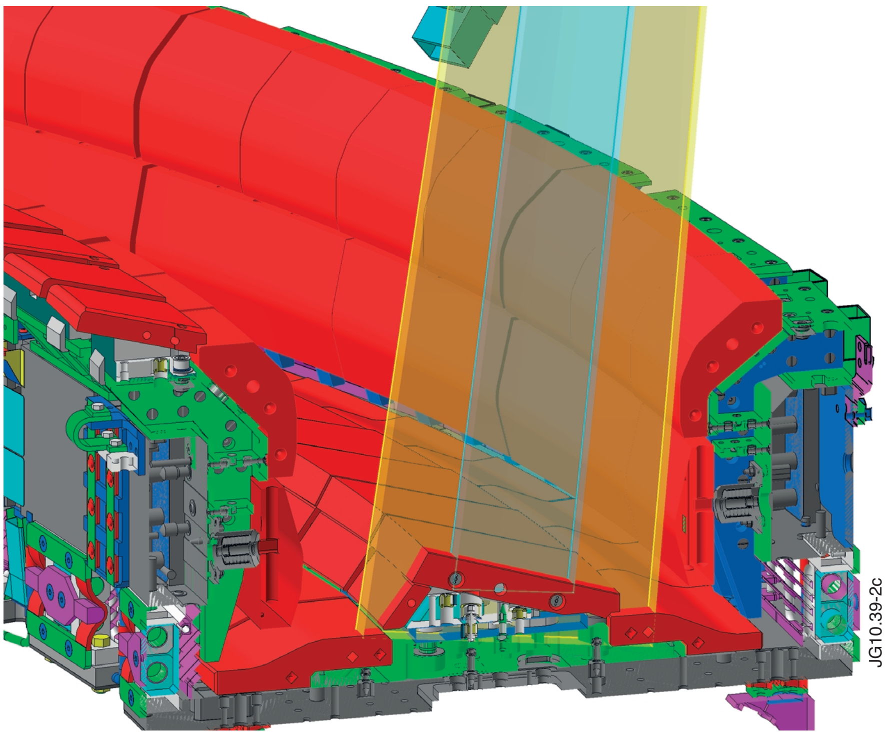

Figure 2: Radial extent for lines of sight: old is inner/dark gray (150mm); outer is orange/light gray (360mm). Both sets of los are centered on the geometrical axis of the port tube. The Septum Replacement Plate (SRP) is the tilted tile over which the LOS are centered.

