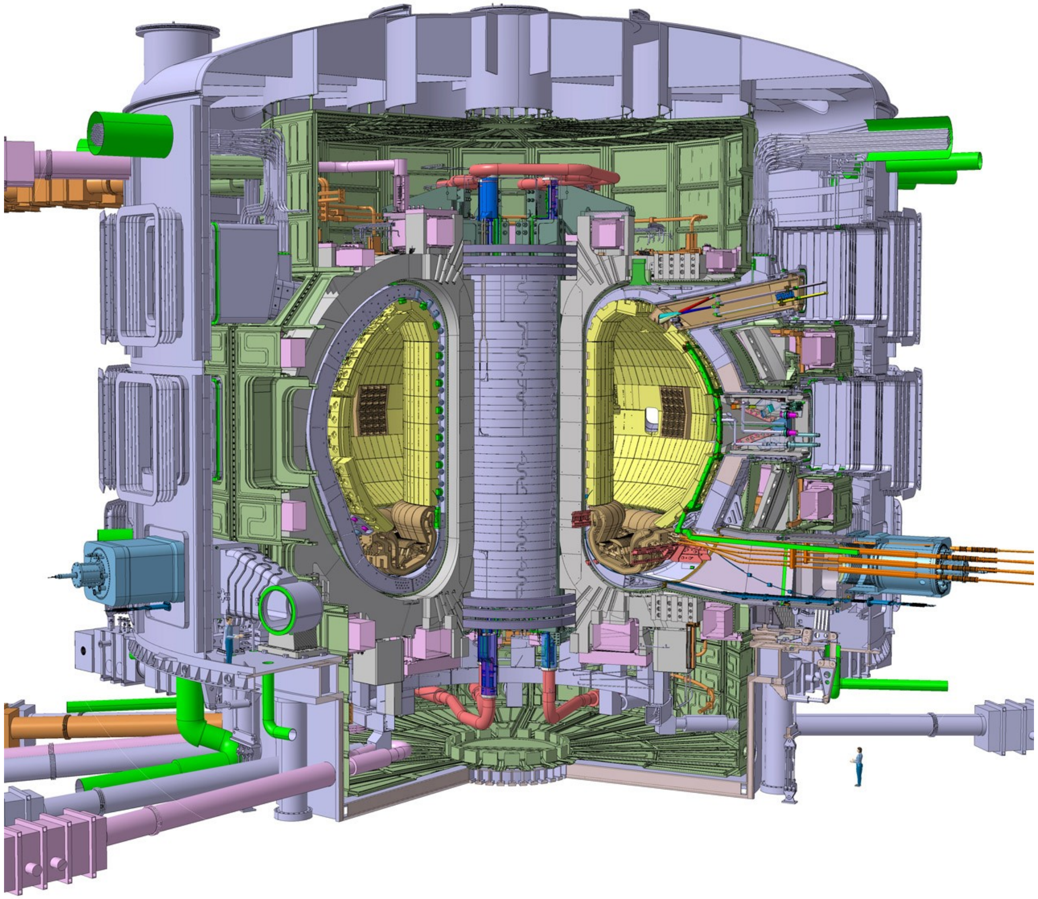


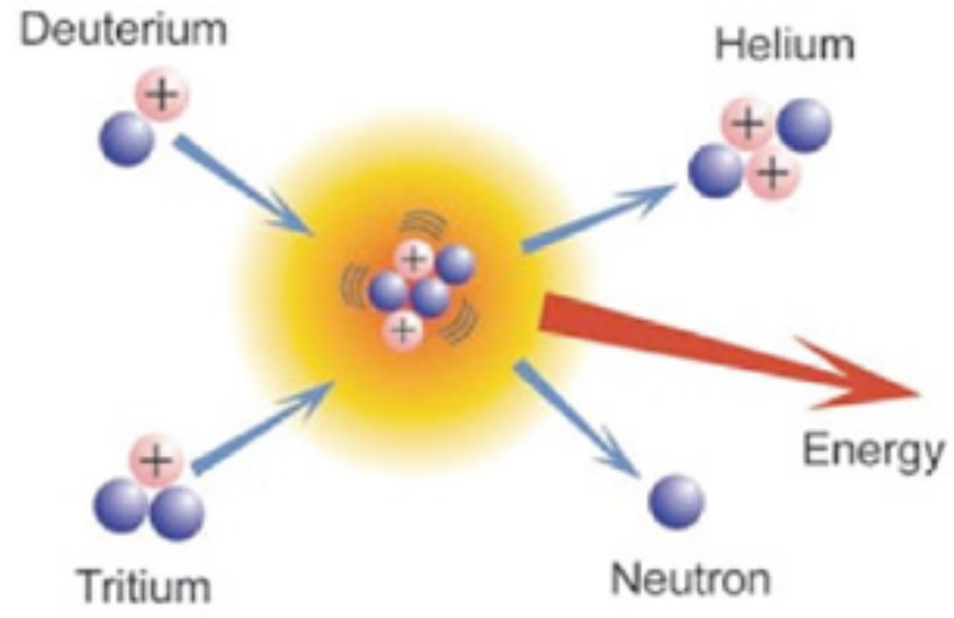
# Steps towards ITER

Extending plasma physics from experimental study to fusion power

Julian Gifford

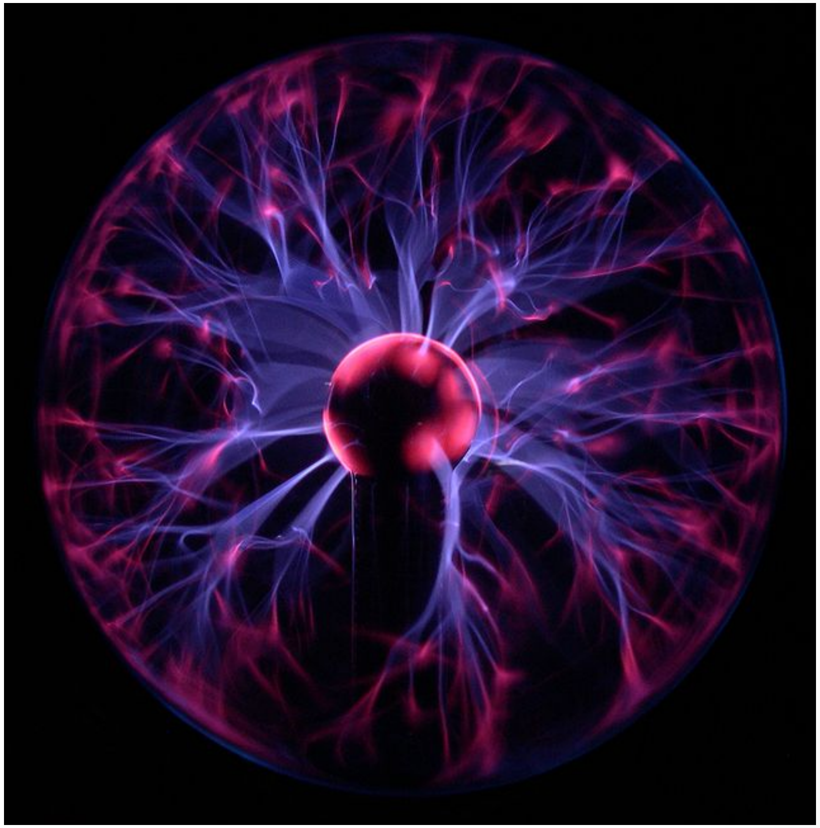
# Where are we Going?

- Plasmas - P
- The Tokamak - T
- Fusion Energy - F
- ITER - I



# (P) What even is it?

- $4^{th}$ state of mater
  - Most common state
- "Ion soup"
  - Electron gas
  - Atomic (n and i) gas
- 'Complex system'
  - Thermal interactions
  - EM interactions
  - Non-equilibrium Stat Mech



