

Advanced Solar Electric Propulsion for Planetary Defense

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John R. Brophy¹
*Jet Propulsion Laboratory
California Institute of Technology, Pasadena, CA, 91109, USA*

Once the current survey to identify all near-Earth objects larger than 140-m diameter is complete, the major hazard from asteroid impacts may be from asteroids in the 50- to 100-m diameter size range. High-power solar electric propulsion systems employed in “slow-push” techniques may be the best way to deflect asteroids in this size range if deflection is warranted. The relative performance of three slow-push techniques—gravity tractor (GT), enhanced gravity tractor (EGT), and ion beam deflection (IBD)—are compared, assuming solar electric propulsion vehicles derived from NASA’s Asteroid Redirect Robotic Mission concept vehicle. Both the enhanced gravity tractor and ion beam deflection concepts are shown to be significantly better than the standard gravity tractor concept. The Hall-thruster based enhanced gravity tractor systems and ion beam deflection systems (based on the use of high-power gridded ion thrusters) are shown to provide comparable performance, i.e., similar deflection times and propellant required. Enhanced gravity tractor systems require the acquisition of material from the surface of the hazardous object in order to achieve the required “enhancement” of the gravitational coupling force. This makes EGT systems sensitive to the rotational state and surface properties of the unknown object, and potentially severely limits its applicability. Ion beam deflection is completely independent of the characteristics of the threat object. In fact, it is the only asteroid deflection technique, slow-push or otherwise, that can make this claim, thus potentially greatly increasing its applicability relative to other deflection techniques. Finally, high-power IBD systems are shown to be capable of deflecting the fictitious asteroid 2015 PDC used in the hypothetical asteroid impact exercise conducted at the 2015 Planetary Defense Conference.

I. Introduction

Over 90% of the near-Earth objects (NEOs) larger than 1 km diameter have been discovered and none are on a collision course with Earth in the next 100 years [1]. NASA is congressionally mandated to identify all NEOs larger than 140 m diameter. It is estimated that about 40% of this population has been discovered. Once this survey is complete, the major risk for damage or loss of life may come from asteroids in the 50- to 100-m diameter class [1]. It is not yet clear if objects of this size warrant intervention or if civil defense would be sufficient. However, if high-power solar electric propulsion vehicles are routinely in use in the future supporting frequent human and robotic exploration missions, then the cost for intervention may be sufficiently low to warrant deflection. The question then becomes what is the best approach for deflecting asteroids in the 50- to 100-m diameter size range?

Many planetary defense concepts were evaluated in the National Research Council (NRC) 2010 study by the Committee to Review Near-Earth Object Surveys and Hazard Mitigation Strategies [2]. This study identified three categories of mitigation methods: “slow-push” techniques, kinetic impactors (KI), and nuclear explosions. The kinetic impactor approach was partially demonstrated in 2005 when the impactor from NASA’s Deep Impact mission slammed into the nucleus of comet Tempel 1 [3]. Tempel 1 is

¹ Engineering Fellow, Propulsion, Thermal and Materials Engineering Section, AIAA Fellow.

approximately $7.6 \text{ km} \times 4.9 \text{ km}$, making it significantly larger than the 50- to 100-m diameter objects considered herein. Recently the feasibility of using kinetic impactors on asteroids in the 100- to 300-m diameter range has been investigated [4]. This investigation identified a significant sensitivity to approach phase angle, with the odds of hitting a 100-m asteroid barely above 50% for a phase angle of 140 degrees, and suggested that such scenarios should be avoided if possible [4].

“Slow push” methods use the continuous application of steady force applied along or against the direction of motion of the near-Earth object [2]. Such techniques were divided into the following four categories in the NRC report:

- Enhancement of Natural Effects
- Enhanced Evaporation of Surface Material
- Application of Contact Force
- Application of Gravitational Force

Of these four techniques, the “Application of Gravitational Force,” better known as the “Gravity Tractor (GT)” [5] was considered to be the most mature concept. Variations on the gravity tractor concept include the use of displaced non-Keplerian orbits [6], and the acquisition of mass from the asteroid itself to enhance the gravitational coupling between the spacecraft and the asteroid, i.e., the Enhanced Gravity Tractor (EGT) [7]. Gravity tractor concepts have the advantage that they are independent of the spin state of the threat object. The use of non-Keplerian orbits (see Fig. 1) eliminates the need to cant the thrusters to avoid plume impingement on the asteroid, and therefore, increases the effective specific impulse of the deflection system. This comes at the expense of reducing the already small gravitational coupling force between the spacecraft and the asteroid. The enhanced gravity tractor provides a way to significantly increase the gravitational coupling force making the use of non-Keplerian orbits more attractive. However, acquiring mass from the asteroid makes the system sensitive to the asteroid characteristics including the spin state—the asteroid cannot be spinning too fast—and the availability of material on the surface that could be acquired by the spacecraft.

Since the 2010 NRC study a new slow-push planetary defense concept has been proposed by Bombardelli, et al. [8]. This concept directs the ion beam of an electric propulsion system to impinge directly on the hazardous object (see Fig. 2) and is similar to the concept proposed by Kitamura [9] for deorbiting large pieces of space debris. The approach is conceptually similar to the kinetic impactor with ions taking the place of the impacting spacecraft to provide momentum transfer to the asteroid. Its main disadvantage relative to a kinetic impactor is that while KI delivers its momentum effectively instantaneously, the ion beam deflection (IBD) approach necessarily delivers the momentum of the impinging ions spread out over months or years depending on the power level of the system. The main advantage of IBD is that the applied force is completely independent of the asteroid characteristics. Unlike GT or EGT, it is independent of the size of the asteroid and unlike EGT it is independent of the asteroid spin state and surface properties. The force applied to deflect an asteroid using IBD is completely under the control of the engineers designing the system and is the only deflection technique, slow push or otherwise, that is completely independent of the physical characteristics of the threat object.

II. Planetary Defense

Since the major hazard from near-Earth asteroids, according to Boslough et al. [1], will likely be from asteroids in the size range of 50- to 100-m diameter, this section begins with the comparison of the potential effectiveness of ion beam deflection (IBD) with that of standard gravity tractors (GT) and enhanced gravity tractors (EGT) for the deflection of diameter asteroids in this size range. However, since the congressional mandate to NASA is to find all near-Earth objects greater than 140-m diameter we will expand our range of interest up to 140 m. The effectiveness of an IBD spacecraft derived from NASA’s Asteroid Redirect Robotic vehicle concept [10] is evaluated for the deflection of the fictitious asteroid 2015 PDC used in the 2015 Planetary Defense Conference exercise [11]. Finally, a concept where IBD could be developed as a payload for an ARRM-derived vehicle is presented.

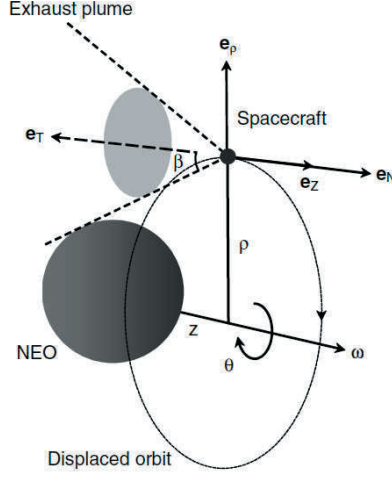


Figure 1. Illustration of a gravity tractor (GT) with a displaced non-Keplerian orbit from McInnes [6].

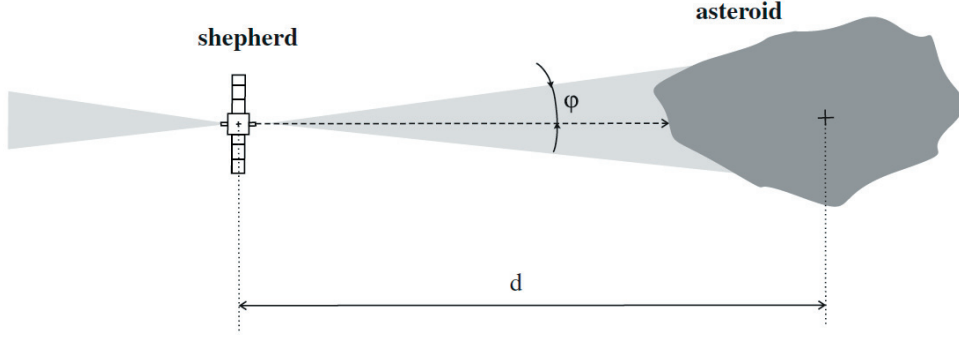


Figure 2. Illustration of Ion Beam Deflection (IBD) from Bombardelli, et al. [8].

