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Innovative Confinement Concepts Workshop—2002: Conference Report

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The Innovative Confinement Concepts Workshop, ICC2002, provided a forum for presentations and exchange of ideas on the science and status of innovative concepts in the U.S. Fusion Energy Program. The workshop, held at the University of Maryland on January 22–24, 2002, included oral presentations addressing the important science and status of the concepts, posters focussed on details of the work, a skunkworks for novel ideas, and breakout sessions preparing for the July 2002 fusion energy Snowmass meeting. This report summarizes the oral presentations. A web site (https://wormhole.ucllnl.org/ICC2002/) has been established with the abstracts and many of the presentations, both oral and poster, from the workshop.

KEY WORDS: Workshop summary, innovative confinement concepts, magnetic fusion energy, inertial fusion energy.

The fourth Innovative Confinement Concepts Workshop, ICC2002, was held at the University of Maryland, College Park, MD, on January 22–24, 2002. The workshop provided a forum for presentations and exchange of ideas on the science and status of innovative concepts in the U.S. Fusion Energy Sciences Program. Outstanding facilities and local support, coordinated by Professors Rick Ellis and Adil Hassam of the University of Maryland, helped make the workshop a great success.

Several experiments in the ICCs have reached a sufficient level of maturity that they are producing significant scientific results. This workshop thus is an important successor to the previous ones at UCLA (Marina del Rey) in 1998, PPPL in 1999, and LBNL in 2000. Those in turn built on three seminal workshops at ORNL in 1994;

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at Monterey, California on September 11–14, 1995; and an IAEA Technical Committee Meeting at Pleasanton, California, October 20–23, 1997.

Oral presentations summarized the science and status of innovative concepts and set the stage for contributed posters where detailed technical information was presented. A “skunkworks” provided a forum for novel ideas, including significant new twists on old ideas, combinations of ideas that together offer a qualitative advantage, and completely new concepts and new opportunities created by technology advances. Breakout sessions considered the relationship of a possible burning plasma experiment to the ICCs, in preparation for this summer’s Snowmass meeting of the U.S. fusion-energy community. An evening town meeting provided an opportunity for discussions with staff from the D.O.E. Office of Fusion Energy Sciences. It was also an opportunity to honor Bill Dove, whose retirement had recently been announced. A plaque was presented to Bill from the community, thanking him for his long-term leadership and interest in innovative concepts in fusion energy.

The workshop agenda and list of 116 attendees can be found on the workshop web site: https://wormhole.ucllnl.org/ICC2002/. In addition, the web site provides a long-term archive for the viewgraphs and posters presented at the workshop, with many of the more than 100 presentations available in PDF format. The oral presentations are briefly described below, with authors’ names in parentheses. Space does not permit summaries of the many other posters, so the reader is urged to visit the web site to review them.

Advances in Energy Confinement in the Reversed Field Pinch (Stewart Prager). Modification of the current density profile in the reversed field pinch (RFP) reduces magnetic fluctuations and improves energy confinement. Careful programming of both the poloidal and toroidal electric field in the Madison Symmetric Torus (MST) has flattened the current profile and greatly reduced the $m = 0$ and 1 magnetic fluctuations, resulting in beta values as high as 15% and electron temperatures up to 1.3 keV. The energy confinement time is about 10 ms, several times the usual empirical scaling. Runaway electrons are confined up to 100 keV, implying that the magnetic surfaces are changing from stochastic to well formed. Extensive diagnostics are being brought on line, including the ability to measure current profiles using polarimetry and to measure electrostatic fluctuations using a heavy ion probe. This is anticipated to be important as losses resulting from magnetic fluctuations decrease and the plasma confinement improves. Future plans include RF wave current drive, oscillating field current drive (ac helicity injection), and neutral beam injection for further plasma control.

