# Impulsive and Slow-push Mitigation Options for 2025 PDC Hypothetical Asteroid Impact Scenario

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## Introduction

This study investigates the deflection performance of the Kinetic Impactor (KI), Nuclear Explosion Device (NED), and Laser Ablation (LA) techniques for mitigating the impact threat posed by asteroid 2024 PDC25—a hypothetical object with a 17-year warning time, created for the 2025 IAA Planetary Defense Conference exercise. The potential impact date of asteroid 2024 PDC25 is projected to be April 24, 2041. Disruption conditions were taken into account to minimize the risk of asteroid fragmentation following the deflection mission.

Simulation results suggest that either a single KI or a single NED would be sufficient to achieve the necessary deflection without disrupting the asteroid. LA produces deflection outcomes comparable to a single KI but offers a reduced risk of fragmentation. Multiple Kinetic Impactors were further investigated to determine the number required for a successful deflection. Additionally, the "Nuclear Cycler" concept [2]—a single spacecraft with a number of NEDs—was investigated to combine high energy efficiency with reduced fragmentation risk.

The approach developed in this study was applied to provide recommendation inputs from the Strathclyde team during Epoch 1 and Epoch 2 of 2025 PDC hypothetical asteroid impact scenario exercise. The results were internally cross-validated with other teams participating in the WP01 Mission Scenarios for Reconnaissance and Deflection Missions of the exercise in SMPAG.

Table 1. Physical properties across percentiles in Epoch 1.

| Physical Property | 5th Percentile | 50th Percentile | 95th Percentile | 100th Percentile |
|---|---|---|---|---|
| Diameter [m] | 77.09 | 127.05 | 191.17 | 277.84 |
| Bulk Density [g/cm$^3$] | 1.886 | 2.062 | 2.417 | 2.794 |
| Porosity | 0.443 | 0.400 | 0.245 | 0.200 |
| Mass [kg] | 4.52E+08 | 2.21E+09 | 8.84E+09 | 3.14E+10 |
| Surface Escape Velocity [cm/s] | 3.96 | 6.82 | 11.11 | 17.36 |
| Absolute Magnitude | 22.40 | 21.77 | 21.35 | 21.44 |
| Albedo | 0.326 | 0.214 | 0.140 | 0.061 |
| Taxonomic Type | S | S | S | S |

Table 2. Physical properties across percentiles in Epoch 2.

| Physical Property | Lowest Mass | 5th Percentile | 25th Percentile | 50th Percentile | 75th Percentile | 95th Percentile | Highest Mass |
|---|---|---|---|---|---|---|---|
| Diameter [m] | 147 | 149 | 149 | 150 | 151 | 152 | 155 |
| Bulk Density [g/cm$^3$] | 1.211 | 1.514 | 1.902 | 2.207 | 2.54 | 2.968 | 3.598 |
| Porosity | 0.595 | 0.57 | 0.402 | 0.313 | 0.244 | 0.093 | 0.039 |
| Mass [kg] | 2.00E+09 | 2.60E+09 | 3.31E+09 | 3.93E+09 | 4.59E+09 | 5.49E+09 | 7.03E+09 |
| Surface Escape Velocity [cm/s] | 6.05 | 6.85 | 7.68 | 8.33 | 9.00 | 9.79 | 10.99 |
| Absolute Magnitude | 21.42 | 22.16 | 21.24 | 21.6 | 21.59 | 21.58 | 22.28 |
| Albedo | 0.221 | 0.109 | 0.253 | 0.179 | 0.179 | 0.178 | 0.09 |
| Taxonomic Type | S | S | S | S | S | S | S |

## Methodology

The deflection performance is measured by the variation of the asteroid $b$ parameter before and after deflection, where momentum transfer from each deflection action is modeled based on the specific strategy.

