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Design considerations for a time-resolved tomographic diagnostic at DARHT

Morris I. Kaufman*, Daniel Frayer, Wendi Dreesen, Douglas Johnson, Alfred Meidinger
NSTec, Los Alamos Operations, 182 East Gate Drive, Los Alamos, NM USA 87544

ABSTRACT

An instrument has been developed to acquire time-resolved tomographic data from the electron beam at the DARHT [Dual-Axis Radiographic Hydrodynamic Test] facility at Los Alamos National Laboratory. The instrument contains four optical lines of sight that view a single tilted object. The lens design optically integrates along one optical axis for each line of sight. These images are relayed via fiber optic arrays to streak cameras, and the recorded streaks are used to reconstruct the original two-dimensional data. Installation of this instrument into the facility requires automation of both the optomechanical adjustments and calibration of the instrument in a constrained space. Additional design considerations include compound tilts on the object and image planes.

Keywords: Tomography, image tilt, optomechanical, mechanism design, automation, calibration.

1. INTRODUCTION

The Dual Axis Radiographic Hydrodynamic Test (DARHT) facility is designed to record high-speed radiographic images of explosively driven hydrodynamic events. The facility accomplishes this by illuminating the test object with short x-ray pulses and recording the resulting radiographic images. The x-ray pulses are generated by illuminating an x-ray converter target with a high-power electron beam.

The 4-view system, designed specifically for the commissioning of the DARHT second axis, is an imaging instrument used in a tomographic diagnostic that records electron beam profiles at high temporal resolution (better than 2 ns for a 2-μs record length). The diagnostic measures the evolution of the beam's cross-sectional profile and position. This information is used for beam steering. The electron beam passes through a thin (200–500 μm) 5-inch-diameter, fused silica target; the 4-view optical system views the Cerenkov radiation emitted by this target. The streak-imaging technology required for such a high level of temporal resolution can only record one-dimensional (1-D) data. Sequential (temporal) data is captured as lines of pixels by the CCD [charge-coupled device] camera. This basic fact necessitates an optical system that creates and records 1-D projections of the original image in various orientations, and a tomographic reconstruction of the two-dimensional (2-D) beam profile from the series of 1-D data sets (Figure 1), as first described by Wilke[1].

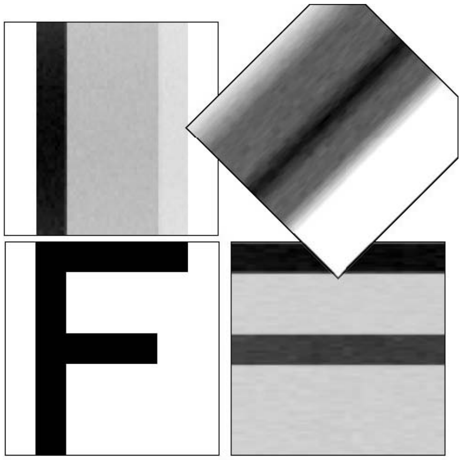

Figure 1. A simulation of projected images for an F pattern

The projections are created by four discrete optical systems arranged in tight proximity and tilted so that their fields of view (FOV) overlap. Each optical subsystem images the target along one axis and uses a cylindrical lens to fully defocus along the perpendicular axis. This defocusing effectively integrates the image data along the defocused axis, creating projections of the beam profile in the imaging axis. Linear optical fiber arrays, each oriented along an axis, relay the projections to a streak tube that deflects the linear image to a CCD camera. The CCD records spatial data in columns and temporal data in rows. Finally, using maximum

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* kaufmami@nv.doe.gov; phone 1-505-663-2034; fax 1-505-663-2003

entropy algorithms as described by Minerbo[2], the 2-D beam data is reconstructed from the four 1-D projections, providing 2-D images.

The 4-view system was a continuation of work done with a 2-view instrument for DARHT as described by Bender[3]. The first 4-view instrument, called the static 4-view, was built and successfully fielded in 2004 (Figure 2). An example of reconstructed beam data captured by the static 4-view system is depicted in Figure 3, which shows the four streak images over time (left) and a snapshot reconstruction of the same data (right).

