Pulsed Fusion Characteristics

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1 Fundamentals of Pulsed Fusion

Thermonuclear fusion is governed by the rate coefficient $\langle \sigma v \rangle$ for fusion reactions, which for a particular reaction is a function only of (ion) temperature T. For the D-T reaction its value is roughly 5×10^{-22} m^{-3}s^{-1} at $T = 20$keV, the typical operating temperature of proposed reactors. The rate peaks a factor of only 2 higher at about 60keV temperature, so it is not generally worth trying to go to higher temperature. For other fusion reactions the rate is at least 10 times less; so they are much more difficult.

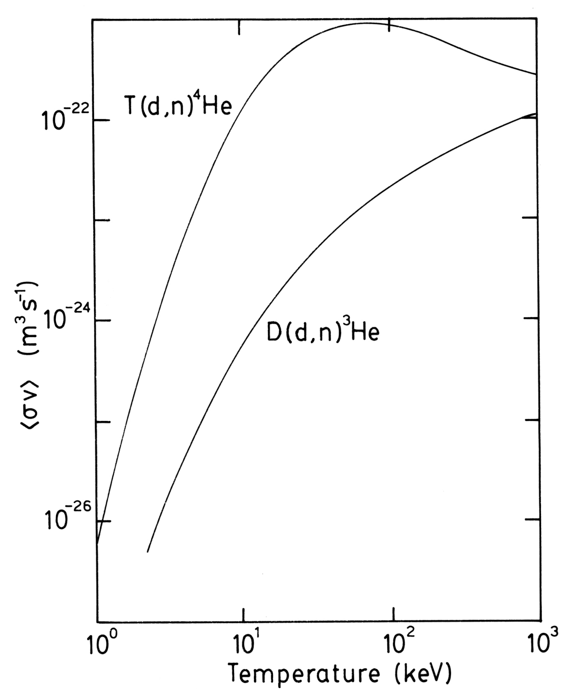

Figure 1: Fusion reaction rate coefficients

Pulsed reactors consider a single complement of fuel which is compressed, heated, reacts and then exhausts. Net energy production requires that sufficient fraction of the fuel experiences a fusion reaction, otherwise the energy consumed in compressing and heating the fuel will surpass the fusion energy released.

In some approaches to pulsed fusion, such as Magnetized Target Fusion, it is supposed that essentially the whole of the fuel is heated. In others, only a fraction of the fuel (the "hot spot" in laser fusion) is supposed to be heated, and its energy yield is supposed to heat up the rest of the fuel. This staged approach is very important because it raises the possible net gain of the entire assembly. To understand the importance, consider initially just that portion of the fuel that is externally heated.

1.1 Gain

Its maximum possible target gain G is equal to the energy yield of a fusion reaction ($E_f =$ 17MeV) divided by the energy required to heat the reacting particles ($\sim 2 \times (3/2) \times T_i$).

$$G_{max} = E_f/3T_i \approx 300 \tag{1}$$

using $T_i = 20$keV. If the ratio of the number of particles that react to the number heated in the first place is f_h, then the the gain is proportional to f_h: $G = G_{max} f_h \approx 300 f_h$. Pulsed fusion differs from steady-state fusion approaches, such as magnetic fusion. The steady-state approaches consider a burning plasma that is continuously fueled with additional D-T, leading to an energy balance that is different.

In particular, for steady fusion, ignition is enough to provide energy self-sustainment, while for pulsed fusion it is not. Pulsed fusion needs high *target* energy gain so that the total *engineering* gain per pulse is substantially greater than 1. There are many losses of efficiency involved in energy conversion and more crucially the driver physics so that $G_{max} = 300$ is a very tight limit. One way to think about "hot spot" ignition is that it is a way of increasing f_h *above unity* by making the number of particles initially heated much less than the number that can eventually react.

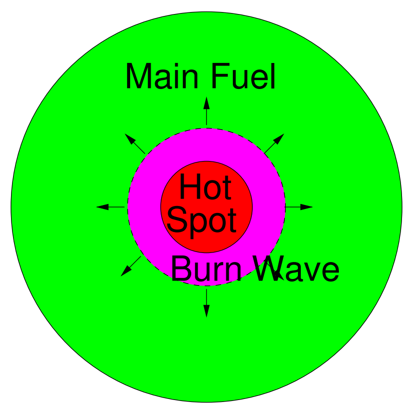

Figure 2: Hot-spot pulsed fusion

1.2 Burn Duration and Fraction

If the electron density (which is twice the density of each of the ion species, of deuterons and of tritons) in the burning state of a pulsed reactor is n_e (particles per cubic meter: m^{-3}) then the initial reaction rate per ion, which is the inverse of the characteristic reaction time is

$$\frac{1}{\tau_r} = \frac{1}{2} n_e \langle \sigma v \rangle \tag{2}$$

It takes, on average, a time τ_r for a fuel ion to react. The burning state must last long enough for a good fraction of the particles to undergo reactions. If the duration of the burning state is τ_b, the fraction of the fuel that reacts can be shown by integration to be