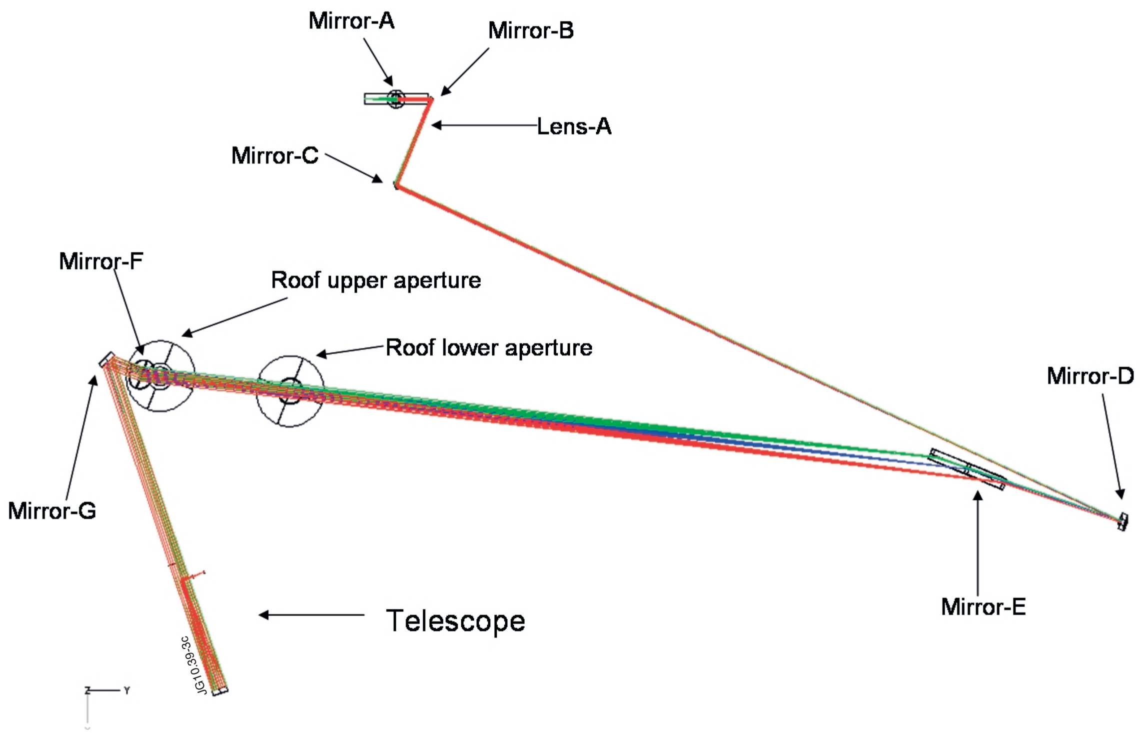

Figure3: Plan view (from above) of the folded optical system.

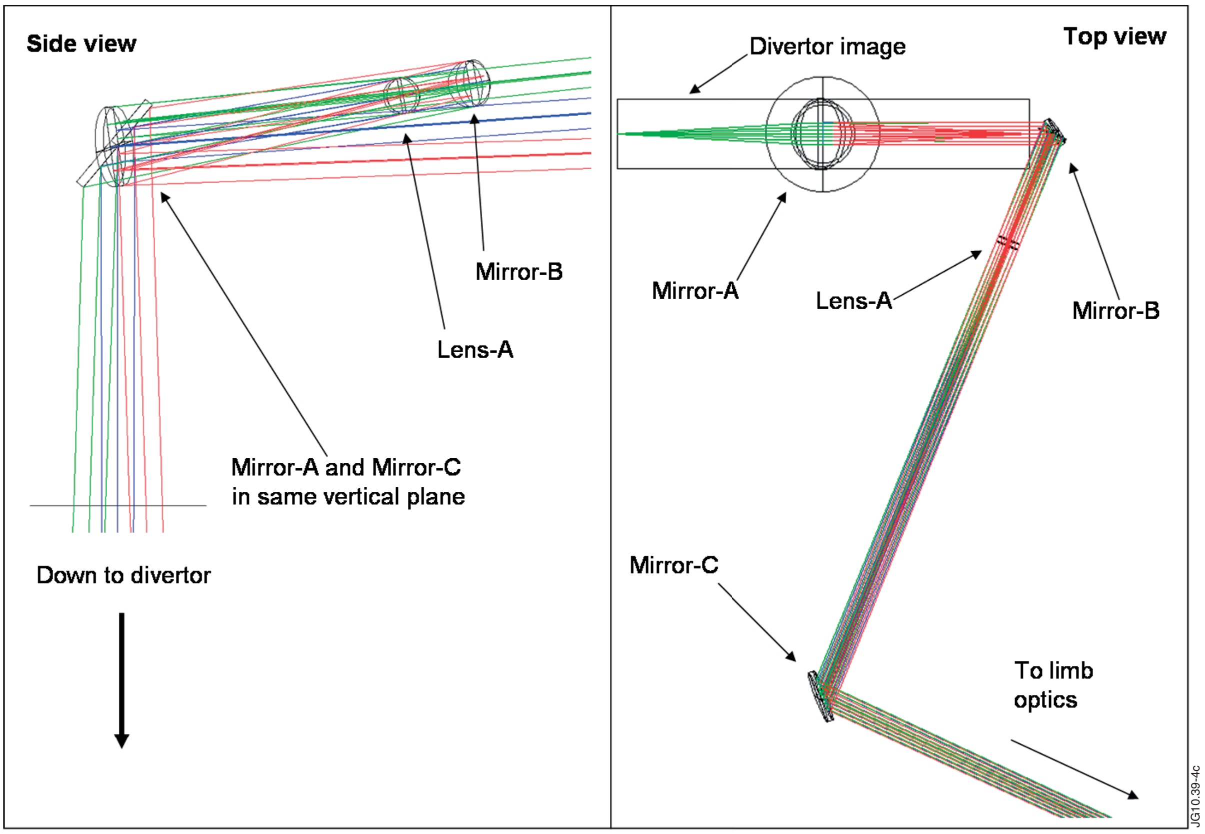

Figure 4: Close up of the 3 mirror dog-leg needed to eliminate image rotation on mirror-D. The side view emphasizes the tilting out of the horizontal plane of mirror-B and lens-A while mirrors A and C remains at the same horizontal position. The top view shows mirror C tangential to mirror-A with respect to the radial line defined by the divertor image.

