Magneto/Hydrodynamic and Beam Equilibrium and Stability Subgroup (Plasma Science Working Group)

R. Betti and E.J. Strait

1. SUMMARY (R. Betti and E.J. Strait)

The goal of this subgroup was to identify the critical issues related to magnetohydrodynamic, hydrodynamic and beam equilibrium and stability in fusion energy science, and outline research activities to address these issues in the next decade. Stability is a fundamental issue for fusion energy, since instabilities can affect fusion plasmas by degrading their performance or by causing a major disruption of the plasma equilibrium. Talks and discussions focused on the science underlying the magnetic and inertial approaches to fusion; the latter includes issues related to high energy density targets and intense beams for heavy-ion drivers. There was a strong emphasis on the development of physical understanding and reliable predictive tools through comparison of theory, modeling, and experiment.

1.1. Magnetic Fusion

In MHD stability of magnetically confined plasmas, three major issues have been identified: resistive wall mode (RWM) stability, neoclassical tearing mode (NTM) stability and the MHD dynamo. Stability against resistive wall modes is crucial for high bootstrap fraction, high beta operation in tokamaks and Spherical Tori, and even more so for reverse field pinches, field reverse configurations and spheromaks which, according to standard MHD theory, are unstable at zero beta. Recent experiments on DIII–D have identified the RWM and studied its behavior in rotating plasmas. RWM stabilization by sufficiently rapid plasma rotation provides an explanation for the mode suppression in DIII–D operation at high beta exceeding the no wall limit. Better theoretical and experimental understanding of the effect of rotation is urgently needed, including quantitative predictions of the critical rotation rate needed for RWM stabilization, more extensive experimental measurements of the critical rotation rate, and predictive models for the rotation profile itself. Realistic modeling is also needed for active feedback control schemes using non-axisymmetric coils.

Beta limits can also be set by resistive instabilities such the neoclassical tearing mode. As in the case of the RWM, the nonlinear evolution of NTMs can lead to either a degradation of energy confinement or to a more catastrophic disruption of the plasma equilibrium. There is a good body of experimental work on the NTM and encouraging results on NTM stabilization with radially localized current drive. A critical issue regarding the NTM is the scaling to larger, reactor-scale plasmas. Here major improvements in experiments, theory, and modeling are urgently needed. The effects of flow shear, ion polarization current and incomplete island pressure flattening need better understanding. Ultimately, the combination of all such effects will determine whether the NTMs are stable or require rf current drive stabilization in future steady state or burning plasma experiments.

With regards to the magnetic dynamo and self-organization effects, the MHD theory is well understood. Important questions however remain in determining the impact of self-organization on energy transport. Plasmas self-organize by reaching their “lowest energy” state. Self-organization generally results from MHD turbulence and therefore poor energy confinement. Better understanding of the energy confinement properties of self-organized plasmas is therefore crucial to determine the future of RFPs and spheromaks as fusion devices.

1.2. Inertial Fusion

Similarly to MHD instabilities in magnetic fusion devices, hydrodynamic instabilities are detrimental to inertial fusion schemes. Rayleigh-Taylor (R-T) instabilities during the acceleration and deceleration phase could quench the hot spot of the ICF implosions as well as compromise the integrity of the shell. Its effects can range from reducing the gain to disrupting the capsule. While the acceleration phase instability is mitigated by the ablation of the shell material (ablative stabilization), the deceleration phase R-T is classical and weakly mitigated only by the finite density gradient effects. A large body of work has been done in the linear theory, simulations and single mode experiments of the acceleration phase R-T. They all seem to agree within reasonable experimental errors and provide a clear understanding of the linear growth. However, when it comes to the nonlinear saturation and multimode interaction fewer experiments have been done. The effect of magnetic field and non-local heat transport are not included in the current theory and simulations.

More theoretical work, 2-D and 3-D simulations and experiments on the deceleration phase R-T and its effects on the hot spot evolution would also be quite useful. Many current simulations only include a few modes while all wavelengths are linearly unstable during the deceleration phase. All these issues need to be better resolved in order to improve the reliability of the code predictions and determine the impact of the deceleration as well as acceleration phase R-T instability on ICF capsule gain.

1.3. Heavy Ion Beams

In heavy ion fusion (HIF), the key issues are beam transport in the driver and in the chamber. The high beam intensity of HIF accelerators results in significant space-charge forces, and the beams behave as a non-neutral plasma with associated collective modes of oscillation. Thus, a key issue for HIF is to maintain a quiescent beam while avoiding growth of the beam emittance caused by any anharmonic fields associated with the intense space charge, beam instabilities, and machine imperfections. Within the accelerator, idealized simulations and theory indicate that there are few instabilities, and those that do exist appear to be controllable via parametric choices or active stabilization, or have limited saturation amplitudes. Other important remaining physics questions relate to effects that do not scale with physical machine size, including electron effects associated with particle loss due to the scattering of beam particles with background gas and tenuous distributions of so-called halo particles that lie outside the main distribution of beam particles. A proposed High Current Experiment (HCX) would investigate these non-scalable issues, allowing design of a larger, multi-beam Integrated Research Experiment (IRE). With the increasing computational power available, it should soon be possible to perform realistic 3-D source-to-chamber simulations of HIF drivers to evaluate better the effect of a large spectrum of machine construction errors and non-ideal effects.

A large variety of apparently viable options exist for transporting the intense pulse of HIF driver energy through the fusion chamber to the target. Most of these require further investigation to fully quantify the widely different physics issues involved. Ideal, unneutralized ballistic focusing has been demonstrated in a small-scale experiment, and appears not to have problems with instabilities. Neutralized ballistic focusing requires less complete neutralization than has already been achieved in light-ion experiments; nonetheless, various possible plasma instabilities such as two-stream, filamentation, and hose instabilities must be evaluated across the wide range of parameters involved. Transport in a pre-ionized channel is the most attractive option from the standpoint of having minimal entrance openings in the fusion chamber, but is also the most uncertain option. Instabilities such as those outlined for unneutralized ballistic transport must be suppressed to acceptable levels. Scaled experiments are being carried out or planned to address many of these issues. Most of the simulations to date have been 2-D, and therefore neglect some instabilities. More effort is necessary to improve existing 2-D and 3-D simulation tools and incorporate better estimates of cross-sections for beam stripping, photo-ionization, etc.

1.4. Common Themes

Despite great differences in the details, the areas of magnetic confinement, inertial confinement, and heavy ion beams share an underlying foundation of plasma science, and a few broad themes are discernible in the key issues for these fields. More realistic modeling will require integration of macro- and micro-scale theory and numerical simulations. Examples include the coupling of resistive MHD fluid codes with turbulence and transport kinetic codes for magnetic fusion, inclusion of hot-electron effects such as heat transport and laser-induced magnetic field generation in fluid simulations for inertial fusion, and inclusion of kinetic effects leading to beam emittance growth in efficient moments codes for HIF driver simulations. Modeling efforts will benefit greatly from increased computing power with the next generation of multi-teraflop, parallel computers. Finally, there is a need for high-resolution 2-D and 3-D diagnostics for imaging of the various instabilities, to allow detailed comparisons of observed mode structure, nonlinear mode interactions, and turbulence with theory and simulations.

