Optical System for Observation of FRIB Target

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Abstract

Facility for Rare Isotope Beams (FRIB) is a next-generation rare-isotope research facility under construction at Michigan State University (MSU). FRIB will produce rare-isotope beams of unprecedented intensities by impinging a 400 kW heavy-ion beam on a production target and by collecting and purifying the rare isotopes of interest with a fragment separator.
A thermal imaging system (TIS) has been developed to monitor the beam spot on the production target. The main features and characteristics of optical system is presented. The prototype of optical system has been tested.

Main Requirements for TIS

- To provide measurement of a temperature distribution in a hot spot with accuracy ± 20K.
- To observe position of a hot spot on a graphite target with spatial resolution 0.1mm. Hot spot size is about 1mm.
- Field of view (FOV) should be about 30mm.
- To provide output signal for Machine Protection System (MPS) if target temperature exceeds allowable threshold. The system of fast thermometry shall have a time response about 10 µsec.
- Optical elements of the system should be compatible to high radiation environment. Due to darkening and luminescence of transparent materials it means in optical system only mirrors should be used.
- For suppressing of neutron streaming the optical system shall have a bend ("dog-leg") inside of radiation shielding.

Description of Optical System

Base on the main requirements for TIS, we decided to split of the optical system into two parts. The first part is placed in vacuum vessel near to the production target and before of radiation shielding and it consists from mirrors exclusively. This part of optical system has design of relay lens with scale factor of transformation equal to 1:1. The relay lens is performed by scheme with mirror symmetry and consisting of two identical Cassegrain type telescopes as shown on Figure 1.

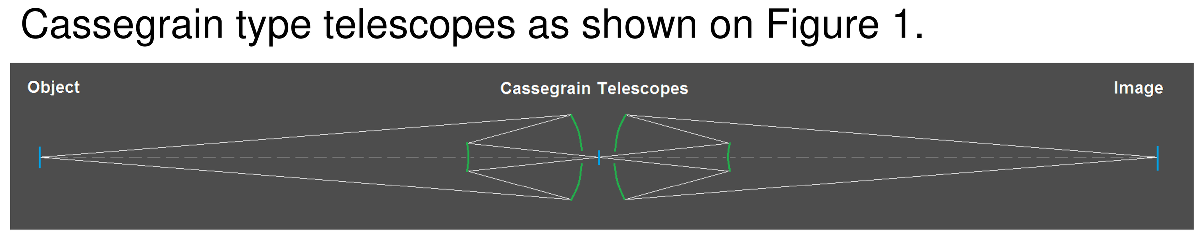

Fig. 1. Optical layout of the relay lens.

Main feature of chosen optical design of the relay lens is possible to use a spherical surfaces in telescopes. In this case, residual spherical aberration allows to use of numerical apertures up to 0.03 at diffraction quality. With our parameters of optical system for completely suppressing of spherical aberration the conic factor on primary mirrors should be -0.055 (aspheric deviation corresponds to about 0.1µm). The secondary mirrors still have spherical surfaces. Another important feature of this design is that mirror-arrangement of telescopes to each other suppresses a coma.
The optical board of relay lens, mounting board with two telescopes and the telescopes themselves are made from invar. This material was used to prevent uncontrollable extension in presence of radiation heating. Because the parameters of relay lens is very sensitive to distances between main elements.

The second part of optical system is placed outside of the vacuum vessel and after of the radiation shielding. This part is realized in form of 2D optical breadboard, where light is distributed between different devices as shown on Figure 2.
Usually, a camera sensor has smaller size than the requested field of view. We use Sill Optics telecentric lens to match the image size to the sensor size.
In system of fast thermometry for MPS will be used method of two-color pyrometry. Base on using of two photodiode modules which will be supplied through two bandpass filters for a different wavelength range. This method of measuring temperature was selected due to its weak dependence from the values of reflection and transmission coefficients, which can significantly vary in presence of high radiation and sublimation of graphite target.

