
EM-D Stream: Test Plan and Validation Record

Bench article definition, measurement methodology, error budget, acceptance criteria, and the complete computed record including every negative result.

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Abstract

This document specifies the bench experiment that settles the central computed claim of the EM-D study, which is that sequential firing of a dynamo cluster produces directed thrust. It defines the test article, a differential null methodology in which every systematic known to plague small-thrust measurement is common-mode to firing order and cancels in the difference, a six-term error budget, and acceptance criteria fixed in advance, including the criterion under which a positive reading must not be called propulsion. The predicted signal sits two to four orders of magnitude above the instrument noise floor, so the experiment can refute the claim as cleanly as it can support it. Sections 8 to 11 carry the complete computed record behind the prediction: fourteen computed results including five self-checks of the numerics, ten configurations that were proposed, simulated and rejected, twelve corrected errors, and a twenty-five-check audit that recomputed every published figure from source and found two defects that had reached print. The negative results and the corrections are published in full, so the claim can be audited rather than taken on trust. Two words are kept apart throughout: verification means a calculation solves the equations it was given, which the record in sections 8 to 10 demonstrates, and validation means a model matches reality, which is what the experiment specified here would decide. This is Revision D, companion to the Revision D specification. It supersedes the 18 August 2026 issue, which was companion to Revision C. Three rows of the verification audit check the Revision C dry mass of 37.4 t and a transit time computed from it; they are marked superseded, because the audit has not been re-run at the Revision D mass of 28.9 t.

1. Purpose and status

This document defines the ground test that would confirm or refute the central computed claim of the EM-D study, which is that sequential firing of a dynamo cluster produces directed thrust. It also records the complete computed evidence supporting that claim.

Two things are deliberately separated. Sections 3 to 7 specify an experiment that could be built now, with no dependency on any unresolved item. Sections 8 to 11 record what has been computed, including the results that failed.

The status of the programme is stated here once and applies to every page that follows. No bench article has been built and

no measurement has been taken. Every number in this document is simulation output, and where a table carries a predicted value the prediction is what the experiment would test rather than a result it has produced. The only laboratory measurement referenced anywhere in the EM-D document set was made by another group on different hardware and is cited in the Specification section 3. Section 15 carries the scope of this document in full.

1.1 Verification against validation

The title of this document contains the word validation, and the word is used narrowly. Verification asks whether a calculation solves the equations it was given: agreement between two independent numerical routes to six significant figures, or between a numerical root and its analytic expression to four decimal places, is verification. Validation asks whether those equations describe the physical situation, and requires an experiment. Sections 8 to 10 are a verification record. The experiment in sections 3 to 7 is the validation, and it has not been performed.

2. Revision status and companion documents

This is Revision D of EMD-TEST-001. It supersedes the issue of 18 August 2026, which was a companion to EMD-SPEC-001 Revision C and to the Revision C issue of the mathematical supplement. Three changes follow from the revision. The verification audit in section 10 was run against the Revision C mass budget and three of its rows are therefore stale; they are marked in place. Two items that section 12 previously listed as open, bubble inflation and plasmoid detachment, were closed by laboratory measurement reported by Slough and are moved accordingly, with a note in section 12 on what that measurement covers and what it leaves open. And the bench article itself is unchanged, because it tests the induction result and not the sail, and nothing in the revision touches it.

The design of record is EM-D Stream: Design Specification (EMD-SPEC-001 Revision D). Derivations for every equation behind the predicted signal are in EM-D Stream: Mathematical Supplement (EMD-MATH-001 Revision D), which also states the assumptions those derivations rest on and where they stop being valid. All three documents carry revision letter D so that the set has a single revision state. Simulation sources are named without paths.

3. Test article

Bench article as specified: every parameter fixed before procurement. Computed: emd_prototype.py.

Parameter	Value
Configuration	4 dynamos, coplanar ring, aligned moments
Ring radius	0.15 m
Predicted nulls	± 0.106 m on axis, from $R/\sqrt{2}$
Core volume	5.0 litres
Core field	93 mT at $785 \text{ A}\cdot\text{m}^2$ per dynamo
Coil	1 000 turns, 100 A, about 5 cm radius
Drive	pulsed, 1 to 10 kHz, sequenced
Delay control	sub-microsecond, independently settable per ring
Chamber	about 1 m, routine vacuum
Plasma source	10^{18} to 10^{19} m^{-3}
Instrument	torsion thrust balance

Hull loading at this scale is negligible: hoop stress at $785 \text{ A}\cdot\text{m}^2$ is far below any structural concern, so the article needs no special structure. The demanding component is the sequencing electronics, which must hold sub-microsecond delay stability across the pulse train.

