6.5.3 Common Driver Subsystems - For both types of drivers, several subsystems with common functions are required even though the specific implementation may vary. The following sections delineate those envisioned common systems.

6.5.3.1 __Power Supplies__ - Due to our limited resources and past conceptual design work[1] on EDEL pulsed power systems by Spectra Technology, Inc. (formerly Math Sciences Northwest), the present study invested minimal effort on defining the details of the pulsed power system. The pulsed power requirements are summarized in Table 6.5.3-1. These are comparable to the earlier design developed by Spectra Technology, Inc.

Table 6.5.3-1 Pulsed Power Requirements for EDEL

Parameter	Discharge	E-Beam
Aperture, A (cm)	44 x 44	44 x 200
Length, L (cm)	200	
Voltage (kV)	200	500
Current Density* (A/cm^2)	60	3
Total Current (kA)	530	38
Impedance (Ω)	1	30
Pulse Duration (ns)	300	300
Energy (kJ)	32	5.7
Inductance** (nH)	60	

* Indicated e-beam current is in gas, 70% diode to gas transmission assumed to find total current.
** Inductance estimated at $\mu_0 A/2L$.

The Spectra Technology, Inc. study[1] compared coaxial and triaxial (Blumlein) pulse forming line PFL configurations with mylar, water, and ceramic dielectrics. They selected a coaxial water dielectric PFL based on its self-healing characteristics and demonstrated capability to meet the design requirements. However, they noted that ceramic PFLs were also very attractive because their higher dielectric constants (~1500 as compared to ~80 for water) led to smaller sizes. In addition, ceramic PFLs can be slow charged which reduces the demands on the charging circuitry. Ceramic PFLs were, therefore, selected for the present design study. Development work is required to realize their full potential in the present application but their packaging advantages over water PFLs make them an attractive alternative, especially given the 2030 timescale of this study.

The resulting PFL design configuration is summarized in Table 6.5.3-2. There are 32 discharge PFLs and 2 e-beam PFLs for each beamline group of 16 EDELs. The overall system is, thus, packaged as indicated in Figures 6.3.1-7 and 6.3.1-8. Two discharge PFLs are arranged end-to-end along the side of each EDEL as indicated in

Figure 6.3.1-9. The discharge lasers are driven by two PFLs in parallel to minimize the connection inductance at the laser. The 1.2 m PFLs provide a relatively flat 250 ns pump pulse for the EDELs. A single e-beam PFL is located in the center vacuum chamber of the group driving all eight e-beam electrodes in parallel.

Costs for the laser pulsed power system are estimated based on $5/Joule of delivered energy. Pulsed power efficiencies are assumed to be comparable to those reported by Spectra Technology, Inc. They are summarized in Table 6.5.3-3.

The pulsed power system for the single-beam heavy ion driver is a key development area. Due to the fast recycle timescales (10-20 kHz), the SBL pulsers will likely require field effect transistor (FET) switching networks. FET technology has already been developed for some high voltage applications but not to the scale needed for the present application. LLNL has evaluated such networks in the context of a recirculating ring accelerator and concluded that they hold significant promise. FET modulators can operate at repetition rates approaching 100 kHz, can provide variable pulse widths, and are inherently long lifetime devices.

Table 6.5.3-2 EDEL Ceramic PFL Design Parameters

Parameter	Discharge	E-Beam
Total Energy (kJ)	32	5.7
Dielectric Constant	1500	1500
Breakdown Voltage (kV/cm)	300	300
Line Length (m)	1.2	1.2
Inner Electrode Diameter (cm)	4	4
Outer Electrode Diameter (cm)	18	53
Load Impedance* (Ω)	2	4
Number Per 16 EDEL Group	32	2

* Since e-beam load impedance is higher, two e-beam PFLs can drive the entire group of 16 EDELs for each beamline.

