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Chair Summaries from the 2006 Innovative Confinement Concepts (ICC) Workshop

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The goal of the ICC program within the DOE Office of Fusion Energy Sciences (OFES) is to improve magnetic and inertial fusion concepts and to advance plasma science. ICC2006 is a continuation of the ICC series, which last year met in Madison, Wisconsin. It provides a forum for an exchange of ideas through presentations and discussions on the science and status of Innovative Confinement Concepts research, and for new ideas. The meeting provides feedback from the ICC community to the DOE OFES. In addition to invited talks on these topics, contributed papers are solicited describing experimental, theoretical, or computational work presently done in the ICC program, and also papers describing new ideas for possible proposals. The contributed papers were presented as posters, which were displayed during the workshop. The program committee also selected a subset of the contributed papers for oral presentation. A "skunkworks" session is included for completely new ideas (and novel twists to old ones).

KEY WORDS: Innovative confinement concepts.

INTRODUCTION

New results were heard from all of the ICCs in the DOE Office of Fusion Energy Sciences (OFES) Program, representing nearly 20 different devices and involving approximately 25 separate research groups (national labs, universities and private companies), including two groups from abroad. The workshop, hosted by the University of Texas, Austin, included 115 contributed papers and 37 oral presentations organized into six sessions [1].

Concept innovation has remained a core component of the U.S. fusion program for over 15 years [2] and the ICC experiments address several programmatic and fusion energy science objectives by: working within a broad range of plasma and fusion energy sciences, including cross fertilization with other fields of plasma science; seeking concepts and innovations that work better or change the paradigm for fusion energy; broadening the physics of toroidal magnetic confinement by operating in parameter regimes inaccessible by the tokamak; strengthening university plasma science and technology programs, engaging faculty by providing opportunities to contribute to plasma and fusion science with small-to-medium size experiments; and attracting bright, young talent with the vision of unlimited energy for mankind while providing the opportunity to participate in experiments they can "get their hands around. [3]

This year, participants were asked to categorize their presentations by the areas of configuration improvement and the areas of plasma science (see Appendix). The meeting had six sessions. The first

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emphasized the reactor advantage of simply connected geometry (in which no material links the plasma core). The primary cost of a fusion reactor results from the need to cover the outside of the first wall that the fusion neutrons encounter with the necessary blanket, shield, and coils, which has approximately a fixed cost per unit area. Simply connected concepts such as Spheromaks, field reversed configurations (FRCs), and open-field line devices therefore stand to have the lowest reactor core costs (for a given confinement) and the Spherical Tokamak (ST) gains part of this advantage through a simply connected blanket and shield. The second session covered high beta concepts (concepts that achieve the highest plasma pressure for a given confining field strength). At a fixed power density, higher beta results in cheaper coils and lower cost reactors. More importantly, the beta needs be high enough so that the optimized reactor produces the maximum power allowed by the grid, while limiting the surface magnetic fields to practical levels. High beta is needed to burn advanced fuels and the FRC and z-pinch are very high beta concepts. The third session was on highly efficient current drive methods. While an enabling technology for steady-state RFPs, FRCs, and spheromaks, such current drive methods would also remove the restriction that profiles must have a high bootstrap fraction as would be needed in tokamak and ST reactors. The fourth session covered centrifugal confinement, STs and stellarators. Stellarators have the primary strength that they do not require steady-state current drive. The fifth session covered other plasma physics experiments, electrostatic confinement experiments, and inertial confinement fusion. The sixth session is traditionally called the Skunkworks session where very new or radical fusion ideas are discussed in a brainstorming-like atmosphere. The conference was brought to a close after a tour of the University of Texas fusion facilities.

Sections "Simply Connected, Spheromak..." to "Skunkworks..." entail the chair summaries by session, and section "Summary" is a summary of the workshop.

SIMPLY CONNECTED, SPHEROMAK, AND COMPACT ST—*DR. BRIAN NELSON, UNIVERSITY OF WASHINGTON*

"Measurements of plasma jets and collimated flux tubes that are the precursors of spheromak self-organization", Prof. Paul Bellan, California Institute of Technology. A brief background of the Taylor minimum energy principle was presented, introducing the questions of 'how does the plasma get in', 'how do the fields evolve', and 'what is the role of axisymmetry'. Previous results from the CalTech experimental program were summarized, including the axial $\mathbf{J} \times \mathbf{B}$ force "gobbling" plasma from the wall, convection of frozen-in flux with the plasma, pile-up of field amplifying B_φ, pinching the flux tube, which then eventually kinks, converting toroidal flux into poloidal flux. New results were presented to support the "gobble" model: the pre-breakdown neutral profile is unrelated to the plasma profile; fast jets (10's of km/s) are seen in Doppler shifts; and high-localized densities (10^{22}–10^{23} m^{-1}) are measured by Stark broadening. The initial neutral density was mapped out with a fast ion gauge, and found to be a much lower density than the plasma density, indicating most of the plasma came from the gas inlets at the wall. A derivation was shown explaining axial compression of B_φ as involving flow, compressibility, and frozen-in flux, also implying paramagnetism is balanced by diamagnetism. The path of the plasma evolution was followed in a stability diagram, proceeding from stable pinch, to (and through) kink instabilities, to high density sausage instabilities, leading to detachment.

"Magnetic reconnection in the spheromak: Physics and consequences", Dr. Bick Hooper, Lawrence Livermore National Laboratory. Comparisons were shown between experimental results in the Sustained Spheromak Physics Experiment (SSPX) and the 3D NIMROD code. Two methods of producing SSPX spheromaks were presented, one where a spheromak is quickly formed and allowed to decay, and another where the spheromak is built up over time. A threshold of poloidal flux amplification over the initial flux, λ_{gun}, was seen when the injection parameter, $\lambda_{gun} = \mu_0 I_{gun}/\psi_{gun}$, was greater than 10 m^{-1}. During strong injector drive, field lines are stochastic, and $T_e < 50$ eV. Much higher values, $T_e > 350$ eV, are achieved during periods of low I_{gun}, or during a driven decay. Spikes on the gun voltage waveforms, similar to those seen in the experiment, are seen in NIMROD simulations. These spikes are interpreted as relaxation events: increases in poloidal flux occur with each voltage spike, and increases in T_e are seen between the events. Detailed comparisons between experimental data and NIMROD simulations are continuing; both to refine the physics included in NIMROD, and to further understanding of spheromak physics. These results are guiding a study of a spheromak reactor scenario, with successive build up and confinement phases. A new flexible solid-state capacitor bank is being installed on SSPX to further study this scenario.

