

ANALYSIS OF IGNITION AND GAIN FOR SMALL FUSION TARGETS

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Tutorial Purpose:

There are many facets of fusion, and at this Symposium we tend to concentrate on only a few. This is because we are mainly interested in creating a fusion reactor as a long-term solution to our to anticipated future terrestrial energy requirements.

It seems prudent to review the progress in our endeavor, and to consider various approaches to fusion for power production that have been taken in the past and whether there are interesting alternatives to be explored.

Here I hope to provide an analysis that illustrates various aspects of the inertial approach to fusion, hopefully pointing out some inherent restrictions, as well as unrealized opportunities.

Simple models and analyses will be used to illustrate various points.

OUTLINE OF TALK

FUSION CATEGORIES

BASIC INERTIAL FUSION PHYSICS

FUSION FUEL DYNAMICS

PATHS TO FUSION IGNITION

SPATIAL PROFILES $T(r)$, $\rho(r)$, $P(r)$, $v(r)$...

TRAJECTORIES IN PARAMETER SPACE

MINIMUM ENERGY FOR FUSION IGNITION

BURN EFFICIENCY

ENERGY DEPOSITION EFFICIENCIES

DRIVER CHARACTERISTICS

MATCHING THE TARGET TO THE DRIVER

ALTERING THE FUSION PHYSICS -- MTF

COMMENTS

FUSION CATEGORIES

BASIC REQUIREMENTS FOR REACTIONS BETWEEN LIGHT NUCLEI

"COLD FUSION" -- POSSIBLE LOWERING OF COULOMB BARRIER
A IN SOLID MATRIX

CATALYZED FUSION -- MUON-FACILITATED FUSION

"BEAM FUSION" -- COLLIDING ENERGETIC CHARGED LIGHT NUCLEI

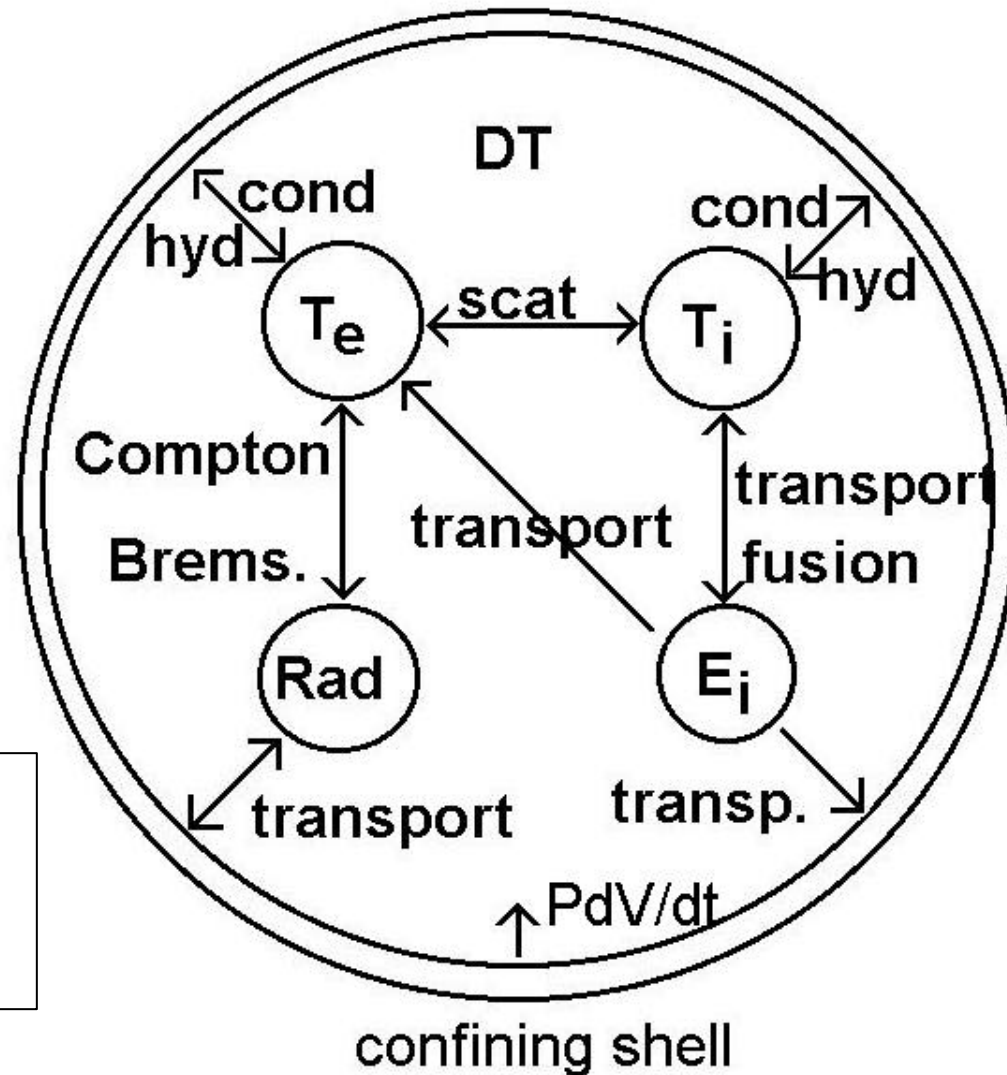
THERMONUCLEAR FUSION -- MAKING USE OF ENERGETIC TAIL
OF MAXWELLIAN

MAGNETIC CONFINEMENT

INERTIAL CONFINEMENT

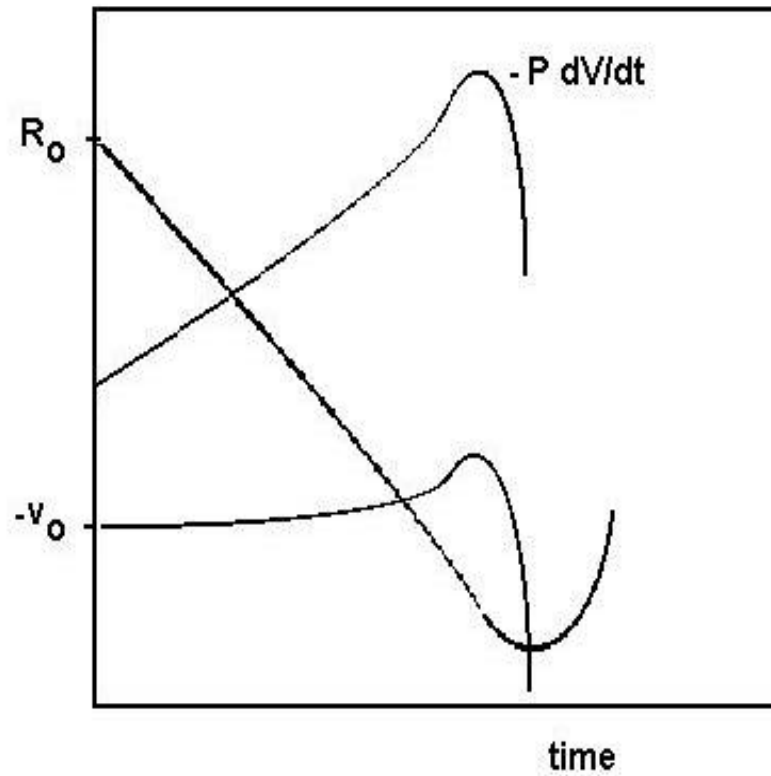
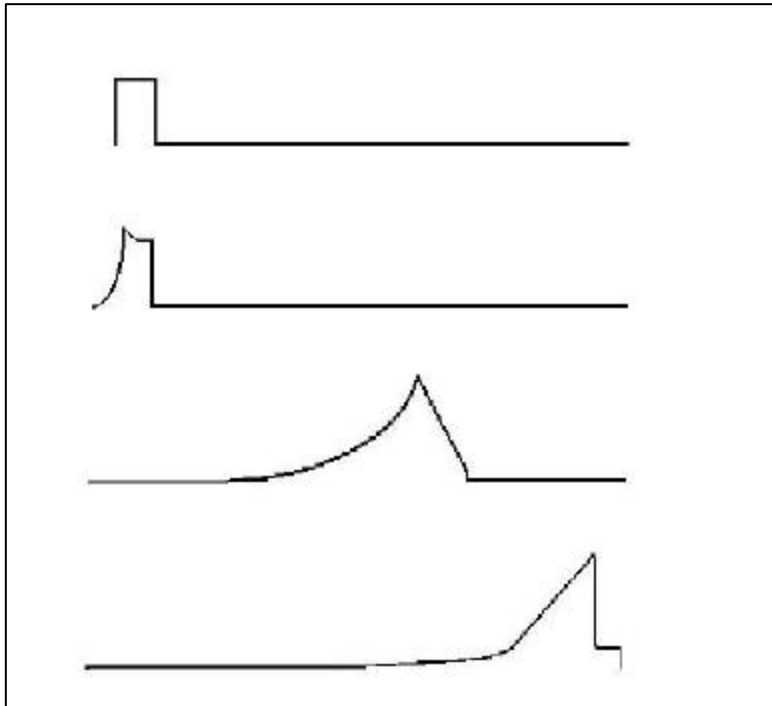
MAGNETICALLY INSULATED INERTIAL FUSION

BASIC INERTIAL FUSION PHYSICS PROCESSES

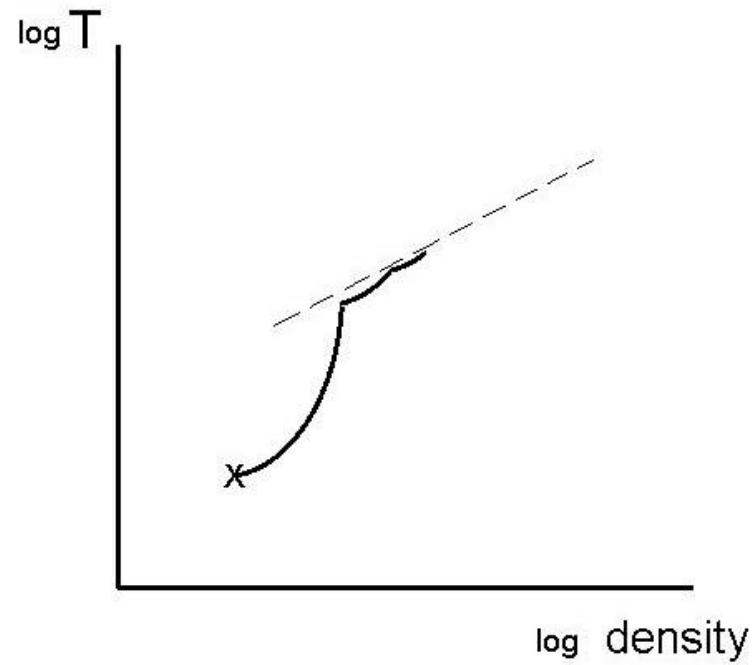


" **Ideal ignition temperature** " =
 temperature at which fusion
 energy production balances
 radiation loss by Bremsstrahlung
 (~ 4.5 keV)

Hydrodyanmics



SHOCKS AND ADABATIC COMPRESSION



FUSION IGNITION

- Required by ICF targets for high gain.
- **Fusion ignition is the transition from externally supported fusion burn to self-supported fusion burn.**
- Ignition requires at least part of the fusion reaction product energy to be deposited in the fusion plasma.
- For ICF this requires $rR > 0.3 \text{ gm/cm}^2$, but for MTF the magnetic field can substantially enhance energy deposition when the field x radius product exceeds $BR \sim 1.0 \text{ Tm (MGcm)}$, so for MTF it appears possible to get ignition with $rR \ll 0.3 \text{ gm/cm}^2$.

