Magnetically Confined Fusion

Jacob Scott

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Review

- Fusion: combining of two smaller nuclei into one larger nucleus.
- Resulting mass deficit $\sim$ energy.
- Two approaches:
  - Inertially confined: Compress fuel pellet isotropically with lasers.
  - Magnetically confined: Use EM fields to trap ions while heating.
- Goal is to achieve ignition: self-sustaining reaction.
  - Never before achieved (except for non-harnessable nukes)

Fuel Cycles

- D-T Fuel Cycle

$$ {}^{2}_{1}D + {}^{3}_{1}T \rightarrow {}^{4}_{2}He + {}^{1}_{0}n $$

$$ {}^{1}_{0}n + {}^{6}_{3}Li \rightarrow {}^{3}_{1}T + {}^{4}_{2}He $$

$$ {}^{1}_{0}n + {}^{7}_{3}Li \rightarrow {}^{3}_{1}T + {}^{4}_{2}He + {}^{1}_{0}n $$

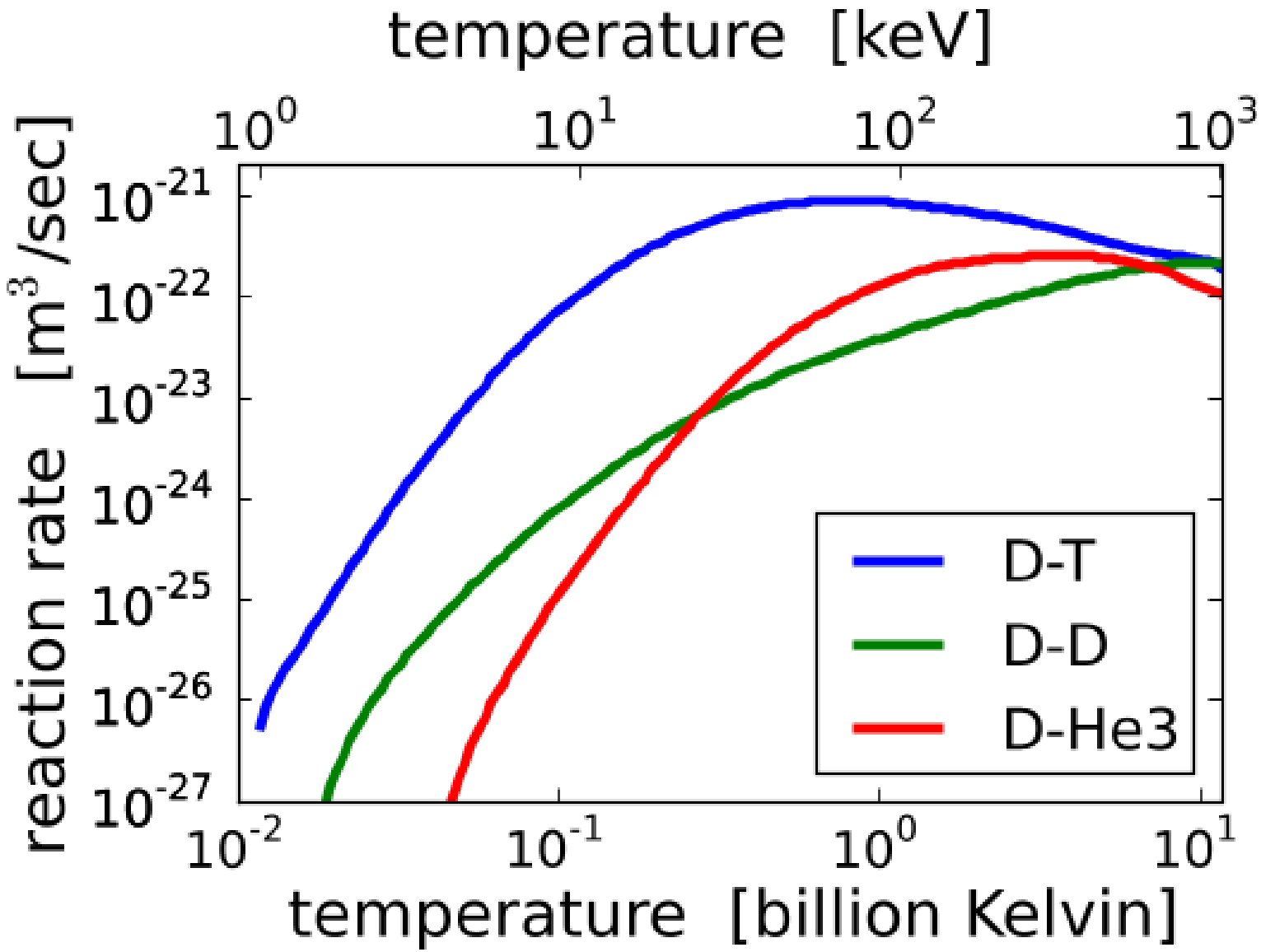
  - Use D and T as fuel
  - Use Li to replenish T (hard to get naturally)

