MTF users perspective:
What is needed from a compression scheme

T. Intrator
P-24 Plasma Physics
LANL

Plasma jet workshop
LANL
24-25 Jan 2008

abstract

Magnetized Target Fusion encompasses a broad variety of schemes for adiabatic compression of a plasma fuel target with some kind of conducting, contracting boundary. From the standpoint of an MTF user who has worked on high density plasma targets for MTF, we discuss some issues related to compression schemes. Some approaches include solid, liquid, and plasma jet compression. Two principal challenges related to a successful MTF plasma compression and fusion breakeven or ignition are achievement of sufficient target areal density $\rho R[\mathrm{gm/cm}^2]$ and a long enough length of time (dwell time t_D) for the compressor to stagnate on the plasma back pressure. Although the initial rr is characteristic of the plasma target, this still implies constraints on the pusher. Since the external compressing pressure must be substantially greater than the target pressure, a large boundary pressure is required. The dwell time is not of concern for ICF, which relies on a propagating burn wave, nor is it a problem for tokamak or other MFE steady state fusion scenarios. However for MTF, the gain, or fractional burnup of fusion D-T particles is proportional to the dwell time, which must be less than the radiation cooling time. This demands high mass compressor technology.

Outline

- Magneto-Inertial, Magnetized Target Fusion rely on magnetic field to relax the ignition pre requisites
  - Adiabatic scaling for compression
  - Gain = Fusion heat / compressor power
  - Fusion ignition gain space
  - Compressor power
  - Dwell time
  - Competition of time scales

MTF ignition space

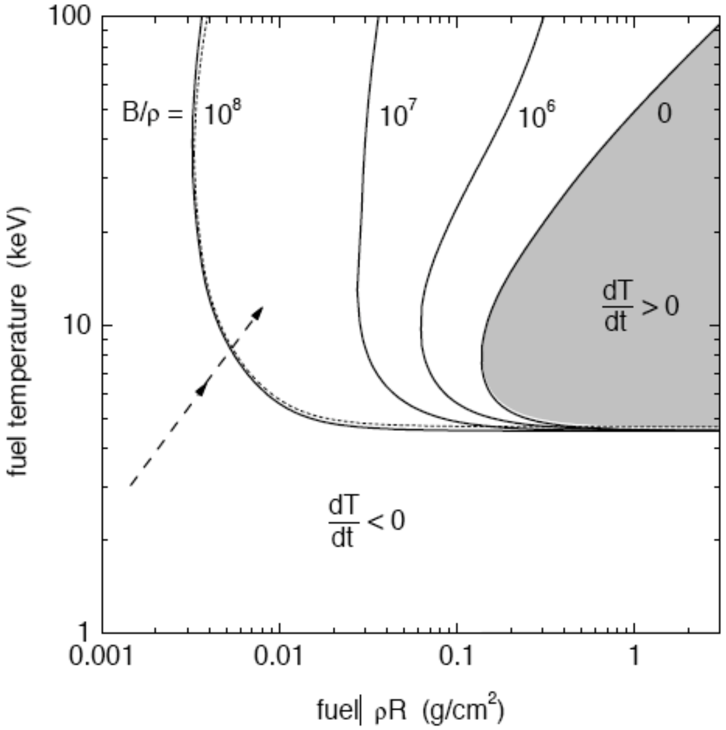


Figure 3. Lindl–Widner diagram for magnetized DT cylinders at stagnation. Solid curves show a series of ignition boundaries in the $\rho R, T$ plane calculated for four fixed values of the parameter B/ρ, given near each curve in units of G cm^3/g. The shaded area is the pure ICF ignition domain at $B = 0$. The dotted curve illustrates the effect of synchrotron radiation losses at $\rho = 1$ g/cm^3, $B = 10^8$ G. Dashed arrows indicate how the fuel states advance towards the ignition boundary in the process of a quasi-adiabatic implosion.

