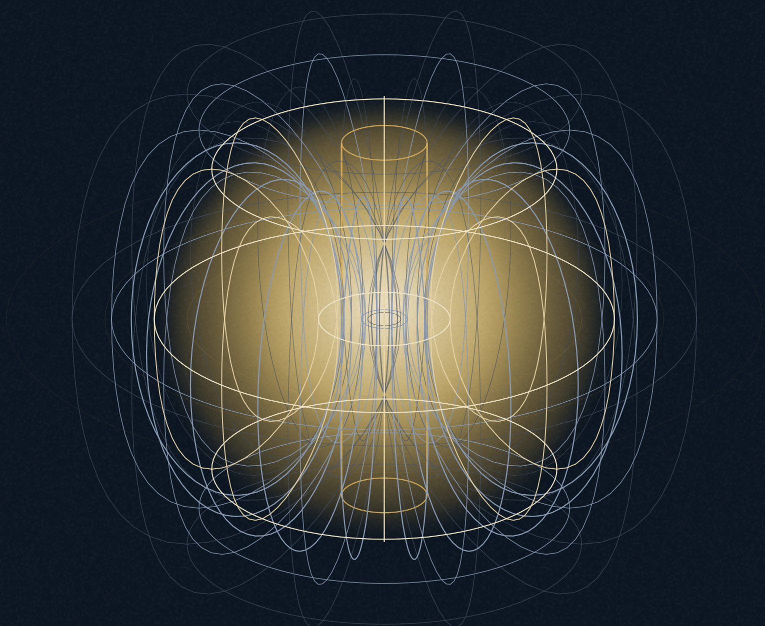
KRONOS FUSION ENERGY



PAPER I OF THE 2026 KRONOS SET

Hyperion

The Tritium Foundry

A compact deuterium–tritium spherical-tokamak breeder, sized to a national strategic-isotope requirement.

Spherical tokamak · D–T · Q 3.424 · 88.7 MW_{fus} · 4.0 kg T/yr

Explore it live — 3-D model · physics validator · film series

PREPARED BY P. I. FORD · G. L. KULCINSKI

2026 · EDITORIAL

KRONOS FUSION ENERGY · 2026

The Kronos Fleet

Fuel follows purpose, not platform.

Hyperion · Aegis · MetroVolt

THE OFFICIAL RECORD

What this document is, and how to read its numbers

This is a combined editorial. It gathers, in one volume, the two design studies Kronos Fusion Energy released in 2026 — a compact spherical-tokamak tritium/helium-3 breeder and a deuterium–helium-3 tandem-mirror generator — together with the intellectual-property estate, the people, and, in the internal edition, the full commercial case. The scientific text is the same text that appears in the arXiv preprints and the journal submissions; the editorial adds the apparatus a reader needs to hold the whole program at once, and nothing in the physics is altered to fit it.

THE HONESTY STANCE IS THE ASSET

Every headline quantity carries an **evidence class** — DERIVED RECOMPUTED MEASURED REQUIREMENT — and, where a number is a modelled extrapolation rather than a demonstrated value, it is labelled as such and its downside is shown next to it. Several quantities in the underlying corpus moved after first publication; where a value has been withdrawn or restated, the record says so plainly. This is deliberate: a diligence team will find the load-bearing assumptions, so the document surfaces them first.

TITLE	The Kronos Fleet — Hyperion · Aegis · MetroVolt: A Combined Design & Commercialization Study
AUTHOR	Priyanca Ford, Founder & CEO, on behalf of Kronos Fusion Energy
EDITION	2026 Combined Editorial · first issue
COMPANION WORKS	The five-paper arXiv drop — (1) Breeder, (2) Burner, (3) REBCO magnet & tape, (4) Direct Energy Conversion, (5) AI/ML/Quantum control — with matching numbered Zenodo deposits, plus the IOP journal and IAEA-FEC submissions. Patents were filed before the drop.
NAMING	Hyperion = the breeder; Aegis (defense) and MetroVolt (data-center) = one generator in two housings. Internal mode letters (D1, L) do not appear on public surfaces.
STATUS	Conceptual design & simulation study. Nothing herein is a construction commitment.

HOW TO READ THIS VOLUME

The fleet at a glance, and the way its numbers are marked

This volume opens with *Orientation*, presents the five research papers as a bound sequence, and closes with the *Apparatus*. *Foundations* sets out the three general results both machines rest on. *Paper One* is the Hyperion breeder; *Paper Two* the Aegis / MetroVolt generator; *Papers Three, Four and Five* are the enabling science — high-field REBCO magnets and tape, direct energy conversion, and the AI / ML / quantum control stack. A *Digital Twin & 3-D Model* part follows, then the *Environmental* profile. The *Economics* and levelized cost and the *Business Case* and diligence record appear in the internal edition only; the *Simulations* proof record and the Apparatus — patent portfolio, team, limitations, and sources — close both editions.

THE FLEET AT A GLANCE

	HYPERION	AEGIS	METROVOLT
Role	Strategic-isotope foundry	Defense installation power	Campus power
Machine	**Spherical tokamak**	**Tandem mirror**	**Tandem mirror**
Fuel	Deuterium–tritium	Deuterium–helium-3	Deuterium–helium-3
Delivers	Tritium · ^{3}He · 14 MeV n	Resilient installation power	Firm campus power
Physics bar	**Fusion gain only**	Closure (gates named)	Closure + lunar ^{3}He
In the fleet	Breeds the fuel	Proves the generator	Commercial destination

HOW THE NUMBERS ARE MARKED

Every headline quantity carries an evidence class — DERIVED from first principles, RECOMPUTED from raw data, MEASURED in hardware, or a REQUIREMENT yet to be met. Financial figures carry a case label and are confined to the internal (confidential) edition. Values that moved after first publication are shown as withdrawn or restated rather than quietly changed. A capability you can evaluate is one whose limits are on the page.

ABSTRACT

Hyperion — The Tritium Foundry

Hyperion is a spherical-tokamak deuterium–tritium breeder that earns on fusion *gain* alone — producing tritium, decay helium-3, and 14 MeV neutrons, so it delivers value without waiting on the net-electricity milestone the rest of the field is still chasing. At the frozen reference point it reaches Q = 3.424 and 88.7 MW of fusion power at 9.86 MA, on a lithium blanket whose breeding ratio is a design lever: demonstrated at a beryllium-multiplied TBR 1.34 (~1.7 kg T/yr net), with 4.0 kg/yr the advanced-blanket target at TBR ~1.8. Every headline number carries an evidence class, and the open items are stated, not hidden.

Companion deposit (code & data, reproducible under CC BY 4.0): DOI 10.5281/zenodo.21746157 (v2 10.5281/zenodo.21795620) · Zenodo community *kronos_fusion_energy*.

Explore it live: interactive 3-D model · run the physics validator · companion film series (the deposited solvers, in the browser).

Keywords: spherical tokamak · tritium breeding · deuterium–tritium · strategic isotopes · negative triangularity

CONTENTS

Table of Contents

What this document is, and how to read its numbers 1
The fleet at a glance, and the way its numbers are marked 2
Hyperion — The Tritium Foundry 3
Symbols, units, and the names of things 5
§ 1 Why a breeder, and why it can be small 6
§ 2 Methods — what was computed, and from what 7
§ 3 Four general results for deuterium plasmas 8
§ 4 Fuel follows purpose — the machine 10
§ 5 Blanket, net helium-3 yield, inventory, and siting 15
§ 6 Enabling subsystems — the magnet and the control layer 19
§ 7 Comparison with prior breeder concepts 20
§ 8 Discussion, capital, and what remains load-bearing 21
§ 9 Limitations 22
§ 10 Conclusion 23

PORTFOLIO, PEOPLE & RECORD

The patent portfolio 25
Founding partners, board, advisors & auditors 26
List of Figures 28
List of Tables 29
Sources 30
How this document was made 32
Notice, status, and distribution 33
One programme, in five papers 34

NOMENCLATURE

Symbols, units, and the names of things

Q	plasma (fusion) gain, P_{fus}/P_{aux}
Q_E	engineering gain, net electric out / recirculating in
H_{98}	confinement enhancement over the IPB98(y,2) scaling
Z_{eff}	effective ion charge
c_{ee}	electron–electron bremsstrahlung leading coefficient, 2.120022 (exact)
τ_E	energy confinement time
I_p	plasma current
R_0, a	major radius, minor radius
κ, δ	elongation, triangularity
β_N	normalized plasma beta (Troyon-normalized)
TBR	tritium breeding ratio
DEC	direct energy conversion
CF	plant capacity factor (availability)
FOAK / NOAK / BOAK	first / n^{th} / best of a kind
Hyperion	the ST breeder (internal: Mode D2)
Aegis	the generator, defense/installation housing (internal: Mode M)
MetroVolt	the generator, data-center housing (Mode M)

§ 1

Why a breeder, and why it can be small

United States tritium supply is structurally fragile. Weapons-stockpile tritium is produced through a *single* commercial reactor, and the federal replacement requirement — tritium decays at **5.5% per year** — has been met by repeatedly increasing irradiation loading rather than by adding a second source. Helium-3 is rationed: the federal auction ceased in **2009**, and demand from neutron detection, sub-kelvin cryogenics and medical imaging exceeds domestic production. A domestic, non-reactor capability to produce both isotopes is therefore of strategic interest independently of whether it is inexpensive.

The obstacle to a *fusion* isotope source has never been the nuclear physics, which is textbook, but the perceived need for a power-plant-scale machine. Hyperion removes that obstacle with a single observation: **a breeder needs fusion *gain* — reactions — not net electricity.** A spherical tokamak that does not close the electrical loop can nonetheless run a driven, sub-breakeven plasma that produces tritium, helium-3 and 14 MeV neutrons at a useful rate. Freed from the requirement to generate electricity, the machine is then *sized to a national supply requirement* — of order kilograms per year — rather than to a market or a power rating, and the size that results is small.

> **THE THESIS IN ONE LINE**
>
> Size the breeder to a named national requirement of order **2 kg yr^{-1}**, and the two obstacles that defeated every prior fusion-breeder proposal — machine scale and tritium inventory — both fall below their binding thresholds. The physics never forbade a small breeder; it forbade a large one.