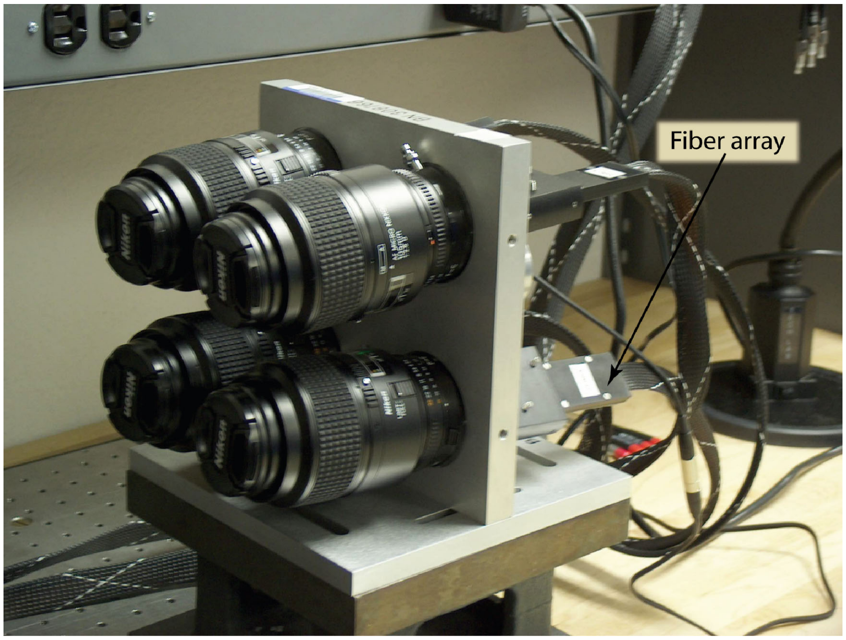

Figure 2. Prototype of static 4-view. Note how the fiber arrays are oriented to capture different projections.

Future fielding at the DARHT second axis will require the 4-view system to operate under much more challenging environmental conditions; furthermore, access to the system will be restricted. These conditions made it necessary to design an automated version of the system. The resulting design, the dynamic 4-view system, is rugged and fully automated. Parameters determined to require remote actuation in the dynamic version of the instrument included zoom, focus, and aperture. The remainder of this paper describes the design considerations for the dynamic 4-view system.

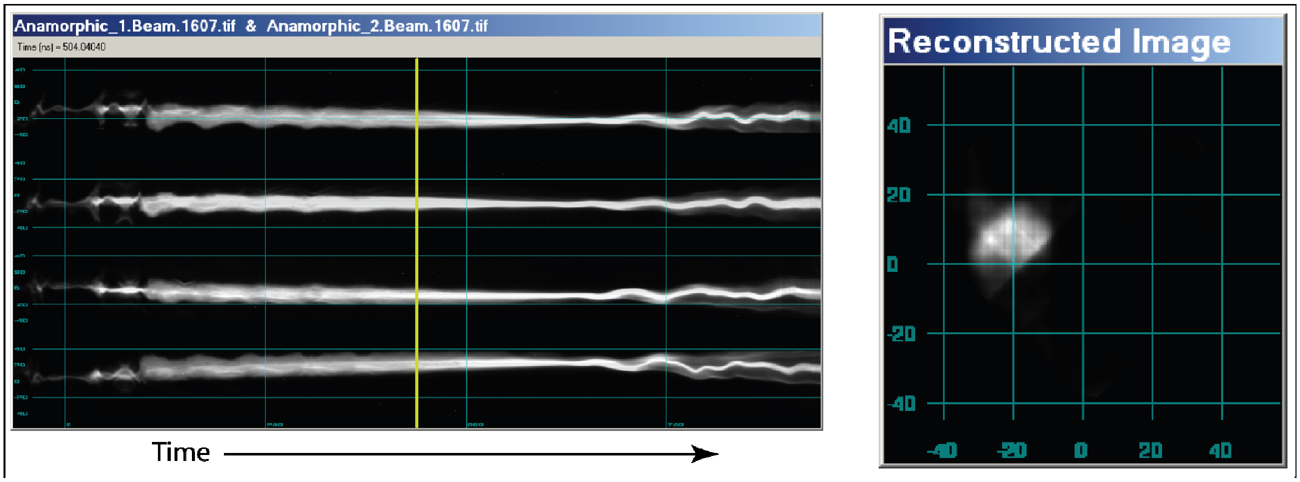

Figure 3. Four streak images taken with the static 4-view system, shown with the image reconstruction at a point in time (indicated as a thicker vertical [yellow] line in the image on the left).

