Fusion without Neutrons Using protons & Boron-11 Fuel

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April 20, 2006: 22.012 Fusion Seminar (MIT)

D-T Fusion

$$D + T \rightarrow \alpha + n + 17.6\ MeV$$

α: $3.5\,MeV$ $\quad$ n: $14.1\,MeV$

- What is GOOD about this reaction?
  - Highest specific energy of ALL nuclear reactions
  - Lowest temperature for sizeable reaction rate
- What is BAD about this reaction?
  - NEUTRONS => activation of confining vessel and resultant radioactivity
  - Neutron energy must be thermally converted (inefficiently) to electricity
  - Deuterium must be separated from seawater
  - Tritium must be bred

Consider Another Nuclear Reaction

$$p + {}^{11}B \rightarrow 3\alpha + 8.7\ MeV$$

- What is GOOD about this reaction?
  - Aneutronic (No neutrons => no radioactivity!)
  - Direct electrical conversion of output energy (reactants all charged particles)
  - Fuels ubiquitous in nature
- What is BAD about this reaction?
  - High Temperatures required (why?)
  - Difficulty of confinement (technology immature relative to Tokamaks)

DT Fusion – Visual Picture

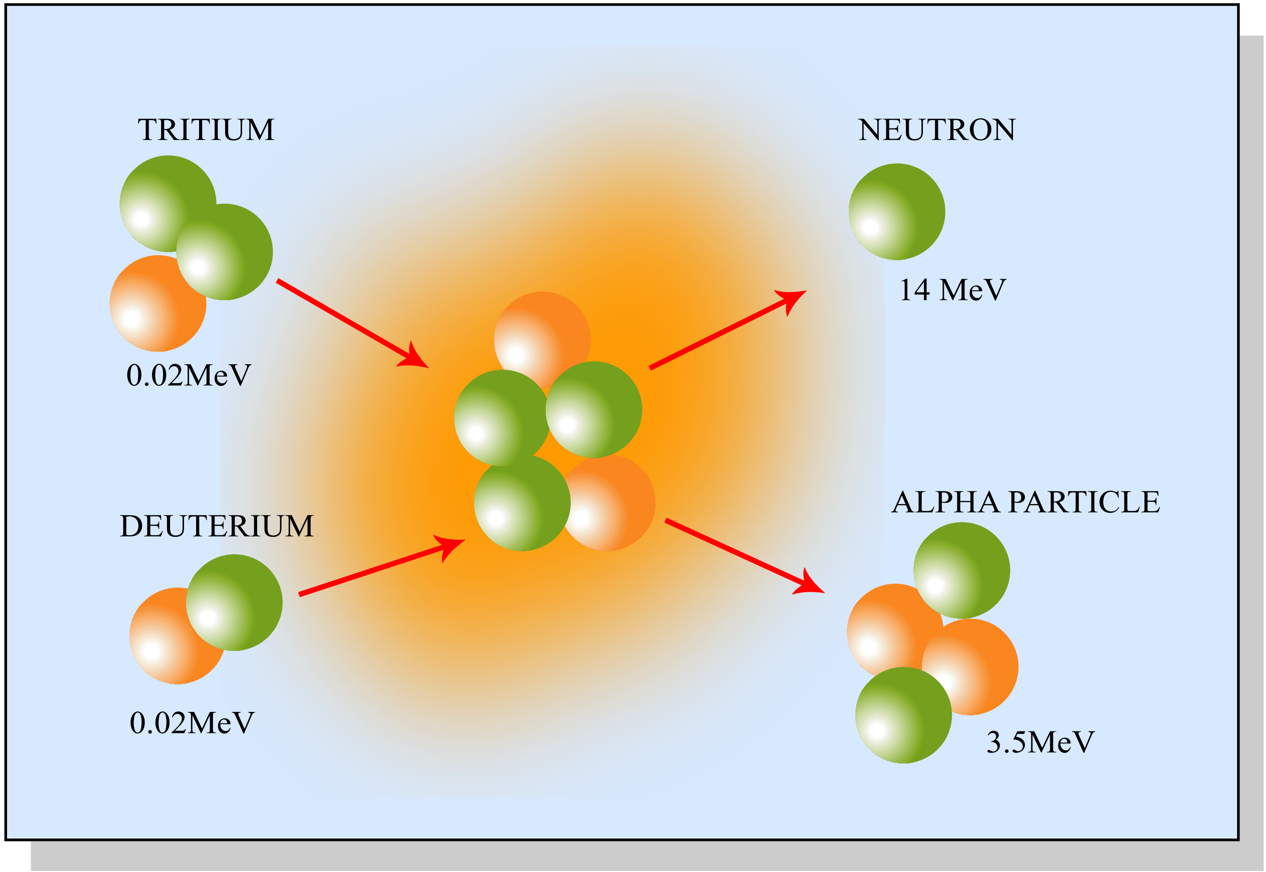
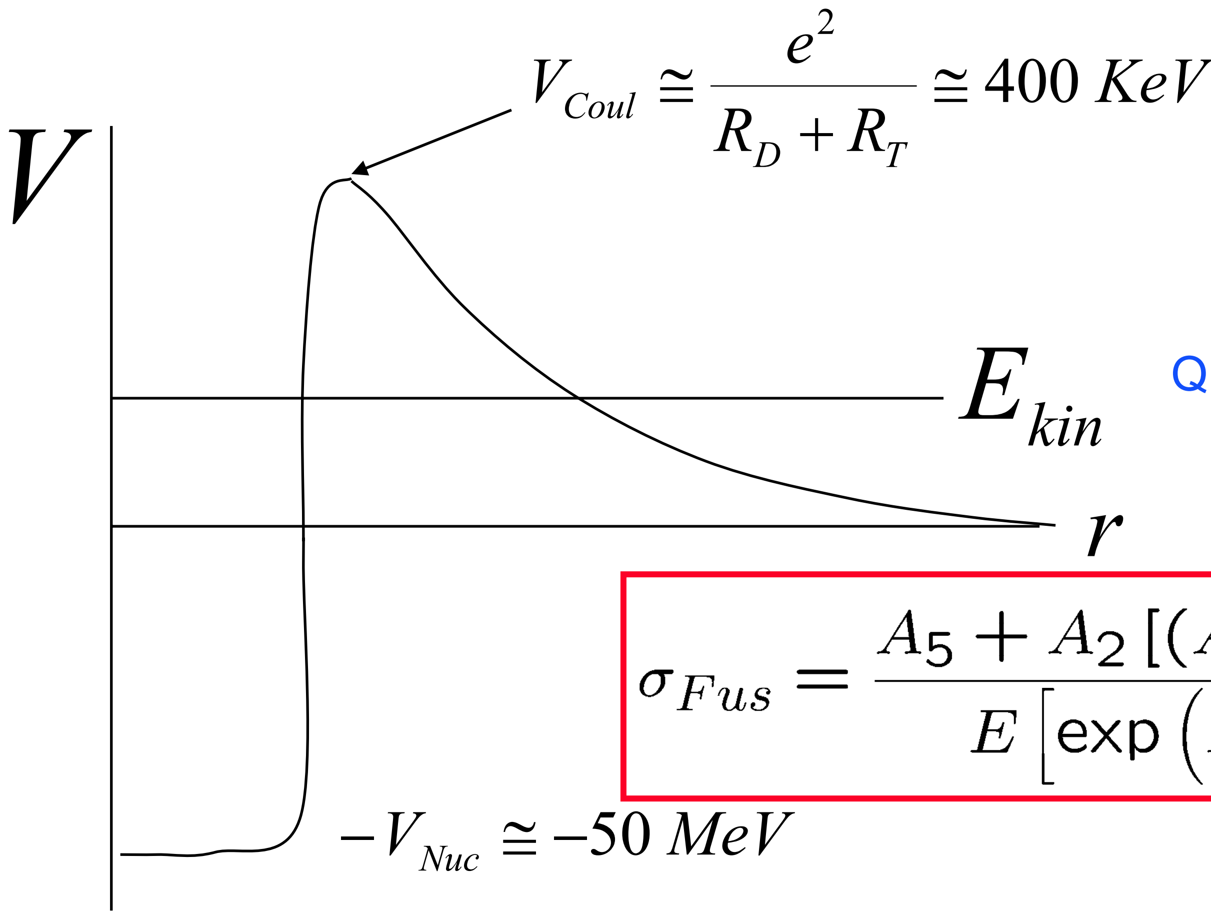


Figure by MIT OCW.