Overview of Recent Results from the SSPX Spheromak Experiment (David Hill). The Sustained Spheromak Physics Experiment (SSPX) is producing 500–600 kA plasmas with edge magnetic fields of 0.25 T using coaxial DC helicity injection. The recent addition of new bias magnetic field coils has lowered the threshold injector current from about $\lambda = \mu_0 j/B = 20\ m^{-1}$ to $10\ m^{-1}$, comparable to the flux conserver eigen value, resulting in reduced magnetic fluctuations and electron temperature as high as 150 eV at densities of 0.5×10^{20} m^{-1}. The current pulse has been lengthened to 3 ms and, in some discharges, the current amplification ($I_{toroidal}/I_{gun}$) is observed to increase until the capacitor bank runs out of energy. The nT_e product follows what appears to be a beta limit corresponding to a peak $\beta_e = 6\%$ and a volume average $\beta_e = 4\%$. Ion temperatures inferred from Doppler-broadening of impurity emission lines show $T_i \sim T_e$, yielding a peak total $\beta \sim 12\%$. The role of magnetic geometry and plasma temperature in controlling the build-up rate are now being explored. The continuous rise of current and field in the spheromak is observed both with and without the presence of large amplitude $n = 1$ fluctuations. Helicity balance measurements point to the importance of determining both the captured magnetic flux and the sheath voltage at the injector electrodes.

Field Reversed Configurations: Issues, Status, and Plans (Alan Hoffman). The Field Reversed Configuration (FRC) is an attractive reactor confinement scheme because of its high beta, simply connected geometry, and natural divertor. FRCs are formed by several methods, including theta pinches, merging of spheromaks with opposing helicity, and ion rings. Recent modeling including kinetic and Hall effects indicates stability to the $n = 2$ and internal tilt modes to higher s (number of internal gyroradii) than previously predicted, becoming more consistent with experiments. Current drive experiments in FRCs using formation by quasi-steady rotating magnetic fields (RMF) are very different from standard theta-pinch formed FRCs, tending to have a large ratio of the plasma separatrix to flux conserver radii, low separatrix density, a flattened B_x profile near the field null, and a contribution to the pressure balance from B_θ.

Experimental magnetic field profiles are in good agreement with theory. Plasmas driven by this method have the potential of increasing the magnetic flux above the 10s of mWb that can be achieved in theta-pinches. Future experiments will generate hot plasmas by the well-known theta-pinch technique, followed by translation into a chamber containing the RMF antennas. Density confinement measurements show improved flux lifetimes at lower resistivities in low density (10^{20} m^{-1}) experiments. Plans also include tangential neutral beam injection to counter RMF-induced torque on the plasma and control the ion spin-up, investigation of stability and confinement at lower densities, and coordination with theoretical efforts on kinetic plasmas.

Heavy Ion Beam Science and Innovative Technology Toward Inertial Fusion Energy (Grant Logan). Heavy ion beams offer an attractive opportunity for inertial fusion energy because of their potential efficiency and effectiveness in the target interaction. High-energy accelerators with megajoule-class beam energies exhibit the efficiency, pulse rate, and durability needed for IFE and the clear-bore magnets used to focus the beams can tolerate target debris and radiation. Good target designs already exist and are being improved through reduction of the ion range in the target material, acceptance of larger beam spot size, and longer pulse widths. Experiments are underway with a high-current transport experiment (HCX) to explore dynamic beam aperture limits, halo losses, and electron effects; a neutralized transport/focusing experiment (NTX) to validate beam-plasma interaction models and focusing, and a 500 kV facility to explore high-brightness plasma sources and multiple beam–interaction physics. These are supported by extensive computational tools and by smaller supporting experiments throughout the community. Both high-energy beam physics and plasma physics resulting from the high beam space charge and background plasma effects are important. After these separate experiments are completed, the next step will be to study transverse and longitudinal emittance growth through injection, acceleration, longitudinal beam compression, and final focus in an integrated beam experiment, IBX.