2. SYSTEM-LEVEL DESCRIPTION

The dynamic 4-view system consists of an automated optical instrument for capturing 1-D data, an automated system for performing ongoing calibration of the optical instrument, fiber optic arrays, two streak cameras for recording 2-D data, and control electronics (Figure 4). System-level customer requirements are listed in Table 1.

The fiber array design requirements influenced major aspects of the optical system design. For example the fiber size and spacing in the array determined the pixel size of the CCD camera. And given the fiber array and image requirements (FOV and resolution) of the DARHT second axis, we knew the dynamic 4-view would need a fast zoom capability.

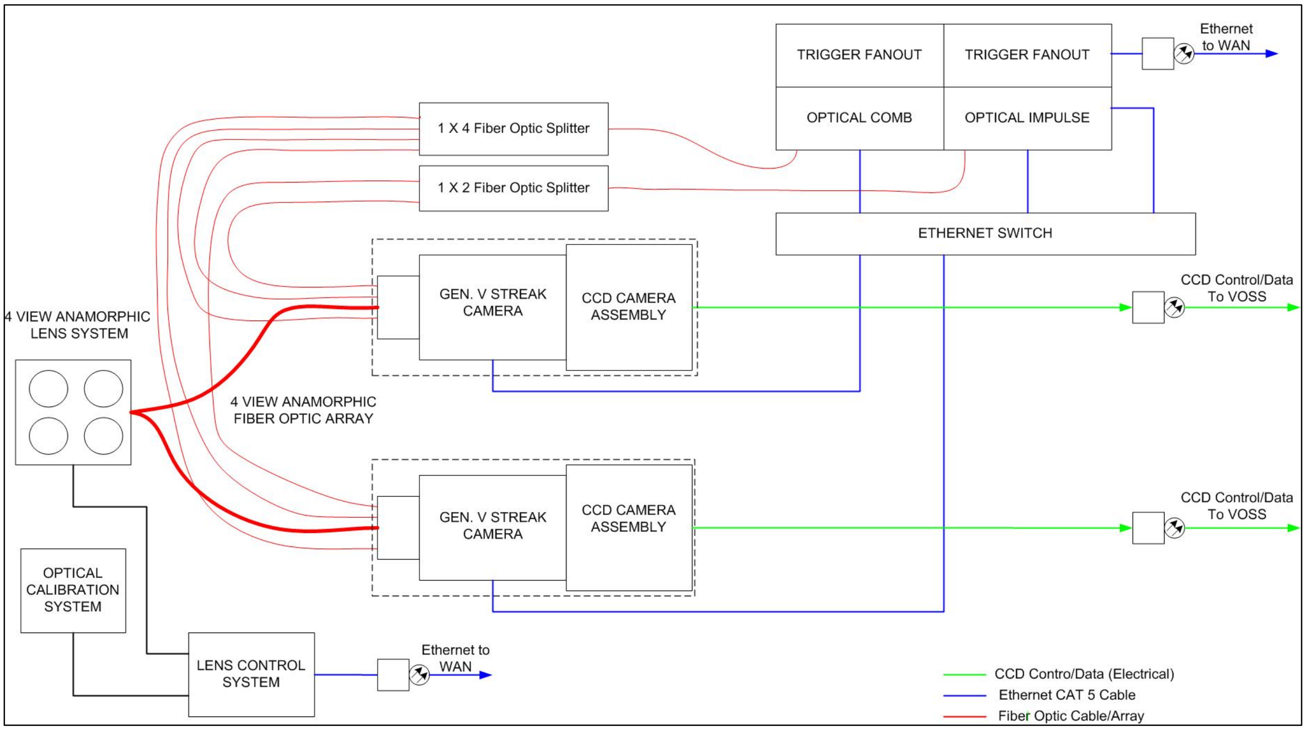

Figure 4. System-level block diagram of the dynamic 4-view system

Table 1. Functional requirements

Characteristics	**Specification**	**Comments**
Location of electron beam centroid	±2 mm	Location accuracy
Temporal resolution	2 ns	2 μs full sweep
Beam diameter	2 to 10 cm	
Resolution	0.48 mm	At target
FOV	132 mm	Diameter
Root-mean-square radius accuracy	<10% of radius	
Ellipticity	<10%	Ellipticity = minor axis/major axis

3. OPTICAL DESIGN