- compressed target
  - ρ = Mass density
  - R = scale size
  - ρR = areal mass density
- Example
  - $N=10^{21}$cm^{-3}
  - R = 0.5cm
  - ρR = 0.001 gm/cm^2

- Magnetic field reduces ρR below ICF expectations, but only by 10-30
- Plot from Basko, **40**, 59, NF (2000)

Deposited alpha energy fraction f_α empirical formula

- MTF is typically marginal, but high f_α requires
  - $R/l_\alpha > 1$ … size > coulomb mean free path
    - high density, ρR
  - $R/r_{G\alpha} > 1$ … size > α gyro orbit
    - High B field, small orbit for 3.5MeV α

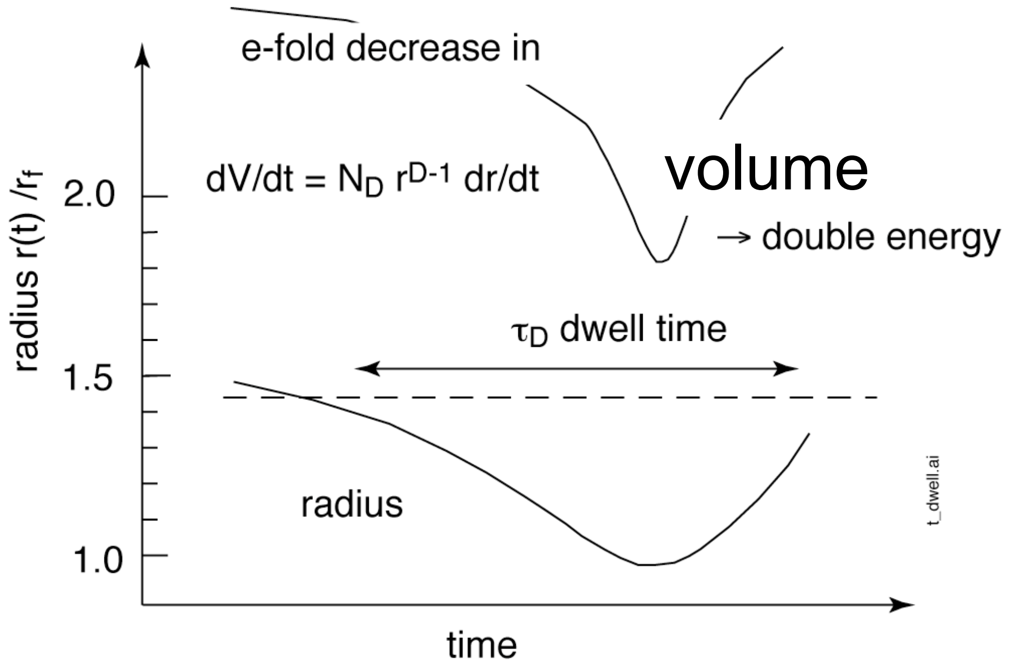
- $f_\alpha = (x_\alpha + x_\alpha^2)/(1 + 13x_\alpha/9 + x_\alpha^2)$
  - $x_\alpha = (8/3)(R_{coul} + b^2/(9b^2 + 1000)^{1/2})$
  - $R_{coul} = R/l_\alpha$
  - $b = R/r_{G\alpha} = R\omega_{c\alpha}/v_{0\alpha}$
  - l_α [cm] = $0.107\ T^{3/2}$[keV]/(ρ [gm/cm^3] L_α)
  - L_α [cm] ≈ 7 (coulomb logarithm)
- For small x_α, $f_\alpha \approx x_\alpha \ll 1$

Adiabatic scaling for wall compression

f	γ	volume	T/T_0	n/n_0	p/p_0	B/B_0	β/β_0	C	1<D<3
	(f+2)/f								
1	3	C^{-D}	C^{2D}	C	C^{3D}	C^2	C^{3D-4}	10	
2	2	C^{-D}	C^{D}	C^2	C^{2D}	C^2	C^{2D-4}	10	
3	5/3	C^{-D}	$C^{2D/3}$	C^3	$C^{5D/3}$	C^2	$C^{5D/3-4}$	10	
general case	(f+2)/f	C^{-D}	$C^{D(\gamma-1)}$	C^{D}	$C^{D\gamma}$	C^2	$C^{D\gamma-4}$	10	
D=2.4, f=3	FRC	$C^{-2.4}$	$C^{1.6}$	$C^{2.4}$	C^4	C^2	1	10	