Status and Prospects for Laser Direct-Drive for Fusion Energy (Andrew Schmitt). Direct drive laser fusion has been an innovative fusion concept for the past 25 years. Its utility for energy is dependent upon the possibility of achieving high energy gains, which puts stringent constraints on the uniformity of the laser and target. Within the past 20 or so years, the implementation of smaller-wavelength lasers and discovery of optical smoothing methods have all but eliminated laser-plasma coupling issues for direct-drive and placed us closer to satisfying the symmetry constraints. More recently, the increased use of large two (and sometimes three) dimensional radiation-hydrocodes have enabled more quantitative assessment of the performance and stability of high-gain target designs. Recent experimental results also show the promise of reducing laser imprint further.

Pulsed Power ICF and IFE Research on Z and ZR (Keith Matzen). Z has become a premiere facility for high-energy density physics research relevant to both ICF and IFE. On Z, the high magnetic field pressures associated with 20-MA load currents implode a wire array z-pinch, generating up to 1.8 MJ of x-rays at powers as high as 230 TW. These intense x-ray x-ray sources have renewed interest in utilizing fast pulsed-power generators to drive ICF capsules. Target design calculations for two specific target configurations (z-pinch–driven hohlraum and dynamic hohlraum) indicate that fusion yields in excess of 500 MJ can be obtained in configurations in which the z-pinch implosions are driven by peak currents of 60 MA. For the z-pinch–driven hohlraum concept, recent experiments on Z with double-pinch hohlraums have demonstrated hohlraum energetics and coupling efficiencies that scale to high yield, and initial radiation symmetry and capsule implosion experiments have also been performed. For the dynamic hohlraum configuration, shock and capsule implosion dynamics have been studied. In addition, we have begun using the Z-beamlet laser (ZBL) to backlight capsule implosions, and have proposed to study fast igniter physics by adding a PW capability to the ZBL laser. For IFE, recent developments have led to a conceptual approach for a rep-rated z-pinch power plant that exploits the advantages of going to high yield ($\sim$ few GJ) at low rep-rate ($\sim$0.1 Hz). This concept uses a recyclable transmission line to provide the necessary standoff between the fusion target and the power plant chamber.

Fast Ignition (Michael Key). Fast ignition has significant potential advantages for IFE relative to conventional hot spot ignition, notably increased gain and reduced requirements for fuel density and compression symmetry. Laser generated relativistic electrons, generated by relativistic ponderomotive forces at the critical density, are the key to fast ignition by electrons or protons. Efficient (30%) conversion of light energy to electrons and their penetration into solid matter have been demonstrated experimentally. At laser power of 5×10^{19} W/cm^2, conversion efficiencies to energetic electrons of 30% have been obtained. 2D and 3D PIC modeling of penetration show the effects of the Alfvén current limit and Weibel-like instabilities, and hybrid models treating the full scale (with less physics) predict magnetic collimation of the electron beam. These results are consistent with experiments on the Pettawatt (PW) laser, in which the x-ray spectrum indicated 300 eV at near solid density in the laser focal spot region. A new fast ignition concept, ignition by ballistically focused laser-generated proton beams is also being studied. Relativistic electrons create a Debye sheath at the rear surface of a foil, which is curved to focus accelerated protons to the ignition hot spot. New PW lasers coming on line in Europe, Japan, and the United States will conduct studies at energies up to full scale. Integrated fast ignition experiments using facilities around the world are also being planned.

