4.2 TARGET INJECTION, TRACKING, AND POINTING

4.2.1 Objectives and Requirements

The objective of this study was to develop conceptual designs of target injection, target tracking, and beam pointing systems for both laser and heavy-ion beam driven IFE reactors. Performance requirements for these systems are quantified and examined for a proposed base conceptual design. Wherever possible, the requirements for the base design are compared with demonstrated state-of-the-art component performance. Development needs for detailed modeling and proof-of-principle experiments are outlined and discussed.

4.2.2 Overview

In order for the driver to ignite the target and produce the gain necessary for an IFE reactor, the final driver beams must all be centered on the target and hit the target simultaneously. Three separate systems must work together to accomplish this.

1) Target delivery to the correct location in the chamber must be as consistent and accurate as possible.
2) A tracking system must be able to detect small variations in the placement of individual targets in time to correct the beam pointing.
3) An active beam alignment system must be able to quickly and accurately point the beams to each target's final location.

The match between the center of the beams and the center of the target must be to within 10% of the capsule radius for a direct-drive laser target (roughly 0.3 mm) or to within 20% of the focus spot radius for heavy-ion indirect targets (roughly 0.5 mm). The accuracy with which one can track the target will be limited by the amount of time required to process the tracking information and steer the beams.

Figure 4.12 is a schematic of the components of a target injection and tracking system that uses a gas gun for target acceleration. The distances and times necessary to characterize the injection and tracking system are also shown in Fig. 4.12. The target is accelerated at a constant acceleration, a, over an acceleration length, L_a. After leaving the acceleration section, the target travels a constant velocity, $\sqrt{2 a L_a}$, to the center of the chamber. A removable sabot is used to protect the target during acceleration. The target is given an angular velocity during acceleration, so the sabot will be separated into two pieces by centrifugal force after acceleration. The distance from the exit of the acceleration section to the center of the chamber is divided into three segments: the sabot removal length, L_{sr}; the tracking length, L_t; and the radius to the outer edge of the chamber, R_c. We also define the following time periods:

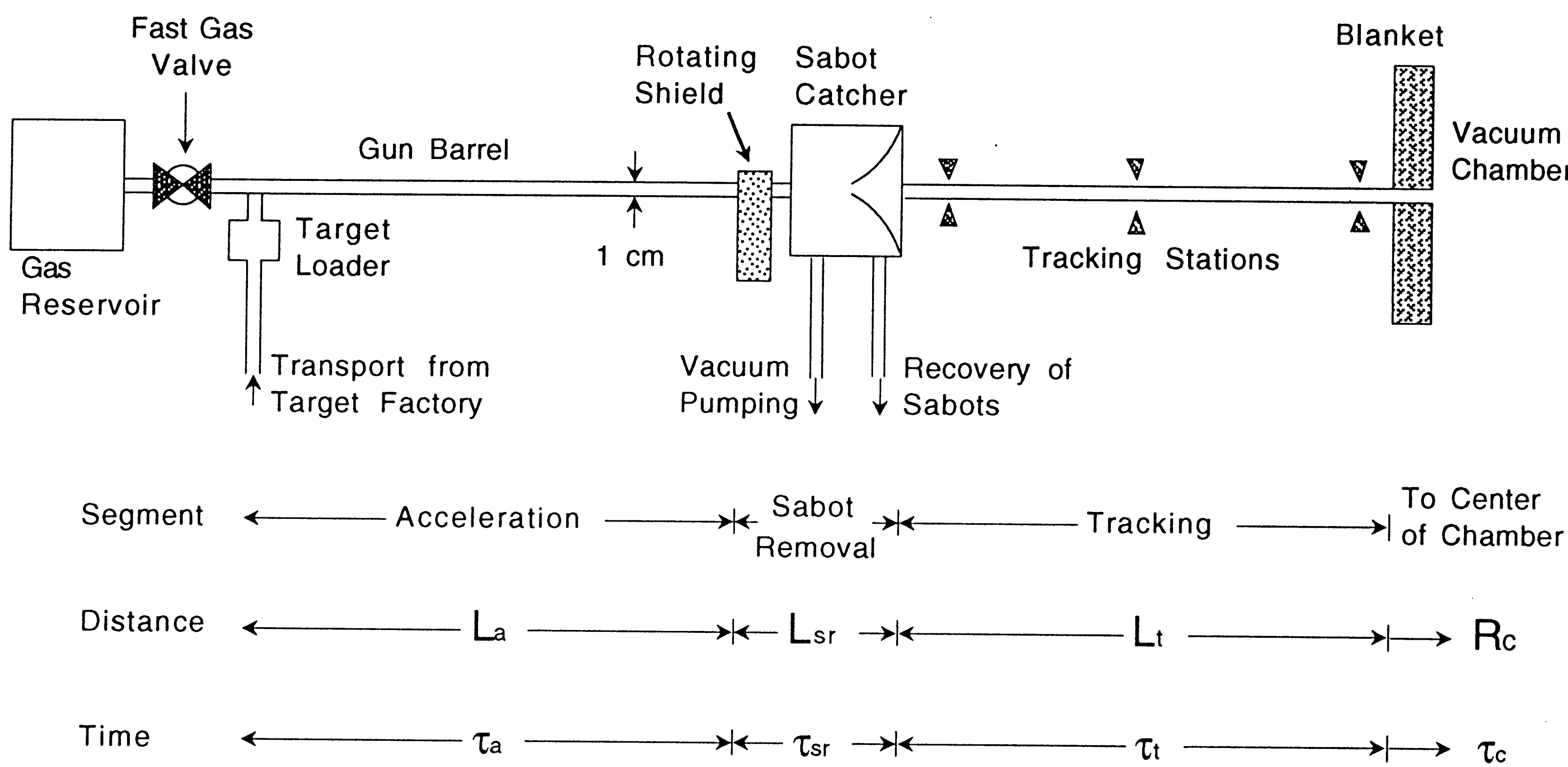


Fig. 4.12. Schematic of target injection and tracking system.