"Solenoid-free plasma start-up in HIT-II and NSTX using transient CHI", Dr Roger Raman, University of Washington. A new method of non-inductive startup, referred to as transient coaxial helicity injection (CHI), has been successfully developed on the HIT-II experiment and applied to NSTX. Toroidal plasma current is rapidly produced by discharging a capacitor bank across the lower divertor flux of HIT-II and NSTX, and encouraging it to reconnect into closed flux current. Transient CHI has produced up to 100 kA of closed flux current in HIT-II and up to 60 kA in initial NSTX experiments. The important requirements were found to be: equilibrium coil currents set to provide equilibrium fields for the target plasma; a narrow flux footprint; a short current pulse; low gas fill density; sufficient pre-ionization; and sufficient capacitor bank energy for ionization and heating. Transient CHI produced plasmas in HIT-II were able to be fully coupled to transformer drive, driving an incremental current, equal to the CHI-produced current, over that of induction alone. Transient CHI-produced plasmas in NSTX had a much higher ratio of plasma current to injector current (over 60) and were longer lived, including some discharges that lasted over 400 ms (until the external fields were turned off).

"Energy transport in high temperature spheromak plasmas", Dr Harry McLean, Lawrence Livermore National Laboratory. High electron temperatures ($T_e > 350$ eV) with reduced electron thermal diffusivity ($\chi_e < 10$ m^2/s) are achieved in the SSPX by increasing the injector current (I_{gun}) and injector poloidal flux (ψ_{gun}) in a prescribed manner. A scan of the parameter $\lambda_{gun} = \mu_0 I_{gun}/\psi_{gun}$, was performed by fixing I_{gun} and varying ψ_{gun}. This showed, after an initial period of driving $\lambda_{gun} > \lambda_{FC}$ ($=9.5$ m^{-1} the Taylor minimum energy state value for the SSPX flux conserver) that the highest T_e (with low magnetic fluctuations) is achieved with $\lambda_{gun} \approx 0.9\ \lambda_{FC.}$ CORSICA equilibrium reconstructions during these periods show the safety factor was in the range $1/2 < q < 2/3$. Magnetic mode analysis is supportive, in that $m/n = 1/1$ before the optimum period and $m/n = 2/3$ afterwards. 3D NIMROD simulations reproduce the observed mode fluctuations and 2D λ, q, ψ, and T_e profiles. Transport profiles for $T_e > 300$ eV shots show good confinement in the core. Core χ_e is well below Bohm, and scales as $T_e^{-5/2}$. A pressure (for $\beta_e = 5\%$) or transport (if $\chi_e \sim T_e^{-3/2}$) limit is observed. To examine these limits, NBI is needed. A modular solid-state injector bank is being installed to extend the pulse length (including the optimum high T_e/low fluctuation period), increase efficiency, and explore multi-pulse buildup.

"Improved stability and confinement in a relaxed extremely high-beta plasma state", Dr Houyang Guo, Redmond Plasma Physics Laboratory, University of Washington. Results from the Translation, Confinement, and Sustainment (TCS) experiment, were presented for a newly discovered high-β plasma configuration: the "field reversed-configuration spherical torus" or FRC-ST. A toroidal magnetic field, B_T, is produced in a translated FRC, mostly existing inside the reversal point. Even though B_T is small, when coupled with the high elongation, the safety factor q profile is like that of a spherical torus, with $\beta \approx 0.85$, and exhibiting significant shear. When Taylor-like minimization of energy is applied to two fluid equations with finite β, *two* helicity conserving constraints are found, one for the electron fluid and one for the ion fluid. When these constraints are applied to the TCS FRC-ST, a broad core is found to be very close to a minimum energy state. (Ion flow measurements are not complete enough to determine conservation of ion helicity.) The FRC-ST plasmas show up to four times improvement in the poloidal flux confinement time, and significantly reduced transport. Despite the absence of external stabilizing fields (multipoles or rotating magnetic fields), remarkable stability to the $n = 2$ rotational instability is observed. This is attributed to the presence of magnetic shear.

"Novel spheromak configurations: Dipole trapped and $m = 1$ tilted", Prof. Michael Brown, Swarthmore College. Results from two methods of operation of the Swarthmore Spheromak Experiment (SSX) were presented. The first is the "dipole-trapped" spheromak, where a single right-handed spheromak is produced in an external dipole field (with attracting currents). The resulting spheromak is tilt-stable and has the magnetic axis near the wall. Equilibrium reconstructions have been made (exhibiting a broad current) and stability was checked with a 3D MHD code. Mode analysis shows the magnetic energy to be predominantly axisymmetric. Results from a 1.33 m ion Doppler spectroscopy instrument (IDS) for C III were shown. T_i (20–40 eV early in the pulse) was shown to inversely scale with density and the ion flows are seen to be small. (T_i values approaching 100 eV have been measured with IDS for counter-helicity merging to an FRC after GDC.) The second configuration presented was the "$m = 1$ tilted spheromak". This configuration was produced by generating two co-helicity spheromaks, but with initially opposite currents, such that they do not reconnect axisymmetrically at midplane. The two spheromaks rapidly reconnect (either by "slipping around each other" or by 3D reconnection) into an object that has predominantly $m = 1$ magnetic energy. This object is long-lived, exhibits "bursty flow", and perhaps is the "Taylor helix" minimum energy state for a prolate flux conserver. 3D simulations by Dr. Elena Belova show relaxation to an $m = 1$ state.

HIGH-BETA & FRC SESSION—*DR. GLEN WURDEN, LOS ALAMOS NATIONAL LABORATORY*

Due to bad weather on the East Coast, and consequent flight cancellations, only four (of six) talks were presented initially: Evolution of the ZaP flow z-pinch equilibria by Dr Uri Shumlak (U of Washington) was the first talk. After the break, Prof. John Slough of the University of Washington presented an overview of the Pulsed High Density (PHD) experiment and its status, Dr. Tom Intrator gave a presentation on the FRX-L high plasma pressure FRC experiment at LANL, and Prof. Alan Hoffman (U of Washington) gave an overview of previous confinement and current drive measurements and recent analyses, in the TCS experiment at Redmond. East coast talks: Hot electron instability on plasma confined in a dipole magnetic field by Dr. Eugenio Ortiz of Columbia University and oblate free-boundary FRCs in the Magnetic Reconnection Experiment (MRX) by Dr. Stefan Gerhardt from Princeton, were given on the following day.

