NEVADA NATIONAL NNSS SECURITY SITE

Managed and operated by
Mission Support and Test Services LLC

Red Sage – Wolfsbane Multi-probe Ejecta Diagnostic

Andrew Corredor

Science & Technology Work-in-Progress Seminar, August 17, 2021

This work was done by Mission Support and Test Services, LLC, under Contract No. DE-NA0003624 with the U.S. Department of Energy, the Office of Defense Programs. DOE/NV/03624--1153

Outline

- Red Sage SCE series
- Current designs for multi-pulse low-energy x-ray systems
- Wolfsbane Diagnostic Development
  - Multi-pulse radiography source development
  - Imaging detector – Kraken digital framing camera
  - Two-wavelength shadowgraphy
- Multi-probe ejecta diagnostic testbed
- Integrated diagnostic design concept
- Conclusions

Red Sage SCE series

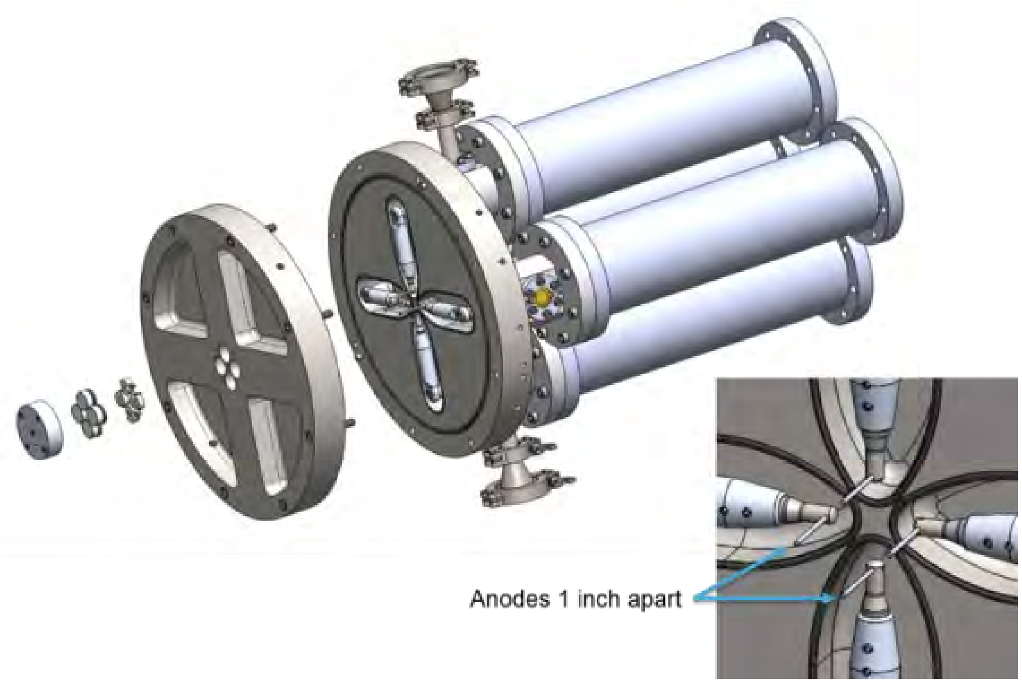
- The Nevada National Security Site (NNSS) has designed a diagnostic to provide increased information on the behavior of plutonium ejecta in explosively driven double shock systems. We intend to implement this new diagnostic capability for the Red Sage Wolfsbane series and other ejecta tests.
- The aim of the Red Sage campaign of subcritical experiments (SCEs) is to measure the dynamic characteristics of plutonium ejecta. Nightshade is planned to be followed by Wolfsbane and Hemlock. Diagnostics on the Nightshade experiments are quantifying the source term for the ejecta emission density into vacuum using two Cygnus 1.8 MeV x-ray radiographs. These diagnostics will not diagnose ejecta particle size.
- The NNSS Radiography and Advanced Imaging Development (RAID) group is pursuing a new multi-pulse 200 keV soft x-ray source with reduced parallax that will be combined with the digital Kraken camera that produces eight frames of continuous images. We will use the ejecta density measurements, plus this new two-wavelength shadowgraphy method, to constrain ejecta particle distribution size.

Multi-pulse low-energy x-ray systems

- Soft x-ray sources operate in a fashion similar to the higher-energy sources, typically using a Marx bank to create a short (tens of nanoseconds), high-voltage (hundreds of kilovolts) pulse across a diode similar in design to the rod-pinch diode.
- The current design used by NNSS is a portable, 37-stage Marx bank called Supersaver, with the capacitor stages charged to –30 kV and discharged over a needle-and-washer diode through a 40-ohm, coaxial transmission line. This flexible transmission line allows the Marx bank to be located away from the experiment in a shielded area.

A modern four-pulse soft x-ray head with Supersaver Marx banks in background

Multi-pulse low-energy x-ray systems



The x-ray head CAD model illustration shows the design placing four anodes as close together as possible to minimize parallax in radiographs from the four separate point sources.

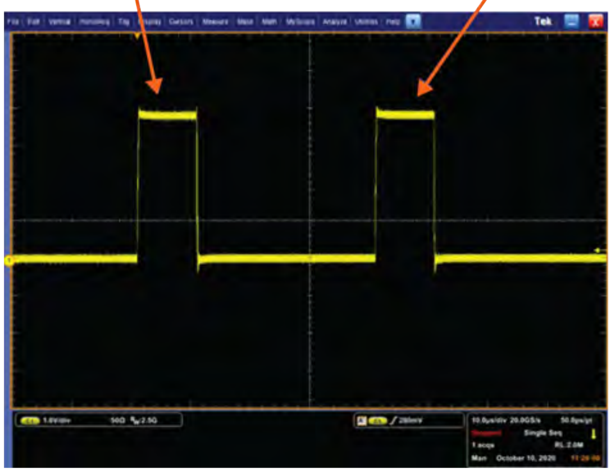
- The system delivers one to four independently triggered flash x-ray pulses at 400 keV with a 35 ns pulse width. The anodes are positioned to minimize image parallax, with each anode located on the corner of a 23 × 23 mm square.
- This source design has been considered for arranging the x-ray head in an experiment confinement vessel to avoid x-ray attenuation of the vessel window. The source parallax problem would be amplified in this configuration and the diode head would also need extensive design modification for the vessel interface.

