University of California, San Diego

UCSD-ENG-090

# Inertial Fusion Energy Chamber R&D Needs: A White Paper

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**April 1998**

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# Inertial Fusion Energy

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*A White Paper*

**6 April 1998**

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## 1. Introduction

During the past several years, significant progress has been made in inertial fusion target and driver research, primarily through the large "stockpile stewardship" programs of DOE's defense programs. This includes, for example, improvements in direct-drive target illumination using beam smoothing techniques [1], development of efficient lasers with high power and high repetition rate [2,3], and indications that "fast ignition" could significantly increase target gain [4,5]. Operation of new inertial confinement fusion (ICF) facilities such as Omega-Upgrade [6] and the National Ignition Facility (NIF) [7] will further the development of ICF targets and drivers.

While this progress in developing targets and drivers renews hope for civilian applications of ICF, the impact of high-yield, high repetition rate shots on the chamber walls and surrounding systems remains a major obstacle. For a practical size of an inertial fusion energy (IFE) power plant chamber, energy release from high-yield, high-repetition rate shots results in such high particle and heat fluxes on unprotected chamber walls and final optics that they will not survive even for a short period of time. Therefore, developing a chamber wall protection concept that is compatible with the requirements of the target/driver system is a central feasibility issue for fusion energy applications. The specific requirements for chambers may vary depending on the choice of driver (*i.e.*, light or heavy ions, gaseous or solid-state lasers) and target system (*i.e.*, direct, indirect, or fast-igniter illumination), but the issues remain generic to all concepts. Defense programs are unlikely to solve this problem, due to the fundamentally different requirements on the chamber and related systems.

Numerous IFE power plant studies have been performed during the past decades. These studies contain a wealth of information on the predicted response of the chamber walls and final optics. They also include many innovative ideas to solve these problems. In principle, either the chamber wall should include a sacrificial, replaceable material (*e.g.*, liquid walls) or the energy from the explosion should be absorbed (*e.g.*, in low-pressure chamber gas) and reradiated at a much slower rate to reduce the incident peak power on the structural walls. These design concepts will require a focussed and coordinated program of R&D in order to understand the underlying physical mechanisms and demonstrate their feasibility.

The phenomena present in high-yield, high-repetition rate target chambers following target ignition are highly complex, and can not be duplicated completely in present experimental facilities. Even a powerful device such as NIF lacks key elements of a reactor chamber, including relevant wall protection materials (*e.g.*, liquid wall or gas protection) and relevant repetition rates. Much of the progress to date has come from numerical modeling with computer codes. For example, chamber phenomona were studied extensively in the late 1970's [17]. More recently, models such as TSUNAMI [8] and BUCKY [9] have been utilized, and a small number of experiments have been performed. These efforts typically explored individual phenomena, such as isochoric heating effects [10], fluid mechanics of liquid jets and porous walls [8,11], shock propagation [12] and x-ray ablation of materials in vacuum [13].

Simulation codes, while sophisticated, still do not contain all phenomena of interest and/or the models are not benchmarked against relevant experimental data, as such data do not exist. As a result, many fundamental uncertainties remain in predicting the chamber response to the blast effects. As a whole, the feasibility of high-yield, high-repetition rate target chambers **has not** been demonstrated. This conclusion also has been observed in several reviews of IFE [14,15]. An expanded and coordinated modeling and experimental activity is needed to achieve a predictive capability to analyze IFE chambers, to be able to verify and/or reject various ideas, and to guide further R&D.

In the following sections, design concepts and their key issues are summarized. A modest program of R&D, including further development and verification of models as well as small-scale simulation experiments, is described and shown to be essential for further progress on IFE.

Chamber R&D **cannot wait** until driver and target systems are demonstrated. As mentioned above, the central issue for attractive IFE applications is compatibility between the chamber wall protection concept and the target/driver system. Further development of targets and drivers without regard to the severe limitations imposed by acceptable wall protection will likely lead down a path to an unattractive end-product.

