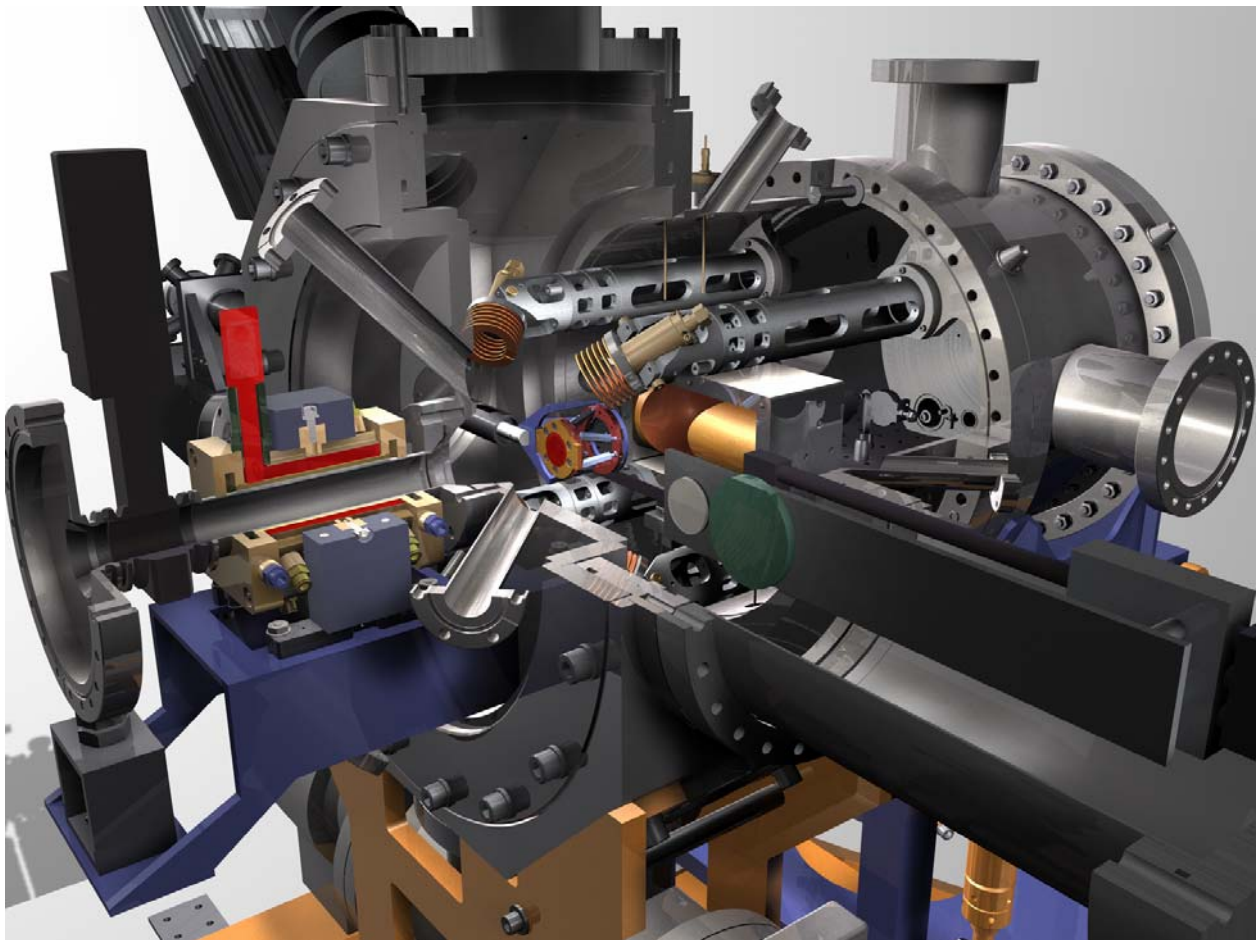


HEAVY ION FUSION SCIENCE VIRTUAL NATIONAL LABORATORY

**4TH QUARTER 2007
MILESTONE REPORT**

***COMPLETE THE CONCEPTUAL DESIGN OF AN
EXPERIMENTAL TARGET CHAMBER FACILITY
FOR NDCX-1A INCLUDING DIAGNOSTICS NEEDED FOR
FIRST TARGET MEASUREMENTS***

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1. SUMMARY

This milestone has been accomplished. The Heavy Ion Fusion Science Virtual National Laboratory (HIFS-VNL) has completed the detailed design of a new experimental target chamber facility and diagnostics for initial Warm Dense Matter (WDM) experiments. The target chamber was fabricated in spring 2007 and has been recently installed on the NDCX-I beamline. The fabrication of the target diagnostics components will be completed by winter 2007. After commissioning, the HIFS-VNL will possess unique and state-of-the-art experimental capabilities to perform target heating experiments using intense heavy ion beams.

2. INTRODUCTION

The HIFS-VNL pursues low-range ion heating to isochorically heat targets. The heating uniformity is maximized by reaching the peak ion energy loss (dE/dx) inside a thin target foil. Since the Bragg peak for most ions and target materials is in the MeV range this technique permits the use of smaller accelerators and makes it possible to perform target experiments on currently existing HIFS-VNL facilities. Figure 1 illustrates schematically the required components for such warm dense matter heating experiments.

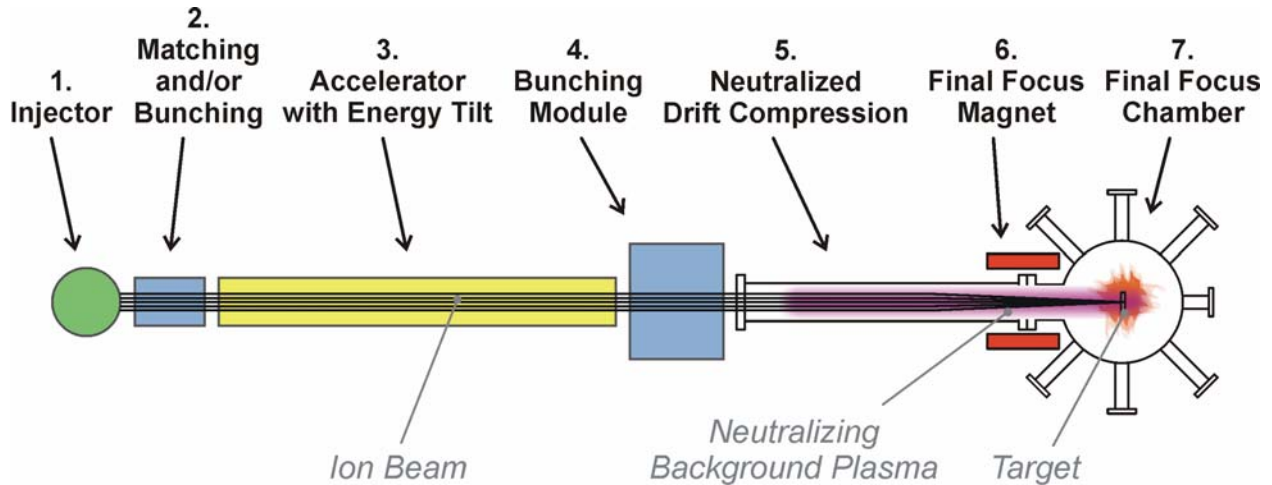


Figure 1: Experimental setup for heavy-ion heated WDM targets.

However, this approach has significant consequences for the experimental target and target chamber setup:

1. Intense (approximately tens of Amperes) ion beam currents must be focused to less than 1 mm diameter on target in order to achieve sufficient heating power for these low kinetic ions. This is only made possible by the neutralized drift compression technique recently developed in the HIFS-VNL.
2. Because of the low ion range thin (micro-meter) targets or foams have to be used.
3. To limit hydro-motion of these thin targets the incident ion beam has to be compressed to a short pulse (approximately 1 nano-second).