Energetics of Fusion



QM “tunneling” required . . .

Empirical fit to data

$$\sigma_{Fus} = \frac{A_5 + A_2\left[(A_4 - A_3 E)^2 + 1\right]^{-1}}{E\left[\exp\left(A_1 E^{-1/2}\right) - 1\right]}$$

$A_1 = 45.95,\ A_2 = 50200,\ A_3 = 1.368\times10^{-2},\ A_4 = 1.076,\ A_5 = 409$

Coefficients for DT (E in KeV, σ in barns)

Tunneling Fusion Cross Section and Reactivity

$$\sigma_{Fus}(E) = \frac{S(E)}{E}\exp\left(-\sqrt{\frac{E_G}{E}}\right)$$

Gamow factor . . .

$$E_G = \left(\frac{2\pi e^2 Z_1 Z_2}{\hbar c}\right)^2 \frac{\mu c^2}{2}$$

$$E_G \approx 22{,}589\ KeV \quad for \quad p - {}^{11}B$$

Compare to DT . . .

$$\langle \sigma v \rangle_{Fus} \equiv \int d^3 v_i d^3 v_j f(v_i) f(v_j) \left| v_i - v_j \right| \sigma\left(\left| v_i - v_j \right| \right)$$

$$= \sqrt{\frac{8T}{\pi\mu}} \left(\frac{1}{T_{eff}}\right)^2 \int_0^\infty dE E \sigma(E) \exp\left(-\frac{E}{T_{eff}}\right)$$

$$= \sqrt{\frac{8T}{\pi\mu}} \left(\frac{1}{T_{eff}}\right)^2 \int_0^\infty dE S(E) \exp\left[-\left(\sqrt{\frac{E_G}{E}} + \frac{E}{T_{eff}}\right)\right]$$

