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FROM ONE-OF-A-KIND TO 500,000 HIGH QUALITY IGNITION TARGETS PER DAY

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Abstract. The increasing fidelity of 3D radiation hydrodynamic computer codes has made it possible to design targets for inertial confinement fusion (ICF) which can compensate for limitations in the existing single shot laser and Z pinch ICF drivers. Developments in ICF target fabrication technology allow more esoteric target designs to be fabricated. These present day requirements require new deterministic nano-material fabrication on micro scale, developing techniques which are synergistic with Inertial Fusion Energy (IFE) target needs. Today's ignition facilities have cryogenic shot rates, which average less than one cryogenic implosion shot per day. To progress to IFE's requirements of ~ 500,000 cryogenic ignition implosions per day for many 100's MW electrical power output requires large changes in target production and alignment techniques, which are being made credible by demonstration in the U.S. ICF institutions.

1. Introduction

Over the last decade the U.S. has made major investments in laser and Z pinch drivers for Inertial Confinement Fusion. Three major facilities, NIF, OMEGA-EP and ZR are being built or refurbished this decade, with ignition as one of the major strategic objectives of the inertial confinement fusion (ICF) program. The goal of achieving ignition by inertial confinement is pursued by the x-ray (indirect)-drive and direct-drive ignition programs in the U.S.[1]. Ignition in the laboratory has very demanding conditions of the facility in heating and compressing the deuterium-tritium (DT) filled targets, because radial convergences of order >30 in radius, i.e. $\gtrsim 30^3$ in volume, are required to achieve ignition with laboratory scale drivers. These high convergences imply a drive symmetry <1/30 which cannot be achieved for x-ray drive in cylindrical hohlraums without engineering the hohlraum to help with symmetrizing the drive [2] or engineering the capsule to minimize the effect of hydrodynamic instabilities [3]. The advent of accurate multi-dimensional codes and increasing sophistication in making and characterizing targets allows innovations in target fabrication to compensate for drive limitations in qualities such as symmetry, drive energy and pulse shape. Moreover other limitations in the facility, such as complications in cryogenic target manipulator can be compensated for by advanced target manufacture. Advances in target fabrication are being achieved to reduce the risk associated with achieving ignition and to compensate for cost and schedule issues or lack of flexibility of the drivers.

These advances in nano-scale fabrication are synergistic with the requirements for IFE targets. However there is a large difference in the shot rate requirement. Ignition on the NIF will be achieved with one of-a-kind targets, with high target costs, and shot rates measured in units of ignition shots per week at best. To go from one of a kind ICF targets to power plant target shooting at 5 times/second, is an extrapolation of about 5 orders of magnitude in target production rate or target costs as well as requiring target injection. We are working on demonstrating a credible pathway to a reliable, consistent, and economical target supply, a major part of establishing that IFE is a viable energy source regardless of the driver technology, x-ray or direct drive and laser or Z pinch.

2. Innovation in Target Fabrication Compensate for ICF Driver Limitations

To achieve ignition in the laboratory with hot spot ignition, a radial convergence of 30 to 40 is required which is limited by hydrodynamic instabilities and asymmetric drive. Hydrodynamic instabilities cause growth of the initial target roughness and non-uniformity of target and drive [3]. Asymmetric drive results from several sources and can be approximated as resulting from implicit asymmetry resulting from the irradiation geometry in hohlraums drive [2] and random asymmetries resulting from real world lasers or targets not being perfectly balanced or round. As a combined result the best convergence that has been achieved to date in ignition scaled implosions on OMEGA is ~20 [1].

Features in the targets can compensate for limitations of the facilities. A well known requirement in target fabrication [2] is to reduce the initial imperfections, simplistically characterized by an initial perturbation of amplitude a_0 so that after growth by a factor G by the hydrodynamic instabilities the size of the perturbation G a_0 is a small fraction of the radius of the compressed fuel, resulting in acceptably low mixing of cold material into an igniting hot spot. Preparing for x- ray drive on the NIF illustrates three aspects of facility limitations being compensated for by features of the targets or the cryogenic target handling system, namely low l mode drive asymmetry, the need for a warm transport target with a fill tube and graded Cu doped Be targets.

