

# Is There a Better Route to Fusion?

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“Thirty-five years ago I was an expert precious-metal quartz-miner. There was an outcrop in my neighborhood that assayed \$600 a ton—gold. But every fleck of gold in it was shut up tight and fast in an intractable and impersuadable base-metal shell. Acting as a Consensus, I delivered the finality verdict that no human ingenuity would ever be able to set free two dollars’ worth of gold out of a ton of that rock. The fact is, I did not foresee the cyanide process... These sorrows have made me suspicious of Consensuses... I sheer warily off and get behind something, saying to myself, ‘It looks innocent and all right, but no matter, ten to one there’s a cyanide process under that thing somewhere.’”

-Mark Twain, “Dr. Loeb’s Incredible Discovery” (1910)

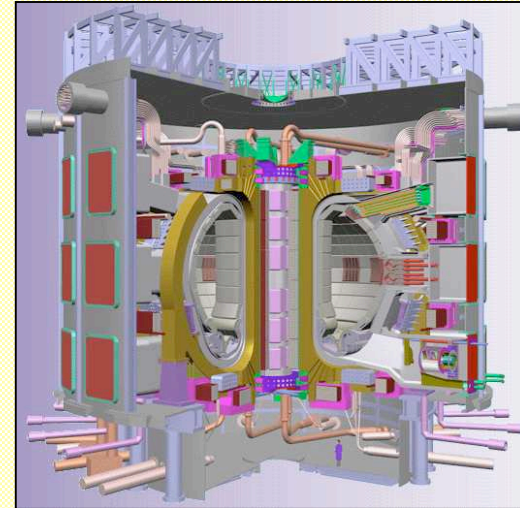
# Motivation



Three Mile Island

## Current fission power approaches are not ideal

- Politically incorrect amount of radioactivity
- Conventional reactors are very expensive (>\$1B each)



ITER

## Current fusion power approaches are not ideal

- Also quite radioactive and more expensive than fission reactors (>\$5B for ITER)
- Still decades in the future after over half a century of work

➔ We will try to “rederive” fusion power from first principles, looking for better approaches at each step along the way.

# **Wish List of Characteristics For the Perfect Nuclear Energy Source**

- **Little or no radiation and radioactive waste**
- **Minimal shielding**
- **Scalable to power everything from computer chips to GW reactors**
- **High-efficiency direct conversion to electricity**
- **Utilizes readily available fuel**
- **Cannot explode, melt down, or frighten Jane Fonda**
- **Not directly or indirectly useful to terrorists or unfriendly countries**

**Can we come closer to meeting these goals?**

# Nuclear vs. Chemical Energy

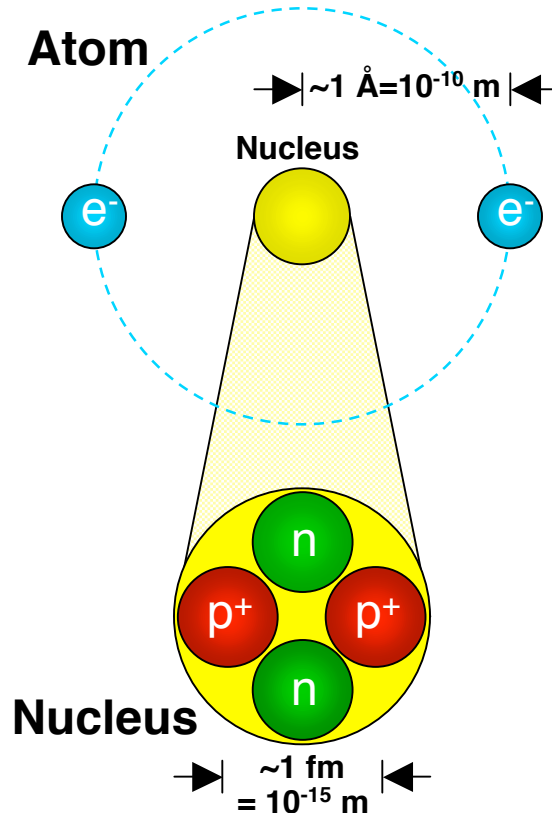
From Coulomb's law:

$$E \sim \frac{e^2}{4\pi\epsilon_0 r}$$

$$= \frac{14.4 \text{ eV}}{r \text{ [in \AA]}}$$

$$\frac{E_{\text{nucl}}}{E_{\text{chem}}} \sim \frac{r_{\text{atom}}}{r_{\text{nucl}}} \sim 10^5$$

(Valid since strong force  $\sim$  Coulomb force in nucleus)



From Heisenberg uncertainty principle:

$$(\Delta p)(\Delta x) \sim \hbar$$

$$E \sim \frac{(\Delta p)^2}{2m} = \frac{\hbar^2}{2m(\Delta x)^2}$$

$$\frac{E_{\text{nucl}}}{E_{\text{chem}}} \sim \frac{m_e}{m_p} \left( \frac{r_{\text{atom}}}{r_{\text{nucl}}} \right)^2 \sim 10^6$$

- Nuclear processes rearrange protons & neutrons and release  $\sim 10^5$ - $10^6$  more energy than chemical reactions, which rearrange atomic electrons (MeV vs. eV)
- A nuclear particle has enough energy to break  $\sim 10^5$ - $10^6$  chemical bonds
  - Can damage reactor components, depending on particle type & component material
  - Especially bad for DNA and other biological molecules

# Contributions to Nuclear Binding Energy $E_B$ (in MeV)

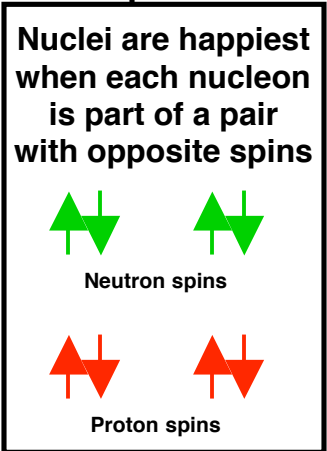
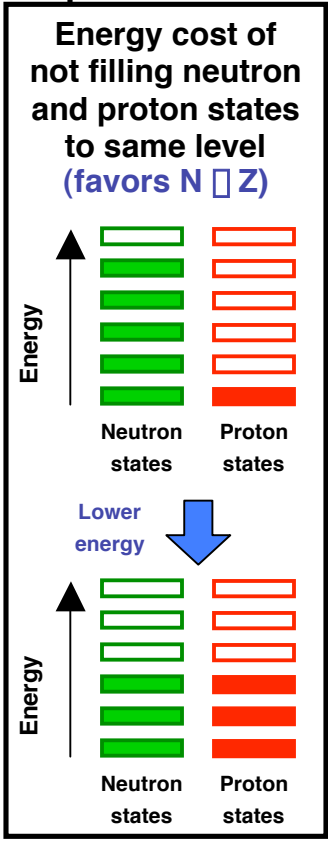
$$E_B = 16 A - 17 A^{2/3} - 0.7 \frac{Z^2}{A^{1/3}} - 25 \frac{(N - Z)^2}{A} + \begin{cases} 34 A^{-3/4} & \text{even } N, Z \\ 0 & \text{odd-even} \\ -34 A^{-3/4} & \text{odd } N, Z \end{cases} + \sim \frac{A}{20} \text{ if } N \text{ or } Z \text{ is magic}$$

Average binding energy of nucleon with nearest neighbors (strong force range  $\sim 1.5$  fm)

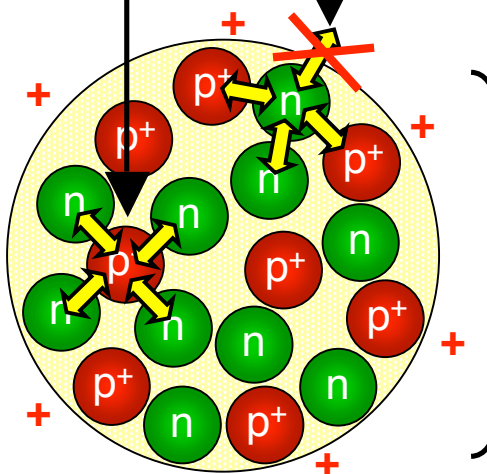
Coulomb repulsion among protons (favors  $N \gg Z$ )