The remainder of this report consists of three sections containing a more detailed discussion of the key equilibrium and stability issues for magnetic fusion (Section 2), inertial fusion (Section 3), and heavy ion beams (Section 4). An appendix lists the talks presented in the M/HD-Beams subgroup sessions.

2. MHD ISSUES FOR MAGNETICALLY CONFINED PLASMAS
(E.J. Strait and J. Callen)

MHD equilibrium and stability are the most basic elements that must be satisfied in order for a magnetically confined plasma to exist. Linear ideal and resistive MHD theory have had many quantitative successes and will continue to be important foundations of fusion science. But there is also a clear need to move beyond these models in the future for a more complete understanding of the behavior of fusion plasmas.

Although the details differ, a number of key issues and opportunities are common to many configurations. Three-dimensional equilibria, and the stability of these equilibria, are important not only for stellarators but also for nominally axisymmetric configurations. Stabilization of ideal MHD modes by a resistive wall, including stability of the resistive wall mode and the role of plasma flow in MHD stability, is an important issue for most configurations. The nonlinear behavior of resistive instabilities, including neoclassical tearing modes, is a key issue that can degrade energy confinement as well as affect global stability of the plasma. The dynamo effect and relaxation toward a minimum energy state are central features of the more “self-organized” configurations; understanding and controlling these processes to improve energy confinement in a manner compatible with sustainment of the configuration is a key challenge. Rapidly oscillating fields are important for modifying and controlling stability properties in many situations.

Scientific understanding and prediction of these and other MHD phenomena requires realistic theory and modeling. Simple MHD models must be augmented with plasma flow and flow shear, three-dimensional geometry and magnetic islands, neoclassical physics, 2-fluid physics, finite Larmor radius effects, and kinetic effects. Implementing these extensions to MHD models in large 3-D nonlinear codes, supported by analytic theory and smaller scale modeling codes, will advance our understanding of the behavior of plasmas in all the various magnetic configurations.

2.1. 3-D Equilibrium

Three-dimensional equilibrium is a fundamental requirement for magnetized toroidal plasmas. Some plasmas such as the stellarator are explicitly three-dimensional, while nominally two-dimensional, axisymmetric plasmas become three-dimensional with the addition of a small symmetry-breaking perturbation such as a field error or long wavelength MHD mode. A saturated tearing mode in a tokamak, for example, can be calculated directly as a 3-D equilibrium.

The existence of magnetic flux surfaces becomes an important issue in 3-D equilibria. The breakup of flux surfaces into islands and chaotic regions with increasing beta can lead to an equilibrium beta limit in stellarators. Early 3-D equilibrium codes assumed the existence of nested flux surfaces, but more modern codes such as PIES and HINT can take account of embedded magnetic islands and the loss of flux surfaces.

Existing 3-D equilibrium codes have been used in stellarator design to calculate the integrity of flux surfaces with increasing beta, including the effects of pressure driven currents, and to provide a starting point for linear 3-D ballooning and kink mode stability calculations. They have also been used to model tearing modes and resonant field errors in tokamaks.

There are several opportunities to improve the existing 3-D equilibrium codes, allowing them to target additional key physics issues. Inclusion of the perturbed bootstrap current in codes with magnetic islands will allow more realistic calculation of equilibrium beta limits due to loss of flux surfaces in stellarators and to neoclassical (finite beta) tearing modes in tokamaks, including effects of field errors. Ballooning stability codes should be developed for equilibria with islands.

Coupling of transport codes with 3-D equilibrium codes would allow modeling of the temporal evolution of 3-D plasmas.

2.2. MHD Stability: Experiment and Theory

MHD stability is a central issue for magnetically confined plasmas. Violation of stability limits can lead to reduced energy confinement, high local heat flux to the walls, or even a sudden termination of the plasma. Accurate predictions of stability limits, and of the plasma's behavior when those limits are crossed, are crucial to understanding and improving the performance of existing devices and to designing new ones.

Ideal and resistive MHD theories have been quantitatively successful in predicting instability thresholds. For example, predictions of tokamak stability limits due to ideal MHD modes are usually accurate to within about 10%, depending on the quality of the internal profile data. Even application of these well-understood theories is not a trivial proposition, because of the wide range of possible magnetic configurations and internal pressure and current density profiles. However, it is also well recognized that additional physics, such as flow and kinetic effects, must be included in MHD models in order to describe some important macroscopic phenomena and the relaxation phenomena that are characteristic of self-organized plasmas.

Ideal MHD Stability. Long-wavelength ideal MHD modes have the best history of predictive capability in tokamaks. They can also be the most dangerous, causing a rapid, large-scale motion or distortion of the plasma. The ideal n=1 kink mode limits beta in the tokamak and ST, and shift and tilt modes must be stabilized in the spheromak and FRC. Tokamak plasmas can be designed with good stability to the n=1 kink mode, but in "Advanced Tokamak" operating regimes where well-aligned bootstrap current is important for steady-state operation, the resulting broad current density profile leads to a relatively low beta limit for n=1 kink modes. Stabilization by a nearby conducting wall can significantly improve the beta limit above the "no wall" limit, and is thus essential for high beta, steady state operation with low recirculating power. Wall stabilization is also crucial for stability of the RFP and spheromak.

In the presence of a resistive wall, the kink mode is not completely stabilized but is transformed into a slowly growing resistive wall mode (RWM). Theory and experiment have shown that the RWM can be stabilized by sufficiently rapid plasma rotation, but experiments in DIII–D suggest that the rotation tends to slow when beta exceeds the no-wall stability limit, eventually leading to an instability. Fortunately, the slow growth makes the RWM amenable to feedback control using external coils. This problem has been solved in tokamaks for n=0 (axisymmetric) stability, giving credence to the possibility of feedback stabilization of the n=1 kink mode above the no wall beta limit. Feedback control is likely to be essential for high-beta, steady state operation in the tokamak and ST, and probably also for the RFP, spheromak, and FRC, but represents a theoretically and technologically challenging problem. Feedback experiments have recently begun in DIII–D. A new approach suggested at the conference is the use of flowing liquid lithium walls, which could take the place of plasma rotation. Another novel approach is dynamic stabilization by rotating magnetic fields, proposed as a method for stabilizing the n=1 internal tilt mode in the FRC.

There are several important theoretical and experimental issues associated with rotational stabilization of the resistive wall mode. A quantitative theoretical prediction for the critical rotation frequency is needed, and can be tested against existing experimental data. A better theoretical and experimental understanding is needed of the observed rotational slowing at high beta. There is some evidence that the slowing may be caused by a small amplitude, saturated resistive wall mode, but low-amplitude saturation is not predicted by present theories.

It remains to be demonstrated how much of the gap in beta between the no-wall stability limit and the ideal-wall limit can be stabilized with feedback control. Both analytic theory and detailed modeling of the entire feedback loop (plasma, sensor, control algorithm, power supply, active coil, and vacuum vessel) are needed to guide the optimization of the feedback control.

Short-wavelength ideal MHD modes (ballooning modes) are often calculated but seldom observed directly. The instability threshold depends on local properties of the plasma and can be calculated accurately. In many cases, experimental pressure gradients reach but do not exceed the calculated ballooning mode limit, suggesting that ballooning modes lead to enhanced transport and prevent the pressure gradient from increasing. Some disruptions in TFTR are attributed to growth of a ballooning mode in regions of high pressure gradient associated with the pressure perturbation of a low-n instability.