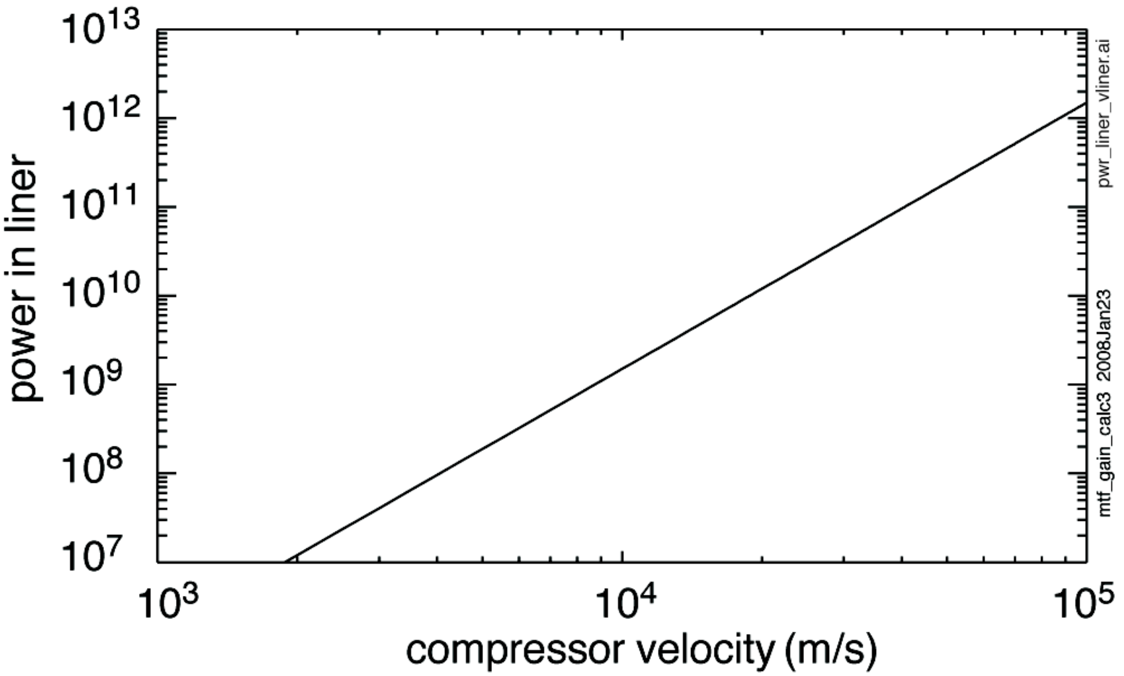
- PV^γ = $nTV^\gamma = NTV^{\gamma-1}$ constant
- f = degrees of freedom
- γ = (f+2)/f polytrope index
- C = radial compression ratio
- D = dimension of compression (FRC => D=2.4)
- Note that $\beta > 1$ for 3D compression, ie MTF can lead to wall confinement
- FRC is the only example that maintains equilibrium during compression

Volume decrease & energy increase define Dwell time



- Adiabatic compresion
  - Volume decrease by e-fold
  - Compressor doubles the energy via PdV work
  - Radius of target converges and bounces $1.5r_f \Rightarrow r_f \Rightarrow 1.5r_f$
    - Depending on degrees of freedom, compression dimension
- Define dwell time $\tau(\text{dwell}) = 2^*(1.5\text{-}1.0)r_f / v(\text{convergence})$