A. GT, EGT and IBD Assumptions

To calculate the effectiveness of slow-push planetary defense techniques, we adopt the approximation used by the NRC [2] in which the deflection distance is approximated by,

$$\Delta s = \frac{3}{2} a t_a (t_a + 2t_c)$$

where a is the asteroid acceleration during time t_a when the deflecting force is applied, and t_c is the time spent coasting after completion of the force application. In addition, we adopt the required deflection distance used in the NRC report of 15,000 km. The total deflection time is the sum of t_a and t_c . To minimize the total deflection time we set the coasting time, t_c , to zero and solve for the required acceleration that minimizes t_a within the constraints of the propulsion system. Note, this approach is reasonable for comparison of different slow-push techniques, but it does not include many real-world effects and so should be considered indicative of the actual performance of such systems.

For the GT and EGT systems we assume a propulsion capability consistent with the electric propulsion system defined by the baseline Asteroid Redirect Robotic Mission (ARRM) concept [10]. This system concept has a maximum input power to the propulsion system of 40 kW, operates at a maximum specific

impulse of 3000 s, and can store and process up to 10 t of xenon. We assume that the system can operate at a specific impulse of 3000 s at any power level of 40 kW or less. This is not strictly true of the ARRM system, but reflects the fact that a propulsion system could be designed to operate at 3000 s for any selected power level ≤ 40 kW. In addition, we adopt the assumptions for GT and EGT systems from Mazanek et al. [7] as summarized in Table 1, except we have increased the vehicle dry mass to 5500 kg to be consistent with the current ARRM vehicle concept.

Table 1. GT and EGT Parameters

Parameter	Value
Spacecraft Dry Mass	5500 kg
Beam Divergence $\frac{1}{2}$ Angle	20 degrees
Specific Impulse	3000 s
Orbit Altitude—Fraction of Asteroid Diameter	0.5
EGT Orbit Type	Displaced Non-Keplarian
Maximum Input Power to the EP System	40 kW
Maximum EP System Thrust	1.63 N
Asteroid Density	2.0 g/cm ³
Required Asteroid Deflection Distance	15,000 km

For the IBD vehicles we assume a power system consistent with the ARRM concept with a maximum input power available for the electric thrusters of 40 kW. In this case, however, we replace the ARRM Hall thrusters with the 20-kW NEXIS gridded ion thrusters developed to TRL 5 for the Jupiter Icy Moons Orbiter (JIMO) mission concept [12]. The NEXIS thruster was developed to operate at power levels up to 20 kWe at a specific impulse of 7000 s for burn times of up to 10 years, corresponding to a propellant throughput capability per thruster of up to 2000 kg. Both flat and dished carbon-carbon ion optics were designed, fabricated, and tested for the NEXIS thruster. To obtain a 10-year operating life the thruster and ion optics were designed to operate at a small fraction of the maximum normalized perveance per grid aperture. The high voltage required for operation at 7000 s with xenon propellant enables the use of relatively thick electrodes. The combination of thick carbon-carbon grids derated to operate at a small fraction of the maximum perveance results in a very long grid service life capability. The use of flat grids minimizes the ion beam divergence, which is the primary feature that determines the maximum spacecraft-to-asteroid separation distance during deflection. The parameters for IBD are summarized in Table 2.

Table 2. IBD Parameters

Parameter	Value
Spacecraft Dry Mass	5500 kg
Beam Divergence $\frac{1}{2}$ Angle	4 degrees
Specific Impulse	7000 s
Maximum Input Power to the EP System	40 kW
EP System Efficiency	0.70
Maximum EP System Thrust	0.82 N
Maximum Force Applied to the Asteroid	0.41 N
Asteroid Density	2.0 g/cm ³
Required Asteroid Deflection Distance	15,000 km

The use of IBD requires that the vehicle thrust nearly equally in opposite directions. In one direction the ion beam impinges on the asteroid transferring the momentum of the ions to the asteroid. Thrusting in the other direction is required to maintain the required spacecraft-to-asteroid separation distance.

Consequently, only half of the available power can be used for deflecting the asteroid, so that the maximum force applied to the asteroid in Table 2 is half of the maximum EP system thrust. Note, the full thrust level is available for transfer of the spacecraft to the asteroid.

B. Comparison of GT and EGT Performance

The performance of a standard gravity tractor (using displaced non-keplarian orbits) is compared in Fig. 3 to that of enhanced gravity tractors where the spacecraft mass for the EGTs has been augmented by either 20 t or 50 t of material acquired from the surface of the potentially hazardous asteroid. As is well known, the standard GT requires a long time to defect even the small asteroids in our size range of interest. For example, Fig. 3 indicates that approximately 14 years are needed to deflect a 100-m asteroid with a standard GT. In this case, the maximum force applied to the asteroid is only 0.027 N, well below the capability of a 40-kW electric propulsion system, and reflects the weak gravitation coupling between the spacecraft and a 100-m asteroid. The 14-year duration does not include the time it would take to travel to the asteroid nor any time required to design, build, and launch the GT spacecraft.

The enhanced gravity tractors reduce the deflection times significantly. Acquiring 50 t of mass from the surface of the threat asteroid can reduce the deflection time for a 100-m asteroid from 14 years to about 4.5 years. For EGTs the deflection times indicated in Fig. 3 do not include the time required after arrival to survey the asteroid, identify target objects to be picked up, and the actual mass acquisition process. Even with 50 t of augmented mass, the maximum force applied to the 100-m asteroid is only 0.26 N, still well below the 1.63 N capability of the propulsion system.

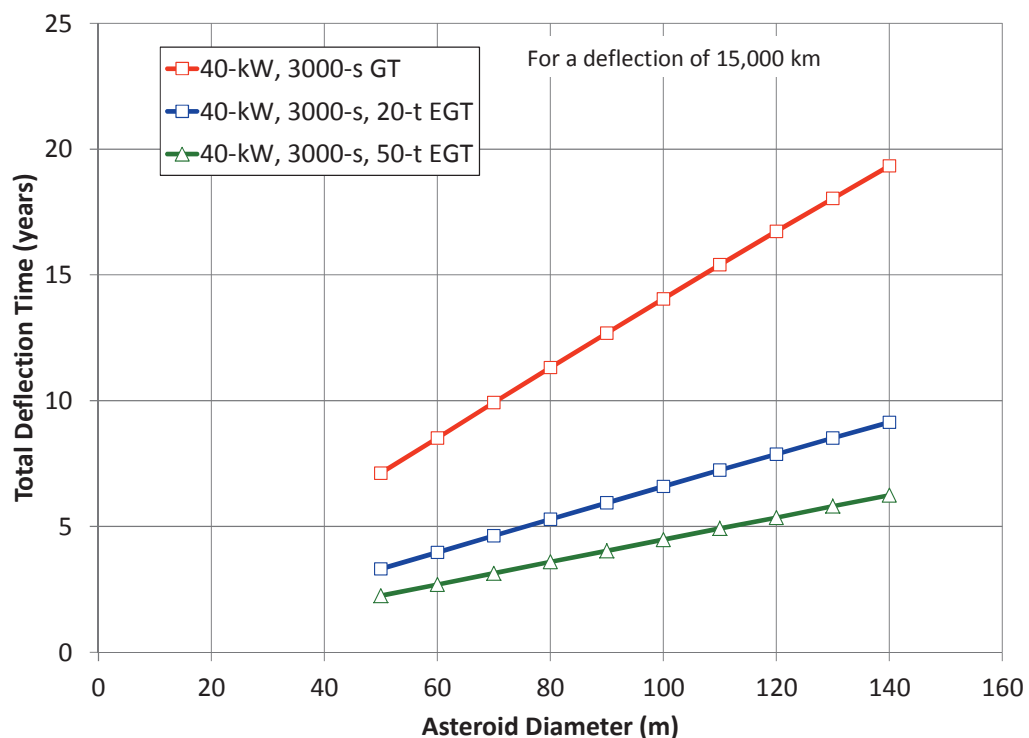


Figure 3. Enhanced gravity tractor (EGT) systems provide significantly better performance than a standard gravity tractor (GT) assuming that either 20-t or 50-t masses are acquired from the threat asteroid for the EGT systems.