Stability of the tokamak H–mode edge is closely related to ballooning stability. The edge pressure gradient often exceeds the ballooning stability limit obtained from a naïve calculation, but modeling indicates that the strong bootstrap current associated with the edge pressure gradient is usually sufficient to open access to the second stable regime. Absence of a ballooning stability limit near the edge then allows the pressure gradient to increase until an intermediate-n kink mode becomes unstable. Modeling and experiments also indicate that the ballooning stability limit can be modified with plasma shaping or other techniques, reducing the edge pressure gradient and avoiding the low-n instability. However, the edge bootstrap current is not accurately measured, and other non-ideal effects have been proposed to account for the stability of the edge.

A clear opportunity exists here to make accurate, high-resolution measurements of the current density near the edge in order to verify the magnitude of the bootstrap current and its role in ballooning stability. Control of ELMs is an important issue for tokamaks, and control of the edge pressure gradient by manipulating the ballooning stability limit is a possible opportunity for such control. The interaction of long and short wavelength modes may be an issue for understanding and avoiding some types of disruptions. The stability of ballooning modes in narrow layers of high pressure gradient and velocity shear, such as in edge or internal transport barriers, is an important issue now starting to be addressed by theory; realistic modeling of these effects is an opportunity for better understanding and prediction of experimental behavior.

Resistive MHD Stability. Low mode number resistive modes (tearing modes) are a significant issue for all magnetic confinement configurations. Such modes are driven by radial gradients of the parallel current density. They can become unstable well before the ideal stability limit is reached. Resistive instabilities can result in magnetic islands or stochastic regions on a large spatial scale, and cause severe degradation of energy confinement or disruption. Resistive instabilities can also have indirect effects, reducing plasma rotation through magnetic interactions with external conducting structures and thereby leading to loss of internal transport barriers.

A relatively recent theoretical prediction is that tearing modes can arise from helical perturbations of the bootstrap current, and thus can be metastable in a high beta plasma; that is, they can be linearly stable but nonlinearly unstable. A “seed island” perturbation of sufficiently large amplitude from some other source can destabilize a neoclassical tearing mode (NTM) at relatively low beta. The existence of NTMs has been confirmed semi-quantitatively in several tokamak experiments, primarily through observation of the metastable nature of the mode, the temporal growth of the mode, the saturated island width’s dependence on beta, and the hysteresis in island size from excitation to re-stabilization at lower beta.

Several opportunities are available for studying the physics of NTMs and reducing their induced island widths and consequent effects. Active current profile control is needed to avoid the onset of NTMs, either by making the tearing mode parameter delta-prime more negative (more stabilizing) or by maintaining the stability of other modes such as sawteeth that could provide a seed island for the NTM. Localized current drive at the rational surface is predicted to reduce the island size or allow complete stabilization; initial experiments have shown promising results in ASDEX-U (using ECCD) and COMPASS-D (using LHCD), and experiments will begin next year in DIII-D.

Neoclassical tearing modes are predicted to be stable when the relative signs of the magnetic shear and the bootstrap current are reversed, as occurs in some stellarator configurations and the central region of negative central shear tokamak plasmas. Experimental results support this prediction in that to date no NTMs have been observed in reversed shear regions in tokamaks. Stellarators can also avoid the effects of NTMs by minimizing the bootstrap current in a quasi-omnigenous configuration. The ST can in principle be optimized to have improved NTM stability properties due to a large stabilizing "Glasser" effect. All of these NTM theoretical predictions need experimental confirmation.

Locking of the NTM and other resistive MHD modes to the wall or other external conducting structures is a problem closely related to the resistive wall mode discussed earlier. When the mode locks, it tends to grow larger as the stabilizing effect of eddy currents in the wall is lost. Opportunities here include the minimization of field errors, thus reducing the torque on the mode, and the injection of angular momentum with neutral beams, rf, or rotating magnetic fields. Feedback control with external coils is also a possibility. However, coils outside the wall cannot couple to the mode until it is nearly locked, while coils inside the wall represent a significant technological challenge in large devices.

A critical issue regarding the NTM is the scaling to larger, reactor-scale devices. Here both experiments and improved theory are needed. The major stabilizing term for NTMs is thought to be the ion polarization current, so that the beta at which NTMs become metastable is proportional to ρ^* (the ratio of the ion gyroradius to the minor radius), a scaling which is unfavorable for large, high field devices. This stabilization mechanism has some experimental support but the theory has recently been questioned; more data and theoretical development are needed. It has also been predicted that the coupling of seed islands to NTMs should become weaker at high Lundquist number (due to a "dynamic shielding" effect), a scaling which is favorable for large, high temperature plasmas. Again, this effect has some experimental support but further measurements and theory are needed. Other possible stabilizing effects also need theoretical and experimental investigation, including incomplete pressure flattening in the island when the island is small compared to various radial scale lengths (perpendicular diffusion, the ion banana width, and the radial correlation length for turbulence), and the effects of flow shear. The competition between these various effects and their scalings will determine whether NTMs are more stable or unstable in future burning plasma experiments, a crucial issue that remains open at present.

Magnetic Field Generation by Dynamos. Magnetic reconnection due to multiple, strongly interacting resistive modes is important in many magnetically confined plasmas. It leads to a dynamo effect that generates a key part of the magnetic field in configurations such as the RFP and spheromak. This relaxation to a minimum energy state is part of the simplicity of these configurations, but is also responsible for significant energy transport. The tension between maintenance of the configuration and improvement of energy confinement is a key issue for "self-organized" magnetic configurations. The physics of magnetic field generation by a dynamo represents an important area of overlap between fusion plasma physics, astrophysics, and geophysics.

The MHD dynamo is fairly well understood in terms of a mean-field Ohm's law that includes the fluctuating velocity and magnetic field. In fusion plasmas these fluctuations are driven by tearing instabilities; in many geophysical and astrophysical situations the velocity fluctuations are driven by thermal convection. Experimental measurements of the velocity and magnetic field fluctuations in RFPs are in agreement with theoretical expectations. However, a more complete analytical nonlinear MHD theory, including 2-fluid effects, is still needed.

Other possible dynamo mechanisms are less well understood, including the Hall dynamo (driven by fluctuating current density), the diamagnetic dynamo (fluctuating diamagnetic current), the electrostatic dynamo (fluctuating electric field), and the kinetic dynamo (electron streaming in a stochastic magnetic field). Comprehensive, self-consistent theory and computational models are needed for these effects. Limited experimental measurements of the Hall, electrostatic, and diamagnetic dynamos in RFPs and spheromaks have produced mixed results; more complete, localized measurements of correlations between all relevant fluctuating quantities are needed to determine the conditions in which the various mechanisms are important. The electron dynamics represent a major challenge that requires diagnostic innovations.

Although the principles of the dynamo are understood, important questions remain for theory, modeling, and experiment to determine the role of the dynamo in magnetic field generation and helicity conservation in self-organized configurations, and in particular its impact on energy transport. Opportunities also exist to investigate the fundamental physics of magnetic reconnection, relaxation phenomena, and dynamo effects in non-fusion experiments, including merging plasma and liquid metal experiments.

2.3. MHD Stability: Computational Models

Present MHD models have been quantitatively successful, for example in predicting the macroscopic equilibrium and stability properties of tokamaks and stellarators. However, a full understanding of some instabilities and the behavior of some magnetic configurations will require physics beyond the usual single-fluid MHD model. Two important pieces now being added to the model are shear flow and 2-fluid effects.