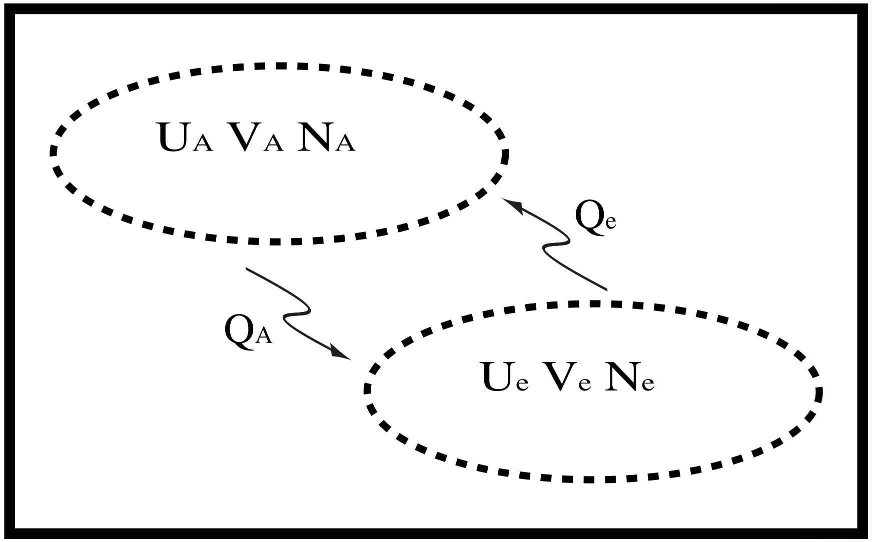
# (P) Descriptions

- *State* of matter: Bulk Properties
- Temperature
  - $\frac{\langle KE \rangle}{K_b}$ or $\frac{\partial U}{\partial S}$
  - Thermal v Non-Thermal (*Equilibrium*)
    - $M_e \ll M_A$
  - Electron Temperature – measure of DoI

- Degree of Ionization
  - Plasma (electron) density : $\frac{N_e^{free}}{V}$
  - "Hot" and "Cold" plasmas
    - Alternative definitions

# (P) Stat Mech to Saha -1

- Discussing bulk properties of matter requires Stat Mech
- *Non*-equilibrium




- (2) $dS = \sum_n dS_n \geq \sum_n \frac{\delta Q_n}{T_n}$
- (1) $dU_n = \delta Q_n - \delta W_n$

$$\delta Q_n = dU_n + p_n dV$$

$$\sum_n dS_n \geq \sum_n \frac{dU_n + p_n dV}{T_n} \qquad 0 \geq \sum_n \frac{dU_n}{T_n} - dS_n + \frac{p_n dV}{T_n}$$

- Fixed T and V: $(d\Im)_{T_n,V} \leq 0$
- *Generalized* Free Energy: Units of S, handles multiple Tn

# (P) Stat Mech to Saha -2

- From Generalized Free Energy, use equilibrium SM machinery:

$$\Im = -\sum_n k_b \ln[Z_n(T_n)] = -k_b \ln[Z_e(T_e) Z_A(T_A)]$$

- Standard (canonical) ideal gas partition functions:

$$Z_c = \sum_\Gamma g_i(\Gamma) e^{-\frac{E_i(\Gamma)}{k_b T}}$$

- Leads to generalized Saha Equation

$$\frac{n_e n_{A^+}^\Gamma}{n_{A^0}^\Gamma} = \frac{g_e g_{A^+}^\Gamma}{g_{A^0}^\Gamma} \left[\frac{2\pi m_e k_b T_e}{h^2}\right]^{3/2} e^{-\frac{(E_+ - E_0)}{k_b T_e}}$$

- Degree of ionization depends on *electron* temperature

# (P) Stat Mech works…So what?

- DoI tells us about amount of charge
  - Net neutral, just separated
- Existence of separated charges means plasmas are strongly EM active
  - Dominates over thermal gas kinetics
  - Plasmas deal with bulk EM interactions

# (P) EM Interactions

- Electric:
  - Get currents – RLC circuits
  - Plasma potential. Exists, but:
    - High conductivity means small Electric Fields
  - Debye length measures strength of electrostatic interactions and length of influence
  - Shielding outside Debye sphere
- Magnetic:
  - Magnetic fields are generated by currents
    - “Plasma heating” EMF due to change in current
  - Existence of charges means plasmas are sensitive to external magnetic fields