RELATION TO PRIOR WORK

The fusion helium-3/tritium breeder has been proposed at least four times and rejected once in print. **Wittenberg** reviewed the artificial helium-3 routes and rejected the tritium-decay route on a licensing/inventory basis — 100 kg yr^{-1} of helium-3 "would need to be continuously separated from 1.8 tonnes of tritium," storage of which "would be difficult to license, probably impossible." **Greenspan and Miley** established the merchant-breeder economic architecture. **Chacón and Miley** analysed a breeder on energy balance *and* economics against a competing lunar supply route, and **Shuy *et al.*** assessed a dedicated breeder on physics, engineering, cost and safety. Every one of these sizes the breeder to a *fusion fleet's* support ratio and rejects it at the 100 kg yr^{-1} scale that a fusion power industry would require.

Hyperion differs on the axis those studies hold fixed: **it sizes to a named non-fusion requirement of order 2 kg yr^{-1}, at which the inventory objection inverts.** The equilibrium tritium inventory is ~**35 kg-class** rather than 1.8-tonne-class — roughly **51× smaller** — and sits inside licensed civil precedent.

WHAT THIS PAPER ESTABLISHES

The paper (i) establishes four machine-independent results for deuterium plasmas that constrain any breeder; (ii) applies "fuel follows purpose" to select deuterium–tritium and derives the minimum plasma current from a **25,200-configuration** scan; (iii) closes the tritium and net helium-3 balance through a lithium-6 blanket, accounting for every loss channel; and (iv) positions the design against prior breeder concepts. Economics are treated in a separate companion and are not a condition of any result here.

§ 2

Methods — what was computed, and from what

Every headline quantity in this paper is regenerable from named scripts reading a declared-parameter table; the method is stated here so the numbers can be checked rather than trusted.

REACTIVITIES AND BRANCHING

Fusion reactivities use standard parametrised cross-sections; the D–D neutron-branch fraction is computed as a *reaction-rate-weighted profile integral* rather than at a label temperature, giving $\mathbf{b_{DDn}}$ = **0.5306** at the 48 keV reference — inside the established 0.532–0.555 band and refuting the round-number 0.500.

RADIATION

Bremsstrahlung uses a relativistic form (Svensson) with an electron–electron term whose leading coefficient is the *exact* analytic value of Eq. (1); the radiation ceiling is cross-checked against the bremsstrahlung-limited treatment of Ochs, Kolmes and Fisch; synchrotron is carried as a lower-bounded loss following the generalised Trubnikov form.

DESIGN SCAN

A spherical-tokamak breeder was scanned across **25,200 configurations** in (R_0, B_0, A, κ, T, n) with the confinement multiplier left free; a configuration "closes" if it meets the national tritium duty at stable normalised pressure without exceeding the wall or current-drive limits. The minimum on-duty plasma current is read off the *raw* scan, not adopted from a summary table, and reproduced by an independent aspect-ratio sweep of $\mathbf{2.36\times10^{6}}$ evaluations to $\mathbf{2.8\times10^{-14}}$ **MA**.

CONFINEMENT, CURRENT DRIVE, AND BLANKET TRANSPORT

Confinement and current drive use the **IPB98(y,2)** baseline with a Sauter-class bootstrap scaling; the driven fraction is reported at the operating point. Blanket transport uses Monte Carlo on retrieved **ENDF/B-VIII.0** tapes rather than an assumed spectral shape. RECOMPUTED FROM SOURCE

§ 3

Four general results for deuterium plasmas

These results depend on branch physics and radiation only. They hold for any deuterium-burning device, and they fence the breeder before any machine is drawn.

3.1 CHARGED SELF-HEATING AND BREMSSTRAHLUNG ARE EQUAL TO WITHIN THE REACTIVITY UNCERTAINTY

In a pure-deuterium plasma the charged products of both branches — the **4.03 MeV** of the proton branch and the **0.82 MeV** helium-3 recoil of the neutron branch — deposit locally, while bremsstrahlung leaves. The ratio of the two peaks at **108 keV**; four independent evaluations give values from **0.984 to 1.121**, all straddling unity. The spread is dominated by the reactivity fit and the electron–electron term, not by the physics: **pure D–D sits *on* a knife edge**, and the sign of (ratio − 1) is not determined by the available basis, because every neglected channel — cyclotron, transport, impurity — is strictly negative.

Table I · Four independent evaluations of the D–D self-heating / bremsstrahlung ratio

ROUTE	SELF-HEATING / BREMSSTRAHLUNG	T (KEV)
Reactivity fit A	0.984	107
Reactivity fit B	0.9842	108
Independent route C	1.007	109
c_{ee} = 1.499 (superseded)	1.1214	108
c_{ee} = 2.120022 (adopted)	1.0349	108

The electron–electron leading coefficient is not a modelling choice; it has the exact analytic value

$$c_{ee} = 5(44 - 3\pi^2) / (24\sqrt{2}) = 2.120022 \qquad (1)$$

A widely circulated form uses 1.499 — Eq. (1) with $\sqrt{2}$ replaced by 2; the ratio is $\sqrt{2}$ to nine figures. Adopting the exact value moves the knife-edge ratio from 1.1214 to 1.0349 and leaves the conclusion unchanged. DERIVED · EXACT

Pure D–D sits on the knife edge, not on either side of it.

3.2 PLASMA GAIN SATURATES UNDER UNBOUNDED CONFINEMENT

In steady state $P_{aux} = W/\tau_E + P_{rad} - f_{dep}P_{charged}$. As $\tau_E \to \infty$ the transport term vanishes but the radiation term does not, because photons leave at the speed of light and are not confined. The gain therefore approaches

$$Q_\infty = P_{fus} / (P_{rad} - f_{dep}P_{charged}) \qquad (2)$$

finite whenever radiation exceeds charged self-heating and infinite (ignition) when it does not. Writing the denominator with the affine Z_{eff} dependence below and solving for its zero gives a critical effective charge; at 108 keV with f_{dep} = 1 we obtain $\mathbf{Z_{eff,crit}}$ **= 1.045**. Improving confinement without bound does not produce unbounded gain in a radiating plasma; it produces a finite asymptote set entirely by the radiation balance. The question "what confinement enhancement does a D–D device need?" is therefore malformed. DERIVED

3.3 THE RADIATION RATIO IS AFFINE IN Z_{EFF}, NOT INVERSE

Bremsstrahlung carries an ion term proportional to Z_{eff} and an electron–electron term that does not, so

$$P_{fus} / P_{brems} \propto 1 / (Z_{eff} + c_{ee} t), \quad t = T / m_e c^2 \tag{3}$$

affine, with a non-zero temperature-dependent intercept, not proportional to $1/Z_{eff}$. Two plasmas at the same Z_{eff} but different impurity species do not share a radiation ratio; an impurity tolerance quoted as a single Z_{eff} is not reproducible unless the species and the temperature are stated. The primary-source ceiling is $\mathbf{P_{fus}/P_{brems} = 1.589}$ **at 108 keV** at $Z_{eff} = 1$. DERIVED

3.4 DIRECTED POWER IS NOT CHARGED POWER

Charged fusion products deposit locally; they are not thereby *directable* into a converter. A three-body final state produces a continuum rather than discrete lines, and a continuum cannot be efficiency-matched to an electrostatic converter the way two discrete lines can. For the proton–boron-11 cycle the charged fraction is **1.000** and the directable fraction is **0.000** — three alpha particles share 8.7 MeV continuously. Any efficiency quoted across two fuels of different final-state multiplicity is wrong on its face. This result is load-bearing for the companion generator study. DERIVED · DEFINITIONAL

§ 4

Fuel follows purpose — the machine

The configuration is a *negative-triangularity* (δ = −0.30, NT) spherical tokamak of major radius $\mathbf{R_0}$ **= 1.2 m**, minor radius **a = 0.48 m**, elongation **κ = 2.0**, aspect ratio **A = 2.5**. It was designed for electricity and does not close the electrical loop on the chosen fuel and geometry — that failure is what motivates the breeder. A breeder needs fusion gain, not net electricity, and the same machine class reaches gain: the machine that failed as a generator is a good isotope foundry.