IGNITION CRITICAL PROFILES ... $T(r)$, $r(r)$

- An attempt to define conditions for fusion ignition.
- Based on an idealized circumstances.

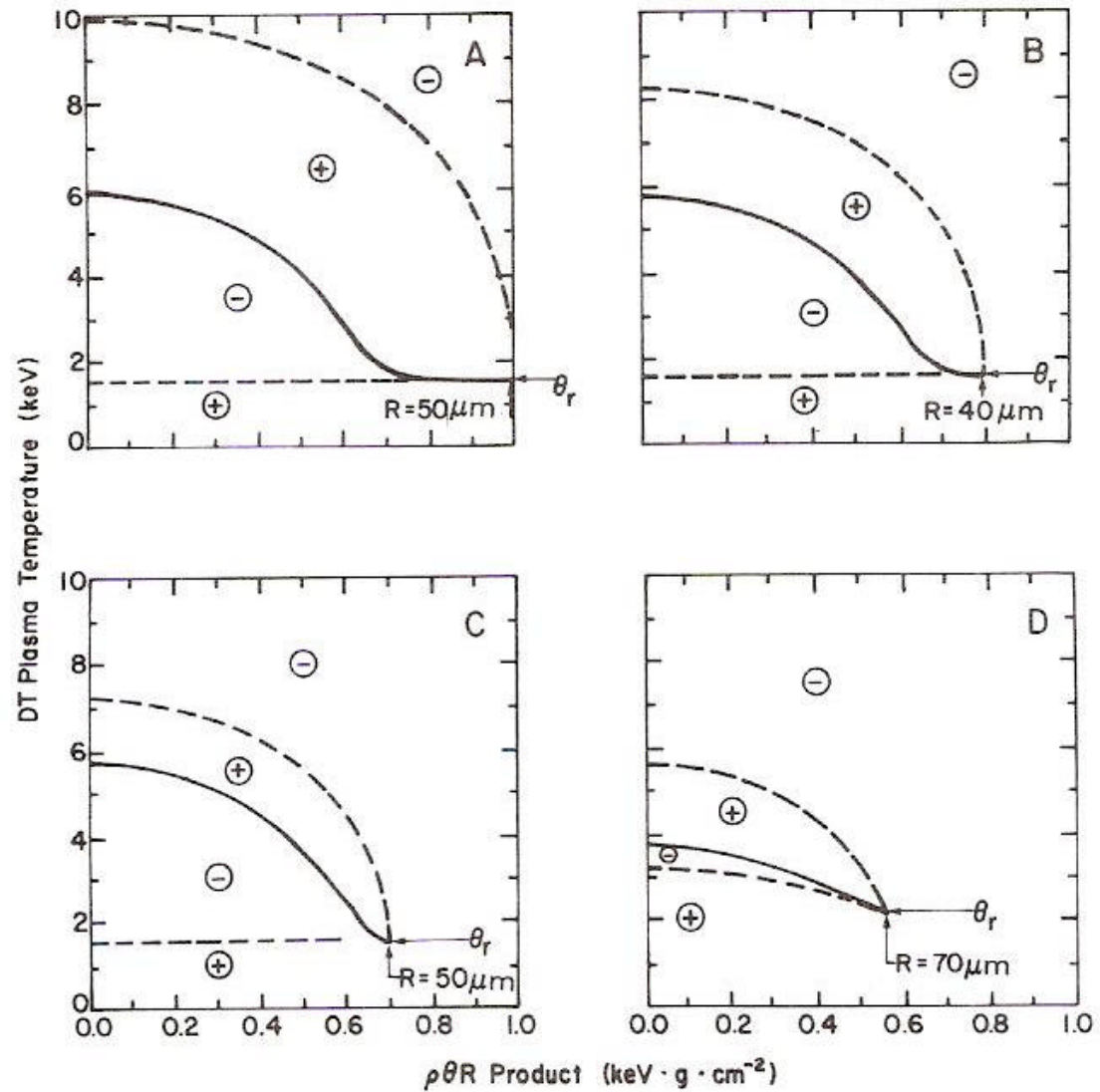
Static -- no hydro at "turn-around" (isobaric).

Radiation dominated by thermal radiation from wall.

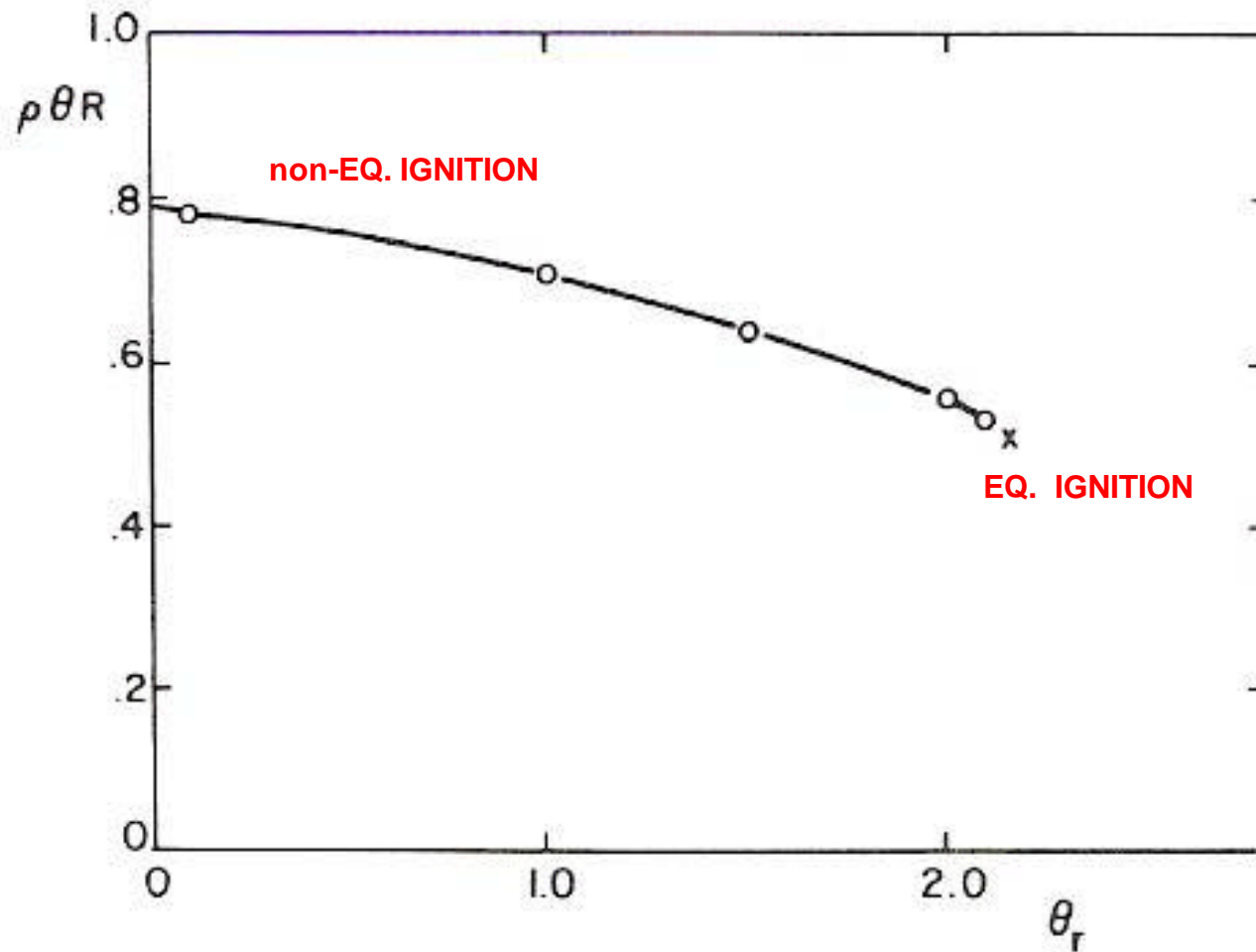
Balance between energy exchange processes.

- A given radiation temperature T_r , pressure P and plasma radius R , defines three profiles, two stable and one unstable. The **unstable** one is "**ignition critical**".