Physics Progress on the NSTX Device (Randy Wilson). The mission of the NSTX research program is to investigate and understand effects of low aspect ratio spherical tori, thereby broadening the understanding of toroidal plasmas, enhancing predictive capabilities, and potentially leading to attractive energy producing devices. NSTX has achieved $\beta_{TO} \approx 25\%$ with neutral beam heating and observed the low aspect ratio (1.26) version of many phenomena characteristic of tokamaks. New phenomena include the compressional Alfvén eigenmode, driven by energetic ions with velocities ~4 times the Alfvén speed. Preliminary evidence suggests that these modes may cause stochastic heating of ions, as a possible explanation of non-classical heating apparently observed in the experiment. Impurity ions have a very low diffusivity; modeling suggests it approaches neoclassical ion-loss rates. High-harmonic fast wave heating couples power to electrons. Analysis of the resulting transport using TRANSP yields electron loss rates consistent with those of trapped electron modes. This rate is reduced by a factor of 3 in the core at low density when high electron temperatures up to 3.7 keV were obtained, suggesting the formation of an electron thermal transport barrier. H modes are generated by RF alone with broad T_e and n profiles and make an excellent target for long-pulse sustainment. Coaxial helicity injection for startup plasmas has generated 390 kA at an injector current of 28 kA; the extent of magnetic flux closure is being investigated.

ET Results and Burning Plasma Options (Robert Taylor). Central plasma confinement times close to 1 second are routinely obtained in the Electric Tokamak (ET) at 1/4 Tesla fields. Consequently, the energy confinement in ET has exceeded predictions by about a factor 5. Some of this improvement is related to higher-than-expected densities and some of it is due to an intrinsic improvement in the neo-ALCATOR scaling coefficient $\tau_E(0) \approx 0.3M(0)RaB^{2/3}$ (MKS), where *M* is the Murakami number. The plasma pulse length has been extended to 3 seconds, and extension to 10 seconds is expected soon. No impurity problems exist with ICRF heating up to the 300-kW level applied on two antennas. Charge exchange data shows ion temperatures increasing from 300 to 600 eV and an ion tail energy of 2 keV with second harmonic heating at 6.7 MHz. More antennas are now ready for high beta operation, but RF interference to the control systems has limited full utilization of the available power. The exceptional confinement results, at 1/4 Tesla fields, extrapolate well to D-T and advanced fuel burners but not yet to an economic fusion reactor without the near unity beta core.

Innovation in the Stellarator Concept: Overview of New U.S. Stellarator Experiments (Stephen Knowlton). New stellarator experiments in the United States will test theoretical advances in which the magnetic configuration exhibits near symmetry in a specific direction together with the development of innovative design optimization techniques. The results are predicted to combine attractive features of both tokamaks and stellarators, potentially yielding steady state plasmas with no disruptions. The operating HSX device at Wisconsin is investigating neo-classical confinement improvement in a quasi-helically symmetric plasma using electron-cyclotron heating at 28 GHz to investigate low collisionality electron transport and plasma viscosity. The results clearly show the improvements attributable to symmetry, with higher stored energy at low effective ripple and reduced viscous damping of plasma flow. The planned proof-of-principle scale NCSX experiment at PPPL will address integrated issues of disruption-free, high-beta operation in a quasi-axisymmetric configuration with high input power. The stellarator will have $R = 1.4$ m, $R/\langle a\rangle = 4.4$, and B ranging from 1.2–1.7 T at full iota and 2 T at reduced iota. At $\beta = 4.1\%$ it is predicted to good magnetic surfaces and to be stable to kink, ballooning, vertical, Mercier, and neo-classical modes. The proposed QPS experiment at ORNL will examine confinement and stability of quasi-poloidally symmetric plasmas in a very low aspect ratio device. It will have $\langle R\rangle = 0.9$ m, $\langle R\rangle/\langle a\rangle = 2.7$, and magnetic fields up to 1 T. Another type of quasi-poloidal configuration is predicted to be ballooning and Mercier stable at $\langle\beta\rangle = 20\%$ and kink and vertical stable at $\langle\beta\rangle = 11\%$. Although predicted bootstrap currents in finite-beta realizations of all of these configurations are lower than in advanced tokamaks, low-aspect ratio stellarators will operate with moderate levels of plasma current. Therefore, the understanding and avoidance of kink instabilities in helical devices is also a component of this innovative program. The small CTH experiment under construction at Auburn will investigate current-driven instabilities and the potential for passive suppression of disruptions in helical configurations.