τ_a = time of acceleration, s

τ_{sr} = time for sabot removal, s

τ_t = time for tracking before entering chamber, s

τ_c = time in chamber, s

τ_p = interpulse time = 1/rep-rate, s

If several tracking points are used over a total tracking length, with the last tracking point at the outer chamber wall, then there are two times of interest: the time between the first tracking data and target ignition, which is given by $\tau_{p1} = \tau_t + \tau_c$; and the time between the last tracking point and ignition, $\tau_{p2} = \tau_c$. The first time interval, τ_{p1}, is the time allowed for preliminary (relatively large) pointing corrections, and the second time interval, τ_{p2}, is the time allowed for final (relatively small) pointing corrections. The total (processing and pointing) response time must be smaller than τ_{p1} for large corrections, and smaller than τ_{p2} for small corrections.

The conceptual design of the target injection system was based on the following design constraints:

1) Only one target is allowed in the accelerator at a time: $\tau_a \leq 0.8\ \tau_p$ (allowing 0.2 τ_p for loading), or

$$L_a \leq \frac{a\,(0.8\ \tau_p)^2}{2}$$

2) The target can be in the chamber for only 1/3 of the interpulse time: $\tau_c \leq \tau_p/3$, or

$$L_a \geq \frac{1}{2a} \cdot \left(\frac{3R_c}{\tau_p}\right)^2$$

3) Pointing commands are received and processed for only one target at a time: $\tau_t + \tau_c \leq \tau_p$, or

$$L_a \geq \frac{1}{2a} \cdot \left(\frac{L_t + R_c}{\tau_p}\right)^2$$

These design constraints are shown in Fig. 4.13 on a map of the acceleration length versus acceleration. The SOMBRERO design parameters of R_c = 7.5 m and τ_p = 0.15 s (rep-rate = 6.7 Hz) were used to generate Fig. 4.13. A sabot removal length of 2.5 m and tracking length of 7.5 m were also assumed. To minimize the forces on the target during injection, the minimum permissible acceleration should be used. The operating point, with L_a = 9.0 m and a = 130 g's, is indicated in Fig. 4.14, and the design parameters for our baseline system are given in Table 4.7. The system is shown schematically in Fig. 4.14.

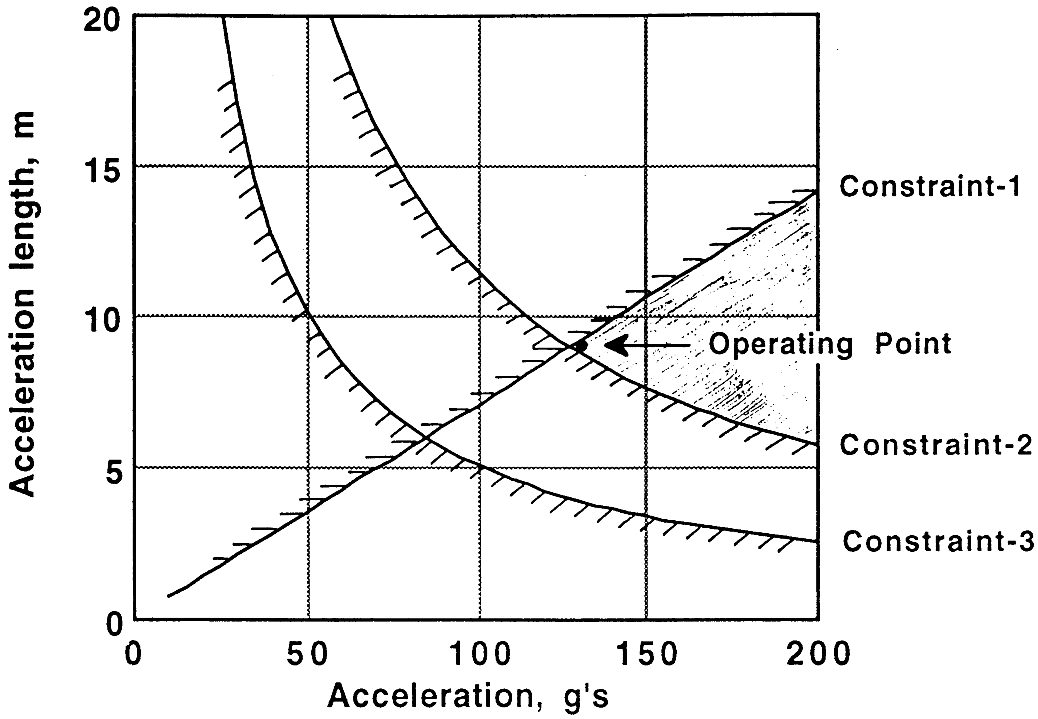


Fig. 4.13. Acceleration length versus acceleration. The three constraints limit the design space as indicated.

