LLNL-TR-427446

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Fission-Fusion Neutron Source Progress Report July 31, 2009

G. Chapline, F. Daffin, R. Clarke

April 8, 2010

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Fission-Fusion Neutron Source

Progress Report July 31, 2009

George Chapline[1], Frank Daffin[1], and Rodney Clarke[2]

[1]LLNL, [2]Grassmere Dynamics, Huntsville, AL

Introduction

In this report we describe progress in evaluating the feasibility of a novel concept for producing intense pulses of 14 MeV neutrons using the DT fusion reaction. In this new scheme the heating of the DT is accomplished using fission fragments rather than ion beams as in conventional magnet fusion schemes or lasers in ICF schemes. This has the great advantage that there is no need for any large auxiliary power source. Our scheme does require large magnetic fields, but generating these fields, e.g. with superconducting magnets, requires only a modest power source. As a source of fission fragments we propose using a dusty reactor concept introduced some time ago by one of us (RC) [1]. The version of the dusty reactor that we propose using for our neutron source would operate as a thermal neutron reactor and use highly enriched uranium in the form of micron sized pellets of UC.

Our scheme for using the fission fragments to produce intense pulses of 14 MeV neutrons is based on the fission fragment rocket idea [2]. In the fission fragment rocket scheme it was contemplated that the fission fragments produced in a low density reactor core would then be guided out of the reactor by large magnetic fields. A simple version of this idea would be to use the fission fragments escaping from one side of a tandem magnet mirror to heat DT gas confined in the adjacent magnetic trap (see Fig 1).

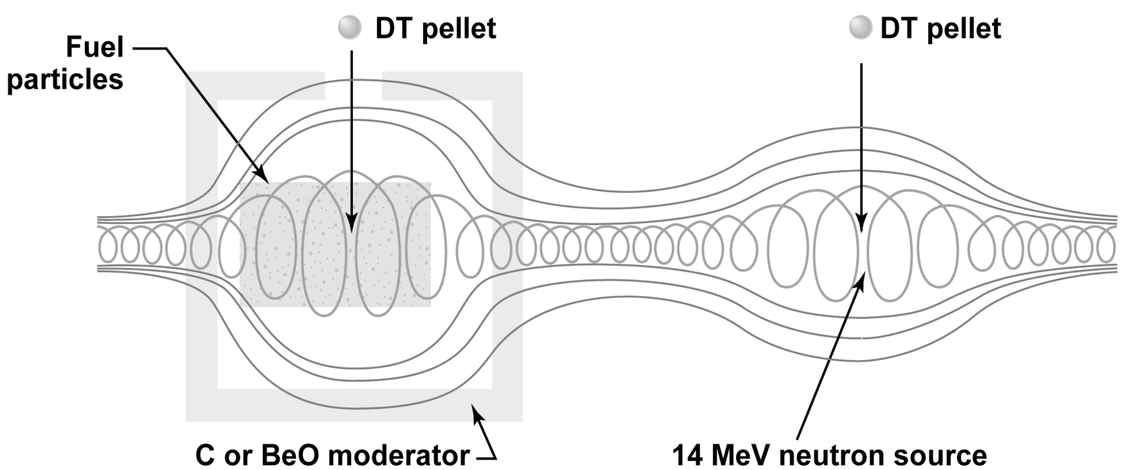

Fig. 1 Scheme for using fission fragments to produce fusion neutrons

An advantage of our concept is that the possibilities and limitations for generating self-sustaining fission in a fission reactor are well understood. For example, a reactor power of 100 MW is well within the temperature limits that would allow passive steady state radiative cooling of a reactor core and moderator. Turning the reactor on and off in a reactor control period (a few seconds) might possibly allow transient powers as high as ~1 GW. At a reactor power of 100 MW one could in principle heat 1 gm of DT to a temperature > 1 keV in less than a second if most of the fission fragment energy is deposited in the DT, at which point the temperature of the DT will "run away" due to boosting of the fission rate by the DT fusion neutrons and self-heating of the DT by alpha particles. In the following we describe our progress in understanding the heating by fission fragments of a DT blanket surrounding a low density reactor core.

