

Assembly and testing of a large zoom lens for proton radiography

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ABSTRACT

A zoom lens has been designed for proton radiography applications. Radiographic images are recorded at the end of an accelerator, where protons exit an aluminum vacuum window, producing a shadowgraph image onto an LYSO (lutetium yttrium orthosilicate) scintillator. Emission from this 5-inch-square scintillator reflects off a pellicle and is then collected by a zoom lens located 24 inches away. Proton radiography can make high-speed, multi-frame radiographs or radiographic movies. This zoom lens provides 2X magnification for viewing different object sizes. The zoom lens incorporates eleven lenses, including a moving doublet that changes the magnification. Refocus of the camera is required when zooming. Only one moving doublet lens is required to change magnification. The stop was anchored to the moving doublet, and its diameter is unchanged throughout magnification changes. The entire lens system is housed in a cylindrical tube. This lens will be used with a 10-frame camera with a 44×44 mm square image format and 1100×1100 pixel resolution. Suppressing stray light is very important in this lens system. Radial compensation is controlled by two locking micrometers on element 9, which relaxes the mechanical tolerancing. A helical cam barrel using a linear rail controls the movement of the doublet. Alignment of the mechanical gears will be discussed.

Keywords: zoom lens, proton radiography, optical alignment, optical tolerance

1. INTRODUCTION

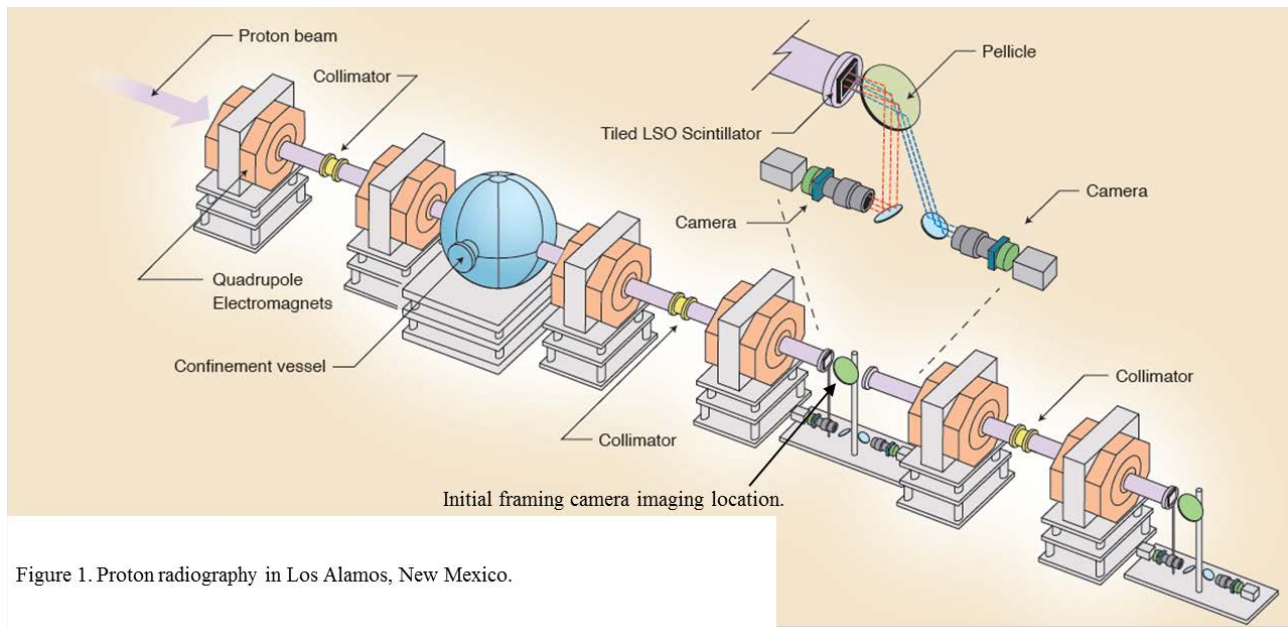


Figure 1. Proton radiography in Los Alamos, New Mexico.

A flash proton radiography facility¹⁻⁴ has been developed at Los Alamos National Laboratory that uses an 800 MeV proton beam with variable burst widths and burst interval times (typically 60 ns pulse widths and 14 bursts). These

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multiple bursts permit generating radiographic “movies” of the temporal behavior of explosively driven objects with approximate areal densities between 10 mg/cm² and 30 g/cm².

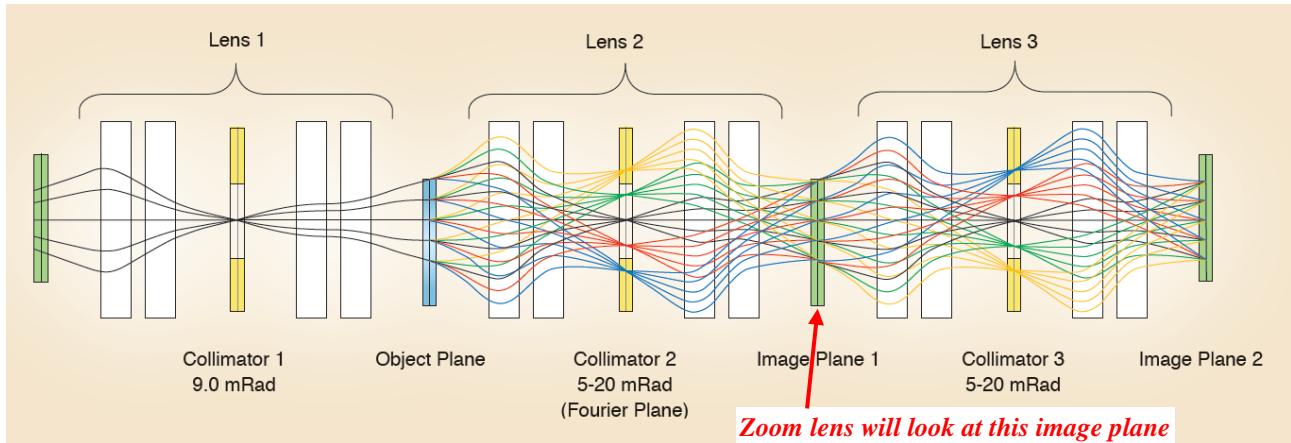


Figure 2. Magnetic lenses relay the proton beam through vacuum pipes. Black lines represent incoming protons and after passing through the object are those protons that are not scattered. Colored rays originating from the object plane represent protons that have undergone scattering.

Figure 1 shows major components of the proton radiography stations. Quadrupole electromagnets guide the protons through vacuum pipes. Current imaging cameras view light from a tiled LYSO scintillator. Cameras with single frame or 3 frames are gated on at different times to record the dynamic motion of target materials located inside the containment vessel. Figure 2 shows more detail as to the quadrupole electromagnets can be used to relay the proton beam. The quadrupole electromagnets are adjusted to produce a minimum spot size of the proton beam at the centers of the collimators.

Proton radiography is analogous to transmission x-ray radiography, but uses protons instead of x-ray photons. Current proton resolution at the scintillator plane is 200 μm. Proposed future upgrades to the quadrupole electromagnets may provide 60 μm resolution. Proton radiography has high penetrating power, high detection efficiency, little scattered background, inherent multi-pulse capability, and large standoff distances between test objects and detectors. Proton radiography can make multi-frame radiographs or radiographic movies. Frames are separated by 200 ns.

2. PROTON RADIOGRAPHY ZOOM LENS REQUIREMENTS

- The lens system will view a 127 × 127 mm square scintillator. The system will also resolve a 60 μm spot at the scintillator. 2X zoom will allow viewing of smaller object sizes.
- Room for shielding is required for radiation sensitive cameras.
- Fast LYSO scintillator emits light from 380 to 550 nm. This requires special glass materials to transmit blue light.
- Manual zoom, focus, and calibration capability in less than 2 hours is desired.
- Clearance from the scintillator to the first lens needs to be 24 inches to allow room for one or two steering mirrors. The camera is not mounted to the lens system.
- A variety of image sensor sizes will be used in the future. Different sensors require different back focal lengths. So, extra back focal distance is desired. Adding an extra doublet lens just before the CCD would change the focal length of the lens system.
- Thermal environment of proton radiography campaigns requires the zoom lens system to operate from 60°F to 95°F.

