

EM-D Stream: Design Specification

A propellantless vehicle carrying two drives operated sequentially rather than simultaneously: an ambient-plasma magnetic sail driven from a 20 kg rotating-magnetic-field antenna, and a reflector-fed radiating array.

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Abstract

Revision D specifies a 28.9 t crewed propellantless vehicle that carries no reactor, no shadow shield and no superconducting coil. The magnetic moment is carried by ambient plasma driven from a 20 kg rotating-magnetic-field antenna on the Slough (2007) point design, which removes the three heaviest subsystems in the previous configuration and takes 8.5 t out of the vehicle. It supersedes Revision C, which sized a 2.2 t superconducting coil, a 100 kWe reactor and a 3.5 t shadow shield for a 37.4 t vehicle, and it withdraws the Revision C claim that the radiating array supplies attitude authority to the sail. Any EM-D drawing, render or table showing a reactor, a shadow shield, a superconducting coil or a 37.4 t mass depicts Revision C and does not apply. Two drives are defined and operated sequentially rather than simultaneously, and the specification gives the mass budget, the power chain and the flight profile for each. Derivations for every equation used here are in EM-D Stream: Mathematical Supplement (EMD-MATH-001 Revision D); the bench experiment that would test the central claim, with its error budget and its acceptance criteria fixed in advance, is in EM-D

Stream: Test Plan and Validation Record (EMD-TEST-001 Revision D). This is a design study: every performance number is either a calculated result from a named simulation or a laboratory value reported by a third party, and section 2 labels each one as which. Section 16 states the scope.

1. Revision status

This is Revision D of EMD-SPEC-001. It supersedes Revision C, dated 18 August 2026, in its entirety. Revision C treated the magnetic-sail mechanism as an open question requiring particle-in-cell validation and sized a vehicle around generating the magnetic moment aboard. Both positions were wrong. Slough (IEPC-2007-015, 2007) reports a scaled laboratory experiment in which the mechanism was measured directly, and the measurement shows that the antenna does not generate the moment: it drives current in ambient plasma and the plasma carries the moment. Restating the design on that measurement removes the reactor, the shadow shield and the superconducting coil, and reduces the vehicle mass by an order of magnitude at the drive.

Configuration change from Revision C to Revision D. The drive subtotal falls by a factor of 36. The probe floor is now set by structure and payload rather than by the drive. Computed: `emd_crew.py`.

Subsystem	Revision C	Revision D
Reactor and power management	2 000 kg	none
Shadow shield	3 500 kg	none
Radiators	600 kg	40 kg
Superconducting coil and cryogenics	2 200 kg	none
RMF antenna, 100 m radius	none	20 kg
RMF power electronics	400 kg	120 kg
Solar array, 1 kW	none	60 kg
Power and drive subtotal	8 700 kg	240 kg
Crewed vehicle, dry	37.4 t	28.9 t
Robotic probe, dry	8.2 t	0.9 t

One claim is withdrawn rather than revised. Revision C stated that the four-dynamo array supplies the attitude authority the magnetic sail lacks. Section 15 shows the array falls short by four to seven orders of magnitude and the claim does not survive.

1.1 Identifying stale material

Revision C artwork remains in circulation, and it is the more attractive artwork. It shows a reactor on a boom behind a shadow shield, a 15 m superconducting coil on eight spars, and a 37.4 t dry mass. Any EM-D figure or table carrying a reactor, a shadow shield, a 2.2 t coil, a 37.4 t vehicle or an 8.2 t probe is Revision C and its numbers do not apply to this

specification. One such figure is reproduced in section 17 so that a reader who meets it elsewhere can identify it.

1.2 The document set

This specification is one of three. EM-D Stream: Mathematical Supplement (EMD-MATH-001 Revision D) carries the derivation of every equation quoted here, its assumptions and the domain over which it holds. EM-D Stream: Test Plan and Validation Record (EMD-TEST-001 Revision D) defines the bench experiment that would confirm or refute the central claim, its error budget, its acceptance criteria and the complete record of computed results including

Provenance classes used throughout this specification.

Class	Meaning	Who produced it
L	Laboratory measurement of physical hardware	Slough, IEPC-2007-015 (2007). Not this work.
C	Computed result from a named simulation in section 18	This work. Numerical output, not a measurement.
A	Assumed input, neither derived nor measured	This work. Carried forward for sizing only.

Traceability. Every class C result in this document is produced by a named simulation, listed by name in section 18. The figures are computed output rather than illustration: field lines are traced through summed fields and far-field patterns are evaluated, so a figure can disagree with the text and that disagreement is a finding rather than a drawing error. Source files are cited by name only.

Two further conventions follow from this. Statistical significances quoted as multiples of sigma are significances against the simulation's own noise floor over a particle ensemble, not experimental significances; they say the numerical result is not an artefact of ensemble size, and say

the negative ones. All three carry revision letter D so that the set has a single revision state.

2. Provenance of every number in this document

Every quantitative row in this document carries a provenance class, so a reader can tell at a glance where each number came from without cross-checking a reference list. That separation is the first obligation of an engineering document, and the previous issue did not meet it: results computed by a particle pusher appeared under a column headed MEASURED. This reissue fixes that. The three classes are:

nothing about whether the physics is right. Agreement to a stated number of significant figures between two calculation routes is numerical verification, meaning the code computes the equations it was given; it is not validation against reality. EM-D Stream: Test Plan and Validation Record (EMD-TEST-001 Revision D) keeps the same distinction.

