Inertial Confinement Fusion & Antimatter Catalyzed Fusion for Space Propulsion

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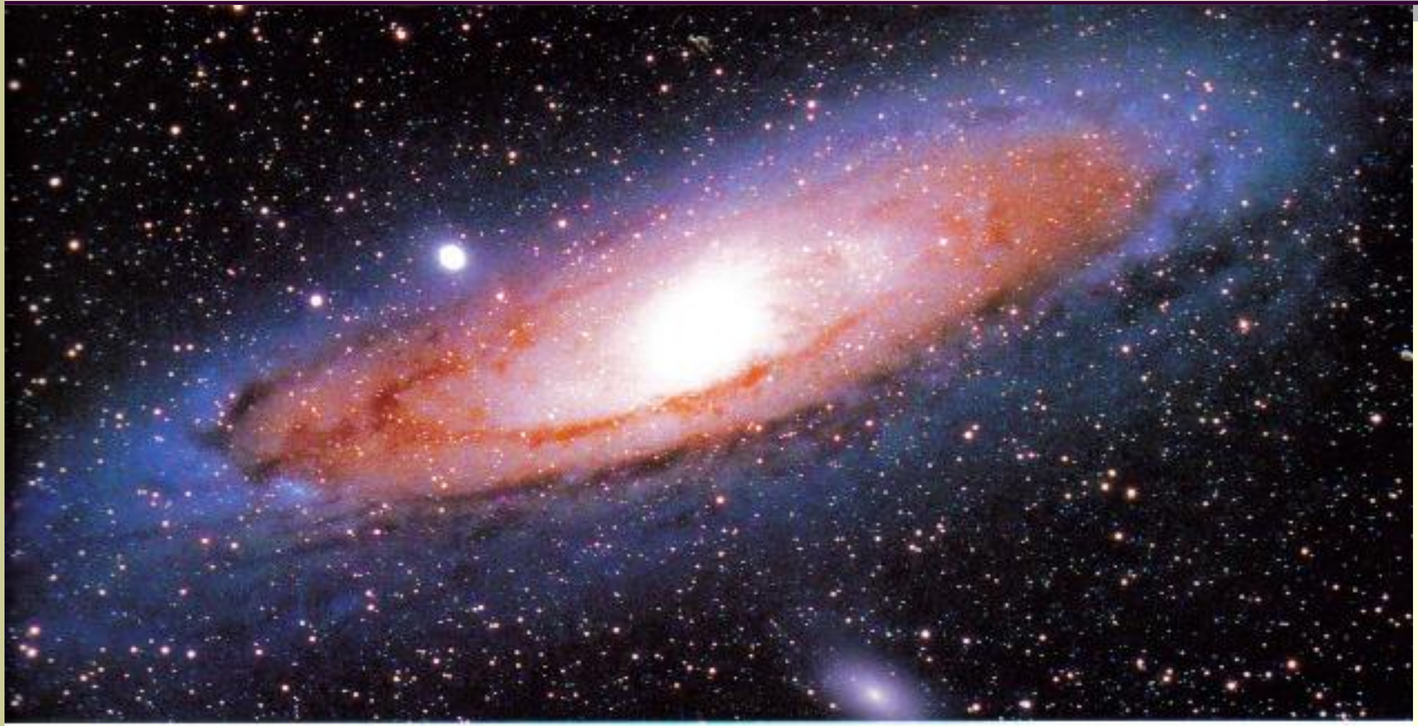
The Tau Zero Foundation

UK Space Conference 2009

http://www.tauzero.aero

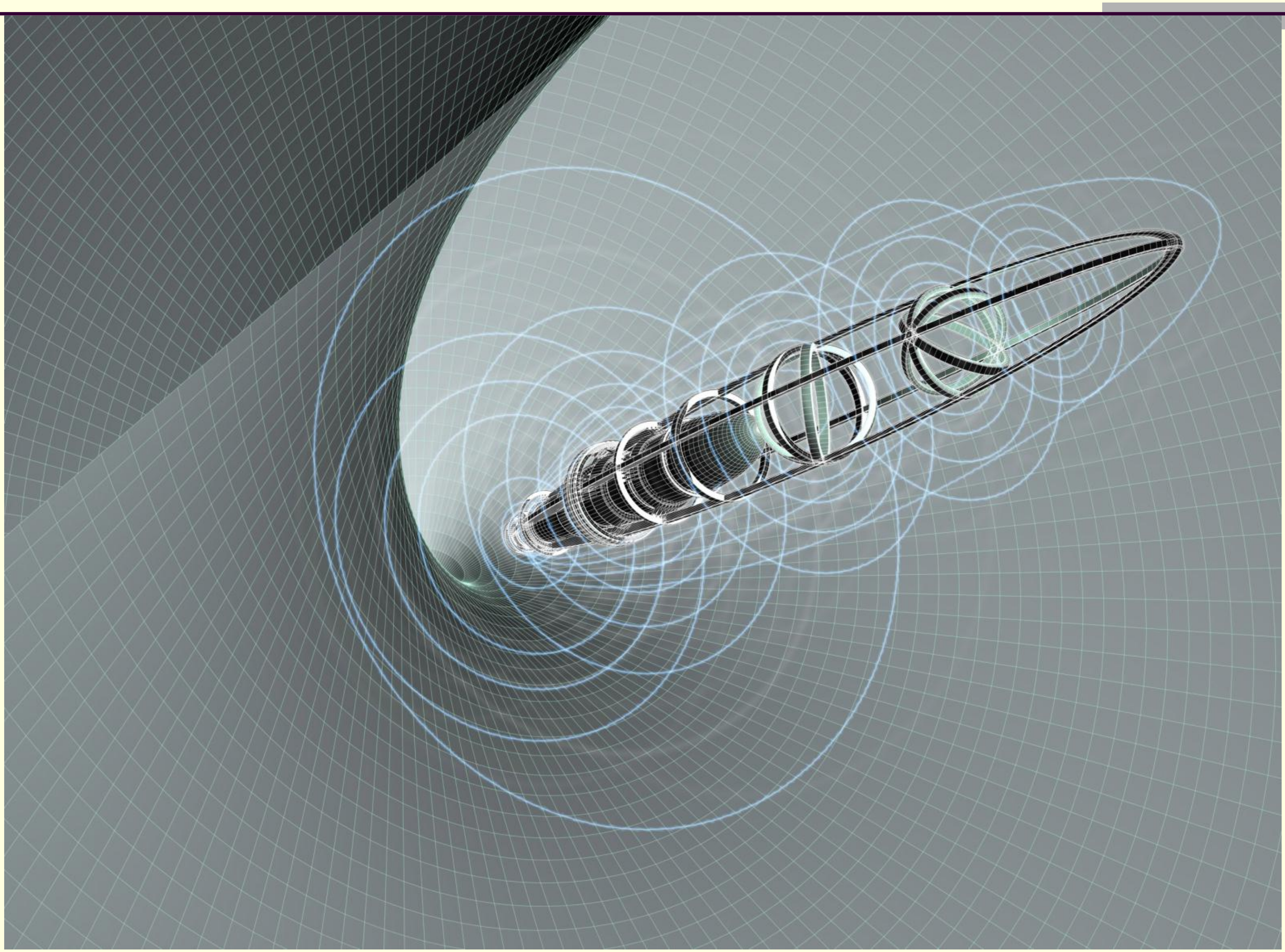
Contents

Ad Astra



- To reach the nearest stars, need to attain
- >10,000km/s or ~3%c for mission duration <100 years.
- For 1ton vehicle, require ~10^{18}J energy, ~50GW power.
- Necessitates high Isp performance & efficient fuel.

Interstellar Shortcuts



External Nuclear Pulse Rocket

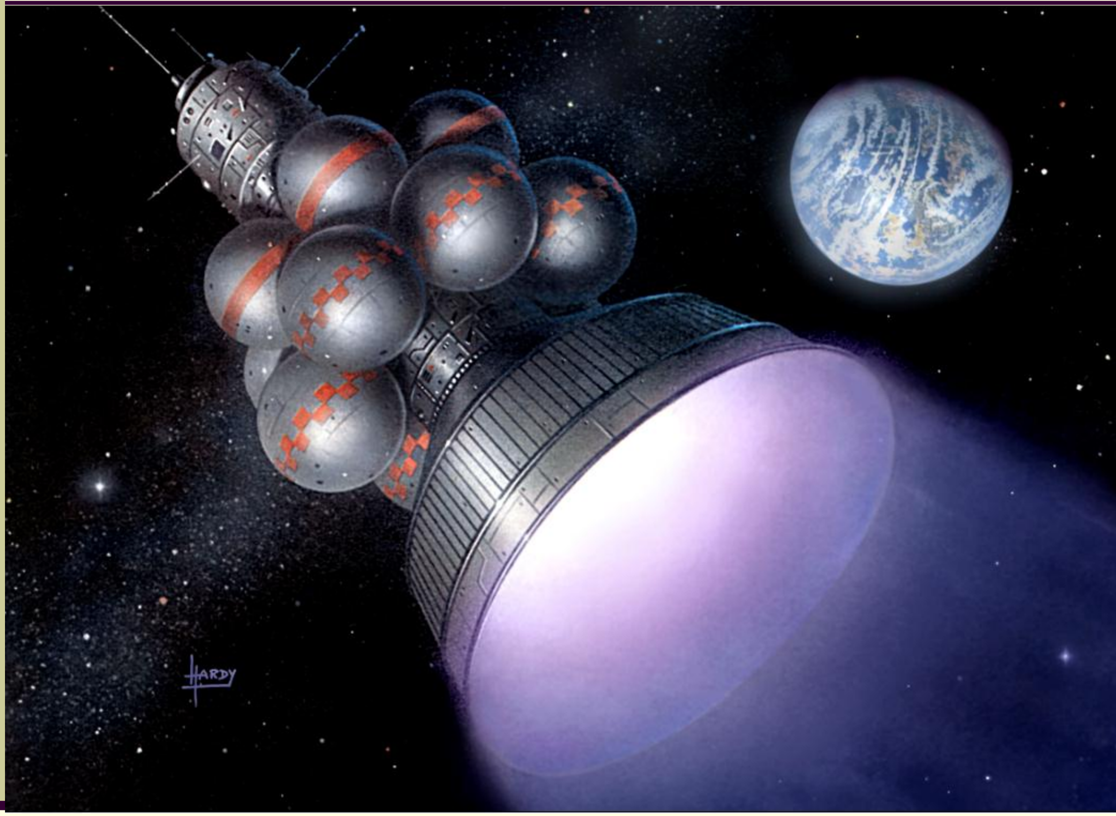
- Project Orion (1950's)
- External Pulsed Plasma Propulsion
- $11million over 7 years.
- Payload mass 20,000tons, total mass 400,000tons including 300,000bombs weighing 1ton each.
- Exploded 1 every 3 seconds pushing vehicle at 1g.
- After 10 days at 1g reaches ~3%c.
- Would take ~140 years to reach Alpha Centauri and ~300 years to reach Tau Ceti and Epsilon Eridani.

