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ANKA-M: a magnetospheric antiproton collector spacecraft concept for Earth's radiation belt – sizing, collection upper bound, power and trajectory analysis

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Research Article

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Abstract

Producing antiprotons on the ground is extremely inefficient, whereas a population of antiprotons magnetically trapped in Earth's inner radiation belt has been measured directly by the PAMELA satellite. This paper sizes a spacecraft concept, ANKA-M, that collects this natural source with its own magnetic field alone, without plasma assistance. The core of the design is a high-temperature-superconductor ring 100 m in diameter carrying 10^7 ampere-turns (central field 0.126 T, stored energy 5.6 MWh). For 200 MeV antiprotons the Størmer radius is 60 m; at the modelled peak flux of the belt the upper bound on the collection rate is 2.3 ng per year, the same order as the modelled natural replenishment of the belt. The annihilation energy of this harvest (0.41 MJ) would feed a 50 kW spacecraft load for about 8 s, so the collected antimatter cannot power the ship; power comes from 1000 m² of solar arrays (408 kW) and propulsion from ion engines (18 N). An Earth gravity assist gives at most about 7.7 km/s per pass. A pass at the 9.86 solar radii reached by Parker Solar Probe implies 192 km/s, 647 kW/m² and a shield temperature near 1600 K, while plasma heating is negligible; however, the Sun is not an antiproton source, so such a pass serves the Oberth manoeuvre rather than collection. The value of the concept lies in supplying antiprotons for antihydrogen and fundamental-physics experiments. All numbers are calculations or published values, not measurements.

Keywords Antiproton · Radiation belt · Magnetic collector · High-temperature superconductor · Gravity assist · Parker Solar Probe

1 Introduction

Antiprotons are at present obtained only at accelerator laboratories, where multi-GeV protons strike a fixed target; worldwide output is of the order of nanograms per year and the energy efficiency of the process is extremely low [1]. This paper approaches the same problem from the opposite side: instead of producing antiprotons, collect those that nature produces.

The idea has observational support. In 2011 the PAMELA experiment detected, for the first time, antiprotons trapped in Earth's inner radiation belt [2]. It also has theoretical support: Bickford and co-workers studied, for the NASA Institute for Advanced Concepts, the collection of antiprotons in planetary magnetic fields with a magnetic scoop [1, 3]. The contribution of this work is to re-size the ANKA-M ship for this purpose, to compute the collection rate with an independent and conservative method, to quantify explicitly how long the ship could run on the collected antimatter, and to include an Earth gravity assist and a close solar pass in the design.

Three working hypotheses behind the original concept are tested by calculation: (i) the Sun can be approached as closely as Parker Solar Probe did, and the tenuous plasma will not harm the ship; (ii) near the Sun, solar arrays are a powerful energy source; (iii) the Sun is the source of the antimatter at the planets, and more antimatter is collected closer to the Sun. The first two are confirmed with conditions; the third is corrected because it is not compatible with measurements and published models (Sect. 3.4).

2 Methods

All quantities are obtained from closed-form relations stated with each result: magnetic rigidity and the Størmer length for the collection cross-section (Sect. 4.2), flux times area for the collection rate (Sect. 5.1), the mass–energy relation for the energy equivalent (Sect. 5.2), the hyperbolic-flyby relations for the gravity assist (Sect. 5.4), and two-body orbital mechanics and radiative equilibrium for the solar pass (Sect. 5.5). Source fluxes and

stocks are taken from the PAMELA measurement [2] and from the model of Bickford [1, 3]; they are identified as measured or modelled wherever they are used. The calculations were coded in Python; the script, an independent verification script that re-derives the key numbers by a second route (for example, the hoop tension of the ring from the numerical derivative of the stored magnetic energy), and the results file are provided as Online Resource 1. The three-dimensional figures were rendered with Blender (Cycles) from a parametric geometric model of the design. They are engineering visualisations of the concept and were not produced by a generative image model; Earth and the star field in them are background only. A large language model (Claude, Anthropic) was used under the author's direction for the literature search, for writing the calculation and modelling scripts and for page layout. The author defined the concept and the design, reviewed the results and is responsible for the content.

3 Where is antimatter found?

3.1 Earth's antiproton belt

When galactic cosmic rays strike nuclei in the upper atmosphere, antineutron–neutron and antiproton–proton pairs are produced. A small fraction of the antineutrons that escape upward decay inside the magnetosphere into antiprotons, which become trapped between magnetic field lines. This is the counterpart of the cosmic-ray albedo neutron decay (CRAND) process that feeds the trapped protons [2, 4].

PAMELA, at 350–610 km altitude on a 70° orbit, counted 28 trapped antiprotons inside the South Atlantic Anomaly in the kinetic-energy range 60–750 MeV. The measured flux is about a thousand times the interplanetary cosmic-ray antiproton flux and is the most abundant source of antiprotons near Earth [2]. In Bickford's model the belt holds about 160 ng of antiprotons in total, is replenished at about 2 ng/yr, has a peak flux of about 3800 m^{-2} s^{-1} above 10 MeV on the $L \approx 1.4$ shell (about 2500 km altitude at the equator), and peaks in energy near 200 MeV [1]. These model values are not measurements; PAMELA measured only the tail in low orbit.

3.2 Giant planets

In the same model the largest source is Saturn: cosmic-ray interactions in the rings inject about 240 µg of antiprotons per year into the magnetosphere; the trapped stock is about 10 µg. About 7 µg/yr and a 6 µg stock are predicted for Jupiter [1, 3]. These values have not been measured directly.

3.3 Galactic cosmic rays

In interplanetary space the antiproton flux is low; AMS-02 and PAMELA have measured it in detail in the GeV region [5, 6]. Bickford gives a peak value of about 3 m^{-2} s^{-1} [1]. This flux is further reduced in the inner Solar System by the magnetic field carried by the solar wind (solar modulation) [7].

3.4 Is the Sun a source of antiprotons?

No. Antiproton production needs several GeV in a single collision; particles accelerated by the Sun are not energetic enough, and the Bickford report excludes the Sun as an external source of the antiproton belt [1]. The antiprotons in planetary belts originate not from the Sun but from galactic cosmic rays arriving from outside the Solar System [1, 2].

The Sun does produce positrons, but they cannot be collected. The RHESSI satellite resolved the 511 keV annihilation line in the flare of 23 July 2002 [8, 9]; according to NASA's announcement about half a kilogram of antimatter was created in that single flare [10]. The observed radiation, however, is the evidence that the positrons annihilated in the solar atmosphere: the antimatter is consumed where it is made and does not reach a spacecraft.

Together these facts mean that approaching the Sun does not increase antiproton collection; it reduces it, because the galactic flux decreases. The benefit of a close solar pass, as shown in Sect. 5.5, lies in power and orbital mechanics.

4 Ship design

Figures 1–6 show the complete ship: a labelled overview (Fig. 1), realistic three-dimensional views from four directions (Fig. 2), close-up views (Fig. 3) and three orthographic views (Figs. 4–6). Figures 7–10 show the four main units from four directions each. Numbers in round brackets in the text are the numbers on the figures. In the design the Sun is in the +x direction; the collection ring lies in the x–y plane and the spine runs along the z axis.

