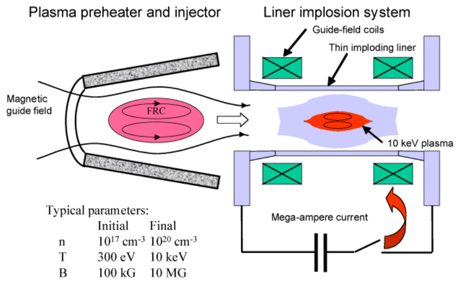
THE PARAMETER SPACE OF MAGNETIZED TARGETS: A SIMPLE IMPLOSION MODEL

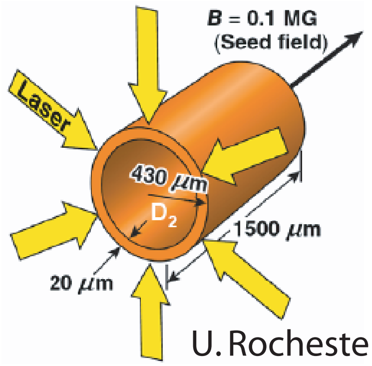
Irvin R. Lindemuth
Adjunct Professor
(sometimes part-time research faculty)
Physics Department
University of Nevada, Reno NV



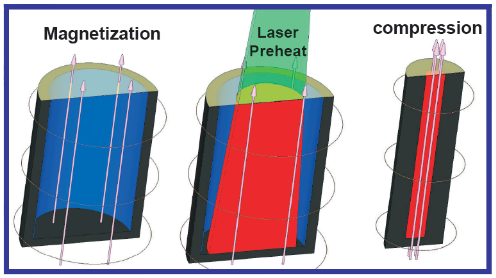
Typical parameters:

	Initial	Final
n	10^{17} cm^{-3}	10^{20} cm^{-3}
T	300 eV	10 keV
B	100 kG	10 MG

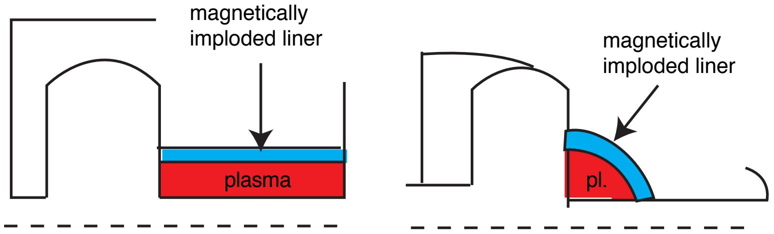
AFRL/LANL/UNR



U. Rochester



SNL

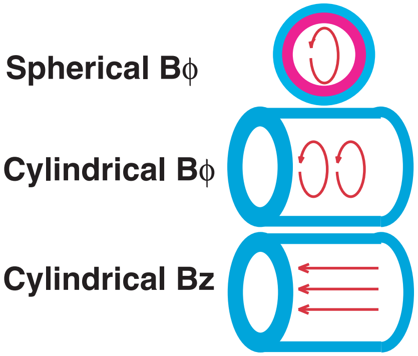


Russian MAGO

Prepared for presentation at ARPA-E workshop on "Drivers for Low-cost Development Towards Economical Fusion Power," Berkeley CA, October 29-30, 2013.

A simple target implosion model to determine energy, velocity and initial plasma requirements for magnetized targets

- "The optimal velocity...is the primary determinant of the minimum size driver for ignition..."--J. D. Lindl, UCRL-119015, 11/95.



- Solve set of coupled ordinary differential equations to:
  - --rapidly scan the potential parameter space
  - --provide a starting point for detailed investigations
  - --increase confidence in large-scale computations
  - --help build an "intuition" about the "trade-offs"
    - driver complexity <--> initial plasma formation
    - initial temperature <--> convergence
  - --give insight into the many competing processes
  - --provide a learning tool

- The model includes:

  Hydrodynamic processes   Magnetic pressure, diffusion, Ohmic heating
  Magnetic reduction of ion, electron thermal conductivity
  Magnetic enhancement of alpha deposition   Lots of caveats