The Challenge of the Spaceship

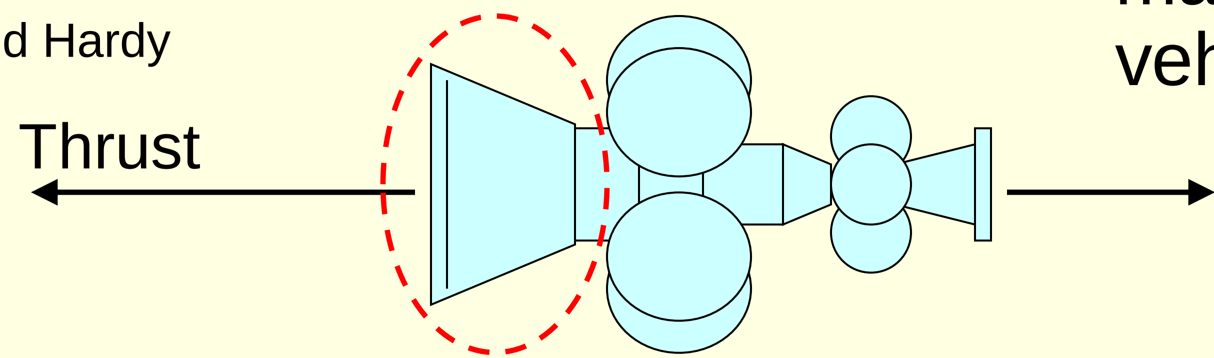
"*We can take it for granted that eventually nuclear power, in some form or other, will be harnessed for the purposes of space flight….The short-lived Uranium age will see the dawn of space flight; the succeeding era of* ***fusion power*** *will witness its fulfilment*".

Arthur C Clarke, 1961.

Daedalus (British Interplanetary Society



David Hardy



- Cleaner than Orion
- Alleviates some shielding problems
- Much smaller energy release
- Much less massive vehicles

Lawson's Criteria (Fusion Triple Product)

Lawson, (Proc.Phys.Soc, 1957)

$$\boxed{n\tau T \geq 10^{21} m^{-3} s KeV}$$

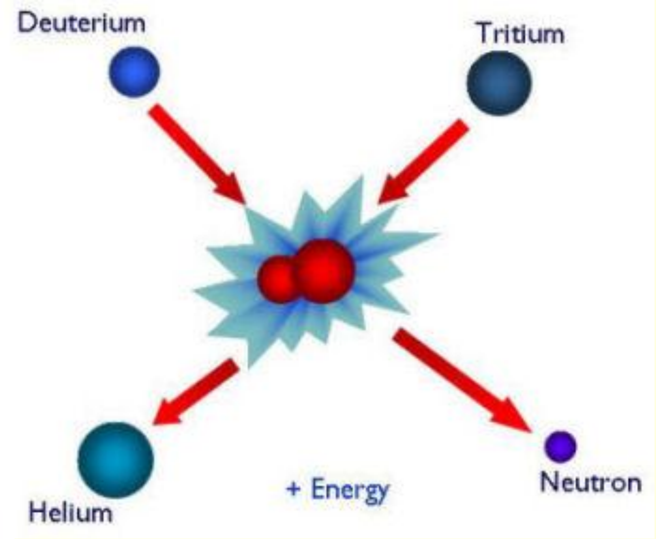
For ~10keV plasma

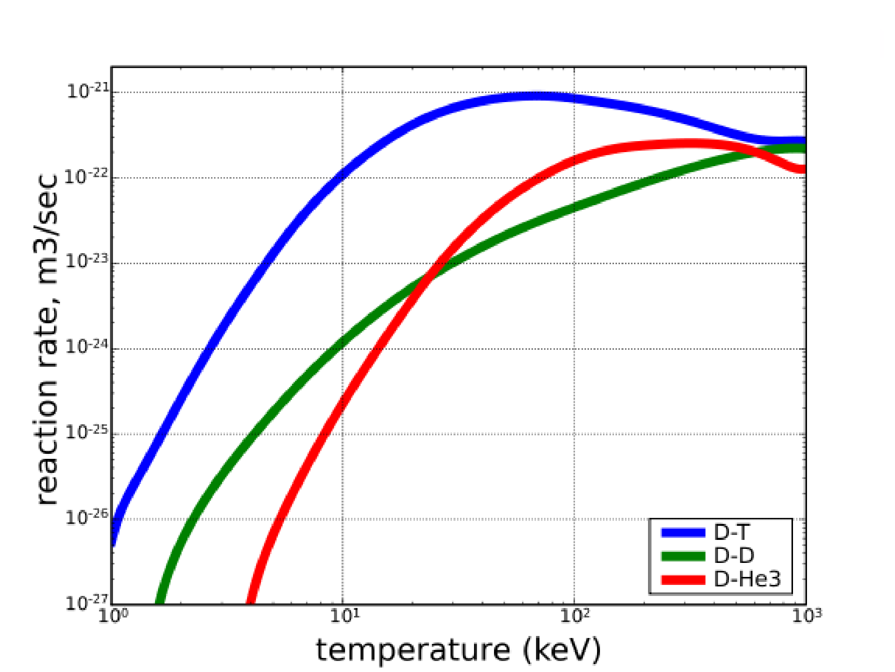
$$\boxed{n\tau \geq 10^{20} m^{-3} s}$$

Confinement	**n**	**τ**
Inertial	**~10^{23}cm^{-3}**	**<1ns**
Magnetic	**10^{-6}cm^{-3}**	**~few sec**

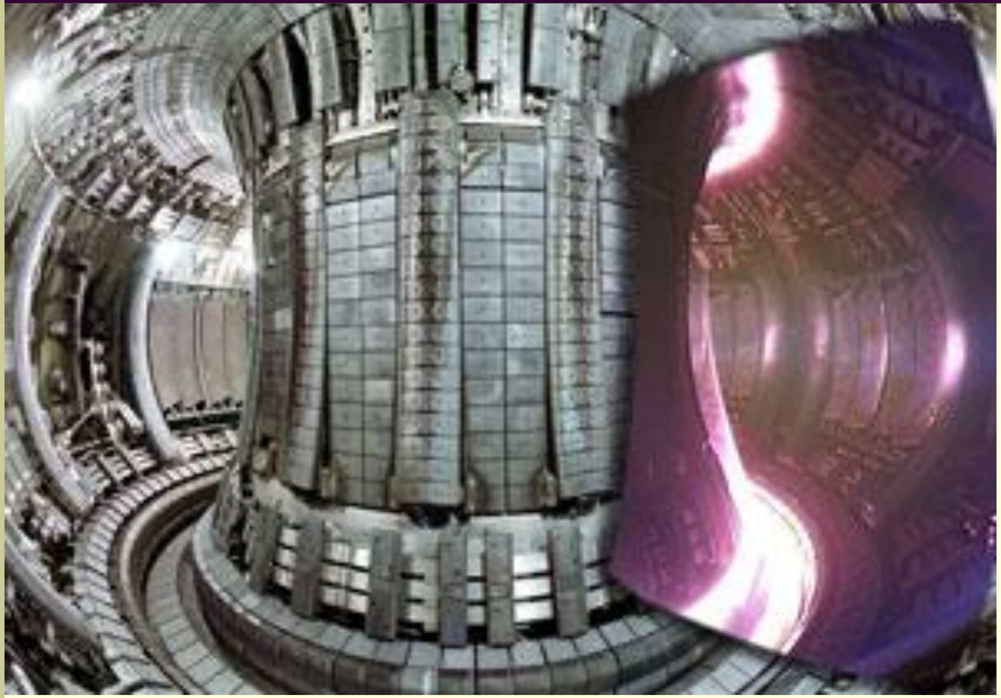
The Physics of Fusion

- D + T → He^4(3.52MeV) + n(14.06MeV)
- D + D → T(1.01MeV) + p(3.03MeV)
- D + D → He^3(0.82MeV) +n(2.45MeV)
- D + He^3 → He^4(3.67MeV) + p(14.67MeV)
- Li^6 + n → T + He^4 + 4.8MeV
- Li^7 + n → T + He^4 + n - 2.5MeV



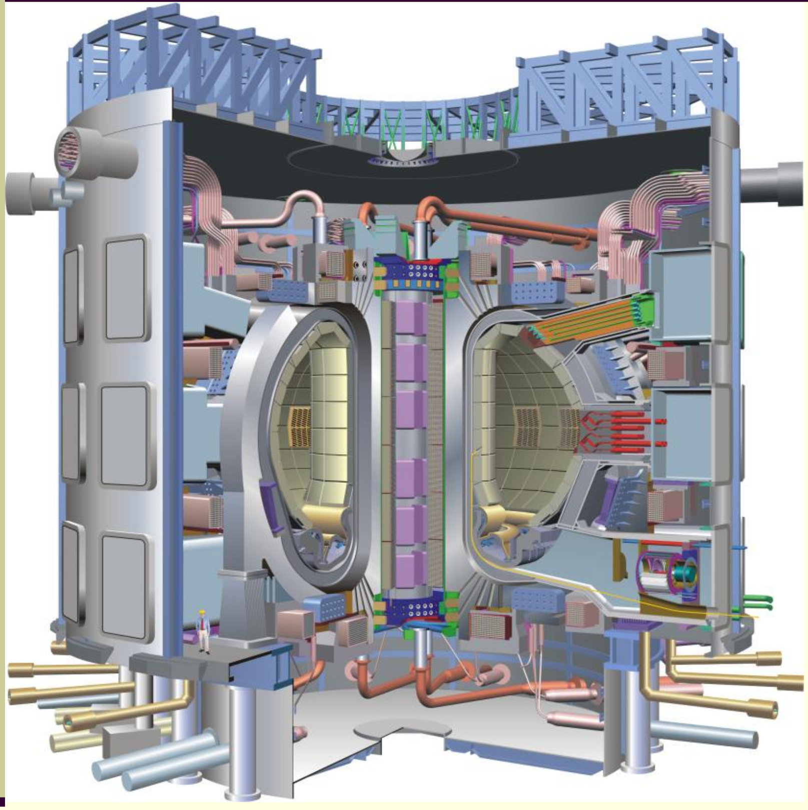


JET (magnetic fusion), Culham, UK



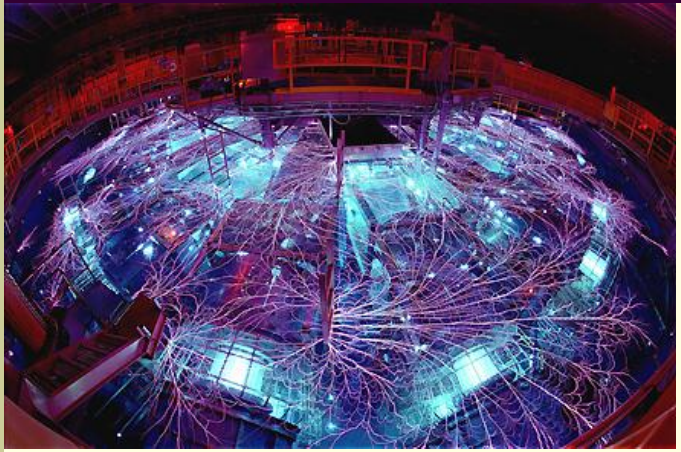
- Construction started in 1978, managed by UKAEA since 1999.
- Began operating in 1983.
- Uses DT fuel.
- Achieved 16MW fusion power and 21MJ of fusion energy equating to Q=0.7.

