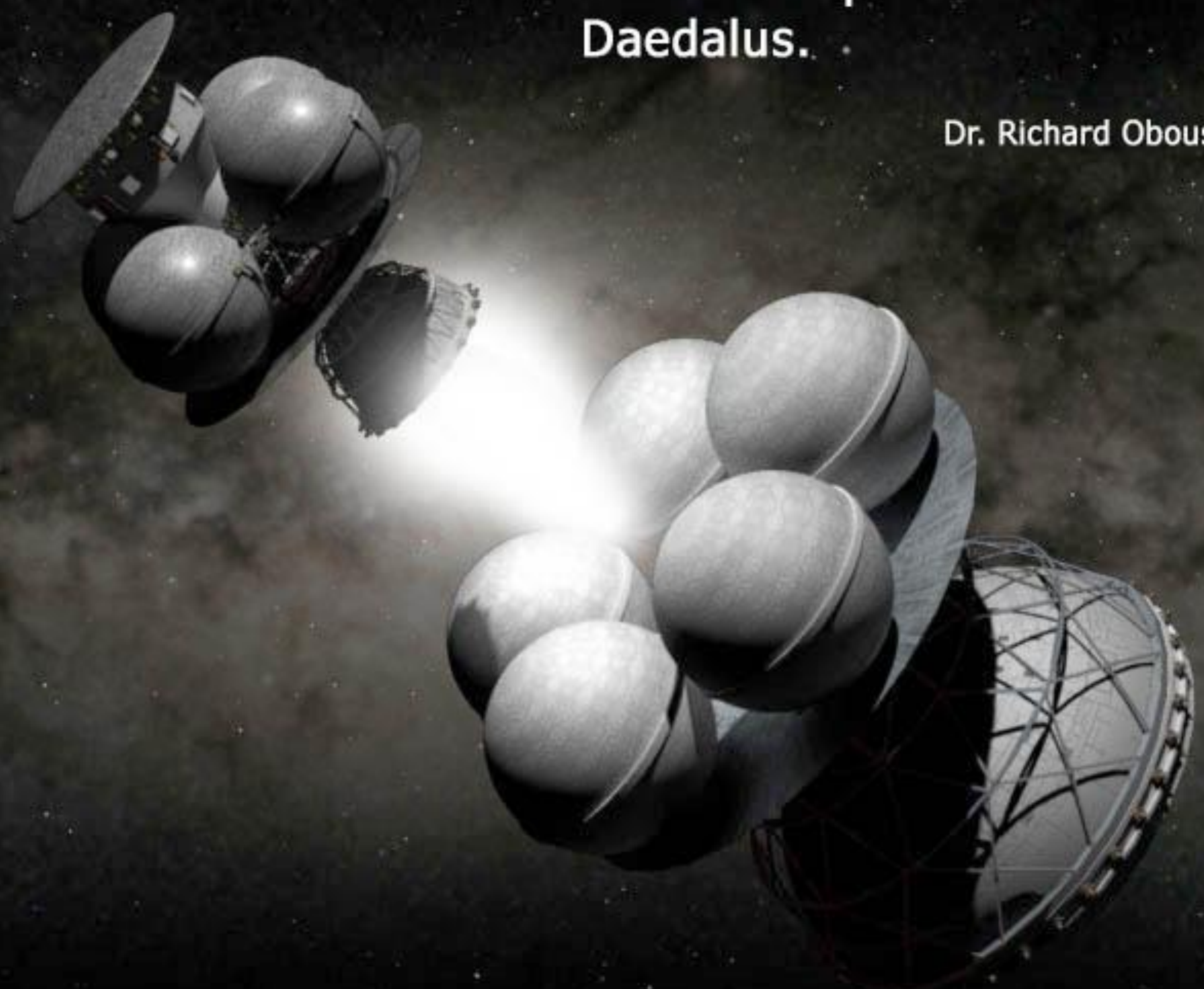
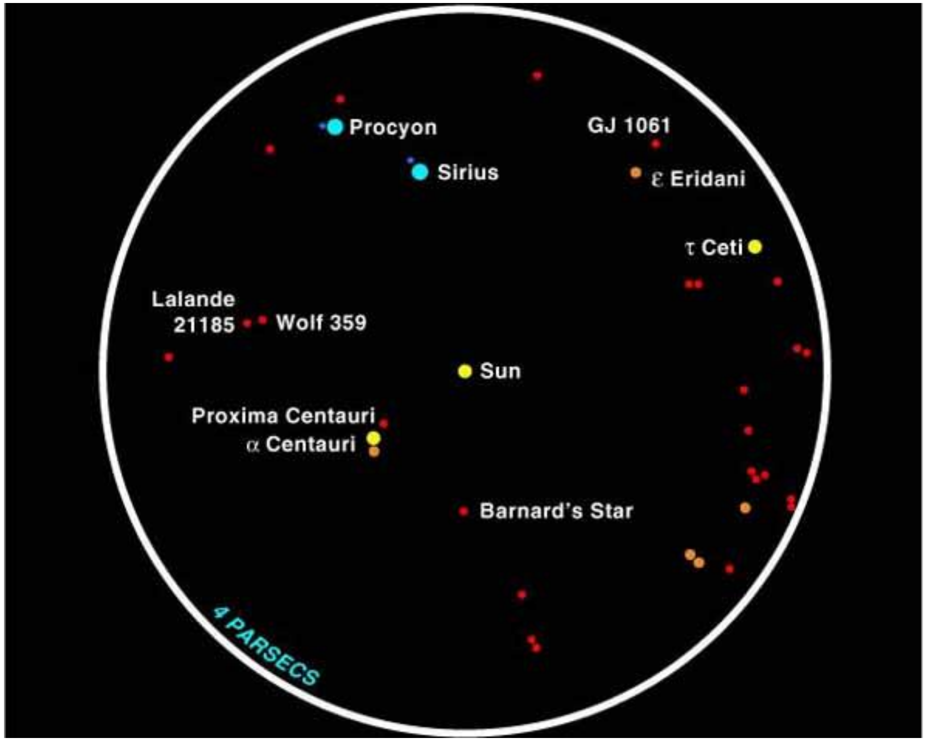
Interstellar Propulsion: Challenges and Developments 30 Years After Daedalus.