Some equilibrium and stability models have been developed which include toroidal flow, and inclusion of poloidal flow is in progress. FAR code modeling shows that low-n and high-n resistive ballooning modes, as well as TAE modes, are stabilized by poloidal flow shear. Strong toroidal flow shear is thought to be important in tokamaks for maintenance of transport barriers, but the implications for MHD stability need further investigation. The Electric Tokamak experiment now under construction relies on strong poloidal rotation for predicted achievement of very high beta values. Two-fluid models, which can also incorporate fluid flow, are likely to be rich in new physics. Such models may be required in order to understand the FRC, for example. Two-fluid equilibrium models have six arbitrary surface functions instead of the usual two found in the Grad-Shafranov equation, but a focus on minimum energy states may help to reduce the complexity. These and other effects can be explored with analytic theory and medium scale codes, and are currently being included in the large-scale 3-D nonlinear MHD codes.

Large nonlinear MHD codes such as M3D and NIMROD incorporate a broad spectrum of plasma physics and numerical algorithms in an effort to achieve more realistic modeling. The wide range of time scales and spatial scales, from the equilibrium and its evolution to short wavelength instabilities, finite Larmor radius effects, and the details of reconnection layers, renders this a difficult problem and has led to a multi-level approach in the M3D code and a comprehensive approach with options in the NIMROD code. These codes now include single-fluid ideal and resistive MHD, 2-fluid physics, and neoclassical effects. A kinetic treatment of hot ions is included in M3D and soon to be included in NIMROD. Stellarator modeling is made possible by a fully 3D mesh in M3D. Inclusion of the vacuum region and vacuum-plasma interface allows NIMROD to model external modes such as the resistive wall mode.

A major issue for the long-term development of the M3D and NIMROD "macro" codes is how they will be joined with the turbulence and transport "micro" codes to provide comprehensive simulations of magnetized toroidal plasmas. In particular, new or expanded analytic fluid moment closures and/or coupled kinetic simulation models are needed to better model dynamic neoclassical, finite Larmor radius and electron kinetic effects. From the macro perspective, the general issue is how to properly obtain needed fluid moment closures from coupled delta-f type simulations, for use in macro-type codes.

One or both of the M3D and NIMROD codes have already been applied successfully to a broad range of nonlinear problems: the nonlinear destabilization of ballooning modes by a kink mode in TFTR disruptions, saturation of neoclassical tearing modes in DIII–D, core fueling by high field side pellet injection, fast-ion stabilization of internal kinks, spheromak sustainment by an applied electric potential, and the equilibrium and ideal MHD stability properties of STs and stellarators. Additions to the physics that are envisioned in the near term include resistive wall, finite ion Larmor radius, and electron inertia effects.

These large, nonlinear 3D codes have the potential to help us understand and predict many outstanding, difficult issues in fusion physics. A partial list of these problems includes: physics of reconnection layers, finite Larmor radius stabilization of resistive ballooning modes, stability of resistive wall modes with plasma rotation, the initiation and saturation of neoclassical tearing modes, stability of stellarator configurations in the presence of islands, spheromak formation and sustainment, the RFP dynamo and relaxation phenomena, stability of the FRC, and the dynamics of burning plasmas.

The greatest challenge and opportunity for exploiting such tools is to make the codes efficient enough to permit the multiple, extended runs that are necessary to explore a new problem, successfully match experimental data, and determine the sensitivity of the results to the input parameters. Both codes have implemented parallel computation with $\sim 10^2$ processors. "Massive" parallelization, increasing the number of processors by 2–3 orders of magnitude, would allow true multilevel physics calculations, including the effects of small-scale physics and kinetics on large-scale plasma phenomena. Other improvements in computational efficiency could come through the use of adaptive meshes and advanced matrix solution methods.

Continuing strong support for analytic theory and small to medium scale codes is essential. These will allow development of the models to be included in the large codes, provide benchmark tests, and will provide insights into the key physics which are sometimes difficult to obtain from large, complex simulations. Present large-scale codes should also be benchmarked against each other. Improved code diagnostics and visualization techniques are important to extract the key results from the large codes. Finally, development of innovative numerical algorithms and use of new computational tools are needed and should be an accepted part of the magnetic fusion program.

3. SUMMARY OF INERTIAL FUSION ENERGY ISSUES AND OPPORTUNITIES FROM THE M/HD-BEAMS SCIENCE SUBGROUP

(M.D. Rosen)

From the discussions and presentations of the M/HD-Beams Science sub-group there emerged three main areas of research that can have an influence on the success of inertial fusion energy (IFE): 1) the impact of the Rayleigh-Taylor (R-T) instability on capsule implosions, and 2) the role of self generated B fields in laser produced plasmas. (The third, HIF drivers, will be discussed in detail in Section 4). For background, the reader is referred to recent simplified reviews (by Rosen[1,2]), as well as extensive reviews (by Lindl[3,4]) of IFE target physics. Nonetheless, some brief overview comments are in order.

Target implosions can be viewed as rockets directed spherically inward. Driver energy couples to the outside of the target, (with efficiency η_C) and heats a thin outer layer, which expands outward, much like the exhaust gasses of a rocket. In a rocket like reaction, the remainder of the target implodes inward and is mostly now in the form of kinetic energy of implosion (with efficiency η_H). Upon convergence to the center, the kinetic energy is reconverted (with excellent efficiency) to internal thermal energy of the high-density assembled fuel that is ready to burn. Thus the process of implosion involves a total efficiency $\eta_T = \eta_C \eta_H$.

There are currently 2 main approaches conceived of for IFE targets: direct and indirect drive. In direct drive, a laser beam directly impinges onto the target. Excellent coupling can be achieved. For example, using 1/3 μm light, at relevant irradiances of 10^{15} W/cm^2, absorption in the neighborhood of 80% can be achieved. Recently, direct drive has made excellent progress in achieving good symmetry via multiple smoothed beams.[5]

The indirect approach involves a target capsule at the center of an enclosure called a hohlraum. Laser or heavy ion fusion (HIF) beams enter the hohlraum interior through laser entrance holes (LEH) located in either end cap of the cylinder. (HIF beams can penetrate the outer wall and do not need LEHs.) The beams are absorbed at the cylinder walls, and converted into soft x-rays. The hohlraum is made of a high atomic number material such as gold, which maximizes the production of x-rays. These x-rays are rapidly absorbed and re-emitted by the walls. Most of the x-rays are ultimately lost into the walls, some escape out the laser entrance holes, and the rest are absorbed by the target capsule in the center of the hohlraum and drive its implosion. The coupling to the capsule is about 0.2 for a power plant scale laser heated hohlraum, and 0.3 for the less lossy, no LEH, HIF hohlraum). Thus, coupling for indirect drive is relatively poor compared to direct drive and gains are lower. On the other hand, x-ray drive, compared to direct drive, provides for more hydrodynamically efficient “rocket” implosions (20% vs. 10%), and for implosions that are more hydrodynamically stable.

The minimum amount of implosion energy investment will occur if the fuel is kept on the lowest allowable isentrope known as the Fermi degenerate (“FD”) isentrope. (It costs energy to compress even cold fuel because we are fighting quantum pressure.) If the fuel is heated and is off this minimum isentrope, it will have increased pressure, and more energy will need to be expended in its compression, and hence the gain (ratio of fusion energy “payoff” to compressional energy “investment”) will be lower.