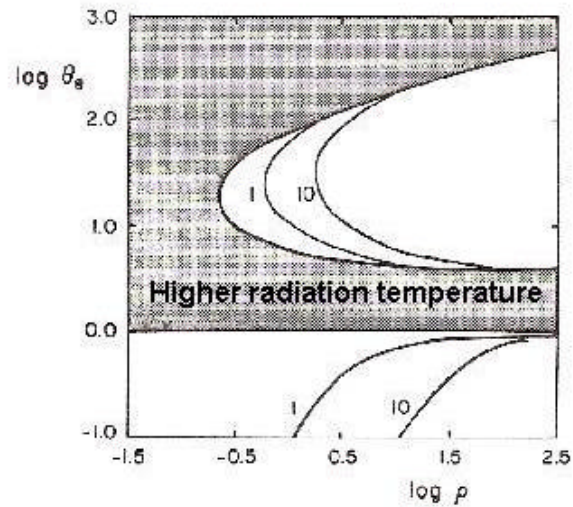
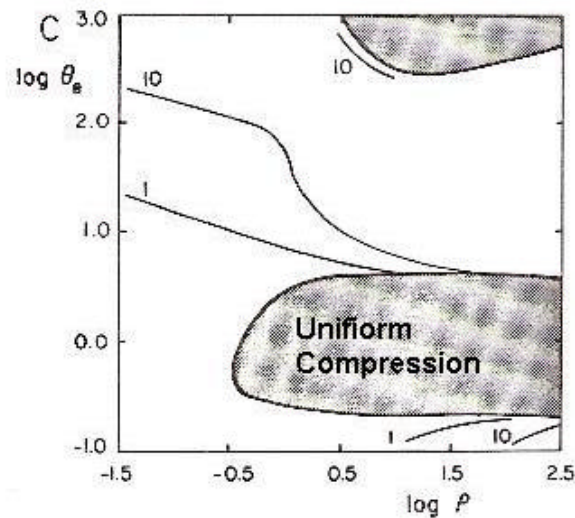
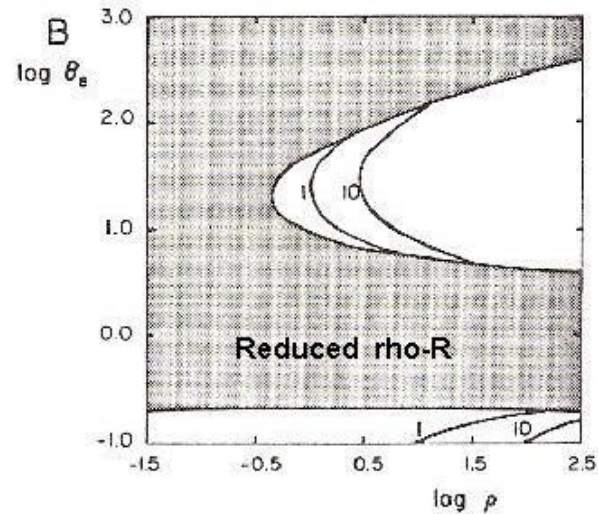
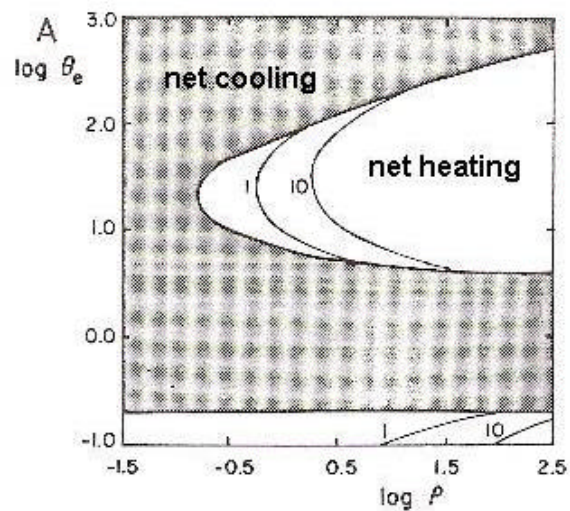
IGNITION CRITICAL PROFILES



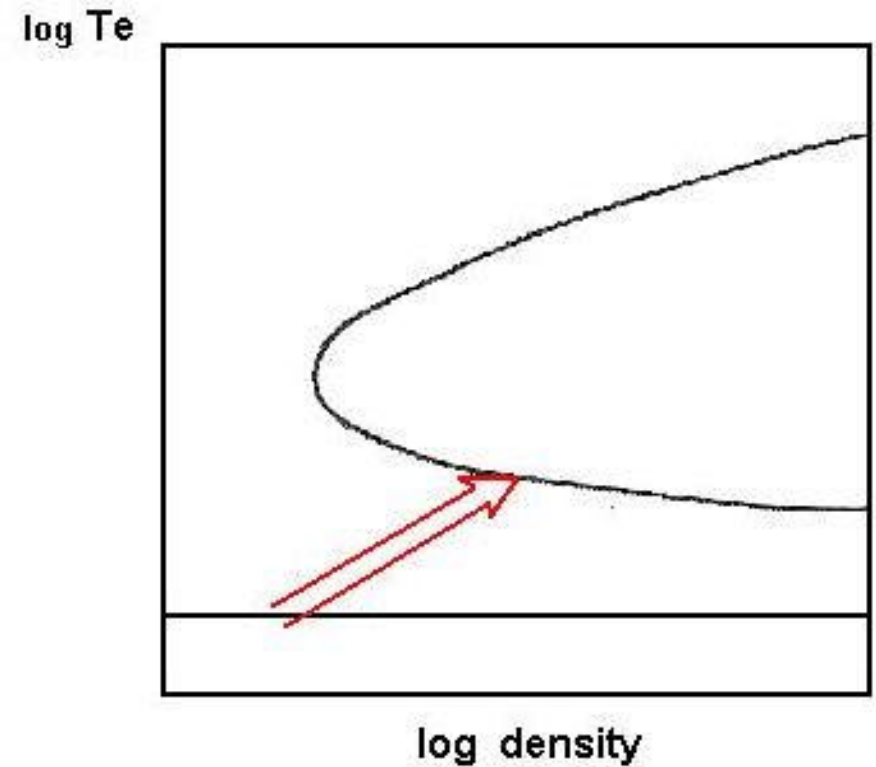
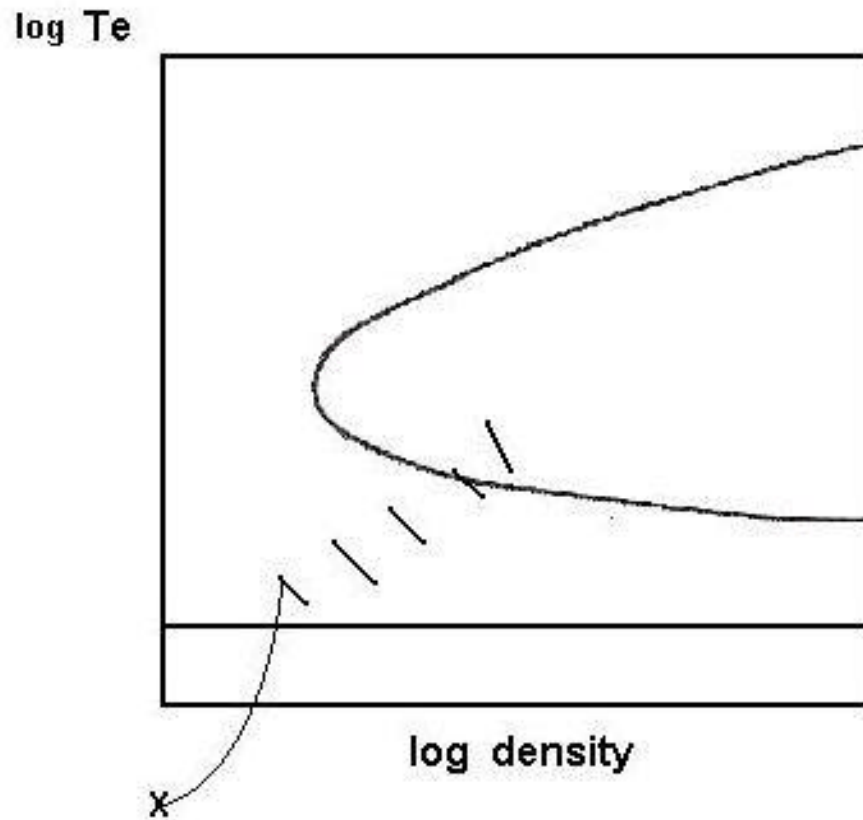
minimum PRESSURE x RADIUS (PR) requirement



PHASE PLANES -- $dT/dt = f(T,r)$

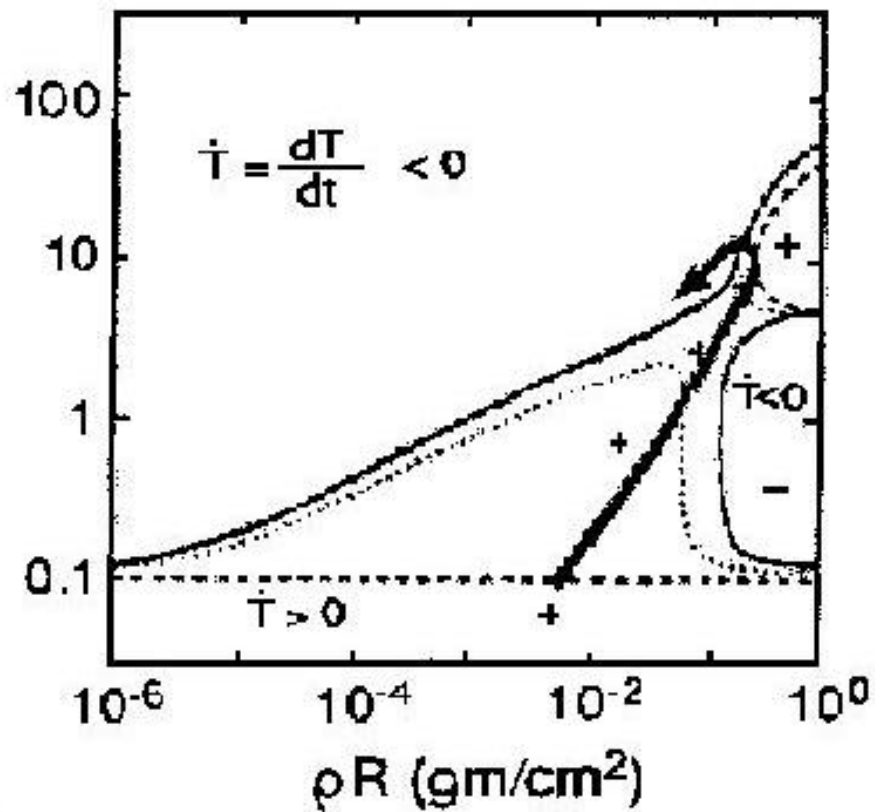
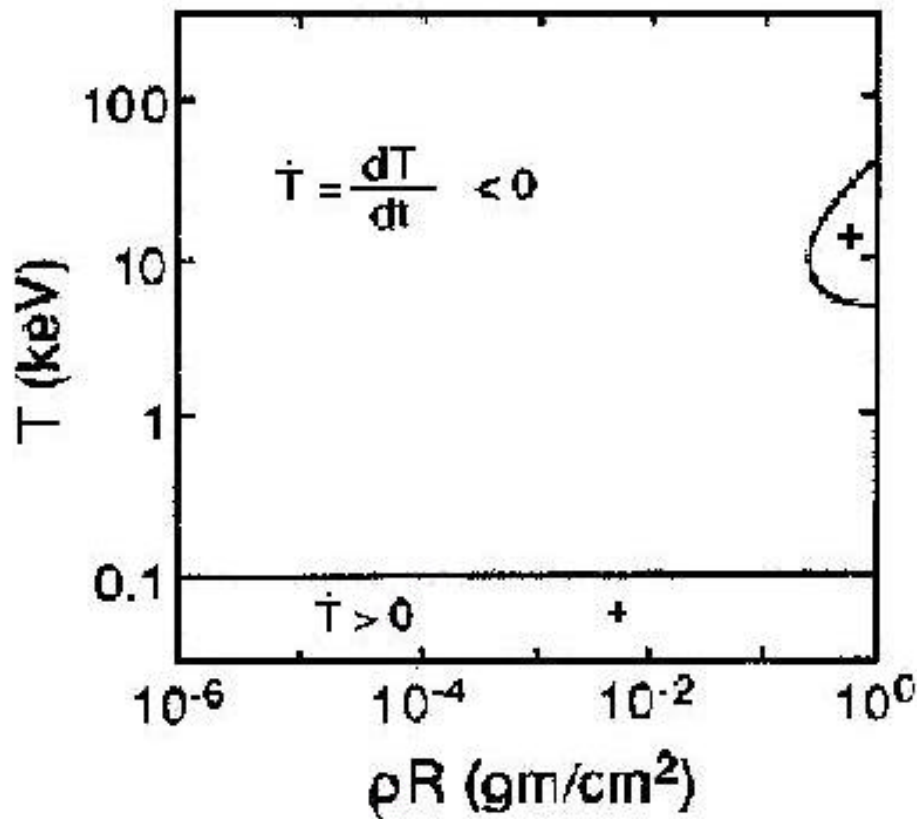


