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Comments on the Critical Issues for a
High-Density Gas-Embedded Z-Pinch CTR
Reactor Concept

University of California

LOS ALAMOS SCIENTIFIC LABORATORY

Post Office Box 1663 Los Alamos, New Mexico 87545

COMMENTS ON THE CRITICAL ISSUES FOR A
HIGH-DENSITY GAS-EMBEDDED Z-PINCH CTR REACTOR CONCEPT

by

Carl A. Ekdahl

ABSTRACT

The issues considered critical for the realization of a CTR reactor are discussed for the high-density gas-embedded z-pinch concept. A simple model of the pinch reactor is presented that gives estimates for Q in substantial agreement with elaborate computer studies. An attempt is made to identify such critical points that are amenable to exploratory experiments. There appears to be no "fatal flaw" in the issues covered that would preclude a viable reactor based on this concept.

I. INTRODUCTION

The high-density, gas-embedded z-pinch (HDZP) has many advantages as an advanced fusion reactor concept, and there have been several reactor studies based on HDZP systems.¹⁻³ These detailed studies used computer codes to investigate the economics and feasibility of HDZP reactor systems. It is possible, however, to make estimates and scaling arguments for these conceptual reactor systems based on a simple heuristic model of the gas-embedded equilibrium pinch (see Appendix). The results of these estimates are in substantial agreement with the computer studies, but the simple model has the advantage that the physics is more readily apparent.

The issues considered critical for the realization of a viable CTR reactor are briefly discussed in turn in this paper. Where required, estimates relating to heating, size, and economics will be made based on the simple heuristic model, if possible, in an attempt to clarify the physical processes

involved. An attempt is also made to identify those critical points amenable to exploratory experiments in the near future.

II. CONFINEMENT CONFIGURATION

A. Equilibrium and Stability

The linear pinch is one of the simplest and most easily generated examples of a plasma equilibrium. However, the configuration is grossly unstable to MHD modes,^{4,5} and successive efforts to control these have led to a class of toroidal devices with high magnetic shear (reversed-field pinches) that show promise as candidates for ohmically-heated reactors. The gas-embedded high-density z-pinch proposed here appears to offer an attractive alternative means of controlling the MHD instabilities in a smaller device with higher energy density by relying on the inertia of the surrounding gas to slow the growth rate of the dangerous modes. There have been a number of experiments performed with results indicating that this approach to controlling MHD instabilities may indeed provide the necessary time to achieve a batch burn of fuel if the retardation of growth rates can be extrapolated to the reactor regime of operation. In a recent study, Hartman, et al.,² assume that the growth rates can be sufficiently retarded, and conclude that a high-Q reactor with low output power is feasible. Hammel¹ and others³ at Los Alamos have independently reached the same conclusion.

B. Energy Losses

An acceptable energy loss time can be calculated by assuming, as did Hammel,¹ that losses are only by bremsstrahlung radiation. Including classical radial ion thermal losses to the problem results in some uncertainty as to the success of the reactor. There have been some theoretical results suggesting that this problem may not be serious (Ref. 4),* but it is a concern, and can be investigated in exploratory experiments.

*This information was supplied by T. Oliphant, August 1979.

The neglect of axial losses is justified in regions of large $\omega\tau$ because then classical transport will be attenuated by $(\omega\tau)^{-2}$, and even if the transport is turbulent (Bohm-like) it should be attenuated by $(\omega\tau)^{-1}$. The thermal energy loss time to the ends is $\tau_{\text{the}} \sim \ell^2/v_{\text{the}}\lambda_{\text{ee}} \sim 2.7 \times 10^{-22} n \ell^2 / T^{5/2}$ μs in the absence of magnetic field. For $n = 10^{21} \text{cm}^{-3}$ and $T = 10 \text{ keV}$, the resultant loss time is $\tau_{\text{the}} \sim 10^{-3} \ell^2 \mu\text{s}$, which is longer than the Lawson time for a pinch length, ℓ , greater than 10 cm. As a consequence, a short 10-cm reactor would only require $\omega\tau \sim 40$ for a $40 \times \tau_L$ burn time and Bohm-like transport energy losses. In the HDZP with 1.1-MA current this value of $\omega\tau$ is exceeded over virtually the entire area, and axial losses can occur only in a very small region near the pinch axis.

However, even if significant axial losses were present a viable reactor would be possible. This was shown by Hartman, who investigated the worst case, which is that of axial free-streaming losses, in his study.³

C. Divertor

One of the distinct advantages of a HDZP reactor is the lack of divertor or high vacuum problems. The DT fuel gas will be at a few atmospheres pressure, and will isolate the pinch from material evaporated from the walls during the burn cycle.