ITER (magnetic fusion)



- International Thermonuclear Experimental Reactor.
- Began construction 2007, France.
- Starts operating 2016.
- Will attain 500MW fusion power for 400s.

Z-machine, Sandia National Lab

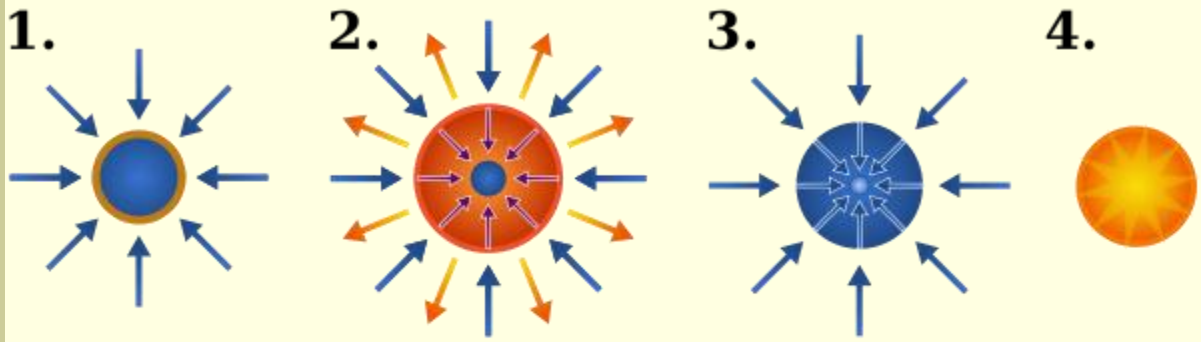


- 40TW Electrical power with 19MA load current, heats & vaporize high Z cylindrical wire array (W).
- Uses **J×B** force to implode capsule.
- Biggest x-ray generator in world.
- Generates 350TW energy output.
- Recent upgrades ZR program gives energy output 390TW with 2.7MJ x-ray energy output.
- Future plans ZN program upgrade to 30MJ.
- Future machines 1000TW power facilities.

ICF History

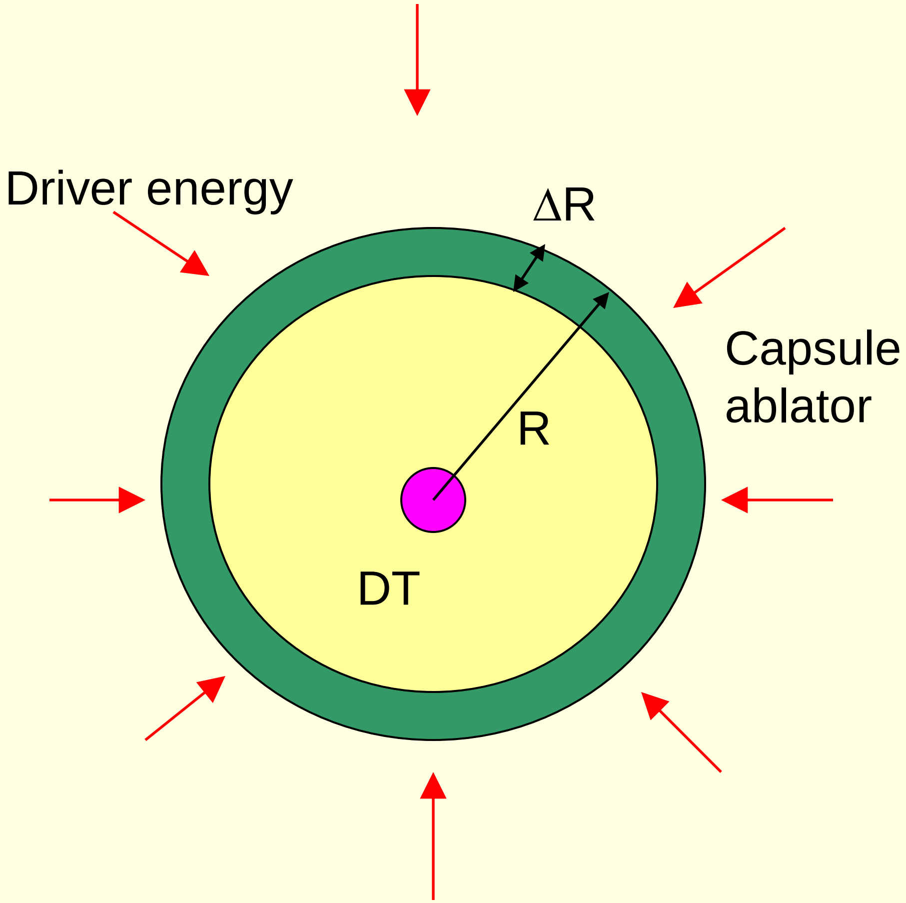
- Nuckolls, J et al., Laser Compression of Matter to Super-High Densities (Nature, 1972).
- ~1KJ laser energy required for DT ignition.
- Using laser intensity 10^{17}W/cm^2, get implosion velocities 10^7-10^8cm/s, pressures 10^{12}atmospheres compression 10^4.
- Require symmetric implosion pressure
- Hydrodynamic instabilities must be controlled
- TN micro-explosions (10^7-10^8J energy output) credible for commercial power production, attain ~GW electric power levels by burning ~100 capsules per s in 10 chambers.
- Predicted ignition requirement of ~1kJ for large compression
- But ~IMJ required for high gain.

Inertial Confinement Fusion



- 1. Laser produced X-rays (typically 70-80% conversion) rapidly heat the surface of the fusion target, forming surrounding plasma envelope.
- 2. Fuel is compressed by the rocket-like blow-off of the hot surface material.
- 3. During the final part of the capsule implosion, the fuel core reaches 20×density of lead and ignites at 100,000,000 ˚C.
- 4. Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.

Inertial Confinement Fusion (ICF)



Symmetry $R/R_h \sim 25\text{-}35$

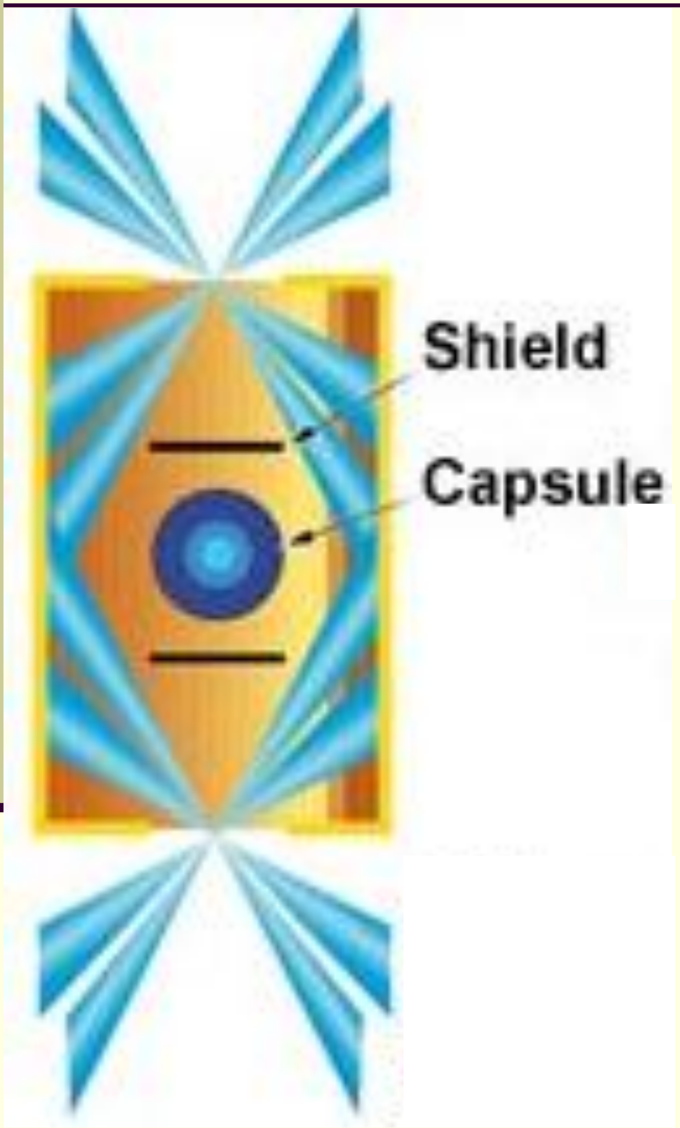
Stability $R/\Delta R \sim 25\text{-}35$