How to read a modest disagreement at bench scale. The derivations treat each coil as a point dipole. At flight scale, coils of order 0.05 m on a 10 m ring, that is comfortable. At bench scale, coils of about 0.05 m on a 0.15 m ring, the separation is roughly three coil radii and the point-dipole form becomes an approximation whose error is not quantified in this record. A

measured null position or core field that differs modestly from the predicted value should therefore be checked against a finite-coil calculation before it is read as a discrepancy in the physics. See the Mathematical Supplement section 3.1.

4. Predicted signal

From the computed impulse per proton, $2.169 \times 10^{-23} \text{ kg}\cdot\text{m/s}$, scaled by the core particle count. The word computed is load-bearing: this figure is the output of the test-particle integration recorded as V-02 in section 8, not a measurement.

Predicted thrust against plasma density and repetition rate. Computed: emd_prototype.py.

Plasma density	Protons in core	Impulse per pulse	At 1 kHz	At 10 kHz
10^{17} m^{-3}	5.00×10^{14}	$1.08 \times 10^{-8} \text{ N}\cdot\text{s}$	$10.8 \text{ }\mu\text{N}$	$108 \text{ }\mu\text{N}$
10^{18} m^{-3}	5.00×10^{15}	$1.08 \times 10^{-7} \text{ N}\cdot\text{s}$	$108 \text{ }\mu\text{N}$	1.08 mN
10^{19} m^{-3}	5.00×10^{16}	$1.08 \times 10^{-6} \text{ N}\cdot\text{s}$	1.08 mN	10.8 mN

A torsion balance resolves sub-micronewton forces routinely. The predicted signal therefore sits two to four orders of magnitude above the noise floor, which is what would make a null result meaningful rather than inconclusive.

5. Measurement methodology

The measurement is forward minus reverse, not an absolute thrust reading. With the inter-ring firing delay set to plus and then minus the same interval, the quantity taken as thrust is half the difference of the two readings. Run the sequence in one order, then the other, and difference. The predicted effect reverses sign; the systematics do not.

Why the differential design is the defensible one: every systematic that historically plagues small-thrust measurement is common-mode to firing direction.

Systematic	Reverses with firing order?	Cancels in the difference?
Thermal drift of the balance	no	yes
Outgassing recoil	no	yes
Electromagnetic interference in the readout	no	yes
Magnetic tare on chamber walls	no	yes
Cable stiffness and tether torque	no	yes
Buoyancy, seismic, tilt	no	yes
Sequential induction thrust	yes	no, it survives

The one effect under test is the only thing in the apparatus that changes sign with the sequence. This is a differential null experiment, which is the most defensible category of small-force measurement. It is also the reason the plan is worth running even though the underlying model is a test-particle calculation: the experiment does not depend on the model being right, only on the model's prediction being distinguishable from zero.

5.1 Required controls

- **Zero-delay control.** Fire all rings simultaneously. Predicted thrust is zero; the simulation returns 2.0σ ,

consistent with null. A non-zero reading here indicates an uncontrolled systematic.

- **No-plasma control.** Full drive sequence, chamber evacuated, no plasma source. Predicted thrust is zero, because the mechanism requires reaction mass.
- **Symmetric-geometry control.** Single ring, aligned. Predicted zero by symmetry; the simulation returns 0.47σ over five seeds.
- **Amplitude-ratio control.** Vary ring strength ratio at fixed delay. Predicted no change in thrust direction, because direction follows order and not ratio.

6. Error budget

Error budget. Magnitudes for the instrument rows are requirements on equipment still to be selected, and section 15 records them as such.

Source	Magnitude	Mitigation
Torsion balance resolution	about $0.1 \mu\text{N}$	below signal by 10^3 to 10^5
Delay jitter	target below 50 ns	signal scales with delay; jitter adds variance, not bias
Plasma density drift	$\pm 20\%$	signal scales with density; monitor with a Langmuir probe
Chamber wall charging	unknown	grounded liner; verify with the no-plasma control
Pulse-to-pulse repeatability	$\pm 5\%$	average over 10^4 pulses or more
Balance calibration	$\pm 3\%$	electrostatic comb calibration in situ

Because the measurement is differential and the predicted signal is large relative to resolution, the dominant uncertainty is expected to be knowledge of the plasma density, which enters linearly. A $\pm 20\%$ density uncertainty yields a $\pm 20\%$ thrust uncertainty, which is acceptable for a first result whose purpose is to distinguish the predicted magnitude from zero.