Multi-pulse radiography source development

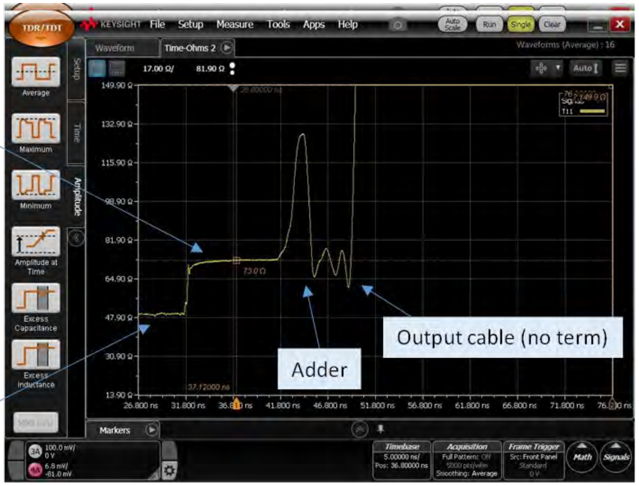
- The NNSS Source Development project is developing next-generation sources to produce brighter, higher-resolution, multi-pulse soft x-ray radiographs.
- In an effort to produce the next-generation low-energy source system, the NNSS is working with Applied Physical Electronics, L.C. (APELC) of Austin, Texas, to design and fabricate modular compact Marx generators and a pulse adder system that will be able to couple multiple sources with a single transmission line.
- The MG15-3C-940PF is a 15-stage, single-rail Marx generator. The device uses ceramic capacitors for energy storage and an acrylic liner for voltage hold-off. It can be charged from 10 to 40 kV, delivering a maximum output voltage of approximately 300 kV onto a 50-ohm matched load.
- This specific Marx generator is capable of delivering fast rise times (800 ps to 5 ns), moderate pulse widths (on the order of 25 ns), and can be operated with repetition rates (>100 Hz) for short durations. This low-energy generator is ideal for soft x-ray applications requiring 300 kV, fast-rise, short-duration pulse or multi-pulse sequences.

Multi-pulse adder

- APELC uses two technologies in its multi-pulse adder design, the first being IGW, which demonstrates the ability to add multiple electrical pulses from unique sources onto a common output transmission line. The second technology, the wave-erection Marx generator, offers extremely fast-rising, high-voltage, short-duration pulses.
- In FY 2020, APELC designed and built a multi-pulse adder to be integrated and utilized with Wolfsbane soft x-ray system. The adder was preliminarily tested with low-voltage inputs for basic electrical performance characteristics with a time-domain reflectometer and a delay generator.



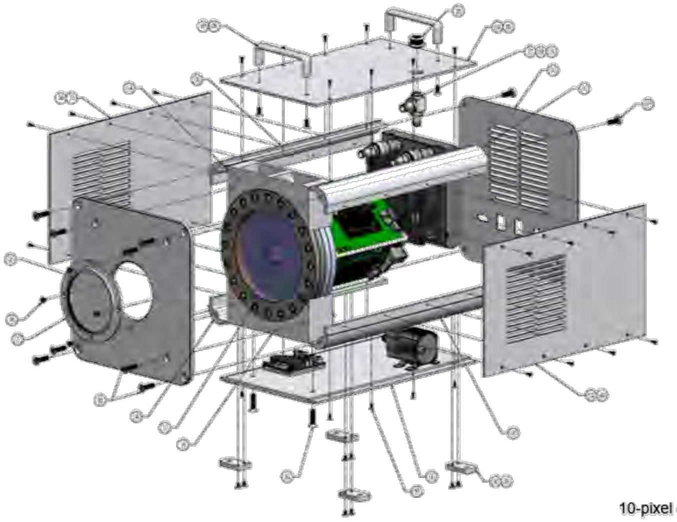
A two-pulse low-voltage measurement of output through the adder



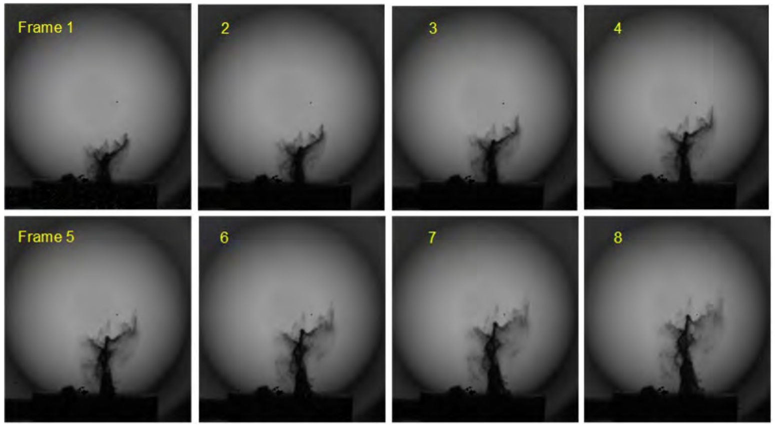
A TDR measurement on the adder showing combined output signals

Imaging detector – Kraken

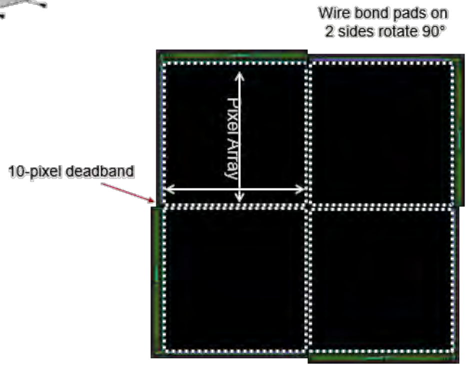
- The Kraken framing camera is an imaging system capable of taking eight frames of images at a 10 MHz frame rate. The system uses a CMOS readout integrated circuit bonded with a silicon detector, with an active area of 24 × 24 mm, resolution from an 800 × 800 pixel array, and a 30 µm pixel width. The sensor, BBAR VIS coated >90% transmission, is a 12-bit monochrome detector. The camera supports an integration time minimum of 50 ns, and an interframe time minimum of 50 ns.
- Future Kraken camera system will be a 49 × 49 mm (70 mm diagonal) active area imager with a resolution of 1600 × 1600 pixels.

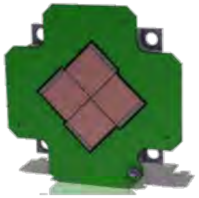


Exploded view of single-sensor Kraken camera



Ejecta shadowgraphy dynamic test performed at NNSS TDI in Los Alamos

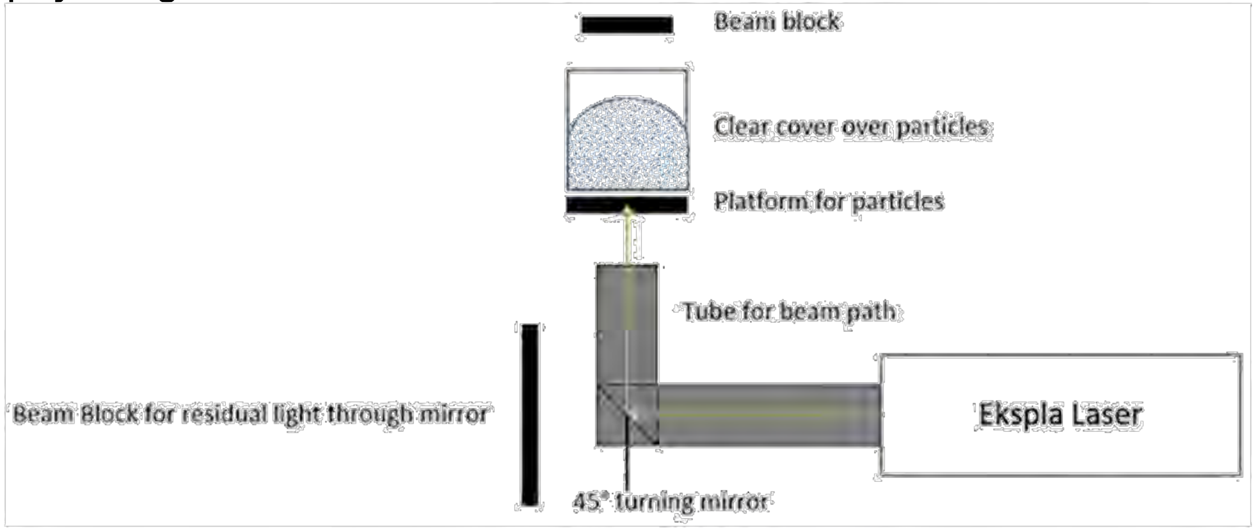




Tiled Kraken sensor (1600 × 1600 pixels) for future large-area imager camera system

