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PROGRESS TOWARD HEAVY ION IFE*

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Abstract: Successful development of Heavy Ion Fusion (HIF) will require scientific and technology advances in areas of targets, drivers and chambers. Design work on heavy ion targets indicates that high gain (60–130) may be possible with a ~3–6 MJ driver depending on the ability to focus the beams to small spot sizes. Significant improvements have been made on key components of heavy ion drivers, including sources, injectors, insulators and ferromagnetic materials for long-pulse induction accelerator cells, solid-state pulsers, and superconducting quadrupole magnets. The leading chamber concept for HIF is the thick-liquid-wall HYLIFE-II design, which uses an array of flibe jets to protect chamber structures from x-ray, debris, and neutron damage. Significant progress has been made in demonstrating the ability to create and control the types of flow needed to form the protective liquid blanket. Progress has also been made on neutron shielding for the final focus magnet arrays with predicted lifetimes now exceeding the life of the power plant. Safety analyses have been completed for the HYLIFE-II design using state-of-the-art codes. Work also continues on target fabrication and injection for HIF. A target injector experiment capable of >5 Hz operation has been designed and construction will start in 2002. Methods for mass production of hohlraum targets are being evaluated with small-scale experiments and analyses. Progress in these areas will be reviewed.

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1. Introduction

Significant progress has been made on the major program elements supporting the development of heavy ion fusion (HIF), including target design, accelerator physics and technology, chamber development, target fabrication and injection, and integrated power plant designs. Over the past four years, several target design options have been developed, and calculations indicate they will produce target gains adequate for Inertial Fusion Energy (IFE). Work on accelerators for HIF has focused on developing the ability to produce and deliver high brightness beams to the target and reducing the driver cost to make IFE more cost effective. Chamber development work has continued on the HYLIFE-II thick-liquid-wall concept, which has the benefit of long lifetime structures using convention steels for the first wall and vacuum vessel. Target fabrication specialist have worked closely with target designers and have produced many of the specialized materials (e.g., high-z doped foams) required by the designs, and techniques for mass production have been demonstrated in bench-top scale experiments. A target injector experiment is currently under construction that will be capable of 6 Hz operation. Good progress has also been made on integrated system issues such as protection of the final focus magnets from radiation damage and overall power plant environmental, safety and economic assessments. Progress in these areas is summarized in the following sections.

2. Target Designs for HIF

A variety of target designs have been analyzed for HIF since 1998. A promising design is the distributed radiator target [1-3]. This target requires illumination by a large number of beams from two sides. The beams are focused to elliptical spots, which are then overlaid in an annular ring on the ends of the target and deposit their energy in radiator material that fills most of the cylindrical hohlraum, hence the term distributed radiator. The radiator material and the hohlraum wall are kept approximately static by pressure balancing a variety of high and low-Z foams. Progress in developing such foams is described under the Target Fabrication section of this paper. The beam spot on the end of the target has an elliptical cross section with a semi-minor axis of 1.8mm and a semi-major axis of 4.2 mm. A key issue for HIF is achieving spots this small from a final focus magnet standoff on the order of 6 m. In detailed 2D Lasnex simulations, the distributed radiator target produces a yield of 390 MJ with an input energy of 5.9 MJ for a gain of about 65. The accelerator efficiency can be as high a 45%, so even with a gain of 65, the recirculating power for the driver is very reasonable at <10%.

Another HIF target design was developed in an effort to reduce the required driver energy and cost and is referred to as the close-coupled distributed radiator [4-5]. The basic design concept is the same as the distributed radiator target, except the relative size of the hohlraum is smaller for a given size fuel capsule; that is the hohlraum to capsule radius ratio is smaller. In one example for which detailed Lasnex simulations were completed, the hohlraum dimensions were reduced to 0.736 of the original design. The result was that the same fusion yield was obtained with 3.3 MJ compared to 5.9 MJ. Cost scaling for the driver indicates that this would reduce the driver cost on the order of 25%, which is quite significant since the driver is the major cost item for the HIF power plant. The close-coupled target design requires very small spot sizes, with elliptical spot size of 2.8 mm × 1.0 mm. This is clearly an advanced approach to HIF that will only be realized with success in controlling beam quality in the accelerator and during propagation through the chamber.

A third HI target design was developed to allow larger spot sizes as a back up to the distributed radiator design. In the Hybrid target design, beams on the order of 5 mm radius are acceptable. The hohlraum radiation symmetry is not as good as the distributed radiator design, and internal shields are needed to get adequate symmetry.