One entry in the budget has no number against it: chamber wall charging is listed as unknown because it has not been estimated, and the no-plasma control is the only thing standing between it and a false positive.

7. Acceptance criteria

Acceptance criteria, fixed before the experiment rather than after it.

Outcome	Interpretation
Thrust reverses with sequence, magnitude within a factor of three of prediction	Confirmed. Mechanism supported; proceed to scaling.
Thrust reverses, magnitude below one third or above three times prediction	Mechanism real, model wrong. Investigate coupling efficiency.
Non-reversing thrust present	Uncontrolled systematic. Do not claim propulsion.
No signal above 3σ with controls clean	Refuted. Sequential induction does not produce usable thrust at this scale.

On a null result. Because the predicted signal is two to four orders above the noise floor, a clean null would be a genuine refutation rather than an inconclusive measurement. That is the point of specifying the test at a density and repetition rate where the margin is large. A result that could only ever confirm is not worth running.

8. Computed record: positive results

Every row below is simulation output. Sigma values are against the simulation's own noise floor over a particle ensemble and are not experimental significances. Rows describing agreement between two routes, or between analytic and numeric, are verification of the calculation and not validation of the model.

Computed record. V-10 through V-14 are self-checks of the numerics. V-01 through V-04 are the claim the bench experiment would test.

ID	Claim	Computed value	Numerical standing	Source
V-01	Symmetric configuration returns zero	$+4.27 \times 10^{-21}$ kg·m/s	0.47σ	emd_vectoring
V-02	Sequential firing, wave toward $-z$	$+5.42 \times 10^{-20}$	8.1σ	emd_vectoring
V-03	Sequential firing, wave toward $+z$	-4.71×10^{-20}	7.0σ	emd_vectoring
V-04	Energy from field, per particle	$+2\,638$ eV	direct output	emd_vectoring
V-05	FRC nulls, analytic against numeric	± 7.0711 m	4 d.p.	emd_rubberband
V-06	Core confines radially, opens axially	0.040 to 0.062 T	direct output	emd_rubberband
V-07	Reflector aperture at 30 dB	$\eta = 0.97480$	97.5% of P/c	emd_aperture
V-08	Phased array, optimum spacing	$\eta = 0.58651$	1 196 of 1 600 above 10^{-3}	emd_elliptical_scan
V-09	Contra-rotating pair	$\eta = 0.38119$	non-zero	emd_contra
V-10	Pull force, potential against Maxwell stress	agree to 6 s.f.	verification	emd_pull
V-11	Closed loop in uniform field	10^{-21} to 10^{-18} N	machine precision	emd_hull
V-12	Hull traction, fore against aft	equal and opposite	5 s.f.	emd_angles
V-13	Hull stress integral convergence	ratio 4.00	second order to zero	emd_angles
V-14	Boris integrator, speed drift with $E = 0$	7.6×10^{-15}	machine precision	emd_particles

9. Computed record: negative results

Recorded in full. These are configurations that were proposed, simulated and found not to work. A record that shows only

successes cannot be audited, and a later reader will otherwise re-propose them.

Negative results. All computed; none measured.

ID	Configuration	Result	Cause
N-01	Alternating ring (+ - + -) as intake	0.000 m ²	null channels are two-dimensional planes, of zero measure in a 3-D flow
N-02	Uniform stretch and release	below noise in all geometries	breathing drives azimuthal E only
N-03	Amplitude-ratio vectoring, 0.30 to 3.00	below noise	direction follows order, not ratio
N-04	Polarity patterns for radiation asymmetry	$\eta = 0$ exactly	real amplitudes give a fore-aft symmetric pattern
N-05	Bare aperture, no reflector	$\eta = 0$ exactly	the J_1 pattern is symmetric about its plane
N-06	Symmetric radiating arrays: 3, 4, ring, stacked	$\eta = 0$	symmetry is symmetry
N-07	Self-generated gravity well	needs 1.9×10^8 T	and cannot pull its own source regardless
N-08	Closed hull-current loop for thrust	0 N exactly	the closed-path integral of the displacement element vanishes
N-09	Static self-force, all EM geometries	7.47×10^{-14} N	numerical floor of the stress integral
N-10	Two positive, one negative slip for radiation	$\eta = 0$	static topology is lopsided, the far field is not

10. Verification audit

Every published figure was recomputed from source and compared against the value printed in these documents. The

harness is emd_audit.py; it re-runs ten simulations, reloads their JSON output, and flags any discrepancy above tolerance. This confirms that the documents agree with the code. It does not confirm that the code agrees with nature.

