

Technical Note TN-02: Permanent Magnet Architecture for an AF-MPD Thruster

Settled Design Configuration for Continuous Operation, with the Magnetic, Thermal
and Discharge Analysis Behind It

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Abstract

This note specifies the permanent magnet subsystem for a 1–5 kW breadboard applied-field magnetoplasmadynamic thruster running on argon, for **continuous** operation, and reports the analysis that backs it. It answers three questions. Can permanent magnets make a strong enough field: yes, 0.631 T at the cathode tip with the magnets at their solved operating temperature, against a 0.40 T floor. Where does the heat go when the thruster runs continuously: axially backwards out of the anode, through a full diameter copper spreader, into an external cold plate, which holds the magnets at 72 °C and the anode at 288 °C with 488 of 500 W leaving through the rear face. And would the thruster work: the discharge model, the magnetic nozzle and a fit to 667 published argon runs all say yes, with a predicted thrust of 186 mN at 100 A. The complete assembly is 7.17 kg and 114 mm across. One requirement is not met and it is stated plainly in Section 6: the recommended build holds its field uniform over 31.5 mm of channel against a written requirement of 40 to 70 mm. Twelve millimetre end caps in place of sixteen meet both, at the same mass, in the same envelope, for 0.511 T. That is the single decision to settle before the magnets are ordered, because magnetisation and thickness are both fixed at manufacture.

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1 Scope and Design Requirements

1.1 Context

This activity supports a 1–5 kW class breadboard electric thruster using argon as propellant. Argon is roughly a thousand times cheaper than xenon and carries none of the supply difficulty of the noble gases used in Hall-effect thrusters, but it does not perform well in a conventional Hall thruster, which is why applied-field magnetoplasmadynamic operation is being pursued instead.

An AF-MPD thruster needs a strong axial magnetic field. Most published work produces it with a solenoid, which brings power and cooling that a small spacecraft does not have. This programme therefore uses a Halbach array of permanent magnets.

1.2 Continuous Thermal Operation and Boundary Conditions

The target application is orbit raising, where **continuous thrust is a key requirement**. Under continuous operation, transient thermal capacity is insufficient to protect the magnetic subsystem: the outer casing would have to reach about 415 °C to radiate the 500 W arc heat load passively, whereas sintered NdFeB grade N48UH degrades above 180 °C and is destroyed at its Curie point of 310 °C.

The design targets are established accordingly: **0.40 T on-axis is a floor, not a ceiling**, with 0.70 T named as the goal, provided the required field shape is preserved. To protect the permanent magnets under steady-state conditions, heat is drawn **axially backwards** out of the anode into the rear mounting face and handed off there to an external cold plate. Everything inboard of that hand-off face is the scope of this technical note.

1.3 The three questions, and where they are answered

Table 1: What was asked, and where the answer is.

Question	Section	Short answer
Can permanent magnets make the field?	3, Magnetic Field	0.631 T hot at the tip
Where does the heat go continuously?	4, Thermal Design	488 of 500 W out of the rear face
Would the thruster actually work?	5, Whole System	186 mN predicted at 100 A

1.4 Requirements this note is judged against

- **Field strength.** Axial flux density at the cathode tip not less than 0.40 T, with 0.70 T as the goal, *with the magnets at their operating temperature*.
- **Field shape.** That field held reasonably uniform over a continuous acceleration length of 40 to 70 mm.
- **Magnet temperature.** 100 °C design target against a 180 °C material rating, in continuous operation.
- **Mass.** 7.5 kg for the complete assembly.

2 The Recommended Build

One build is recommended. It came out of a sweep of 143 magnetostatic cases and 84 thermal cases, judged on the field at the cathode tip once the magnets are at their solved operating temperature, against the 0.40 T floor, the magnet temperature limit and the mass limit. Eighteen builds meet all three; this is the strongest of them.

2.1 Geometry

Two-dimensional axisymmetric. $z = 0$ is the **front face of the mounting plate**, the surface the plasma sees, and $+z$ is the exhaust direction. That is the datum on every drawing in this package.

Table 2: Radial build at the anode station. Every figure in the left column is a radius; the drawings dimension diameters.

Radius (mm)	Feature	Material	Drawing
0 to 3.175	cathode rod	W, 2% thoriated	AFMPDT3-010
3.175 to 13	discharge bore	argon	—
13 to 15	anode, 2 mm wall	Cu OFHC C101	AFMPDT3-002
15 to 16	evacuated thermal break	vacuum	—
15.35 to 15.65	radiation shield, 0.3 mm	304 stainless, polished	AFMPDT3-005
16 to 18	standoff sleeve	Macor MGC	AFMPDT3-005
18 to 47	magnet tiles, 40 off	NdFeB N48UH	AFMPDT3-003
47 to 57	return casing, 10 mm wall	1010 / DC01 steel	AFMPDT3-004

Table 3: Axial build. The three rear layers constitute the axial thermal conduction architecture, providing the complete thermal management solution.

z range (mm)	Feature	Drawing
−18 to −16	isolation plate, aluminium nitride, full diameter	AFMPDT3-008
−16 to −10	spreader, copper, full diameter	AFMPDT3-007
−10 to 0	mounting plate: copper hand-off boss to $r = 17$, Macor magnet shelf from $r = 18$	AFMPDT3-006
0 to 50	anode barrel; cathode tip at $z = +50$	AFMPDT3-002
0 to 80	magnet stack, sleeve and casing	AFMPDT3-003
80 to 86	front retaining ring	AFMPDT3-009

The 1 mm radial gap between the copper boss and the Macor shelf is a **thermal choke**. It stops the hand-off path from feeding heat sideways into the magnet shelf, and it is worth about 10 K on the magnets.

2.2 Magnetisation, which is the one thing that cannot be corrected later

Table 4: Magnetisation of each ring. This is the most build-critical information in the package.

Ring	z range (mm)	Magnetisation	Tiles
1, rear cap	0 to 16	radially outward	8
2, 3, 4, core	16 to 64	axial, toward the exhaust	24
5, front cap	64 to 80	radially inward	8

Magnets are magnetised at manufacture and cannot be re-polarised afterwards. If the two end cap rings are ordered or fitted the other way round, the field at the cathode tip falls from 0.669 T to 0.072 T, a factor of five, and the thruster fails its field requirement before it is ever powered. This is the single most likely way to waste a magnet order.

Three things guard against it. The directions are on drawing AFMPDT3-003 as arrows on three end views and again as a written schedule; each tile carries a part suffix, -R, -A or -F, which appears in the parts list and has to appear on the purchase order; and the built stack is checked with a gaussmeter down the bore before the thruster is fired, which catches the error if the first two guards fail.

2.3 Mass

Table 5 is the complete assembly, computed part by part from the drawing dimensions by `scripts/report_bom.py`. The solved geometry, which is idealised rings with no holes in them, comes to 7.156 kg; the difference of 0.018 kg is the cathode bore, the gas plenum, the fasteners and the insulating bushes, none of which are in the model.

Table 5: Bill of materials for the recommended build. Masses in grams, totals for the quantity shown.

Item	Description	Material	Qty	Mass g	Drawing
1	Mounting plate, hand-off boss	Cu OFHC C101	1	74.7	AFMPDT3-006
2	Mounting plate, magnet shelf	Macor MGC	1	229.2	AFMPDT3-006
3	Anode barrel, 2.0 mm wall	Cu OFHC C101	1	78.8	AFMPDT3-002
4	Radiation shield, 0.3 mm wall	304 SS, polished	1	11.7	AFMPDT3-005
5	Standoff sleeve	Macor MGC	1	43.1	AFMPDT3-005
6	Magnet tile, rear cap, RADIAL OUT	NdFeB N48UH	8	710.6	AFMPDT3-003
7	Magnet tile, core, AXIAL +z	NdFeB N48UH	24	2131.9	AFMPDT3-003
8	Magnet tile, front cap, RADIAL IN	NdFeB N48UH	8	710.6	AFMPDT3-003
9	Iron return casing, 10 mm wall	1010 / DC01 steel	1	2047.4	AFMPDT3-004
10	Front retaining ring	304 SS	1	425.0	AFMPDT3-009
11	Spreader, full diameter	Cu OFHC C101	1	531.0	AFMPDT3-007
12	Isolation plate	AlN, sintered	1	65.5	AFMPDT3-008
13	Cathode rod, 6.35 dia	W, 2 % ThO2	1	58.7	AFMPDT3-010
14	Cathode insulating bush	Macor MGC	1	1.3	AFMPDT3-010
15	Screw insulating bush	Alumina 99.7 %	6	2.4	AFMPDT3-007
16	ISO 4762 M4 x 30 socket head	A2-70	6	28.2	standard
17	ISO 4762 M4 x 16 socket head	A2-70	6	16.8	standard
18	ISO 7089 4 mm flat washer	A2	12	4.2	standard
19	Feed tube stub, 1/8 in x 0.7 wall, brazed	Cu	1	3.0	AFMPDT3-007
Complete assembly				7174	

7.17 kg against a 7.5 kg limit, in a 114 mm outside diameter, 104 mm long from the hand-off face to the front of the retaining ring.