Compressor power increases as v^3



Example for 500 gram solid liner

Lighter plasma liner will have less energy, but scales similarly

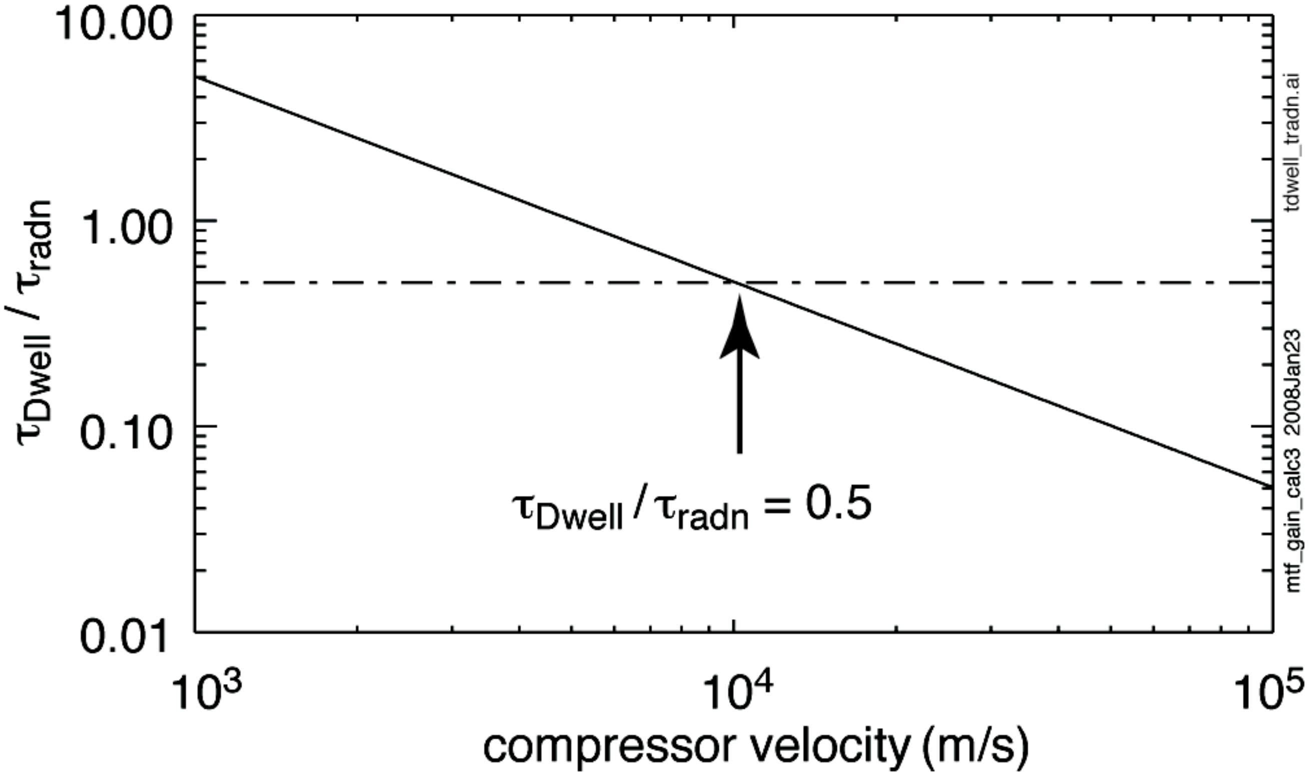
Parameters

compressn ratio =12.00
dimension of compression= 2.4
rho-R= 1.92e-03gm-cm^-2
mass liner= 2.00e-05kgm
n1_target= 1.73e+27m^-3
n0_target= 1.00e+24m^-3
r1_target= 3.33e-03m
r0_target= 4.00e-02m
pwr_den_radn= 1.21e+19
pwr_den_fusion = 2.14e+18

R/mfp = 5.88e-05
magnetization b = 1.28e-01
alpha burnup fractn= 1.16e-03
x alpha = 1.16e-03
B1 = 720Tesla
B0 = 5Tesla
tau_radn= 1.32usec