Of course, if the DT gas did reach kilovolt temperatures, it could no longer be confined in the magnet trap for more than a short time; perhaps for only the Bohm diffusion time, which is about a millisecond. Even so we expect that our scheme can produce bursts of up to 10^{22} fissions in the reactor core. Conceptually the fission fragments from these fissions can be used to heat DT gas in the adjacent magnetic trap of the tandem mirror as indicated in Fig 1, leading to a large burst of fusion neutrons from the adjacent trap. Since there is no moderator surrounding the adjacent tandem mirror trap, all the 14 MeV neutrons produced in the second trap can escape into the surrounding space. Simulating the transport of the fission fragments between the magnetic traps is beyond our current capabilities. However we hope by the end of this initial study to verify the boosting effect with numerical simulations, and estimate the numbers of fission and fusion neutrons that could be produced.

Criticality Calculations

Although we have already 10 years ago estimated the critical masses of Pu239 and U235 required for the fission fragment rocket, we show in Table 1 some recent results for critical masses calculated using the latest version of the Los Alamos Monte Carlo neutron transport code MCNP. The fuel was assumed to be homogeneous U235 in the chemical form UD or UC and the moderator was chosen to be either deuterated polyethylene using C13 or heavy water. A cross-section through the central axis of the cylindrical geometry used in these calculations is shown in Fig. 2

Table 1

Fuel	Moderator	Fuel dimensions	Average fuel density	Critical mass
UD	50cm CD_2	4 m x 10m	0.2 mg/cm^3	24 kg
UD	110 cm CD_2	4 m x 5 m	0.2 mg/cm^3	12 kg
UD	250 cm CD_2	6 m x 5 m	0.1 mg/cm^3	14 kg
UC	200 cm D_2O	6 m x 5 m	0.1 mg/ cm^3	14 kg

The core parameters were chosen keeping in mind that only average fuel densities on the order of or less than about 0.1 mg/cc are acceptable from the point of view of allowing a significant fraction (~ 10%) of the fission fragments to escape from the reactor core. One could increase the fraction of fission fragments that are useful for heating the DT by lowering the density, but this would increase the size of the reactor core. The case shown in the top line of Table 1 had been previously calculated using the Monte Carlo code TART. The previous result for k_{eff} was 1.046±.032, while using the current MCNP code we obtain k_{eff} = 1.015±.002. The last line in Table 1 is what we now use as our "baseline" reactor core.

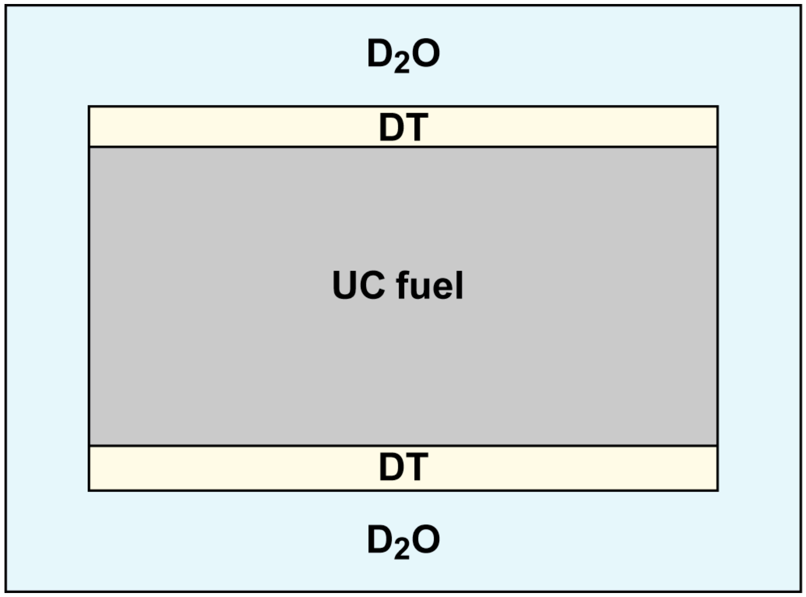

Fig. 2 Cross-section of cylindrical geometry used in numerical calculations

For the reactor criticality calculations shown in Table 1 it was assumed that the fuel was uniformly distributed throughout the core. An obvious question though is what would happen to the reactor criticality if the dust suspension system should fail, and the dust fuel fell to the bottom of the reactor core. We show in Fig's. 3 & 4 how k_{eff} varies when the fuel in our baseline case is allowed to sage towards the bottom of the core, keeping the mass of the fuel constant. The "Free Surface Height" in Fig 3 is the distance from the central axis of the core to the top surface of the fuel.

