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PIC simulation of Electric Sail with explicit trapped electron modelling

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Abstract. The solar wind electric sail (electric sail, E-sail) is a new and potentially revolutionarily efficient method of interplanetary propulsion. The E-sail taps the momentum flux of the solar wind with the help of long, thin, highly positively charged and centrifugally stretched tethers. According to estimations, a full-scale E-sail could weigh 100-200 kg and produce 1 N thrust at 1 AU. The thrust would scale as $1/r$ where r is the distance from the sun and the thrust direction could be vectored by $\sim 30^{\circ}$ away from radial by inclining the sail. Here we present new particle in cell (PIC) simulation results of the E-sail thrust. The challenge in modelling the E-sail from first principles is the possible existence of trapped electrons. We sketch a way by which the PIC simulations might be possible to extrapolate to the natural limit in the future.

1. Introduction

The electric solar wind sail (E-sail) spacecraft propulsion system (Janhunen 2004; Janhunen and Sandroos 2007; Janhunen et al. 2010; Janhunen 2009a, 2010a, 2009b) consists of long, thin, conducting, charged and centrifugally stretched tethers (Fig. 1). The positive charging of the tethers is maintained by a continuously operating onboard electron gun. The electric sail presents itself as a technically feasible way of using the natural solar wind dynamic pressure for producing spacecraft thrust and thereby achieving the capability to move rather freely in the solar system without consuming propellant.

The E-sail has two main limitations. The first limitation is that the E-sail cannot produce thrust inside Earth's magnetosphere because there is no solar wind there. One can, however, use an E-sail type "Plasma Brake" device for deorbiting satellites (Janhunen 2010b). Concerning other magnetised planets the details have not been worked out, but it might be possible to sail with the fast corotating plasma flow of a giant planet magnetosphere.

The second limitation of the E-sail is that while it can be used to "tack" inward in the solar system by inclining the sail (thrust vectoring of up to $\sim 30^{\circ}$ is feasible) in such a way that it brakes the orbital motion of the spacecraft around the Sun, the traveltime is proportional to the orbital period of the starting planet. A trip from Earth to Mercury would be fast, less than one year, but a return trip from Pluto, for example, would take a prohibitively long time. Thus the E-sail can be used for reasonably fast two-way travel in the inner solar system (up to and including the asteroid belt) and fast one-way travel to outer solar system targets. If combined by impulsive chemical burns, it could also be potentially used for fast two-way travel to the giant planets (Quarta, Mengali and Janhunen 2010), although the technical details have not been worked out. This is

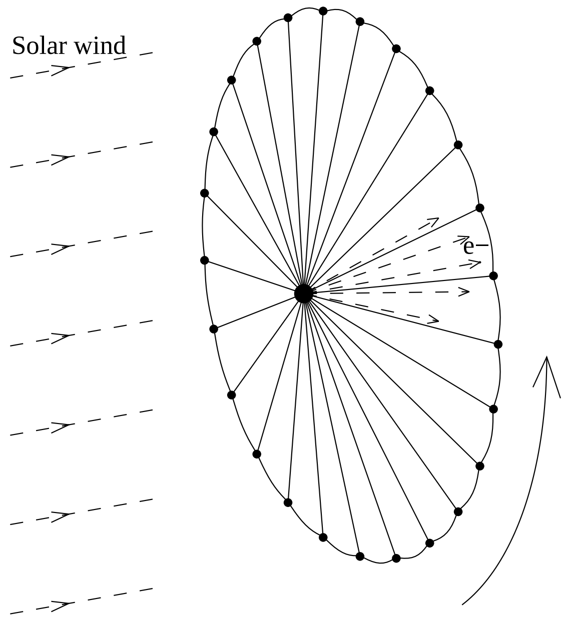

Figure 1. Schematic presentation of the electric solar wind sail deep-space propulsion method.

possible because of the large mass of the giant planets: one can inject the spacecraft to relatively high hyperbolic return velocity by a moderate chemical burn.