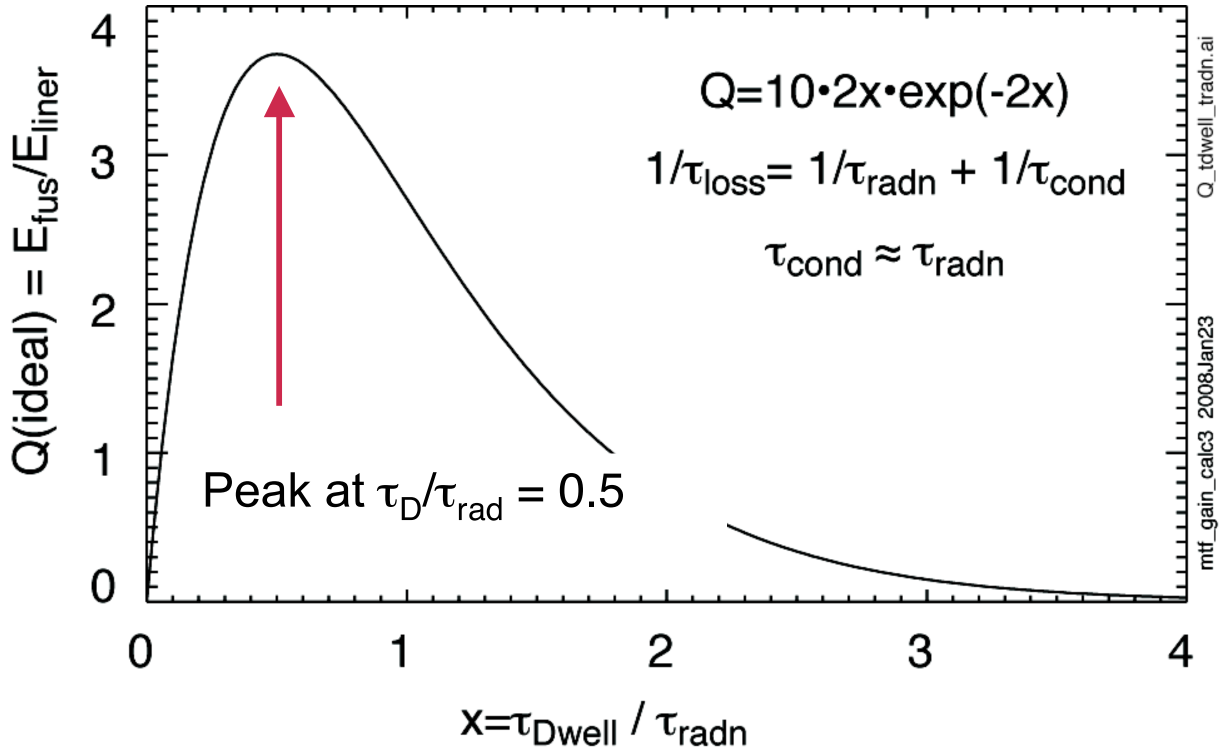
Q ≈ 1for this example

Dwell time < loss time



- τ(dwell) << τ(radiation) ⇒ not enough time for fusion α heating
- τ(dwell) >> τ(radiation) ⇒ all the energy radiates away
- Conduction loss can be as large as bremsstahlung radiation

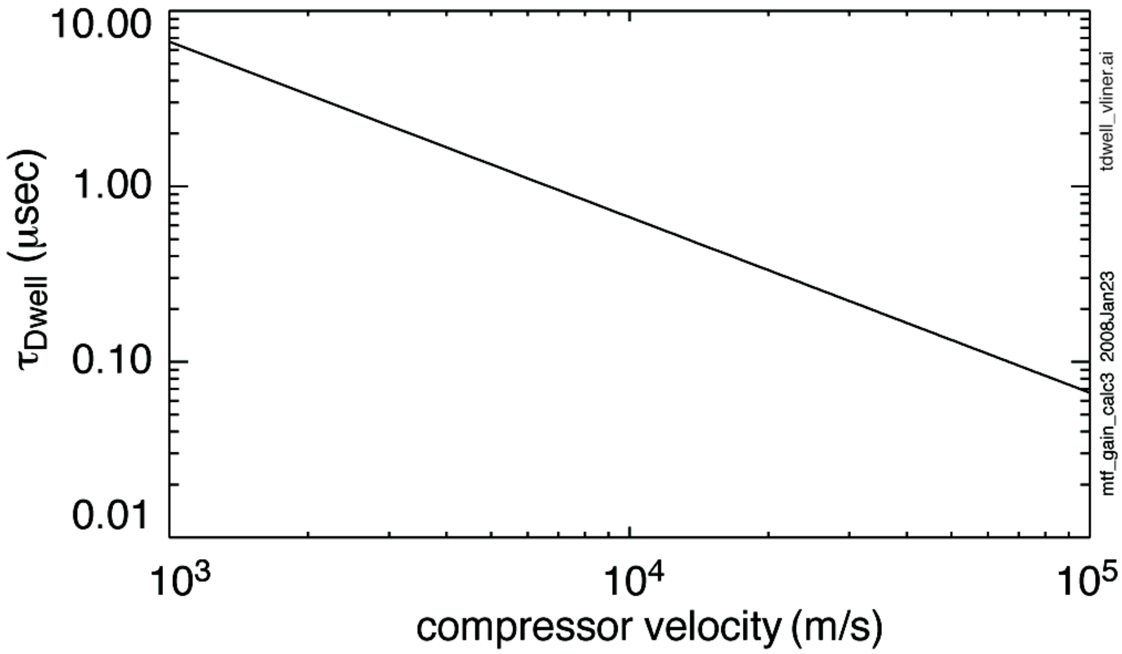
Fusion gain vs dwell & loss time scales



- At T=10keV, for D-T $<\sigma v>$
  - $Q(n\tau T) \approx 10^{20}\ n[m^{-3}]\ \tau(\mathrm{dwell})\ [\mathrm{sec}]$
  - $\tau(\mathrm{radiation}) \approx 10^{21} / n[m^{-3}]$
- $Q \approx 10 \cdot 2\tau_D/\tau_{rad} \exp(-2\tau_D/\tau_{rad})$

- Note Q is not large
- Argument from Ryutov, cm size liner, 6th Intl Conf Z pinch (2005)

Dwell time decreases with velocity, mass$^{-1/2}$



- Large dwell time increases deposited α energy fraction
- This favors massive compressor schemes
  - This example for 500gm mass, note $\tau_D \approx$ mass$^{1/2}$

Conclusions

- Large dwell time allows absorbed α energy fraction f_α to increase
  - Requires high mass compressor
  - Typical MTF $f_\alpha \approx 0.01$-5%
- Large ρR = requires high mass target plasma
  - High compression is not sufficient because it lowers R
- Need to be clever to increase Q maximum