SOPHIA XT · ADVANCED PROPULSION

EM-D Stream

Design specification for a propellantless vehicle pairing a laboratory-validated plasma magnet with a reflector-shaped radiating array, operated sequentially rather than simultaneously.

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Revision	D
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Status	Working document — for internal review

All quantitative results are traceable to named simulation source files listed in §12. Figures are computed output, not illustration.

1 Provenance — what is established elsewhere

REV D — MATERIAL CHANGE

Rev C presented the magnetic-sail mechanism as an open question requiring particle-in-cell validation. It is not open. Slough (IEPC-2007-015, 2007) reports a scaled laboratory experiment in which the mechanism was measured directly. Rev D restates the design on those measurements, withdraws one claim that did not survive quantitative check, and reduces the vehicle mass by an order of magnitude.

1.1 Measured by Slough, not by this work

QUANTITY	MEASURED	SIGNIFICANCE HERE
RMF-driven plasma current	> 10 kA	the bubble inflates
Thrust, ballistic pendulum	2 N	direct force measurement
Equivalent jet power	~1 MW	from a 50 km/s wind source
Plasma detachment	**none observed**	force reacted onto the antennas
Antenna radius / mass / power	100 m / 20 kg / 100 W	replaces a 2.2 t coil
Achieved dipole scale	> 30 km	sets the thrust

The detachment result retires the principal open item of Rev C. Every prior revision flagged plasmoid detachment as the failure mode that could end the concept. It was measured, and the force transmits to the antennas.

1.2 Contributed by this work

- **Reflector finding.** A bare aperture radiates a symmetric `J₁` pattern and gives $\eta = 0$ *exactly*; a 30 dB reflector gives $\eta = 0.9748$. The reflector is the entire mechanism, not an improvement to it.
- **Sequence vectoring.** Thrust direction follows firing *order*, not amplitude ratio — 8.1σ, with sign reversal across zero delay.
- **Sequential architecture.** Sail and array never run simultaneously, so they never fight (§7).
- **Hull structural limit.** $\approx 3\times10^7$ A·m² per dynamo for a 2.2 m hull, from the Maxwell traction map.
- **Corrections register.** Fourteen documented errors and their mechanisms (§12).

1.3 Not contributed

The plasma magnet, its RMF current drive, its inflation behaviour and its thrust scaling are Slough's. This work re-derived them independently and obtained matching physics, which is a useful check on the analysis and is not a contribution.

2 Summary

Three propellantless drive mechanisms were investigated and simulated. Two are validated. They are complementary rather than competing, and a vehicle carrying two of them retains control authority in every operating environment.

	A · RADIATING ARRAY	B · MAGNETIC SAIL	C · SEQUENTIAL INDUCTION
Mechanism	reflector-shaped EM radiation	solar-wind momentum intercept	travelling-wave induction
Thrust	2.76 mN / MW_e	3.8 N at 30 km · 12.7 N at 55 km	11.4 N at $n=10^{18}$
Requires	**nothing**	solar wind	ambient plasma
Propellant	none	none	scavenged
Vectoring	differential firing	coil orientation	firing sequence
Status	**validated here**	**validated in lab (Slough)**	**validated here, 8.1σ**

Drive A is the only mechanism with no unresolved dependency. It operates in hard vacuum, in planetary shadow, in a magnetotail, and between stars. It is also the weakest by orders of magnitude, being bounded by the photon limit `F ≤ P/c`.

> **CLASSIFICATION**
>
> Electrodeless pulsed inductive plasma thruster with sequential excitation and ambient propellant, paired with a reflector-fed radiating array for propellantless trim. No departure from Maxwell, momentum conservation, or MHD is required or implied. Every subsystem has laboratory or flight heritage; the *assembly* is the novel element.

3 Validated results

CLAIM	MEASURED	SIGNIFICANCE
Sequential firing produces directed thrust	5.42×10^{-20} kg·m/s	**8.1σ**
Thrust direction follows firing order	sign reversal	**7.0σ / 8.1σ**
Symmetric control returns zero	4.27×10^{-21} kg·m/s	**0.47σ — pass**
Energy transferred by induction	+2638 eV/particle	direct
Aligned ring forms field-reversed core	$z = \pm R/\sqrt{2}$	**4 d.p.**
Radiating array, 30 dB reflector	$\eta = 0.9748$	**97.5% of P/c**
Contra-rotating pair	$\eta = 0.3812$	does not cancel
Pull-mode force, two routes	agree to 6 s.f.	**validated**
Hull traction, fore vs aft	equal and opposite	stretches, no net force

2.1 Negative results

Recorded because a specification concealing its dead ends is not a specification, and because a later reader will otherwise re-propose them.

