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Abstract

The authors explore the capability of a VASIMR® or HiPEP solar slingshot concept to send a large spacecraft to Uranus, Neptune and beyond. The VASIMR® performs a slingshot pass or Oberth manoeuvre close to the Sun. With solar electric propulsion, the effect of the Oberth manoeuvre is boosted by using the high level of available solar energy to produce a sustained burst of high thrust. This trajectory provides enough kinetic energy to the probe within one AU to reach Jupiter orbit or beyond. This study identifies the important parameters in the propulsion system operation (power level, propellant mass, payload release point, distance of closest approach to the Sun). The solar array is assumed a planar array rather than a concentrator since it will have to operate near the Sun, where a concentrator would overheat photovoltaic cells. The VASIMR® powered solar Oberth manoeuvre reaches a speed > 60 kps at maximum velocity. In order to stop at Saturn, the VASIMR® must retrofire from 1 AU to 5 AU. So far, the best-case Saturn model assumes 30 mT in LEO, and a 5 kps Earth departure velocity from the chemical launch system. The simulation arrives at 1.1×10^6 km from Saturn with a velocity of 3.3 kps. Using chemical SOI, the simulated system delivers an 8.5 mT payload in 4.44 years transit time. The paper also discusses Uranus, Neptune. Eris, and thousand AU simulation results. Simulations reach Eris in 10-15 years.

Keywords: VASIMR®, mission concept, electric propulsion, electric Oberth maneuver, Saturn, Ice Giants, KBO's

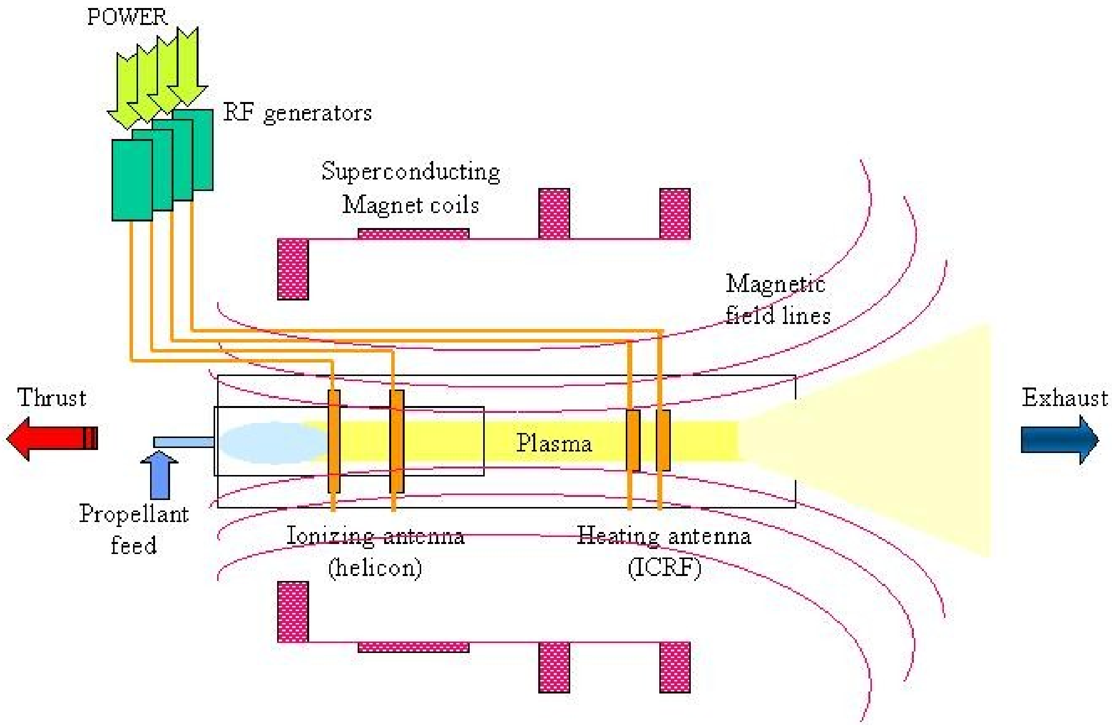


Fig. 1. Cartoon block diagram of the VASIMR™ system, illustrating the basic physics.