The target design group is continuing work on variations of these designs. They are also working with the target fabrication experts and chamber designers to account for practical consideration of the types of materials that can be used and the effects of target material on the chemistry of the liquid wall chamber.

3.0 Heavy Ion Accelerators

The requirements for heavy ion accelerators will be set by target designs including results from future ignition experiments on NIF. As indicated in the section above, much potential exists for innovation through improved target designs, and it is clear that achieving small focal spots is very important. The HIF Virtual National Laboratory (VNL) carries out the US HIF program, which is based on induction linear accelerator (linac) technology. Principal participants are Lawrence Berkeley Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), and Princeton Plasma Physics Laboratory (PPPL). Several other institutions, including Sandia National Laboratory (SNL), Mission Research Corporation, U. of Maryland, and U. of Missouri also play key roles in the HIF VNL. The focus of the US program is on beam science that could reduce the focal spot size, which as indicated above, could lead to large reduction in the required energy and cost of a driver for IFE. International ion storage-ring accelerators providing useful data on handling high average power ion beams and GeV heavy-ion plasma interactions complement the U.S. program. Future U.S. steps in HIF driver development will need more integrated beam physics experiments and also more investment in technology to reduce costs (induction modules, transport magnets) in order to provide the basis for an Integrated Research Experiment (IRE). The IRE will be a multiple beam induction linac with prototypical driver technology and will be capable of testing driver-relevant beam focusing in a chamber and ion-target interactions. The IRE, together with the National Ignition Facility (NIF) and other IFE development, would provide the basis for a high average fusion power Engineering Test Facility (ETF) to follow the NIF.

The HIF VNL is organized around key scientific issues in the following areas:

1) Source and Injection - What physics determines beam brightness in heavy-ion sources and low energy transport?

2) High Current Transport and Acceleration - What dynamical phenomena affect the quality of space-charge-dominated beams undergoing transport and acceleration?

3) Final Focus and Chamber Transport - What role do non-linear processes and beam-plasma interaction play in beam chamber propagation and focusing onto a target?

The Modeling and Computations group within the VNL plays a critical role in determining how to best apply and improve computational tools to provide the needed support for experiments, exploration of issues, and planning for the future.

3.1 Sources and Injection

This area of R&D includes experiments, theory, and simulation for the development and improvements to injectors needed in the transport and focusing experiments, and for future experiments such as the Integrated Beam Experiment (IBX) and IRE. A 500 kV Source Test Stand (STS-500) was recently commissioned at LLNL (Fig. 1). This facility will enable research not only on ion sources and injectors, but also contribute to understanding multiple beam physics, long-pulse beam-gas interaction, and voltage gradient limits. We anticipate that experiments with high current density sources and injection will lead to brighter, more durable, and more compact injectors for future HIF experiments. A major research focus will be a better understanding of issues that dictate the choice of large-area sources versus compact merged-beam sources wherein a large beam is formed by merging many small beamlets.

The experiments on multiple beam physics and long-pulse (10-20 μsec) beam-gas interaction are important to the design of future multiple beam induction linacs such as the IRE and drivers, since beam-beam repulsion within acceleration gaps must be accounted for in beam centering within each transport channel. The advanced high-gradient tests will potentially reduce IRE and driver accelerator length, and therefore cost, by a factor of 2 to 3.

High voltage gradient insulators and vacuum gaps will be investigated in the first tests of the STS-500. Initial testing is to confirm voltage-holding capacity of periodic metallic-dielectric insulating structures developed by LLNL and Honeywell. Vacuum gap breakdown will be studied with various surface cleaning and processing techniques. A follow-on set of experiments will determine insulator performance in the presence of an ion beam. Initial plasma source experiments are to be conducted on the STS-100 (an existing test stand within the Source Test Laboratory at LLNL with 100 keV capability).

3.2 High-Current Transport and Acceleration

Over the next two years, the HIF VNL plans a series of separate experiments in the areas of high current beam transport. The High Current Experiment (HCX) will use an existing injector and transport the beam (1.8 MeV, 0.6A) through a series of electric and magnetic quadrupoles to address a variety of issues, but primarily:

1. Alignment, beam sensing and steering.
2. Radial extent of a beam halo resulting from, e.g., envelope mismatch and beam distribution nonlinearities.
3. Gas generated by lost ions impinging on the transport lattice aperture and the influence of secondary electrons on beam dynamics.