Table 6.5.3-3 Laser Pulsed Power System Efficiency Summary

Parameter	Discharge	E-Beam
HV-DC Power Conversion (%)	94	94
Intermediate Storage (%)	92	92
PFL (%)	90	90
Output Line and Switch (%)	–	92
Load Transfer (%)	–	92
Gas Transfer (Habachi/Foil (%)	–	70
Rise/Fall Time Losses (%)	83	83
Net Pulsed Power Efficiency (%)	65	38

The main issue relative to such switching networks is cost. The pulsed power system cost factor for the SBL is, therefore, increased by a factor of ten above the $10/Joule value used for the MBL. Even with this assumption, the total SBL pulsed power system cost is comparable to that for the MBL because the total energy it must deliver per cycle is reduced by the number of beamlets. Technology development will nevertheless be required to realize this cost goal; however, comparable cost reductions are not unprecedented for advanced semiconductor devices.

System efficiencies for the SBL pulsed power system are comparable to those for the laser system. Power conversion, energy storage, and utilization are budgeted at 71%. Pulse forming and shaping are budgeted at 85% which is slightly lower than the laser system because pulse shape is more critical in an induction linac context.

6.5.3.2 Vacuum Systems - The laser driver system does not require a major vacuum system. Some local vacuum requirements may exist for maintenance purposes. There is a vacuum pumping requirement at both sides of the laser neutron pinhole to prevent beam breakdown in each of the 60 beamlines within the reactor building. This is conceptually illustrated in Figure 6.5.3-1.

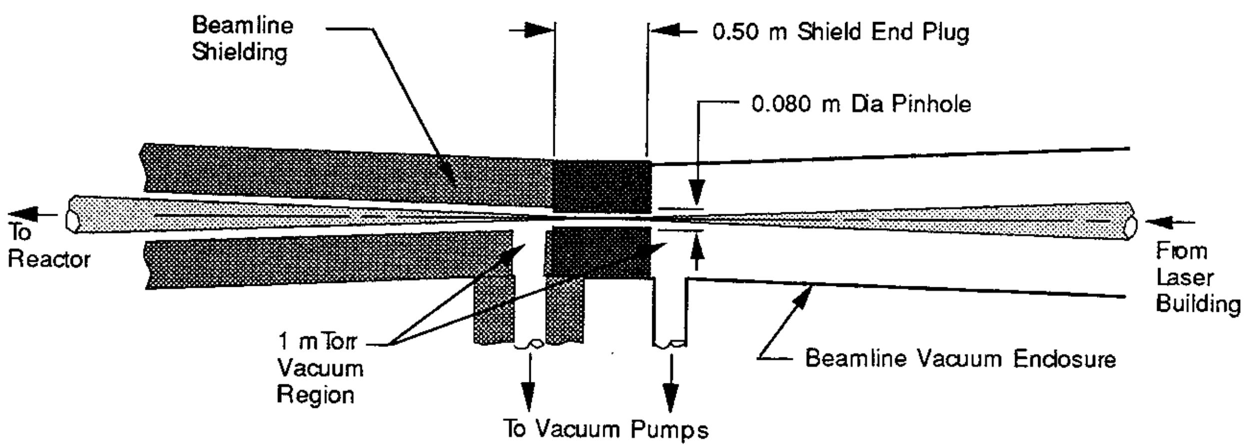

Figure 6.5.3-1. Conceptual Design of Neutron Pinhole to Limit Neutron Propagation into Driver Building (Typical 60 Places)

The heavy ion beam driver requires vacuum pumping in the region of the final ballistic focus of the beams. Figure 6.5.3-2 depicts the general arrangement. An enclosure provides a common vacuum plenum. The ion beam vacuum requirement in this region is 10^{-5} torr. Two cryogenic vacuum pumps are provided to achieve that level of vacuum. If additional pumps are needed for extra capacity or redundancy, they can easily be accommodated. The plenum region extends through the shield and vacuum enclosure to adjoin the back face of the blanket. This arrangement should provide minimal leakage into the plenum. The enclosure is modular which allows easy replacement and access to remove the blanket modules and associated plumbing.