- Future applications will require the lens to tilt relative to the scintillator. This will require insertion of a tilted stop to keep light levels across the CCD camera uniform. The camera also needs to be tilted relative to the lens system. The tilted image plane will require mechanical decoupling of the camera from the lens housing.
- Field of view of the LYSO scintillator ranges from 127 to 60 mm in diameter. To compare images recorded at different magnifications, scintillator mapping errors have to be better than one pixel on the image sensor.
- A factor of 2.5x more light is desired over the current fixed lens collection system.
- The zoom lens housing should be <600 mm long.

3. PROTON RADIOGRAPHY ZOOM LENS DESIGN

Our initial optical model was based on a telecentric zoom lens⁵⁻⁷ used for a large x-ray source that collects light from a large, thick LYSO scintillator. That zoom lens system operates close to the scintillator and includes two moving doublets, a moveable stop, and a moveable camera for refocus adjustments. In modifying this large zoom lens to meet the new requirements described in Section 2, we discovered that the second moving doublet's position could be fixed; this change resulted in smaller lens diameters for the new system. Our first attempt⁸ at this design required viewing the scintillator at an angle. Much analysis was done to prepare this design for the production of a large number of lens systems. However, initial prototype operations of this framing camera technology will not require viewing the scintillator. Our prototype design views the scintillator at normal incidence. Our prototype design views the scintillator at normal incidence.

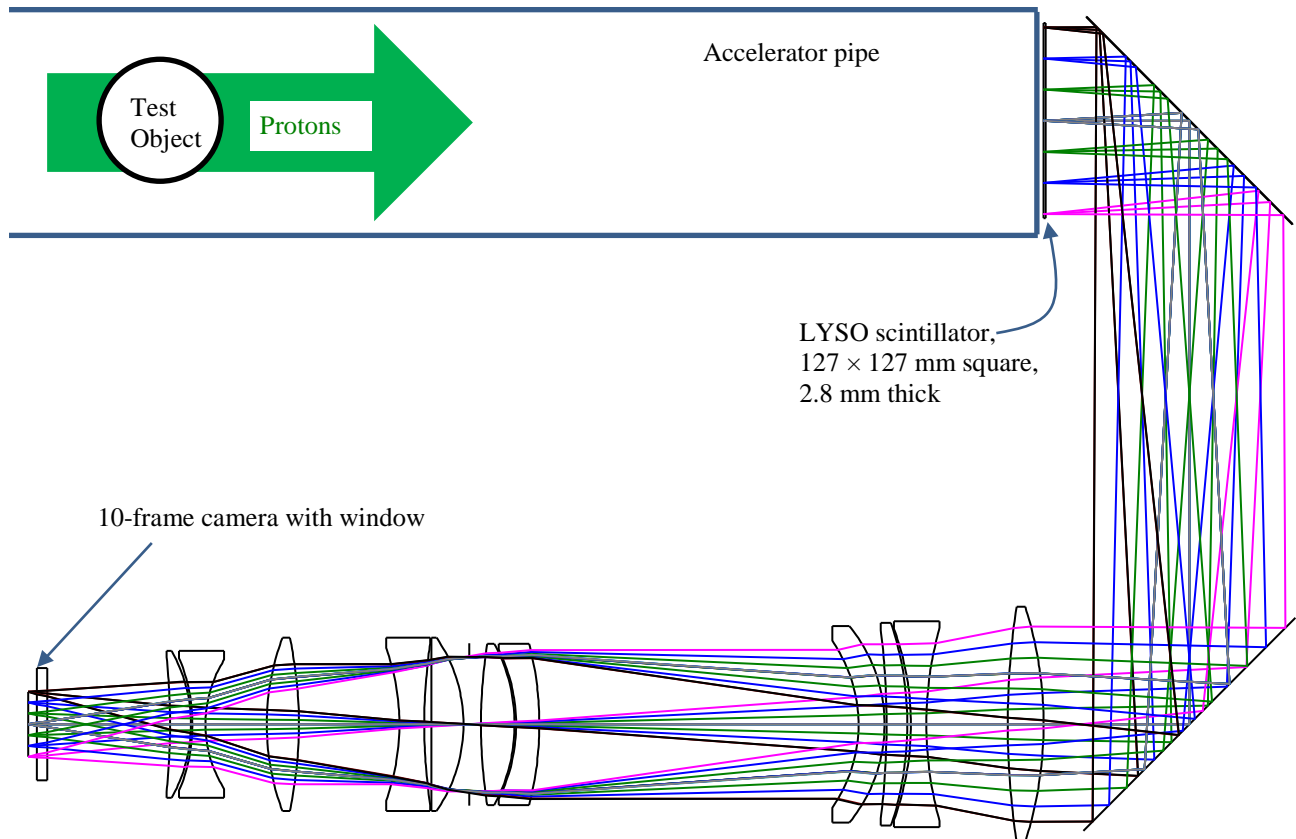


Figure 3. LYSO scintillator is attached to the exit port of the proton accelerator. Turning mirrors deliver light to framing camera inside a shielded enclosure (not shown). The test object is actually much further downstream from the scintillator. Quadrupole electromagnets used to relay the proton image to the scintillator are not shown.

The design for this lens system is not telecentric, as the scintillator is thin. The camera is required to have its own tilting platform to find the image plane. The camera positions are upstream from the end of the proton accelerator pipe to

provide shielding from proton scatter. Optical modeling was performed for four different zoom magnifications for each of the four imaging systems. Figure 3 shows only one zoom position, which is the full field view. LYSO emits light with a numerical aperture (NA) of greater than 0.56.

Figure 4 shows optical modeling of the zoom lens at four different magnifications. Clearance distance between the zoom lens and the camera was maximized in the design so that if a smaller-diameter CCD camera is used, a doublet could be inserted into this air gap to change the magnification range. Several types of CCD cameras are envisioned for future use with the proton radiography zoom lens.

This 35 μm resolution is better than what the 10-frame camera can see, since it can only resolve 1 part in 1100 across its image. The framing camera is tilted at two angles, decentered in both X and Y, and has a gamma rotation.