In the early nineties the ignition designs for x-ray drive used vacuum hohlraums. Advances in computational capability and experiments on Nova led to an understanding that the during the several nano-second laser pulse, there was sufficient motion of the x-ray emitting spot that low l mode drive asymmetry could not be controlled sufficiently [2]. As a result target fabrication advances in the strength of thin polyimide windows [4] allowed gas filled hohlraums to be used where the gas fill inhibits motion of the x-ray emitting spot sufficiently to overcome limitations in the number of rings of laser beams.

For x-ray drive ICF a low Z ablator surrounds the cryogenic fuel. Currently ablator materials being considered are doped plastics such as Ge-doped CH, or doped beryllium such as Cu-doped Be where the dopants limit the penetration of the harder part of the x-ray drive spectrum. It has been known for some time [5] that capsules with beryllium ablators offer improved target performance because of Be's low opacity, and high initial density. However Be has several problems as an ablator namely: (i) it cannot be diffusion filled, (ii) its optical opacity precludes optical characterization of the cryogenic DT ice (iii) the beta layering which drives the smoothing of the cryogenic ice, cannot be augmented by infra-red heating [5]. For this reason the point design for the NIF ignition targets has, until very recently been doped plastic which can be diffusion filled, optically characterized and have augmented beta layering, although smoother surface finishes are required. A remarkable achievement of the US target fabrication community [1,8] is the achievement of adequately smooth surface finishes in plastic, as shown in Fig. 1 and Section 3.

Plastic targets have a sufficiently high porosity that they can be diffusion filled at temperature with deuterium (D) or tritium (T). A fill, cool, layer, transport, insert, align and shoot sequence is possible as shown in Fig. 2, is followed on OMEGA at LLE [6]. Such a capability was needed for the OMEGA program in direct drive and was of great value in developing critical community experience for the more difficult and expensive NIF cryogenic target handling system (NCTS). As illustrated in Fig. 2, there are nine operations for "cold transport". (1) A fragile target shell is filled at room temperature to about 1100 atm of DT gas. (2) The target is cooled to cryogenic temperatures (about 20°C above absolute 0 or –253°C) to the freezing point of DT ice. (3) The target is transported to the NIF or OMEGA. (4) A small amount of infrared (IR) heating is then applied to the target to form a uniform DT ice layer with a very smooth inside ice surface. (5) The target must be characterized

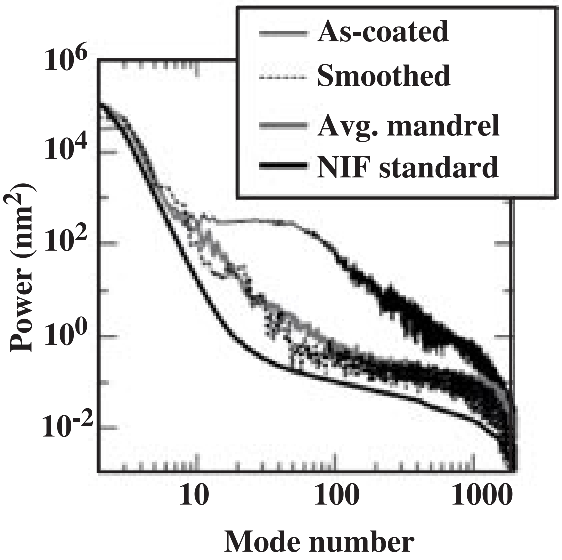


Fig. 1. The surface finish power spectrum of plastic mandrels compared to NIF specification.

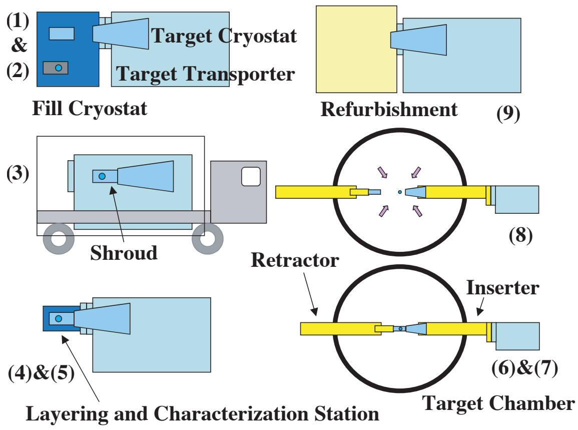


Fig. 2. The separate operations of a cold transport cryogenic target handling system such as on OMEGA. A warm transport system could eliminate at least three sub-systems.

continuously to verify that the ice is formed with a smooth enough surface. (6) The target is transported to the target chamber while keeping the target cryogenic with the IR heating applied to the ice to keep it smooth. (7) The target, contained in a thermal shroud, is inserted into the target chamber, and aligned. (8) Just before the laser shot, the target is exposed by rapidly retracting the shroud (1/10 second) without disturbing the target alignment. This complex set of operations has a high cost.