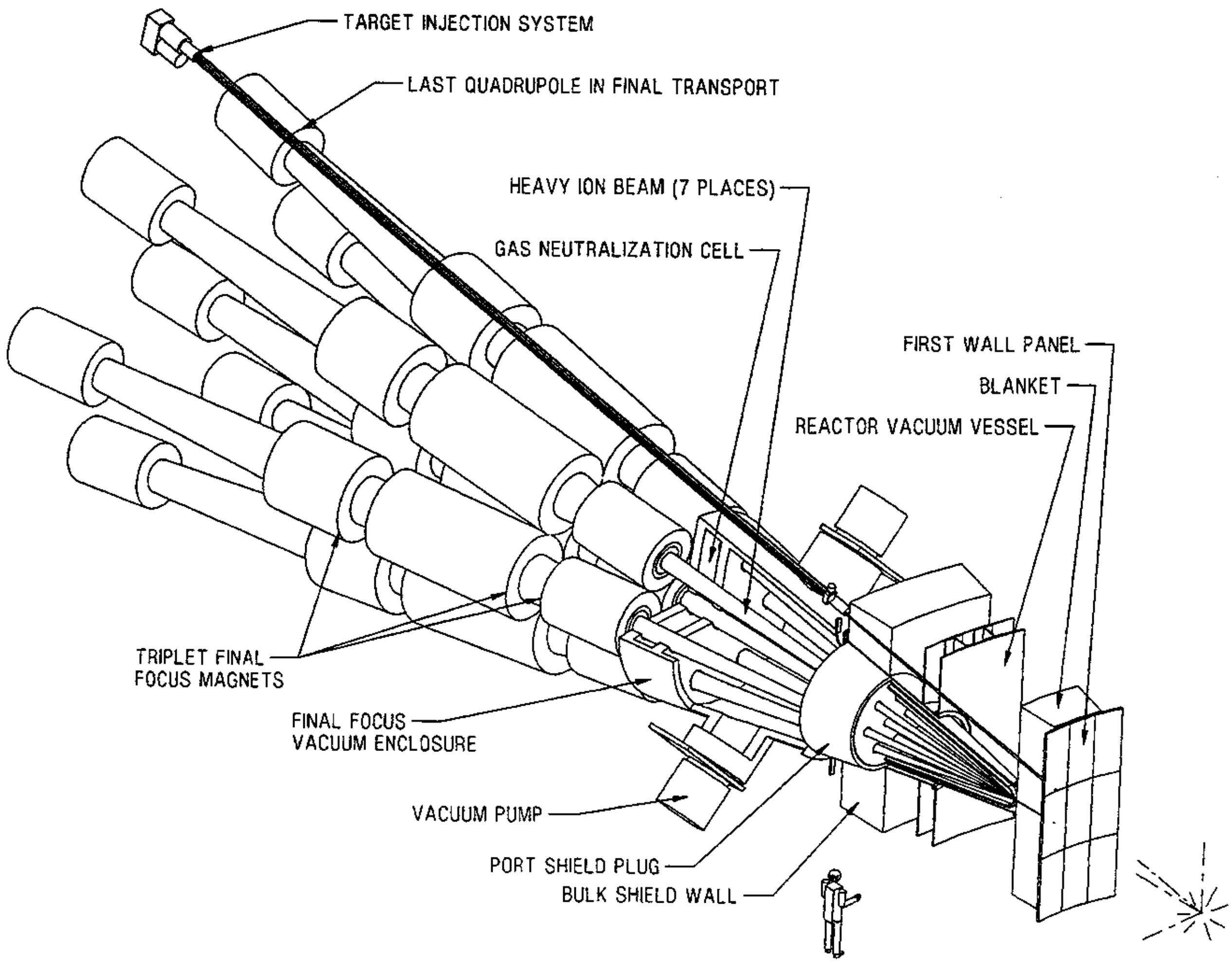

Figure 6.5.3-2. Common Enclosure of Heavy Ion Beams Provides Plenum for Attaining 10^{-5} torr Pressure Level