Dr. Richard Obousy



The Challenges of Interstellar Missions

What is 'wrong' with current rocket propulsion technology?



~25 star systems in 4 parsec radius

Rockets

Common measure of rocket efficiency:

Specific Impulse

$$I_{sp} = \frac{V_e}{g}$$

Tells us how much Impulse (force x time) per unit mass of propellant expelled.

Propellant	I(secs)
Hydrogen-Flourine	528
Hydrogen-Oxygen	460
O_3H_2	607
$F_2Li\text{-}H_2$	703
$O_2/Be\text{-}H_2$	705

One-way Proxima Centauri Fly-through mission

I(secs)	Mass Ratio
500	1.3×10^{1328}
1,000	1.1×10^{664}
5,000	6.5×10^{132}
10,000	2.6×10^{36}
50,000	1.9×10^{13}
100,000	4.4×10^{6}
200,000	2.1×10^{3}

V_{cruise} = 5% c

t_{trip} ~ 86 yrs

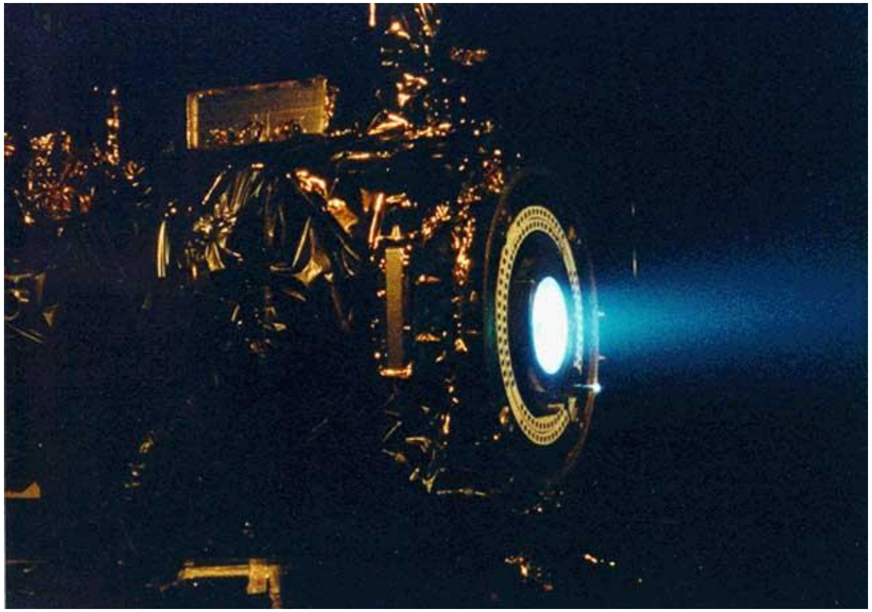
Rocket Alternatives

Chemical

$$I_{sp} \approx 1{,}000s$$

Rocket Alternatives

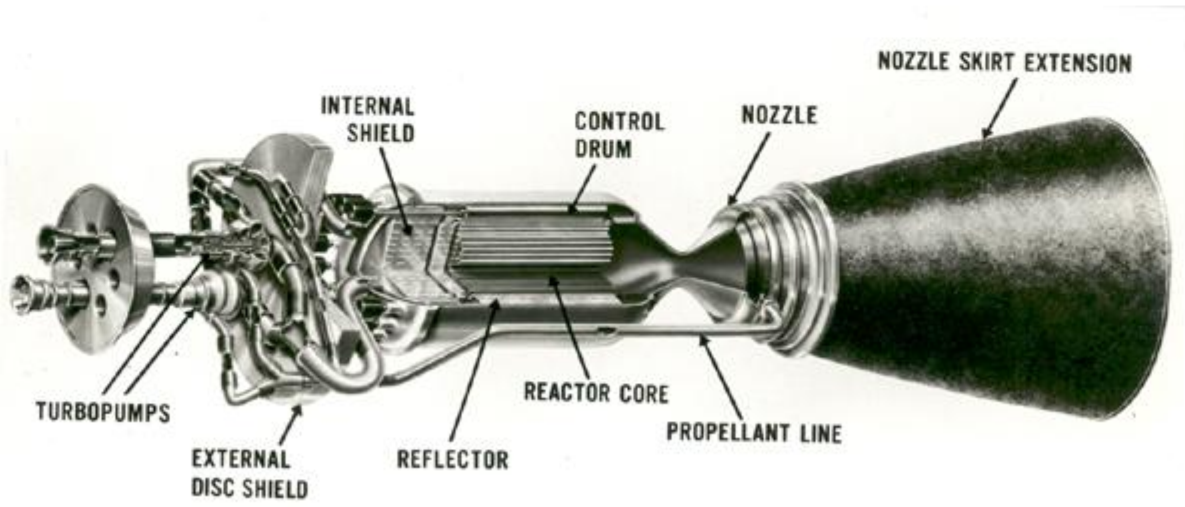
Electric



$$I_{sp} \approx 2{,}500 - 10{,}000s$$

Rocket Alternatives

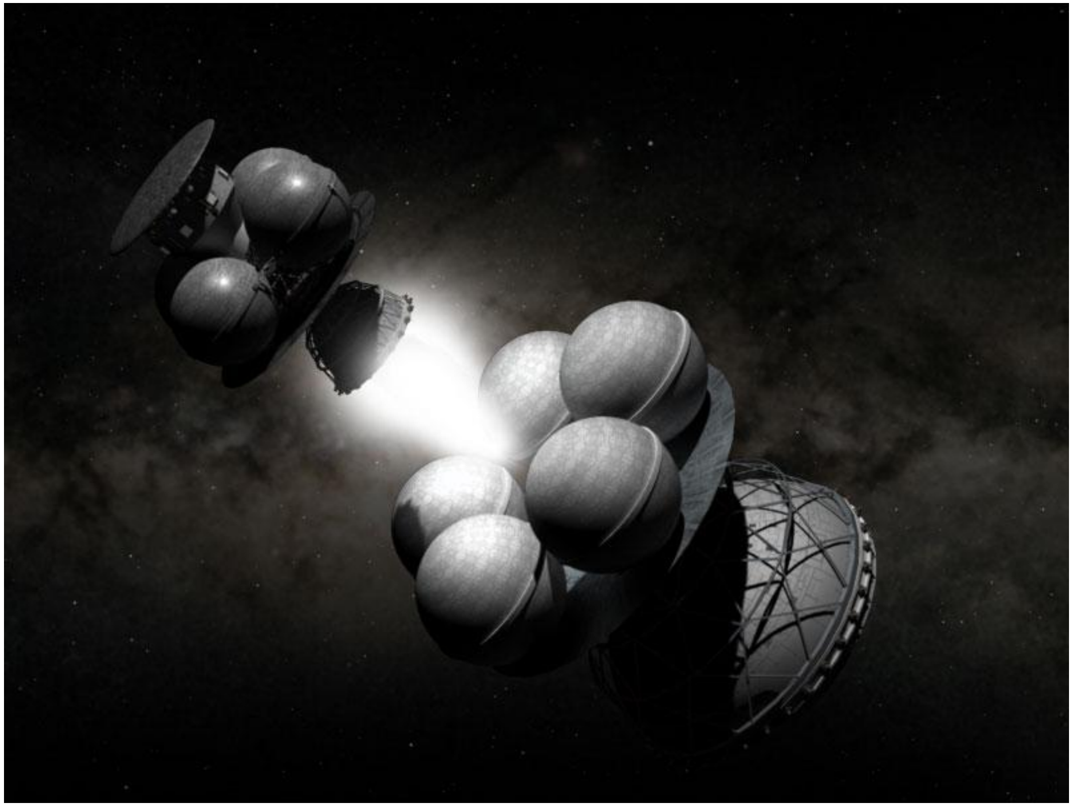
Nuclear Fission



Solid Core	Liquid Core	Gas Core
$I_{sp} \approx 500 - 1{,}100s$	$I_{sp} \approx 1'300 - 1'600s$	$I_{sp} \approx 3'000 - 7'000$