There is no PEEK anywhere in the assembly. Rather than using an external manifold, the gas plenum is integrated directly as an annular groove in the copper spreader, with injection holes machined through the hand-off boss. The two insulating parts incorporated into the assembly are the cathode bush (Macor MGC) and the six screw bushes (high-purity alumina). Both are vacuum compatible and match materials proven elsewhere in the thruster.

3 The Magnetic Field

3.1 What the recommended build produces

Figure 1 is the field on the axis, cold and at the magnets' solved operating temperature, and Figure 2 is the flux path that produces it.

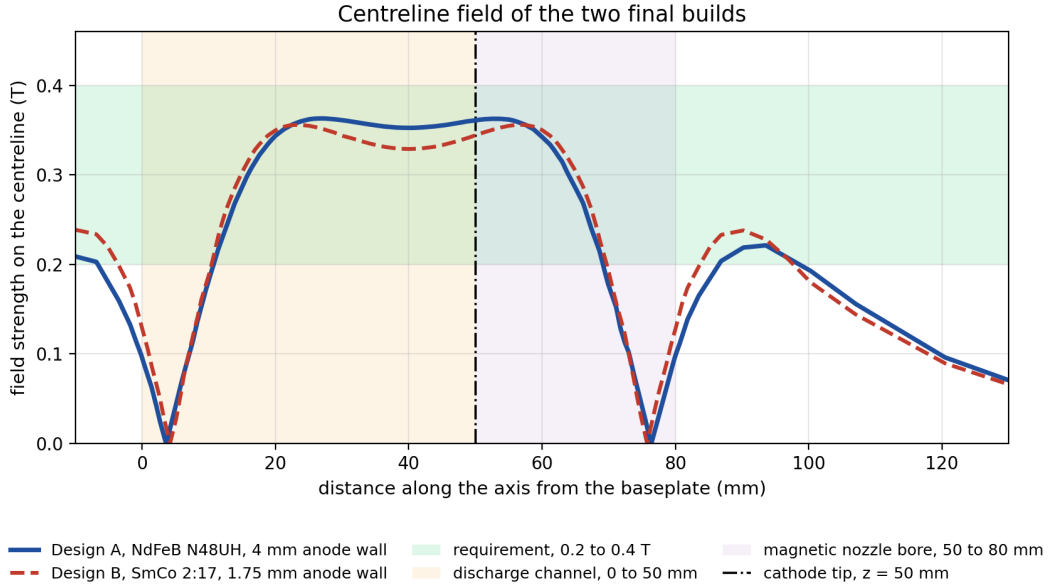


Figure 1: Centreline field of the recommended build. At the cathode tip it reaches 0.669 T cold and 0.631 T with the magnets at the 72 °C the thermal model solves for. The whole channel from $z = 20$ to $z = 50$ mm stays above 0.50 T hot, well clear of the 0.40 T floor. A baseline unoptimised Halbach configuration is shown for contrast at 0.359 T. The staircase on the curves is the 0.8 mm axis mesh, not a feature of the field.

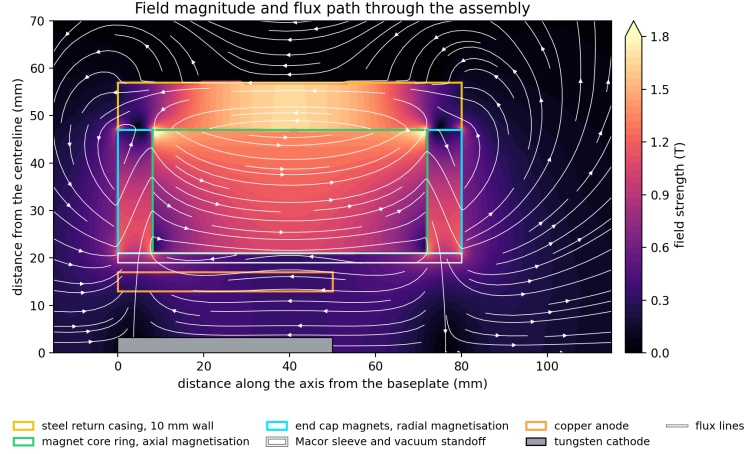


Figure 2: Flux leaves the core ring, runs axially along the steel casing, re-enters through the end caps and crosses the bore. That crossing is the field the discharge sees, and it is the reason the end caps matter so much: without them a magnet tube has almost no bore field at all. The full field map was exported for three builds; this is the nearest to the recommended one and differs only in cap thickness.

Table 6: Field of the recommended build, on the axis. Hot figures are the cold solution scaled by the remanence coefficient at the solved magnet temperature; that scaling is checked against solved hot cases in Section 3.2.

Quantity	Cold, 20 °C	Hot, 72 °C
$ B_z $ at the cathode tip, $z = 50$ mm	0.669 T	0.631 T
Mean over the channel, $z = 20$ to 50 mm	0.657 T	0.619 T
Weakest point in the channel	0.534 T	0.503 T
Strongest point, at $z = 37$ mm	0.677 T	0.638 T
Ripple over the channel	21.9%	
Length held within 10% of the peak	31.5 mm	
Peak flux density in the steel casing	1.58 T	

Three things follow.

The field requirement is met with margin. Every point in the 30 mm discharge channel is above 0.50 T hot, against a 0.40 T floor. The thruster does not merely scrape the requirement at one probe point.

The iron is not saturated. The peak flux density in the casing away from the magnetisation corners is 1.58 T against a saturation knee near 2.1 T, so the return path works in its linear region and the field is set by the geometry rather than by the steel grade or its temperature. The raw maximum over the whole casing reads 2.51 T, but that is a mathematical singularity at the four lines where a radially magnetised cap meets an axially magnetised core against the casing bore. It does not converge under mesh refinement: measured 2.44 T at a 1.5 mm element and 2.97 T at 0.25 mm, still climbing. Real sintered tiles have a finite transition region and no such line exists, so the corner-excluded figure is the one that answers the question, and it is stable to four figures across a fourfold mesh refinement.

The uniform region is 31.5 mm, and the requirement is 40 to 70 mm. This is the one requirement the recommended build does not meet. Section 6 deals with it, because the fix is cheap and it has to be decided before the tiles are made.

3.2 Verification

Figure 3 shows the cross-code benchmark between independent COMSOL and FEMM implementations. The models were constructed independently in two distinct solvers using identical baseline geometry and material definitions.

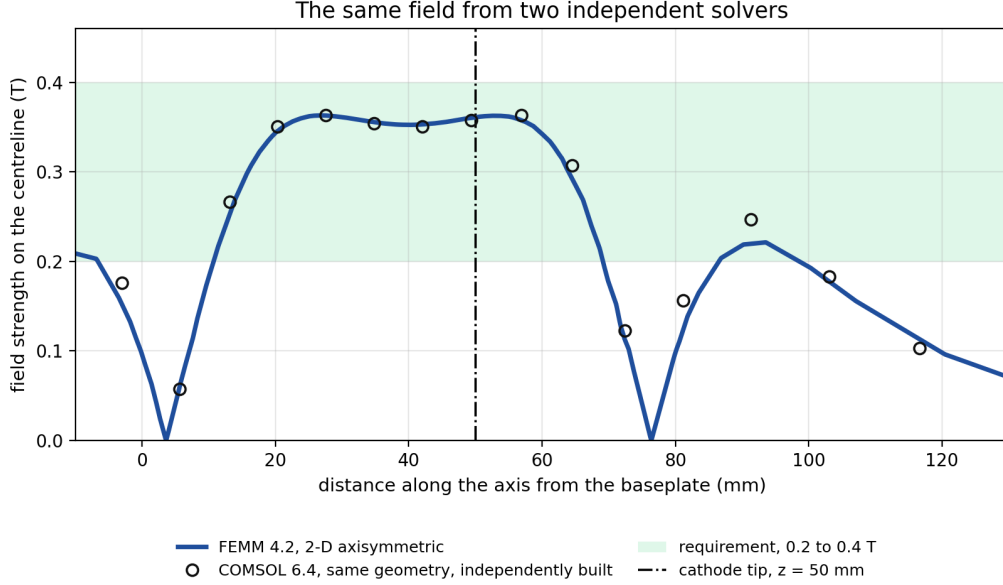


Figure 3: Cross-code verification: FEMM 4.2 against COMSOL 6.4 on the baseline magnet stack. They agree to better than half a percent through the channel. This serves as a benchmark test ensuring solver fidelity before parametric sweeps are executed.

Table 7: The four checks the field results rest on.