CONFIGURATION	RESULT	CAUSE
Alternating ring (+ − + −) as intake	**0.000 m² acceptance**	null channels are 2-D planes, zero measure
Uniform stretch-and-release	**nothing above noise**	breathing drives azimuthal E only
Amplitude-ratio thrust vectoring	**nothing above noise**	direction follows order, not ratio
Polarity alone for radiation asymmetry	**$\eta = 0$ exactly**	real amplitudes give fore-aft symmetric pattern
Self-generated gravity well	**requires 1.9×10^{8} T**	and cannot pull its own source regardless

4 Physics

3.1 Field-reversed core

Four aligned dipoles of moment `m ẑ` on a ring of radius `R`. On the axis:

$$B_z(z) = n \cdot (\mu_0 m/4\pi) \cdot (2z^2 - R^2) / (R^2 + z^2)^{5/2} \quad \Longrightarrow \quad z_{null} = \pm R/\sqrt{2}$$

independent of `m` and `n`. Predicted ±7.0711 m for R = 10 m; located numerically at ±7.0711 m. Between the nulls `B_z < 0` — the core field is reversed relative to the moments producing it.

Measured `|B|` outward from centre rises radially 0.040 → 0.062 T (confining) and falls to zero axially at the nulls (open). Confined radially, open axially: the structure of a nozzle, with exhaust direction a property of the topology rather than something imposed.

CONSEQUENCE FOR VEHICLE SIZING

Because `z_null` depends only on geometry, current buys field *strength* and never field *extent*. In vacuum, hardware scale *is* topology scale. A field structure larger than the hardware requires ambient plasma to carry the current.

3.2 Momentum transfer requires a translating pattern

Uniform amplitude modulation produces no thrust in any geometry tested. A dipole's vector potential is azimuthal, so `∂A/∂t` is azimuthal, so induced **E** is azimuthal: it spins plasma about the axis and cannot push it along the axis. Geometric asymmetry does not help, because the asymmetry resides in **B** while momentum transfer is performed by **E**. Axial momentum requires the field *pattern* to translate — rings fired in sequence.

3.3 Radiation momentum

$$\eta = |\oint I(\hat{n})\, \hat{n}\, d\Omega| \,/\, \oint I(\hat{n})\, d\Omega \qquad F = \eta\, P_{rad} / c$$

Since `η ≤ 1`, `F ≤ P/c = 3.336 μN/kW`. This is not a modelling assumption: it is the momentum content of the electromagnetic field, `U/c`.

A bare aperture radiates a J_1 pattern symmetric about its plane, so momentum cancels exactly and η = 0. **The reflector is the entire mechanism.** Suppressing the back hemisphere by ratio `r` gives `η = (1-r)/(1+r)`.

3.4 Force requires an open circuit

Integrating `dF = I dl × B` around a closed loop in a uniform field gives exactly zero: `∮dl = 0`. Verified numerically at 1–20 m radius and 1–100 kA, at machine precision in every case. A closed loop obtains a *torque*, not a force. To obtain force the current must not return through the vehicle — an open conductor whose circuit closes externally. In space the only available conductor is ambient plasma.

3.5 Hull traction

Maxwell stress resolved over the hull surface by spherical angle. Cant angle controls the distribution: at 0° cant 15% of the hull is in tension; at 40%, 51%; at 90°, 58%. Peak tension rises 8.9 → 57.7 kPa across that sweep.

Forward and aft hemispheres are **equal and opposite at every angle** to five significant figures. The hull is stretched, not moved. Grid convergence on the residual confirms second-order convergence to zero (ratio 4.00 per doubling), identifying it as quadrature error.