The ZaP talk contrasted the pure z-pinch and conventional pinch stabilization techniques with shear flow stabilization, and provided an overview of the ZaP concept and experimental design. A period of low MHD activity is identified in ZaP during the presence of shear flow in the experiment. Density profile measurements showing a discrete plasma pinch (via holographic interferometry, no $\sim 3 \times 10^{17}$ cm^{-3})) are used to suggest that there is a hot plasma core (T $\sim$ 150–250 eV) in ZaP. This discrete pinch is coincident with the presence of a confined plasma, as determined by internal magnetic field measurements (utilizing multi-chord Zeeman spectroscopy of the CIV doublet lines at 580.1 and 581.2 nm from methane impurity doping).

The PHD experiment has been designed, and is being built at the U of Washington by a team led by Dr. John Slough. Its goal is to generate both static and translating FRCs with keV temperatures, and to investigate the FRC stability boundaries. PHD aims to operate with magnetic fields strengths and pressures that are below material yield strengths, unlike magnetized target fusion. PHD will use individually controlled magnetic coils, to optimize FRC formation in a 0.8 m diameter (former) LSX source section, which is under construction. In-situ Rotating Magnetic Fields (RMF) high-s FRC formation studies are reported using an existing 0.4 m diameter coil set.

The FRX-L experiment at Los Alamos, reported here by Dr. Tom Intrator, has been operating with an improved main bank crowbar system, resulting in FRCs with plasma pressures of 20–30 atmospheres (corresponding to 2–3 Tesla magnetic fields). His team has studied high density, highly collisional regimes, where the collision mean-free path is comparable to the machine size, and found anomalous resistivity of order 10× classical Spitzer resistivity. An integrated FRC plasma on liner experiment has been designed for eventual construction at the Air Force Research Laboratory Shiva Star machine in Albuquerque, for the first magnetized target fusion implosion experiments.

Confinement and current drive measurements for steady-state FRC plasmas, using RMF were reported by Prof. Alan Hoffman from the Redmond Plasma Physics Laboratory (U of Washington). They used the measured plasma density and absorbed RF power to obtain information about the resistivity profile as RMF builds up and sustains the magnetic flux. RMF plasmas in TCS have been sustained up to 10 ms at a time, (limited only by the power supplies), but the power required depends on the cross-field plasma resistivity. The UW group is concerned with the limits on flux build-up during RMF drive, which for a given drive field strength and frequency, involves a mix of density, temperature and impurity parameters. Generally, the lower the resistivity, the higher the possible flux for a given RMF power. Consequently the new TCS/upgrade machine is being designed to reduce impurity sources by employing careful vacuum design with an ultra-high vacuum/bake-out capability.

Dr. Eugenio Ortiz gave a talk on the effects of hot electron interchange instability in the Levitated

Dipole Experiment (LDX) dipole magnetic fields. The LDX at MIT, is a joint project between Columbia University and MIT. It is presently able to make microwave-driven plasma discharges, up to 10 s at a time, with peak plasma betas of more than 20%. The superconducting magnetic coil is not yet levitated, but supported by three thin supports. Microwave sources at 2.45 and 6.4 GHz drive electron populations with mean energies above 50 keV. Due to the fast electron interchange instability, a high-pressure, high-beta plasma is only possible when sufficient background plasma density is present to stabilize the fast electron populations. Otherwise, the instabilities resonate with the magnetic field drift motion of the fast electrons, and cause rapid radial transport. The hot electron instability is modeled with a self-consistent nonlinear numerical simulation, and it reproduces many features of the experiment. Electrostatic and magnetic fluctuations produced by the hot electron instability are monitored by probes, and are used to interpret the perturbed pressure profiles.

Finally, Dr. Stefan Gerhardt gave a talk on the equilibrium and stability of oblate free-boundary FRCs in MRX at PPPL. The MRX at Princeton can be used to study the formation of FRCs by the merging of two counter-helicity spheromak plasmas. This has recently been made possible by upgrades to MRX, including extensions to the vacuum vessel, new shaping field magnets, a central column to stabilize spheromaks during formation and translation, and new power supplies. Plasmas with a range of triangularity and elongation have been studied. Oblate plasmas with the most negative triangularity (−0.5), are tilt stable, and last long enough to merge and form FRCs, for all gases studied (hydrogen, deuterium, argon). However, for plasmas in the tilt unstable regime, the tilt growth rate is slow enough only for argon to allow merging and FRC formation before the plasmas dissipate. This indicates the importance of non-MHD effects in FRC plasmas. Future plans for the SPIRIT high-s machine were also discussed.

CURRENT DRIVE AND RFP—*DR. DARREN CRAIG UNIVERSITY OF WISCONSIN-MADISON*

The session on Current Drive and the RFP was composed of six presentations. The first was given by Gary Taylor of Princeton Plasma Physics Lab on Electron Bernstein Wave (EBW) physics in NSTX and Pegasus. EBW is a promising candidate for off-axis current sustainment and profile tailoring in overdense plasmas. EBW emission has been measured in NSTX implying efficient ($\sim$80% in some cases) mode coupling at the plasma edge. In H mode plasmas, damping of the EBW at the upper hybrid layer reduces the coupling efficiency. Modeling of current drive for NSTX shows that the Ohkawa mechanism is dominant and that 3 MW of 28 GHz power should be sufficient to drive $\sim$ 100 kA in NSTX. Experimental studies of high power EBW coupling, electron heating, and current drive will begin shortly in the Pegasus spherical torus at the University of Wisconsin.

Dr. Paul Sieck presented first results on spheromak formation in the HIT-SI device at the University of Washington. HIT-SI uses a pair of half-torus helicity injectors to maintain a steady helicity injection into a main central chamber supporting a spheromak. Peak toroidal currents of 13.7 kA have been achieved with 3 MW of input power. Both internal (probe) and external magnetic measurements indicate the formation of a spheromak (with unidirectional poloidal field). The measurements have been interpreted with a model which describes the field structure as a superposition of different Taylor states which take into account the asymmetric injectors along with a symmetric contribution.

Dr. John Sarff discussed recent results of Oscillating Field Current Drive (OFCD) in the Madison Symmetric Torus (MST) at the University of Wisconsin. OFCD is a technique for sustaining a DC toroidal current via purely AC inductive loop voltages. Partial current drive ($\sim$10%) has been demonstrated in MST by oscillating both the toroidal and poloidal loop voltages. The phase between the two drive waveforms for maximum current drive is slightly shifted from that for maximum helicity injection, perhaps due to the interaction of the fluctuations with OFCD or to synergistic effects between OFCD and the simultaneously applied steady toroidal induction. Implications for quasi-steady state reactors were discussed in which the current is built up with OFCD and then allowed to decay for good confinement and burn.