1. Introduction

THE ongoing exploration of the solar system will be one of the defining scientific tasks of this century. One of the obvious challenges faced by this enterprise is the scale size of the system under study, 10^{11} - 10^{14} m. Over distances on this scale and given the performance of present day rockets, the mission designer is faced with the choice of accepting multi-year or even decadal mission time lines, paying for enormous investment in rocket propellant compared to useful payload, or finding a way to improve the performance of today's rockets. For human space flight beyond Earth's orbit, drastic thruster improvement is the only choice to make. For robotic missions beyond Mars, mission time lines of years can be prohibitive obstacles to success, meaning that improvements in deep space sustainer engines are of importance to all phases of solar system exploration. The need for high performance interplanetary transfer vehicles has been underlined by many recent discoveries at Jupiter and Saturn. The scientific interest provoked by these observations has prompted funding of the Europa Clipper and Dragonfly projects. This paper will explore the role that solar electric propulsion can play in facilitating and enhancing such missions. The paper will show that use of a solar electric Oberth manoeuver[1] offers a significant reduction in flight time.

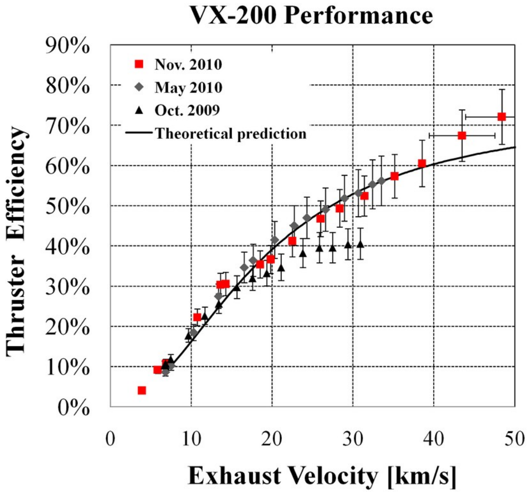


Fig. 2. Thruster efficiency vs exhaust velocity (specific impulse x 10). Results are shown for three separate experimental campaigns in October 2009, May of 2010 and November of 2010.

Better thruster performance can only be achieved by using an external energy source to accelerate or heat the propellant[2]. High-power electric propulsion thrusters can reduce propellant mass for heavy-payload orbit-raising missions and cargo missions to the Moon and near Earth asteroids and can reduce the trip time of robotic and piloted planetary missions.[1,3,4] The inverse square law increase in solar radiation when approaching the Sun means that the available electric power also increases similarly. One example of a system that can be used is the Variable Specific Impulse Magnetoplasma Rocket (VASIMR®). The VX-200 engine is an electric propulsion system capable of processing power densities on the order of 6 MW/m^2 with a high specific impulse and an inherent capability to vary the thrust and specific impulse at a constant power[5, 6, 7, 8, 9].

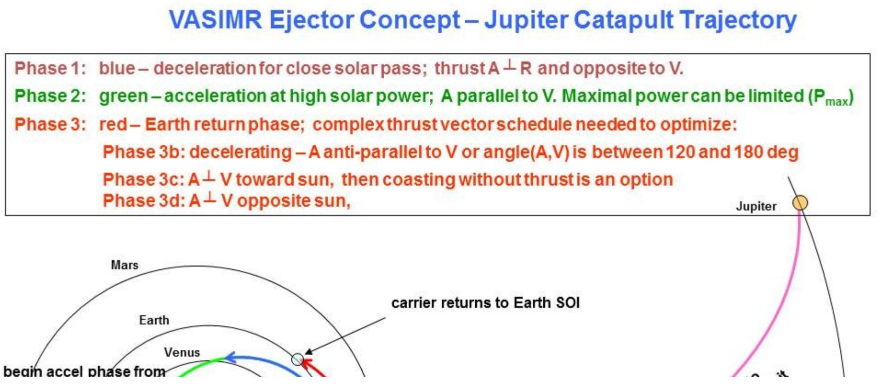
The VX-200 engine was tested using a propellant flow rate of 107 mg/s, a helicon coupled RF power level of 29 kW, and an ICH coupled RF power level from 0 to 172 kW, which yielded results that give a total force of up to 5.8±0.4 N, at an I_{sp} of 4900±300 s, and a 72±9% thruster efficiency, as shown in Figure 2.