$$f_r = \tau_b/(\tau_b + \tau_r) \approx \tau_b/\tau_r. \tag{3}$$

The burn duration we seek will ideally be a good fraction of the reaction time so that f_r is close to one (e.g. 0.5) and the gain is large. It doesn't help much to make the confinement time much greater than the reaction time, because all the fuel would already be burnt. If the energetics of the scheme under consideration is dominated by external heating (as in MTF), then $f_r = f_h$. If instead we are considering just the hot-spot of a triggered pulse fusion scheme, then the fractional burn of just the heated spot ions, f_{rs}, is required only to be big enough to give substantial target gain and hence to generate a burn wave propagating into the rest of the fuel. Since only the alphas (whose fusion energy is one fifth of the total) give energy to the fuel, a tripling of the fuel energy requires e.g. $G \gtrsim 10$, and $f_{rs} \gtrsim 0.03$.

In all cases, to achieve a certain burn fraction requires a certain burn duration relative to the reaction time. We can invert eq. (3) to find the ratio of burn to reaction time needed for any given f_r, and we denote that ratio for convenience as f_q:

$$\tau_b/\tau_r = f_r/(1 - f_r) \equiv f_q. \tag{4}$$

At low burn fraction, $f_r \approx f_q$.

Then we can find the Lawson parameter $n_e\tau_b$ by, substituting into eq. (2), as

$$n_e\tau_b = f_q 2/\langle\sigma v\rangle \quad [= f_q\, 4 \times 10^{21}\mathrm{m}^{-3}\mathrm{s}]. \tag{5}$$

When we compare this with the idealized ignition criterion (where E_c is the charged-particle energy yield per reaction)

$$n_e\tau_E = 12T/E_c\langle\sigma v\rangle, \tag{6}$$

we see that taking $\tau_E = \tau_b$ ignition corresponds to

$$f_q = 6T/E_c = 6 \times 20/3500 = 0.034. \tag{7}$$

But this low (3%) burn fraction is inefficient. It provides a target energy gain of only $f_q G_{max} \sim 10$. In pulsed fusion, therefore, to obtain sufficient gain for energy production, one must reach Lawson parameters approximately 10 times those necessary simply for ignition. This contrasts with steady fusion, where ignition (or even just below) is sufficient.

The burn duration that is actually achieved in pulsed fusion is generally dictated by the fact that the pressure of the reacting plasma, which tends to make it expand, is balanced by the inertia of something. That something might be the plasma itself, or it might be the inertia of some "casing" or "pusher" which is responsible for compressing the plasma. In MTF, for example, the plasma is supposed to be compressed by a magnetic field which itself is sustained by metal casing. The metal might be Lithium-Lead which is supposed to be compressed by a converging mechanical shock. Generally, the effects of pressure and inertia travel at the sound speed c_s in the relevant material. If therefore, the size of the burning assembly is approximately R_b, the duration of the burn is roughly the time it takes for disassembly at the relevant sound speed

$$\tau_b \approx R_b/c_s \tag{8}$$

If the relevant confining material is the plasma itself, then the sound speed is the plasma ion acoustic speed

$$c_s = \sqrt{\frac{T_e + 3T_i}{m_i}} \tag{9}$$

At $T_e = T_i = 20$keV for $m_i = 2.5m_p$, this is $c_s = (4 \times 20 \times 1.6 \times 10^{-16}/2.5 \times 1.67 \times 10^{-27})^{1/2} = 1.8 \times 10^6$ m/s. By contrast, the sound speed in Lithium-Lead, determined by the material's elastic modulus, is approximately $c_s = 2$ km/s.

How big must the burn assembly radius R_b be to give a certain fractional burn-up? Substituting from our previous relations (2), (3), (8), we find

$$R_b \approx c_s\tau_b = c_s\tau_r f_r/(1 - f_r) = \left(\frac{2c_s f_q}{\langle\sigma v\rangle}\right)\frac{1}{n_e}. \tag{10}$$

1.3 Yield

Now we must consider the energy yield of the pulse:

$$Y = f_r N_t E_f \tag{11}$$

where N_t is the total number of Tritons in the burning assembly. Perhaps counterintuitively, the main objective is to make this as *small* as possible (while keeping the gain large). There are two main reasons. First, given limited gain, the required driver energy, which we would like to keep small, is some non-negligible fraction of the target yield. Second, this is, after all, a pulsed energy yield, which is a euphemism for an explosion. There is debate about how large an energy yield can be managed. The upper limit in the literature is generally considered to be in the vicinity of 1GJ (10^9). This is the energy release of an explosion of about 20kg of TNT so it is a very substantial blast. Less might be more manageable, but let's be optimistic. This yield defines the approximate repetition rate for a pulsed reactor. If the reactor's thermal power is $\sim$ 1GW, then we need 1GJ pulses once per second: 1 Hz repetition rate.