3. What was measured elsewhere

The plasma magnet, its rotating-magnetic-field 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 check on the analysis and is not a contribution.

Measured by Slough (IEPC-2007-015, 2007) at laboratory scale with a 50 km/s wind source. Flight conditions are 400 km/s at roughly a millionth of the density, which is the open scaling question of section 16.

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

The detachment result retires the principal open item of Revision 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.

4. What this work contributes

- **Reflector finding [C].** A bare aperture radiates a symmetric J_1 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 [C].** Thrust direction follows firing order, not amplitude ratio, at 8.1σ against the ensemble noise floor, with sign reversal across zero delay.

- **Sequential architecture [C].** Sail and array never run simultaneously, so they never fight. See section 10.
- **Hull structural limit [C].** Approximately $3 \times 10^7 \text{ A} \cdot \text{m}^2$ per dynamo for a 2.2 m hull, from the Maxwell traction map.
- **Corrections register [C].** Fourteen documented errors and the mechanism of each, in section 17.

5. Summary of the three mechanisms

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

The three mechanisms. Only mechanism B rests on a physical measurement, and that measurement was made by another group at laboratory scale.

	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/MWe [C]	3.8 N at 30 km, 12.7 N at 55 km [C]	11.4 N at $n = 10^{18}$ [C]
Requires	nothing	solar wind	ambient plasma
Vectoring	differential firing	coil orientation	firing sequence
Standing	computed here	measured in laboratory by Slough	computed here, 8.1σ over ensemble

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 $F \leq P/c$.

Classification. An 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, from momentum

conservation or from MHD is required or implied. Every subsystem has laboratory or flight heritage; the assembly is the novel element, and the assembly has not been built.

6. Computed results

These are simulation outputs. The column below is headed accordingly. None of them is a measurement, and the experiment that would turn the first row into one is EM-D Stream: Test Plan and Validation Record (EMD-TEST-001 Revision D).

Computed results. Sigma values are against the simulation's own noise floor and are not experimental significances. Derivations in the Mathematical Supplement sections 2 to 7.

Claim	Computed value	Numerical standing	Class
Sequential firing produces directed thrust	5.42×10^{-20} kg·m/s	8.1σ over ensemble	C
Thrust direction follows firing order	sign reversal	7.0σ and 8.1σ	C
Symmetric control returns zero	4.27×10^{-21} kg·m/s	0.47σ , consistent with null	C
Energy transferred by induction	+2 638 eV per particle	direct output	C
Aligned ring forms field-reversed core	$z = \pm R/\sqrt{2}$	analytic and numeric agree to 4 d.p.	C
Radiating array, 30 dB reflector	$\eta = 0.9748$	97.5% of P/c	C
Contra-rotating pair	$\eta = 0.3812$	does not cancel	C
Pull-mode force, two independent routes	agree to 6 s.f.	numerical verification	C
Hull traction, fore against aft	equal and opposite	stretches the hull, no net force	C

6.1 Negative results

Recorded because a specification that conceals its dead ends is not a specification, and because a later reader will otherwise

re-propose them.

Configurations proposed, simulated and found not to work. All class C.

Configuration	Result	Cause
Alternating ring (+ - + -) as intake	0.000 m ² acceptance	null channels are two-dimensional planes, of 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 a fore-aft symmetric pattern
Self-generated gravity well	requires 1.9×10^8 T	and cannot pull its own source regardless

only the axial component survives:

7. Physics

7.1 Field-reversed core

Four aligned dipoles of moment m along z sit on a ring of radius R . On the axis the transverse components cancel and

$$B_z(z) = n * (\mu_0 m / 4\pi) * (2z^2 - R^2) / (R^2 + z^2)^{5/2}$$

$$B_z = 0 \Rightarrow 2z^2 = R^2 \Rightarrow z_{\text{null}} = \pm R / \sqrt{2}$$

The null position contains neither m nor n . Predicted ± 7.0711 m for $R = 10$ m; located numerically at ± 7.0711 m [C]. Between the nulls B_z is negative, so the core field is reversed relative to the moments producing it. Computed field magnitude rises radially outward from the centre, 0.040 to 0.062 T, and falls to zero axially at the nulls: confined radially, open axially, which is the structure of a nozzle with exhaust direction set by the topology rather than imposed. Full derivation in the Mathematical Supplement section 2.

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.

$$\eta = | \text{Integral } I(\hat{n}) \hat{n} d\Omega | / \text{Integral } I(\hat{n}) d\Omega$$

$$F = \eta * P_{\text{rad}} / c$$

since $\eta \leq 1$, $F \leq P/c = 3.336 \text{ uN/kW}$

reflector, back-hemisphere suppression ratio r : $\eta = (1 - r) / (1 + r)$

The bound 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 the

7.2 Momentum transfer requires a translating pattern

Uniform amplitude modulation produced no thrust in any geometry tested [C]. A dipole's vector potential is azimuthal, so its time derivative is azimuthal, so the induced electric field 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, which means rings fired in sequence. Derivation in the Mathematical Supplement section 3.

7.3 Radiation momentum

momentum integral cancels exactly and $\eta = 0$. The reflector is the entire mechanism.