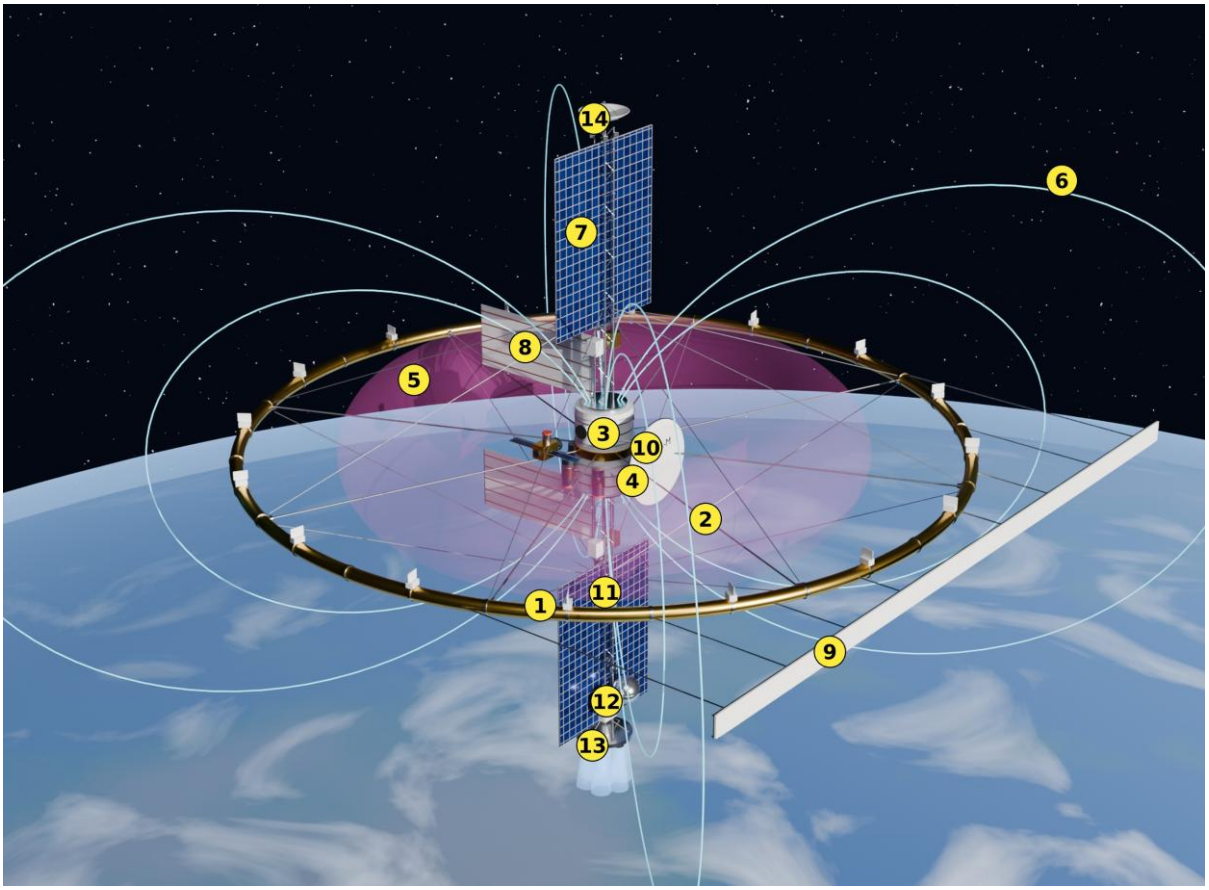


Fig. 1 Overview of ANKA-M/MAC. Ring thickness, cable and field-line diameters are exaggerated for visibility; the pink cloud and blue lines are schematic. Key: 1 HTS collection ring (Ø 100 m, 10^7 A-turns); 2 Tension cables (8); 3 Central hub: cryogenic body; 4 Exchangeable Penning-trap cassettes (6); 5 Trapped antiproton cloud (artificial belt, schematic); 6 Magnetic field lines (schematic); 7 Solar arrays (2 × 500 m²); 8 Radiators; 9 Ring sunshade strip (104 × 3 m); 10 Hub sun shield (Ø 12 m); 11 Truss spine (90 m); 12 Xenon tanks (4); 13 Ion-engine cluster (7); 14 High-gain antenna

4.1 General layout

The ship is uncrewed. From the central hub (3) eight tension cables (2) run to the 100 m collection ring (1). The 90 m truss spine (11) on the ring axis carries, at its two ends, the solar arrays (7), radiators (8), antenna (14) and the propulsion module (12, 13). The ring is kept edge-on to the Sun, so that the narrow sunward profile is shaded by a 104 m × 3 m shade strip (9). The hub is protected by a separate shield (10).

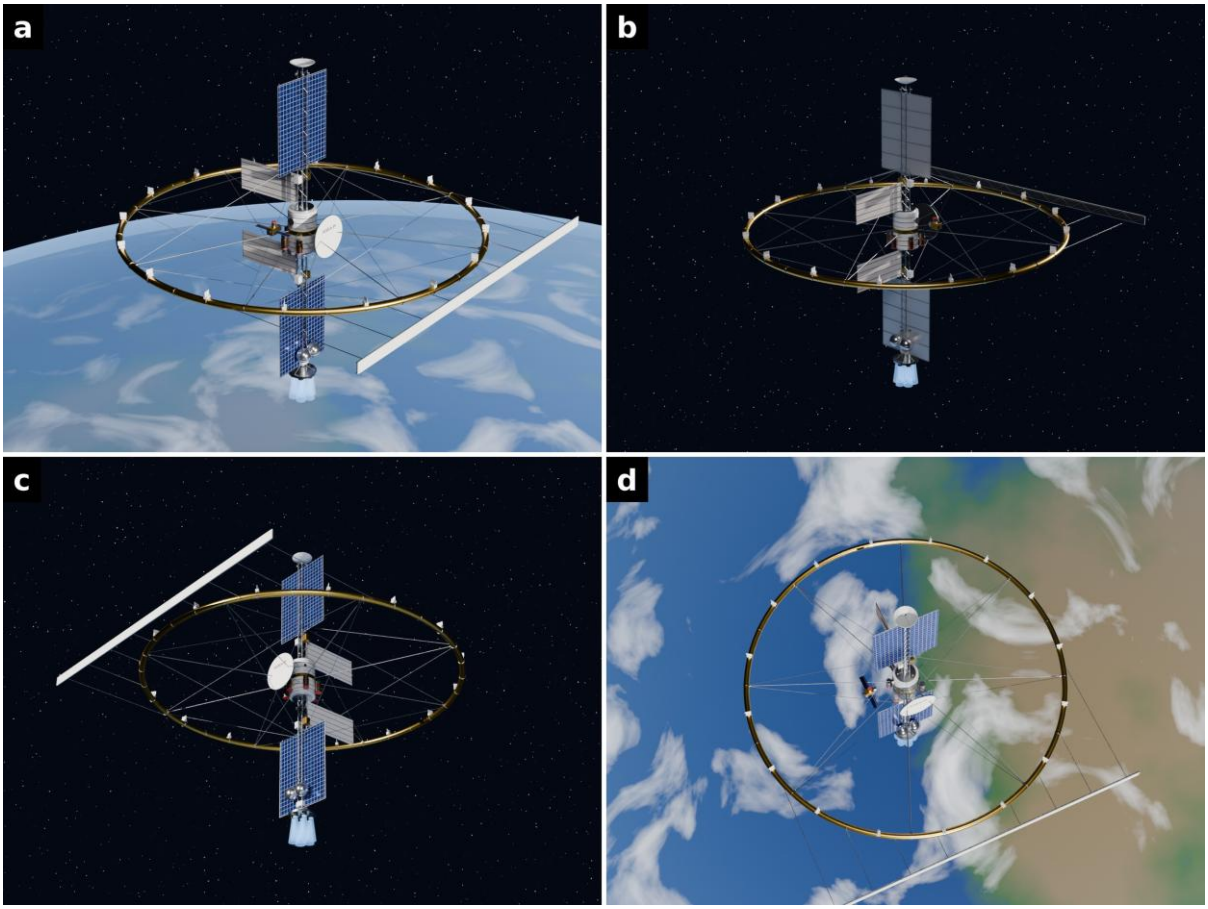


Fig. 2 Realistic three-dimensional views of the complete ship from four directions: a from the sunward side and above, with Earth's limb behind; b from the anti-sunward side; c from below; d from above, with Earth behind. The schematic field lines and antiproton cloud are not shown in these images; Earth and the stars are background only

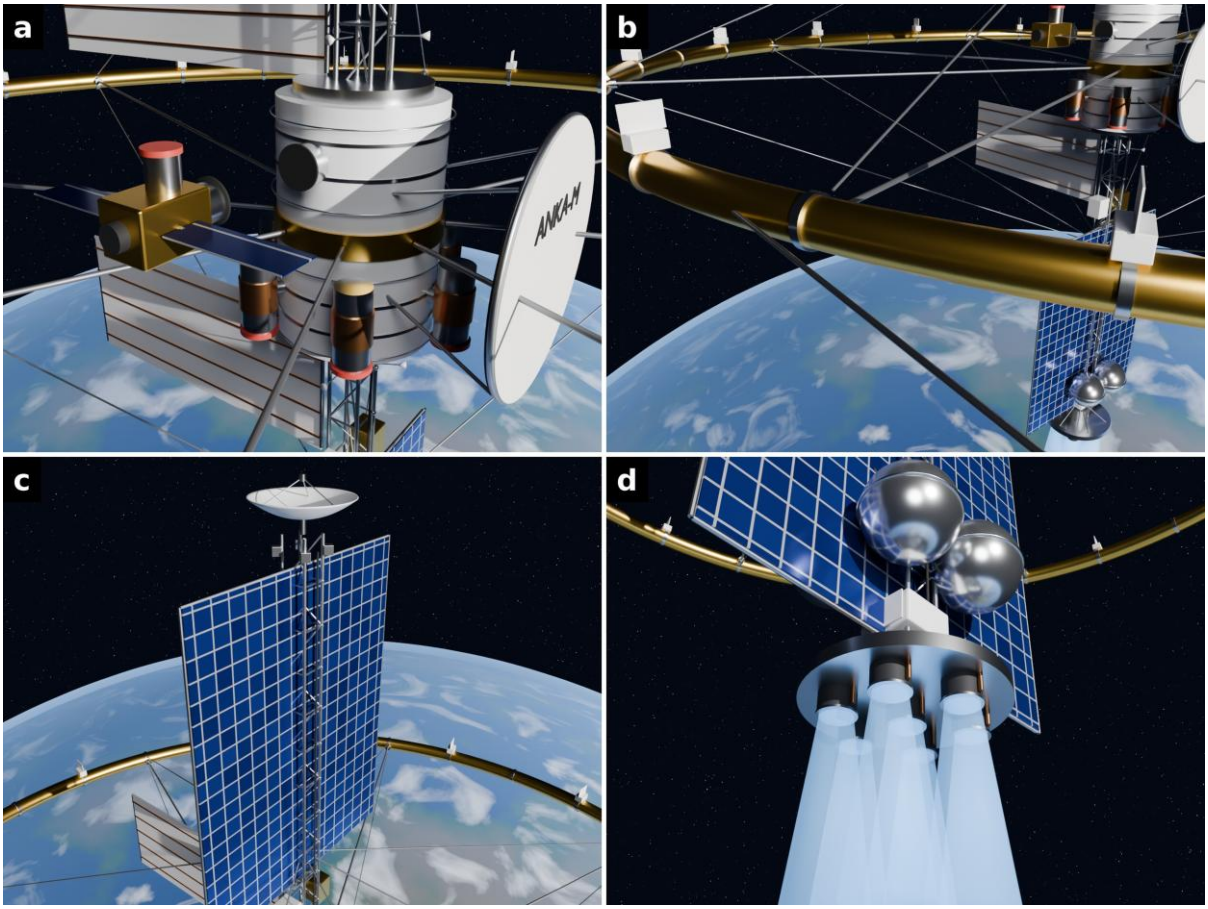


Fig. 3 Close-up realistic views: a central hub, trap cassettes and the cassette carrier vehicle approaching the docking port, b a section of the collection ring with flanges, cryocoolers and tension cables, c solar-array wing and high-gain antenna, d ion-engine cluster in operation and xenon tanks. Earth and the stars are background only