Evolving Profiles approximated by Trajectories

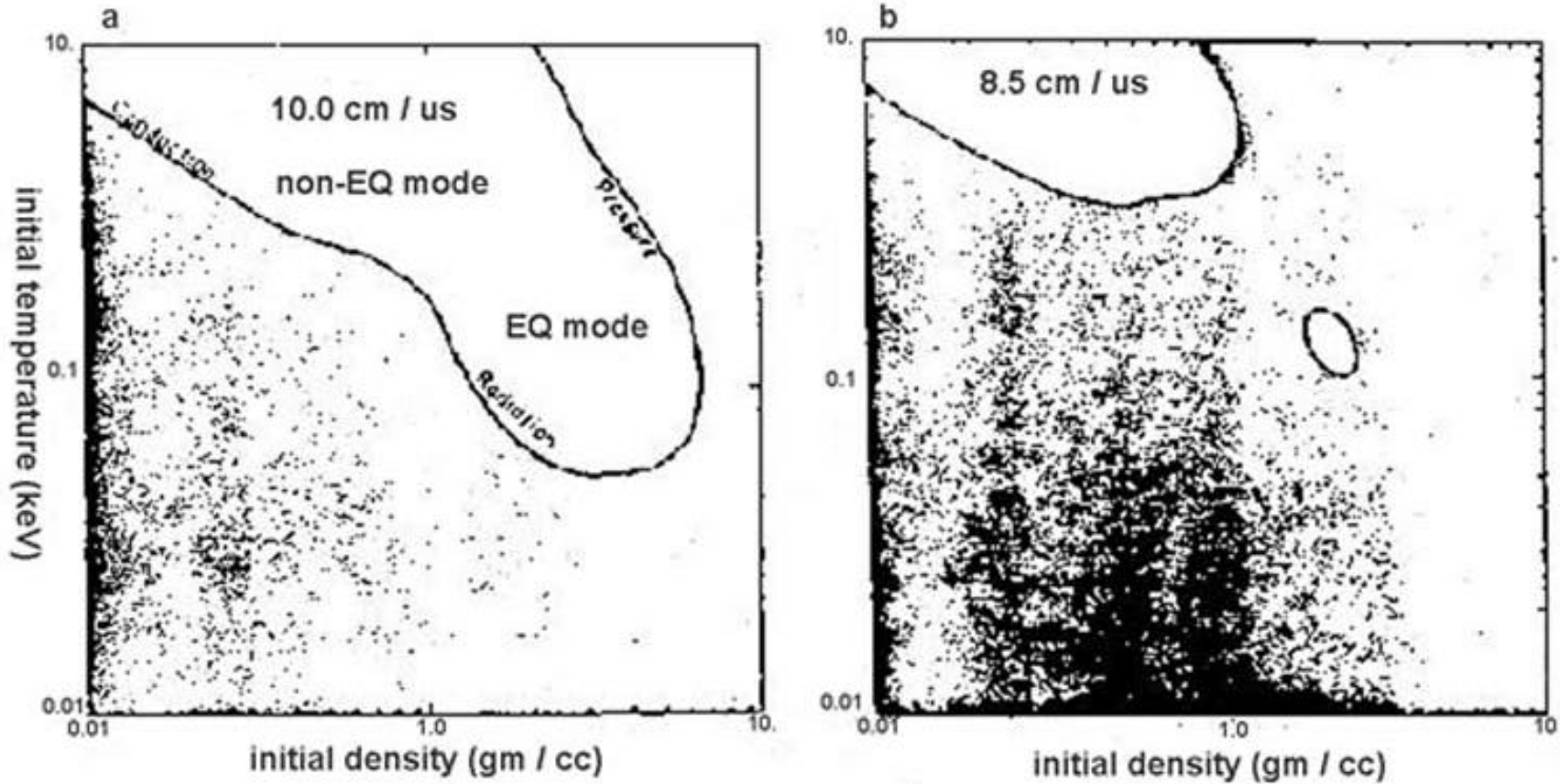


LINDL - WIDNER DIAGRAMS:

$$dT/dt \text{ or } dE/dt = f(rR, T)$$



TWO MODES OF IGNITION

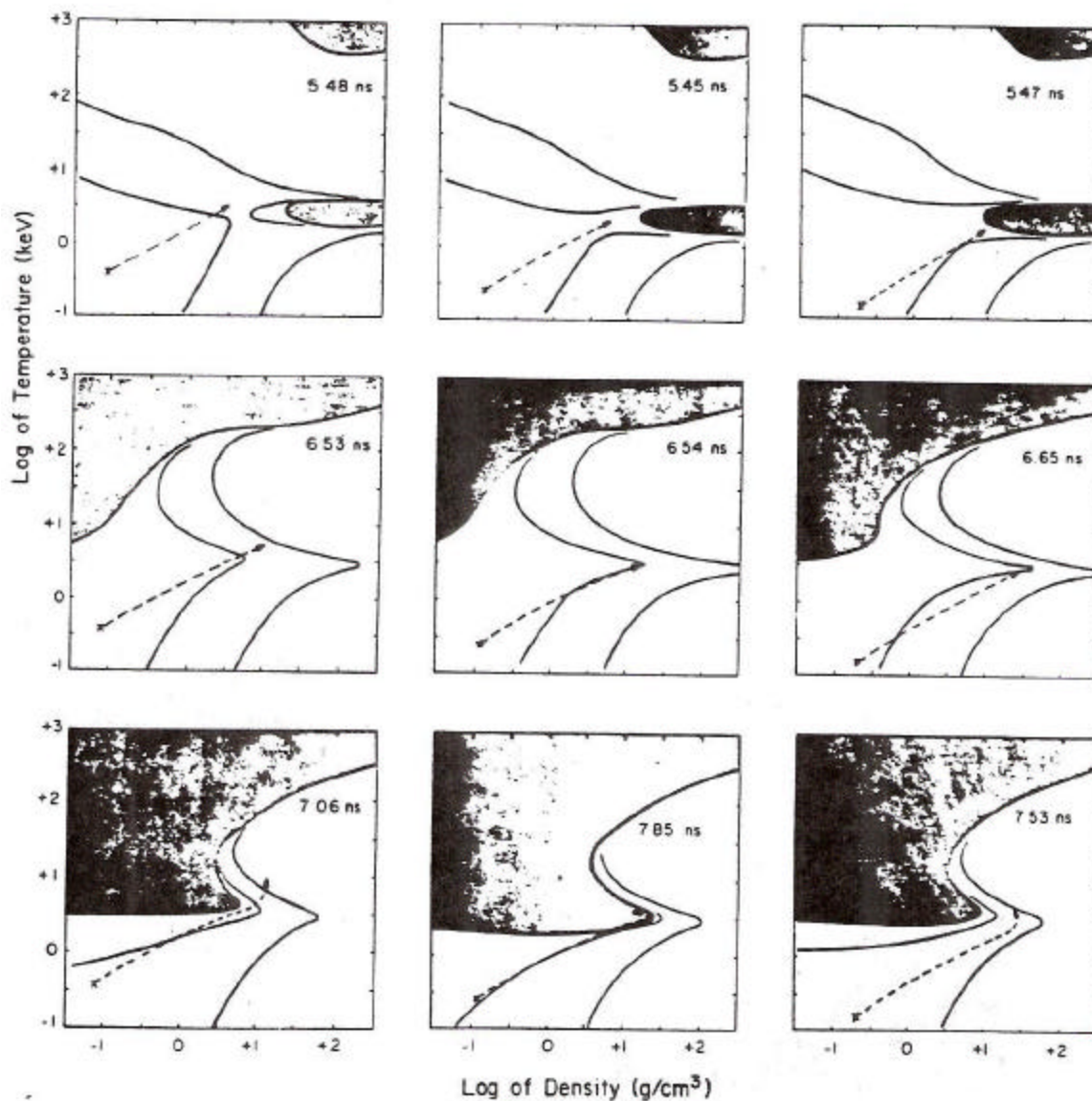


NOTE: A minimum v_0 is need to achieve ignition.

12 PARAMETER BURN CODE TRAJECTOREIS

Trajectories for 3 DT masses:
84, 126, and 220 μg .