3.1. Hydrodynamic Instabilities as a Constraint on Gain

The Rayleigh-Taylor (R-T) instability is prevalent in ICF implosions. An inverted glass of water is in principal in equilibrium (the atmosphere's 14 lb/sq. inch can keep the water in the glass) but it is a R-T unstable equilibrium. The dense water would “prefer” to lower the energy of the system by being lower in the gravitational potential than the lighter air it will soon replace (on its way to the soon-to-be-wet floor!). An ICF capsule is similar. The low-density ablated material accelerates the dense shell. The shell feels a huge "gravity" much like the gee force an astronaut feels at launch time. Thus again we have dense matter in a "gravity" field wishing to exchange places with low-density matter. The target crinkles on its way towards implosion. The instability is mitigated somewhat by the ablative acceleration process — the ablation tends to effectively burn-off or smooth the perturbations. Upon deceleration at the culmination of the implosion, the low-density hot spot DT gas, holds up the dense DT shell, again in an effective gravity. An unstable R-T situation arises yet again, and the cold shell mixes into the hot fuel. Understanding these quantitatively is required to ascertain just how physically smooth an initial target must be, and how uniform the drive on it must be, since initial perturbations will grow due to the R-T instability.

For an initial perturbation of wavelength λ, at the interface of a dense fluid of density ρ_1, on top of a less dense fluid of density ρ_2, in an effective gravity field g, the classical growth rate of the R-T instability is given by $\gamma_{CL} = A_{\#} (2\pi\, g/\lambda)^{1/2}$, where the Atwood number, $A_{\#}$, is given by $(\rho_1 - \rho_2)/(\rho_1 + \rho_2)$. In ICF where the gravity is simply the reaction of the target due to the ablation driven acceleration, there is a stabilizing term due to the ablation which is heuristically approximated as $\gamma = \gamma_{CL} - 2\pi\, \beta\, V_{abl}/\lambda$. (Here β is a factor between 1 and 3). This "ablation stabilization" mitigating factor plays a very important role in having the target survive its implosion without completely breaking up. Betti has derived a more complex but more accurate expression for the ablative stabilization.[6]

Because laser light is absorbed at densities much lower than where x-rays are absorbed, V_{abl} is much smaller for direct drive than for indirect drive. Thus indirect drive capsules typically have thicker shells (more mass is ablated to get the rocket "payload", namely the remaining unablated part of the imploding shell, comparable in mass to the direct drive capsule) and thus inherently are more R-T stable than direct drive targets. Moreover they have more R-T ablative stabilization as well. Direct drive can try to mimic these stabilizing effects by having a thicker, faster ablating shell, by lowering the shell's density. Unfortunately this usually means that the shell is on a higher isentrope which will lower gain. Present efforts[5] at direct drive target design are aimed at perhaps "ruining the isentrope" only in the ablation region and not in the main fuel so as to avoid that penalty in gain.

Jill Dahlburg of NRL presented laser direct drive approaches to doing just that. Two tailored-adiabatic pellet designs are currently being investigated at NRL. The first design, which consists of a carbon low-density foam ablator with a DT fuel inner layer, relies on double-shock heating of the ablator to provide the stabilization. Gains approaching 100 are achieved with this design. Published results [Gardner et al., Phys. Plasmas **5**, 1935 (1998)] of 2D FAST pellet code calculations provide surface finish and laser nonuniformity limits at which the advanced foam pellet design can survive. The second design, which may be easier to implement in a reactor system, uses radiation preheat to tailor the pellet adiabatic profile and provide R-T stabilization. This pellet consists of a plastic foam-DT ablator, with a solid DT inner layer, and thin surface coatings of high-Z material and possible admixtures of dopants in the foam. X-rays are emitted from the coatings and absorbed in the dopants, providing adiabatic control. One-dimensional calculations for this design produce gain 130 at 1.3 MJ. The current challenge is to assess accurately in 2-D (and later in 3-D) whether the target will survive the R-T instability given a reasonable initial physical target surface smoothness and uniform laser drive. Dahlburg also presented impressive results of code-validation multi-mode simulations in both 2-D and 3-D that appear to agree well with planar ICF laser-target experiments. Like for the pellet design simulations, high spatial resolution is required, for agreement with experiment, as well as accurate non-LTE atomic physics and radiation packages in the hydrodynamic simulation.

Similarly Richard Town of UR/LLE showed equally impressive agreement of 2-D and 3-D simulations of single mode and multimode laser direct drive R-T growth with planar experiments. He showed how the data also fit the Betti predictions for ablative stabilization better than the heuristic formula. He called for further experiments at higher spatial and faster temporal resolution, that could explore frozen fuel, and in convergent geometries.

Questions arose as to the need, particularly in direct drive, to have a more fundamental (kinetic, Fokker Planck) level of description of electron heat transport somehow incorporated into the hydro simulations. It is, after all, electron heat transport that affects direct drive ablation, as well as laser imprint smoothing. It may be that current designs have sufficiently low laser irradiance so as to remain more nearly Spitzer/classical. Perhaps future designs may be in greater need of such a micro/macro marriage. Similarly unresolved is the question as to whether self-generated B fields affect the R-T growth.

John Lindl reviewed the status of R-T theory, and compared direct drive R-T issues, as discussed above, with indirect drive issues. In indirect drive too there exists an impressive body of simulation work in 2-D and 3-D that agrees well with planar single mode and multimode experiments. Future work will continue on simulations of a full sphere in 3-D which will involve the coupling of lower modes ($P_{2,4,6}$) that are seeded by the asymmetry of the hohlraum drive with higher R-T modes that are seeded by target surface finish imperfections.

In all approaches a continuation of work that involves simultaneous simulation of more modes, and following carefully the growth of modes into the moderately nonlinear, saturated growth regime is called for, both in terms of experiment and simulation, and doing so in convergent geometries.

While not discussed specifically in our sub-group, it is obvious that Z pinch wire arrays have a host of R-T issues, and proper understanding of them can lead to even more efficient and more powerful sources of x-rays.

Summarizing: the R-T instability is particularly challenging for the laser direct drive approach to IFE, but there exist a number of strategies in target design to mitigate it. Those strategies often come with a penalty in operating off the minimum isentrope, which can lower gain, so the real opportunities here are to extensively study those schemes that minimize that gain penalty while mitigating the R-T instability, and to innovate other solutions as well.

3.2. Laser Induced Magnetic Fields

Laser heated plasmas can generate hot electron flows, and ensuing return currents within the target. These currents can act as sources for magnetic field generation. One of the best known “source terms” is the “grad n X grad T” term. An electric field arises which is proportional to ([grad P]/n). Then dB/dt is proportional to curl E and hence to grad n X grad T. In a laser heated round spot there is naturally a grad n axially into the target, and a grad T, azimuthally symmetric around the spot pointing into the heated spot. Thus a toroidal grad n X grad T B field arises, that surrounds the laser heated spot with a “right hand rule”— if your right thumb points along the laser beam direction into the target, your four other fingers describe the direction of the toroidal B field that will arise. Fields of order a megagauss can normally be expected for typical IFE irradiances. While the B field is too weak to affect the hydrodynamics, it is strong enough to affect cross-field heat transport. Moreover there are a number of terms in Ohm’s law that can give rise to these B fields, and they are in various directions, as are the heat transport effects. Thus in reality laser induced B fields can be a very complex 3-D problem- difficult to simulate and difficult to measure, especially in 3-D.