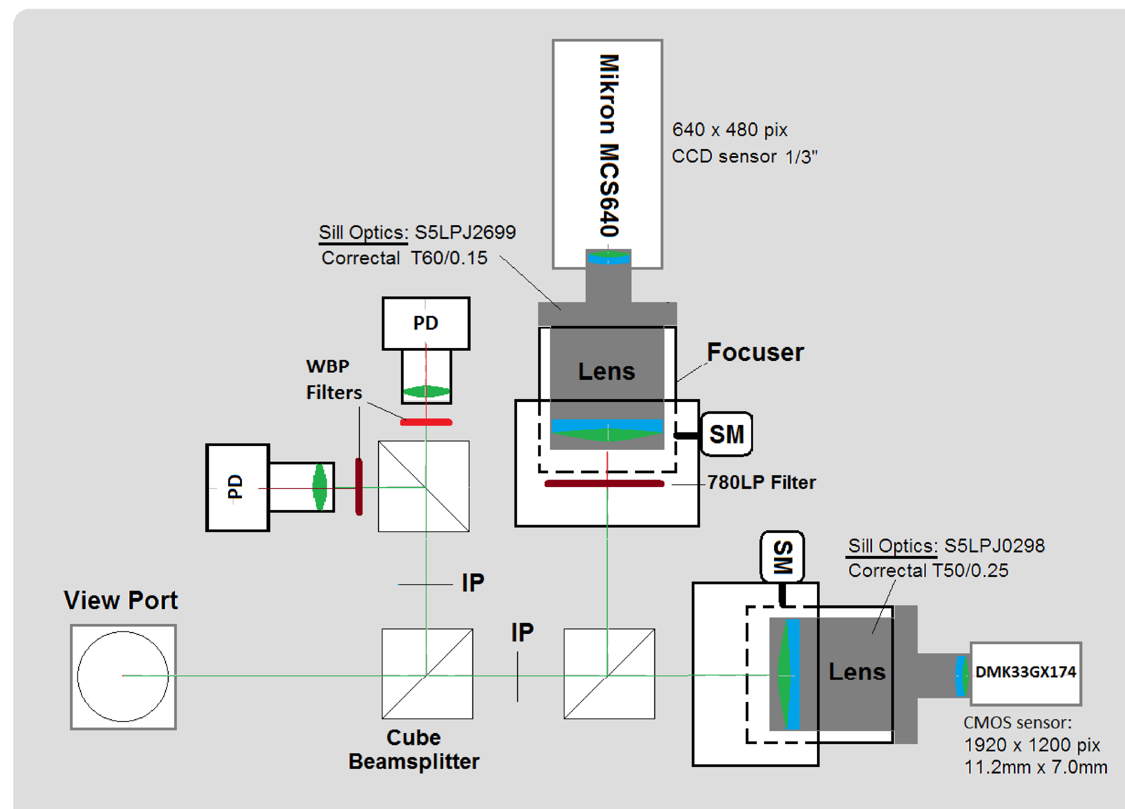

Fig. 2. Optical breadboard diagram. The cube beam splitters have 50% by 50% ratio. Here is IP – image plane; SM – stepper motor; PD – photodiode; WBP – wide bandpass filter. 780LP – longpass filter with cut wavelength 780 nm.

Modeling of Optical System

For modeling of the optical system and its matching with 3D mechanical design of the production target Zemax software was used. Alignment tolerances for optical elements were estimated using the Monte-Carlo method and after were made adjustments to the mechanical design of optical system.
At modeling the wavelength range 0.6 – 1µm was used.
On the first step, of modeling the quality of the relay-lens was investigated. Point Spread Functions for different points on the target relative of optical axis are shown on Figure 3. The side of a blue squares has a size 0.1mm. For all points light spot does not exceed a fraction of the blue square.
Modulation Transfer Functions for the same points relative of optical axis are shown on Figure 4. Visible sagging of contrast at medium spatial frequencies cause due to central obscuration in telescopes
On the next step, we made a selection of telecentric lenses which are better work near infrared range.