III. HEATING METHOD

The proposed method of heating the HDZP is classical ohmic heating. This predominantly heats the plasma electrons, which then must transfer their energy to the ions. In most laboratory plasmas, the equilibration of energy between electrons and ions is a slow process, and because it is implicit in the governing equations for the HDZP that the ions and electrons are at all times at the same temperature, the validity range for this assumption should be examined. Comparison of the ohmic heating rate with the rate of energy transfer to ions shows that the condition for the equilibration to be faster than the heating is $N_e > 10^{16} \text{cm}^{-3}$. Furthermore, comparing the equilibration rate with the rate of energy loss from bremsstrahlung radiation yields the condition on the electron temperature for equilibration to be faster; $T_e < 250 \text{ keV}$. These conditions are easily satisfied in either the proposed

experiment, or in any reactor based on the HDZP concept, and the assumption of constant equilibrium between electrons and ions appears well-founded.

A. Influence of the Heating Method on Confinement Configuration

The heating current in the high density pinch also provides the equilibrium, which is grossly unstable to MHD modes as predicted by Suydam and Newcomb.^{5,6} It is expected that these modes can be stabilized by gas-embedding for a time sufficient to achieve a batch burn. The investigation of the physics of the stabilization process should be a primary aim of any exploratory research.

B. Physics of Heating Method

The reactor concept relies only on classical ohmic heating for success, and the physics of this method is well-established. Anomalous heating can come about in such devices, but, although beneficial, anomalous heating is not essential for a reactor.

Alpha particle heating may not be completely effective in such devices because the alpha gyroradius will be somewhat larger than the pinch radius for the assumed reactor parameters. The concept does not, however, require significant alpha energy deposition to reach high Q.

C. Heating Energy and Power Requirement

The minimum energy per unit length that must be supplied to heat the plasma in the absence of radiation is $W/\ell = 2 N_e kT \sim 1.3 \text{ kJ/cm}$ for the required line density and temperature. In addition, radiation losses must be balanced during this phase. The radiated energy is $W_{\text{rad}} \sim 5.4 \times 10^{-31} n^2 T^{1/2} (\pi r^2 \ell) \tau \text{ J}$. An estimate of the ohmic heating time can be worked out from Hammel's solution for the time required to reach the equilibrium pinch final temperature.* This is $\tau_{\text{oh}} \sim 10^{15}/n$ seconds for the final temperature $T = 10 \text{ keV}$. With the equilibrium line density $N_e \sim 4 \times 10^{17} \text{ cm}^{-1}$, this gives a radiation loss during heating of $W_{\text{rad}} \sim 700 \text{ J/cm}$, which is certainly an overestimate because the final temperature was used. Ohmic heating must supply enough energy to make up for losses during the burn time. The

*This information was supplied by R. H. Lovberg, August 1979.

bremsstrahlung energy loss at 10 keV is $W_{\text{rad}}/\ell = 1.7 \times 10^{-30} n^2 (n\tau) N_\ell \text{ J/cm}$. Again taking $n\tau \sim 4 \times 10^{15}$ and $N_\ell \sim 4 \times 10^{17} \text{ cm}^{-1}$ gives a bremsstrahlung loss of $W_{\text{oh}}/\ell \sim 2.7 \text{ kJ/cm}$, and the total heating energy needed including all of these requirements is $W_{\text{oh}}/\ell \sim 4.7 \text{ kJ/cm}$. Comparing this energy input requirement with the neutron energy output, $W_n/\ell \sim 90 \text{ kJ/cm}$ (see Appendix), gives a simple Q of about 19. Additional loss mechanisms (such as radial transport) will reduce this estimate of Q , and it is, therefore, important to determine the net energy deposition rate in such high-density pinches. This should be a prime objective of exploratory experiments.

The heating time is $\tau_{\text{OH}} \sim 10^{15}/n \text{ sec}$ for a final temperature of 10 keV. The high density reactors proposed by Hartman and Hammel have a density of $n > 10^{21} \text{ cm}^{-3}$, which would give heating times $\tau_{\text{OH}} < 10^{-6} \text{ sec}$, and a heating power requirement of $P_{\text{oh}}/\ell > 2 \text{ GW/cm}$ during the formation stage. The heating power needed during the 4- μs burn is much more modest: $P_{\text{oh}}/\ell \sim 0.7 \text{ GW/cm}$. If the first wall is at a radius of 5 cm, then the radiation loading is $\sim 22 \text{ MW/cm}^2$ from bremsstrahlung, again emphasizing the need for a continuously renewable wall.

The power needed for heating is, of course, only a fraction of the total requirement. Much of the energy is stored in the magnetic field, and the amount can be estimated by assuming that the ratio of the pinch radius to that of the coaxial current return is $\sim 1:500$. The inductance per unit length is then $L/\ell \sim 13 \text{ nH/cm}$, and the magnetic energy for the 1.1-MA final current is $W_B/\ell \sim 8 \text{ kJ/cm}$. The practical Q of the reactor will be affected by the efficiency of recovery of this energy, but even if none were recovered the Q for this simple model would be no less than about 7.

D. Technological Requirements for Heating

The energy requirements for a HDZP reactor are within the realm of present pulsed-power technology. Power supplies capable of delivering several Terrawatts have been constructed and used to deliver energy to systems for time scales ranging from a few tens of nanoseconds (eg. Blackjack) up to a few microseconds (eg. Scyllac).

