# Power Systems for Miniature Interstellar Flyby Probe

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**In the last few years, the concept that an ultra-lightweight probe could be sent to one of the nearby stars pushed by a laser beam reflecting from a lightweight sail has moved from science fiction into conceptual design. A candidate interstellar sail envisions a two- to three-gram "starchip" micro probe, flying past a planet of Proxima Centauri after a 20 year voyage. With the probe moving at 60,000 km/sec, the flyby encounter at the target planet is within 1 AU of the target planet at most a few hours, and in the case of an encounter with a planet of Proxima Centauri, is close to the star for only a few minutes. With current technology, no power system exists that can produce the required power with a mass of less than one gram.**

## Nomenclature

*AU* = Astronomical Unit

$E$ = Energy (J)

I = Solar intensity (W/m$^2$)

$L_\odot$ = Luminosity of the sun (unit for comparison)

$P$ = Power (W)

$P_o$ = Power at distance $r_o$ (W)

$P_p$ = Power at planet's distance $r_p$ (W)

*RTG* = Radioisotope Thermoelectric Generator

$r$, $r(x)$ = radial distance from the star (AU)

$r_o$ = Closest pass distance (AU)

$r_p$ = Distance of planet from star (AU)

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$t$ = time (seconds). (In some places, this is used to refer to the time it takes the spacecraft to traverse a distance equal to the planet's semimajor axis.)

$v$ = Spacecraft speed (m/s)

$V$ = Voltage (V)

$x$ = Distance travelled (AU)

$\eta$ = Electrical conversion efficiency (unitless)

## I. Introduction

Over the last few years, the concept that an ultra-lightweight probe could be sent to fly by a planet of a nearby star has become the subject of considerable research [1-3]. The baseline concept is that an extremely high power phased-array laser could focus light on a highly-reflective, low mass sail, to accelerate it to a significant fraction of the speed of light over a boost phase lasting only minutes. The difficulty, however, is that for a reasonable laser power level, the payload that could be carried by such a fly-by probe would be extremely small. For example, Breakthrough Starshot project envisions a two- to three-gram "starchip" micro spacecraft that is attached to a sail and accelerated by laser to a velocity of 20% of the speed of light, flying past the recently-discovered planet of the nearest star, Proxima Centauri after a journey across interstellar space lasting 20 years [3].

With no means to decelerate at the destination, the spacecraft would fly past the target planet at high velocity: about 60,000 km/sec, in the baseline scenario. Thus, the flyby encounter at the target planet lasts at most a few hours, during which period all measurements and observations of the target planet must be done. Furthermore, the spacecraft must then communicate its observations to Earth, at distance of 4 light years (41 trillion kilometers). In the baseline configuration, the spacecraft makes observations during the flyby, and then relays the information generated back to Earth in the period following the encounter, when the probe has returned to interstellar space. .

The "spacecraft on a chip" concept, with an allowable mass of only a few grams, however, makes this mission difficult. For comparison, spacecraft used for planetary fly-bys in the solar system have masses on the order of hundreds of kilograms (*e.g.,* 400 kg for the New Horizons probe to Pluto); the interstellar micro-probe would require a mass that is five orders of magnitude less.

## II. Power Systems

In particular, electrical power will be required to operate the spacecraft, both during the flyby observations, and to provide power for the communications system operating after the encounter. With current technology, no electric power systems exist that can produce the required power with a mass of less than one gram.

Power will be needed during four mission phases:

1. *Launch*: ~10 minutes under laser acceleration. Current concepts propose the spacecraft will be passively stable in the laser beam, bur a more realistic scenario is more likely that some amount of power will be required for control.
2. *Cruise*: 20 years of cruise in interstellar space. No observations; the spacecraft hibernates. Very little power needed in cruise.
3. *Encounter*: The spacecraft will take observations during the fly-by over a period of time that may range from a few minutes to a few hours spent near the target star.
4. *Post-encounter*: during the post-encounter phase, the spacecraft will communicate observations to Earth. The post-encounter phase may continue for 1 year or more after fly-by.