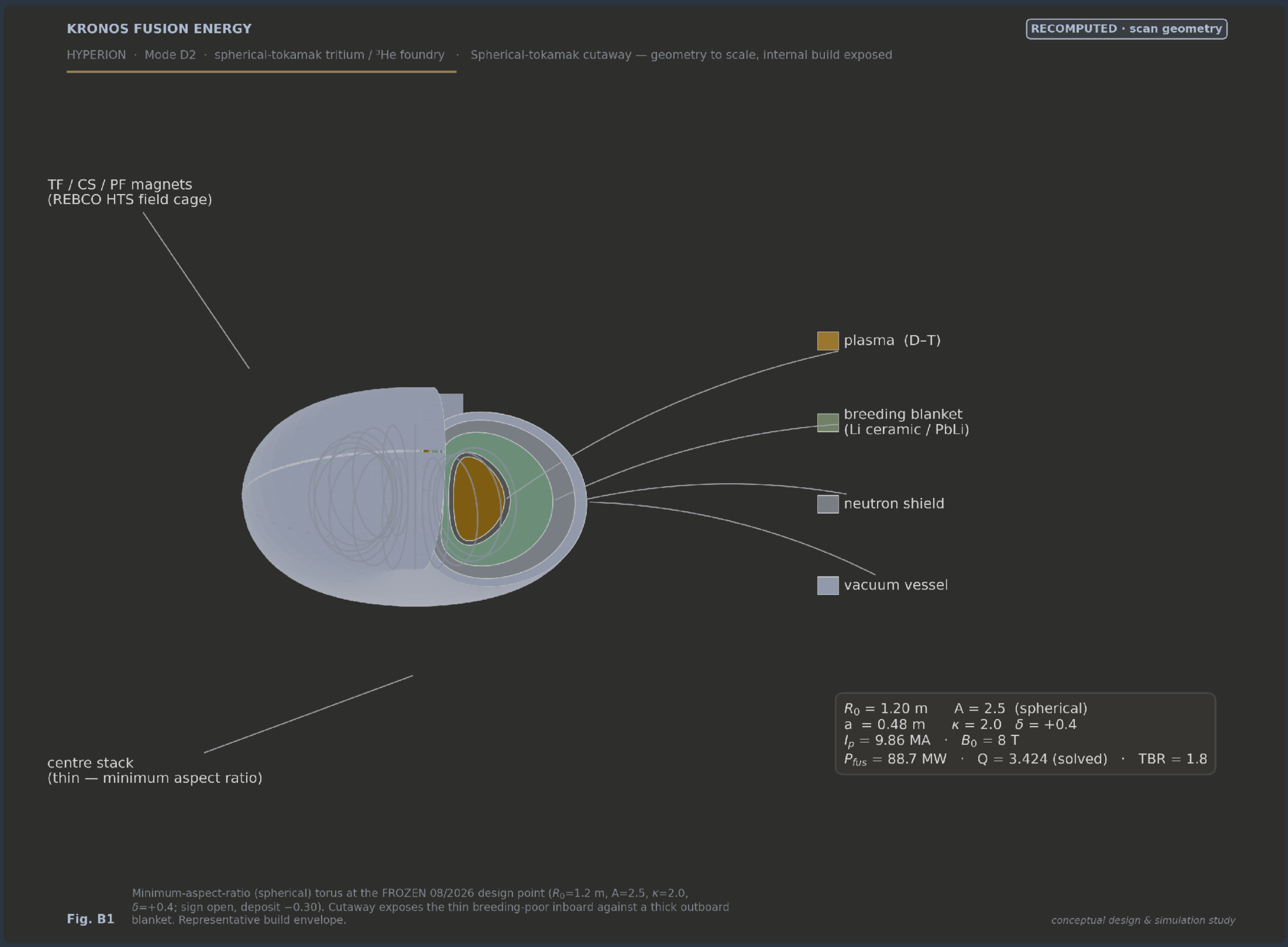


FIGURE 1. Hyperion spherical-tokamak cutaway with the internal build exposed — a negative-triangularity (δ = −0.30) minimum-aspect-ratio torus (conceptual design; no machine has been built). RECOMPUTED

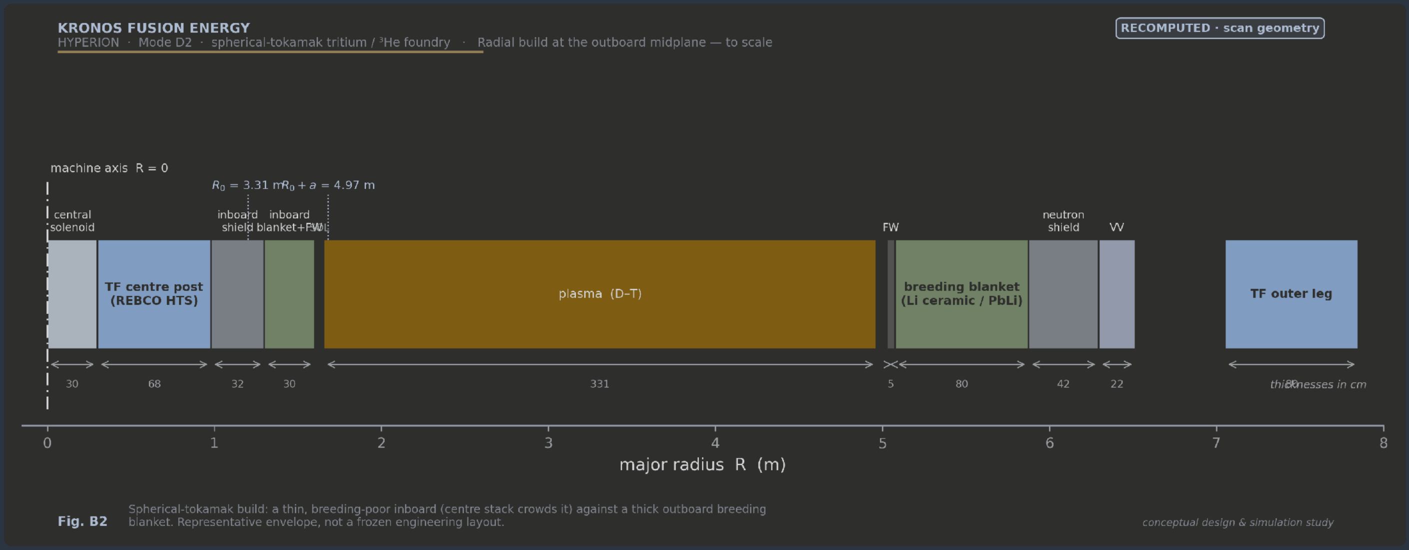


FIGURE 2. Hyperion radial build from the centrepost outward: centre-column magnet, vacuum vessel, breeding blanket, and neutron shield. RECOMPUTED

4.1 THE DESIGN POINT AND THE FUEL RESULT

Of the 25,200 configurations, **213 D–T and 71 pure D–D** close without wall violation and meet the national duty of 1.87–4.0 kg yr^{-1}.

Table 2 · The fuel result at the closing minima (recomputed from the raw 25,200-row scan)

QUANTITY	D–T	PURE D–D
Minimum plasma current	4.93 MA (2.17 MA driven)	15.52 MA
Against ITER's 15 MA	33%	103%
Tritium per unit fusion power	0.0451 kg $yr^{-1}MW^{-1}$ (net, TBR 1.8)	**0.135 kg $yr^{-1}MW^{-1}$ (prompt)**

The two tritium-per-MW figures are on *different bases* and are not a like-for-like ratio: the D–T value is net production at a breeding ratio of 1.8 — the advanced-blanket *target*; the demonstrated blanket reaches TBR 1.34 with a beryllium multiplier (§5), for **≈1.7 kg yr^{-1}** net — while the D–D value is prompt (unburned) production. Both reproduce from first principles. RECOMPUTED

The frozen design point (config **22021**) is *solved* at demonstrated confinement rather than scaled to it: the plasma reaches **Q = 3.424** with fusion power **P_{fus} = 88.7 MW** at a plasma current of **I_p = 9.86 MA**, on a lithium blanket at TBR 1.8 delivering 4.0 kg yr^{-1}. The heating power density is **2.37 MW/m^3 — 2.22× SPARC** — a physicality check against a built device, not a size artefact. COMPUTED · FROZEN

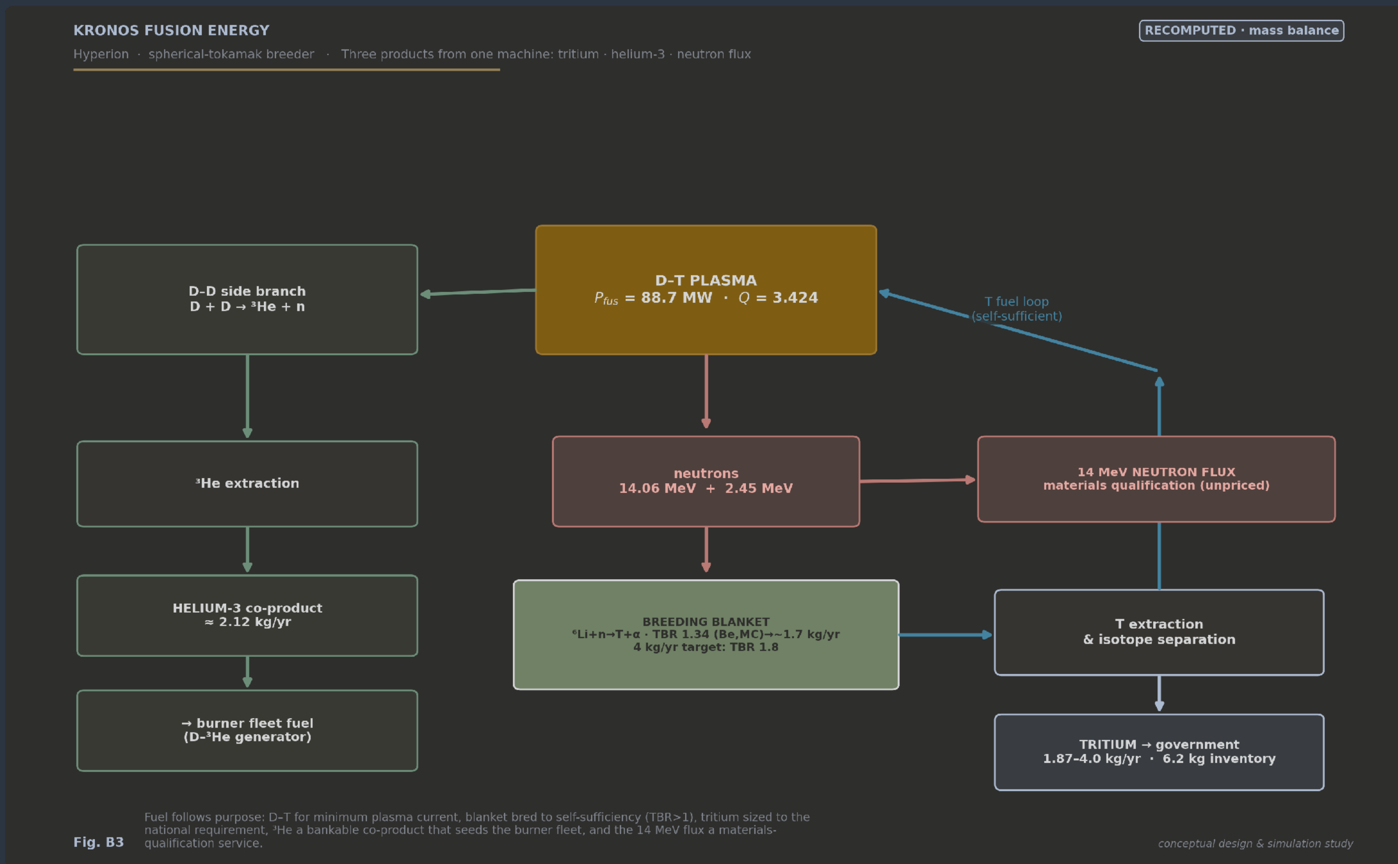


FIGURE 3. Hyperion fuel cycle: deuterium fuelling, the D–D and D–T branches, tritium and helium-3 extraction, and the tritium-decay helium-3 bank. RECOMPUTED

4.2 THE TRADE-OFF, STATED RATHER THAN RESOLVED IN THE DESIGN'S FAVOUR

D–T requires **3.15× less plasma current**; pure D–D yields **11.9× more tritium** per unit fusion power. These are different optima and the paper does not claim one fuel dominates. This work optimises plasma current, the binding engineering constraint: a 4.93 MA machine is a fraction of ITER's current rather than a multiple of it. The reason D–T wins on current despite the lower tritium per unit fusion power is that a tokamak at fixed β is *pressure-limited*, and D–T's **≈19× higher reactivity** permits the same duty at a lower current. Fuel follows purpose.

