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Fission-Fusion Neutron Source Progress Report Sept 30, 2009

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Introduction

In this report we describe the progress made in FY09 in evaluating the feasibility of a new concept for using the DT fusion reaction to produce intense pulses of 14 MeV neutrons. In this new scheme the heating of the DT is accomplished using fission fragments rather than ion beams as in conventional magnet confinement fusion schemes or lasers in inertial confinement schemes. As a source of fission fragments we propose using a dust reactor concept introduced some time ago by one of us (RC) [1]. An attractive feature of this approach is that there is no need for a large auxiliary power source to heat the DT plasma to the point where self-sustaining fusion become possible. Our scheme does require pulsed magnetic fields, but generating these fields requires only a modest power source. The dust reactor that we propose using for our neutron source would use micron-sized UC pellets suspended in a vacuum as the reactor fuel. Surrounding the fuel with a moderator such as heavy water (D_2O) would allow the reactor to operate as a thermal reactor and require only modest amounts of HEU.

Our scheme for using fission fragments to generate intense pulses of 14 MeV neutrons is based on the fission fragment rocket idea [2,3]. In the fission fragment rocket scheme it was contemplated that the fission fragments produced in a low density reactor core could be guided out of the reactor by large magnetic fields used to form a "rocket exhaust". Our adaptation of this idea for the purposes of making a neutron source involves using the fission fragments escaping from one side of a tandem magnet mirror to heat DT gas confined in the adjacent magnetic trap (Fig 1).

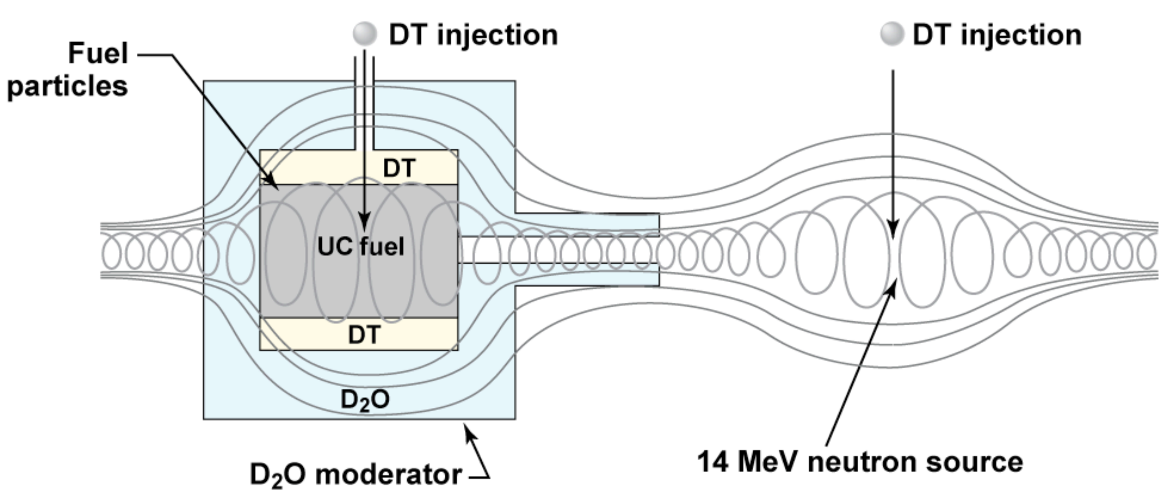

Fig. 1 Concept for using fission fragments to produce DT fusion

A great advantage of our fission-fusion approach to producing fusion in DT is that the possibilities and limitations for achieving self-sustaining fission are well understood. For example, in the case of a reactor using fuel in the form of micron-sized dust particles or thin wires a reactor power of 100 MW is within the temperature limits that would allow passive radiative cooling of the reactor core and moderator [1,4]. Radiative cooling is very effective because of the large surface area of micron-sized particles, and might permit transient powers as high as ~1 GW. Our expectation is that at a transient reactor power ~ 200 MW one could use a dust reactor to heat a small mass of DT to a temperature > 2 keV, at which point the temperature of the DT in our reactor 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 conventional fusion schemes one must heat the DT plasma to at least 4 KeV in order for alpha particle heating to overcome bremsstrahlung radiation from the hot DT plasma. In our scheme we expect that the DT only needs to be heated to 2 KeV to get to the threshold for self-sustaining fusion because of the coupling of fission and fusion. Unfortunately bremsstrahlung radiation does limit the allowed density for the DT gas, and at allowed densities the DT layer would have to be 100s of meters thick in order to capture the fission fragments. The way we propose getting around this problem is to use a strong magnetic field so that the fission fragments cycle many times within the DT before escaping. A 2 Tesla magnetic field ought to sufficient to capture most of the fission fragment energy.