The operational lifetime during the encounter phase can be a trade-off against the power level. The highest power use is expected to be the communications system for data relay back to Earth, and this requirement will be the main driver of the analysis in this review. The bit rate of communication is directly proportional to the power. Thus, to relay a given amount of data, the power system can higher power and communicate at a high rate for a short time, or alternately can be a low power system, and store the data to communicate for a longer period after the fly-by encounter at a lower bit rate.

Based on analyses of the mission [3] and the communications requirements [4] assumes a laser communications system, the baseline for the current analysis is that the power system should meet the following requirements:

- *Weight*: 1 gram or less
- *Energy produced:* 300 kJ (equivalent to 10 mW (average) for one year after encounter)
- *Lifetime*: 20 year cruise, followed by encounter phase.

The baseline requirements are subject to later detailed analysis.

The baseline requirement of 10 mW average is a minimum; and higher power levels are desirable (since the amount of data transmitted is directly proportional to the power). While the average power here is assumed to be 10 milliwatts, the laser may be pulsed with an average duty cycle of 100:1. This may require storage, possibly in the form of an ultracapacitor. Any storage required, however, is not analyzed here.

### A. Categories of Power Systems

The electrical power systems considered can be divided into two classes, continuous power and power generated during encounter.

In the continuous power generation category, electrical power is generated by on-board source which operates independent of environment. These primarily include isotope power systems:

- Radioisotope thermoelectric generation (RTG)
- Radioisotope direct generation (alphavoltaic, betavoltaic)

However, a system which generates power from the interstellar medium would also fit into this category. For these power systems, the power target is to be achieved is 10 mW of average power for one year of operation, at a specific power of 10 mW/g.

The category of generation at target category assumes that power will be generated only during encounter. These include:

- Photovoltaic power from illumination of target star
- Power from motion through magnetic field/plasma of target star

For this category, the power target is that 300 MJ of energy must be provided during the portion of the trajectory after the flyby of the target planet.

### B. Radioisotope Power Systems

Existing missions to destinations in the far outer solar system have utilized radioisotope thermoelectrical generator ("RTG") power sources for electrical power. The best existing spacecraft RTG power systems produce a specific power approaching the required levels. For example, the New Horizons probe produced 420 W (at beginning of life) from an RTG of mass= 57 kg, of which 11 kg was the $PuO_2$ fuel. This comes to a specific power of 7 mW/g; due to the radioactive decay, this decreases to 5 mW/g after the 25 year transit time. Decreasing mass by a factor of 2 would produce the needed specific power, if specific power could be maintained at lower system size.

Unfortunately, while smaller thermoelectric power supplies have been made, the specific power of these has been much poorer. Analysis shows that radioisotope thermal power system scale poorly to small sizes, due to the cube-square scaling factors: thermal losses scale with surface area, while power generation scales with mass. A thermoelectric power system would be orders of magnitude too heavy for such a microprobe.

An alternative proposal would be to use direct energy conversion, rather than thermal conversion. In a betavoltaic cell, the energy from the high-energy electrons emitted from the decay of a radioisotope is converted by a semiconductor device. Betavoltaic devices scale well to low power levels, and commercial units are available at power levels of ~60 nW.

Several isotopes are possible as the beta emission source. A tritium ($^3$T) beta source has the following properties:

- Half-life = 12.3 years
- beta decay e- energy 19 keV

These parameters lead to a decay power, at the isotope level, of 324 mW per gram.

After 20 years of interstellar cruise (1.6 half-lives) the power at arrival will 32% of initial power (105 mW/gram at the isotope level.). Thus, the power at the isotope level is high enough, however, the isotope itself is not the highest mass element in the system

Betavoltaic devices are commercially available and are in the process of being developed for NASA missions. Existing betavoltaic cells have typical specific power of about 0.1 W/kg at beginning of life, with development to levels of 1 W/kg anticipated (power at encounter will be about 32% of this). This is too high mass to be a useful power source for the micro-probes anticipated here.

Another difficulty may be in making the tritium source thermally robust to accept possible high temperatures during the initial phase of laser launch.

An alternative radioisotope direct conversion technology could be alphavoltaic, in which the energy of alpha particles from spontaneous fission are used. A wide range of possible isotopes can be used as the source, including plutonium-238 with a half-life of 87.7 years, or curium 244, with a higher initial power, but a slightly lower half-life of 17.6 years. The semiconductor alphavoltaic converters, however, are subject to alpha-induced degradation, and currently existing devices will not make the long lifetimes required.