Correction: nuclei at surface have fewer neighbors for binding energy

Favors  $N$  a bit larger than  $Z$ , especially for large nuclei



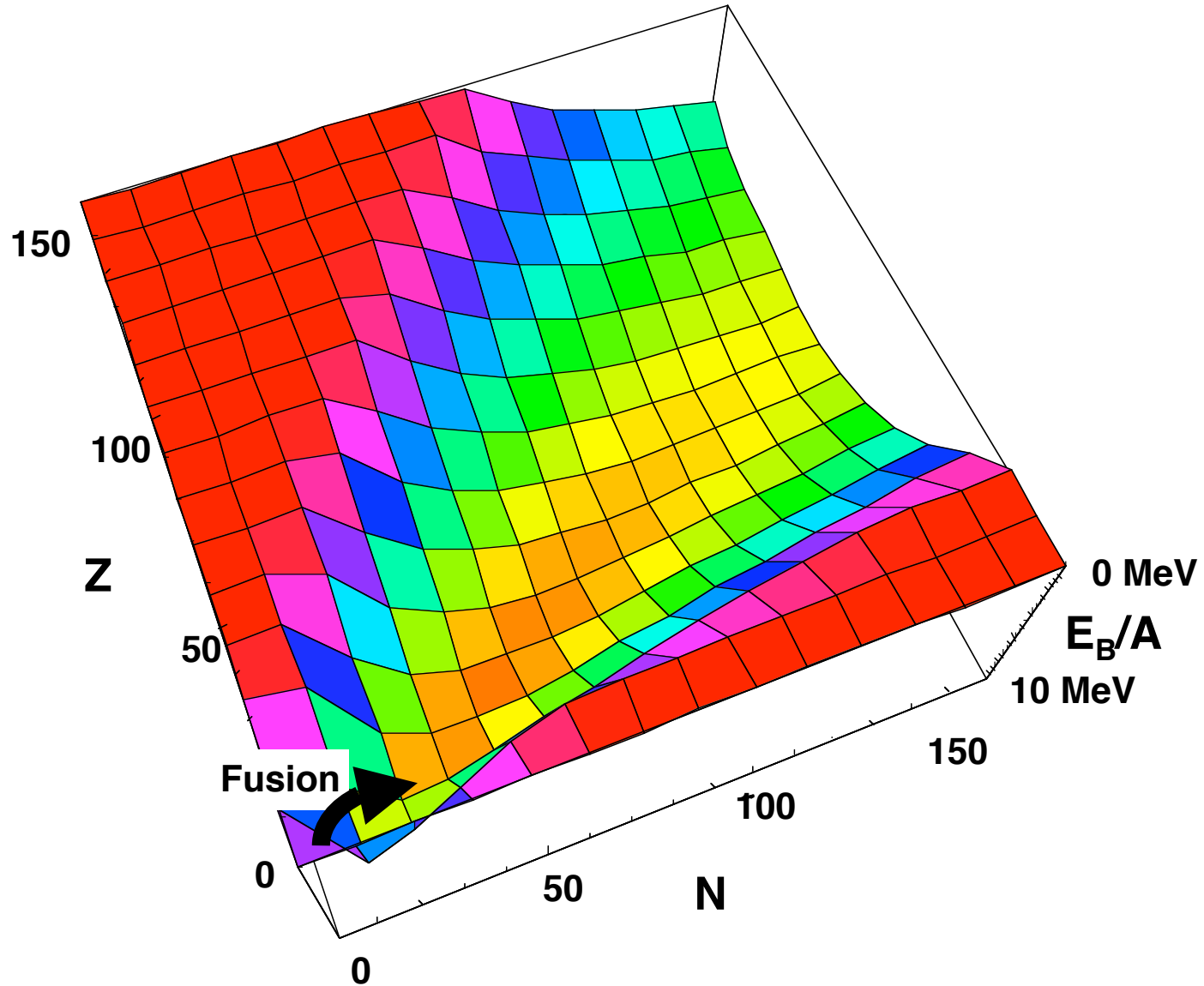
Bonus for filled nucleon energy shells at magic numbers of  $N$  and  $Z$ : 2, 8, 20, 28, 50, 82, 126, ... (similar to atomic electron shells)



Valid for  $A \geq 15$

Radius  $\sim A^{1/3}$   
Surface area  $\sim A^{2/3}$   
Volume  $\sim A$

# Binding Energy per Nucleon And Methods of Tapping It



# Possible Fusion Reactions

Output energy Peak cross section at CM input energy
Theoretically feasible
Borderline
Not feasible

Input nucleus 1	Input nucleus 2						
	n	<sup>1</sup> H	<sup>2</sup> H	<sup>3</sup> H	<sup>3</sup> He	<sup>4</sup> He	<sup>6</sup> Li
n	Negligible						
<sup>1</sup> H	2.2 MeV 0.3 b thermal	1.4 MeV >10 <sup>-25</sup> b at >1 MeV					
<sup>2</sup> H	6.3 MeV 5x10 <sup>-4</sup> b thermal	5.5 MeV 10 <sup>-6</sup> b at 1 MeV	3.65 MeV >0.1 b at >150 keV				
<sup>3</sup> H	Negligible	-0.76 MeV	17.6 MeV 5 b at 80 keV	<sup>3</sup> H	11.3 MeV 0.16 b at 1 MeV		
<sup>3</sup> He	0.76 MeV 5000 b thermal	19.8 MeV Negligible	18.3 MeV 0.8 b at 300 keV	13 MeV >0.2 b at >450 keV	<sup>3</sup> He	12.9 MeV >0.15 b at >3 MeV	
<sup>4</sup> He	Negligible	Negligible	1.5 MeV 10 <sup>-7</sup> b at 700 keV	2.5 MeV	1.6 MeV	<sup>4</sup> He	Negligible except stellar 3α fusion
<sup>6</sup> Li	4.8 MeV 950 b thermal	4.0 MeV 0.2 b at 2 MeV	5.0 MeV 0.1 b at 1 MeV	16.1 MeV	16.9 MeV >0.03 b at >1 MeV	-2.1 MeV	
<sup>7</sup> Li	2.0 MeV 0.04 b thermal	17.3 MeV 0.006 b at 400 keV	15.1 MeV >0.5 b at >1 MeV	8.9 MeV >0.2 b at >4 MeV	11-18 MeV	8.7 MeV 0.4 b at 500 keV	
<sup>7</sup> Be	1.6 MeV 50,000 b thermal	0.14 MeV 2x10 <sup>-6</sup> b at 600 keV	16.8 MeV	10.5 MeV	11.3 MeV	7.5 MeV 0.3 b at 900 keV	
<sup>9</sup> Be	6.8 MeV 0.01 b thermal	2.1 MeV 0.4 b at 300 keV	7.2 MeV >0.1 b at >1 MeV	9.6 MeV >0.1 b at >2 MeV		5.7 MeV 0.3 b at 1.3 MeV	
<sup>10</sup> Be	Negligible						
<sup>10</sup> B	2.8 MeV 3800 b thermal	1.1 MeV 0.2 b at 1 MeV	9.2 MeV >0.2 b at >1 MeV				
<sup>11</sup> B	3.4 MeV 0.005 b thermal	8.7 MeV 0.8 b at 600 keV	13.8 MeV >0.1 b at >1 MeV	8.6 MeV			
<sup>11</sup> C							
<sup>12</sup> C	4.9 MeV 0.003 b thermal	1.9 MeV 1x10 <sup>-4</sup> b at 400 keV					
<sup>13</sup> C	8.2 MeV 0.001 b thermal	7.6 MeV 0.001 b at 500 keV					
<sup>14</sup> C	Negligible						

Neglect:

- Nuclei with  $t_{1/2} < 1$  min
- 3-body fusion

$Z_1 Z_2 \geq 8$  →

Coulomb barrier is too high ↓

$Z_1 Z_2 \geq 7$  Coulomb barrier is too high ↓

# Physical Factors in Fusion Cross Section (in barns)

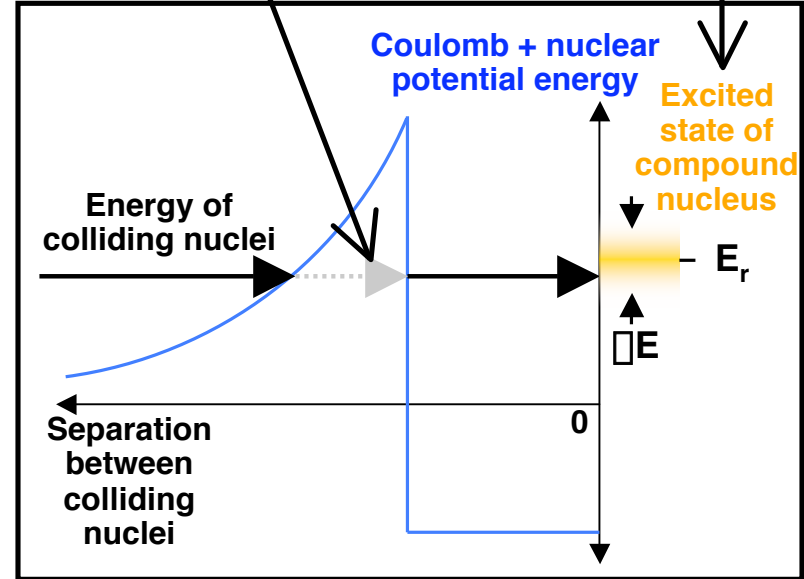
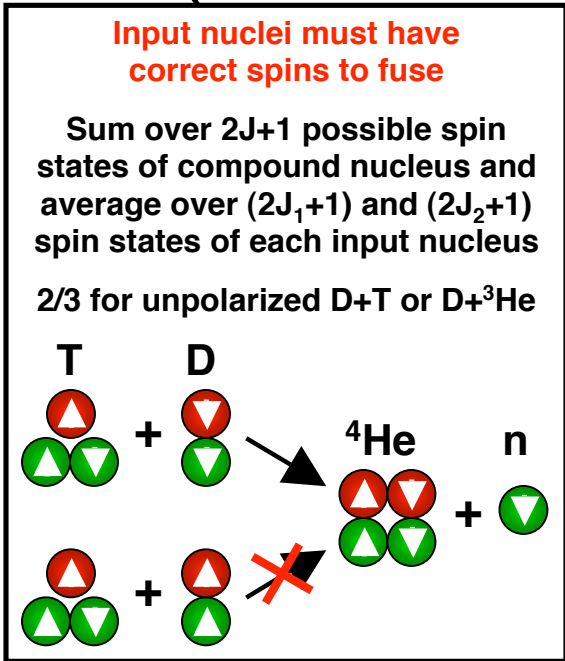
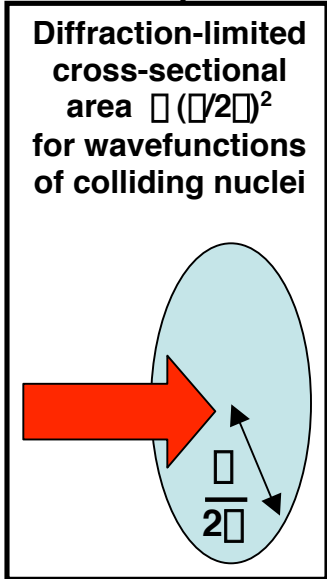
As a Function of Center-of-Mass Energy  $E_{CM}$  (keV)