Table 4.7. Baseline Target Injection Parameters

Acceleration (a)	130 g
Accelerator Length (L_a)	9 m
Final Injection Velocity (v_f)	151 m/s
Time in Accelerator (τ_a)	119 ms
Sabot Removal Length (L_{sr})	2.5 m
Time for Sabot Removal (τ_{sr})	17 ms
Rotational Velocity for Sabot Removal	570 RPM
Time for Tracking (τ_t)	50 ms
Time in Chamber (τ_c)	50 ms
Total Time from Target Firing to Ignition (τ_{tot})	235 ms
Time Allowed for Coarse Corrections (τ_{p1})	100 ms
Time Allowed for Fine Corrections (τ_{p2})	50 ms

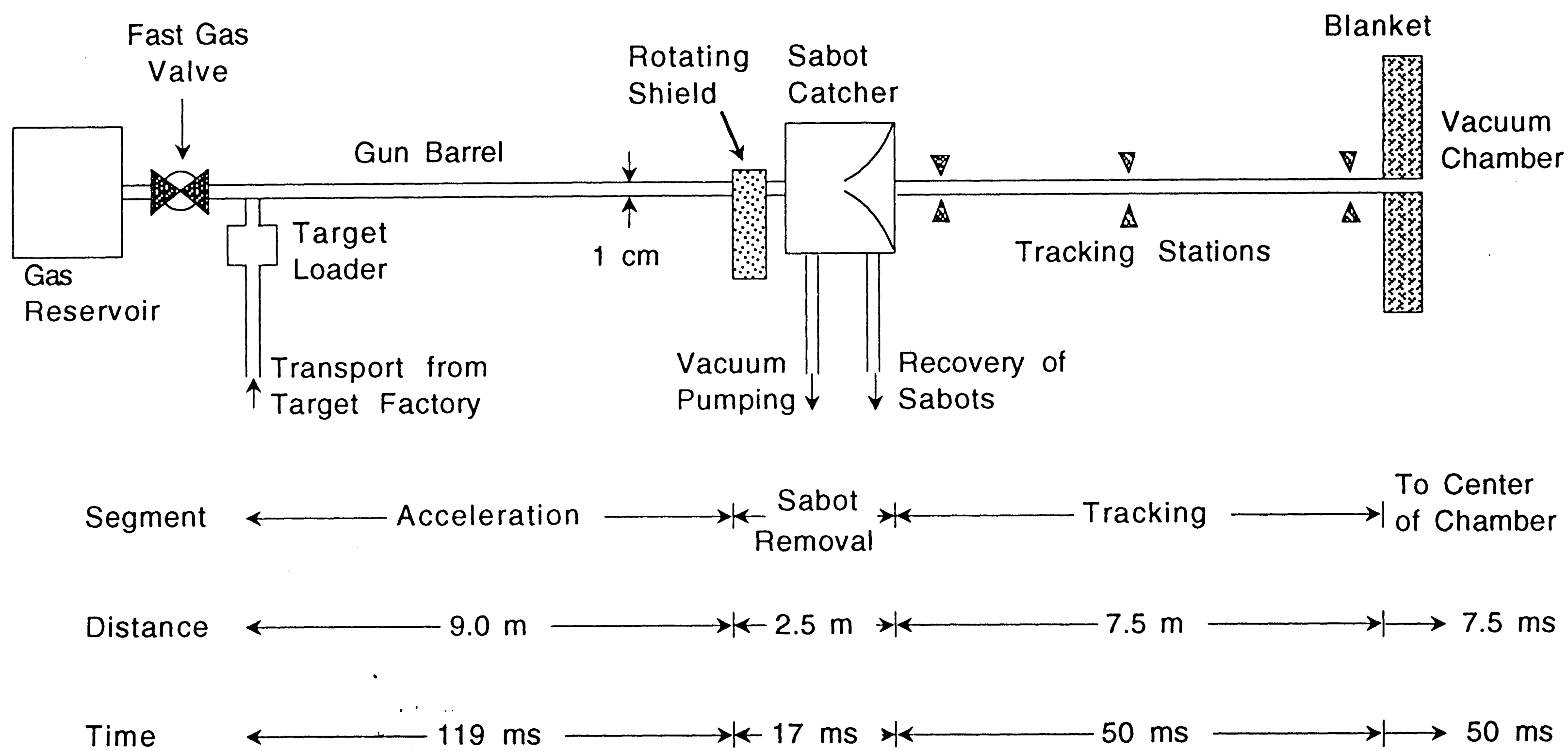


Fig. 4.14. Schematic of the reference design for the target injection and tracking system.

This injector meets the goal of only tracking or accelerating one target at a time, but one target will be tracked while the next target is accelerated. The required rotational velocity is set by the sabot velocity, the length allowed for sabot removal (2.5 m), and displacement (~ 0.5 cm) needed to separate the sabot from the target. If lower rotational velocities are desired, longer regions must be allowed for the sabot catcher, or the separation of the halves of the sabot could be assisted by a plastic spring integral to the sabot design. If targets can not tolerate acceleration on the order of 100 g, accelerators and tracking systems that can accommodate two or more targets with separation less than the acceleration and/or tracking length must be designed or two systems could operate in an alternating fashion.