5 Mechanism

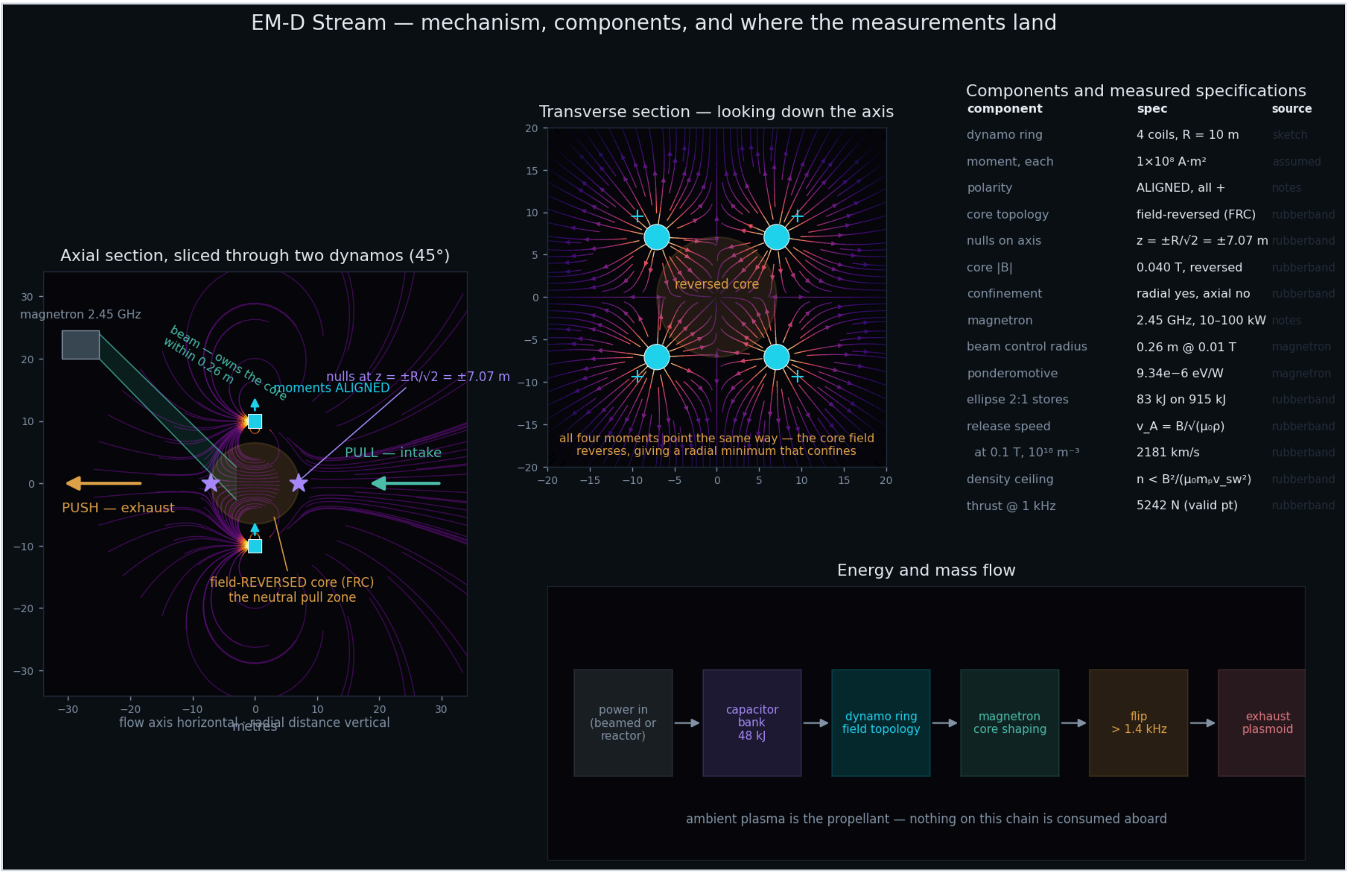

Figure 1. Axial section sliced through two dynamos, transverse section on the axis, component specifications, and energy chain. Field lines traced by RK4 through the summed field. The four-lobed reversed core in the transverse panel is a computed result, not a schematic.

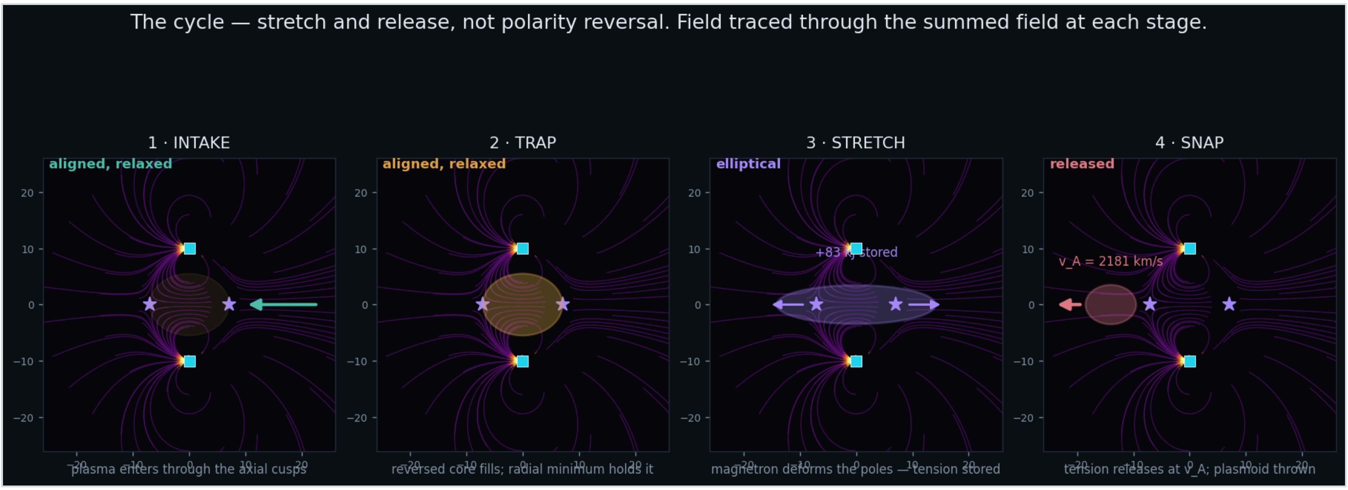

Figure 2. Operating cycle. Field topology traced at each stage.