Dr. Ben Hudson described measurements and modeling of fast ion confinement in MST. A short pulse neutral beam injector produces a population of fast ions and the decay of these is monitored with a neutron detector which senses neutrons from D–D fusion with the bulk ions. The decay is longer than anticipated if fast ions followed the stochastic magnetic field lines and is consistent with at least a 20 ms fast ion confinement time. Modeling of the ion motion in the stochastic field reveals that ion drifts cause a change in the resonant response between the ions and magnetic field fluctuations, yielding good confinement for a range of energies and radial locations.

Dr. John Finn of Los Alamos National Laboratory discussed feedback stabilization of tearing modes in RFPs with a resistive wall above the ideal wall limit. Sensing of both the radial magnetic field and the tangential field can improve the success of feedback schemes both in theory and in some experiments. Calculations indicate tearing modes can be stabilized by such a scheme below and above the threshold for stability with a perfectly conducting wall. Ideal modes can also be stabilized but only below the threshold for stability with a perfectly conducting wall.

Dr. Per Brunsell of the Alfven Laboratory in Stockholm, Sweden presented results of active control of Resistive Wall Modes (RWM) in the Extrap T2R machine in Stockholm, Sweden and the RFX-mod machine in Padua, Italy. In T2R, the time behavior of the RWM is in good agreement with MHD modeling and with feedback control, suppression of all 16 unstable modes is accomplished for the entire discharge. This results in higher plasma rotation rates and a three-fold increase in pulse length. In RFX-mod, an array of 192 coils is used to create a virtual shell and active RWM control has been demonstrated at high (800 kA) plasma current. Plasma resistance is significantly reduced and the normally strong locked mode deformation of the outer plasma surface is strongly reduced.

STELLARATOR, ST, AND OTHER MAGNETIC—*PROF. ROBERT GOLDSTON PRINCETON PLASMA PHYSICS LABORATORY, DR. S. WOODRUFF UNIVERSITY OF WASHINGTON*

This session included six presentations: the measurement of beta limits in the W7AS stellarator and their implications for the new NCSX experiment (Zarnstorff); an overview of compact stellarators (CS) (Knowlton); transport improvements in stellarators with quasi-symmetry (Anderson); the effects of lithium wall coatings in the Current Drive experiment-Upgrade (CDX-U) tokamak (Majeski); electron plasma equilibria in the Columbia Non-neutral Torus (CNT) stellarator at Columbia (Kremer); and the measurements of rotational velocity profiles in the Maryland Centrifugal experiment (Teodorescu).

Dr. Zarnstorff reported on quasi-stationary, MHD-quiescent discharges with average beta up to 3.5% (peak up to 8%) that were sustained in the W7-AS stellarator for more than 100 energy confinement times. The achieved beta is limited by confinement, not stability, and is significantly above the linear ideal stability threshold calculated at $\sim$2%. MHD instabilities were not observed near peak beta and there were no disruptions. Neutral beam heating power scans were analyzed for vacuum iota values of 0.445 and 0.575. The scans saturate at beta values of 3.1% and 2.1%, respectively. Both scans show confinement saturating with increasing power and beta. In both cases, only the central T_e responds to increasing power; T_e and its gradient do not change appreciably in the outer region of the plasma as power increases, indicating an increase in local thermal diffusivity. The role of the magnetic flux topology has been analyzed using the PIES 3D equilibrium code for these scans. The code calculates that a stochastic field region forms at the edge with increasing beta, and that it reduces the minor radius by $\sim$30% at the saturated beta value. In the higher iota scan, this occurs at lower beta and the stochastic region has a shorter connection length, reduced Te gradient, and lower saturated beta. Adjustments of control coil currents that resulted in higher beta limits also reduced edge stochasticity in the calculations. Similar analyses applied to the LHD experiment give qualitatively similar features. This indicates that the stellarator beta limit may be controlled not by MHD instabilities but rather by magnetic field stochasticity. Indeed low level, non-disruptive low-n oscillations are observed as the theoretical beta limits are crossed, but these do not impede further increases in beta. The NCSX experiment is designed with sufficient flexibility in coil currents and in control coils to take advantage of these results.

Dr. Knowlton gave an overview of the U.S. compact stellarator program. Because the helical magnetic field of the stellarator is dominantly generated by currents in external coils, the stellarator concept has long offered the promise of steady-state operation of fusion reactors with no need for recirculating power to drive current. Moreover, stellarators that operate nearly free of driven or bootstrap current are observed to be immune from disruptions to which tokamak systems are susceptible. New CS such as NCSX and QPS will nonetheless operate with modest fractions of rotational transform produced by plasma current because (1) pressure-driven currents cannot be zeroed, even on a volume average, by design of the magnetic spectrum in low-aspect ratio configurations, and (2) the additional transform from plasma current can reduce the complexity of the twisted modular coils which is useful in machine design, so long as it does not lead to disruptive instabilities. A major goal of CS research is to verify that current-driven instabilities from a low level of plasma current may be avoided by external control of the shear, transform, and other shaping properties afforded by control of the external helical field. Previous experience in stellarators with current indicates that avoidance of edge transform equal to 0.5 ($q = 2$) is important to maintain resistance to disruptions. Other critical issues for current-carrying stellarators include the quality of magnetic surfaces and reliable techniques for determining the magnetic equilibrium from external measurements. The Columbia Non-Neutral Torus is examining electron confinement in a very low-aspect ratio (~1.9) torus. The Quasi-Poloidal Stellarator, under design at ORNL, will study a low aspect ratio (~2.5) poloidally symmetric configuration, complementing the toroidally symmetric NCSX experiment under construction at PPPL and the helically symmetric HSX operating at U. Wisconsin. Initial flux-surface mapping with e-beams in the Compact Toroidal Hybrid experiment at Auburn shows good agreement with the design properties of the device. The CTH program is also addressing the need to provide accurate equilibrium reconstructions of fully 3-D plasmas for equilibrium and stability analysis, and initial studies of W7AS equilibria are promising.