## 2. Background

### *2a. Chamber Design Concepts*

The primary channels of energy release in an ICF target blast are photons (mainly XUV and soft x-rays) and debris, where debris can be in the form of ionized particles, condensates, and/or shrapnel. Ignited targets also produce high-energy neutrons and alpha particles. All of these result in distinctly different phenomena, as they propagate in a different manner through the chamber, arrive at the chamber walls and optics at different times, and interact with materials quite differently.

For a practical physical size of an ICF chamber, the energy released from a high-yield, high-repetition rate shot results in such high particle and heat fluxes on unprotected chamber walls and final optics that they will not survive even for a short period of time. Roughly 10 μm of wall (corresponding to 20 kg or more of material) would be lost during each pulse. Unlike magnetic fusion, in which design concepts usually adopt solid first walls exposed to the burning plasma, inertial fusion chamber designs must address the high instantaneous damage rate. Various designs incorporate gases, liquids, flowing granular media or solid shields between the targets and the surrounding structures.

Many IFE chamber studies have been carried out during the past decades (several dozen, in fact). These studies contain a wealth of information on the response of the chamber walls and final optics. They also include many innovative ideas to solve these problems. In principle, either the chamber wall should include a sacrificial, replaceable material (*e.g.*, liquid walls) or the energy from the explosion should be absorbed (*e.g.*, in low-pressure chamber gas) and reradiated at a much slower rate to reduce the incident power on the structural walls. Table 1 summarizes the main design categories. (Ref. 16 provides a good summary of the status of IFE reactor designs prior to 1985.)

In general, an increasing level of wall protection corresponds with a higher degree of difficulty assuring acceptable conditions for target and driver propagation. In the thick liquid wall scheme, jets of liquid protect the solid walls of the chamber. These curtains of liquid are intended to be so thick that even neutrons are absorbed, alleviating to a large extent the problem of neutron radiation damage. Propagating targets and beams into such a device will be a difficult task, requiring effective and rapid chamber clearing.

A “wetted” first wall provides greater flexibility in tailoring the wall geometry to accommodate beamlines and other penetrations. Since absolute integrity of the first structural wall is not required, there is some benefit with respect to radiation damage and failure modes as compared with solid first walls. Both thick jet and wetted wall concepts have development issues associated with the choice of working liquid, including recombination rates of ablated material, effects of different constituent elements on driver propagation, interaction with solid wall materials, *etc.*

More conventional solid wall design concepts typically use a “high” pressure (up to 1 Torr), high-Z (*e.g.*, Xe) gas to attenuate the x-rays and particle debris. While high gas pressure can reduce the particle and power fluxes on the chamber walls and final optics to manageable levels, two critical issues arise: propagation of the driver beams through a high-pressure gas, and chamber gas response to high-yield, high-repetition energy release.

Granular wall protection is similar to liquid protection, except that the medium allows lower vapor pressure at elevated temperature, which may be a requirement in some systems. Recondensation of the vaporized solid remains a critical feasibility issue, as does control of free flowing particulates that exhibit no cohesive forces.

Finally, the novel “Starlight” concept [30] proposes to provide a Li shield of ~1 kg around each and every target. This allows a “dry” chamber wall, although the inner surfaces likely would act as condensers and therefore resemble wetted surface designs.

In an IFE power plant, the materials behind the first surface are essential for fuel breeding, energy conversion and shielding. Table 1 summarizes the technologies adopted in various power plant studies for the “blanket” functions. The blanket embodies a wide range of development issues of its own. In this document, attention is restricted to only those issues arising from wall protection and chamber dynamics.