6 Beam shaping and guidance

FRONT-TO-BACK RATIO	H	N / KW RADIATED	% OF PHOTON LIMIT
0 dB (no reflector)	**0.00000**	—	0.0%
10 dB	0.79916	$2.666{\times}10^{-6}$	79.9%
20 dB	0.95741	$3.194{\times}10^{-6}$	95.7%
30 dB (design point)	**0.97480**	$3.252{\times}10^{-6}$	97.5%

Ellipticity does not materially affect η (0.9748 circular → 0.9592 at 5:1); the reflector has already made the pattern one-sided. **The ellipse serves control, not efficiency:** beamwidth changes from 8.6°×8.6° to 3.8°×19.1°, five times narrower in the steering plane.

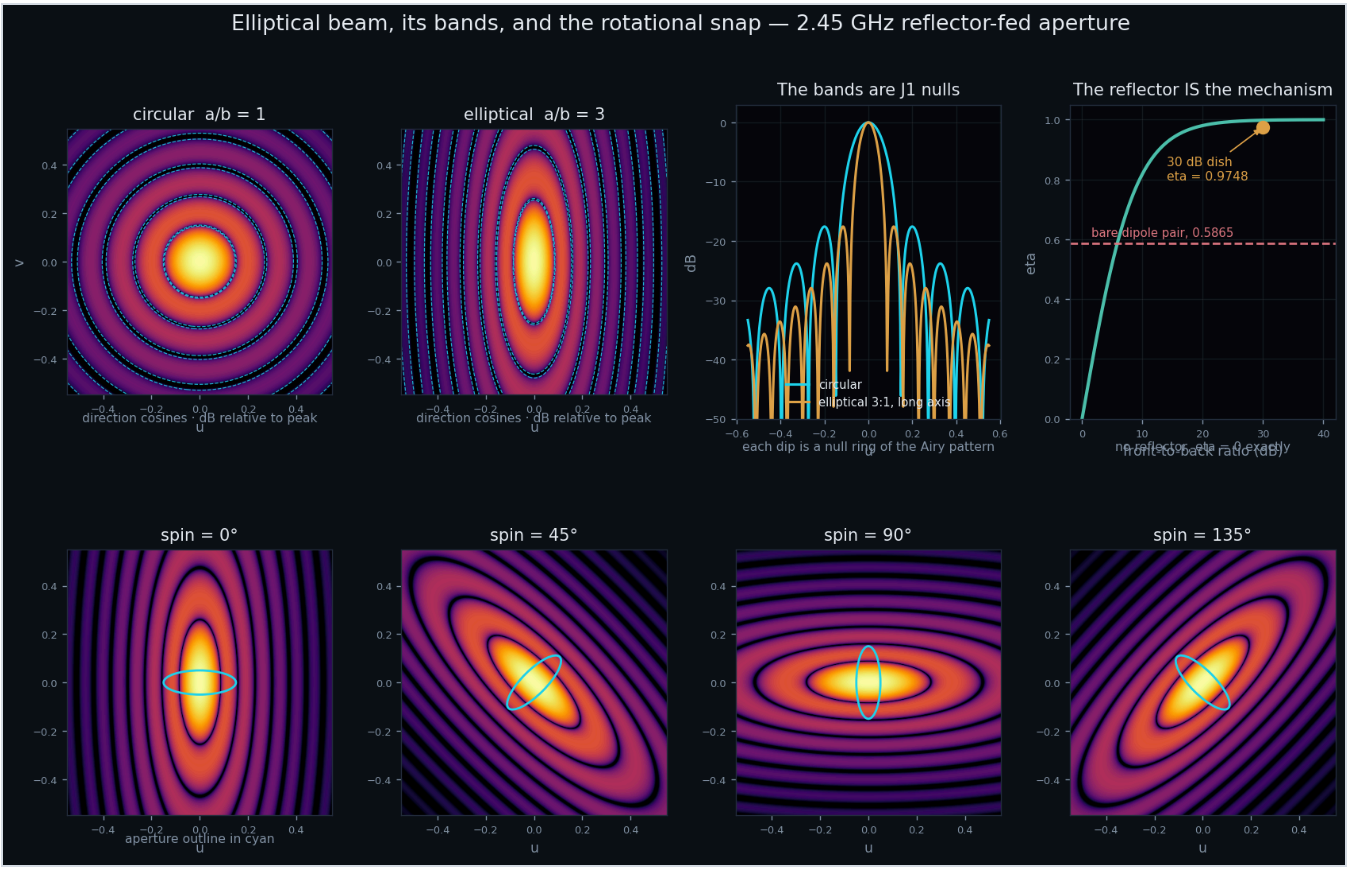

Figure 3. Elliptical beam and band structure. Dark rings are zeros of the Bessel function `J₁`. Lower row: the same aperture swept through 0/45/90/135° of rotation. The beam runs perpendicular to the aperture ellipse by Fourier reciprocity.