A set of optical requirements, derived from the customer requirements, are given in Table 2.

We selected a commercial zoom lens that met the requirements for zoom range, remote focusing capability, and remote aperture control capability. A commercially available cylindrical lens was implemented to optimally defocus the image along the integrating axis, as described above, by imaging the lens' aperture stop in that axis (Figure 5).

Table 2. Optical system requirements

Characteristics	Low Magnification	High Magnification	Comments
FOV	132 mm		At the target
Resolution		2.05 line pairs/mm	At the target, 20% contrast
Minimum focal distance	18 in	18 in	Object to image
Wavelength	Cerenkov light	Cerenkov light	Visible, weighted in the blue
Aperture			f/8 typical

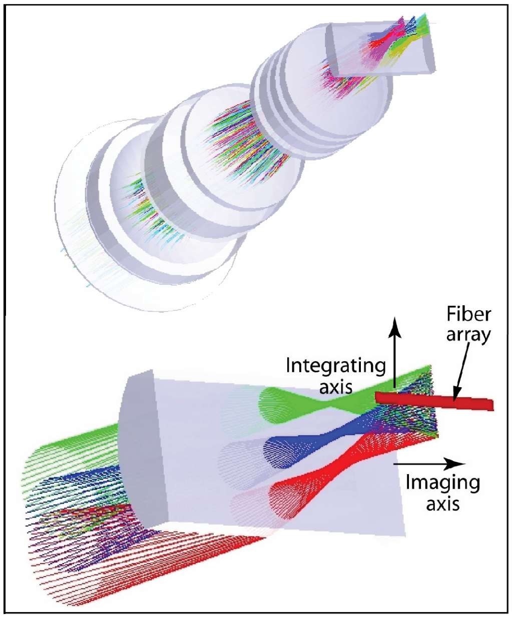

Figure 5. The optical line of sight. Lenses shown are for illustration purposes only. Note: the object is imaged in the integrating axis considerably before the imaging plane; at the imaging plane, the aperture is imaged in the integrating axis.

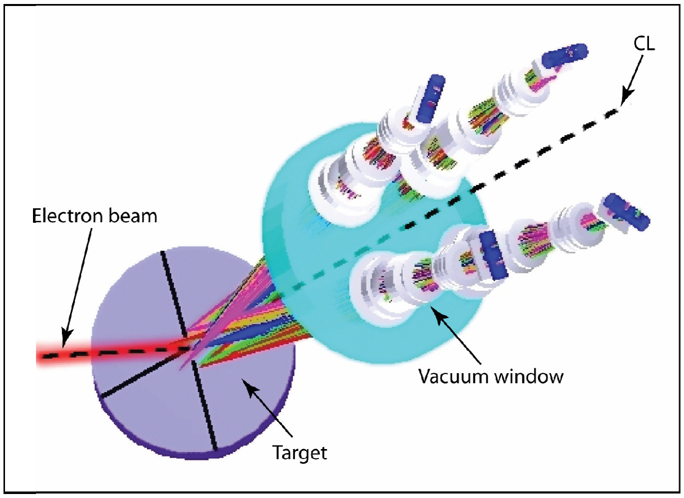

Figure 6. Four lens assemblies with the target and viewing window. "CL" indicates the mechanical center line.