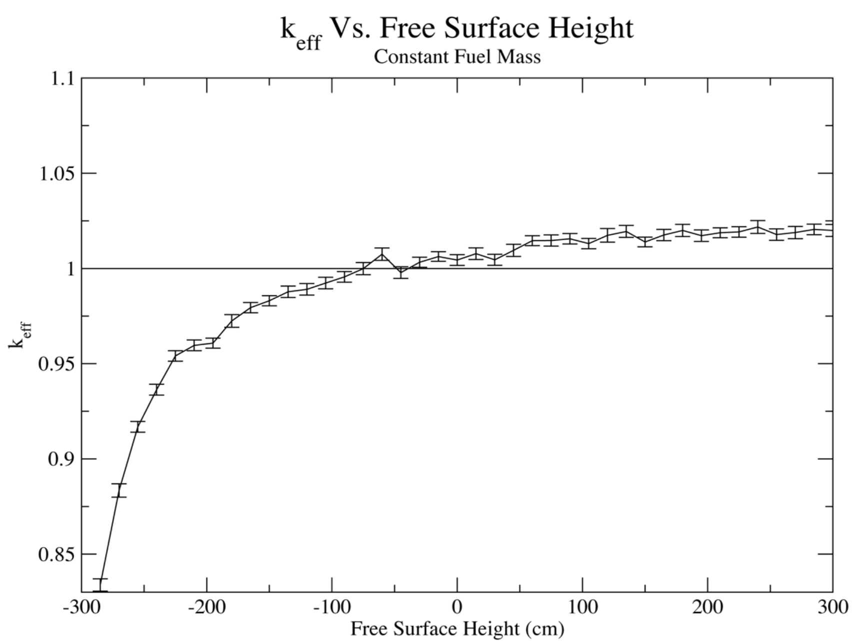

Fig. 3 Variation in k_{eff} when the fuel falls to the bottom of the reactor core

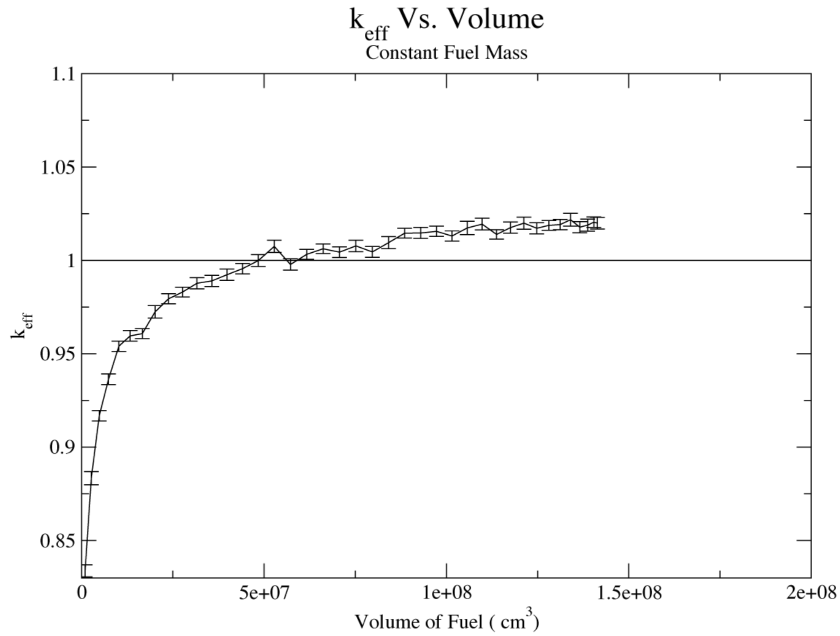

Fig. 4 Same as figure 3, but as a function of the volume occupied by the fuel

We show in Fig. 4 how k_{eff} varies when the fuel is compressed parallel to the axis of the core. If one used a tandem mirror as shown in Fig. 1 one would need to allow room within the reactor core for the converging magnetic fields used to guide the fission fragments.

