Hazards of Interstellar Propulsion

Would you want a 100 GW beamer in your back yard or a fusion rocket anywhere close to Earth?

David F Gahan

Both of the most feasible means of interstellar travel involve enormous powers. Project Starshot and earlier proposals suggest laser beamers with powers of hundreds of GigaWatts (GW) - see work by Professor Philip Lubin [1], i4is projects Dragonfly and Andromeda [2]. The Daedalus study and its successors, the Icarus studies, notably Firefly, which have been most recently reported in Principium 43 *BIS Symposium brings Project Icarus to a close* (i4is.org/principium-43/), require fusion rockets releasing enormous energies from their 'exhausts'.

In this article David F Gahan examines the 'close to home' physics and engineering consequences implied by these two routes to the stars. If we don't get these right then we are not going!

More about David Gahan in Principium 43 November 2023 page 13. See also his article *AMiTe Treffpunkt in* Principium *32*.

The Icarus Firefly probe
Project Icarus was a series of studies aiming to build on the BIS Project Daedalus work in the 1970s. Rob Swinney, i4is Deputy Executive Director acted as Project Manager. The Firefly design is the most mature result of the Icarus programme. One of the design leaders, Michel Lamontagne, has produced a number of visualisations. An early design appeared on the rear cover of Principium 41, May 2023. This has three larger fin-like radiators sized for a D-D reaction rather than He3. It is assembled in LEO ready to be taken to a safer distance for launch.

[1] *A Roadmap to Interstellar Flight*, arxiv.org/abs/1604.01356
[2] *Dragonfly: Sail to the Stars*, www.researchgate.net/publication/317491721_Dragonfly_Sail_to_the_Stars,

An engineer (ing director) would want to know more about that interesting expression '**Would you want?**'; what is the figure-of-merit for 'want', and more especially its converse 'not want'. What counts as a 'hazard', and what as an engineering or economic challenge? Australians don't currently want the Commonwealth Games in their back-yard, but that's mostly a matter of *'moolah'*. While we can forward to a time when an advanced robotically effected design/construction facility doesn't actually impinge on the 'human economy', that currently seems far away. So, for 'close-to-present', we should consider how to minimize constructional and operational costs and also any environmental penalties needing 'clean-up' costs. But are there any clear and present dangers in the physics of operation?

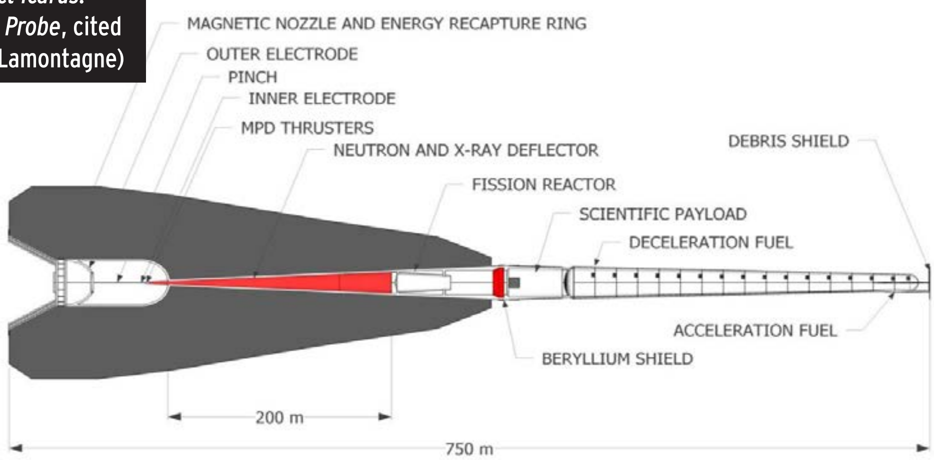
Here's a fun calculation. In $E = \frac{1}{2}mv^2$, put m = 1 kg and v = 10% c (3×10^7 m/s). 1 kg of mass needs 450 Terajoules (at perfectly impossible efficiency) to reach 0.1 c, which would need the entire electric generating capacity of the USA operating for at least 500 seconds for each measly kilogramme accelerated. Whether you put energy in via a heavy onboard system or from an external source pressing on the craft you're going to need lots of it and had better not stand too close to the exhaust or in the beam.

For both the main current studied concepts for interstellar propulsion, current fusion development seems to offer the most secure route to the prodigious energies required, either on board or by a beamer connected to a fusion power grid. However, space based solar may have a role here especially in a reconfigurable mode, supplying power to otherwise remote places for relatively short periods (beamer launch campaigns or fusion fuel production) before reconfiguring for general grid supply to population centres. This could lower capital costs by avoiding 'stranded assets'.