Figure 6 shows the four lines of sight (LOS) converging on the quartz target. Note that the object is tilted at a 45° angle with respect to the mechanical centerline of the optical instrument, introducing a number of optical issues. The mechanical centerline forms equal angles with the four optical centerlines. The image will be tilted, with the exact angle of tilt being determined by the longitudinal magnification. Consequently, the imaging plane containing the fiber array, being normal to the optical axis, will have a gradient in both defocus and magnification. The magnification gradient leads to keystone distortion, with two LOS suffering keystoning. The distortion introduces varying nonorthogonality in the imaging and defocusing axes at the image plane, creating blur in the projection along the optical axis (Figure 7) resulting in information loss that degrades the reconstruction.

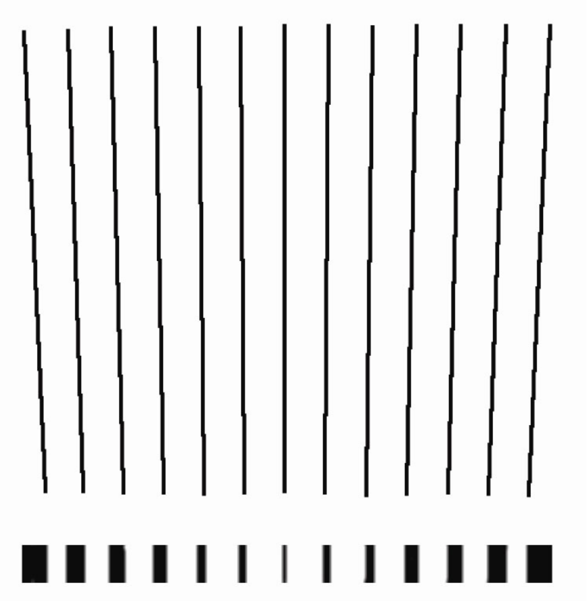

Figure 7. Result of keystone distortion in the imaging axis

Because the resolution is strongly limited by the fiber array, these issues do not become problematic. As such, the defocus gradient is negligible, with the resultant lowered resolution of the optics still being considerably higher than the best resolution capable with the array. Additionally, data for which the given customer requirements are truly needed occur only at the center of the FOV rather than at the edge. Simulations showed that resolution would be adversely affected in the outer 40% of the data set, whereas data in the inner 60% would adhere to the requirements. The customer found the achievable resolution acceptable.

The fiber array was constructed to optimize light throughput and resolution. The fibers chosen had a core diameter of 50 μm and an overall diameter of 65 μm. Besides presenting fabrication problems, smaller cores would have resulted in a lower core-to-overall-diameter ratio, decreasing throughput and possibly necessitating a move to custom fibers. Larger cores, while yielding greater throughput, would have degraded resolution to values below customer requirements. The input face on the streak camera determined the number of fibers, and thus, the total number of resolution elements.

At present, the static 4-view system is manually calibrated with a strobe lamp and various calibration targets. However, when the dynamic 4-view system is installed in the DARHT second axis the calibration routine must be remotely controlled. In the dynamic 4-view conceptual design, the entire lens assembly is mounted on a rotating gimbal that allows the device to view either the target or the calibration stage. This calibration stage will have multiple backlit targets necessary for executing various phases of the calibration process. The requirements for this process are listed in Table 3.

Table 3. Calibration requirements

Characteristics	**Specification**	**Comments**
Flat field	>95% uniform	
Dark field	>99% of light blocked	
Size determination	>5 resolution lines	Resolution lines are mapped to a template via software to determine pixels/mm
Orientation	Qualitative check	A special target to verify the sense of the fiber array (upside down or right side up)
Aperture	Small size, ~1–5 mm	Ensure pointing accuracy of system

4. OPTOMECHANICAL DESIGN

There are three main optomechanical elements to the 4-view system: (1) the optical instrument (Figure 8), (2) the fiber-optic arrays, and (3) the steak/CCD recording device.