These effects are real. Laser induced B fields have been measured in laser produced plasmas for many years. Mordy Rosen delivered a paper by Jim Hammer of LLNL that described the following important recent result. Experiments that have measured laser heated plasma temperatures (via Thomson scattering) in the central blowoff region of laser heated hohlraums, have been simulated successfully only when the B field generation has been included in the simulation.[7] Laser plasma instabilities in such plasmas are an important effect in indirect drive laser hohlraums. If they grow too large there can be a loss in coupling efficiency into the hohlraum and hence a drop in gain. We do not currently have a first principles predictive capability for the non-linear saturation levels of such plasmas. (To prepare for NIF we have created on NOVA, a relevant section of a NIF hohlraum scale plasma, and empirically learned how to mitigate the instabilities). When such time comes that we do produce a predictive capability, an important input into such a tool will be plasma conditions such as temperature. Hence we will need to routinely include B field generation packages into our simulations then.

There are several saving graces, however. For indirect drive hohlraums, the present driver of choice is a heavy ion beam not a laser. For direct drive IFE, laser deposition is relatively uniform, minimizing gradient sources of B fields.

Another area of IFE for which laser induced B fields play a role (and probably a more crucial one!) is in the fast ignitor approach.[8] In that approach, once a fuel assembly is achieved, a high power, short pulse laser or particle beam impinges on the outside of the assembled dense fuel, heats a small spot on the outside to 10 keV, and it acts as an ignition hot spot and starts a propagating burn into the main fuel. The advantage of this approach over the conventional approach is that now the hot spot is **not** in pressure equilibrium with the main fuel. Both the conventional and fast ignitor hot spots have similar pressures, but the fast ignitor assembled main cold dense fuel can be at much lower pressure than the conventional approach. Namely it can be at lower density, and less compressional energy is needed to be invested, and hence the gain can be larger.

Of course there are many challenging issues of properly coupling the ultra high power auxiliary source into the target and creating that external hot spot. The relativistic channeling of the laser and its creation of MeV electrons all give rise to tight return currents and extremely powerful B fields, that in fact help enforce the beam channeling and transport to a higher density future hot spot. Here the challenge is to accurately measure those fields and of course to calculate them in general. Due to the short time duration of fast ignitor experiments, there exist the possibility of more sophisticated tools than standard hydrodynamic simulations being brought to bear on the problem, namely PIC codes or hybrid particle/fluid approaches.

Summarizing: Laser induced B fields are real and can affect thermal transport. They are especially crucial in helping the fast ignitor approach succeed. More diagnostics and more simulations are needed to properly treat this phenomenon.

3.3. References for Section 3

1. M.D. Rosen, Phys. Plasmas **3**, 1803 (1996).
2. M.D. Rosen, Phys. Plasmas **6**, 1690 (1999).
3. J.D. Lindl, Phys. Plasmas **2**, 3933 (1995).
4. J.D. Lindl, “Inertial Confinement Fusion”(AIP Press: an imprint of Springer-Verlag New York Inc., New York, 1998).
5. S.E. Bodner, D.G. Colombant, J.H. Gardner, R.H. Lemberg, S.P. Obenschain, L. Phillips, A.J. Schmitt, J.D. Sethian, R.L. McRory, W. Seka, C.P. Verdon, J.P. Knauer, B.B. Afeyan, and H.T. Powell, Phys. Plasmas **5**, 1901 (1998).
6. R. Betti, V.N. Goncharov, R.L. McRory, P. Sorotokin, and C.P. Verdon, Phys. Plasmas **3**, 2122 (1996).
7. S.H. Glenzer, W.E. Alley, K.G. Estabrook, J.S. Degroot, M.G. Haines, J.H Hammer, J.P. Jadaud, B.J. MacGowan, J.D. Moody, W. Rozmus, L.J. Suter, T.L Weiland, and E.A. Williams, Phys. Plasmas **6**, 2117 (1999).
8. M. Tabak, J. Hammer, M.E. Glinsky, W.L. Kruer, S.C. Wilks, J. Woodworth, E.M. Campbell, and M.D. Perry, Phys. Plasmas **1**, 1626 (1994).

4. INTENSE BEAM PHYSICS ISSUES FOR HEAVY-ION FUSION

(S.M. Lund and A. Friedman with R.O. Bangerter, J.J. Barnard, C.M. Celata, R.C. Davidson, A. Faltens, and E.P. Lee)

The high beam intensity of Heavy Ion Fusion (HIF) accelerators results in significant space-charge forces. These forces (defocusing, because of the mutual repulsion among ions) are comparable to those externally applied to focus (confine) the beam and much stronger than forces associated with the thermal pressure of the distribution of beam particles. This contrasts with the more usual situation in accelerators for high energy physics — where the pressure forces dominate the space-charge forces. HIF beams behave like non-neutral plasmas with associated collective modes of oscillation. The fundamental issue in the driver is to maintain stable (quiescent) beams over ~km propagation distances while mitigating degradations in beam quality (growth in phase-space area, i.e., beam emittance) that would compromise focusability.

Several accelerator architectures are capable of achieving the needed range of beam parameters on target for HIF. For reasons of cost, efficiency, and the ability to produce flexible pulse profiles on target, the U.S. community has decided to explore induction-based accelerators, while the European community continues to investigate rf-based accelerators. Within the scope of this U.S. down selection to the induction approach, numerous possible linear and ring machine configurations are possible. The baseline U.S. approach considered in this overview is linear with multiple beams (16–100s) arranged in a transverse array that threads common induction cores for acceleration. The beams are injected from arrays of ion sources producing high-current beamlets of singly ionized particles. In the absence of nonideal effects [such as nonlinear (anharmonic) focusing and space-charge effects, background gas, etc.], these beamlets are transported and accelerated unneutralized with conserved measures of phase-space volume (i.e., normalized emittances) to a final system of magnetic optics that focuses the beams onto the target. The beams are transported through a ~5 m standoff in the fusion chamber from the final optics to the target while (perhaps) undergoing partial neutralization in order to limit space-charge effects. Detailed considerations determine the number of beams needed, and typically, 6-D, statistical phase-space measures of the beams emerging from the sources can afford to grow by factors of 1,000–10,000 and still be focusable on the target. This large "budget" in emittance growth provides a fundamentally solid foundation to HIF.

In spite of this intrinsically large budget in emittance growth, processes leading to growth must be understood to avoid excessive growth. Moreover, a most cost-effective driver will exploit these growth factors to optimize the machine. For example, transverse beam merging can result in significant emittance growth, but offers the prospect of a beam transport system closer to optimal cost at low and high energy. The main issue appears to be achieving a balance between cost and beam quality, which is limited by nonideal effects (resulting from anharmonic multipole fields, material defects, construction errors, possible instabilities, etc.) in a real machine.