These aspects are reflected in the actual target chamber design, which must provide:

1. sufficiently dense (10^{12} to 10^{14} cm^{-2}) plasma injection to neutralize the space charge of the incoming ion beam,
2. a strong (8 to 15 Tesla) final focus solenoid for radial ion beam compression,
3. vacuum pumping,
4. retractable ion beam diagnostics,
5. a retractable target holder with in-situ alignment capabilities,
6. fast optical target diagnostics with access to the front, side and back of the target foil,

7. provisions for electrical current measurements across the target foil,
8. accurate (micron range) alignment capabilities, as well as
9. provisions to exchange target foils without venting the accelerator vacuum system.

The following sections describe in detail these subcomponents of the new HIFS-VNL target chamber facility.

3. TARGET CHAMBER COMPONENTS

Figure 2 displays a schematic view of the new target chamber facility with the major components highlighted. The longitudinally compressed ion beam enters from the left and is focused to less than 1 mm diameter by a strong, pulsed solenoid. Because of the low energy of the incoming ion beam the focal length of the final focus solenoid is short (~40 cm). This puts a major constraint on the target chamber design since each sub-component has to be tightly packed in space.

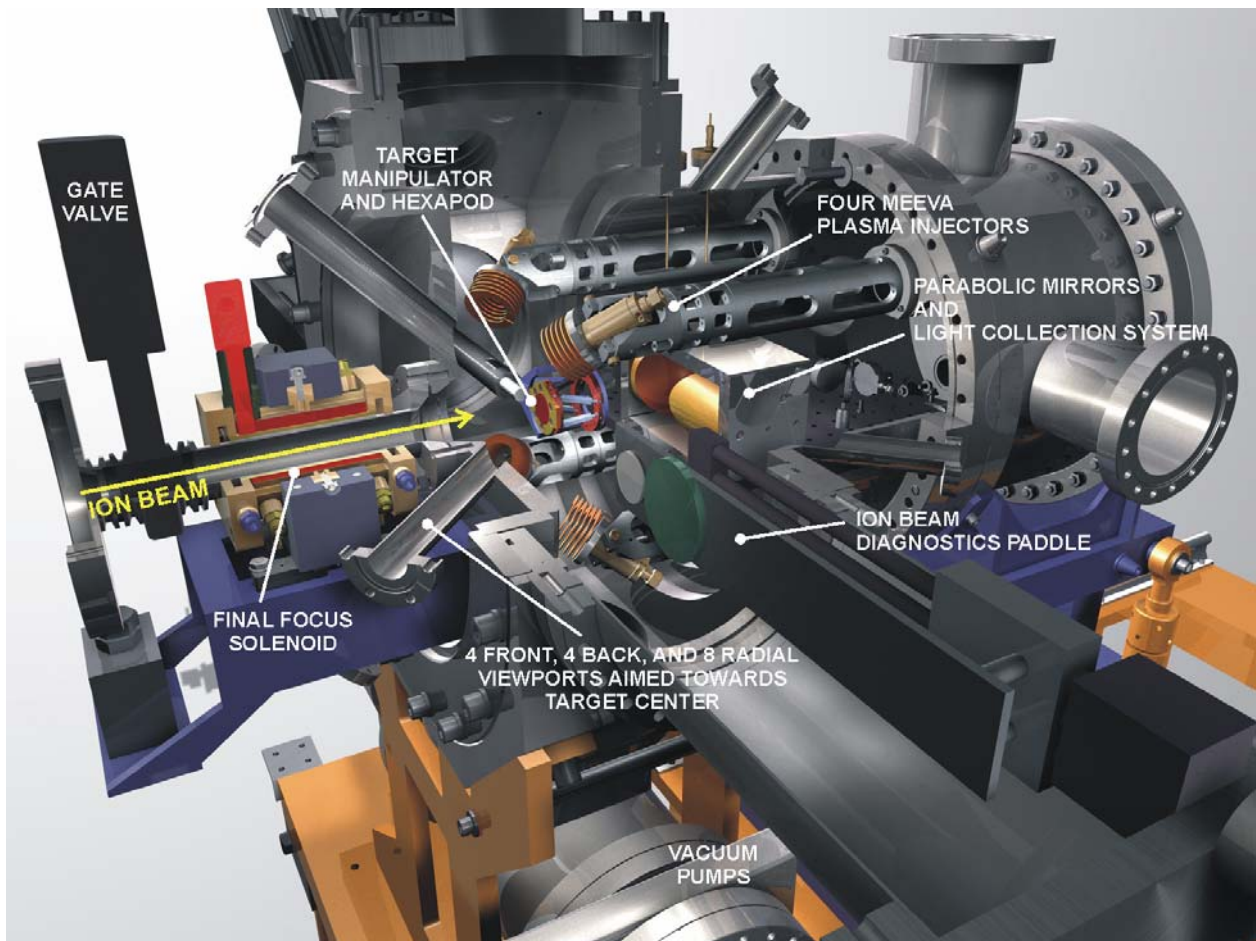


Figure 2: 3D CAD view of the new target chamber facility.

3.1. VACUUM SYSTEMS

The target chamber is a precisely machined octagon made of 304 stainless steel as shown in figure 3. The octagonal shape allows the precise arrangement of different diagnostics around the side of the target which is located in the exact center of the chamber. In addition, the front entrance flange as well as the exit flange provide 4 vacuum ports each which allow viewing the target straight through the target plane.

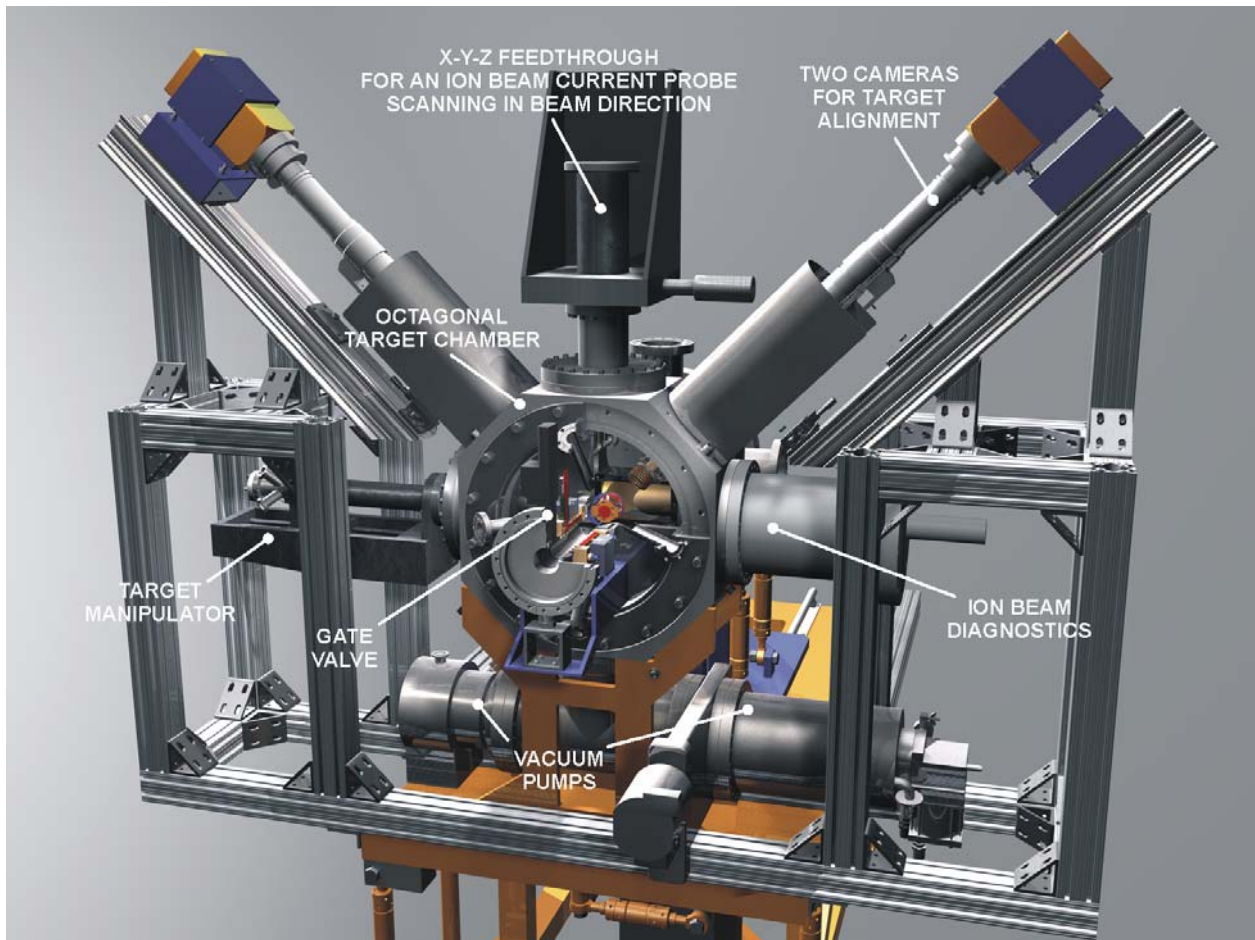


Figure 3: View of the octagonally shaped target chamber. The target foil is mounted in the exact center of the chamber with the ports aiming at the target location.