C. Comparison of GT and IBD Performance

The performance of the IBD technology is compared to the standard GT in Fig. 4. This figure indicates that IBD also significantly reduces the deflection time relative to the standard GT. Considering a 100-m diameter asteroid again, IBD reduces the deflection time to 3.6 years. In this case, the full force of the IBD system of 0.41 N is applied to the 100-m asteroid. In fact, the IBD applied force is independent of the asteroid size as long as the spacecraft-to-asteroid distance is set so that the entire ion beam is intercepted by the threat asteroid. The spacecraft-to-asteroid distances for IBD are compared to GT and EGT in Fig. 5. The GT and EGT distances to the asteroid surface are identical by assumption. The GT and EGT characteristics given in Table 1 include the optimistic assumption that the spacecraft-to-asteroid surface distance is only half the asteroid diameter. This results in spacecraft-to-asteroid surface distances of 25 m to 70 m for asteroid diameters of 50 m to 140 m. Safely maintaining GT or EGT operations in such close proximity to the asteroid surface for years would likely be a challenge. For IBD the spacecraft-to-asteroid distance is determined by the divergence of the ion beam. For the NEXIS thruster operating conditions and grid design, the CEX2D ion grid code [13] calculates a beam divergence angle of 3.3 degrees. Assuming the NEXIS flat carbon-carbon grid design, and rounding this up to 4 degrees results in the spacecraft-to-asteroid distances indicated in Fig. 5. These distances are in the range of 300 m to 900 m for 50- to 140-m diameter asteroids, or more than an order of magnitude greater than the GT and EGT systems. Note that larger separation distances are possible with GT and EGT systems, but this significantly degrades the system performance since the gravitational coupling force decreases as the square of the separation distance.

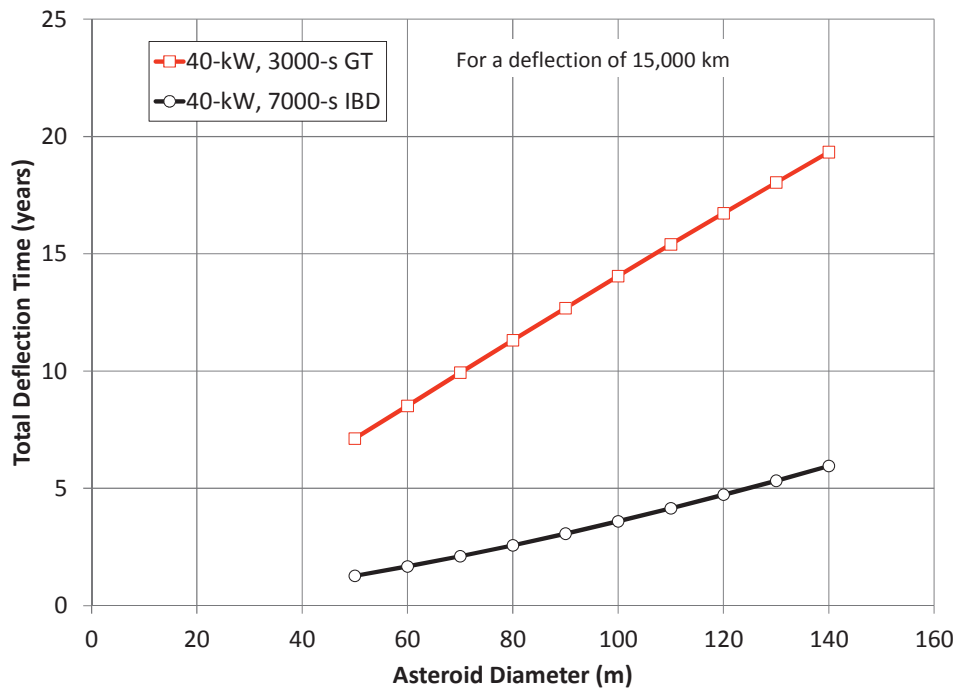


Figure 4. Ion beam deflection (IBD) technology provides significantly better performance than the standard gravity tractor (GT).

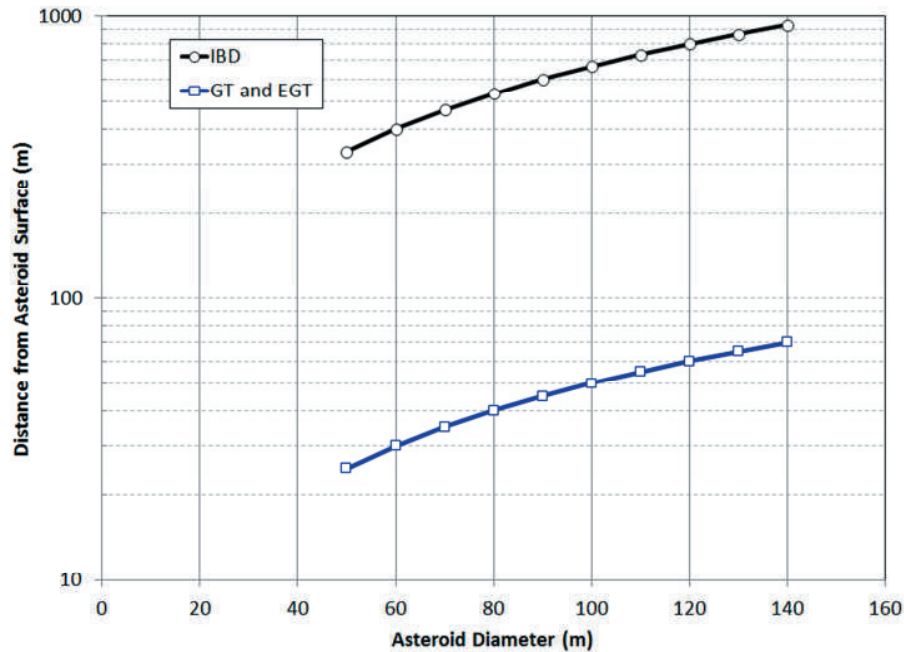


Figure 5. Comparison of IBD, GT and EGT spacecraft-to-asteroid surface separation distances. Separation distances for GT and EGT are sub-hundred meters for small asteroids. IBD typically provides more than an order of magnitude increase in separation distances for these sized objects.

D. Comparison of IBD and EGT Performance

The performance of EGT and IBD are compared in Fig. 6. The top chart in Fig. 6 indicates that IBD and EGT with 50 t of acquired mass provide roughly comparable deflection times for asteroids in the 50- to 140-m size. Again the deflection times in Fig. 6 for the EGT systems do not account for the time required to survey the asteroid surface and acquire the necessary mass. The bottom chart in Fig. 6 indicates that these two systems also require approximately the same amount of xenon. Note the xenon usage for IBD includes both the xenon used for the ion beam transferring momentum to the asteroid as well as the xenon used to hold the spacecraft position relative to the asteroid. The higher specific impulse of the IBD system (7000 s) relative to that of the EGT system (3000 s) makes up for the need for the IBD systems to thrust in both directions. Significantly, Fig. 5 indicates that even for 140-m diameter asteroids, the required propellant masses are of order 2500 kg or less, which are well within the 10,000-kg capability for the ARRM baseline conceptual design.