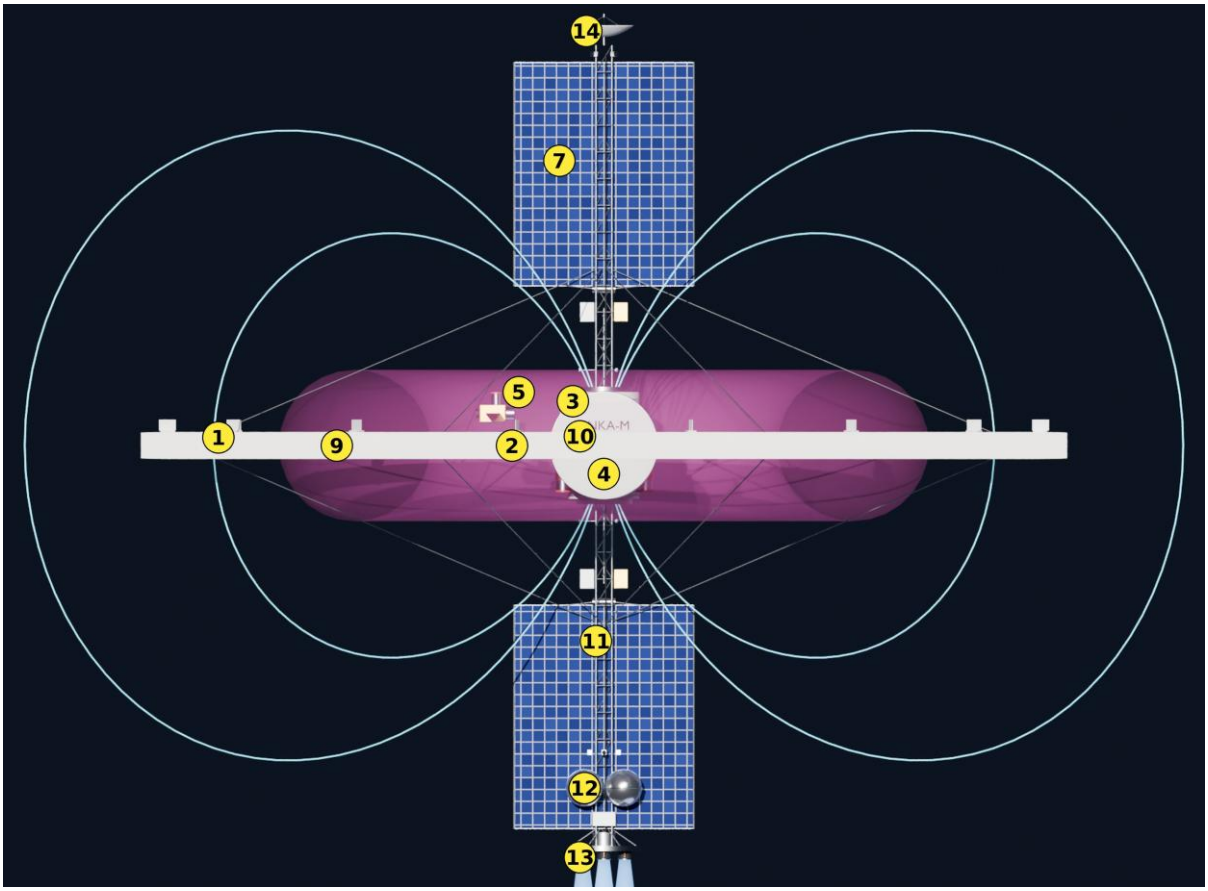


Fig. 4 View from the Sun direction (front), orthographic. Key: 1 HTS collection ring (Ø 100 m, 10^7 A-turns); 2 Tension cables (8); 3 Central hub: cryogenic body; 4 Exchangeable Penning-trap cassettes (6); 5 Trapped antiproton cloud (artificial belt, schematic); 7 Solar arrays (2 × 500 m²); 9 Ring sunshade strip (104 × 3 m); 10 Hub sun shield (Ø 12 m); 11 Truss spine (90 m); 12 Xenon tanks (4); 13 Ion-engine cluster (7); 14 High-gain antenna

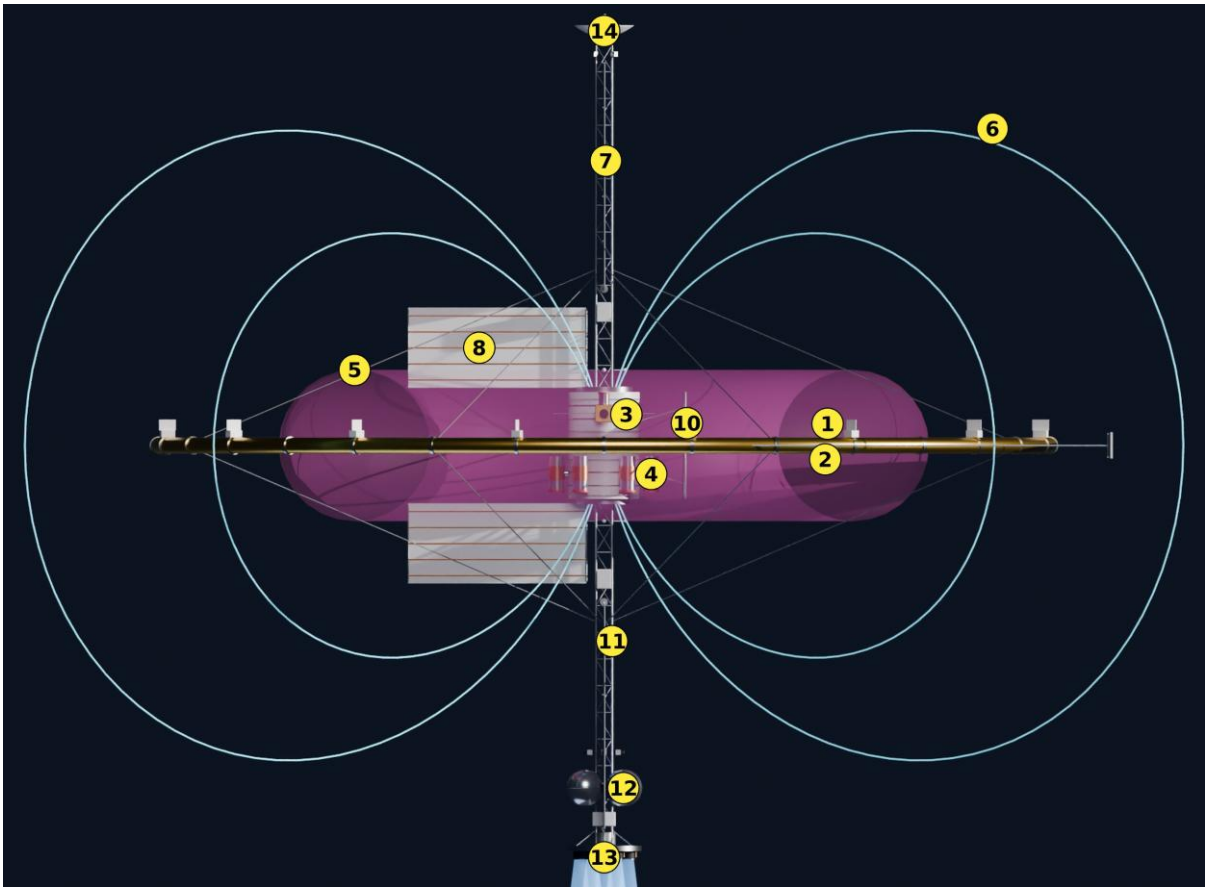


Fig. 5 Side view, orthographic: spine, solar arrays, radiators and propulsion module. Key: 1 HTS collection ring (Ø 100 m, 10^7 A-turns); 2 Tension cables (8); 3 Central hub: cryogenic body; 4 Exchangeable Penning-trap cassettes (6); 5 Trapped antiproton cloud (artificial belt, schematic); 6 Magnetic field lines (schematic); 7 Solar arrays (2 × 500 m²); 8 Radiators; 10 Hub sun shield (Ø 12 m); 11 Truss spine (90 m); 12 Xenon tanks (4); 13 Ion-engine cluster (7); 14 High-gain antenna