In the early stages of the NIF facility it is now proposed to use a warm transport system delaying the need for three of the subsystems of Fig. 2. In one incarnation, a warm transport target has a small (~6 μm) fill tube as shown schematically in Fig. 3. The capsule is mounted centrally in a hohlraum and placed, warm at the centre of the target chamber. It is filled *in situ* by cryo-condensation, layered and then shot. Several subsystems of Fig. 2 are not required for warm transport, at a large cost saving but at the expense of designing and fabricating a target which can withstand the hydrodynamic and cryogenic perturbation of a fill tube. Another incarnation of a warm transport system is a Be shell strong enough to withstand the bursting pressure of the DT fill at non-cryogenic temperatures [9].

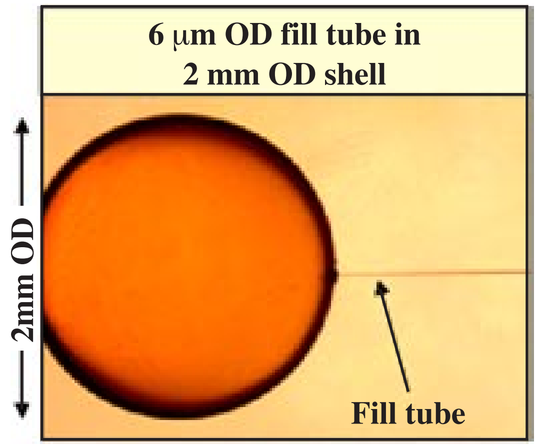


Fig. 3. A 2 mm NIF scale ignition target with a 6 μm fill tube.

This concept has been made possible by the new target design in Fig. 4 [5], which has a graded layer of Cu doping in the Be ablator to reduce the hydrodynamic growth rate sufficiently low to with stand the initial perturbation of the fill tube. At this stage a few Be shells with a graded dopant have been made but research on surface finish and characterization of the dopant levels is ongoing. Fabrication of the fill tube and its joint to the shell to precision specifications is also challenging, but monolithic nano-technology techniques look promising.

All aspects of the progression of concepts here are driven by target fabrication capability. As of this time most of the concepts have been shown to be credible but much of the development work remains to be performed. Other examples are polar direct drive, shims to control symmetry in x-ray drive and double shell targets to reduce pulse shaping and cryogenic requirements.

3. Synergy with Target Fabrication Technology Development Between ICF & IFE

The starting point for the fabrication of plastic and one type of beryllium x-ray drive capsule is a spherical mandrel onto which the ablator is coated. The sphericity of this mandrel largely determines the sphericity of the final capsule, especially at low to intermediate modes [8]. A major advance in target fabrication has been the development of micro-encapsulation techniques fro ICF (Section 2) to produce a large number of high quality mandrels in batch mode. In addition the development of the decomposable mandrel route, in which the initially formed shells are over-coated with a thermally more stable layer and the mandrel is then de-polymerized, has markedly increased our flexibility. We can overcoat these thermally stable mandrels with plasma polymer, vapor deposited polyimide, or sputtered Be with unparalleled wall thickness and composition control. For plasma polymer and Be a dopant of Ge or Cu, respectively, can be added with excellent control, providing either uniform or radially banded dopant regions. An alternative technique for fabrication of Be shells is to micro-machine hemi-shells from bulk Cu-doped [9] Be material and diffusion bond them together. Substantial progress has been made in metallurgical techniques for refinement of grain size of the bulk metal since it is suspected that these inhomogeneities may seed hydrodynamic instabilities. Plastic and polyimide shells can be diffusion filled (operation 1 of Fig. 2) with DT. A cryogenic layer of DT ice can be formed on the inner surface, which can be optically characterized. However Be shells present filling and characterization challenges because of their impermeability and high opacity respectively. Current schemes for filling both coated and micro-machined shells involve “drill and plug” scenarios using lasers for drilling and weld sealing of the hole after filling. Bonding of hemi-shells under DT pressure also continues to be pursued. X-ray phase contrast microscopy has shown great promise in providing DT ice layer information in Be shells.