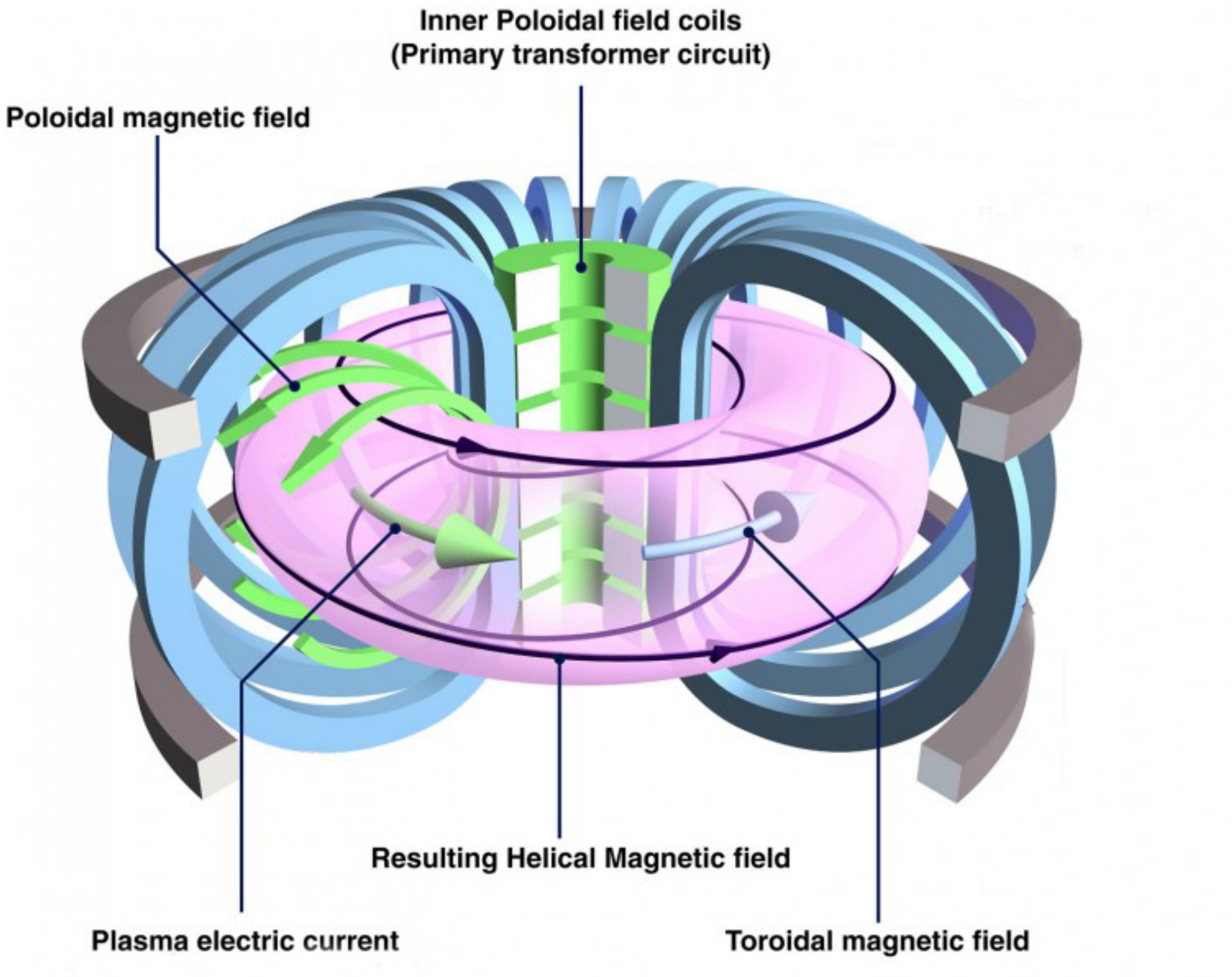
# (P) Complex EM behavior

- RLC Circuits, inductance, plasma heating
- Filamentation (lightning)
- Double layers
- Non-neutral vs. quasi-neutral
    - E vs. B
- Cellular structure