4.1. Beam Transport Issues in Induction Based Drivers

In typical linear HIF drivers, the ions are nonrelativistic, interact primarily electrostatically, and typically undergo ~10 to several hundred characteristic transverse (betatron) oscillations and ~1 longitudinal (synchrotron) oscillation. Furthermore, the voltage waveforms applied to induction cores for acceleration and pulse compression and the transverse focusing geometry vary along the machine. Thus, it is unclear if the distribution of beam particles can relax to a quasi equilibrium and the classic equilibrium/stability approach may not be appropriate. The beam evolution may be better thought of as a self-consistent Vlasov evolution from initial conditions at the source.

Although the combination of intricate geometries, applied waveforms, and intense self-fields render analytic theory complicated, it is still valuable. Approximate models guide the design of optimal machine "lattices" of focusing and accelerating elements. Moreover, any lack of stability within idealized models suggests the presence of problematic modes in the real machine. More detailed analysis is often used to derive reduced models for efficient numerical simulation. The initial-value nature of beam evolution is especially well suited to simulation. Well-developed codes based on truncated moment models are used to rapidly design optimal lattices and waveforms. Multidimensional particle-in-cell (PIC) codes are frequently used to analyze higher-order transverse and longitudinal effects and more accurately evaluate whether performance goals of ideal designs will be met.

Idealized simulations and theory indicate no fundamental problems with the regime of intense beam transport envisioned for HIF drivers. This has been substantially validated in scaled experiments which, though not having the full current of the driver beams, have the same ratio of space charge to focusing forces. For beam distributions expected from the ion source, there appear to be few instabilities (transverse, longitudinal, or 3-D), and those that do exist appear to be controllable via parametric choices, or have limited saturation amplitudes. The principal instabilities of concern are a 3-D kinetic mode that transfers transverse thermal energy to the longitudinal direction and a fluid-like longitudinal mode associated with the impedances of the beam environment. The former is believed to only weakly influence design. For some machine parameters the latter is limited to acceptable levels, while for others it may require active feed-forward stabilization. Studies are needed to test whether multi-beam manifestations of this instability are problematic.

Detailed simulations and analytic estimates are being employed to set bounds on allowed random errors in focusing fields, machine alignment, waveforms for beam acceleration and compression, vacuum, etc. Simulations and theory have been benchmarked against scaled experiments. The convergence of these results indicates that a fundamental understanding of beam transport is emerging. The most important questions remaining relate to whether this understanding of transport might change in full driver scale beams due to so-called "dirty" physics issues which include particle loss due to the scattering with background gas and the impact of tenuous distributions of so-called halo particles on the machine aperture. These lost particles can result in activation of the accelerator (at the high energy end of the machine) and also produce electrons and desorbed gases. Free electrons can be drawn into the core of the beam due to the strong self-fields (~10 kV potential well). This possibility is of greater concern with magnetic quadrupole focusing than with electric focusing. The former, which will be employed in the longest section of the driver, lacks any intrinsic electric sweeping fields to inhibit trapping of electrons. Non-negligible electron components can lead to streaming instabilities, induced space-charge nonlinearities, etc. Such possible modes need to be understood to quantify needed machine-aperture to beam-edge clearances. Without machine errors and non-ideal effects from "dirty" physics, the optimum would be a large number of small beams. Finding the optimum is important in developing the best possible driver.

A relatively inexpensive, single-beam "high current transport experiment"" (HCX) with magnetic focusing and driver-scale line-charge density is being designed by the Virtual National Laboratory for HIF. Non-scalable issues such as the roles of electrons, halo, vacuum, etc., that may influence transport limits at high beam intensity will be studied. Results should solidify the understanding needed for the design of a larger, multi-beam Integrated Research Experiment (IRE) planned to test a range of driver operating modes. There is consensus within the HIF community that the HCX should be carried out on a 2–4 year horizon to optimize IRE designs leading to next-step experiments in 5–10 years. HCX must push transport to failure at high intensity, so that actual limits can be understood — whether more or less conservative than now assumed.

The increasing power of simulations with multi-teraflop parallel computers also presents a valuable opportunity to the HIF community. Extensive, well-benchmarked, 2- and 3-D electrostatic PIC codes, some already running on parallel computer architectures, have been developed. These codes model field and alignment errors, multiple particle species, detailed focusing geometries with hierarchies of applied field and space-charge models, self-consistent source injection, detailed waveforms, etc. It should soon be possible to do realistic 3-D source-to-chamber simulations of HIF drivers to evaluate better the effect of machine construction errors and non-ideal effects. By linking these codes to the codes used for chamber transport and then to radiation-hydrodynamic codes for target physics, it is foreseeable to carry out full source-to-target modeling. Such simulations promise to lend a higher degree of credibility to the baseline approach and should be expedited. Moreover, efforts must be made to incorporate more "dirty" physics in the codes, because such effects will influence practical limits of full-scale drivers. Efforts should also be undertaken to firm up cross-sections for the stripping of singly charged heavy-ions by carrying out experimental measurements and theoretical analyses.

The growing computational power available has also enabled full Vlasov simulations to be carried out on multidimensional phase-space grids. Such Vlasov methods may resolve subtle phenomena that can be obscured by the statistical noise of PIC methods. These simulations promise more accurate modeling of collective modes of beam oscillation resulting from both "mismatches" of the beam to the lattice and instabilities. They can test whether PIC models have missed any pathological higher-order wave effects — unlikely, but warranting verification.

Progress in theoretical modeling has also opened the possibility of various efficient simulations to complement the PIC methods that are presently emphasized. Such methods include low-noise, perturbed Vlasov (delta-f) methods based on tracking deviations from beam equilibria. These promise a better understanding of beam equilibrium and stability properties and could thereby identify operating regimes that minimize emittance growth and the production of beam halo. The main challenge in this approach is to obtain better (preferably analytic) descriptions of beam equilibria in periodic focusing channels. Also under study are methods to include kinetic effects leading to beam emittance growth in rapid-running moment codes used in systems design. This would enable more rapid exploration of parameter space. The challenge is to capture phase-space dilutions (emittance growth) using truncated moment expansions of the Vlasov equation.

Cost will be a practical issue for any driver for the production of inertial fusion energy. Present estimates of the direct cost of a complete HIF driver system based on volume quotes from vendors range from 0.5 to 1.5 billion U.S. dollars. The HIF program must diligently pursue technology development to reduce cost, especially for components associated with induction acceleration (wound ferromagnetic cores, high voltage modulators, etc.), multiple-beam transport arrays (electric and magnetic quadrupoles, control systems for alignment and steering, etc.), and high-current injectors (rep-rated systems capable of matching multiple beams into transport arrays). Much progress has been made in these areas and work continues to address remaining issues. But it is also important to maintain diligence to take advantage of new technology. Cost goals are presently within ranges where it is appropriate to engineer, prototype, and work with manufacturers to achieve incremental cost gains across the spectrum of sub-systems needed. This would also enable more concrete projections of system performance and reliability.

4.2. Transport Issues in the Fusion Chamber

A necessary feature of any practical concept for inertial fusion energy is a viable means of transporting the beam energy through the fusion chamber to the target. This must be done at >1 Hz without damaging the focusing system, which must be shielded from neutrons, photons, and target debris. In HIF, this is a high leverage area that is attracting increasing attention. There exist a variety of apparently viable transport options and few of these have been investigated in detail sufficient to quantify the widely different physics issues involved. The overall issue of chamber transport for HIF was explored more thoroughly in the Inertial Fusion Energy Concepts Working Group of the Snowmass meeting (Drivers and Standoff Subgroup) and a more detailed overview appears there. Here we outline the range of chamber transport options for HIF, issues associated with each, and near term steps that can be taken to help address these issues.