Actually if the DT gas did reach kilovolt temperatures, it could no longer be confined in the magnet trap for very long; perhaps for only the Bohm diffusion time, which is about a millisecond. Even so we expect that our scheme can produce very large bursts of neutrons. 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. At the present time we have not investigated in any detail the confinement of the DT plasma or the transport of the fission fragments between the magnetic traps. However we have begun to do realistic calculations of the DT heating in the magnetic trap containing the reactor core due to fission fragments escaping from the reactor core. Due to time step problems associated with cycling of the fission fragments in a magnetic field, we have not yet been able to accurately simulate the non-linear coupling between fission and fusion. What we can report though are simulations suggesting that the DT can be heated to KeV temperatures, and the effect of DT fusion on the fission rate can be very large.

Needless to say translating these theoretical possibilities into practice involves many significant challenges. We contemplate that the fuel particles in our reactor core can be kept levitated using electrostatic fields. In fact levitation of micron sized dust particles in a plasma has been demonstrated in a variety of ways. Of particular interest are experiments that have been carried out at the High Energy Density Research Center in Russia which demonstrate levitation of micron sized CeO_2 particles which have become charged as a result of exposure to a Cf^{252} spontaneous fission source [5,6]. In these experiments as well as our proposed reactor the particles are kept apart by their mutual electrostatic repulsion. While the laboratory results with dusty plasmas are encouraging, none have the volume required in our fission-fusion scheme. However there does not appear to be any physics limitation to the scale up of these lab results.

Criticality Calculations

Already 10 years ago we 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 of the cylindrical geometry used in these criticality 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 (i.e. >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 our current "baseline" reactor core.

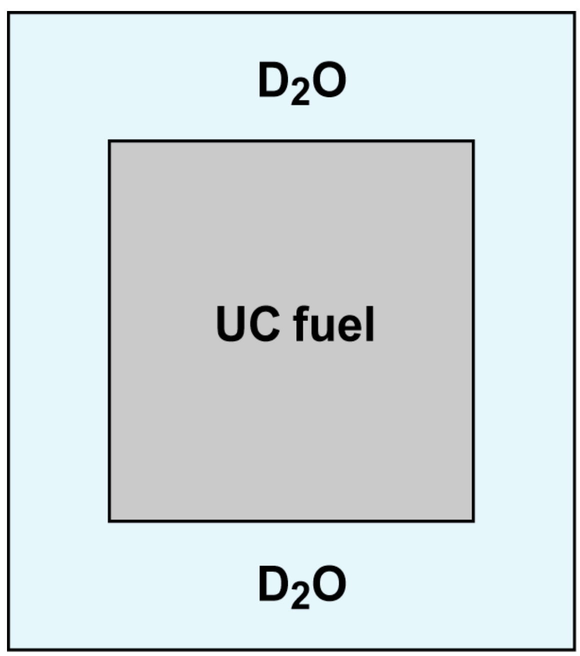

Fig. 2 Cross-section of cylindrical geometry used in criticality calculations

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 sag 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.

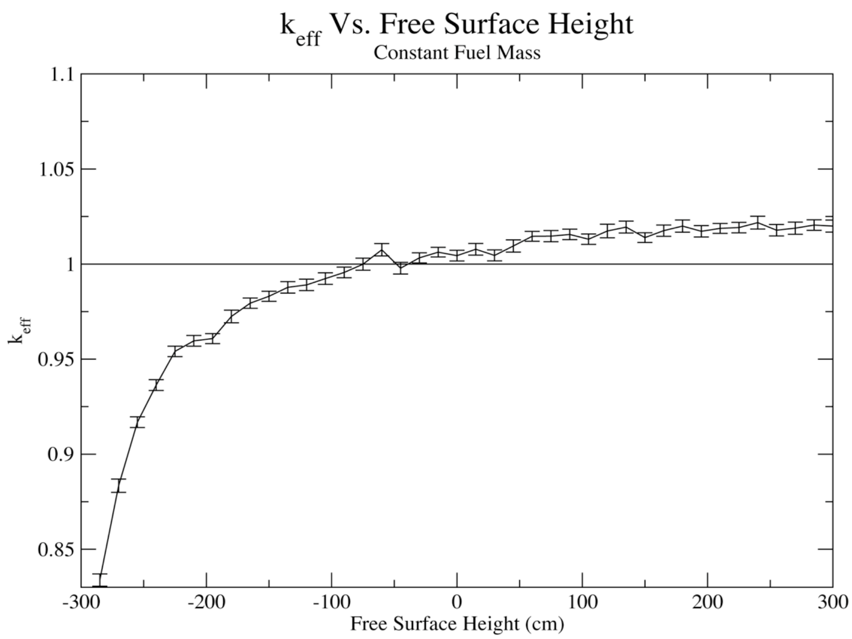

Fig. 3 Variation in k_{eff} when the fuel falls to the bottom of the reactor core