Progress in Levitated Dipole Research (Darren Garnier). The levitated dipole magnetic geometry is approximated by a simple magnetic dipole and has closed field lines. Without rotational transform, the plasma equilibrium is stabilized by plasma compressibility rather than by average good curvature. The marginal condition for stability requires that the plasma pressure profile be stationary under an adiabatic interchange of flux tubes. Another consequence of closed field line geometry is that the plasma potential is not necessarily a flux function, leading to the possibility of convective cells that move plasma particles without convecting energy in plasmas with constant entropy profiles. Understanding the behavior of plasmas stabilized by compressibility, the formation of convective cells, and the resultant transport properties are the major challenges of levitated dipole research. Recent study of linear drift wave stability in dipoles includes the effect of varying plasma temperature and density profiles. The Levitated Dipole Experiment, LDX, currently under construction and nearing first operations, consists of a 1/2 ton, 1.5 MA, 5-T magnet levitated within a 5-m diameter vacuum vessel. The floating coil (F-coil), with its advanced Nb3Sn superconductor and state-of-the-art cryostat will be cooled by a cryogenic heat exchanger and then charged inductively by a 13-MJ NbTi superconducting charging coil. First plasma experiments will focus on the stability of high-β dipole plasmas produced by ECRH, with the F-coil initially in a supported mode. In later experiments the coil will be levitated to eliminate mirror losses and allow for higher plasma β.

Overview of Research and Issues for Ion-Injected IEC Fusion (George Miley). Gridded IEC devices are currently employed for ion injection experiments to create a potential well, which in turn traps the second species; the ultimate goal is the formation of a "double well." Such experiments are presently under study at various labs, including the University of Illinois, the University of Wisconsin, LANL, Kyoto University, and the University of Sydney. Several fundamental physics issues remain to be resolved. Experimental and theoretical studies verify double well formation, but the volume of the ion trap created is too small in relation to the total device size for a practical fusion unit. Increased ion angular momentum has been proposed as a solution, but this remains to be verified. Stability under high injection current conditions also remains as an issue for scale up to practical devices, although preliminary studies suggest a stability "window" exists. Finally, methods to create and inject ions while maintaining a very low neutral background density remain as a critical issue. Along this line, results from recent RF ion gun injection experiments were presented.

Experimental and Theoretical Studies of Electrostatic Confinement (Rick Nebel). Recent theoretical work has suggested that a tiny oscillating ion cloud may undergo a self-similar collapse that can result in the periodic and simultaneous attainment of ultra-high densities and temperatures. Theoretical projections indicate that such a system may have net fusion gain even for an advanced fuel such as D-D. Schemes have also been suggested in which a massively modular system consisting of tens of thousands of these spheres can lead to a very high mass power density device (comparable to an LWR). Such systems should be very economically competitive. However, a major uncertainty in this plasma system is the behavior of the electrons. Previous theoretical work has shown that the required electron cloud is susceptible to an instability that is analogous to the Rayleigh-Taylor mode present in fluid mechanics. In the kinetic limit (counter-streaming electrons), one expects this instability to go over to a type of two-stream instability. Simple two-stream analysis suggests that the mode may be absolutely stable at a finite value of ratio of the Debye length to plasma radius. This conclusion is consistent with previous experimental results. These experiments are presently being redone on the INS-e IEC. Results indicate fluctuations in the electron plasma frequency ($\sim$60 MHz) range that show bursting behavior. The plasma is also showing coherent fluctuations at lower frequencies ($\sim$100 kHz). Electron dynamics are also being studied in the Penning Fusion eXperiment—Ions (PFX-I). A virtual cathode is produced in this device by a nonthermal electron plasma confined in a modified-geometry Penning trap. Ions are then confined in the virtual cathode. RF signals resulting from instability caused by the trapped ions serve as a nondestructive diagnostic of the density of the electron plasma at the virtual cathode. Trapped ions can also be destructively detected by a negatively biased microchannel plate located below the trap by dumping the electrons out the top of trap, thereby destroying the virtual cathode and releasing the ions.