Check	What was done	Result
Two independent codes	FEMM and COMSOL on identical geometry, models built separately	0.359 T against 0.361 T
End cap polarity	The same stack solved with the caps reversed, as an enforced ratio rather than an absolute	factor of 5.0
Remanence scaling	The hot field scaled from the cold solve, against a uniform temperature sweep at 60, 100, 140 and 180 °C	0.3% worst case
Scaling against a coupled solve	The same scaling against the thirteen cases solved with both physics together in the same temperature band	0.1% high to 1.4% low
Iron saturation	Peak flux with a 1 mm skin around the magnetisation corners excluded, across a fourfold mesh refinement	stable to four figures

The remanence check matters because every hot field in this note is a cold solve scaled by $1 + \alpha_{Br} \Delta T$ with $\alpha_{Br} = -0.11\%$ per kelvin, using the *peak* magnet temperature. Two things have to hold for that, and they are separate.

The field has to be linear in remanence. It is: over the 52 K rise this design sees, scaling the cold solve reproduces the separately solved uniform temperature cases to 0.03%.

And the peak has to stand in for a stack that is not isothermal. This one runs from 60 °C in the front cap ring to 72 °C in the rear, and scaling by the hottest point treats all of it as the hottest point. Measured against the thirteen cases that were solved with both physics coupled, in the same temperature band, scaling by the peak lands between 0.1% high and 1.4% low, and low in twelve of the thirteen. **So 0.631 T is a slightly conservative figure rather than an optimistic one**, and a coupled solve of this exact build would be expected to return between 0.631 and 0.640 T.

3.3 Demagnetisation

The magnets sit in their own reversed field, so the working point has to be checked against intrinsic coercivity rather than assumed safe. Figure 4 is that check.

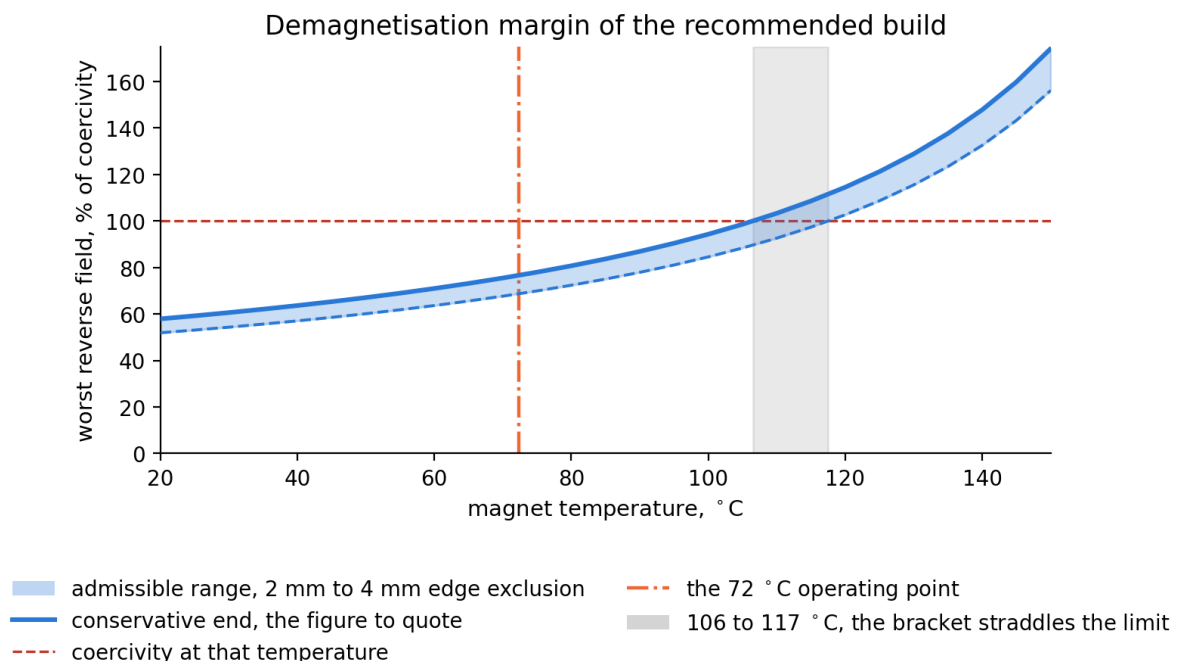


Figure 4: The worst reverse field anywhere in the magnet body, as a percentage of the coercivity at that temperature. At the 72 °C operating point the conservative reading is 77% and the wider one 69%, so the margin is at least 23% and no part of the magnet body is past coercivity. The demagnetised volume fraction is zero.

The reverse field is singular at eight edges, where the cap and core magnetisations meet and where the magnetisation stops at the ends of the stack. Masking a skin around those edges does not converge: a sweep from 0.5 to 10 mm falls monotonically the whole way, because unlike the iron singularity, which sits on isolated points, the magnet reverse field is largest along an extended region of the bore. So the pair of mask widths is a *bracket*, not a convergence test.

It is still enough to answer the question, for two reasons. Every mask below 2 mm returns a field above the physical self-demagnetisation bound B_r/μ_0 and is therefore still reading the singularity, which puts a floor on the admissible range. And widening the mask only ever reduces the magnitude, which makes the narrow end the conservative one. **Quote bounds, not values:** “at least a 23% margin at the operating point” is safe and “a 23% margin” is not. Between about 106 and 117 °C the two widths straddle the limit and nothing should be quoted there at all. That is well clear of the 72 °C the design runs at.

4 Thermal Design

4.1 Thermal Management Requirements and Architecture Trade

For continuous operation, relying on transient thermal mass to absorb the 500 W arc deposition is unfeasible. Figure 5 evaluates four rear interface architectures side by side under continuous 500 W load.

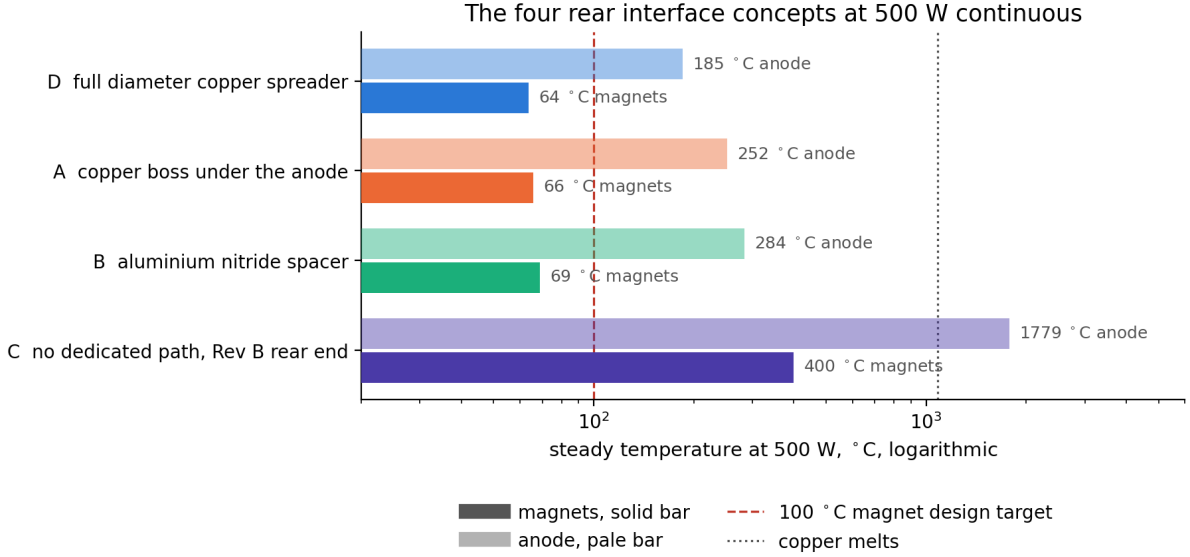


Figure 5: Evaluation of four rear interface concepts at 500 W continuous thermal load on a logarithmic scale. Concept C represents an uncooled baseline without axial heat extraction: the anode reaches 1779 °C (exceeding copper’s melting point) and magnets reach 400 °C (exceeding Curie temperature). Concepts A, B, and D all successfully maintain the magnets between 64 and 69 °C.

The four are compared on one common radial build, with a 4 mm anode wall and a 2 mm break, so that the only thing that differs between them is the rear end. The recommended build has a thinner anode and a narrower break and therefore runs hotter than the Concept D bar shown here; its own temperatures are in Table 8.

Concepts A, B and C are the three the brief asked for. **D was added**, and the reason is arithmetic worth keeping. Concept A hands the heat off over the anode footprint only, an annulus of $1.1 \times 10^{-3} \text{ m}^2$. Spread the same heat over the full 114 mm rear face, $1.0 \times 10^{-2} \text{ m}^2$, and the same interface coefficient is nine times better. That is the argument, and it costs one copper disc.

The run says the argument is directionally right and quantitatively overstated, and that is worth knowing. Concept A does not fail: it puts the magnets at 66 °C and the anode at 252 °C, against 64 and 185 for Concept D. The small footprint costs 67 K on the anode, not the hundreds of kelvin the area ratio implies. What rescues it is the isolation plate, which is aluminium nitride at 170 W/(m·K) running the full diameter, so it spreads the heat before the cold plate whatever sits above it. **Concept D is still the better build and is the recommended one**, but the margin is 67 K on the anode rather than a pass and a fail.