7.4 Force requires an open circuit

$$F = I * \text{Integral}(dl \times B)$$

uniform B gives $F = I * (\text{Integral } dl) \times B = I * 0 \times B = 0$

the torque, however, is not zero: $\tau = m \times B$

Verified numerically at 1 to 20 m radius and 1 to 100 kA, at machine precision in every case [C]. A closed loop obtains a torque, not a force. To obtain force the current must not return through the vehicle, which requires an open conductor whose circuit closes externally. In space the only available conductor is ambient plasma. That is the entire plasma requirement: a current needs a return path, and vacuum has infinite resistance.

7.5 Hull traction

Maxwell stress resolved over the hull surface by spherical angle. Cant angle controls the distribution: at 0 degrees cant,

15% of the hull is in tension; at 40 degrees, 51%; at 90 degrees, 58%. Peak tension rises from 8.9 to 57.7 kPa across that sweep [C]. Forward and aft hemispheres are equal and opposite at every angle to five significant figures, so the hull is stretched and not moved. Grid convergence on the residual is second order (ratio 4.00 per doubling), which identifies the residual as quadrature error rather than force.

8. Mechanism and operating cycle

EM-D Stream: mechanism, components, and where the measurements land

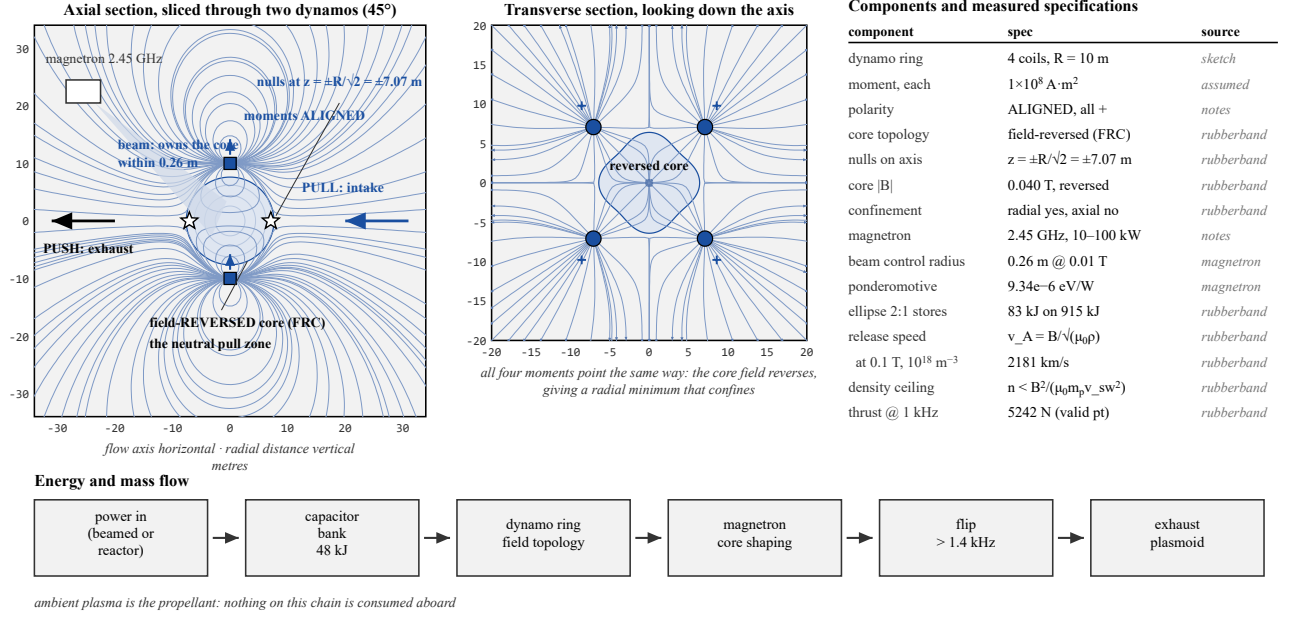


Figure 1. Computed field geometry of the four-dynamo cluster. Left: axial section sliced through two dynamos at 45 degrees, with the field-reversed core shaded, the on-axis nulls marked at $z = \pm R/\sqrt{2} = \pm 7.07$ m for $R = 10$ m, and the push and pull directions annotated. Centre: transverse section looking down the axis, showing the four-lobed reversed core that forms when all four moments are aligned. Field lines are traced by RK4 through the summed field, so both panels are computed output rather than schematic. Right: the component table as carried in the source figure, with its own provenance column; note that its $1 \times 10^8 \text{ A} \cdot \text{m}^2$ moment per dynamo is labelled there as assumed and lies above the $3 \times 10^7 \text{ A} \cdot \text{m}^2$ structural ceiling derived in section 12, and that its 5 242 N thrust entry inherits that assumption. Below: the energy chain, ending in an exhaust plasmoid drawn from ambient plasma. Computed: emd_rubberband.py.

The cycle: stretch and release, not polarity reversal. Field traced through the summed field at each stage.