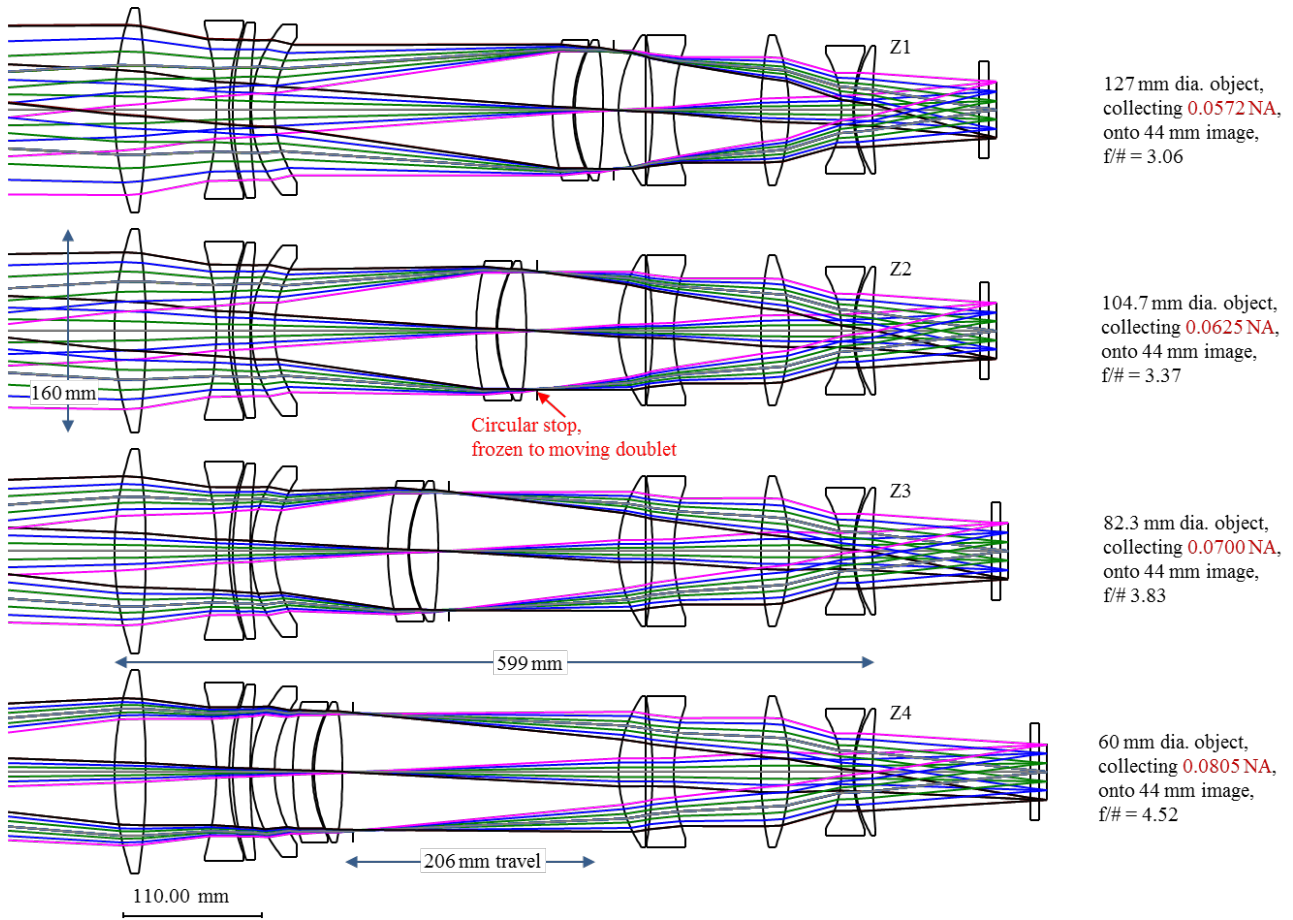


Figure 4. Only one moving doublet lens is used to change image magnifications.

Figure 4 shows that magnification changes are accomplished with the movement of only one doublet and the axial shift of the framing camera. The stop is circular and is secured to the moving doublet. There is a lot of air space between the zoom lens and the framing camera housing, allowing adequate room for camera tilt/decenter adjustments.

Glasses have to be carefully chosen to maximize transmission at blue wavelengths. The peak emission of LYSO is at 435 nm. Figure 5 shows the glass types to be used. One lens has been chosen as a radial compensator. The tilt and decenter of the camera are also critical compensators for reducing tolerances. Ohara glass S-FPL51 is always difficult to use. But it was required to get the best resolution for UV/blue wavelengths.

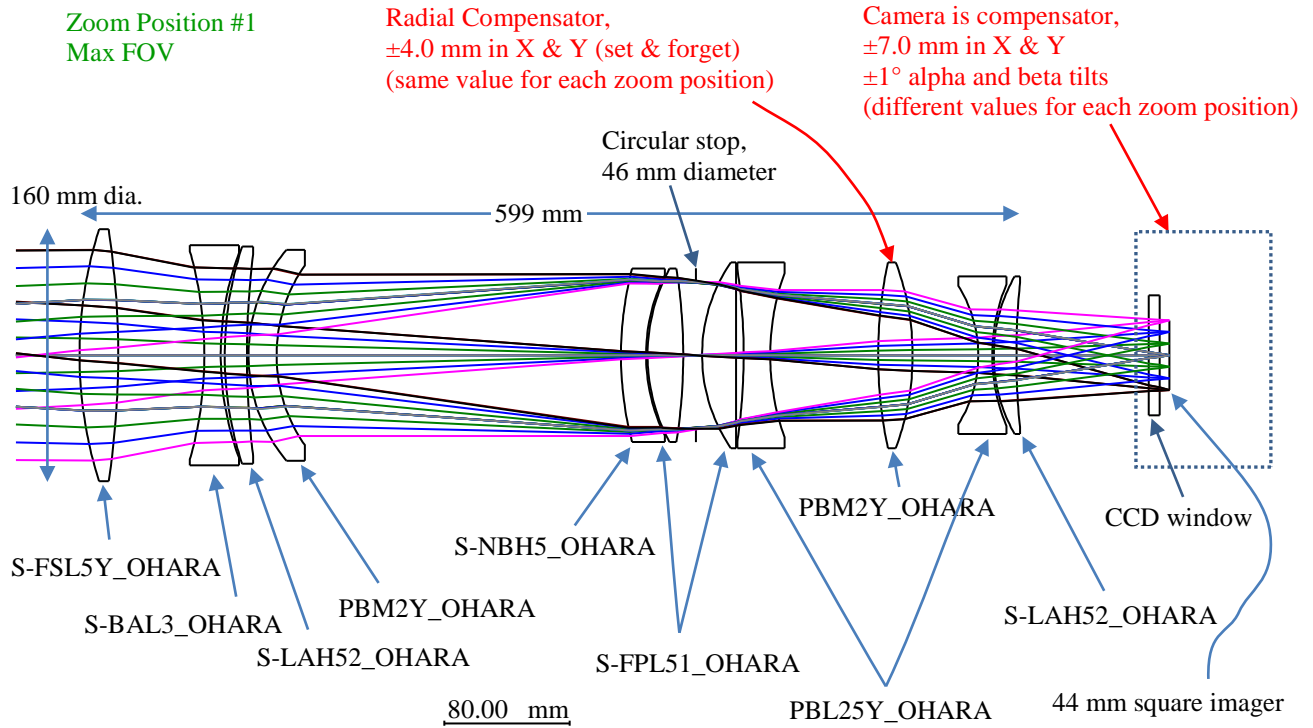


Figure 5. Zoom lens housing has flat base for mounting to tilting platform. Light enters from the left. The camera (dotted box) is to the left. Knobs at rear control the compensator lens. Total weight of the 11 lenses is 19.4 lbs.

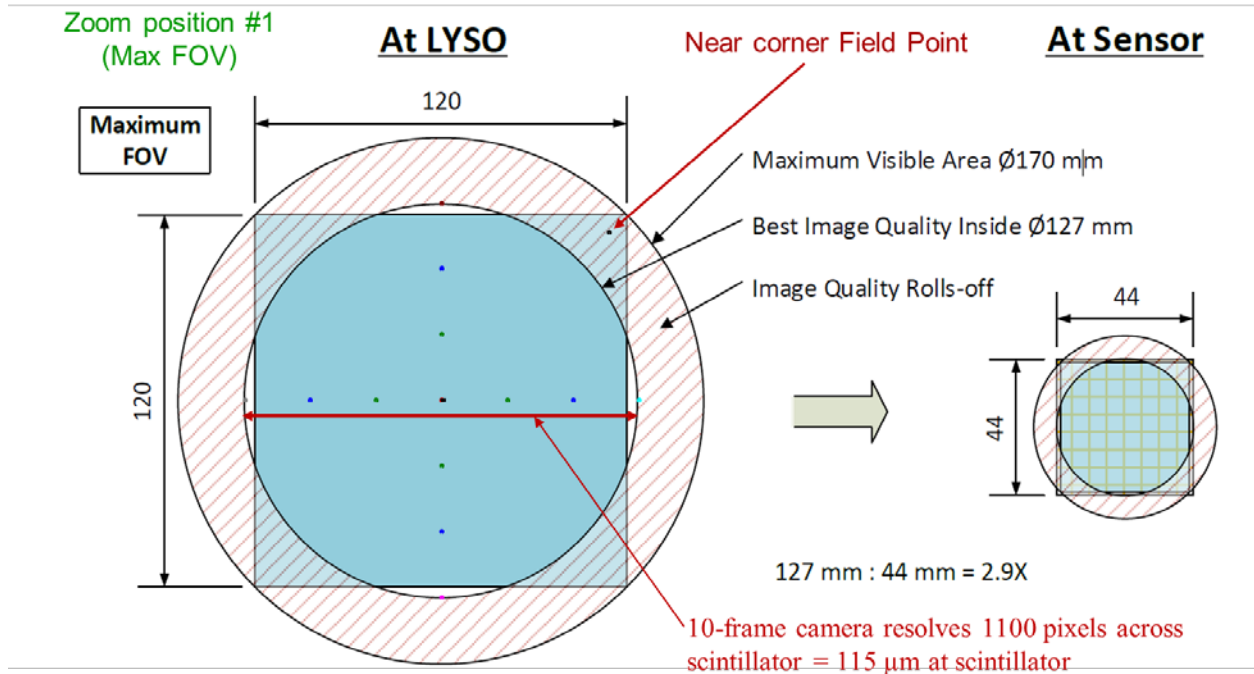


Figure 6. Mapping out the field of view from the scintillator to the framing camera.