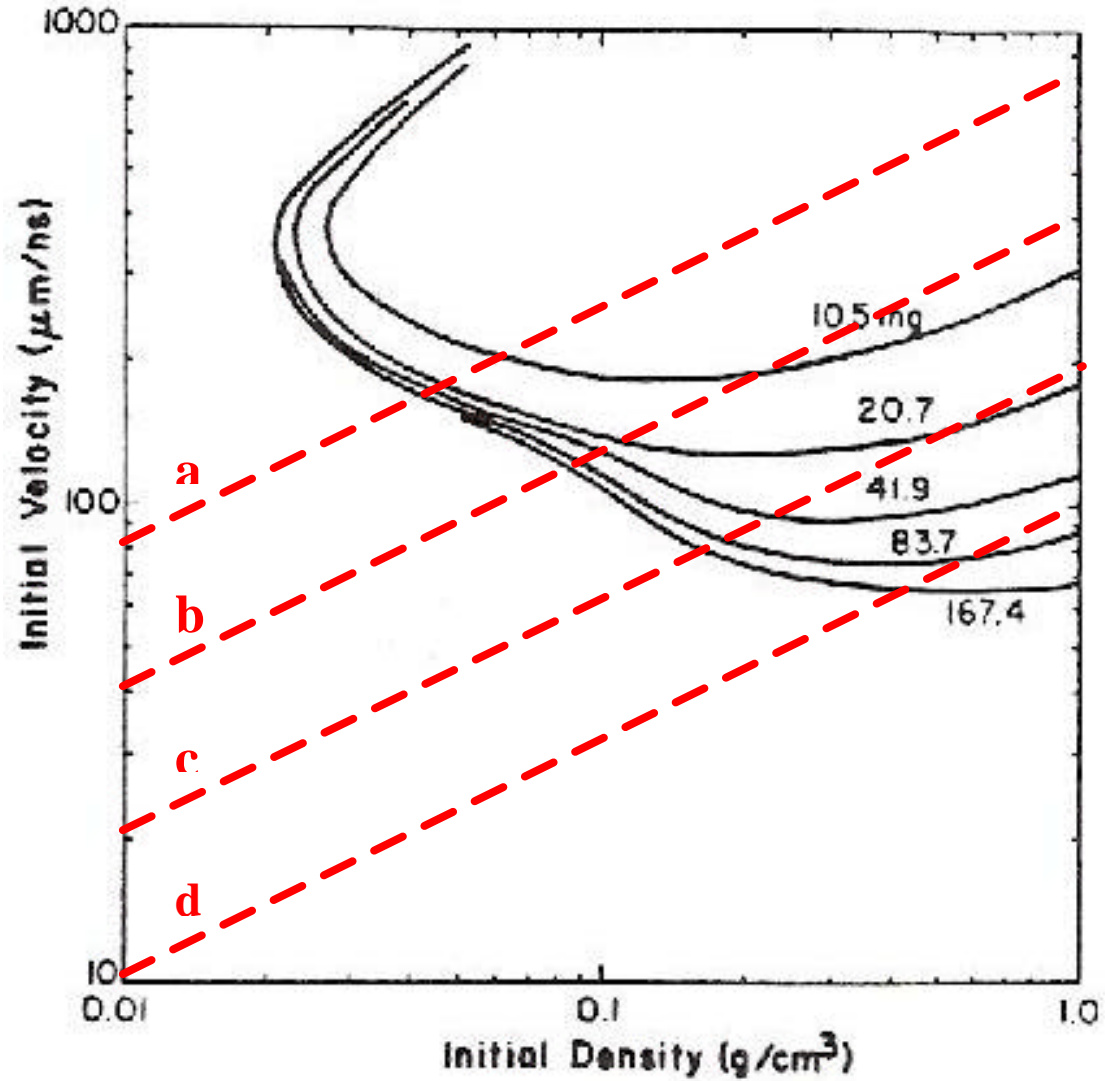
$M = 42 \text{ mg}$, $R_0 = 0.63 \text{ mm}$, $v_0 = 100 \text{ mm} / \mu\text{s}$,
 $\gamma = 2$, $e_0 = 100 \text{ kJ/g}$,
 $\kappa_0 = 300 \text{ cm}^2/\text{g}$
at 1 keV ($n=2$).
Equal dT_e/dt contours
for 0 keV/ns,
1 keV/ns, & 10 keV/ns.



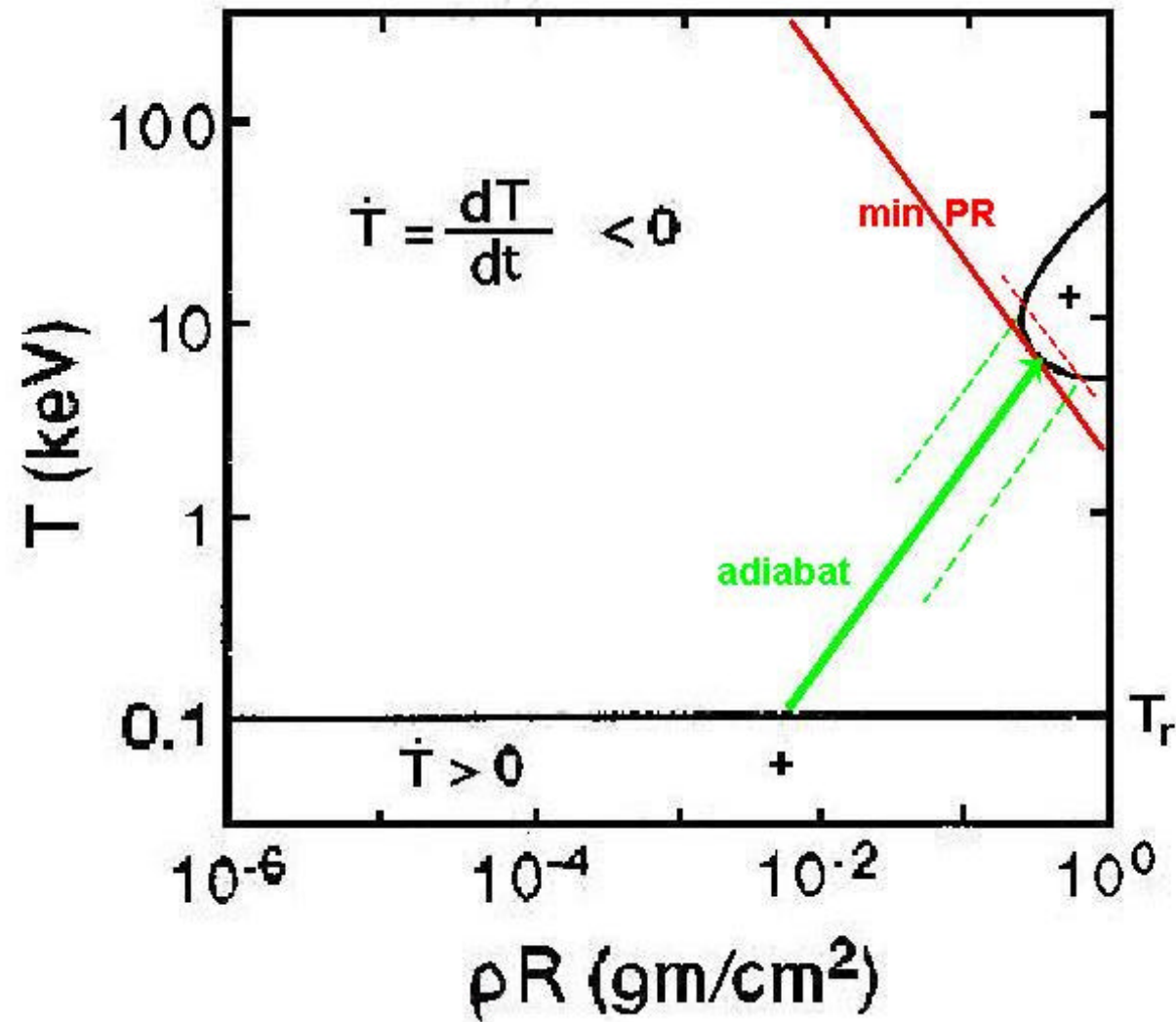
MAXIMUM GAIN (in initial condition space)

Assumes $T_o \sim v_o^2$

- a** = 2.1 / M (gm)
- b** = 8.4 / M (gm)
- c** = 33.6 / M (gm)
- d** = 134.4 / M (gm)



HOW **minimum PR** RELATES TO HYDRO



MINIMUM ENERGY FOR IGNITION *

ENERGY CONSERVATION :

INITIAL ENERGY in TARGET = ENERGY at TURN-AROUND

$$\frac{1}{2} M v_o^2 \approx E_s(P) + \frac{1}{3} 4p(PR_{\min})^3 / P^2$$

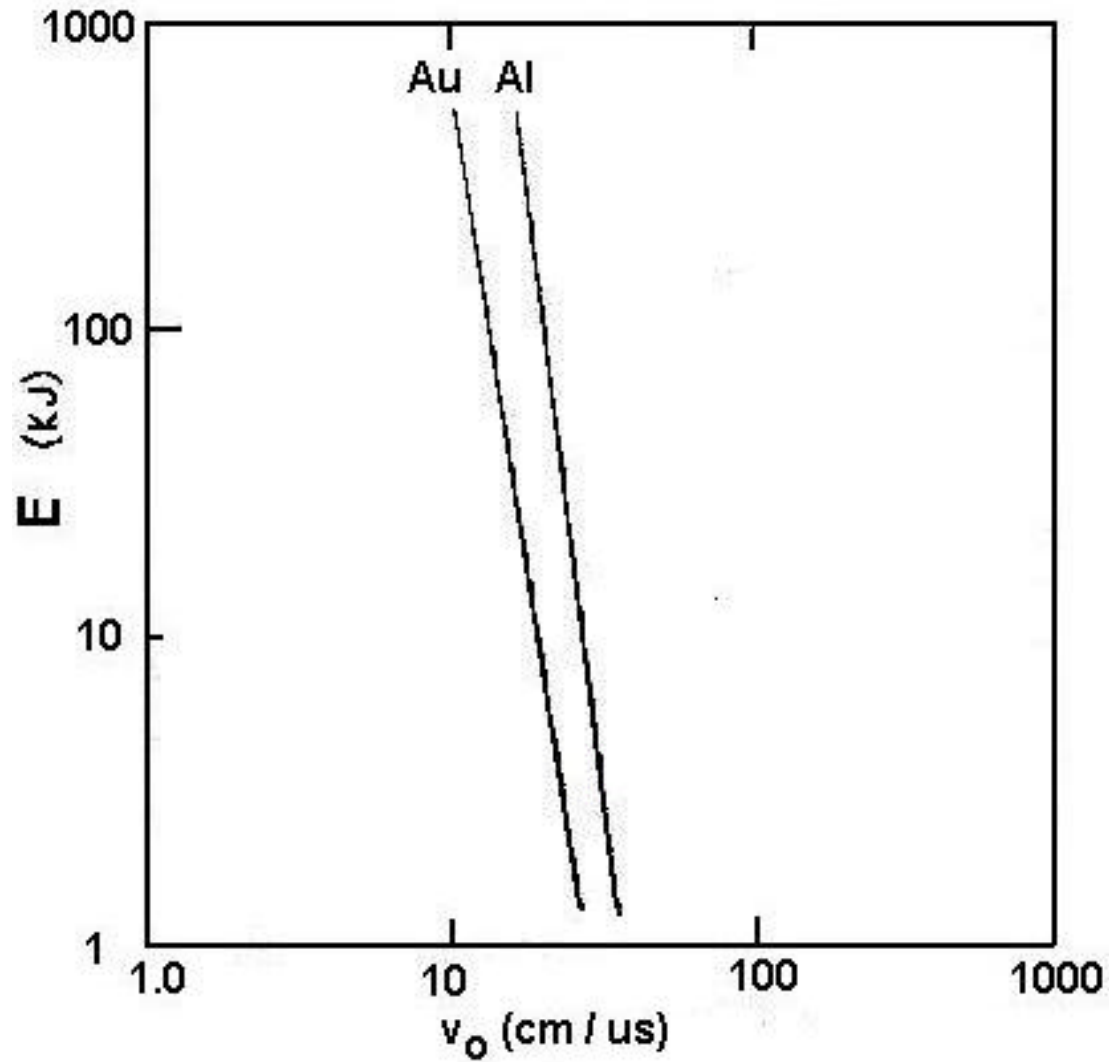
SOLVE dE/dP for optimum $P = P_{\text{opt}}$ and substitute into eq.
above to get $E = f(v_o)$

USING the COLD CURVE for EOS to get $E_s(P)$ yields least $E(v_o)$.