The E-sail thrust scales as $1/r$ where r is the solar distance. The thrust is the product of the solar wind dynamic pressure and the effective sail area. The dynamic pressure scales in the same way as the plasma density, i.e. as $1/r^2$. The sail area scales as the plasma Debye length, i.e. as inverse square root of the density giving linear scaling in r, so the thrust scales as $1/r$.

The underlying elementary process of the solar wind electric sail propulsion system is the interaction of the solar wind plasma stream with a positively charged tether. The computational problem is to predict the thrust force per unit length that the plasma stream exerts on the tether when the tether is artificially kept in a 15-40 kV voltage. Since the force per unit length is approximately equal to the sheath width multiplied by the solar wind dynamic pressure, the problem is closely related to the prediction of the collisionless electron sheath width in flowing plasma conditions, a problem tackled recently e.g. by Sanmartín et al. (2008).

In this paper we report on new particle in cell (PIC) simulation results concerning E-sail thrust.

2. Simulation model

Our simulation model is a traditional 2-D momentum-conservative PIC code with area weighting and explicit time stepping. The grid is uniform 511×256 and the code is parallelised by domain decomposition in one coordinate axis. The runs reported here used 32 processors. The grid spacing is 2.5 m and the domain is -319 m $< x <$ 956 m, $0 < y <$ 638 m. The solar wind flows along positive x axis and symmetry in y is assumed so that only the upper half-plane is simulated. Average solar wind parameters at 1 AU are used: density 7.3 cm^{-3}, speed 400 km/s, electron and ion temperature 8 eV, 2.5 % helium number fraction. These parameters yield a Debye length of 8 m. The baseline run has 100 electrons and 100 ions per grid cell and uses 31.25 ns timestep. The duration of the run is 100 ms so the run contains 3.2 million timesteps. The simulation tether is a single wire with 10 μm radius and with 50 MV/m surface electric field. When translated to a realistic multiline tether with 1 mm effective electric radius Janhunen and Sandroos (2007), this surface electric field corresponds to 5.6 kV tether potential with respect to the solar wind plasma.

To mimic electron chaotisation at the spacecraft for 500 m long tethers, the velocity vector direction of each electron is randomised after each 1 km travel of the electron along z (the tether direction). To mimic trapped electrons colliding with the tether, an electron is removed if it has circled more than 30 times around the tether. The latter process is applied probabilistically with an exponential decay law. The trapped removal rate is intentionally made much larger than in reality, corresponding to the artificially large trapped electron formation rate by numerical fluctuations. This point is elaborated in the Discussion.

3. Simulation results

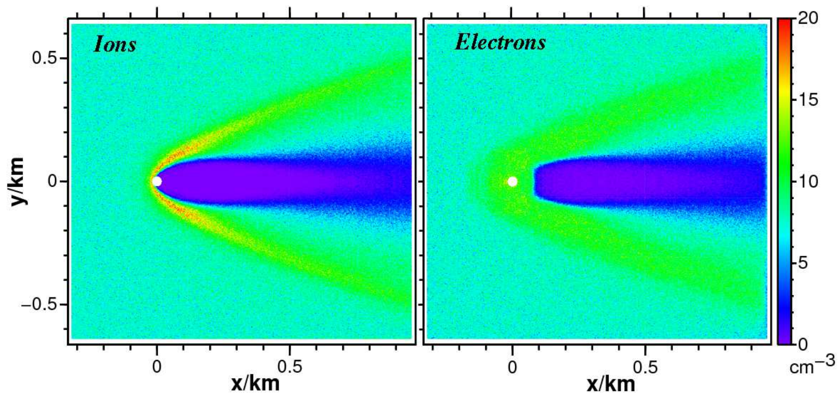

Figure 2. Instantaneous ion and electron density after 100 ms run.

Figure 2 shows the instantaneous (non-smoothed) ion and electron densities at the end of the 100 ms long baseline run. The solar wind ions arrive from the left and are deflected by the tether's 5.6 kV potential. Behind the tether there is an elongated wake which is empty of ions. Most parts of the the wake are also empty of electrons. The electron density roughly follows the ion density, but has smoother overall features around the tether.