- D-D Fuel Cycle

$$ {}^{2}_{1}D + {}^{2}_{1}D \rightarrow {}^{3}_{1}T + {}^{1}_{1}H $$

$$ {}^{2}_{1}D + {}^{2}_{1}D \rightarrow {}^{3}_{2}He + {}^{1}_{0}n $$

  - Less power
  - Requires better confinement


temperature [keV]
10^0
10^1
10^2
10^3
reaction rate [m^3/sec]
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
D-T
D-D
D-He3
10^{-2}
10^{-1}
10^0
10^1
temperature [billion Kelvin]

Wikipedia

Safety

- Fusion reactors would be much safer than fission reactors
  - Effectively no chance of meltdown
    - If conditions change in the reactor, reaction will fail to achieve ignition $\implies$ reaction quickly stops
- Less radioactive waste
  - Core becomes radioactive, with lower half-lives than for fission
    - Easier to dispose of
- Explosion would release minimal radioactive products (tritium)
  - Would be diluted to "legal levels" almost immediately (Wikipedia)
    - Short half-life
    - Doesn't build up in tissue
- Contain much less fuel (injected as necessary)
- Much less useful for weapons research/production

Fusion for Energy-Production: Feasible?

Early fusion skeptics.

http://www.smbc-comics.com/index.php?db=comics&id=1868#comic

Magnetic Mirrors

- Charged particles tend to follow magnetic field lines in helices
  - $F = qv \times B$

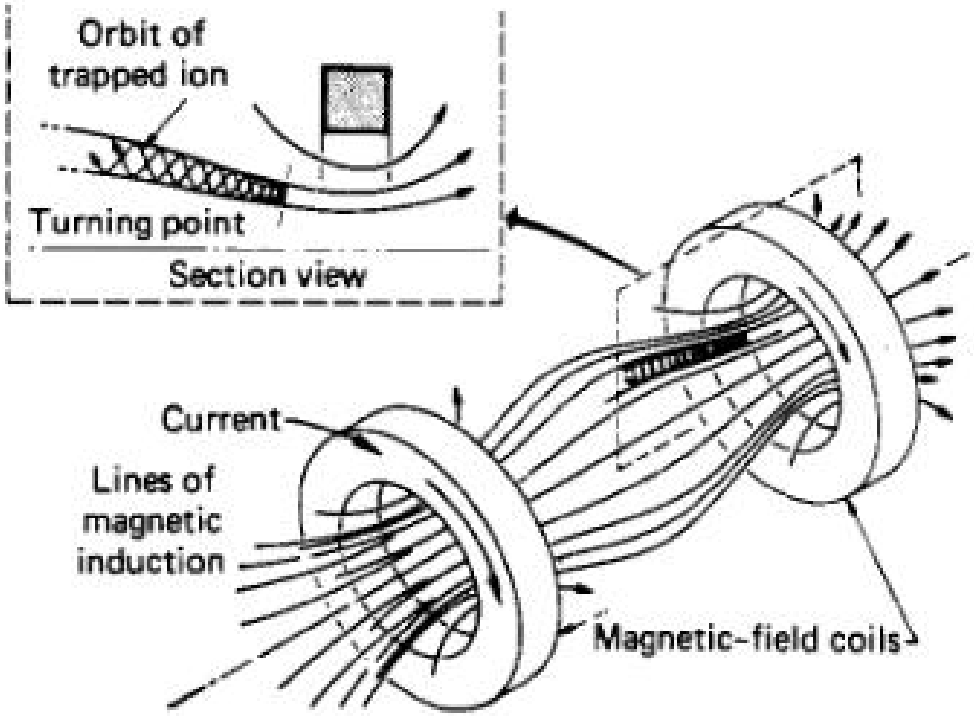


Fig. 2. Particle orbits are contained within an axisymmetric mirror machine. Particles with sufficient perpendicular energy are reflected by the regions of stronger field, called mirrors.