The obvious objection to Concept D is that a copper disc at full diameter sits directly behind the magnets, which is exactly the leak path the brief warns about. But the disc runs between 63 and 83 °C, not 400. The magnets sitting on a 10 mm Macor shelf above it do not care. **The conflict between getting the heat out and keeping it off the magnets is far weaker than it looks, as long as the spreader runs cold.**

4.2 What the recommended build actually does

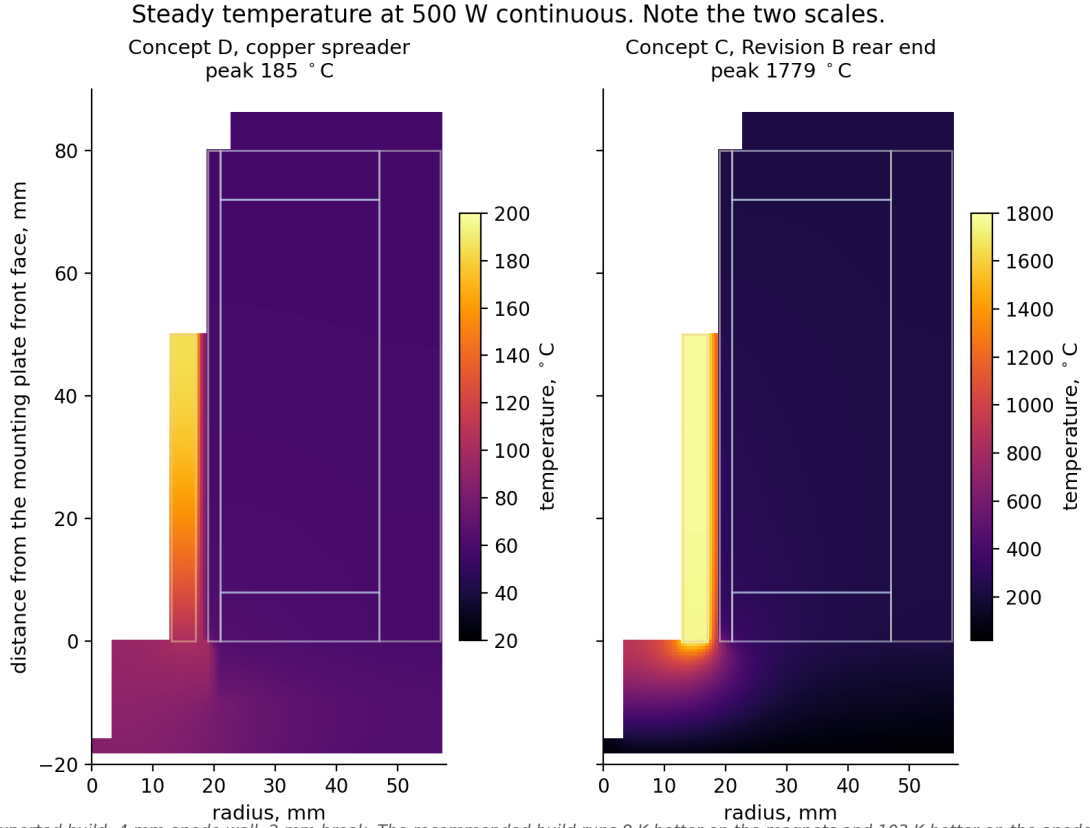


Figure 6: Steady-state temperature distribution at 500 W continuous: settled Concept D architecture compared to the uncooled baseline configuration. Note the distinct colour scales reflecting a tenfold thermal divergence. In Concept D, heat conducts axially backwards through the anode and dissipates across the rear stack, keeping all components outboard of the thermal break near 60 °C.

Table 8: Steady temperatures of the recommended build at 500 W continuous, with the rear interface at 1000 W/(m²·K).

Location	Peak, °C	Minimum, °C
Anode, at the exit plane	288	110
Radiation shield	135	106
Standoff sleeve	106	59
Magnets, rear cap ring	72	61
Magnets, core rings	66	60
Magnets, front cap ring	60	60
Iron casing	62	60
Macor magnet shelf	83	61
Isolation plate	89	62
Cold plate face	63	

The magnets peak at 72 °C against a 100 °C design target and a 180 °C rating. The hottest magnets are in the rear cap ring, nearest the hand-off, which is why the Macor shelf under them is deliberately not a conductor.

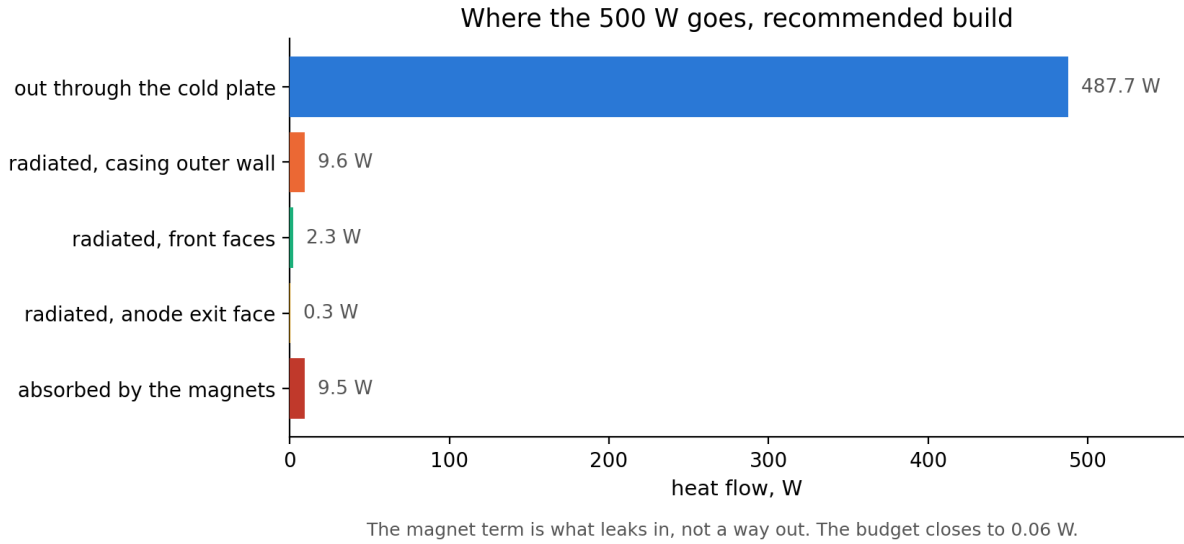


Figure 7: Where the 500 W goes in the recommended build. Almost all of it leaves through the cold plate; 9.6 W radiates from the casing outer wall, and 9.5 W leaks into the magnets. That last term is not a way out, it is what gets in. The budget closes to 0.06 W here and to better than a third of a watt on every one of the 84 thermal cases, which is the check that the model conserves energy.

4.3 Why these dimensions, and not thicker ones

The central design tension is that both thermal levers, a thicker anode wall and a wider evacuated break, push the magnet bore outwards, and the bore field of a Halbach stack falls steeply with bore radius. Figure 8 is that trade measured rather than argued.

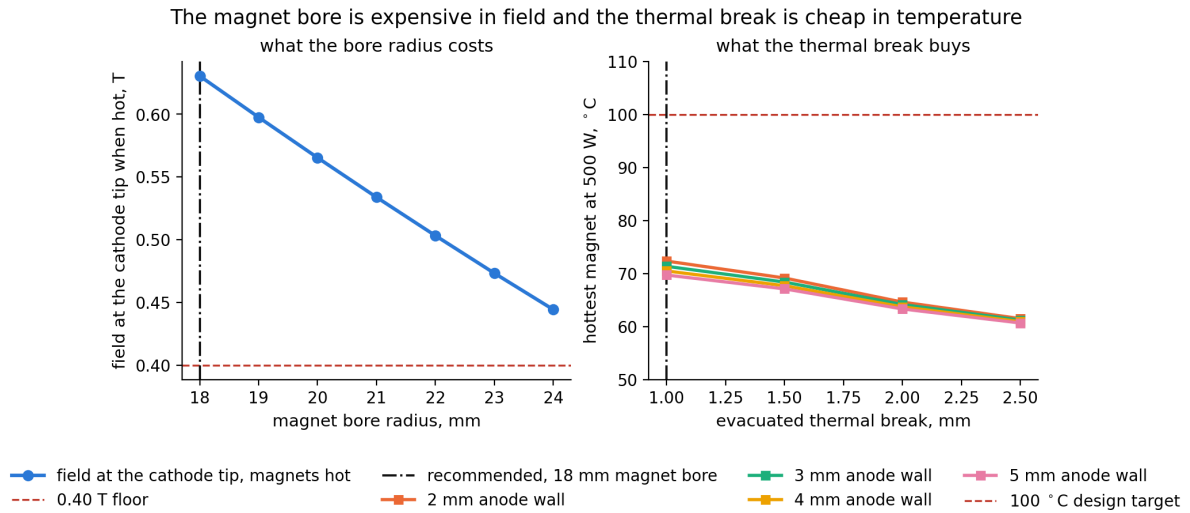


Figure 8: Left: field at the cathode tip against magnet bore radius. Every millimetre outwards costs about 0.031 T. Right: the hottest magnet against the width of the evacuated break, for four anode wall thicknesses. Widening the break from 1.0 to 2.5 mm buys 11 K and costs 0.05 T, and the 11 K is margin the design does not need.