For the sake of this estimate, let's take the burning assembly to be roughly spherical so that its volume is $\frac{4}{3}\pi R_b^3$. It therefore contains $N_t = \frac{2}{3} n_e \pi R_b^3 \approx 2 n_e R_b^3$ tritons. Since from eq (10) $R_b \propto 1/n_e$, the number of tritons in the assembly is inversely proportional to n_e^2

$$N_t \approx 2 n_e R_b^3 = 2 \left(\frac{2 c_s f_q}{\langle \sigma v \rangle} \right)^3 \frac{1}{n_e^2} \tag{12}$$

Getting this number and hence Y down to a managable level pushes us to a high density (n_e). When $Y = 1$GJ, the number of reactions is $f_r N_t = Y/E_f = 3.68 \times 10^{20}$.

1.4 Density

Rearranging eq (12) gives

$$n_e = \left[2 \left(\frac{2 c_s f_q}{\langle \sigma v \rangle} \right)^3 \frac{f_r E_f}{Y} \right]^{1/2} . \tag{13}$$

We notice that the important parameter characterizing the type of pulsed confinement is the normalized speed of disassembly:

$$s \equiv \left(\frac{2 c_s}{\langle \sigma v \rangle} \right) = 7.2 \times 10^{27} \mathrm{m}^{-2} (\text{inertial}) \qquad \text{or } 8 \times 10^{24} \mathrm{m}^{-2} (\text{MTF}). \tag{14}$$

(evaluated at $T_i = 20$ keV). We summarize and contrast the density, assembly size, and burn duration, based upon the two different values of this parameter we have been considering, and $f_r = 0.5$ burn fraction[1], in table 1. We see, therefore, that the approximate required characteristics of pulsed fusion can readily be deduced in a few lines of arithmetic from

[1]MTF advocates usually cite a density target of about 10^{26} m^{-3}. This corresponds to $f_r \approx 0.2$, $R_b \approx$ 20mm, $\tau_b \approx 10$ μs, and a gain of $G \approx 60$.

Table 1: Estimate of density, radius, and time for uniform pulsed fusion with yield $Y = 1$ GJ and fractional burn $f_r = 0.5$ ($f_q = 1$) at temperature 20keV.

Parameter	s (m^{-2})	n_e (m^{-3})	R_b (m)	τ_b (s)
Formula	$2c_s/\langle\sigma v\rangle$	$(2E_f s^3 f_q^3 f_r/Y)^{1/2}$	sf_q/n_e	R_b/c_s
MTF	8×10^{24}	1.2×10^{27}	7×10^{-3}	3.4×10^{-6}
Plasma	7.2×10^{27}	3.2×10^{31}	2.2×10^{-4}	1.3×10^{-10}

fundamental physics knowing just the fusion reaction rate and yield, and how big an explosion one can handle.

2 Inertial Plasma Confinement

2.1 Lawson Criterion as ρR requirement

In confinement where the inertia of the plasma itself is the important mechanism, it is customary to express the Lawson parameter $n_e\tau_b = f_q 2/\langle\sigma v\rangle$ in a different way. Multiplying it by the sound speed gives $n_e R_b \approx f_q 2c_s/\langle\sigma v\rangle = f_q s$. This quantity is the product of density and radius. Unfortunately, tradition dictates that this be expressed instead as *mass* density ρ times radius (multiplying by the average ion mass $2.5m_p$), and that the resultant be expressed in CGS units (grams and centimeters).

$$\rho R(/\text{g.cm}^{-2}) = m_i n_e R_b/10 \approx 0.25 m_p f_q s = 3f_q \qquad (15)$$

(using $s = 7.2 \times 10^{27}\text{m}^{-2}$). It is thus commonly stated that for *high gain* $\rho R \approx 3$ g/cm^2 is required. [Sometimes different coefficients are used, such as $R_b \approx 3c_s\tau_b$ (to allow for a hollow fuel shell) but then letting $f_q = 0.3$ arriving again at $\rho R = 3$g/cm^2 .] If we substitute the *ignition* requirement, eq (7) $f_q = 0.034$, we get $\rho R \approx 0.1$g/cm^2.

2.2 Alpha Confinement

In magnetic confinement, it is presumed that the alpha particles are confined by the magnetic field so that they slow down on the bulk plasma and transfer their energy to it. In inertial fusion, no such magnetic confinement is assumed. Instead, a new criterion on the burning assembly arises: that it be deep enough to slow down the alphas and extract their energy before they leave. The range (λ_α) of fusion (3.5 MeV) alphas is inversely proportional to the density (but only approximately so because of quantum degeneracy effects). In a DT plasma it can be approximated [John Lindl, *Development of the indirect-drive approach to inertial confinement fusion and the target physics basis for ignition and gain*, Phys. Plasmas, **2**, 3933 (1995)] as

$$\rho\lambda_\alpha(\mathrm{g/cm^2}) = \frac{0.015(T_e/\mathrm{keV})^{5/4}}{1+0.0082(T_e/\mathrm{keV})^{5/4}} \tag{16}$$

The result for T_e =10-20 keV is $\rho\lambda_\alpha$ = 0.23-0.47 g/cm^2. Identifying $\lambda_\alpha = R$, we see that the Lawson criterion for ignition (15) is less demanding than the requirement for capture of the alpha energy (which is also required for ignition to take place). Minimally then, to trap alphas, ρR must be at least ~ 0.3 g/cm^2. This is a key factor in defining the parameters of the "hot-spot". Whereas a full burning assembly with sufficient ρR for high gain ~ 3 g/cm^2, traps alpha energy rather easily.