### Multiple Kinetic Impactor

Considering $n$ KIs in the MKI mission, the departure date $t_{dep}$ and transfer time $\Delta t$ sequences are defined as

$$\mathbf{x} = \left[t_{dep}^{[1]}, \Delta t^{[1]}, t_{dep}^{[2]}, \Delta t^{[2]}, \dots, t_{dep}^{[k]}, \Delta t^{[k]}, \dots, t_{dep}^{[n]}, \Delta t^{[n]}\right] \tag{1}$$

where $t_{dep}^{[k]}$ and $\Delta t^{[k]}$ represent the departure date and transfer time of the $k$-th KI, respectively. The arrival date of the $k$-th KI is then given by $t_{arr}^{[k]} = t_{dep}^{[k]} + \Delta t^{[k]}$. Each trajectory arc between $(t_{dep}^{[k]}, t_{arr}^{[k]})$ is solved using Lambert's problem. Note that in Eq. (1) the sequence of KIs is determined by their departure dates, while the arrival dates do not necessarily follow the same order, the KIs are reordered based on their arrival dates for subsequent calculations.

Assuming a perfectly inelastic collision between two spheres, and applying the law of conservation of momentum, the velocity increment of the asteroid after the $k$-th impact is given by

$$\delta \boldsymbol{v}_{ast}^{[k]} = \beta \frac{m_{sc}^{[k]}}{m_{sc}^{[k]} + m_{ast}} \left(v_{sc}^{[k]} - v_{ast}^{[k-1]}\right) \tag{2}$$

where $\beta$ represents the momentum enhancement factor. $\boldsymbol{v}_{ast}^{[k-1]}$ represents the asteroid velocity after $(k-1)$-th impact at the arrival time $t_{arr}^{[k]}$ of the $k$-th KI. Therefore, the asteroid velocity after the $k$-th impact is updated as

$$\boldsymbol{v}_{ast}^{[k]} = \boldsymbol{v}_{ast}^{[k-1]} + \delta \boldsymbol{v}_{ast}^{[k]} \tag{3}$$

### Nuclear Cycler

Consider a spacecraft carrying $n$ NEDs. The low-thrust trajectory arc between $(t_{dep}, t_{arr})$ is solved using a spherical shaping method [1]. After arrival, the spacecraft detonates the NEDs sequentially, starting with the first at $t_{detonate}$ and maintaining the specified separation until the $n$-th detonation. Each NED employs a standoff explosion configuration, detonating at a certain distance above the asteroid's surface. The total velocity increment of the asteroid includes debris from the device and radiation of x-ray, neutron and gamma ray.

