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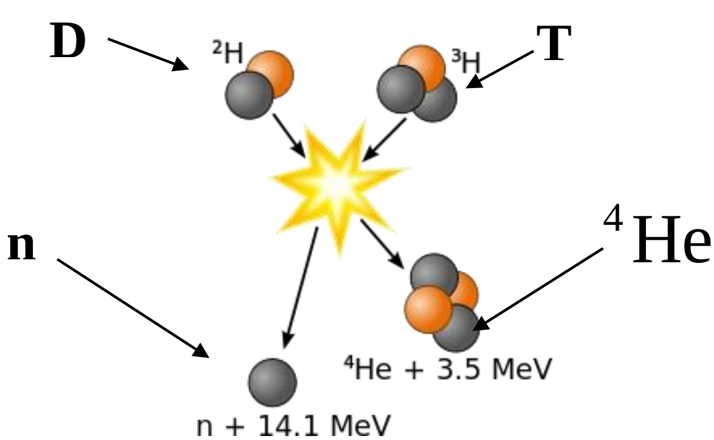
Talk given at the: Sigma Pi Sigma Induction Ceremony
UW Dept. of Physics and Astronomy, 4/28/14

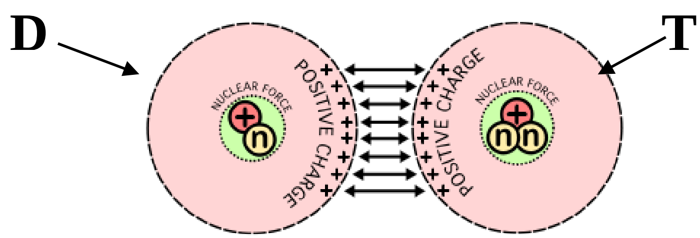
Fusion – A Viable Energy Source – <u>Questionable?</u>

1.1 **Plasma Physics** and **Associated Fusion Research Began Around 1950** (in Russia) **To Produce** energy from **Thermonuclear Fusion** (Which Powers Stars). The **Key Nuclear Reaction** at the heart of fusion physics as the **Fusion Of** Deuterium (**D**) and Tritium (**T**) **Ions**, $D+T \rightarrow {}^{4}He(3.5MeV) + n(14.1MeV)$, **D-T** - **Liberates 17.6MeV Of Energy** in Alpha Particle (Helium Nucleus, ${}^{4}He$) and High Energy Neutron (n).



1.2 **Typical Conditions** which produce fusion reaction **Incorporate Plasma** (**High Temperature Gas** of Electrons & Ions) **Nuclear Ingredients** at conditions: **Density** of $n \approx 10^{20}\,\mathrm{m}^{-3}$, **Temperature** of $T \approx 10\mathrm{keV}$

Objective: **Overcome D-T Electrostatic Repulsion**:



Ignition (fusion sustained) **Metric-Lawson Criteria:**

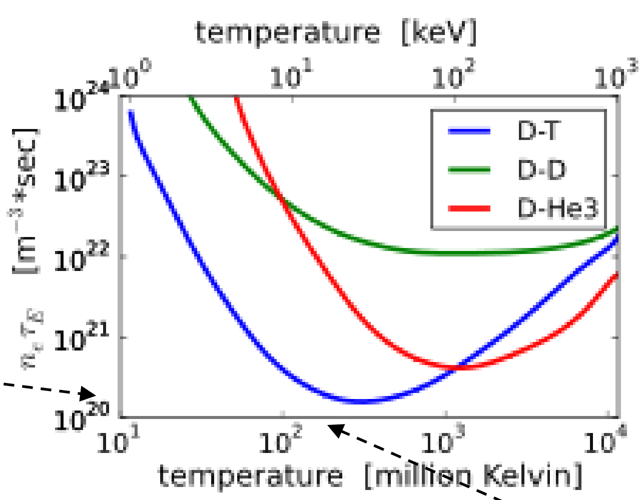
Density (n_e)***Energy Confinement Time** $(\tau_{\mathrm{E}}) = n_e \tau_{\mathrm{E}}$