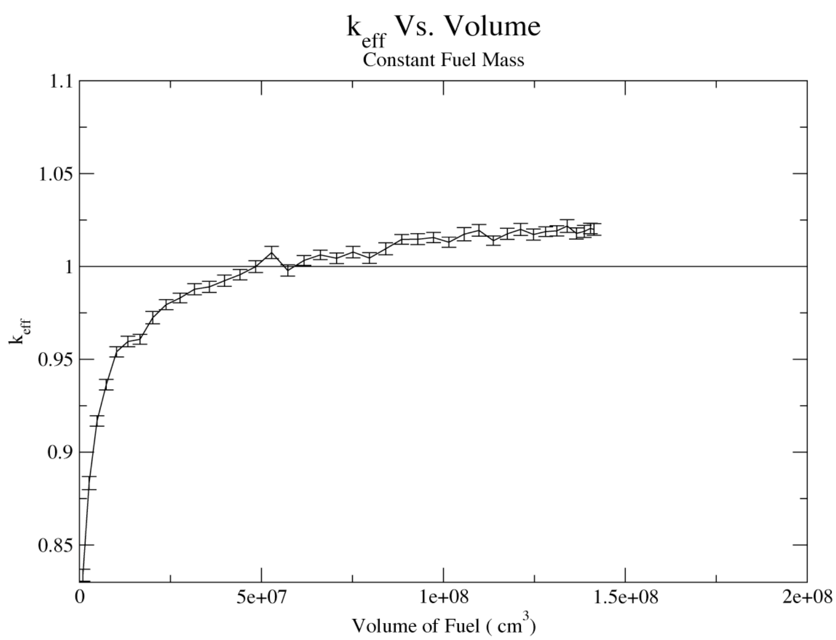

Fig. 4 Same as figure 3, but as a function of the volume occupied by the fuel

The calculations shown in Fig 3 and 4 show that there is some flexibility in how a critical mass is configured within the moderator. In Fig. 5 we show 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.

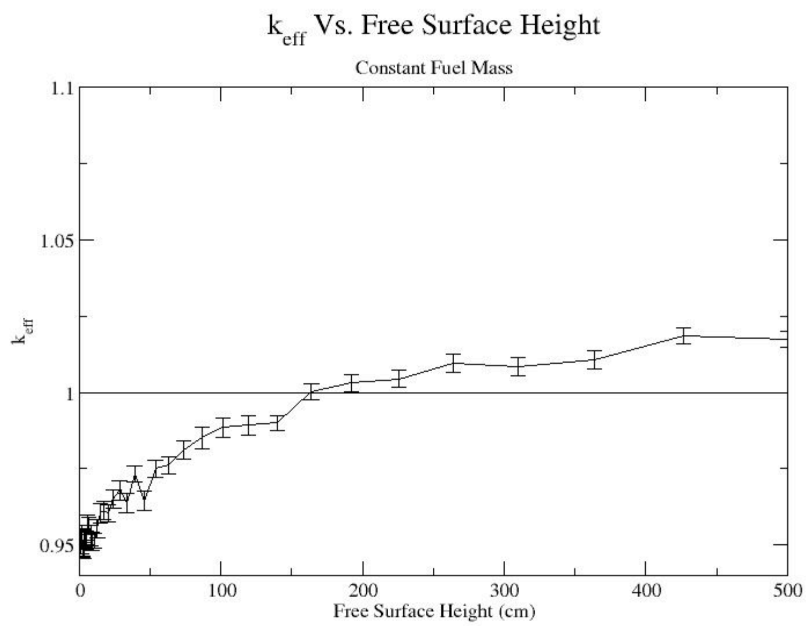

Fig 5 Variation in k_{eff} if the fuel doesn't extend the full length of the core

DT Heating Calculations

Fission fragments have a range in solid UC ≈ 10^{-3} cm [7]. If the UC fuel were evenly spread out this would mean that only U atoms within ~ 1 m of the surface can contribute to heating DT external to the core. In actuality the escape depth will be somewhat larger due the granularity of the fuel. If fuel is in the form of 10 micron diameter particles, then the fission fragment escape probability from each pellet is approximately 80%. In the case of our baseline reactor and a fission fragment range of 1 m the fraction of U atoms that would contribute to heating DT external to the core will be ≈ 0.8(1-4/9) = 0.44. There will also be some heating of the DT inside the fuel region, but the range of the fission fragments in the DT plasma will be much greater than the range determined by interactions with the UC fuel. If we neglect the heating of the DT within the fuel region, the overall efficiency for DT heating will be simply the escape probability for fission fragments from the fuel region (0.44) times the fraction of the DT that is external to the core. One could achieve somewhat 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. A reactor much larger than our baseline might not be practical. It seems reasonable to assume that in practice ~40% of the reactor power will be available for heating DT.