This analysis also yields the optimum ratio $E_s / E_{DT} \approx 4$.

* The original analysis by Colgate & Petschek (1992) optimized M rather than P .

DEPENDENCE OF MINIMUM ENERGY ON v_0



ENERGY LOSS INTO AN OPAQUE WALL *

$$L = Cr^z q x_0 \gg \left\{ \frac{32S}{3} \int_0^t \left[\int_0^{f(t)} \frac{c_v}{k} q^4 |_{t} dq \right] dt \right\}^{1/2}$$

for a power law opacity $k = k_0(q_0/q)^n$, this leads to

$$dL / dt \gg \frac{1}{2} K q^{n+5} / \left\{ \int_0^t q^{n+5} dt \right\}^{1/2} \gg \frac{1}{2} K q^{n+5} / L$$

Therefore, upon sudden exposure to an intense source of radiation, the initial loss rate is very high but rapidly falls as the exposure continues.

E_{\min} analysis including energy transfer from DT to inside of shell is leads to optimization of a loss integral.

* based on the uniform flux approximation

ACCEPTANCE TIME ... (MATCHING DRIVER & TARGET)

A target with radius R requiring v_o for ignition has an acceptance time

$$Dt_a < R / v_o .$$

Since associated with v_o there is a minimum energy E_{\min} .

$$P_{\min} \gg E_{\min} / Dt_a > v_o E_{\min} / R = f(v_o, R) .$$

Likewise, $F_{\min} > P_{\min} / 4\pi R^2 > v_o E_{\min} / 4\pi R^3 ,$

This sets a minimum hohlraum temperature for a indirect drive ICF target:

$$sq^4 > v_o E_{\min} / 4\pi R^3 > 5 m_{DT} c_v v_o / 4\pi R^3 .$$

INDIRECT DRIVE TARGETS

The penetration depth $x_0 \gg \left\{ \frac{32\sigma}{3} \int_0^{\tau} \left[\int_0^{\phi(\tau)} \frac{c_v}{\kappa} \theta^4 |_{\tau} d\theta \right] d\tau \right\}^{1/2} / Cr^Z q$

limits the useful radiation temperature to a level that does not let radiation penetrate into or through the target so quickly that the deposited energy is insufficient to drive the target.

Therefore, there is probably an optimum radiation temperature, which depends on the target EOS and the opacities of certain components of the target. One would hope that the target design process finds the optimum for a particular target design, but currently the rather low hohlraum temperatures being achieved experimentally are probably far below any optimum for an ICF target.

Also, the penetration depth x_0 is important for the final stages of compression, during which the energy loss into the confining shell (the "pusher") increases the share of the implosion energy going into compressing the shell itself. This steals some energy which would otherwise go into raising the temperature in the DT.

INSTABILITIES

There are a wealth of potential sources of instabilities in small fusion targets. These range from target imperfections as seeds for Rayleigh-Taylor instabilities and Helmholtz instabilities to shocks triggering Richtmyer-Meshkov instabilities to material inhomogeneities. Modeling these sources and their consequences in target simulations continues to be a challenge.

One reality that seems to be missed is that different types of instabilities can have different impacts on different targets, or even the same target with a different drive or DT mass.

Next, we will provide an example to illustrate this fact using a simple model in a simplified burn code.

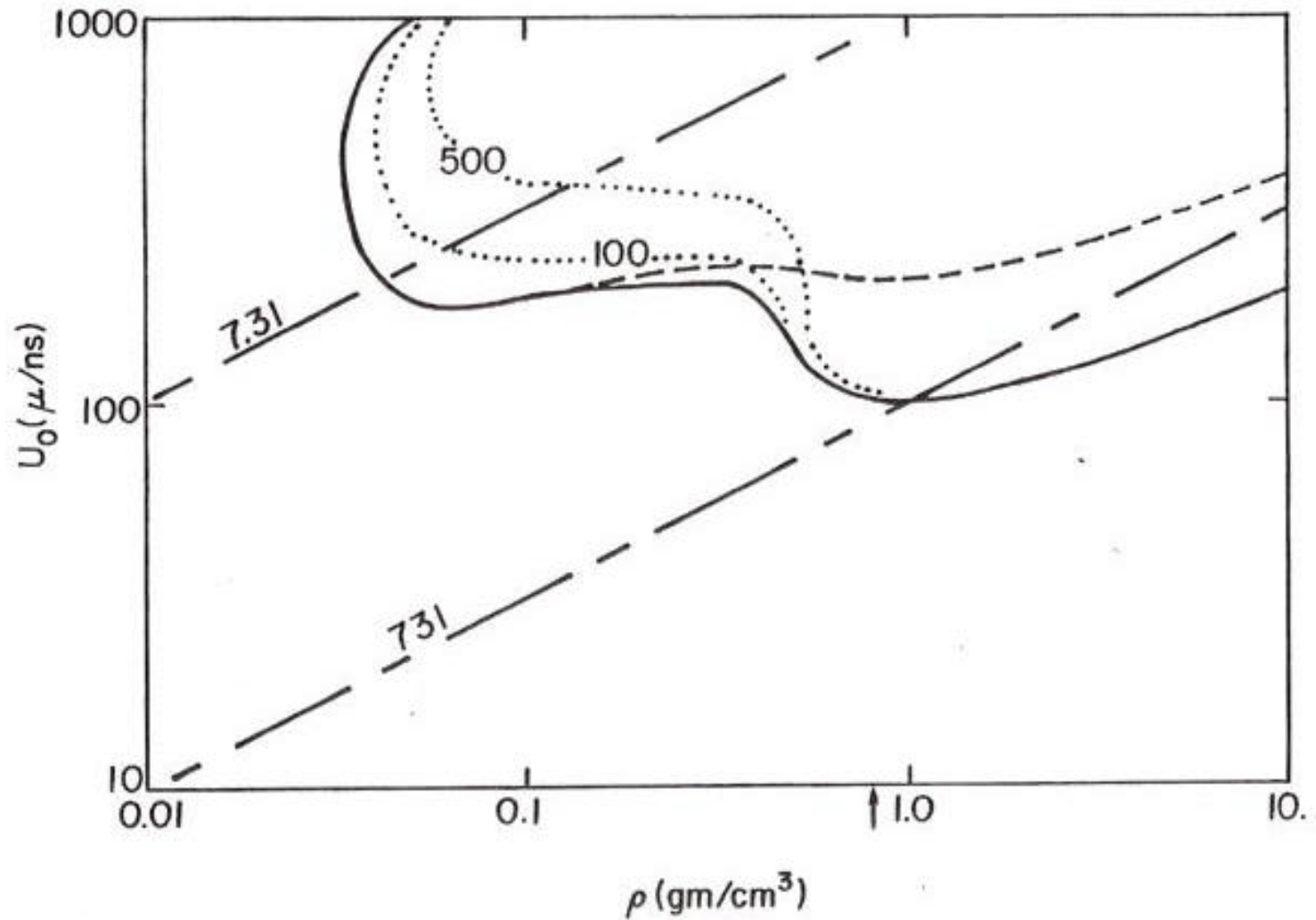
SUPPRESSION OF DT IGNITION BY INSTABILITIES

Some years ago we inserted the Plesset equation for instability growth in a converging incompressible fluid into our 12-parameter burn code to create a 21-parameter burn code. We modeled the bubbles and spikes in the R-T growth as pyramids with an amplitude dictated by the Plesset equation.

As an example we show the initial condition space (r_0, v_0) for an opaque target with an initial perturbation of 3.15 μm and $n = 10$. When the interface at r is R-T stable, the amplitude of the instabilities oscillate like waves on an ocean. The added area provides an enlarged sink for the radiation from the DT plasma. Depending on the phase of the oscillations near turn-around, there may be more or less loss from the DT.

We also modeled shock ejecta by adding an impurity at $t = 0$. The impacts of these two aspects of instabilities are compared in the next slide.

IMPACTS OF TWO TYPES OF INSTABILITIES



MAGNETIC INSULATION OF THE FUSION FUEL

The minimum areal density $\langle rR \rangle$ and therefore the minimum PR for ICF is set by two dominant processes, electron thermal conduction and charged fusion product transport. Both the escape of heat through thermal conduction and the escape of the 3.5 MeV DT alphas can be reduced by imposing a strong magnetic field. Then the field times radius parameter BR augments the rR needed for fusion ignition.

Calculations and modeling we have done so far indicate that within the MTF regime both the PR and v_0 needed for fusion ignition can be drastically reduced. However, the energy required depends on heating the DT mass to above the ideal ignition temperature, thereby setting a minimum energy for ignition.

For sufficiently high density the suppression of electron thermal conduction should be classical (not Bohm).