$$\sigma_{fus} = \frac{650}{A_{red} E_{CM}} \frac{(2J+1)}{(2J_1+1)(2J_2+1)} \exp\left[-31.4 Z_1 Z_2 \sqrt{\frac{A_{red}}{E_{CM}}} + 1.154 \sqrt{Z_1 Z_2 A_{red} (A_1^{1/3} + A_2^{1/3})}\right] \frac{(\Delta E)^2}{(E_{CM} - E_r)^2 + (\Delta E/2)^2}$$

$$A_{red} \equiv \frac{A_1 A_2}{A_1 + A_2}$$

Probability of tunneling through Coulomb barrier between nuclei

Collision energy  $E_{CM}$  must be within  $\sim \Delta E/2$  of excited state energy  $E_r$  of compound nucleus



# Improve Spin Polarization Factor in $\beta_{\text{fus}}$

**Need better evidence (especially experimental) for or against:**

- **Potential benefits of spin-polarized nuclei**
  - Increase  $\beta_{\text{fus}}$  by 50% for D+T/D+<sup>3</sup>He, 50-100% for D+D, 56% for p+<sup>11</sup>B [1: pp. 161-168]
  - Suppress neutron-producing D+D side reactions in D+<sup>3</sup>He plasmas [1: pp. 161-168]
  - Control angular distribution of products [1: pp. 169-178 & 269-271; 2]
- **Methods of producing spin-polarized nuclei**
  - Spin-exchange optical pumping [3]
  - Cryogenic, neutral beam, and other methods [1: pp. 213-247; 2]
- **Depolarization mechanisms (two-body collisions don't affect spin [2])**
  - Interactions with first wall [4]
  - Interactions with magnetic inhomogeneities or fluctuations [2]
  - Interactions with waves [5]
  - Spin-orbit and spin-spin interactions [6]
  - Long-range three-body collisions

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[1] Brunelli & Leotta (eds.), *Muon-Catalyzed Fusion and Fusion with Polarized Nuclei* (Plenum Press, 1987)

[2] R. M. Kulsrud, E. J. Valeo, & S. C. Cowley, *Nuclear Fusion* 26, 1443 and *Phys. Fluids* 29, 430 (1986)

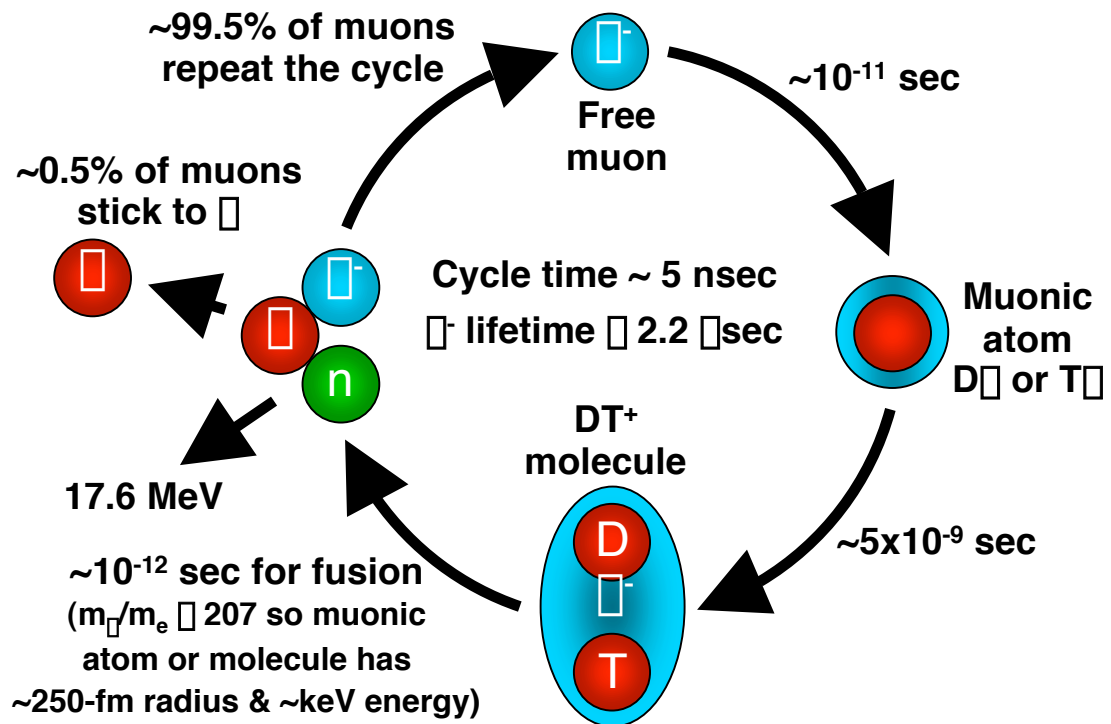
[3] S. G. Redsun *et al.*, *Phys. Rev. A* 42, 1293 (1990); M. Poelker *et al.*, *Phys. Rev. A* 50, 2450 (1994)

[4] H. S. Greenside, R. V. Budny, and D. E. Post, *J. Vac. Sci. Technol. A* 2, 619 (1984)

[5] B. Coppi *et al.*, *Phys. Fluids* 29, 4060 (1986)

[6] W. Y. Zhang and R. Balescu, *J. Plasma Physics* 40, 199 and 215 (1988)

# Improve Tunneling Factor in $\kappa_{fus}$ : Muon Catalysis [1]



Input ( $\mu^-$ ) Energy	
( $\mu^-$ rest energy	106 MeV)
Made from $\mu^-$	139 MeV
Make stuff other than $\mu^-$	x 10
Lab vs. CM frame	x 2
Accelerator efficiency	x 2
<hr/>	
Present $\mu^-$ production	~5 GeV
<b>Need more efficient methods</b>	

Output (Fusion) Energy
1 $\mu^-$ catalyzes $\sim(0.5\%)^{-1} \mu$ 200 fusions before sticking to $\mu$
200 fusions x 17.6 MeV x 1/3 eff. $\mu$ 1 GeV useful output per $\mu^-$
<b>Need unsticking methods</b>
Could then catalyze 2.2 $\mu$ s / 5ns $\mu$ 440 fusions before $\mu^-$ decays
<b>Need way to reduce cycle time [2]</b>

Performance is much worse for reactions other than D+T

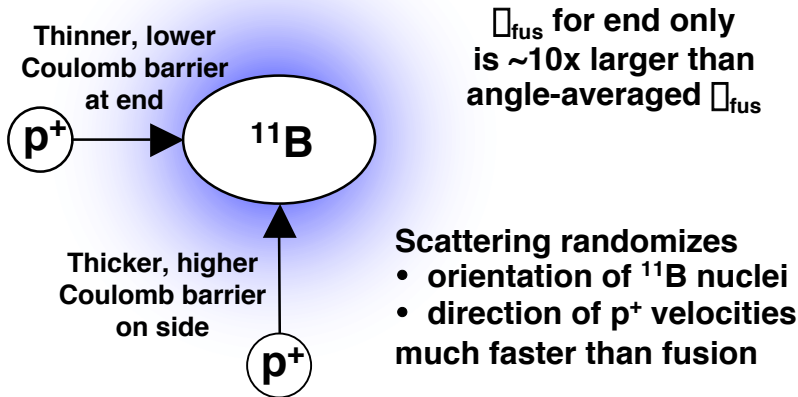
**Other massive negative particles:**

- Antiprotons are a loser [3]
- Other particles are harder to produce and shorter-lived than  $\mu^-$
- Large effective  $e^-$  mass or charge in solids does not help [4]

[1] Brunelli & Leotta (eds.), *Muon-Catalyzed Fusion and Fusion with Polarized Nuclei* (Plenum Press, 1987)  
 [2] M. C. Fujiwara *et al.*, *Phys. Rev. Lett.* 85, 1642 (2000) only decreases the time for the *first* cycle, not later ones  
 [3] D. L. Morgan, L. J. Perkins, and S. W. Haney, *Hyperfine Interactions* 102, 503 (1996)  
 [4] J. R. Huizenga *et al.*, Report DOE/S-0073 (Nov. 1989), [www.newenergytimes.com/DOE1989/contents.htm](http://www.newenergytimes.com/DOE1989/contents.htm)