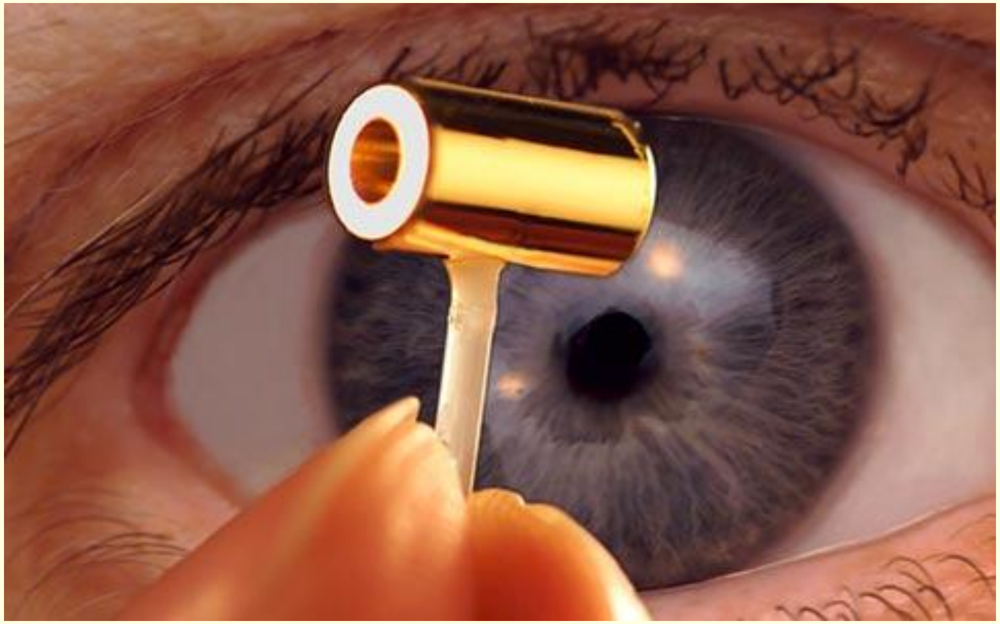
Ignition $T = 10\,\text{keV}$, $\rho \Delta R_h \sim 0.3\,\text{g/cm}^2$

Implosion $V_{imp} \sim 10^7\,\text{cm/s}$

Energy driver 1-2MJ

Indirect Drive

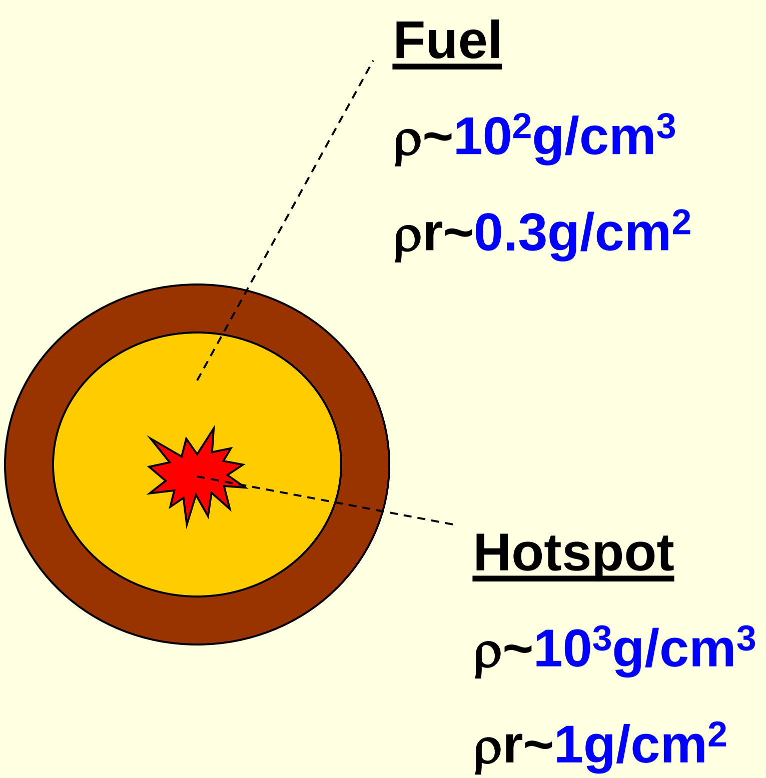




Lawson's Criteria (Fusion Triple Product)

$$\boxed{n\tau T \geq 10^{21} m^{-3} sKeV}$$

- ICF ρR requirement:
- $\rho R > 0.1 g/cm^2$
- But inefficiencies & losses raise requirement
- $\rho R > 0.8 g/cm^2$
- Leads to ignition requirement ~IMJ

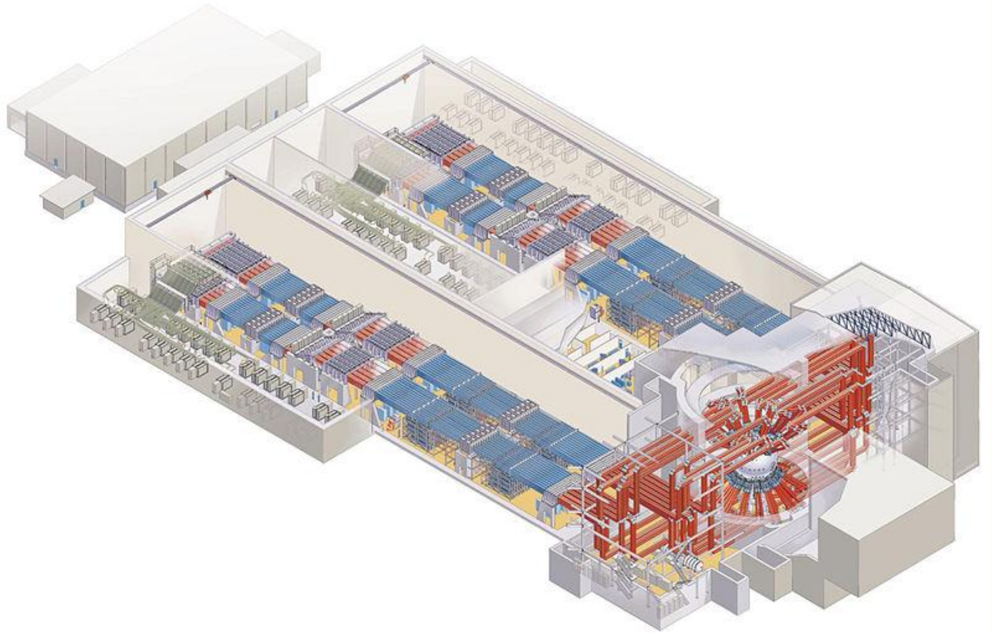


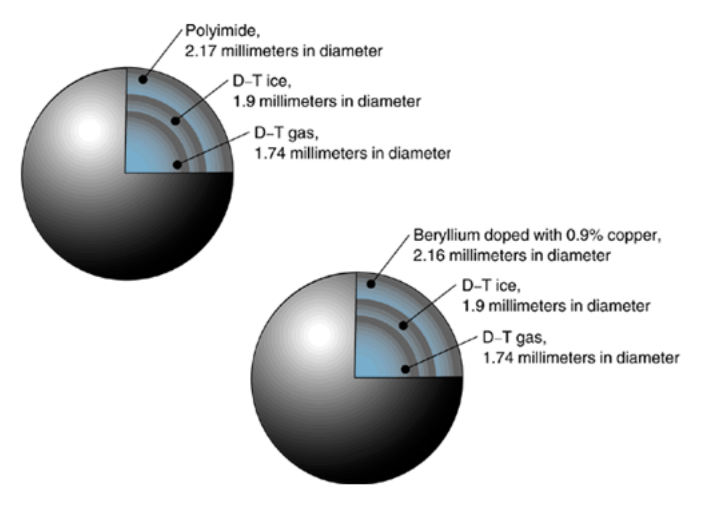
This is the NIF baseline target

NOVA

- Operated 1984-1999.
- Input power insufficient to achieve ignition.
- But provided insights into plasma hydrodynamics.
- Useful for design of NIF.

National Ignition Facility (NIF)





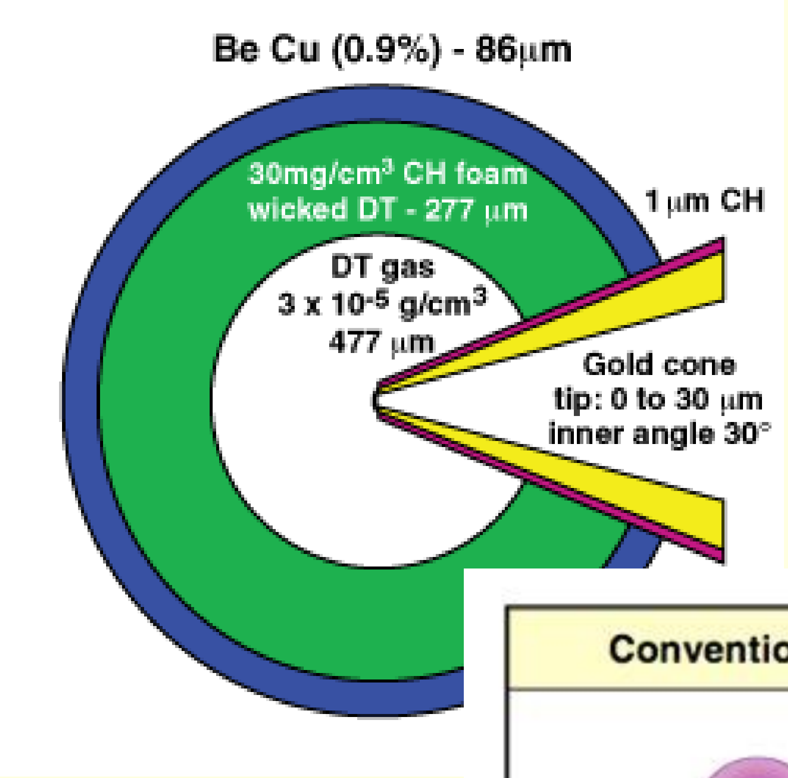
- Neodymium glass laser
- Start operation 2009.
- 192 beams
- Deliver 1.8MJ to target.
- Potential output power 20MJ for ~ns but could be high as 45MJ.
- Achievable gains >10.