$$T_{eff} = \frac{m_1 T_1 + m_2 T_2}{m_1 + m_2}$$

Reactivity for DT Fuel

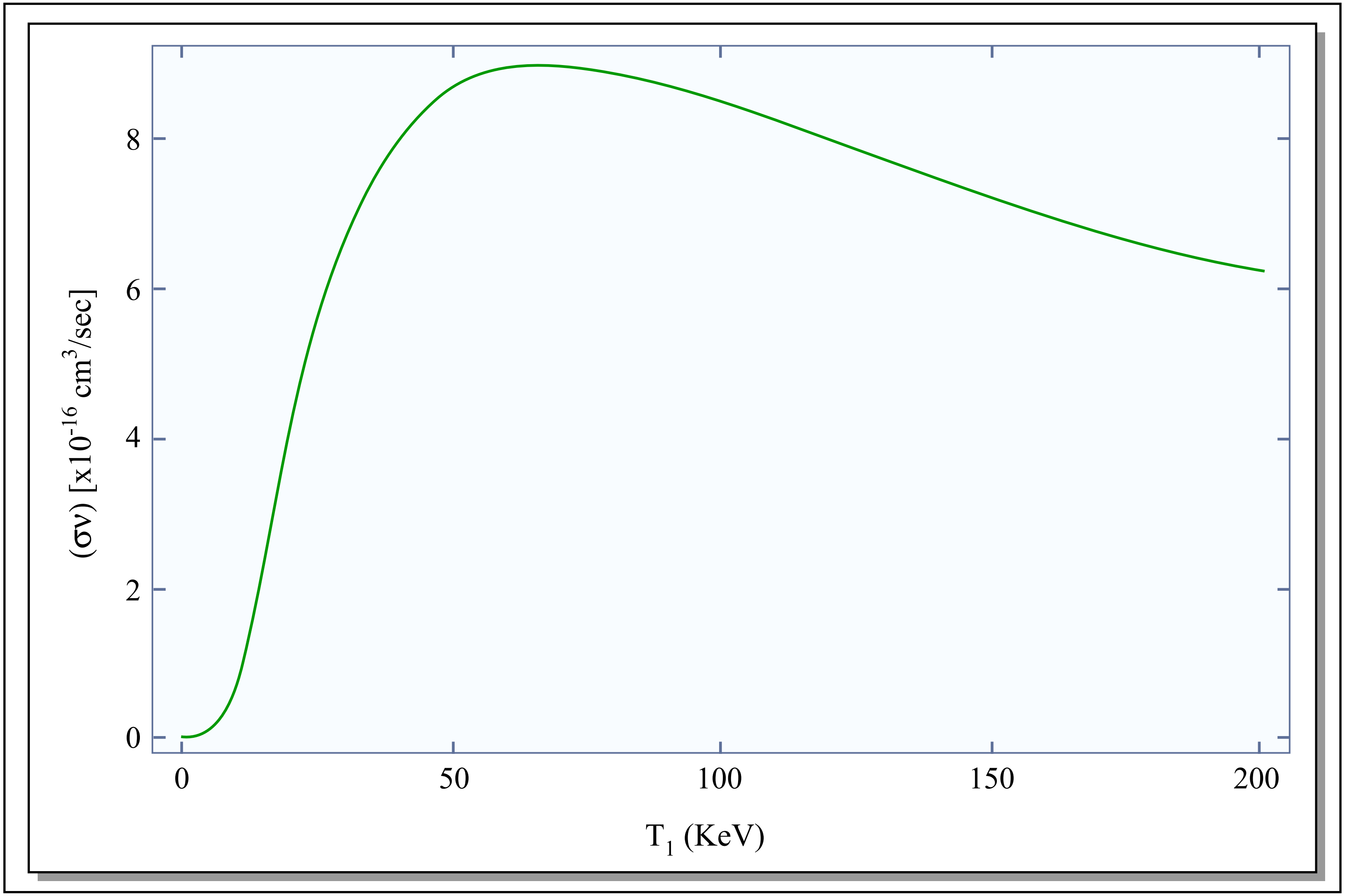
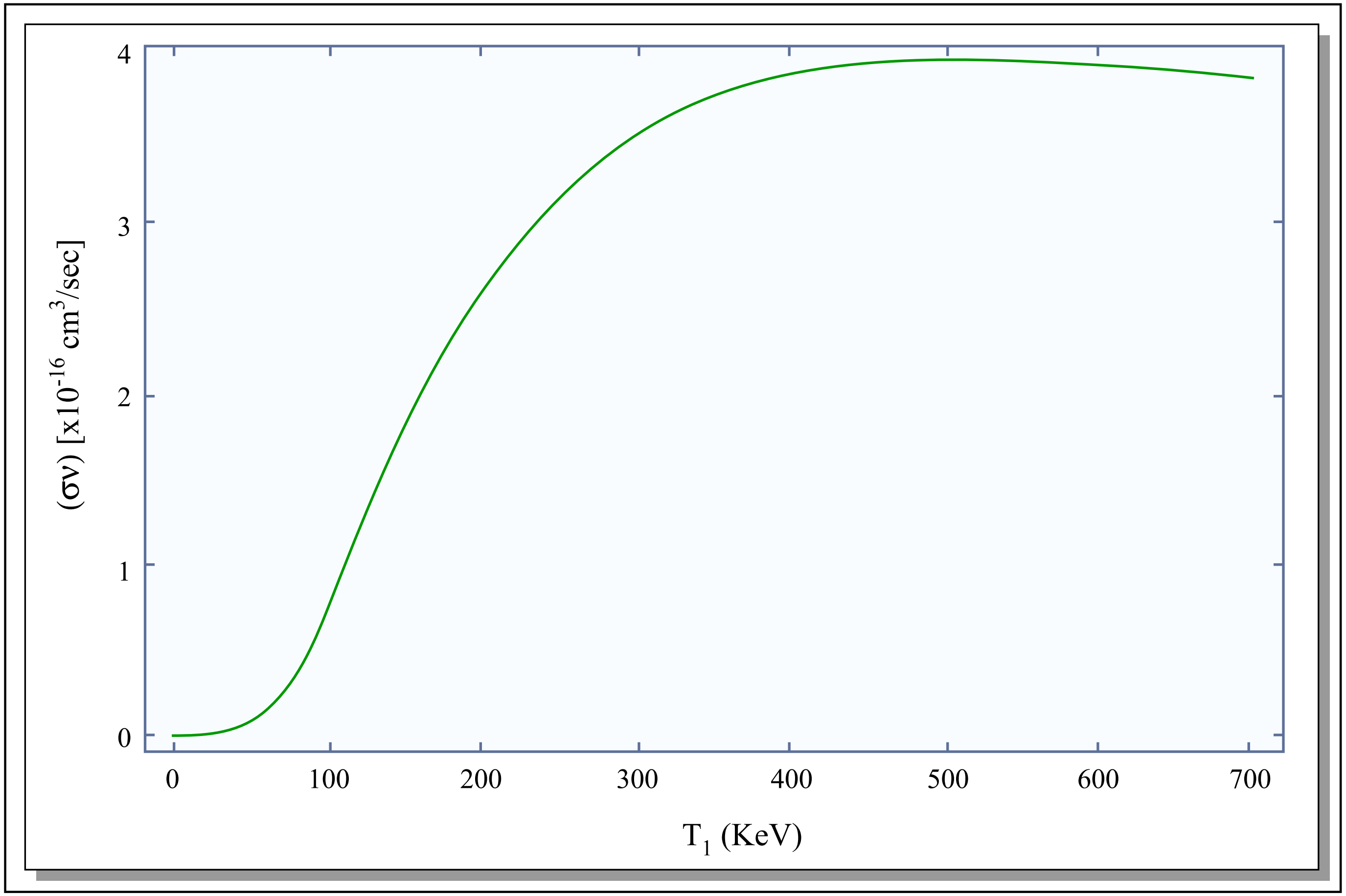