**Table 1**
**Summary of Chamber Design Concepts**

| | Wall protection type | Blanket features | References |
|---|---|---|---|
| **Thick liquid streams** | | | |
| HYLIFE-I | gravity-driven flow, Li | Li | [17] |
| HYLIFE-II | advanced flow injection, Flibe | Flibe | [18] |
| SENRI-I | magnetically-guided | Li/steel | [19] |
| **Wetted wall** | | | |
| HIBALL | INPORT tubes | PbLi-filled C-fiber | [20] |
| SENRI-II | porous ceramic guide tubes | Li/steel | [21] |
| LIBRA | INPORT tubes | PbLi/SiC | [22] |
| Prometheus-L and -H | Porous wetted wall | $Li_2O$/SiC/He | [23] |
| KOYO | Porous wetted wall | $Li_2O$/SiC/He | [24] |
| OSIRIS | Porous tent, spray condenser | Flibe | [25] |
| **Gas protection ("dry wall")** | | | |
| SOLASE | dry-wall, 0.25 Torr Xe | graphite, $Li_2O$ pebbles | [26] |
| SIRIUS | 3D graphite, 1 Torr Xe | Li/V, Be | [27] |
| SOMBRERO | Dry wall, 1 Torr Xe | $Li_2O$ | [25] |
| **Granular protection** | | | |
| CASCADE | centrifugally rotated | BeO, $LiAlO_2$, SiC | [28] |
| "falling balls" | gravity-driven free-fall | Li ceramic, SS | [29] |
| **Solid protection** | | | |
| Starlight | Li target cover | steel/He/$Li_2O$ | [30] |

### *2b. Chamber Issues*

Recent studies have assessed a wide range of issues requiring R&D in order to establish a practical IFE energy system [*e.g.*, 31–34]. The classes of issues that concern wall protection and chamber dynamics are summarized below and in Table 2. This set of issues is most strongly tied to the driver and target system design, and thus are essential in the near-term development plan.

1. Chamber dynamics and achievable clearing rate. For most wall protection concepts, the key uncertainty is whether or not the chamber volume will return to a sufficiently quiescent and low-pressure state following a target explosion to allow a second shot to be initiated within 100–200 ms. The chamber condition following a shot in an actual chamber geometry is not well known. 1D computer predictions suggest that recondensation will occur rapidly [35], but a variety of possible phenomena may affect this conclusion dramatically. Some examples of processes which may play a role include in-flight recondensation leading to aerosol production, complex geometric effects (such as beamlines) on gas-dynamics and heat transfer, and macroscopic fluid effects such as splashing and jet break-up.

2. Propagation of targets and beams. Since the goals for chamber clearing arise from the requirements of driver and target injection, it is important to establish the sensitivity of the beams and targets to the chamber environmental conditions: pressure of various species, temperature, aerosol or droplet content, residual gas-dynamic motions, etc. A fundamental requirement for laser propagation is to avoid absorption and scattering due to gas ionization, which is a function of incident intensity and gas pressure [36]. In order to propagate a beam at $10^{14}$–$10^{15}$ W/cm$^2$, the background gas pressure must be less than about 0.1–1 Torr, depending on the constituent gas. Prior to full gas breakdown, non-linear processes such as stimulated Raman and Brillouin scattering may contribute to distortion of the wavefront. Since beam uniformity is such an important criterion to avoid target instabilities, requirements may be more stringent that the ionization limit. In addition, since ignitor beams for the fast ignition concept may exceed $10^{18}$ W/cm$^2$, pressure limits may be further reduced. Effects of aerosols and droplets on beam quality have not yet been addressed.

3. Flow control. Except for dry wall concepts, the ability to form a continuous protective medium around all exposed surfaces is a difficult challenge. Studies suggest that films can break up or detach due to both surface pressure pulses and volumetric (isochoric) heating. Controlling the flow around beamlines and other penetrations (like diagnostic and target injection ports), and especially protecting the upper chamber walls will be difficult.

4. Protection of final optics. Some elements of the chamber may be difficult or impossible to protect with continuous liquid shields. For example, the final optical element of a laser driver, whether it's a window or a mirror, must have direct, line-of-sight access to the target area. This is a particularly difficult design problem due to the stringent requirements on purity and uniformity to allow proper beam characteristics.

5. Surface interactions. For dry-wall concepts, or for in-vessel components that can not be effectively coated with liquids, response of the surface to the blast must be better understood. This includes, for example, material response to short-pulse thermal and pressure stresses, erosion and redeposition of surface materials, and fracture mechanics under neutron irradiation and cyclic loading.