6.5.3.3 **<u>Instrumentation and Control</u>** - The general subject of instrumentation and control for systems as large and complicated as the Prometheus-L KrF laser driver and the Prometheus-H heavy ion driver requires an extensive research and development program itself in order to accomplish the enormous task of defining and specifying these important subsystems. For the current study, a brief overview of some of the control characteristics, problems, and issues will be provided. The major purpose of this brief discussion is to initiate an in-depth study of the problem, together with appropriate future development programs, to address the tasks in a timely manner.

Adequate instrumentation and associated controls required for the two driver systems, Prometheus-L and Prometheus-H, must be based upon careful utilization of the following elements:

(1) Parallel processors
(2) Detailed integration of fast-response sensors with control circuits
(3) Emphasis on sensor and control redundancy
(4) Extensive use of artificial intelligence
(5) Development of expert systems to permit computer control over every aspect of Prometheus driver operation

Significant emphasis needs to be placed on fail-safe sensing and control methodology to insure that the basic safety features designed into the drivers are adequately exploited by the control system.

An example of this sensor and control methodology is the problem presented by the control systems monitoring the pulsed power to the electric-discharge excimer lasers (EDELs). The sensor set required to monitor the performance of each of the 1020 large EDELs would measure performance data. The control system data processing system would then normally record the current performance data and compare it with historical references.

Two general types of sensor and control operation have been identified:

(1) Deterioration and probable failure of an EDEL in normal operation
(2) Sudden failure occurring essentially without prior warning

For the first type of problem, the associated expert system would have pre-programmed the appropriate EDEL control system to recognize a potential failure mode in its early stages and schedule a shutdown for the EDEL prior to any catastrophic breakdown.

The second type of problem also requires implementation of expert system technology, but in this case there must be a pre-programmed shut-down mode to minimize further damage to the EDEL concerned and any other affected subsystem.

In the case of the Prometheus-H heavy ion driver, a comparable example of the operation of sensors and controls would be the placement of heavy ion beam sensors within the ramp and constant gradient sections of the linac for monitoring radiation levels and temperatures of cryogenic elements associated with the superconducting magnets. If significant numbers of ions from the beam were drifting into the cold magnet elements, prompt expert system analysis of the problem and a corrective action would have to be taken quickly to prevent possible magnet damage, loss of superconductivity, loss of beam current, and eventual shut down of the reactor.

Since human reflexes are at least six orders of magnitude too slow to deal with rapid developments within the Prometheus drivers, implementation of a state-of-the art instrumentation and control system is critical to permit these drivers to perform at their inherent design capabilities. Thus if a particular driver process can undergo a deterioration occurring on a microsecond time scale, an overall calculation of the length of time for the sensor to make the measurement, transmit the data, alert the control system, and still give the control system sufficient time to exercise a remedy will produce a series of specifications for the required speed of each of these operations.

The principal functions of the driver instrumentation include the following tasks:

(1) Monitor normal driver functions at data rates appropriate for the required response times for possible corrective action.
(2) Monitor abnormal driver functions (associated with catastrophic driver failures); these circuits must have priority over normal monitoring activities.
(3) Provide redundant inputs to detect, quickly sense, and/or control malfunction.

In many cases, the respective sensor must be orders of magnitude faster than the driver process being monitored, if abnormal operation is detected, in order to permit data to be collected, a corrective action taken, and the results analyzed.

The general controls category consists of five elements:

(1) Priority data way for abnormal driver function data.
(2) Normal operation data way for monitoring driver performance and needs for maintenance.
(3) Dedicated parallel processors for abnormal data evaluation, programming with expert system procedures to recommend a particular course of control action, together with high speed data links with the required driver elements involved in the expert system corrective action.
(4) Multilevel, multispeed, multipriority data ways with the central processing unit (CPU) responsible for overall driver control and performance evaluation.
(5) High speed apparatus for invoking control commands generated by CPU analyses.