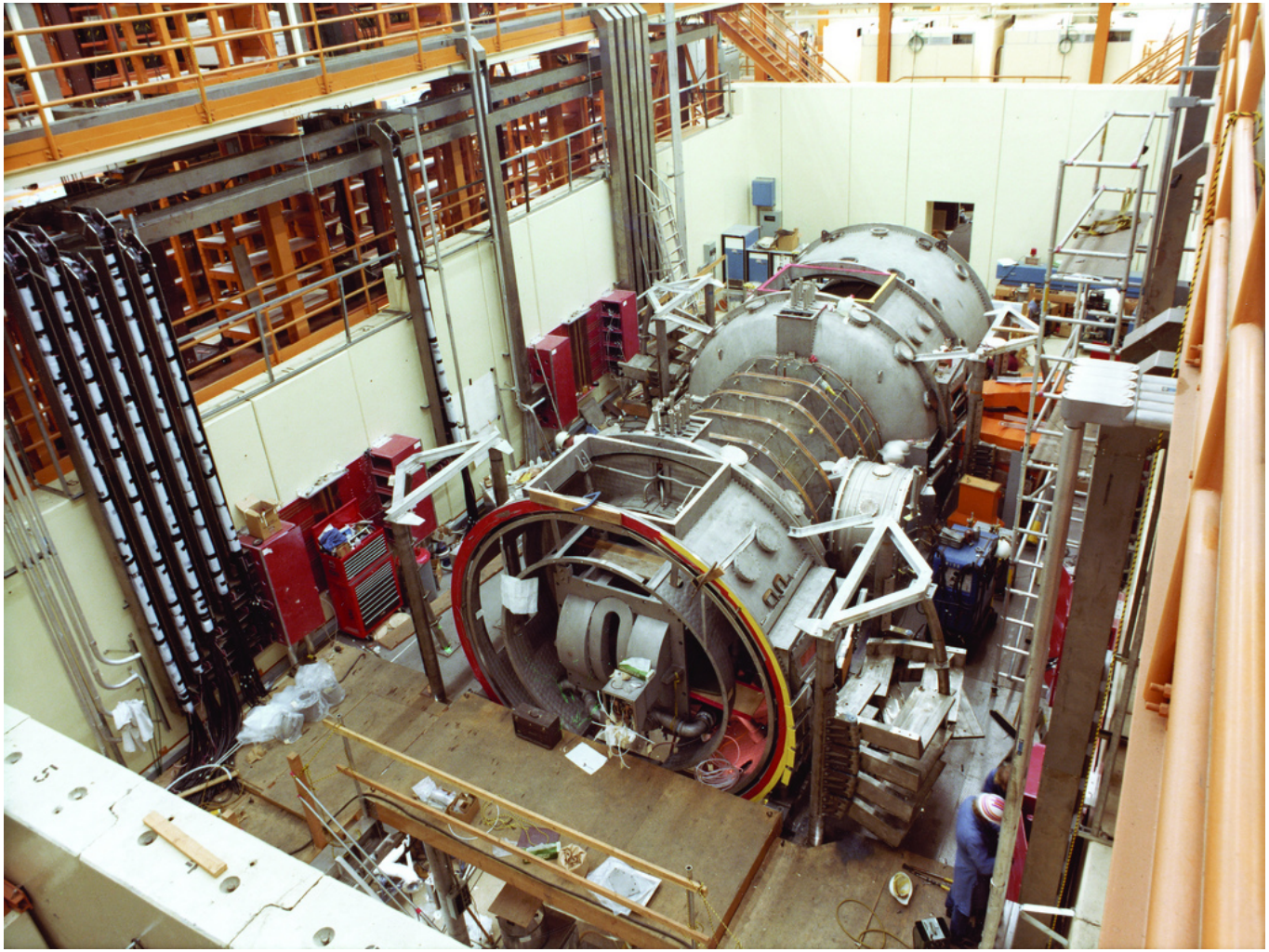
Experimental Progress in Magnetic-Mirror Fusion Research, Simonen 1981