4.2.3 Injection System Design

4.2.3.1 Injector System Selection

Several acceleration options exist for a target injector.[4-10] The concepts receiving the most interest are light gas guns, centrifuge launchers, and rail guns. The light gas gun is chosen as our base injector, but the advantages and drawbacks of each of these concepts are briefly discussed.

Light Gas Guns. A light gas gun uses a high pressure hydrogen, deuterium, or helium gas to accelerate the frozen pellets of fuel through a tube or barrel. The velocity of the pellet is limited by the driving gas parameters and the projectile size and mass. Rifling of the barrel can be used to provide the required spin rate for sabot removal. A gas gun will require that the sabot form a tight seal with the barrel of the injector. Light gas guns have been demonstrated at a number of locations. In the mid 1980's, ORNL successfully demonstrated high velocity operation of a light gas gun at greater than 2 Hz.[4.11] Barrel wear and pellet heating are issues which must be addressed in the injector design.

The light gas gun is chosen as our base injector because of its relative technical maturity, low risk, and its ability to give accurate target placement at required repetition rates. Preliminary calculations indicate that the gas gun can be modeled as a constant pressure accelerator with a mass flow rate of 2 mg/s for a helium gun. The final pellet velocity should be repeatable to within 3%, and the shot-to-shot variation in pointing should be on the order of ± 1 mrad. These variations are small enough to be consistent with our tracking and pointing system designs.

Centrifuge Injector. A centrifuge injector for adding fuel to tokamaks has been developed by ORNL.[4.12] In this injector, radial u-shaped channels in a rotor cut off a section of extruded frozen hydrogen near the rotor spin axis and then accelerate the pellet toward the outer radius of the rotor. The pellet exits the tube with a velocity which may exceed the velocity of the rotor tip by a factor of almost two. One such centrifuge consists of a Kevlar-epoxy hoop with a built-ion pellet chute. With a 1-m-diameter hoop rotating at 20,000 RPM, pellets of 1.3 mm diameter have been accelerated to speeds of roughly 800 m/s with injection rates of 20 Hz. This technique would require significant development before it could be used with sabots and targets, and the shot-to-shot pointing variations for such an injector could be prohibitively large.

Electromagnetic Railgun Accelerator. Railguns are receiving increased attention as candidates for injectors. The railgun accelerates a projectile along parallel tracks by connecting a capacitor bank (or other voltage source) to each of the rails, with a conducting projectile or sabot completing the circuit. The current loop carries a current, I, and creates a magnetic field, B, with an accompanying force of I×B on the projectile. The energy stored in the circuit is given in terms of the inductance, L, by $E = 1/2\ LI^2$, and the force for a constant discharge current is given by dE/dx, or $F = 1/2\ I^2\ dL/dx$. A railgun using a conducting sabot with an open front could decelerate the sabot at the end of the injector to recover the sabot while allowing the target to continue into the reactor.

Because of the need for high injection velocities and a cryogenic target, it is difficult to design an electrical connection between the sabot and the rails. A sliding contact or a plasma discharge could be used to complete the circuit, but both would produce heating of the sabot. A proposed injection system for HIBALL[4.13] avoids this problem by using a solenoid in the injection barrel with a ferromagnetic recoverable sabot. This system gives electromagnetic acceleration without requiring contact between the sabot and the barrel. Cryogenic railguns operating at high repetition rate with repeatable velocity and pointing will require further research and experiments to be credible.

Other Acceleration Concepts. Electrostatic accelerators and laser rocket accelerators have also been proposed for injectors, but these systems have not been sufficiently developed for a feasibility analysis to be possible.

4.2.3.2 Critical Issues for the Base Injector

Acceleration Limit on Targets. Careful design is required for the pellet support within a sabot or an indirect target. The amount of acceleration that can be tolerated by the pellet was estimated by LLNL[4.14] to be ~ 170 g. More detailed information on the design of direct and indirect drive targets is needed to examine this limit.

Heating and Wear of Sabots. The sabot must be designed to protect the pellet from heating from either the propellant gas or the friction from the barrel. Reusing sabots would simplify the demands on the target factory, but will require that the sabots survive several launches and recoveries. Because of the need for consistent target placement, even small damage to the sabot surface could prevent them from being reused.

Barrel Wear. Because of the need for a tight seal between the sabot and the barrel, any damage to the barrel surface will affect the injector's performance. Requirements for barrel cleaning, maintenance, and replacement will need to be investigated.

Loading, Recovery, and Refilling of Sabots. Unless multiple barrels are used (as in a gatling gun), the time allowed for reloading the injector is small (~ 0.03 s). If the sabots are to be reused, they need to be recovered, inspected, cooled, and reloaded in an automated processes. A more likely scenario is that recovered sabot material would be used in the production of new sabots with the required tolerances.