If we assume that 40% of the reactor power is available for heating the DT, a transient reactor power of 200 MW should be sufficient to heat 1 gm of DT to 1 keV in a time ~1 second. Estimates for the fission fragment heating, α-particle heating, and radiation energy loss in a layer of pure DT adjacent to the fuel when the reactor is initially running at a power of 200 MW are given in Table 2:

Table 2

T(keV)	Initial FF heating	Alpha heating	Bremsstrahlung loss	Boosted FF heating
1	2 MW/m^3	1 kW/m^3	0.5 MW/m^3	2 MW/m^3
2	2 MW/m^3	.03 MW/m^3	0.8 MW/m^3	4 MW/m^3
5	2 MW/m^3	2 MW/m^3	1.2 MW/m^3	100 MW/m^3

The bremsstrahlung loss in Table 2 assumed $n_H = 10^{15}cm^{-3}$. One question that always needs to be kept in mind though when considering whether DT can be heated to kilovolt temperatures 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. However, even after losing 99% of their energy, fission fragments are still moving with a velocity of 10^8 cm/sec, so even with a 10^{19} FFs/sec source (corresponding to a power ~ 200MW), the density of fission fragments inside the DT layer is only ~10^6 cm^{-3}. Therefore radiation loss from these fission fragments is negligible. However, U and C impurities may exist in the fuel region. Due to efficient radiation cooling though the fuel particles never get very hot, so sublimation of fuel atoms should not be significant. On the other hand spallation of the fuel by hot ions may not be negligible. Allowing room for a layer of pure DT adjacent to the fuel would mitigate this problem.

The "boosted FF heating" shown in Table 2 is the heating of the DT by fission fragments taking into account the increase in the rate of fission due to fusion neutrons. These estimates suggest that the coupling between the fusion and fission reactions will lead to a very large increase in the fusion and fission rates if the DT can be heated to temperature between 1 and 2 KeV. In reality the increase in fusion and fission rates will be cut off by the magnetic confinement time for the DT plasma or mechanical strength of the reactor structure. Obviously the reactor will have to designed so the increase is cut off by the plasma confinement time, and the peak plasma or magnetic pressure doesn't exceed the yield strength of structural materials. At a temperature of 10 KeV the DT plasma pressure would ~30 atmospheres, so it might be feasible to design a containment structure that would allow transient heating up to a temperature ~10 keV.

We have not yet been able to couple numerical calculations of the fission rate in a critical dust reactor with numerical simulations of heating of a DT layer by fission fragments created within the fuel of a dust reactor. However we have carried out numerical calculations which demonstrate how the heating of DT gas by fission fragments can affect the fission rate in the reactor. The geometry used in these calculations is shown in Fig. 3. The DT temperature for a DT density of $9x10^{14}$ cm^{-3} ($3.5x10^{-5}$ g/cc) and a constant fission fragment heating rate corresponding to 2 MW/m^3 is shown in Fig. 4. The induced rate of neutron production n the UC fuel as a function of time is shown in Fig. 5. The induced fission rate in the UC fuel when the DT has reached temperatures of 2 keV and 5 keV are shown in Fig's 6 and 7. The fission rates shown correspond to reactor powers of 260 MW and 10 GW respectively. These results are consistent with the estimates given in Table 2. In these calculations there was no magnetic field. In order to simulate the effect of a magnetic field in preventing the fission fragments from escaping too quickly from the region inside the moderator the range of the fission fragments was reduced by a factor of 10^4, while keeping the rate of energy deposition the same. While this allows us to simulate the heating of the DT by fission fragments, the fission fragments could not escape from the UC fuel. In order to compensate for the fission fragments not being able to escape from the fuel the fission fragments were introduced into the region containing only DT by hand.