A small vacuum gate valve in front of the final focus solenoid allows decoupling the target chamber vacuum from the accelerator beamline in order to vent the target chamber for target changes, maintenance, or swapping of diagnostics. The bottom chamber ports are reserved for two vacuum pumps, a 1000 l/sec cryopump with gate valve and a 500 l/sec turbo pump, an ion gauge and a vent port.

3.2. FINAL FOCUS MAGNET

Because of its short focal length the pulsed final focus solenoid is an integral part of the target chamber design. The parameters of the magnet are summarized in table 1. Figure 4 shows a cross-sectional view of the magnet location. Figure 5 shows the magnetic field profile on axis.

TABLE 1: FINAL FOCUS SOLENOID DATA	
LITZ WIRE DIMENSIONS	0.431 INCH X 0.062 INCH
NUMBER OF STRANDS	24
STRAND DIAMETER	0.032 INCH
NUMBER OF TURNS	32
INNER COIL RADIUS	1.00 INCH
OUTER COIL RADIUS	1.32 INCH
WINDING PACK LENGTH	3.96 INCH
MAXIMUM CURRENT	$\sim 22 \times 10^3$ AMPERE
MAXIMUM VOLTAGE	$\sim 2.5 \times 10^3$ VOLT
STORED ENERGY	$\sim 9 \times 10^3$ JOULE
PULSE LENGTH	785 MICRO-SECONDS
MAXIMUM FIELD ON AXIS	8 TESLA

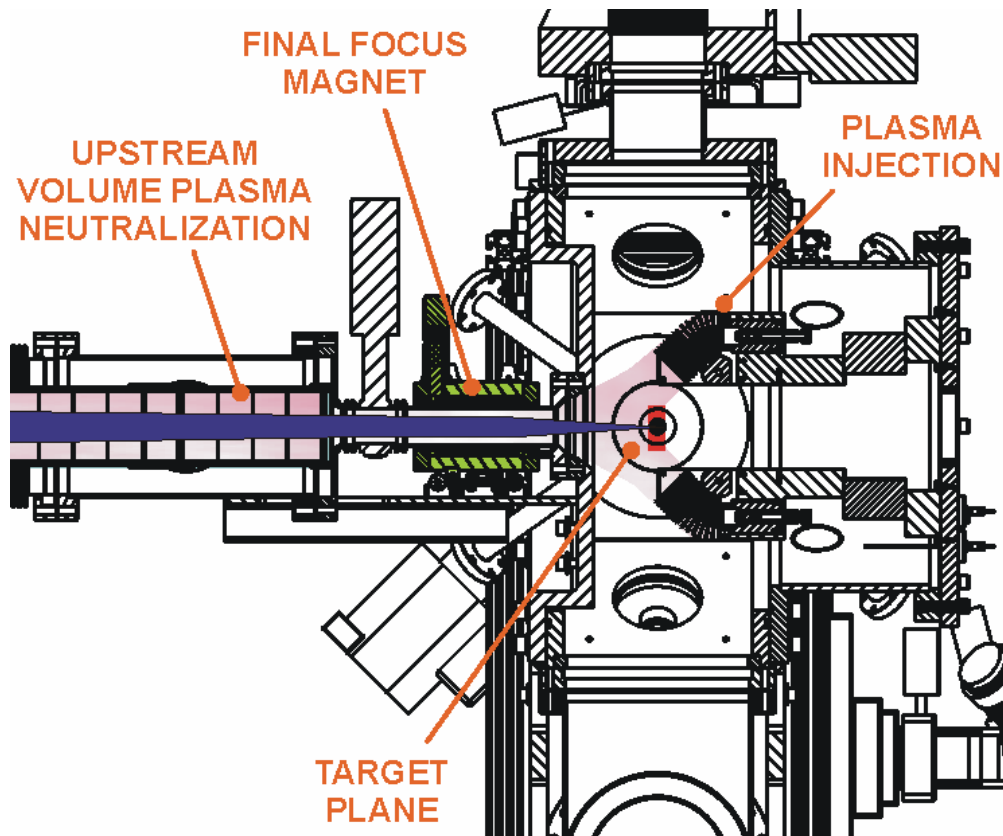


Figure 4: Final focus magnet position with respect to plasma injection.

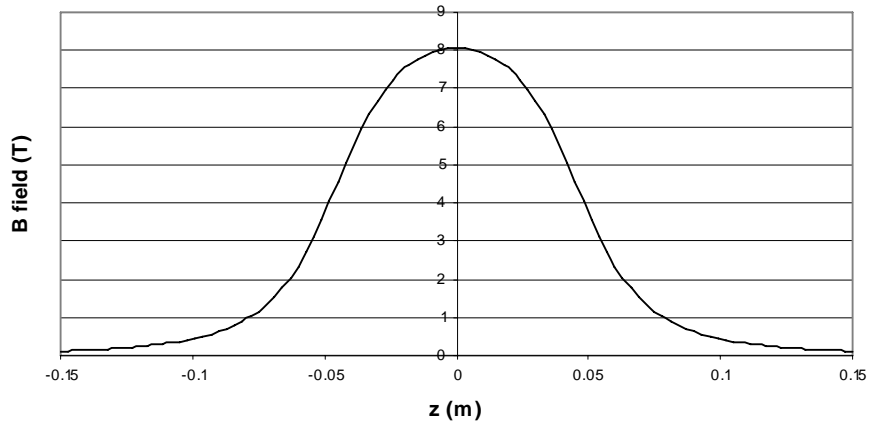


Figure 5: Magnetic field along the center of the final focus solenoid.

Currently, the magnet is pulsed up to 8 Tesla magnetic field. At this field strength the copper wire already starts to yield. Therefore, we have decided to surround the magnet coil by a stainless steel water housing to allow sufficient mechanical support for the coil. This design will allow us to eventually push the magnetic field beyond 10 Tesla.

The stainless steel water jacket is shown in figure 6 highlighting its thin walled structure with grooves to minimize eddy currents. The magnet coil, which is wound around a G-10 winding mandrel using Litz wire (to also minimize eddy currents inside the coil), is inserted into the stainless steel housing and potted using highly viscous epoxy CTD-101K from Composite Technology Development.

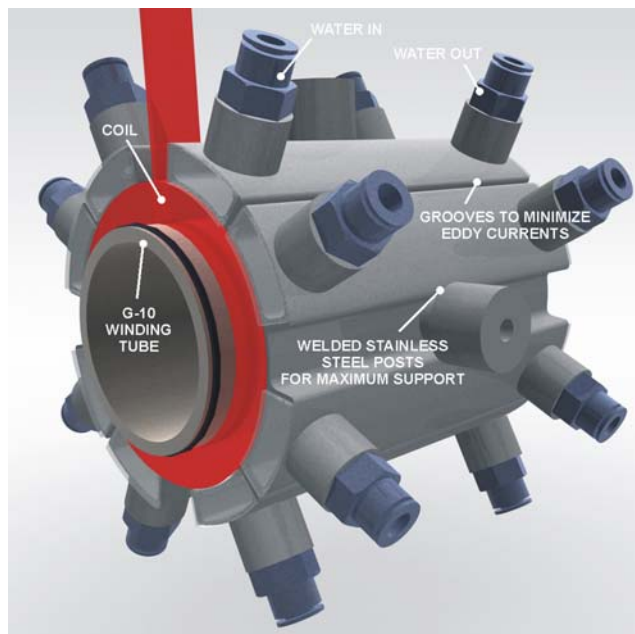


Figure 6: The Litz wire winding pack (red color) is inserted into a thin walled, welded stainless steel housing for efficient water cooling and structural support. The shell support will allow increasing the final focus fields to beyond 8 Tesla.