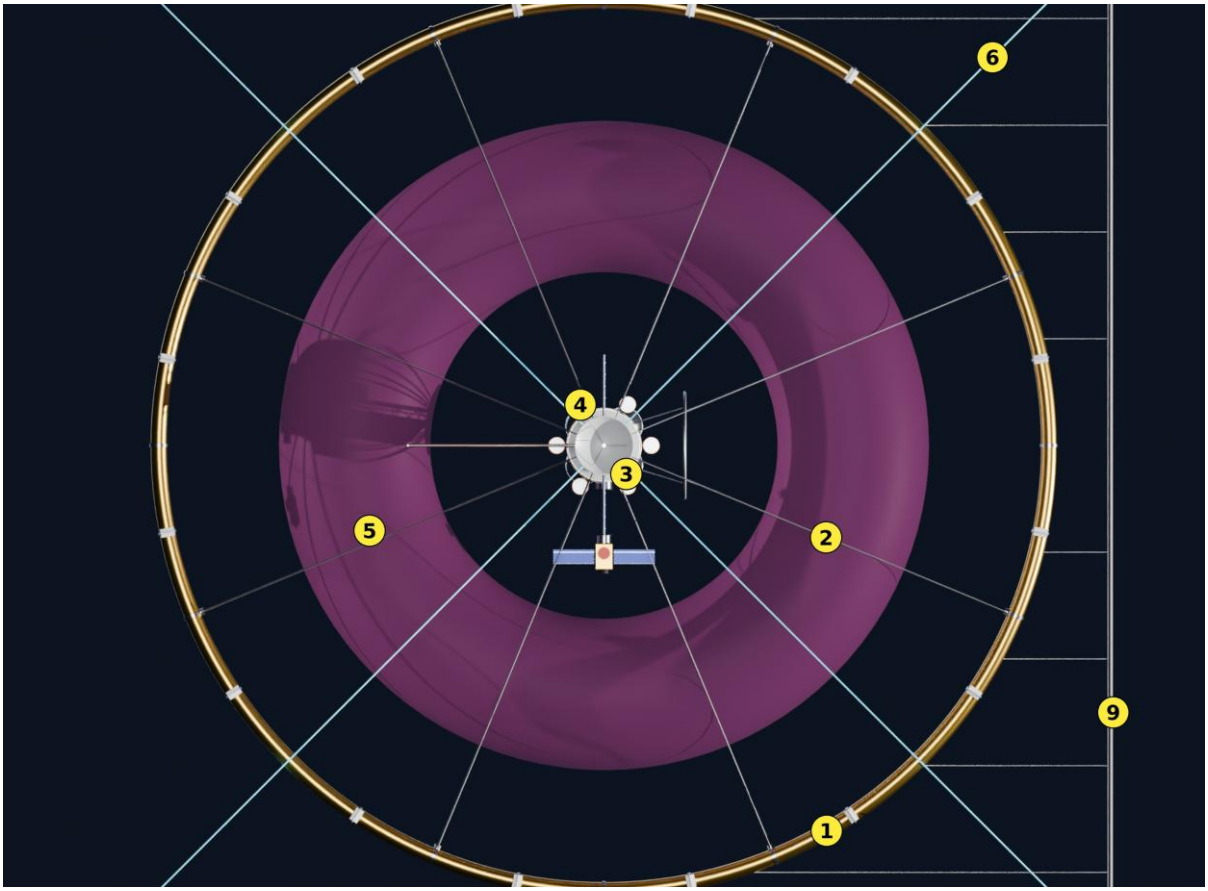


Fig. 6 Top view, orthographic: collection ring, tension cables, cryocoolers and shade strip. Key: 1 HTS collection ring (Ø 100 m, 10^7 A-turns); 2 Tension cables (8); 3 Central hub: cryogenic body; 4 Exchangeable Penning-trap cassettes (6); 5 Trapped antiproton cloud (artificial belt, schematic); 6 Magnetic field lines (schematic); 9 Ring sunshade strip (104 × 3 m)

4.2 Collection ring

How hard a charged particle is to bend in a magnetic field is set by its magnetic rigidity Bρ:

$$B\rho = \frac{p}{e}, \quad B\rho\,[T\,m] = 3.3356\,p\,[GeV/c], \quad p = \sqrt{T^2 + 2Tm_pc^2} \tag{1}$$

At 200 MeV, the peak energy of the belt, p = 644 MeV/c and Bρ = 2.15 T·m (1.14 at 60 MeV, 4.68 T·m at 750 MeV). The scale over which a dipole of magnetic moment m can deflect such particles is the Størmer length [11]:

$$r_{St} = \sqrt{\frac{\mu_0}{4\pi}\frac{m}{B\rho}}, \quad m = N\,I\,\pi\,R^2 \tag{2}$$

A ring radius R = 50 m and a total current N·I = 10^7 ampere-turns are chosen. Then m = 7.9×10^{10} A·m², the central field is B = $\mu_0 NI/2R$ = 0.126 T and r_{St} = 60 m at 200 MeV (83 m at 60 MeV, 41 m at 750 MeV). At the centre the gyroradius of a 200 MeV antiproton is 17 m, i.e. it stays inside the ring. A weaker ring (for example 10^5 A) cannot hold these particles; this is why the Bickford design relies on inflating the field with plasma [1, 12]. No plasma assistance is assumed here; only the ring's own field is counted.

The conductor is REBCO tape; assuming an engineering current density of 400 A/mm² (at 20–30 K and low field; consistent with values demonstrated in high-field magnets [13]) the cross-section is 250 cm² and the conductor mass about 70 t. The stored magnetic energy is 2.0×10^{10} J (5.6 MWh) and the force trying to stretch the ring is 7.4×10^7 N. A carbon-fibre casing carrying this force at an allowable stress of 1.5 GPa has a mass of about 25 t. This agrees with the lower bound obtained from the stored magnetic energy by the virial theorem (≈ 21 t); the

heaviest part of the ring is the conductor. Earth's field (about 1.15×10^{-5} T at 2500 km) exerts a torque of up to 9.0×10^{5} N·m on the ring; this torque aligns the ring axis with the local field line and can be used for attitude control.

From outside to inside the ring consists of (Fig. 7): multilayer insulation (16), carbon-fibre structural casing (15), 50 K thermal shield (17), 20 K cold mass (23), REBCO conductor bundle (18) and helium cooling channel (19). Sixteen cryocoolers (20) are distributed along the ring, and the ring is built from 32 segments joined at flanges (30).

