SABERCROWN HARDWARE RESEARCH

SCME — Selective Mineral Extraction

Plasma Mass-Sorting of Vaporized Ore: Concept Whitepaper

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PLANNING-STAGE — NOTHING BUILT

Abstract

SCME proposes a mining head that skips comminution and wet chemistry entirely: a klystron or other high-voltage source vaporizes the uppermost layer of exposed ore into plasma; high-power electromagnetic fields capture that plasma and sort it by ion mass into four weight classes while it is still hot — the sort happens in-flight, within the microsecond-to-millisecond window before recombination; each weight class condenses into its own sealed container; and a spectrometer then audits every container, producing a per-bag manifest of the atoms and molecules actually collected. This paper states the concept, its physics basis and prior art, a six-iteration bench development plan (P1–P6), and the open risks that could invalidate it. It is deliberately non-overclaiming: nothing described here exists yet.

1. Concept Overview

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[Ore Face]
   |  klystron / pulsed-HV energy delivery
   ▼
[Stage I — Vaporize]  uppermost layer only → hot plasma plume
   |  extraction electrodes + magnetic guide coils
   ▼
[Stage II — Capture]  steer plume into separation channel while ionized
   |  crossed E×B / sector fields, single transit
   ▼
[Stage III — Mass Sort]  4 weight classes: W1 W2 W3 W4
   |  cooled condensation liners
   ▼
[Stage IV — Contain + Audit]  sealed containers → spectrometer → manifest
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The end-state vision (see the concept render on the project page) is element-labeled bins — Au, Cu, rare earths, Ag, waste. The buildable intermediate is coarser: mass separation into four weight classes, with a spectrometer audit telling you which bag actually holds what. The manifest is the bridge between weight classes and element bins.

2. Stage I — Surface Vaporization (Klystron / HV)

Energy is delivered to the exposed ore face so that only the uppermost layer (micrometre scale per shot) is vaporized and partially ionized — surface stripping, not bulk fracturing. The concept targets a klystron-class microwave source for directed, repeatable energy delivery; the bench plan starts with a current-limited pulsed HV arc and a magnetron RF path, which reach the same physics at survivable cost and power.

Energy budget

The specific energy to take rock from ambient to vapor is the sum of sensible heat, fusion, and vaporization terms:

$$E_v = c_p \Delta T + L_f + L_v \approx 10\text{–}30\ MJ/kg$$

where $c_p \approx 1\text{–}1.2$ kJ/(kg·K), $\Delta T \approx 2500\text{–}3000$ K for silicates, $L_f \approx 0.3\text{–}0.5$ MJ/kg, and L_v dominates at ~5–25 MJ/kg depending on mineralogy.

The ablated mass per shot and the resulting surface-layer depth follow directly from the pulse energy and coupling efficiency η:

$$m_{shot} = \eta E_{pulse} / E_v, \quad \delta = m_{shot} / (\rho A_{spot})$$

Example: a 100 J pulse at $\eta = 0.3$ and $E_v = 25$ MJ/kg ablates $m_{shot} \approx 1.2$ µg; over a 1 mm² spot at $\rho = 2700$ kg/m³ that is $\delta \approx 0.45$ µm — consistent with the µm-scale surface-stripping requirement.

For the RF path, microwave power deposits volumetrically through dielectric loss:

$$P_{abs} = \tfrac{1}{2}\omega\varepsilon_0\varepsilon''_r|E|^2$$

with ω the angular frequency and ε''_r the loss factor of the ore — strongly temperature-dependent, which produces the thermal-runaway heating that makes microwave rock treatment attractive.

Ionization fraction

EM capture only acts on ions, so the fraction of vapor that ionizes is first-order. In local thermodynamic equilibrium it is governed by the Saha equation:

$$n_e n_i / n_0 = 2\,(g_i/g_0)\,(2\pi m_e k_B T / h^2)^{3/2}\,\exp(-E_i/k_B T)$$

First ionization energies span Na 5.1 eV, Fe 7.9 eV, Si 8.2 eV, Au 9.2 eV — so a plume needs $k_B T$ approaching ~1 eV (≈11,600 K) for a useful ion fraction, and lighter-ionizing elements ionize preferentially, biasing what the sorter can even see.

> **Energy reality:** heating, melting, and vaporizing silicate rock costs on the order of 10–30 MJ/kg (roughly 3–8 kWh/kg) before any ionization energy is spent. This bounds throughput for any given source power and is the single largest economic question mark of the concept.

