4.0 TARGET SYSTEMS

4.1 TARGET PRODUCTION

4.1.1 Overview of the Reference Design

The baseline design of the target production facility contains a deuterium-tritium (DT) handling and storage facility, a fuel container (capsule) production facility, a system for filling the capsules with DT fuel, a measurement system for quality assurance (QA) purposes, and a target storage and delivery section. Figure 4.1 is a block diagram of the IFE reactor target production facility showing the major production steps.

The facility has several important features. The production equipment and overall building area are quite compact. This is largely the result of using production techniques that minimize the production time per target and thus the inventory of targets being handled at any one time. The compact design also helps minimize target production costs. Operational safety and the minimization of total tritium inventory have been considered to be critical aspects of the facility design. The tritium inventory is minimized by 1) using rapid production techniques and 2) reducing the inventory of filled targets in storage. The inventory of filled targets can be small because the system is very reliable. As indicated in Fig. 4.1, the proposed production facility is 100% redundant in order to give high reliability. Under normal conditions, each production line operates at half of its possible production rate. If a component on one line fails or requires repair, the other line is brought to full production capacity. To further enhance the safety characteristics of the production facility, the production stages and components are compartmentalized to reduce the consequences of a tritium leak in any one part of the system.

In order to produce targets economically, the production facility must be operated as a completely automated factory, not as a research facility. We assume that all processes to be employed in producing the capsules, filling the capsules with fuel, adding sabots as target carriers, and handling and manipulating targets will have been developed, tried, tested, integrated and demonstrated in a pilot plant, and perfected before use in an IFE power plant. One of the major implications of this assumption is that complete characterization of the individual targets is not required. Only an occasional measurement will be made to ensure the several fabrication processes are operating as they should.

The design is based on the production of direct drive targets as used in the SOMBRERO reactor. Production steps for indirect drive targets would be the same, except for the final step of loading the capsule into a hohlraum. Depending on its characteristics, the hohlraum could possibly serve as the sabot for the indirect drive target, thus eliminating the sabot loading step. From the