Table 9: Anode wall thickness against the two temperatures it sets, at a 1 mm break. The wall is the anode’s own conduction path to the rear. The field column is read off the magnet bore radius, because nothing between the bore and the magnets is magnetic, so a millimetre of copper and a millimetre of vacuum cost exactly the same field.

Anode wall	Hottest anode, °C	Hottest magnet, °C	Cold field, T
2 mm	288	72	0.669
3 mm	220	71	0.634
4 mm	185	71	0.600
5 mm	163	70	0.566

The 2 mm wall is chosen because 288 °C is comfortably below the 400 °C at which copper begins to soften, and because each millimetre of wall costs 0.035 T while buying nothing at all on the magnets. The anode is the only part that gets hot, and it has 112 K of margin.

The evacuated break is kept at 1 mm for the same reason. It does most of the work of keeping heat off the magnets: at mid channel the anode outer wall sits at 244 °C and the sleeve bore at 62 °C, so 1 mm of vacuum drops 182 K. Widening it to 2.5 mm buys a further 11 K on the magnets and costs about 0.05 T. The 0.3 mm polished radiation shield inside it is worth about 1 K and may be deleted without consequence if the 0.35 mm clearance each side proves awkward to build.

4.4 The requirement this design places on somebody else

Everything above assumes the external interface at $z = -18$ mm can take the heat away. It is modelled as a contact coefficient and swept over a factor of fifty, because nobody knows it yet.

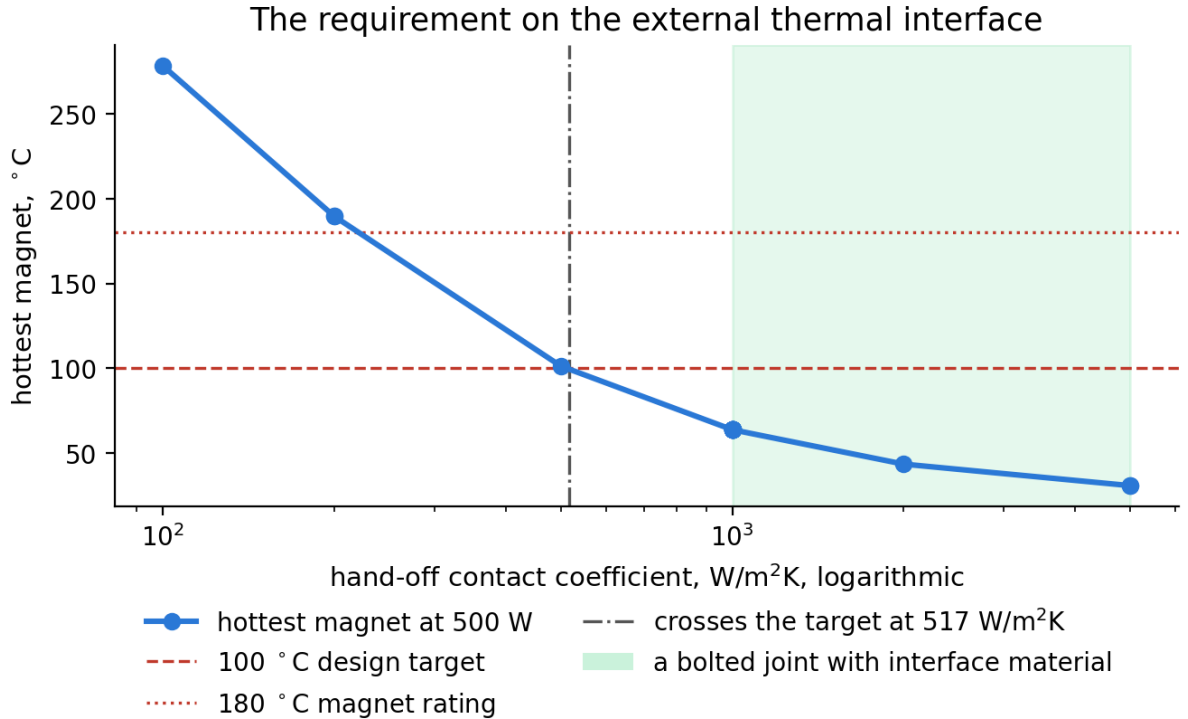


Figure 9: The single number to hand to whoever designs the cold plate. Below about 520 $W/(m^2 \cdot K)$ the magnets pass the 100 °C design target; above about 2000 the design has margin to spare. A bolted joint with a thermal interface material lands between 1000 and 5000, so the requirement is achievable, but it is a requirement and not an assumption.

Specify 1000 W/(m²·K) or better at the hand-off face. That is the value every number in Table 8 is computed at, and it is a routine figure for a bolted joint with interface material. The sweep was run on the 4 mm anode build; the recommended build runs about 9 K hotter on the magnets, so treat the 520 W/(m²·K) crossing as an absolute floor rather than a target.

4.5 If 500 W is wrong

The nominal design point assumes 500 W of arc power deposited into the anode. For a 1 to 5 kW class thruster the real figure could be several times that, so the sweep runs to 1500 W.

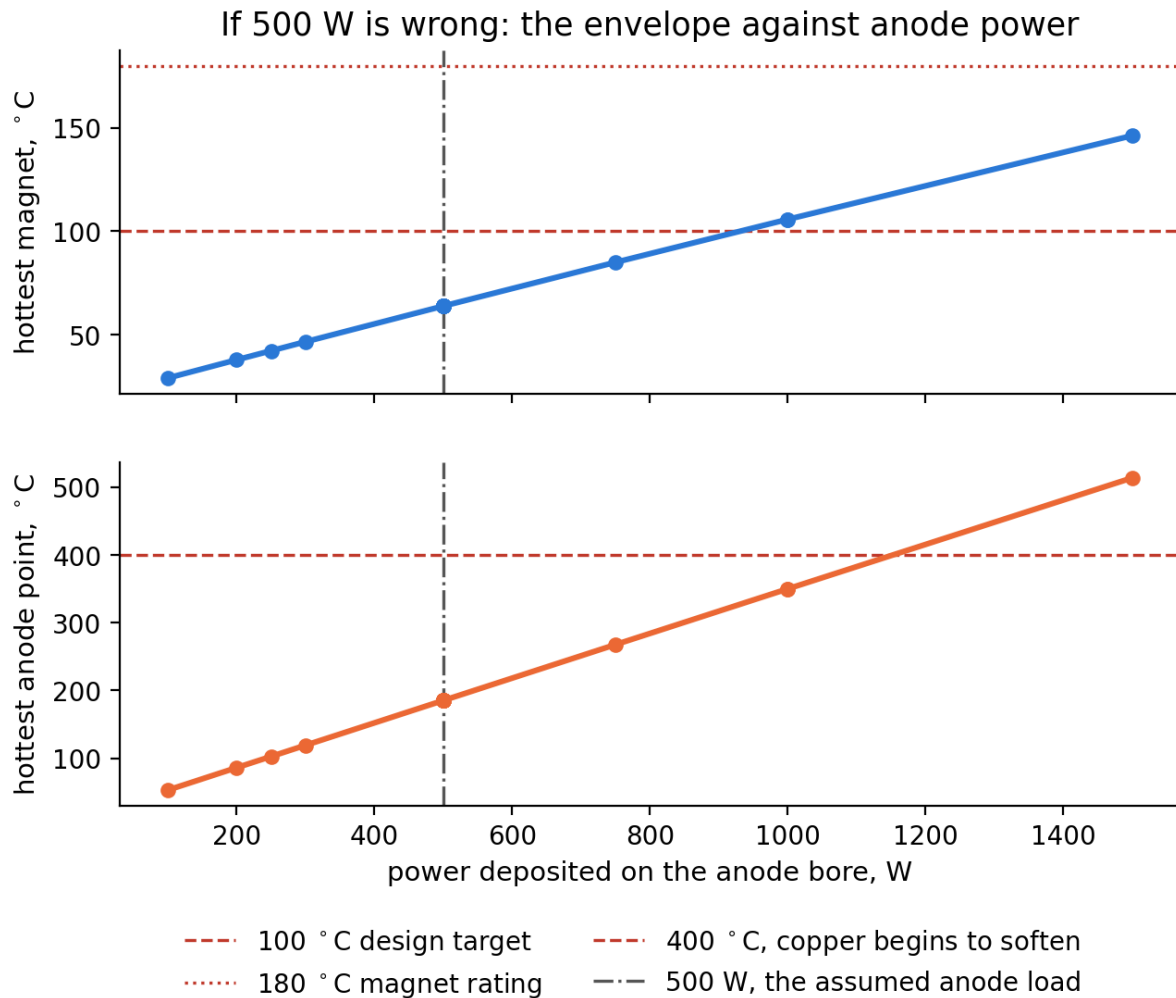


Figure 10: Operating envelope against anode power, for the 4 mm anode wall the sweep was run on. At the design interface coefficient the magnets stay inside the 100 °C target to about 900 W and inside the 180 °C rating well beyond 1500 W, and the anode reaches 400 °C near 1150 W. The recommended 2 mm wall runs hotter: scaling its 500 W result gives 100 °C magnets near 760 W and a 400 °C anode near 700 W.