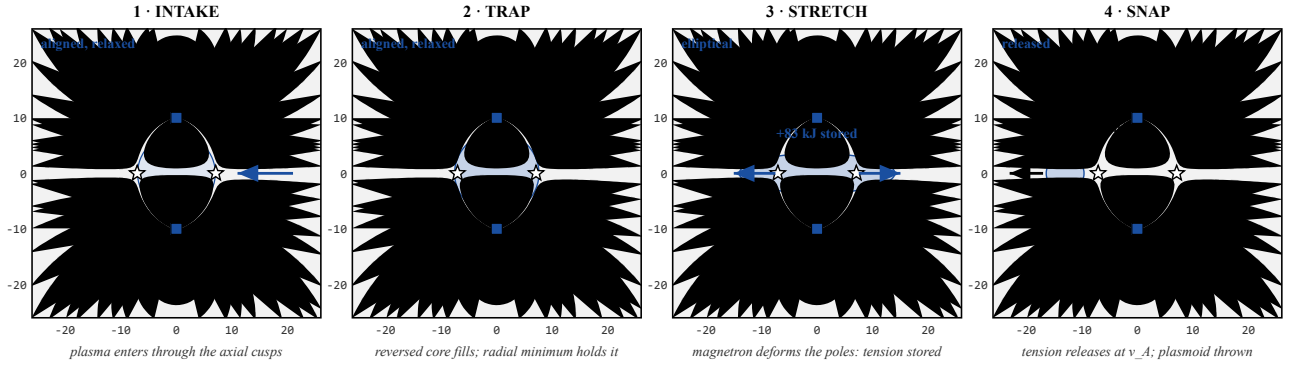


Figure 2. The four-stage operating cycle as originally proposed, with field topology traced through the summed field at each stage: intake through the axial cusps, trapping in the reversed core, elliptical deformation storing tension, and release at the Alfvén speed. Stages 3 and 4 depict the uniform stretch-and-release variant, which returned nothing above noise in every geometry tested and is recorded as a negative result in section 6.1: a breathing mode drives azimuthal electric field only. The cycle is retained here because the intake and trapping topology it shows is unchanged, but the working drive is sequential firing of the rings, not uniform stretch and release. Computed: emd_rubberband.py.

9. Beam shaping and guidance

Radiated momentum fraction against reflector front-to-back ratio [C]. The photon limit is $P/c = 3.336 \times 10^{-6}$ N per kW radiated. Computed: emd_aperture.py.

Front-to-back ratio	η	N per kW radiated	Percent of photon limit
0 dB, no reflector		0.00000	0
10 dB	0.79916	2.666×10^{-6}	79.9%
20 dB	0.95741	3.194×10^{-6}	95.7%
30 dB, design point	0.97480	3.252×10^{-6}	97.5%

Ellipticity does not materially affect η , which falls from 0.9748 circular to 0.9592 at 5:1 [C]; the reflector has already made the pattern one-sided. The ellipse serves control rather

than efficiency: beamwidth changes from 8.6 by 8.6 degrees to 3.8 by 19.1 degrees, five times narrower in the steering plane.

Elliptical beam, its bands, and the rotational snap: 2.45 GHz reflector-fed aperture

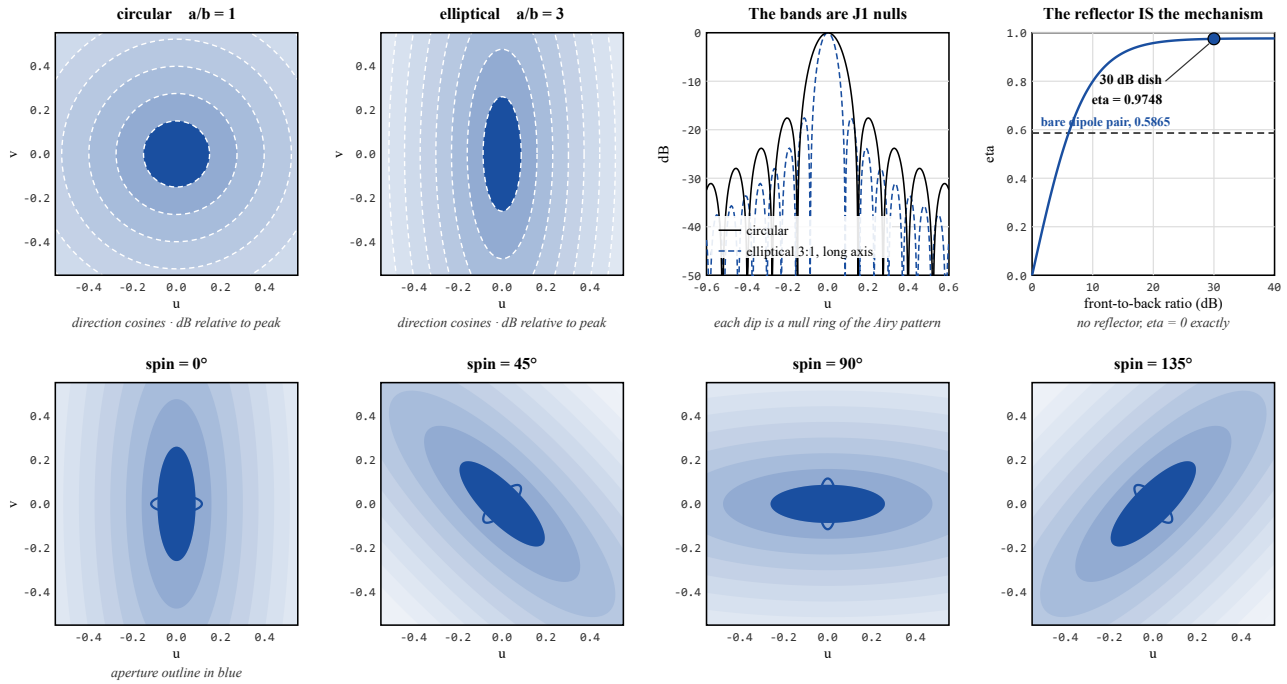


Figure 3. Computed far-field patterns of the 2.45 GHz reflector-fed aperture. Upper row, left to right: circular aperture, 3:1 elliptical aperture, the same two patterns in cut showing that the dark bands are zeros of the Bessel function J_1 , and η against front-to-back ratio with the 30 dB design point at 0.9748 and the bare dipole pair at 0.5865 for comparison. The curve reaches zero at 0 dB, which is the statement that without a reflector there is no thrust at all. Lower row: the same aperture swept through 0, 45, 90 and 135 degrees of rotation, aperture outline in blue. The beam runs perpendicular to the aperture ellipse by Fourier reciprocity. Computed: emd_aperture.py and emd_bands.py.