Dr. Anderson showed experimental results from the HSX stellarator at the University of Wisconsin, in which |B| is helically symmetric in Boozer coordinates. HSX is an element of the national stellarator PoP Program, and also the ICC Program. It is the first of the quasi-symmetric stellarators to become operational, and is producing results showing transport improvement through quasi-symmetry compared with conventional stellarators over a remarkable range of phenomena. Losses of deeply trapped electrons are greatly reduced with quasi-symmetry, compared with a configuration with spoiled symmetry, as measured on external plates. Similarly much larger hard X-ray fluxes are measured, with longer decay times, with electron cyclotron heating (ECH) heating in the quasi-symmetric configutions. As expected quasi-symmetry leads to reduced viscous damping and higher flow speeds for a given torque. Density profiles are more peaked in quasi-symmetric configurations, consistent with a prediction of reduced thermodiffusion, observed in non-symmetric stellarators. Electron temperatures are significantly higher in quasi-symmetric configurations with the same absorbed power.

Dr. Majeski reported on the CDX-U at PPPL which has now been operated with the vacuum vessel wall and limiter surfaces coated with lithium. Lithium wall coatings were applied with two techniques—electron beam-induced evaporation of a toroidal lithium-filled limiter, and vapor deposition from a resistively heated lithium-filled oven. In addition the plasma was operated in contact with a tray ~½ filled with liquid lithium. Operation of CDX-U with lithium wall coatings produced discharges with global recycling coefficients estimated at ~30%, the lowest ever obtained for a tokamak plasma. Water traces were removed from the chamber, and oxygen signals were dramatically reduced. Furthermore, low recycling discharges exhibited global energy confinement times, as measured by equilibrium reconstruction, which exceeded previous CDX-U results by a factor of 5 or more. Confinement times for these discharges also exceeded the ITER98pby1 confinement scaling, which includes data from the START device, by up to a factor of 4. This is the largest confinement enhancement ever observed in an ohmically driven tokamak. Indeed confinement times measured here already exceed those anticipated in the proposed LTX experiment, under construction. LTX will feature a 300 C shell, coated with liquid lithium, to provide a very low-recycling environment for the plasma. Success in LTX could lead to a highly attractive Component Test Facility.

Dr. Kremer reported on the CNT, which is a small ($R \sim 0.3$ m), ultra-low aspect ratio ($A \sim 1.9$) stellarator, not optimized for quasi-symmetry, but containing good flux surfaces. CNT is a simple configuration constructed from four circular, planar coils (two of which are interlocking) designed for the study of non-neutral, partly neutralized, and anti-matter plasmas. A major goal of the experiment is to aid in the understanding of how large electric fields affect plasma equilibrium, stability and confinement, since non-neutral plasmas typically exhibit $e\phi >> T$, unlike conventional stellarators. Such potentials can both close loss orbits, mitigating ripple effects, and reduce turbulence through sheared flows. Electron plasmas with densities high enough that the size scale is much greater than the Debye length are presently being studied in CNT. These plasmas are created by placing a negatively biased, heated tungsten filament, supported by an insulated probe rod, near the magnetic axis. The plasmas are diagnosed using similar filaments as emitting or collecting probes. Macroscopically stable equilibria of these plasmas have been observed. Electron confinement times are ~20 ms, limited by the presence of the bulk insulating material of the probe rod in the confining region, as shown by the reduction in confinement when an additional probe rod is inserted. Confinement improves with B, consistent with a picture where the probe rods create perturbuations in the electric potential, and so create radial $\mathbf{E} \times \mathbf{B}$ flows and loss channels. Temperature ~ 5 eV, density $\sim 10^{12}/\text{m}^3$, and potential profiles ~ 200 V were were presented.

Dr. Teodorescu reported on results from the Maryland Centrifugal Experiment (MCX). The mission of MCX is to test the concept of centrifugal confinement and investigate velocity shear stabilization of the interchange instability of simple mirrors. Measurements of the radial profiles of rotational velocity have been made employing multi-chord high-resolution spectroscopy of impurity ion spectral lines. MCX has a mirror geometry with an inner coaxial core biased with respect to the vacuum vessel, thus producing a radial electric field which drives azimuthal rotation; plasma fills the radial region between the core and the wall. Load voltages are in the range of 5 kV and load currents in the range of 1.5 kA. The plasma remains in a high rotation mode for ~2.5 ms, and then drops to a mode with lower voltage and higher load current (greater drag). Spectroscopic measurements were made of Doppler shifted spectral lines for five chords viewing at different radial impact parameters across the plasma column. Abel-like inversion techniques were then employed to obtain the plasma species averaged rotation velocity at five radial locations. Results from spectroscopy were reported giving supersonic peak rotational velocities of ~100 km/s. Within error bars the different charged carbon species at a given radius were seen to rotate with approximately the same angular velocities, consistent with $\mathbf{E} \times \mathbf{B}$ being the dominant drift speed. The velocity shear observed in in the high rotation mode is greater than that theoretically necessary for stabilization of the interchange mode, while the lower rotation mode, with higher viscous drag, is below the criterion for stabilization. Stronger shear also correlates with decreased magnetic activity amplitude at the outer edge of the plasma.

PLASMA SCIENCE AND OTHER CONFINEMENT—*DR. CARL SOVINEC UNIVERSITY OF WISCONSIN-MADISON*

The Plasma Science and Other Confinement session was held on Wednesday, February 15, and six invited talks were presented. The results and discussion highlighted the fact that innovation is still very much a part of the magnetic fusion energy (MFE), inertial electrostatic confinement (IEC), and inertial fusion energy (IFE) programs. Here, we present brief summaries for each of the presentations.

''Observation of the enhanced helicity injection mode in a rotating plasma annulus'', Dr. Zhehui Wang, Los Alamos National Laboratory. The new Flowing Magnetized Plasma (FMP) experiment has been developed to investigate the effects of flow on magnetic relaxation, a potentially important aspect that was not considered in the original Taylor hypothesis. The laboratory device uses the 4.5 m long 1.5 m diameter vacuum chamber from the decommissioned Compact Toroid eXperiment (CTX), but the center electrode is extended in the new FMP configuration. This reduces the value of $\lambda(\equiv \mu_0 \mathbf{J}\cdot\mathbf{B}/B^2)$ required to force the plasma discharge from the injection region, and it allows greater electrical impedance through the aid of an externally imposed axial magnetic field. The capacitor bank that drives the discharges stores 300 kJ of energy and applies 900 V across the electrodes. The copper flux conserver used for CTX discharges has been removed, and the characteristic magnetic field strength is 0.01 T. The plasma discharges are diagnosed with Mach probes, ion Doppler spectroscopy, magnetic probes, and Langmuir probes.