4.2.4 Target Tracking

4.2.4.1 Tracking Requirements

A tracking and pointing system is required to aim the driver at the pellet and to assure that the target will ignite. The match between the center of the beams and the center of the target must be to within 10% of the pellet radius for a direct-drive laser target (roughly 0.3 mm) or to within 20% of the pellet radius for heavy-ion indirect targets (roughly 0.5 mm). If tracking and final pointing elements are 10 m from the target, this limits the tracking, alignment, and pointing errors to the order of 10 microradians or less. If the final pointing element for a laser driver is on the order of 100 m from the target, it will need an accuracy on the order of a microradian. The required pointing accuracy has been demonstrated in various Directed Energy Weapons programs sponsored by the Strategic Defense Initiative Organization (SDIO).[4.15] Tracking systems with these accuracies were built and flown aboard the Airborne Laser Laboratory.[4.16] An alignment transfer system, ARTS, was built and tested as part of the Alpha/LODE program.

A critical problem is the alignment of the tracker's measurement system with the device's line of sight. An alignment laser in the optical train can help sight a laser driver, but some kind of bore sighting is required for the injector and the heavy-ion driver. The total alignment accuracy should be less than a third of the total tracking error budget, or less than a microradian. The ability to periodically measure the pellet position at intercept would help the alignment system. This could be done simply by imaging the target x-ray output through a pinhole to determine the location of the last target. If tracking at intercept is not possible for ignited targets, periodic adjustment could be made with a low powered marker (e.g. laser) aligned with the device and aligned to hit a dummy target.

"Beam bug" techniques developed at LLNL and the beam position monitor developed at LANL could provide a solution to the HIB sensing problem if the accuracy of the sensing can be on the order of 0.1%. An alignment system must still be developed. Pointing of the HIB will be accomplished using a pair of crossed steering dipoles at the end of the final focusing. These steering coils could be incorporated in the windings of the final focusing quadrupole and should achieve a steering bandwidth on the order of a MHz, well beyond pointing requirements.

The target can either be tracked prior to entering the chamber, or it can be tracked inside the chamber. Figure 4.15 shows a representative system for tracking the target outside the chamber. This system is described in more detail in the following section. An alternative design, shown in Fig. 4.16, uses laser tracking to track the target within the chamber.[4-17] Although the second system would give more accurate tracking of the final target trajectory, we chose the first system as our base design because it is protected from the harsh reactor environment, and it allows more time for beam pointing corrections after the final tracking measurements.

4.2.4.2 Description of Tracking System

Our base tracker consists of a laser Doppler velocimeter followed by a series of crossed light axis position and time detectors as shown in Fig. 4.15. The assumed pointing accuracy for the gas gun (10 microradians) and the expected shot-to-shot velocity variation (± 3 %) combine to set limits on tracker field of view. The tracker design must be sized to accommodate these variations in gun performance.

A possible one-dimensional tracker for use in an x-y position detector could consist of a Ga-As laser diode beam which is expanded to approximate 5 cm in diameter and then be refocused on a silicon diode array of 40×100 elements for Y direction and 20×100 for the X direction to accommodate the initial pointing inaccuracy. Each array will be scanned at 10 MHz to assure that the pellet is repeatedly sampled as it passes through the beam. This approach allows at least ten totally independent measurements of the target position at each station (two pair of cross-axis laser and detector rings), providing noise reduction and accuracy improvement in each axis. Noise performance should not be a limiting factor since the laser diode can be selected to permit high signal levels. Further, by using knowledge of the approximate time of arrival of the pellet, gating techniques can be applied to reduce the background signal. Should crosstalk between the laser diode pairs become a problem, the laser diodes can be doped to operate at slightly different wavelengths and appropriate filters can be used on the sensors.

Processing of the data will utilize matched filter techniques to generate a best estimate of target location for each scan. This data will then be processed using a tracker, such as the Fitts-gradient tracker developed as part of the Airborne Laser Laboratory program, to an accuracy of better than 1/20 of a detector element. Resultant accuracy of each station's target position data will be approximately 10^{-5} m.

State-of-the-art laser diodes allow operation at about 100 MHz, and trackers have been built and tested with tracking accuracies of 1/100 of a detector element. While difficult to meet, the target tracking requirements for IFE are well within the state of the art.

Velocity will be estimated at each station. Because of the limited distances between measurements, the accuracy of the velocity measurement can be greatly improved by using at least