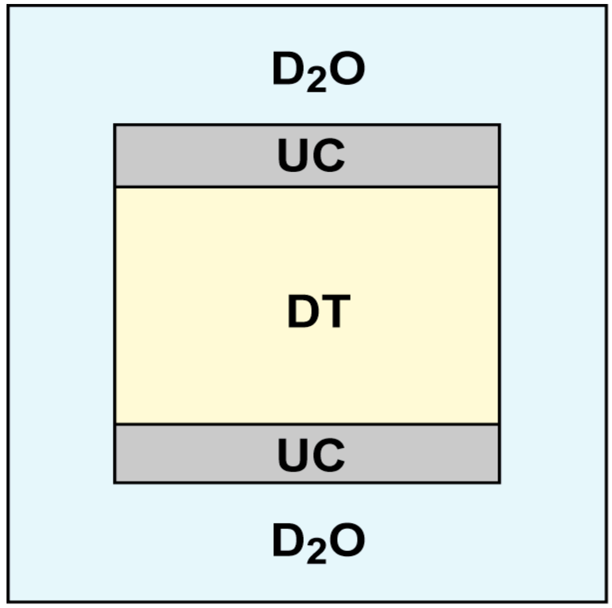

Fig.3 Geometry used for studying the effect of DT heating on U fission

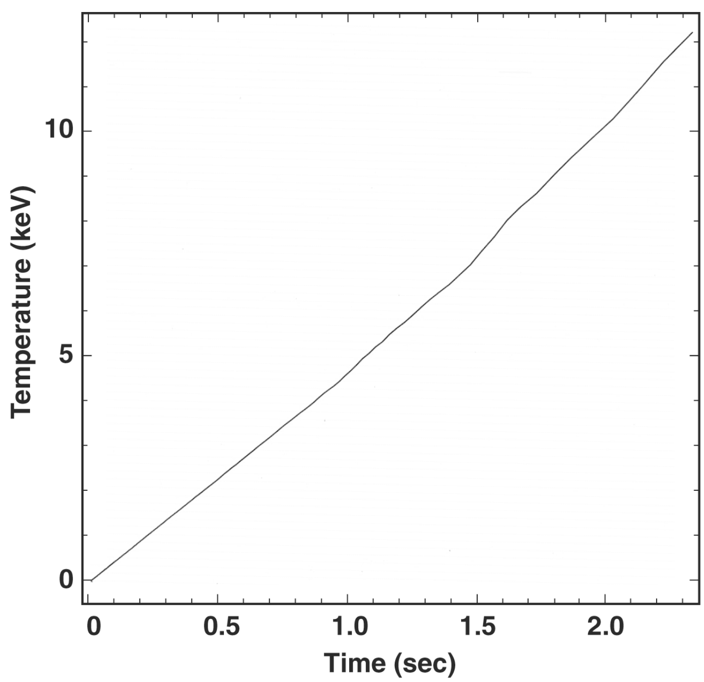

Fig.4 DT temperature vs. time with fission fragment range multiplier

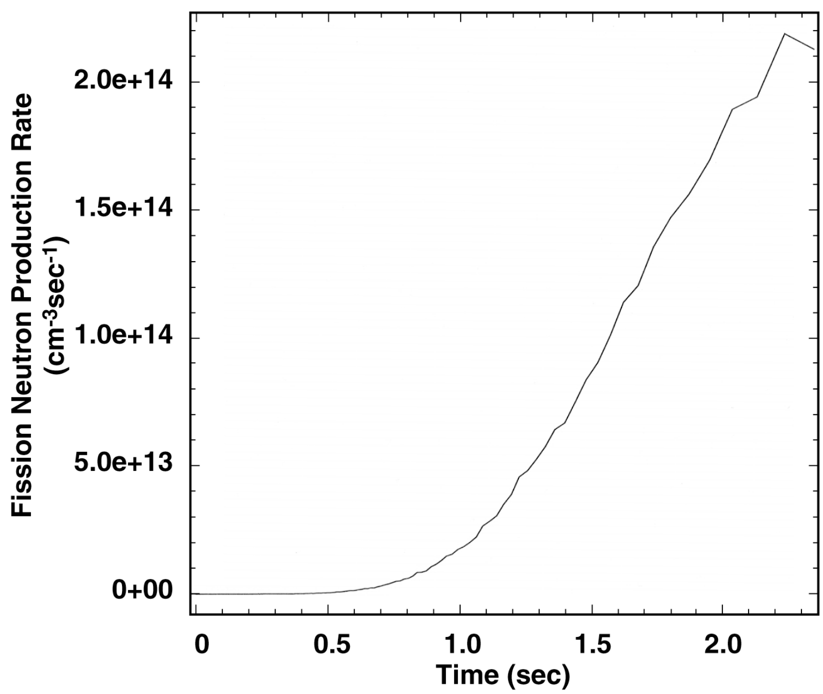

Fig 5 Rate of fission neutron production induced by fusion neutrons

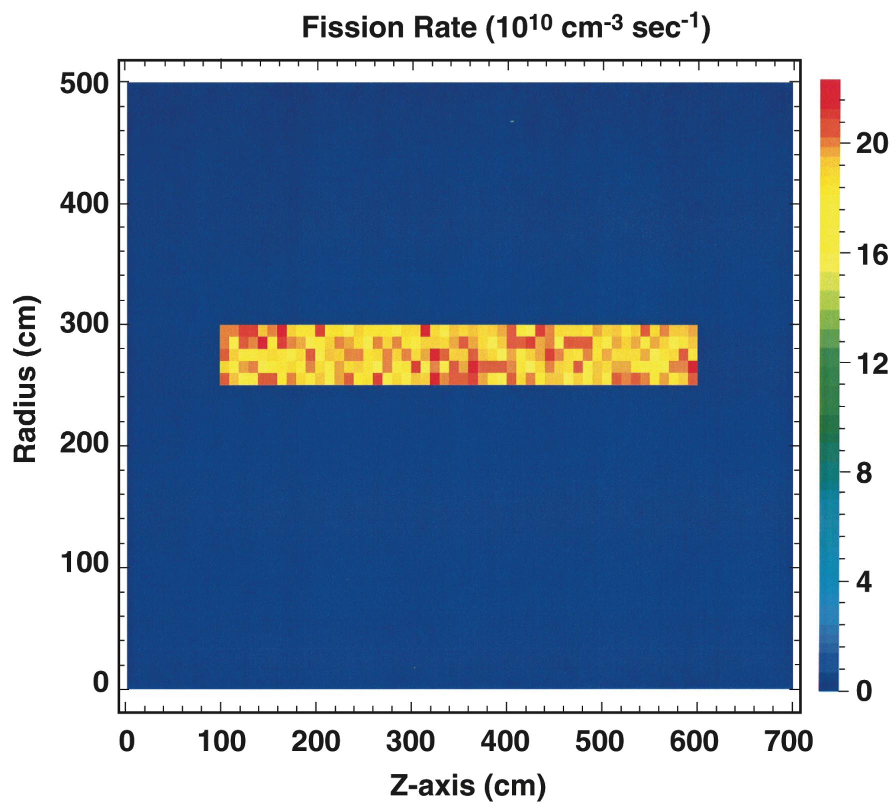

Fig. 6 Induced fission rate in UC fuel when DT temperatue is 2 keV

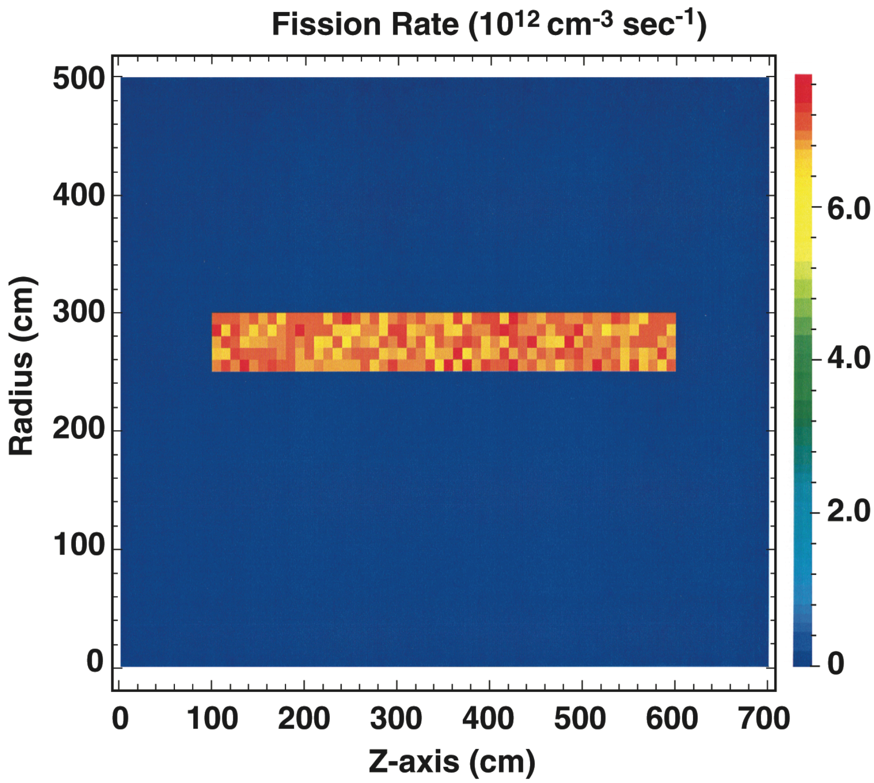

Fig. 7 Induced fission rate in UC fuel when DT temperature is 5 keV

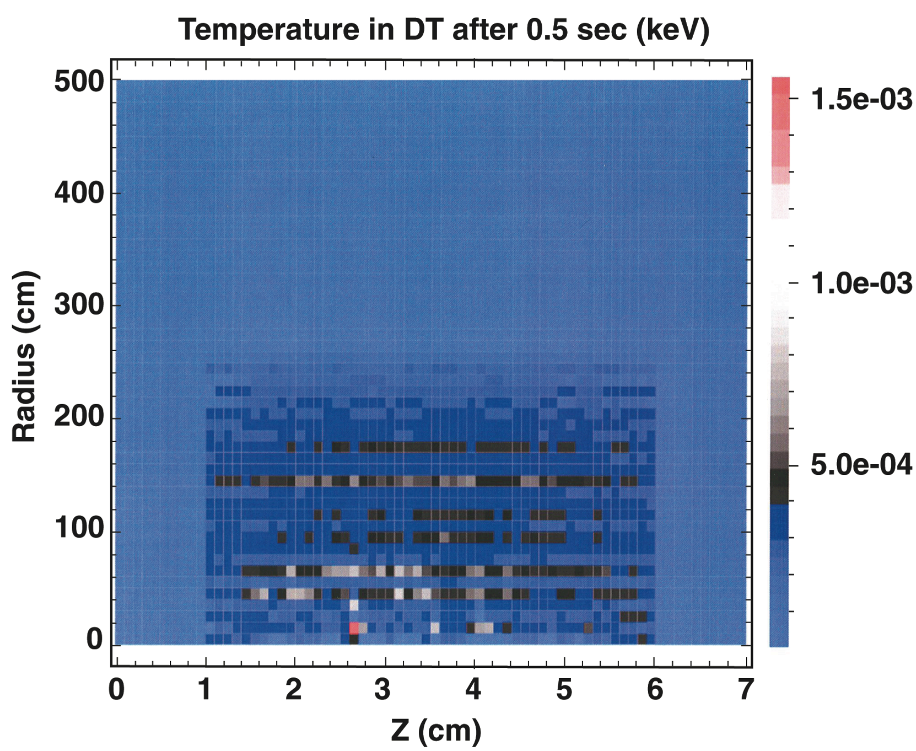

Fig 8 Temperature in the DT at .05 sec with a 2 T magnetic field with no fission fragment range multiplier

In Fig 8 we show a preliminary result for the heating of DT in the presence of a 2 Tesla magnetic field, but with no transport multiplier. Unfortunately because of time step problems we have only been able to calculate the DT heating up 0.05 