- Plasma is contained in center, following field lines
- "Bounces" when it reaches an end (region of higher B density)
  - B field lines point inward, so $F = qv \times B$ has component inward
- $v_{\parallel}/v_{\perp} = \sqrt{B_{max}/B_{min} - 1}$ (Wikipedia)
  - Pitch angle
  - Independent of particle mass or speed
- Affects the overall confinement of the system
- Some particles escape, so need constant influx of ions

Prospects for Magnetic Mirrors in Fusion

- Main problem: insufficient confinement
  - Confinement time on the order of milliseconds.
    - ★ Actually expanded to seconds by the Tandem Mirror Experiment
    - ★ Added a solenoid
- Research stopped around 1990 in the US in favor of the tokamak, when support for fusion research in general was decreased by Reagan.
  - Still continuing somewhat in Germany and Japan
- Mirror Fusion Test Facility: canceled just as it was completed.

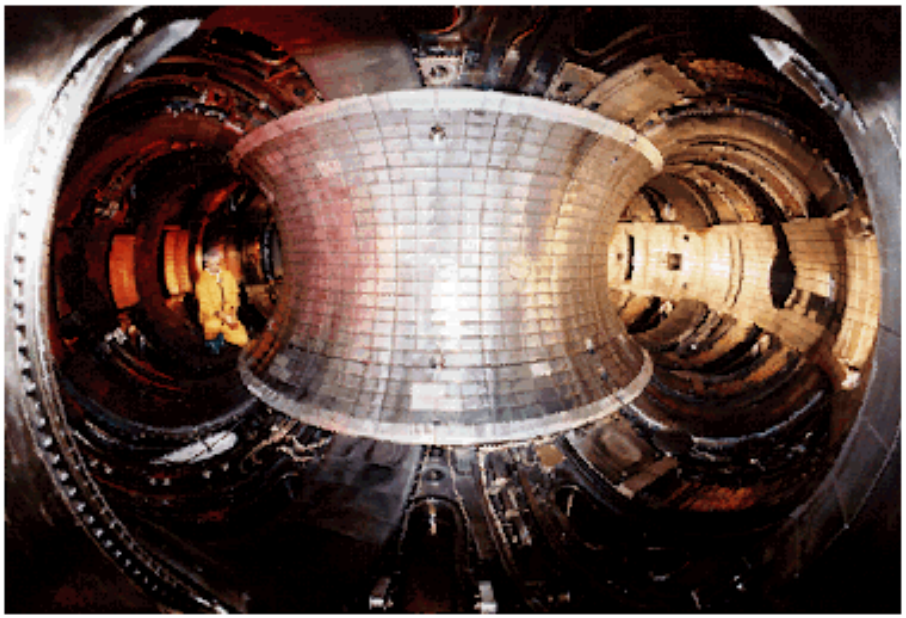
Tandem Mirror Experiment

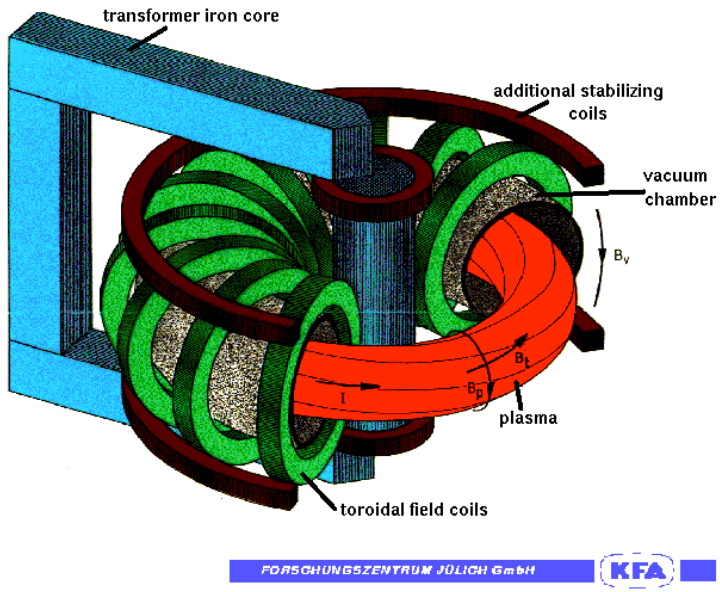


Lawrence Livermore National Labs

Toroidal Magnetic Confinement

- Main research interest in magnetically confined fusion nowadays.
- Device called *tokamak*.



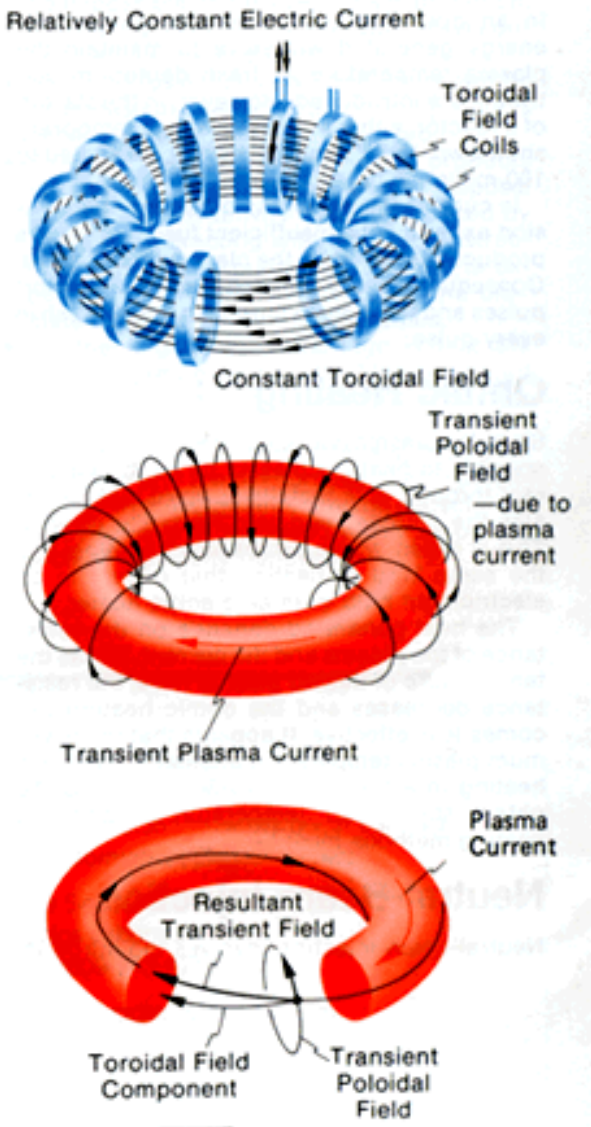


http://ippex.pppl.gov/fusion/fusion4.htm www.rmki.kfki.hu

Tokamaks

- Toroidally arranged (electro)magnets.
- Ions follow the field lines in helices.