The time evolution of the ion density is shown in Fig. 3. We keep the tether's potential constant throughout the run and linearly ramp up the solar wind density during

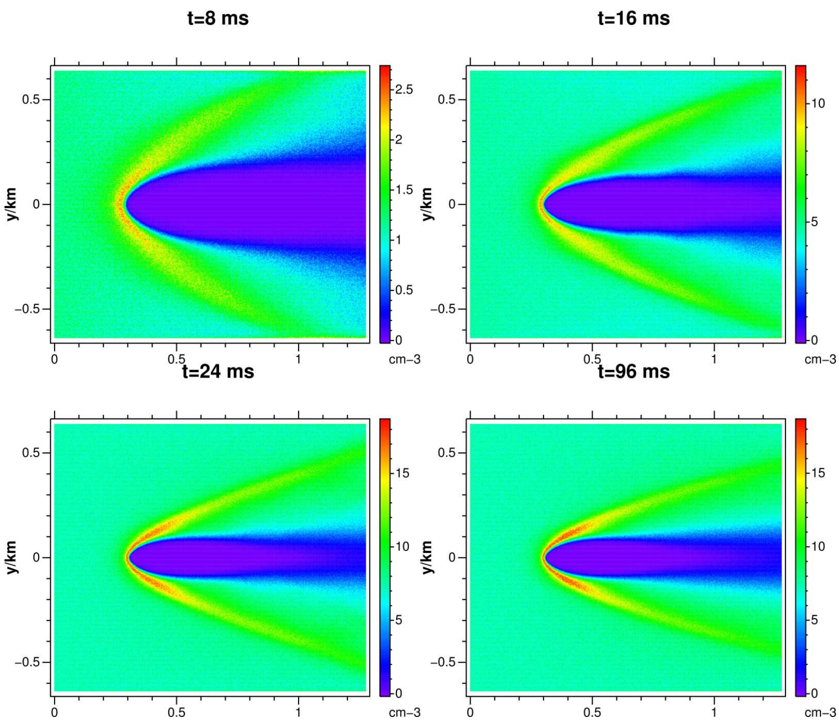

Figure 3. Time history of ion density at 8, 16, 24 and 96 ms.

the first 20 ms. This is why the sheath is wider at first in Fig. 3 and gets compressed when the solar wind density reaches its final value.

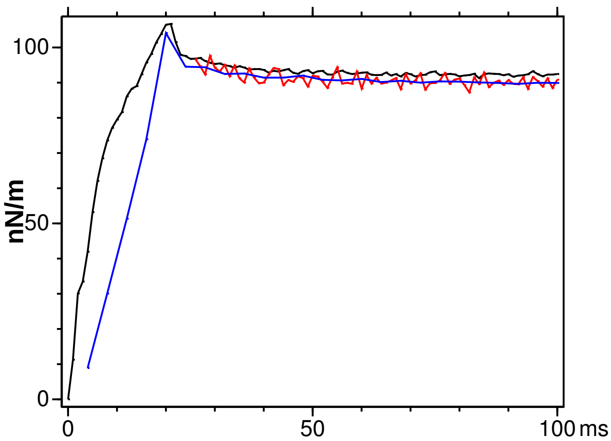

Figure 4. E-sail thrust per tether length calculated by three methods (see text).

Figure 4 shows the time history of the E-sail thrust per tether length, determined by three different methods: (1) tether linear charge density multiplied by the plasma-induced electric field evaluated at the wire (black curve, Janhunen and Sandroos (2007)), (2) particle momentum budget entering and leaving the simulation box (red curve, Janhunen and Sandroos (2007)) and (3) plasma charge density times electric field integrated over the simulation box (blue curve). In method 3, the integral gives the force acting on the plasma which is by Newton's third law equal in magnitude to the force acting on the wire. All three force determination methods agree nicely with each other. After an initial transient the thrust settles to a nearly constant value at 30 ms. After that, the thrust seems to asymptotically approach a value which is slightly smaller than that reached at 30 ms. After 50 ms the thrust changes only very little and is 92 nN/m at 5.6 kV equivalent tether voltage.