Rocket Alternatives

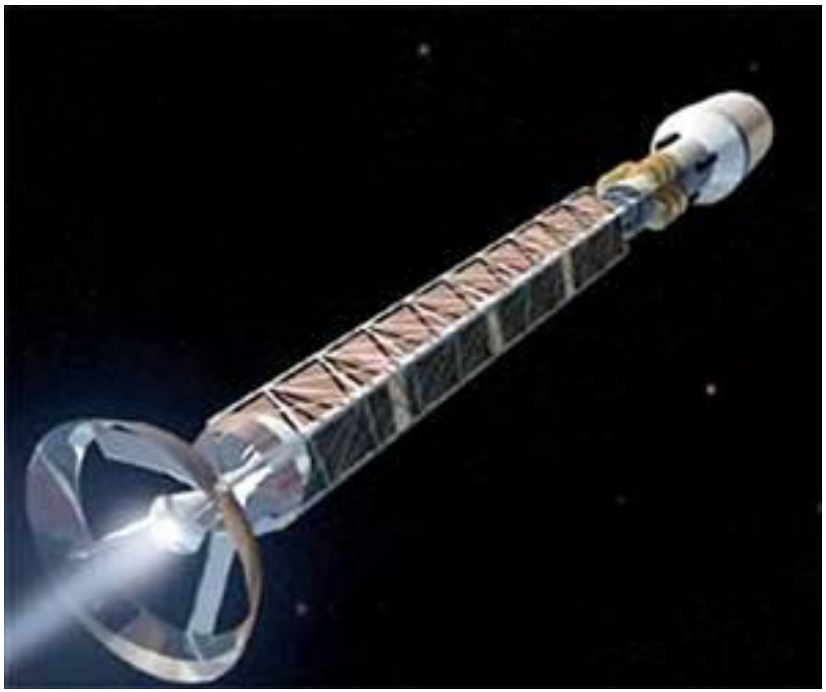
Nuclear Fusion



$$I_{sp} \approx 2'500 - 200'000s$$

Rocket Alternatives

Antimatter



3 Possibilities

i. Use AM annihilation products for propulsion
ii. Heat a working fluid for propulsion.
iii. Heat a fluid to generate electricity to power electric spacecraft.

2 Typical Reactions

$p\tilde{p}$ Charged mesons

$e^{-}e^{+}$ Gamma rays

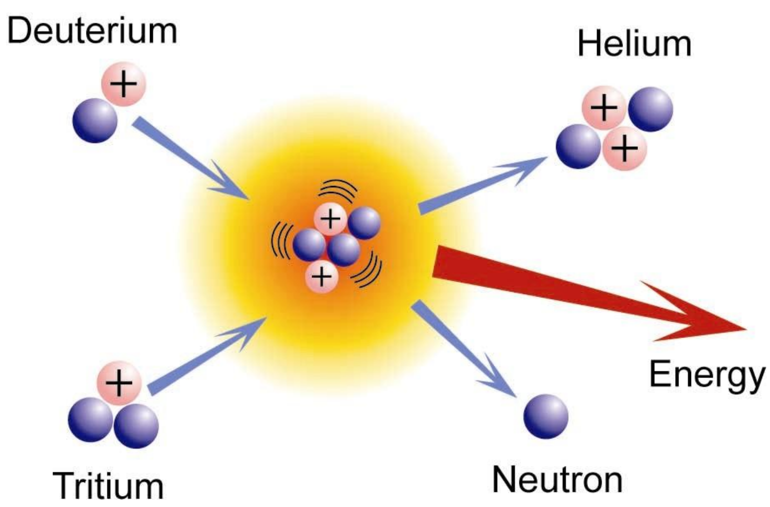
$$I_{sp} > 10^{6} s$$

Fusion Principles

Fusion an attractive option

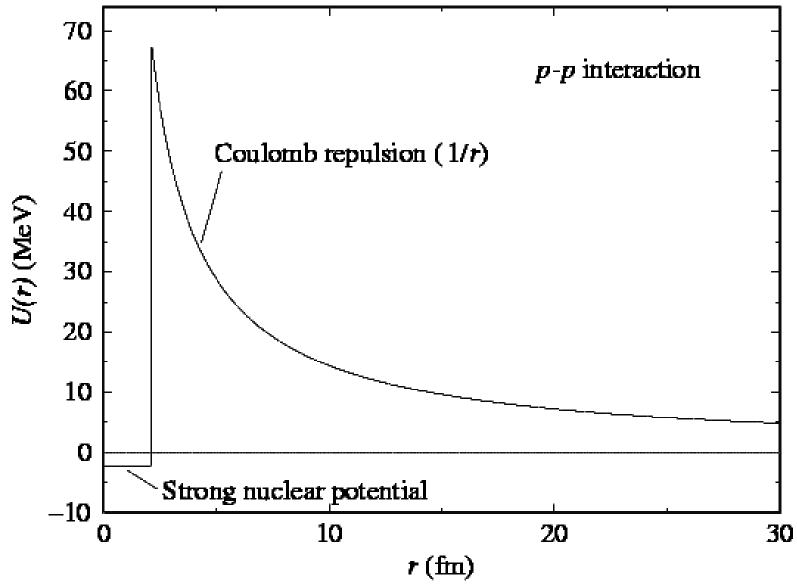
- ❑ Fusion well understood
- ❑ High specific impulse
- ❑ Produces less radiation than a fission rocket
- ❑ Greatest energy density (neglecting matter/antimatter)