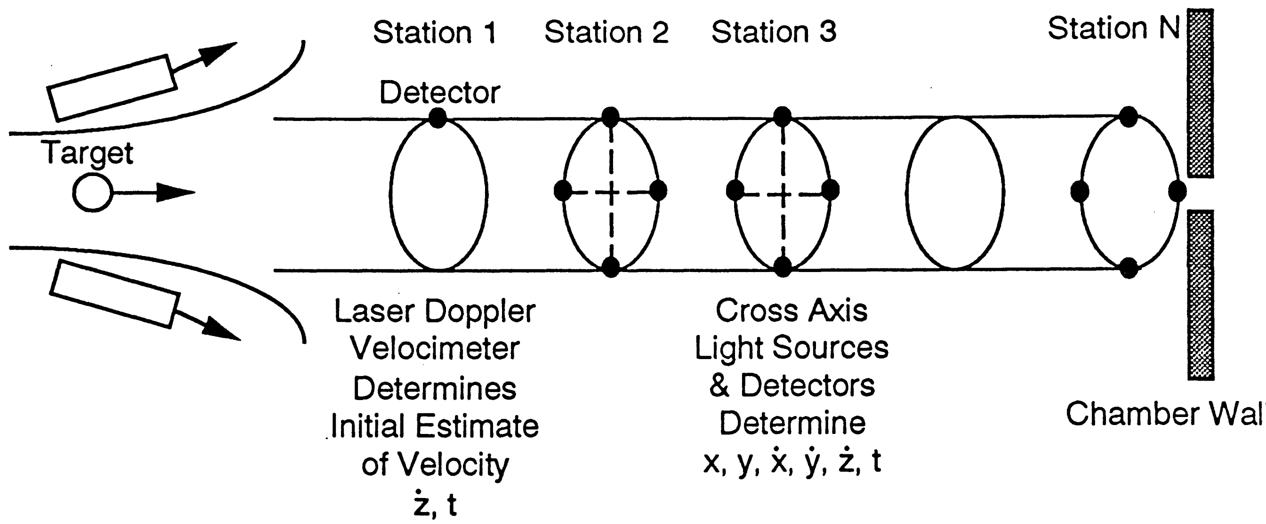


Fig. 4.15. Tracking system using multiple tracking stations.

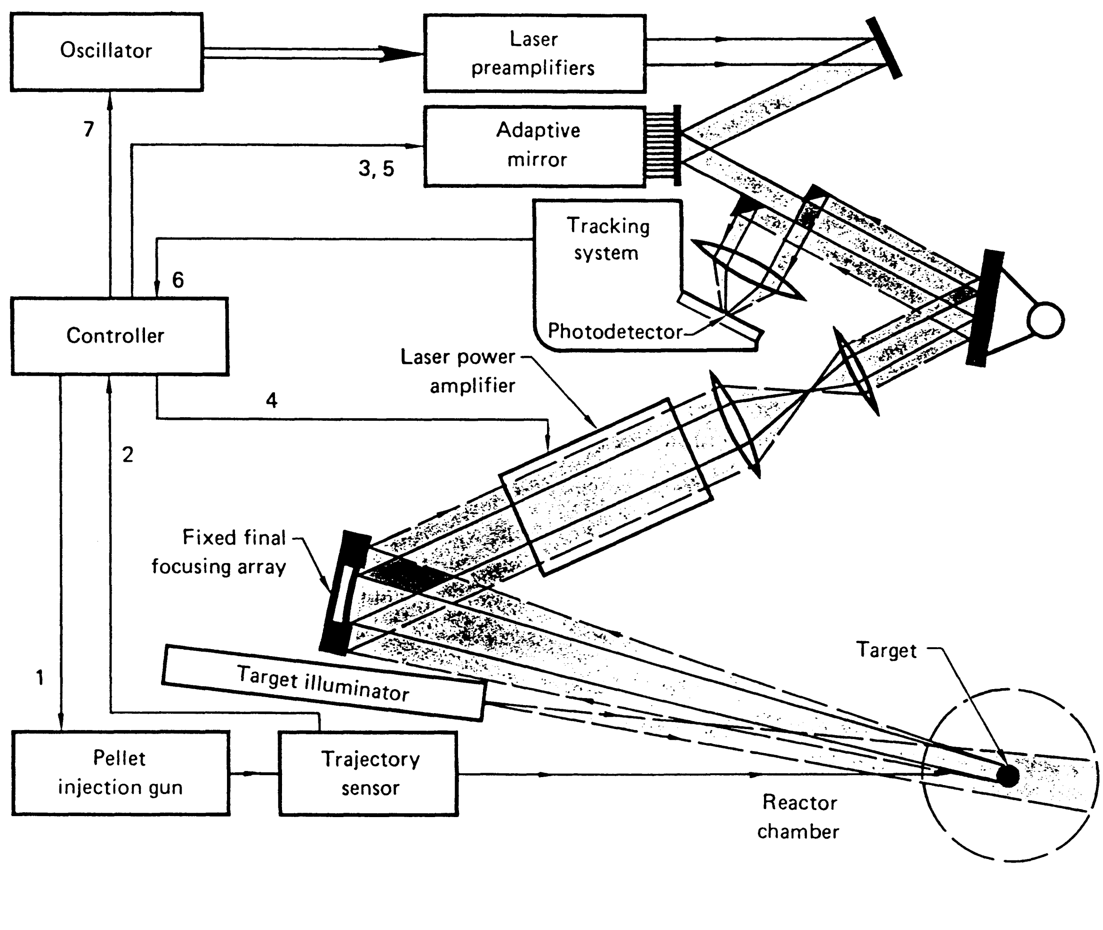


Fig. 4.16. Alternative tracking system that uses a laser to track the target within the chamber.

four sets of stations. These stations will give independent velocity measurements separated by 10 ms, and Kalman filter prediction algorithms will be developed to estimate the target trajectory to the intercept point. If greater accuracy is needed, additional stations can give accurate estimates of higher order derivatives of the trajectory to be used in the estimator / predictor. The first estimate of intercept location and time will be available 100 ms before intercept, requiring that the beam pointing element have a bandwidth of > 100 Hz. This will allow at least ten time constants for the system to accurately settle and match the intercept location. This estimated settling time can be reduced by application of modern control techniques such as dead beat digital control algorithms.

4.2.5 Beam Pointing

4.2.5.1 Laser Beam Pointing

If the pointing system has most of the 100 ms available for settling, the requirements on fast steering mirrors are minimized. Fast steering mirrors with settling times well below 100 ms have been built as part of SDIO programs.[4.18] One example is the cooled fast steering mirror system with a 600 Hz bandwidth used by United Technology Optical Systems for the FEL program, but these highly accurate cooled mirror systems are expensive and complex. The uncooled 10 cm size, 100 Hz bandwidth mirrors needed by this design are less complicated and have lower demands; they should not be a driving cost item in the laser system.