Let's talk fusion rockets such as *Project Icarus: Designing a Fusion Powered Interstellar Probe* (zenodo.org/record/3747274/files/AF12.2020.47.pdf). The Icarus team worked hard to update the visionary thinking of BIS Daedalus, helped by some recent progress on alternative ways to achieve fusion ignition and maintenance or repetition of 'burn'. In the far future, with full solar-system resources at our disposal, there could be a Helium3 economy in the outer planets and, hey, it would make sense to launch starships from there (and maybe make some energy economies by a swing round Jupiter). But the Icarus team sensibly focused for the next hundred years on D-D fusion, ie deuterium fuel, and that means seawater-sourced and starship launch from the Earth-Moon system.

There's a great storyboard by Michel Lamontagne, one of the Icarus principals, on a mission scenario in "Flight of the Firefly": (www.deviantart.com/michel-lamontagne/gallery/84479459/flight-of-the-firefly). The 800 m long Firefly – see below for diagram from the project read-out - is built in 500 km LEO (compare ISS at 405 km).

Outline schematic of Firefly from *Project Icarus: Designing a Fusion Powered Interstellar Probe*, cited above, figure 2. (Image credit: Michel Lamontagne)



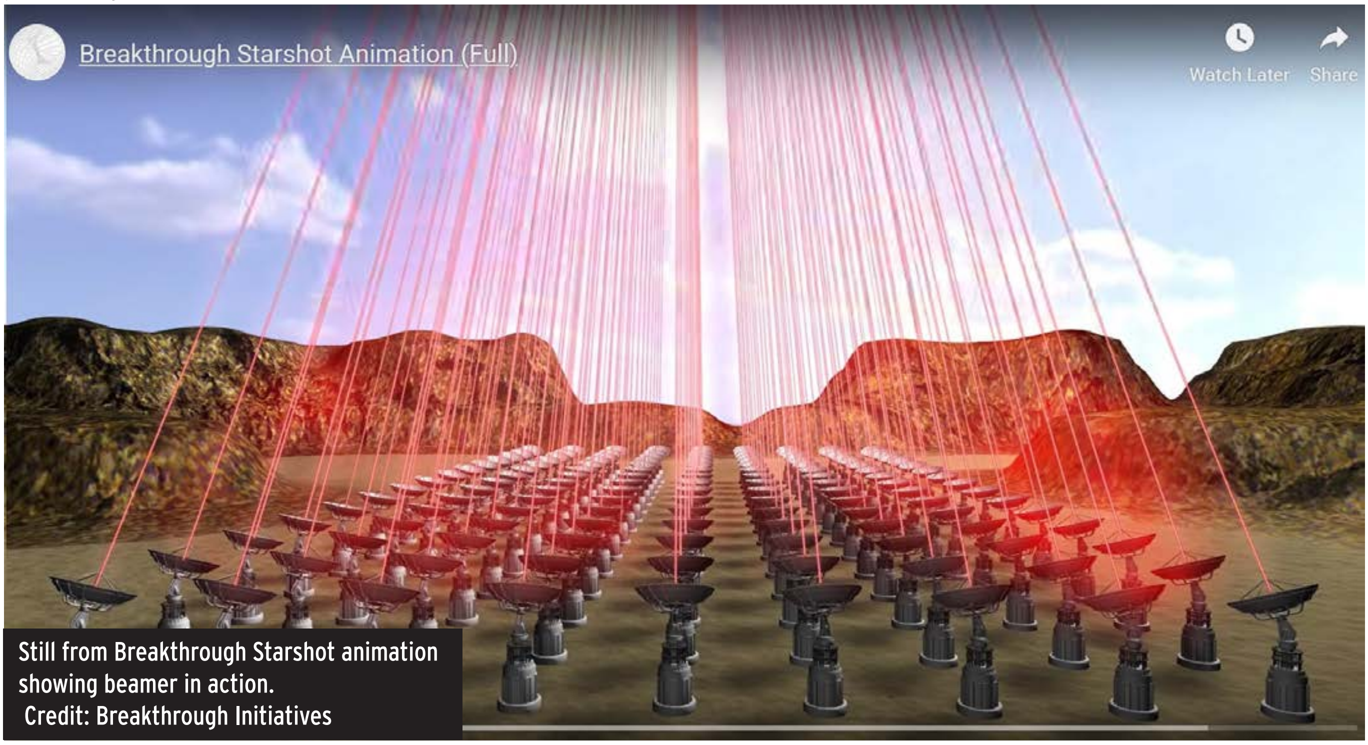
The deuterium fuel it requires is put at 18,000 tons and the dry mass is 2,500 tons, although there's a total mass given in the document of 24 k ton. Spaceship and fuel are united at the 'high orbit fuel depot' at the gravitationally stable L5 (trailing) point of the Earth-Moon system. This is expensive in extra energy to reach and to establish fuelling infrastructure (needing a space-station?). Is it needed?
Deuterium fusion releases almost half of its energy in the form of high-energy neutrons, and the high densities and temperatures in the 'Z-pinch' drive region yield significant X-ray radiation. This is a challenge for ship design, ie to prevent radiation damage to the ship's functionality and gives rise to the elegant dart shape (long and thin) incorporating shielding for both species of radiation. There's a good discussion of this in the document. But does it cause hazards to Earth or to other space hardware, eg necessitating the 'expensive' L5 Launch option?
At first glance, the Earth's atmosphere should be sufficient to stop/absorb both X-Ray and neutrons and prevent direct effects at ground level. The linear absorption coefficient for 14 MeV neutrons (produced by an 'unwanted' side-reaction) gives a 1/e length of around 100 m at STP, plenty enough through the entire atmosphere. Atmospheric Nuclear Effects [1] gives the 'stopping altitude' for prompt neutrons as 25 km (see also Wikipedia which gives the 'effective radius of a neutron bomb' as 1-2 km. For X-Rays, [1] gives stopping distance as 80 km: an x-ray photon passing through the atmosphere will encounter as many atoms as it would in passing through a 5 metre thick wall of concrete. However, total radiated energies are large. Operating the Firefly's 13 TW drive for 100 seconds burns through as much energy as is yielded from a 300 kT nuclear weapon, so atmospheric ionisation would be expected which would cause local interference with GPS signals due to signal attenuation.
But the more significant problem would be with other LEO and even geostationary satellites. There's no attenuation in free space apart from the inverse-square law so a high dose of radiation would be received, not to mention the blinding of any Earth-observation satellites by the intense black-body radiation of the 'naked' Z-pinch reaction zone. And exposure times are long due to the low acceleration: just 0.003 g (divide 600 kN thrust by 20 thousand tonnes). The ship will take 2 days to reach the moon's orbit and a week to achieve Solar System escape velocity and 10 years to achieve 4.7% c. So, in your backyard (LEO)? – maybe No, but the L5 launch point does look a reasonable option for a ship using Earth-sourced nuclear propellants. We'd still get a good look as it boosted away, about as bright as Mars for several days; and maybe a similar colour owing to its great orange-hot glowing radiator fins (hence: 'Firefly').
However, it's worth including in the energy budget the cost of launching maybe 30,000 tons of spacecraft, constructors, propellant and L5 space-station. A SpaceX Starship [2] is capable of lifting 100-150 tons to LEO or 27 tons to Geosynchronous transfer, and, 'fully refueled' (ie extra launches) 100 tons to the Moon/L5. We'd need of the order of 500-1,000 Starship launches.
The vast energy requirements per kilogramme for getting to an appreciable fraction of c was a strong incentive for the Breakthrough Starshot approach of reducing probe mass to a bare minimum by using ground-based energy to transfer momentum via powerful lasers. For estimating hazards, here are some of the 'must haves' from Breakthrough Starshot - Wikipedia [3] sites:

- Building a ground-based kilometre-scale multi-laser phased array beamer at high altitude in dry conditions.
- Generating and storing a few gigawatt hours of energy per launch (later amended to about 1 TJ energy delivered to each ~5 m diameter sail, with total laser power 100 GW for 600 seconds per individual craft)
- Launching a 'mothership' carrying thousands of miniature probes to a high-altitude orbit.
- Taking advantage of adaptive optics technology in real time to compensate for atmospheric effects.
- Focusing the light beam on the lightsail to accelerate the individual probes to the target speed within minutes.

[1] *Atmospheric Nuclear Effects*, Professor David Jenn faculty.nps.edu/jenn/EC3630/AtmNucEffects(v1.3).pdf
[2] en.wikipedia.org/wiki/SpaceX_Starship
[3] en.wikipedia.org/wiki/Breakthrough_Starshot and Breakthrough Initiatives breakthroughinitiatives.org/concept/3

A word about the 'kilometre-scale' bit. This spatial scale is absolutely necessary (for beam diffraction reasons) to be able to hit a 5 m diameter target with 'only' 98% energy missing target as distances approach 20 million km, the far end of the 100 km/s^2 acceleration phase (at which nominal velocity is 0.2 c). It also requires the individual emitters to be connected by optical fibres to maintain phase stability so as 'to act as one' over a 1 km spread, and to have well-nigh perfect adaptive optics correction for atmospheric turbulence (for exactly the same reason). Luckily they are all pointing at Proxima Centauri, which is bright enough (just) to act as a 'guide star' and give a common reference for the adaptive optics algorithms.