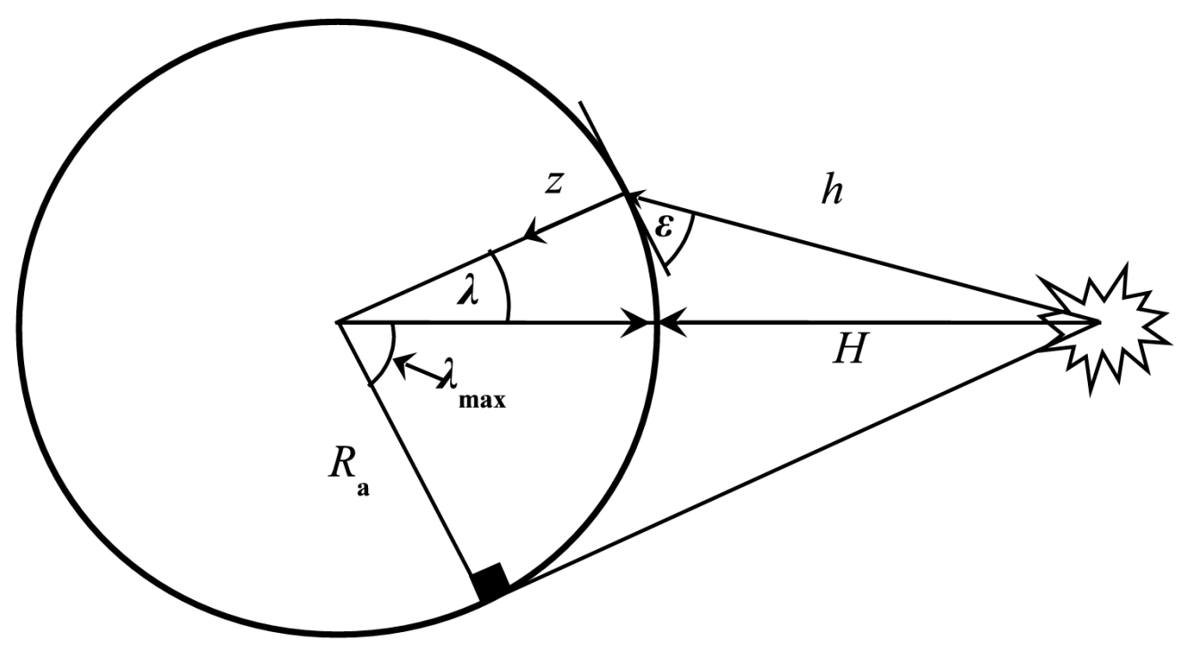

Figure 1. Standoff explosion configuration.

$$\delta v_{radiation} = \frac{\pi R_{ast}^2}{m_{ast}} \int_0^{\lambda_{\max}} \int_0^{z_{\max}(\lambda)} \rho_{ast} \sqrt{2\left(E(\lambda, z) - E_v\right)}\, dz\, \sin\lambda \cos\lambda \, d\lambda \tag{4}$$

where $E(\lambda, z)$ represents the amount of energy absorbed per unit mass at a given depth, and $E_v$ represents total vaporization enthalpy per unit mass.

In this study, 100 kton NEDs are considered. Each NED is modeled as a fusion device with a Yield-to-Weight ratio of 1.8 kton/kg, with 250 kg allocated for free-flyer equipment. $E_v$ is assumed to be 5 MJ/kg.

### Laser Ablation

Model assumes that deflection actions commence as soon as the spacecraft has rendezvoused with the target and the deflection action continues until the close approach date. The thrust is given by

$$F_{\text{LS}} = \eta_{LS} C_m P_{in} \tag{5}$$

where $\eta_{LS}$ is the electrical-to-optical conversion efficiency, $C_m$ is the thrust coupling coefficient, and $P_{in}$ is input power. A value of 40 μN/W is used for the thrust-coupling coefficient and is a conservative value to account for uncertainty in the shape of the asteroid.

## Results

The mission is launched no earlier than 2 years 4 months after the reconnaissance observer arrived the asteroid on 2031-12-31. Falcon Heavy (Expendable) is considered. A full chord distance is considered with 2.1842645764747E+04 km, and assuming 70% full chord deflection distance represents a successful southward deflection. $\beta = 2$. Constraints are:

## Results

- Minimum separation between impacts/explosions: 14 days.
- DLA allowed: -28.5deg - 28.5 deg.
- Minimum Sun-Spacecraft-Earth (SSE) angle allowed: 3 deg.
- disruption condition: $\delta v_{ast} < 4\% V_{esc}$

### Multiple Kinetic Impactor

For the highest-mass case, Figure 2 shows the deflection distance as a function of the earliest launch date from 2028, for varying numbers of KIs. Results suggest that a single KI cannot achieve successful deflection. With a launch constraint of no earlier than 2034, at least 7 KIs are required. Detailed mission design results are shown in Table 3, and the corresponding trajectories are shown in Figure 3. For the lowest-mass case, simulations results suggest that a minimum of 19 KIs is needed for successful deflection.