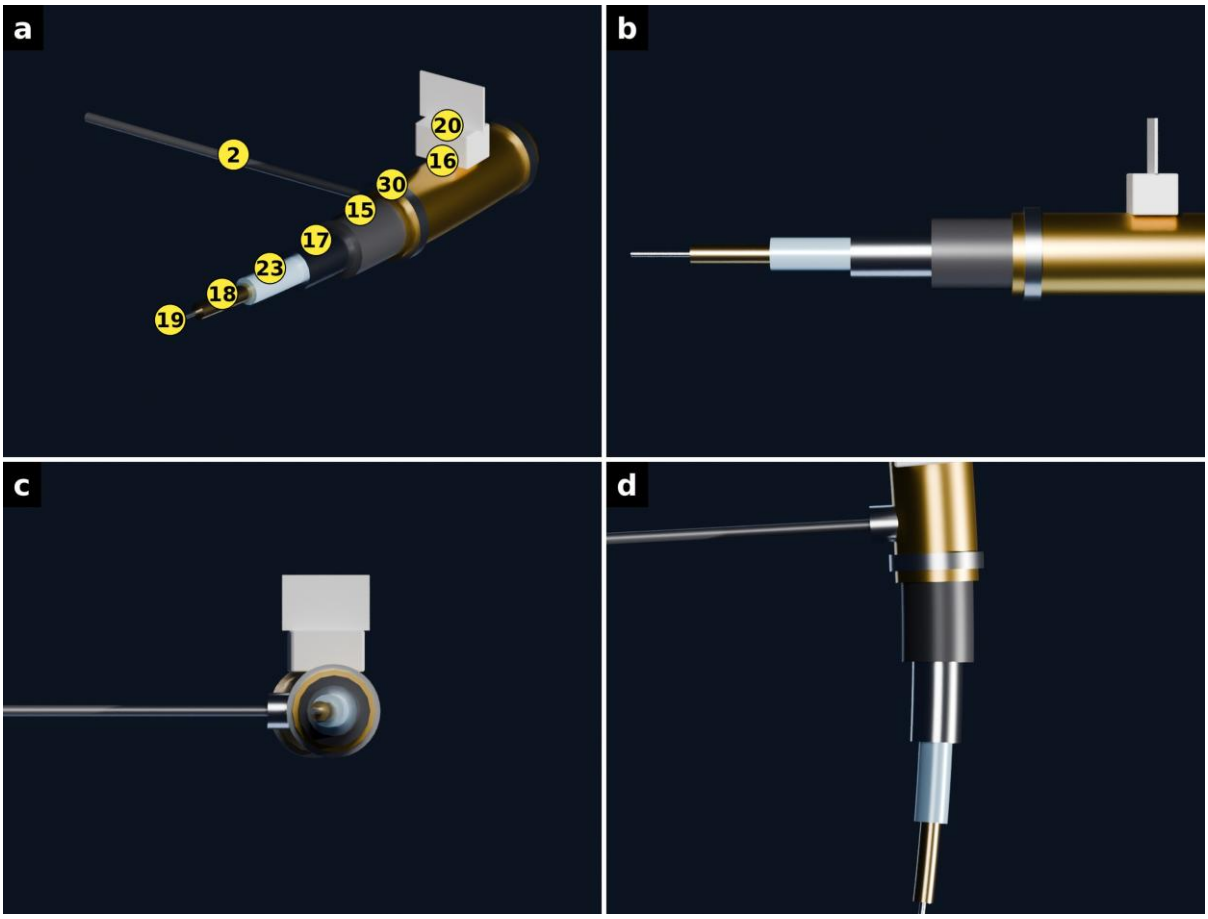


Fig. 7 Cross-section unit of the collection ring, from four directions. The layers are shown with a stepped cutaway. a oblique view, b from the Sun direction, c side, d top. Key: 2 Tension cables (8); 15 Carbon-fibre structural casing; 16 Multilayer insulation (MLI); 17 50 K thermal shield; 18 REBCO conductor bundle; 19 Helium cooling channel; 20 Cryocooler; 23 20 K cold mass; 30 Ring segment flange

4.3 Hub, artificial belt and trap cassettes

The collected antiprotons are not slowed down; they keep circulating in the ring's own dipole field as an artificial radiation belt (5) surrounding the ship. This is the storage mode of the Bickford concept, for which a capacity of 110 ng is given for that design [1]. Because it is a dilute cloud in a large volume, the space-charge problem that limits small traps is not the governing limit here.

The six exchangeable Penning-trap cassettes (4) in the hub (3) serve to carry small samples to a laboratory. The capacity of a Penning trap is limited: the largest trap mentioned in the Bickford report holds about 10^{12} antiprotons (≈ 1 pg) [1]; the BASE experiment has kept antiprotons trapped for more than a year [14]. Transfer into cassettes requires slowing 200 MeV antiprotons to the keV level; the efficiency of that step is not calculated here and is an open item.

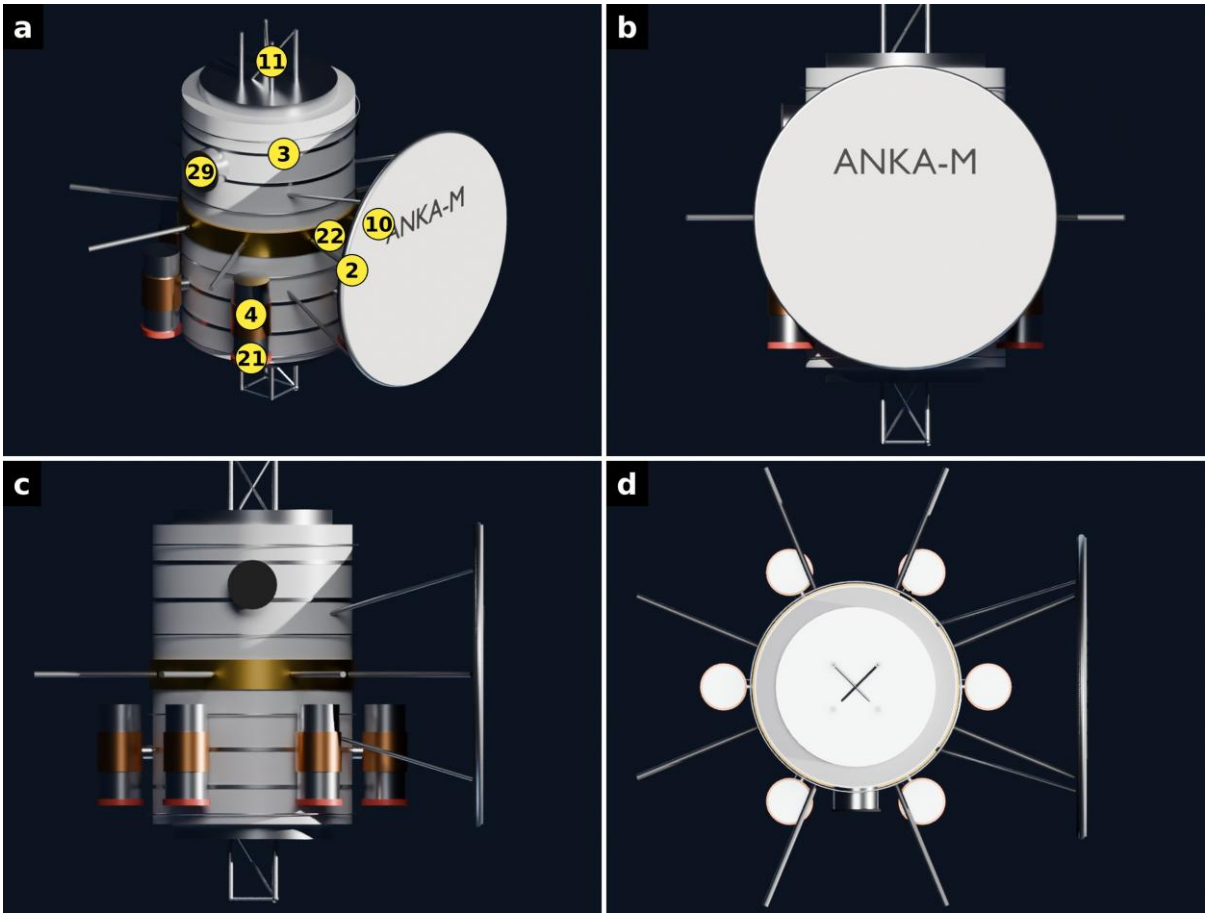


Fig. 8 Hub unit, from four directions: cryogenic body, trap cassettes, hub shield and cable attachments. a oblique view, b from the Sun direction, c side, d top. Key: 2 Tension cables (8); 3 Central hub: cryogenic body; 4 Exchangeable Penning-trap cassettes (6); 10 Hub sun shield (Ø 12 m); 11 Truss spine (90 m); 21 Cassette docking cap; 22 Cable attachment band; 29 Docking port

4.4 Power and thermal control

The 1000 m² of solar arrays (7) in two wings deliver 408 kW at 1 AU at 30 % efficiency. The cryocoolers, avionics and ion engines run on this power; batteries (25) cover eclipses. The radiators (8) are edge-on to the Sun. This power is about 8335 times the year-averaged power of the claimed annual harvest of the Bickford scoop (Fig. 12).

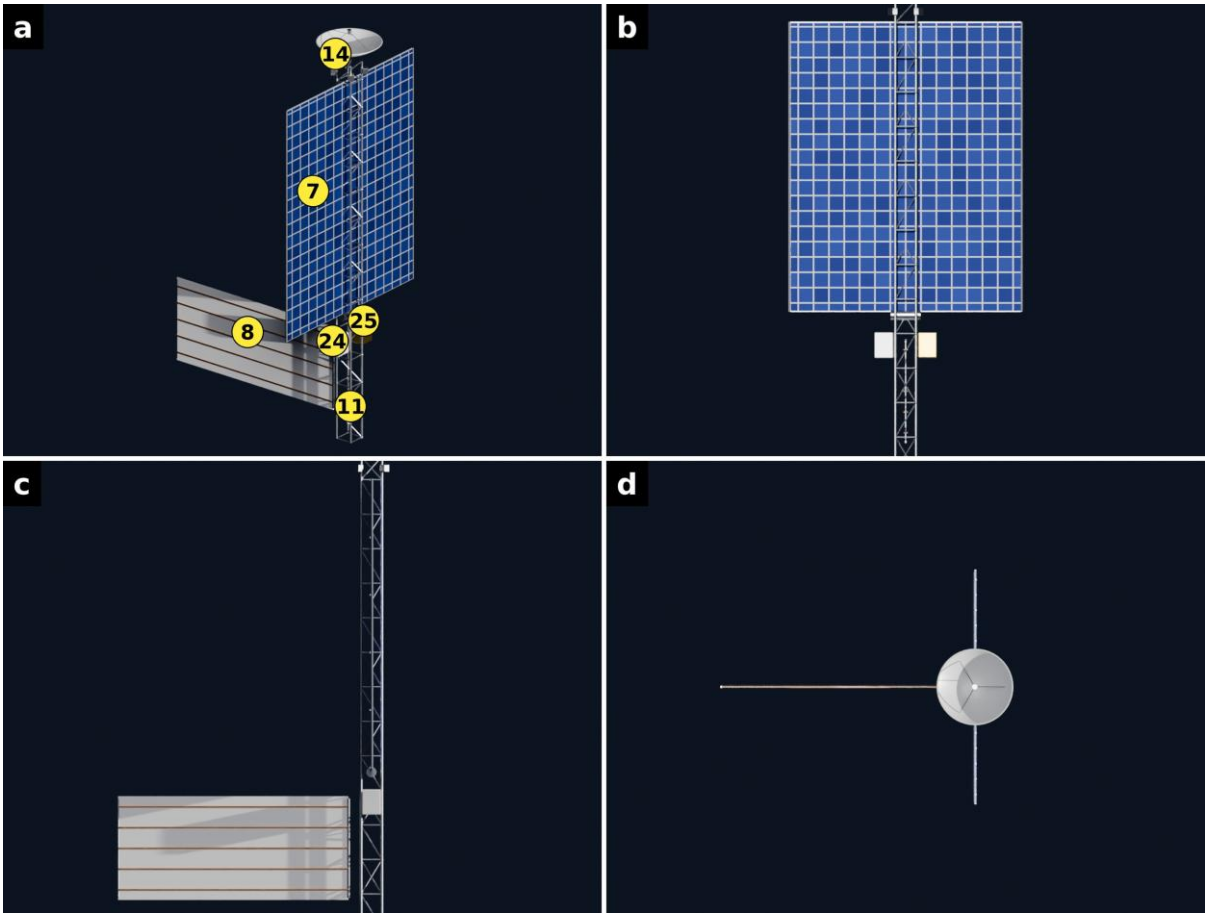


Fig. 9 Power and thermal unit, from four directions: solar-array wing, radiator, power conditioning (24), battery (25) and antenna. a oblique view, b from the Sun direction, c side, d top. Key: 7 Solar arrays (2 × 500 m²); 8 Radiators; 11 Truss spine (90 m); 14 High-gain antenna; 24 Power conditioning unit; 25 Battery