These issues can be addressed through a modest coordinated program of R&D that seeks to elucidate the underlying physical processes and to demonstrate the feasibility of design concepts and their compatibility with various target/driver systems. An R&D plan that achieves these objectives is described in the following section.

**Table 2**
**Main classes of chamber dynamics issues which can be explored in near-term experiments**

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**Chamber dynamics and achievable clearing rate**
- Homogeneous and inhomogeneous condensation
- Aerosol and particulate generation
- Geometric effects (*e.g.*, beamlines)

**Propagation of targets and beams**
- Gas ionization
- Wavefront distortion from nonlinear scattering
- Nonideal chamber conditions (aerosols, droplets, spatial inhomogeneities, ...)

**Flow control**
- Flow path control
- Coverage of all exposed elements
- Flow extraction from vacuum chamber

**Protection of final optics**
- Blast mitigation and effects
- Contamination from chamber materials
- Neutron damage

**Dry wall lifetime**
- Erosion/redeposition
- Thermal and mechanical effects

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# 3. R&D Plan

Given that appropriate large-scale chamber facilities are not currently available, the near-term research plan must utilize simulation experiments and modeling. Modest near-term experiments together with analytical and computational modeling used in an iterative process can provide a sound predictive capability of IFE chamber response and confidence in moving forward to larger devices. Modeling tools should be used to design simulation experiments which address issues that depend mainly on a limited set of environmental conditions and parameter ranges. The results from the experiments then can be used to verify and benchmark the analytical and computational tools and/or highlight inadequacy of the models. The improved predictive tools then can be used to plan the next generation of more integrated and prototypical experiments as well as future conceptual designs of IFE reactors.

Modeling and experimental needs are briefly summarized here. These R&D needs are then integrated into a chamber R&D "roadmap" that explains the logic of a focussed and coordinated program to develop and demonstrate practical chambers.

## *3.a Modeling needs*

Some calculational tools already have been created, allowing designers to predict some of the behavior of reactor chambers. However, much more simulation will be required to successfully and confidently determine the evolution of the chamber environment. Both classified and unclassified models exist; here we restrict our attention to models available in the open literature for unclassified energy research. It would be helpful to the IFE community at large to see some declassification of additional modeling tools or at least their capabilities.

Modeling needs are described in the categories of liquid flow control, interactions at interfaces, multi-dimensional gas dynamics, and laser and heavy ion propagation in gases and aerosols.

1. Liquid Flow Control. Basic studies of thin and thick liquid flows under the geometrical and loading conditions typical of IFE applications must be performed to verify that such flows are indeed possible and controllable, and that underlying surfaces can be adequately protected. The state-of-the-art in computational fluid dynamics (CFD) has advanced to such a degree that 3D free-surface flows can be modeled over fairly large areas. This means that with some effort, it is possible to simulate the flow of oscillating liquid jets, of films around beamline penetrations, and other geometrical elements of IFE chambers. Calculations of this type would allow initial designs to be refined to the point where meaningful gas dynamics calculations in appropriate geometrical configurations could be performed.

Problems or inaccuracies may stem from: (1) incomplete modeling of turbulence at these large length scales in the presence of free surfaces, (2) compressible response to impulsive loading on wavy free surfaces, and (3) energy deposition, phase change and heat transfer at short time scales. These phenomena must be addressed in a more fundamental way before they can be included in a "global" analysis of this type.

2. Interactions at Interfaces. Prediction of x-ray energy deposition, ablation of material, and initial gas dynamics close to the ablation surface has been the subject of past computational efforts using the BUCKY [9] and ABLATOR [37] computer codes. The power of these one-dimensional codes is that many phenomena can be simulated and physics models tested, without the burden of a multi-dimensional implementation. Physics models that could be tested on such a platform are non-Fourier heat conduction at the nanosecond time scale, fracture of liquid (or solid) wall materials induced by shock and rarefaction waves, in-flight recondensation of super-cooled vapor, *etc.* Once the general effects of the micro-scale physics are understood, results can be used as initial or boundary conditions for macro-scale, multi-dimensional codes, or models of desired phenomena can be integrated implicitly into the codes.

