Summary of Physics Aspects of Some Emerging Concepts

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Field Reversed Configurations (FRC's)
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FRC's are attractive because of the simplicity of configuration. There is no central column and there are no toroidal fields. Once formed in the lab, they are robust - they are stable, can be compressed, and can be translated with ease. This immediately leads to the question, which remains the central question of FRC research and future direction: why are FRC's so stable? In particular, all field lines are closed and the curvature is unfavorable, hence, the flux tubes should be interchange or kink unstable according to well known MHD theory.

The answer is simple: ideal MHD theory is inapplicable.   MHD theory is applicable only in systems where there are many ion Larmor radii across the system scale. In addition, Alfvenic forces, the stabilizer of MHD theory, are the correct paradigm only in systems where there are many ion collisionless skin depths across the system. For the FRC's created in the lab to date, both these conditions fail. The maximum number of Larmor radii for an FRC in the lab is probably about 4 and since FRC's are by definition beta = 1 devices, the collisionless skin depth is equal to the Larmor radius.

Thus, MHD notions cannot be applied and, apparently, FLR effects and Alfven -> whistler effects are stabilizing. There is also another effect - the elongation. FRC's are generally elongated objects and the usual MHD instabilities, such as interchanges and kinks, have reduced growth rates with elongation. To be sure, there is theory that corroborates the above. The theory, however, is not easy and the last word does not seem to be in yet. In addition, in this regime, 2-fluid numerical simulations are numerically more challenging than the corresponding MHD simulations in that the whistler frequency goes like k**2 (whereas Alfven waves go linearly with k).

While FRC's show remarkable stability properties, the fact remains that to achieve the Lawson Criterion, FRC's would have to have about 20-30 Larmor radii across the small scale. This latter requirement can be derived by assuming even classical cross field heat transport. This then is the FRC's biggest challenge and determines future directions: can an FRC be stably made in the lab with a short scale ~ 20 Larmor radii. Attempts to achieve this on LSX met with difficulty in formation. Furthermore, what does 2-fluid theory indicate in this regime? It is because the FRC is such an attractive configuration and is currently so robust that these questions take up large importance.

Ion Rings

Ion rings are FRC's in which a substantial fraction of the plasma current is carried by large-orbit ions, with Larmor radius equal to the system scale. Stability is predicted for such rings by kinetic theory in a range of ion current distributions. Ion rings are perhaps the most strongly kinetic magnetic confinement concept, and ring experiments with varied distribution of large-orbit ion current can provide a good laboratory for investigating experimental stability and testing theoretical understanding. Kinetic stabilization of MHD modes, and Alfven modes driven by large-orbit ions also have relation to effects of energetic fusion products in other magnetic confinement concepts.

One of the challenges for this scheme is to develop the method of formation of these ring configurations with the desired ion current distributions. (an experiment is presently underway at Cornell).

Electrostatic Confinement Fusion via Penning Fusion

The idea here is to completely confine electrons by a combination of external electrostatic and magnetic fields, a la a Penning Trap, and then feed in ions to be held in by the resulting negative electron cloud.

The majority electron plasma is confined by well known non-neutral plasma techniques, i.e. by a combination of applied magnetic and electrostatic fields. The electrons required to produce the high electrostatic potential (several 100 kV negative in a reactor) are fed into the trap at the ends of the rods, where the insulator is isolated from the reacting plasma. Electrons are emitted and collected by an emitter at one end. Internal negative potentials, if required, may be produced by charging plasma-facing conductors with these electrons. The conceptually simplest such system has a uniform B-field and a quadrupole E-field. Such a system forms an effective spherical, harmonic well for electrons with small canonical angular momentum about the axis defined by B-field.

More complex systems, which have a non uniform B-field produced by magnetically soft iron flux shapers, may approximate the desired spherical confinement with reduced applied E-field.

The space charge of the confined uniform-density electron plasma produces a spherical, harmonic well for ion confinement and spherical focussing. Two possible ion-focussing modes are SCIF (Spherically Convergent Ion Flow) and POPS (Periodically Oscillating Plasma Sphere). SCIF is the "traditional" IEC (Inertial Electrostatic Confinement) mode in which ions continuously focus near r=0 by continuous injection and loss. POPS is the large-amplitude spherical compression/expansion operation in which ions periodically attain a high-density focus near r=0.

