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Author(s):

IRVIN R. LINDEMUTH, XPA

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**THE ROLE OF Z-PINCHES AND RELATED CONFIGURATIONS IN
MAGNETIZED TARGET FUSION**

Irvin R. Lindemuth
Los Alamos National Laboratory, Los Alamos NM, USA

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The Role of Z-Pinches and Related Configurations in Magnetized Target Fusion

Irvin R. Lindemuth

Los Alamos National Laboratory, Los Alamos, New Mexico

Abstract. Magnetically driven z-pinch liners coupled with z-pinch plasma formation schemes may make the achievement of controlled fusion conditions in the laboratory possible in a shorter time frame and at much lower cost than with any other approach.

As discussed in these proceedings (1), z-pinches were one of the earliest candidates to heat a deuterium-tritium (D-T) plasma to thermonuclear conditions. Unfortunately, violent instabilities prevented the early approaches from achieving the goal of controlled fusion, and fusion in the laboratory has been an elusive goal for more than four decades. As many different approaches have been tried and abandoned, controlled fusion research has evolved into two mainline approaches, magnetic confinement (MFE, or magnetic fusion energy), as now embodied primarily in tokamaks, and inertial confinement fusion (ICF), as now embodied primarily in laser driven targets. Each approach has reached a funding crossroads, with proponents of each proposing two multi-billion, multi-year next-generation facilities, ITER (International Toroidal Experimental Reactor) for MFE and NIF (National Ignition Facility) for ICF.

Although many approaches have been tried in the four decades or so of fusion research, the plasma conditions that must be achieved have remained essentially unchanged. In general, these conditions are stated as an ion temperature, T_i , greater than 4 keV and either a number-density/confinement-time product, $n\tau$, greater than 10^{14} s/cm³ (MFE) or an areal density, ρR , greater than 0.4 g/cm². It is the inability of any approach to obtain all of the required conditions simultaneously that has frustrated fusion researchers, and even after forty years of increasing knowledge about the behavior of plasmas, there remains no guarantee that next-generation machines, after a major capital investment, will finally achieve the long sought goal.

To achieve the required temperature, all approaches must involve one or several heating processes to overcome plasma cooling processes that increase rapidly with temperature. At the risk of oversimplification, this fundamental challenge can be written as

$$\frac{dT_i}{dt} = \text{heating processes} - \text{radiation losses} - \text{thermal conduction losses}.$$

Tokamaks use such processes as microwave heating and neutral beam injection to provide the plasma heating, whereas ICF relies entirely on compressional (pdV) heating. In principle, at least, magnetic confinement schemes eliminate the last term, since the plasma is not in contact with its cold surroundings. Nevertheless, such losses are not eliminated, and such things as "anomalous transport" are encountered in tokamaks. Even though such losses are not totally eliminated, it is hoped that they can be held at a sufficiently low level that confinement times exceed 1 second will be achieved.

In contrast, in ICF, electron thermal conduction is a dominant loss mechanism. The thermal loss rate is so high that confinement times are limited to less than, say, 1 ns. Concurrent with the nine or ten orders of magnitude in confinement times between MFE and ICF is a nine or ten orders of magnitude difference in densities, with typical tokamak densities being $10^{14}/\text{cm}^3$ and ICF densities near $10^{24}/\text{cm}^3$. The high density of ICF means that the radiation loss rate, as well as the thermal conduction rate, is many orders of magnitude higher than can be tolerated in MFE.

The compressional heating rate in a target implosion is proportional to the target pusher's implosion velocity. To overcome the losses, the implosion velocity of a fusion target containing unmagnetized fuel must exceed 30 cm/ μs . Furthermore, prior to the main heating phase, the fuel must experience carefully timed shocks to raise the fuel "adiabat" from the initial, ambient temperature value so that fusion conditions can be reached at an achievable target final radius. Nevertheless, NIF ignition targets require the final radius to be smaller than 1/30 of the initial radius, a formidable challenge requiring an extremely symmetric implosion. Initial fuel densities must therefore be greater than $10^{19}/\text{cm}^3$.

Various computational models (e.g., 2), including the LASNEX code on which the US ICF program is based, predict that fusion can be achieved under much less stringent implosion conditions if the compressed fuel is preheated and magnetized prior to implosion. Although the possible benefit of a magnetic field in a fusion target was recognized in the 40's by Fermi at Los Alamos and at approximately

the same time by Sakharov in the former Soviet Union, it is only in light of recent advancements in plasma formation techniques, implosion system drivers, plasma diagnostics, and large-scale numerical simulation capabilities that the prospects for fusion ignition using this approach can be evaluated.