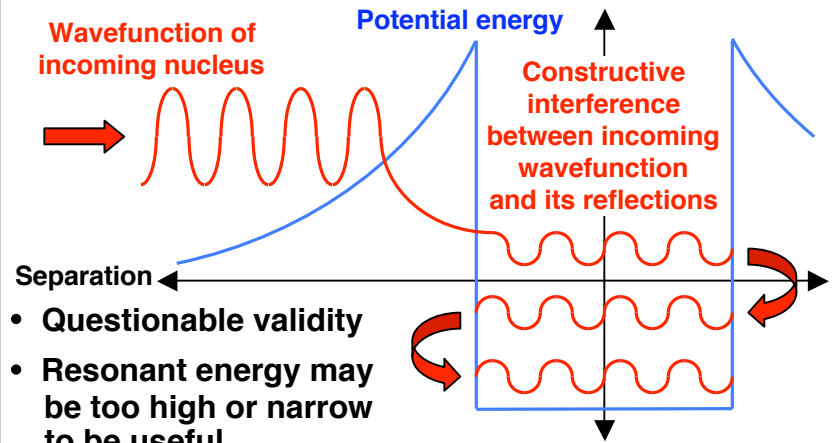
# Improve Tunneling Factor in $\Gamma_{fus}$ : Other Methods

## Shape-polarized fusion



L.J. Perkins, *Phys. Lett. A* 236, 345 (1997)

## Resonant tunneling



X.Z. Li et al., *Phys. Rev. C* 61, 024610 (2000)

## Liquid metallic hydrogen

H isotopes in liquid metallic state

$T < 0.1$  eV

$P > 100$  Mbar

S. Ichimaru,  
*Rev. Mod. Phys.*  
65, 255 (1993)

$\Gamma_{fus}$  is greatly increased by

- electron screening of Coulomb potential
- many-particle correlations among nuclear states

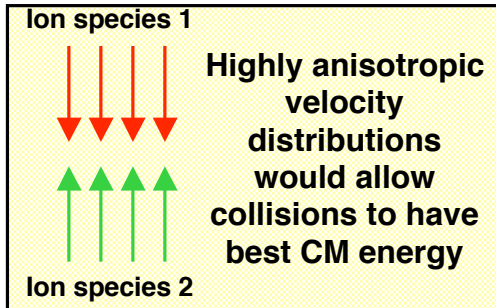
- Is there a better way to beat the Coulomb barrier?
- Can one show that these ideas completely cover the phase space of methods for dealing with the Coulomb barrier?
- Are there ways to improve the other two factors in  $\Gamma_{fus}$ ? (Doubtful)

# Why Ions Won't Behave

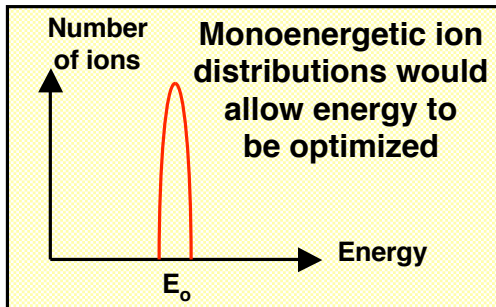
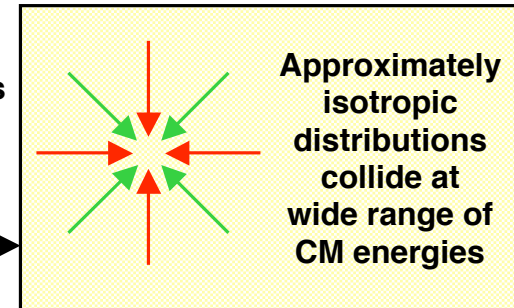
**Desired property:**

**Why you can't have it:**

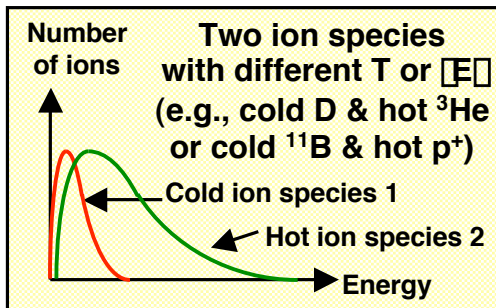
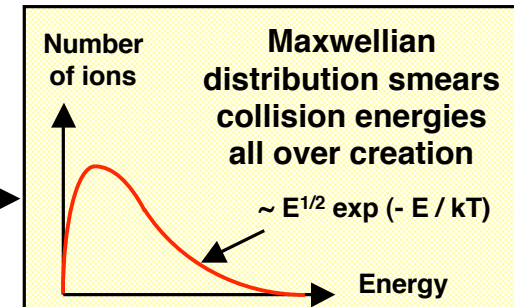
**What you're left with:**



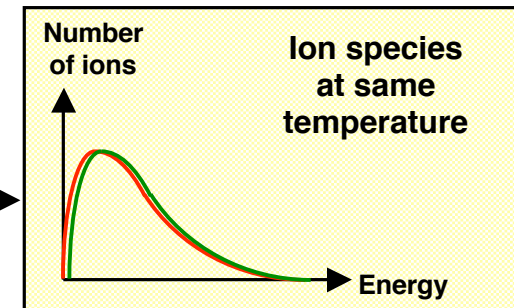
Two-stream, Weibel, & other instabilities run amuck in highly anisotropic distributions  
Elastic collisions make velocity distributions isotropic on timescale  $\tau_{col} \ll \tau_{fus}$



Elastic collisions make ion distributions Maxwellian on timescale  $\tau_{col} \ll \tau_{fus}$



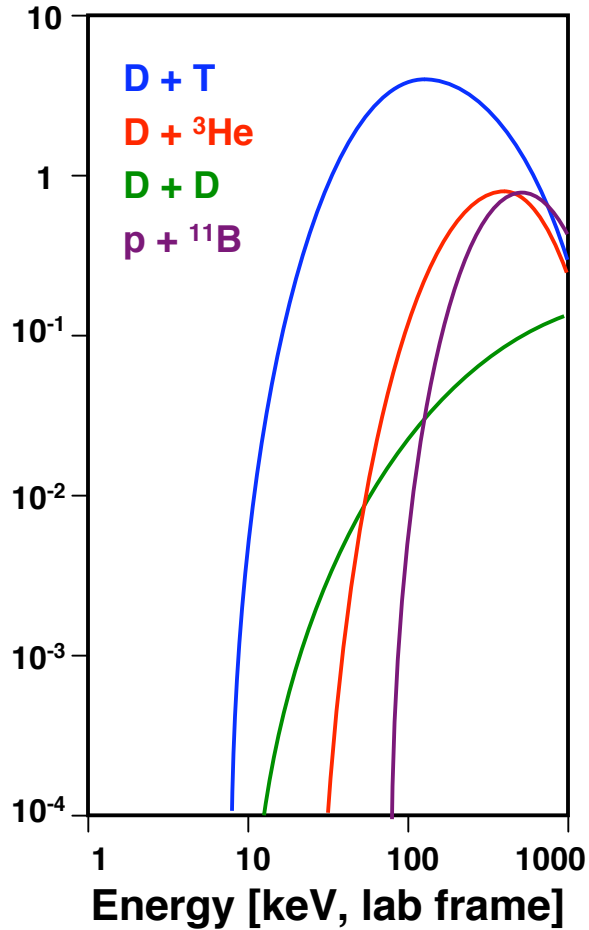
Collisions equilibrate temperatures of two ion species on timescale  $\tau_{col} \ll \tau_{fus}$



T. H. Rider, *Phys. Plasmas* 4, 1039 (1997) and Ph.D. thesis, MIT (1995)

# Cross Sections for Major Fusion Reactions

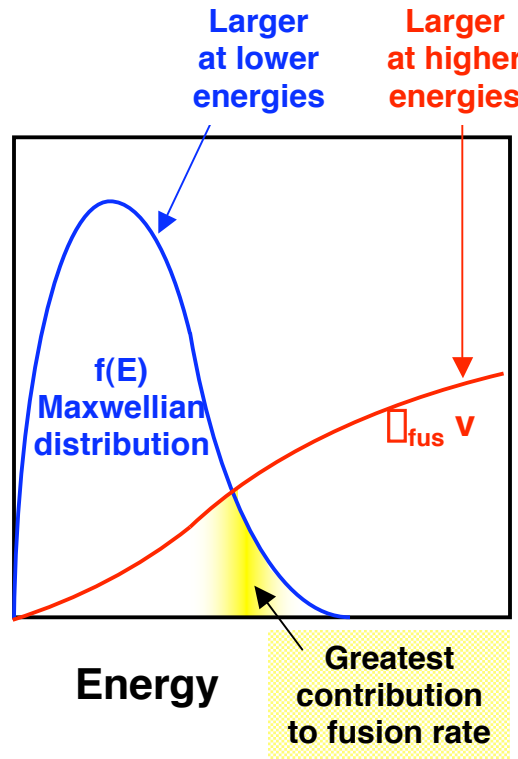
$\sigma_{\text{fus}}$  [barns] for major reactions