For EGT to work it must be capable of acquiring mass from an unknown potentially hazardous object. For this mass acquisition to be successful there has to be material on the surface that can be acquired with whatever mass acquisition system the EGT spacecraft has and the asteroid must have a spin state that is also compatible with the spacecraft and mass acquisition system. If the asteroid is spinning or tumbling too rapidly it may not be possible for the EGT spacecraft to successfully acquire the necessary mass.

Asteroid spin rate data from “The Asteroid Lightcurve Database” [14] is given in Fig. 7 where the least reliable data (spin quality code of 1) has not been included. The horizontal dashed line indicates the cohesionless spin barrier. These data indicate that no large asteroids, i.e., those greater than 1 km diameter, spin faster than this rate. The two vertical dashed lines indicate the 50-m to 140-m diameter asteroid size range of interest in this study. It is clear from these data that the majority of near-Earth asteroids in this size range, for which spin data is available, have spin rates periods significantly less than 2 hours. Such fast spin rates have the potential to greatly complicate the processes needed to acquire the mass for an EGT system.

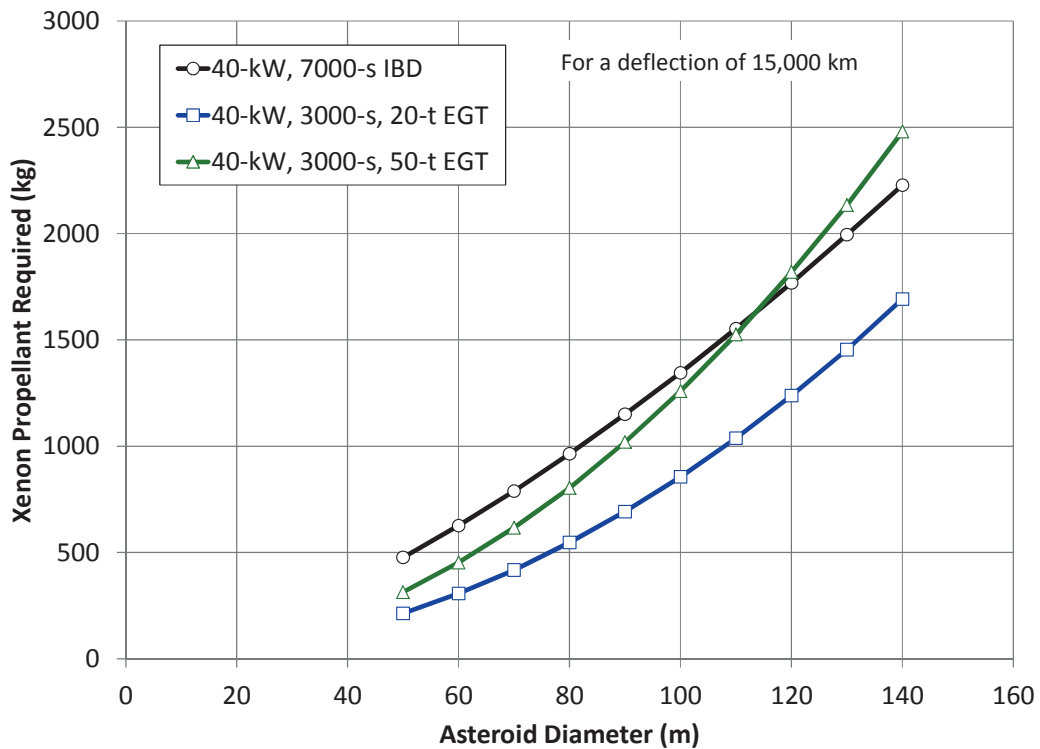
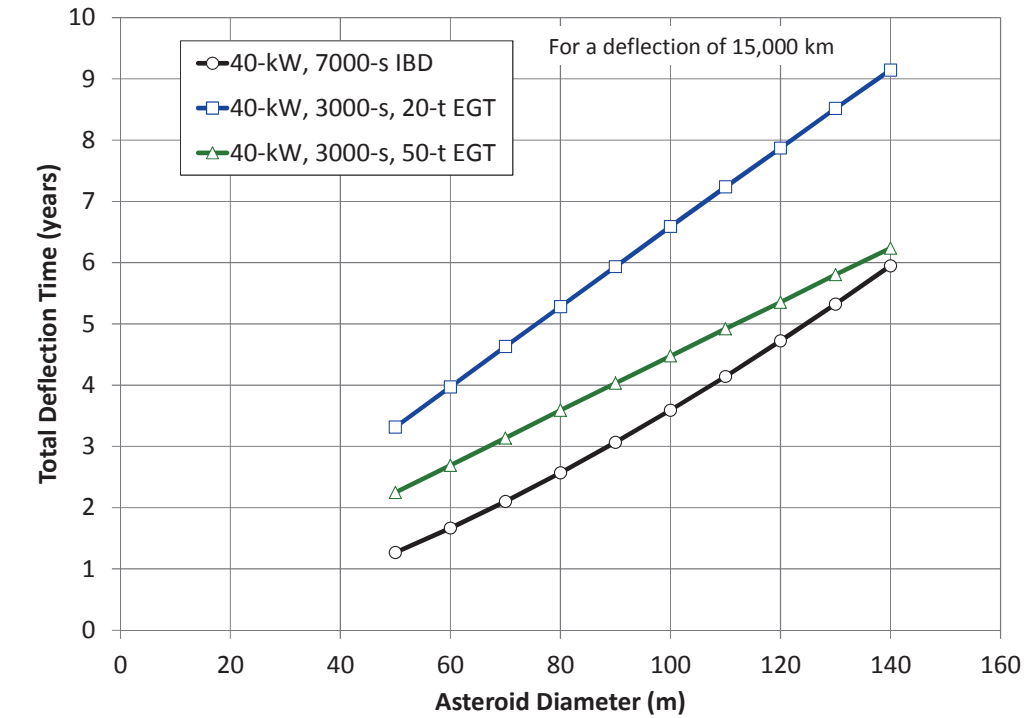


Figure 6. Comparison of deflection times (top) and xenon mass required (bottom) for IBD and EGT, with the EGT systems augmented by 20 t or 50 t of acquired mass. IBD and EGT with 50-t of acquired mass require approximately the same xenon loads for deflection.

The blue curve in Fig. 7 indicates the spin rate limit from Sanchez and Scheers [15] assuming asteroids have weak internal cohesion of 25 Pa. Sanchez and Scheers speculate that asteroids spinning slower than the blue curve are consistent with being rubble piles and those spinning faster than this limit are monolithic. If this is correct, then a significant fraction of asteroids in the size range of interest could be both fast spinners and monolithic, potentially making it very difficult to acquire mass from such objects.

For IBD to work it is necessary that the pressure from the ion beam on the asteroid surface does not disrupt the asteroid. The IBD pressure at the asteroid surface is given in Fig. 8 as a function of asteroid size assuming the IBD parameters in Table 2. This figure indicates that the pressure from the ion beam is at least five orders of magnitude less than the 25 Pa cohesion estimated by Sanchez and Scheers [15], suggesting little likelihood that the IBD process would disrupt the asteroid. Similarly, the power deposited by the ion beam ranges from roughly 1.3 W/m^2 for 140-m asteroids to about 10 W/m^2 for 50-m ones. These power densities are two to three orders of magnitude less than the solar input of approximately 1350 W/m^2 at 1 AU, again suggesting that IBD deflection would not disrupt the asteroid.

Finally, there's the question of whether the ion beam would successfully transfer its momentum to the asteroid. Ground tests performed by Longmier et al. [16] demonstrate that ion thruster exhaust impinging on a surface imparts a force approximately equal to the thrust (within a couple of percent). In these tests a "plasma momentum flux sensor" was positioned to intercept the entire exhaust plume of a Hall thruster and showed that the sensor feels a force equal to the thrust produced by the thruster as measured independently by an inverted pendulum thrust stand.

Sputtering of the asteroid surface by the ion beam will not affect the momentum transfer. Sputtered products resulting from ions in the energy range of interest, 800 V to 6000 V, are known to leave the surface with low velocities relative to that of the incoming ions. Since sputtered products typically leave with a component of velocity opposite of the incoming ions, if anything the effect of sputtering should very slightly increase the momentum change of the asteroid. This effect has been neglected in this study. Charging of the asteroid by the ion beam is also not a concern since the thruster exhaust contains the same flux of ions and electrons.