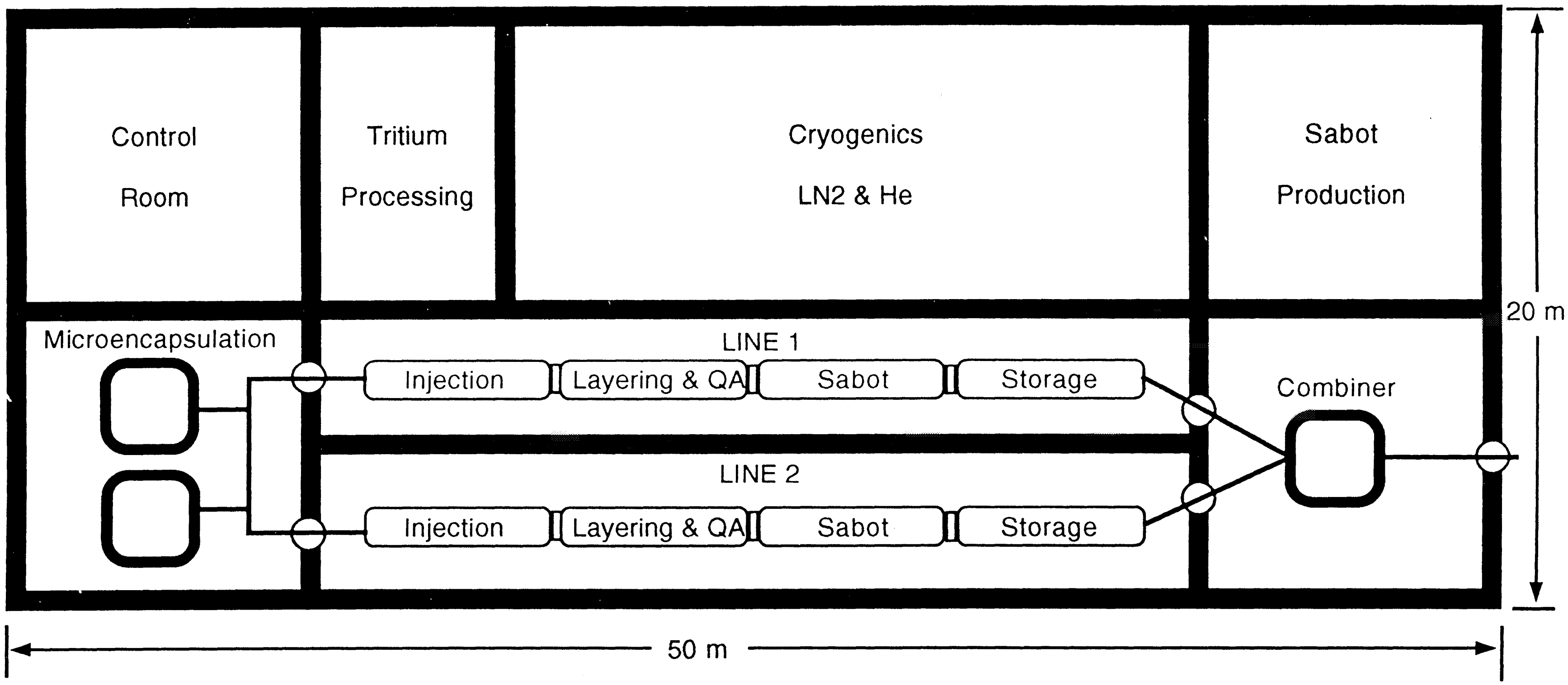

Fig. 4.1. Layout of baseline target production facility.

various options for each of the production steps, we have chosen a reference design approach listed in Table 4.1. The choices were made after considerations of several options for each of the elements of the target production facility. The options and the reasons for the choices are discussed in Chapter 4 of Volume 2.

Table 4.1. Baseline Target Production Techniques

Production Step	Chosen Technique
Capsule Production	Drop Generator / Microencapsulation
Fuel Fill	Injection Fill Techniques
DT Layer Formation	Freeze - Laser Pulse Vaporization - Refreeze

4.1.2 Capsule Production

Several techniques can be used to produce the hollow, spherical, thin wall capsules necessary for the IFE targets. The option selected for capsule production in the base case is the combination of drop generators to produce uniform liquid drops of water layered with a solution of an appropriate polymer. This has been called the controlled microencapsulation technique. It combines the advantages of the drop generator technique, which produces droplets with a fractional standard deviation in diameter of better than 10^{-5}, and the microencapsulation technique, which delivers shells which are round and have uniform wall thicknesses. A drop generator is used to produce uniform drops of polystyrene or other suitable polymer. The drops are injected directly into a liquid where they are treated to form shells as in the microencapsulation technique. Thus, shells will have uniform mass, diameter, wall thickness, and shape like those produced by the shake-type microencapsulation technique.

4.1.3 Fuel Filling

Several techniques were considered for the fuel fill step in target production. Because of the use of radioactive tritium, two major considerations were tritium inventory and safety for operating personnel.

A new and undeveloped method, called injection fill, has been selected for the DT fuel filling process because the presently available method of diffusion fill was judged to be unattractive. The basic approach to the injection fill technique is as follows:

1) A very small hollow fiber or needle is inserted through the wall of a capsule,
2) Liquid DT flows through the needle into the capsule,
3) The needle is removed from the capsule wall, and

4) The wall smoothed to a quality sufficiently high for use as an IFE target.

A hollow optical fiber could be used as the transport tube for the liquid DT fuel. The wall of the fiber forms an optical waveguide for a laser pulse that softens the wall of the capsule allowing the tip of the hollow fiber to easily penetrate the capsule. The outside surface of the fiber can be coated with a material which does not "wet" the capsule wall material. Thus, when the fiber is inserted through the wall, the wall material does not become attached to the fiber, and the wall is not severely damaged. When the fiber is removed, none of the wall material is removed by the fiber. As the end of the fiber leaves the wall, a pulse of laser light can be used via the fiber wall to heat the material around the hole. This will allow the material around the hole to flow back into the hole to repair any irregularities left by the fiber.