SELF-HEATING IN A MAGNETIZED PLASMA

- **There are two important aspects to be considered in calculation of the charged fusion product interaction with a magnetized plasma:**
 - 1) The increased charged particle path length due to the bending of the path by the magnetic field, and**
 - 2) The effect of the magnetic field on the stopping power (dE/dx) of the plasma.**
- **It is important to sort out how these two aspects of interaction of an energetic charged particle with a magnetized plasma impact MTF.**

STOPPING POWER

- **Early calculations of the slowing of an energetic charged particle by an unmagnetized plasma were based on Rutherford scattering by both plasma electrons and ions. [e.g., Evans, LA-5448-MS (1973)].**
- **More recently several authors have used a dielectric theory which considers the distortion of the Debye sphere around an energetic charged particle. One crucial parameter is the ratio of the Debye length and the electron Larmor (or gyro-) radius, which is the same as the ratio of the electron cyclotron radius to the plasma frequency ω_b/ω_p .**
- **The most complete treatment is that of Nersisyan, et al. [Phys. Rev, 61 (2000) 7022], who considered the case of an anisotropic plasma, which can also be reduced to the isotropic case.**

STOPPING IN AN ISOTROPIC PLASMA

- It is not possible to maintain a significantly anisotropic electron distribution function in fusion plasma because the electron relaxation rate outstrips the fusion heating rate.
- Nersisyan, et al., derived general expressions for weak and strong magnetic fields and for low and high energetic particle velocities:

$$S = dE/dx = S_0 + h^2 S_1,$$

where $h = w_b/w_p$, S_0 is the stopping power for no field, and $h^2 S_1$ provides a correction for the field in the weak approximation.

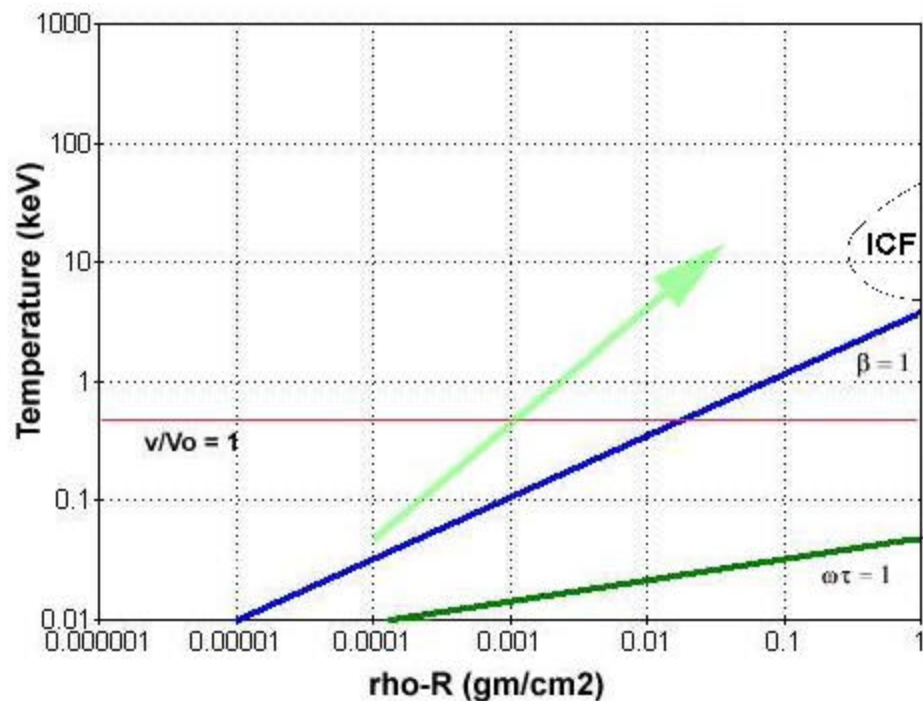
- Also, MTF falls into the weak field category, i.e., $w_b/w_p < 1$, and upon evaluation one finds

$$(h^2 S_1) / S_0 \ll 1$$

PLASMA PARAMETERS

- For MTF we wish to suppress thermal conduction, so that we want $w_e t_e \gg 1$.
- Also, we want to suppress plasma instabilities by operating with $b > 1$.
- When the field is frozen to the plasma, as a target plasma undergoes a 3-D compression, $B \sim r^{2/3}$, so that $B \sim (rR)$.
- For an adiabatic compression $T \sim r^{2/3}$, so that also $T \sim (rR)$.
- If one chooses initial values for the warm target plasma, then the lines of constant $w_e t_e$ and b can be drawn in the (rR, T) plane, where the region for fusion ignition burn of DT in an ICF target occupies position on the upper right side.

MTF PARAMETER SPACE



- Green arrow represents adiabatic compression.
- ICF regime in upper right, and extends to higher rR .
- Drawn for $r_0 = 10^{-4}$ gm/cc, $T_0 = 50$ eV, $B_0 = 30$ tesla.
- The above (rR, T) plane is called a Lindl-Widner diagram.

DT alpha TRANSPORT IN THE MTF REGIME

- Stopping power dE/dx essentially unchanged by field within the MTF parameter space.
- Field bends charged particle path, and if the Larmor radius r_L can be made small enough, it can significantly increase the particle's path length through the plasma. For a significant increase, it is necessary to have:

$$r_L = mV/qB < R, \quad \dots \quad r_L B = 0.296 \text{ MGcm (Tm)}$$

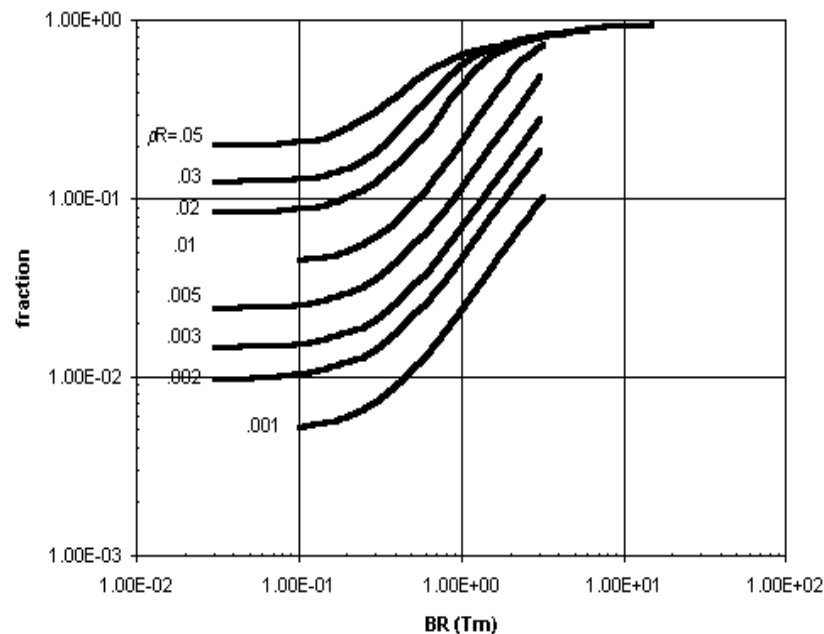
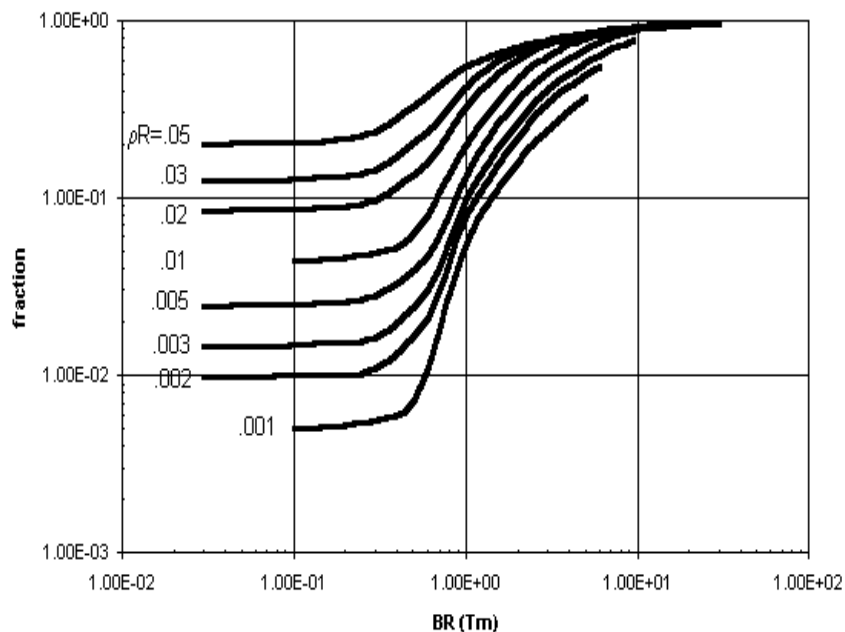
where mV is the particle's momentum, q is its charge, and R is the target plasma radius.

- For a closed field (e.g., B_q), the particle will spiral as it moves in the B_q direction. Due to drift caused by the centrifugal force and magnetic field gradient, the spiraling particle will travel in a helical path around the direction of the z-axis until escape.

NUMERICAL CALCULATIONS

- **We have done numerous calculations using a particle tracking code to quantify the percent of DT alpha energy deposited within a target plasma for ranges of rR and BR values.**
- **The particle tracking code is efficient for low values of BR, but for high BR, the particle can spin a long time before either escaping or stopping within the plasma.**
- **High BR results are not only time consuming, but are potentially less accurate due to the many time steps involved.**
- **Therefore, it is desirable to check the high BR result with some analytic results, if possible.**

PARTICLE TRACKING RESULTS

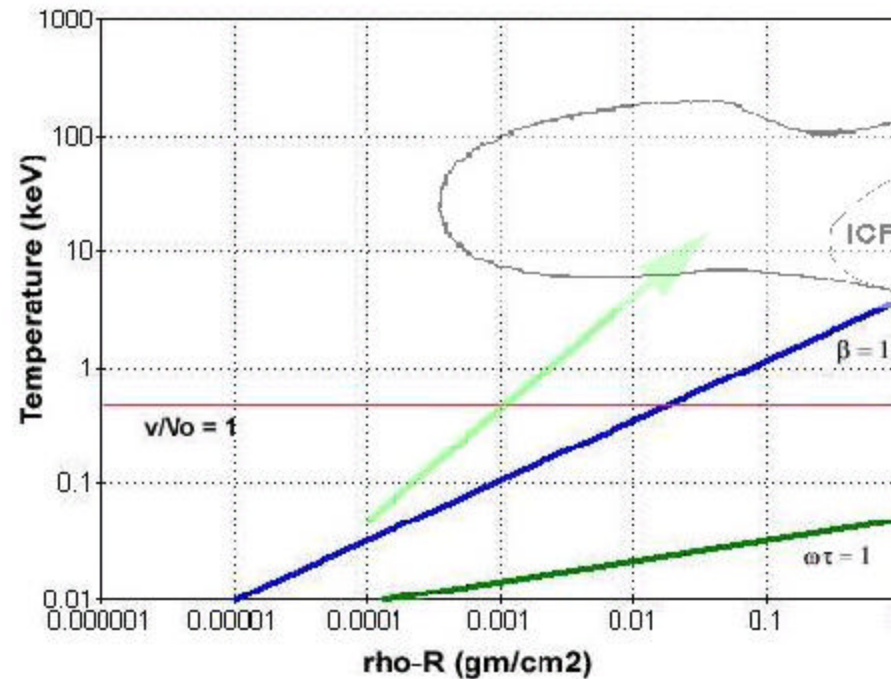


- The results above are for uniform B_q .
- These results are for B_q due to an on-axis current.
- The changes due to the field gradient are clearly visible in the second set of curves.