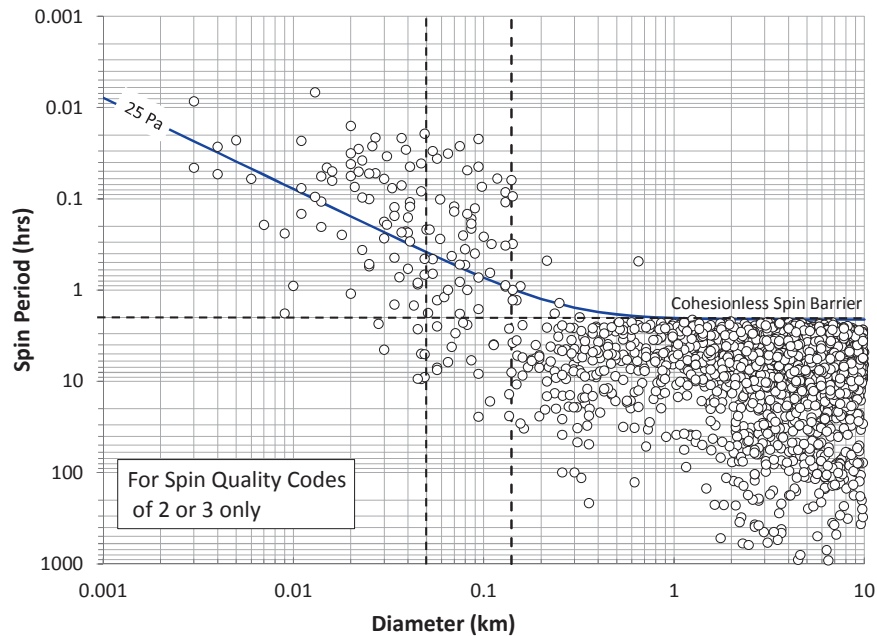


Figure 7. Asteroid spin data as of November 2014 using only the highest quality spin data (spin quality codes 2 and 3). The blue line indicates the theoretical spin limit for a cohesion of 25 Pa from Sanchez and Scheeres [13]. The horizontal dashed line is the cohesionless spin barrier. The vertical dashed lines indicate the range of asteroid sizes of interest in this study (50- to 140-m diameter).

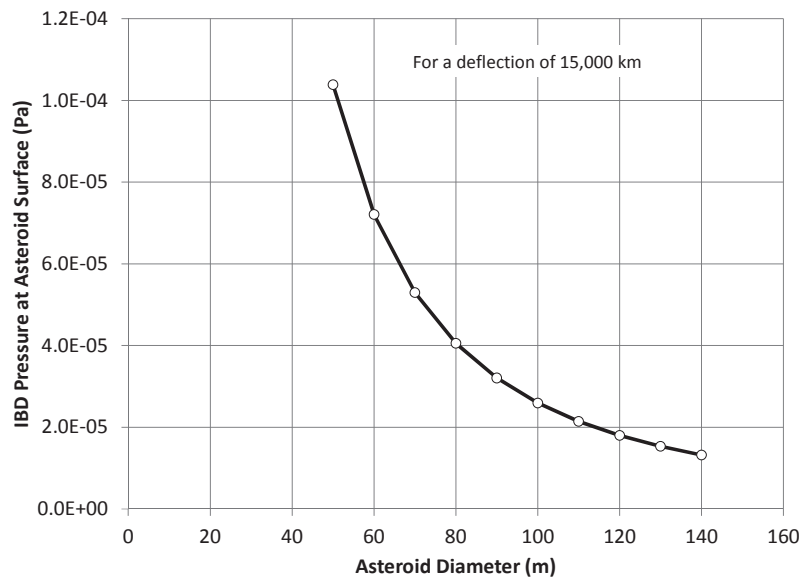


Figure 8. The calculated pressure at the asteroid surface due from the ion beam during IBD operation is at least four orders of magnitude less than the 25 Pa cohesion binding the asteroid together from Sanchez and Scheeres [14] suggesting that IBD activities are very unlikely to disrupt the asteroid.

E. Improving EGT and IBD Performance

The performance of EGT systems can be improved through the acquisition of greater masses from the threat object. In Fig. 9 the EGT performance with optimized mass acquisition is compared to the 40-kW IBD system. Optimized mass, in this context, means that for the parameters given in Table 1 sufficient mass from the surface of the asteroid is acquired so that the full thrust of the electric propulsion system can be utilized. For example, for a 100-m asteroid, acquisition of a 345-t boulder is necessary to enable EP thrusting at its full thrust level of 1.63 N. For a 50-m asteroid this mass increases to 700 t because of the lower mass of the threat object. Optimizing the EGT acquisition mass in this way reduces the deflection time by approximately a factor of two relative to the 40-kW IBD system, as indicated in Fig. 9. The disadvantage, as mentioned previously, is that it may not be possible to pick up such large masses from an arbitrary threat object in the 50- to 140-m size range.

The performance of IBD systems can be improved by simply increasing the power and propellant capability of the IBD vehicle. NASA is evaluating concepts that would increase the power of the baseline ARRM concept vehicle from 40-kW (into the EP system) to 150-kW. A 150-kW, ARRM-derived IBD concept vehicle could have 8 NEXIS thrusters on the “back” end to provide transportation in heliocentric space and 4 on the “front” end for the IBD system. It could store up to 16 t of xenon. Eight NEXIS thrusters would be needed on the back to be able to utilize all of the available 150 kW for transportation to the threat object. Only 4 NEXS thrusters would be needed on the front for the IBD system since the power is shared equally between the front and back thrusters during IBD operations. The performance of a 150-kW IBD vehicle concept is compared to the 40-kW IBD system in Fig. 10 showing that the higher power IBD vehicle provides about a factor of two reduction in deflection time relative to the 40-kW system. The 150-kW IBD system performance is compared to the 40-kW EGT system with optimized mass acquisition in Fig. 11 (top chart). It is clear that both system concepts provide essentially the same deflection times over the range of asteroid sizes considered. The total propellant masses required for these systems are compared in the bottom chart in Fig. 11. These data indicate that both systems require approximately the same amount of propellant as well.

So it is clear that IBD and EGT systems can be engineered to provide essentially the same deflection performance for the range of asteroid sizes considered in this study. The question then becomes which of these systems would be easier to implement and subsequently operate? EGT systems are highly dependent on the characteristics of the threat asteroid; it cannot be spinning or tumbling too rapidly and it must have material on the surface that can be successfully acquired by the EGT vehicle. IBD systems, on the other hand, are completely independent of the physical characteristics of the threat object potentially making them more broadly applicable.

It should be noted that it could be possible improve the performance of EGT systems beyond that shown in Fig. 11 by increasing the power level. Higher power EGT vehicles, however, would require the acquisition of significantly greater boulder masses to make use of the higher power level. For example, a boulder mass of 2610 t would be necessary to optimize the performance of a 150-kW EGT vehicle for a 50-m asteroid. Such a boulder would be about 13.6 m in diameter (assuming a density of 2 g/cm³). This is roughly 25% of the diameter of the 50-m asteroid suggesting that acquisition of such a large mass from a small body would be unlikely.