Two-wavelength shadowgraphy

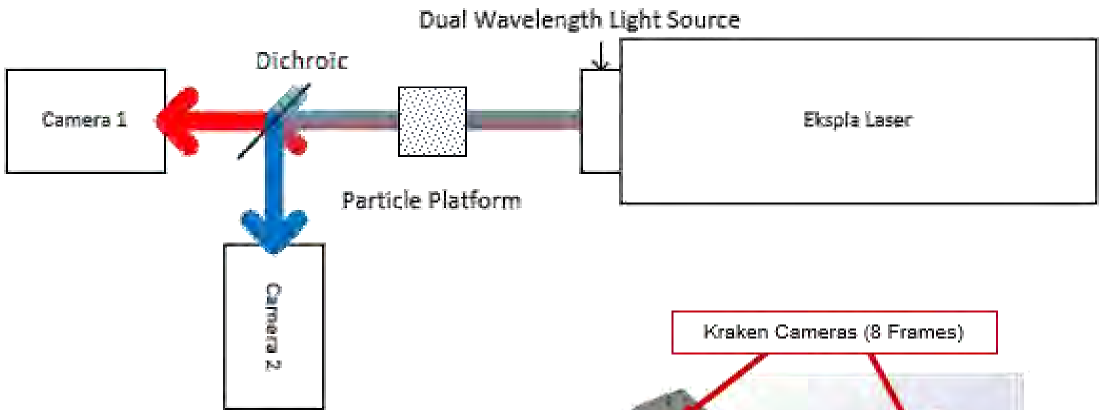
- The diagnostic will provide spatially and temporally resolved images of ejecta emitted from a shocked surface utilizing a light source at two different wavelengths. Up to 16 images will be acquired with a newly developed high-speed framing camera (Kraken).
- The data will provide qualitative, spatially and temporally resolved information about the evolution of an ejecta cloud. In addition, with the multiple wavelengths and an areal density measurement, the average particle size can be estimated with much smaller uncertainty than previously possible.
- We have developed a two-wavelength, single-frame system to evaluate the diagnostic and to determine to what level of accuracy an average particle size can be extracted from the shadowgraphy images.

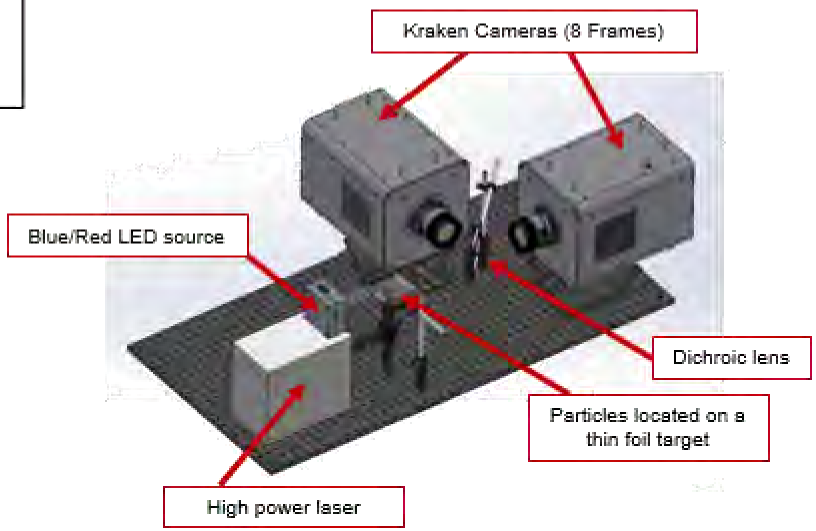


Side view (not to scale) of ejecta test layout; cameras and dual wavelength light source are not shown.

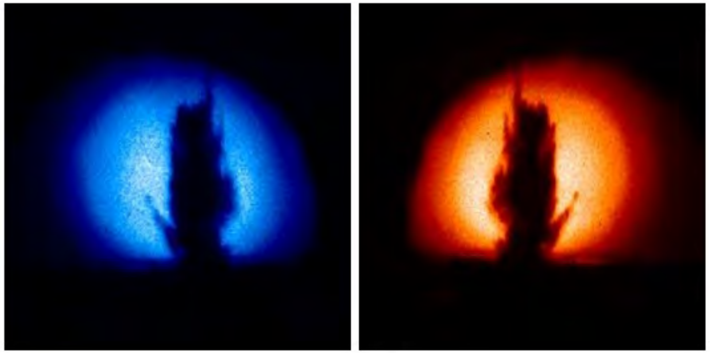
Experimental layout for dynamic tests

- The target platform contains a packet of particles with a predetermined mass and known particle diameter distribution. When the incoming laser beam hits the target, the shocked surface sends the particle cloud up into a field of view where the data are recorded with two cameras for two LED light sources operating at different wavelengths.