A large number of capsules can be filled simultaneously by using a manifold of the hollow fibers which are inserted into an equal number of capsules carried by a tray with an array of holes or cups similar to an "egg crate." The entire injection process will be carried out at cryogenic temperatures as shown in Fig. 4.2. Filling the capsules at cryogenic temperatures will ensure that there will be no disruption of the capsules because of excessive internal pressure of the fuel.

4.1.4 Developing a Uniform Fuel Layer

Some of the most stringent requirements imposed on IFE targets are on their geometry (i.e., the limits of surface roughness, wall thickness variations, concentricity of inner and outer surfaces, and volumetric uniformity of the capsule materials). The limits are particularly stringent when applied to the fuel layer inside the capsule. The fuel layer is required to be the correct thickness (i.e., correct quantity of fuel), and uniformity. If the capsule is filled with fuel in either liquid or gaseous form, in a subsequent step the fuel must be frozen into a uniform layer on the inner surface of the capsule.

Several techniques have been developed to cause the original freezing process to produce a uniform layer or to remelt and/or vaporize the fuel and implement a refreeze process leading to a very uniform layer. For our reference design, we combine the use of gas jets to levitate the capsule with a pulsed laser for rapid heating and refreezing. This technique has been demonstrated experimentally at small scale with thin fuel layers.[14] We proposed that this could be the last step just prior to insertion into the sabot and transport to the chamber. We also note that simultaneous interferometric monitoring would be possible during the layer step.

4.1.5 Capsule Handling and Transport

After they are formed, the capsules will be handled and transported in egg-crate type trays holding approximately 2000 capsules in each tray. The construction of the trays will permit handling by conveyers, robots, and other automated equipment needed to move the filled trays