4.5 Propulsion

The seven gridded ion engines (13) are a scaled-up form of the technology proven on the Dawn spacecraft [15]. Assuming a specific impulse of 3000 s and a total efficiency of 65 %, the thrust is 18.0 N and the xenon consumption 53 kg per day. For the 265 t ship this means 2.15 km/s of velocity change and 19.4 t of xenon per year. The ship accelerates slowly but continuously.

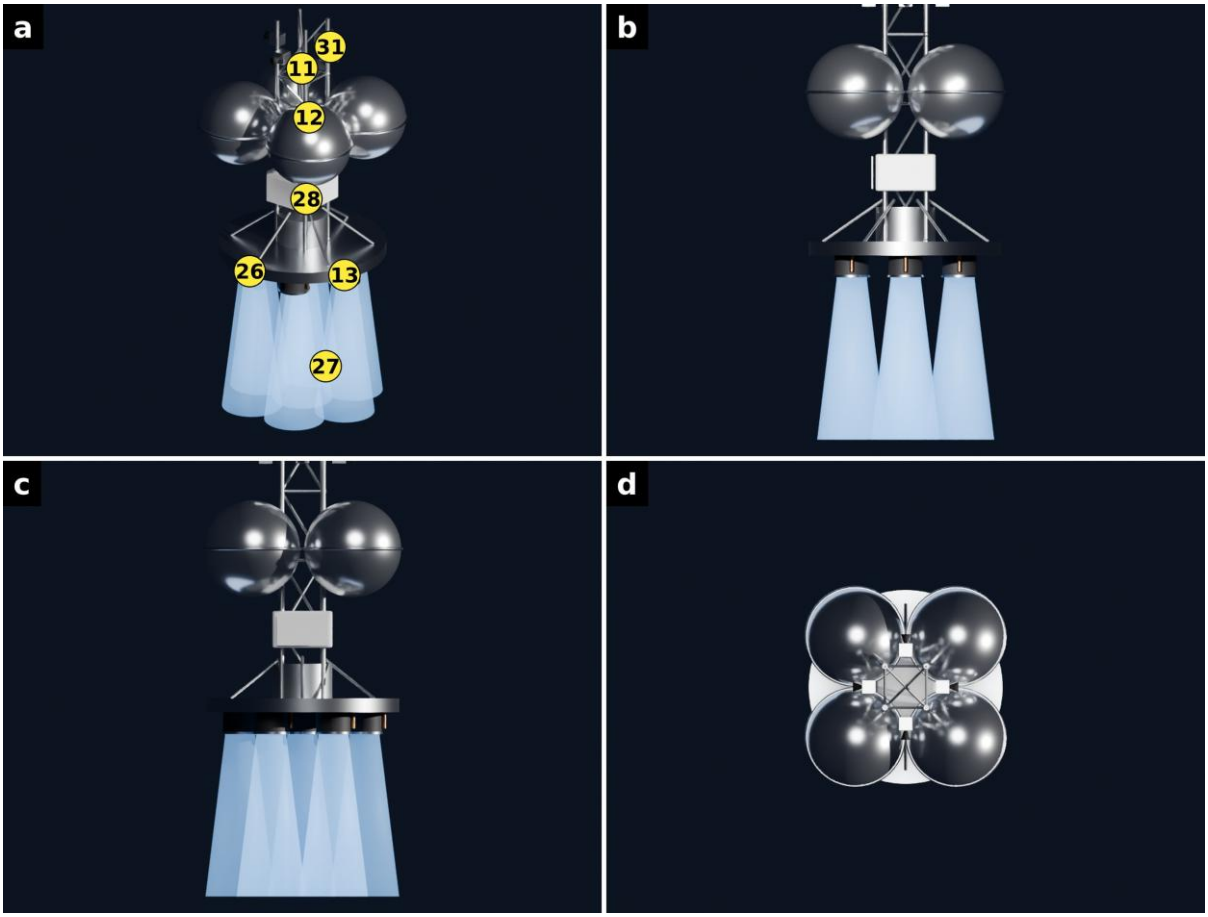


Fig. 10 Propulsion unit, from four directions: xenon tanks, power-processing unit (28), engine mounting plate (26), ion engines and ion beam (27). a oblique view, b from the Sun direction, c side, d top. Key: 11 Truss spine (90 m); 12 Xenon tanks (4); 13 Ion-engine cluster (7); 26 Engine mounting plate; 27 Ion beam; 28 Power-processing unit; 31 Attitude-control thrusters

Table 1 Mass budget (concept-level estimate)

Item	Mass (t)	Basis
Ring conductor (REBCO)	70	Calculation, 400 A/mm²
Ring structural casing (carbon fibre)	25	Calculation, 1.5 GPa
Cryogenics and shades	30	Assumption
Hub and trap cassettes	15	Assumption
Power system	20	Assumption
Propulsion system (dry)	15	Assumption
Xenon	60	≈ 3 years of consumption
Bus and margin	30	Assumption
Total	265	—

This mass requires several heavy launches and in-orbit assembly. The ring cannot be folded for launch; it has to be carried in segments and joined in orbit.

5 Calculations

5.1 Collection rate

A conservative upper bound on the collection rate is obtained by assuming that every antiproton crossing the Størmer disc is captured:

$$\dot{N} = F\,\pi\,r_{St}^2\,, \quad \dot{m} = \dot{N}\,m_p \tag{3}$$

The collection cross-section is $\pi \cdot r_{St}^2 = 1.15\times10^4$ m². With the modelled peak flux of the belt, F = 3800 m⁻² s⁻¹, $\dot{N}$ = 4.4×10^7 s⁻¹, i.e. 6.3 picograms per day and 2.3 nanograms per year (1.4×10^{15} antiprotons per year). For comparison, with a flux roughly derived from the spectrum PAMELA measured in low orbit (≈ 173 m⁻² s⁻¹; a mean of 20 m⁻² s⁻¹ sr⁻¹ GeV⁻¹ × 0.69 GeV × 4π, a rough integration made for this work) the rate falls to 0.11 ng per year, and with the galactic cosmic-ray flux alone (3 m⁻² s⁻¹) to 1.8 picograms per year.

Table 2 Collection scenarios

Scenario	Rate	Status
ANKA-M ring, belt peak flux	2.3 ng/yr	This work; upper bound, 100 % efficiency assumed
ANKA-M ring, PAMELA altitude	0.11 ng/yr	This work; rough flux integration
ANKA-M ring, galactic flux	1.8 pg/yr	This work
Natural replenishment of the belt	≈ 2 ng/yr	Bickford model [1]
Total stock of the belt	≈ 160 ng	Bickford model [1]
Bickford plasma-assisted scoop	25 ng/day (≈ 8.6 µg/yr)	Concept claim [1]; unverified
Saturn ring injection	≈ 240 µg/yr	Bickford model [1, 3]

