A Brief Historical Summary of Fusion Alternatives

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Following declassification of controlled thermonuclear fusion in 1956 and the subsequent Geneva conference in 1958 a number of concepts emerged for creating thermonuclear fusion by magnetic confinement of a hot plasma. The possibilities fall into two basic categories, those with open field lines i.e. mirror plasma confinement systems which require anisotropic plasma pressure for confinement and closed field systems. An exception is the Stellarator family in which vacuum field lines map out a closed toroidal surface but the lines do not close. Fundamental to all closed line systems is the self- constricting discharge, or Z pinch, Z being the direction of current.**1** Early experiments concentrated on the snowplow pinch in which a discharge along a column of gas ionizes the gas and the Btheta field of the current sweeps up the gas radially inward. (The word snowplow is a misnomer, what the action actually is that of a snow scoop.) Pinching continues until the plasma pressure increases to the field pressure. After a short bounce the plasma undergoes a rapid instability which causes the pinch to periodically neck off somewhat like a string of sausages. While the implosion phase is stable the sausage instability grows rapidly on the first bounce generating more than the expected thermonuclear neutrons. However, it was recognized that the implosion was stable and that controlled fusion reactions could be made significant with a large enough pinch. 2 This possibility was not pursued because thermonuclear conditions could be maintained only for a brief sound transit time which would result in a very small yield. A more promising application of the z pinch is to compress a solid cylindrical liner containing thermonuclear fuel to the point of ignition and confine the ignited plasma by the inertia of the liner. Magnetic drive for ICF 3 has recently emerged from a security blanket in a project conducted at Sandia labs. Another ICF application is of a snowplow pinch in a radiating gas. This approach, in which the imploding shock radiates its internal energy to become a dense liner moving inward at high velocity to compress a DT core to ignition.4

The Z pinches discussed above have all been pulsed, more suited for reactor applications is the continuous flow Z pinch. First generated around 1965 by John Marshall at LANL with a crowbared Marshall gun. The slow component of magnetized plasma, low B2/rho, flowed out of the gun, forming a flow pinch which was stable and lasted roughly 200 microseconds. Subsequently, it was shown theoretically 5 that a flow pinch, made stable to sausage instability by a diffuse pressure profile could also be made stable to kink modes by shear in the flow velocity. The flow pinch is possibly the simplest fusion reactor alternative. Liquid walls can be employed, 6 confinement and heating are provided by the pinch effect, and the plasma parameters can be adjusted to burn D-D. An experimental program at University of Washington has confirmed, in detail, the theoretical stability predictions.

Having discussed the multiplicity of z pinch possibilities we now turn to discuss the pinch with theta directed current, the theta pinch. The earliest suggested theta pinch was suggested by Nicholas Christofilus at the Geneva conference called Astron. 7 The Astron concept was basically a toroidal theta pinch formed, maintained and stabilized in a solenoid field by the injection of a beam of high-energy particles. Uniquely, experiments on Astron were conducted at LLNL on a scale close to that required of a reactor core. Formation of the toroidal theta pinch depended on the buildup of beam current to generate sufficient field to reverse the solenoid field so that the field lines encircle the circular orbit of the beam. Considerable difficulty was encountered in achieving field reversal and as the reversal difficulties were beginning to be overcome an administrative edict resulted in the cancellation of Astron and along with nearly all of the alternate research in the fusion program. This was a major administrative blunder that set back fusion research on alternatives decades and led to ITER as the sole possibility for fusion power.

At Los Alamos, LANL, theta pinch research had come to a close with a toroidal theta pinch SYCILLAC shown experimentally to be unworkable. Experiments with z pinches wrapped in a circle ( LANL’s Perhapsatron) exhibited large kink and sausage deformations so that pinch research shifted to the toroidal “Belt pinch” which proved to be more stable but as produced had an axial center conductor. At LANL work with a cylindrical theta pinch showed that on the capacitor ring- back the reverse of the initial field was injected at large radius. The reversed field injected reconnected with the inner radius field at the ends to form a closed line configuration, ”belt pinch” with no center conductor and was called a Field Reversed Configuration(FRC). 8 In spite of being predicted to be unstable, surprisingly long lasting FRC’s were observed. The FRC configuration is essentially the same as that of Astron, the field reversal current being supplied by theta directed plasma current rather than an injected beam. Recently a new configuration of Astron has emerged by the field reconnection of two oppositely directed FRC’ s. 9

In the late 1960’s a Russian developed toroidal stabilized pinch was confirmed to have confinement of plasma with significant parameters. Since then a number of experiments on tokamaks of increasing size have formed the basis for the large international effort now called ITER. At the time of the initiation of the ITER project there was considerable skepticism that **practical** fusion could be obtained with this device. Skepticism arose from the geometrical complexity, low beta of the confined plasma, hence low-power density, combined with superconducting coils which inevitably would lead to a very large, expensive machine. Some referred to ITER as a superconducting Cathedral, which appears to be an apt historical comparison.

In the Early 1980’s another member of the family of closed field configurations was introduced. The new member, called SPHEROMAK (SPM) after an earlier publication 10 completes the family of compact toruses, CT’s with beams (Astron), with plasma currents and pressure(FRC), and now with theta and poloidal field (SPM).

Efficient formation of the SPM can be done with a magnetized gun 11 by either dynamic expulsion of pre- established magnetic field from the gun or by slower helicity injection current drive. Experiments have shown the SPM force free, minimum energy 12 field configuration to be very stable against major deformations as in the Compact Torus Accelerator(CTA) 13, and to support an electron beta of 10%. 14 As an alternative to ITER, the SPM has the advantages of simplified geometry with smaller size, no superconductors, and the possibility of liquid walls.15 An even simpler possibility is the CT string reactor which requires no external magnetic fields at all. 16 **I**n summary, out of all the alternatives to ITER, the CFP and the CT magnetic field configurations are most likely to provide a small scale, continuous source of fusion power. However, it should be noted that magnetically driven ICF is in the early stages of development and has the potential of overcoming many of the drawbacks of magnetic confinement fusion. In particular, the possibility of burning nearly neutron free p11B with direct conversion to electricity would be a highly desirable end state for this quest.

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