The diagnostics clearly show two modes of operation, labeled 'normal' and 'enhanced.' The enhanced mode is characterized by increased plasma density (factor of 20) downstream of the injector (or plasma annulus), larger poloidal flux amplification, and larger edge magnetic field strength. Most of the discharge current flows through the plasma annulus, unlike the normal mode, where a significant amount of current remains in the injector region. The magnitude of the total current in the plasma annulus is about the same for the two modes. The potential drop in the injector during the enhanced mode is sustained by the ideal electric field associated with axial magnetic field and azimuthal rotation. The effect of plasma flow (rotation) can be seen from the IV characteristics in terms of an equivalent capacitance, consistent with previous theories on rotating plasmas. The presence of the flow correlates with other signatures of the enhanced mode, so it is considered important. Edge kinetic energy density is measured to be about 10–20% of the local magnetic energy density.

"Effects of energetic beam ions on stability properties of field reversed configurations", Dr. Elena Belova, Princeton Plasma Physics Laboratory. Recent operations in the MRX and the SSX have renewed interest in forming FRCs by merging plasmoids. Unlike conventional theta-pinch formation, plasmoid merger tends to create FRCs with low elongation parameters (E). The S^*/E ratio is large (where $S^* \equiv R_s/\rho_i$, the ratio of magnetic separatrix radius to ion Larmor radius), so kinetic effects are relatively weak. This study considers the linear and nonlinear stability properties of these conditions, and numerical results are obtained with the HYM code [4].

The results of the study clearly distinguish the stability properties of prolate ($E >> 1$) and oblate ($E < 1$) FRCs. The $n \geq 1$ modes (where n is the azimuthal Fourier index) in prolate FRCs tend to be internal, so conducting shells have little stabilizing effects. In contrast, the $n = 1$ tilt and radial shift modes in oblate FRCs excite external magnetic perturbations and can therefore be stabilized by close-fitting conducting shells. Simulations at $E = 1.1$ show significant reduction in growth rate, confirming this expectation. Modes with $n \geq 2$ tend to be internal, however, and are also less influenced by kinetic effects than their counterparts in prolate FRCs. In conditions with $E < 0.5$, relevant to MRX, strong shaping through the mirror ratio can stabilize $n = 1$ and improve the stability of $n = 2$ but modes with $n \geq 3$ are too localized to show much effect.

Previous studies published by Lovelace, Finn, Barnes, Nishimura and others have considered the effects of injecting a beam of energetic particles. Self-consistent computations of equilibria with the energetic species show confinement of the beam between the magnetic null and separatrix, near the midplane, so modes localized away from the null receive little benefit. The interaction of thermal and energetic species was computed and found to be stabilizing for $n\Omega > \omega_\beta$ (where Ω is the beam rotation rate and ω_β is the betatron frequency). The present study reconsiders the interaction for even and odd modes, and the analytic relations show instability for sufficiently large values of Ω. These findings are consistent with results from numerical computations. Clearly, many effects come into play in the full nonlinear system. However, simulations show that modes driven unstable by the beam tend to saturate at very small amplitude, and the stability of the $n = 1$ mode remains the primary concern. A simulation with $E = 1.1$ demonstrates successful longevity: a close fitting conducting shell stabilizes the radial modes and reduces the growth rate of the $n = 1$ tilt mode, beam injection at injection velocity $V_b \sim V_A$ stabilizes the residual $n = 1$ and $n = 2$ modes, and high-n modes saturate at small amplitude. The configuration remains intact as long as current drive is maintained [5].

"Sheared plasma flow generation—a new measure for stellarator optimization", Dr. Donald Spong, Oak Ridge National Laboratory. Stellarator confinement has been improved significantly in recent years through efforts to produce greater symmetry of the magnetic-field amplitude ("mod-B") distribution. This study seeks further and potentially equally significant improvement through optimization of parallel transport. The primary motivation is to improve confinement with respect to turbulence-induced loss. Sheared flows can successfully break-up eddies that lead to transport, and whereas tokamaks rely on external momentum input to induce H-mode (very large input for ITER and beyond), stellarators can be designed to produce such flows naturally. The perpendicular component of flow arises from diamagnetic and $\mathbf{E} \times \mathbf{B}$ drifts, but neoclassical viscous drag tends to impede flows that do not follow constant values of mod-B. Depending on the magnetic configuration (quasi-helical symmetry, quasi-poloidal symmetry, or quasi-toroidal symmetry), this can lead to relatively large parallel flows.

This study has analyzed flows in stellarators using the moments method to describe neoclassical transport. The moments method relates parallel viscous stresses, particle-flow, and heat-flow to parallel forces, parallel heat flow, and gradients of density, temperature and electrostatic potential. Recent theoretical work by Taguchi and by Sugama and Nishimura has related the DKES transport coefficients to viscosities, and the results have been incorporated into a suite of codes that together determine parallel flow profiles, along with parallel heat flow and perpendicular particle and heat fluxes. The model is applied to both the ECH regime and the ion cyclotron heating (ICH) regime in stellarators to find the respective roots where ambipolar particle flux is achieved.

When applied to existing and planned configurations, the results show large variation in flow profiles. The W7-X configuration tends to produce little parallel flow in either ECH or ICH regime, whereas the quasi-helically symmetric HSX produces large parallel flows. Flux-surface averages do not reveal all of the important physics, however. Visualization methods have been applied to shows two-dimensional flows within the complicated flux surfaces shapes. Geodesic shearing (within flux surfaces) occurs over much shorter scales than in tokamaks, and this may impact MHD ballooning and interchange stability in addition to microturbulence. Among the different configurations, the quasi-poloidally symmetric QPS design has the largest variation in poloidal flow. The shearing rates for this design approach estimates for the linear growth rate of ion temperature gradient (ITG) modes; this is enough to improve confinement even without any external momentum input. The QPS design with ECH also shows shearing rates of approximately ½ the inverse of the Alfvén time, so a significant influence on MHD stability is also likely.

"Overview of experimental and theoretical studies of the Periodically Oscillating Plasma Sphere (POPS"), Dr. Richard Nebel, Los Alamos National Laboratory. The POPS is a unique IEC configuration that relies on basic properties of the harmonic-oscillator potential to compress ions. A virtual cathode is formed by injecting electrons into a spherical chamber of high vacuum. Ions are then confined electrostatically, and the relatively uniform spatial distribution of electrons creates a spherically symmetric potential distribution, where the inward force is proportional to the distance from the center. Regardless of their initial radius, all ions created in this potential oscillate through the center (assuming negligible angular momentum) with the same period. The electron source can be oscillated to phase-lock the motion of the ions and periodically achieve high number density and high temperature at the center of the sphere. Theoretical results show that the ions repeatedly exchange potential and kinetic energy while maintaining local thermodynamic equilibrium throughout the cycle. If successful, small modular versions of this configuration can be strung together for a reactor power core that has a mass power density that is more than two orders of magnitude larger than the planned ITER experiment.