Magnet end plates, made out of Delrin, guide water to cooling channels on the inside of the magnet between the G-10 winding mandrel and the stainless steel beam pipe. The massive cooling flow on the inside and outside of the magnet allows pulsing the magnet every ten seconds.

3.3. PLASMA INJECTION

Figure 7 shows the location of the four plasma guns used to inject plasma into the final focus region right in front of the target. Figure 8 shows a detailed photograph of the Metal Arc (MEEVA) plasma guns with their subcomponents.

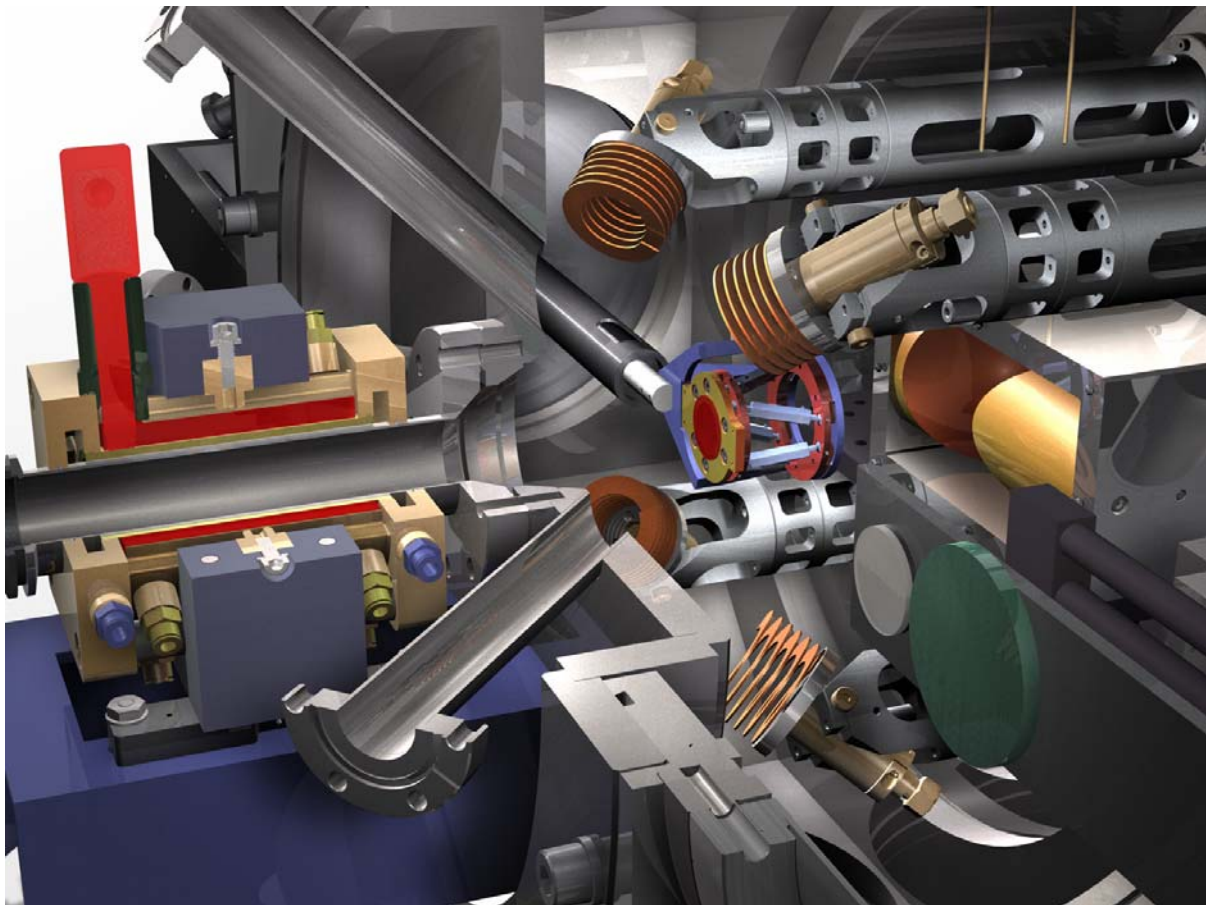


Figure 7: Four MEEVA arc plasma guns (aimed towards the front of the target) inject plasma for ion beam space charge neutralization.

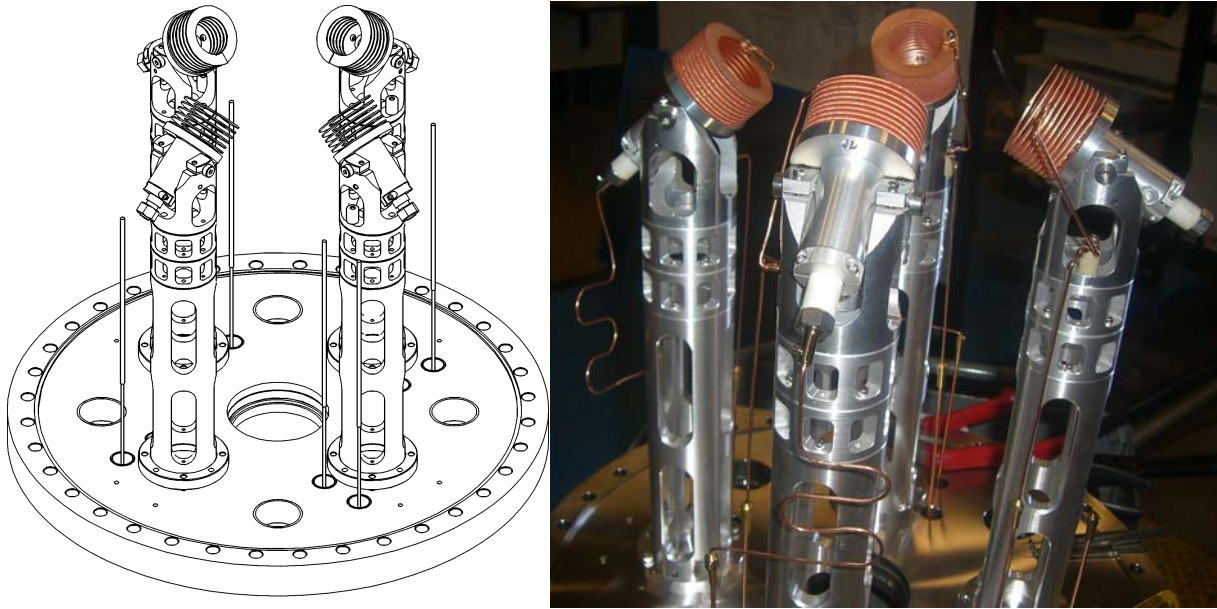


Figure 8: Detail view of the MEEVA arc plasma guns.

Significant time has been expended to minimize the size of the target holder and ion beam diagnostics footprint in order to maximize the plasma flow to the target area. The plasma flow is slowed down once entering the high field region of the final focus solenoid and becomes confined in front of the target. Figure 9 shows a photograph of the plasma flow inside the target chamber.



Figure 9: Photograph showing the plasma glow during the firing of the MEEVA arc plasma injectors.

3.4. ION BEAM DIAGNOSTICS

Two target chamber ports are reserved for ion beam diagnostics in order to be able to sufficiently characterize the ion beam before any target experiment. A fast Faraday cup and a scintillator plate are mounted on a horizontal paddle as can be seen in figure 10. The top vertical port is reserved for a future x-y-z feedthrough to install a current probe scanning along the beam axis.