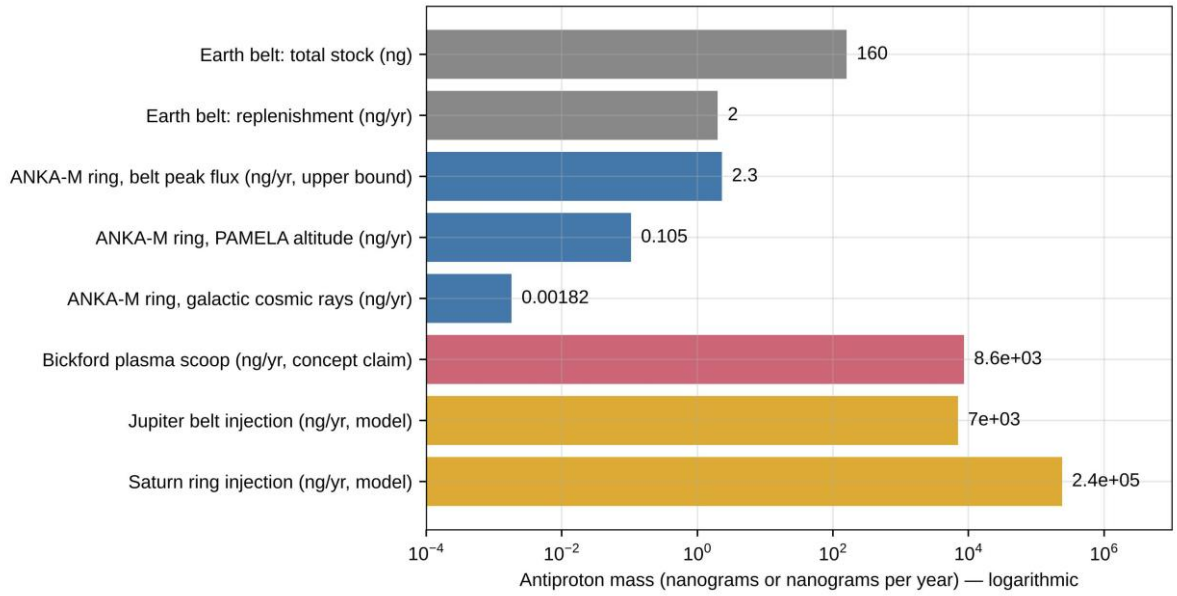


Fig. 11 Comparison of antiproton sources (logarithmic). Grey: Earth's belt (Bickford model); blue: ring calculation of this work; red: Bickford's plasma-assisted scoop claim; yellow: giant-planet models

Two points deserve attention. First, the ring's harvest is at the level of the belt's replenishment rate, so the ship can operate for a long time without exhausting the belt (the whole stock would last about 69 years at this rate). Second, the 25 ng/day figure in the Bickford report, read together with the report's own stock (160 ng) and replenishment (2 ng/yr) values, cannot be a sustainable rate; it would empty the belt in a week. It is given here only as an optimistic upper scenario.

5.2 How long does the collected antimatter run the ship?

When antiprotons of mass m annihilate with an equal mass of matter the energy released is

$$E = 2\,m\,c^2\,, \quad for\ 1\ ng\colon\ E = 2 \times 10^{-12}\ kg \times (2.998 \times 10^8\ m/s)^2 = 180\ kJ \tag{4}$$

Not all of this energy is usable; a large part of the annihilation products escapes as neutrinos and high-energy gamma rays. The durations below show the ideal case in which all the energy is turned into useful work and are therefore upper bounds.

Table 3 Energy equivalent of the collected antimatter (ideal upper bound)

Source	Energy	50 kW ship load	400 kW ion engine	Velocity gain (265 t)
ANKA-M, 1 yr (2.3 ng)	0.41 MJ (0.11 kWh)	8 s	1.0 s	1.8 m/s
Entire Earth belt (160 ng)	28.8 MJ (8.0 kWh)	9.6 min	72 s	15 m/s
Bickford scoop, 1 yr (8.6 µg)	1546 MJ (429 kWh)	8.6 h	1.1 h	108 m/s
Saturn injection, 1 yr (240 µg)	43.1 GJ (11983 kWh)	10.0 days	30 h	571 m/s

The conclusion is plain: the antimatter ANKA-M collects in a year runs the ship for seconds, and the whole of Earth's belt for minutes. Even if all of Saturn's annual injection could be collected the average power would be 1367 W; the solar arrays deliver hundreds of times that continuously. The collected antimatter cannot be the ship's fuel. The literature contains propulsion concepts in which nanograms of antiprotons trigger fission or fusion and release far more energy; the Bickford report relays the claim that 100 ng could drive a 1 t payload to 100 km/s [1]. In those concepts the energy comes from nuclear fuel, not from the antimatter, and none has been tested; they are not counted here.

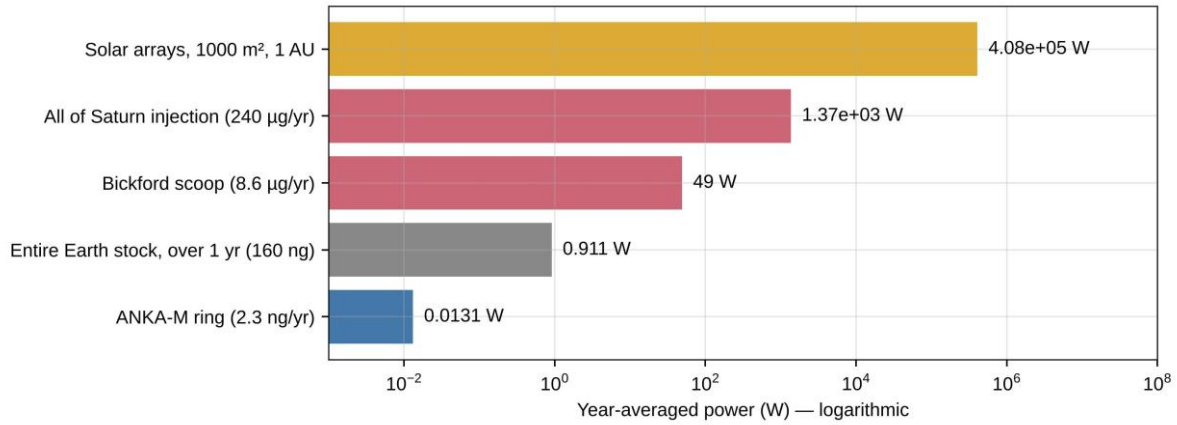


Fig. 12 Comparison of year-averaged power (logarithmic): solar arrays versus the ideal energy equivalent of the collected antimatter

5.3 The real value of the antimatter

One nanogram contains 6.0×10^{14} antiprotons. 2.3 ng per year is far above the quantities used by antihydrogen experiments and of the same order as annual production on Earth (Bickford's 2006 figure: about 10 ng per year [1]). ANKA-M is therefore meaningful not as an energy project but as an antiproton source: antiprotons carried in cassettes can be combined with a high-flux positron source (for a concept of such a source see [16]) to make antihydrogen.

5.4 Earth gravity assist

A vehicle passing a planet keeps the magnitude of its velocity relative to the planet but changes its direction; its velocity relative to the Sun rises or falls as a result [17]. For an approach speed v_∞ and closest-approach radius r_p the turn angle δ and the velocity change are

$$\sin\frac{\delta}{2} = \frac{1}{1 + \frac{r_p v_\infty^2}{\mu}}, \quad \Delta v = 2\, v_\infty \sin\frac{\delta}{2} \tag{5}$$

For Earth (μ = 398 600 km³/s², flyby at 300 km altitude) Δv = 5.2 km/s at v∞ = 3 km/s, 7.0 km/s at 5 km/s (turn 90°) and 7.5 km/s at 10 km/s. The maximum, ≈ 7.7 km/s, occurs at v∞ ≈ 7.7 km/s (Fig. 13a). Earth's speed around the Sun is 29.78 km/s; the slingshot transfers part of it to the vehicle.

There is an important constraint: a vehicle leaving Earth cannot use an Earth slingshot while its speed relative to Earth is near zero. To benefit, it must first complete a loop around the Sun and return to Earth with a v∞. ANKA-M does this with its ion engines: a year of thrust slightly changes the orbit, and at the Earth encounter a year later the slingshot converts that difference into a direction change of several km/s. The same method can be repeated in combination with Venus flybys.

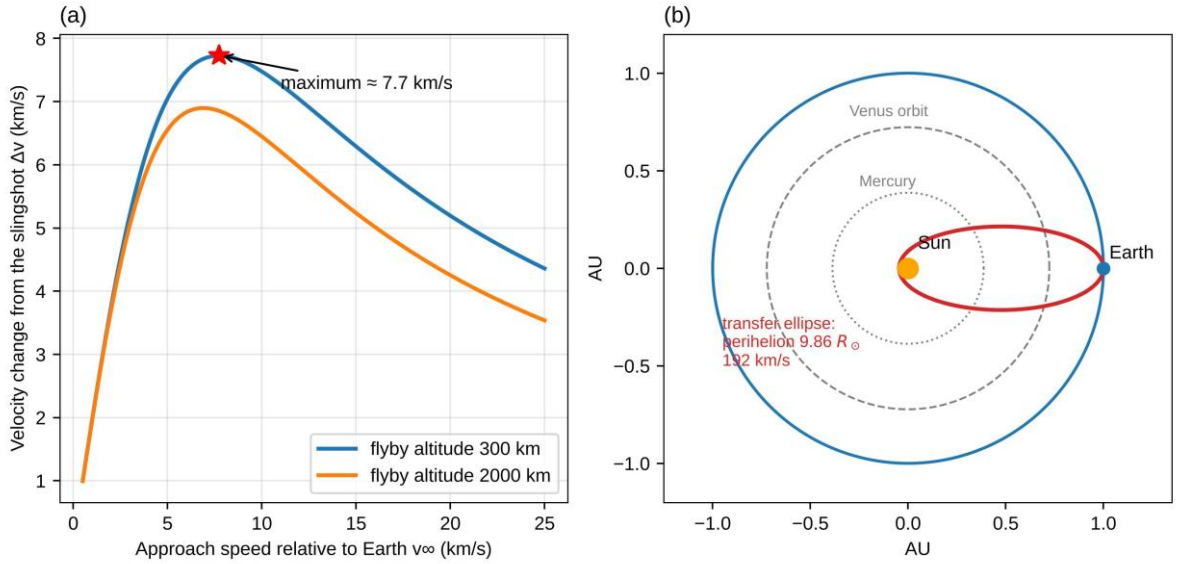


Fig. 13 a Velocity change gained in an Earth slingshot. b Transfer ellipse from 1 AU down to 9.86 solar radii (to scale)

5.5 Close solar pass

On 24 December 2024 Parker Solar Probe came within 9.86 solar radii of the Sun's centre, about 6.1 million km from the surface, and reached about 191–192 km/s [18, 19]. For an ellipse with aphelion at 1 AU and perihelion at this distance (0.0459 AU) the calculation gives: perihelion speed 192.3 km/s, aphelion speed 8.82 km/s, descent time from Earth to perihelion 69 days. Since Earth's speed is 29.78 km/s the vehicle must be slowed by 21.0 km/s relative to Earth; done directly from low Earth orbit this costs 15.9 km/s. Parker Solar Probe closed this gap with seven Venus flybys [18]. The route is the same for ANKA-M: a combination of ion thrust with Venus and Earth slingshots; an Earth slingshot alone is not enough.