# (T) Controlling Plasmas

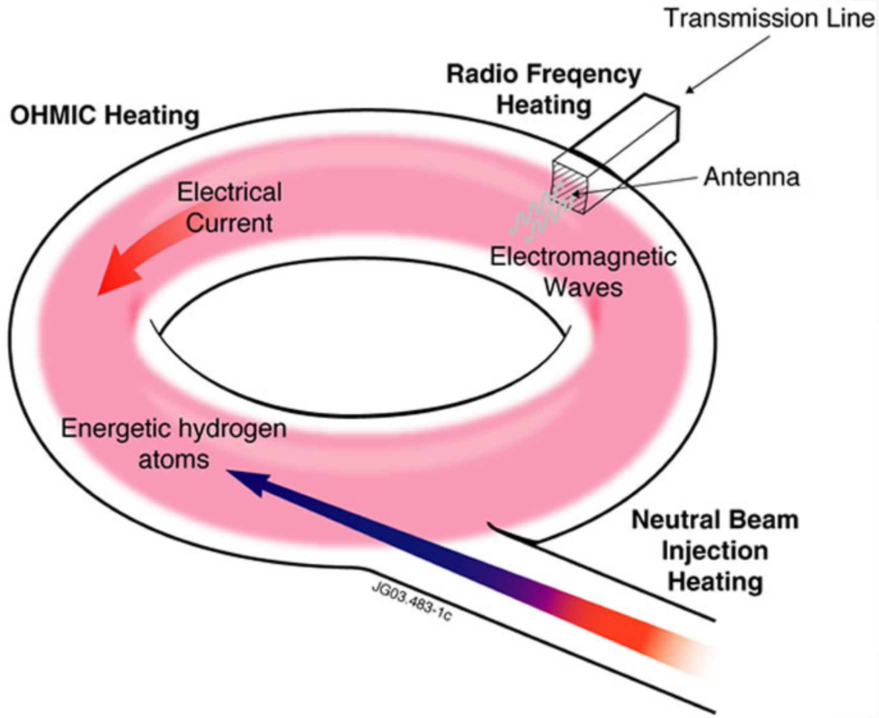
- Plasmas are hot
- Quasi-neutrality requires magnetic confinement
- Tokamak (1968):
  - Two B fields:
    - Toroidal – simple electromagnet
      - Generates uniform B field along toroid
      - Lorentz force alters turns radial motion into toroidal motion
    - Poloidal – Transformer (mutual inductance)
      - Changing magnetic flux in plasma induces current and poloidal field
        - Pulsed process
      - Lorentz force keeps current in center of 'doughnut'
    - Together they make a helical B-field that confines plasma
  - Only charged particles are confined

# (T) Tokamak B-Fields



# (T) Heating

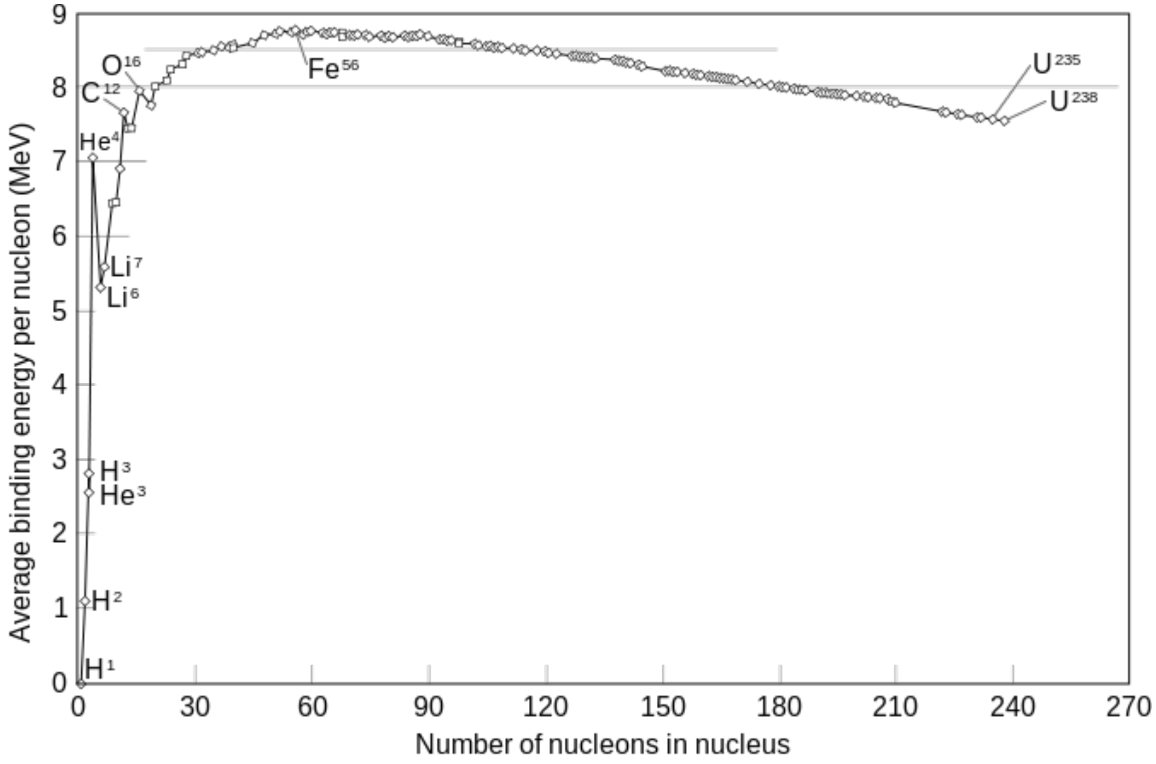
- Plasma current leads to Ohmic Heating
  - Max temperature from OH: 20-30 million degrees Celsius
  - Limited by max primary coil current and decreasing plasma resistance