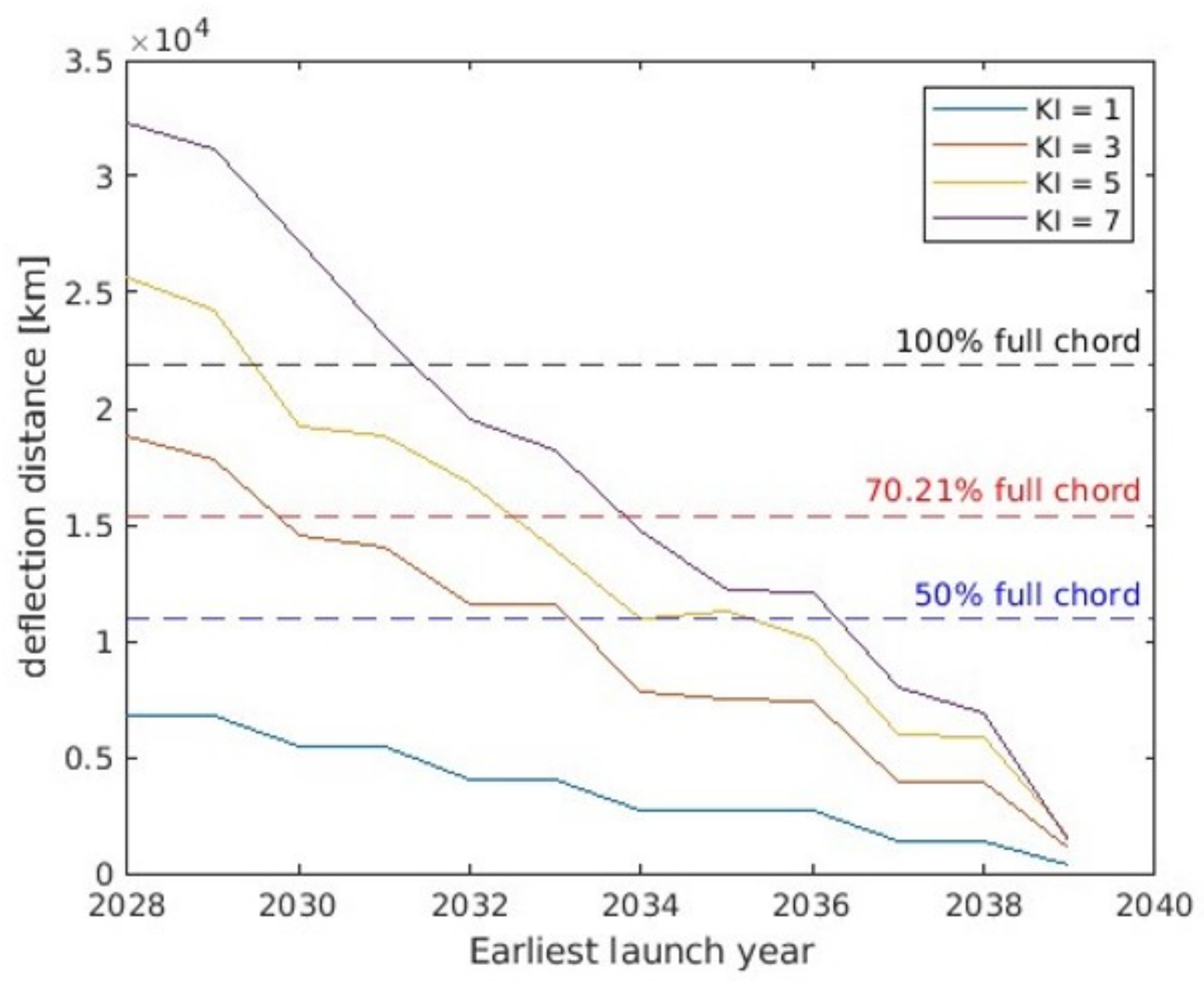

Figure 2. Deflection performance of different numbers of KIs

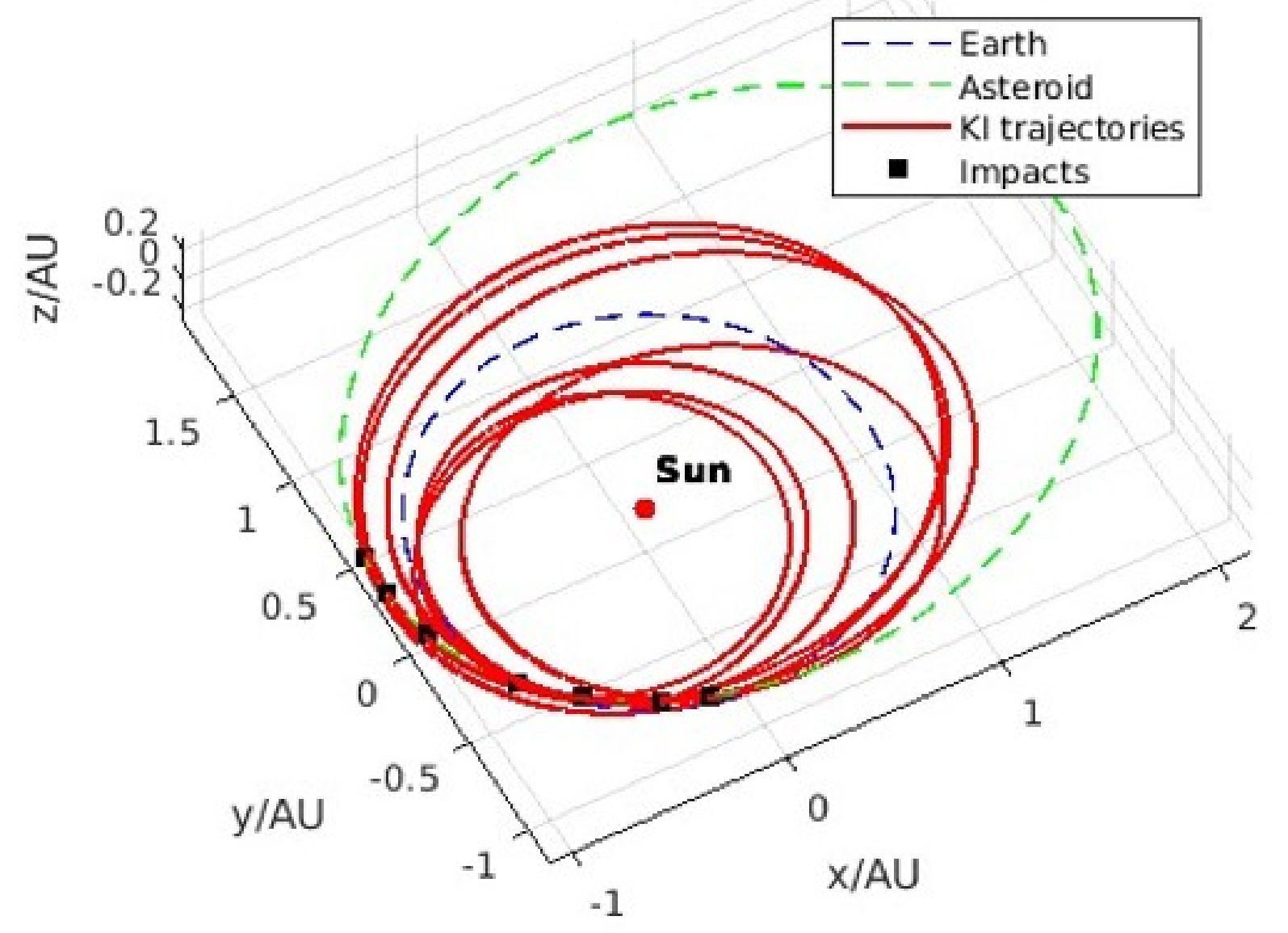

Figure 3. MKI trajectory

Table 3. Results of MKI for highest mass case

| KI | Departure Date | Arrival Date | $C_3$ [km$^2$/s$^2$] | $m_{sc}$ [kg] | % LV | $v_{sc}$ [km/s] | $\delta v_{ast}$ [mm/s] | % $V_{esc}$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 2034/4/20 | 2037/1/31 | 33.29 | 4644.06 | 61.66 | 3.32 | 4.4 | 4 |
| 2 | 2034/5/1 | 2036/11/24 | 37.37 | 4043.13 | 58.63 | 3.81 | 4.4 | 4 |
| 3 | 2034/5/23 | 2036/11/10 | 31.56 | 2978.40 | 38.10 | 5.18 | 4.4 | 4 |
| 4 | 2035/4/5 | 2037/1/15 | 9.67 | 1792.74 | 14.63 | 8.60 | 4.4 | 4 |
| 5 | 2036/3/17 | 2037/1/1 | 35.52 | 1261.24 | 17.57 | 12.22 | 4.4 | 4 |
| 6 | 2036/5/17 | 2036/12/8 | 62.10 | 1186.72 | 31.29 | 12.99 | 4.4 | 4 |
| 7 | 2037/10/18 | 2039/4/8 | 69.12 | 2496.43 | 81.21 | 6.18 | 4.4 | 4 |

### Nuclear Cycler

Considering the option of launch in 2034, and deflection in 2036. Figure 4 shows the deflection distance by different number of NEDs for both highest mass and lowest mass cases. Simulation results suggest that at least 7 NEDs are required for highest mass case and 12 NEDs are required for lowest mass case. Detailed mission design results are shown in Table 4, and Figure 5 showcase the trajectories of the highest mass case.