A simple schematic of the instrumentation and control methodology is illustrated below in Figure 6.5.3-3.

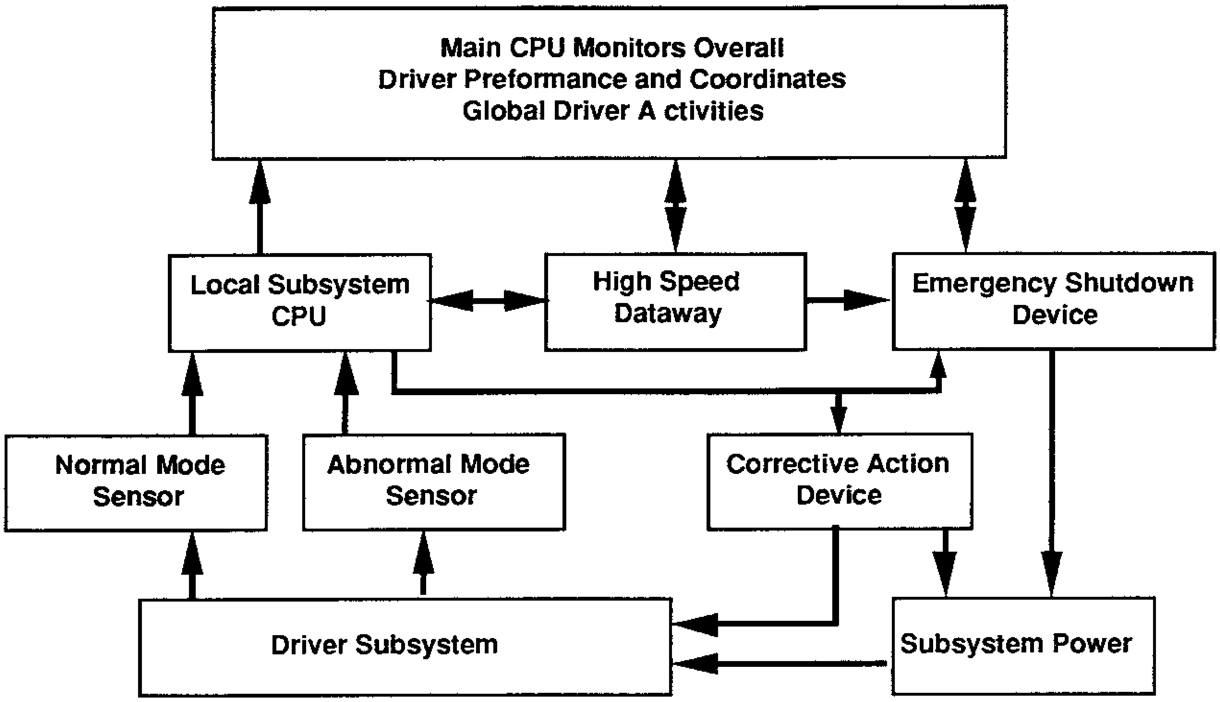

Figure 6.5.3-3 Prometheus Instrumentation and Control Methodology

In general, design, development, and engineering of instrumentation and control systems for large driver systems is a developing field which can draw upon the recent advances made in data processing, reduced instruction set computers, parallel processing, dedicated processors, etc., together with integration of the control methodology into the design of the monitoring sensors themselves. By fixing the technological cutoff for the year ~2030, the Prometheus driver designs have made assumptions regarding significant cost reductions for the instrumentation and control equipment, while giving this crucial subsystem the importance it deserves.

6.5.3.4 Driver Maintenance Equipment. - The maintenance of the components of the two driver systems within the Reactor Building is assumed to be a part of the Reactor Maintenance Equipment. This is partially because of the common location and also because of the commonality of the high radiation environment. However, maintenance of these systems will be briefly discussed. The final optics for the laser driver, the final focus mirrors and the GIMMs are long lived, perhaps the lifetime of the reactor. Nevertheless, these components must be replaceable with a short MTTR as replacement of one of these elements will bring the plant off-line. Dedicated maintenance equipment will service these optical elements.