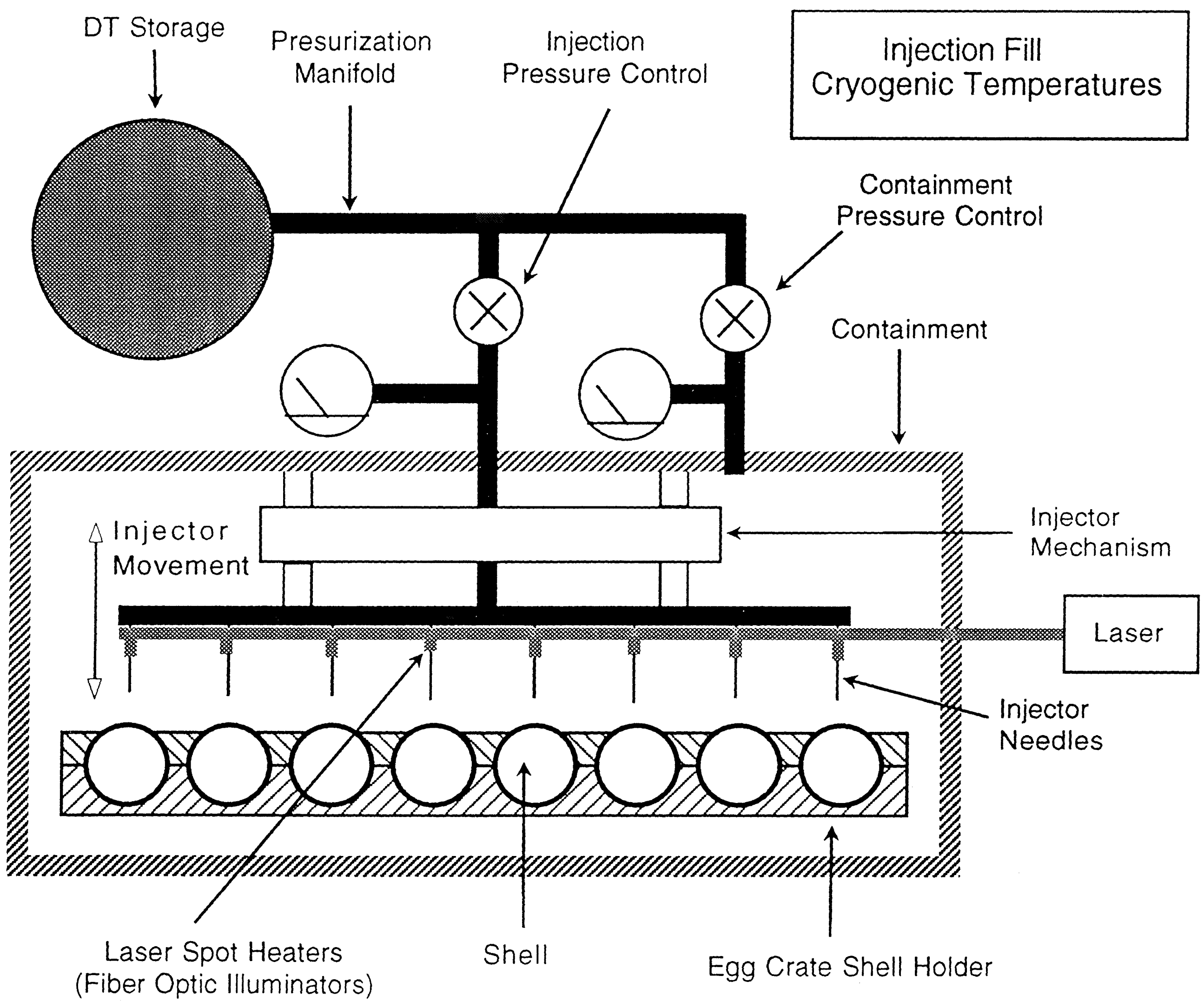

Fig. 4.2 Schematic of cryogenic injection fill system.

through the various stages of the target fabrication process. The trays will also permit automated stacking for storage and retrieval of the finished targets. To deliver targets one-at-a-time to the reactor, the trays must be unloaded and each target inserted into a sabot. The sabot is used to protect the target during transport from the production facility to the target injector and during acceleration by the injector.

4.1.6 Quality Assurance

Because the target fabrication processes must be completely industrialized by the time an IFE reactor power generation plant is built, there is no need to do a detailed characterization of each target. It will only be necessary to statistically monitor the various processes to ensure that the processes are not degrading with time. A laser interferometer will be used to generate real-time interferograms or holograms, which will be read by a high speed camera (e.g., a CCD array camera) and compared by a computer with a hard-wired, built-in pattern to determine if a given target matches the reference pattern within some predetermined limits. If differences exceed the chosen limits of size, wall and/or layer thickness, uniformity of wall, sphericity, or other parameters, alarms can alert operating personnel to potential problems.

4.1.7 Target Protection by Sabots

During the process of acceleration and transport to the outer wall of the reactor chamber, the targets will be protected by a solid sabot. The sabot will be ejected prior to entering the chamber. The sabot material will be recycled and would not add to the gas loads and contaminants dumped into the chamber at each shot. It is also advantageous to remove the sabot prior to entry into the chamber in order to keep the sabot material out of the high radiation environment.

4.1.8 Target Storage

With two production lines, each operating at half capacity, it should not be necessary to store more than 6000 finished targets in each line for a total of 12,000 targets (~30 g of tritium). This would provide for 1/2 hour of reactor operation in the event of a failure of one production line. The probability is high that the remaining line could be brought to full-up capacity in the half-hour provided by the stored targets. Because the target production processes will have been tested and perfected, reliability should be very high by the time an operating target facility is constructed.

4.1.9 Tritium Inventory

The tritium inventory of the entire target production facility can be determined within the bounds of the assumptions made for target storage, target transport during fabrication, fill process tritium requirements, and tritium in pipes leading to the fill stations. Table 4.2 provides a

Table 4.2. Total Tritium Inventory

Process Step	Inventory (g)
Injection Step	210
Layering and Q/A Steps	10
Sabot Loading	10
Storage of Complete Targets	29
Transport Chain to Chamber	1
Piping and Purge Lines	40
Total Tritium Inventory	300

tabulation of the tritium inventory for the IFE fusion reactor target production facility. The estimated total tritium inventory for the target production facility is about 300 g.