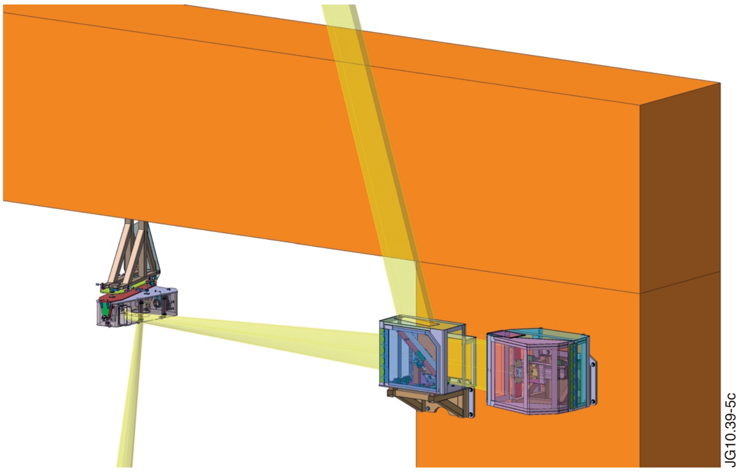

Figure 5: Overview from the side of the torus hall components. Left is the port mirror box (mirrors A-C and lens-A) and right are the mirror boxes E and D.

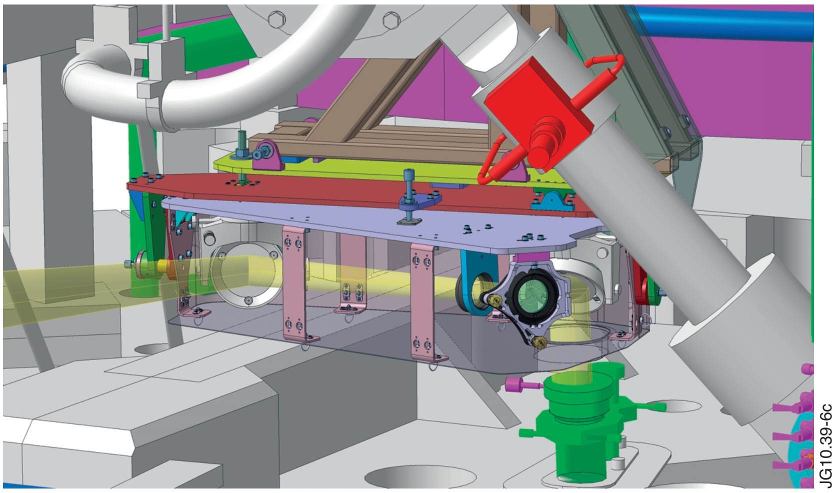

Figure 6: Port Mirror Box. Left-to-right are mirror-C, lens-A, mirror-B and then mirror-A and the port (below). The pivots can be seen on the left and right which tilt the mirror plane ABC about the line AC.

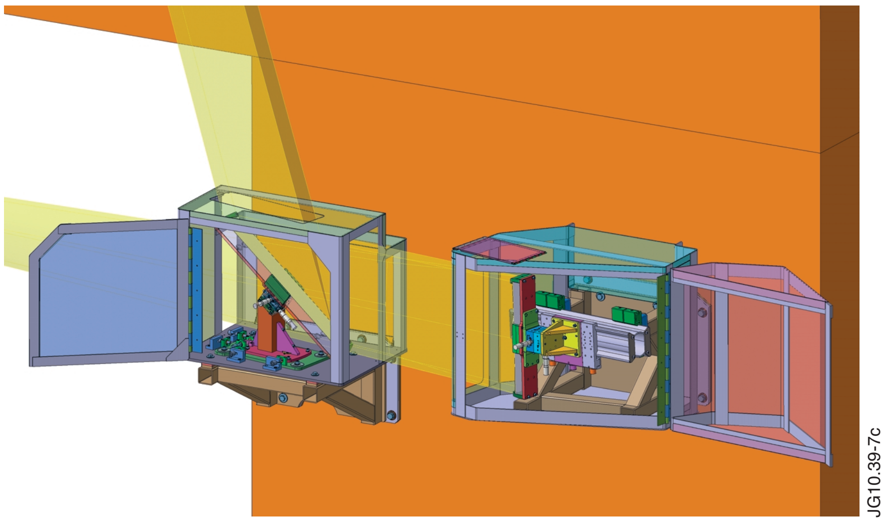

Figure 7: Mirror-D (right) and mirror-E (left) assemblies. The rail at mirror-D allows the intermediate image from lens-A to be focused into the biological penetration tube.