The VNL plans to add two induction modules to HCX to study longitudinal control of the ends of the ion beam bunches and acceleration issues. In FY03, an induction module will be installed on HCX, which will apply correction waveforms to the head and tail of the beam to correct for space-charge effects and regulate the flat top of the beam energy with a solid-state amplifier architecture designed by First Point Scientific. A prototype induction module will be installed on HCX in FY04 to be used in later experiments to apply various acceleration waveforms to the beam to study acceleration issues and velocity tilt, and possible effects of the acceleration gap on electron physics. There are also continuing studies into the characterization of ferromagnetic materials produced using novel insulation techniques that allow for annealing of the core after being wound.

In a heavy-ion fusion driver, arrays of superconducting quadrupoles will transport parallel beams through a sequence of induction acceleration cells. The beam transport system is expected to be one of the most expensive and critical parts of the driver. Cost reduction is a primary design goal for the quadrupole array, together with high field gradient and tight transverse packing (to minimize the size and cost of the induction cores). These special features lead to different optimization strategies for the quadrupole array with respect to conventional designs for high energy and nuclear physics. In particular, configurations based on flat racetrack windings have received considerable interest, since they simplify fabrication and have good packing properties.

Superconducting magnet development for heavy-ion fusion is carried out by the VNL in collaboration with MIT Plasma Science and Fusion Center and Advanced Magnet Lab (AML). Although pulsed magnets are a viable alternative for near-term experiments, superconducting technology is the most attractive in view the ultimate driver application. Two designs for single aperture quadrupoles with parameters suitable for HCX have been developed by LLNL and AML, and prototypes of each type have been tested at LBNL and MIT [6,7]. All prototypes met the minimum specification for use in HCX. The LLNL design was recently selected for further optimization, having demonstrated higher field gradient and better training performance. It is based on two layers of double-pancake coils, prestressed against stainless steel holders by iron inserts with keystoned wedges (Fig. 2). Development of a prototype cryostat with two quadrupoles is also underway. Challenging packing results from short lattice period (45 cm) and the need of gaps between cryostat tanks to allow axial space for induction acceleration, diagnostics and pumping ports. The prototype cryostat will be installed in HCX in FY03.

3.3 Final Focus/ Chamber Transport

This area of R&D includes experiments and supporting theory/simulations on longitudinal drift compression, final focus and ion optics for ballistic and pinched beams, and heavy-ion stripping. It also includes beam plasma interaction in the chamber, particularly, plasma neutralization of beam space charge in the primary approach using ballistic chamber focusing. Plans for the next three years include more heavy-ion stripping experiments on existing heavy-ion beam accelerators in the US, Germany and Japan, as well as a high current neutralized beam transport experiment that uses an existing 400 kV injector and an electron cyclotron resonance (ECR) plasma source developed to control the chamber plasma parameters.

4.0 Chambers

The leading candidate for a HIF chamber is the HYLIFE-II concept [8], which uses a thick protective region of flowing flibe (F, Li, Be molten salt) to protect chamber structures from direct exposure to target x-rays, debris and neutrons. This concept promises long-life structural components with ordinary steels and minimizes fusion materials development requirements. Key issues being addressed include the formation of the liquid jets required to provide protection and recovery of the protective configuration after disruption by the fusion pulse at 5-10 Hz. Figure 3 illustrates schematically the oscillating liquid jets that surround the target and the stationary crossed jets that create an array of ports for beam entry.

Several universities are conducting small-scale experiments and modeling of the fluid dynamics of the various types of jets needed to form the protective liquid blanket. The University of California, Berkeley (UCB) has developed the type of oscillating jets needed to form the oscillating pocket. Their recent work has included demonstration of multiple disruptions and recovery of an oscillating 96-jet array using rapid chemical detonations [9]. UCB has demonstrated the generation of highly smooth and precise cylindrical liquid jets for use in forming grids for beam arrays [10]. Work on the interface between the accelerator and the chamber in the area of the final focus magnets has led to an innovative liquid vortex protection scheme. UBC has also recently experimentally demonstrated the performance of a new nozzle for creating a smooth liquid vortex within a circular tube, which can be used in the bore of the final focus magnets to prevent direct exposure to x-rays and debris and will also serve as a condensation region for hot vapor that flows up the beam lines. Recent studies have also investigated the addition of sodium fluoride to flibe, creating flinabe, to lower the melting temperature. This allows the molten salt to be used at temperatures below 400°C in the beam tubes, creating extremely low vapor pressure in this region.