Experimental measurements from the POPS experiment at Los Alamos show a peak in the time-delay for the decay of the virtual cathode as the oscillation frequency is varied. The POPS resonance and ½ harmonic occur at the resonance frequencies expected from self-similar analytical solutions. The formation and stability of the virtual cathode have also been investigated numerically with two-dimensional computations using the CELESTE code. The computed results show an electron-electron two-stream instability with a hollow cathode above the expected stability boundary. Space-charge neutralization is an important consideration, because it is necessary for maintaining the favorable potential distribution throughout the oscillation cycle. Kinetic computations confirm some degree of space-charge neutralization during standard operation, allowing a compression ratio of 6.3/1, but greater compression ratios of 23.2/1 are achieved by focusing the electrons. Programing is being developed to achieve greater focusing.

"The status of advanced target concepts for ICF and IFE", Dr. John Perkins, Lawrence Livermore National Laboratory. Construction of the National Ignition Facility (NIF) is on-schedule for ignition experiments with a gain of ten in the year 2010, and this event will provide a major boost to the fusion energy program a full ten years before the completion of ITER. We therefore ought to consider what advances can make laser-driven IFE economically viable as a source of power, and the main factor with respect to cost is the driver. The target itself is relatively simple, but improvements in target design lessen the driver requirements.

The first set of NIF ignition experiments will use indirect drive with a hohlraum made of gold and uranium. A 15 ns pulse from 192 laser beams will deliver 300–400 TW of power mostly in the last 3 ns of the pulse. The target material will reach implosion velocities of up to 3×10^7 cm/s to create a 10 keV hot spot and ignition at a density of 1000 g/cm^3. During burn, temperatures will increase to 100 keV over a 30–40 ps period. To avoid damage to the optics, the early experiments will use 1 MJ of stored energy to create 10 MJ of fusion energy, but later experiments will use up to 1.8 MJ of stored energy to create up to 30 MJ of fusion energy.

An economical plant can be envisioned when the driver energy requirement is reduced, the target illumination does not require full 4ℵ solid-angle coverage, the chamber design is improved (possibly with liquid walls) to avoid downtime, and through non-thermal energy conversion. Regarding the first of these, a considerable fraction of the driver energy is lost on the hohlraum when using indirect drive, and direct drive can deliver 3–4 times more energy to the target. The High Average Power Laser (HAPL) program therefore focuses its efforts on improving direct drive. Among the ideas being considered is 'fast ignition,' where compression and ignition are decoupled by using a separate fast-pulse laser for heating. While this approach has benefits, it also requires two operational laser systems. Another approach is 'polar direct drive,' which uses a plastic ring that surrounds to target to distribute laser energy directed at poles of the target to nearly 4π coverage. [Two-sided drive is particularly important for reducing the facility size and cost.] 'Shock ignition' is somewhat similar to fast ignition in that a slower compression precedes a fast heating phase, but this can be achieved with a single laser system.

These ideas can be tested on NIF in the near term. Numerical computations in two spatial dimensions show that significant gains can be achieved with good stability properties from (1) low energy targets, (2) high-stability thick targets, and (3) high-gain NIF reactor targets.

''Ion beam compression in space and time for HEDP applications'', Dr. Art Molvik, Lawrence Livermore National Laboratory. Compressing beams of heavy ions has important applications for high energy density physics (HEDP) and for IFE, where the beams replace lasers as the driver. The Heavy Ion Fusion Science-Virtual National Laboratory (HIFS-VNL) is studying the physics common to both applications. There are five principal science thrust areas: (1) high brightness beam transport, (2) focusing onto targets, (3) longitudinal beam compression, (4) advanced theory and simulation tools, and (5) beam-target interaction. Here, we consider topics (1)–(4).

Electron cloud physics is an important problem area that limits the performance of many high-energy physics accelerators, and may limit heavy-ion fusion accelerators. The High-Current Experiment (HCX), together with numerical simulation, provides a unique world-class capability. The 2 kV potential of the ion beam provides radial confinement for an electron cloud, and negatively biased rings at either end trap the electrons axially. This forms an effective Ion Beam Electron Trap (IBET) experiment for studying electron accumulation in an ion beam. Clearing electrodes provide a mechanism for pumping electrons out to reduce their accumulation and effects, extending the range of electron clouds available for study.

Electrons also provide a solution to space-charge expansion that can limit radial focusing and longitudinal compression of ion beams for HEDP or IFE. The effect of using electrons to neutralize the beam during focusing is considerable. The neutralized transport experiment (NTX) creates neutralizing plasma separately in two different parts of the chamber, and applying both leads to the smallest beam spot size. Without neutralization, the full-width-at-half-max (FWHM) of the beam focal spot is 2.71 cm, whereas with neutralization, the FWHM is 2.14 mm. Electron neutralization of an ion beam successfully avoids limitations due to space-charge effects.

Axial/temporal compression of the beam is equally important for HEDP. The energy loss rate per unit distance in a target has a strong maximum at the Bragg peak. If we are able to compress a heavy ion beam of 20 MeV down to a few nanosecond pulse length, we will be able to measure equation-of-state properties of ~3 μm thick targets—and test equation-of-state models—of solids such as aluminum at very extreme conditions. A numerical study conducted by Welch, Rose, and Kaganovich with the LSP-PIC code has investigated sending a beam through a background plasma with densities greater than that of the beam. The results show that the plasma can focus the beam to a spot radius of 1 mm with the axial length compressed by a factor 120, increasing the beam intensity by 50,000. In addition, instabilities are controllable with sufficiently large plasma density and axial magnetic field. Such predictions are being realized in experiments. The neutralized drift compression experiment (NDCX) has achieved a 50-fold axial compression for a pulse width of 5 ns. These compressed beams will be able to achieve the 'warm dense matter' regime that is similar to the interior of giant planets and low-mass stars.