The real limitation of present technology for this application may well be the ability to generate the required current waveform for the equilibrium HDZP. To maintain a true equilibrium from time zero would require an infinite rate of increase. This ideal cannot be achieved because of the finite

inductance of the pinch. One objective of exploratory experiments should be to study the transition between contraction and expansion phases of the pinch. From the results of such experiments much could be learned concerning the consequences of power supply "mis-match" for HDZP reactor systems.

IV. SIZE AND ECONOMICS

A. Beta, Q, Range of Output Power

The best answers to these questions must come from detailed reactor studies, of course. The naive model used here only suggests that a HDZP reactor can operate at economical Q values. It also appears that the power output can be easily adjusted by simple length scaling of the device. No external fields are required for this concept, so the high-beta, high-field questions that arise in connection with other reactor concepts are somewhat irrelevant.

B. Inherent Simplicity

Inherent simplicity is one of the strongest points in favor of the HDZP fusion reactor concept.

- Geometrical simplicity requires reduced engineering effort.
- High density operation avoids vacuum and impurity problems: no divertors are required.
- No external magnetic field coils are required.
- Ohmic heating requires no developmental effort: no high-technology heating is needed.
- Small plant size with low power output appears possible.
- Presently available pulse-power technology may prove sufficient for heating and confinement.

V. TECHNOLOGICAL FACTORS

As discussed above, there do not appear to be readily identifiable major technological problems relating to the power supply for an ohmically-heated HDZP reactor. If these exist, they will only become apparent when more is

learned from the results of exploratory experiments and from the results of detailed reactor systems studies.

The "critical path" for the HDZP reactor appears to be the technology of replacing the walls at a high enough repetition rate and low enough cost to make the reactor economical. Perhaps this can be accomplished in a continuous fashion with lithium waterfalls or whirlpools such as those suggested for inertial-confinement fusion concepts. Hartman, et al., have examined such renewable wall containment vessel concepts in their HDZP reactor study,² and conclude that they are indeed a viable option.

VI. ANTICIPATED VALUE

I believe that the value of the HDZP reactor lies in the possibility for a relatively inexpensive and compact fusion power source with little need for extrapolation of present technology. It is, of course, a high risk option because so little has been done experimentally to date, and as a consequence little is known about the physics of these devices. This only emphasizes the need for strong experimental programs to explore the critical issues.

VII. SUMMARY

The reactor concept based on the HDZP is, I believe, sufficiently credible at this stage of understanding that physics experiments and reactor systems studies should be supported as soon as practicable.

A relatively small level of effort will greatly expand the physics knowledge of gas-embedded pinches, and yet should not have a great financial impact on other ongoing programs.

APPENDIX

HDZP REACTOR MODEL

In this naive model it is assumed that the pinch remains in a state sufficiently close to equilibrium to enable the axial current to increase in time to the limiting Pease current, $I_p \sim 1.1$ MA, as described by Hammel.¹ A 50-50 mixture of DT is the fill gas, and a final burn temperature of $T \sim 10$ keV is assumed after reaching the limiting current. The pinch reactor is assumed to run as an un-ignited power amplifier for a burn time τ after reaching the 1.1 MA Pease current. The DT Lawson criterion at this temperature is $n\tau_L = 10^{14}$ s/cm³, and the Maxwellian DT reactivity is $\langle\sigma v\rangle \sim 10^{-16}$ cm³/s. The specification of the temperature and current fixes the plasma line density, N_ℓ . For the DT reactor temperature, $T \sim 10$ keV, this is $N_\ell \sim 4 \times 10^{17}$ cm⁻¹. Previous studies of HDZP reactors assume a plasma density $n > 10^{21}$ cm⁻³. When required, the estimates given here use $n = 10^{21}$ cm⁻³, which corresponds to a pinch radius, r , of 1.1×10^{-2} cm. Note that the Lawson time, $\tau_L \sim 10^{14}/n$, for this density is only 0.1 μ s.

The neutron energy output is $E_n = 1/4 n^2 \langle\sigma v\rangle (\pi r^2 \ell) \tau \times 14$ MeV, and thus the neutron energy output per unit length is $E_n/\ell \sim 5.6 \times 10^{-29} (n\tau) N_\ell$ J/cm. The fraction of fuel burned in time τ is estimated to be $f \sim 1/2 \langle\sigma v\rangle (n\tau) \sim 5 \times 10^{-17} (n\tau)$. Thus, for a burnup of 20% of the fuel, $n\tau \sim 4 \times 10^{15}$, which gives a burn time of about 40 Lawson times, and a thermonuclear neutron output $E_n/\ell \sim 90$ kJ/cm. With a first wall at 5 cm, this would result in a neutron loading of ~ 700 MW/cm², which would necessitate renewal of the first wall after each burn cycle, perhaps by using a flowing-lithium blast-containment vessel as suggested by Hartman.²

Thus, assuming a 30% thermal recovery efficiency from the flowing lithium, a 1 MW reactor would require a length $\ell \sim 370$ cm if the repetition rate were one burn cycle each 10 seconds.

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