Figure by MIT OCW.

Reactivity for proton-Boron Fuel



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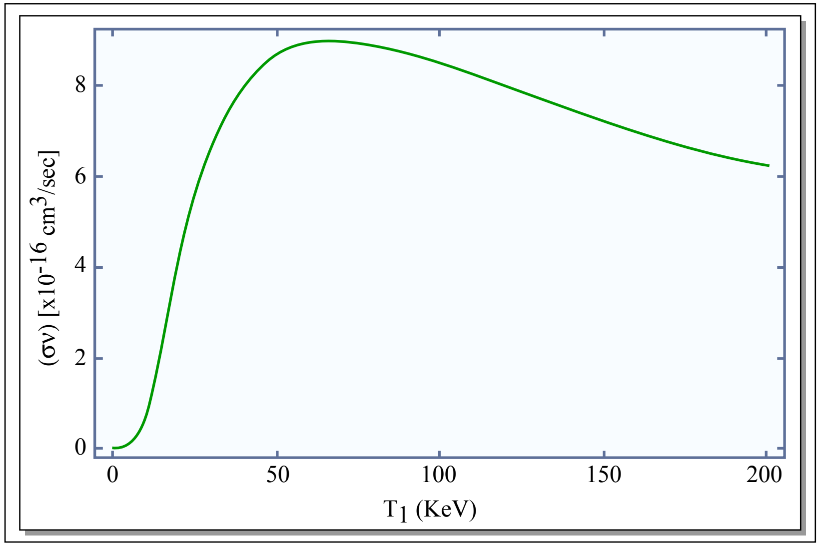
Comparison Reactivities



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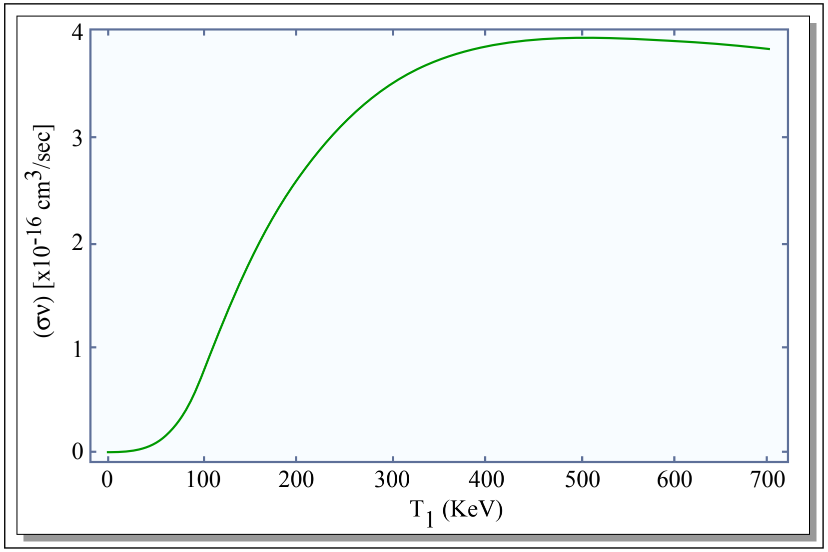

Figure by MIT OCW.