Some important physics issues which are to be resolved within the next decade are:

* Combined trap operation and ion source effects
* Demonstrate POPS ion oscillations
* Complete theoretical power balance, including field errors,
relativity and other "non ideal" effects
* Improved diagnostics
* PF neutrons production
* Tolerance to field errors

Dipole

The dipole confinement concept is based on the idea of generating pressure profiles near marginal stability for low-frequency magnetic and electrostatic fluctuations. From ideal MHD, marginal stability results when the pressure gradient is sufficiently gentle to satisfy an adiabaticity condition. This condition leads to dipole pressure profiles that scale with radius as $r^{-20/3}$, similar to energetic particle pressure profiles observed in the Earth's magnetosphere. Since the magnetic field of a dipole is poloidal, there is no drift off of flux surfaces and therefore no ``neo-classical'' degradation of confinement as seen in a tokamak.

It has been pointed-out that a plasma that satisfies the MHD interchange stability requirement may be intrinsically stable to drift frequency modes. Stability of low frequency modes can be evaluated using kinetic theory stability requires that the curvature drift frequency exceed the diamagnetic drift frequency the and this result is consistent with the MHD requirement given above. This property implies that the pressure scale length exceed half the radius of curvature, which is a physical property that distinguishes a dipole confined plasma from other approaches to magnetic fusion plasmas. Additionally, when the interchange stability criterion is satisfied, it can be shown that localized collisionless trapped particle modes and dissipative trapped ion modes become stable. Low frequency modes that are driven by parallel dynamics (i.e. the universal instability) also tend to be stable due to the requirement that the parallel wavelength of the mode fit on the closed field lines. Theoretical work on anomalous inward diffusion (towards the ring) due to high frequency, drift-cyclotron instability supports the view that both stability and confinement can be extremely good in a levitated dipole.

A dipole has closed field lines and non axisymmetric heating could generate large scale convection on the heating time scale (even if the system is interchange stable). These cells can then lead to particle transport and in the inner plasma (between the internal ring and pressure peak) convective cells could lead the energy transport. In the outer plasma (between the pressure peak and the outer vacuum chamber wall) the particle transport is not accompanied by energy transport at marginal stability. The resulting transport of particles without energy transport could provide an ideal mechanism for fueling in a reactor.

By levitating the dipole magnet end losses can be eliminated and conceptual reactor studies supported the possibility of a dipole based fusion power source that utilizes advanced fuels. The ignition of an advanced fuel burning fusion reactor requires high beta and good energy confinement. Additionally advanced fuels require steady state and efficient ash removal. A levitated dipole may provide uniquely good properties in all of these areas. The chief technology drawback of the dipole approach is the need for a levitated superconducting ring internal to the plasma but recent advances in high temperature superconductors coupled with an innovative concepts relating to the use of internal refrigerators to maintain cryogenic temperatures when the ring is embedded within a fusing plasma may provide a solution to the technological difficulties.

The dipole confinement approach can be tested in a relatively modest experiment which profits form the development of the technology of superconductors, gyrotrons and pellet injectors. A concept exploration experiment is presently being built jointly by Columbia University and MIT.

Magnetized Target Fusion (MTF)
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In this concept, an FRC is created, injected into a cylindrical liner with an ambient axial B field, and the liner is then imploded by discharging current through it. The implosion adiabatically compresses the FRC - density and temperature go up until fusion conditions can be reached in principle.

The obvious questions that are immediately raised for this scheme can be answered. Is the liner implosion stable to sausage modes? Yes, an implosion with a radius ratio of 13 has been demonstrated recently. Is the FRC stable during implosion? Yes, within reasonable educated guessing: the FRC database shows that the there is a stability boundary in s* - E space, where s* is the number of Larmor radii across the machine and E is the elongation. By using adiabatic compression laws, it can be shown that the trajectory of the imploding FRC in this space is such that it always stays inside the stable region, from maximum to minimum radius, R, of implosion. Why doesn't the FRC simply squirt out axially? Again, the adiabatic compression laws show that the FRC cigar actually shrinks in the axial direction - thus there is no squirting cigar. The latter fact is important in that the density in the FRC builds up as R**(-2.5) - faster than even a case of no longitudinal squirting. What about heat transport during implosion? Several transport models can be used - ranging from classical to Bohm - to show that Lawson's Criterion can be achieved for the parameters chosen regardless of transport model.