4.1.10 Production Facility Building

We propose that the capsule production, fill system, transport, storage, sabot production and loading, and other target handling functions will all be accomplished in clean (10-100 class), enclosed "boxes." Thus, it will not be necessary to build the target production facility building to clean room specifications. It will be sufficient to have the entire facility at 10,000 to 100,000 class cleanliness. The entire apparatus in which targets are filled, transported, manipulated, and stored will be constructed for total containment of the tritium so the building itself need not be more costly than ordinary construction.

4.1.11 Summary

The follow points summarize the features of the target production facility design:

- Our design approach will lead to high reliability due to 100% redundancy of process lines.
- The tritium inventory is minimized by using fill and layering techniques that can be completed in seconds instead of hours.
- A small capsule storage inventory is judged to be acceptable because of the redundancy and high reliability.
- The required building is compact, which should lead to acceptably low cost.
- Much of the technology is unproven and requires development.
- The payoff in pursuing these innovative target production approaches is very high in terms of reducing the tritium inventory and the size and cost of production equipment and buildings.

4.2 TARGET INJECTION, TRACKING, AND POINTING

4.2.1 Introduction

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.

4.2.2 Injector System

Figure 4.3 is a schematic of the baseline target injection and tracking system that uses a gas gun for target acceleration. After leaving the acceleration section, the target travels a constant velocity 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, the tracking length, and the radius to the outer edge of the chamber. Design parameters for the injection system are given in Table 4.3.

Table 4.3. Baseline Target Injection Parameters

Acceleration (g)	130
Accelerator Length (m)	9
Final Injection Velocity (m/s)	151
Time in Accelerator (m)	119
Sabot Removal Length (m)	2.5
Time for Sabot Removal (m)	17
Rotational Velocity for Sabot Removal (RPM)	570
Time for Tracking (ms)	50
Time in Chamber (ms)	50
Total Time from Target Firing to Ignition (ms)	235
Time Allowed for Coarse Corrections (ms)	100
Time Allowed for Fine Corrections (ms)	50