Principles



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

Fusion Principles



Coulomb Force

Infinite range, repulsive

$$\vec{F} = \frac{kq_1q_2}{r^2}\hat{r}_{21}$$

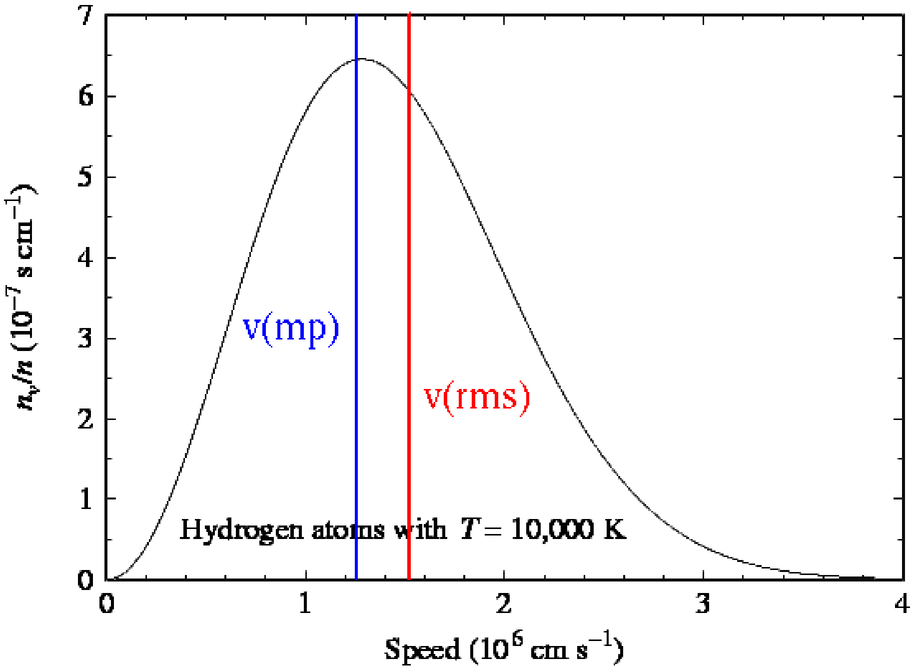
Nuclear Force

Short range, attractive

$$V(r) = -g^2 \frac{e^{-mr}}{r}$$

Fusion Principles

To overcome the Coulomb potential we need to make energetic nuclei



$$P(E)dE \propto \sqrt{E}e^{-E/KT}dE$$

$$v_{mp} = \sqrt{\frac{2KT}{m}}$$

$$v_{rms} = \sqrt{\frac{3KT}{m}}$$

mp = most probable
rms = root mean square

Fusion Principles

Particles need sufficient thermal energy to exceed Coulomb repulsion

$$\frac{3}{2}k_B T > \frac{ke^2}{r_{nuc}}$$

Thermal and Coulombic energies

Rearrange

$$T > \frac{2ke^2}{3k_B r_{nuc}}$$

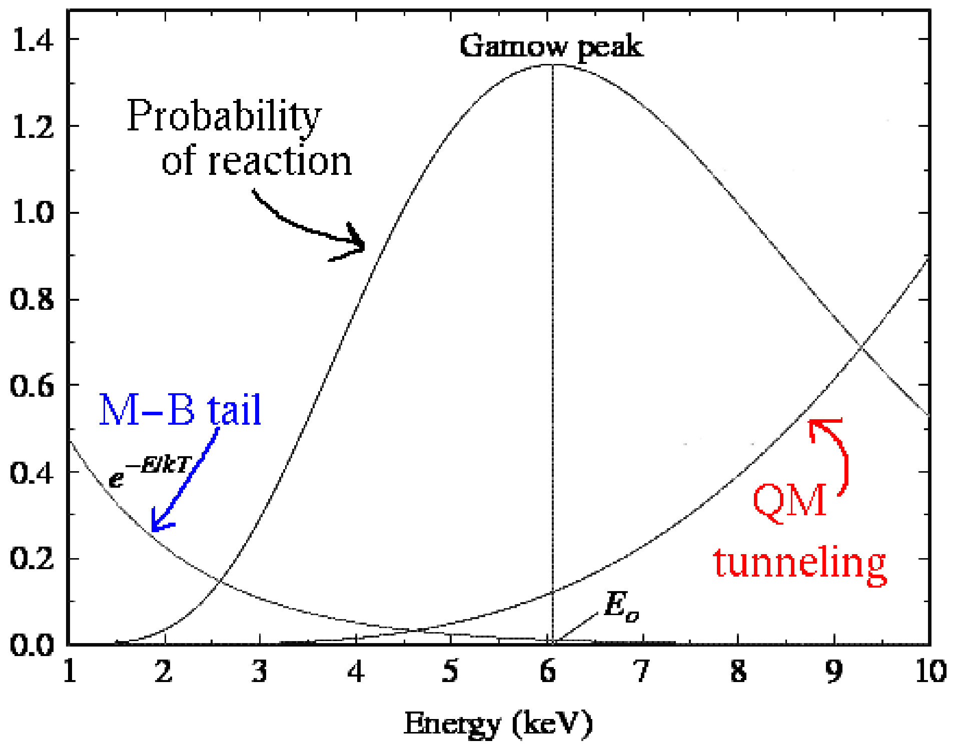
Expression for temperatures

$$T > 10^{10} K$$

Fusion Principles

Fortunately Quantum Mechanics Comes to the Rescue