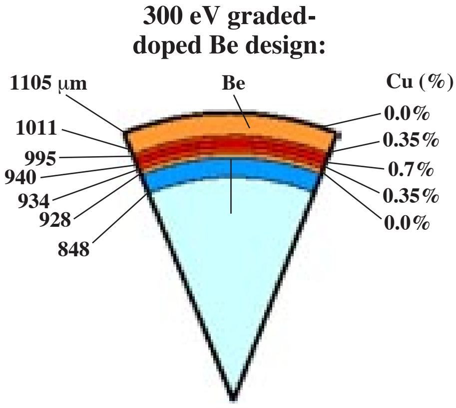


Fig. 4. Laser fusion baseline high-gain target and expected target specifications.

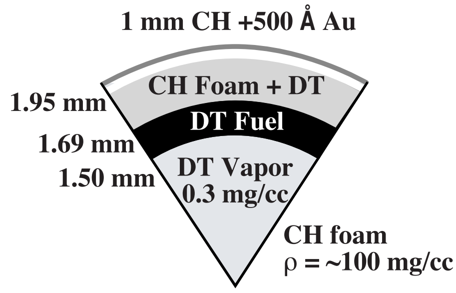
For direct drive the ablator is the cryogenic fuel with the thin plastic non-cryogenic part of the capsule providing a skeleton to form the fuel. The high aspect ratio plastic shells needed for the all DT direct drive design can now be made to the ignition specifications (1,10). Alternate designs use a cryogenically-wetted low Z foam. Low Z foams have now been made for ignition scaled cryogenic and non-cryogenic experiments on OMEGA at the Laboratory for Laser Energetics (LLE) [10]. A full density gas tight permeation seal has been successfully deposited for retention of the fill gas at room temperature or the ice at cryogenic temperatures. Room temperature gas filled foam shells as well as cryogenic foam shells have been shot with good results on OMEGA.

All of the above activities and more are developing the techniques for target fabrication for IFE. However the processes are in batch mode, often by hand. For a production line, feeding a laser or Z pinch driver at shots/second, the boutique techniques of Section 3 must be redesigned to work in a production line mode.

4. Requirement of 500,000 Targets a Day for an IFE Power Plant

The shot rate of the existing ICF facilities described in Section 2 is measured in shots per day. For example the design specification for the NCTS is one shot/every eight hours. In contrast the many hundreds of MW(e) output required for an economic inertial fusion power facility, requires a target shot rate of many per second. The “Target Fabrication Facility” of an IFE power plant must then supply more than 500,000 targets per day, including manufacturing the spherical target capsule and other materials, filling the capsules with the DT fusion fuel, redistributing the frozen DT uniformly around the inside of the capsule (layering), and possibly assembling the capsule in a hohlraum (for indirect drive) or with transmission lines for Z pinch fusion energy. The feasibility of developing successful fabrication and injection methodologies at the low cost required for energy production (about $0.25/target for direct laser drive) is a critical issue for inertial fusion [11,12]. This change of order a million in the capability or cost of the targets from the current situation is very high in the list of difficult technology advances required for economic IFE. Demonstrating a credible pathway to a reliable, consistent, and economical target supply is a major part of establishing that Inertial Fusion Energy (IFE) is a viable energy source, for laser-driven, heavy-ion driven or Z pinch driven concepts. IFE target fabrication research has concentrated on investigating and developing the various materials needed by the target designs and on fabrication techniques that could eventually scale to low cost and high production rate.

A major strategic objective of the on-going ICF program in the U.S. is demonstrating ignition using existing facilities with x-ray drive and then direct drive. The basic target design for an IFE high gain direct drive target is shown in Fig. 5. Regardless of drive a demonstration of ignition will unequivocally establish the credibility of the physics and the computer codes involved in ICF. Features include hot spot ignition and burn, adiabat shaping and drive uniformity. In parallel there is a program in the U.S. to address the feasibility of economic power generation developing the technology required for IFE such as repetitively pulsed-lasers, final-optics, chambers, targets and target injection. Progress on the targets and injectors is described below albeit only for laser direct drive because of space restrictions.