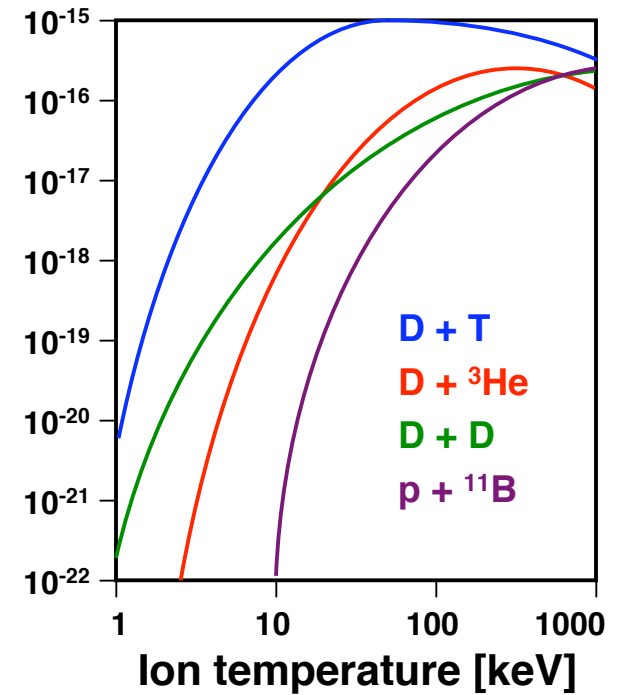
Reaction rate/volume

$$= \int \sigma_{\text{fus}} v f(E) n_{i1} n_{i2} dE$$

$$\int \sigma_{\text{fus}} v f(E) dE$$



$\int \sigma_{\text{fus}} v$  [cm<sup>3</sup>/sec] for major reactions



# Electrons

## You Can't Live Without Them

Space-charge-limited Brillouin density for ions without electrons:

$$\left[ \text{Confining field energy density} \right] > \left[ \text{Ion rest energy density} \right]$$

$$\rightarrow n_i < \frac{B^2/2\mu_0}{m_i c^2}$$

$$\sim 5 \times 10^{11} \text{ cm}^{-3} \text{ for } A \sim 2 \text{ \& } B \sim 20 \text{ T}$$

Fusion power density limited to:

$$P_{\text{fus}} \sim 1 \times 10^{-7} E_{\text{fus, MeV}} \left[ \nu \right]_{\text{cm}^3/\text{sec}} n_i^2 \text{ cm}^{-3} \text{ W/m}^3$$

$$\sim 100 \text{ W/m}^3$$

**Electrons must be present to reach useful fusion power densities.**

## You Can't Live With Them

Ion-electron energy transfer

rate ( $P_{ie}$ ) if  $T_i \gg T_e$ :

$$\frac{P_{ie}}{P_{\text{fus}}} \sim \frac{3 \times 10^{-16} Z^3 \ln \Lambda}{E_{\text{fus, MeV}} \left[ \nu \right]_{\text{cm}^3/\text{sec}} A T_i^{1/2, \text{ keV}} \left( \frac{T_i}{T_e} \right)^{3/2}}$$

$$\sim 1 \text{ for } Z \sim 1, \ln \Lambda \sim 20, E_{\text{fus}} \sim 18 \text{ MeV}$$

$$\left[ \nu \right] \sim 2 \times 10^{-16} \text{ cm}^3/\text{sec},$$

$$T_i/T_e \sim 5, A \sim 2, T_i \sim 100 \text{ keV}$$

$$P_{\text{fus}} \gg P_{\text{input}}, \text{ so } P_{ie} \gg P_{\text{input}}$$

**Thus  $T_e$  must be  $\sim T_i$  in equilibrium.**

**There are  $Z$  electrons for every ion, so electrons soak up  $\sim Z/(Z+1)$  of the input energy without directly contributing to the fusion process.**

**Actually it's worse—see next slide...**

# Electrons Lose Energy via Bremsstrahlung Radiation

If photons are confined

Photon vs. ion energy densities for equilibrium ( $T_{\text{photons}} \approx T_i = T$ ):

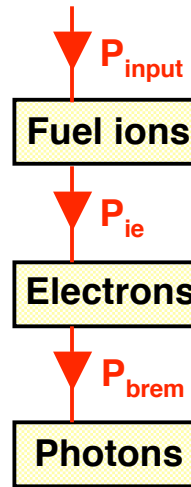
$$\frac{E_{\text{photons}}}{E_{\text{ions}}} \approx \frac{8 \sigma_{\text{SB}} T^3}{3 c k_B n_i}$$

Maximum achievable temperature before radiation soaks up most of the input energy ( $E_{\text{photons}} > E_{\text{ions}}$ ):

$$T_{\text{keV}} \approx 2.6 \times 10^{-8} n_{i, \text{cm}^{-3}}^{1/3}$$

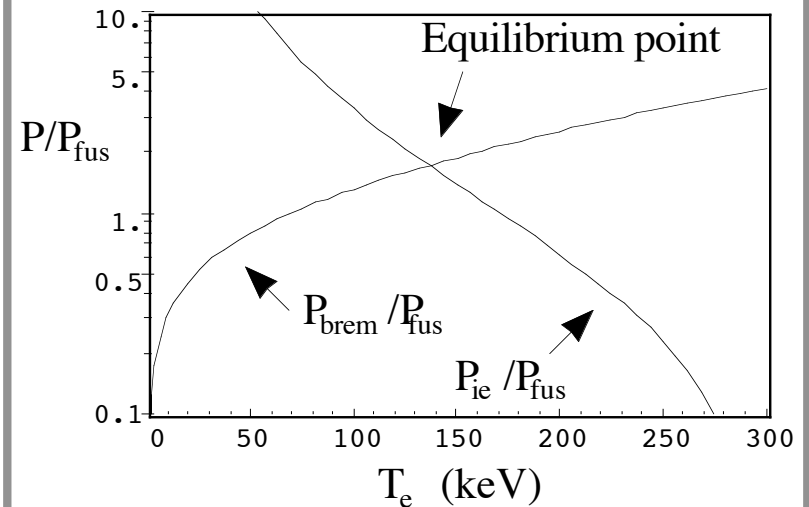
Just ~10 keV even for a stellar core ( $n_i \sim 10^{26} \text{ cm}^{-3}$ )

Photons must be allowed to escape in order to reach useful ion temperatures at attainable densities (& thus useful power densities)



If photons escape

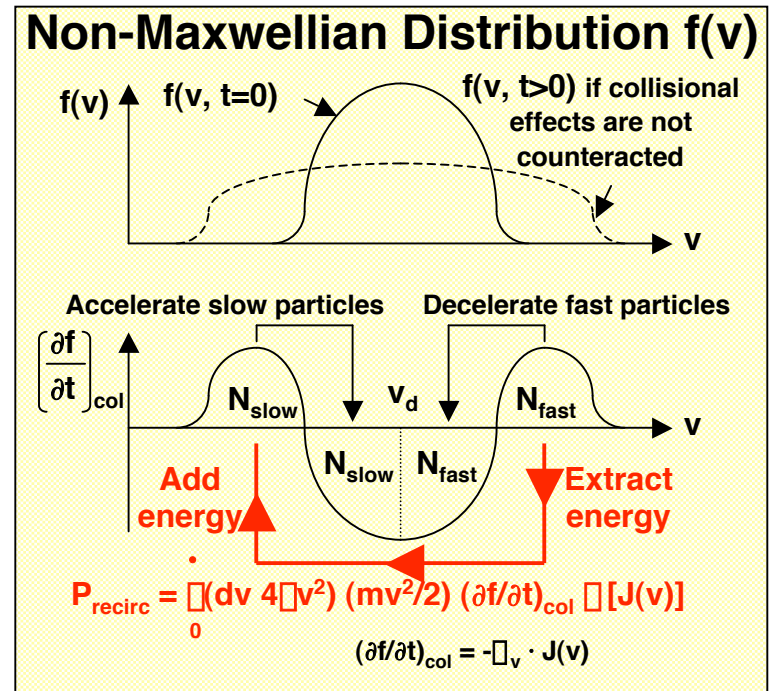
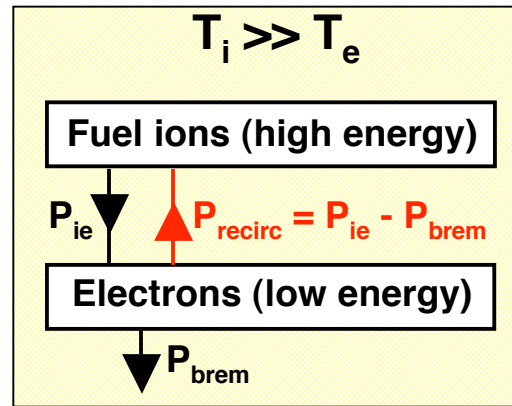
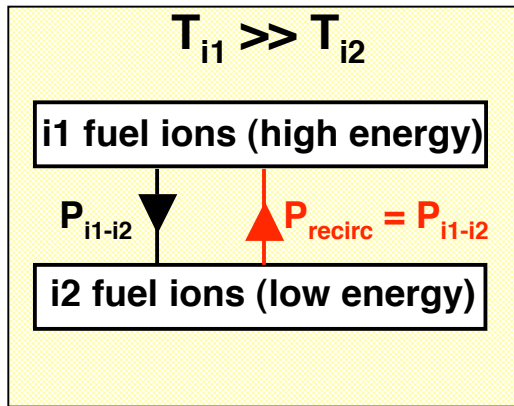
E.g.: 5:1  $p+^{11}\text{B}$  with  $T_i=300 \text{ keV}$