- Unfortunately, this doesn't quite work: electrons and ions separate, creating E field that moves particles' helical paths outward.
  - As particle escapes radially, need to force path back in
- Fixed by making B field "twist"
  - Field line that is on outside of torus at one point is inside at another
  - Particles cannot as easily drift out

Twisting B Field



Wikipedia

Heating the Tokamak

- Ohmic heating
  - Send current through plasma; resistance causes energy dissipation
  - Max temp: 20-30 million C° (Wikipedia)
- Injection
- Particles become charged, follow field lines
- Compression
  - Also increases plasma density
- EM waves
  - Heat via bombardment with EM waves of the right λ (microwaves)
- Energy extraction relatively easy: just harness byproduct neutrons

Lawson Criterion

- What is sufficient for ignition?
- Triple-product $nT\tau_E$
  - $n =$ plasma density
  - $T =$ temperature
  - $\tau_E = W/P_{loss} =$ confinement time
- Lawson's criterion: $fE_{ch} \geq P_{loss}$
  - $f =$ volume rate - measure of heating
  - $E_{ch} =$ energy of charged particles
- Equivalent to $nT\tau_E \geq \frac{12k_B}{E_{ch}} \frac{T^2}{\langle \sigma v \rangle}$
  - $\sigma =$ cross section for fusion ($\sim$ interaction chance)
  - $v =$ relative velocity
- For $D-T$ reactions, this is $nT\tau_E \geq 10^{21}\text{keV s/m}^3$.