“Basic” NRL Target

Some Expected Direct Drive Specifications

Capsule Material	CH (DVB) foam
Capsule Diameter	~4 mm
Capsule Wall Thickness	290 μm
Foam shell density	20-120 mg/cc
Out of Round	<1% of radius
Non-Concentricity	<1% of wall thickness
Shell Surface Finish	~20 nm RMS
Ice Surface Finish	<1 μm RMS
Temperature at shot	~15 - 18.5K
Positioning in chamber	– 5 mm
Alignment with beams	<20 μm

Fig. 5. Baseline NRL high gain direct drive target.

The basic direct drive high gain target uses a divinylbenzene foam shell [13] to contain the cryogenic DT fuel. Density matched micro-encapsulation has been used in the laboratory to produce these shells. This fabrication step is relatively well-understood and demonstrated for ICF, although work remains to scale the process to larger batches and to increase product yields for IFE capsules [14]. The principal technical issues are meeting non-concentricity and out-of-round requirements when fabricating the CH capsules at large diameter and with thick walls. Filling of polymer capsules with hydrogen isotopes by permeation through the wall, removal of the excess DT after cooling to cryogenic temperatures (to reduce the capsule internal pressure and prevent rupture), and transport under cryogenic conditions has been demonstrated in the laboratory.

Layering [6], is the process of redistributing the cryogenic DT fuel into a smooth uniform layer inside the ablator. Layering requires establishing an extremely precise (~250 μK), uniformly spherical temperature distribution at the surface of the capsule. A cryogenic fluidized bed experiment has been designed to demonstrate this process with hydrogen isotopes in a batch-mode. This concept is for the fluidized bed to rapidly randomize the targets yielding a very uniform time-averaged surface temperature. Layering in a fluidized bed is followed by a very rapid (a few seconds or less) removal of the layered capsule from the bed, and assembly into a sabot for injection. The sabot protects the cryogenic target during injection, and springs apart and is deflected from the capsule trajectory prior to its entering the target chamber. The target in the back half of the sabot is supported by a thin membrane which distributes the load and prevents point-contact loading of the fragile capsule during the ~1000 g acceleration.

A potential option for the laser fusion target that helps protect it from thermal radiation during its injection is a “foam-insulated” target which uses a relatively thin layer of foam to reduce the heat load to the cryogenic DT [15]. The degree of heating of the target during injection is determined by the radiation heating from the chamber first wall and by heating from the gas in the chamber.

The cost of the target is also a key issue in the IFE target supply. Laser fusion targets have been the subject of the most extensive and well-documented analyses for future target manufacture of all the IFE concepts considered. We have prepared preliminary equipment layouts, [16] and determined floor space and facility requirements for nth-of-a-kind production of high-gain laser-driven IFE targets. The results for a 1000 MW(e) baseline plant indicate that the installed capital cost is about $100M and the annual operating costs will be about $19M (labor $9M; materials/utilities $4M; maintenance $6M), for a cost per target of slightly less than $0.17 each.

To arrive at this cost, a number of process assumptions have been made, based on 1) preliminary requirements for the NRL high gain direct drive targets, 2) discussions with researchers in each of the enumerated process steps to reflect their latest findings, and 3) interactions with vendors of process equipment that is adaptable to this service – such as critical point driers. The plant conceptual design includes a process flow diagram, mass and energy balances, equipment sizing and sketches, storage tanks, and facility views (plan, elevation, and perspective). The cost estimating process uses established cost-estimating methods and factors for the chemical process industry. Recycle and beneficial reuse of process effluents is designed into the facility. A detailed material and energy balance was prepared to provide information on flow rates and quantities of raw materials, finished products, and byproducts for the entire plant. All of the cost calculations for chemical, utilities, and waste disposal use mass quantities calculated in the material and energy balances.

The feasibility of fabricating specific foam capsules needed for high gain IFE targets has been shown. Further work is underway to improve capsule quality, reproducibility and large-scale production. The work with DT over foam has shown that the system can be cooled down well below the DT triple point, so the target can withstand the acceleration during injection, and has more margin for heating during its transit across a high temperature chamber.

Proof-of-principle layering experiments have been performed with multiple targets in a fluidized bed using a surrogate fuel material at room temperature to simulate DT ice. These experiments provide a demonstration that fluidized bed technology could be used to form DT ice layers in production mode.