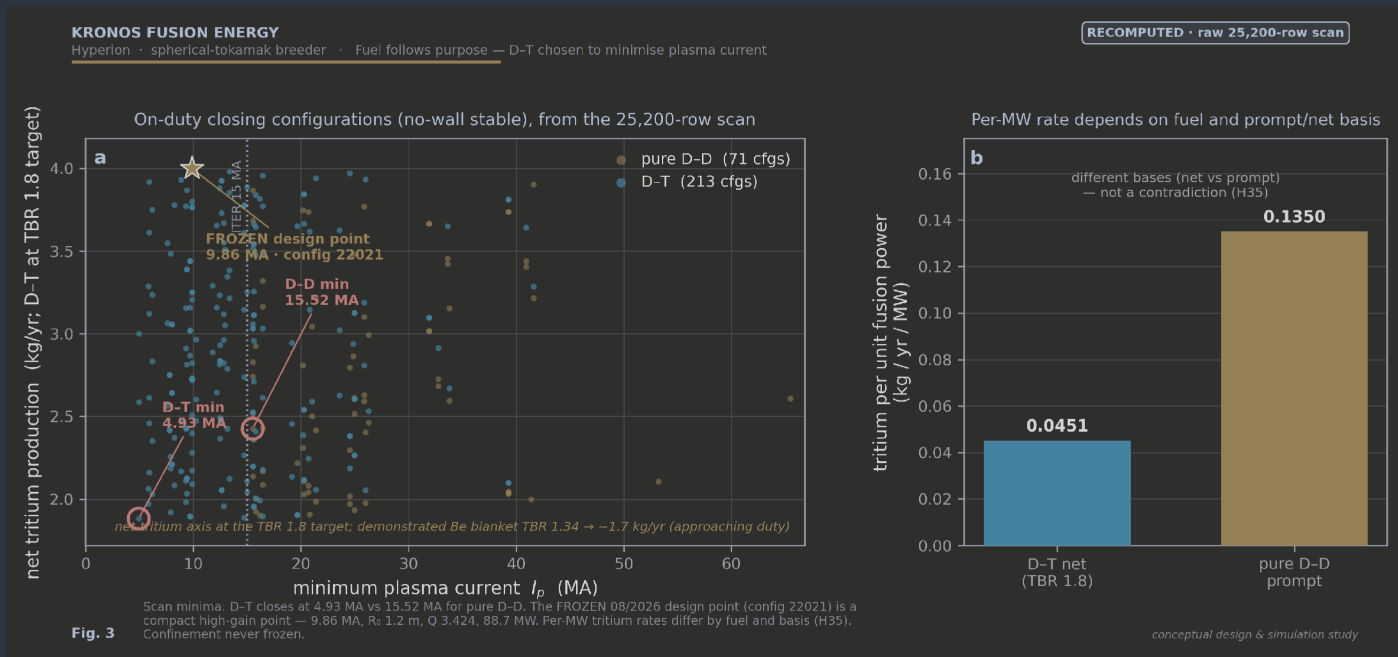


FIGURE 4. Net tritium production against plasma current for all on-duty closing configurations (213 D–T, 71 pure D–D); the two minima are marked at 4.93 and 15.52 MA. The D–T net-tritium axis is on the TBR ≈ 1.8 advanced-blanket *target* basis; the demonstrated beryllium-multiplied blanket reaches TBR 1.34 (≈1.7 kg yr^{-1} net, §5). RECOMPUTED

4.3 WHY THE CURRENT REQUIREMENT IS STRUCTURAL

Three levers were tested and none provides relief.

THREE INERT LEVERS

Toroidal field. Inert within the admissible range — no configuration closes between 16 and 20 T.

Elongation. Adverse: raising κ from 2.0 to 2.6 *increases* the D–T minimum from 4.93 to 5.82 MA.

Aspect ratio. A full sweep of 374 (A, κ) cells finds lower-current solutions, but the minima sit at A = 3.4–3.5 on the edge of the searched range — a *conventional* tokamak, not the spherical configuration under study — so the relief is not claimed.

The current requirement is a property of the design space, not of a poorly chosen operating point. RECOMPUTED

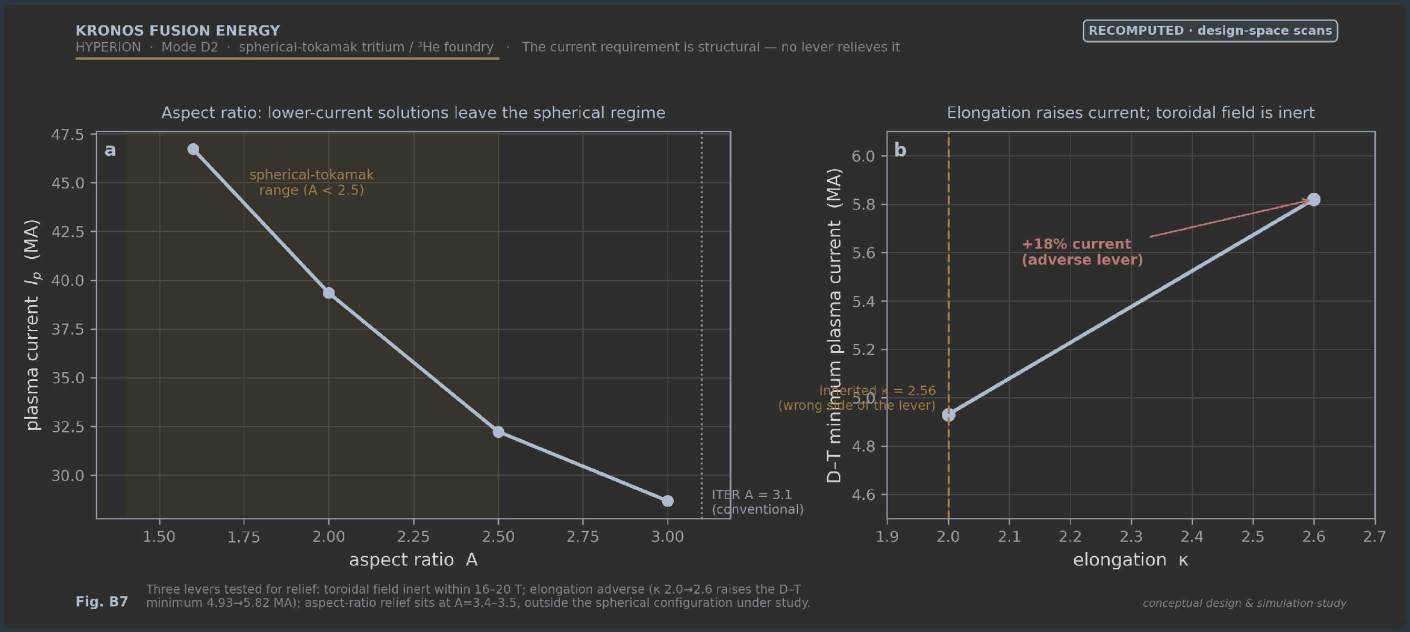


FIGURE 5. The three levers tested for current relief — toroidal field (inert), elongation (adverse), and aspect ratio (relief only off the searched range). RECOMPUTED

§ 5

Blanket, net helium-3 yield, inventory, and siting

Tritium breeding is not a fixed property of the machine; it is a **design lever**, and the honest statement of where that lever sits today is the load-bearing disclosure of this paper.

THE TRITIUM HONESTY FRAMING — READ THIS BEFORE ANY BREEDING NUMBER

TBR 1.8 and the headline **4.0 kg yr^{-1}** are the *target*, corresponding to an advanced blanket. The *demonstrated* blanket TBR in the deposited neutronics is **1.34** (beryllium-multiplied), which nets about **1.7 kg yr^{-1}** of tritium — approaching, not meeting, the 1.87–4.0 kg yr^{-1} national duty. The full 4.0 kg yr^{-1} figure is carried as a stated blanket-development target, *never* as a demonstrated result. Helium-3, the strategic product, is bred independently of the blanket and carries no breeding-ratio dependence.