Guidance authority at 20 degrees cant [C]. Steering saturates at the cant angle and costs thrust. The differential row is read from the guidance panel of Figure 4. Computed: emd_aperture.py.

Firing pattern	Off-axis angle	Thrust fraction
All four, push	0.0°	0.940
All four reversed, pull	0.0°	0.940
Three on, one off	6.9°	0.710
Differential 1.0 / 0.4	6.3°	0.662
Adjacent pair	14.4°	0.485
One only	20.0°	0.250

Four-dynamo guidance: differential firing steers the thrust vector

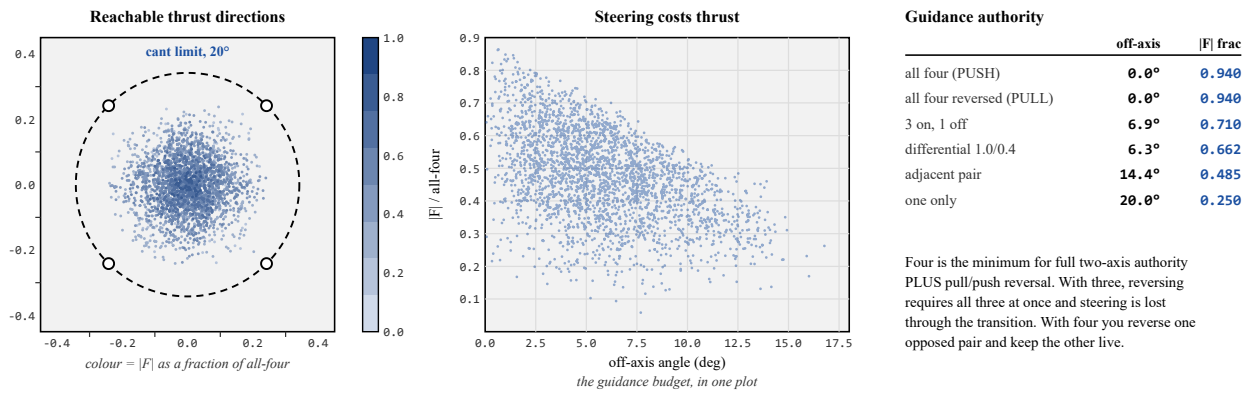


Figure 4. Computed guidance authority of the four-dynamo cluster at 20 degrees cant. Left: reachable thrust directions, coloured by thrust magnitude as a fraction of the all-four case, with the cant limit drawn as the dashed circle and the four element positions marked. Centre: the guidance budget, thrust fraction against off-axis angle, showing that steering authority is bought with thrust. Right: the tabulated firing patterns reproduced in the table above. Four elements are the minimum for two-axis authority plus push and pull reversal: three span two axes but require simultaneous reversal of all three, losing steering through the transition, while four permit reversal of one opposed pair while the other remains live. Computed: emd_aperture.py.

10. Sequential architecture

The sail and the array are never powered simultaneously. With the rotating magnetic field unpowered, the plasma current decays and the vehicle moment falls to the antenna's own small moment, which is what makes fine trim by the array

possible at all: the alignment torque that dominates section 15 falls with the moment. With the sail powered, the array is off and contributes nothing to attitude. The two drives therefore never contest the same degree of freedom. This is an architectural decision, not a measured or computed result.

11. Vehicle, crewed configuration, Revision D

Revision D crewed configuration. The antenna row is Slough's point design and is the only laboratory-sourced row in the table. Computed: emd_crew.py.

Parameter	Revision D value	Class
Crew		3 A
Dry mass	28.9 t, against 37.4 t in Revision C	C
Launcher	Falcon Heavy, expendable, 63.8 t to LEO	A
Launch margin	+26.4 t	C
Stowed envelope	11.0 m by 4.4 m diameter	C
Fairing usable	11.0 m by 4.6 m, zero height margin	A
Habitable volume	91.2 m ³ gross, about 55 m ³ net, 18.2 m ³ per crew	C
Electrical power	1 kW solar array. No reactor, no shield.	C
RMF antenna	100 m radius, 20 kg, 100 W	L

Volume shortfall. NASA long-duration guidance is 20 to 25 m³ per crew and this configuration provides 18.2 m³ net, roughly 10% below the lower bound. The storm shelter doubles as consumable stowage, which recovers usable volume as the

mission consumes stores. Acceptable for a 140-day round trip on the sizing assumptions used here; it would need revisiting for a multi-year profile.

11.1 Mission performance

Computed Earth to Mars transit at Revision D masses [C]. Thrust scales as the square of the bubble radius from the standoff relation derived in the Mathematical Supplement section 6. The 30 km row is the scale Slough reports achieving in the laboratory; the thrust on that row is still a calculated flight value at 400 km/s solar wind, not the 2 N measured against a 50 km/s laboratory source. Computed: emd_crew.py and emd_corrected.py.