2.3 Mass-density requirement

Returning to the formulas of Table 1, the inertial confinement density there, 3.2×10^{31} m^{-3}, is very roughly 1000 times the density of normal liquid (or solid) DT ($\sim 5 \times 10^{28}$ m^{-3}).

Conversion from electron density to CGS DT mass density is

$$\rho\ (\mathrm{g/cm^3}) = 4.18 \times 10^{-30} n_e\ (\mathrm{m^{-3}}) \tag{17}$$

which means the density can be expressed as $\rho \approx 130$ g/cm^3 (in comparison with liquid DT ~ 0.2 g/cm^3). The corresponding mass of the plasma is $\rho 4\pi R^3/3 \approx 6 \times 10^{-3}$ grams. Generally, a yield Y somewhat less than 1 GJ is used, resulting in a somewhat higher density requirement than Table 1, smaller radius, and smaller plasma mass.

The factor 1000 density enhancement would require a 3-D compression in radius of at least 10 starting from liquid density. Obtaining this compression by the rocket-like ablation of plasma from the surface of a capsule is the job of the driver. The compression phase is where most of the research effort for the past 40 years or more has been devoted. Laser drivers are the ones in practical use for ignition experiments. Pulsed charged-particle drivers and z-pinch (so-called "pulsed power") drivers have also seen substantial development, but are further from engineering feasibility.

2.4 Hot-spot Power Balance

The central hot-spot is generally compressed in a gaseous state where its pressure is kinetic: $p = 2n_eT$ and assumed uniform. How that pressure evolves, as the compression proceeds, depends upon power balance between compression work, thermal conduction, radiative loss, and eventually alpha-heating. Radiative losses are less important than conduction if the temperature is high enough, so for now ignore radiation and alpha heating.

If the radius within the hot-spot is r at which the implosion velocity is v, then the total rate of compression work on it per unit volume is

$$P_p = \frac{pv4\pi r^2}{(4\pi r^3/3)} = 3p\frac{v}{r} = 6Tn_er_h\frac{v_h}{r_h^2} \tag{18}$$

where subscript h refers to the radius of the whole hot-spot.

Notice that if the implosion velocity within the hot-spot is proportional to radius, preserving the density profile, then the compression power density is uniform if p is. Spitzer electron conductivity gives heat power flux density

$$q = -\kappa\nabla T_e = -KT_e^{5/2}dT_e/dr \tag{19}$$

which gives a net divergence of conduction power density, P_e, (conduction power loss density) which we take to be uniform:

$$4\pi r^3 P_e/3 = -4\pi r^2 KT_e^{5/2}dT_e/dr \tag{20}$$

Integrating, we find

$$(P_e/3K)[r^2/2] = -[\frac{2}{7}T_e^{7/2}] \tag{21}$$

and approximating $T_e = 0$ at $r = r_h$ we get

$$T_e^{7/2} = (7P_e/12K)(r_h^2 - r^2) = T_{e0}^{7/2}(1 - r^2/r_h^2). \tag{22}$$

The conduction power loss per unit volume is then

$$P_e = K\frac{12}{7}\frac{T_{e0}^{7/2}}{r_h^2}. \tag{23}$$

Power balance $P_e = P_p$, using central density and temperature values therefore occurs when

$$T_{e0}^{5/2} = n_e r_h \frac{7v_h}{2K} = \left(\frac{\rho R_h}{\mathrm{g.cm^{-2}}}\right) v_h \frac{7}{2K4.18 \times 10^{-28}} \tag{24}$$

For a given compression velocity, v_h, this is a simple power-law relationship between T_e and ρR_h. Substituting for the conduction coefficient K, it is traditionally written

$$\left(\frac{T_e}{\mathrm{keV}}\right) = 9.6 \left[\left(\frac{\rho R_h}{\mathrm{g.cm^{-2}}}\right)\left(\frac{v_h}{10^7\mathrm{cm/s}}\right)\right]^{2/5} \tag{25}$$

Thus for compression successfully to $\rho R_h = 0.3$ g/cm^2, it appears that a compression velocity approximately $v_h = 3.3 \times 10^7$cm/s $= 3.3 \times 10^5$ m/s is sufficient to heat to 10 keV temperature and hence ignite. A more complete analysis including alpha heating and radiation leads to a quadratic equation for ρR at given T_e, the path to the ignition region closes when $v_h \lesssim 10^7$ cm/s. These velocities are of order 1/10th of the (20keV) sound speed, so the presumption of pressure balance is a good approximation.

Fig. 3 shows regions of power gain (unshaded) and loss (shaded) for a particular compression velocity (3×10^5 m/s). The expectation is that as compression proceeds, the hot-spot travels from left to right approximately along the upper boundary of the unshaded region. When ρR exceeds roughly 0.1 g/cm^2, alpha particle heating becomes important, provided the temperature is high enough, and the boundary deviates upward from eq. (25).