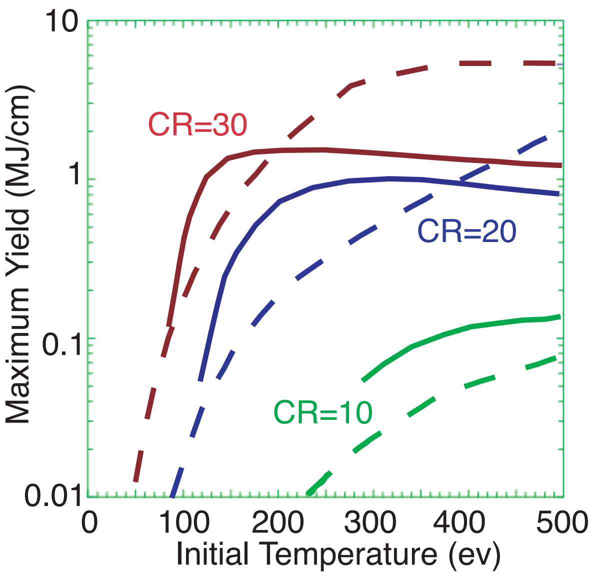
Spheres: Lindemuth & Kirkpatrick, "The parameter space for magnetized fuel targets in inertial confinement fusion," Nuclear Fusion 23, p. 263 (1983); "The promise of magnetized fuel: high gain in inertial confinement fusion," Fusion Technology 20, p. 829 (1991).

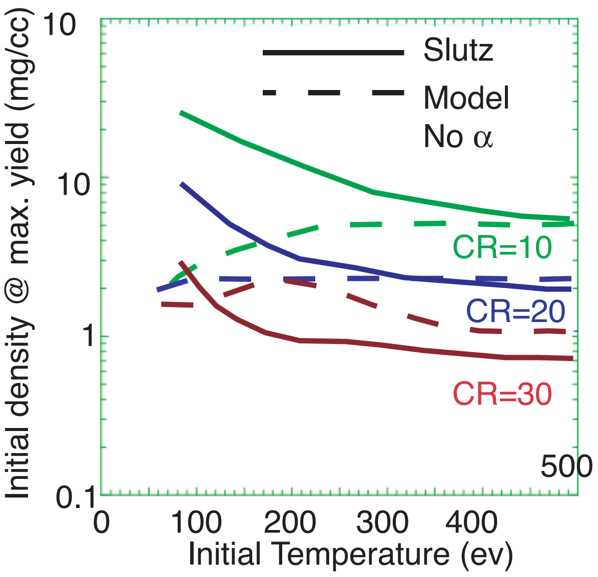
FRC: Armstrong & Morgan, "Liner compression of magnetically-confined FRC plasmas," Proc. MG-IV Conf. (1986).

Intended to give "ballpark" values, the model gives results similar to the MagLIF calculations of Slutz (POP 17, 056303, 2010).

Initial parameters same as Slutz: 250 eV, 3 mg/cc, 30 T, R=2.7 mm, L=5 mm
Other required initial parameters: 600 kJ, 5 cm/μs

	Slutz	Full model	Turn off endloss	+ turn off Nerst	+ turn off B α enhancement	+turn off all α deposition	Full model B = 0
Yield (kJ)	500	560	647	1270	561	485	10
convergence	25	24.8	23.9	21.2	23.3	24.1	50
Max T_i (kev)	8	4.4	4.6	5.9	4.5	4.3	1.7
Max B (MG)	130	138	128	133	160	171	--
Max ρR (g/cm²)	0.01	0.020	0.019	0.017	0.019	0.020	0.04
Max $R/R_{\alpha B}$	5.2(>3)	5.4	5.3	6.3	6.8	7.1	--