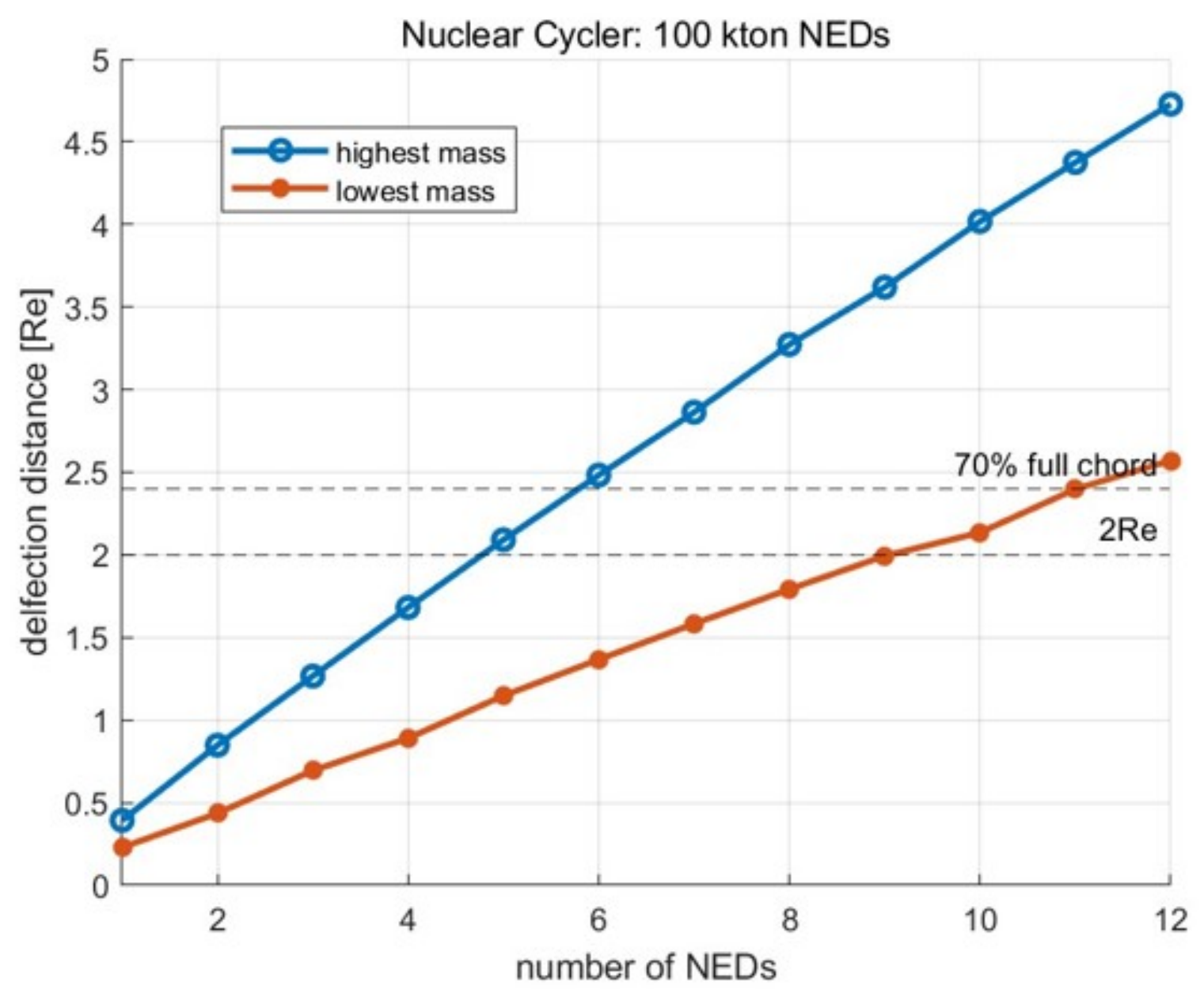

Figure 4. Deflection performance of different number of NEDs

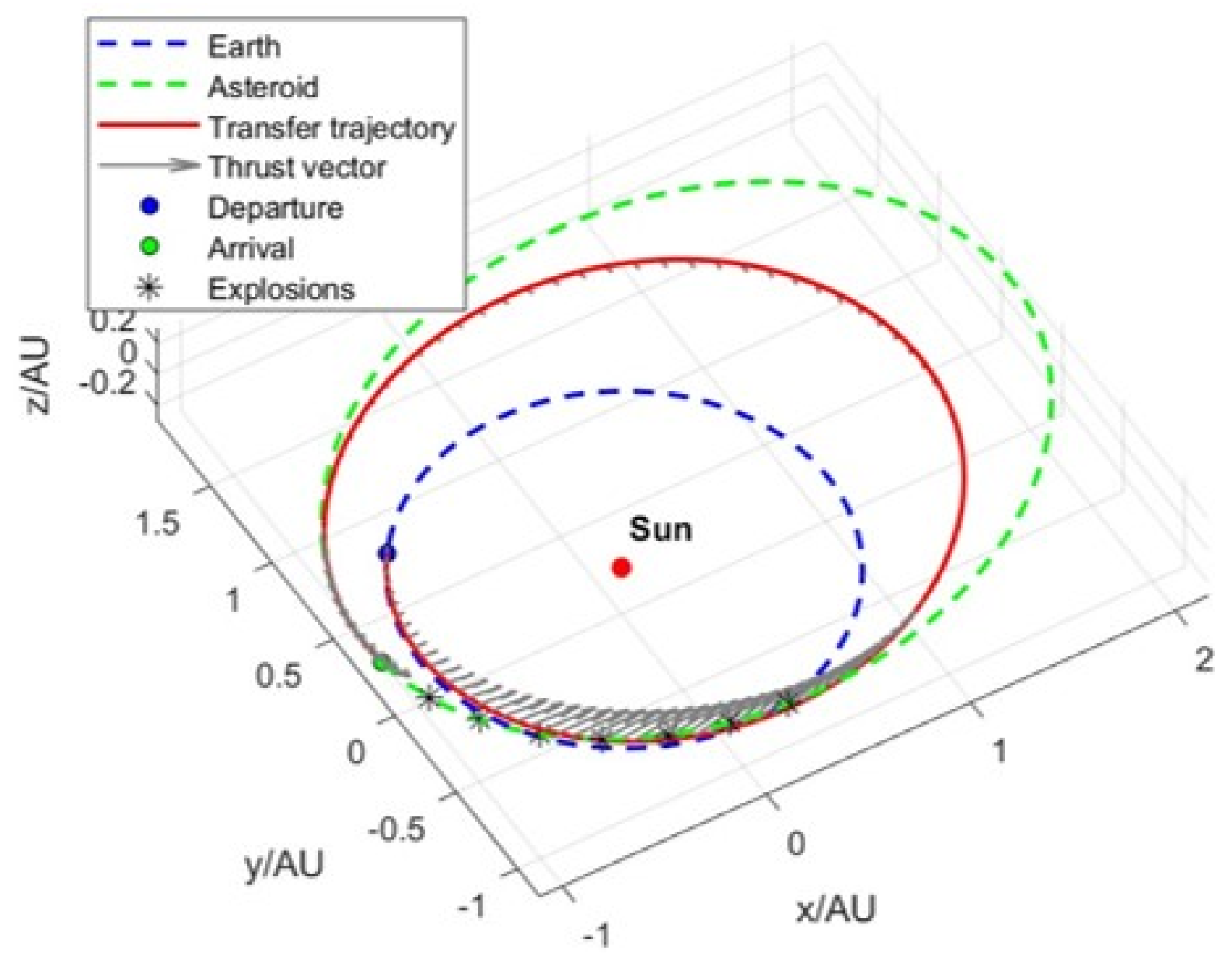

Figure 5. Nuclear Cycler trajectory

Table 4. Results of Nuclear Cycler options.

| Case | Number of NED | Departure Date | Arrival Date | First Detonation Date | $C_3$ [km$^2$/s$^2$] | Rendezvous Mass [kg] | $\delta v_{ast}$ [mm/s] | Deflection Distance $[R_E]$ |
|---|---|---|---|---|---|---|---|---|
| Low Mass | 12 | 2034/3/31 | 2036/8/23 | 2036/11/3 | 1.40 | 8888.61 | 2.33 | 2.59 |
| High Mass | 7 | 2035/2/13 | 2036/11/26 | 2036/12/12 | 0.78 | 10505.92 | 4.24 | 2.86 |

### Laser Ablation

The deflection performance of LA is investigated based the highest mass case in Epoch 1. Detailed mission design results are shown in Table 5, suggesting that LA provides comparable deflection distance to a single KI.