3. Stage II — Plasma Capture

Electromagnetic fields only act on charged particles, and an ablation plume cools and recombines fast. The usable window in which the plume is a steerable plasma is expected between

microseconds and milliseconds, depending on density and ambient pressure. Stage II therefore consists of biased extraction electrodes and DC magnetic guide coils that pull the plume into a drift channel immediately after the shot. Timing — transported charge versus delay after the shot — is the core dataset. Material that leaves the surface neutral cannot be steered and is lost to the sort; the achievable ionization fraction is a first-order unknown.

Timing and field sizing

The plume expands at roughly the ion-acoustic speed, which sets how long Stage II has to act:

$$c_s = \sqrt{(\gamma Z k_B T_e / m_i)}$$

For Fe^+ at T_e = 1 eV, $c_s \approx 1.7$ km/s — the plume crosses a 10 cm capture channel in ~60 μs. All capture and sorting fields must act inside that transit.

The guide field is sized from the ion Larmor (gyro) radius, which must be smaller than the channel bore:

$$r_L = m_i v_\perp / (ZeB)$$

A thermal (1 eV) Fe^+ ion at B = 0.1 T has $r_L \approx 1$ cm — so ~0.1 T coils confine mid-mass ions in a few-cm channel; heavier ions at the same energy need proportionally more √m field.

The plasma stays sortable only until it recombines. With recombination coefficient α, the characteristic window is:

$$\tau_{rec} \approx 1 / (\alpha n_e)$$

α ~ 10^{-19}–10^{-17} m^3/s (radiative + three-body, falling with T_e) and n_e ~ 10^{19}–10^{21} m^{-3} give τ_{rec} anywhere from microseconds to milliseconds — a four-order-of-magnitude uncertainty that P2 exists to measure.

4. Stage III — In-Flight Weight-Class Sort

While hot and guided, the ion stream passes a crossed-field (E×B / magnetic-sector) separation region. Deflection depends on mass-to-charge ratio, dispersing the stream so that a four-aperture exit manifold splits it into weight classes in a single transit:

CLASS	WORKING MASS RANGE	EXAMPLE CONTENT
W1 · Light	≤ ~30 amu	O, Na, Mg, Al, Si
W2 · Mid-light	~30–70 amu	Ca, Ti, Fe, Cu
W3 · Mid-heavy	~70–150 amu	Ag, lighter rare earths
W4 · Heavy	≥ ~150 amu	W, Au, Pb

Class boundaries are working assumptions, set by aperture geometry and tuned during the bench program. Two effects are expected to dominate sort quality: the velocity spread of ablation ions

(which blurs mass dispersion and may force a velocity-filter stage) and space-charge repulsion at useful throughputs.

Separation physics

A pure E×B drift is mass-independent ($v_d = E/B$), so it cannot sort — but that same property makes crossed fields a velocity filter: only ions with $v = E/B$ pass undeflected (Wien filter), which is the standard cure for the ablation velocity spread. Mass dispersion then comes from the magnetic sector, where the bend radius scales with mass:

$$r = m_i v / (ZeB), \quad or \quad r = (1/B) \cdot \sqrt{(2 m_i V / Ze)}$$

for ions accelerated through potential V. Example: Fe^+ at V = 500 V and B = 0.2 T bends at r ≈ 12 cm — benchtop scale. Since $r \propto \sqrt{m}$ at fixed V, the W1/W4 boundary masses (30 vs 150 amu) differ in radius by $\sqrt{5} \approx 2.2\times$ — four apertures a few cm apart resolve that easily; the fight is against velocity spread, not geometry.

Throughput is where the physics bites. A bare ion beam is space-charge limited (Child–Langmuir):

$$J = (4\varepsilon_0/9) \cdot \sqrt{(2Ze/m_i)} \cdot V^{3/2}/d^2$$

and even ignoring that limit, mass flow per ampere of ion current is tiny:

$$\dot{m} = I \cdot m_i / (Ze)$$

One full ampere of Fe^+ is only ≈ 2 g/h. This single number explains both the calutron's scale and why SCME's sorter must operate as a quasi-neutral plasma flow (electrons riding along, neutralizing space charge) rather than an extracted ion beam — exactly the regime the plasma mass filter prior art works in.