Data resolution means different things to camera operators who think in terms of line pairs per millimeter and the physicists who think in terms of μ m resolution at the scintillator. So both views of resolution have to be shown in the

MTF diagrams. Figure 6 is an attempt to understand everyone's resolution needs. Field points above the red line and one corner point are shown in the MTF diagram of Figures 7&8. Note that resolution is calculated for both the object and the image planes.

At maximum field of view, the resolution is excellent across the image, as shown in Figure 7. The zoom lens will be tested with a Scientific Instruments SI 1100s camera, shown as the green dotted vertical line. This 4K-pixel CCD camera has a larger imager size measuring 62 × 62 mm. The blue vertical line shows the expected resolution and contrast when using the 10-frame framing camera. The black vertical line shows the current resolution achieved by the proton radiography machine at the scintillator, today. So, at full field of view, this new lens design will exceed the resolution requirement. However, with future upgrades to proton radiography, it is anticipated that 60 μm resolution at the scintillator can be achieved. This lens system will still match the higher resolution requirement, with excellent contrast. However, a more advanced version of the 10-frame framing camera will be needed in order to record this future proton resolution.

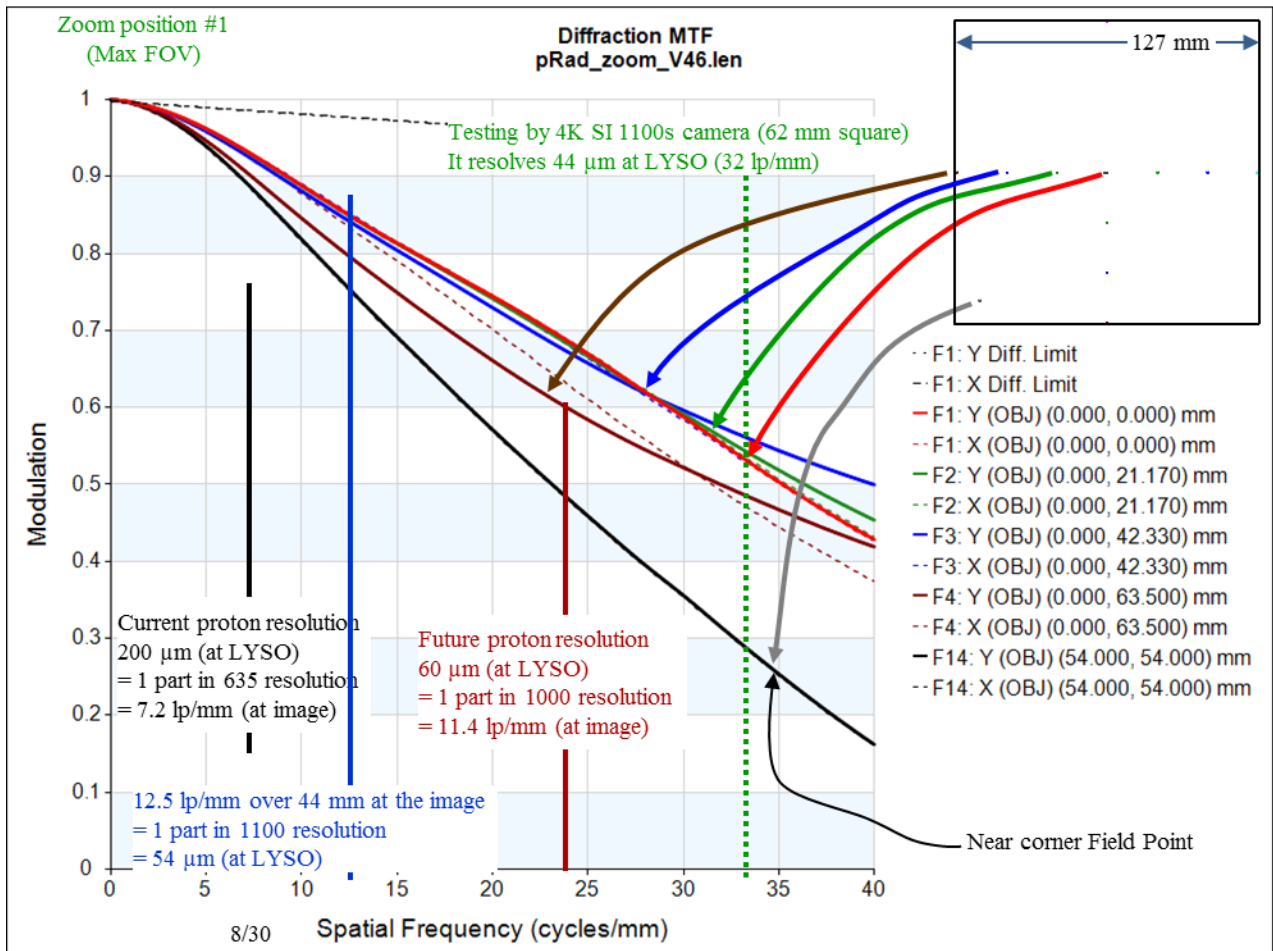


Figure 7. Resolution when viewing the full field of view. The black vertical line shows previous resolution of data collected. This lens system has to perform much better to accommodate future proton beam upgrades.

We specify the resolution at both the image and object planes. Inserting a picture of the field points onto the MTF chart is easier to understand than interpreting the legend listing of the field points. The camera operators care about lp/mm resolution of the camera as they insert different calibration targets at the scintillator position. Physicists are primarily concerned about the spot size resolution at the scintillator and the micron resolution of the test object that is undergoing dynamic testing.

At minimum field of view, the resolution is excellent across the image, as shown in Figure 8. At this magnification, the 10-frame framing camera will still resolve the smaller spot sizes of the future upgraded proton radiography machine. So, the existing 10-frame camera will see excellent image contrast when the field of view is zoomed to a minimum size.