Verification audit, run 18 August 2026. Twenty-five checks are tabulated. The three rows marked superseded check the Revision C dry mass of 37 400 kg and the transit time computed from it; the Revision D mass is 28.9 t and the audit has not been re-run against it. The remaining rows are mass-independent and stand.

Check	Published	Recomputed	Standing	
FRC null position	7.0711 m		7.07113	ok
FRC core field	−0.040 T	−0.040		ok
η , no reflector		0 3.99×10 ^{−17}		ok
η , 20 dB reflector		0.95741	0.957414	ok
η , 30 dB reflector		0.97480	0.974804	ok
η at 5:1 ellipse		0.95922	0.959221	ok
η , same handedness		0.586514	0.586514	ok
η , contra-rotating		0.381193	0.381193	ok
Scan configuration count	1 600	1 600		ok
Hull peak traction	3.351×10 ⁴ Pa	33 505.4		ok
Hull hoop stress	3.686×10 ⁴ Pa	36 856		ok
Closed-loop force, worst case		0 7.93×10 ^{−18} N		ok
Ram pressure	1.3381×10 ^{−9} Pa	1.3381×10 ^{−9}		ok
Understatement factor		134.5	134.52	ok
Sail thrust at 120 km	60.53 N		60.5341	ok
Moment for 120 km	1.002×10 ¹⁵	1.00209×10 ¹⁵		ok
Crewed Mars transit	40 d		40.04	Revision superseded C,
Crewed dry mass	37 400 kg	37 400		Revision superseded C,
Habitat volume	91.2 m ³		91.2319	ok
N per kW electrical, 85% magnetron	2.764×10 ^{−6}	2.76385×10 ^{−6}		ok
Bench thrust, 10 ¹⁸ at 1 kHz	1.0841×10 ^{−4} N	1.08412×10 ^{−4}		ok
Bench null position	0.10607 m		0.106066	ok
Files using wrong pressure for thrust		0	0	ok
Habitat volume against pi r ² L		91.2319	91.2319	ok
Crew against corrected: transit agreement	0.109637 yr		0.109637	Revision superseded C,

A count that does not reconcile. The audit summary in the superseded issue reported 30 of 30 checks passing while tabulating 25. The five unlisted checks cannot be identified from the published record, so this reissue reports what the table contains, which is twenty-five checks, and records the discrepancy in section 15 rather than repeating a total it cannot support.

10.1 Errors the audit found

The audit was not merely confirmatory. Two defects were discovered by running it, both of which had propagated into published figures.

- **Habitat volume.** The mass-budget note read about 70 m³ while the same file computed 91.2 m³ from the habitat geometry, and the specification carried the 70 figure forward. Corrected to 91.2 m³ gross and 18.2 m³ per crew, which is better than published: it moves the configuration from 30% below NASA long-duration guidance to roughly 10% below.

- **Residual ram-pressure error.** The factor-of-134 correction had been applied in one source file but not in the two that computed the crewed and ship configurations, which still derived magsail thrust from interplanetary magnetic pressure. All crewed transit figures in those files were understated by 134 times. Now corrected, and the audit searches every source file for the wrong expression so it cannot recur.

Method note. The second defect passed a naive audit because the JSON output was internally consistent: the file agreed with itself while disagreeing with physics. Cross-file coherence checks were added specifically for this, so the harness now inspects source code for the incorrect pressure expression and not only the numerical outputs.

11. Corrections register

Errors found and fixed during the investigation, with the mechanism of each. The register in the Specification section 17 is the same list carried to fourteen entries; the twelve below are those that fall within the scope of this document.

Corrections register. Entries 13 and 14, the withdrawn attitude-authority claim and the replacement of the superconducting coil by the RMF antenna, are in the Specification section 17 because they are configuration changes rather than calculation errors.

#	Previously	Corrected to	Mechanism of error
1	Alternating ring polarity	Aligned	wrong reading of source geometry
2	Tension release as ejection	Sequential firing	azimuthal E not recognised
3	Counter-rotation cancels	$\eta = 0.381$	tested only at 0.0067 wavelength; scale artefact
4	Scan covered handedness	It did not	the rotation matrix never conjugates
5	1 MW reactor	100 kWe	sail is area-limited, not power-limited
6	Mission 10 t, budget 29.8 t	Both 8.2 t	inconsistent mass carried between files
7	Thrust per kW radiated	Per kW electrical	conversion efficiency omitted
8	Radiator for reactor only	Reactor and drive	drive waste heat uncounted
9	QUAD acceptance 3.17 m^2	0.000 m^2	a 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 contradicted its source; caught by audit
12	Crew and ship files used IMF pressure	ram pressure	the $134\times$ correction applied in one file but not others

12. Open items not addressed by this test

12.1 Closed by laboratory measurement since Revision C

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

What the detachment measurement does and does not cover.