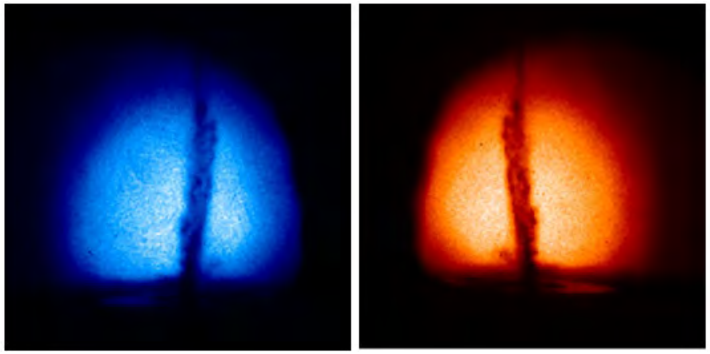




Laser-driven ejecta particle testing using two Kraken cameras



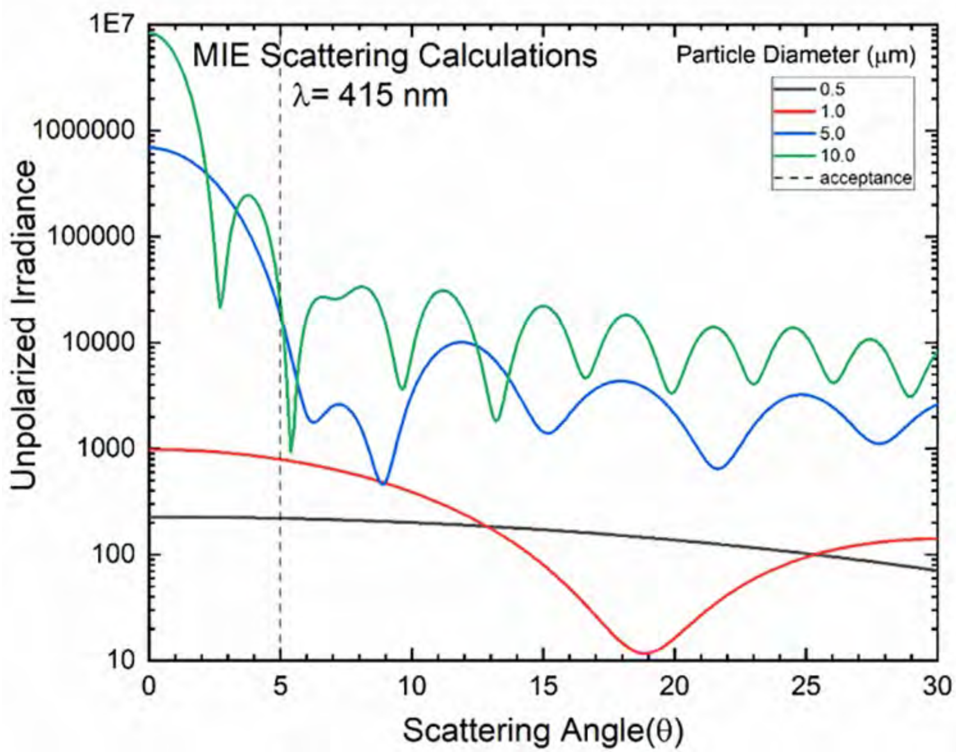
300 nm alumina particles



Silica spheres 5–90 µm in diameter

Two-wavelength shadowgraphy analysis

- Used Mie theory to describe light scattering from particles.
- For a given wavelength, large particles scatter light in the forward direction with a much higher cross section than smaller particles. The cross-section differences make it impossible to determine from a shadowgraph (transmission measurement) what size particles are scattering the light. However, if x-ray radiography is performed at the same time that mass areal density is measured, then the following general statements can be made:
  1. If the ejecta cloud is optically thin (high transmission) and radiographically thick, ⟹ large particles