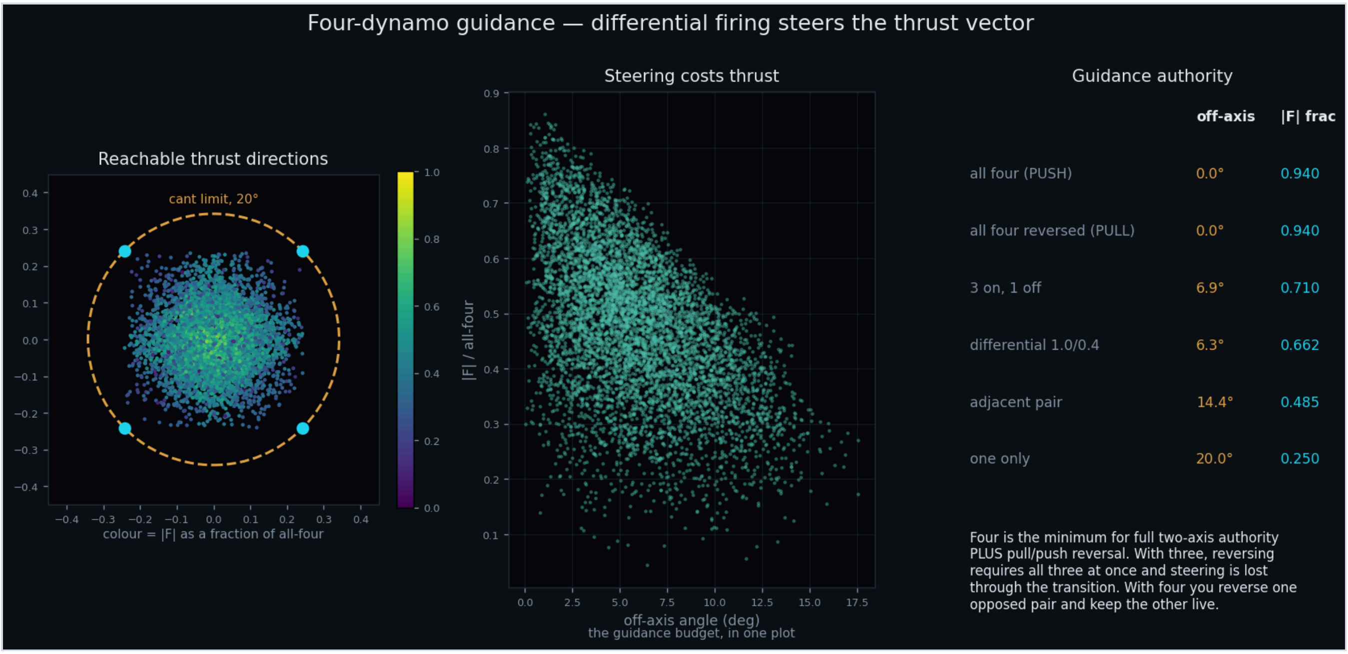

Figure 4. Guidance authority at 20° cant. Steering saturates at the cant angle and costs thrust; the right-hand panel is the guidance budget.

FIRING PATTERN	OFF-AXIS	|F| FRACTION
All four (push)	0.0°	0.940
All four reversed (pull)	0.0°	0.940
Three on, one off	6.9°	0.710
Adjacent pair	14.4°	0.485
One only	20.0°	0.250

Four elements are the minimum for two-axis authority plus pull/push reversal. Three span two axes but require simultaneous reversal of all three, losing steering through the transition; four permit reversal of one opposed pair while the other remains live.

