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September 26, 2011

Mr. Tom Tamarkin

5545 El Camino Avenue

Carmichael, California 95608

Ref: Response to Pulsed Jet Magneto Inertial Fusion Feasibility Questions

Dear Tom:

Thank you for the kind words--writing the dipole propulsion paper was an enjoyable experience. Unfortunately, DOE cut funding for the dipole experiment at MIT last year that was addressing some of the key issues.

Here are some brief answers to your MIF questions which are restated in blue bold below:

(i) Are there any obvious fundamental physics flaws with the concept that the proponents of the concept have overlooked? If so, please identify and discuss.

I continue to do research on MIF because there do not appear to me to be any fundamental physics flaws. The jury remains out, however, on whether MIF can make economic fusion power. There are significant physics issues related to how the implosion and explosion fusion burn dynamics works, whether plasma instabilities are significant as the jets merge and the target implodes, and how the equations of state affect the dynamics, especially that of the plasma jets at low temperature. My MIF research relates only to the first and third of these.

(Tamarkin) Can you please explain this line in more detail in terms of what the critical path is to "economic power:" "The jury remains out, however, on whether MIF can make economic fusion power." Emphasis by me on the word economic and your choice of it.

(Dr. Santarius 9/28/2011) "Economic fusion power" to me means that the technology potentially can be developed at reasonable cost and then break into the marketplace. Most of my thinking in the realm of fusion development has concentrated on advanced fusion fuels, as discussed in the attached paper for the D-3He fuel cycle (my apologies for the quality of the copy). The crucial point is that the development path requires overcoming obstacles not only in physics, but also in the areas of engineering, safety, and environment. The mainline concepts have historically tended to focus on the physics, nearly to the exclusion of the other issues.

Some reactors burning conventional D-T fuel might overcome the hurdles and break in, such as the high power density magnetic fusion concept the field-reversed configuration (FRC) or the inertial-electrostatic confinement (IEC) Polywell concept. Others include MIF and the fast-ignition and shock-ignition versions of inertial fusion energy (IFE), because predictions of the required input power are greatly reduced from those of conventional IFE power. If a concept's engineering and maintenance, for example, are excessively complicated and the cost of electricity only competes with fission power and the other options, what utility executive would buy that concept?

Note, please, that few would consider me unbiased, for I have done funded research related to almost all of the above concepts, including the mainstream tokamak and ICF concepts.

(ii) Are there insurmountable engineering challenges associated with the approach that you can foresee at this stage? If so, please identify and discuss.

Plasma-jet MIF has the advantage over solid-liner MIF in that solid electrodes within about one meter of the explosion are not destroyed by it and do not have to be replaced. The trade-off is that plasma jets require engineering development. Significant progress on constructing guns to create plasma jets is being made by Doug (F. Douglas) Witherspoon's company, HyperV. Another important challenge for pulsed-power concepts, like MIF and Z-pinch fusion, is that fusion yields can be 100s of MJ to GJs, and the reactor chamber's first wall must survive that blast. Thus the chamber wall's radius is typically at least 5 meters.

(iii) Have the proponents conducted plausible computer simulations and analysis to provide a plausible expectation of the fusion gain achievable by the approach?

There are a modest number of MIF researchers, including myself, doing computer simulations and analytic calculations. Consensus has not been reached, and the results vary somewhat depending on the assumptions used. The computer simulations need to be benchmarked by experiments before the codes can be used confidently for prediction. The key MIF experiments, which should produce results relatively soon, are the merging plasma-jet experiment led by Scott Hsu (LANL), and the metal liner implosion on field-reversed configuration (FRC) target experiment led by Jim Degnan (AFRL) and Tom Intrator (LANL). The papers by Hsu, et al. and Awe, et al. that you sent earlier should reference the key related papers on both the simulations and experiments. The Awe, et al. paper also discusses the problem with low-temperature equations of state (EOS).

(iv) A major challenge for the concept is the ability to produce an imploding liner from the merging of the jets. What is your assessment that the proponents are likely to succeed in achieve this technical goal, given adequate resources? Do they have credible concepts and approaches for achieving this goal?

The answers to i, ii, and iii above pretty much cover my thinking on this. We theorists can argue the details, but it will come down to the plasma-jet experiments.

(v) Another major challenge for the approach is the ability to get the imploding plasma liner to generate pressures up to 50 mega-bars? What is your assessment that the proponents are likely to succeed in achieving this technical milestone, given adequate resources? Do they have credible concepts and approaches for achieving this goal?

Given adequate resources, I believe that achieving sufficient pressures to access what is called "warm dense matter" is realistic and reaching the "high energy density plasma" (HEDP) regime is likely. Whether MIF achieves economic fusion power will require prototype and demo experiments beyond the present generation of proof-of-principle experiments. Experimental progress so far has been very good, and the experimental facilities to test the concepts will not require the multi-billion dollar price tags of ITER or NIF.

(vi) Yet another crucial challenge to any fusion scheme is its ability to reach the temperature needed for thermonuclear fusion reactions to occur. For a mixture of deuterium and tritium, the canonical temperature for this purpose is 100 million degrees K. Please comment on the ability of the PJMIF scheme to reach such temperatures in principle and/or any issues you see in connection with this goal.