  2. If the ejecta cloud is optically thick (low transmission) and radiographically thin, ⟹ small particles



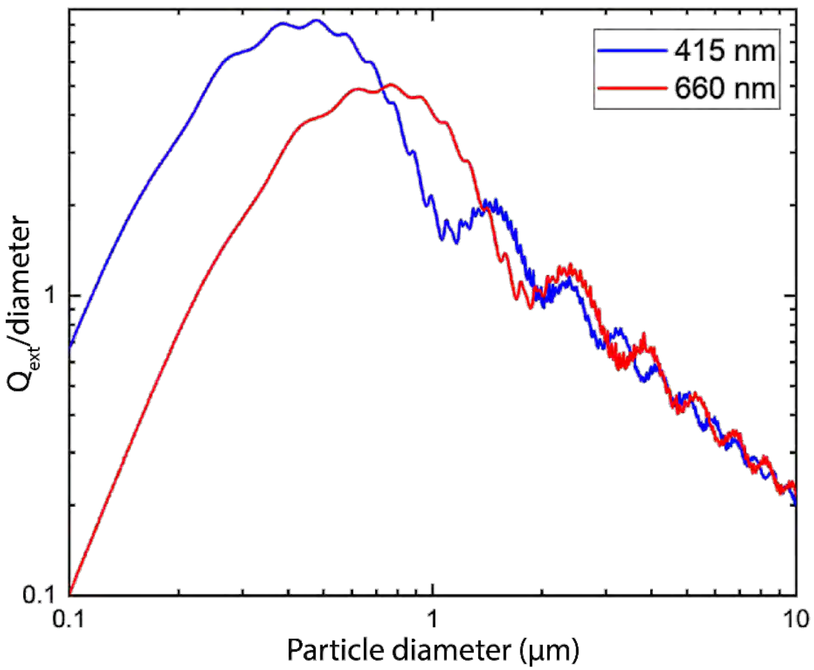
Two-wavelength shadowgraphy analysis

Mie theory applied to transmission measurements:

$$\frac{q_{ext}}{D} = \frac{2 \cdot \rho_p \ln(T)}{3\sigma}$$

Solve the right-hand side of the expression using the experimental data for the optical transmission (T) and the mass areal density (σ) from the x-ray radiography. D is particle size, and q is extinction coefficient.

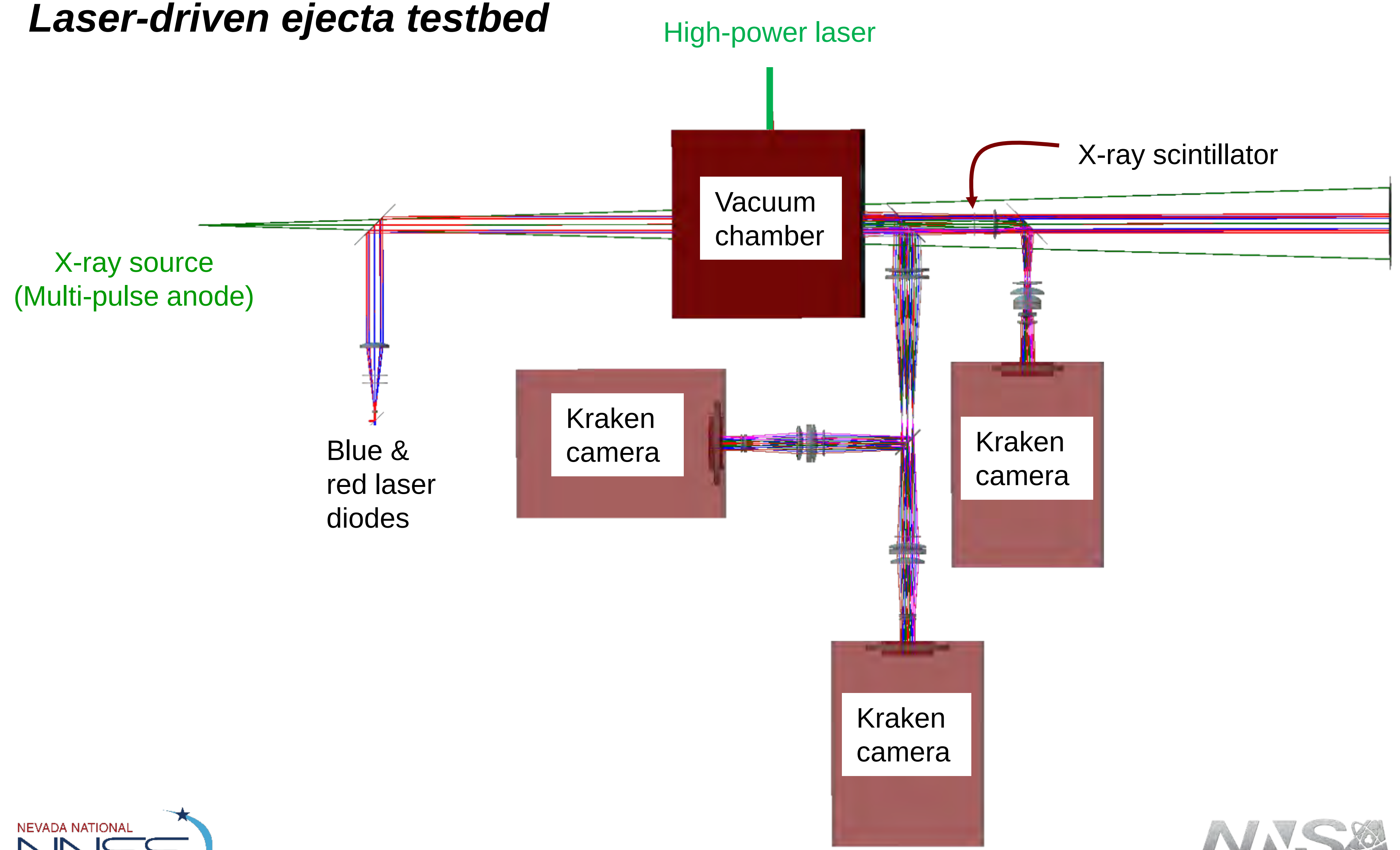
For a single wavelength, there can be some ambiguity, as two particle diameters can correspond to the same value of the left-hand side of the equation. With two wavelengths, however, we can remove this ambiguity and achieve a tighter constraint on the particle size.