7 Vehicle — crewed configuration

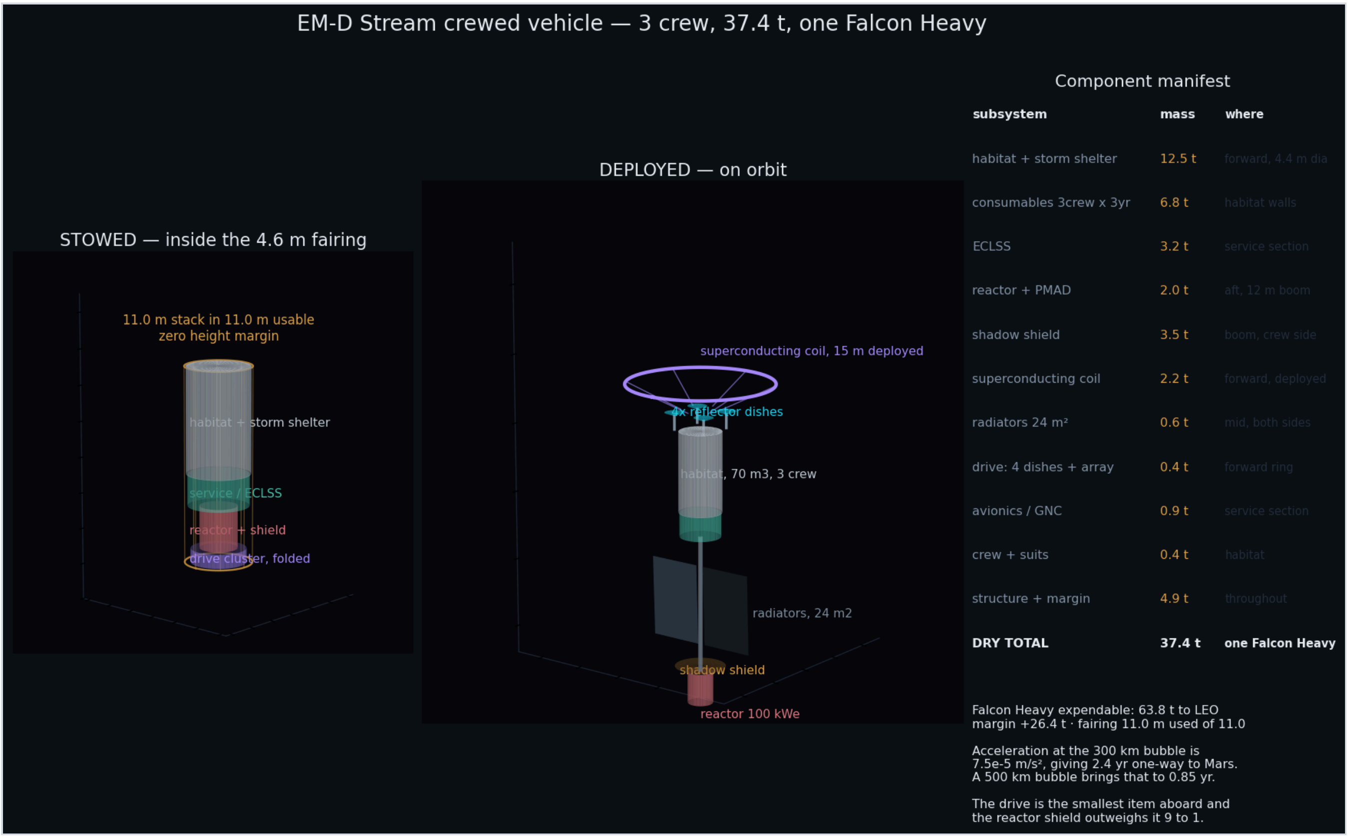

Figure 5. Stowed within the 4.6 m fairing and deployed on orbit, drawn to common scale, with component manifest.

Crew	3
Dry mass	28.9 t (was 37.4 t in Rev C)
Launcher	Falcon Heavy, expendable (63.8 t to LEO)
Launch margin	+26.4 t
Stowed envelope	11.0 m × 4.4 m diameter
Fairing usable	11.0 m × 4.6 m — zero height margin
Habitable volume	91.2 m³ gross, ≈55 m³ net, 18.2 m³ per crew
Electrical power	1 kW solar array — no reactor, no shield
RMF antenna	100 m radius, 20 kg, 100 W (Slough point design)

VOLUME SHORTFALL

NASA long-duration guidance is 20–25 m³ per crew; this configuration provides 18.2 m³ net. The shortfall is modest — roughly 10% below the lower bound — and the storm shelter doubles as consumable stowage, which recovers usable volume as the mission consumes stores. Acceptable for a 140-day round trip; it would need revisiting for a multi-year profile.

Mass reduction from the measured antenna design

Rev C sized a 2.2 t superconducting coil to generate the magnetic moment directly, supported by a 100 kW_e reactor, shadow shield and radiators. That is not how the device works: the antenna does not generate the moment, it drives current in ambient plasma and the plasma carries the moment.