4.6 What the thermal model does and does not include

Stated plainly, because a reader who does not know these will over-trust the numbers.

- **The evacuated break is modelled as a conducting solid** whose conductivity is the linearised radiation analogy $k = 4\sigma FtT^3$, which is exact for grey diffuse exchange between

long concentric cylinders. The shield splits it into two such exchanges in series. One case was checked against a true surface-to-surface solve: 62.1 °C against 63.7 °C on magnet peak temperature, a difference of 2.6%, with 0.99 W crossing the voided gap, which is also the proof that the radiation features were live rather than silently doing nothing.

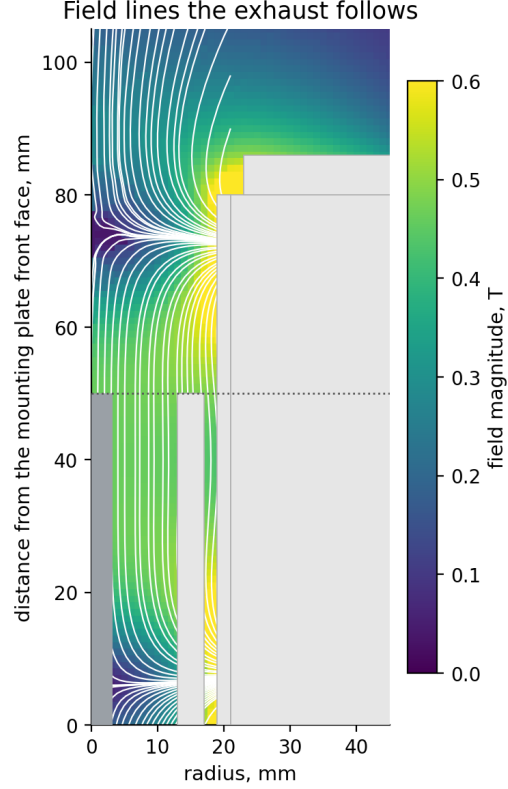
- **Joints inside the assembly are perfect.** No contact resistance between the anode and the mounting plate or between the rear layers. The one interface that is not assumed perfect is the hand-off face itself, which is why it is swept.
- **The cathode is not in the thermal model.** It carries its own heat load and its own conduction path to the rear, and putting it in properly needs a plasma sheath boundary condition that does not exist yet. This is a known omission and it makes the results slightly optimistic.
- **The magnet stack is a smeared ring, not 40 discrete tiles.** Circumferential ripple from the eight-tile rings is not captured by an axisymmetric model. 3D finite-element evaluations confirm that this azimuthal modulation has a negligible effect on the centreline.

5 Would the Thruster Actually Work

A field of the right strength in the right place is necessary and not sufficient. This section is the evidence that the rest of the machine follows.

5.1 The magnetic nozzle

Downstream of the cathode tip the field is no longer confining the discharge, it is steering the exhaust.



Nearest exported build: 12 mm end caps. Hardware is drawn solid; the dotted line is the cathode tip.
The axis mesh coarsens past 60 mm, so the plume is indicative rather than resolved.

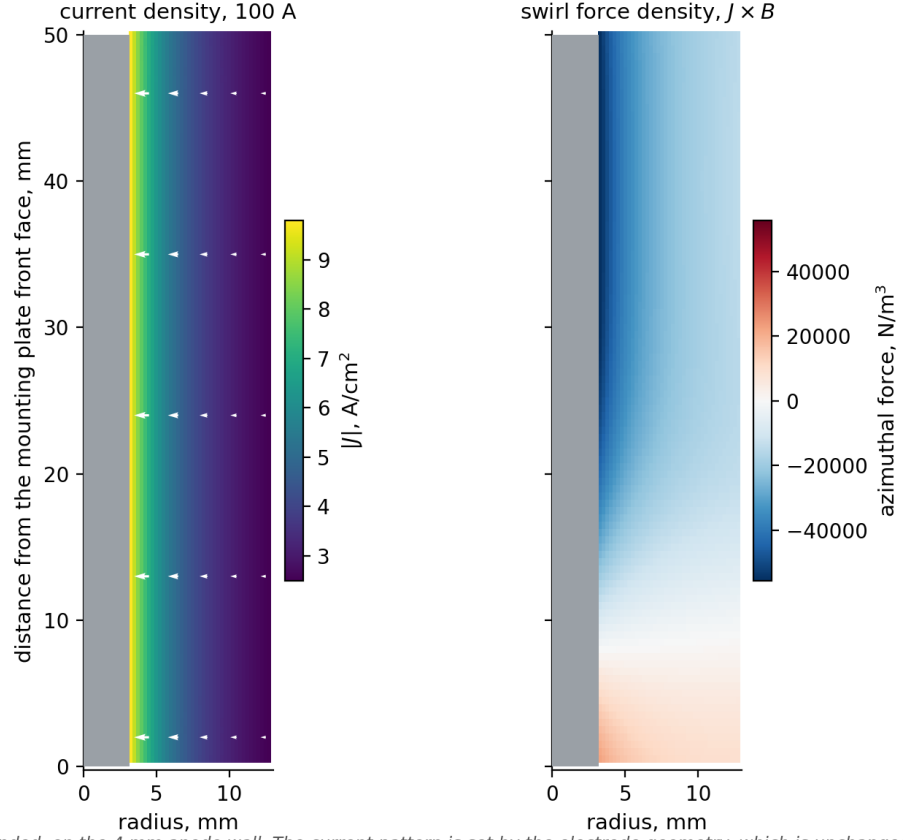
Figure 11: Field lines the exhaust follows. Plasma is tied to field lines, so where the lines go the exhaust goes. They converge through the channel, pass the cathode tip, and then diverge into the plume. No divergence angle is quoted: tracing a line through the field reversal near $z = 70$ mm is ill conditioned and the mesh out there is coarse.

On the centreline the field passes through zero twice, at $z = 8$ mm and $z = 70$ mm. This is intrinsic to a permanent magnet ring and cannot be designed out: inside the bore the field opposes the magnetisation and outside it aligns with it, so a reversal near each end face is unavoidable. Parametric investigations evaluated six end configurations, including substituting either cap with soft iron and incorporating an iron snout; none eliminates the nulls, they merely translate their axial positions.

What can be said instead turns on a distinction worth being careful about: *the centreline is not the discharge*. The cathode is a 6.35 mm tungsten rod running the full length of the anode, so the plasma occupies an annulus from $r = 3.175$ mm out to the anode bore at $r = 13$ mm. The axis inside that rod is solid metal. That places the upstream null *inside the cathode rod*, where no plasma reaches it, and the downstream null 20 mm past the cathode tip, out in the plume and clear of all hardware. In the annulus the plasma actually occupies, the weakest field anywhere is 0.056 T and 98% of the annulus is above 0.1 T. Those two off-axis figures were measured on the 12 mm cap build, which is the nearest one for which the bore was mapped off the axis; they are indicative for the recommended build rather than solved for it.

5.2 Where the current flows and what it does

The discharge, and where it accelerates the propellant



16 mm end caps as recommended, on the 4 mm anode wall. The current pattern is set by the electrode geometry, which is unchanged.

Figure 12: The argon column modelled as a uniform conductor between the real electrode surfaces. Current runs almost straight out from the cathode to the anode wall. Crossed with the applied field it gives an azimuthal force that spins the propellant up, strongest over the downstream two thirds of the channel, and that swirl is recovered as thrust in the nozzle.

This is not a plasma simulation. There is no ionisation, no separate electron and ion temperatures, no sheath physics at the electrodes and no flow. For a medium of uniform conductivity the *shape* of the current pattern is set by the electrode geometry and not by the conductivity value, which is what makes it worth solving without a plasma code, and that shape is a large improvement on assuming the current spreads uniformly.

Two results come out of it that are worth stating. At 100 A the field the discharge makes is **0.33% of the field the magnets make**, so the magnetostatics and the discharge can legitimately be solved in sequence rather than simultaneously; that ratio is computed rather than assumed. And the self-field thrust, the Maecker term that a self-field MPD thruster runs on, is 2.2 mN. **This thruster is applied-field dominated by two orders of magnitude**, which is the whole premise of the programme and is now a number rather than an assertion.