Existing ICF facilities have the luxury of a solid support to position the targets to the required accuracy of ~1% of the initial capsule radius, set by the ~40 fold convergence of the target. Introducing a target so rapidly on a solid support would be very difficult and so the system approach adopted for laser driven IFE is to accelerate the fragile cryogenic target outside of the chamber in a protective sabot fast enough (~400 m/s) that it enters the chamber (without the sabot) cleared of the debris from the previous shot. Background gas in the target chamber makes shooting the capsule accurately enough for passive laser beam focus is more difficult than the concept presently adopted of shooting the target close (~5 mm) to the center of the chamber, tracking its exact trajectory and steering and timing the implosion laser beams onto the target once its anticipated position is tracked to within about 20 μm within the 5 mm focusing box.

At General Atomics a new and versatile facility for studying target injection has been constructed as shown in Fig. 6. [16] The accelerator is a full scale simulator of an IFE reactor target chamber and its target injector, with the goal of eventual repetitive cryogenic injection of targets into a chamber held at reactor chamber temperatures. The phase I version is limited to single shot, room-temperature target injection using a gas gun initially, to be replaced with an electric accelerator. The facility has been operational for 1 year, successfully demonstrating sabot separation needed for handling of direct drive targets. We must predict target position to within ±14 mm at a distance at least 16 m from the gun barrel and 9 m from the nearest detector used for the prediction [16] as neutron shielding requires that the detectors must stand back from the target injection path more than about 0.5 m. Future work will convert the system for use with cryogenic targets injected into a high-temperature chamber at 5–10 Hz. Elements of the facility include mass production (in batch mode) of cryogenic targets, injection into the chamber (under simulated background gas and wall temperature conditions), and steering of a low-energy pulsed laser onto the target in flight.

5. Conclusions

One of the most critical aspects of Inertial Fusion Energy remains the credibility of the capability to make at cost a million precise targets per day and place them with precision at the center of a reactor target chamber. Target fabrication technologies for today's single shot ICF facilities are demonstrating that target features compensate for limitations in ICF driver's capabilities such as energy, symmetry or pulse shaping. Some of these same target fabrication technologies are being extended to mass production demonstrations for IFE requirements. A full scale pellet injector is now in operation to demonstrate target tracking capability to establish credibility of placing a targets in an IFE reactor chamber. Although much work remains to be done, our initial results are promising and suggest that a credible pathway to a reliable, consistent and economical target supply is within reach.

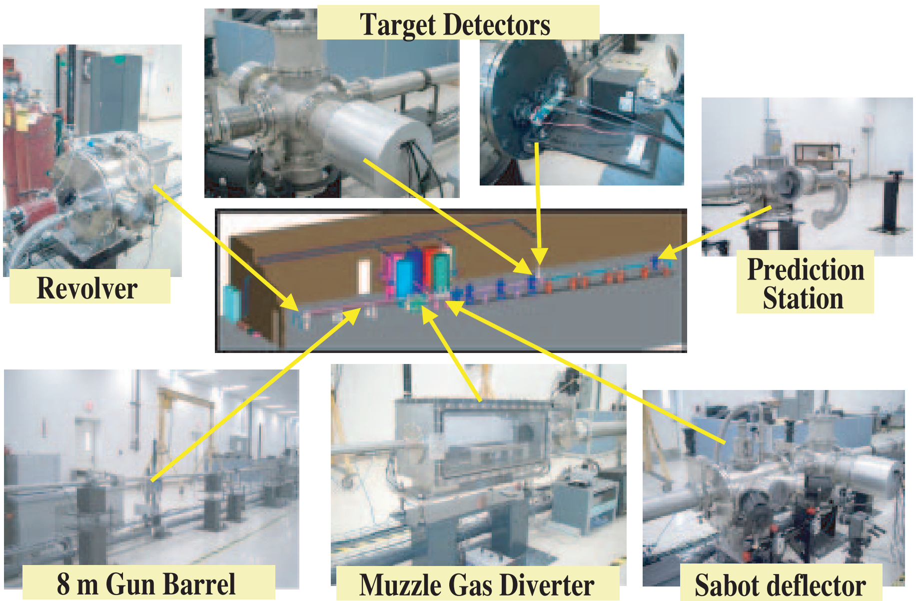


Fig. 6. Components of experimental system to develop and demonstrate target injection and tracking methodologies.

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