The University of California, Los Angeles (UCLA) has recently built an experiment to study the vaporization and condensation of flibe [11]. They are using a plasma gun to produce rapid vaporization (creating a few-eV plasma) and then diagnose vapor flow and condensation in a test chamber. The test chamber is being adapted to include liquid films and jets to simulate condensation in a HYLIFE-type chamber.

Georgia Institute of Technology (GT) has also done experiments on oscillating liquid jets using water. The current focus of their work is on characterization of the surface ripple on jets [12]. Producing high quality jets with minimal surface ripple is important for the crossing jets that form the beam ports. The goal is to have these jets as close to the beams as possible (to provide good neutron shielding) while avoiding any clipping of the incoming beams by the jets. Results to date indicate that with proper nozzle design, the ripple on the order of a couple millimeters over the characteristic distance will be achievable. New work at GT will investigate mechanisms for drops being ejected from the surfaces of jets, which could be an issue if these drops interfere with target injection or beam propagation.

5.0 Target Fabrication

The basic requirement for the Target Fabrication Facility of an IFE power plant is to provide about 500,000 targets per day (at ~6 Hz) with precision geometry, and with precision cryogenic layered DT fuel. Target fabrication for inertial fusion is being investigated by a number of institutions throughout the world, including Russia [13], Japan [14], China [15], France, and the USA. The feasibility of developing successful fabrication methodologies at the low cost required for energy production (about $0.25/target, about 10^4 less than estimated current costs) is an important issue for IFE. Target fabrication work in support of HIF has concentrated on investigating and developing the various materials needed by HIF target designs and on fabrication techniques that could eventually scale to low cost and high production rate. General Atomics (GA) and Los Alamos National Laboratory (LANL) are carrying out this work as a joint effort. In the area of materials, LANL has developed very low-density foams doped with high-z materials, which is one approach to providing the energy deposition material in the distributed radiator designs. W and Au doped foams have been made at 2 atom percent loading by the incorporation of nanosized powder into the foam polymerization process (Fig. 4). Development of additional foam fabrication methods is underway, including Laser-assisted Chemical Vapor Deposition (LCVD). LCVD has the capability to deposit materials in localized areas, producing growth of micron-scale controlled structures that may allow in-situ fabrication of the hohlraum foam components.

GA has also built a small-scale fluidized bed to demonstrate a potentially promising method for reducing the cost of producing ablators for targets. Fluidized beds are well known in industry as a cost-effective mass-production technique that can be scaled to industrial sizes. A fluidized bed was used to extend the Glow Discharge Polymer (GDP) coating technique that has been used to provide high-quality ablators for ongoing experiments. The fluidized bed was used to deposit GDP coatings on polymer mandrels. The coatings were smooth and uniform and were very consistent. Once developed, it is estimated that this process could provide the 500,000 targets per day needed for a power plant with only two 9-inch-diameter fluidized bed coaters.

Layering, the process of redistributing the cryogenic DT fuel into a smooth uniform layer inside the fuel capsule, is a critical step in target fabrication. Layering requires establishing an extremely precise (~250 μK), uniformly spherical temperature distribution on the outside of the ablator. A process to accomplish layering in controlled-temperature, cryogenic tubes while they are being staged to the injection system is being developed. Thermal analyses have demonstrated that in-hohlraum layering is possible, however, it will require careful control of hohlraum dimensions, alignments and material properties to remain within the required temperature variations.

6.0 Target Injection

GA has designed and is currently assembling a 6 Hz experimental target injector (Fig. 5) that can accelerate and track either direct-drive targets (currently proposed for laser-driven IFE) or indirect-drive targets (proposed for HIF). The first phase of this experiment will operate with room temperature targets and will demonstrate high rep-rate operation and the accuracy of target delivery. Future upgrades will include cryogenic operation and a high-temperature simulated target chamber. The experimental target injection and tracking system will be able to inject targets at high velocity (up to ~400 m/s), position them to within ± 5 mm, and track the targets to less than about ±200 μm. The targets will be placed into sabots and loaded into a 12-shot revolver chamber. A gas gun provides the target acceleration. It includes a gas reservoir (not shown) and high-speed (<2 ms open/shut time) gas valve that is being built at Oak Ridge National Laboratory. The propellant gas removal system removes most of the propellant gas to minimize the effect of the remaining gas on the heating and trajectory of the targets, primarily issues for direct-drive targets [16]. After leaving the gun barrel, the spring-loaded sabots separate from the targets and are removed from the target path by the sabot deflector. (Note that sabots may not be needed for future indirect-drive targets since the hohlraum may be able to serve the protective functions.) Target position detectors will optically sense the target's location as it passes and provide data to predict the time and position of the target in the test chamber. Overall, significant progress has been made towards demonstrating a credible pathway for successful target supply and fuelling of an HIF power plant.