## C. Photovoltaic Power at the Target Star

In the category of generating power at the target star, the first approach would be to simply use a photovoltaic array to produce power from the light of the target star. Photovoltaic arrays are the most common form of power system used for spacecraft, however, since power is generated only when the illumination from the target star is high, the communications would be limited to only the portion of the trajectory near the fly-by.

The spacecraft will image and take measurements as it flies past the planet in the target solar system, then when it has passed the planet, will communicates images as it leaves solar system, and communication ends when solar power is unavailable. Thus, power is available for minutes to hours, not years.

### *1. Solar cell technology*

The baseline assumption will be that a solar array can be deposited directly on sail; that is, no added mass is available for the array. This assumes that at least some portion of the sail will be intact for the fly-by. Current monocrystalline triple-junction solar cells achieve light to electrical conversion efficiencies well over 30%, however, since our goal is to minimize mass, this approach will assume a single junction cell.

One approach would be to use a thinned crystalline cell, since single-crystal cells currently produce the highest efficiency and lifetime in space. To achieve the low mass required, the active cell must be removed ("peeled") from the thick growth substrate to produce a cell of micron thickness, which would be affixed to the sail. The possible material choice would be GaAs, which could achieve an efficiency of about 20%. The alternate approach would be to use a deposited thin-film material. Current thin-film solar cells made using amorphous silicon, copper-indium diselenide, or CdTe thin films, have much lower efficiencies than single-crystal cells, however, a new technology of perovskite solar cells are very promising. These are thin films that can be directly deposited in sub-micron thickness on the plastic substrate, and efficiencies of the best perovskite cells are approaching single crystal efficiencies. As of now, lifetime is limited, and this technology has not yet been demonstrated in space, but assuming that the technology of this (or a related material system) will continue to improve, and that thin-film materials like perovskites can be deposited directly on the sail and achieve efficiency comparable to GaAs single crystal cells, an efficiency of 20% should be achievable with the mass characteristic of thin films.

After passing the planet, the probe can continue to a closer pass to the star. This would allow the array to be illuminated at a higher incident power density, and thus the same amount of power could be generated with a smaller array. If efficiency were independent of temperature and intensity, the power generated would be inversely proportional to the closest-pass distance, and since the duration of the pass close to the sun is proportional to distance, the total energy generated would be inversely proportional to the closest-pass distance. However, at very high intensities, photovoltaic efficiency decreases due to resistance and temperature. For the order of magnitude calculations here, we will choose a minimum distance at closest approach equivalent to 0.5 AU, achieving 4 times Earth-orbit solar intensity (roughly equivalent to Venus orbit). This allows us to use conventional solar technology.

A better solution might be to use a solar cell optimized for concentration and temperature (*i.e.*, a wide-bandgap solar cell) and make a much closer pass to the sun. However, since the spacecraft first makes a close pass by the planet, a subsequent close pass to the star at a distance would only be possible if the target planet has an orbital plane that is nearly edge on to the direction of travel. If the closest pass $r_o$ is at a distance from the star $r_o/r_p$ of the planet's orbital distance, the planet's orbit must be aligned to within $\sin^{-1}(r_o/r_p)$ of edge on for the close pass to be possible. This becomes increasingly unlikely for small values of $r_o/r_p$.

To get the total energy generated, a number of assumptions are made. Most importantly, an assumption is made that power generated is strictly proportional to intensity, neglecting the change of photovoltaic voltage and efficiency with temperature and intensity. In fact, this assumption is of limited accuracy; solar cells are more efficient at low temperatures (at farther distances from sun); but it may be difficult to use power that is changing in voltages and current as the craft approaches the star. For the current calculation, however, it is assumed that this is not a problem.

### *2. Integrated Power over Flyby Trajectory:*

Figure 1 shows the geometry of the spacecraft passing the star. The speed is much higher than the star's escape velocity, and hence the trajectory can accurately be modeled as a straight line.