2. The Jupiter Catapult Mission

The recent discovery of geysers on Europa has resulted in a renewed interest in a Europa mission. Sending a payload to Jupiter directly from the surface of the Earth with a single launch vehicle is difficult. The typical transfer orbit involves multiple gravity slingshot Earth and Venus flybys in order to gain enough energy to get to Jupiter and can take upwards of 6 years. Right now, using a Jupiter flyby to decrease transit time to Saturn or the Ice Giants is ruled out by relative orbital positions. Solar electric propulsion spacecraft have never been seriously considered because the required high-power electric propulsion engines have not existed and the inverse square law limits the region where electric propulsion is practical to the region inside the orbit of Jupiter. The VASIMR® engine is one of the required high power systems. This paper will present a mission profile called the ejector or catapult plan that works by generating most of the energy required when close to the Sun. Several missions are evaluated, including missions to Jupiter, Saturn, the Ice Giants, Eris, and 1000 AU.

2.1 The VASIMR® Ejector Catapult

The VASIMR® ejector catapult takes advantage of the inverse square law increase in solar radiation when approaching the Sun to


VASIMR Ejector Concept – Jupiter Catapult Trajectory

Phase 1: blue – deceleration for close solar pass; thrust A ⊥ R and opposite to V.

Phase 2: green – acceleration at high solar power; A parallel to V. Maximal power can be limited (P_{max})

Phase 3: red – Earth return phase; complex thrust vector schedule needed to optimize:

Phase 3b: decelerating – A anti-parallel to V or angle(A,V) is between 120 and 180 deg

Phase 3c: A ⊥ V toward sun, then coasting without thrust is an option

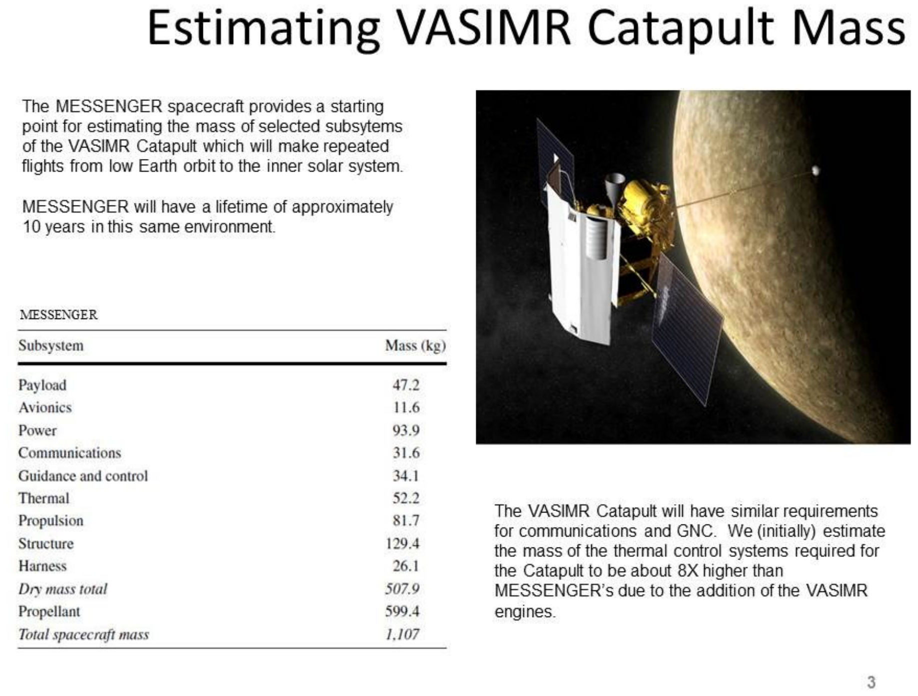
Phase 3d: A ⊥ V opposite sun,

g r orbit. The mission plan h sting anti-parallel to the heliocentric velocity of the vehicle (Figure 3). In phase 2, the spacecraft accelerates at high solar power, exploiting the increasing solar energy flux. The thrust is parallel to the velocity vector. The spacecraft's trajectory will pass within the orbit of Venus to a perihelion distance of ~0.5 AU. Phase 3 begins at about 0.75 AU. In the concept studies done so far, the payload now has sufficient energy to coast to Jupiter, arriving in about 3 years. The concept plan then returns the carrier spacecraft to Earth. This plan has the disadvantage of re-quiring more return fuel mass than the payload mass. Alter-natively, the VA-SIMR® could continue to provide thrust all the way to Jupiter.