This question is a focus of my MIF research, to which I am applying a computer code that we more typically use for inertial-confinement fusion (ICF). The fusion burn dynamics of the MIF target implosion and explosion remain dependent on a variety of assumptions, and I have no definitive answers yet. The question is not just the temperature, but also how the hydrodynamics of the target evolves and whether the timing of the temperature and the density peaks nearly coincide for a sufficient time. The low-temperature equation of state issues that I alluded to earlier remain a difficulty that needs to be overcome (this is the subject of one recently graduated UW student's PhD thesis and of active research in our ICF group).

(vii) A typical criticism of any pulsed approaches to fusion from the researchers in the mainstreams of government funded research in steady-state magnetic fusion is that pulsed approaches to fusion cannot produce useful or practical power (Ref: Francis Chen: "An

Indispensable Truth: How Fusion Energy Can Save the Planet".) I would appreciate any comments or insight you can share with me on that assertion.

Frank Chen is a top-notch plasma physicist, whose "*Introduction to Plasma Physics"* has remained for decades the best introductory text on plasmas. Whether pulsed approaches to fusion can be economic, however, is a question that combines physics, engineering, and systems issues, and I know of no definitive argument that rules out pulsing as such. The crucial pulsing issues typically relate to input energy per pulse, adequate repetition rate, and the ability of materials to withstand the higher radiation and plasma fluxes per pulse. The conceptual fusion reactor studies that our Fusion Technology Institute research group has performed for some four decades have not found huge differences between the predicted costs of electricity for steady-state magnetic fusion energy compared to pulsed inertial fusion energy (http://fti.neep.wisc.edu/pubs/major).

Hope this helps.

Regards,
John

On 9/22/11 10:56 AM, Tom Tamarkin wrote:
Dr. Santarius:

Your record of publications and research speaks for itself. Your 1991 paper with Drs. Edward Teller, T. Ken Fowler, et al, speaks volumes; Dr. Teller's ***"Fusion 1981 Volume 1 Magnetic Confinement"*** set of collected works still sits on my desk.

The simple equations defined in the above captioned paper showing $Pw = (1/2\ Mw\ VC^2) / t$ says it all with respect to a non tokamak approach and the relatively small mass of the propulsion system and Ken Fowler's involvement became apparent in Section II and the description of the "tandem mirror" fusion configuration. That seems to be consistent with the formula proposed by Lindemuth and Siemon for reactor cost within the fusion parameter space.

It would appear that the needs of the space program and the needs of widely available fusion energy production on Earth are one and the same, generally speaking.

I would very much appreciate it if you could find the time to address the questions I posed below. The fact that you have been involved in this field gives you unique insight. The time frame you mentioned is fine and I very much appreciate your offer and look forward to reading your comments.

Cordially,

Tom Tamarkin

2006 Bio, Dr. John Santarius

Education

BS 1973, Physics, California Institute of Technology
PhD 1979, Physics, University of Texas at Austin

Research Interests

- Magnetic fusion reactor design
- Inertial-electrostatic confinement fusion
- Inertial-confinement fusion physics
- Lunar volatiles, particularly helium-3
- Space applications of fusion

Career Highlights

- Most of my career at UW has been in magnetic fusion reactor design, with an emphasis on plasma physics, energy conversion engineering, and systems analysis. Configurations studied include tokamaks, field-reversed configurations (FRCs), dipoles, tandem mirrors, and stellarators.

- In 1986, Layton Wittenberg, Jerry Kulcinski, and I published the initial paper connecting the large lunar resource of helium-3 with its potential use in D-3He fusion reactors. D-3He fuel would lead to reactors requiring more advanced physics but reducing many engineering problems. Refining the arguments and evaluating the viability of the lunar helium-3 resource remains an ongoing effort. One interesting possibility is that a D-3He fusion reactor could be designed to be proliferation-proof.

- The interesting nonlinear physics of radiation transport and shock-wave propagation must be understood for viable inertial-fusion reactors to be designed. My research in this area focuses on long mean-free-path ion interactions with shock waves plus our 1-D radiation hydrodynamics code, BUCKY.

- Electrostatically focusing ions into a dense core in spherical geometry to produce fusion has the advantage that the high energies required for advanced fuels are relatively easy to attain. These so-called inertial-electrostatic confinement systems have the important advantage that they can potentially produce valuable fusion products, such as neutrons and protons, at useful levels for applications such as clandestine-materials (e.g., highly enriched uranium or explosives) detection using D-T or D-T neutrons plus positron production using D-3He protons.

- D-3He magnetic fusion reactors appear able to provide propulsion capabilities dramatically more efficient for long-range space travel than those of chemical, fission, and D-T fusion rockets. My contention, developed in several published papers, is that fusion will be necessary to open the Solar-System frontier.

Web pages for my lectures in the UW Resources from Space course:

- Space travel overview (from 2004)
- Plasma thrusters (from 2004)
- Fusion propulsion (from 2004)
- Travel to asteroids and moons (from 2004)

Publications

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