Calculated Q_{ext}/particle diameter for the two wavelengths of 415 nm (blue curve) and 660 nm (red curve). Mie calculations were performed for SiO_2 particles.

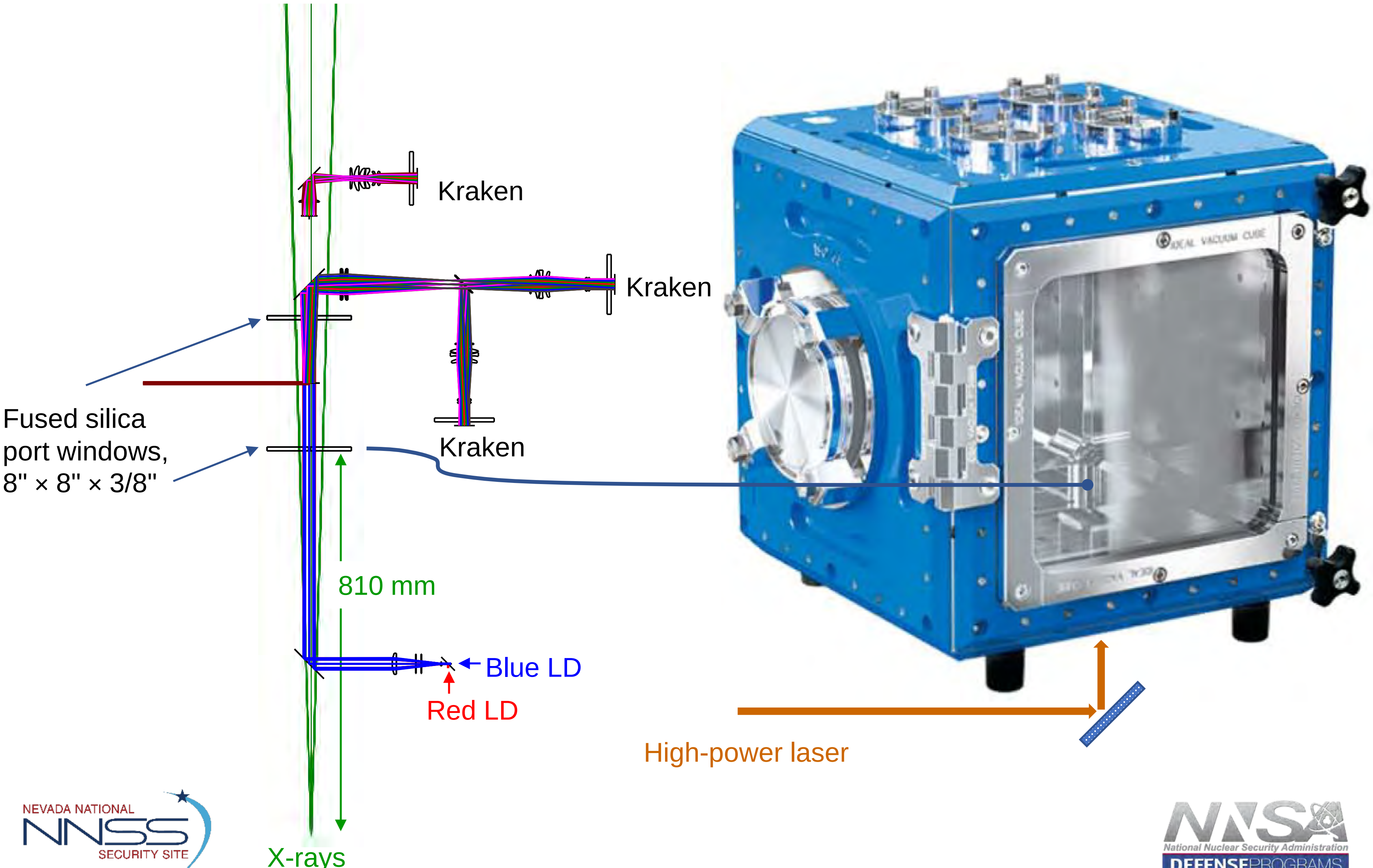
Multi-probe ejecta diagnostic testbed

Laser-driven ejecta testbed

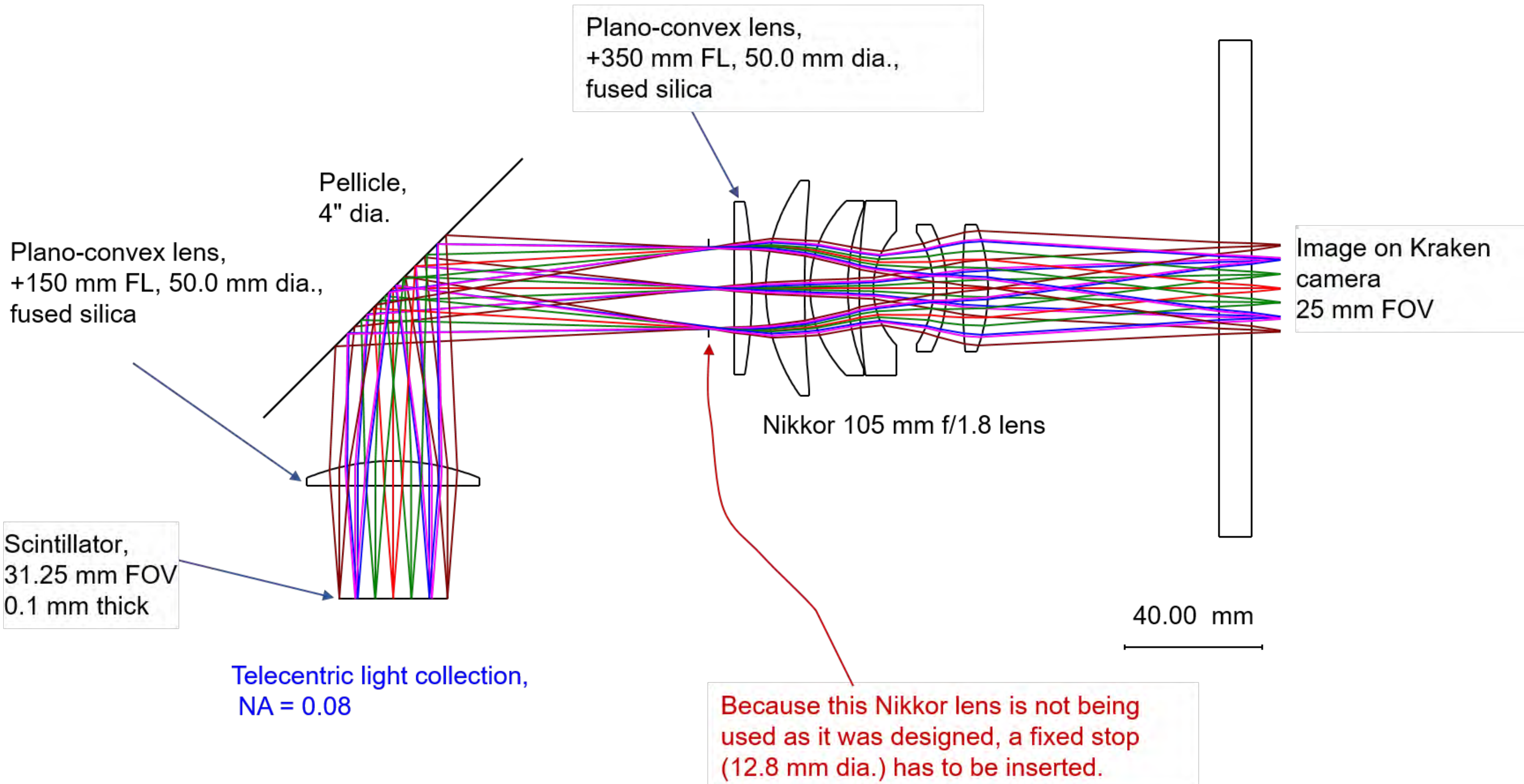


Multi-probe testbed (top view)