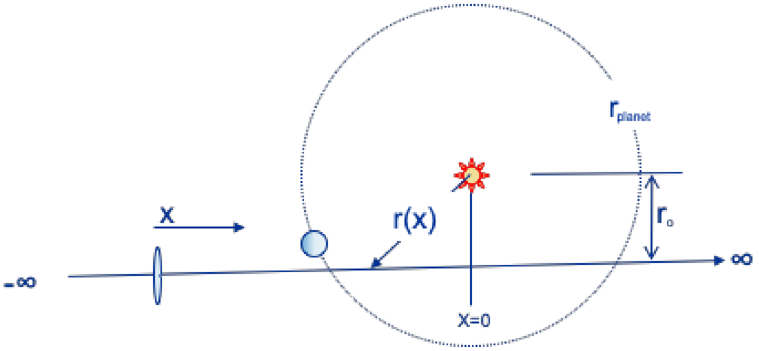

Figure 1: geometry of spacecraft passing the target star

Define $r_o$ as the distance of closest approach to the star, $I_o$ as the solar intensity at closest approach, and $P_o$ as power at closest approach. At any distance r, then

$$P(r) = P_o(r_o/r)^2 \tag{1}$$

We want to integrate the power produced across the total trajectory from $x = -\infty$ to $\infty$. The spacecraft is moving at velocity v, so $dx = v\,dt$, and thus

$$E = (P_o r_o^2/v)\int(r(x))^{-2}\,dx = (P_o r_o^2/v)\int(x^2+r_o^2)^{-1}\,dx \tag{2}$$

This is exactly integrable. For the total power:

$$E = (P_o r_o/v)\,(\tan^{-1}[x/r_o]) \tag{3}$$

Evaluating this expression from $x/r_o = -\infty$ to $\infty$

$$E = \pi(P_o r_o/v) \quad (4)$$

A more useful calculation, however, would be to solve for the amount of power generated from the time the spacecraft passes the planet's orbit until it departs the solar system at infinity (since there will be little or no data to transmit during the initial portion of the entry into the solar system, when the planet is still far away, the probe only requires communications power after it makes passes the planet and then begins to transmit data). If we assume the closest approach to the star is half the orbital distance of the planet ($r_o/r_p = 0.5$), and the planet is passed on the portion of its orbit closer to Earth, then the integral l is from $-\sqrt{3}r_o$ to $\infty$ :

$$E = 5/6\pi(P_o r_o /v) \quad (5)$$

A more convenient way to express this is in terms of the time it takes the probe to travel a distance equal to the planet's orbital radius ($t = r_p/v$), and call the power generated at the planet's orbital radius, $P_p$. Again assuming that the probe's minimum approach to star $r_o$ is 0.5 $r_p$, then:

$$E = 5.23\ P_p t$$

*3. Example calculation: sunlike star*

For an example calculation, consider the case that the target is a planet of a star assumed to be identical to the sun.

Intensity I at planet's distance is 1.36 kW/m$^2$ (*i.e.* one solar intensity, for R measured in AU), if we assume efficiency $\eta$=20%, the power at planetary distance $P_p$ is 270 W/m$^2$.

Using v = 1/2500 AU/s, the time to traverse 1 AU is 2500 sec. Thus:

$$E = 5.23\ P_p t = 3.5\ \mathrm{MJ/m^2}$$

The 300 kJ requirement for communications translates to 0.085 meter$^2$ of solar array.

*4. Example calculation: Proxima Centauri b planet*

For the planet of Proxima Centauri, based the bolometric luminosity 0.0017 $L_\odot$ with the planet at 0.048 AU, $I_p$ is 1 kW/m$^2$ (Not too different from Earth orbit intensity, which is no surprise, since solar intensity defines the habitable zone). Assume that the efficiency $\eta$=15%, which accounts for the lower bandgap of the solar cell required for optimization for the red spectrum, the power at planetary distance ($P_p$) is 150 W/m$^2$. With the planet at $r_p$ = 0.048 AU, the time of passage t is 120 seconds. Thus

$$E = 5.23\ P_p t = 95\ \mathrm{kJ/m^2}$$

The 300 kJ requirement for communications requires 3.2 meter$^2$ of solar array. This is probably unfeasible due to mass.

This brings out a very fundamental problem with the concept of generating power at the target system, when the target system is a dim red star: the very short residence time in the system. If we were indeed to generate 300 kJ in 2 minutes, the required power would be 2.5 kW.