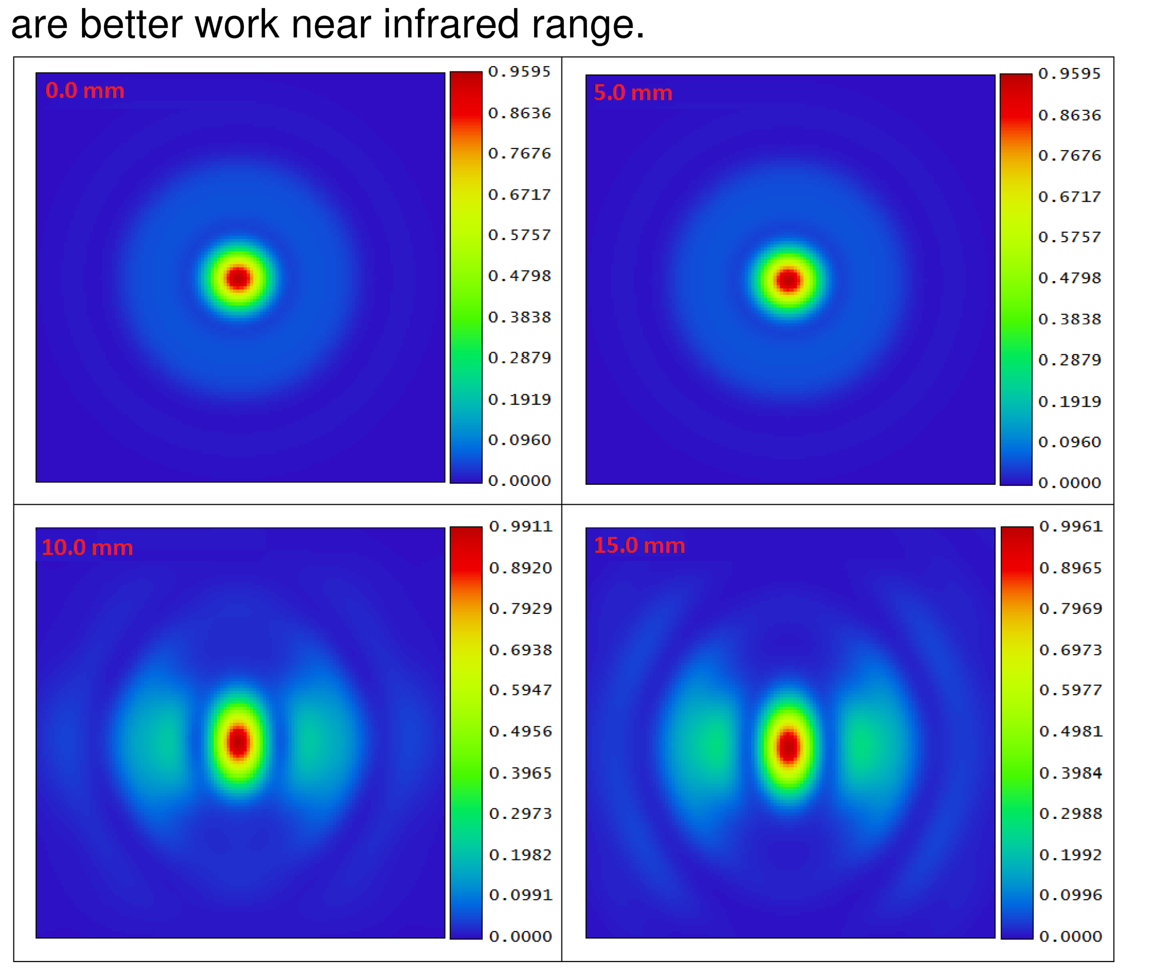

Fig. 3. Point Spread Functions for axial point and for points at 5mm, 10mm and 15mm from axis.