$$\Delta x \Delta p_x \geq \frac{h}{4\pi}$$



Fusion Cycles

Important Fusion Cycles

$$D + {}^3He \rightarrow p(14.68 MeV) + {}^4H(3.67 MeV)$$

$$D + T \rightarrow n(14.07 MeV) + {}^4H(3.52 MeV)$$

$$D + D \rightarrow n(2.45 MeV) + {}^4H(0.82 MeV) \quad 50\%$$

$$\rightarrow p(3.02 MeV) + T(1.01 MeV) \quad 50\%$$

$${}^3He + {}^4He \rightarrow 2p + {}^4He \quad 12.86 MeV$$

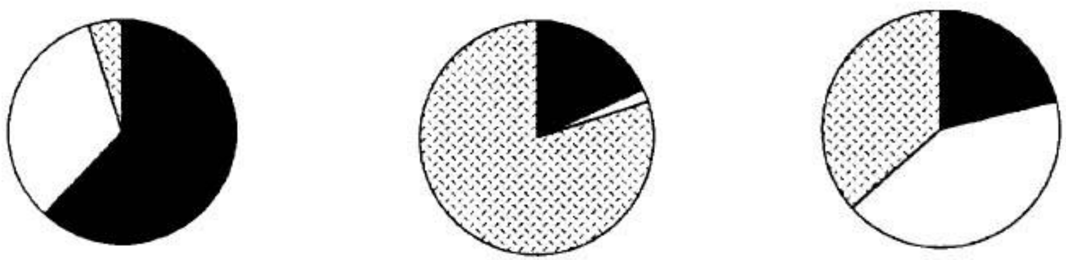
$$p + {}^{11}B \rightarrow 3\,{}^4He \quad 8.7 MeV$$

$$p + {}^6Li \rightarrow {}^3He(2.3 MeV) + {}^4He(1.7 MeV)$$

$D + {}^6Li \rightarrow$ 5 Primary reactions

Fusion Cycles

$D+{}^3He$ | $D+T$ | $D+D$

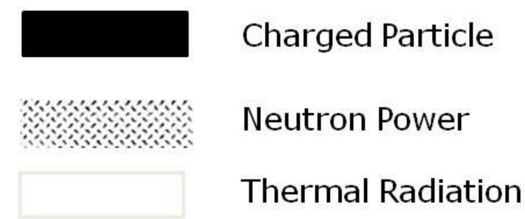


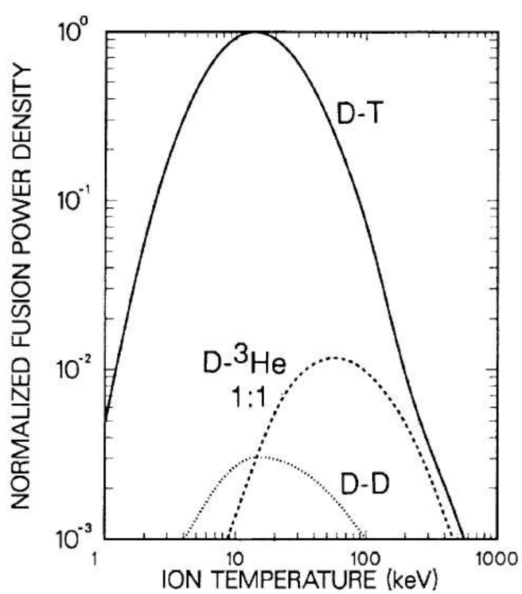
Large fraction of charged particles

Lowest burn temperature

Fuel is most plentiful on Earth

Legend

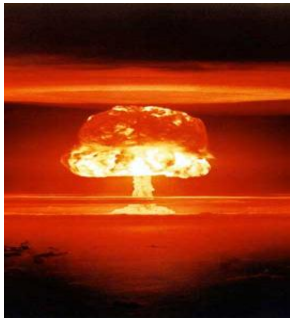




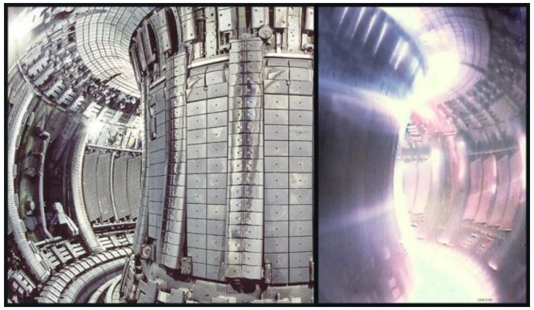
Power densities for important fusion fuel cycles