The thrust is expected to scale approximately linearly with voltage after subtracting the 1 kV stopping voltage of solar wind protons (Janhunen 2009b). Under this scaling, the thrust at 20 kV tether voltage (nominal value intended to be used in E-sails) would be 380 nN/m. Earlier we obtained the thrust 500 nN/m when assuming no trapped electrons and using approximate analytic considerations (Janhunen 2009b). That is, the trapped electron population seen in the right panel of Fig. 2 and whose density is approximately 1.5 times the background density gives rise to $\sim$25 % reduction of the E-sail thrust. While this estimate is not rigorous because different approximations were made in the PIC simulation and in the earlier analytic considerations, it is a plausible number suggesting internal consistency. However, we emphasise that the thrust derived from the particular PIC simulation run presented in this paper must not be interpreted as a quantitative estimate (not even as our present best guess) of the actual E-sail thrust.

4. Discussion

If one would know the electron density distribution around the tether, computing the self-consistent ion deflection and thereby predicting the thrust would be relatively easy by PIC simulation or other methods. Furthermore, the non-trapped part of the electron density is relatively easy to compute, so the problem of predicting E-sail thrust boils down to computing the trapped electron population around the wire or showing that a trapped population does not exist.

An electron that arrives from the solar wind and moves inside the tether's potential well may possibly become trapped only if the potential well deepens during the time that the electron travels through it or if the electron loses energy by some mechanism. The electron might lose energy by radiation or by Coulomb collisions with other electrons, but both loss processes are very inefficient in tenuous solar wind plasma conditions. Temporal fluctuations of the potential structure well can trap electrons, but they can also release previously trapped electrons from their confinement.

A trapped electron may be removed not only by temporal fluctuations of the potential, but also if the electron collides with the tether wire or the spacecraft. For tether collisions to be possible, the trapped electron's orbit must be chaotic at least to some extent. The orbit is chaotised at each time that the electron visits the vicinity of the spacecraft, because near the spacecraft the potential structure has a complicated 3-D "starfish" shape. Under chaotisation, a typical trapped electron lifetime against tether collisions is a few minutes (Janhunen 2009b).

In a PIC simulation, the electron trapping rate is much higher than in reality because of numerical fluctuations. Correspondingly, in the computations presented we have employed an elevated rate of trapped electron removal due to tether collisions. For a fixed trapped removal rate, the trapped density decreases if the number of particles per cell is made larger. Analogously, for a fixed number of particles per cell the trapped density decreases if the trapped removal rate is made higher. It seems from the simulations performed thus far that if one doubles the number of particles per cell and halves the trapped removal rate, the trapped density stays approximately constant. This gives us some hope that it might be possible in the future to extrapolate the PIC results to the natural limit.

Thus far we have not seen any coherent wave activity in the PIC simulation results. If waves would exist, they might create new trapped electrons or remove existing ones, depending on whether energy is transferred from particles to waves or vice versa. One might also speculate about intentional creation of waves by e.g. modulating the electron gun voltage, with the purpose of removing trapped electrons by energising them (Janhunen and Sandroos 2007). It is important that when the first E-sail solar wind test mission flies, these and other possibilities are tested experimentally in a comprehensive way.

5. Conclusions

An accurate prediction of the E-sail thrust from first principles is a challenging problem since the result depends on the trapped electron population which is in turn affected by slow processes that are difficult to model accurately in the PIC framework. PIC simulations performed thus far have not produced surprises in comparison to earlier analytic considerations and no unstable waves have been seen in them. We presented a parametrisation for the slow processes which might allow us to extrapolate the PIC results to the natural limit in the future. We hope to extend the PIC simulations in the future by including the possible modifications caused by the interplanetary magnetic field. In any case, a solar wind test mission is needed to measure the E-sail thrust experimentally.

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