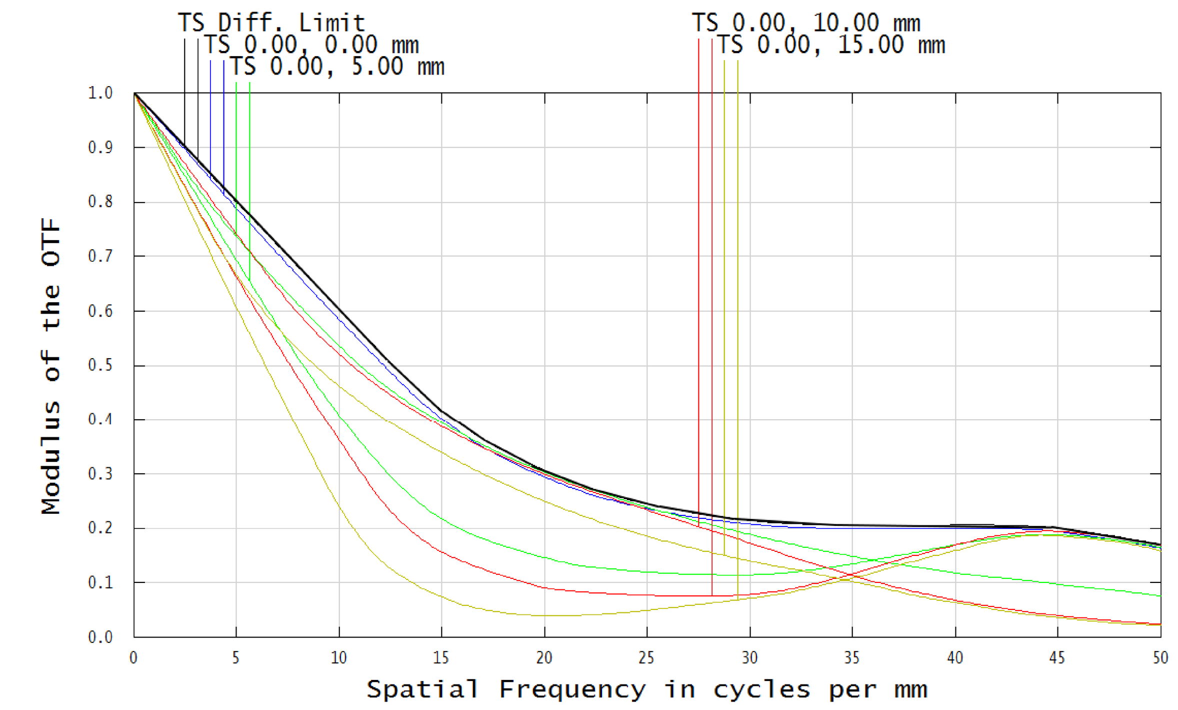

Fig. 4. Modulation Transfer Functions for axial point (blue) and for points at 5mm (green), 10mm (red) and 15mm (yellow) from axis. The black solid line describes contrast dependence for diffraction limited optical system.

Optical System Prototype Testing

Light pass and mounting frame with prototype board with optical elements of relay lens are shown on Figure 5. The mounting frame with the optical board will be placed in the target vessel.
For resolution test we used USAF-1951 test-object which was placed instead of the target on mockup frame (not show here). The test-object was illuminated by incandescent lamp. Image of central part of the test-object in focal plane of the relay lens is shown on Figure 6. Element 3 in group 5 of USAF-1951 test-object was resolvable that corresponds to the resolution about 40 lp/mm. The expected resolution according to modeling is about 70 lp/mm for ideal optical system.