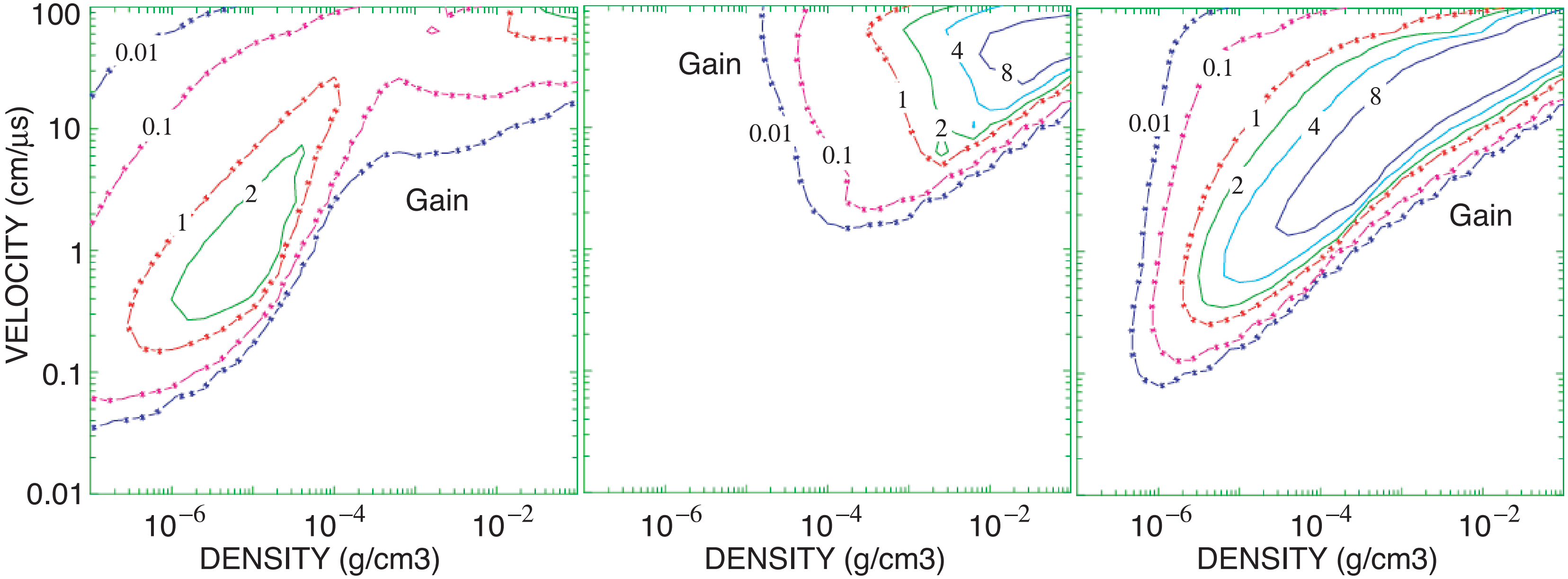




- **The model cannot compute Slutz cold boundary layers; such layers may be unstable (Lindemuth et al., "Unstable behavior of hot, magnetized plasma with a cold wall," Phys. Flu. 21, p. 1723 (1978))**

The model allows a rapid survey of the (v_o-ρ_o) parameter space in which magnetized targets are apt to work.

- **An example: E = 1 MJ, M = 0.2 mg, T = 500 eV, B = 300 kG, Ro/R < 30 (no α, no Nernst).**