Availability of Fuel

- Protons?
- => Overwhelmingly available in seawater (deuterium extraction not even required!)
- Boron?
- Widely found in nature as alkali or alkaline borates or as boric acid (Boron11 constitutes 80.2% of the natural abundance)

Power Density Comparison

p - ^{11}B has almost 3 times the alpha energy of DT, so even with ½ the reactivity it produces LARGER alpha heating than DT => in that sense self-sustaining fusion is easier to maintain if high temperatures can be stably confined.

$$P_{Fus} = E_\alpha \langle \sigma v \rangle_{fus} n_p n_B$$

Example Numbers:

$$\begin{aligned} T &= 250 \quad KeV \\ n_p &= 0.5 \times 10^{15} \\ n_B &= 1.0 \times 10^{14} \\ P_{Fus} &\simeq 22 \; Watts/cm^3 \end{aligned}$$

Compare to losses (Bremstrahlung):

$$\begin{aligned} P_B &= 5.34 \times 10^{-31} n_e^2 T_e^{1/2} Z\_eff \\ &= 26 \quad Watts/cm^3 \end{aligned}$$

Whoops!

How to beat Bremstrahlung losses?

- Some Radiation can be recovered via wall aborption and conversion
- But really must Run at lower electron temperature:

$$T_e < T_i$$

- Example:

$$T_e = 85\ KeV$$

$$T_i = 235\ KeV$$

$$P_B = 16\ Watts/cm^3$$

$$P_{Fus} = 20\ Watts/cm^3$$

- Still marginal Power balance

ITER Comparison for Reference

$$P_{Fus} = E_{Fus} \langle \sigma v \rangle_{fus} n_1 n_2$$

$$\begin{aligned} T &= 10 \quad KeV \\ n_D &= 0.5 \times 10^{14} \\ n_T &= 0.5 \times 10^{14} \\ B &= 5.0 \ Tesla \\ P_{Fus} &\simeq 2 \ Watts/cm^3 \\ P_B &= 0.1 \ Watts/cm^3 \end{aligned}$$

What losses dominate in this Tokamak scheme?

Requirements for Aneutronic Fusion

- Magnetic Pressure must balance particle pressure for confinement:

$$\frac{B^2}{8\pi} > (n_e T_e + n_i T_i)$$

$$\frac{B^2}{8\pi n} \approx 248\,KeV \;@\; n = 1\times 10^{15} \;\&\; B = 10\,Tesla$$

- ⇒ High beta plasma
- $T_e < T_i$
- Highly efficient direct energy recovery system (High recirculating power levels)

Field Reversed Configuration (FRC)

Diagram removed for copyright reasons.

See Figure 1 in Rostoker, N., A. Qerushi, and M. Binderbauer. "Colliding Beam Fusion Reactors.“ *Journal of Fusion Energy* 22, no. 2 (June 2003): 83-92.

Questions

- What about "negative" moving ions?
- What about electrons?

Formation Scenario

- Form cold target plasma in axial guide field
- Blast target plasma with proton and Boron beams at high energy
- This provides fuel, initial heating and confining current (electrons confined by positive electrostatic potential)
- Assume power balance all works out and one has a “win” that is self-sustaining thermonuclear fusion
- Collect energy (direct electric conversion) from escaping alphas

FRC Formation

Figure removed for copyright reasons.

A different view of the FRC configuration.

Problems?

- Do you recognize this geometry from schemes presented during semester?
- It's an elongated Tokamak tiped sidewise with no toroidal magnetic field!!??
- What gross stability issues would worry you?
- Kink & Sausage modes (toroidal varieties) – gross MHD instability like Z-pinch
- Proposed to be "solved" via high energy, large orbit ions – system surely NOT MHD -- and possibly feedback control
- Efficiency requirements for ion beam systems, alpha and radiation energy recovery are daunting
- Some FRC properties demonstrated experimentally but BIG scale ups in all physical parameters will be required

The Challenge

**If this Aneutronic fusion scheme
can be realized in practice
it is without question
THE technology
for electrical power production
world-wide**

A Good

Basic Science

Research Problem