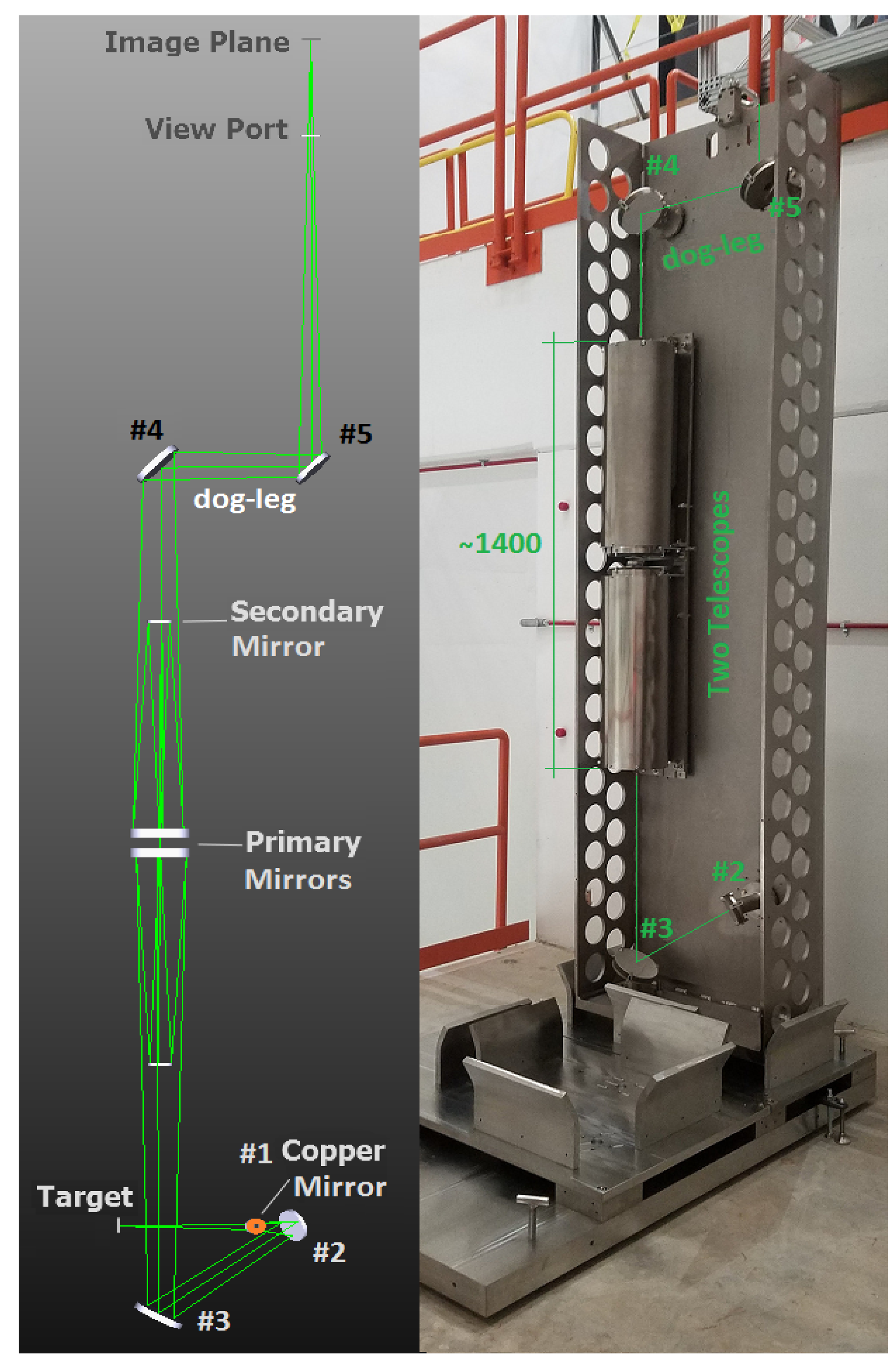

Fig. 5. Left side is the light pass in the relay lens. Right side is the target vessel mounting frame with prototype board with optical elements of relay lens. The detection module with cameras is not shown here.