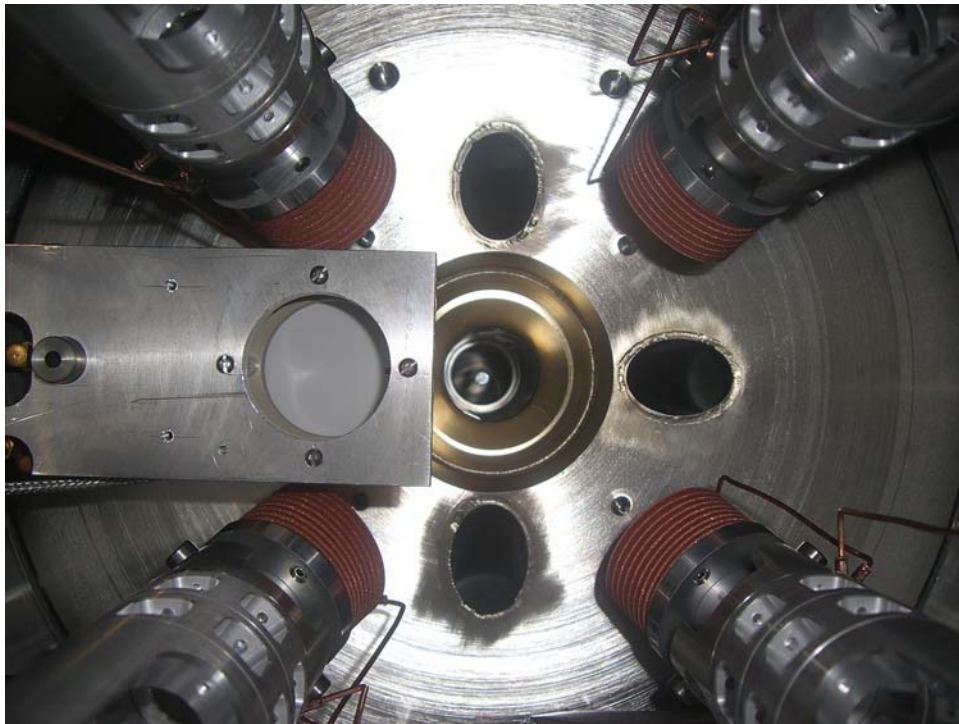


Figure 10: Photograph taken from the back of the target chamber. The ion beam diagnostics paddle is mounted on a linear feedthrough and moves in and out from the left of the picture. It fits in between the 4 MEEVA plasma nozzles. A scintillator and a fast Faraday cup are mounted on top of the paddle.

3.5. TARGET MANIPULATOR AND POSITIONER

Since the thickness of the target foil is only a micron or less, the correct positioning of the target is particularly critical. It must be aligned to both, the incoming ion beam and the array of target diagnostics devices. We decided to design a manipulator with the future development of a target robot system in mind. In the final development stage (for a WDM user facility) the goal is to have a robotic target handling system which can automatically choose and position from 20 to 50 preloaded target assemblies without breaking vacuum.

The target has to be able to be aligned in x-, y-, and z-direction, as well as in roll, pitch, and yaw with respect to the ion beam axis. The most compact device for this type of positioning is a "parallel kinematic manipulator", or hexapod. As a future development goal we are envisioning a

robot arm, which grabs a preloaded target from a vacuum load lock system and moves it into the target area. On the end of that robot arm sits a miniature hexapod which performs the in-situ target alignment.

Our current target manipulator consists of such an arm with a manually adjustable hexapod on top as shown in figure 11. A long vacuum translational feedthrough allows retracting the target from the target chamber center in order to be able to insert ion beam diagnostics. Once the ion beam has been tuned up, the target manipulator moves the target holder into the center of the target chamber.

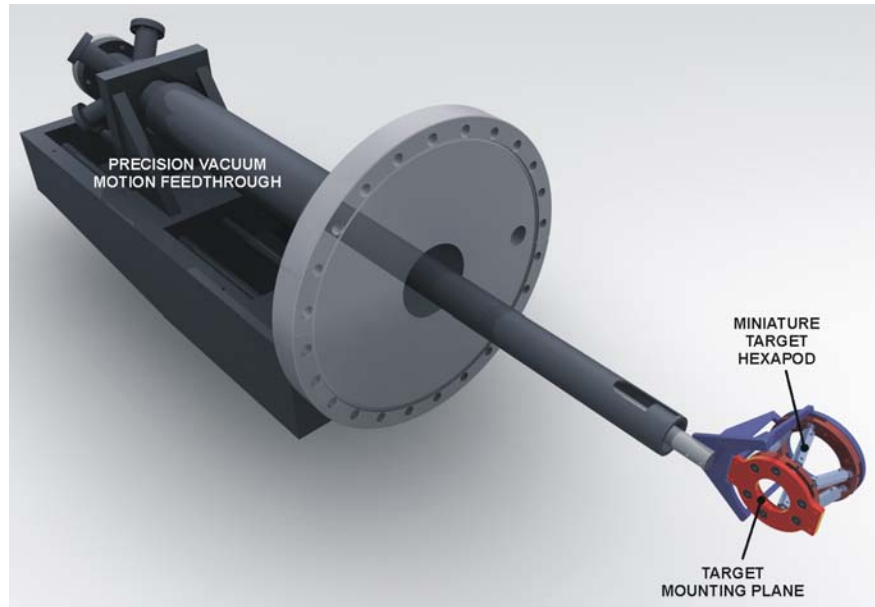


Figure 11: A long vacuum translational feedthrough allows retracting the target from the target chamber center in order to be able to insert ion beam diagnostics. The target itself is mounted on top of a miniature hexapod for alignment purposes.

The miniature hexapod has to be compact in order to minimize shadowing of the injected neutralizing plasma flow. At the same time it has to allow visual access to the side, the back, and the front of the target foil. No such hexapod is commercially available. We have decided to develop our own system by first implementing a manually adjustable hexapod. That way we will be able to determine the usefulness of our chosen design strategy, and we will be able to continually improve it for an eventually fully automated robot system. This careful development path is necessary since a vacuum-compatible miniature hexapod system will be very expensive (several hundred thousand dollars).

During the first target experiments we will test the capabilities of the miniature hexapod. We are in possession of a laser tracker alignment system which will allow us to align the targets in x, y, z, roll, yaw, and pitch to within less than a thousandth of an inch. Currently, in order to mount the next target foil after an experiment, the target chamber has to be valved off the accelerator beamline vacuum and vented to air. As a next step we plan to incorporate a vacuum load lock system to facilitate a quicker target turn around.

3.6. TARGET DIAGNOSTICS

The target is mounted in the center of the octagonal shaped target chamber and has diagnostics access to the front, back as well as to the side. The current diagnostics configuration has two cameras mounted at a 90 degree angle looking at the side of the target. The primary purpose of these cameras is to allow visual alignment of the target sample. See figure 12 for the setup of the camera mounts.