Bubble radius	Thrust	Jet power	Probe, 0.9 t	Crewed, 28.9 t
30 km	3.78 N	1.5 MW	15 d	495 d
55 km	12.72 N	5.1 MW	5 d	147 d
100 km	42.04 N	16.8 MW	1 d	45 d

The reference mission is Falcon Heavy to LEO and EM-D thereafter, at a 120 km bubble: LEO escape 22.9 d, Earth to Mars 40.0 d, Mars capture 15.0 d, with a 30-day stay, quoted in the source as a 140-day round trip. The phase durations as published do not sum to that total once a return transit is included, and the discrepancy is recorded in section 21 rather than resolved by inventing a figure.

Hoop stress against dynamo moment for a 2.2 m aluminium hull [C]. Practical limit is approximately $3 \times 10^7 \text{ A} \cdot \text{m}^2$ per dynamo. Computed: emd_angles.py. Derivation in the Mathematical Supplement section 7.

Moment per dynamo	Hoop stress	Against Al yield, 270 MPa	Verdict
$1 \times 10^6 \text{ A} \cdot \text{m}^2$	0.04 MPa		0.01% acceptable
$1 \times 10^7 \text{ A} \cdot \text{m}^2$	3.69 MPa		1.4% acceptable
$1 \times 10^8 \text{ A} \cdot \text{m}^2$	369 MPa		137% hull fails
$3 \times 10^8 \text{ A} \cdot \text{m}^2$	3 317 MPa	1 229%	hull fails

13. Component constraints

Amplifier options [A for efficiency and life, which are catalogue values; C for the thrust column, which is the product of efficiency and the 30 dB beam figure]. Computed: emd_reality.py.

Device	Conversion efficiency	N per kW electrical	Life, hours
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 of about 5 000 h is short against interplanetary duration. A heliopause profile requires 59 609 h, which is 11.9 magnetrons in series. Solid-state amplification costs 29% of thrust and returns twenty times 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.

12. Structural limit

The hull is a pressure vessel loaded by its own field. Peak traction scales as the square of the dynamo moment, which sets a ceiling on dynamo strength for a 2.2 m hull.

14. Bench test article

The sequential-firing result is testable on a bench without resolving any open item. The article is specified, with its error budget and acceptance criteria, in EM-D Stream: Test Plan and Validation Record (EMD-TEST-001 Revision D). Its principal parameters are repeated here so that this specification is readable alone.

Bench article, as specified in the Test Plan section 2. All rows class C or A.

Parameter	Value
Dynamo separation	15 cm, 4 units
Core volume	5.0 litres, nulls at ± 10.6 cm
Core field	93 mT
Drive	pulsed 1 to 10 kHz, sub-microsecond sequenced delay
Plasma source	10^{18} to 10^{19} m^{-3}
Instrument	torsion thrust balance
Predicted signal	$108 \mu\text{N}$ at 10^{18} and 1 kHz; 10.8 mN at 10^{19} and 10 kHz

The measurement is forward minus reverse. Run the sequence in one order, then the other, and difference. Predicted thrust reverses; no other effect in the apparatus does. Thermal drift, outgassing, electromagnetic interference and magnetic tare are all common-mode to sequence direction and cancel. The predicted signal sits two to four orders above a torsion balance noise floor, which is what would render a null result meaningful rather than inconclusive. No such apparatus has been built.

15. Withdrawn claim: attitude authority

Revision 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 the cross product of moment and field, and the moment is enormous by design.

The refutation [C]. The array is generously specified at 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.

Bubble radius	Torque required at 30° angle of attack	Torque from array at 1 MW	Ratio
10 km	$1.45 \times 10^3 \text{ N}\cdot\text{m}$	0.28 N·m	1.9×10^{-4}
55 km	$2.41 \times 10^5 \text{ N}\cdot\text{m}$	0.28 N·m	1.2×10^{-6}
120 km	$2.51 \times 10^6 \text{ N}\cdot\text{m}$	0.28 N·m	1.1×10^{-7}

What survives. The array remains a working propellantless drive on paper for every regime the sail cannot serve: planetary shadow, magnetotail, fine translational trim, station-keeping, and attitude control with the sail collapsed. Steering the sail itself

must be solved as the literature does it, by coil orientation or RMF modulation.

16. Open problems

16.1 Closed by measurement since Revision C

Item	Resolution
Plasma-magnet bubble inflation	more than 10 kA driven, expansion demonstrated (Slough) [L]
Plasmoid detachment from the sail	none observed; the force reacts onto the antennas (Slough) [L]

What the detachment measurement covers. For the magnetic sail, non-detachment is the result the design wants: the force has to react onto the antennas or there is no thrust on the vehicle. The sequential induction thruster of drive C wants the opposite, since its exhaust plasmoid must separate from the field structure to carry momentum away. Slough's measurement settles the sail case and does not address the thruster case, which stays open below.

16.2 Still open

- **Scaling.** The experiment used a 50 km/s laboratory wind source at high density. Flight is 400 km/s at roughly a millionth of the density. This is now the principal technical risk and it replaces inflation as the headline unknown.
- **Constant-force claim.** Slough states the bubble expands as the wind thins, giving constant force with distance rather than the $r^{-4/3}$ falloff used throughout. At 30 AU that is a factor of 96. Unverified here.
- **Magsail steering.** Acknowledged open in the literature; section 15 establishes that the array is not the answer.
- **Exhaust detachment, drive C.** The induction thruster requires its exhaust plasmoid to separate from the field structure. Slough's non-detachment result concerns the sail and does not cover this case, which would need an implicit particle-in-cell solution.