The kinetic energy that must be imparted to the imploding capsule is approximately $v^2/2$ times the fuel mass. It makes sense to use v_h for the fuel velocity because most of the fuel is just outside the hot-spot edge. For a fuel mass of 5mg (corresponding to 1GJ yield at full burn-up) and implosion velocity $v = 3.3 \times 10^5$ m/s, the fuel kinetic energy is 2.7×10^5 J, or 0.27 MJ.

If we try to ignite smaller fuel mass, so as to reduce the driver energy requirement, the hot-spot must still satisfy the alpha trapping requirement $\rho R_h \sim 0.3$ g/cm^2 and be hot. Denoting by N_{eh} and $N_{e,fuel}$ the total number of electrons in the hot-spot and fuel regions, the thermal energy that has to be deposited into the hot-spot is $3TN_{eh} \sim N_{eh}(3/2)m_i c_s^2/2$ (using $c_s^2 = 4T_e/m_i$) , which is approximately equal to the kinetic energy of the fuel when $(3N_{eh}c_s^2)/(2N_{e,fuel}v_h^2) \sim 1$. Beyond this point, little further driver energy reduction is achieved by reducing the fuel mass. Taking $c_s/v_h \sim 5$ this occurs when the hot-spot contains $\sim 3\%$ of the particles and hence of the fuel mass.

As the fuel region becomes a smaller fraction of the assembly mass and volume, the hot-spot radius becomes a large fraction of the total, e.g. $R_h \sim 0.5R$.

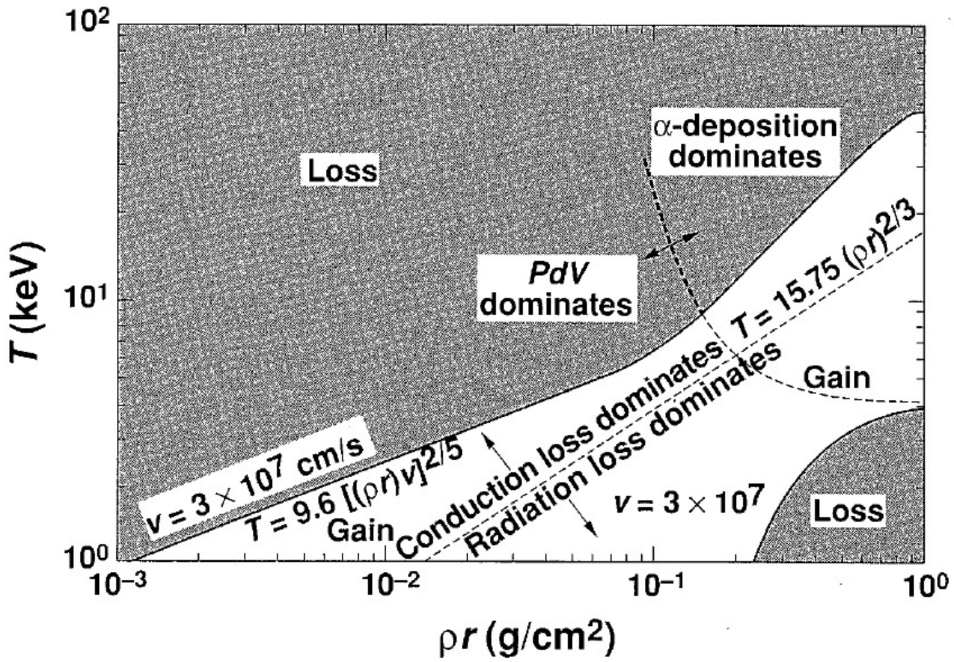

Figure 3: Ignition path for inertial fusion. From J.Lindl, 1995.

3 Driver and Compression Physics

The general idea of pure inertial fusion is that a capsule of DT is compressed by the rocket-effect of plasma streaming from its surface when it is irradiated by a very intense pulse of energy.

3.1 General Character

Limiting our discussion to laser fusion in this section, as illustrated by Fig. 4 there are two approaches: Direct or Indirect drive. In Direct drive, the lasers impinge directly on the outside of the spherical capsule and cause the ablation by absorption near the layer where $n_e \sim n_c$ (or slightly less) with electron conduction of the heat to the ablation front. In Indirect drive, the lasers impinge upon the inside of a "Hohlraum" cavity, made from heavy elements, and inside which the capsule lies. The Hohlraum absorbs the laser and re-radiates much of the energy in the form of x-rays. The x-rays are then what ablates the capsule surface and causes the implosion.