5.1 NET HELIUM-3 AFTER EVERY LOSS

On the pure-D–D reference (**140 MW** fusion), the gross prompt helium-3 rate is **0.1443 kg yr^{-1}** per MW of D–D fusion power (reproducing the established value to 0.8%). After the dominant loss — in-plasma self-burn of the helium-3 ash, **25.6%** — the plant nets **≈15 kg yr^{-1}** of prompt helium-3 plus **≈36 kg yr^{-1}** of tritium, whose decay adds **≈15.6 kg yr^{-1}** of helium-3 on a ten-year horizon. The destructive n + ^{3}He → p + T channel is *not* a design driver: it removes only **0.18 ppm** of the helium-3 on the staged-extraction path, and stays below 8 ppm even on a conservative bound holding the entire inventory in peak blanket flux for a full day. RECOMPUTED

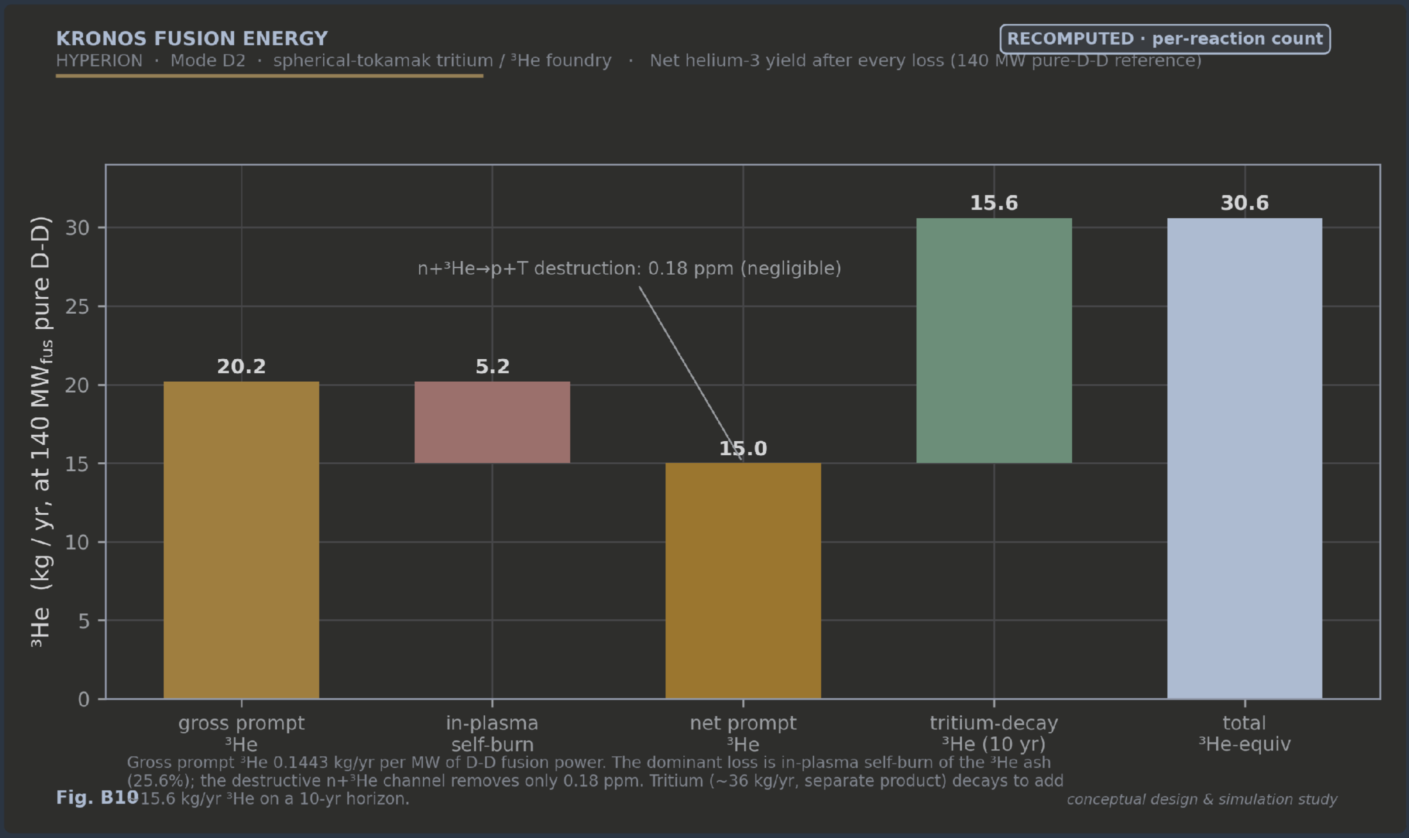


FIGURE 6. Net helium-3 yield after every loss at the 140 MW pure-D–D reference: gross prompt ^{3}He, the 25.6% in-plasma self-burn, the net, and the tritium-decay contribution. The destructive n + ^{3}He channel (0.18 ppm) is negligible. RECOMPUTED

5.2 THE BLANKET ABSORBS NEUTRONS; IT DOES NOT MODERATE THEM

Monte Carlo transport on ENDF/B-VIII.0 gives a blanket-averaged ^{3}He capture cross-section of **0.92 b**, not the 113.88 b that an assumed 1/E spectral shape produces; the hazard to route around is hydrogenous material (σ_{eff} = 2708 b in water) and long holdup, not the lithium. On 2.45 MeV (D–D) neutrons a ^{6}Li-enriched Li_2O blanket reaches TBR 0.86–0.91; on the 14.06 MeV (D–T) spectrum the *bare* blanket gives TBR 0.78–0.86, and a beryllium multiplier (f_{Be} = 0.3) raises it to **TBR ≈ 1.34** in the deposited neutronics — *net-breeding*.

At the demonstrated f_{Be} = 0.3 point (TBR 1.34) the machine burns **4.97 kg yr^{-1}** and nets **≈1.7 kg yr^{-1}** of tritium, approaching the 1.87–4.0 kg yr^{-1} national duty; the full 4.0 kg yr^{-1} figure corresponds to an advanced blanket at **TBR ≈ 1.8**, above the demonstrated 1.34 and carried as a stated blanket-development target, not a demonstrated result. DEMONSTRATED TBR 1.34 TARGET TBR 1.8

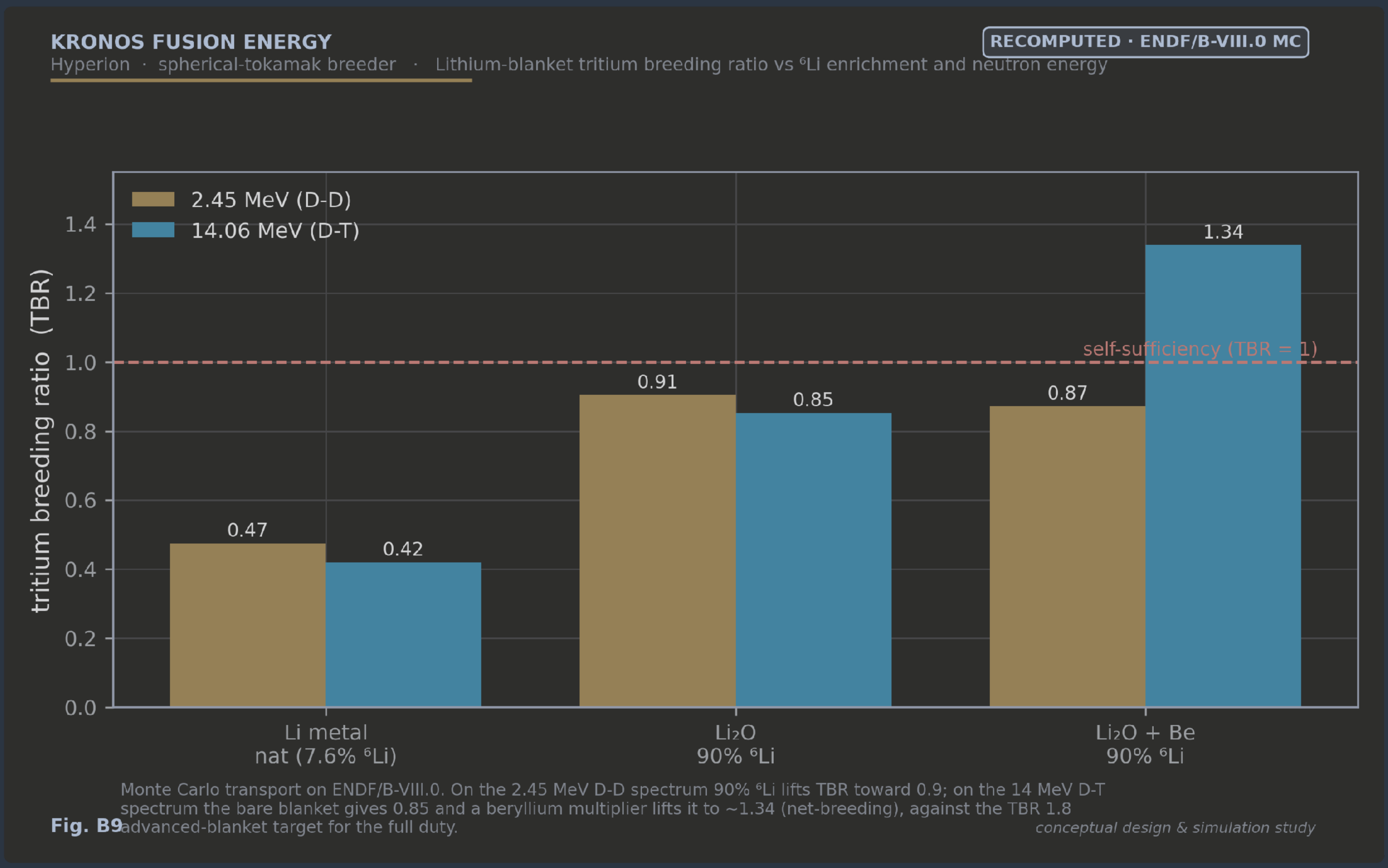


FIGURE 7. Lithium-blanket TBR versus ^{6}Li enrichment and neutron energy: on the 14 MeV D–T spectrum the bare blanket reaches 0.78–0.86 and a beryllium multiplier lifts it to ≈1.34 (net-breeding), against the TBR ≈ 1.8 advanced-blanket target for the full duty. RECOMPUTED