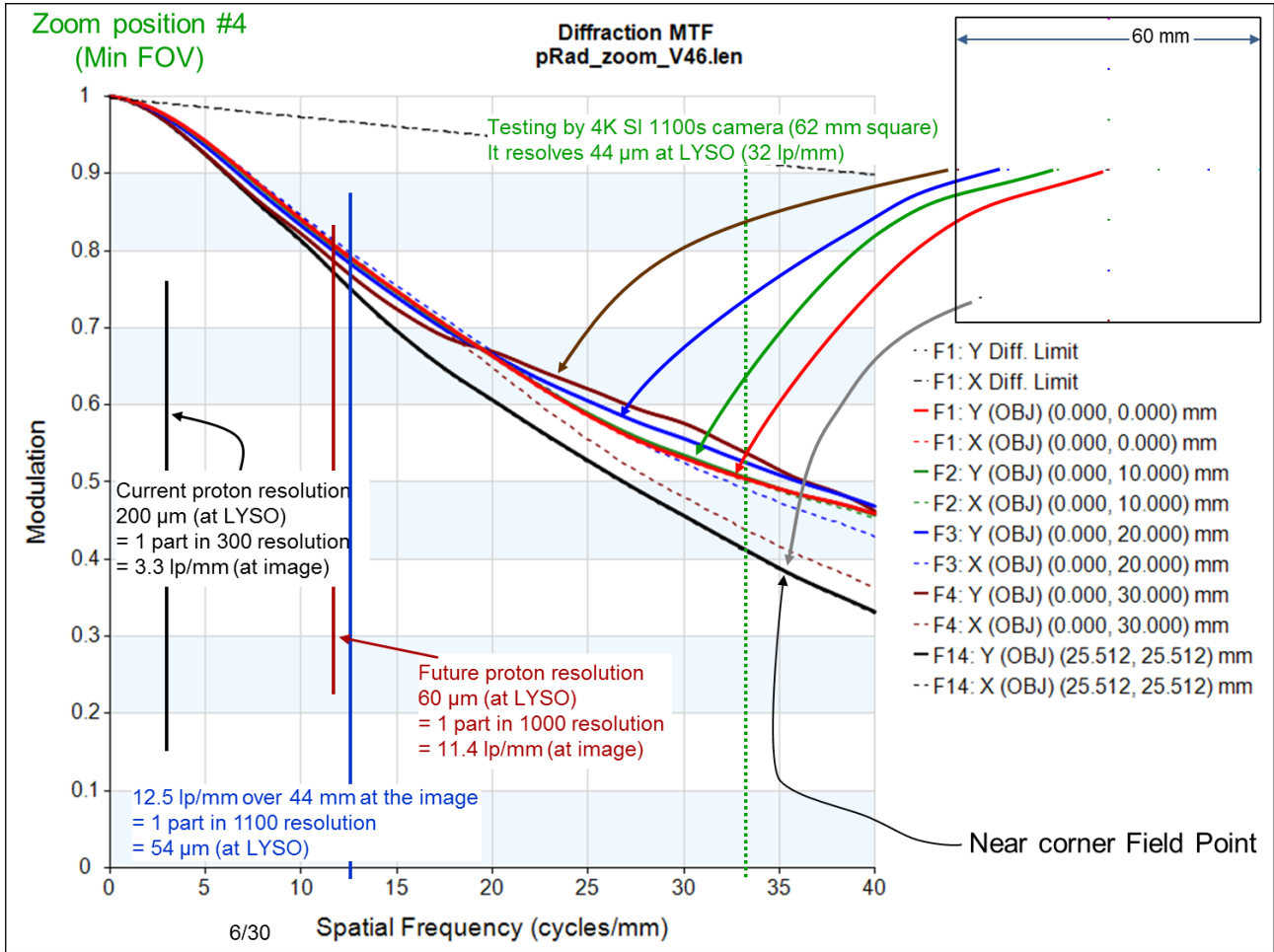


Figure 8. Resolution when viewing the minimum field of view. Resolution improves when zooming into smaller fields of view.

4. OPTOMECHANICAL DESIGN

Two of the completed lens housings are shown in Figure 9. The brass ring moves the internal doublet, allowing magnification changes. The large black metal flange in the center of the housing was a customer mounting requirement that includes slots for hand carrying. Total weight of each assembled lens is 88 lb.

Figure 10 is a photo taken after removing the housing front that contains the first four lenses. This removal exposes the doublet cell that moves along guide rails. Movement of the doublet is controlled by a double helical cam barrel. This barrel is made from 6061-T6 aluminum.

A schematic of the lens housing is shown in Figure 11. We attempted to maintain a decenter tolerance of 50 μm for the assembly of this zoom system. Outer metal housing cylinders are pinned together. In some cases, push/pull bolts are used to separate outer cylinders parts because of the tight tolerances used. Some of the outer edges of inner lens cells feature rolled edges (see insert of Figure 11). With near-zero clearances between the large lens cells and the housing

bore, there is still the possibility of the lens cell cocking and getting stuck. Consequently, we used an extremely small amount of Nye damping grease at key interfaces.

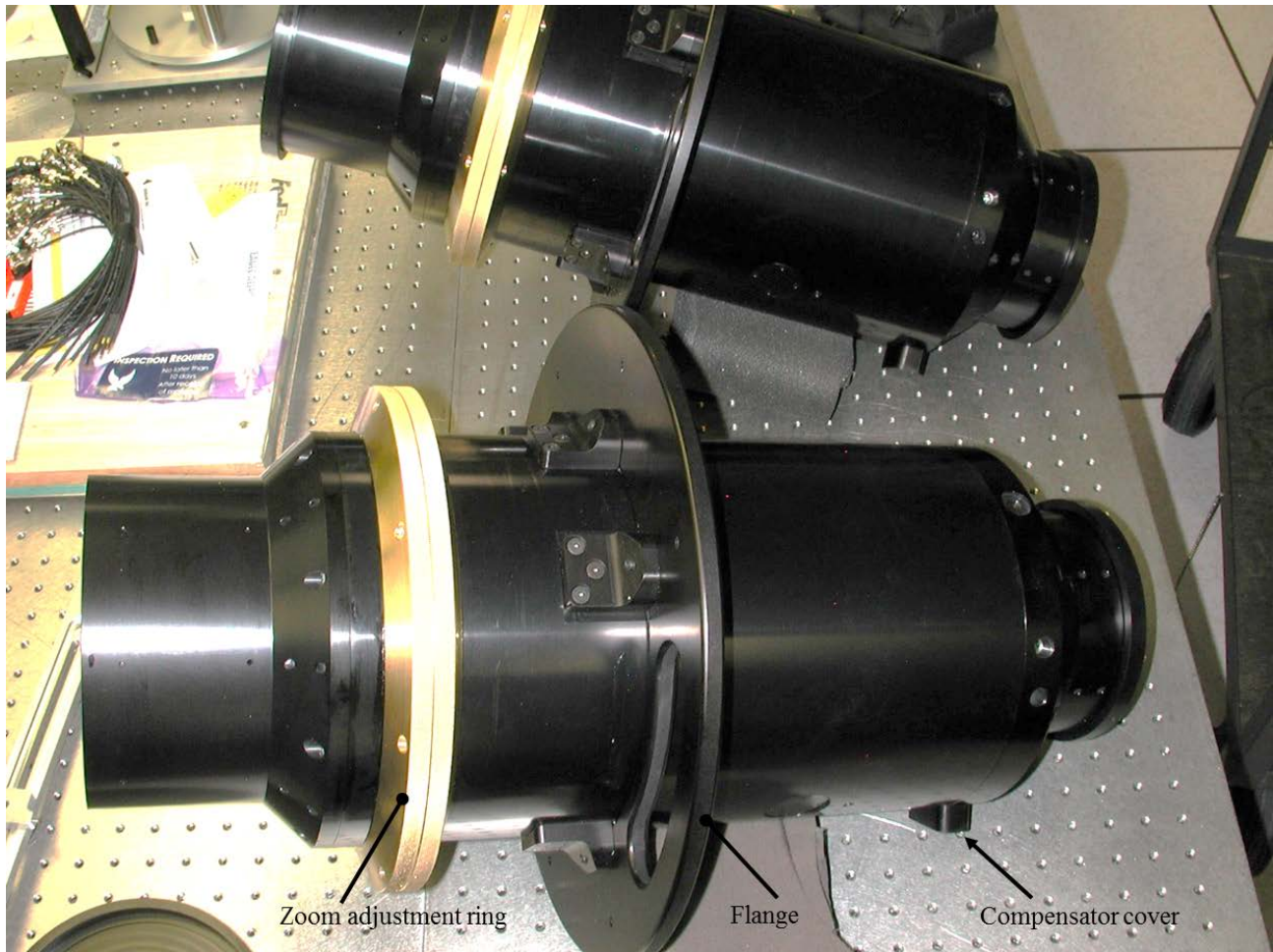


Figure 9. Zoom lens housing has a brass ring to change magnifications. Light enters from the left. The camera (not shown) is to the right. Knobs at rear control the X-Y decentering of the compensator lens.