2.2 VASIMR® Ejector Catapult Mass

The mass of the VASIMR® catapult system has been esti-mated using the Mess-enger spacecraft as a template, as shown in Figure 4. Two major changes were made to the Messenger design. The thermal control systems were estimated to be a factor of eight larger than on Messenger and the propellant mass and associated tankage were increased by more than an order of magnitude. The resulting system mass estimates are shown in Figure 4. The masses assume that the Catapult is being reused and the new propellant load and the payload are being separately delivered to LEO. The full system will have a ~22-25 mT wet mass in LEO.

2.3



Estimating VASIMR Catapult Mass

The MESSENGER spacecraft provides a starting point for estimating the mass of selected subsytems of the VASIMR Catapult which will make repeated flights from low Earth orbit to the inner solar system.

MESSENGER will have a lifetime of approximately 10 years in this same environment.

MESSENGER

Subsystem	Mass (kg)
Payload	47.2
Avionics	11.6
Power	93.9
Communications	31.6
Guidance and control	34.1
Thermal	52.2
Propulsion	81.7
Structure	129.4
Harness	26.1
Dry mass total	*507.9*
Propellant	599.4
Total spacecraft mass	*1,107*

The VASIMR Catapult will have similar requirements for communications and GNC. We (initially) estimate the mass of the thermal control systems required for the Catapult to be about 8X higher than MESSENGER's due to the addition of the VASIMR engines.

3

Fig. 4. The masses of the MESSENGER spacecraft subsystems used as the starting point for the Catapult mass analysis.

Mass Analysis With Catapult Return

The initial exploration of the parameter space considered a mission with an initial mass in low earth orbit (IMLEO) of 25 mT and a payload mass of 5 mT. These models produced a range of solutions that either forced the payload to be smaller than assumed or did not have enough argon left to get the Catapult back to Earth. However, the transit time was only 36 months, which is half the time required for Galileo to reach Jupiter. Further exploration of parameter space simulated missions with a 4 mT payload and a 22 mT IMLEO. Optimized solutions were found for this case that delivered the payload to Jupiter in 34.7 months (Figure 5). The major disadvantage of this mission is that it takes more argon to return the Catapult to Earth than it delivers payload to Jupiter.

3. Saturn and Beyond

3.1 Saturn Simulations

The Jupiter study was done using MATLAB. For the rest of the work, the authors used the NASA/University of Texas package Copernicus. The first model mission used Argon with a specific impulse of 5200 s and the same power as the previous section. Solar electric power levels scale as $1/r^2$. Argon thrust was sustained until the orbit crossed 1 AU. At 1 AU, the VASIMR® reaction gas was changed to hydrogen at an *Isp* of 32,800 s. The thruster was cut off at Jupiter orbit. The simulated mission coasted to Saturn in a usefully short time interval. However, the model arrives at a speed of 27 kps, without enough chemical propellant to decelerate into Saturn orbit. This model forms the initial basis of the Ice Giant models discussed below.