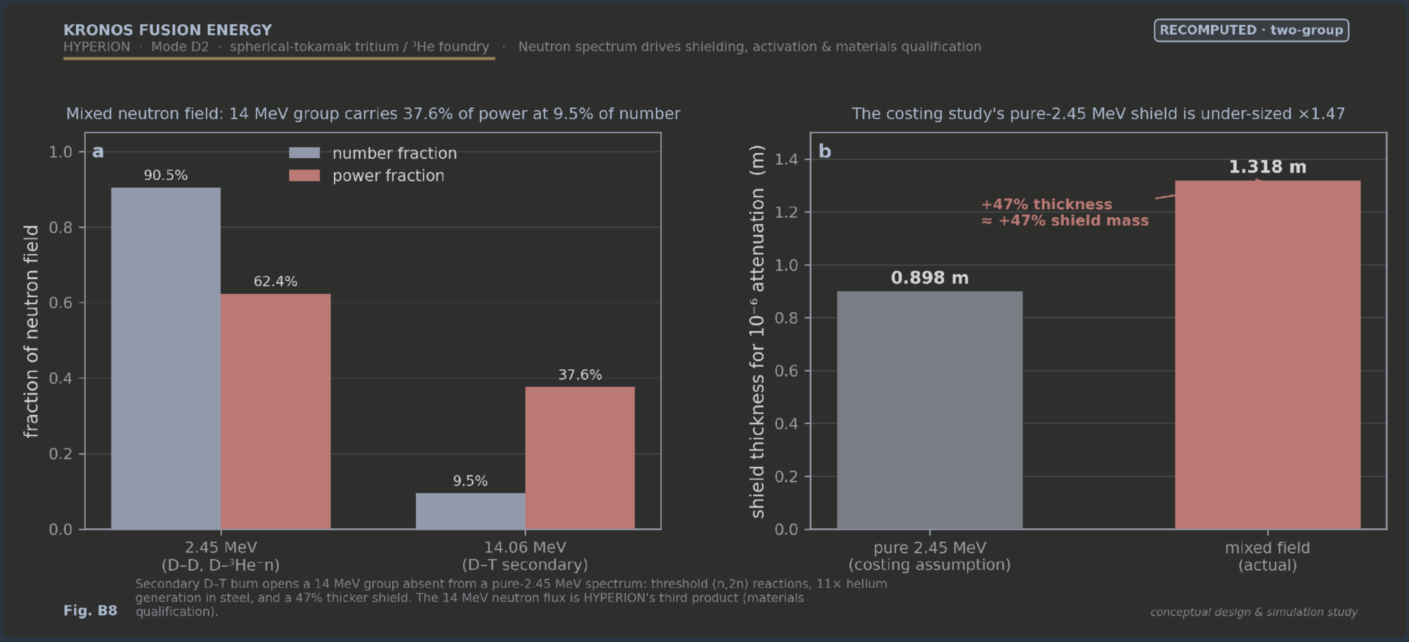


FIGURE 8. Neutron spectrum and shielding for the breeder. Neutrons are the point of a breeder; cleanliness is the generator's story, not this one. RECOMPUTED

5.3 INVENTORY AND SITING

Startup inventory is **≈12–24 kg** (nominal, one-year holdup) and the equilibrium inventory is **6.2 kg** at the reference point (band 3.9–39.4), inside the **≈35 kg** civil licensing precedent. The hazard-category inventory is the binding licensing constraint and points the facility toward a government-hosted or laboratory site; the governing standard was not retrieved in full, so the siting constraint is treated as an inference rather than a citation. INFERRED, NOT A RETRIEVED STATUTE

5.4 EXHAUST: NEGATIVE TRIANGULARITY TRADES A TRANSIENT PROBLEM FOR A STEADY ONE

Negative triangularity's strongest element is the elimination of edge-localised modes (ELMs), and it is demonstrated: a fully ELM-free edge was sustained at $\delta_{avg} = -0.5$ across an entire DIII-D campaign, with **no ELM in any discharge**. An uncontrolled Type-I ELM deposits 5–20% of the pedestal energy in 0.2–1 ms and would exceed tungsten's ≈20 MW m^{-2}, 300-cycle qualification *per event*; NT removes the phenomenon rather than mitigating it. MEASURED

The penalty is steady rather than transient and falls on the divertor. At a poloidal field of **2.60 T** the Eich scaling gives a scrape-off-layer width **λ_q = 0.202 mm** and an upstream parallel heat flux of **14.3 GW m^{-2} — 14× ITER**. Holding the target below ≈100 MW m^{-2} at that width requires a radiated fraction of **≈90%**. That width, however, is an *extrapolation*: the Eich scaling was fitted at B_{pol} = 0.2–1.0 T, so 2.60 T is **2.6×** out of the fitted range. At a broadened λ_q of 0.5–1.0 mm the required radiated fraction falls to **75.2%–50.4%** — within demonstrated detached operation (≈0.9 in JET/ASDEX, 0.6–0.7 in ITER's design).

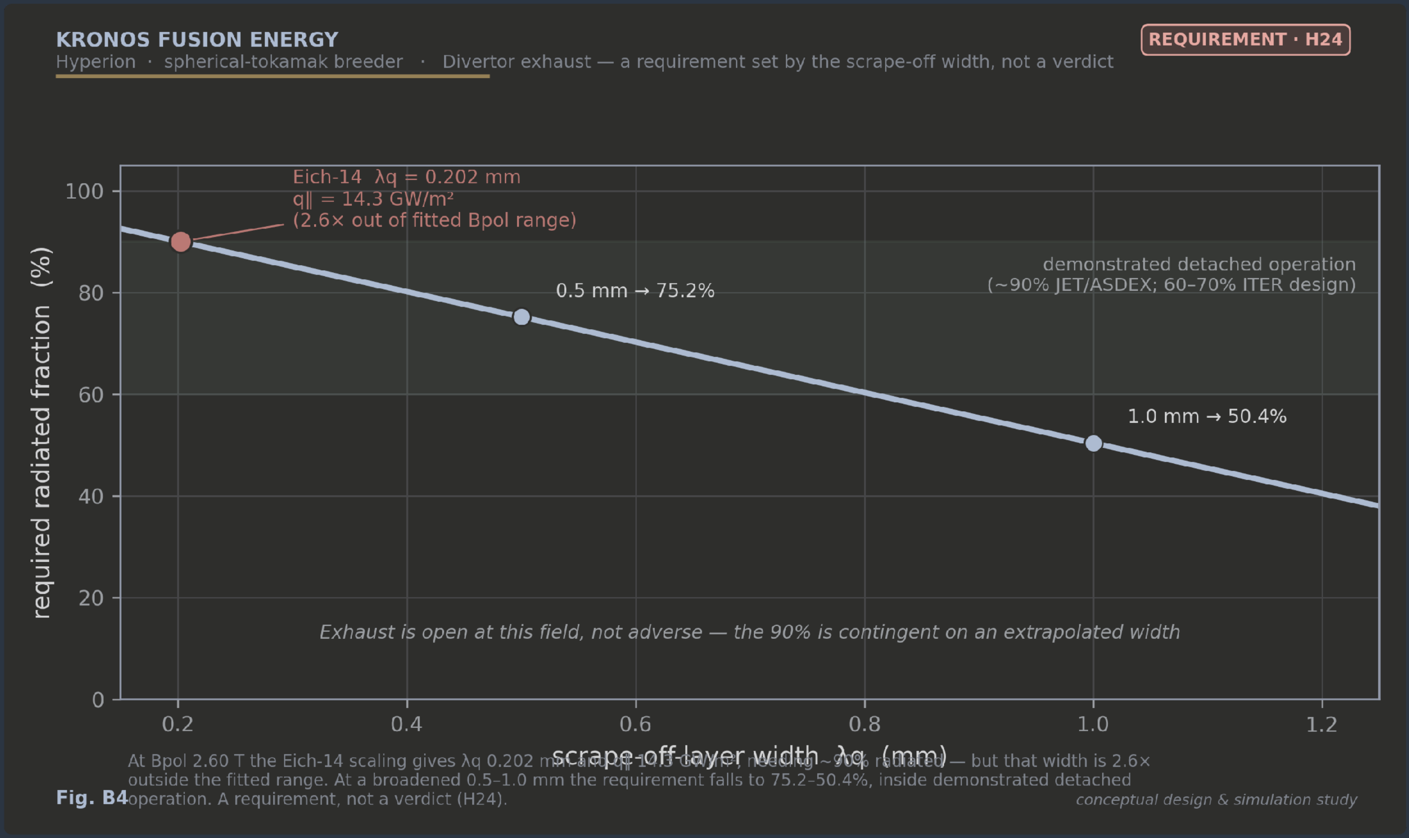


FIGURE 9. The required radiated fraction is set by the scrape-off-layer width. At the Eich-14 width (λ_q = 0.202 mm) the requirement is ≈90%, but that width extrapolates 2.6× beyond the fitted B_{pol} range; at a broadened 0.5–1.0 mm it falls to 75.2–50.4%, within demonstrated detached operation. The exhaust is open at this field, not adverse. OPEN REQUIREMENT

The exhaust is therefore *open at this field, not adverse*: the ≈90% figure is a requirement contingent on the extrapolated width, not a verdict. Sustaining a high radiated fraction, should the extrapolated width hold, requires continuous impurity seeding (nitrogen, neon or argon), a term the present duty model omits. Seeding raises Z_{eff} — from ≈1.16 unseeded toward ≈1.66 for argon — and dilutes the fuel, so that fusion power, which scales as n_D^2, and hence the tritium duty fall (from ≈2.2 toward ≈1.8 kg yr^{-1} across the seeding range). This is the affine-Z_{eff} result made concrete: the divertor imposes its penalty through *duty* rather than through geometry, and it is an engineering, not a physics, gate. SEEDING CARRIED OPEN

5.5 TWO DECLARATIONS THE RECORD REQUIRES

Triangularity

The design uses *negative* triangularity, **δ = −0.30** (NT), the configuration's defining geometric choice and the value carried through the deposit; a scan variant carried δ = +0.4, a numerically modest (**2.3% current**) difference that must not be conflated with the design value.

Helium ash

The scan applied a 5% helium-4 fraction to D–T and zero to pure D–D. The zero is physically correct — neither D–D branch makes helium-4 — but the asymmetry runs *against* the fuel that wins, so the 3.15× current advantage is understated rather than inflated; the machine's ash fraction is reported as undetermined (particle balance admits 0.0002–0.017). UNDETERMINED

§ 6

Enabling subsystems — the magnet and the control layer

The high-field magnet and the real-time control system are shared, at the technology level, with the companion tandem-mirror generator; their status is summarised here and the detailed treatments are deferred to the companion papers.

6.1 THE REBCO CENTREPOST AND A SHARED STRESS-MANAGED ARCHITECTURE

The centrepost peak on-conductor field is **16.84 T**, within the demonstrated REBCO envelope, so for the breeder the magnet is **stress-comfortable**: the binding limit is not hoop stress but the neutron lifetime of the coil behind a compact inboard shield, which points to a demountable or consumable centrepost — a maintenance cadence rather than a fundamental limit. The conductor architecture is strain-first and stress-managed, and is developed against the more demanding case, the burner plug coil at **26.49 T**. SCOPING MODEL, FEA PENDING

Table 3 · REBCO plug-coil feasibility tiers (26.49 T burner-plug field, shared conductor architecture)

TIER	WINDING BORE	SHIELD	BUILD	STRAIN VS. CAP	BASIS
Bare winding (published bound)	0.648 m	30 cm passive	—	4.6–6.5× over	infeasible
Stress-managed (reference)	0.50 m	15 cm structural	14 cm	0.4× (60% margin)	design-study, FEA pending
Frontier (development target)	0.45 m	10 cm advanced	7 cm	0.4×	not yet qualified

The reference tier closes the far harder 26.49 T plug at ≈60% strain margin by making the neutron shield *structural* — a tungsten-based jacket serving as shield, pre-compression shell, and reinforcement. The breeder centrepost (16.84 T) sits comfortably inside that reference regime.