- Fusion needs T > 100 million degrees Celsius
  - Neutral-beam injection
    - Charged Deuterium accelerated and neutralized
  - RF Heating
    - EM Waves heat by ‘microwaving’

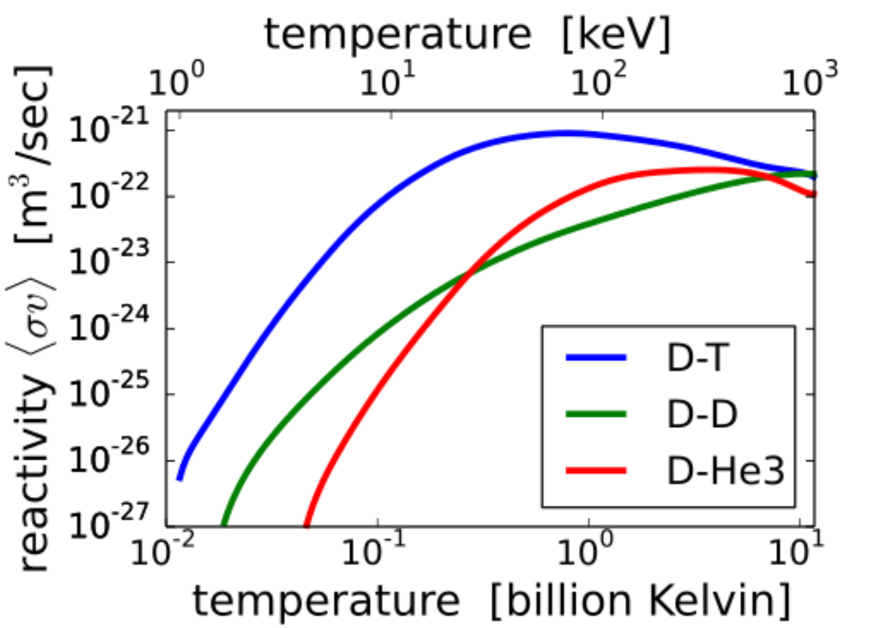
# (F) The Fusion Reaction

- Hot nuclei get close enough that the strong interaction overcomes EM repulsion
- Fusion of light nuclei is exothermic (H + H → He + E)



# (F) Heavy is better

- The sun fuses H-H → He + E at 15 million Celsius
- Best bet for earth fusion:
  - D-T → $He^4 + n_0 + E$ at 150 million Celsius
  - σ is reaction cross section
  - 'Coldest' reaction



# (I) The business side

- ITER (International Thermonuclear Experimental Reactor)
  - 7 countries, 16 billion Euro, delayed to 2027
- Largest Tokamak
  - 830 $m^3$ plasma volume (Twice as big as JET)
- Will use D-T fusion reaction
  - Deuterium is common, 33 mg per liter of sea water
  - Tritium is rare – global inventory of ~ 20 kg
- 1000 MW coal-plant needs 2.7 million tons of coal/year
  - ITER will need 175 kg D and 175 kg T (Really Li eventually)

# (I) Major Features

- Expanded plasma volume means increased power output
  - JET has output power record: 70% of input power
  - Tore Supra duration time record: 6.5 minutes
  - ITER will reach plasma energy breakeven
    - 50 MW input, 500 MW output
    - Hopes to sustain plasma duration for 16.5 minutes
- Will breed rare and necessary Tritium
  - Ejected neutron from fusion reacts with Lithium breeding blanket
  - $n_0 + Li \rightarrow T + He$
- Passing breakeven means practical fusion power
  - Other neutrons will collide with chamber walls
  - Collision energy heats walls.
  - This heat is turned to steam power in DEMO

# Conclusion

- (P)
  - Plasma is an ion soup described by pseudo-equilibrium stat mech
  - Charged nature leads to numerous, complex EM interactions
- (T)
  - Using magnetic confinement plasmas can be safely created and controlled
  - To reach fusion temperatures, three forms of heating must be used
- (F)
  - DT fusion is our best chance for nuclear energy
- (I)
  - Output power sustains reaction. Electricity through steam
  - Breeds rare Tritium. Low and sustainable fuel requirements.

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