The final system of precision magnetic optics that focuses the beam onto the target from a ~5 m standoff must be considered part of the integrated system for chamber transport. Viable designs must address constraints in arranging these optics around the chamber, shielding, cost, and must include compensations for beam errors (i.e., residual spread in beam axial momentum, etc.). The vacuum aperture of the magnet makes protection of this system easier than for driver approaches using material optics, but details depend strongly on the method of chamber transport. Although both theoretical and experimental studies indicate that targets can be injected with sub-mm precision, sensing the target position (nearly stationary on beam time-scales) and flexibility in beam pointing remain important. System studies of final focus options should be carried out in greater detail and integrated with chamber transport studies.

Chamber transport modes for HIF can be broadly grouped as: unneutralized ballistic; neutralized ballistic; and channel (including pinch-mode). In all these options, neutron / debris shielding with thick liquid walls of Flibe (Fl, Li, Be molten salt) is being considered. Other dry and wetted wall chamber options are also possible. In unneutralized ballistic transport, the beam is transported in low background pressures (10^{-3} through 10^{-4} Torr range or below) with negligible stripping or neutralization. In neutralized transport, typically ~> 90% of the beam's space-charge is neutralized by electrons from a number of possible sources: pre-ionization of chamber gas; beam induced ionization of chamber gas; photo-ionization by target x-rays; emission from chamber walls and Flibe; co-injection of electrons; passing the beam through a disposable foil or gas puff. Finally, in channel transport, the beams are focused in high background pressure (0.01–1.0 Torr) using strong azimuthal magnetic fields generated by longitudinal currents from a plasma discharge, a current carrying wire, or beam ions highly stripped by a foil or gas (i.e., a self-pinch mode with space-charge, but not current, neutralization). The ballistic modes are the "baseline" but the channel transport options are appealing if they can work.

Issues for these options are quite different. Ideal, unneutralized ballistic focusing has been simulated and demonstrated in a 1/10-scale experiment. There appear to be no problems with instabilities. The main issues are how many beams will be needed to keep space-charge forces at acceptable levels (too many result in chamber shielding and packing problems) and the effect that large self-field forces would have on electrons in the chamber arising from beam stripping on residual gas, photo-ionization by target x-rays, etc. This option becomes easier at beam kinetic energies above 4 GeV with ion mass numbers ~200 but is not as well matched to the class of distributed radiator targets most recently studied, which employ shorter range, lower kinetic energy ions. In neutralized ballistic focusing, the issues are uncertainties in the neutralization fraction (though desired neutralizations are modest compared to those achieved in light-ion fusion) and possible plasma instabilities, such as two-stream, filamentation, and hose. Techniques to form pre-ionized channels, while appearing viable, have not been evaluated in sufficient detail, and cross-sections for many of the processes involved are lacking. However, ranges of cross-sections should be easily explored by varying chamber gas pressures, temperature, etc. Finally, channel transport is the most attractive option from the standpoint of having minimal entrance holes and relaxed driver requirements for beam emittance and momentum spread. However, it is also the most uncertain option. Discharges with sharply bent return current paths near the target must be controlled to form stable, uniform channels for at least the brief beam propagation time. Also, instabilities must be suppressed to acceptable levels. Self-pinch propagation is similarly uncertain.

Scaled experiments are being carried out to address the viability of unneutralized ballistic transport, and to address a range of issues in neutralized ballistic and channel transport options.

Electromagnetic PIC simulations indicate that several unneutralized and neutralized ballistic focusing options are viable. However, most of these have been 2-D (neglect multi-beam effects and cannot properly address the filamentation and hose instabilities) and employ uncertain stripping cross-sections (the effects of which can be studied parametrically). More effort is necessary to improve existing simulation tools and incorporate photo-ionization, etc. Other codes developed outside HIF using implicit hybrid fluid-particle methods can be exploited to study the dense plasma regimes in channel transport. Moreover, chamber transport is an area where the Light-Ion Fusion and the larger plasma physics communities have skills and tools to make contributions, and collaborations should be sought.

APPENDIX: TALKS PRESENTED TO THE M/HD-BEAMS SUBGROUP

3-D Equilibrium

A. Reiman (PPPL) *Calculation of 3D Equilibria in Tokamaks and Stellarators*
R. Davidson (PPPL) *Intense Beam Equilibrium and Stability Properties for Heavy Ion Fusion*

Stability Limits (for IFE, MFE, Beams)

Experiments

R. Town (U Rochester), *Rayleigh-Taylor Instability Experiments*
R. Bangerter (LBNL), *Beam Physics Experiments*
G. Navratil (Columbia U), *Experiments on Beta Limits*

Theory

J. Freidberg (MIT), *Stability Limits in Magnetic Fusion Devices*
J. Lindl (LLNL), *Rayleigh-Taylor Theory and Effects on ICF Capsule Gain*
J. Manickam (PPPL), *Summary of the PPPL MHD workshop*
J. Finn (LANL), *Resistive Wall Modes and Locking**

Computational

H. Strauss (NYU), *MHD Simulation with M3D*
J. Dahlburg (NRL), *Simulation of the Rayleigh-Taylor Instability in ICF*
R. Nebel (LANL), *NIMROD: An Extended-MHD Simulation Tool for Fusion Devices*
S. Lund (LBNL), *Beam Transport Simulations*
T. Hayashi (NIFS/Japan), *Simulations of MHD Relaxation Phenomena**

Resistive MHD and Magnetic Field Generation

R.J. La Haye (GA), *Resistive MHD Stability*
S. Prager (U Wisconsin), *Magnetic Field Generation by Dynamos*
M. Rosen/J. Hammer (LLNL), *Laser Induced Magnetic Fields*
L. Steinhauer (U. Washington), *Two Fluid Effects on MHD Instabilities**
J.N. Leboeuf (UCLA), *Sheared ExB Flow Stabilization of Global MHD Modes**
S. Cohen (PPPL), *Dynamical Stabilization of the Field-Reversed-Configuration Internal Tilt Mode by Rotating Magnetic Fields: A Physical Picture**
J. Finn (LANL), *Spheromak Sustainment and Dynamo**
M. Yamada (PPPL), *Magnetic Reconnection Physics and Control of Self-Organized Plasmas**
H. Ji (PPPL), *Comments on Dynamo Effects in Fusion Plasmas**
P. Bellan (Caltech), *Applications of MFE to Solar Prominences**

Hybrid Kinetic-Fluid Macro/Micro Simulations (Joint Session with Turbulence and Transport Subgroup)

G. Hammett (PPPL*), Opportunities for Comprehensive Simulations and Experimental Tests*
S. Parker (U Colorado), *Future of Plasma Computation, Merger of Kinetic-MHD/Turbulence*
J. Callen (U Wisconsin), *Future of Plasma Simulations = Chapman-Enskog-like Approach?*
W. Manheimer (NRL), *A Distant Mirror, Some Medieval Thoughts on Marginal Stability and Macro/Micro Interactions*
D. Newman (U Alaska), *Methods for Comparison of Theory and Experiment**

S. Luckhardt (UC San Diego), *2D and 3D Imaging and Visualization of Plasma Modes and Turbulence: A Grand Diagnostic Challenge for 2000-2010**

*Contributed paper.