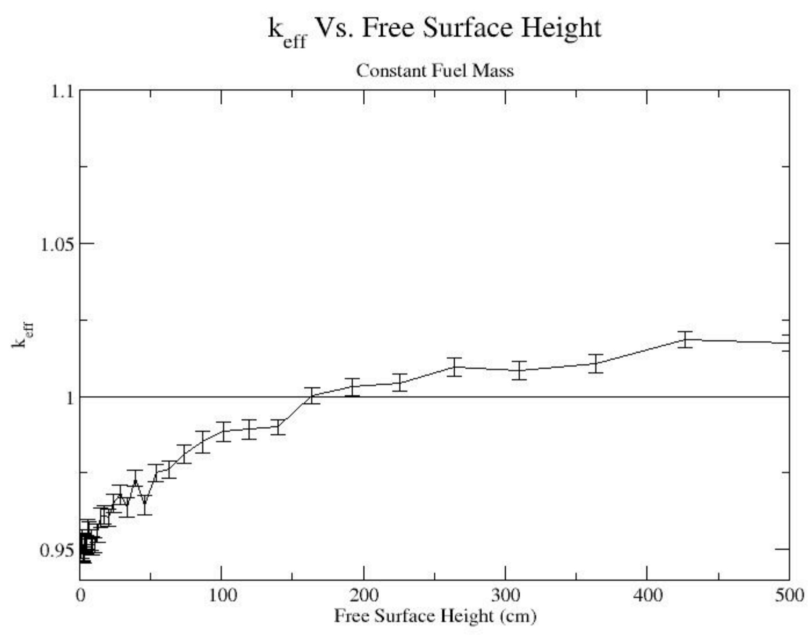

Fig 5 Variation in k_{eff} if the fuel doesn't extend the full length of the core

DT Heating

Fission fragments have a net charge on the order ~ 20 when they are born; which gives them a range in matter ~ 1 mg/cm^3 [3]. The DT heating rate is determined by the number of U atoms within a fission fragment mean free path and the reactor power. When the fission fragment mfp is small compared to the fuel radius, the number of U atoms per cm^2 contributing to the heating of the DT layer in Fig. 2 is

$$\# \text{ U atoms/cm}^2 \approx \text{mfp x } (\rho_{fuel} / m_U) \approx 3.\ 10^{18}/\text{cm}^2 ,$$

where m_U is the mass of a uranium atom. In our baseline reactor configuration only about 7% of the fuel contributes to heating the DT external to the fuel. This means that in order to heat 1 gram of DT to a KeV in less than a second a transient reactor power of ~ 600 MW would be needed. One could achieve higher efficiencies for using the reactor power to heat DT by lowering the fuel density, but this would require increasing the reactor volume in order to keep the critical mass constant. For example one could in principle increase the heating rate by a factor ~ 10 by increasing the radius of the fuel by a factor of 2 and the length by a factor of 3. However, such a large reactor would certainly be more expensive and perhaps impractical.

One question that always needs to be kept in mind when considering whether DT can be heated to the point where self-sustaining fusion reactions are possible is whether radiation from impurities in the plasma prevents its heating. In our case impurities in the form of fission fragments are always present, and so an obvious question whether radiation from these fission fragments can prevent heating of the DT. Fortunately this does not appear to be a problem. Even after losing 99% of their energy fission fragments are still moving with a velocity of 10^8 cm/sec; therefore even with ~10^{18} fission fragments per second escaping from the reactor core (corresponding to a reactor power of ~ 1 GW), their density is very low ~ !0^6 cm^{-3}. The bound-free radiation from such a low density of impurities is negligible.