Maintenance equipment within the Driver Building will also be dedicated equipment specific to handling precision optical elements, gas flow systems, and high power devices. These may be mounted off an overhead crane or a track mounted maintenance device. It is envisioned that the optical elements will have sensing devices which will self-diagnose their condition and make appropriate adjustments. Largely, maintenance will be only replacement of failing elements.

The heavy ion beam final focus coils are designed to be life-of-plant with very long MTBF requirements. This is required as a failure would cause the plant to be shutdown until the component is replaced. Again dedicated maintenance machines would replace the individual final focus coils. If the final focus vacuum plenum would need to be removed, some or all of the coil sets would be removed to gain access. For blanket removal, sufficient clearance would be provided to allow removal of the blanket and plenums.

The maintenance equipment within the heavy ion accelerator tunnel will be overhead crane-mounted equipment and rail-mounted manipulators to remove and replace linac components. Several sets of equipment will be required to enable parallel operations at different locations along the linac.

6.5.3.5 Driver Shielding - Care has been taken to provide adequate shielding to protect the personnel and equipment within the Driver Buildings and to provide personnel access to the Reactor Building within 24 hours of shutdown. The thicknesses of the laser and heavy ion beamlines were based upon the effectiveness of the composite bulk shield, the relative size of the beamline openings in the blanket and bulk shield, the distance from the neutron source, and (for the laser configuration) attenuation provided by beamline bends.

The general shielding provided by the laser beamlines is shown in Figure 6.5.3-4. Bulk shielding closely encloses the beamlines from the beam penetration through the bulk shielding wall to the GIMM, the final focusing mirror, and on to the neutron pinhole region. A neutron trap region is provided behind the GIMM to capture the high energy neutrons which penetrate the GIMM. The shielding material is the same B_4C, Pb, SiC, and water composite material which is used in the bulk shielding. The shielding thickness of the conical sections is 25 cm out to the final focus mirror, and thereafter the thickness is 20 cm. A shielding thickness of two meters is provided at both the end of the neutron trap and the end of the beamline at the final focus mirror. The thickness of the shield at the pinhole is 0.8 meters which is shown in Figure 6.5.3-1. Following the neutron pinhole, the beamline will be enclosed with a lightweight enclosure to the vacuum window at the beamline penetration at the reactor building wall.