Progress

- Tokamak Fusion Test Reactor (Princeton)
  - Produced 10.7MW of power.
  - Had a triple product around 10^{20} keV s/m^3.
- ITER (International Thermonuclear Experimental Reactor)
  - Expected completion time: 2018
  - Expected triple product: 6.5-8 (10^{21}keV s/m^3)
  - Expected ratio E_{out}/E_{in}: $Q = 10$
- Is nuclear fusion practical?

Tokamak Progress

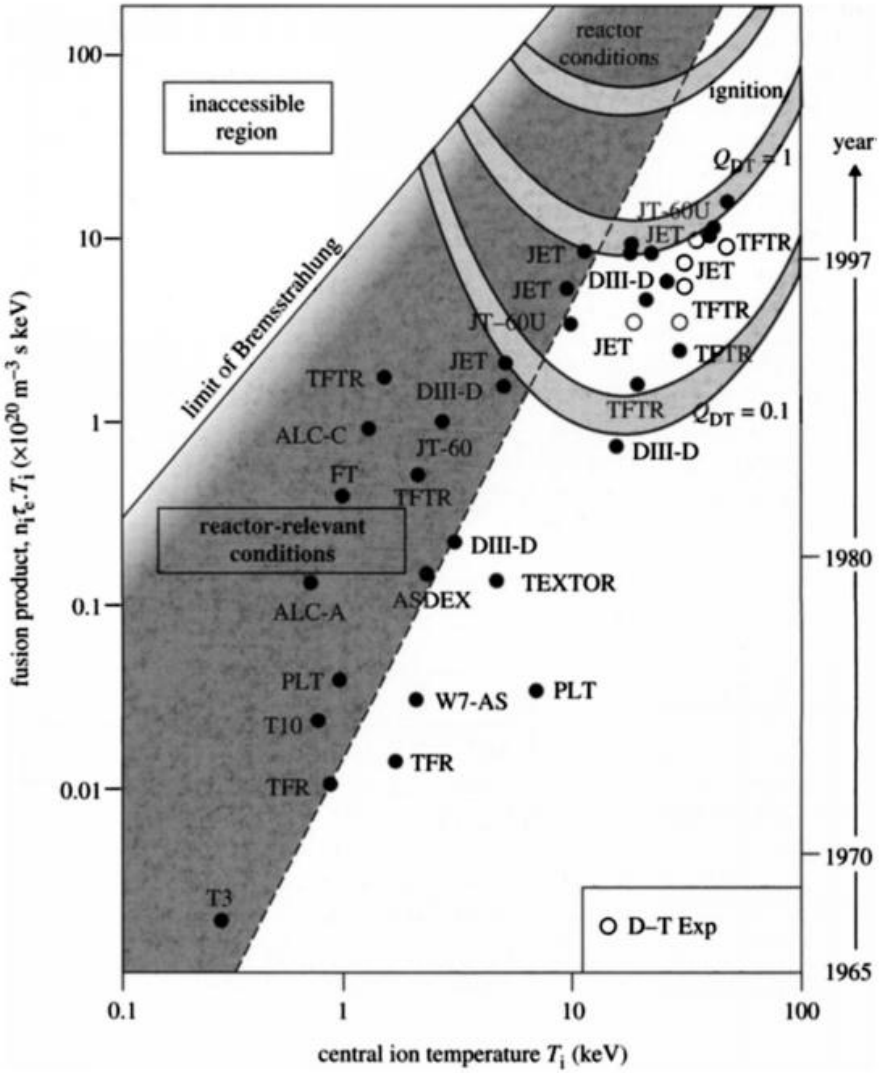


Figure 4. $\langle n\tau_e T_i \rangle$ versus T_i.

History of the Approach to Ignition [and Discussion], Bickerton et al.