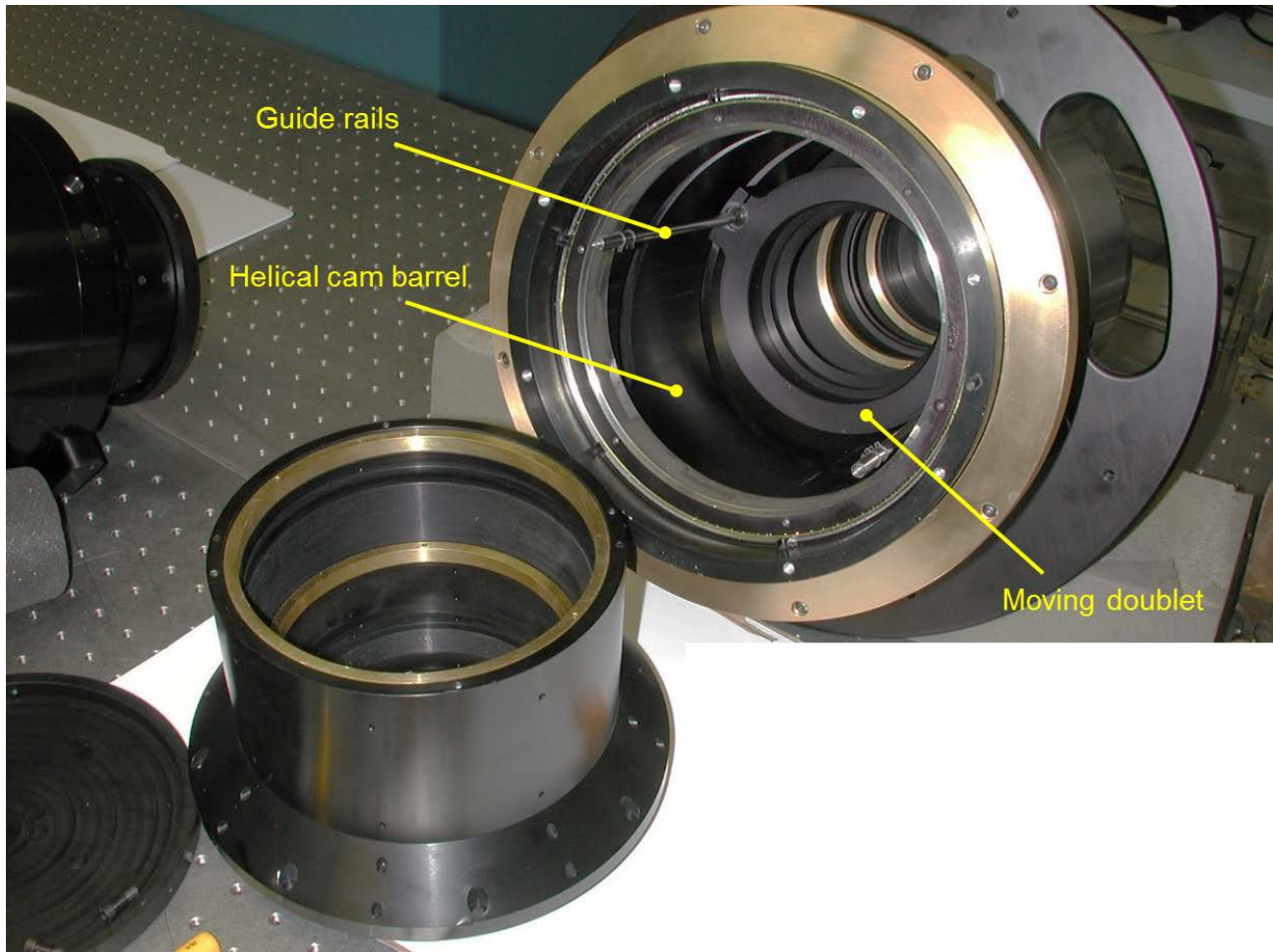


Figure 10. Housing for first four lens elements has been separated from the main housing to expose the guide rails that the doublet lens moves along.

Figures 10, 11, and 12 show details of the moving doublet parts. Crowned cam followers are inserted into the slots of the double start helical barrel. Crowned cam followers convert rotation of the double start helical cam barrel to smooth axial motion of the doublet along guide rails. There is a toroidal curved surface on the cam follower to provide this smooth axial motion. The moving doublet slides on the guide rails shown in Figure 10. We found that a double-wide ball bushing and a single-wide self-aligning bushing resulted in smooth motion of the moving doublet. The fact that the stop moves with this lens is an interesting feature of the optical design. The stop does not change diameter with the zoom position.

The cam barrel assembly is held in place at the fore end by a thin-section, four-point bearing and a bushing at the aft end (see Figure 11). The bearing-bushing arrangement was chosen because of assembly considerations. The bushing performance improved considerably with a small amount of Nye damping grease.

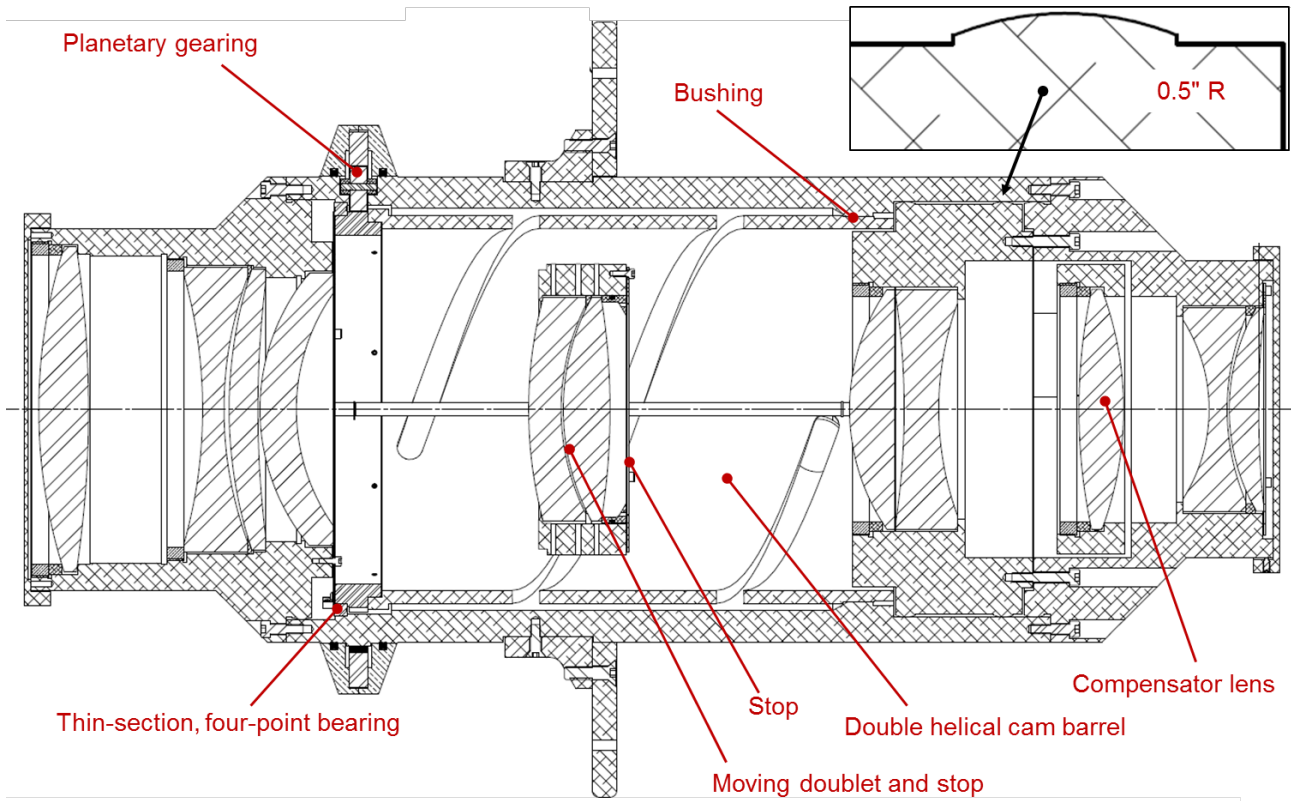


Figure 11. Inside schematic of the zoom lens housing. Insert shows that inner cells have rounded sides to ease insertion. The stop is attached to the moving doublet.