The 4-view instrument will be located inside a sealed (non-ventilated) steel shed without cooling or heating controls. Consequently, the temperature may vary between –10º to 140ºF. Access will be restricted in this location and conditions are not suitable for data recording. Water may be present during certain experiments, so the system may operate near the dew point. During experiments the shed has high levels of radiation and electro-magnetic interference (EMI). Therefore, the light must be transmitted 30 meters (via fiber optics) to a location that is suitable for the streak cameras and associated electronics.

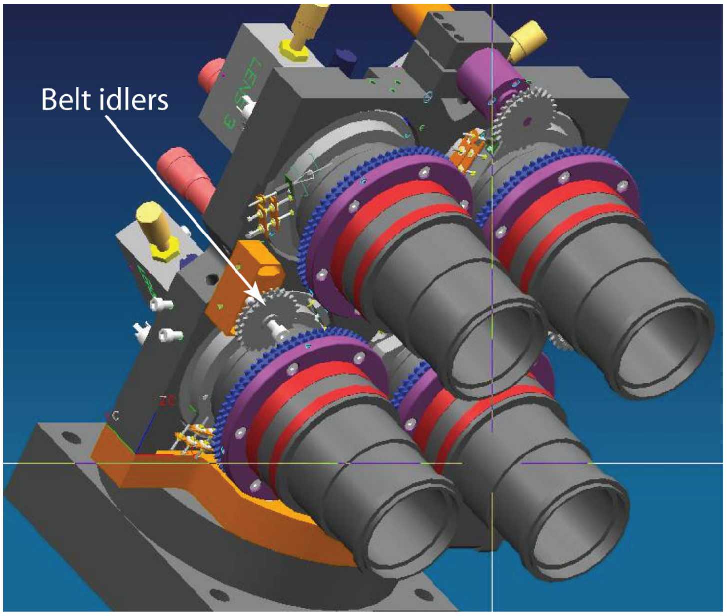

Figure 8. Dynamic 4-view instrument (3-D belt not shown)

Figure 9. Solenoid-driven shutter

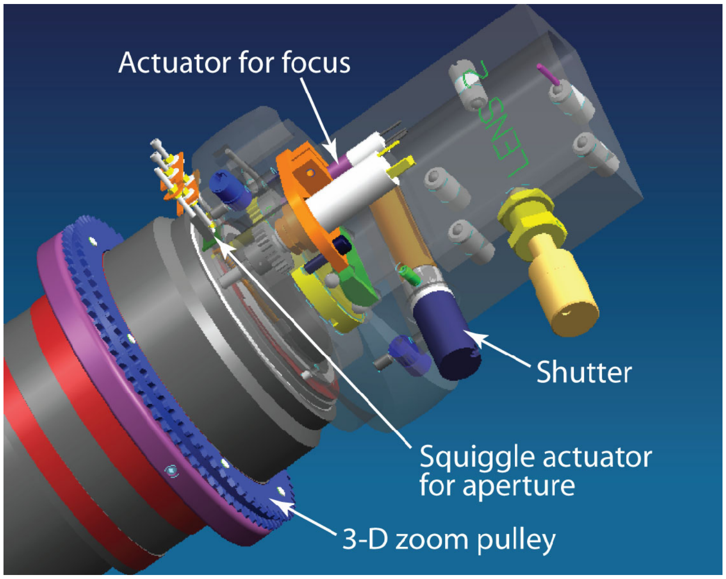

Figure 10. One LOS. The array holder is shown as semitransparent reveals internal details

The 4-view instrument needs to be adjusted and calibrated in a harsh environment on an ongoing basis. Each optical LOS has the following automated adjustments: (1) zoom, (2) aperture, (3) focus, and (4) shutter for dark-field calibrations (Figures 9 and 10), for a total of 16 possible automated adjustments. We reduced the number of remote actuators to 13 by simplifying the design to consolidate the zoom feature into a single independent adjustment.

The zoom feature makes use of a special belt and pulley system from Berg. The Min-E-Pitch 3-D belt and pulley system tolerates significant misalignment of the pulleys. The usefulness of the misalignment tolerance comes from the fact that the four pulleys that drive the four zoom adjustments are not coplanar. Each LOS has an included angle of 7º with respect to a mechanical centerline. We found that the 3-D belt system could accommodate this misalignment if the idlers were tilted in slightly.