6.2 CONTROL AND COMPUTATION

Real-time control of a nuclear-regulated device is treated in a companion study: a layered digital-twin architecture in which physics-informed machine learning is *deployable now* inside a deterministically clamped safe set, quantum sensing is a near-term diagnostic tier, and quantum *computation* is an offline calibration tier with **no resource crossover this decade**. The design point and results of this paper do not depend on that layer; it is the certification and operations path, carried separately. NO QUANTUM CROSSOVER THIS DECADE

§ 7

Comparison with prior breeder concepts

The physics of a fusion isotope breeder is common prior art; what is distinctive about Hyperion is the sizing, the customer, and the resulting inventory. The inventory objection that sank the large concept *inverts* at the small one.

Table 4 · Hyperion against prior fusion breeders

AXIS	PRIOR FUSION BREEDERS	HYPERION
Confinement concept	Inertial-electrostatic / mirror / tokamak	**Spherical tokamak**
Sizing driver	Support ratio to a fusion fleet	A named national requirement (≈2 kg yr^{-1})
Customer	Fusion satellite reactors	Non-fusion market + a defence procurement authority
Scale considered	≈100 kg yr^{-1} helium-3	≈kg yr^{-1} tritium
Inventory	**1.8-tonne-class (rejected as unlicensable)**	**≈35 kg-class (inside precedent)**

§ 8

Discussion, capital, and what remains load-bearing

The result of this paper is not a new nuclear physics but a *reordering* of an old one: once a breeder is freed from the electricity requirement and sized to a national supply need, the two obstacles that defeated every prior fusion-breeder proposal — machine scale and tritium inventory — both fall below their binding thresholds.

What remains load-bearing is the plasma gain. The design point requires a gain the field has approached but not demonstrated (**Q ≈ 0.7** best to date), and that is carried openly as a design-point target rather than a result. The path forward is a driven, sub-breakeven plasma at demonstrated confinement, which is a materially easier target than net electricity and is what a breeder — unlike a generator — actually needs. GAIN IS A DESIGN-POINT TARGET

CAPITAL: BUILT BY STRUCTURE, NOT BY SCALING

The design point requires fusion gain, not net electricity, and its capital follows from *structure* — the machine is sized to the customer's requirement, not scaled up until an economic optimum appears. Any economic analysis is reported in a separate companion and is **not a condition of the physics result**; nothing in this paper's power balance depends on it.

§ 9

Limitations

The honesty stance is the asset, so the load-bearing caveats are collected here rather than distributed and softened.

- The load-bearing **gain is a design-point target, not a demonstrated result** — no device has exceeded Q ≈ 0.7.
- The confinement multiplier, the current-drive fraction, and the ash fraction are stated with their evidence class rather than assumed.

The re-derivation of the minimum plasma current is internally consistent but **awaits independent replication**.

The **bare blanket TBR falls short of unity** on a 14 MeV spectrum (0.78–0.86); a beryllium multiplier restores net breeding (TBR 1.34), and the full 4.0 kg yr^{-1} duty needs an advanced blanket at TBR 1.8.

The **siting constraint is an inference**, not a retrieved statute.

§ 10

Conclusion

Sized to a national tritium requirement rather than to an electrical output, a compact spherical-tokamak breeder closes its power balance at demonstrated confinement: at the frozen design point (config **22021**) the plasma reaches **Q = 3.424** with P_{fus} = **88.7 MW** at a wall loading of **1.97 MW m^{-2}** and an equilibrium inventory (**6.2 kg**) inside civil licensing precedent.

Net tritium export scales along the blanket lever: the demonstrated beryllium-multiplied blanket (TBR 1.34) nets **≈1.7 kg yr^{-1}**, approaching the national duty, and the full **4.0 kg yr^{-1}** (roughly twice the current world commercial flow) corresponds to an advanced blanket at **TBR ≈ 1.8**, above the demonstrated 1.34 — a stated blanket-development target. The demonstrated, breeding-independent product is **helium-3**.

Once the machine is freed from the net-electricity requirement, machine scale and tritium inventory both fall below their binding thresholds, and the choice of D–T over pure D–D follows from minimising the plasma current (**4.93 MA** minimum on duty, against 15.52 MA for D–D and ITER's 15 MA). What remains load-bearing is the plasma gain, carried openly as a design-point target: no device has exceeded Q ≈ 0.7, and the path forward is a driven, sub-breakeven plasma at demonstrated confinement — a materially easier target than net electricity, and the one a breeder actually needs.

The hard part — the power balance —
is solved; what remains is engineering.

APPARATUS

Portfolio, People & Record

The intellectual-property estate, the people who built it, the limitations that gate it, and the sources it rests on.

1	4	40	27
GRANTED PATENT	2026 PROVISIONALS	TEAM MEMBERS	2022 PROVISIONALS

INTELLECTUAL PROPERTY

The patent portfolio

The estate spans a granted high-field magnet patent, pending utility and 2026 provisional filings that map to the two products, a digital-twin control provisional, a registered trademark application, and the original 2022 provisional family. Every patentable disclosure in the five-paper arXiv drop was protected **before** publication: the breeder and burner provisionals were filed 1–2 August, and a publication-gap omnibus filing the evening before the drop swept up the DEC, plasma-control, and REBCO-winding matter of the three otherwise-unprotected papers. Patent numbers and application serials are matters of public record; claim scope is summarised, not reproduced.

GRANTED & PENDING UTILITY

US 12,009,112	High-field tilted graded-REBCO magnet architecture (KRONO-002A) · *app. 17/878,550*	GRANTED
US 17/878,507	Core device / method (KRONO-001A) · *utility*	PENDING

2026 PROVISIONAL FILINGS — MAPPED TO THE PRODUCTS

64/124,209	Hyperion — spherical-tokamak tritium / helium-3 foundry · *breeder · filed Aug 2026*	FILED
64/124,220	Aegis / MetroVolt — synchrotron-cutoff, fuel-selection & plug-winding · *generator · filed Aug 2026*	FILED
64/115,167	KRONOS-CTRL digital-twin plant control · *provisional · filed Jul 2026*	FILED
64/005,440	Integrated spherical-tokamak fusion architecture · *early integrated-architecture filing · filed Mar 2026*	FILED
64/105,530	Negative-triangularity spherical-tokamak architecture · *foundational ST filing · filed Jul 2026*	FILED
64/128,097	Publication-gap omnibus — quasineutral two-species expander DEC · provenance-gated / latency-split plasma control · as-built high-field winding & conductor architecture · *filed 7 Aug 2026, the evening before the arXiv drop*	FILED

TRADEMARK & ORIGIN

FTK-98801894	Kronos Fusion Energy — trademark application	FILED
KR-2022-*	Original provisional family (KR-2022-00001 … 00027) · *27 filings, 2022*	PRIORITY

The narrow, defensible magnet novelty — the specific conductor and the digital-twin winding optimisation, not high-field REBCO as a category — is the commercial core that can earn ahead of any Q > 1 milestone, with markets in fusion magnet supply, MRI/NMR, accelerators, and proton therapy. The claim is scoped honestly: the high field is a *system field* result, not a stand-alone-coil record; the small-bore plug coil is structurally infeasible as a bare winding but resolved by a stress-managed structural shield (feasible-pending-FEA); and the winding-tape experiment returned a *null result*. The value is the method, not a field record.

THE TEAM

Founding partners, board, advisors & auditors

Kronos is built by a bench of advanced-fuel-fusion, high-field-magnet, direct-conversion, and materials specialists, with a board and operations team drawn from defense, national laboratories, and industry. Dates are shown as ranges; where a tenure has ended or is term-ending, the range says so.

FOUNDING PARTNERS — SCIENCE

Dr. Gerald Kulcinski
Co-Founder · Helium-3 & Advanced-Fuel Fusion
UW–Madison · 2023–Present

Dr. Carl Weggel
Chief Scientist / S.M.A.R.T. Design
MIT Alcator Program · 2022–Present

Dr. Robert J. Weggel
Magnetic Field Design
MIT Magnet Lab · 2022–Present

BOARD

Priyanca Ford
Founder & CEO · Executive Board
2022–Present

Bandel Carano
Finance / Strategy
Oak Investment Partners / Stanford · 2025–2026

Patrick Schweiger
Fusion Device Engineering
Oklo / CFS / TerraPower · 2025–Present

SCIENTIFIC ADVISORS

Dr. Steven O. Dean
Fusion Policy & History
DOE / Fusion Power Associates · 2025–Present

Dr. Patrick H. Diamond
Plasma Turbulence & Transport
UC San Diego · 2025–Present

Dr. Jack J. Dongarra
HPC & Numerical Algorithms
Turing Award · 2025–Present

Dr. Nasr M. Ghoniem
Chief Material Scientist
UCLA · 2025–Present

Dr. Siegfried Glenzer
Plasma Physics & Laser Fusion
Stanford / SLAC · 2022–Present

Dr. David A. Hammer
Pulsed-Power Fusion
Cornell · 2025–Present

Dr. Donald A. Spong
Plasma Theory & Confinement
ORNL · 2025–Present

Dr. Curtis Smith
Risk Assessment & Nuclear PRA
MIT / Idaho National Lab · 2025–Present

RADM (Ret.) David Goggins
Naval Engineering & Power-Plant Design
U.S. Navy · 2023–2026

Dr. Konstantin Batygin
Mathematician
Caltech · 2022–2025

Dr. Ruben Fair
Magnet Design / ITER Liaison
PPPL / Jefferson Lab · 2022–2025

Dr. Paul S. Weiss
Materials & Nanotechnology
UCLA · 2022–2025

SCIENTIFIC AUDITORS

Dr. Wilfred A. Cooper
Plasma Equilibrium Theory
EPFL / Swiss Plasma Center · 2025–Present