Cylindrical, Bϕ, L=2/3 R_o **Cylindrical, Bz, L=2/3 R_o** **Spherical, Bϕ**

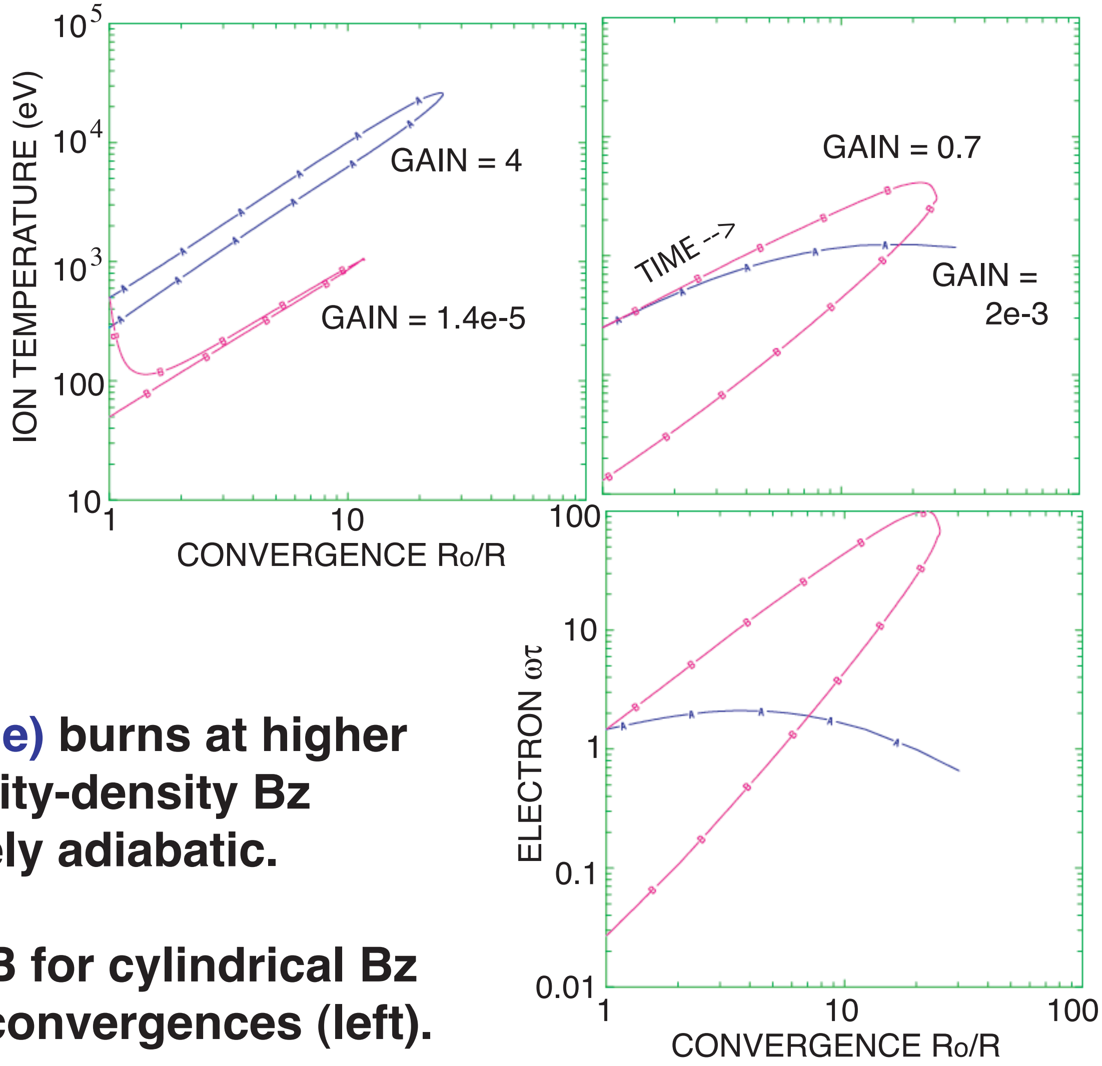
- **Bz cylindrical geometries are more apt to work at the higher end of the density spectrum, whereas Bϕ cylindrical geometries are more apt to work at the lower end.**

Cylindrical Bz targets do not work at low velocity-density because of end losses (unless very long), whereas cylindrical Bϕ targets do not work at high velocity-density because ωτ increases too slowly.

- **Two examples:**

	left	right
E =	1	0.6 MJ
v =	1	5 cm/μs
B =	300	300 kG
T =	500	250 eV
ρ =	0.01	3 mg/cm3
Ro =	18.5	2.7 mm
L =	18.5	5 mm

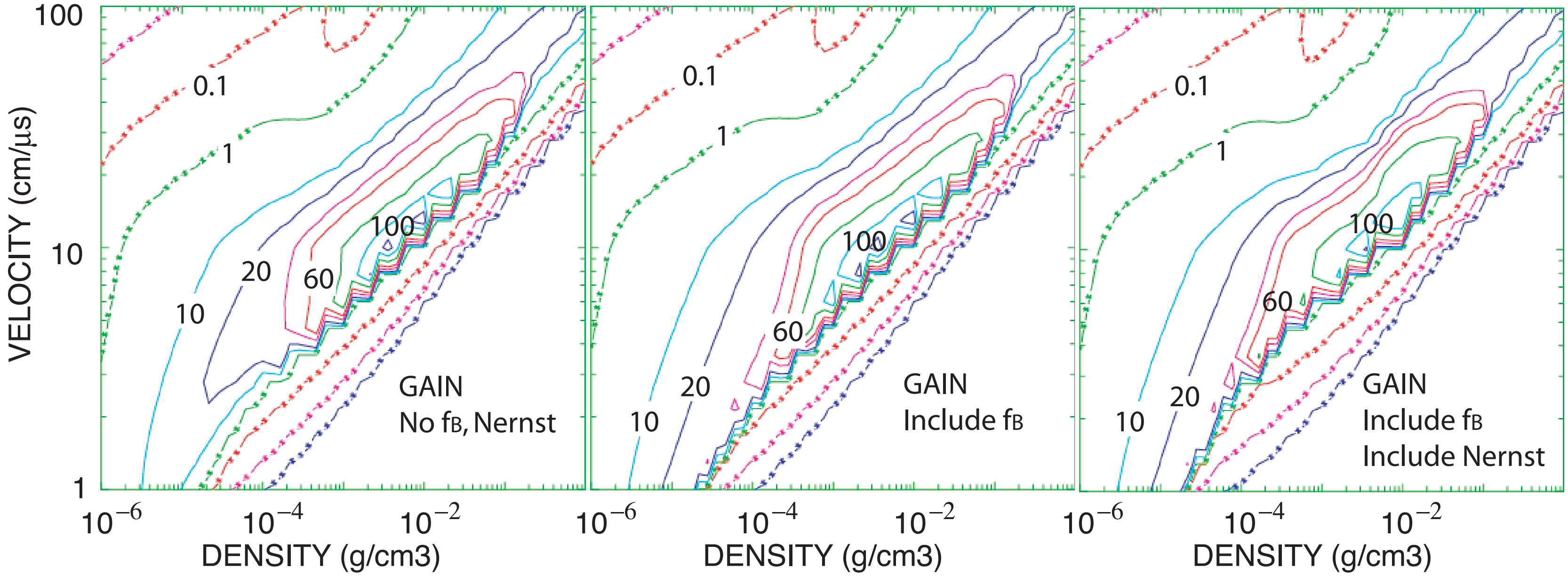
(no α, Nernst)