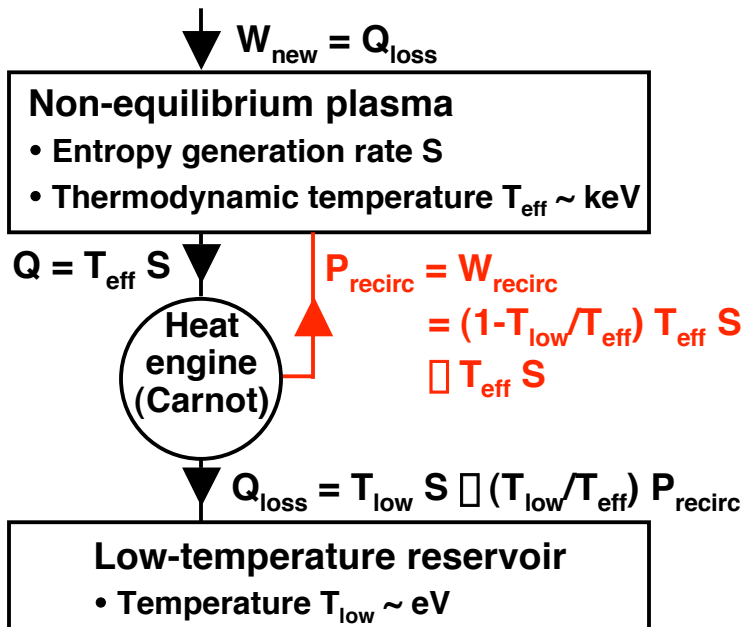
Minimum  $P_{\text{brem}}/P_{\text{fus}}$

D+T	0.007	} Feasible
D+ <sup>3</sup> He	0.19	
D+D	0.35	
<sup>3</sup> He+ <sup>3</sup> He	1.39	} Ouch
$p+^{11}\text{B}$	1.74	
$p+^6\text{Li}$	4.81	

# Required Power to Maintain Nonequilibrium Plasma



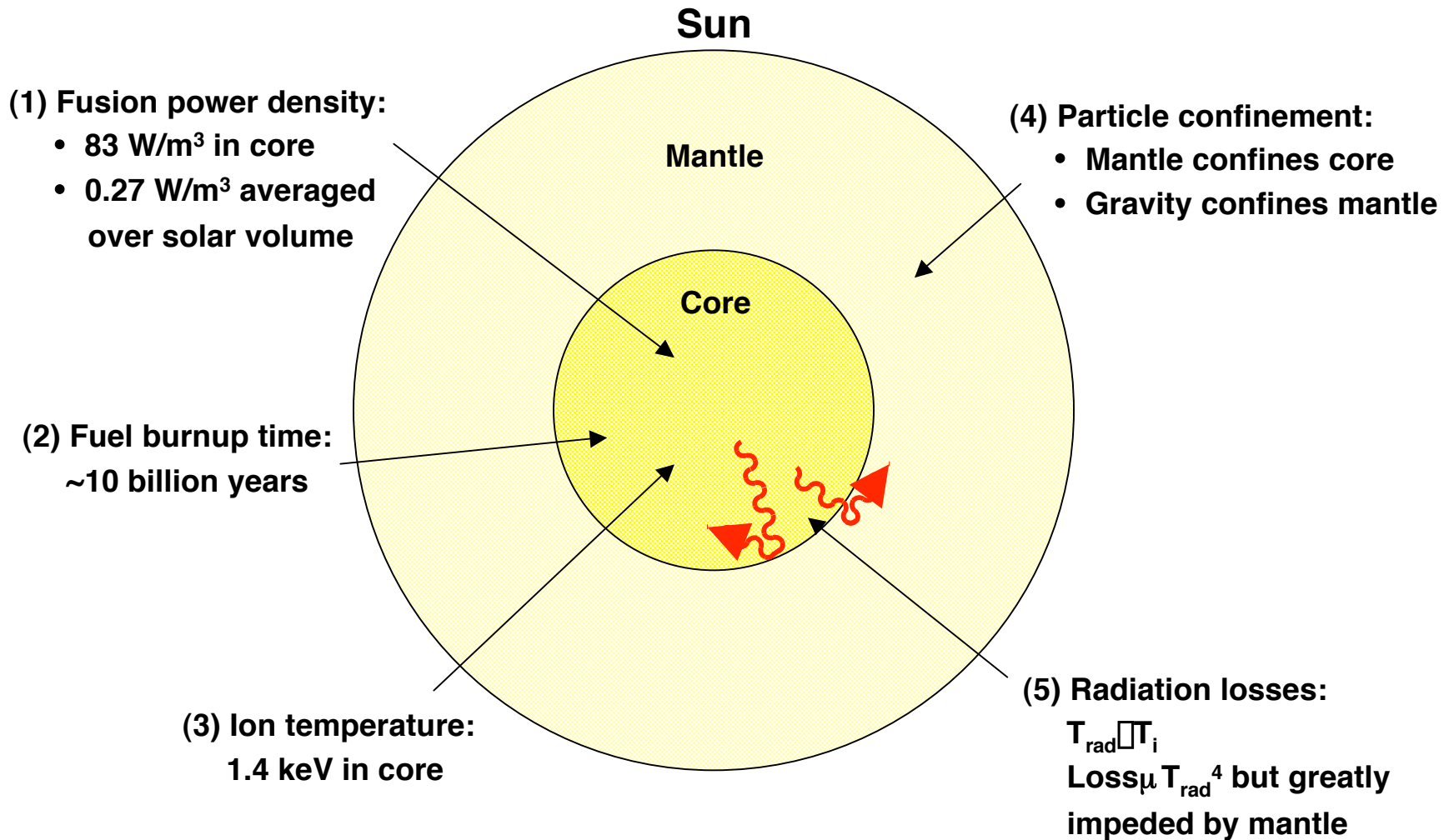
## Idealized System for Recirculating Power to Maintain a Nonequilibrium Plasma



- $P_{recirc}/P_{fus} \sim 5-50$  for most interesting cases
- Direct electric converters, resonant heating, etc. would lose too much power during recirculation
- Need novel approaches (e.g., nonlinear wave-particle interactions) that
  - Are >95% efficient
  - Recirculate the power *inside the plasma* without running  $P_{recirc} \gg P_{fus}$  through external hardware
  - Are resistant to instabilities

# Stellar Confinement of Fusion Plasma

## Key Differences from Fusion Reactors



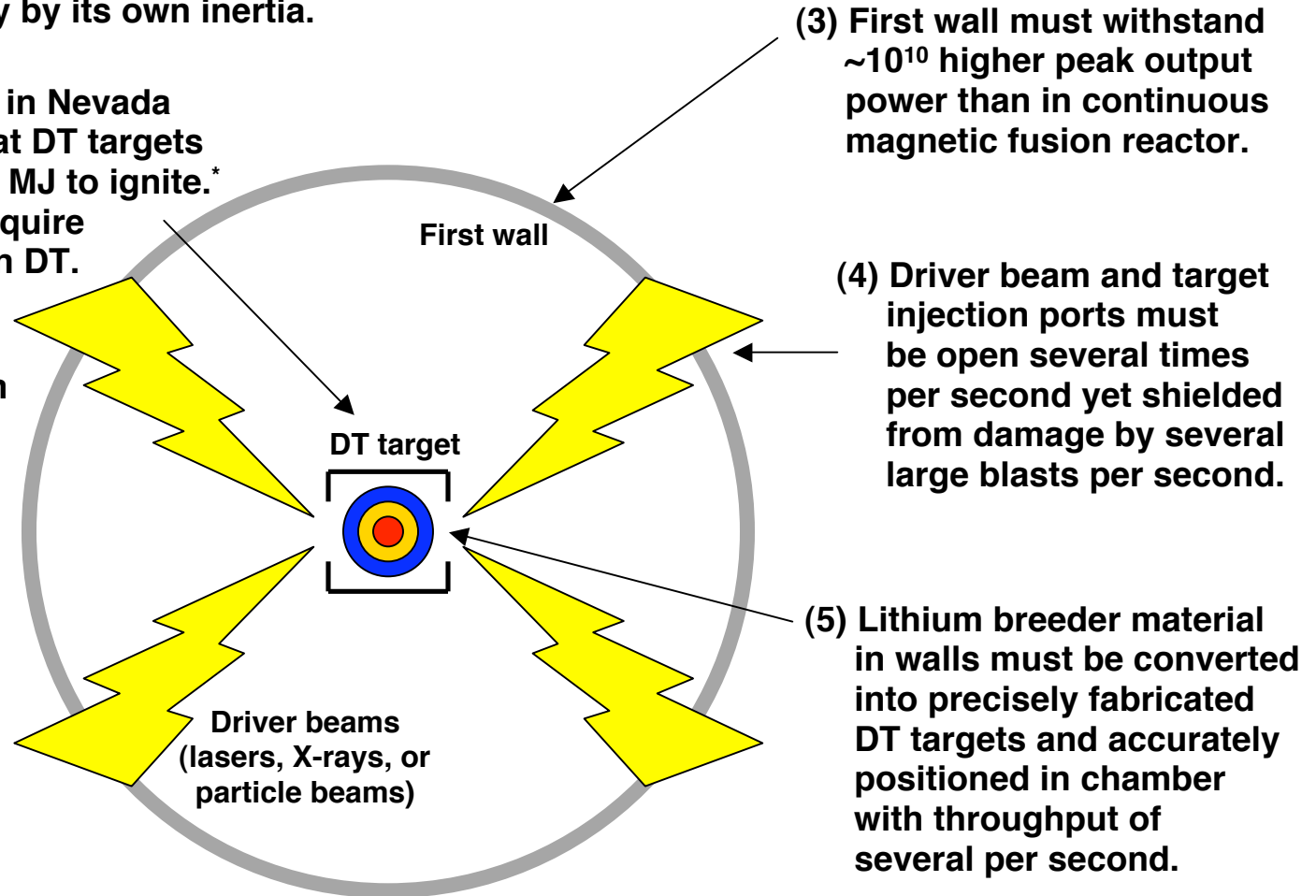
# Inertial Confinement of Fusion Plasma

- Density  $\sim$  stellar core & temperature  $>$  stellar core, so pressure  $>$  stellar core.
- Without weight of an entire star to confine it, plasma expands rapidly, limited only by its own inertia.