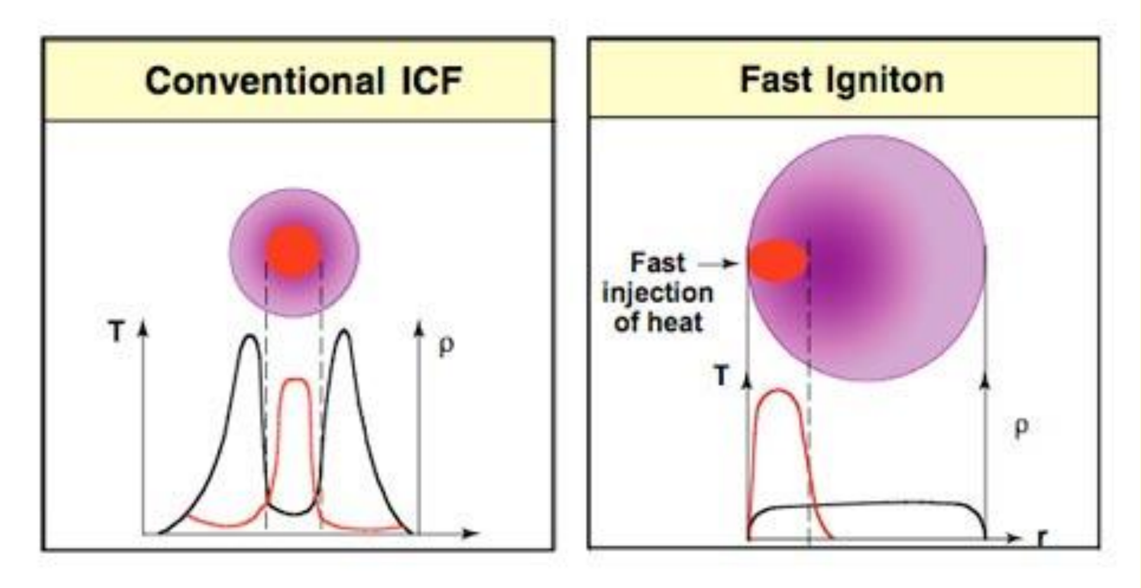
Laser Mégajoule

- France.
- Starts operating 2010.
- Aims to deliver 1.8MJ power to the target.

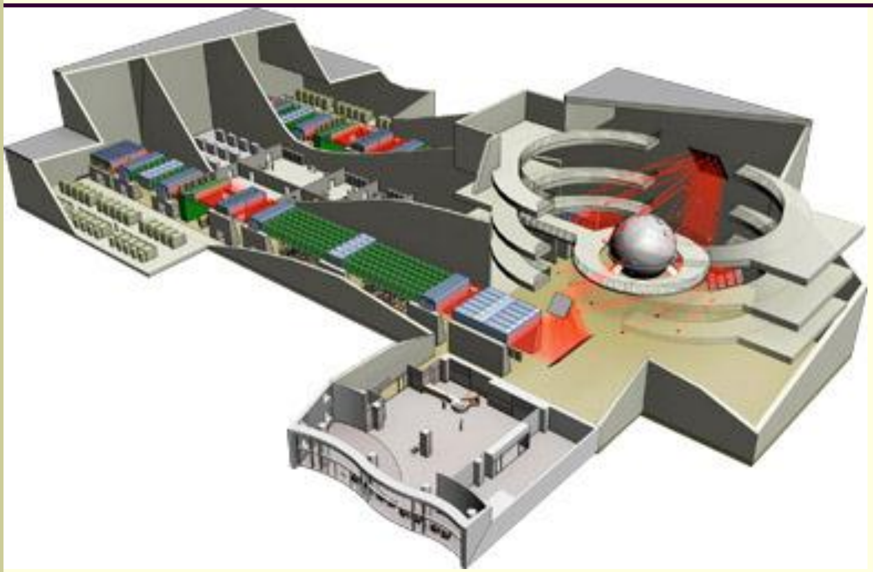
Fast Ignition Approach to ICF

Laser compression of capsule followed by heating of high density fuel for ignition by second short pulse laser. Decoupling the heating and compression phases of the implosion



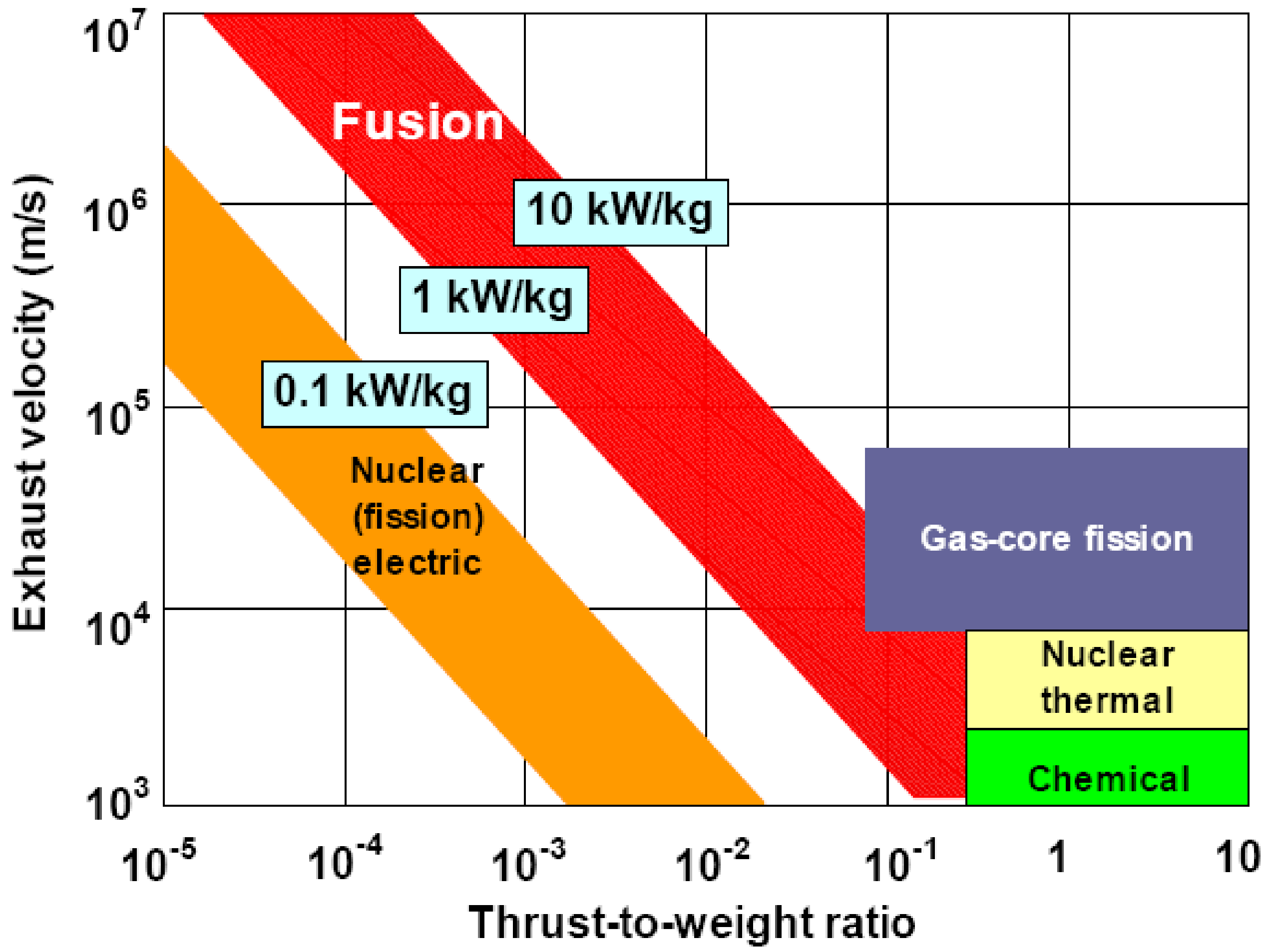


HiPER (inertial fusion)



- High Power Laser for Energy Research.
- Hope to begin construction 2010.
- Fast ignition approach.
- Laser: 250kJ ns long pulse + 100KJ ps short ignition pulse.
- Produce 30MJ power output.
- Gain ~100 attainable.

Comparative Propulsion Performance



J.F.Santarius, University of Wisconsin.

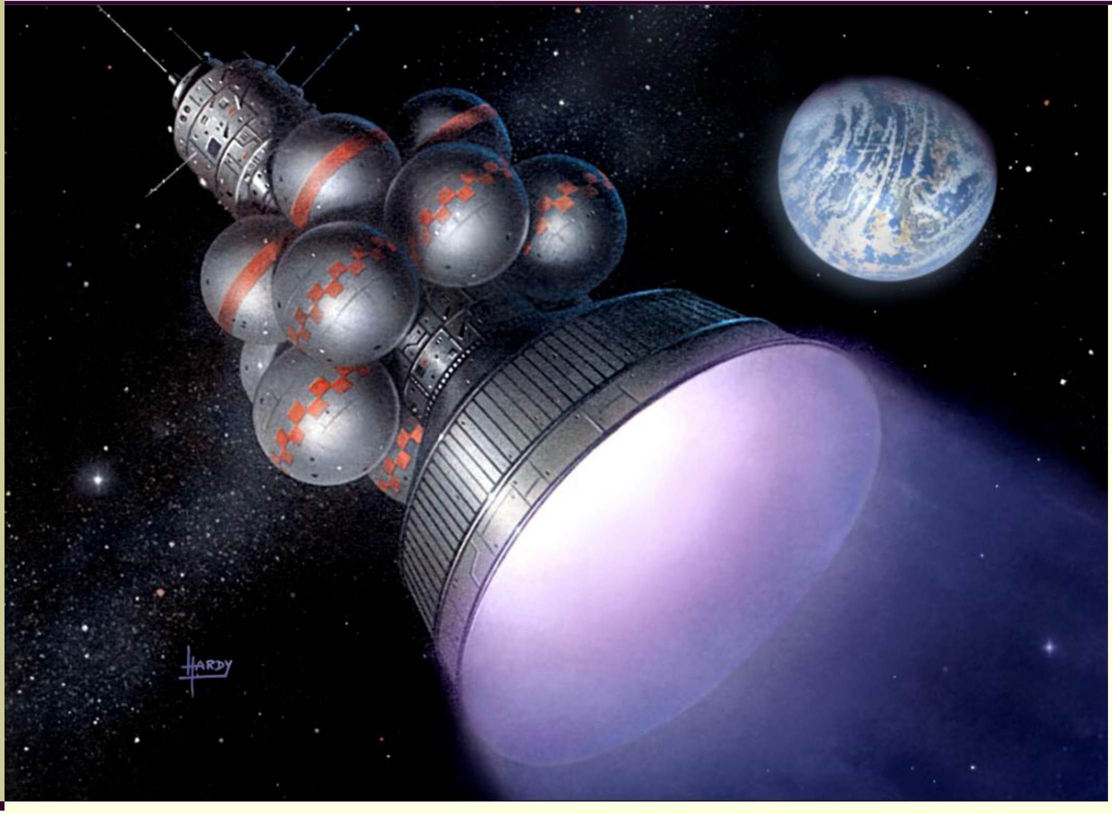
Likely Fusion Performance

- Specific Power 1-10kW/kg
- Specific Impulse: 2500 – 10^6s
- Exhaust velocity: 10,000-36,000km/s
- Fraction light speed: 3% - 12%c
- Thrust-mass ratio: 10^{-4} – 10^{-5}
- Mission duration 50-100 years.
- Use of small fission reactor to power systems.