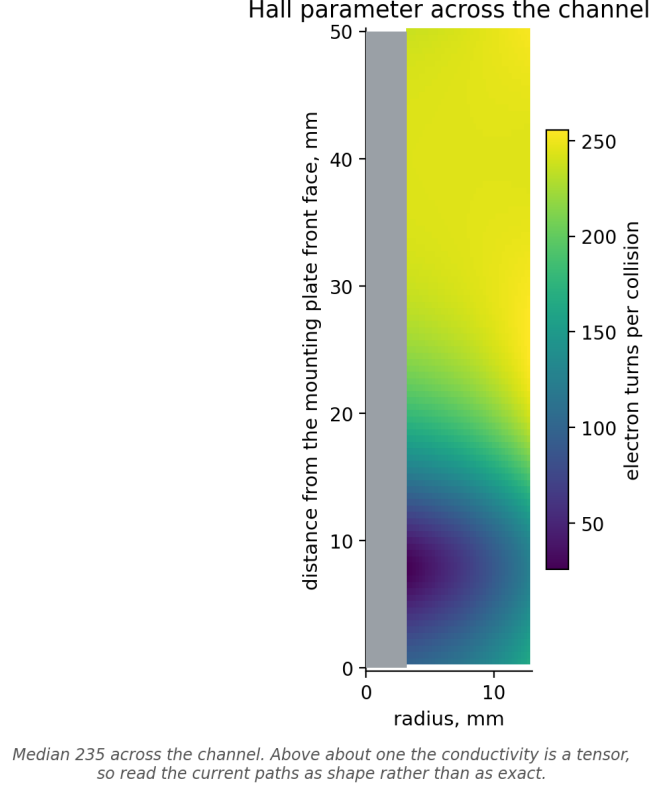


Figure 13: The Hall parameter, the number of turns an electron makes around a field line between collisions. The channel median is 235. This is the honest limitation of the previous figure: above about one the real conductivity is a tensor rather than a scalar, so the current paths should be read as indicative of shape rather than as exact.

5.3 Predicted thrust

Thrust is predicted by interpolating measured hardware rather than by simulating a plasma, because until this thruster exists and is fired there is nothing to validate a plasma model against. The AFMPDT database holds 2672 published runs, of which 667 are argon. Applied-field thrust scales as the product of discharge current, applied field at the cathode tip and anode radius; fitting that scaling to the 62 argon runs nearest this operating point and evaluating it for this geometry gives:

- **Best estimate: 186 mN** at 100 A with 0.631 T at the cathode tip.
- **Likely range: 93 to 226 mN**, from the interquartile spread of the fit residuals.

Two caveats, both real. The fitted runs cover 0.10 to 0.40 T, so 0.63 T is an extrapolation of about 58% beyond the data, and the scaling is linear in field so the extrapolation is at least well behaved. And the spread is wide because the measured data is scattered, which is a feature of AF-MPD performance rather than a shortcoming of the fit. For contrast, an unoptimised baseline geometry yields 106 mN under identical evaluation.

5.4 The feasible set, and the 0.70 T goal

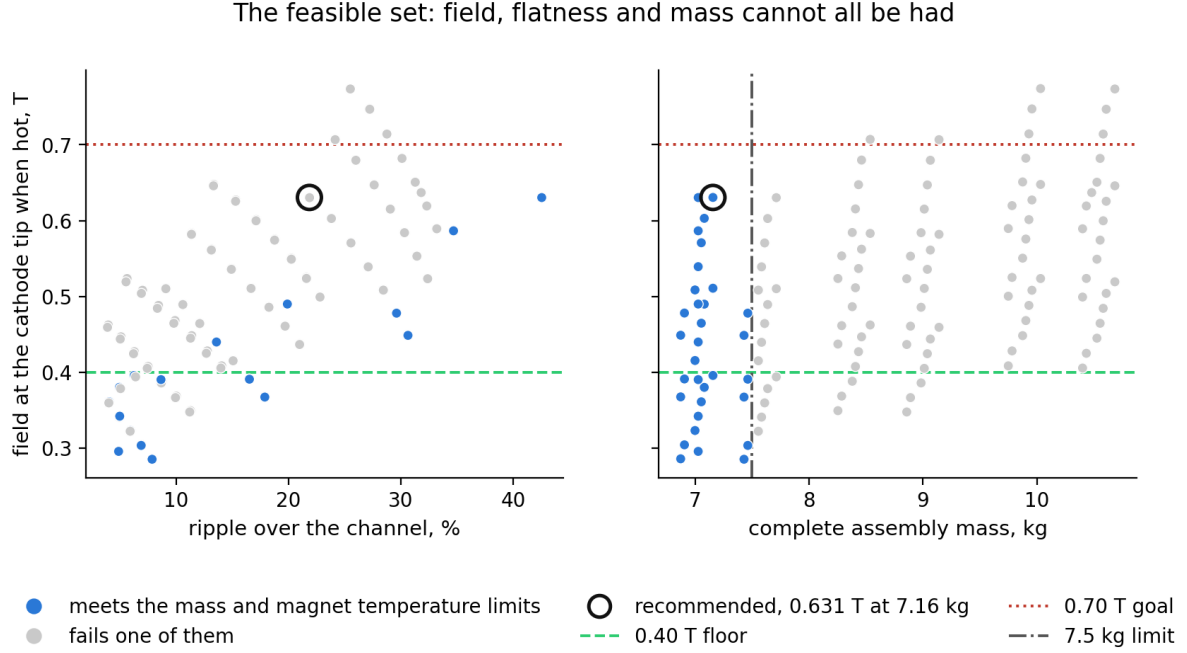


Figure 14: Every one of the 136 cold magnetostatic builds, scaled to its own solved magnet temperature. The recommended build is circled: it is the strongest field available anywhere inside the 7.5 kg mass limit.

The 0.70 T goal is not reachable inside 7.5 kg, and the magnetics are not what stops it. The lightest build in the whole sweep that reaches it gives 0.707 T at 8.54 kg, and it differs from the recommended build in one dimension: the magnet outside diameter goes from 94 to 104 mm, taking the thruster from 114 to 124 mm across. Every other part is unchanged. So the trade the customer faces is 0.63 T at 7.17 kg against 0.71 T at 8.54 kg, and it is a mass decision, not a magnetics one.

6 The One Decision to Settle Before the Magnets Are Ordered

The recommended build meets the field floor with margin, meets the magnet temperature target with margin, and meets the mass limit. It does not meet the field *shape* requirement, and that is worth putting plainly rather than burying.

End cap thickness is the cheapest lever in the whole design and also the most expensive one. Thicker caps push more flux across the bore, which is where the field comes from, but they also concentrate it near the ends, so the profile stops being uniform. Table 10 is that trade at constant mass, in the same envelope, with every other part identical.

Table 10: End cap thickness, with the radial build and the envelope held fixed. Only the tile schedule changes between these three. “Uniform length” is how many millimetres of axis are held within 10% of the peak field.

End caps	Cold field	Hot field	Uniform length	Mass
8 mm	0.420 T	0.396 T	48.0 mm	7.16 kg
12 mm	0.542 T	0.511 T	40.8 mm	7.16 kg
16 mm, as recommended	0.669 T	0.631 T	31.5 mm	7.16 kg

Read the middle row carefully. **Twelve millimetre caps meet every requirement in this note at once:** 0.511 T hot against a 0.40 T floor, 40.8 mm of uniform field against a 40 mm requirement, the same 72 °C magnets and the same 7.16 kg. Sixteen millimetre caps buy 23% more field and give up a quarter of the uniform length, taking it below the written requirement.

Which is right depends on something only the customer can answer: whether the 40 mm figure is a real requirement or a target inherited from solenoid practice. The supervisor's own words were that 0.7 T would bring advantages *provided the field shape is still what is needed*, so the question is already half asked.

It has to be answered before the tiles are made, because thickness and magnetisation are both fixed at manufacture and neither can be changed afterwards. Nothing else in the package moves: the same casing, the same sleeve, the same rear stack, the same eight-tile rings, the same drawings. Only the ring heights on AFMPDT3-003 change, from five rings of 16 mm to a rear cap of 12, four core rings of 14 and a front cap of 12.

7 Limitations

1. **The recommended build was not solved in the coupled solver, and the reason is an ordering defect in the study rather than a judgement.** The coupled script runs before the down-selection and its case list was written in advance, one or two parameters at a time off the baseline, to answer specific questions: which rear concept, how good the sink has to be, what thicker caps buy, what a larger envelope buys. The down-selection then picked a build that changes three of those at once, a 2 mm wall with a 1 mm break and 16 mm caps, and that combination is not in the list. The nearest coupled case has the 16 mm caps on the baseline wall and break. The summary script guards against the coupled results being missing altogether but not against the selected build being absent from them, so nothing flagged it.