A more subtle question is for how long can thermonuclear burn last? As the compression proceeds, the temperature will rise until it gets to fusion temperatures of 10 KeV or so. Fusion burn can happen only as long as the temperature stays in this vicinity - this can only be in a small time at the nadir of the implosion. Thus, the "tau" in n*tau may be determined by this "dwell time." Thus, the parameters of the initial implosion have to be chosen such that all the three conditions - "good" s*-E trajectory, transport loss minimization, and attainment of Lawson in a dwell time - can be met simultaneously. Work in this area as well as 2D numerical simulations of the implosion could flesh out the MTF concept.

Flow-Through Z-Pinch
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The flow-through Z-Pinch is an experiment to test the idea that a velocity shear can stabilize interchange and kink modes. There are at least three theories that suggest that these modes can be stabilized in a Z-Pinch if there are axial flows in the pinch which, according to these theories, range anywhere from ~ 10% of the Alfven speed to several times the sound speed (in a Z-Pinch, the sound and Alfven speeds are roughly comparable). The ZAP experiment at the University of Washington seeks to test this idea by making a Z-Pinch that is expected to have flow through speeds of the order of the Alfven speed.

The flow through Pinch is open at either end. Thus, the plasma pressure will naturally want to expand axially at sonic rates. As such, the confinement time is sonic and very short, leading to difficulty in satisfying the Lawson Criterion. The experiment nonetheless will shed light on the physics and feasibility of velocity shear stabilization of ideal MHD instabilities. A central issue that could be settled by this experiment is the discrepancy within the three theories of such stabilization. The programmatic effort should include an understanding of the underlying assumptions of these theories so that an informed contact can be made with the data when it becomes available.

Tandem Mirror and Gas Dynamic Trap

In open ended mirror systems the plasma confinement region has a finite length along the magnetic field lines. Mirrors have been demonstrated to support high beta plasmas and the simple linear geometry is appealing for reactor applications. In a "simple mirror" confinement results from the conservation of the first adiabatic invariant but a velocity-space loss cone will be present and collisional diffusion into the loss cone presents a fundamental limitation on the plasma confinement. Several ways to improve confinement have been demonstrated.

In a tandem mirror electrostatic barriers are erected along the field lines for the ions which have been demonstrated to exponentially improve confinement. So-called thermal barriers present electrostatic barriers for electrons and further improve energy confinement (in the electron channel). However thermal barriers are seen to significantly complicate the tandem mirror design.

An alternative approach to mirror confinement is provided by a gas dynamic trap, in which the plasma parameters and system size are chosen so that the system length exceeds the plasma mean free path. A long low field magnetic cylinder is bounded by high field axisymmetric mirror coils and beyond the mirror peak the field flares in such a way that the outflowing plasma provides the average good curvature that is necessary for MHD stability. In such a system the energy loss rate is limited to thermal flow through the small area of the high field magnet and for sufficiently high field at the mirror throat and a sufficiently long low field "central cell" a fusing plasma can ignite. This system is also promising as a neutron source. In this application "sloshing" ions can be injected into the central cell and the accumulation of density at the ion bounce points would provide a locally high fusion power density.

Centrifugally Confined Plasmas (CCP's)
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The modern version of the Centrifugal Confinement idea rests on two prongs: first, centrifugal forces from induced large rotation can be used to augment the usual magnetic confinement (which is what motivated the early CCP experiments); second, the large velocity shears from the rotation can suppress microturbulence, hence improved transport, and possibly suppress even macroscopic MHD instability.