Prior art

- **Calutrons** (WWII electromagnetic isotope separation) prove EM mass sorting of vaporized/ionized feedstock works at scale — and document how energy-hungry it is.
- **Plasma mass filters** (Ohkawa filter; the Archimedes project for nuclear-waste separation) demonstrate rotating-plasma light/heavy separation at laboratory scale.
- **Laser ablation + ICP mass spectrometry** routinely does the whole chain — ablate, ionize, mass-separate, detect — at nanogram scale. SCME is, bluntly, an attempt to scale that chain's physics from analysis to extraction.

5. Stage IV — Container Audit via Spectrometer

Each weight class condenses on a cooled, removable liner — the “bag” — which is sealed, weighed, and labeled per run. A spark/LIBS emission spectrometer then samples every container's deposit and produces a manifest: run ID, weight class, detected elements, line intensities, estimated mass. Trust in the sort comes from measuring every bag, not from assuming the fields worked. The manifests also provide the physics cross-check: heavy elements must trend toward W3/W4, every run.

Quantification physics

In the spark/LIBS plasma, the emission line intensity of species s follows the Boltzmann distribution over excited states:

$$I_{ki} \propto (n_s g_k A_{ki} / \lambda_{ki} U_s(T)) \cdot exp(-E_k / k_B T)$$

where n_s is the species number density, g_k and E_k the upper-level degeneracy and energy, A_{ki} the transition probability, and $U_s(T)$ the partition function.

Plotting $\ln(I\lambda/gA)$ against E_k for several lines of one element gives a straight line of slope $-1/k_B T$ — the Boltzmann plot that yields the plasma temperature. With T and n_e known (the latter from Stark broadening of a reference line), the Saha–Boltzmann relation links neutral and ion lines of each element, allowing calibration-free estimates of relative element fractions in the deposit. PoC v1 treats these as semi-quantitative and anchors them against the single-element reference deposits from P3 calibration runs.

6. Development Plan (P1–P6)

Six bench iterations, each with pre-registered binary acceptance gates. Full detail (schematics, BoM, test setups, open questions) lives on the project page.

PERIOD	BUILDS	HEADLINE GATE
P1	HV vaporization source bench (arc first, waveguide flange reserved)	Ablated mass per shot repeatable within ±20%; plume on ≥90% of shots
P2	Plasma capture channel (extraction electrodes + guide coils)	≥10% of plume charge transported; field-on/off contrast ≥10×
P3	In-flight E×B weight-class sorter, 4 apertures	Single-element shots ≥70% charge in correct class; monotonic W1→W4 ordering
P4	Cooled condensation liners → sealed containers	Correct-container deposit after 100 shots; <5% adjacent-liner contamination
P5	Per-container spectrometer audit + manifest pipeline	Dominant elements correct in ≥85% of audits; ordering matches class
P6	Frozen PoC v1, blind demonstrations, this whitepaper's data package	Expected mass ordering all demo days; manifests match sealed assays

7. Safety Baseline

- All vaporization inside a sealed, interlocked, shielded chamber; lid opening kills the supply.
- HV supplies current-limited; RF stages (magnetron/klystron) behind waveguide containment with leakage monitoring at the operator position.
- Fume extraction through HEPA/carbon filtration; sealed containers for all collected material.
- No open-beam operation of any kind in the PoC program.

8. Open Risks

- **Ionization fraction:** if most ablated mass leaves neutral, the EM sort acts on a small minority of the material.
- **Recombination window:** if the plasma window is shorter than transport + separation transit time, the in-flight sort fails.
- **Velocity spread and space charge:** both blur mass separation; both worsen with throughput.
- **Energy economics:** ~3–8 kWh/kg to vaporize before sorting; no known bound yet makes bulk ore processing economic. The credible near-term niches are high-value targets: precious-metal concentrates, rare-earth streams, or off-Earth use where wet chemistry is impossible.
- **Klystron availability:** cost/availability at PoC power levels may keep the program on magnetron/arc sources longer than planned.

9. Conclusion

SCME's chain — vaporize the top layer, capture the plasma hot, mass-sort it in-flight into four weight classes, and audit every container with a spectrometer — is composed entirely of individually demonstrated physics (ablation, plasma guiding, EM mass separation, emission spectroscopy). What is unproven is the combination at extraction scale and its energy economics. The P1–P6 bench program is designed to answer the cheapest invalidating questions first; the gate at the end of P6 — blind-run manifests matching sealed assays — is the minimum credible evidence that would justify scaling power toward a true klystron stage.