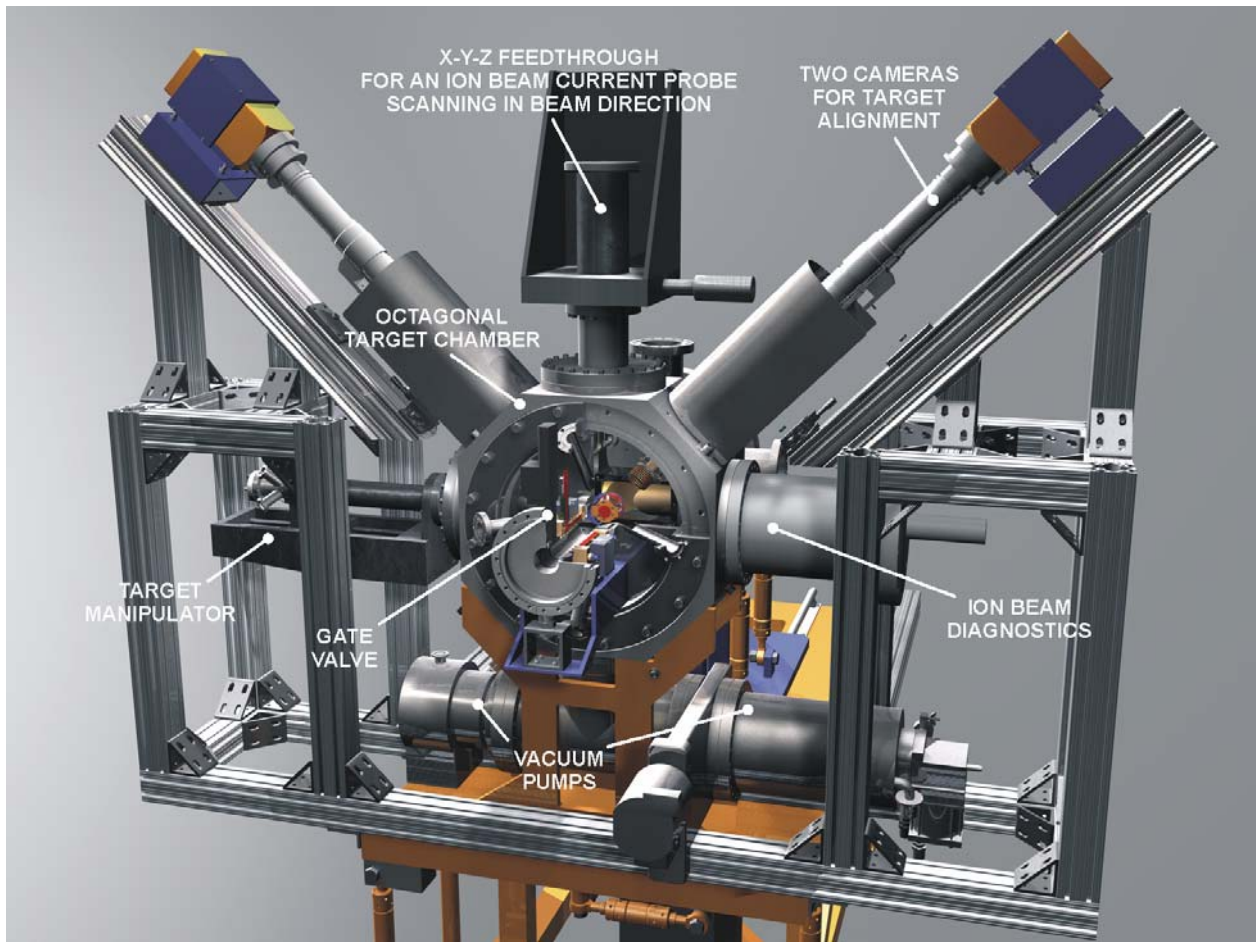


Figure 12: Front view of the target chamber facility. The target foil is mounted in the exact center of the octagonal chamber with the ports aiming at the target location.

The primary target diagnostics are a fast pyrometer for temperature measurements and an optical camera for viewing the target from the back. The fast pyrometer uses a light collection system shown in figure 14, to be mounted on the optics breadboard shown in figure 13, and fiber optics lines and fiber optics feedthroughs.

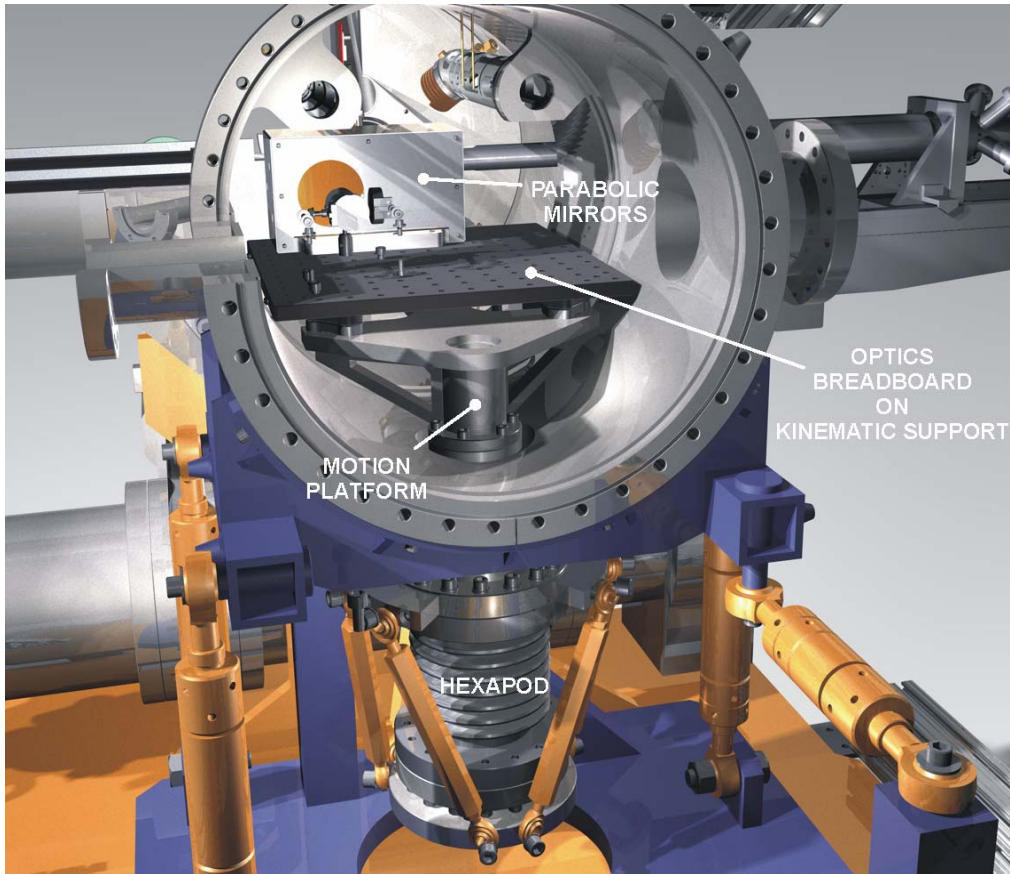


Figure 13: The light collection system is installed in a separate vacuum spool, which can be removed from the main target chamber vessel for servicing. A hexapod, adjustable from outside the vacuum, allows precision alignment of the optical table.

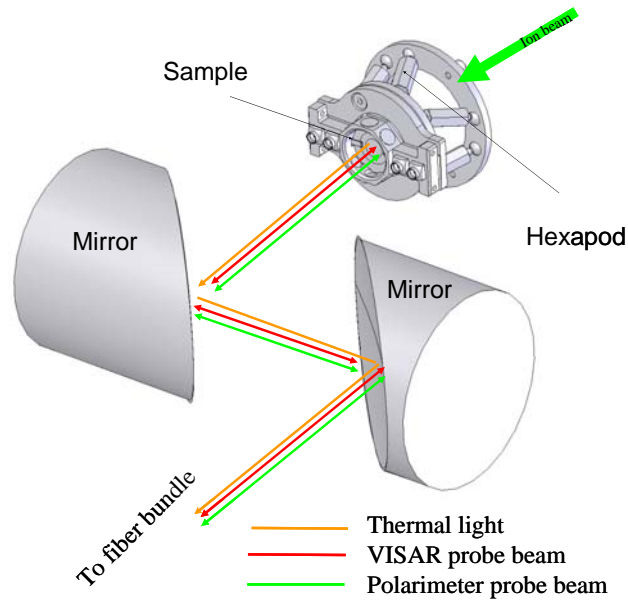


Figure 14: Schematic setup of the light collection system located behind the target.

Existing beam diagnostics will characterize the parameters of the incident heating beam, such as its energy, and its transverse and longitudinal distributions incident on and downstream of the target. These diagnostics include a high-resolution electrostatic energy analyzer (EEA) and optical diagnostics. An alternative measurement of beam energy distribution that can provide some of the same information as the EEA is time of flight (TOF). A beam that is focused longitudinally by phase space rotation has a large energy spread (up to ~30%) at the target but is localized in time, providing a well-defined time marker for the TOF measurement.