7.0 Integrated Systems

7.1 Final Focus Magnet Protection

Even though the final focus magnets are out of the direct line of site of fusion neutrons, neutron leakage and streaming up the beam lines is a design issues. LLNL has done detailed analyses of the shielding of the final focus magnets for driver designs that use 72 to 288 beams [17]. Key considerations are the total dose (neutron plus gamma-ray) to the insulators, fast neutron flux to the superconductor, and production of radioactive waste due to the superconductor. With proper design, a magnet lifetime greater than 40 years appears possible. Results, however, are sensitive to the shielding and magnet array configuration. If the final focus magnets are close packed, neutron scattering between ports is higher and the lifetime will be less. Also, very small standoff between the incoming beams and chamber/shielding port walls and cross flibe jets is needed for the good performance. If larger standoff is needed, magnet life will be lower. Tests of the allowable standoff from high current, short pulse ion beams are proposed for future HIF experiments such as the IBX and IRE.

7.2 Safety and Environmental

Over the past 3 years, significant progress has been made in developing codes for analyzing the safety of IFE power plants. Analyses of accident scenarios for HYLIFE-II were completed and reported [18]. The findings show that the key safety issue in an accident is release of tritium. For average weather conditions, the site boundary dose is less than 1 mrem, which is that level below which no evacuation plan is needed. If worst-case weather is assumed, which now appears to be the standard, the dose exceeds this limit. Work is continuing to refine these analyses. Other recent and ongoing work in this area includes safety analyses for a target fabrication facility [19], a safety and environmental assessment of possible target materials [20], and the study of a fusion waste management system that maximize the amount of fusion materials that can be cleared or recycled [21].

8.0 Summary

Work continues on developing the science and technology needed for IFE using heavy ion accelerators, and excellent progress has been made in all the areas that need to be integrated in a HIF power plant. There have been recent advances in a variety of target designs that are predicted to give adequate gain for IFE. The driver development issues, including source production, high current transport and acceleration, final focusing and transport through the fusion chamber are being addressed by the HIF VNL with computer simulations and experiments. Key aspects of thick-liquid-wall chambers involving creating high quality jets and restoring chamber conditions after each shot are being addressed and the work is showing promising results. Several techniques that may scale to low cost target fabrication have been demonstrated and are being developed, and an experimental target injection and tracking system is now being built. Significant progress has also been made in designing the interface of the accelerator with the chamber and understanding safety and environmental issues. Continued R&D is planned in all these areas to address the remaining issues.

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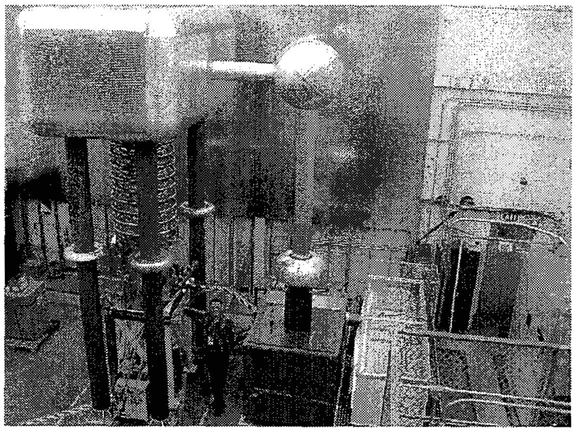

Fig. 1. 500 kV Source Test Stand (STS-500) at LLNL.

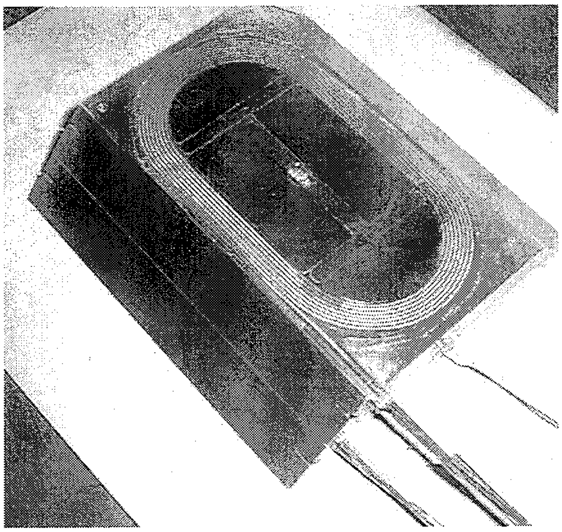

Fig. 2. Racetrack coil module quadrupole.