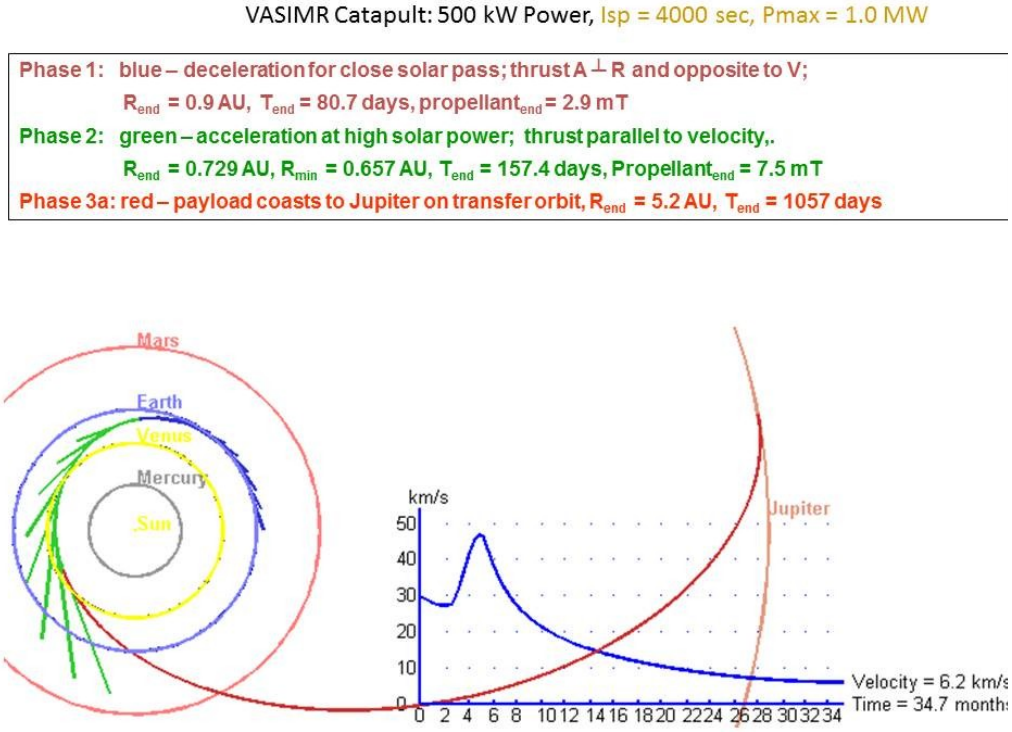


Fig. 5. Model transfer orbit of a 4 mT payload, 22 mT IMLEO simulation.

A second, more refined, model assumed a 30 mT spacecraft departing from Earth's SOI in 2027 with an assumed 5 kps Earth departure velocity imparted by the launch vehicle. One interesting requirement was that it was found necessary to establish the same heliocentric orbital inclination as Saturn right at the start. At 1 AU outbound, the used Argon tankage was jettisoned. The vehicle turned over and began decelerating toward Saturn using Hydrogen as the propellant. Thrust terminated and the solar array was jettisoned at 5 AU. The simulation took 4.4 model years enroute and arrived at Saturn at 3.3 kps, as shown in Figure 6. There was enough fuel capacity for a chemical rocket burn to achieve SOI and deliver an 8.5 mT payload. No Jupiter flyby was required.

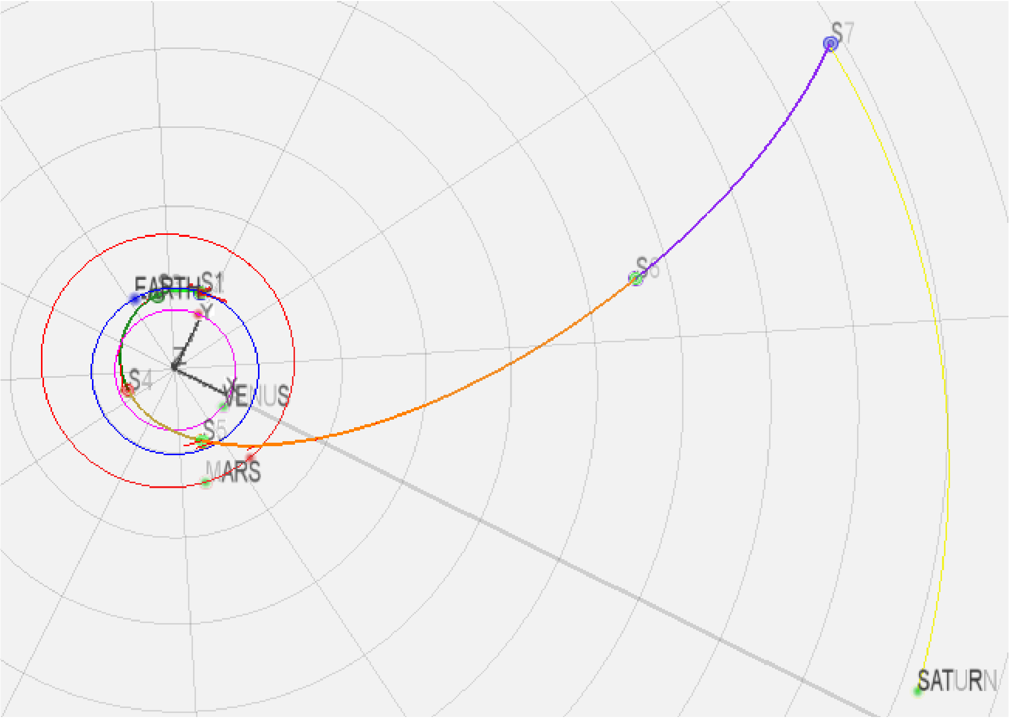


Fig. 6. Diagram of the Saturn simulation discussed in the text.