The presence of radiation and EMI limits the use of electronic circuitry. Encoders were abandoned in favor of stepper motors with potentiometers and limit switches to establish limits of travel.

There are also set-and-forget adjustments for the 7° viewing angle and the side-to-side location of the fiber-optic array. These are useful for the initial instrument setup.

The gimbals, along with the many adjustment features, fit into a 203-mm square. The 4-view instrument is dense with pulleys, belt idlers, actuators, potentiometers, limit switches, and manual adjusters. The squiggle actuator that controls the aperture is the smallest that is commercially available.

Each LOS images onto a fiber optic array (Figure 2) that maps onto larger arrays that couple to two streak tubes. To reduce mishaps in fiber array assembly and reassembly after service, a poka-yoke design feature (Figure 11) was used to eliminate multiple connection possibilities. Poka-yoke is a Japanese fail-safe design methodology.

The larger fiber array optically couples to a streak tube that outputs to a CCD camera (Figure 12). The camera is mounted to a three-axis gimbal so that its mass centroid coincides with the gimbal axes. This allows the operator to optically couple the camera without damaging the delicate optical fiber plugs. It also allows the operator to execute a precise rotational adjustment to align the CCD rows with the array fibers.

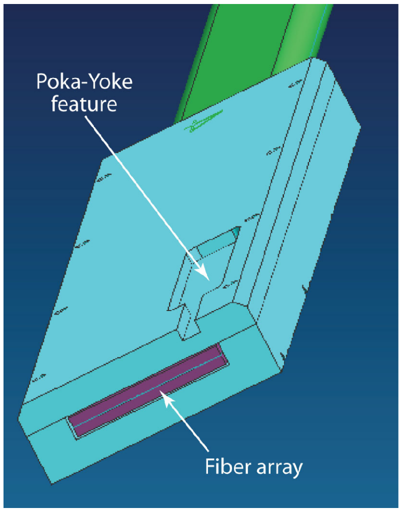

Figure 11. Fiber array with poka-yoke feature

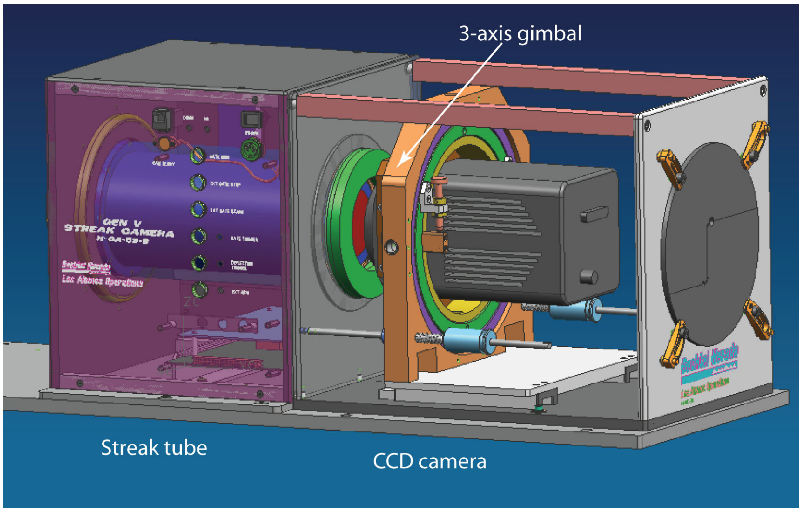

Figure 12. Streak tube/CCD camera assembly

5. CONCLUSION

The static 4-view system is currently installed at DARHT. Data from this instrument has proven vital to the commissioning of the DARHT second axis. For the design of the dynamic 4-view system, a zoom capability, not on the static version, was added. The zoom allows fast switching of the viewing angle onto an area of interest without having to physically move the instrument. The dynamic version adds functionality and is robust enough for a harsh environment. The dynamic 4-view system integrates instrument automation with an automated calibration system, has fast zoom capability, and one-way assembly techniques for components that need ongoing service.

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