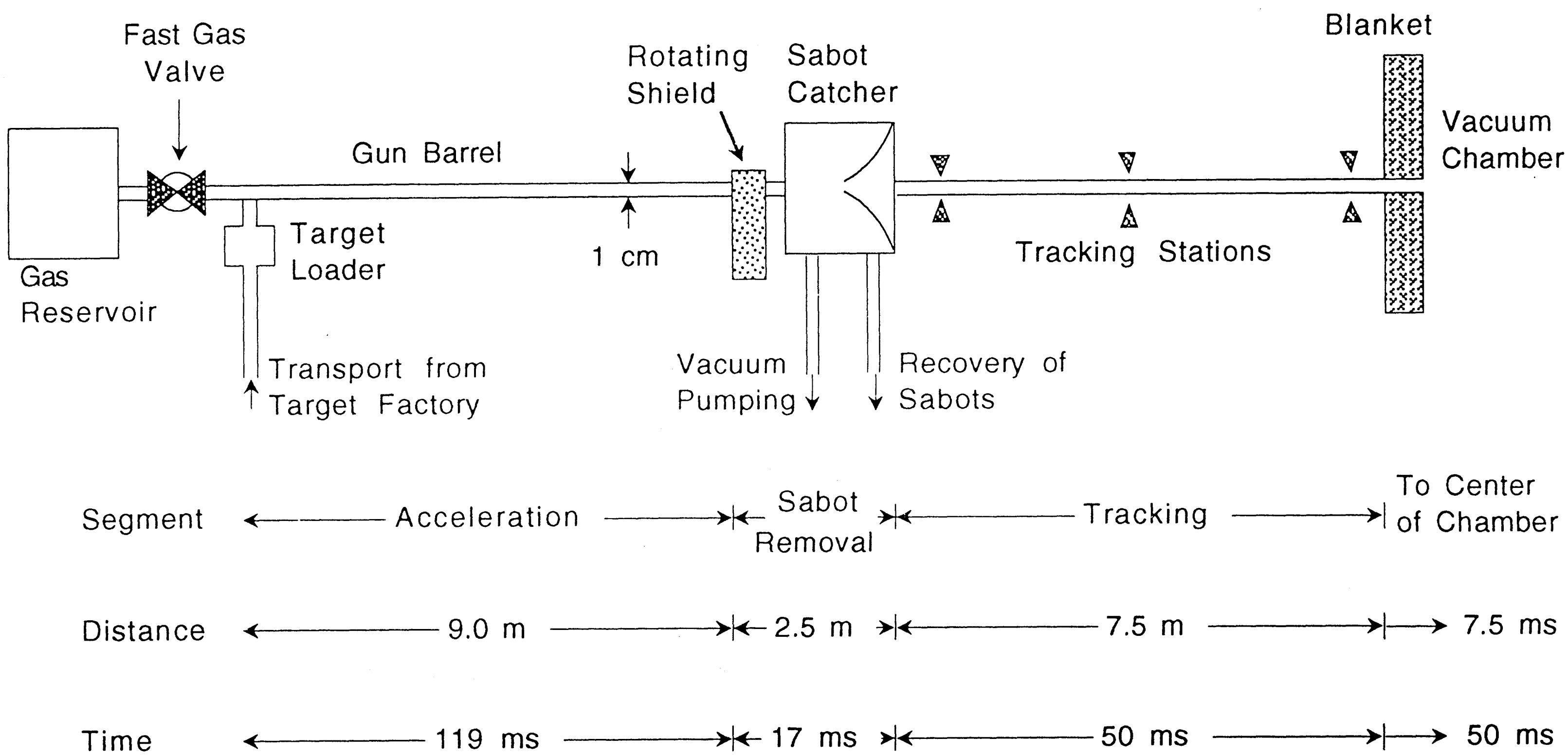

Fig. 4.3. Schematic of the reference design for the target injection and tracking system.

The light gas gun was 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. 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. Acceleration limits on targets, heating of the sabot, barrel wear, and loading, recovery and refilling of sabots are critical issues which must be addressed.

4.2.3 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. 4.4. 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.

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 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. 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.

4.2.4 Beam Pointing

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.[15] One example is the cooled fast steering mirror system with a 600 Hz bandwidth used by United Technology