Fusion Rocket

- 1966, Spencer, NASA JPL, '*Fusion Propulsion for Interstellar Missions*', suggested D+He^3 fusion, attain ~180,000km/s (0.6c), 50 year mission to nearest star.
- 1973, Winterberg, University of Nevada, "*Micro-fission Explosions and Controlled Release of TN Energy*", Nature. proposed using magnetic compression reactors powered by Marx generators and use electron beams to initiate fusion.
- Use $\mathbf{D + He^3 \rightarrow He^4(3.67MeV) + p(14.67MeV)}$
- For DT fuel, need to create T on board due to short half life.
- Focus charge particles using high temperature superconducting magnets.
- Use of 'leaking' magnetic bottle for plasma stream.
- Detonate many hundreds micro-explosion capsules per second.
- Use of shielding to protect systems from high energetic particles.

Project Daedalus (1973-1978), BIS



David Hardy

- Three guidelines:
- The spacecraft must use current or near-future technology.
- The spacecraft must reach its destination within a human lifetime.
- The spacecraft must be designed to allow for a variety of target stars.

Project Daedalus

- 54,000 tons + 450tons payload. 190m length.
- Two stage craft. Burn ~2 years with thrust 754,000N up to ~7%c, then burn ~1.8 years with thrust 663,000N up to ~12%c.
- Then cruise for 46 years at ~10,000km/s
- Propelled by D/He^3 ICF using electron beams. 250 capsules detonated per sec, with plasma directed by magnetic nozzle.
- Included autonomous probes to be deployed to nearby planets. The probes were powered by nuclear ion engines.

Project Daedalus

Project Daedalus: The Vehicle Configuration

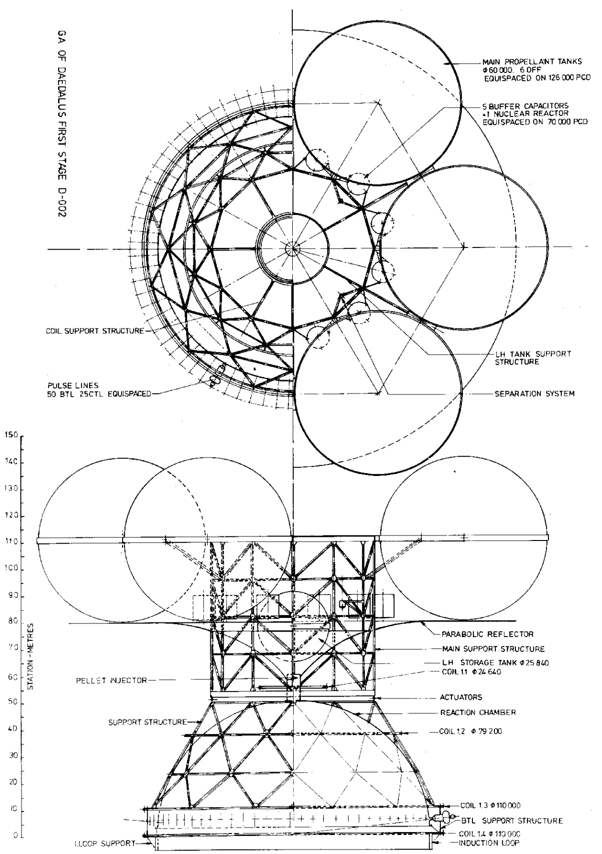


Fig. 3. Daedalus vehicle first stage configuration.

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Project Daedalus: The Vehicle Configuration

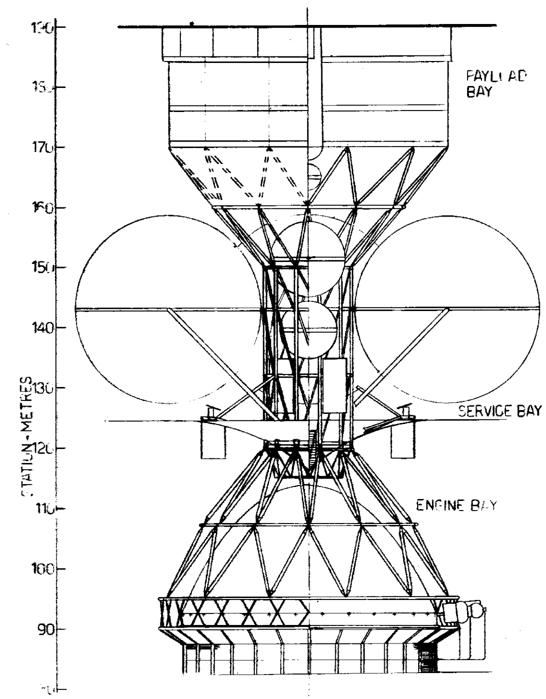

Fig. 5. Second stage structural configuration favoured at the close of the study.

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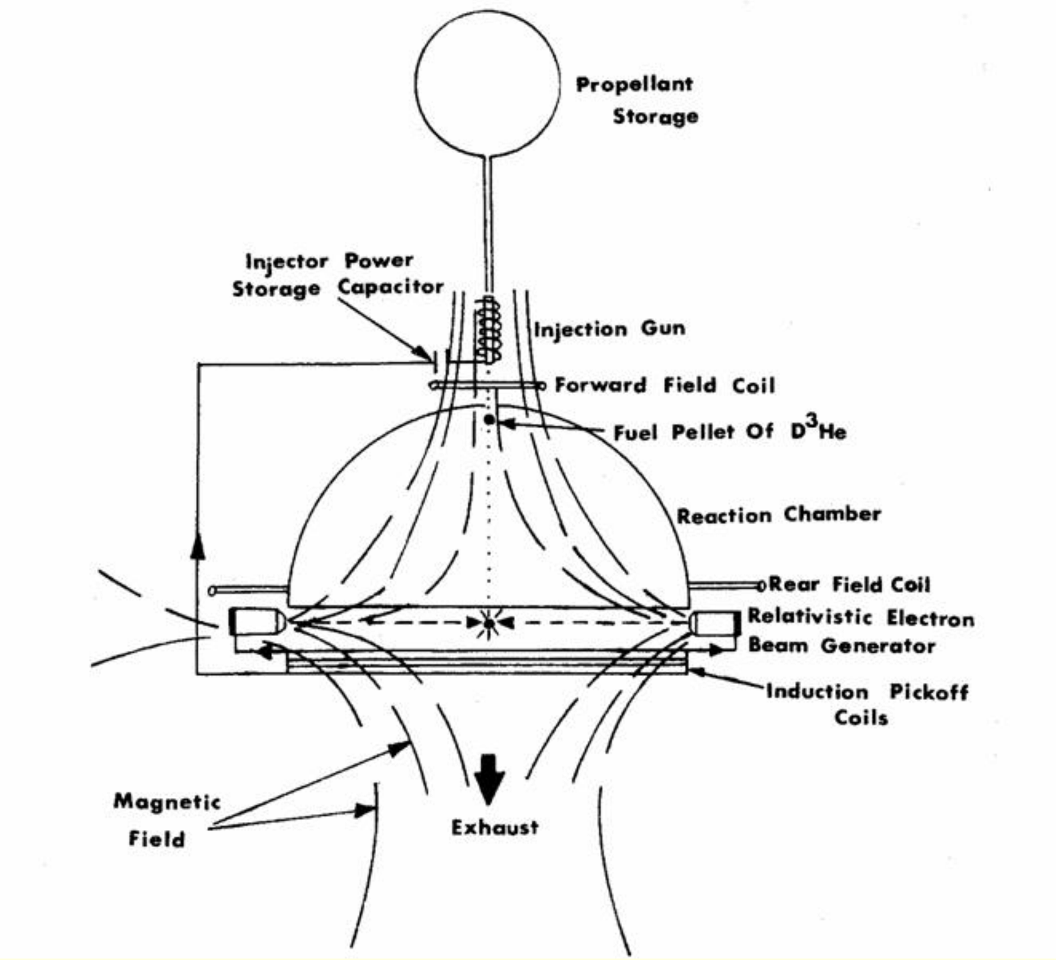
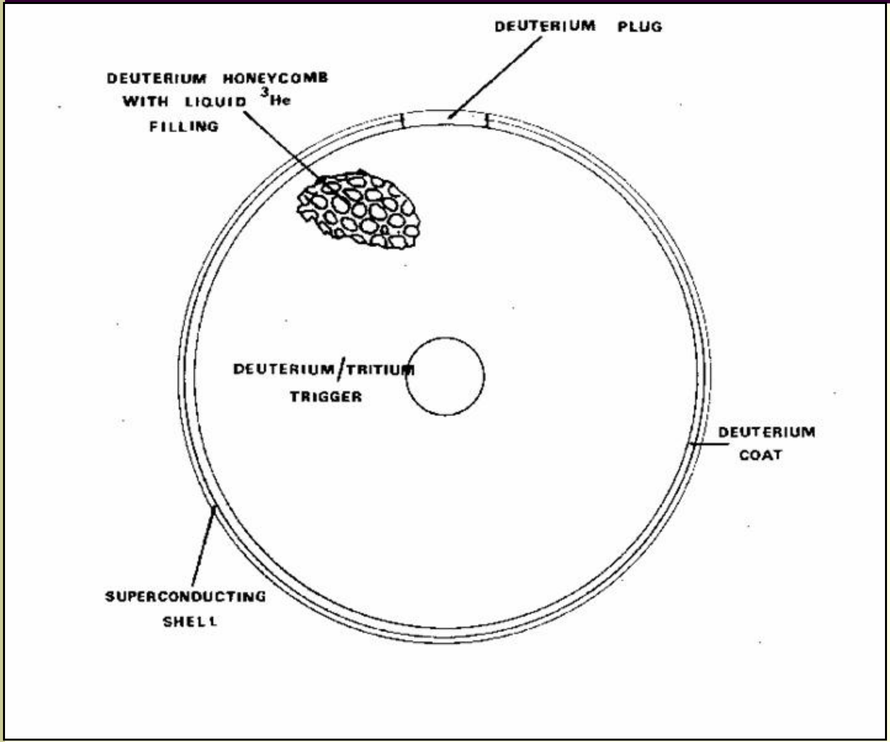
Daedalus (Propulsion System)



British Interplanetary Society

- Electromagnetic gun accelerates capsule, via superconducting shell around capsule.
- Electron beams target capsule
- Implode to ignition.
- Automated capsule manufacture