Indirect drive has advantages in rocket efficiency and uniformity because the x-ray wavelength is smaller and the cavity helps to smooth out asymmetries. Its disadvantage is the

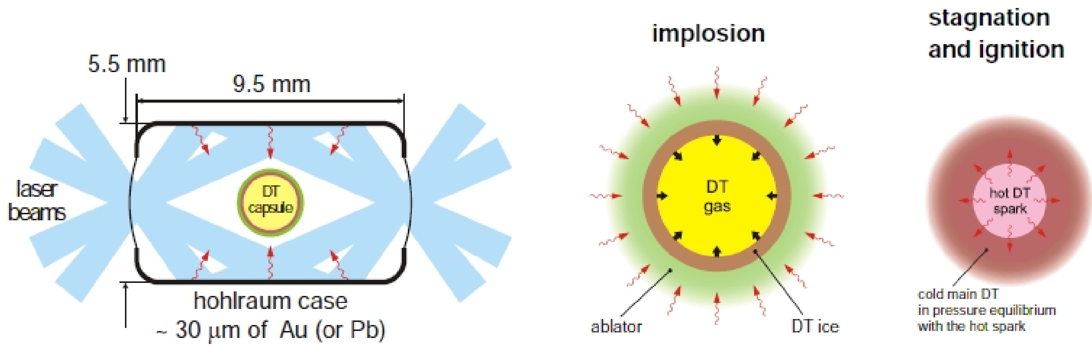

Figure 4: Schematic of inertial fusion compression. [From M.M.Basko. Vilamoura 2004 IAEA.]

loss of efficiency by the extra conversion step. A major long-term disadvantage for energy production is that the hohlraum is a complicated, massive, and expensive object that gets destroyed at each compression.

In order to obtain a central hotspot as illustrated in Fig. 5 the compression is carried out with a *shell* of solid DT of fairly high aspect ratio. This means the compression is actually predominantly 2-dimensional rather than 3-dimensional and so the ratio of its intial to final radius (known as the convergence-ratio) must be roughly 30. Large aspect ratio $R/\Delta R$ of the fuel shell is advantageous for obtaining peak compression, but more susceptible to disruption by Rayleigh-Taylor instabilities. $R/\Delta R \sim 30$ is a typical objective. Similarly, larger implosion velocity is advantageous for compression and ignition but requires more powerful drive, which is limited by driver technology and plasma instabilities.

The peak drive intensity required is in the vicinity of $I \sim 10^{15}$ W/cm^2 which (in Indirect fusion) is often expressed as an equivalent radiation temperature $T_r \approx 300$ eV. $[I(/\mathrm{W.cm}^{-2}) = 10^{-4}\sigma T_r^4 = 5.67 \times 10^{-12}(11600\ T_r/\mathrm{eV})^4 = 1.03 \times 10^5 (T_r/\mathrm{eV})^4 = 8 \times 10^{14}$ at $T_r = 300\mathrm{eV}.]$

The objective is to keep the main dense fuel *cold* so as to make it easy to compress. Ideally the compression energy then mostly has to overcome the degeneracy force associated with the Fermi energy (rather than the thermal pressure force) in the main fuel. The hot-spot must of course reach high enough temperature and confinement parameter to ignite. Its pressure will be similar to the main fuel pressure, so its density is a lot less. Therefore, while it has only a small fraction of the mass of the capsule, it takes up a substantial fraction of the inner volume.