F. Deflection of the Fictitious Asteroid 2015 PDC

The 2015 Planetary Defense Conference created a fictitious potentially hazardous asteroid named 2015 PDC as the basis for evaluating potential responses to this threat. Bombardelli, et al. [16], proposed the use of an IBD system based approximately on the capabilities of the Dawn spacecraft to move the projected Earth-impact point of the asteroid. The characteristics of their “baseline” system are given in Table 1. Bombardelli, et al., emphasized the use of IBD to move the impact point of 2015 PDC to more benign locations on the Earth’s surface. At the end of their paper, however, they discussed what it would take to move the impact point completely off the Earth’s surface—what they term “full deflection.” The size of the fictitious asteroid 2015 PDC was deliberately made to be uncertain to reflect a likely real-world situation. The size estimates ranged from 150-m to 400-m diameter. Bombardelli, et al., determined the size of IBD systems that would be necessary to fully deflect the asteroid if it was 250-m in diameter and if it was 400-m diameter. These systems were described in multiples of their baseline system. The parameter values in Table 3 were derived from the information provided by Bombardelli, et al. To fully deflect the asteroid if it was 250-m diameter would require 5 baseline vehicles, each operating in parallel, to provide a total force on the asteroid of 0.85 N thrusting continuously for 33 months. A total of 4240 kg of xenon and a total power level of 43 kW input to the electric propulsion systems (sum of the xenon and power for all 5 vehicles) would be required. To fully deflect the 400-m diameter version of the asteroid in the same 33 months would require 20 baseline vehicles, and a total of 200-kW and 19,940 kg of xenon.

Table 3. Summary of IBD System Characteristics from Bombardelli, et al.

Parameter	Bombardelli, et al. [16]		
	Baseline System	System for Full Deflection Assuming 250-m dia. Asteroid	System for Full Deflection Assuming 400-m dia. Asteroid
Number of Vehicles	1	5	20
Specific Impulse [s]	3500	3500	3500
Total Thrust [N]	0.40	1.7	8.0
IBD Thrust [N]	0.2	0.85	4.0
Power to EP Systems [kW]	10	43	200
EP System Efficiency	0.69	0.69	0.69
Total Xe Flow Rate [kg/s]	1.17×10^{-5}	4.95×10^{-5}	2.33×10^{-4}
IBD Duration [months]	Variable	33	33
IBD Total Impulse [N-s]		7.27×10^7	3.42×10^8
Total Xe Required [kg]		4240	19940

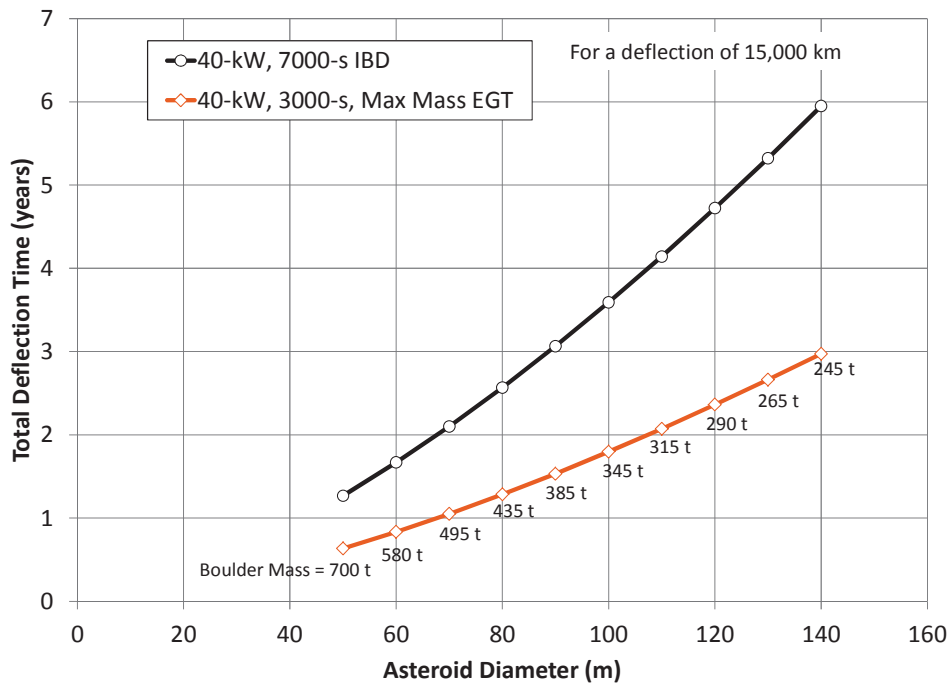


Figure 9. Optimizing the boulder mass acquired from the threat asteroid can result in significantly shorter deflection times relative to a 40-kW IBD provided such boulder masses can actually be acquired from asteroids in the size range of interest.

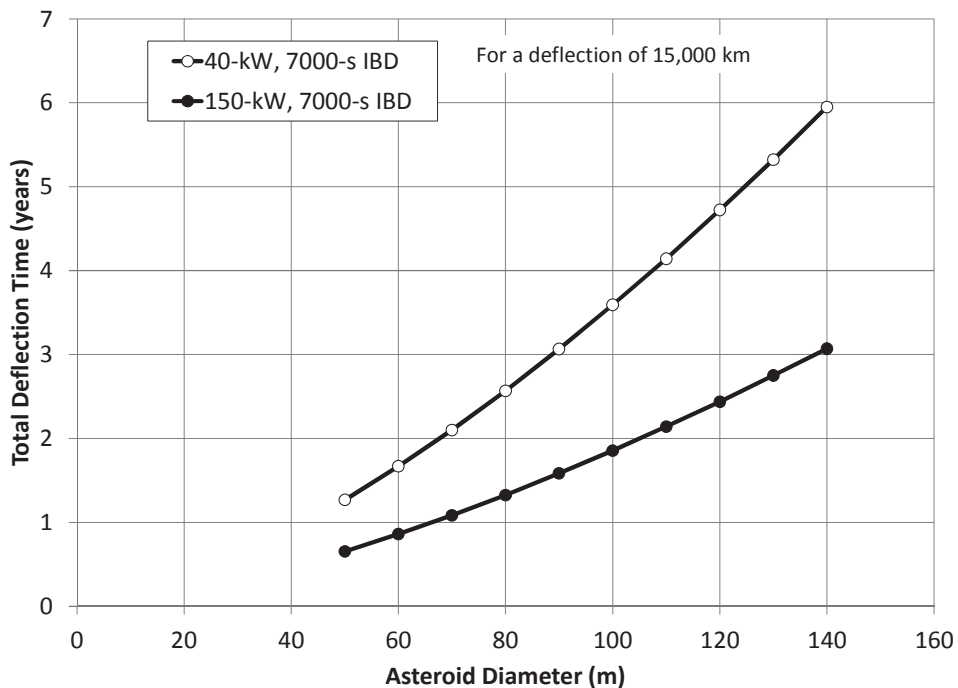


Figure 10. Increasing the power level of the IBD vehicle from 40 kW to 150 kW reduces the deflection times by roughly a factor of two.