Thermal environment: at 9.86 solar radii the solar flux is 647 kW/m², 476 times that at Earth. The front equilibrium temperature of a shield with an insulated back and an absorptance-to-emittance ratio of 0.6 is T = (α·S / ε·σ)^¼ ≈ 1618 K (1345 °C), consistent with the design value of the Parker shield (about 1400 °C) [18, 19]. This hypothesis is therefore confirmed: approaching to this limit is demonstrated technology.

Tenuous plasma: assuming a density of 10^4 cm^{-3}, a temperature of 10^6 K and a relative speed of 400 km/s (illustrative, upper-range values for the coronal region Parker has entered [20]) the heat flux carried by the plasma is only ≈ 0.7 W/m², 1×10^{-6} of the sunlight. The second hypothesis is also confirmed: the corona is very hot but so tenuous that almost all the heat load comes from radiation.

The real difficulty is the size of the ship. Parker's shield is 2.3 m in diameter [18]; ANKA-M's 104 m × 3 m shade strip must intercept 202 MW at perihelion and the hub shield 51 MW. The ring behind the shade has to be held at 20 K. This is beyond present technology. Solar arrays have a limit too: Parker's arrays are largely retracted into shadow at perihelion and cooled by pumped fluid [18, 19]. If 5 suns (≈ 0.45 AU) is taken as a reasonable limit for uncooled arrays, the flux at 0.30 AU is 15.1 kW/m² and arrays can work only tilted and with active cooling. Energy is abundant near the Sun, but to use it the heat has to be rejected.

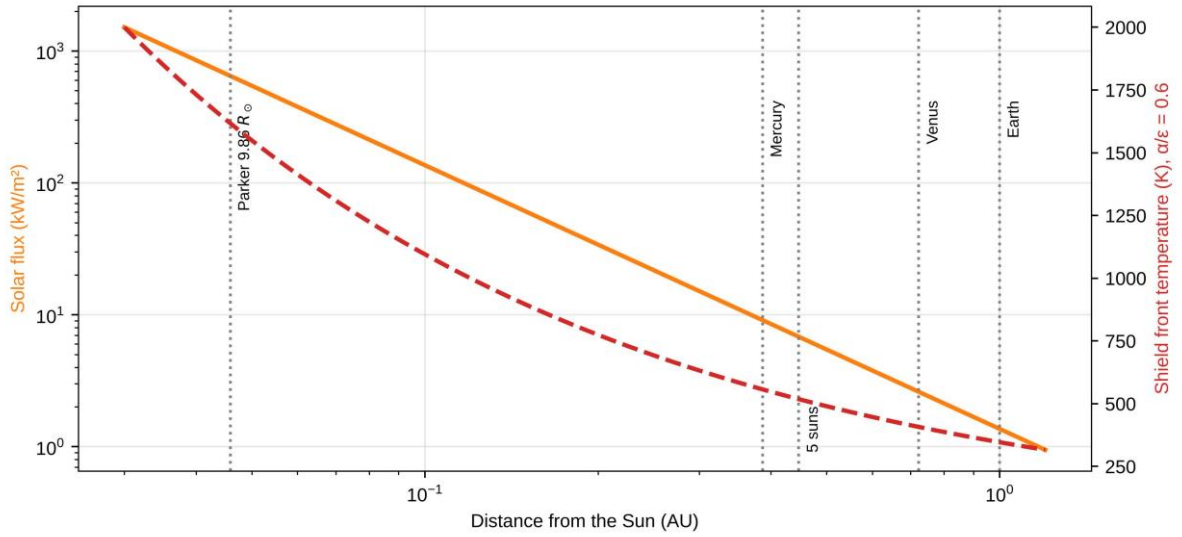


Fig. 14 Solar flux and shield front temperature versus distance from the Sun

Oberth manoeuvre: burning propellant at perihelion is most effective because the orbital energy gained is proportional to speed. A 1 km/s impulse at perihelion raises the aphelion from 1 AU to 1.31 AU; with 4.4 km/s the vehicle reaches solar escape speed (196.7 km/s); with 10 km/s it leaves the Solar System at 47 km/s. This gain is available only to engines that deliver large thrust in a short time (chemical or nuclear thermal); ion engines cannot deliver meaningful impulse in the few hours spent at perihelion.

6 Mission plan

- Assembly: the ring and spine are joined in low Earth orbit over several launches; the magnet is cooled and energised.
- Orbit raising: the ion engines take the ship to a 1500 km × 3500 km collection orbit in the equatorial plane (the orbit proposed by Bickford [1]; period ≈ 139 minutes).
- Collection: over several years the ring accumulates antiprotons in its artificial belt (upper bound 2.3 ng per year).
- Transfer: samples are loaded into trap cassettes and taken by a carrier to a laboratory or to an antihydrogen station in orbit.
- Second phase (optional): with ion thrust and Earth–Venus slingshots the ship travels to the outer Solar System, to Saturn, the richest source according to the model.
- Close solar pass (optional): with the ring removed or de-energised, used with a high-thrust stage for an Oberth manoeuvre; it serves no collection purpose.

7 Discussion

7.1 Hypotheses confirmed and corrected

Table 4 Working hypotheses compared with the calculations

Hypothesis	Outcome	Reason
The Parker limit can be approached	Correct (demonstrated for a small craft)	Shield ≈ 1618 K; Parker achieved it [18, 19]. For a 100 m ship the shade load is 202 MW
Tenuous plasma does no harm	Correct	Plasma heat flux ≈ 0.7 W/m²
Solar arrays are a powerful energy source	Correct, with a thermal limit	408 kW at 1 AU; cooling needed closer in
The Sun is the source of planetary antimatter	Corrected	The source is galactic cosmic rays [1, 2]

Hypothesis	Outcome	Reason
More antimatter is collected closer to the Sun	Corrected	The Sun makes no antiprotons [1]; positrons annihilate in place [8–10]; the galactic flux decreases [7]
The collected antimatter runs the ship	Corrected	A year's harvest equals 8 seconds of ship load

7.2 Limitations and open items

- The belt flux, stock and replenishment values are model results; PAMELA measured only the tail at 350–610 km.
- The collection rate is an upper bound: every antiproton crossing the Størmer disc is assumed to be stably trapped; no particle tracking was done.
- The ring also collects the far more abundant trapped protons; separation of the antiprotons and stability of the artificial belt have not been studied.
- Radiation in the inner belt degrades the superconductor, arrays and electronics; no lifetime estimate was made.
- A space magnet 100 m in diameter with 10^7 ampere-turns has never been built; cooling, quench safety and in-orbit assembly are open items.
- The efficiency of slowing 200 MeV antiprotons for transfer into cassettes is unknown.
- Cost is not evaluated.

8 Conclusion

Re-designed as a magnetospheric antiproton collector, ANKA-M targets a measured source. With its own field alone, the 100 m superconducting ring can collect at most 2.3 ng of antiprotons per year from Earth's belt, the same level as the belt's natural replenishment and the scale of production on Earth. This quantity is not an energy source for the ship; the ship runs on solar power and ion thrust. An Earth slingshot gives at most ≈ 7.7 km/s per pass and must be used together with ion thrust. Approaching the Sun to the Parker limit is thermally demonstrated and valuable for the Oberth manoeuvre, but it does not increase antimatter collection. The defensible value of the project is that it offers a natural source of antiprotons for antihydrogen and fundamental physics.

Declarations

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Competing interests The author has filed a patent application with the Turkish Patent and Trademark Office (TÜRKPATENT, application no. 2026/011037) for a ground-based antimatter production system that is not the subject of this article, and is the owner of HB ZECHMANN Company. The author declares no other competing interests.

Data availability The calculation script, the verification script and the results file that support the findings are provided as Online Resource 1. No measured data were generated.

Author contributions H.B. conceived the concept, planned the study, designed the spacecraft, and reviewed and approved the manuscript. The literature search, the calculations and the page layout were carried out with the assistance of an artificial-intelligence tool, as described in Sect. 2.

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