sec, where its effect on the fission rate is not yet significant. However, up to the time where we have so far been able to carry the simulation the heating is close to what is expected. The implication of these calculations is that fission fragment heating in a strong magnetic field shows promise for heating DT to temperatures where self-sustaining fusion will take over and lead to large increases in the fission and fusion neutron production rates. A total fusion neutron fluence of 10^{20} may be approachable.

Next Steps

The results shown in Fig's 4 and 5 do not take into account the back reaction of the fission rate on the fusion rate. In order to realistically simulate the dramatic increase in the rate of fission, fusion, and neutron production after the DT reaches a temperature > 2 keV we need to solve the problem of how carry out the calculation of the DT heating in a magnetic field for extended times.

Another essential step is to carry out calculations in which the neutrons in a critical dust reactor core supply the initial DT heating. This will require introducing a better model for thermal neutrons in the DT heating calculation. We also need to model and include the effects of U and C impurities in the DT plasma. Finally we need to begin to address the question of plasma confinement in the mirror magnetic field.

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. This is close to the density and size of the UC particles in our standard model for the reactor core. Of course the size of our reactor core is much larger than the chambers that have been used in either plasma etching machines or laboratory dusty plasma experiments, so it remains to be demonstrated that a volume the size of our reactor core can be filled with UC particles .

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 [5,6] 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.