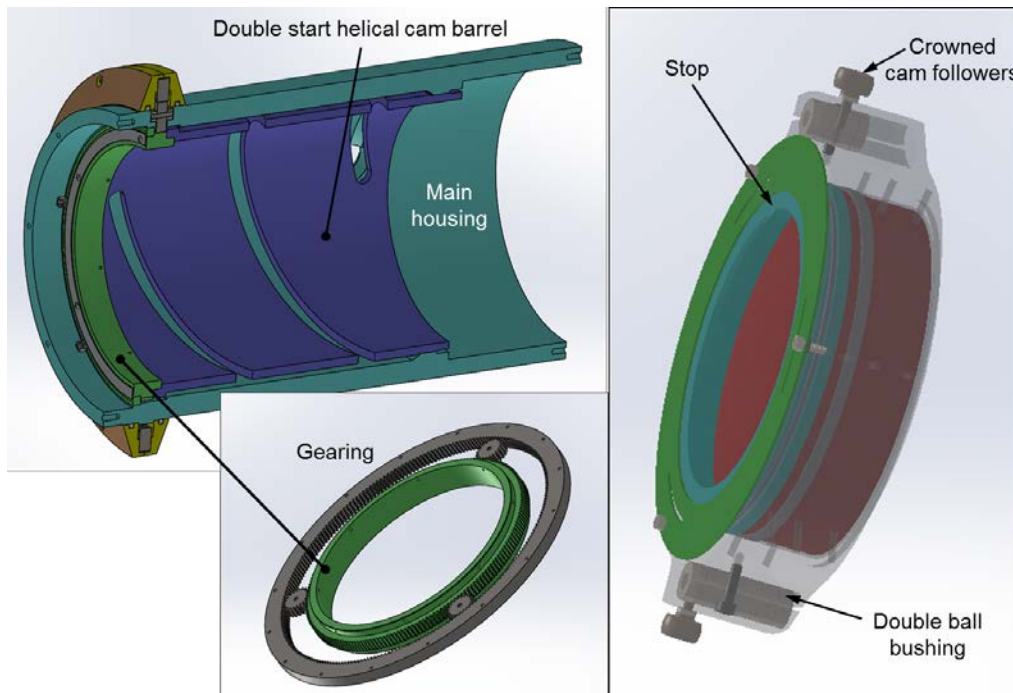


Figure 12. Inside schematic of the zoom lens housing.

We had some manufacturing difficulty with the double-start helical cam barrel made from 6061-T6 aluminum. The first barrel sprung out of round after machining. So, the second barrel was only rough cut, annealed to remove stresses, after which a second heat treatment was performed, and the final cut made. The gears were wire EDM cut from 303 stainless steel. The gears were specified to class 9 using the AGMA 2000-A88 specification, as it was preferred by the gear maker for this application over a more recent standard. The double-start helical cam barrel is shown in Figure 13.

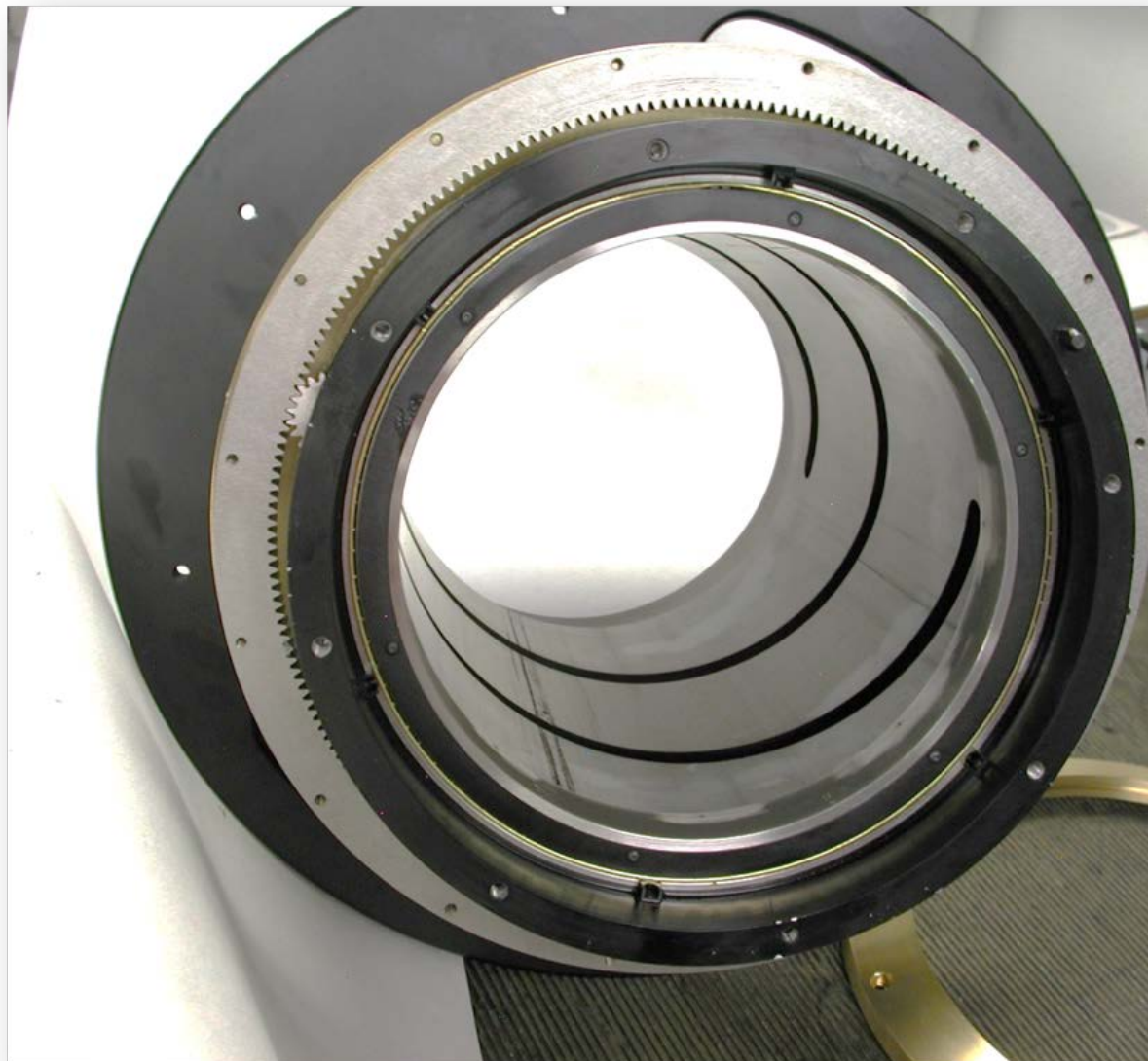


Figure 13. The housing for the first four lenses has been removed to expose the double start helical cam barrel. Brass cover has been removed from the planetary gearing.

Figure 14 shows details of the compensator doublet assembly. Two spring plungers provide counter force to the two micrometers. Micrometers push into a V-groove as the lens is decentered in the horizontal and vertical directions. The V-groove prevents lens tilt as the lens is undergoing decenter adjustments. The V-groove is made from Bal-tec hardened 440-C steel tooling

An example of gluing a lens inside its cell is shown in the insert to Figure 14. Gauge pins are used to center each lens into its housing while the RTV glue is setting. Each lens is glued into its own metal cell. Cells are then inserted into the main lens housing.