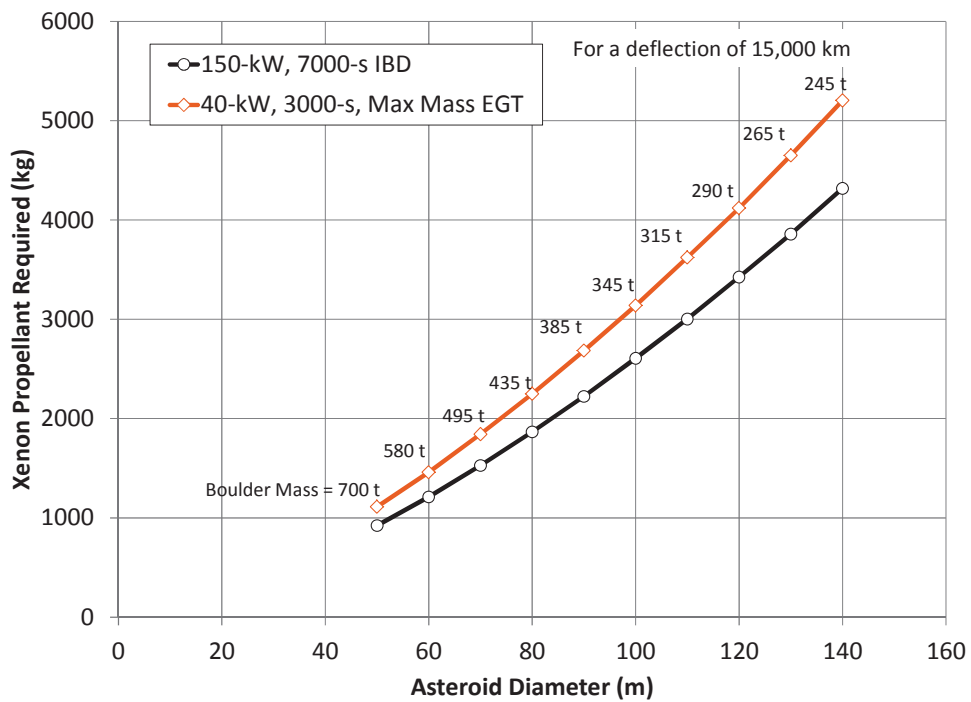
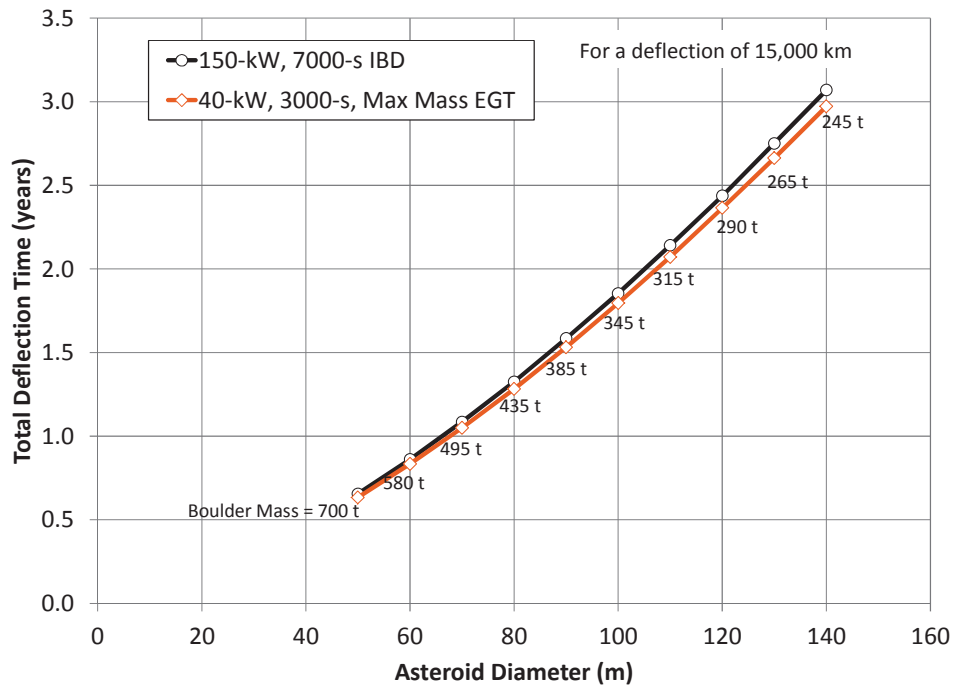


Figure 11. Comparison of 150-kW IBD systems with 40-kW EGT in which the EGT system is assumed to be capable of acquiring the amount of mass necessary to fully utilize its electric propulsion system. The “Boulder Mass” numbers indicate the required mass necessary for the EGT system. Both systems provide the same deflection times and require essentially the same propellant masses.

If we assume the use of ARRM-derived IBD vehicles instead of the Dawn-derived systems assumed by Bombardelli, et al., and match the thrust levels, then we get the results indicated in Table 4. For the “NEXIS Only” cases in which NEXIS ion thrusters are used on both ends of the vehicle this table indicates that two 40-kW IBD vehicles would be needed. Each vehicle would operate with 21 kW driving the IBD system and 21 kW used to hold the vehicle in place relative to the asteroid. This two-vehicle system would require a total of 2140 kg of xenon to deflect the asteroid in 33 months. The total xenon required would be less than the corresponding case in Table 3 because of the higher specific impulse of the NEXIS ion thrusters. Full deflection of the 400-m asteroid would require three 150-kW ARRM-derived vehicles with all NEXIS thrusters as indicated in the third column from the left in Table 4. In this case each of these three vehicles would operate at 133 kW to provide the necessary total force on the asteroid to deflect it in 33 months.

Table 4. ARRM-derived IBD Vehicles for Deflection of the Fictitious Asteroid 2015 PDC.

Parameter	NEXIS Only		ARRM Hall / NEXIS	
	System for Full Deflection Assuming 250-m dia. Asteroid	System for Full Deflection Assuming 400-m dia. Asteroid	System for Full Deflection Assuming 250-m dia. Asteroid	System for Full Deflection Assuming 400-m dia. Asteroid
Number of Vehicles	2	3	2	2
Vehicle Class	ARRM Baseline	150-kW ARRM Derivative	ARRM Baseline	150-kW ARRM Derivative
Translation thrusters / IBD Thrusters	NEXIS / NEXIS	NEXIS / NEXIS	ARRM Hall / NEXIS	ARRM Hall / NEXIS
Specific Impulse [s]	7000	7000	3000 / 7000	3000 / 7000
EP System Efficiency	0.7	0.7	0.6 / 0.7	0.6 / 0.7
IBD Duration [months]	33	33	33	33
Parameters below are the sum of all vehicles				
Total Thrust [N]	1.7	7.8	1.7	8.0
IBD Thrust [N]	0.85	3.95	0.85	4.0
Power to EP Systems [kW]	42 / 42	200 / 200	21 / 42	100 / 200
Total Xe Flow Rate [kg/s]	2.50×10^{-5}	1.17×10^{-4}	$3.89 \times 10^{-5} / 1.24 \times 10^{-5}$	$1.36 \times 10^{-4} / 5.83 \times 10^{-5}$
IBD Total Impulse [N-s]	7.34×10^7	3.42×10^8	7.27×10^7	3.42×10^8
Total Xe Required [kg]	2140	9970	3530	16620

G. IBD as an Attachment to an Asteroid Redirect Vehicle

An alternative approach that may make better use of the ARRM concept vehicle and its possible higher-power derivatives would be to use the Hall propulsion systems in those vehicles “as is” and develop a NEXIS-based IBD “payload” for the front end. For the baseline ARRM concept vehicle the IBD payload module would replace the Capture Module. The IBD Module would consist of two NEXIS ion thruster strings (one operational and one cold spare). Each string would consist of a NEXIS ion thruster, a power processing unit (PPU), a xenon flow controller, and a two-axis thruster-gimbal assembly. The IBD Module would also include the radiators and thermal control for the PPUs and the necessary structure to support the module components. The baseline ARRM vehicle would require minor modifications so that it could provide command and control, power, and xenon propellant to the IBD Module. The estimated mass for a 20-kW IBD Module based on the NEXIS ion thrusters is given in Table 5. The total mass of ~480 kg would be nearly a factor of three less than the mass of the ARRM Capture Module, suggesting that the ARRM vehicle structure could easily accommodate the IBD Module.

Table 5. Mass Estimate for a 20-kW, 7000-s Ion Beam Deflector Module.

Component	Unit Mass (kg)	# of Units	Current Best Estimate (kg)	Mass Growth Allowance (%)	Maximum Expected Mass (kg)	Source
Thruster	30	2	60	30%	78	AIAA 2005-3890 [18]
PPU	82	2	164	30%	213	Scaled from AIAA-2006-4319 [19] and AIAA-2007-5214 [20]
XCA	0.5	2	1	30%	1.3	Xenon Control Assembly, AIAA 2003-4551 [21]
Tubing	2.0	2	4	30%	5.2	Estimate
Harness	N/A	1	14.9	30%	19.4	5% of Propulsion Mass (JPL Team X scaling)
Thermal	N/A	1	35.0	30%	45.5	PPU Radiators: 25 kg/kW, 93% efficient PPUs
Structure	N/A	1	54.4	30%	70.7	15% of Component Masses
Subtotal			333		433	
Margin				10%	43.3	
Total					477	

For an asteroid deflection mission, the Hall thruster system would be used for transfer to the asteroid. During IBD operations, the NEXIS thruster would operate at ~21 kW directed at the asteroid and the Hall thruster system would be operated at ~10.5 kW to provide the thrust necessary to maintain position relative to the asteroid. Two such vehicles operating in parallel could fully deflect the 250-m diameter version of the fictitious asteroid 2015 PDC in 33 months using 3530 kg of xenon as indicated in Table 4. The required xenon is greater than the “NEXIS Only” cases because of the lower specific impulse of the Hall thrusters, but the required total power is also lower for the same reason.