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 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 remains open below.

12.2 Still open

Open items. The bench test in sections 3 to 7 depends on none of them. That is deliberate: it isolates the one claim that can be settled with existing hardware, and settles it either way.

Item	What it blocks	Method required
Laboratory-to-flight scaling: 50 km/s at high density against 400 km/s at roughly a millionth of the density	every sail mission figure	flight or a facility that can reach the regime
Constant force with distance against $r^{-4/3}$ falloff, a factor of 96 at 30 AU	every transit time beyond Mars	analysis, then flight
Exhaust detachment for the induction thruster	induction thruster efficiency	particle-in-cell, implicit
Exhaust velocity 31 times short for scoop mode	ram-scoop operation only	pulsed-power development
Magsail steering	attitude control with the sail deployed	coil orientation or RMF modulation, as the literature does it
Beam interception on a 30 m vehicle	flight configuration	ray trace, straightforward
Differential spacecraft charging	flight configuration	standard charging analysis
Structural modes under kilohertz pulsing	flight configuration	modal analysis

13. What this plan establishes

- That the central computed claim is testable now, on a bench, for the cost of a small vacuum chamber and a torsion balance, without resolving any open item in the EM-D study.
- That the test is a differential null experiment, in which every systematic known to plague small-thrust measurement is common-mode to firing order and cancels in the difference, while the effect under test is the only thing in the apparatus that changes sign with it.
- That the predicted signal sits two to four orders of magnitude above the instrument noise floor, so a clean null would refute the claim rather than leave it open.
- That the acceptance criteria are fixed in advance, including the criterion under which the result must not be called propulsion.

- That the computed record behind the claim is complete, including ten negative results and twelve corrected errors.

14. What this plan does not establish

- That sequential induction produces thrust. Nothing here has been measured. The document is a proposal to find out.
- That the predicted magnitude is right. It comes from a test-particle calculation in a prescribed field, with no feedback from the plasma current onto the field. The self-consistent calculation was attempted and did not converge.
- That the bench result, whatever it is, would transfer to flight. The article is a 0.15 m ring in a chamber; the vehicle is a 10 m ring in the solar wind.
- That the verification audit covers the current configuration. It was run against the Revision C mass budget, three of its rows are superseded, and it has not been re-run.
- That the code is correct beyond the checks listed. The audit compares the documents against the code and the code against analytic limits where those exist. No independent reimplementations have been made.

15. Honest scope and limitations

This document is worth what a pre-registration is worth: it fixes the prediction, the method and the acceptance criteria before any measurement exists, so that a later result cannot be reinterpreted to fit. That is its entire contribution. It is not evidence.

- **Nothing has been run.** Every predicted value, every control outcome and every significance in this document is simulation output. No chamber, balance, plasma source or sequencing electronics has been procured.
- **An unreconciled count.** The superseded issue reported 30 of 30 audit checks passing while tabulating 25. This reissue tabulates the 25 that are on the record. The five unlisted

checks are not identifiable and the audit should be re-run and re-published before any count is quoted.

- **A stale audit.** The audit predates Revision D by two days and checks the Revision C mass. Three rows are marked superseded here. The correct remedy is to re-run the harness against the Revision D configuration, which has not been done.
- **An unbounded term in the error budget.** Chamber wall charging is entered as unknown. Until it is estimated, the no-plasma control is the only defence against a false positive from it.
- **Instrument figures are targets.** The balance resolution, delay jitter and calibration accuracy in section 6 are requirements on equipment not yet selected, not measured performance of a specific instrument.
- **The prediction carries an unquantified modelling error at bench scale.** The point-dipole treatment is pressed harder at 0.15 m ring radius than at 10 m, and the resulting error in predicted null position and core field has not been computed. Section 3 records this against the acceptance criteria, where it matters: a factor-of-two disagreement might be the model rather than the physics.

References

- Slough, J. (2007). Plasma Magnet. IEPC-2007-015, 30th International Electric Propulsion Conference. The only laboratory measurement referenced in the EM-D document set.
- EM-D Stream: Design Specification (EMD-SPEC-001 Revision D). The design of record, including the configuration and mission figures this plan does not test.
- EM-D Stream: Mathematical Supplement (EMD-MATH-001 Revision D). Derivations behind the predicted signal, the assumptions they rest on, and where they stop being valid.
- EMD-TEST-001, issue of 18 August 2026, companion to EMD-SPEC-001 Revision C. Superseded in its entirety by this document.