What is not negligible though is the bremsstrahlung radiation from a hot DT plasma. At a temperature of 1 keV the bremsstrahlung energy loss is ≈ $(n_{DT}/10^{17}\text{ cm}^{-3})^2$ MW/m^3 . This limits the density of the DT gas. In DT with an atomic density of 10^{17} per cc this corresponds to mean free path (mfp) of ~ 10 m, which means that the thickness of the DT layer would have to be 10s of meters thick in order to capture the fission fragments. The way we propose getting around this problem is to cycle the fission fragments in a strong magnetic field. The magnetic rigidity, *Br* , of fission fragments is about 0.5 Tesla-meters. This means that a 2 Tesla magnetic field would confine most of the fission fragments in a 20 cm thick layer. We have carried out some preliminary numerical calculations of the DT heating in a 20 cm layer without a magnetic field, where we simulated the increase of mean free path due to the magnetic field by increasing the DT density. However, this way of simulating the magnetic field requires turning off the bremsstrahlung radiation. We hope in the remainder of this fiscal year to do a realistic numerical calculation of the DT heating in the presence of a magnetic field and bremsstrahlung radiation.

Proof of Principle Experiments

Dusty plasmas are of great interest in astrophysical contexts and for semiconductor processing. In fact the dusty plasmas we require for our reactor core are not very different from the dusty plasmas commonly used for plasma etching in the semiconductor chip industry. These plasma etching machines typically use 2 μm diameter SiO_2 particles with a density of 10^8 particles per cc. Remarkably, this is essentially identical with our standard model for the reactor core, which would use ~1 μm diameter UC particles with a density ~10^8 particles per cm^{-3}.

We contemplate that the fuel particles in our reactor core can be kept levitated using electrostatic fields. Experiments demonstrating this possibility using micron sized CeO_2 particles have been carried out at the High Energy Density Research Center in Russia [4,5] In Fig. 7 we a picture of the suspended CeO_2 particles in one the Russian experiments where the CeO_2 particles become charged as a result of exposure to a Cf252 spontaneous fission source. The particles are kept apart by their mutual electrostatic repulsion.

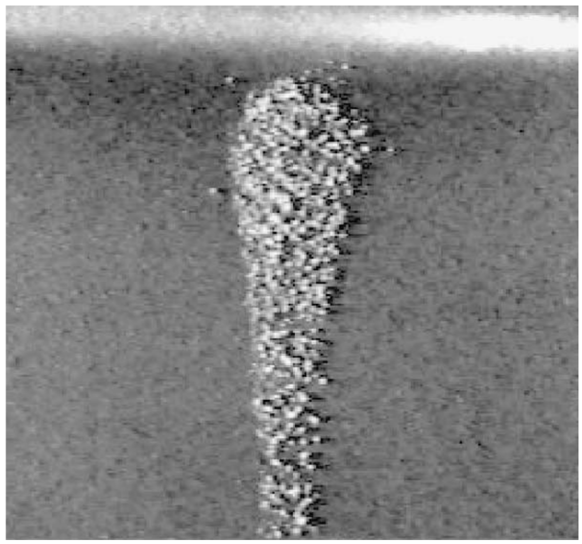

Fig. 7 Suspended micron size CeO_2 particles

As a first step towards evaluating the feasibility of suspending a critical mass of micron sized UC particles in a vacuum, it will be necessary to understand how the emission of fission fragments from these particles and exposure to fission gamma rays affects their charge state in the presence of a hydrogen plasma. As a first experiment we propose measuring the equilibrium charge of an americium or californium grain suspended in a Paul Trap in the presence of a gamma source. Once we have this basic information we could then proceed to design a prototype dusty reactor to could be used heat DT.

References

1. R. Clark and R. Sheldon, "Dusty Plasma Based Fission Fragment Nuclear Reactor", AIAA Paper 2005-4460 (2005).
2. G. Chapline, W. Howard, and B. Schnitzler, "Fission Fragment Rockets – a New Frontier" in *50 Years with Nuclear Fission* ed. J. Behrens and A. Carlson, American Nuclear Society (1989).
3. A. Chung and M. Prelas, " The Transport of Heavy Charged Particles in a Cylindrical Nuclear Pumped Plasma", Nucl. Sci. and Eng. 86, 267 (1984).
4. V. Fortov et. al. "Dust Particles in a Nuclear-Induced Plasma", Phys. Lett. A258, 305 (1999).
5. V. Fortov et. al. "Dust Grain Charging in a Nuclear-Induced Plasma", Phys. Lett. A284, 118 (2001).