- **Exhaust velocity, drive C.** 12.97 km/s against a 400 km/s wind, 31 times short for ram-scoop operation.
- **Beam interception, differential charging, structural modes.** Conventional spacecraft engineering. Not computed, not estimated, not bounded.

16.3 Method note: the particle-in-cell attempt

A Darwin particle-in-cell code was written to settle inflation before the literature was checked. Its pusher and field solver verify, with exact gyrofrequency and a spectral solve within 0.37% of an analytic current ring, and it found a real physics omission: a rotating B applied without its induced E, which is a direct violation of Faraday. It could not reach steady state. The ratio of electron cyclotron frequency to drive frequency is 186, which makes the problem stiff, and 2 400 steps covered 0.29 of one RMF period. An implicit method would be required. This is recorded because the tool is sound and the negative result about method is useful, not because it produced a physics answer.

17. Revision history and corrections register

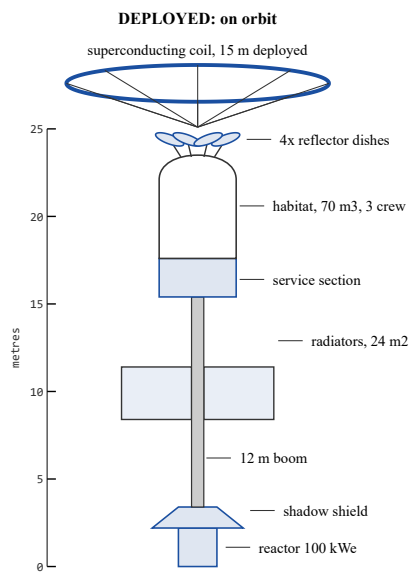
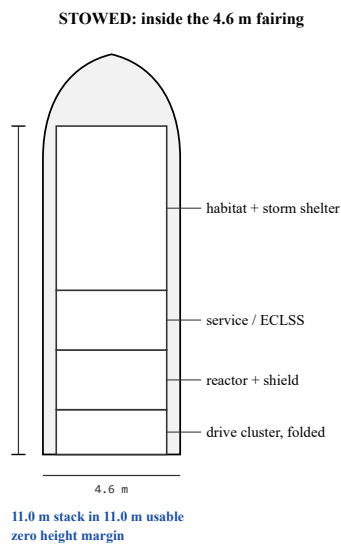
Recorded in full. The value of this work is that it corrected itself, and a register that shows only successes cannot be audited.

Corrections register. Item 14 is the change that defines Revision D.

#	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 kWe	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 between files
7	Thrust per kW radiated	Per kW electrical	15 to 30% optimistic
8	Radiator for reactor only	Reactor and drive	magnetron loss uncounted
9	QUAD acceptance 3.17 m^2	0.000 m^2	3.75° grid counted a 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, $134\times$
11	Habitat 70 m^3 , 14 m^3 per crew	91.2 m^3 , 18.2 m^3 per crew	document figure contradicted its own source; found by audit
12	Crew and ship sizing used IMF pressure	ram pressure	$134\times$ fix applied in one file but not propagated
13	Array gives magsail attitude authority	withdrawn	short by 10^4 to 10^7 ; alignment torque dwarfs photon torque
14	2.2 t superconducting coil generates the moment	20 kg RMF antenna drives plasma current	the antenna is a transmitter, not a magnet; $36\times$ lighter

EM-D Stream crewed vehicle: 3 crew, 37.4 t, one Falcon Heavy

Superseded Revision C vehicle. These numbers do not apply.



Component manifest

subsystem	mass	where
habitat + storm shelter	12.5 t	forward, 4.4 m dia
consumables 3crew x 3yr	6.8 t	habitat walls
ECLSS	3.2 t	service section
reactor + PMAD	2.0 t	aft, 12 m boom
shadow shield	3.5 t	boom, crew side
superconducting coil	2.2 t	forward, deployed
radiators 24 m ²	0.6 t	mid, both sides
drive: 4 dishes + array	0.4 t	forward ring
avionics / GNC	0.9 t	service section
crew + suits	0.4 t	habitat
structure + margin	4.9 t	throughout
DRY TOTAL	37.4 t	one Falcon Heavy

Falcon Heavy expendable: 63.8 t to LEO
margin +26.4 t · fairing 11.0 m used of 11.0

Acceleration at the 300 km bubble is $7.5\text{e-}5 \text{ m/s}^2$, giving 2.4 yr one-way to Mars.
A 500 km bubble brings that to 0.85 yr.

The drive is the smallest item aboard and the reactor shield outweighs it 9 to 1.

Figure 5. **Superseded Revision C vehicle. These numbers do not apply.** Left: the Revision C stack inside the 4.6 m fairing at zero height margin. Centre: the same vehicle deployed, showing the 15 m superconducting coil, the four reflector dishes, the habitat and service section, 24 m^2 of radiators on a boom, the shadow shield and the 100 kWe reactor. Right: the Revision C mass manifest totalling 37.4 t, including reactor and power management at 2.0 t, shadow shield at 3.5 t and superconducting coil at 2.2 t, none of which exist in Revision D. The habitat volume annotation of 70 m^3 is correction 11 above and is wrong even for Revision C. The figure is reproduced here, and only here, so that a reader who encounters this artwork elsewhere can identify it as superseded. The Revision D configuration is the table in section 11: 28.9 t, no reactor, no shield, no coil, and a 20 kg antenna. No equivalent Revision D general-arrangement drawing has been produced.