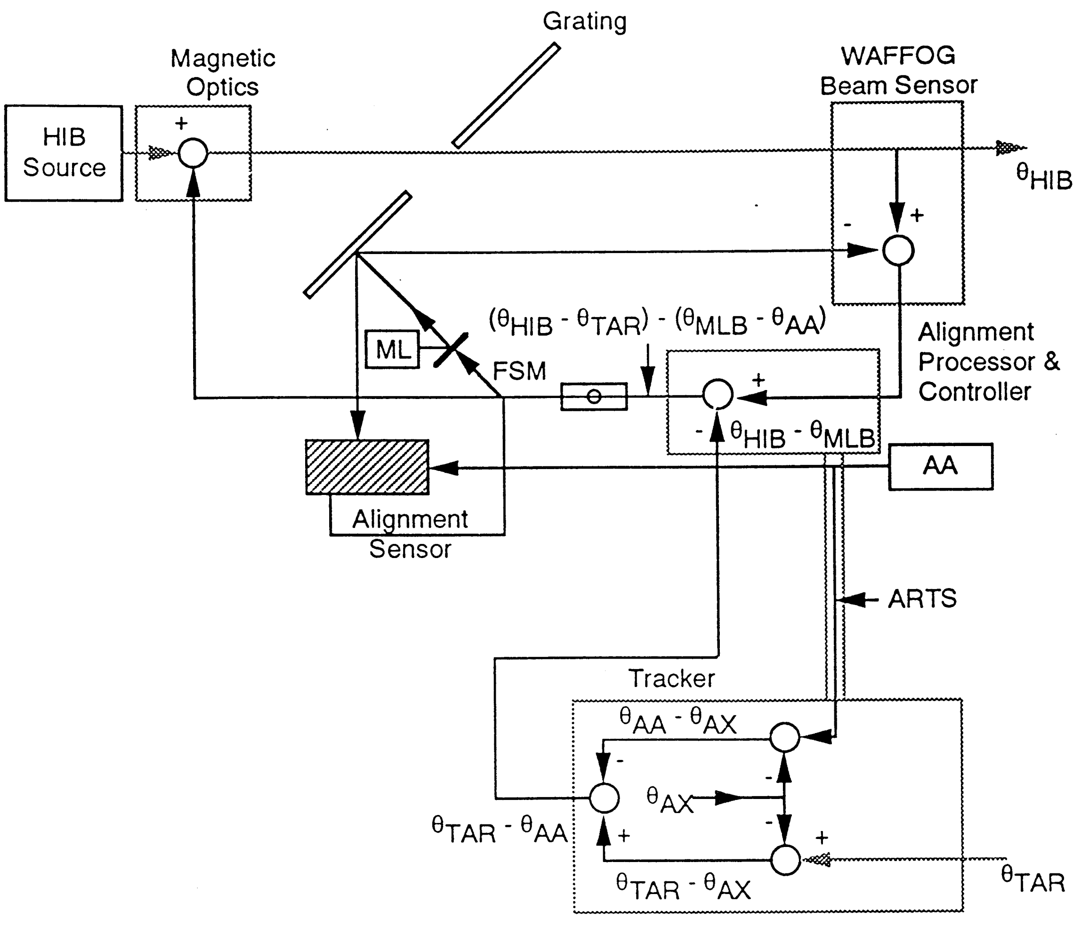
4.2.5.2 Heavy-Ion Beam Pointing

Pointing the HIB requires measuring the location an direction of the beam and referencing it to the tracking system. The first problem is to measure the beam location. While it is unlikely that a beam measurement on a single shot could be used to focus that same shot, beam sensing can be used for shot-to-shot corrections of a driver. Beam bug techniques developed at LLNL and the beam position monitor developed at LANL for the SDIO Neutral Particle Beam (NPB) program could be used to provide the basis for a beam-sensing design.

Pointing of the heavy-ion beams will be done by a pair of crossed dipole steering magnets. These steering magnets could consist of coils inside the final focusing quadrupole magnets. Preliminary calculations give steering bandwidths on the order of 100 kHz which far exceeds the required response time for an IFE pointing system. Critical issues which must be investigated are the linearity, repeatability, and accuracy of the steering magnets. In the NPB program, third order magnetic optics models are used to obtain adequate system performance at larger steering angles.

4.2.6 Integrated Target Injection, Tracking, and Pointing Systems

The architecture of the tracking equipment is an important consideration. A method to reference the tracker and the driver must be incorporated in the pointing system. One architecture which may be applicable to the IFE is shown in Fig. 4.17. Although this architecture is configured with the Wire and Fluorescent Fiber Optical Grid (WAFFOG) in mind as the beam sensor, it is not limited to the WAFFOG beam sensor. The technique can be reconfigured for other beam sensing techniques. Some of the key architectural factors are shown in Table 4.8.



ARTS - Alignment Reference Transport System

FSM - Fast Steer Mirror

HIB - Heavy Ion Beam

MLB - Measurement Laser Beam

WAFFOG - Wire And Fluorescent Fiber Optical Grid

Fig. 4.17. A method to reference the tracker and beam for a HIB driver.