Lawson Criteria

$n_e \approx 10^{20} m^{-3}$

$\tau_{\mathrm{E}} \approx 1s$

$\rightarrow n_e \tau_{\mathrm{E}} \approx 10^{20} m^{-3} s$



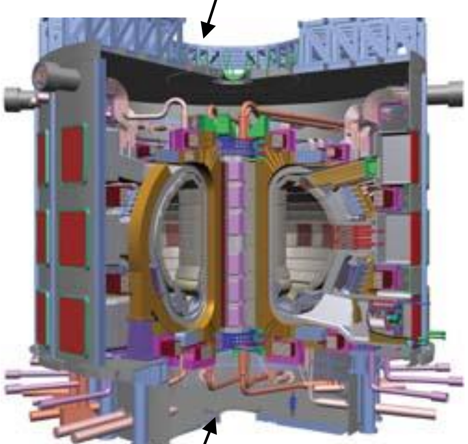
For D-T Fusion

$T_e \approx 10keV$ or

Approx. 100M degree C

1.3 **Fusion Reactions Occur Naturally In Stars**, due to tremendous **Gravitation Forces**, $\mathbf{F} = m\mathbf{g}$, which **Radially Confine Plasma - Allow Sustained Fusion**. **However**, **Laboratory Fusion Plasmas** must utilize **Electromagnetic Forces**, $\mathbf{F} = q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$, typically **Achieved Using: 1) Toroidal Magnetic Field Devices – Tokamak – Large Confining B Fields**; or **2) Inertial Confinement Fusion – ICF – Devices** numerous large **Lasers Provide Implosion Pressure**.

1) ITER – International Thermonuclear Experimental Reactor

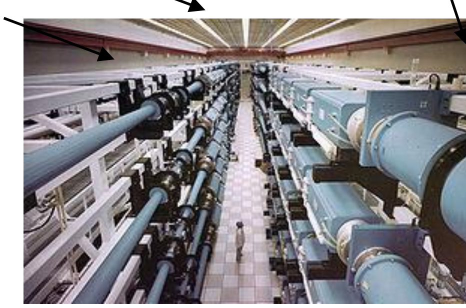


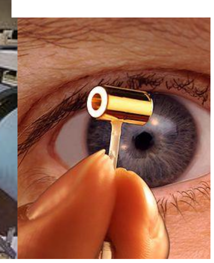
Largest Tokamak To Date – Online in 2020

2) NIF – National Ignition Facility

Lasers **Hohlraum**

Contains D-T Fuel Pellet 2mm in size

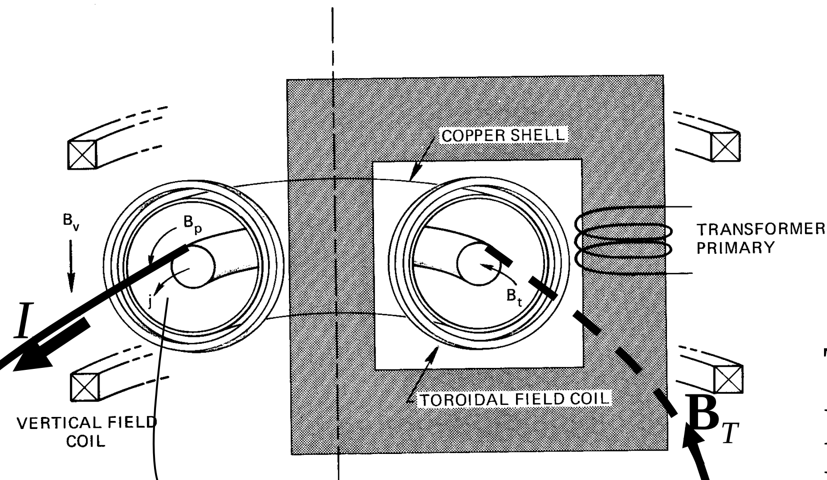




192 Laser Beams First Fired in 2009

1.4 **Tokamak** (donut or toroidal shaped device):

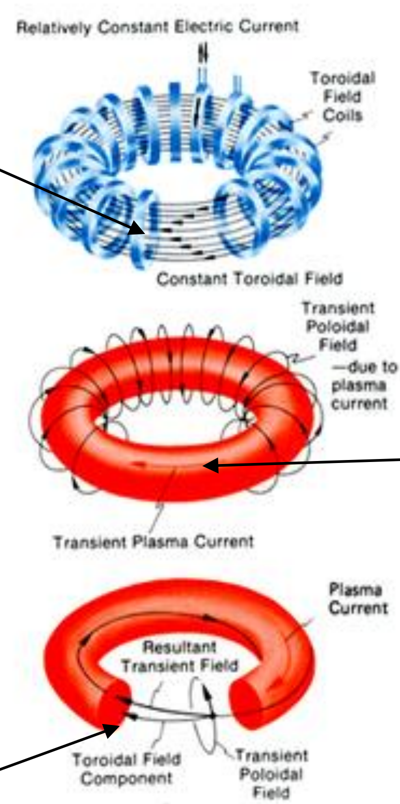
Toroidal Current, I, Ohmically Heats Plasma