## *5. Design Considerations for Photovoltaic Power*

The spacecraft will accumulate a radiation dose during 20-year cruise. This dose will degrade the performance of photovoltaic cells. There are two primary sources of radiation: cosmic rays, and the radiation due to probe's motion through ambient interstellar medium. Cosmic rays are, for the most part, energetic enough that they will pass through the thin solar cells without causing much damage; this radiation may be a significant factor for the spacecraft electronics design, but is not important to the photovoltaic performance. However the ambient interstellar medium is primarily neutral and ionized hydrogen, with about 4% helium. The primary radiation is thus:

- 10 keV electrons
- 19 MeV protons
- 25 MeV helium

The density of the interstellar medium, and hence the flux, depends on the direction of travel [5]. For the Proxima Centauri mission, the travel direction is outside the local cloud. Expected density is ~0.001 to 0.05 H per $cm^3$. For example, Voyager-2 measured $0.04/cm^3$ after it crossed into the interstellar medium [6] south of the ecliptic plane). At the high end, $0.05/cm^3$ density, the 20-year total fluence will be on the order of $10^{17}/cm^3$. However, if the array is flying at an angle to the direction of motion (optimally, edge on), the fluence will be proportionally decreased. By spacecraft photovoltaic standards, this represents a high-radiation dose, but still in the range over which data is available. At these energies, most of the electrons stop in ~1μ of material, while protons and helium ions will pass directly through both the cover and the active material.

A design approach to minimizing degradation is to use extremely thin active layers to minimize radiation degradation (which will have the advantage of also decreasing mass), and to use a thin dielectric film to stop the 10 keV electrons. Intersection with interstellar dust will also create holes in the photovoltaic film. As with the impact of the interstellar plasma, is assumed that this can be reduced by orienting the sail edgewise to the incident flux.

These assumptions must be verified if the photovoltaic option is selected.

The absorption coefficient of $PbI_3$ perovskite is >2 $10^4$/cm in the range of 300-800 nm, and so a 0.5μ thick layer would could absorb >63% of the light of a full thickness cell. Incorporating rear surface reflection, 20% efficiency should be possible. These are optimistic assumptions for a 20% efficient cell, but not impossible. For estimation of mass, I assume 1 micron of transparent coating at density 2.7 g/cm$^3$, 0.5 micrometer active cell at density 5.3, and 0.5 micrometer thickness of contact metallization, at density 2.7. Thus, the area weight is 6.7 grams/m$^2$.

The mass of the 0.085 meter$^2$ solar array (sunlike star mission) is 0.6 grams.

The mass of 3.2 meter$^2$ solar array (Proxima Centauri mission) is 21 grams.

The array mass for photovoltaic power is the right order of magnitude, but too high for the Proxima planet mission

However, note that the assumptions are very optimistic, and include no margin: does not include wires, does not include power management (assumes same efficiency at all distances), and does not include any allocation for efficiency loss due to degradation during cruise. Other issues not discussed include that this will require photovoltaics to operate at wide range of intensities, and also may require that the photovoltaics be high temperature tolerant for the boost phase.

## III. Advanced Concepts

An alternate approach, currently being analyzed, is to generate power from the spacecraft's energy of motion. Since the spacecraft is moving at 20% of the speed of light, if we could tap our own energy of motion, there would be plenty of energy available. Since, of course, the spacecraft is not moving in its own reference frame, we can only access this energy from the fact that the spacecraft are moving with respect to something. In this case, the spacecraft with respect to the interplanetary medium (of the system we're entering), and with respect to the interstellar medium (when travelling). So, in the spacecraft's reference frame, we are asking whether it is possible to tap the energy of the interplanetary or interstellar medium moving past us.

### 1. *Magnetic field*

The first approach would be to use the magnetic field of the target star. Power can be generated by the vxB potential of spacecraft movement in the star's magnetic field. This would be similar to the "electrodynamic tether" concept, studied previously in the context of spacecraft in Earth orbit [7]. In order for the induced voltage to be translated into power, current must flow through the system, Figure 2 shows this in schematic, where a conductive strip on the sail allows a current to flow; the current must have a return loop via contact to the ambient plasma, not shown in the image. (The figure shows the sail oriented face-on to the direction of motion, but an edge-on configuration would also work).