SKUNKWORKS—*DR. SIMON WOODRUFF, UNIVERSITY OF WASHINGTON*

Seven talks were presented: Spherical torus with a plasma center column (ST-PCC) by Dr Scott Hsu of LANL, a plasma centrifuge heat engine, by Dr Dan Barnes of Coronado Consultancy; Dr Dick Post of LLNL presented an overview of his Kinetic stabilizer concept, followed by a talk on a rotating mirror as a magneto-inertial fusion target plasma by Dr Andrew Case of Hyper-V Corp. After the break, Prof John Slough of the University of Washington presented an overview of the compression, heating, and fusion with colliding plasmoids and a Z-theta driven plasma liner. Dr Rusi Taleyarkhan of Purdue University presented a talk on nuclear emissions during acoustic cavitation and finally, Prof Freidwardt Winterberg presented a talk titled 'Thinking of different ways to combine fission with fusion'.

In the ST-PCC it is proposed to use a plasma central column in place of a material conductor to solve the problem of radiation damage to the central conductor. Such a proposal is similar in many regards to the SPHERA experiment at Frascati, Italy in which many emissive electrodes are arranged to provide the current along the central column. Stability calculations were presented and power requirements were discussed for which the configuration may be practicable in the instance that the open column remains at high temperatures (hence reducing the ohmic dissipation there).

The plasma centrifuge heat engine is a variation of a centrifugally confined plasma in which the configuration is forced to rotate by applying a bias along lines of magnetic force generated by a dipole magnetic field [6]. Further, by varying the field strength, the plasma is forced into an oscillation that provides a compression and expansion perpendicular to the direction of the magnetic field. The compression and expansion provides a thermal cycle in which heat can be recovered as mechanical energy. A machine point design was presented in which $B \sim 5$ T, $R \sim 1$ m, $a \sim 0.2$–1 m, and a total voltage of $\sim$1.5 MV. Two patents relating to this design are pending.

Conventional tandem mirror systems require non-symmetric magnetic fields to insure magnetic stability. In the Kinetic Tandem, the high density plasma peaks that create the plugging potentials are formed by the injection, magnetic compression, and stagnation/reflection of ion beams injected inward along the diverging field lines at the ends of a solenoidal magnetic field, but to be practicable, need to be very long. The kinetic stabilizer operates by creating a density peak outside the mirror of an open system to provide stability to the plasma inside the axi-symmetric mirror cell, thereby allowing the return to simpler axi-symmetric mirror systems of practicable length. Results of stability calculations (analytic and code) were presented.

The possibility of exploring a rotating mirror as a target for compression was outlined by Case. The outline entailed analytic stability considerations, and the possibility of using plasma jets as the driver for the compression. Viscous heating of the rotating plasma during late stages of compression were conjectured as an important means for generating a hot plasma.

A summary of published results of neutron measurements from cavitation in deuterated liquids were presented by Taleyarkhan. Results from control (non-deuterated) cavitation, were contrasted with those produced with deuterated liquids. A discussion of present efforts to replicate the results was given.

The compression of a FRC by use of a plasma liner was discussed by Slough. The concept entails the merging of two high velocity (20 μs/s) FRCs and subsequent radial compression by use of either an axial discharge or by use of a theta pinch coil (similar to early experiments by Wells). A discussion of the experimental facility being constructed to test this concept was given.

Two concepts to combine fusion with fission were outlined by Winterberg. The first entailed the laser heating of a spherical solid DT target surrounded by a natural uranium (thorium) shell, with propagating burn into a DT cylinder inside a liner. The second entailed a DT z-pinch surrounded by a boron plasma and outside that a water neutron moderator.

SUMMARY

This is a very exciting time for fusion with ITER and NIF moving forward to demonstrate net fusion energy production in the laboratory, but much additional work needs to be done in parallel. The ITER-like and NIF-like fusion reactor concepts need considerable improvements for competitive electricity generation. This workshop is for presentation of results and ideas about concepts that might make large steps towards practical fusion power, complementing the important steps of ITER and NIF.

The ICC experiments also complement the mainline concepts in the advancement of plasma science. These experiments test the general validity of plasma physics and technology in wider parameter regimes, develop new fusion plasma physics outside the mainline, and cross-fertilize with other fields of plasma science.

APPENDIX A SUBMISSION CATEGORIES FOR THE ICC WORKSHOP

A. For Magnetic Fusion

A1. Simply connected first wall and/or blanket. The ITER-like concept requires a doubly connected toroidal first wall and blanket. For an optimized reactor the cost could be greatly decreased with a simply connected concept.

A2. Higher beta. Beta is the ratio of plasma pressure to magnetic pressure. The reactor cost will be decreased considerably if beta could be increased to above 10%.

A3. Better sustainment of magnetic and density profiles. High efficiency current drive methods, would remove the restriction that profiles must have high bootstrap fraction in the ITER-like reactor. In addition, current drive and profile control at high power efficiencies would be an enabling technology for many attractive innovative confinement concepts. Present methods of sustaining the plasma density and composition profiles in a reactor, also need improvement. Concepts ameliorating these issues are also needed.

A4. Improved plasma chamber/first wall. Chamber lifetime is a major cost issue with fusion where 14 MeV neutrons must be absorbed without overly damaging or activating the first wall. Concepts that lead to systems that have better first wall and chamber solutions are needed.

A5. Other improvements for magnetic confinement.

B. For Inertial Fusion

B1. Better targets. Higher gain, lower required energy, asymmetric (non-4 pi) illumination and lower cost targets would improve the economics of IFE reactors.

B2. Better drivers. More efficient, lower cost, and high repetition rate drivers are needed.

B3. Lower cost power input areas and chamber clearing methods. Transmitting the power from the source through the chamber wall and onto the target at a high repetition rate with a low-cost and low-maintenance-cost system is required.

B4. Improved plasma chamber/first wall. As in magnetic fusion, chamber lifetime is a major cost issue where 14 MeV neutrons must be absorbed without overly damaging or activating the chamber/first wall. Concepts that lead to systems that have easier first wall and chamber solutions are needed

B5. Other improvements for inertial confinement.

C. For Plasma Science the Following Questions Need to be Addressed

C1. How does magnetic field structure impact plasma confinement?

C2. What is the maximum beta that can be achieved in laboratory plasma?

C3. How can external control and plasma self-organization be used to improve performance?

C4. How does turbulence cause heat, particle, and momentum to escape from plasma?

C5. How are electromagnetic fields and mass flows generated in plasmas?

C6. How do magnetic fields in plasmas reconnect and dissipate energy?

C7. How do hydrodynamic instabilities affect implosions to high energy density?

C8. How do electromagnetic waves interact with plasma?

C9. How do high-energy particles interact with plasma?

C10. Other than the above.

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