To fully deflect the 400-m diameter version of 2015 PDC two 150-kW ARRM-derived vehicles would be required, with a correspondingly larger IBD Module. In this case the IBD Module would have 5 NEXT thruster strings and be capable of operating at input powers up to 100 kW. Two such vehicles would be required to deflect the 400-m asteroid in 33 months as indicated in Table 4. Each vehicle would use 100 kW for IBD operation and 50 kW in the Hall thruster system for asteroid stationkeeping. Again relative to the “NEXIS Only” case the “ARRM Hall / NEXIS” hybrid vehicle would require more xenon but lower power.

IV. Conclusions

For asteroids in the 50- to 140-m diameter size range, which may constitute the population of asteroids that will pose the greatest hazard for major property damage or loss of life after NASA completes the current survey of near-Earth asteroids greater than 140-m diameter, both enhanced gravity tractor (EGT) and ion beam deflection (IBD) technologies promise significantly better performance than a standard gravity tractor. Ion beam deflection systems derived from NASA’s Asteroid Redirect Robotic Mission (ARRM) concept vehicle can be configured to provide performance comparable to that of ARRM-derived EGT systems, that is, IBD can provide deflection times and required xenon propellant loads comparable to EGT systems. Practical implementation of IBD systems would require electric thrusters with small ion beam divergence angles to maximize the spacecraft-to-asteroid separation distance during deflection. One version of the NEXIS gridded ion thruster developed for the Jupiter Icy Moons Orbiter mission was configured with flat carbon-carbon grids and produced an ion beam divergence half-angle of less than 4

degrees at a specific 7000 s with xenon propellant. This thruster technology is well suited for the development of IBD systems that could be operational in the 2020s, and enables order of magnitude larger spacecraft-to-asteroid separation distances than EGT systems. The higher specific impulse of the NEXIS thruster compared to the 3000-s specific impulse of the ARRM Hall thrusters results in IBD systems that would require approximately the same xenon load as EGT systems for the deflection of the same sized asteroid. The higher specific impulse, however, requires that IBD systems operate at significantly higher power levels compared to EGT systems.

Since both EGT and IBD can provide comparable performance, the choice between these technologies reduces to assessment of the cost and risk associated with the development and operation of systems necessary to acquire the needed mass from an unknown threat object vs implementation of a higher-power vehicle for IBD. Spin data and analyses suggest potentially significantly limited applicability of EGT. A large fraction of asteroids in the size range 50- to 140-m diameter may be spinning too fast to reasonably acquire mass from their surfaces. Furthermore, many rapidly spinning asteroids in this size range may be monolithic, which could make acquisition of the needed mass impractical. IBD has none of these limitations and is completely independent of the characteristics of the threat object making it applicable to all hazardous objects in this size range.

Finally, Bombardelli et al., investigated the use of IBD for the deflection of the fictitious asteroid 2015 PDC from the 2015 Planetary Defense Conference. Matching the thrust levels used in Bombardelli's analyses with ARRM-derived IBD systems we show how these systems could deflect the fictitious asteroid for assumed diameters of 250-m and 400-m. If the fictitious asteroid has a diameter of 250-m corresponding to approximately the middle of its size uncertainty, such an object could be deflected in the same 33 months using two 40-kW ARRM-derived IBD vehicles. If, instead the asteroid was at the upper end of the size range, i.e., 400-m diameter, the two 150-kW ARRM-derived IBD vehicles would be required to deflect it in 33 months. Practical IBD vehicles could be developed as derivatives of the ARRM vehicle concept in which the ARRM Hall propulsion systems in those vehicles are used "as is" and a NEXIS-based IBD Module is developed as a "payload." For the baseline ARRM concept vehicle the IBD Module would replace the Capture Module. The IBD Module would consist of multiple NEXIS ion thruster strings. Higher-power versions would include more NEXIS thruster strings.

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References

1. Boslough, M., Brown, P. and Harris, A., "Updated Population and Risk Assessment for Airbursts from Near-Earth Objects (NEOs)," 2.1203, 36th IEEE Aerospace Conference, Big Sky, MT, Mar 7-14, 2015.
2. Committee to Review Near-Earth Object Surveys and Hazard Mitigation Strategies, National Research Council, *Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies*, (2010).
3. [https://en.wikipedia.org/wiki/Deep_Impact_\(spacecraft\)](https://en.wikipedia.org/wiki/Deep_Impact_(spacecraft))
4. Bhaskaran, S., and Kennedy, B., "Closed loop terminal guidance navigation for a kinetic impactor spacecraft," *Acta Astronautica* 103, (2014) 322-332.
5. Lu, E. T., and Love, S. G., "Gravitational Tractor for Towing Asteroids," *Nature (London)*, Vol. 438, No. 7065, 2005, pp. 177-178.
6. McInnes, C.R., "Near Earth Object Orbit Modification Using Gravitation Coupling," *J. of Guidance, Control and Dynamics*, Vol. 30, No. 3, May-June 2007.
7. Mazanek, D.D., et al., "Enhanced Gravity Tractor Technique for Planetary Defense," IAA-PDC-15-04-11, presented at the 4th IAA Planetary Defense Conference—PDC 2015 13-17 April 2015, Frascati, Roma, Italy.
8. Bombardelli, C., et al., "The ion beam shepherd: A new concept for asteroid deflection," presented at the 2011 IAA Planetary Defense Conference, 09-12 May 2011.
9. Kitamura, S., "Large Space Debris Reorbiter Using Ion Beam Irradiation," IAC-10-A6.4.8, 61st International Astronautical Congress, September 2010.

10. Muirhead, B.K., and Brophy, J.R., "Asteroid Redirect Robotic Mission Feasibility Study," presented at the 2014 IEEE Aerospace Conference, Big Sky, MT.
11. <http://neo.jpl.nasa.gov/pdc15/>.
12. Polk, J.E., et al., "Performance and Wear Test Results for a 20-kW-Class Ion Engine with Carbon-Carbon Grids, AIAA 2005-4393, presented at the 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 10-13 July 2005, Tucson, AZ.
13. Brophy, J.R., Katz, I., Polk, J.E., and Anderson, J.R., "Numerical Simulations of Ion Thruster Accelerator Grid Erosion," AIAA 2002-4261, 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 7-10 July 2002, Indianapolis, Indiana.
14. <http://www.minorplanet.info/lightcurvedatabase.html>
15. Sanchez, P. and Scheeres, D.J., "The Strength of Regolith and Rubble Pile Asteroids," arXiv:1306.1622v2 [astro-ph.EP] 5 Mar 2014.
16. Bombardelli, C., et al., "Mission Analysis for the Ion Beam Deflection of Fictitious Asteroidj 2015 PDC," presented at the 4th IAA Planetary Defense Conference—PDC 2015 13-17 April 2015, Frascati, Roma, Italy.
17. Longmier, B.W., et al., "Validating a Plasma Momentum Flux Sensor to an Inverted Pendulum Thrust Stand," *J. of Propulsion and Power*, Vol. 25, No. 3, May-June 2009.
18. Patterson, M.J., et al., "Herakles Thruster Development for the Prometheus JIMO Mission," AIAA-2005-3890, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit' 10 - 13 July 2005, Tucson, Arizona.
19. Brophy, J.R., et al., "Development and Testing of the Dawn ion Propulsion System," AIAA-2006-4319, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference AIAA-2006-4319, 9-12 July, 2006, Sacramento, California.
20. Pinero, L.R., et al., "Performance of the NEXT Engineering Model Power Processor Unit," AIAA-2007-5214, 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 8 - 11 July 2007, Cincinnati, OH.
21. Fisher, J., et al, "The Development and Qualification of a 4.5 kW Hall Thruster Propulsion System," AIAA-2003-4551, 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 20-23 July 2003, Huntsville, Alabama.