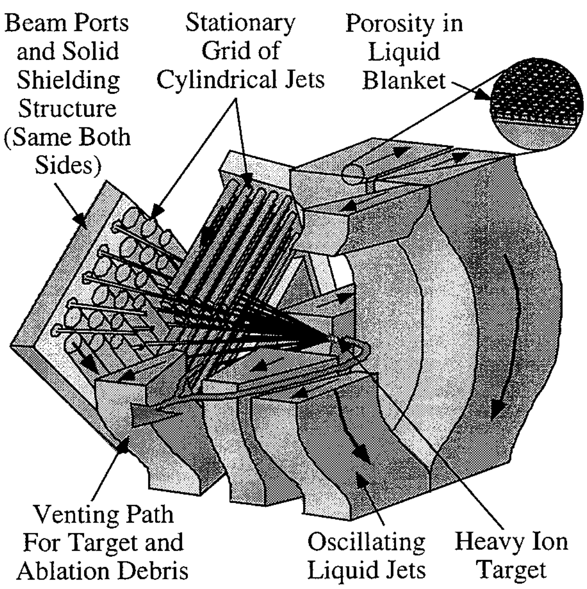

Fig. 3. Schematic of a thick-liquid pocket, showing major pocket features.

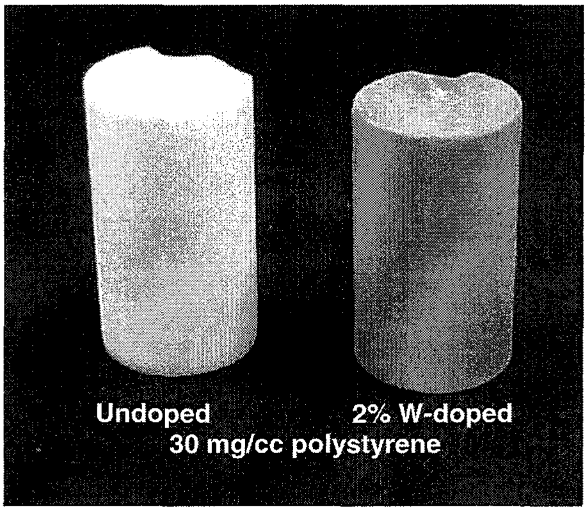

Fig. 4. High-Z doped foam. *(Courtesy W. Steckle, LANL)*

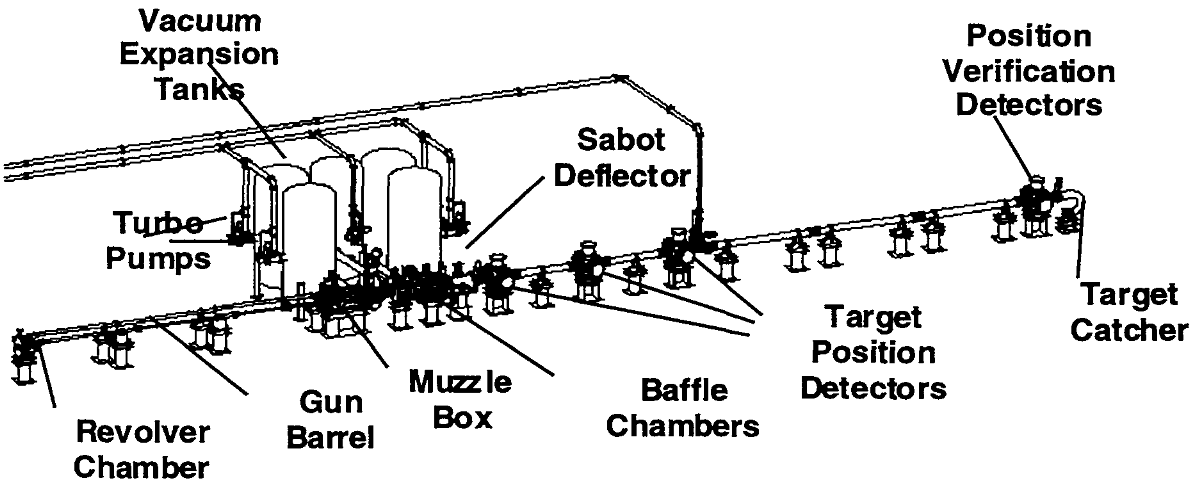

Fig. 5. Target injection tracking system overview.