- **Low velocity-density Bϕ (blue) burns at higher temperature than high velocity-density Bz (magenta) and is more closely adiabatic.**
- **The more-rapid increase in B for cylindrical Bz (magenta) can inhibit large convergences (left).**

With modest initial parameters, spherical hot, magnetized “central ignitor” can ignite “cold” fuel, obtain gain > 100 at the energy, velocity of existing drivers and at modest convergence.

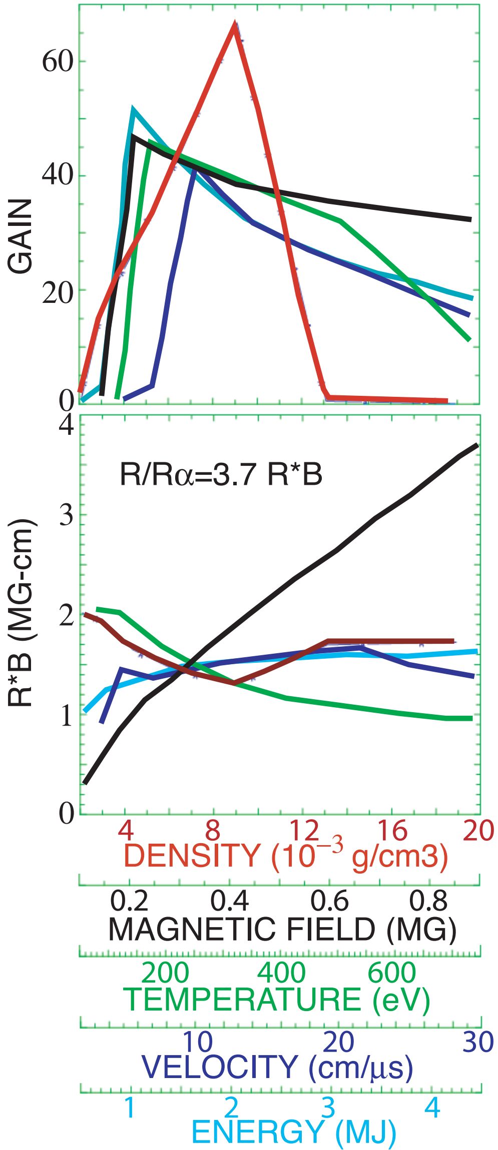
- **An example: E = 300 kJ, M = 0.072 mg, Mc = 0.36 mg,T = 50 eV, B = 100 kG**



v(cm/µs)	ρ(mg/cm3)	Ro/R	Gain	Gain (no Mc)	Gain (B=0)
6	0.5	30	72	35	6e-3
10	2	25	150	35	0.1
20	10	16	97	25	24

- **Does ignition of cold fuel indicate a possible propagating burn wave?**

Parameter sets can be found for cylindrical Bz targets that ignite at low ρR (< 0.1), Ro/R < 30



- An example: E = 1.5 MJ, M = 620 µg, ρ=6.3e-3 g/cm3, T = 250 eV, B = 300 kG, v= 10 cm/µs, R=2.5 mm, L = 5 mm ---> G=42, Ro/R = 23.2, ρR = 0.037 g/cm2, Ti = 70 keV (if adiabatic, 16.5 keV)

- Gain is insensitive to initial parameters (left).