Table 4.8. Key Architectural Factors

Component	Issues/Concerns
Beam Sensor	Alignment Bandwidth Accuracy
	Large Angular Range
	Temporal Resolution / Processing Time
Magnetic Optics	Control Bandwidth
	Intrapulse Control
	Steering Range
	Structural Dynamic Input
	Induced Aberrations

In this architecture, the basic reference can be considered to be alignment beam generated by the box labeled AA. This Reference Alignment Beam (RAB) is injected into the Alignment Sensor and into the Tracker via an Alignment Reference Transfer System (ARTS). The ARTS injects the RAB into the tracker by displacing it while keeping parallel to the original direction. The tracker also detects radiation (either thermal emissions, reflected ambient light, or from an illuminator) from the target. Since both the RAB position and the target position are measured with respect to the optical axis of the tracker block in Fig. 4.17, these measurements relative to the optical axis are processed to yield the target position relative to the alignment beam. Before considering how we use this relative measurement, we consider the relationship of the RAB to the Measurement Laser Beam (MLB).

The MLB is directed onto a fast steering mirror, which directs the MLB onto a diffraction grating. This grating directs diffracted beams into the particle beam path and onto the Alignment Sensor. These diffracted orders beam a definite angular relationship to each other so that by controlling one, the other is also controlled. The order that is diffracted into the Alignment Sensor is the order that is measured and directly controlled.

The order that is diffracted into the Alignment Sensor is measured with respect to the RAB. This difference signal is the error signal which drives the servo loop which includes the fast steering mirror. By driving this error to zero, the MLB is aligned to the RAB. Actually, this diffracted order of the MLB is driven to specific direction with respect to the RAB. For now let us select 90 degrees as the relative angle. Let us also select 90 degrees as the relative angle between this diffracted order and the diffracted order that is injected into the particle beam path. Thus, the beam injected into the particle beam path and the RAB are now parallel. Hereafter, we will call the diffracted order injected into the particle beam path the MLB.

The MLB is now injected into the Beam Sensor which measures the position of the particle beam relative to the MLB. This relative measurement then goes to a processor which subtracts the signal from the track processor. This difference signal, whose terms are grouped for clarity, is:

$$\Delta\theta = \left(\theta_{HIB} - \theta_{TAR}\right) - \left(\theta_{MLB} - \theta_{AA}\right)$$

Remembering that the MLB has been aligned to the RAB, the difference signal is ideally given by

$$\Delta\theta = \left(\theta_{HIB} - \theta_{TAR}\right)$$

This signal drives the beam steering loop which nulls this error signal. Thus, without needing to accurately reference the beam sensor itself to the tracker reference, the HIB is directed to the target.

4.2.7 Injection, Tracking, and Pointing Errors

To quantify the sensing and control requirements, one can separate the HIB line errors (deviations of the beam from the desired direction) into divergence and pointing components. That is, the variance of the driver line errors is given by

$$\sigma^2_{HIB} = \sigma^2_{DIVERGENCE} + \sigma^2_{POINT}$$

where

$$\sigma^2_{DIVERGENCE} = \sigma^2_E + \sigma^2_J + \sigma^2_C + \sigma^2_S + \sigma^2_M$$

and

$$\sigma^2_{POINT} = \sigma^2_{BS} + \sigma^2_T + \sigma^2_B + \sigma^2_{AA} + \sigma^2_{PA}$$

Both components contribute to the overall beam divergence as averages over the entire ensemble of engagements.

The principal contributors to the divergence and pointing errors are given in Tables 4.9 and 4.10, respectively. The contributions to the pointing error (as defined here) consist of the error inherent in the output beam sensing system and the tracking and pointing system errors. The beam jitter due to tracker errors is also a function of the control loop servo characteristics. In general, this beam jitter component can be written as follows:

$$\sigma^2_J = G(F_{bw}) \cdot \sigma^2_{tr}$$

where G(F) is a function of the servo characteristics, F_{bw} is the control bandwidth, and σ^2_{tr} is the variance of the single-look tracker error.

Table 4.9. Principal Contributions to Beam Divergence

Component			Influenced By
σ_E	=	Transverse Emittance	Output Beam Radius
σ_J	=	Mechanical Jitter	Platform Stability
σ_C	=	Chromatic Aberration	Output Lens Radius, Drift Length
σ_S	=	Spherical Aberration	Output Lens Radius, Drift Length
σ_M	=	Steering Magnet Jitter	Beam Steering Dynamic Range

Table 4.10. Principal Contributions to Pointing Errors

Component			Influenced By
σ_{BS}	=	Beam Steering	Beam Sensing Technique
σ_T	=	Track Loop Jitter	Track Sensor, Algorithm, Servo Loop
σ_B	=	Boresight Error	Transfer of Beam Sensor Info to ATP/FC
σ_{AA}	=	Auto-Alignment Errors	Alignment Sensors and Servo Loops
σ_{PA}	=	Point Ahead Errors	Tracker, Estimation Algorithms

4.2.8 Summary

Target systems for target injection, target tracking, and beam pointing all require significant development work. Fortunately, many of the required elements have been demonstrated by directed energy weapon research programs. We have presented a conceptual design for an integrated injection, tracking, and pointing system using existing technology which should be able to meet all the requirements of an IFE reactor after a significant design development effort.