3.2 Ice Giants and Beyond

The Ice Giants, Uranus and Neptune, will not be accessible using a Jupiter gravity assist in the late 2020's. Consequently, we modeled these missions using a Saturn gravity assist. An improved, optimized version of the "thrust outward the whole way to Jupiter orbit" model from the previous section was used to reach Saturn. Unfortunately, the two Ice Giants are too far apart to make a dual flyby practical, so we modeled the two missions separately. The Neptune flyby also served as a gravity assist for an Eris flyby and coast to 1000 AU. The Uranus model took 2.8 years and the Neptune model took 3.5 years (Figure 7). The Eris flyby took 9.6 years. This simulation reached 1000 AU in 125 years.

3.3 Direct to Eris with Alternate Architectures

We explored alternative architectures using high-power solar-electric boost phases for missions to the outer solar system. As a comparison the performance of VASIMR® propulsion, we modeled a smaller New Horizons-like[10] (~450 kg dry weight, RTG spacecraft power) fast flyby mission of Eris using three HiPEP-like[11] (670 mN thrust, 7 mg/s flow rate, 39.3 kW power demand) motors and solar array performance based on existing thin-film CIGS arrays (Ascent Solar Large-Scale Bare Module Group, 863 W/kg, de-rated by a factor of 2 to account for degradation and structure). A simple thrust-along-velocity trajectory (Figure 4) with an Earth departure speed of zero and no gravity assists can deliver a 450 kg dry weight bus (plus 500kg of solar arrays and support structure) to Eris (at 94 AU) in under 15 years after consuming a total of 300kg of propellant (for a total wet mass of 1250 kg at launch). To explore this concept architecture, we model the trajectory of the spacecraft with a leapfrog integrator on one-day timesteps. The spacecraft begins with a power surplus with respect to the demands of the three motors (~200kW capacity vs. ~120kW demand), but this rapidly reduces as the spacecraft climbs away from the Sun. The spacecraft passes the orbit of Jupiter after just under one year, producing 6400 W of solar power. Thrust continues until propellant is exhausted, and total mission duration depends only weakly on when this occurs. In our non-optimized scenario, cutoff occurs at 2 years into the mission at a heliocentric distance of 13 AU, where the arrays are still generating over 1 kW of power. At this point, the spacecraft jettisons the arrays (switching to RTG power for spacecraft operation) and cruises on a ballistic trajectory to its target, in this case reaching Eris at 94 AU from the Sun (and 16 AU out of the Ecliptic plane) in just under 15 years. Using a solar Oberth trajectory with this architecture does not reduce transit time very much. It does reduce the array size required (factor of two, down to 100kW) and the propellant required (down to 200 kg total). This mission duration is comparable to current deep outer solar system flyby mission durations, however the flyby speed at Eris is more than twice current flyby speeds at ~30 km/s. To enable a compelling science mission at Eris under such a flyby architecture, development of larger-aperture instruments would be beneficial to extend the useful range of high-resolution observations and improve the signal-to-noise in the very low light regime at 94 AU.