When these two prongs are put together, the optimized device features 4 advantages: steady state, no disruptions, enhanced cross-field confinement, and possibly simpler coil configuration. These advantages flow respectively from the facts that all the currents are external, lack of parallel plasma currents obviates kink modes and disruptions, velocity shear can suppress microturbulence, and velocity shear can also significantly suppress the interchange flute modes.

The latter point is of primary interest in any new experiments. The optimistic scenario is that the magnetic field can be purely poloidal and that toroidal field is not needed to stabilize the flute interchange on account of the large toroidal flow shear. Analytic and numerical calculations show that this scenario is not unreasonable. However, the numerical simulations seem to indicate that the suppression of the flutes is not complete - there is a residual wobble (in about 5-10% of the discharge) that seems to persist even at high Mach numbers. In addition, there could also be a weakly growing Kelvin-Helmholtz instability. For this reason, a weak toroidal magnetic field may be required to suppress any remaining instability. The earlier experiments did not incorporate any toroidal field, and evidence for MHD instability was reported. It would be prudent for any future experiments to allow such a field and test for the critical field required. In addition, elongation helps to reduce the interchange growth rates - this could be tested in a new experiment. An experiment with toroidal field and elongation is currently under consideration (MCT at the U of Maryland).

When scaled to a reactor, simple transport analysis suggests that a CCP can achieve breakeven provided the Mach number exceeds about 4. Other scaled parameters are also reasonable for reactor regimes. The greatest challenge in these regimes would be technological - primarily in the design of an insulator that, in the presence of crossed E and B fields, could sustain voltage drops in its neighborhood on the order of several

MV/m. Another challenge is the rotation which needs to be maintained and constitutes a circulating power fraction on the order of 50%.

Spheromak

The Spheromak is a self-organized plasma configuration in which the current is sustained by a magnetic dynamo associated with the inward transport of helicity from the edge plasma. The configuration has a simple toroidal magnetic geometry, and if energy confinement is sufficiently good it would make an attractive reactor. Advantages include a simply connected geometry without linked toroidal field coils, a compact system, steady state current drive using electrostatic (or other) helicity injection, and high ohmic heating with possible ignition without auxiliary heating. However, the current drive is associated with symmetry-breaking magnetic fluctuations which allow energy transport at a high level. Although some modeling indicates that these losses should decrease rapidly enough with plasma temperature that a reactor is attractive, the data is limited and mechanisms not well identified experimentally. Consequently, a new experiment, the Sustained Spheromak Physics Experiment, SSPX, has been initiated to make the profile and parameter measurements, including magnetic field profiles and fluctuations, necessary to determine and study helicity, energy, and particle transport. Additional effects, including collisionless magnetic reconnection, anomalous ion heating, density control, edge physics, and electrostatic turbulence are expected to be addressed in the course of the experiment.

In addition to the steady-state opportunities for fusion energy, dense spheromaks are potential targets for Magnetized Target Fusion and for other pulsed fusion power devices. This provides opportunities for reactors in which the plasma has relatively short confinement time (but still meets the Lawson criterion). For example, it may be possible to live with Bohm diffusion at sufficiently high density. Results from SSPX will be considered in light of this option as well as the primary steady-state reactor.

Spheromak physics was explored in detail in joint sessions with the magnetic confinement group, and is discussed in the sections prepared by that group.

Reversed Field Pinch (RFP)

The reversed field pinch is a low magnetic field, low safety factor configuration. The low magnetic field yields potential reactor advantages, but also leads to relatively high levels of magnetic fluctuations. Hence, a key goal of the RFP program is to suppress the magnetic fluctuations and the related transport. The main strategy for fluctuation reduction and confinement improvement is to alter the current density profile to one which is more favorable for stability. To this end, lower hybrid current drive will be attempted in RFP experiments. Other key goals of the RFP program are to develop techniques for current sustainment (e.g., through oscillating field current drive in which a steady current is ohmically produced via oscillating toroidal and poloidal loop voltages), to determine the beta limit (through auxiliary heating, now feasible in the improved confinement discharges obtained in recent experiments), to control the resistive wall instabilities which can occur at zero beta, and to develop power and particle handling techniques.

A more detailed exposition of the RFP scientific issues is available in the MFE section.