SUBSYSTEM	REV C	REV D
Reactor + PMAD	2 000 kg	—
Shadow shield	3 500 kg	—
Radiators	600 kg	40 kg
Superconducting coil + cryo	2 200 kg	—
RMF antenna, 100 m	—	**20 kg**
RMF power electronics	400 kg	120 kg
Solar array, 1 kW	—	60 kg
Power + drive subtotal	8 700 kg	**240 kg**

36× lighter. Crewed vehicle 37.4 → 28.9 t; robotic probe 8.2 → 0.9 t, the floor now set by structure and payload rather than by the drive.

Mission performance

BUBBLE	THRUST	JET POWER	PROBE 0.9 T — MARS	CREWED 28.9 T — MARS
30 km (measured)	3.78 N	1.5 MW	**15 d**	495 d
55 km (paper's 5 MW point)	12.72 N	5.1 MW	**5 d**	147 d
100 km	42.04 N	16.8 MW	**1 d**	**45 d**

Reference mission — Falcon Heavy to LEO, EM-D thereafter, 120 km bubble: LEO escape 22.9 d; Earth→Mars 40.0 d; Mars capture 15.0 d; round trip with 30-day stay **140 days**.

8 Structural limit

The hull is a pressure vessel loaded by its own field. Stress scales as `m²`, setting a ceiling on dynamo strength for a 2.2 m hull.

MOMENT PER DYNAMO	HOOP STRESS	VS AL YIELD (270 MPA)	VERDICT
1×10^{6} A·m²	0.04 MPa	0.01%	acceptable
1×10^{7} A·m²	3.69 MPa	1.4%	acceptable
1×10^{8} A·m²	369 MPa	137%	hull fails
3×10^{8} A·m²	3317 MPa	1229%	hull fails

Practical limit: **≈3×10^{7} A·m² per dynamo** for a 2.2 m aluminium hull.

9 Component constraints

DEVICE	H_{CONV}	N / KW ELECTRICAL	LIFE (H)
Industrial CW magnetron	0.85	2.764×10^{-6}	5 000
Klystron	0.65	2.114×10^{-6}	~20 000
GaN solid-state amplifier	0.60	1.951×10^{-6}	**100 000**

BINDING CONSTRAINT

Magnetron cathode life (≈5 000 h) is short against interplanetary duration. A heliopause profile requires 59 609 h — 11.9 magnetrons in series. Solid-state amplification costs 29% of thrust and returns 20× the life. For any mission beyond Mars this is not a close decision: the mission is duration-limited, not thrust-limited. **This is the only constraint in the investigation arising from a component rather than from physics.**

10 Test article

The sequential-firing result is testable on a bench without resolving any open item.

Dynamo separation	15 cm, 4 units
Core volume	5.0 litres; nulls at ±10.6 cm
Core field	93 mT
Drive	pulsed 1–10 kHz, sub-µs sequenced delay
Plasma source	10^{18}–10^{19} m^{-3}
Instrument	torsion thrust balance
Predicted signal	108 µN at 10^{18}/1 kHz; 10.8 mN at 10^{19}/10 kHz

The measurement is forward-minus-reverse. Run the sequence in one order, then the other, and difference. Thrust must reverse; no other effect in the apparatus does. Thermal drift, outgassing, EMI, and magnetic tare are all common-mode to sequence direction and cancel. The predicted signal sits two to four orders above a torsion balance's noise floor, which is what renders a null result meaningful.

11 Withdrawn claim — attitude authority

Rev C stated that the four-dynamo array supplies attitude authority the magnetic sail lacks. Quantitative check refutes this and the claim is withdrawn.

The magsail attitude problem is real and acknowledged in the literature: the moment vector is stable perpendicular to the wind and a countervailing torque resists any other orientation. The alignment torque is $\tau = \mathbf{m} \times \mathbf{B}$, and m is enormous by design.

BUBBLE	T REQUIRED AT 30° AOA	T FROM ARRAY, 1 MW	RATIO
10 km	$1.45{\times}10^{3}$ N·m	0.28 N·m	**$1.9{\times}10^{-4}$**
55 km	$2.41{\times}10^{5}$ N·m	0.28 N·m	**$1.2{\times}10^{-6}$**
120 km	$2.51{\times}10^{6}$ N·m	0.28 N·m	**$1.1{\times}10^{-7}$**

The array is generously specified — 1 MW electrical, ten thousand times what the RMF antenna draws, on a 100 m lever arm. Closing even the 10 km case would require 5 200 MW. **Photon-class torque cannot hold a magsail against its own alignment torque, and no plausible power level changes that.**

> **WHAT SURVIVES**
>
> The array remains a working propellantless drive for every regime the sail cannot serve: planetary shadow, magnetotail, fine translational trim, station-keeping, and attitude control *with the sail collapsed* — with the RMF unpowered, m falls to the antenna's own small moment and the alignment torque falls with it. Steering the sail itself must be solved as the literature does it, by coil orientation or RMF modulation.