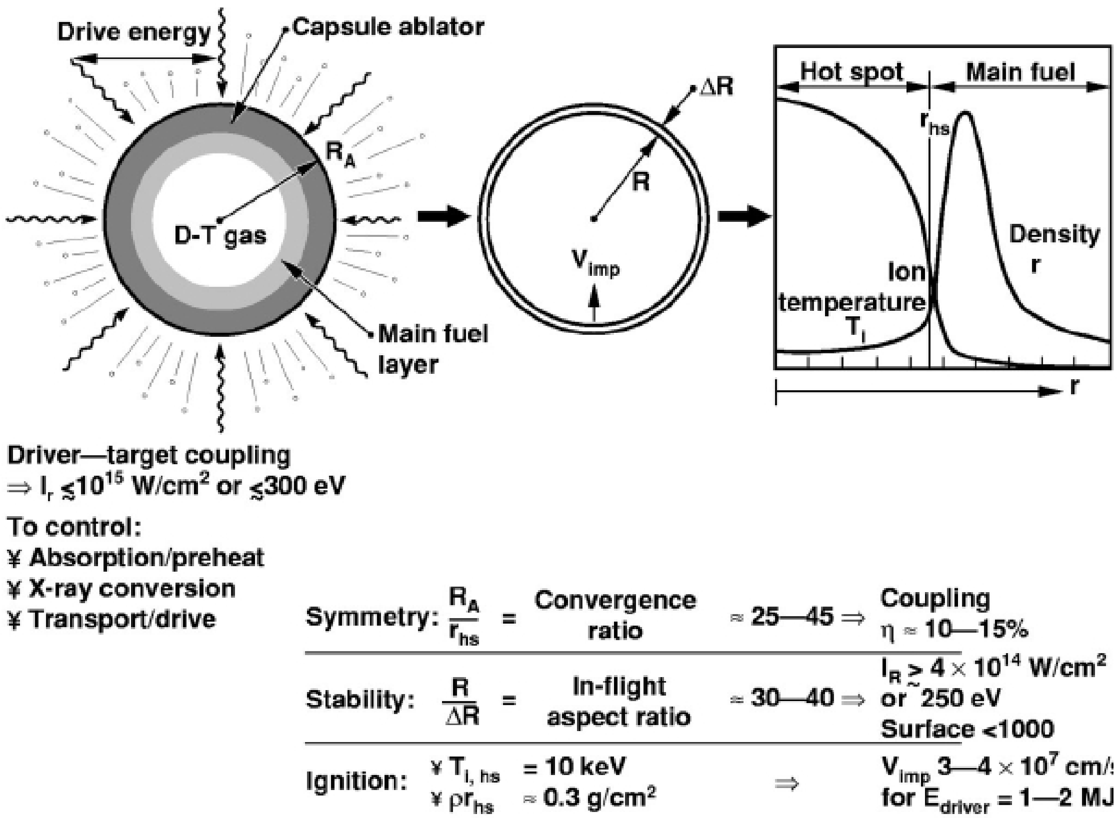

Figure 5: Profiles of hot-spot ignition and requirements for compression. From Lindl et al Phys Plasmas 11, 339 (2004).

3.2 Rocket and Ablation Dynamics

The rocket equation governs the implosion dynamics. One also requires the relation between the exhaust velocity of the ablating material and the impinging driver intensity (and wavelength). Those relationships involve lots of complicated physics, and we won't explore them here. We'll just summarize.

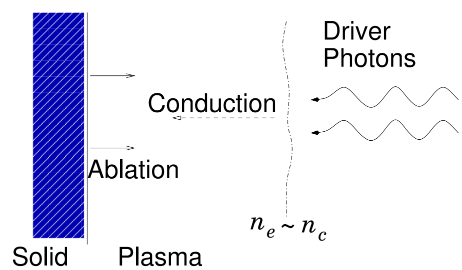

Figure 6: Key aspects of compression by rocket ablation.

The achievable efficiency with which energy incident on the capsule is turned into kinetic energy of the imploding shell can be estimated with some degree of confidence. For Direct drive it is about 5-10%. This is substantially (perhaps a factor of 5) less than rockets themselves can achieve, mostly because the energy is being deposited into the already-ablated material. Indirect drive is somewhat more efficient, roughly 15-20% of the incident x-ray energy is turned into implosion kinetic energy. However only approximately 10-20% of the laser energy in Indirect drive ends up in x-rays on the capsule. So the overall efficiency (laser$\rightarrow v_{implosion}$) of Indirect drive is only perhaps 1.5-4%.

These efficiencies then tell us how large a (laser) driver energy is required for a capsule of a certain mass. A 1 GJ (5 mg) capsule needs 0.3MJ of kinetic implosion energy, which requires a laser of energy 3-6MJ (Direct) or 7.5-20MJ (Indirect). NIF has laser energy 1.8MJ. So it is limited to capsules considerably smaller than 5 mg fuel mass. Since the required density of smaller capsules increases proportional to $Y^{-1/2}$, the convergence-ratio required then becomes larger, challenging the limits imposed by in-flight aspect ratio and stability.

4 MTF and Compact Toroid compression

4.1 Compression-factor and duration

Suppose that the burning state is to be obtained by compression of a magnetically confined plasma by a factor of $k = R_p/R_b$ in linear dimensions (R_p is the initial, pre-compression, radius). If that compression is adiabatic and flux-conserving, then the magnetic field magnitude increases by a factor k^2, the conservation of particle magnetic moment implies the transverse particle energy (temperature) increases by k^2, and if the compression takes place in all three dimensions (rather than just 2) the conserved-particle density increases by a factor k^3. Actually such a density scaling is too optimistic, because if such a 3-D compression took place it would increase the ratio of particle to magnetic pressure $\beta = p2\mu_0/B^2$ by a factor of k. Since the pre-compressed plasmas are usually taken to have $\beta \sim 1$, such a β increase is not possible. A magnetically confined plasma can't have β significantly larger than 1 because of elementary force balance,

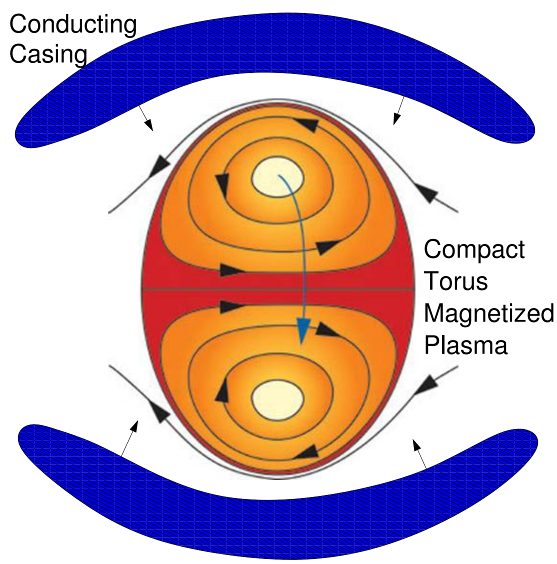

Figure 7: Schematic of Magnetized Target Fusion. The plasma is confined by magnetic field, but the field is compressed dynamically by the inertia of a converging conducting casing.

so something has to give. Nevertheless, the MTF proponents generally take the optimistic view that adiabatic scaling of both the temperature and density can be applied for a compression factor $k \approx 10$.