Dr. Ahmed Hassanein
Plasma–Material Interactions
Purdue / Argonne · 2025–Present

Dr. Patrick E. Hopkins
Extreme Thermal Materials
U. of Virginia · 2025–Present

Dr. Peter Hosemann
Materials Joining & Structural Integrity
UC Berkeley · 2025–Present

Dr. Travis W. Knight
Advanced Nuclear Fuels & Systems
U. of South Carolina · 2025–Present

Dr. Philippe Lebrun
Cryogenics & Magnet Cooling
CERN · 2025–Present

Dr. Nitendra Singh
Nuclear Safety & Fuel Cycle
ITER · 2025–Present

Dr. Guido Van Oost
Magnetic Confinement & Fusion Systems
Ghent University · 2025–Present

Dr. Gary S. Was
Radiation Materials & Structural Integrity
U. of Michigan · 2025–Present

Dr. Ray Sedwick
Direct Energy Conversion
U. of Maryland · 2025

OPERATIONS

Michael Laughlin
Chief Operating Officer
2022–Present

Martin Owens
Chief Strategy Officer
LANL / GE Hitachi · 2022–Present

MG (Ret.) Paul Pardew
Chief Contracting Officer
Army Contracting Command · 2022–Present

David Beck
Fusion Commercialization
U.S. Space Force · 2024–Present

Sushma Bhatia
Environmental & Legislative
Google · 2022–Present

Michael De Frenza
Technology Licensing
2023–Present

MG (Ret.) Robin L. Fontes
Cybersecurity & Defense
Army Cyber Command · 2022–Present

Vijay Gehani
Supply Chain & Components
INOX India · 2024–Present

Jon Michel Greenwood
IT & AI Infrastructure
Live Nation · 2023–Present

Brian C. O'Neill
National Security
CIA / ODNI · 2022–Present

Gen. (Ret.) Gustave F. Perna
DoD Liaison
Operation Warp Speed · 2022–2023

Andrea Romero
Marketing Lead
2022–Present

Legal counsel is retained; those roles are held on the internal roster and are not listed here.

List of Figures

Figure 1 — Hyperion spherical-tokamak cutaway with the internal build exposed — a negative-triangularity... 10
Figure 2 — Hyperion radial build from the centrepost outward: centre-column magnet, vacuum vessel, breeding... 11
Figure 3 — Hyperion fuel cycle: deuterium fuelling, the D–D and D–T branches, tritium and helium-3... 12
Figure 4 — Net tritium production against plasma current for all on-duty closing configurations (213 D–T, 71... 13
Figure 5 — The three levers tested for current relief — toroidal field (inert), elongation (adverse), and... 14
Figure 6 — Net helium-3 yield after every loss at the 140 MW pure-D–D reference: gross prompt 3 He, the... 15
Figure 7 — Lithium-blanket TBR versus 6 Li enrichment and neutron energy: on the 14 MeV D–T spectrum... 16
Figure 8 — Neutron spectrum and shielding for the breeder. Neutrons are the point of a breeder; cleanliness is the... 17
Figure 9 — The required radiated fraction is set by the scrape-off-layer width. At the Eich-14 width (λ q... 18

LIST OF TABLES

List of Tables

Table 1 · Four independent evaluations of the D–D self-heating / bremsstrahlung ratio 8
Table 2 · The fuel result at the closing minima (recomputed from the raw 25,200-row scan) 11
Table 3 · REBCO plug-coil feasibility tiers (26.49 T burner-plug field, shared conductor architecture) 19
Table 4 · Hyperion against prior fusion breeders 20

REFERENCES

Sources

[1] H.-S. Bosch and G. M. Hale, "Improved formulas for fusion cross-sections and thermal reactivities," *Nuclear Fusion* **32**, 611 (1992).

[2] A. S. Richardson, *NRL Plasma Formulary*, Naval Research Laboratory (2019).

[3] I. E. Ochs, E. J. Kolmes, and N. J. Fisch, "Bremsstrahlung and the electron–electron contribution in fusion plasmas," *Physics of Plasmas* (2024).

[4] T. H. Rider, "Fundamental limitations on plasma fusion systems not in thermodynamic equilibrium," *Physics of Plasmas* **4**, 1039 (1997).

[5] ITER Physics Expert Groups, "ITER Physics Basis," *Nuclear Fusion* **39**, 2137 (1999).

[6] N. A. Uckan and J. Sheffield, "Tokamak scaling and confinement," in *Tokamak Concept Improvement*, IAEA (1989).

[7] O. Sauter, C. Angioni, and Y. R. Lin-Liu, "Neoclassical conductivity and bootstrap current," *Physics of Plasmas* **6**, 2834 (1999).

[8] F. Troyon *et al.*, "MHD limits to plasma confinement," *Plasma Physics and Controlled Fusion* **26**, 209 (1984).

[9] J. P. Freidberg, *Plasma Physics and Fusion Energy*, Cambridge University Press (2007).

[10] R. F. Post, "The magnetic mirror approach to fusion," *Nuclear Fusion* **27**, 1579 (1987).

[11] D. E. Baldwin, "End-loss processes from mirror machines," *Reviews of Modern Physics* **49**, 317 (1977).

[12] T. K. Fowler, R. W. Moir, and T. C. Simonen, "A new simpler tandem mirror," *Nuclear Fusion* **57**, 056014 (2017).

[13] G. L. Kulcinski and J. F. Santarius, "Advanced fuels and the D–^{3}He cycle," University of Wisconsin Fusion Technology Institute.

[14] W. L. Barr and R. W. Moir, "Test results on direct energy converters for mirror reactors," *Nuclear Technology/Fusion* **3**, 98 (1983).

[15] D. B. Go *et al.*, "Thermionic energy conversion in the twenty-first century," *Frontiers in Mechanical Engineering* **3**, 13 (2017).

[16] M. Wang *et al.*, "The AME 2020 atomic mass evaluation," *Chinese Physics C* **45**, 030003 (2021).

[17] J. E. Menard *et al.*, "Fusion nuclear science facilities and pilot plants based on the spherical tokamak," *Nuclear Fusion* **56**, 106023 (2016).

[18] A. J. Creely *et al.*, "Overview of the SPARC tokamak," *Journal of Plasma Physics* **86**, 865860502 (2020).

[19] T. P. Wright, "Factors affecting the cost of airplanes," *Journal of the Aeronautical Sciences* **3**, 122 (1936).

[20] U.S. Department of Energy / NNSA, *Stockpile Stewardship and Management Plan*, FY2024.

[21] J. F. Santarius, G. L. Kulcinski, and L. A. El-Guebaly, "A strategy for D–^{3}He fusion energy development," *Journal of Fusion Energy* **17**, 33 (1998).

[22] M. A. Abdou *et al.*, APEX advanced blanket concepts, *Fusion Engineering and Design* (1999–2003).

[23] Federal Register, notice on supply of tritium to non-federal entities (1999).

[24] Kronos Fusion Energy, "Simulation register and reproducibility deposit," Zenodo (2026).

[25] A. O. Thome *et al.*, "ELM-free negative-triangularity edge on DIII-D," *Plasma Physics and Controlled Fusion* (2024), doi:10.1088/1361-6587/ad6f40.

[26] T. Eich *et al.*, "Scaling of the tokamak near scrape-off layer power width," *Nuclear Fusion* **53**, 093031 (2013).

[27] J. Lim *et al.*, "Scrape-off-layer width in negative-triangularity plasmas," *Nuclear Fusion / Plasma Physics and Controlled Fusion* (2023).

[28] A. O. Nelson *et al.*, "Prohibition of second-stability access at negative triangularity," *Plasma Physics and Controlled Fusion* **64**, 124002 (2022).

COLOPHON

How this document was made

The Kronos Fleet — Combined Editorial, 2026 is set in **Fraunces** (display), **Gelasio** (text), and **IBM Plex Mono** (data & equations), carried forward from the Kronos editorial design system.

The figures are rendered at 300 dpi from the deposited generator scripts; the document is composed as a single self-contained file with embedded fonts and imagery, paginated to US Letter, and rendered to PDF through a headless Chromium engine in matched light and dark editions.

Every headline quantity carries an evidence class; withdrawn and restated values are marked as such. Nothing herein is frozen beyond the founder-approved Tier-A set.

Explore it live — turn the interactive 3-D model, run the deposited solvers in the physics validator, and watch the companion film series.

LEGAL NOTICE

Notice, status, and distribution

Conceptual design & simulation study. This document reports a conceptual design and simulation study. It is not a construction commitment, a safety-analysis report, a regulatory filing, or an offer of securities. Forward-looking statements — schedules, costs, market sizes, and performance — are estimates subject to the limitations set out in the Simulations part and may change.

Numbers and their classes. Quantities are reported with evidence classes and case labels; modelled, assumed, and requirement-class values are identified as such and are not to be quoted without their labels.

Public edition. This edition carries the physics and design only; all financial, funding, and defense-commercial content has been removed for public distribution. The scientific text corresponds to the arXiv and journal submissions.

THE 2026 KRONOS SET

One programme, in five papers

This editorial is one of five that together describe the Kronos fusion programme — a breeder that funds a generator, and the magnet, conversion, and control science that enable both. Each is published open-access with a reproducible companion deposit.

PAPER I	**Hyperion — The Tritium Foundry** *(this paper)* · 10.5281/zenodo.21746157
PAPER II	**Aegis & MetroVolt — The Generator** · 10.5281/zenodo.21746479
PAPER III	**High-Field REBCO Magnets & Tape** · 10.5281/zenodo.21842514
PAPER IV	**Direct Energy Conversion** · 10.5281/zenodo.21842864
PAPER V	**AI, ML & Quantum Control** · 10.5281/zenodo.21842371

Explore the whole programme live: the interactive 3-D model, the in-browser physics validator, and the companion film series.

KRONOS FUSION ENERGY

Hyperion

Explore the science — live, in your browser.

kronosfusionenergy.com/3D-Model

kronosfusionenergy.com/physics-Validation-Simulation

Companion film series · YouTube

Zenodo · DOI 10.5281/zenodo.21746157