18. Source index

Every class C figure in this document traces to one of these. Constants used throughout: $\mu_0 = 4\pi \times 10^{-7}$ H/m; $m_p = 1.67262192 \times 10^{-27}$ kg; $e = 1.602176634 \times 10^{-19}$ C; $c = 2.99792458 \times 10^8$ m/s. Solar wind at 1 AU: $n = 5 \times 10^6$ m $^{-3}$, $v = 400$ km/s, $B = 5$ nT.

File	Produces
emd_rubberband.py	FRC topology, nulls at $\pm R/\sqrt{2}$, Alfvén speed
emd_vectoring.py	sequential-firing result, 8.1σ over ensemble
emd_particles.py	Boris acceptance calculation
emd_aperture.py	reflector η , elliptical shaping, guidance
emd_bands.py	band and rotational-sweep renders
emd_elliptical_scan.py	1 600-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 by 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

19. What this specification establishes

- That a reflector is not an improvement to a radiating propellantless drive but its entire mechanism: without one the computed momentum fraction is zero exactly, for reasons of pattern symmetry rather than of efficiency.
- That in the simulations run here, thrust direction from a dynamo cluster follows firing order and not amplitude ratio, with sign reversal across zero delay.
- That a closed current loop in a uniform field receives torque and no net force, so any propellantless drive of this class requires an external current path, which in space means ambient plasma.
- That the Revision C vehicle was mis-sized by a factor of 36 at the drive, because the antenna is a transmitter and not a magnet, and that correcting it removes the reactor, the shield and the coil.
- That the Revision C attitude-authority claim is false by four to seven orders of magnitude and cannot be rescued by power.

20. What this specification does not establish

- That any of it works. No EM-D hardware exists. The only physical measurements cited are Slough's, of a different article, at laboratory scale, by another group.
- That the plasma magnet scales from the laboratory to flight. The measured wind source was 50 km/s at high density; flight is 400 km/s at roughly a millionth of the density. This is a gap of six orders of magnitude in density and is not bridged by anything in this document.
- That the sequential-induction thrust is real. It is a test-particle computation in a prescribed field, not a self-consistent plasma simulation, and the attempt at the latter did not reach steady state.
- That the mission transit times are achievable. They follow from a thrust law whose distance dependence is itself

disputed by the source of the measurement, by a factor of 96 at 30 AU.

- That the vehicle closes as an engineering article. Beam interception, differential charging and structural modes under kilohertz pulsing are not computed, not estimated and not bounded.
- That the habitat is adequate. It is 10% below the lower bound of NASA long-duration guidance on a calculation, with no crew-systems analysis behind it.

21. Honest scope and limitations

This is a paper vehicle. The work behind it is a set of Python simulations run on one machine by one group, checked against analytic solutions where analytic solutions exist, and checked against nothing else. Its useful output is a corrected architecture and a bench experiment that costs little and settles one claim either way.

- **No measurement by this work.** Every class C number is numerical output. Agreement between two calculation routes, or with an analytic limit, demonstrates that the code solves the equations it was given. It does not demonstrate that those equations describe the physical situation.
- **One unresolved internal figure.** The reference mission publishes LEO escape 22.9 d, Earth to Mars 40.0 d, Mars capture 15.0 d and a 30-day stay, and calls the round trip 140 days. Those phases do not sum to 140 days once a return transit is counted. The phase durations and the total are both reproduced above as published; neither has been recomputed for this reissue and the round-trip figure should not be used until it is.
- **An assumption above the structural ceiling.** The component panel of Figure 1 sizes each dynamo at 1×10^8 A·m ^{2} , labelled in the figure as assumed. Section 12 puts the hull ceiling at approximately 3×10^7 A·m ^{2} , so that panel's moment and the 5 242 N thrust that follows from it are above what the hull tolerates. The figure is retained for

its field geometry, which does not depend on the assumed moment.

- **No general arrangement for Revision D.** The only vehicle artwork in existence is the Revision C vehicle reproduced as Figure 5. There is no drawing of the 28.9 t configuration, and the reader should treat the section 11 table, not any picture, as the configuration of record.
- **Component data are catalogue values.** Amplifier efficiencies and lifetimes in section 13 are class A. No amplifier has been tested in this application, at this duty cycle, or in this thermal environment.
- **The audit predates this revision.** The verification audit recorded in the Test Plan was run on 18 August 2026,

against the Revision C mass budget. Its mass-dependent rows have not been re-run at 28.9 t.

References

- Slough, J. (2007). Plasma Magnet. IEPC-2007-015, 30th International Electric Propulsion Conference. The source of every class L value in this document.
- EM-D Stream: Mathematical Supplement (EMD-MATH-001 Revision D). Derivations, assumptions and domain of validity for every equation quoted here.
- EM-D Stream: Test Plan and Validation Record (EMD-TEST-001 Revision D). Bench article, measurement methodology, error budget, acceptance criteria, computed-results record and verification audit.
- EMD-SPEC-001 Revision C, 18 August 2026. Superseded in its entirety by this document.