Hot Plasma In Toroidal Vacuum Vessel

Toroidal Magnetic Field, $\mathbf{B}_T$, Confines Plasma

Toroidal Field, $\mathbf{B}_T$, Is the Main Confining Tool



Ohmic Heating, Through Induced Toroidal Current, I, Is the Main Heating Tool

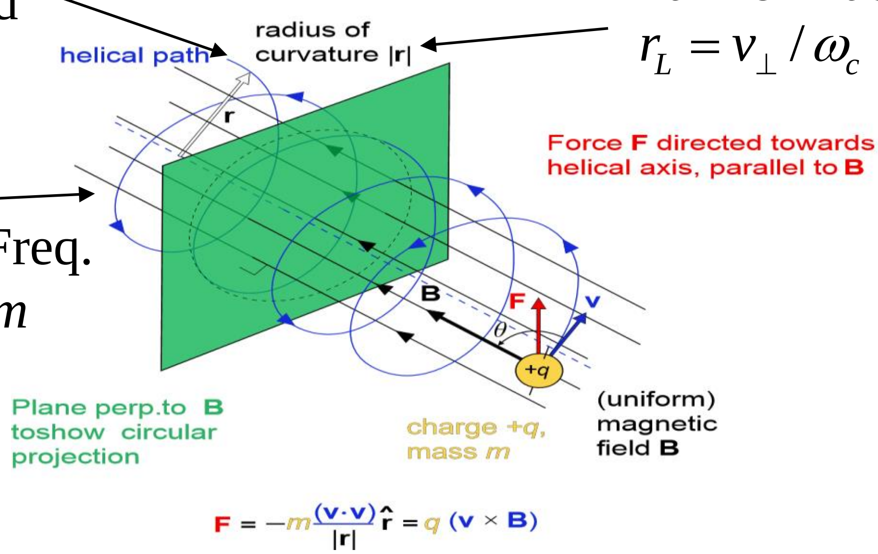
Helix Combination of Toroidal Field, $\mathbf{B}_T$, and Induced Poloidal Field, $\mathbf{B}_P$, Helps With Stability

Magnetic Confinement Of Charged Particles, q, **Due To** total **Magnetic Field**, $\mathbf{B} = \mathbf{B}_T + \mathbf{B}_P$, are **Tied To Magnetic Field Lines**, **Through Magnetic Force**, $\mathbf{F} = q\mathbf{v} \times \mathbf{B}$, **Gives Helical Orbit** along field:

Larmor Radius
$r_L = v_\perp / \omega_c$

Charged
Particle
Path

Cyclotron Freq.
$\omega_c = |q| B / m$

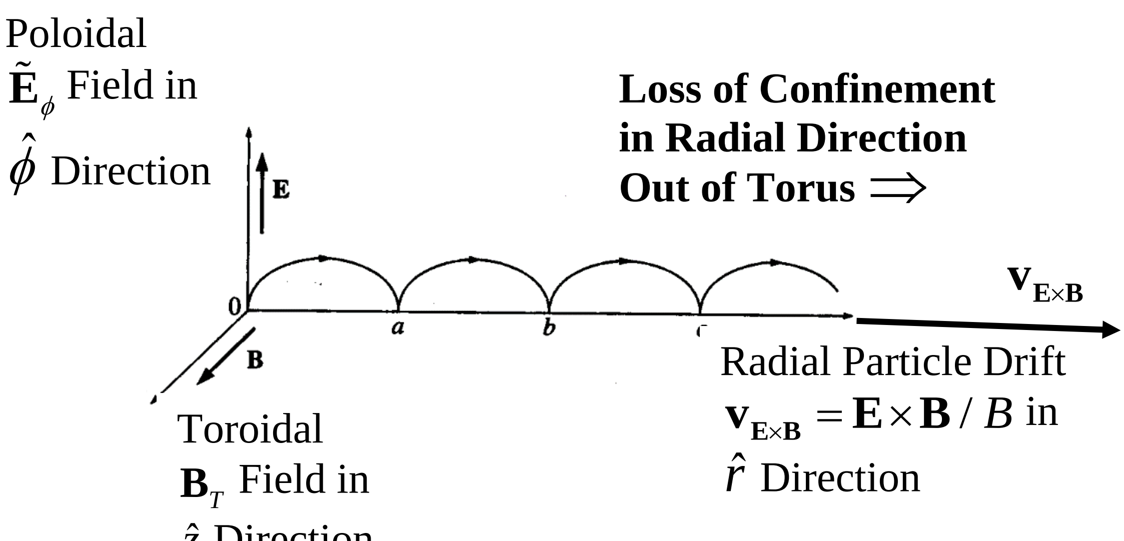


Electrons have much Smaller Larmor Radii Than Ions

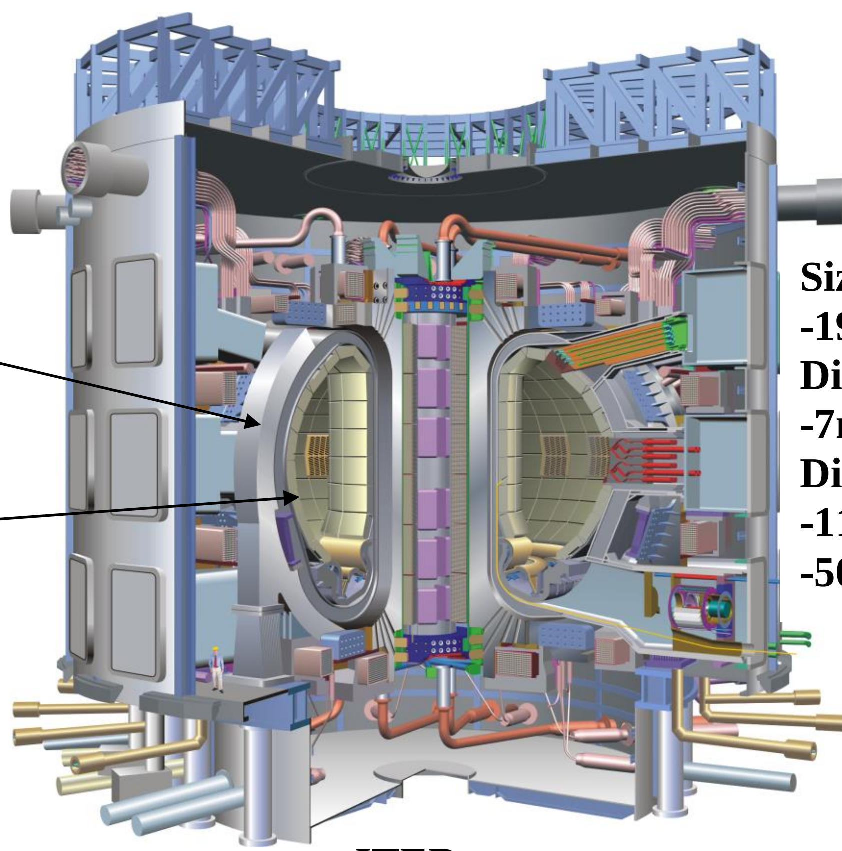
$r_{Le} / r_{Lp} = \sqrt{m_e / m_p} \approx 1/\sqrt{1837} \approx 1/43$.

Cyclotron Frequency Is $\omega_c = |q| B / m$, **Larmor Radius Is** $r_L = v_\perp / \omega_c$, and **Perpendicular Velocity**, $v_{\perp p,e} = \sqrt{2kT / m_{p,e}}$, **Depends On Temperature**, T.

1.5 **Unfortunately**, **Loss Of Confinement Due To Severe Micro-Turbulent Instabilities**, **Such As** the **Universal** (or drift wave) **Instability**, **Due To** natural **Radial, r, Density, $n_{e0}(r)$, Gradient Of All Confined Plasmas**, **As** $dn_{e0}/dr < 0$. Specifically, azimuthal (poloidal) **Electric Field Fluctuations, $\tilde{\mathbf{E}}_\phi$, Result; Which Provides $\mathbf{E} \times \mathbf{B}$ Radial Particle Drift**, $\tilde{v}_r = \tilde{\mathbf{E}}_\phi \times \mathbf{B} / B^2$; **Particles Turbulently Transport Out Of Bulk Plasma**, **Flux Is** $\tilde{\Gamma}_r = \langle \tilde{n}\tilde{v}_r \rangle \propto \langle \tilde{E}_\phi{}^2 \rangle$; **"Free Energy" Relaxation $\Rightarrow$ Confinement Loss**.