SPECIAL CASES

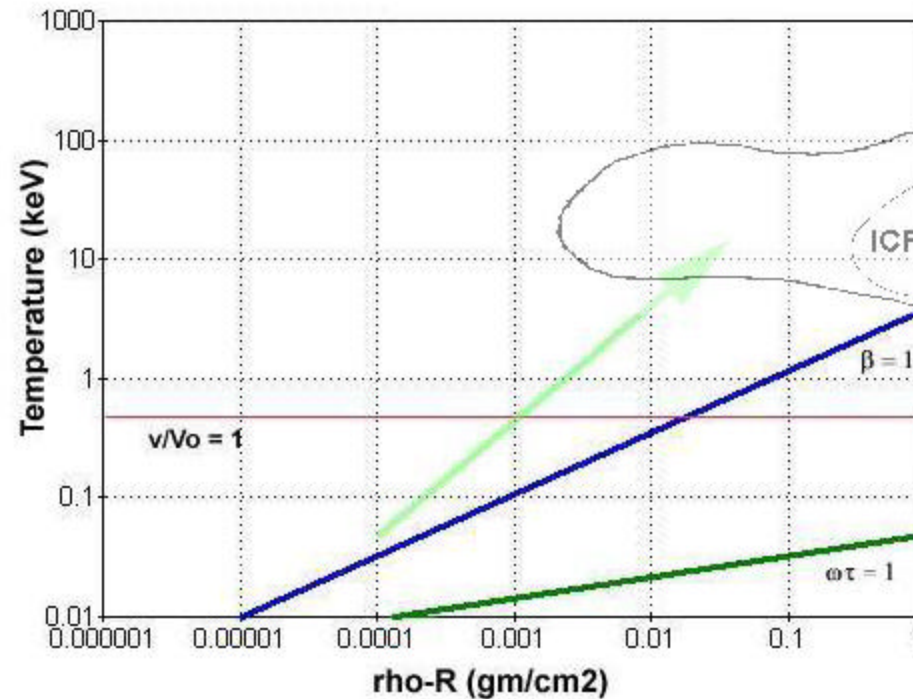
- **For the cases of uniform B_q and B_q due to an on-axis current, it is possible to get analytic results for different parts of the problem.**
- **This is because for these two cases, the driving force for the drift and strength of the field, which determines gyro-radius conspire to make the range in the drift direction constant for a given angle that the particle makes with the magnetic field.**
- **We continue to work in this direction. It is hoped that this will result in more reliable scaling laws than currently employed.**
- **Using an empirical fit to the numerical calculations, it is possible to construct Lindl-Widner diagrams showing the region where fusion ignition appears to be possible for MTF.**

LINDL-WIDNER DIAGRAM FOR UNIFORM B_q



- The fusion region in this Lindl-Widner diagram is based on an empirical fit to the particle tracing results.
- Notice the huge potential reduction in the ρR required for fusion ignition.

LINDL-WIDNER DIAGRAM FOR B_q WITH GRADIENT



- The added drift due to a strong field gradient diminishes the size of the fusion ignition region.
- Nevertheless, ignition can potentially occur at only a hundredth of the rR required for ICF.

MINIMUM ENERGY FOR MTF

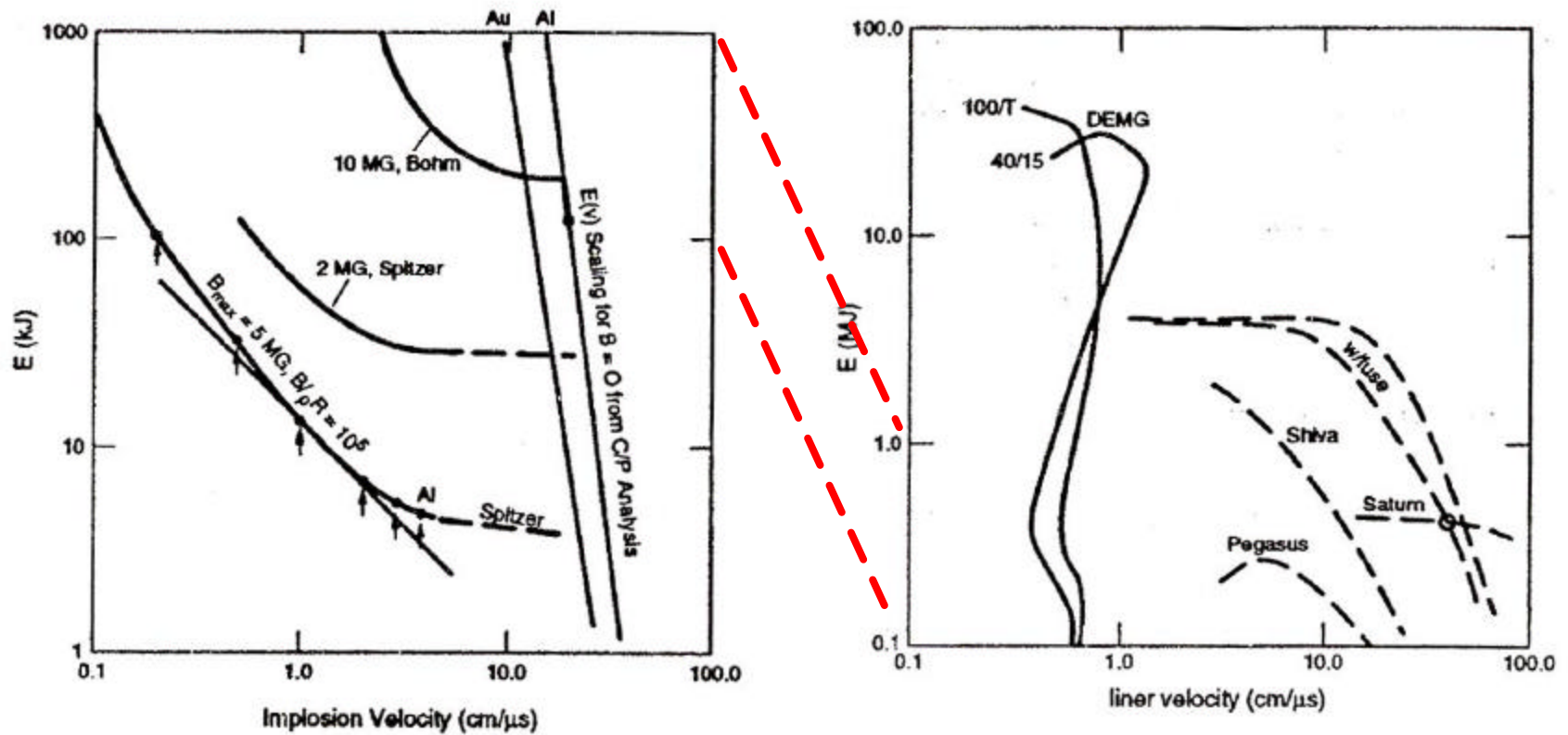
The parameter $(PR)_{\min}$ is a constant in the Colgate/Petschek (C/P) analysis of how the minimum energy for ignition depends on the implosion velocity v_0 . Constant $(PR)_{\min}$ is a very good approximation for ICF, but not for MTF. It is possible to revise the C/P analysis to include the dependence of $(PR)_{\min}$ on mass. One gets

$$E = \frac{v^2}{v^2 - 2e_0(\langle PR \rangle^{3/2} / \sqrt{mc_v T / 2\pi})^a} mc_v T .$$

where $\langle PR \rangle = (PR)_{\min}$. This equation can be used to derive the dependence of the energy needed for ignition on the compression velocity v .

SCALING OF E_{\min} FOR ICF AND MTF

Drivers are readily available for MTF:



Note the difference in energy scales (kJ vs MJ).

PROSPECTS FOR MTF (and Fusion in General)

While magnetized target fusion appears to have some advantages over other inertial fusion approaches, it also has some complications.

Creating a magnetized target plasma: The chief advantage of MTF (as compared to ICF) is attributable to its rather low compression rate for getting to fusion ignition. This means that (unlike ICF), there is insufficient shock heating of the DT to set it on a proper adiabat. Also, it is necessary to start with a magnetized plasma (i.e., with an embedded magnetic field), which requires heating the plasma to over 50-100 eV, so that its conductivity is high enough to keep the field in the plasma. So far, creating the target plasma has been the major focus for MTF. The first MTF experiment was very low level, but nevertheless successful. There is no obvious barrier to overcome in producing a target plasma, but it does require a dedicated effort.

PROSPECTS (cont'd)

The second complication is common to all target-based approaches to fusion. If targets must be manufactured, then their cost must figure into the economics for a fusion reactor based on that scheme. The stand-off drive scheme proposed by Thio appears to have the potential to overcome the target cost problem. Also, it may lead to other fusion applications such as fusion for space propulsion.

PROSPECTS (cont'd)

One of the major barriers to the development of fusion for energy (or any other use) is financing the necessary research. There are lots of ideas that all deserve some degree of respect, but they all compete for the same pot of money. This is because fusion is considered to be big science with a need for deep pockets. This is so for the extreme approaches, but probably not for some others. In fact, various deserving low-level projects are under way, and as a community we should give them all the support we can.

MAGNETIZED TARGET FUSION

- **A strong magnetic field can significantly alter the stopping power of a plasma, but in the MTF regime it does not. HOWEVER, it does turn the charged particles and thereby increases the lengths of their paths through the plasma.**
- **An analytic solution for the DT alpha energy is desired and seems possible for two special cases, but in the interim empirical fits to numerical results have been used to map out the parameter space for MTF.**
- **MTF continues to look attractive as an alternate path to fusion energy, but more work is needed in order to confidently assess its real potential. It appears that the necessary drivers are readily available.**

COMMENTS and DISCUSSION:

Current NIF target designs - ... fast ignition

Prospects for conventional ICF as a basis for IFE

Prospects for MTF (for IFE & in general)

The Fusion Landscape

How to get there from here ? A road map ?

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