Table 5. Results of Laser Ablation options.

| Departure Date | Arrival Date | Rendezvous Mass [kg] | Maximum Thrust During Transfer [N] | Laser Input Power [kW] | Deflection Action Duration [yrs] | Deflection Distance $[R_E]$ |
|---|---|---|---|---|---|---|
| 2035/1/11 | 2037/2/3 | 10685.37 | 6.13 | 145.04 | 4.22 | 0.2219 |

## Conclusions

Considering disruption constraints, either a Kinetic Impactor (KI) or a Nuclear Explosive Device (NED) can be employed for asteroid deflection. A Multiple Kinetic Impactor or Nuclear Cycler strategy is essential to ensure mission feasibility for both approaches.

Taking highest mass case as an example, 7 KIs or 7 NEDs are required, while lowest mass cases require 19 KIs or 12 NEDs. The Multiple Kinetic Impactors strategy demands multiple launches, whereas the Nuclear Cycler enables a single-launch solution. Laser ablation techniques can achieve deflection performance comparable to a single KI, with lower fragmentation risk and higher deflection accuracy, but remains at lower TRL.

Future work will incorporate aleatory and epistemic uncertainties into deflection design using robust optimization techniques [3], supporting reliable early-stage decision-making under limited asteroid information.

## References

[1] Daniel M Novak and Massimiliano Vasile. Improved shaping approach to the preliminary design of low-thrust trajectories. *Journal of guidance, control, and dynamics*, 34(1):128–147, 2011.

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