An Overview of Progress on MTF Research (Dick Siemon). Magnetized Target Fusion (MTF) has emerged in recent years as a qualitatively different approach or "pathway" to fusion energy. The major MTF issues have been identified, and progress is reported on several issues here and in posters. (1) Target formation with adequate temperature, lifetime, and density: A new FRC target generator, FRX-L, is beginning to operate with the needed electrical parameters to form a suitable MTF target; New theoretical results appear to explain the longstanding puzzle of FRC stability for the case of a highly prolate geometry; Wall-confined oblate FRC targets have been studied that might allow MTF target formation at high-s while avoiding ideal MHD tilt and interchange instability. Studies show that drift instabilities in the MTF, $\beta > 1$, strongly collisional regime are generally weaker than in previously studied collisionless regimes. The MACH2 code has been modified to allow study of FRC formation. Calculations suggest that the basic physics of a wall-confined target plasma could be studied using the Nevada Terawatt Facility. (2) Liner heating (wall compression) without mixing impurities: Reasonable efficiency is found with a theta-pinch-coil–driven liner, which avoids z-pinch tapered electrodes and is more suitable for target injection. 3D hydro calculations show that plasma jet liners can be formed, and the implied energy requirements, implosion trajectories, and fusion gain appear suitable to NASA. (3) The application of MTF technology to practical energy or space propulsion: A simple generic argument for MTF shows semi-quantitatively why MTF is less expensive than conventional fusion approaches. In system studies for space propulsion, MTF appears to deliver the required specific power and specific impulse with relatively low system mass at low Earth orbit.

Evidence of Stabilization in the ZAP Z-Pinch Experiment (Uri Shumlak). The ZaP Flow Z-Pinch Project at the University of Washington seeks to experimentally determine the connection between stability and plasma flow by generating z-pinch plasmas with an inherent axial flow. The experiment produces z-pinch plasmas 50 cm in length by initiating the plasma with a 1-m coaxial gun. The coaxial gun generates the axial plasma flow. After leaving the coaxial gun the plasma assembles along the axis to form a flow z-pinch. Magnetic probes measure the acceleration and assembly process, as well as the evolution of fluctuation levels of the azimuthal modes $m = 0, 1, 2$. Axial flow profiles are determined by measurements of the Doppler shifts of impurity lines. Experimental results show a stable period over 700 times the expected instability growth time in a static z-pinch. The experimentally measured axial velocity shear is greater than the theoretical threshold during the stable period and approximately zero afterward when the magnetic mode fluctuations are high. Time-dependent density measurements are made using a laser interferometer. Gross plasma motion is determined by using a fast-framing camera to detect visible emission.

The Maryland Centrifugal Experiment: Motivation and Status (Rick Ellis). The concept of centrifugal confinement is to employ centrifugal forces from supersonic rotation to enhance magnetic confinement along magnetic field lines allowing an open magnetic configuration. Rotation is driven by an applied electric field that is perpendicular to the confining magnetic field (ExB rotation). The plasma rotation will be nonuniform, resulting in large velocity shear that should stabilize MHD instabilities and possibly quell microturbulence, leading to near classical confinement. MCX is designed to test these ideas. The geometry of the magnetic field is that of a solenoid with axisymmetric mirror end fields. Biasing of an inner core relative to the outer wall produces a radial electric field that will drive supersonic azimuthal rotation, and the resulting centrifugal force will contain plasma to the solenoidal portion. Simple theoretical calculations, as well as detailed 3D MHD+transport modeling (Numerical Maryland Centrifugal Experiment), were presented, all of which support the concept. In brief, MCX is approximately 4 m in length with a central diameter of 0.6 m with B in the 0.2–2 T range; expected parameters are plasma density $1–10 \times 10^{13}\ cm^{-3}$, temperature 10–50 eV, Mach number greater than 2.