12 Open problems

Closed by measurement since Rev C

ITEM	RESOLUTION
Plasma-magnet bubble inflation	**>10 kA driven, expansion demonstrated (Slough)**
Plasmoid detachment	**no detachment; force reacted onto the antennas**

Still open

1. **Scaling.** The experiment used a 50 km/s laboratory wind source at high density; flight is 400 km/s at ~10^6 lower density. This is now the principal technical risk and replaces inflation as the headline unknown.
2. **Constant-force claim.** Slough states the bubble expands as the wind thins, giving constant force with distance rather than the $r^{-4/3}$ used throughout. At 30 AU that is a 96× difference. Unverified here.
3. **Magsail steering.** Acknowledged open in the literature; §11 establishes that our array is not the answer.
4. **Exhaust velocity, drive C.** 12.97 km/s against a 400 km/s wind — 31× short for ram-scoop operation.
5. **Beam interception, charging, structural modes.** Conventional spacecraft engineering, not computed.

Method note — the PIC attempt

A Darwin particle-in-cell code was written to settle inflation before the literature was checked. Its pusher and field solver validate — gyrofrequency exact, spectral solve 0.37% against an analytic current ring — and it found a real physics omission: a rotating **B** applied without its induced **E**, a direct violation of Faraday. It could not reach steady state: $\omega_{ce}/\omega = 186$ makes the problem stiff, and 2400 steps covered 0.29 of one RMF period. An implicit method would be required. Recorded because the tool is sound and the negative result about method is useful, not because it produced a physics answer.

13 Revision history and corrections

Recorded in full. The value of this work is that it corrected itself.

#	PREVIOUSLY	CORRECTED TO	CAUSE
1	Alternating ring polarity	Aligned	alternating yields zero-measure null planes
2	Tension release as ejection	Sequential firing	breathing drives azimuthal E only
3	Counter-rotation cancels	$\eta = 0.381$	earlier test sub-wavelength; artefact of scale
4	Scan covered handedness	It did not	`rot_z` never conjugates
5	1 MW reactor	100 kW_e	sail is area-limited; 1 MW cost 18 t for nothing
6	Mission at 10 t, budget 29.8 t	Both 8.2 t	inconsistent mass
7	Thrust per kW radiated	Per kW electrical	15–30% optimistic
8	Radiator for reactor only	Reactor + drive	magnetron loss uncounted
9	QUAD acceptance 3.17 m²	0.000 m²	3.75° grid counted cell open from its edge
10	Sail thrust 0.45 N at 120 km	**60.5 N**	used IMF magnetic pressure, not wind ram pressure — **134×**
11	Habitat 70 m³, 14 m³/crew	**91.2 m³, 18.2 m³/crew**	document figure contradicted its own source; found by audit
12	Crew/ship sizing used IMF pressure	**ram pressure**	134× fix applied in one file but not propagated
13	Array gives magsail attitude authority	**withdrawn**	short by 10^4–10^7; $\tau = mB$ dwarfs photon torque
14	2.2 t superconducting coil generates the moment	**20 kg RMF antenna drives plasma current**	antenna is a transmitter, not a magnet — 36× lighter

14 Source index

FILE	PRODUCES
emd_rubberband.py	FRC topology, nulls at ±R/√2, Alfvén speed
emd_vectoring.py	sequential-firing validation, 8.1σ
emd_particles.py	Boris acceptance measurement
emd_aperture.py	reflector η, elliptical shaping, guidance
emd_bands.py	band and rotational-sweep renders
emd_elliptical_scan.py	1600-configuration η scan
emd_contra.py	handedness scan
emd_angles.py	hull traction by spherical angle
emd_hull.py	closed-loop force, circuit constraint
emd_pull.py	pull-mode force, two independent routes
emd_corrected.py	ram-pressure correction
emd_crew.py	crewed mass budget, fairing fit
emd_reality.py	conversion, thermal, lifetime
emd_prototype.py	bench article sizing

Constants: $\mu_0 = 4\pi\times10^{-7}$; $m_p = 1.67262192\times10^{-27}$ kg; $e = 1.602176634\times10^{-19}$ C; $c = 2.99792458\times10^{8}$ m/s. Solar wind at 1 AU: $n = 5\times10^{6}$ m^{-3}, $v = 400$ km/s, $B = 5$ nT.