## Major problems:

(1) Halite-Centurian tests in Nevada apparently showed that DT targets might require up to 20 MJ to ignite.\* DD and D<sup>3</sup>He would require even more energy than DT.

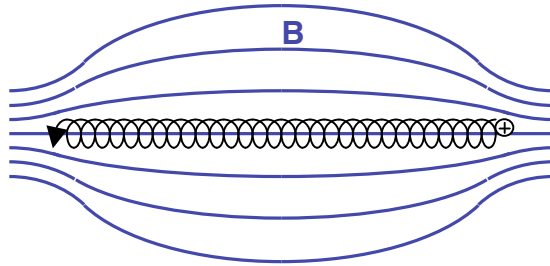
(2) Cost: National Ignition Facility (NIF) is  $>$ \$4B and is still not a full-fledged reactor (0.6 MJ driver energy).



\* C. E. Paine, M. McKinzie, and T. B. Cochran, *When Peer Review Fails* Natural Resources Defense Council, [www.nrdc.org/nuclear/nif2](http://www.nrdc.org/nuclear/nif2) (2000)

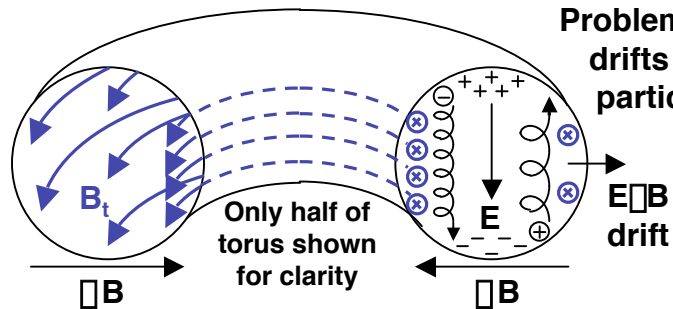
# Magnetic Confinement of Fusion Plasma

Charged particles spiral along magnetic field lines  $B$  and cannot easily cross them to escape



**Problem 1: Large particle losses at ends, even with magnetic mirrors, electrostatic plugs, etc.**

**Solution 1: Eliminate the ends by bending lines into a closed toroidal field  $B_t$**



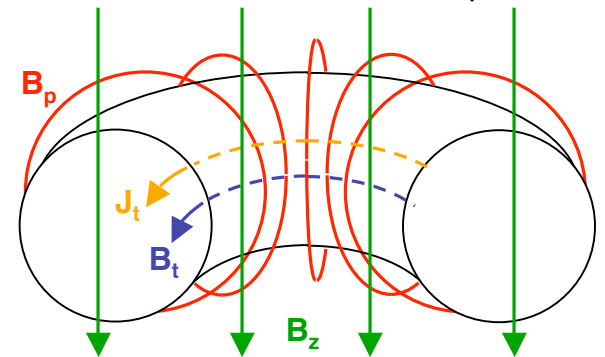
**Problem 2:  $\nabla B$  &  $E \times B$  drifts together let particles escape**

**Solution 2: Add poloidal field  $B_p$  to mix particles in inner & outer regions of torus**

**Goals (somewhat conflicting):**

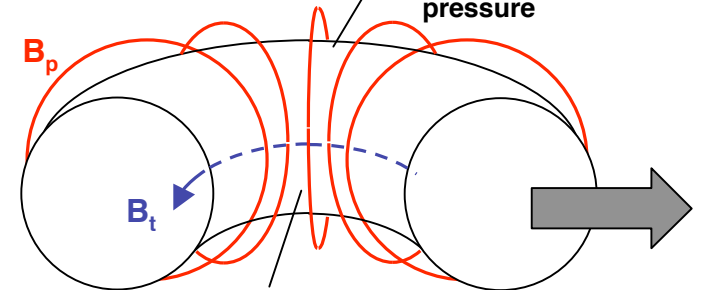
- Maximize  $\beta$  = plasma pressure / magnetic pressure
- Minimize  $B$  inside plasma to avoid cyclotron radiation losses
- Maximize fusion power density to minimize hardware cost
- Inner hardware subject to radiation damage is inexpensive and easily accessible
- Confine fuel ions and electrons but let charged products escape
- Provide for lithium-6 blanket if necessary

Tokamaks, stellarators, RFPs, FRCs, etc. differ in how they create the plasma current and  $B_t$ ,  $B_p$ , &  $B_z$



**Solution 3: Add vertical field  $B_z$  that acts on toroidal current  $J_t$  to balance outward forces on plasma**

Outer wall of torus:  
 • Less magnetic pressure  
 • More area for plasma pressure

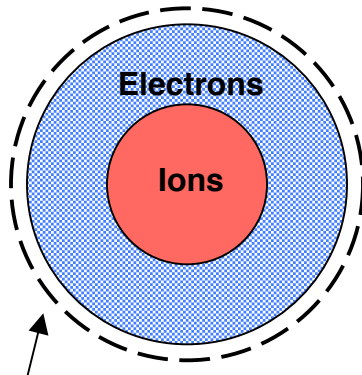


Inner wall of torus:  
 • More magnetic pressure  
 • Less area for plasma pressure

**Problem 3: Net outward force on plasma**

# Other Confinement of Fusion Plasmas (1)

## Electrostatic



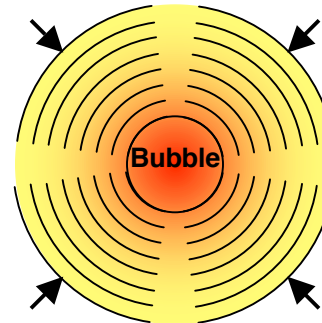
High-voltage grid  
or polyhedral cusp  
magnetic field

- Electron potential well confines ions but ion upscattering losses are prohibitive
- Grid or cusp field confines electrons but electron losses are prohibitive

T.H. Rider, *Phys. Plasmas*  
2, 1853 (1995)

## Acoustic (Sonoluminescence)

Acoustic waves in deuterated acetone

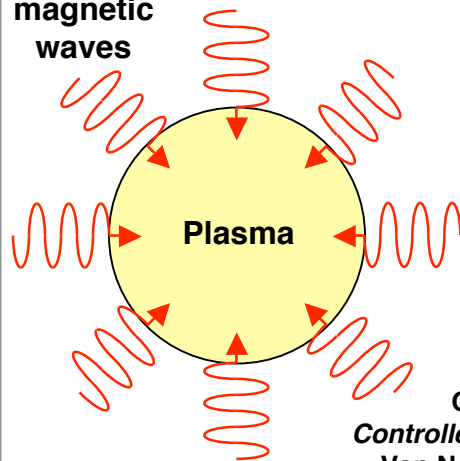


- Acoustic waves in the acetone compress bubbles to fusion conditions (?)
- Thermal conduction losses from heated region to surrounding liquid are prohibitive

R.P. Taleyarkhan *et al.*, *Phys. Rev. E* 69, 036109 (2004)  
D.J. Flannigan & K.S. Suslick, *Nature* 434, 52 & 33 (2005)

## Electromagnetic

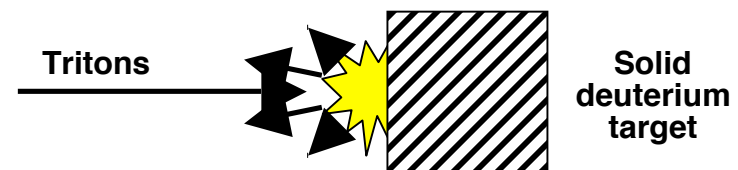
Electro-  
magnetic  
waves



- Electromagnetic wave pressure confines plasma
- Power input is prohibitive

Glasstone & Lovberg,  
*Controlled Thermonuclear Reactions*,  
Van Nostrand (1960), pp. 437-445