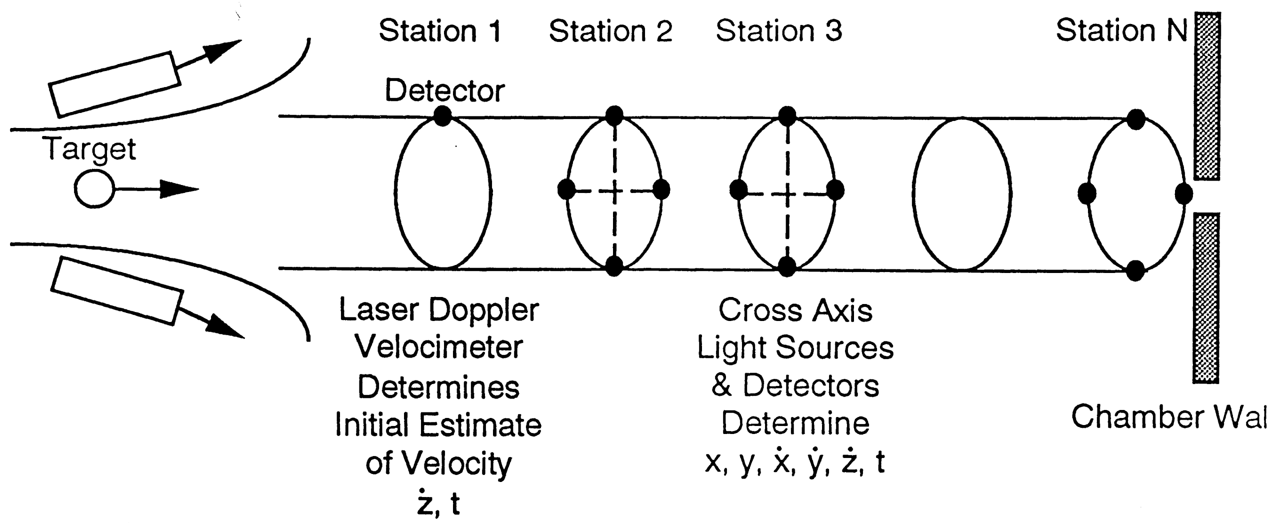

Fig. 4.4. Tracking system using multiple tracking stations.

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.

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.

4.2.5 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.

4.3 TARGET HEATING DURING INJECTION

4.3.1 Introduction

The targets contain cryogenic fuel, which must not liquefy or vaporize prior to implosion. The targets also have very precise dimensions in their non-fuel shells, which must be maintained prior to irradiation by the driver beams. The required vapor pressure inside the central void of the target is a strong function of the fuel temperature and must also be maintained at a prescribed level. A preliminary assessment was made of the effects of heating due to radiation from the target chamber walls and due to convective heat transfer from the target chamber gas.

4.3.1 Heat Loads

We have considered two types of heat loads on the surfaces of both target types; convective heat transfer from the chamber gas to the target and radiative heat transfer from the target chamber walls. The gas conditions are very different in the two reactor designs. The target velocity for both reactor concepts are ~150 m/s. The approximate heat loads for the two target are given in Table 4.4.

Table 4.4. Target Heat Loads

	SOMBRERO	Osiris
Wall Temperature (K)	1758	923
Gas Temperature (K)	1758	923
Gas Density (cm^{-3})	3.55×10^{16}	3.55×10^{12}
Gas Species	Xenon	Flibe
Conductive Heat Load (W/cm^2)	4.2	6×10^{-5}
Radiative Heat Load (W/cm^2)	54.2	4.1
Total Heat Load (W/cm^2)	58.4	4.1

4.3.3 PELLET Computer Code

The PELLET computer code was developed at the University of Wisconsin to simulate the heating of ICF targets by the target chamber environment. PELLET uses information on the target geometry and the surface heat load to calculate the temperature at every position in the target as a function of time. Temperature dependent material properties were used in the calculations.

4.3.4 Results

The results of the PELLET code calculations are summarized in Table 4.5. The peak temperatures in the different parts of the target are given.

Since the Osiris target must travel ~ 5 m through the chamber and is injected at a velocity of 150 m/s, ~33 ms will be required for the target to reach the ignition point. At the estimated heat load of 4 W/cm^2, the fuel would only reach about 8 K by this time.

The targets for SOMBRERO must travel 6.5 m through the chamber before it is imploded and if the targets travel at 150 m/s, the target surface is heated for 43 ms. At 58 W/cm^2, we estimate the outer fuel temperatures to be ~17 K. This is still below the triple-point, but there is only a 4 K margin for error. While the fuel remains below the triple point, the outer surface temperature of the polystyrene capsule is ~700 K. Since this is well above the melting point of polystyrene, it will be necessary to protect the capsule during transit through the chamber. One possibility is to keep the capsule in the sabot for most of the transit time. Another option is to freeze a thin layer of inert gas (e.g., xenon) on the outer surface of the capsule. The frozen gas would act as a sacrificial heat sink and evaporate as the capsule transits the chamber. This could reduce the time that the bare capsule is exposed to the hot chamber to a few milliseconds. Clearly, this is an area that requires further investigation.

Table 4.5. Peak Temperatures in Different Parts of Target

	Osiris	SOMBRERO
Time (ms)	33	43
Hohlraum	22	N/A
Capsule	22	700
DT Fuel	8	17