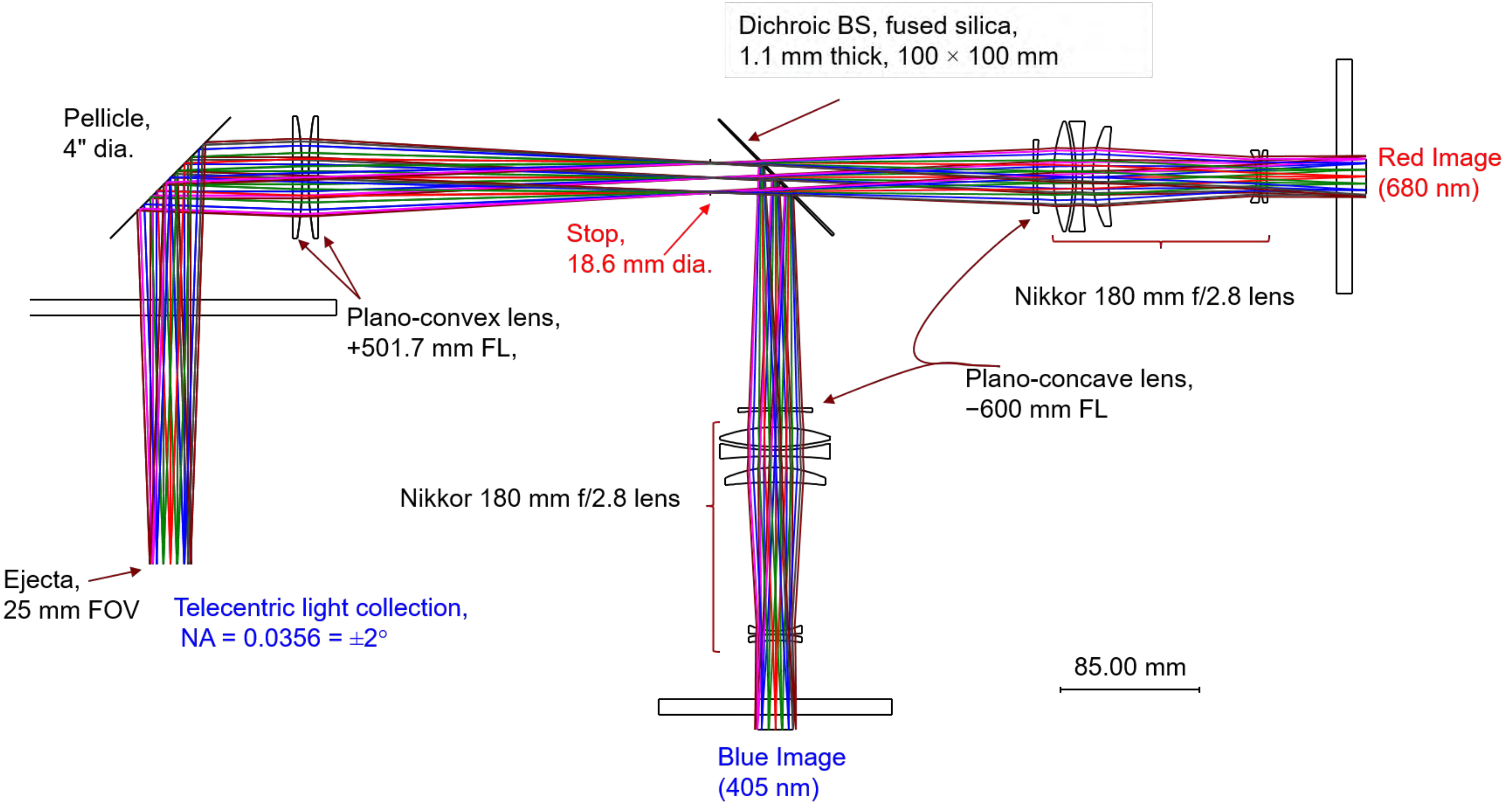
Multi-probe ejecta diagnostic testbed



X-ray imaging



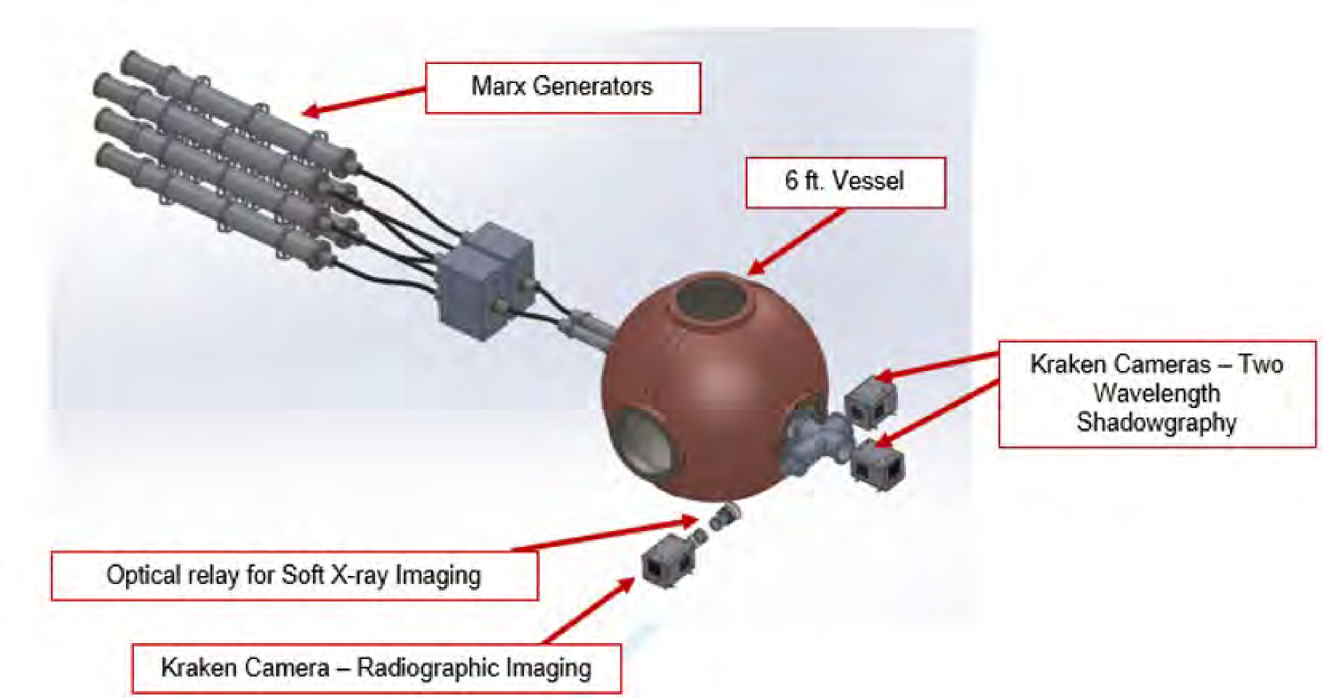
Shadowgraphy imaging



It is very important to control the stop diameter. This sets the light collection angle.
Nikkor lenses are opened up to f/2.8 to eliminate vignetting.

Integrated diagnostic design concept

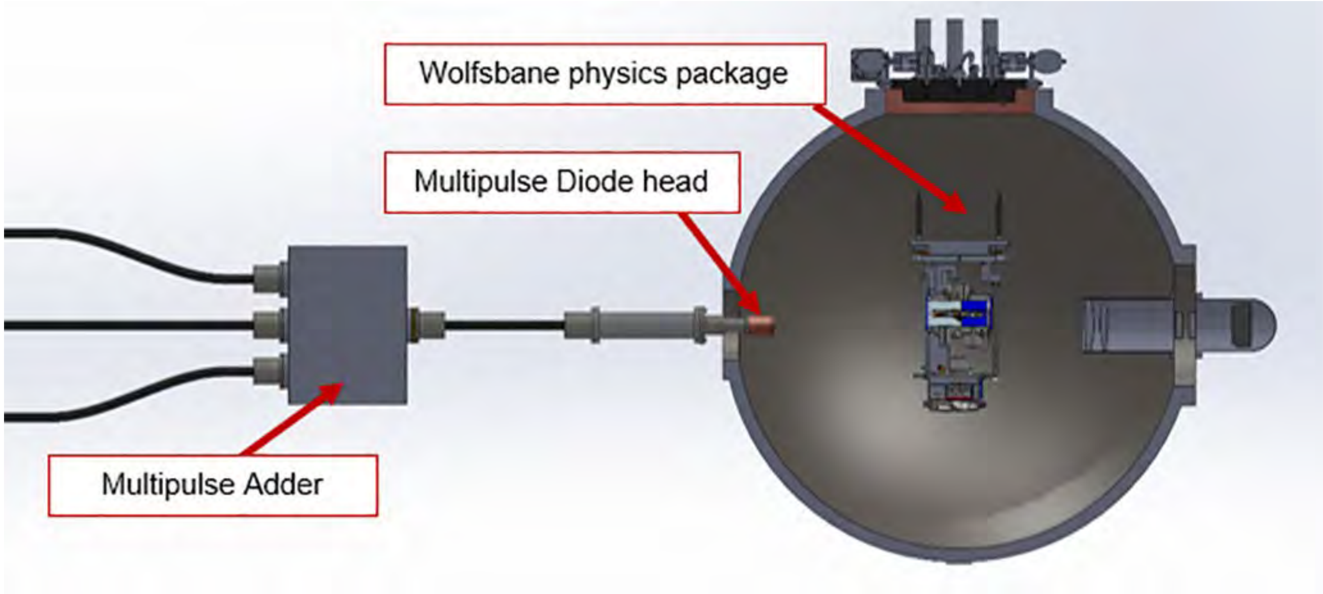
- We designed the system using the Nightshade package as an initial physics model.
- The physics package is assumed to be contained in a six-foot vessel and the diagnostics to be integrated on the vessel's windows in such a way that they will capture the relevant ejecta data on the same line of sight.



Conceptual multi-probe diagnostic for Wolfsbane (x-ray and shadowgraphy imaging)