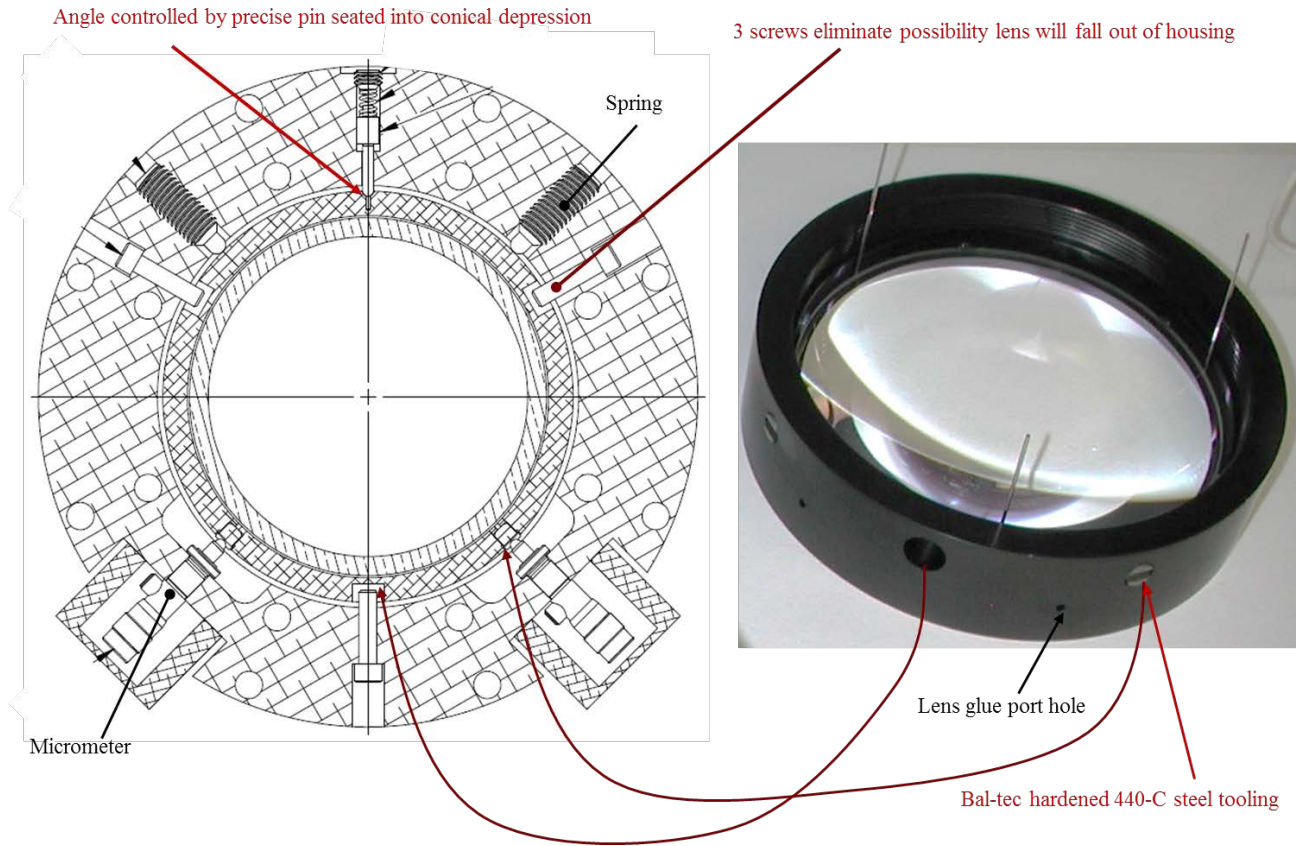


Figure 14. The housing for compensator lens has many components. Outer housing has many control points. Micrometers push against opposing springs and pivot the lens cell around a pin seated into a divot. Micrometers are secured inside a protective enclosure. Photo insert shows gauge pins used to center lens during glue operation.

5. FUTURE DESIGN WORK

We are also considering modifications to our design that will expand the zoom lens' capabilities for viewing the scintillator; this would entail maximizing the number of zoom lenses that would surround the proton accelerator pipe. Figure 15 shows a concept for a system using eighteen framing cameras⁸. The inner ring collects light at 20° to the LYSO. The outer ring collects light at 38°. Resolution loss is increased slightly with this higher viewing angle. Angular light distribution emitted by the LYSO at 38° will be reduced. The total distance from the LYSO to the first lens surface is unchanged at 24". Each zoom lens and each framing camera will have to have their own tilt and decentering platforms. The end of the accelerator pipe will have to be reduced in diameter from 12" to ~9". This arrangement of framing cameras would be a very expensive proposition. For now we are pursuing the building of only a few of the 10-frame zoom lens systems, which will be an improvement over the current proton radiography recording system.

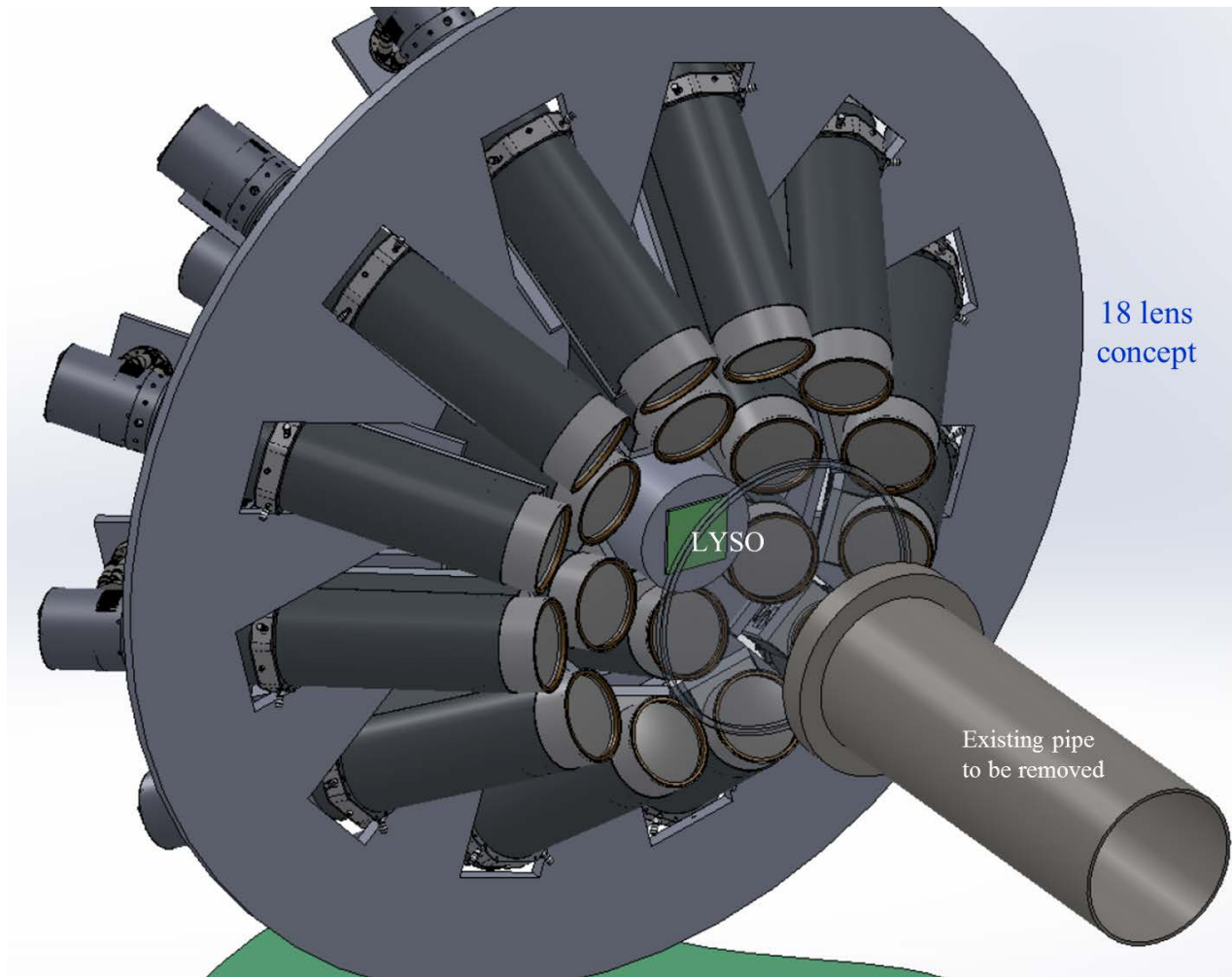


Figure 15. Eighteen zoom lenses are wrapped around the end of the proton accelerator pipe. The end diameter of this pipe is 9". The LYSO measures 127×127 mm. The inner ring of zoom lenses views at 20° , and the outer ring views at 38° . Emission is from the green-colored LYSO scintillator. The LYSO is viewed from the front. Only the frame of the turning mirror is shown.

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