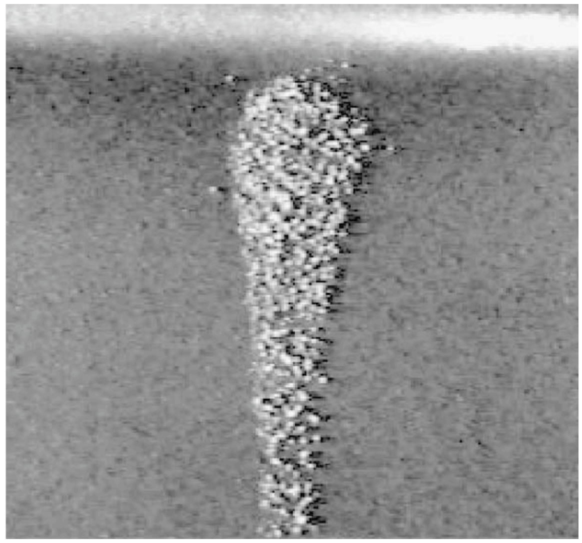

Fig. 9 Suspended micron size CeO_2 particles

A device for producing a volume dusty plasma with a dust density close to what we require has been demonstrated at the University of Iowa (Fig 10). In this device the dust is confined by a combination of electrostatic forces and magnetic forces, not just electrostatic forces. The dust is confined by the DT plasma in which it is embedded. The plasma is contained by a combination of magnetic field and the electrostatic forces. To accomplish this dust must have a charge. In the device illustrated in Fig 10 the dust is charged by potassium ions and electrons. In our case the dust will be charged up by the fission process. Each fragment carries a $\sim +22$ charge which should cause the dust to become negatively charged. This method of dust charging almost certainly works, but there does not exist a wide body of scientific knowledge and experience on this subject as dusty plama researchers normally choose not to work with radioactive dust. Around each dust grain a plasma sheath forms. The grains become embedded in the plasma.

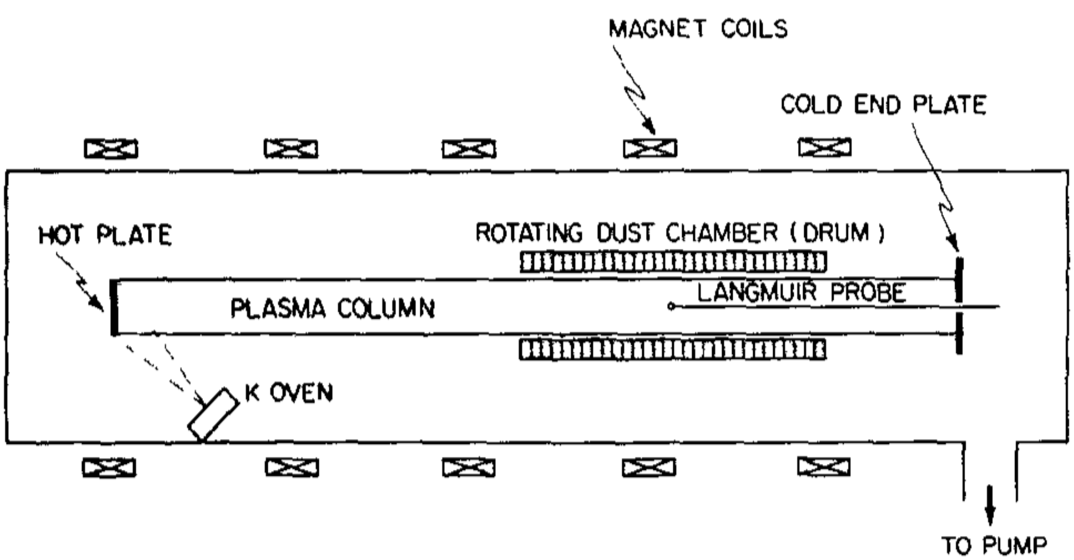

Fig 10 University of Iowa apparatus for producing volume dusty plasmas

As a first step towards evaluating the feasibility of suspending a critical mass of micron sized UC particles in a vacuum, we would like to first understand how the emission of fission fragments from these particles and exposure to fission gamma rays affects their equilibrium charge state in the presence of a hydrogen plasma. As a first experiment we propose measuring the charge of an americium or californium grain suspended in a Paul Trap in the presence of a gamma source. Following the single grain experiment we would want to demonstrate to the suspension of a dust cloud in a radioactive environment. It seems to us that a reasonable sequence of proof of principle experiments would be:

1.) Single radioactive grain charging experiment using the set up at the NASA/MSFC Dusty Plasma Lab. The purpose here is to find the equilibrium charge on a fissioning dust grain. We plan to use a grain of Cf252 which undergoes spontaneous fission. Ones we know this charge we can better determine the dust containment.

2.) The second experiment would use an apparatus similar to the U Iowa apparatus with a dust cloud of Cf252 or maybe an alpha emitter to investigate containment of a dust cloud which is charged by radioactivity. As mentioned above this has not been tried before. This experiment would be sealed and use only a few micro-curies of Cf252.

3.) The third experiment would duplicate experiment two but in a neutron flux and with UC dust substituting for Cf252 dust. For this we will take the same apparatus as in two but place it in a materials test reactor such as the one at ORNL. This would simulate the environment in a full scale dust reactor. It would demonstrate fuel particles can be contained in a reactor environment, as well as escape of fission fragments from a dust cloud.

Once we have in hand the basic information provided by the first experiment, we could proceed to design a prototype dusty reactor. The second and third experiments would provide the experience needed to proceed with building a prototype reactor.

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