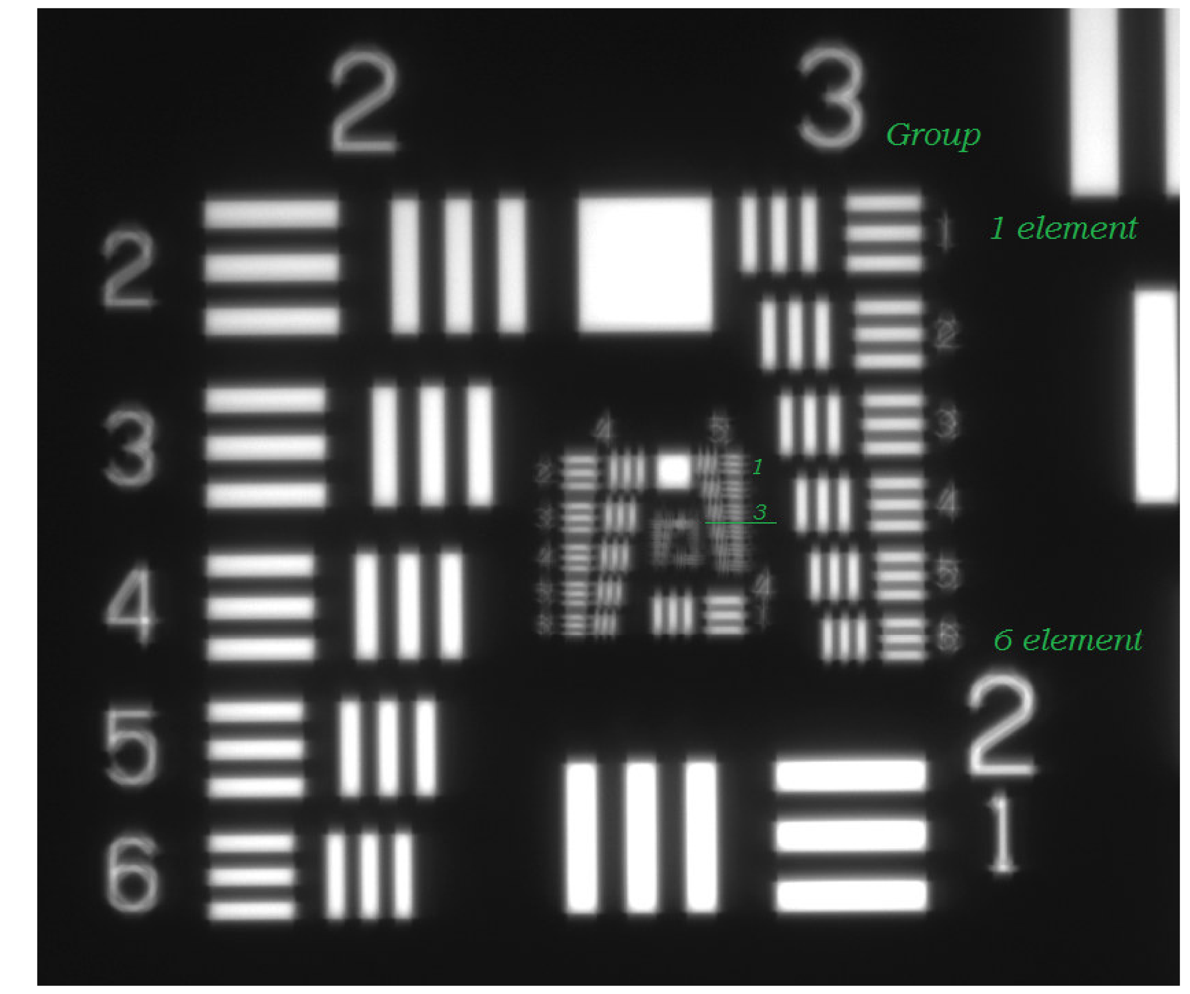

Fig. 6. Image of USAF-1951 in focal plane of the relay lens. Resolution is about 40 line pairs/mm and it is limited by astigmatic secondary mirror of second telescope. To obtain this image a camera with a 5.86µm square pixel was used.