If the velocity of compression is approximately equal to c_{sl}, again because of the properties of the driver material, then the duration of the compression is

$$\tau_c \approx R_p/c_{sl} = kR_b/c_{sl}, \tag{26}$$

i.e. a factor of k longer than the burn time. The compression duration is thus roughly 100μs. For compression to be accomplished it is therefore necessary that the important characteristic decay times of the plasma in the pre-compressed state, and during compression, exceed approximately this duration.

MTF proposes that the burning plasma assembly be created by compressing a pre-formed compact toroid (CT) either a Spheromak or a Field Reversed Configuration (FRC). There are some differences between these configurations. The Spheromak is expected to be less efficiently compressed compared with the pure FRC (with no toroidal field). The FRC is MHD unstable. However, present experiments show that it lasts longer than would be anticipated on the basis of MHD theory. It is widely accepted that this better-than-MHD stability performance arises from the fact that the ion Larmor orbits of gyration around the field are about the same size as the plasma gradient-scale-length in existing experiments.

4.2 Pre-Compression

Broadly speaking, the scientific challenge for MTF is to demonstrate first that the pre-compression magnetically confined plasma can be stably created and placed inside the liner, and second that it can be stably compressed to achieve the burning plasma state. Neither of these stages has yet been experimentally demonstrated.

Experimental demonstration is the only way to provide a convincing demonstration that CTs are stable enough and confine plasma well enough to serve the purposes of MTF. One of the most successful and better documented experiments of recent years is the FRX-L facility at LANL, whose plasma size ($R \sim 3$cm) is approximately ten times smaller than desired for the pre-compression state. It has observed densities of order 2×10^{22} m^{-3}, sum of electron and ion temperatures approximately 300eV, lasting for characteristic times approximately 10μs. This best performance should be compared with what one would need for the pre-compressed state if a linear compression factor of $k = 10$ were anticipated, namely $n \approx 10^{23}$

m^{-3} , $T \sim 200$ eV, $\tau_c \approx 100\mu$s. The achieved density is a factor of 5 short of that necessary, and the duration/time-constants are a factor of 10 short.

The issue of size is also very important. It might be hoped that a larger FRC would last proportionally longer. However, because FRC stability is believed to depend upon the relative size of the Larmor orbit, it seems highly likely that a larger FRC with comparable temperature and magnetic field will in fact not last longer, but may become unstable sooner. Therefore while the FRC-L results are considered promising by the proponents, and they do achieve a high density exceeding prior experiments (albeit still short of what is required), there is no convincing reason to assume that they can be extrapolated to the 0.2m pre-compression radius required.

To summarize the MTF pre-compression plasma experimental situation: no FRC plasma with integrated performance even close to what is required has been experimentally demonstrated. As far as we know, this is not because of shortcomings in technology, but because of the physics of plasmas. It is not known whether there is some way to overcome the current limitations. Spheromaks do not have even as much track record as the FRCs to draw on.

4.3 Compression and Burn

By the scaling of expected compression in a CT, the ratio of the Larmor radius ρ_i to the plasma size R remains constant during compression. This can be considered an advantage. It means that the s parameter which is approximately proportional to R/ρ_i and governs the finite-larmor-radius stabilization in an FRC does not change significantly during compression. Therefore if an FRC that satisfies the pre-compression requirements could be demonstrated (with sufficient life-time of course), there is some hope that it might survive compression. Compression does of course change the characteristic times by a large factor, for example the ion gyro frequency increases by a fact of 100, so growth rates that scale in that parameter will lead to growth times 100 times shorter. Such instabilities, if present, will likely grow to non-linear levels, and may completely destroy the plasma. There is, however, a big problem for the FRC if R/ρ_i is limited to a few. It is that the ρ for alpha particles is far larger than the thermal ions. Therefore, they will not be confined by the magnetic field. For this reason spheromaks (which don't have the s parameter limitation) are preferred by some MTF proponents.

There are many concerns in respect of the interaction of the plasma with the wall compressing it. The foremost is probably that the plasma becomes polluted with impurities from the wall, diluting the fuel and causing greatly enhanced radiative energy loss that might prevent the burn.

Since the anticipated magnetic fields of hundreds of tesla in the compressed state are not achievable in standard magnetic field coils, it seems likely that compression experiments are *required* if we are going to explore the regimes of interest.

There is a whole host of unknowns regarding the burn phase, if it is reached. From a pure plasma physics viewpoint, the alpha particle heating, if adiabatic, is sufficient to raise the pressure of the plasma by a factor of 10. That is unsupportable if we start the burn at $\beta \sim 1$ already; so what presumably will happen (no one really knows) is that before such a high pressure is reached instabilities will arise to limit the pressure rise. These might conceivably be benign self-regulation by energy transport. More likely they will result in a violent disruption of the plasma. The result might prematurely terminate the burn (or even the compression before burn is even reached) either by dumping the plasma on the wall or by mixing in sufficient radiative impurities to quench the reactions. All of these and the many other possible challenges are almost entirely unexplored at the parameters required.