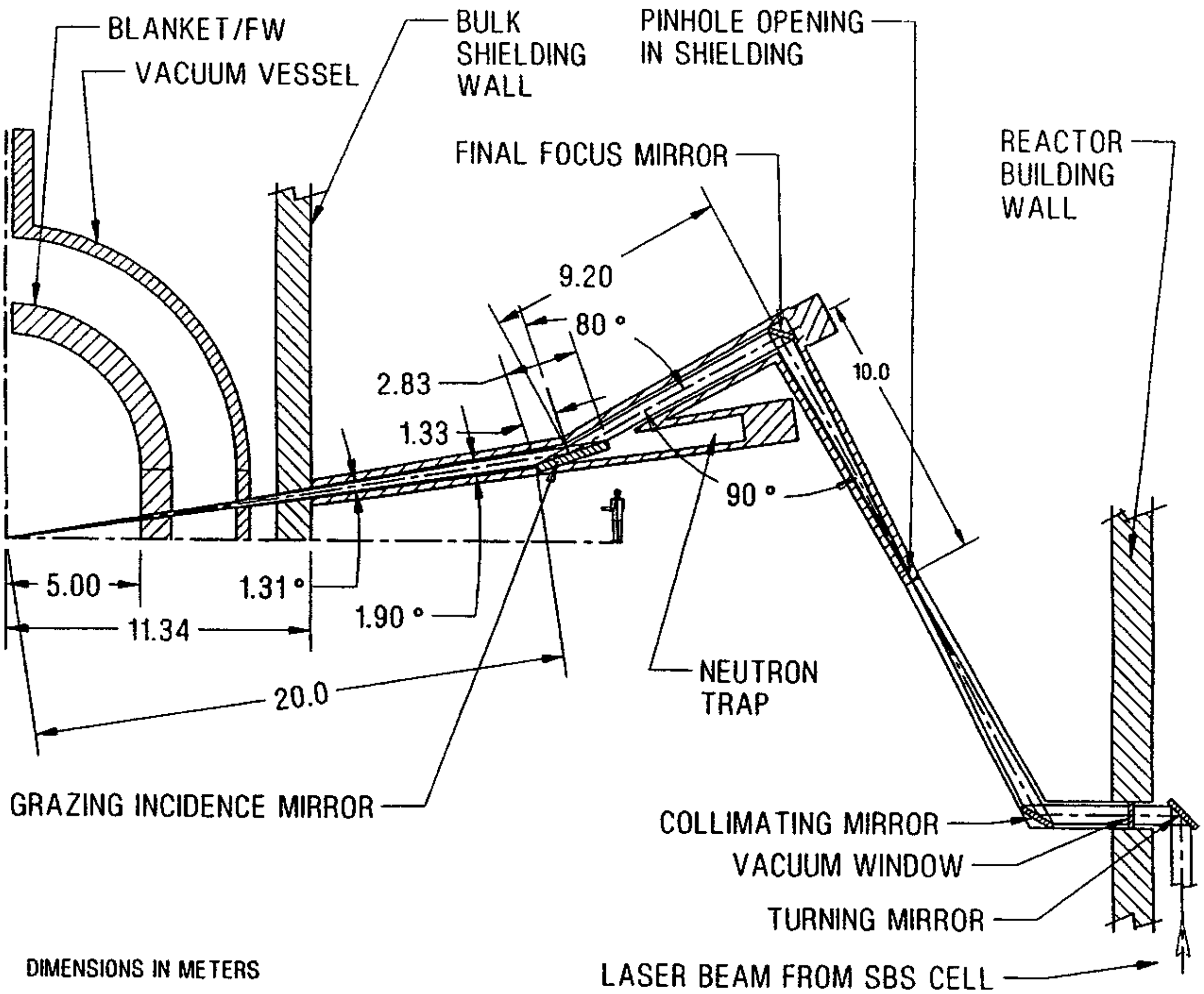

Figure 6.5.3-4. Shielding of Final Laser Optics Contains Radiation Within the Beamline

The beamlines of the heavy ion beams are afforded more protection by the blanket region. This is because the penetrations through the blanket are only 2 cm in diameter. Only the central beamline has direct line of sight through the shield and the blanket to the target as shown in Figure 6.5.3-5. All other beamlines have direct line of sight only to the back of the blanket. A port shield plug is sized to cover all areas except for the beams and the necessary radial clearances. The conical surfaces of the final focus vacuum enclosure is constructed of 15 cm of the composite shield materials. The vacuum pump extensions are 25 cm thick. The two disk-shaped shield elements just in front of the coils serve as shielding as well as a plenum region for the lead vapor neutralizing zone. Each of these disk elements is 25 cm thick to shield the ends of the superconducting coils. The only remaining parts to shield are the inner