Another topic in interface interactions is turbulent heat transfer at liquid free surfaces. The time scale for this phenomenon is much longer than that discussed above. But turbulent motion will play an important role in the recondensation of liquid vapor, as it will likely determine the liquid surface temperature seen by the vapor. Computational analysis of this problem is possible using direct numerical or large eddy simulations of turbulent flows coupled with free surface models.

3. Multi-dimensional Gas Dynamics. The behavior of the chamber gas after pellet explosion involves interations with both the target energy sources and the surrounding surfaces. Radiation transport, density and temperature profile evolution will be affected by the wall geometry and will in turn affect the condensation rate and spatial dependencies within the chamber. Models like the 2D TSUNAMI code and and new 3D codes must include complex geometries, radiation transport, and accurate vapor sourcing and sinking capabilities. Chemical reactions may be important for some wall protection schemes. Ultimately, coupling between the dynamics and heat and mass transfer in the wall must be coupled to that in the gas. This is especially true for the thick liquid jet approach where the gas and liquid are intimately interpenetrating. This will be a difficult task, but ultimately may be possible given the current trends in CFD and computer capabilities.

4. Laser and Heavy Ion Propagation in Gases and Aerosols. Dry wall concepts rely on propagation through relatively high gas pressures, whereas wet wall environments will likely have some vapor pressure of non-noble gases, as well as aerosols and even droplets floating in the beam lines. The interaction of high intensity laser light or high charge density ion beams with this background may be the determining feasibilty issue associated with the selection of a wall protection scheme. Codes such as HYADES [38] can be used to model the basic interaction of lasers with materials, although more sophisticated tools will be needed to include non-linear effects and interactions with more complex background media. The beam quality may degrade long before gas breakdown prevents the incident photons from propagating. Ion transport models are available [39,40] for similar studies of heavy ion propagation.

### *3.b Facility characteristics and experimental plan*

Experiments which are needed to resolve the issues have been discussed previously (*e.g.*, beam propagation, fireball dynamics and radiative energy transfer processes, chamber clearing, and first surface response [31–34]). Except for flow control studies, a central concern for simulation experiments is the source of pulsed x-ray and debris energy. The energy spectra, pulse shape, and particle and power fluxes are all important parameters in determining whether the energy source is sufficiently prototypical to simulate the necessary environmental conditions for the phenomena that are under study. Certain phenomena that occur in a relatively "long" time scale, such as mass transport and recondensation, are more sensitive to the chamber geometry and spatial dependencies than to the exact shape and spectra of the initial energy pulse. Certain other phenomena, such as first surface response, are more critically dependent on duplicating the initial energy burst.

Table 3 summarizes the key parameters and their prototypical reactor values that should be attained in simulation experiments. These numbers are scaled from a generic spherical power plant chamber with 5-m radius, 500 MJ total yield – 400 MJ in neutrons and 100 MJ in photons and particles. (Note, the instantaneous surface energy density depends strongly on the wall protection scheme and yield spectrum. With high-pressure chamber gas and/or soft x-ray spectrum, most of the energy is absorbed before reaching the first surface.)

**Table 3**
**Reactor Prototypical Values of Chamber Parameters**

| **Phenomenon to simulate** | **Key experimental parameter** | **Reactor value** |
|---|---|---|
| X-ray spectrum | target temperature | 200–500 eV |
| Surface effects | surface energy density: | |
| | instantaneous (attenuated) | 20–200 kJ/$m^2$ |
| | time-integrated | 300 kJ/$m^2$ |
| Volume effects | volume energy density | 200 kJ/$m^3$ |
| Laser propagation limits | laser intensity | |
| compression beam | | $10^{14}$~$10^{15}$ W/$cm^2$ |
| ignition beam | | ~$10^{18}$ W/$cm^2$ |

**Table 4**
**Energy Sources for Simulation Experiments**

| | |
|---|---|
| Flow loops | [41,42] |
| Shock tubes (*e.g.*, LJAST liquid jet array shock tube) | [10] |
| Plasma guns | [43] |
| e-beams | [44] |
| Flashlamps | |
| Commercial lasers (ablation & propagation studies) | |
| | |
| Dense z-pinches (*e.g.*, SATURN) | [45] |
| ICF laser facilities (*e.g.*, NOVA, Omega, NIF) | |
| Dedicated x-ray source | |

A range of potential facilities can be used for selected simulation experiments (see Table 4). Traditional methods for producing short energy pulses include direct laser interaction with materials, dense Z-pinches, and laser illumination of metal foils to create x-rays. Longer time-scale simulations can be performed with plasma-based sources such as a Marshall gun, e-beams, or possibly flashlamps.