When an ion beam strikes a vacuum wall, a cloud of gas is desorbed. Care must be taken to include gas cloud emission in interpreting optical emission data from the target. In addition a promising diagnostic is the use of the optical emission from the gas cloud generated at the intense beam focal spot. This is a self-healing alternative to other beam diagnostics such as a scintillator or a fast Faraday cup which may be limited in their lifetime, linearity or bandwidth.

Some measurements of transmitted beam can be performed in thin-foil target experiments including collecting beam transmitted through the foil in a Faraday cup, measuring the transmitted beam energy distribution, and using a downstream scintillator to image beam scattering in the foil.

Because of the short time scales of these experiments, high speed diagnostic capability is essential. Diagnostics in hand include two Princeton Instruments high-speed cameras as shown in figure 12, an optical spectrometer, a fiber Doppler VISAR system, and a streak camera system.

For measurement of target temperature, we are constructing a fiber-coupled multi-channel optical pyrometer with sub-ns response, and temperature sensitivity to as low as 1000 C. Position resolution is 400 micron or less, depending on the diameter of the coupling fiber to be used. The required positioning accuracy of the beam and target is much less than the position resolution of the diagnostic. Fig. 14 shows a schematic layout of the light collection optics for the pyrometer (thermal light) and other diagnostics such as the VISAR and laser (polarimeter) probes. Figure 15 shows a CAD drawing of the initial 2-channel pyrometer system now under construction. The optical emission from the target is carried from the light collection optics of figure 14 through a set of optical fibers to the pyrometer shown in figure 15. The light (yellow) passes through a beam splitter that separate the light into visible and infrared components. The two high-speed detectors (green) detect the light after a second beam splitter and after passing through bandpass filters at independently-selected wavelengths, for example 750 and 1500 nm. We plan to extend the number of channels to as much as 7 in the future.

The fiber-coupled VISAR (Velocity Interferometer System for Any Reflector) is a commercial probe (Martin Froeschner and Associates) that will measure the surface motion of the target after being heated by the beam. Bench test of the probe has been completed. VISAR can provide accurate measurement of the target expansion velocity with sub-ns time resolution as an alternative to the streak camera.

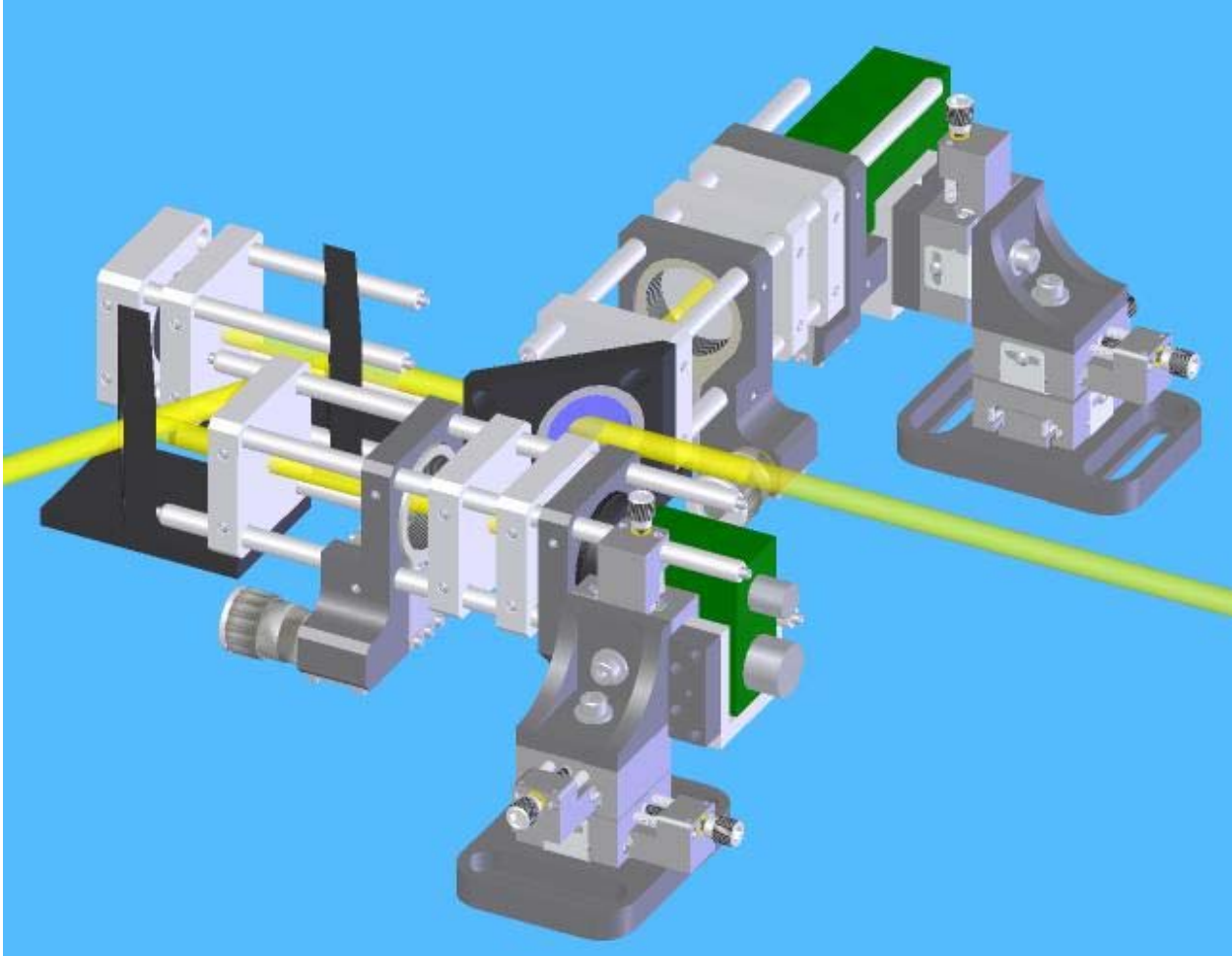


Figure 15. CAD drawing of the 2-channel fast optical pyrometer.

The image-intensified Hamamatsu streak camera is now undergoing bench test. It will be capable of imaging the target with ps time resolution. In conjunction with the spectrometer it will provide detailed spectral information on the light emission from the target. It may also provide an alternative target temperature diagnostic, in addition to the fast optical pyrometer.

Initially the target will be a thin 5- or 10-mm diameter self-supporting metallic foil, for example gold or aluminum, mounted on a rigid support ring, or a thin film deposited on a glass or sapphire substrate. These target materials are commercially available. The thickness of the target will be comparable to the range of the ion beam in the material, which varies from 100-300 nm at solid density for the NDCX-1 beam (300-350 keV K^+). Targets for later experiments could be any of a number of materials of interest, such as porous material or a thin layer of halogen atoms deposited on the substrate. The target can be designed to completely stop the beam allowing target diagnostics at the rear of the target without interference from the beam. Alternatively a thinner target would allow the beam to exit through a hole in the substrate to be measured downstream with beam diagnostics as described above.

3.7. ALIGNMENT CAPABILITIES

The target chamber and the light collection system are mounted on a kinematic 6-strut system (see figure 16). Fiducial posts welded on the outside of the target chamber allow us to align the chamber with the help of a laser tracker.