Element 3 in group 3 has a spatial frequency 10 lp/mm which corresponds to the requirement.
After matching the sensor size to the required FOV with help of telecentric lens in detection module, the final resolution is reduced to 16 mostly due to increasing of the effective pixel size from 5.86µm to about 23.4µm.

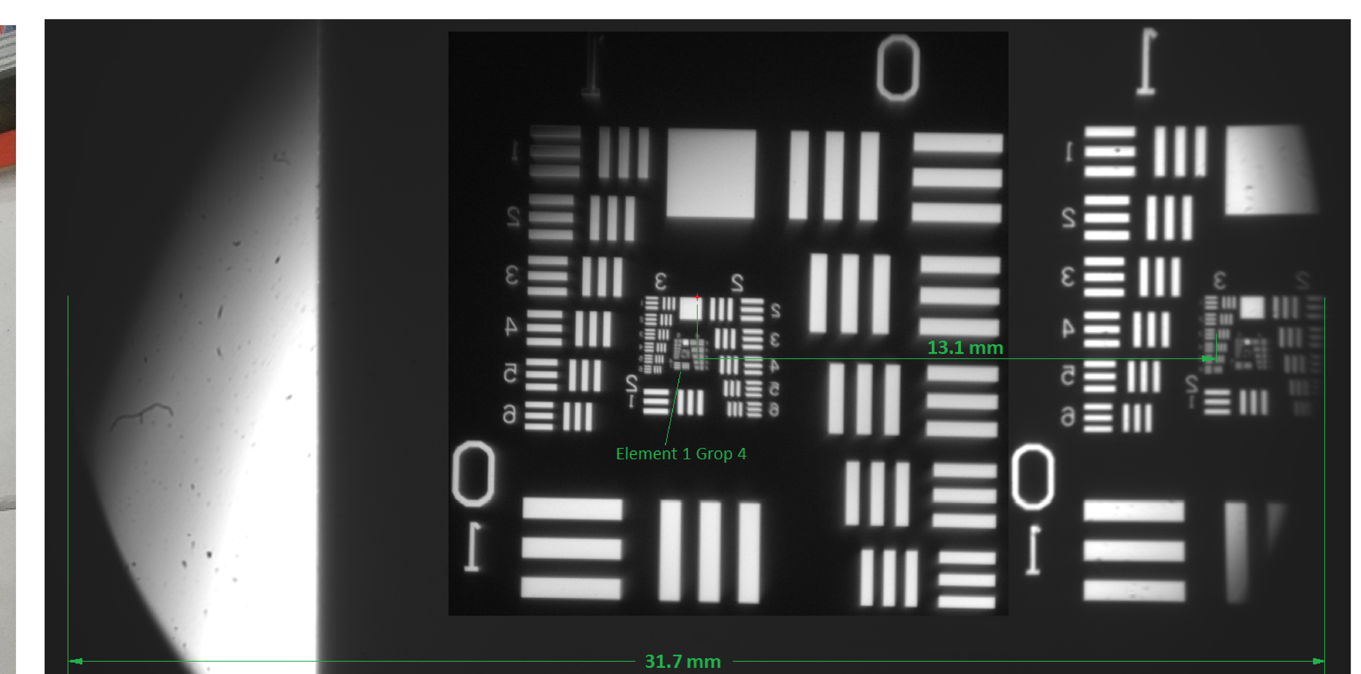

Fig. 7. Image of USAF-1951 on camera sensor after telecentric lens. Two images near center and edge of FOV are merged in one picture. Measured FOV is 31.7mm. Near center the element 1 in group 4 is still resolvable that corresponds to resolution 16 lp/mm. Resolution is reduced to 10 lp/mm at 13.1mm from the center.

Summary

The selected optical design of thermal imaging system meets with basic requirements. This was confirmed by the prototype test results. Resolution 16 lp/mm (in center) and 10 lp/mm (near FOV edge) after passing through all optical elements was obtained. Measured FOV is more than 30mm.

FRIB Facility for Rare Isotope Beams
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