1. Liquid Flow Control Facilities. Perhaps the easiest small-scale experimental apparatus to envision and implement is a flexible liquid flow loop where flow control issues can be investigated. Such loops currently are in operation and/or under development at UC Berkeley (using water) and UCLA (using a low melting point liquid metal). Both facilities are used to study the dynamics of liquid jets in vacuum, relevant for the HYLIFE thick liquid pocket design, but could be expanded to examine other flow control issues. For example, other topics which could be investigated in such a facility include: oscillating liquid jet arrays in vacuum, film flow through porous media and around 3D penetrations, film flow on inverted and vibrating surfaces, and heat transfer at turbulent free surfaces. The possibility exists to attempt surface pulse testing on liquid surfaces by use of a flashlamp, shocktube, or other type of explosive shock source.

2. Lasers and Ion-beams for Propagation and Ablation Studies. Commercially available lasers offer a range of output yields (up to a few Joules), wavelengths (266–1064 nm) and pulse width (from nanoseconds to sub-picosecond) for propagation studies. Similarly, small-scale ion beam facilities can be used to study transport issues in simulated chamber media. These same facilities can also be used in a limited way to produce surface ablation and evaporation to explore surface damage mechanisms and evaporation/condensation physics.

3. Defense Program Facilities. Surface interaction and ablation experiments have previously been performed in NOVA [13] and SATURN [45,46], and piggy-back ablation-condensation experiments have been proposed for NOVA [47]. Access limitations and cost restrict the quantity of data and turnaround time. Restrictions on the presence of high background gas

pressure and evaporating species further limit the range of possible experiments. Experimental packages may be designed to provde isolation between the device chamber and the experimental chamber, allowing a wider range of possible experiments [48].

4. Dedicated X-ray Source Facilities. A need exists for simulation experiments which can provide both appropriate background conditions as well as appropriate blast characteristics. A dedicated facility with adequate output and/or repetition rate could satisfy these requirements. Well-diagnosed complex geometry, liquid and solid wall experiments could be tested with a faster turnaround time. Such tests would complement NOVA and NIF testing, and even allow pre-testing of NOVA/NIF test apparati. Table 5 shows the range of phenomena which could be studied as the energy yield increases. Clearly, a facility in the class of 100–500 J is very desirable to provide sufficient volume to allow careful diagnosis as well as enable the proper physical interactions to take place.

**Table 5**

**Possible Chamber-Related Experiments vs. Energy Yield**

**0 J**
Flow studies in typical geometrical configuations

**1-10 J**
Beam propagation and focussing
Near-surface physics
Testing of (some) wall protection design concepts
Diagnostic development and demonstration of experimental techniques