Achieving Fusion

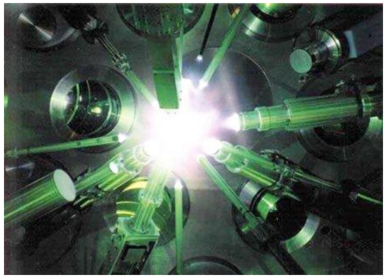
Detonation of Atomic Weapon



Magnetic Confinment



ICF

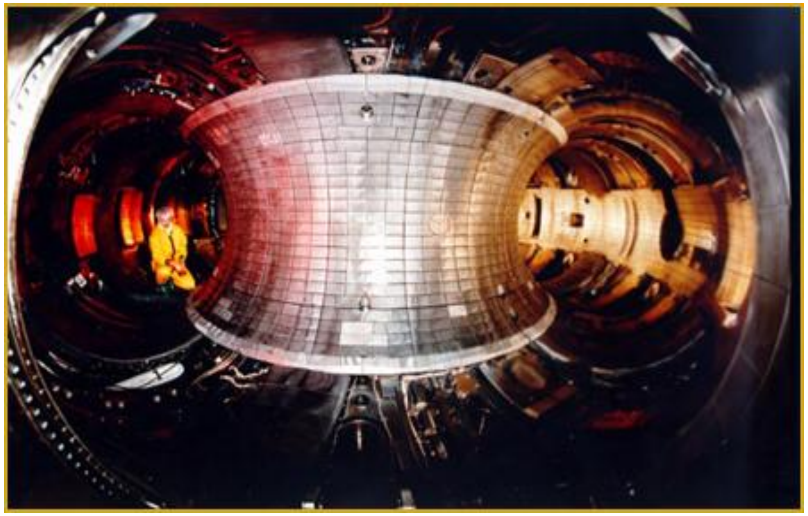


Magnetic Confinment

❑ Tokamak

Heating Achieved via:

- Ohmic Heating
- Neutral Beam Injection
- Magnetic Compression
- RF Heating



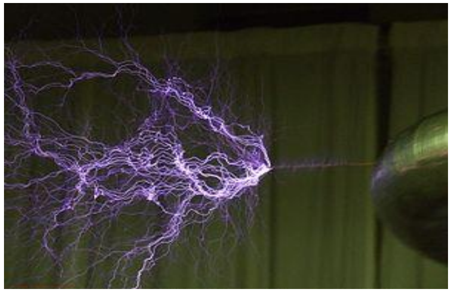
20 Tokamaks Currently Operating

Notable Reactor: ITER

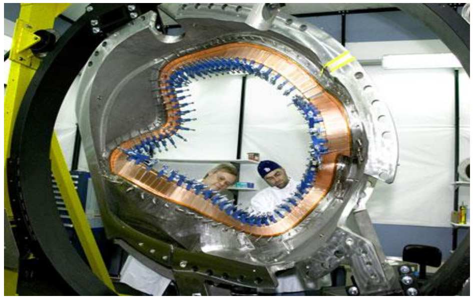
30 Years Program
Production of 500 MW for 1,000 s
0.5g Deuterium/Tritium Mix
840m^3 Reactor
Scheduled to be switched on in 2018
Produce steady-state plasma Q>5

Magnetic Confinment

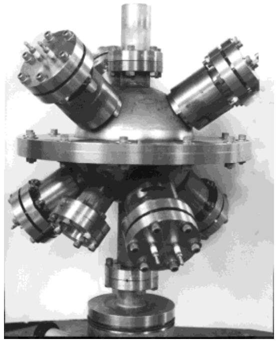
- Z-pinch



- Stellarator



- Fusor



Inertial Confinement

ICF Principles

- High energy beams of laser/ions/e^-
- Pellet (usually D/T)
- Capsule ablation

Ablation

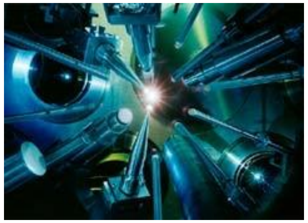
- Absorption
- Energy Transport
- Compression and burn

Aim

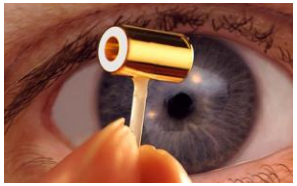
To generate sufficient Temperature/Pressure for fusion process. Preferably gain.