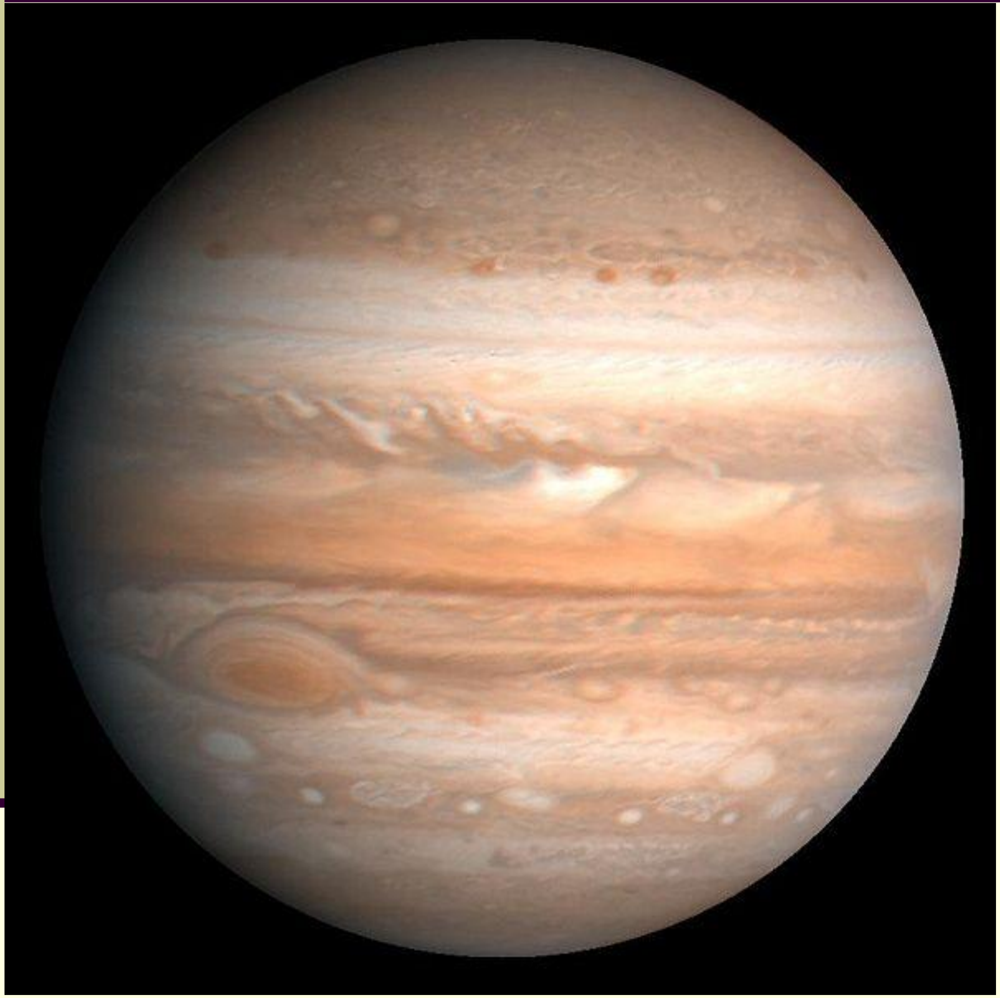
Daedalus (Capsule design)



British Interplanetary Society

- Diameter 3.94cm (1st stage) 1.832cm (2nd stage)
- Require ~3×10^{10} capsules.
- If production was for 1 year, would need to make ~1000 capsules per second.
- Neutrons per pulse: 6×10^{21} (1st stage) 4.5×10^{20} (2nd stage)
- Neutron production rate: 1.5×10^{24}n/s (1st stage) 1.1×10^{23}n/s (2nd stage).
- But large capture X-section of He^3 attenuate majority of neutron flux.

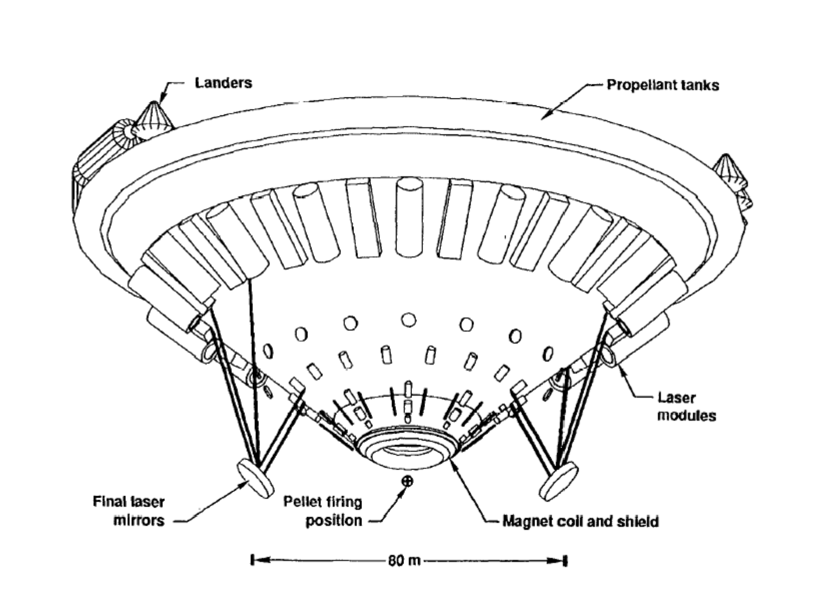
Mining He^3 from Jupiter



NASA

- Factory processes 680kg/s of Jovian atmosphere and produces 1.15g/s (He^3) 0.77g/s (D), 3.67g/s (H)
- <u>Alternatives</u>
- Other planets
- Solar wind
- Comets
- The Moon

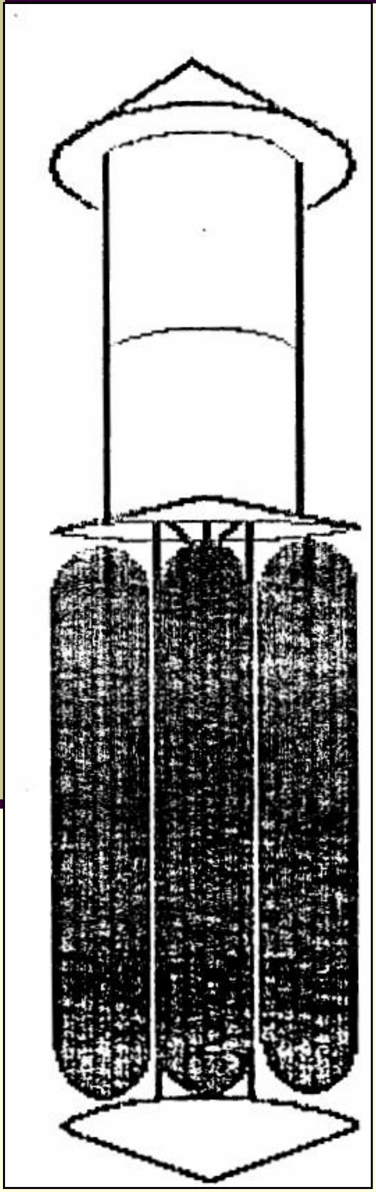
Project Vista (1986-1987)



- Develop viable, realistic spacecraft based on ICF technology projected available first half of this century.
- In orbit assembly

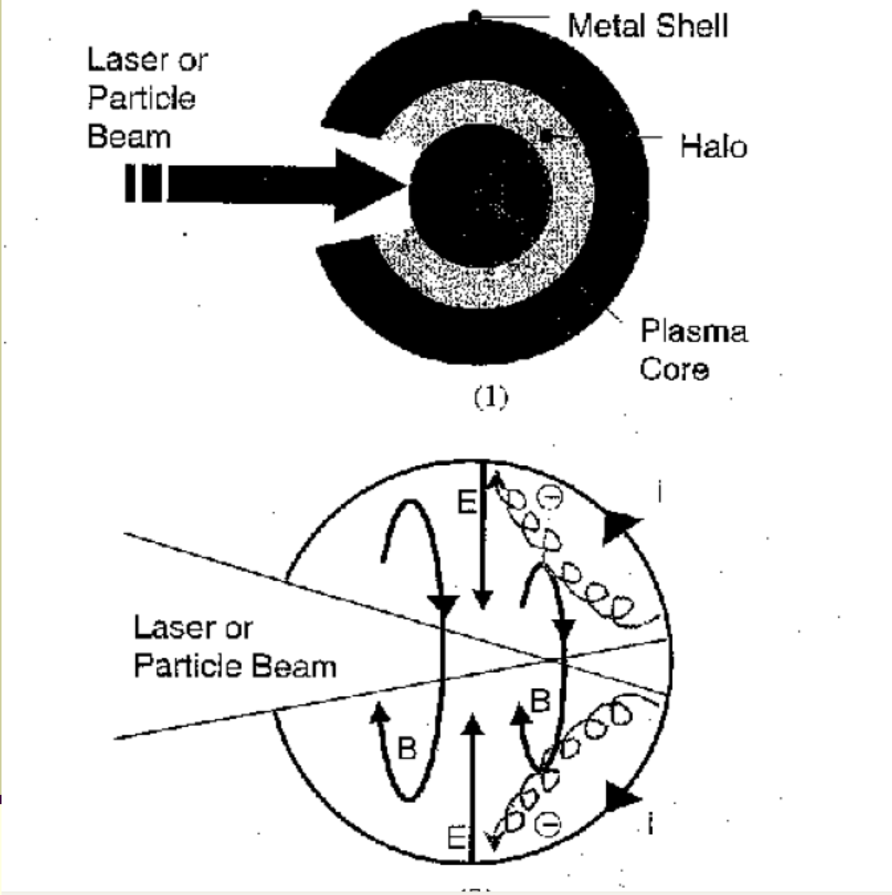
- ICF with DT fuel, 5MJ laser driver energy.
- ~100ton payload, ~4000ton fuel, ~6000ton vehicle.
- Isp~10^4s. Use fast ignition high target gain >1000.
- Capsule compression by 200ps 10^{18}W/cm^2 laser pulse to channel to core.
- Followed by 30ps 10^{20}W/cm^2 laser pulse to ignite the fuel
- Round trip to Mars ~6months.
- Round trip to any planet in solar system ~7years.