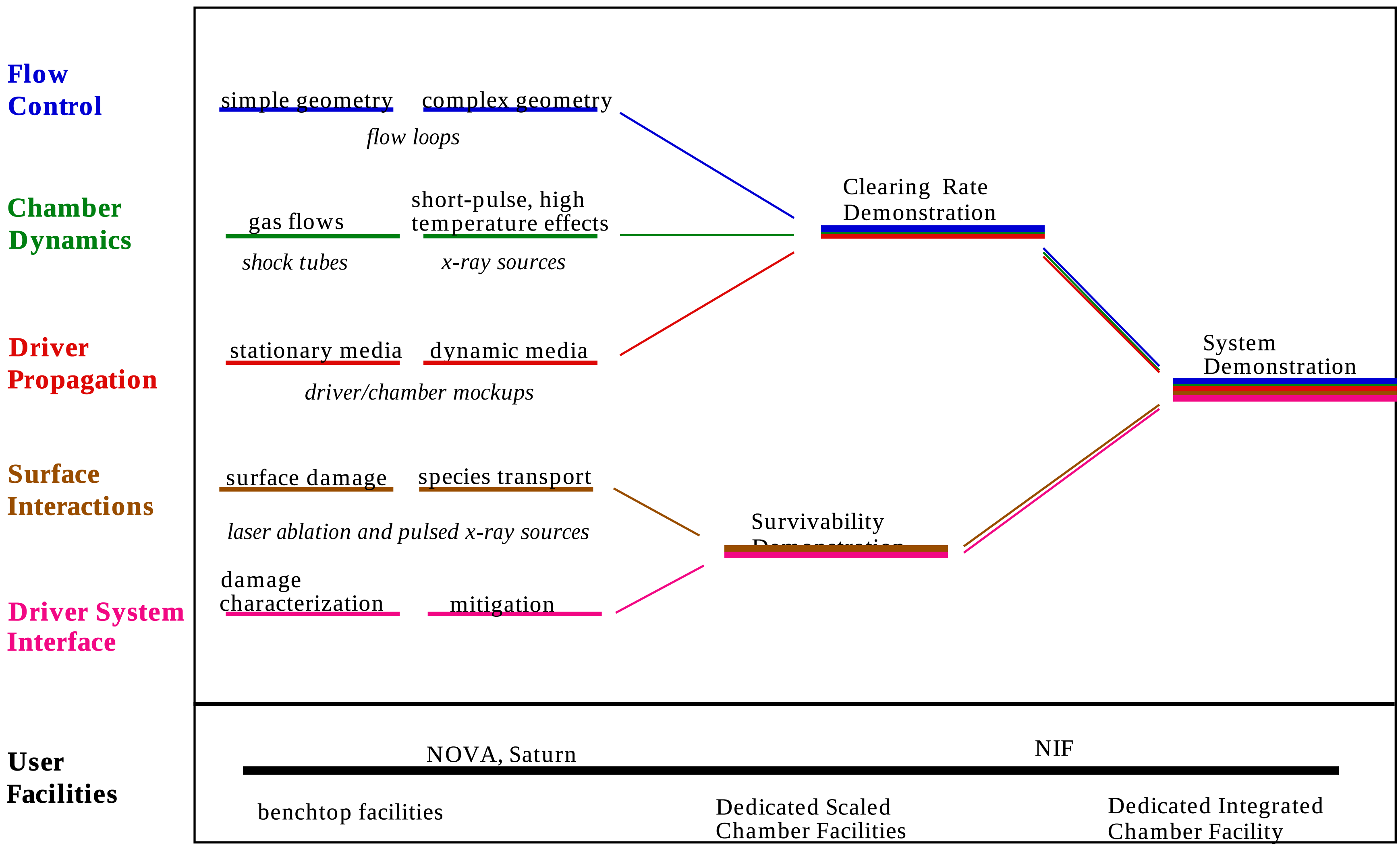
**100-500 J**
Chamber dynamics in limited volume (~1 liter)
Integrated (simultaneous) surface and volume effects

**1–10 kJ**
Large-volume tests for geometrically prototypical testing

**>10 MJ (incl. neutrons)**
Integrated prototypical chamber testing

The R&D needs discussed above are shown schematically in Figure 1. The figure shows a range of small-scale testing and model development which can be extended in the near-term to include more complex interactions. The ultimate objective of the R&D plan is to develop and demonstrate a chamber design concept that is compatibile with target and driver systems. Full system demonstration in an integrated test facility has been shown to require a nuclear facility with ~10% of reactor prototypical values [49]. However, prior to that large step, one can envision intermediate devices that provide simulation of a range of interactions needed for wall protection and chamber clearing demonstrations. These integrated non-nuclear tests would interface with prototypic target/driver systems in order to develop and demonstrate a self-consistent target/driver/chamber combination.

# Chamber R&D Plan



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