The use of a magnetic field within a fusion target is now known as Magnetized Target Fusion in the US and as MAGO (Magnitnoye Obzhatiye, or magnetic compression) in Russia (3). In contrast to direct, hydrodynamic compression of initially ambient-temperature fuel (e.g., ICF), MTF involves two steps: (a) formation of a warm (e.g., 100 eV or higher), magnetized (e.g., 100 kG), wall-confined plasma of intermediate density (e.g., $10^{18}/\text{cm}^3$) within a fusion target prior to implosion; (b) subsequent quasi-adiabatic compression and heating of the plasma by imploding the confining wall, or pusher. In many ways, MTF can be considered a marriage between the more mature MFE and ICF approaches, and this marriage potentially eliminates some of the hurdles encountered in the other approaches. When compared to ICF, MTF requires lower implosion velocity (perhaps as low as 1 cm/ μs), lower initial density, significantly lower radial convergence (e.g., $< 1/10$ of initial radius), and larger targets (e.g., 1-10 cm), all of which lead to substantially reduced driver intensity, power, and symmetry requirements. When compared to MFE, MTF does not require a vacuum separating the plasma from the wall, and, in fact, complete magnetic confinement, even if possible, may not be desirable. The higher density of MTF and much shorter confinement times should make magnetized plasma formation a much less difficult step than in MFE.

The substantially lower driver requirements and implosion velocity of MTF make z-pinch magnetically driven liners, magnetically imploded by existing modern pulsed power electrical current sources, a leading candidate for the target pusher of an MTF system. Although the most elementary liner z-pinch is a simple cylinder (e.g., 4), a z-pinch current drive can provide quasi-spherical implosion of a liner (5). The attractiveness of z-pinch liners stems from the fact that existing magnetic flux compression generators, and possibly existing and near-term pulsed power machines, appear to exceed the energy necessary to implode a suitable plasma chamber and demonstrate fusion ignition. For example, a Russian Disk Explosive Magnetic Generator (DEMG) has delivered a 100 MA current pulse to an imploding liner, which achieved a kinetic energy of more than 20 MJ at a velocity greater than 0.7 cm/ms (6).

Whereas the fundamental driver technology for MTF exists, a plasma formation scheme for MTF's pre-implosion plasma cannot readily be identified from "off-the-shelf" approaches. The cryogenic fiber z-pinch, once pursued as a

fusion source (1), is perhaps the simplest candidate. As predicted computationally at the Second Dense Z-Pinch conference (7), and subsequently confirmed by second generation experiments (8), previous attempts to drive fibers directly to fusion conditions encountered the "classical," explosive $m=0$ instabilities even though initial data suggested some "anomalous stability." Although the direct Ohmically heated fiber z-pinch had to be abandoned as a fusion concept, recent two-dimensional MHD computations predict that the exploding plasma will settle into a Kadomtsev-stable wall confined plasma when it contacts its confining walls (9). With proper choice of initial fiber diameter, driving current, and outer wall radius, the late-time, wall-confined plasma may have the parameters required for MTF's pre-implosion plasma. Fiber z-pinch experiments are underway at Los Alamos to confirm or refute these new computational predictions.

The Russian MAGO plasma formation scheme is a leading candidate for MTF's pre-implosion plasma because detailed two-dimensional computations, which match preliminary and yet incomplete data, predict near ideal pre-implosion conditions (10). The unique MAGO chamber combines features of coaxial guns, dense plasma foci, inverse z-pinches, and hard-core z-pinches. However, it differs from all of these in that, during the initial dynamic phase, two distinct current paths drive two distinct, but interacting magnetically driven shocks. The two-dimensional computations indicate that the late-time state of the MAGO plasma is a quiescent, Kadomtsev-stable z-pinch configuration with density, temperature, and magnetization appropriate for subsequent implosion. Although the early, dynamic interaction of the two shock-heated, magnetized plasmas is not of primary interest from an MTF perspective, a small fraction (e.g., 5 %) of the plasma is briefly heated to temperature above 1 keV and emits a pulse of 10^{13} fusion neutrons, the highest number of reactions ever achieved in a Los Alamos fusion experiment.

Experimental diagnosis of the plasma and liner conditions in an MTF system looms as a major challenge to MTF. Our experience to date suggests that MTF will require a strong synergism between experimental and computational endeavors, since MTF success will be determined not simply by liner and plasma stability or lack thereof, but by a detailed understanding of the long-term, non-linear evolution of instabilities including, perhaps, the evolution of one unstable configuration into a new, and stable, configuration as computations predict for the fiber pinches(9). Our success to date in predicting and interpreting z-pinch experimental data through detailed multi-dimensional computational modeling (7-11) is encouraging.

Because the economy in the Soviet Union could not sustain the long-term development of high-energy capacitor bank technology such as developed in the US, Russian scientists use the much cheaper magnetic flux compression techniques (the US also pursued similar technology, but at a much lower level) for both liner implosion and plasma formation. Russia has developed "one-shot" devices which can produce higher magnetic fields, higher electrical currents, and higher electrical energies than any US "off-the-shelf" technology. Magnetic flux compression generators offer to the fusion scientist a low-cost way to do scientific experimentation which, today, cannot be performed in any other manner. For MTF in a fusion energy context, of course, high-explosive energy sources would be replaced by a capital intensive non-explosive facility, but this investment would be made only after the MTF physics had been unquestionably demonstrated so that only engineering uncertainties remained.

Existing magnetic flux compression generators and existing pulsed power systems and near-term systems being developed in other contexts (e.g., the Los Alamos Atlas facility) mean that the cost of research in MTF is devoted primarily to plasma physics, not to driver technology or voluminous plasma containment vessel investments. Hence, Z-pinches and related configurations in an MTF context hold out the prospect of achieving controlled fusion in a shorter time frame at substantially lower cost than any other known path.

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