What this costs is smaller than it sounds. Both inputs are solved exactly for this geometry: the field by the magnetostatic sweep and the temperatures by the thermal sweep. What is missing is letting the remanence read the local temperature point by point instead of applying one scale factor, and Section 3.2 measures that difference across thirteen coupled cases and finds it conservative by up to 1.4%. **The fix is one more coupled case and about thirty minutes of solver time**, and it should be run before the magnets are ordered.

2. **Four figures are drawn for the nearest exported build rather than for the recommended one**, and each says so on its own face. Full spatial maps were exported for a handful of builds because they are large; every scalar quantity in this note is for the recommended build. Nothing quantitative rests on those four figures.
3. **The discharge model is a uniform conductor** at a median Hall parameter of 235, where the real conductivity is a tensor. Read the current paths as shape, not as exact values.
4. **The cathode is absent from the thermal model**, which makes the reported temperatures slightly optimistic.
5. **Propellant injection manifold design.** Six 0.9 mm injection orifices distributed on a 16 mm pitch circle maintain the plenum pressure between 7.6 and 25.4 Torr across a 9 to 30 mg/s argon flow rate, ensuring stable operation on the high-pressure branch of the Paschen curve. The external propellant connection and cathode feedthrough both interface at the rear, requiring planar co-integration with the external cold plate assembly.

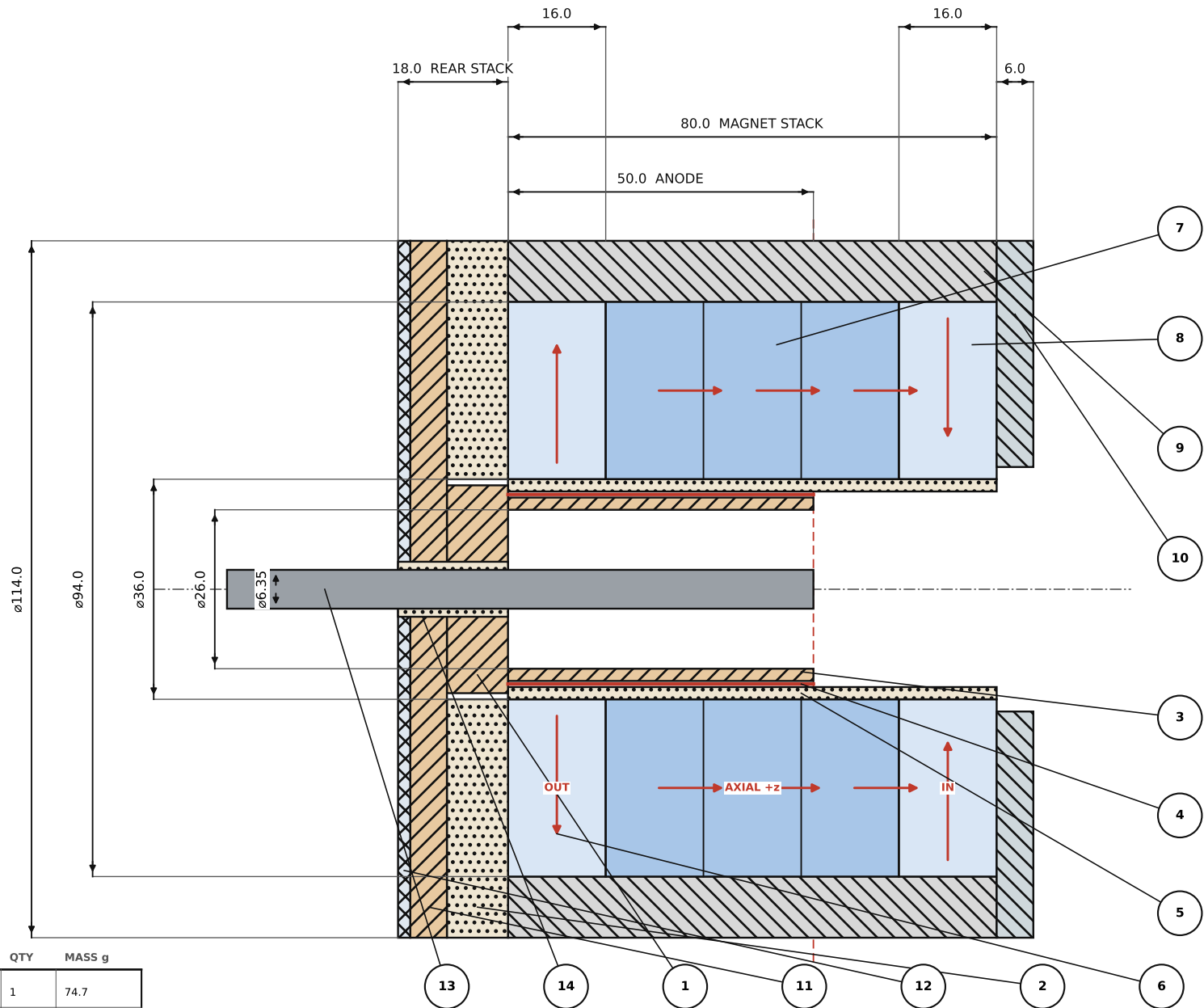
6. **Vacuum facility pumping speed is still unknown.** It sets the testable flow rate and therefore which part of the operating map can actually be demonstrated.
7. **Nothing above 130 °C should be quoted for demagnetisation,** for the reason given in Section 3.

8 Drawings

Ten sheets follow, at A3. They are produced by `scripts/report_drawings.py` from the same dimensions the analysis uses and the same file the parts list in Table 5 is computed from, so a dimension cannot move in one place and not the other.

Table 11: Drawing index.

Sheet	Content
AFMPDT3-001	General arrangement and bill of materials
AFMPDT3-002	Anode barrel
AFMPDT3-003	Magnet tiles and the magnetisation schedule
AFMPDT3-004	Iron return casing
AFMPDT3-005	Standoff sleeve and radiation shield
AFMPDT3-006	Mounting plate: hand-off boss and magnet shelf
AFMPDT3-007	Spreader
AFMPDT3-008	Isolation plate
AFMPDT3-009	Front retaining ring
AFMPDT3-010	Cathode rod and insulating bush



PARTS LIST

ITEM	DESCRIPTION	MATERIAL	QTY	MASS g
1	Mounting plate, hand-off boss	Cu OFHC C101	1	74.7
2	Mounting plate, magnet shelf	Macor MGC	1	229.2
3	Anode barrel, 2.0 mm wall	Cu OFHC C101	1	78.8
4	Radiation shield, 0.3 mm wall	304 SS, polished	1	11.7
5	Standoff sleeve	Macor MGC	1	43.1
6	Magnet tile, rear cap, RADIAL OUT	NdFeB N48UH	8	710.6
7	Magnet tile, core, AXIAL +z	NdFeB N48UH	24	2131.9
8	Magnet tile, front cap, RADIAL IN	NdFeB N48UH	8	710.6
9	Iron return casing, 10 mm wall	1010 / DC01 steel	1	2047.4
10	Front retaining ring	304 SS	1	425.0
11	Spreader, full diameter	Cu OFHC C101	1	531.0
12	Isolation plate	AlN, sintered	1	65.5
13	Cathode rod, 6.35 dia	W, 2 % ThO2	1	58.7
14	Cathode insulating bush	Macor MGC	1	1.3
15	Screw insulating bush	Alumina 99.7 %	6	2.4
16	ISO 4762 M4 x 30 socket head	A2-70	6	28.2
17	ISO 4762 M4 x 16 socket head	A2-70	6	16.8
18	ISO 7089 4 mm flat washer	A2	12	4.2
19	Feed tube stub, 1/8 in x 0.7 wall, brazed	Cu	1	3.0
	COMPLETE ASSEMBLY			7174

NOTES

- Datum z = 0 is the front face of the mounting plate. Exhaust is +z, to the right. The assembly runs z = -18 to z = +86 and is 114 mm across.
- The cathode tip sits at z = +50, flush with the anode exit, on the dashed line. That is where the applied field is defined and the field falls steeply behind it.
- Magnetisation direction is shown by the red arrows and is specified per ring on AFMPDT3-003. It is set at manufacture and cannot be changed afterwards.
- The rear face of item 12, at z = -18, is the thermal hand-off face. It mounts to an external cold plate and must be flat within 0.05 over the full diameter.
- The 1.0 radial gap between items 1 and 2, and the 1.0 evacuated break between the anode and the sleeve, must remain clear and evacuated. Both are thermal breaks. The 0.3 radiation shield, item 4, floats in the second of these.
- Items 16 to 18 pass through insulating bushes, item 15, in the spreader, so that the cold plate stays isolated from the anode.
- Complete assembly mass 7.17 kg.

GENERAL ARRANGEMENT - RECOMMENDED BUILD

AF-MPDT Breadboard / Rev 3

DRG No.
AFMPDT3-001

MATERIAL
ASSEMBLY

SCALE
1:1

DATE
2026-09-12

ALL DIMENSIONS IN mm. GENERAL TOL. ±0.1 UNLESS STATED.
REMOVE ALL BURRS AND BREAK SHARP EDGES 0.3. DO NOT SCALE.