Project Longshot (1987-1988)



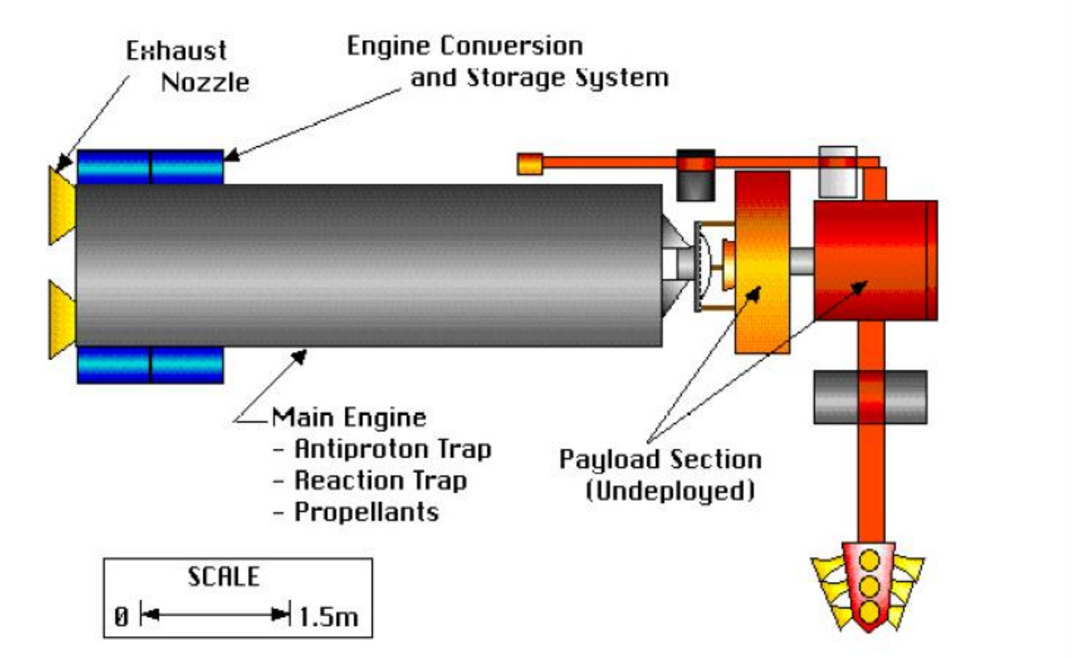
- Design study to reach Alpha Centauri in ~100 years.
- ~400ton vehicle with ~30ton payload.
- ~300kW nuclear fission reactor powers lasers for ICF propulsion using ~260tons D/He3 fuel.
- Isp~10^6s, peak velocity ~14,000km/s (0.05c).

Antimatter Catalysed Fusion



- Beam of antiprotons reacts with DT coated wall, annihilates protons producing hot plasma.
- Initiates fusion in DT fuel.
- Self generated magnetic field thermally insulates plasma from metal containment shell
- Isp~10^6s, T~10^5N.
- Gain ~3000
- ~10,000AU in ~50 years.
- NASA Marshal developing antiproton trap to hold 10^{13} particles.

Project AIMStar (1990's)



Continuous acceleration for ~4-5 years, then coast. Designed to reach ~10,000AU (Oort cloud) within ~50 years at coast velocity of ~960 km/s (0.003c).

Reach Mars in one month.

- AIMStar – Antimatter Initiated Micro-fusion Star ship
- 800ton ship with 220lb probe
- Uses ~30-130milligrams antiprotons to initiate fusion in capsules.

The Tau Zero Foundation

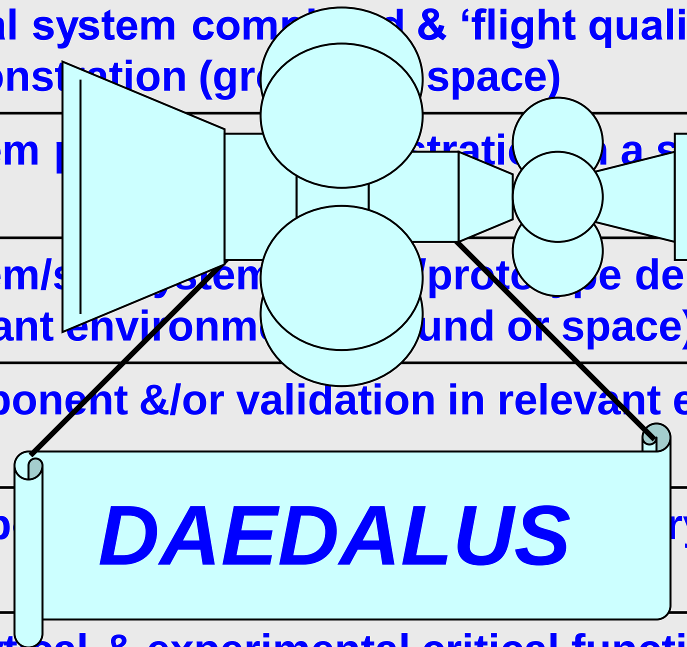
- Volunteer scientists, engineers, artists, writers, entrepreneurs dedicated to addressing the issues of interstellar travel.
- Private non profit corporation supported through donations.
- Fills research gap in industry that's not being pursued with priority.
- Not a space advocacy group.
- The Foundation Practioners support incremental progress in interstellar spaceflight (not just BPP).

The Tau Zero Foundation

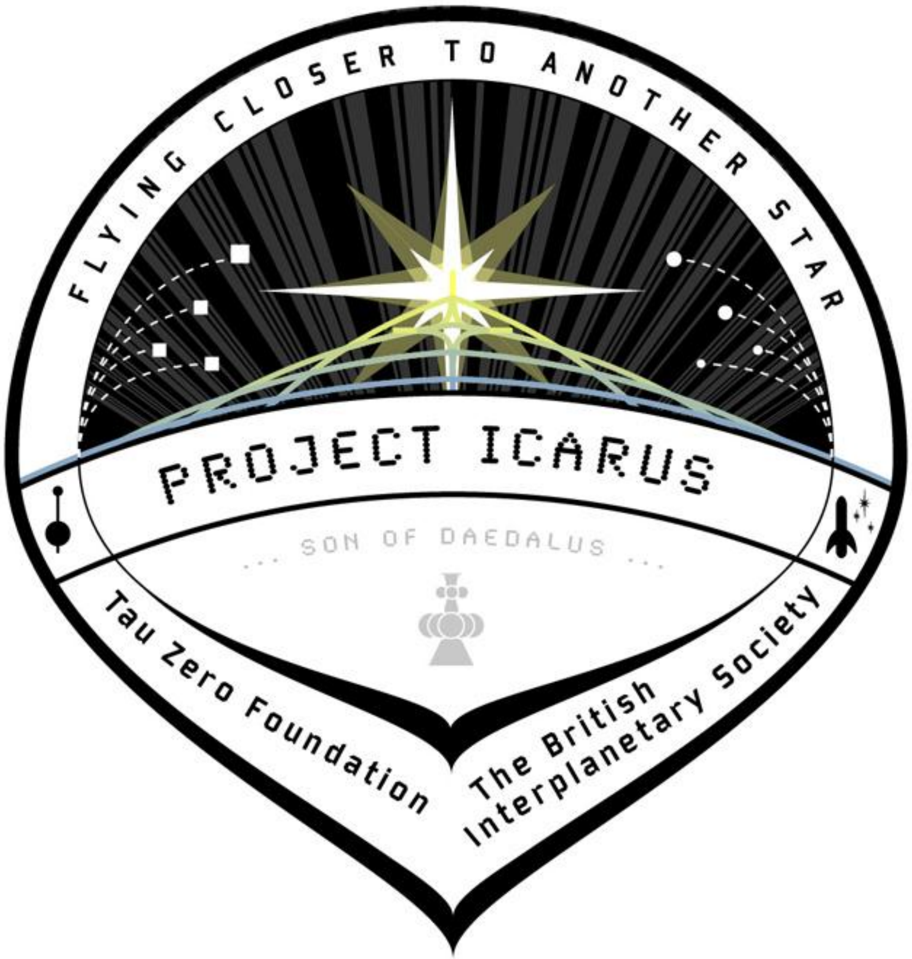
- **Support students through Scholarships.**
- **Provide inspirational educational products.**
- **International conferences.**
- **Support for interstellar design studies.**
- **Support BPP research topics through competitive selections when funding available.**
- **Foundation seeks credible, rigorous scientific research.**
- **Cash awards for visionary research.**

Technology Readiness Levels

TRL 9	Application tested	Actual system 'flight proven' through successful missions
TRL 8	Application proven	Actual system com[illegible]d & 'flight qualified' through test & demonst[illegible]tion (gr[illegible] space)
TRL 7	System proof	System p[illegible]stratio[illegible] a space environment
TRL 6	Prototype proof	System/s[illegible]system[illegible]/proto[illegible]e demonstration in relevant environm[illegible]und or space)
TRL 5	Component proof	Component &/or validation in relevant environment
TRL 4	Physics proof	Comp[illegible]ry environment
TRL 3	Science	Analytical & experimental critical function &/or characteristic proof of concept
TRL 2	Speculation	Concept and/or application formulated
TRL 1	Conjecture	Basic principles observed/reported



Project Icarus



- Phase 1:
  Assemble team (sep 09-Jan 10)
- Phase 2:
  Build Work programme (Jan 10-Apr 10)
- Phase 3:
  Work Begins (Apr 10-)
- Project Duration:
  3-5 years.

Icarus (Purpose)

- Design credible interstellar probe that is a concept design for a potential mission this century.
- Allow a direct technology comparison with Daedalus and provide maturity assessment fusion based propulsion.
- Generate greater interest in the real term prospects for interstellar precursor missions that are based on credible science.
- To motivate a new generation of scientists to be interested in designing space missions that go beyond our solar system.

Icarus (Terms of Reference)

- Design unmanned flyby probe.
- Deliver useful scientific data about the target star, associated planetary bodies and solar environment.
- Use current or near future technology
- Credibly launched by 2050.
- Must reach destination fast a time as possible, not exceeding 60 years but ideally much sooner.
- Must be designed to allow for a variety of target stars.
- Must be mainly fusion based propulsion.
- Mission designed to allow a modification to the trajectory with minimum fuel for a second target destination.
- **CREDIBLE- PRACTICAL- SCIENTIFIC- NEAR FUTURE.**

Conclusions

- Fusion technology offers a good performance capability for missions to the nearest stars and the outer parts of the solar system.
- However, the technology is not yet mature for application to space power and the critical parameters are likely to be engine mass (including laser) and gain.
- Future projects like ITER and HiPER will demonstrate this technology. The problem then is engineering it for space flight.
- The next 20-30 years should be interesting.
- Daedalus→Icarus→Future Design.
- Will lead to design for first interstellar probe.

- "***Ad Astra Incrementis***"