Inertial Confinement

❑ Direct Drive



- Spherical fuel pellets
- Heated by driver



❑ Indirect Drive

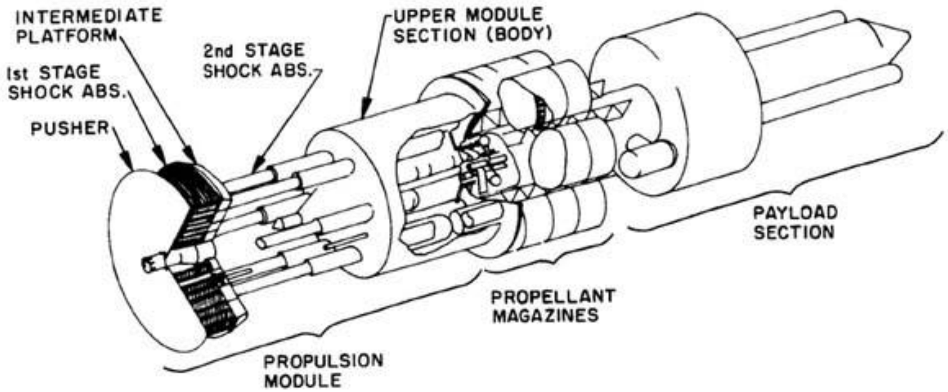
- Fuel pellet placed inside Hohlraum
- Hohlraum heated via driver, then re-radiates x-rays to heat fuel

❑ Fast Ignition

- Target compressed using laser driver
- Implosion reaches maximum density
- 2^{nd} ultra-short PW pulse heats core

Nuclear Spacecraft

❑ Orion



- 1958-1965
- Nuclear Pulse Propulsion
- Interplanetary
- 3-5% c (fission)
- 8-10% c (fusion)
- Earth to Pluto and back in less than a year!

$$I_{sp} = \frac{C_0 V_e}{g}$$

C_o Collimation factor

$$I_{sp} = 2000 - 6000s$$

$$I_{sp} = 10{,}000 - 20{,}000s$$

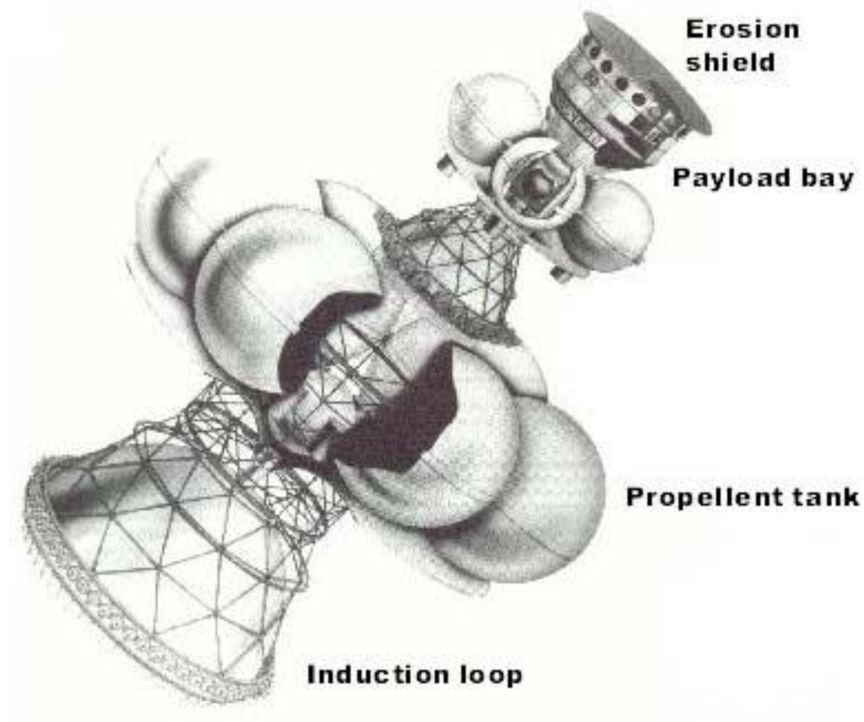
Nuclear Starships

❑ Daedalus

- 1973-1978
- Fusion Pulse Propulsion
- Barnard's star
- 12% c

Numerous advantages over Orion:

- Does not require large size associated with Orion
- No radioactive pollution



$$I_{sp} = 10^6 s$$

Nuclear Starships

The Propulsion Process

1. Propellant carried as spheres at crogenic temperatures in disposable tanks.
2. Pellets injected into reaction chamber, at high velocity.
3. Pellet hit by high powered e^- beams.
4. Ablation of outer layer, fuel is compressed and shockwave heated. Core reached fusion temperatures.
5. Resulting plasma ball directed axially via the field arrangement.
6. Plasma KE stored in magnetic field. Plasma direction is reveresed and ejected at high velocity along the engine axis.
7. Momentum is transferred into the reaction chamber and thrust is generated.