That would create a hazard in itself, and would need bare rock foundations to avoid 'that sinking feeling'. But at least there aren't many aircraft overflying the dangerous beams. The Southern Hemisphere has some experience in building Square Kilometre Array (SKA) - Wikipedia [2], now enjoying excellent radio spectrum views of our galaxy's central black hole (radio telescopes don't need 'dry' conditions, viz Jodrell Bank, which is actually the base of operations for SKA). But the Meerkat National Park - Wikipedia [3] (30deg South), home of the South African station of SKA does look pretty dry and is above 1,000 metres altitude (if the contour colours in my old Times atlas are accurate - couldn't find



Still from Breakthrough Starshot animation showing beamer in action.
Credit: Breakthrough Initiatives

a spot-height). One imagines that the radio-astronomers don't take kindly to overflights by aircraft and have things well-sorted with the authorities, so the Cape-Town/London route won't be an issue. Other 'high places' might include La Silla Observatory - Wikipedia [4], the southernmost of the ESO sites in Chile, at 29° South. At least a scientific infrastructure is already in place, including the world's best practical expertise in adaptive optics, so relevant early experiments eg on beam forming can be performed.

The point about turbulence and adaptive optics jives with the project's requirement for a beamer 'at high altitude in dry conditions'. Proxima/Alpha Centauri are at -62° declination which demands the Southern Hemisphere for an Earth-based beamer. Eyes tend to stray towards Antarctica for high'n'dry conditions. It would be great but... would take a vast industrial effort in a pristine wilderness, not least to deal with a 100 GW of waste heat. High power lasers are at best 50% Wall Plug efficient [1] for over 1,000 launches at 600 seconds.

[1] www.ipgphotonics.com/en_uploads/widget/widget_item_pdf_907.pdf?_=4187811544
[2] en.wikipedia.org/wiki/Square_Kilometre_Array
[3] en.wikipedia.org/wiki/Meerkat_National_Park
[4] en.wikipedia.org/wiki/La_Silla_Observatory

◀ High, but lonely places still exhibit the dilemma concerning what to do about the enormous power (and waste-heat, overlook that aspect at your peril!) needs for what is an essentially one-off launch program. 100 GW of electricity production is greater than the UK's 2016 total (see World electricity production [1]) but we more likely need 200 GW of raw power at 50% laser efficiency, if not more. That's a lot of power stations, usually situated by the sea or on rivers for waste-heat rejection as demanded by the laws of thermodynamics. So, lots of long power lines.

To reduce the demands on raw power production, energy storage in the form of enormous flywheels (en.wikipedia.org/wiki/Flywheel_energy_storage) would be the best answer. Those at the Joint European Torus can deliver (each) 3.75 GJ at up to 400 MW, so, about 10 seconds to discharge. We would need 60 for 600 seconds discharge at @400 MW, or 3,000 for 100 GW laser power for 600 seconds @50% efficiency. Again, a lot of real estate is needed just for the flywheels which argues against a mountain site but at least the flywheels could charge up, serially, from a continent wide supergrid. For beamers at 30 deg South (South Africa or Chile), Proxima/Alpha Centauri wouldn't always be at appropriate altitude for beaming since, clearly, we want to go through the minimum of atmosphere. But maybe that's not so bad if we need to limit launches to one per night to avoid the lights going out. However, disposing of 60 TJ of waste heat (that 50% efficiency loss has to go somewhere) and keep the lasers from blowing up - for each and every launch. This would seem to be a huge local problem for the semi-desert Northern Cape. That's enough energy, per launch, to raise from 20°C temperature to boiling point a cube of water 56 m on a side. Which seems pretty onerous for the local environment and water supply. New thinking in heat transport and novel methods of recovery and dissipation would be required, since it can't just be radiated in vacuo like 'Firefly'.

An artist's impression of the future SKA-Mid site in South Africa. Ultimately, 197 dishes will be erected.
Credit (image and caption): SKAO

Engineering is often a matter of constraints and sometimes the 'gotchas' can produce new approaches. The numbers used here are all based on published mission parameters but these can maybe be refined and new concepts emerge. At present we'd probably none of us want to get too close to a star-drive, or have one in our back-yard. But, by considering initially non-obvious aspects such as hazards and cooling we might come up with new solutions. ■

Meerkat Radio Telescope Array, South Africa, maximum baseline 8 km, 64 dishes.
Credit: JoburgBBC

[1] www.cia.gov/the-world-factbook/about/archives/2021/field/electricity-installed-generating-capacity/country-comparison