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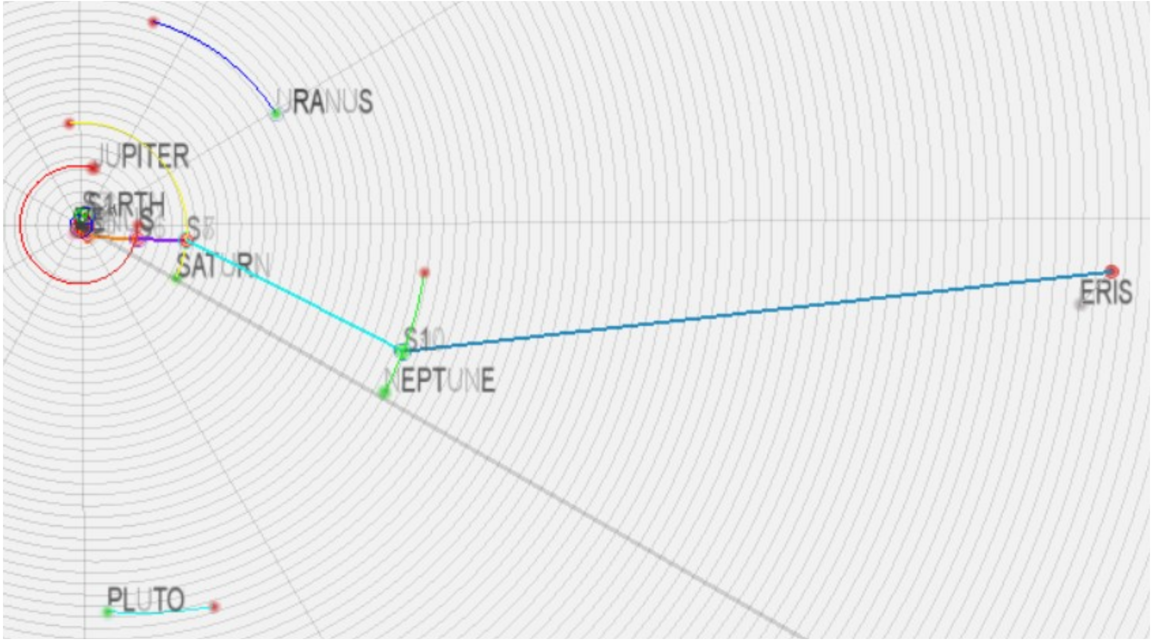

Fig. 7. Neptune and Eris flyby mission simulation

4. Conclusions

The use of VASIMR® or HiPEP SEP propulsion for missions to the Outer Planets will enable a mission to arrive in half the time required by a chemical propulsion system. The use of a solar Oberth manoeuver provides ~4 times the thrust near perihelion than can be obtained in a direct outbound trajectory. It will deliver a spacecraft that is larger and more capable than the one a chemical propulsion system will deliver. If the solar arrays and VASIMR RF generators are retained for the entire Jupiter mission, one will arrive at Jupiter with a 20 kW power system and the high power RF core of a very capable ice penetrating radar. Finally, we have shown that thrusting outbound all the way to Jupiter orbit will get spacecraft to the Ice Giants even when Jupiter is phased so that a Jupiter-assist flyby is unhelpful.

Fig 8. New Horizons-like mission with 3 HiPeP thrusters as discussed in the text.

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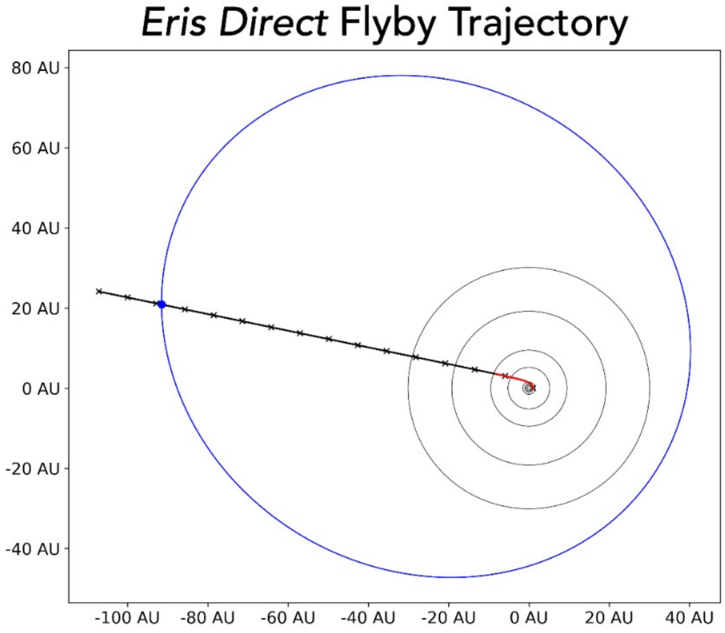

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