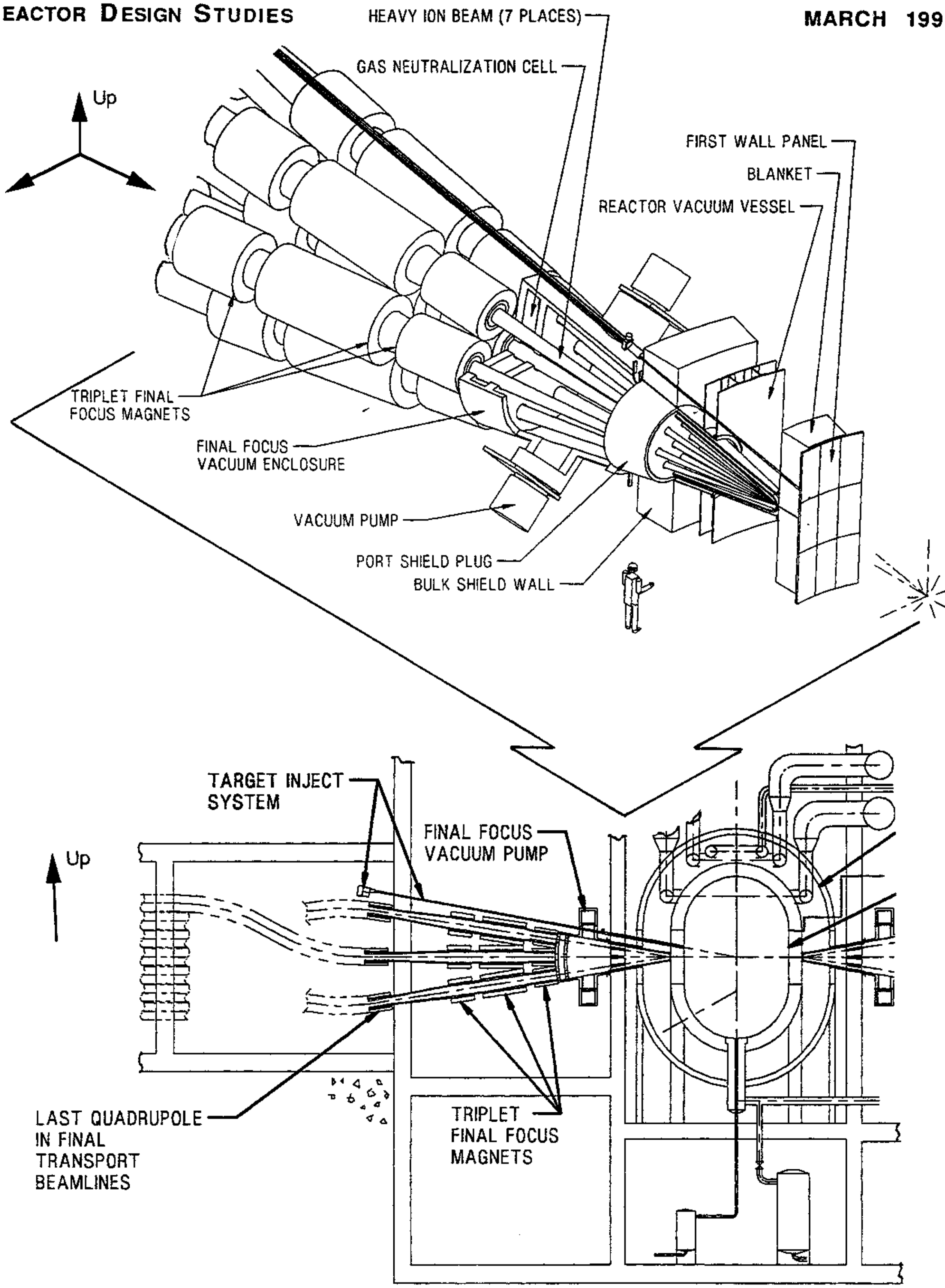

Figure 6.5.3-5. Details of Heavy Ion Beam Final Focus Shielding

bores of the superconducting coils. The coils have been sized to enable a layer of shielding within the inner bores of the triplet magnets and dipoles. This shielding will extend down the beamline until the damage in the coils and insulators reaches acceptable levels. The lower half of Figure 6.5.3-5 indicates how the beams will be shifted out of plane before exiting the next building boundary.

Reference for 6.5.3

1. Mark Kushner, et al., "New Technologies for KrF Laser Fusion Systems," Interim Report for Los Alamos National Laboratory by Spectra Technology, Inc., Seattle, WA, 1989.