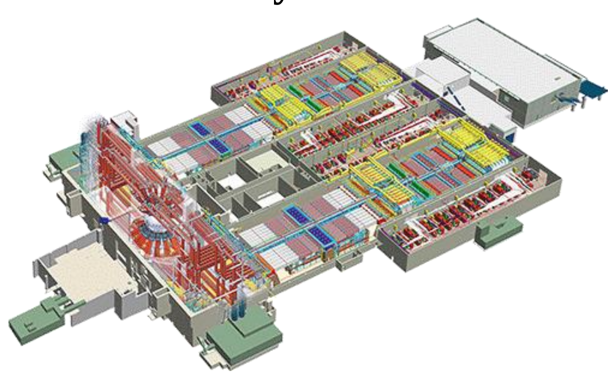


1.6 **ITER** – International Thermonuclear Experimental Reactor – **7 Country Participation** – EU, India, Japan, China, Russia, South Korea, and US – near Cadarache, France – **Began** in **2007** – proposed **Completion** in **2020** – full **DT Operation** in **2027** – **Designed To Achieve Ignition** and provide sustained (**1000s Run**) fusion generation of **500MW Power Output** – Q=10 Factor of Energy Output **- $13B Cost**

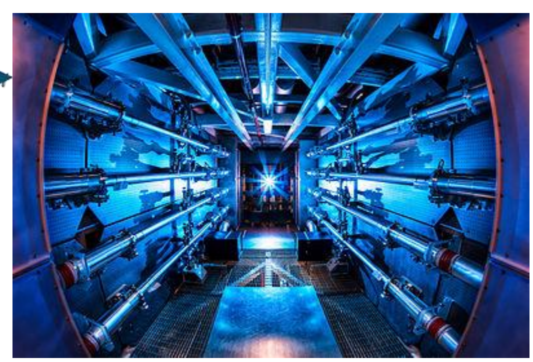


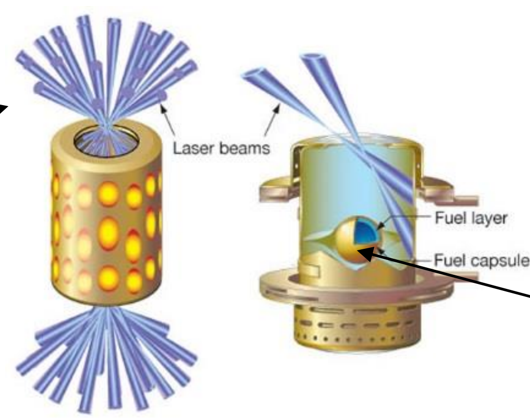
1.7 **NIF** – National Ignition Facility – **192 Lasers Active Since 2010** – housed at Lawrence Livermore National Lab. (LLNL) in CA – facility is 3 football fields in size – **Achieved 500TW** peak light flash to implode a 2mm size D-T pellet – during a few pico-seconds shot - **Imparting 2MJ Energy**– Q>1 **Break Even Achieved** – *Nature – 20-February-2014, Vol. 50, p. 343*

NIF Facility



Pre-Amplifier





Lasers Entering Hohlraum

D-T Fuel Pellet

NIF:
Breakeven Operation in 2014

1.8 **Conclusion: Steady State Fusion Energy** production:

Questionable?

<u>Big Difference:</u> **<u>"Breakeven"</u>** or **<u>"Ignition"</u>**

1) ***Sustained Magnetic Confinement Fusion – Ignition - Difficult To Achieve*** - **Highly Turbulent Plasma Environment** – ***Plasma Turbulently Transported Radially Out*** *of device*; **No Radial Restoring Forces** (unlike in the gravitational confinement found in stars)

<u>Are Bigger Tokamaks Better? – ITER Size?</u>

2) ***ICF Achieves Breakeven*** - **Sustained Fusion? – *Consider Repetition Rate Needed*** (as in gas engines) **– NIF - Hohlraum Burned During Each Shot –** how to *"Reload Quickly?"* **– Breakeven Q>1 Good Enough?**

<u>Consider Overall Facility Size of NIF Device?</u>

1.9 ***Hope for Future* – Young Scientists Need to:**

"Think Outside of the Box"

Alternative Approaches Needed?

For Example **Consider Devices with Radial Symmetry**:

1) **Polywell** – Using Electrostatic Attraction and Six Electromagnetics with a Null at Center:

2) **Fusor** – Large Voltage Drop to Trap Ions in Center