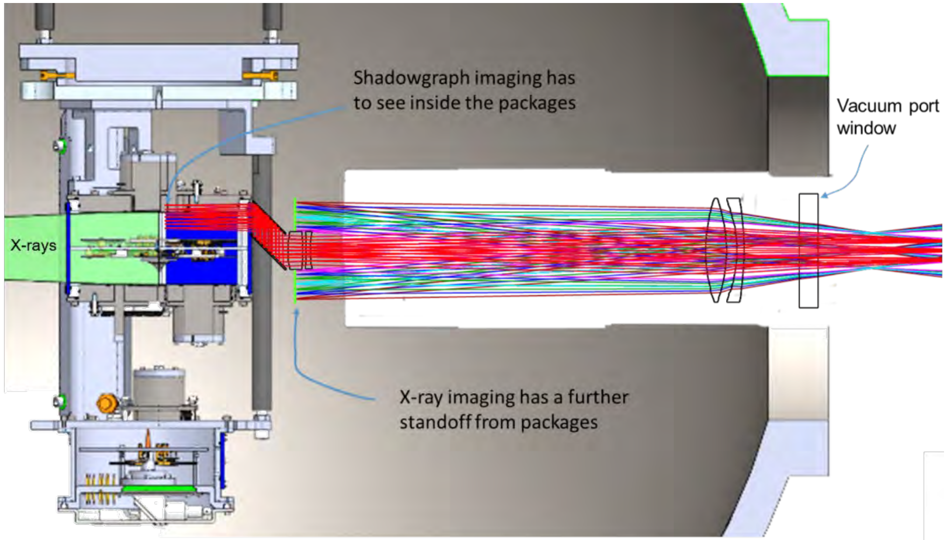
Integrated diagnostic design concept

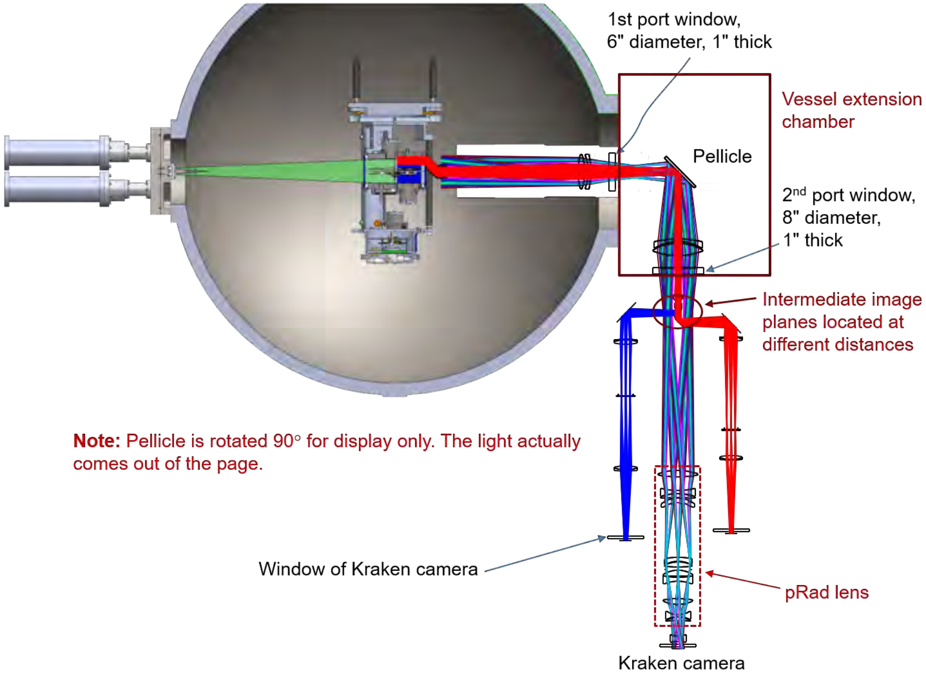
- The soft x-ray source consists of six Marx generators, two pulse adders, and two diode heads. The diode heads were designed to reside inside the vessel and to cover the field of view of the top and bottom targets in the package.



Integrated diagnostic design concept

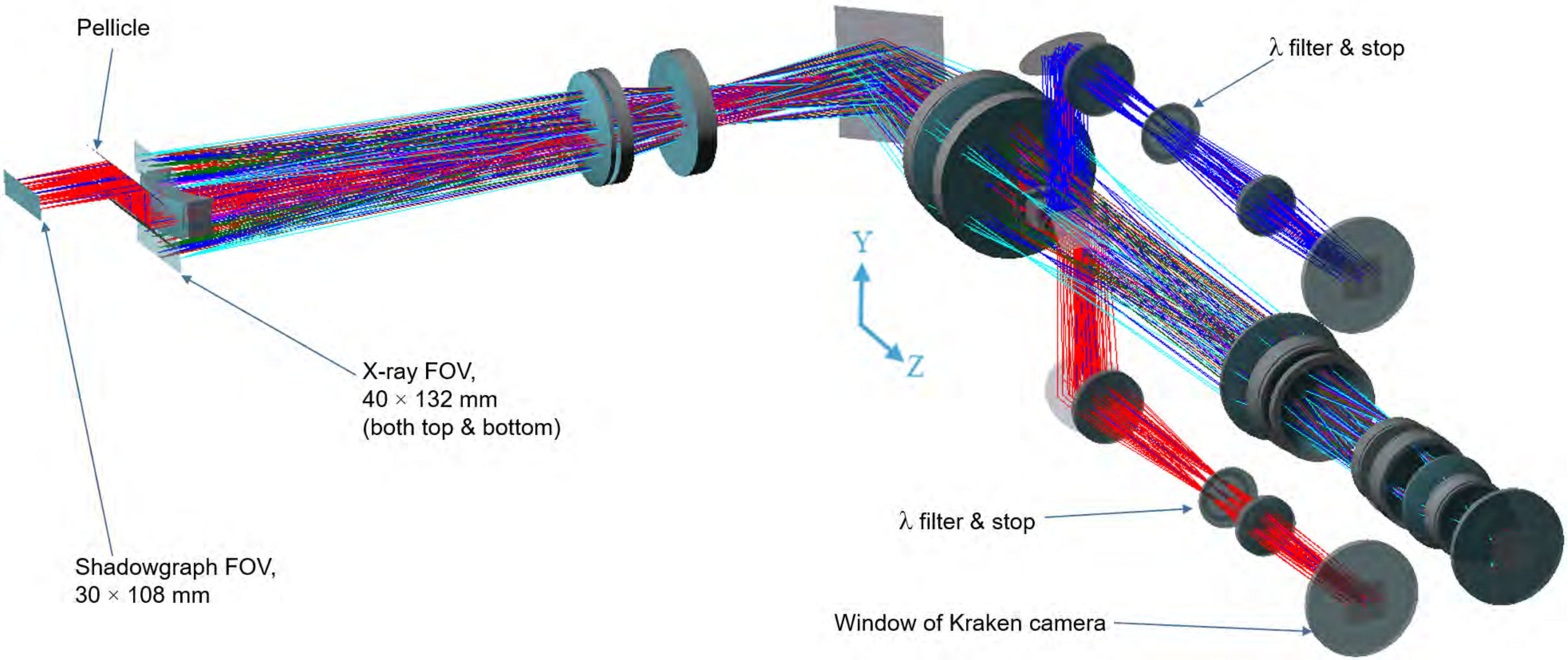
- When combining x-ray and shadowgraphy imaging within the same optical relay system, it is required that the sources of light be collected from different object distances. The shadowgraphy imaging has to see inside the packages, whereas the x-ray imaging has a further standoff from the packages.





Integrated diagnostic design concept

- Imaging systems
  - The system with only blue rays is for the blue LED shadowgraphy imaging.
  - The system with only red rays is for the red LED shadowgraphy imaging.
  - The center imaging system can record both x-ray and shadowgraph images.



Optical systems for two-wavelength shadowgraphy and x-ray imaging

Conclusions

- Our proposed concept combines six-pulse soft x-ray radiography with two-color shadowgraphy over the same field of view and line of sight to add capacity for particle size evaluation.
- The single-anode multi-pulse soft x-ray source coupled with digital multi-frame Kraken imager recording will not only greatly enhance the thin material ejecta density measurement but also provide more complete information about the evolution of the dynamic test.
- The two-wavelength multi-frame shadowgraphs synchronized with x-ray images will constrain the range of particle size in the ejecta cloud.
- Future work
  - Develop and evaluate multi-pulse soft x-ray source, along with vessel interface
  - Complete large-format, tiled Kraken camera system
  - Explore other dynamic experiment platforms (pRad)