## Beam + Solid Target

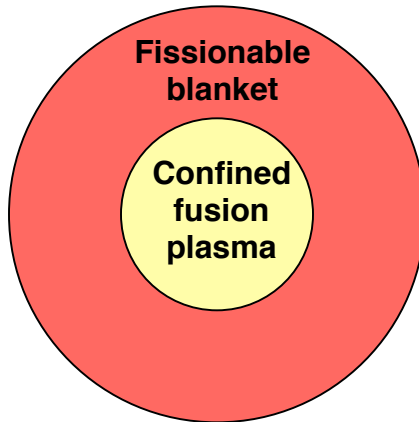


- Electrons in the target absorb far too much of the beam energy for breakeven

Glasstone & Lovberg, *Controlled Thermonuclear Reactions*, Van Nostrand (1960), pp. 64-68

# Other Confinement of Fusion Plasmas (2)

## Fusion-Fission Hybrid

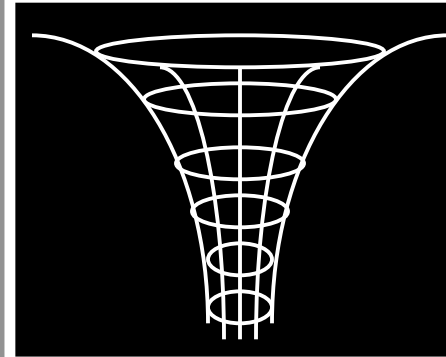


Has disadvantages of both fusion & fission:

- Fusion plasma requires expensive and complicated confinement system
- Fission blanket creates radioactive fission products and actinide waste

## Small Black Hole

Compresses and heats matter to fusion conditions before it reaches the event horizon

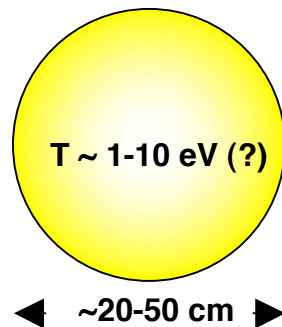


- No signs of natural small black holes in our solar system
- Creating a black hole via implosion is orders of magnitude more challenging than even ICF

L.L. Wood *et al.*, *Annals NY Acad. Sci.* 251, 623 (1975)

## Ball Lightning

Observed lifetime > 2-5 sec



- What is the confinement mechanism, especially in view of the virial theorem?
- Can this be applied to  $T > 10$  keV fusion plasmas?

Mark Stenhoff, *Ball Lightning*, Kluwer/Plenum (1999)  
K.H. Tsui, *Phys. Plasmas* 10, 4112 (2003)

- Are there other confinement approaches?
- Can one show that these ideas completely cover the phase space of confinement approaches?

# Conversion to Electrical Energy

## Heat

Carnot limit:

$$\text{Efficiency} < 1 - \frac{T_{\min}}{T_{\max}}$$

~ 0.3 - 0.4

for  $T_{\min} \sim 300^\circ\text{K}$ ,  $T_{\max} \sim 500^\circ\text{K}$   
(before something melts)

- Conventional methods add moving parts and fluids
- Thermoelectric conversion
- Thermoacoustic conversion

## Light nuclei ( $p^+$ , $\alpha$ , etc.)

Direct converter problems in magnetic plasmas<sup>1</sup>:

- Field that lets enough fusion products out lets too many fuel ions & electrons escape
- Arcing at high voltages and densities

Trav. wave direct converters?<sup>2</sup>

Other methods?

<sup>1</sup> Rosenbluth & Hinton, *Plasma Physics & Controlled Fusion* 36, 1255 (1994)

<sup>2</sup> Momota *et al.*, *Trans. Fus. Tech.* 27, 551 (1995)

## Heavy (e.g., recoil) nuclei

Travel <10 um in solids—

- Difficult for them to reach a direct electric converter before their K.E. becomes heat
- Widely spaced <10-um-thick sheets are theoretically feasible but generally impractical

Ronen, *Nucl. Instr. A522*, 558 (2004)  
Slutz, *Phys. Plasmas* 10, 2983 (2003)

## $\alpha$ and $\beta^+$

- Direct electric converters (generally most efficient when tuned to particular  $\alpha$  energy, but nuclear-emitted  $\alpha$  and electrons escaping from plasmas tend to have a range of energies)
- Let positrons annihilate and convert 511-keV photons

## Neutrons

Novel methods of extracting energy from:

- Neutrons directly???
- Recoil nuclei hit by neutrons
- (n, $\alpha$ )-produced gamma rays
- Electrons excited by those gamma rays

L.J. Perkins *et al.*, UCRL-93988 (1986)  
& *Nucl. Instr. Methods A271*, 188 (1988)

## Photons (esp. X & $\gamma$ rays)

Let photons impart their energy to electrons via:

- Photoelectric effect
- Compton scattering
- Pair production
- Etc.

Then extract that energy from the electrons

L.L. Wood *et al.* UCID-16229 & 16309 (1973)

# Fundamental Constraints on Fusion Approaches

## (Barring Miracles—Wait One Slide...)

### Fusion approaches that cannot work

- Nonmagnetic confinement (inertial, electrostatic, electromagnetic, and acoustic), excluding stars and bombs
- Plasma systems operating substantially out of thermodynamic equilibrium
- Advanced aneutronic fuels ( $^3\text{He}+^3\text{He}$ ,  $\text{p}+^{11}\text{B}$ ,  $\text{p}+^6\text{Li}$ , etc.)
- Most high-efficiency direct electric converters

### Best foreseeable 1 $\text{GW}_e$ (3 $\text{GW}_t$ ) magnetic fusion reactors:

- D+T: 2.4 GW of 14-MeV neutrons, 1.6 giga-Curies (G Ci) of T stockpile/year
- D+D w/o product burnup: 1 GW 2.5-MeV neutrons, 1 GW X-rays, 70 G Ci T
- D+D with product burnup: 1.1 GW mainly 14-MeV neutrons, 180 MW X-rays
- D+ $^3\text{He}$  w/o product burnup: 30 MW 2.5-MeV neutrons, 500 MW X-rays, 1.8 G Ci T
- D+ $^3\text{He}$  with product burnup: 150 MW mainly 14-MeV neutrons, 500 MW X-rays
- Mainly thermal (Carnot-limited) conversion of fusion energy to electricity

# Potential Thesis (or Nobel Prize) Topics

## Fusion reactions

- In the table of possible fusion reactions, should additional reactions be green? (Consider competing side reactions and idealized breakeven against bremsstrahlung.)
- Are there any promising reactions not in the table (due to higher Z or shorter nuclide half-life)?

## Can one provide better evidence (especially experimental) for or against spin polarized fusion?

- Benefits of spin-polarized fusion (especially for D+D reaction enhancement or suppression).
- Methods of producing polarized nuclei.
- Mechanisms and rates of depolarization relative to the fusion rate.

## Fusion catalyzed by massive negative particles

- Are there more efficient muon production methods?
- Are there practical methods for unsticking muons from alpha particles?
- Are there methods to reduce the muon catalysis cycle time?
- Are there any massive negative particles that are more suitable than muons for catalysis?
- Can the effective electron mass or charge be increased in useful ways?

## Other ways to improve the tunneling factor

- Is there a way to keep scattering from hindering shape-polarized fusion?
- Is the resonant tunneling model valid, and does it have useful consequences?
- Is fusion of light elements in liquid metallic states scientifically valid and practical to achieve?
- Are there other ways to improve the tunneling factor?
- Can one prove we have covered the complete phase space of ideas for improving the tunneling factor?

## Other improvements to $\sigma_{fus}$

- Are there ways to improve the wavefunction cross-sectional area factor in  $\sigma_{fus}$ ?
- Are there ways to improve the Breit-Wigner compound nucleus energy resonance factor in  $\sigma_{fus}$ ?
- Are there any other categories of ways to influence  $\sigma_{fus}$ ?

# More Potential Thesis (or Nobel Prize) Topics

## Fusion products

- Are there practical ways to influence the reaction channels and products?

## Plasma properties

- Are there realistic ways to recirculate power and maintain ions in a monoenergetic or anisotropic state, or two ion species at different temperatures (e.g. hot  $^3\text{He}$  and cold D or hot  $\text{p}^+$  and cold  $^{11}\text{B}$ )?
- Are there practical ways to reduce ion-electron energy transfer or recirculate power from the electrons back to the ions?
- Are there ways to reduce/convert radiation power losses, especially bremsstrahlung?

## Confinement of particles and energy

- Are there practical lessons we can learn from stellar fusion and use to improve fusion reactors?
- Are there ways to overcome the main practical difficulties with inertial confinement fusion?
- Which existing magnetic confinement approach is best, or can a better one be created?
- Can the conduction losses be reduced to make acoustic confinement practical?
- Can fusion-fission hybrids be made more attractive?
- How is ball lightning confined, and can fusion reactors employ a similar approach?
- Is there any feasible way to create a small black hole?
- Are there any other confinement approaches worthy of investigation?

## Direct conversion

- What are the most efficient/compact thermal-to-electric converters?
- What are the best converters for light nuclei—traveling wave converters, etc.?
- Are there practical ways to directly convert the energies of recoil nuclei or other heavy nuclei emitted by solid materials?
- What are the best converters for electrons?
- How feasible and efficient are the neutron energy conversion methods of Perkins *et al.*?
- How feasible and efficient are the X-ray and  $\gamma$ -ray energy conversion methods of Wood *et al.*?

# Binding Energy per Nucleon And Methods of Tapping It