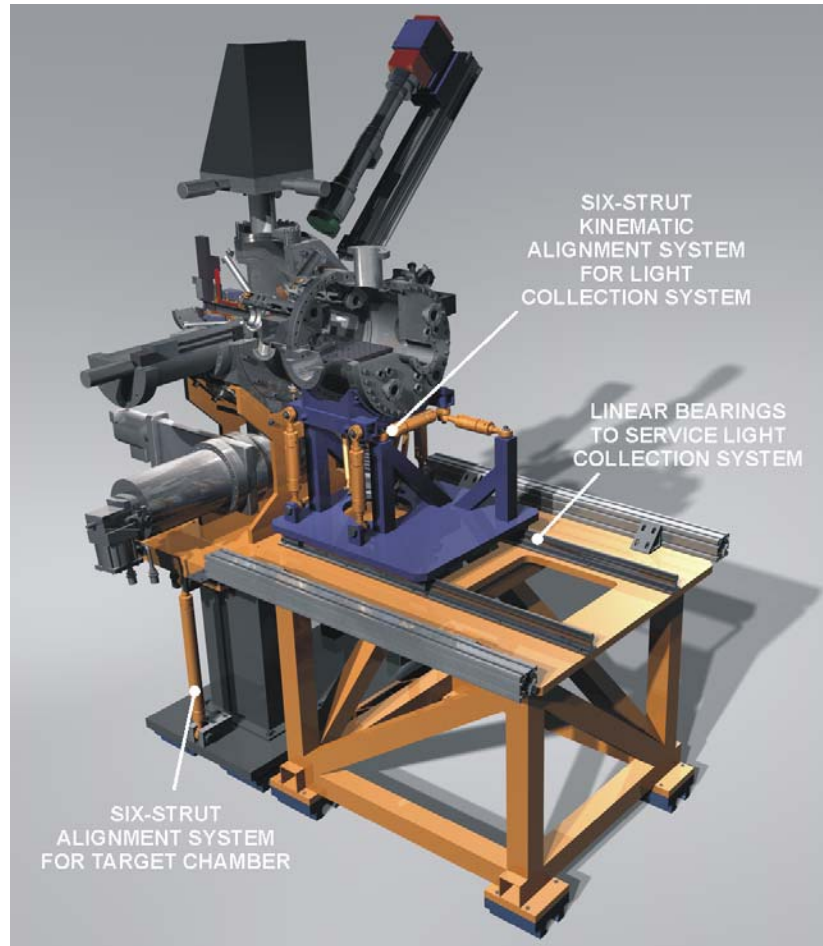


Figure 16: Support system of the target chamber facility. The light collection system has an independent six-strut support system in order to be able to roll it away from the target chamber vacuum vessel for servicing. The whole target chamber assembly is mounted on linear ball bearings which allow it to be rolled in and out of the NDCX-I experiment.

All optical diagnostic devices are mounted on optical rails and x-y-z translation stages in order to be able to align them to the target position. The light collection system on the back of the target is mounted on an optical breadboard with a kinematic support. That way we can remove the light collection system from the target chamber for servicing and pre-alignment without losing the alignment to the target center position. The support for the light collection system is mounted on a larger hexapod which is adjustable from the outside of the vacuum chamber (see section 3.6).

The target itself is aligned in situ using its own miniature hexapod (See section 3.5).

4. COMMISSIONING ON NDCX-I

Figure 17 shows the installation of the target chamber on NDCX-I. The target chamber facility is mounted on linear rails to be able to move it in and out of the beamline for servicing and experimental re-arrangements. In support of the target chamber facility we are installing a separate laser room facility in the floor below the target chamber. The laser room can be used for optical target diagnostics pre-alignment and tests. The whole setup including the laser room will be a core capability for any future WDM user facility in the HIFS-VNL.

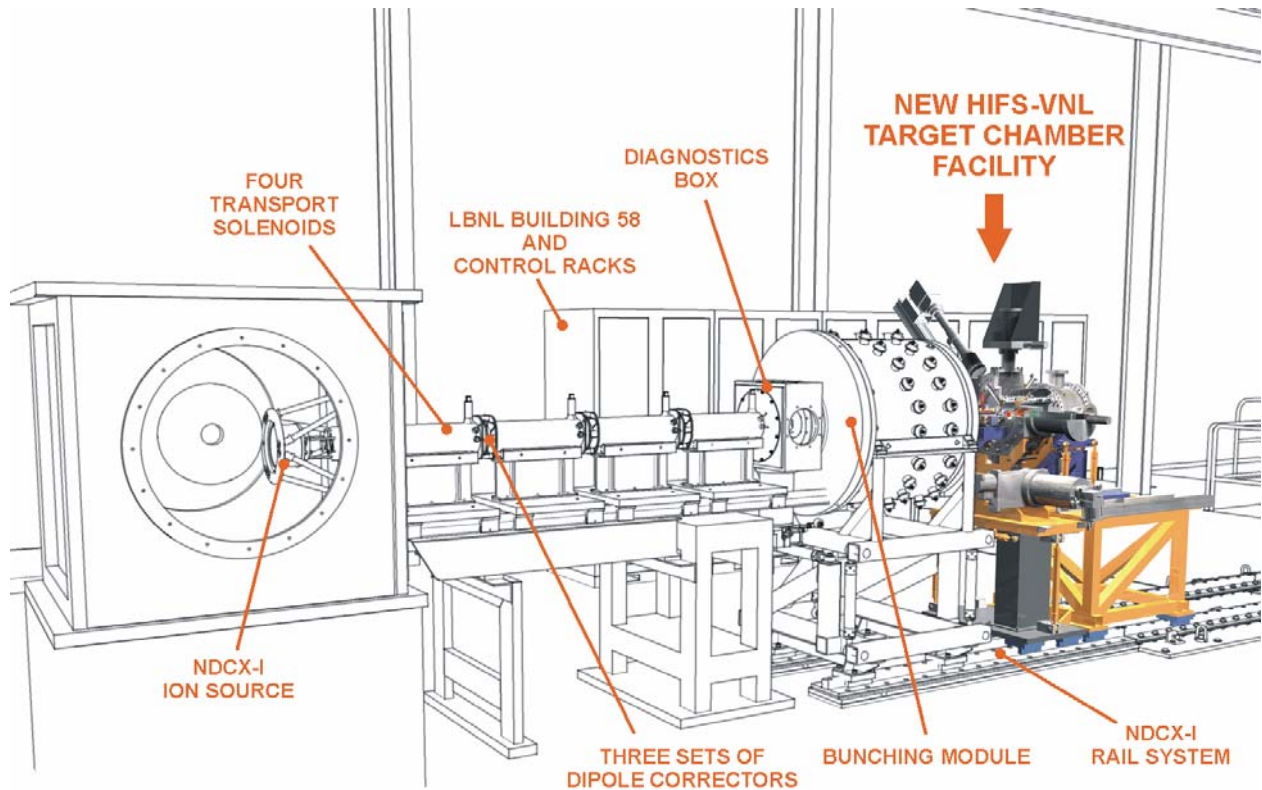


Figure 17: View of the new HIFS-VNL target chamber facility installed on NDCX-I.

5. SUMMARY AND POSSIBLE FUTURE IMPROVEMENTS

We have described the main components of a novel target chamber facility for the Heavy Ion Fusion Science Virtual National Laboratory. The target facility will be commissioned in winter 2007, and afterwards will be available for target experiments on NDCX-I. The same target chamber facility can also be used on future experiments, e.g. NDCX-II, which could provide significantly more beam power.

Several improvements to the target chamber design are conceivable. We will focus on the following three upgrades as soon as possible:

1. Especially for a user facility a robotic target handling system will be required in order to be able to use up to 50 targets without interrupting the experimental program. Such an upgrade will require a vacuum load lock system and a custom designed, vacuum-rated robotic target handling system.
2. Experimental feedback will allow us to refine the design of the optical target diagnostics setup. We plan to move most optical components into the vacuum vessel as close to the target as possible, which will eventually require a new and larger target chamber vacuum vessel.
3. The optical target diagnostics components are currently mounted on manually adjustable x-y-z translation stages. We plan to move most alignment stages into vacuum as close to the target as possible. This will require multiple, vacuum-rated, motorized translation stages.

We will start implementing these improvements once we have gained sufficient experimental experience with the current setup. As future plans for target experiments will evolve we will improve and continually update the target chamber facility to advance the challenging experiments with ion-beam driven, isochorically heated warm dense matter.

7. APPENDIX

- CAD rendering of the target area for presentations
- CAD rendering of the target chamber facility for presentations
- Assembly Drawing Target Chamber
- Assembly Drawing Light Collection System