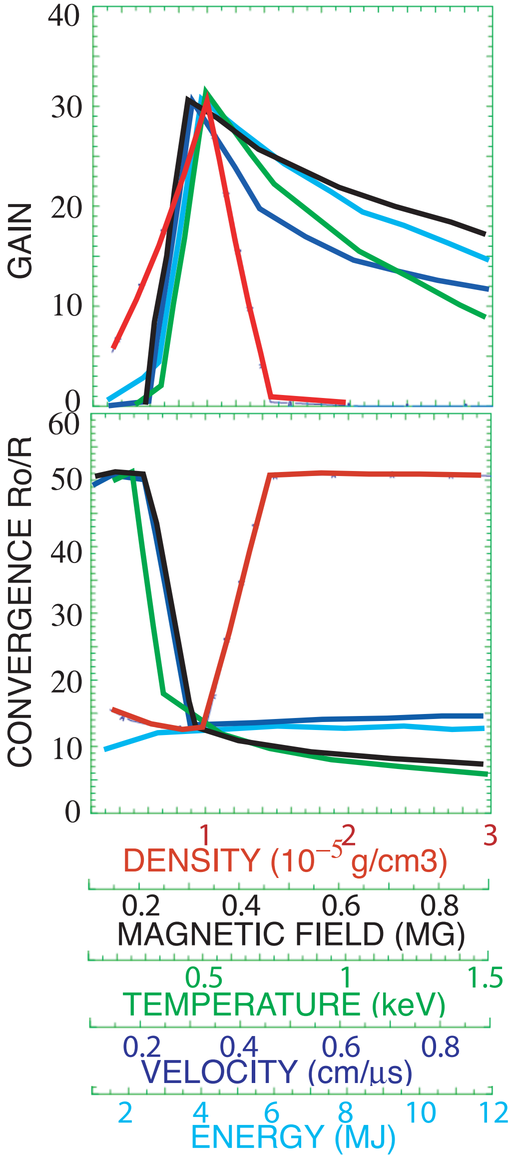
- These results appear consistent with the results of Slutz & Vesey, PRL 108, 025003 (2012) although the gain may be higher.

- If magnetic α enhancement and Nernst effect are not included, gain is reduced to 8.5, range is ~ 1-15.

- Higher gain may be possible at Ro/R > 30.

- The peak burn power of 5e16 W should be sufficient to ignite cold fuel (cylindrical cold fuel model not yet incorporated).

Cylindrical Bϕ targets can ignite at very low density, velocity; ignition can occur at Ro/R < 20 (or even 10).



- R*B is approximately constant or decreases during implosion; for ignition at low ρR, t=0 R*B > 1 MG*cm.

- An example: E = 4 MJ, M = 1.57 mg, ρ=1e-5 g/cm3, T = 500 eV, B = 300 kG, v= 0.3 cm/µs, R=5 cm, L = 2 cm ---> G=30.7, Ro/R = 12.7, ρR = 0.00064, Ti = 57 keV (if adiabatic, 15 keV)

- The peak burn power of 5e13 W may not be sufficient to ignite cold fuel; all examples at left have burn power < 1e14 W.

- Parameter sets at left that do not ignite have high Ro/R (limited to 50), do not bounce, and reach temperatures < 10 keV even at Ro/R = 50.

A path forward: must focus on the fusion physics (no “done deal”).

- "Producing an ignited plasma will be a truly notable achievement for mankind and will capture the public's imagination... Ignition is analogous to the first airplane flight or the first vacuum-tube computer. As in those cases, the initial model need not resemble the one that is later commercialized"---President's Committee of Advisors on Science and Technology (PCAST), Report on Fusion Research (July, 1995), p. 22.

- Reactor concepts make many unproven assumptions (miracles??)
  - Codes predict breakeven with existing drivers, but the codes are
    - not benchmarked over full ρ(> 1e4 range)-v (>1e2 range)-T-B space
  - What if existing drivers cannot reach breakeven?

- Not demonstrated over required ρ(> 1e4 range)-v (>1e2 range)-T-B space:
  - Plasma formation for most concepts   Classical (or Bohm) transport
  - Fusion burn in magnetized plasma   Magnetic enhancement of alpha
  - Plasma-wall interaction

- Methodically exploit existing and near-term drivers to prove the fusion physics, e.g., T_f=2 T_o, T_f=1 keV, T_f=breakeven, T_f=ignition, “cold-fuel”

- Parallel develop multiple target plasmas for each driver (universities?)

- Driver development if required to enhance fusion proof.