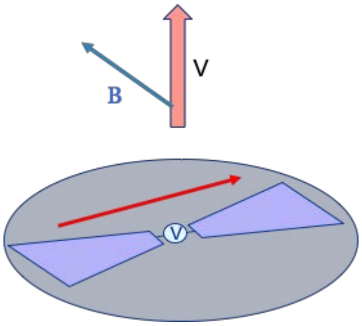

Figure 2: a conductive strip on a sail can generate an induced vxB potential in an external magnetic field.

The current loop must be closed outside of the sail (since the voltage around the full loop will be zero; the simplest way to close the current loop would be to capture electrons from the plasma in the interplanetary medium. At the target star, the interplanetary medium is the solar wind, which consists of equal numbers of both protons and electrons (the minor amount of higher mass particles (D, He) can be neglected). Only the electrons are stopped in sail. The density of solar wind at Earth's distance from the sun is about 4/cm$^3$ during a "quite" period of solar activity, and should be similar or higher at Proxima Centauri, and at v=6E7 m/s, the closure current is 2.4E10 e$^-$/cm$^2$s, corresponding to a current of 0.04 mA/m$^2$.

The magnetic fields of M-dwarf stars (like Proxima Centauri) are high [8,9]. Assuming a dipole field drop-off of 1/r$^3$, at the estimated distance of Proxima Centauri's planet, the field is 0.3 Gauss to 1.2 Gauss. (As a comparison, the lowest value (equal to 30 microTesla), is comparable to Earth's surface magnetic field.) At our velocity, the vxB induced field is 3000 V/m. At current of 0.04 milliamps/m$^2$, this corresponds to power of 0.12W/m$^3$. (The /m$^3$ units are because the power is proportional to the collected current, and hence the area, times the length of the conductor.)

The total energy harvested can be calculated by a similar integral to the one done for solar energy harvesting, with the dipole field of 1/r$^3$ substituting for the 1/r$^2$ power law for solar power; the integral comes to

$$E = 2(P_o r_o / v) \tag{6}$$

Unfortunately, for exactly the same reason that the Proxima Centauri mission is difficult to power with solar power, the very short time of passage makes magnetic energy harvesting unfeasible as well: it simply is not feasible to generate the required 3 kW of average power during the 120 seconds that the spacecraft is traversing the magnetic field.

### 2. *Plasma power*

The second approach would be to attempt to harvest power by passage through the plasma environment of the target star. As noted earlier, the environment at encounter is primarily protons and electrons (ambipolar plasma). The environment also includes neutrals, but the neutrals are expected to be ionized with contact with the sail. The spacecraft motion produces E (electron) = 10 keV, E (proton) = 19 MeV, and E(He) = 76 MeV (about 4% of the flux, but 16% of the energy). It is easy to capture electrons, but more difficult to capture protons, which pass through the thin sail. An issue is that power would be generated at characteristic voltages of 10 keV (electrons) to 19 MeV (protons). It is not clear that such power could be used at this voltage or transformed to lower voltage without excessive mass.

Current at 20% of c would be 0.04 milliamps/m$^2$ for both electrons and protons (again assuming that the Proxima Centauri plasma environment is similar to the Sun's), giving a total power available of 0.4 W/m$^2$ electrons, 760 W/m$^2$ protons, and 490 W/m$^2$ for the He. Since the plasma environment drops off less steeply than the solar or dipole magnetic field, this may be feasible to harvest; the analysis is continuing.

We also might get power during cruise from probe's motion through ambient interstellar medium, at about 0.05/cm$^3$. This would be at a lower power level, but continuous both before and after passage.

Results of this analysis will be reported in the NIAC Phase 1 report.

## IV. Conclusion

Providing an ultra-lightweight power system, even for the very small amounts of power required, is hard. It's not a solved problem. However, several approaches to the power system seem to hold promise.

## Acknowledgments

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Finally, I would like to thank NASA Glenn student intern Mark Tarlavsky (Rensselaer Polytechnic Institute), who has been working on modeling and simulating the electrodynamics, results of which are to be reported later at a later time.

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