NOTES ON THE MULLINS MARK I CYCLOTRON

# The Electromagnet

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|---|---|---|---|---|---|
| **Author** | Mark1 AI instance, driven by Chris Mullins | **Date** | 2026-09 | **Revision** | v0 draft |
| **Configuration** | magnet as built 2017–2018, configuration continuous through 2025-02-02 | | | | |
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**Machine at a glance**

| | |
|---|---|
| Type | Classical single-dee proton cyclotron, internal beam only |
| Magnet | H-frame, 1018 steel, 8 in poles, 1.42 in gap (as built); 538 turns of ¼ in copper refrigeration tubing, air-cooled |
| Field | 0.851 T maximum at 55 A; operated at 570–596 mT in the beam era |
| RF | ~9 MHz, ~50 W solid-state chain; dee voltage ~800 V nominal, uncalibrated |
| Chamber | 304 stainless ring, ≈9.75 in bore, 1.000 in interior, ten KF16 ports, two 0.200 in lids |
| Vacuum | Edwards SI100 diffusion pump + 3 cfm rotary; gate $1\times10^{-5}$ torr (5.0 V on the ion gauge) |
| Ion source | Tungsten filament (ES-020) in hydrogen at $\sim10^{-5}$ torr, mass-flow controlled |
| Detection | Copper collector ("Faraday cup") on a linear translator, Keithley 617 electrometer |
| Best beam on record | −3.1 nA vs −0.55 nA background (5.6×), 596 mT / 9.033 MHz, 2023-10-14; ~150 keV-class computed |
| Built / operated | 2017–2018 build; 176 logged runs on 44 dates, 2018-12-16 → 2025-02-02 |

## 1. Summary

The Mark I magnet is a conventional H-frame electromagnet built from cut-to-size 1018 cold-rolled steel plate, with 8 in diameter poles and two series-connected coils wound from ¼ in copper refrigeration tubing. It was designed in the spring of 2017, the iron was machined and test-fitted in October 2017, the first coil was finished and set on the frame on 2017-10-22, and the second coil went on in May 2018. It has not been modified since. The 2023–24 loan of the magnet to an unrelated bolt-testing project happened in place on the cyclotron cart; the magnet never left the bench and its configuration is continuous from 2018 to the last cyclotron run on 2025-02-02.

| Parameter | Design (2017) | As built / measured |
|---|---|---|
| Pole face diameter | 8 in | 8 in (6 in poles + 1 in extensions) |
| Pole gap | 1.5 in | 1.421 in measured |
| Ampere-turns | 25,000 (538 turns × 46 A) | 538 turns; up to 55 A = 29,600 A-turns |

| Parameter | Design (2017) | As built / measured |
|---|---|---|
| Center field | 0.824 T at 46 A(ideal-gap formula) | 0.851 T at 55 A; ~0.73 T at 46 A |
| Coil resistance | ~1 Ω hot | 0.96 Ω at 72 °F; ≈1.03 Ω hot |
| Power at full current | 46 A / 45 V ≈ 2.1 kW | 55 A / 55 V ≈ 3.0 kW |
| Iron weight | ~760 lb | 757 lb (frame 558, poles 171, extensions 29) |
| Copper weight | — | 145 lb |
| Cooling | Water through the tubing bore | Never installed; air-cooled with a duty limit (§6) |
| Operating point, beam era | — | 570–596 mT (~35–37 A), set by the RF chain, not the iron |

## 2. Design intent and sizing

The design target was a field of about 0.8 T across an 8 in pole. The sizing is the textbook one. Treating the iron as a perfect conductor of flux, the coil must supply the magnetomotive force to push the field across the air gap:

> $NI = B \cdot g / \mu_0 = 0.824\ \text{T} \times 0.0381\ \text{m} / (4\pi \times 10^{-7}) \approx 25{,}000$ ampere-turns.

That number was set with a 1.5 in gap and became the fixed point of the coil design: 538 turns at 46 A. The chalkboard version of the calculation (figure 1) carried an efficiency factor η in the denominator, and an early test with 80 turns of extension cord on the bare frame gave η ≈ 0.83 (figure 3) — pessimistic, as it turned out; the finished magnet reaches 87–95 % of the ideal-gap value depending on current (§7).

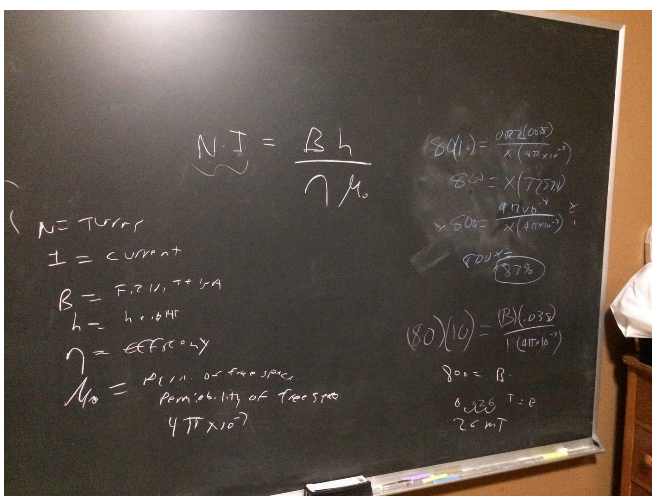



Figure 1. Chalkboard, 2017-10-21. The ampere-turn formula NI = Bh/(ημ₀) with the symbols defined, and at right the prediction for the extension-cord test: 80 turns × 10 A across the 0.038 m gap gives 26 mT at η = 1. The measured result was recorded as "83 %".

The rest of the iron followed from the pole. The pole cross-section is $\pi \times 4^2 \approx 50$ in². The flux returns through two legs, so each leg needs at least ~25 in²; the 3 in × 8 in plate chosen for every frame member gives 24 in² per leg, adequate with the field split and checked in FEMM (§8). The attractive force between the poles at 0.82 T is about 8.8 kN (2,000 lbf). The workbook's stiffness check puts 4,000 lb on the 17.4 in window span and finds 18 mil deflection in the top plate — acceptable, and in the direction that closes the gap slightly rather than opening it.

A proof-of-concept mini-magnet (0.75 in poles, 0.5 in gap, 400 turns) reached 0.33 T at 10 A in May 2017 and validated both the formula and the FEMM workflow before any large steel was bought.

## 3. Iron

All frame members are 1018 cold-rolled steel, 3 in thick and 8 in wide, bought cut to length and then machined locally (Metals Supermarket for the plate; BRMW for machining). The poles are 8 in diameter × 6 in long 1018 round bar, and each carries a 1 in thick, 8 in diameter pole extension so that the gap faces are replaceable and can be machined flat independently of the frame.

| Member | Size | Qty | Weight |
|---|---|---|---|
| Top / bottom plates | 8 × 3 × 28 in | 2 | 176.8 lb each |
| Side plates | 8 × 3 × 15.5 in | 2 | 102 lb each |
| Poles | 8 in dia × 6 in | 2 | 171.3 lb (pair) |
| Pole extensions | 8 in dia × 1 in | 2 | 28.6 lb (pair) |
| **Iron total** | | | **757.5 lb** |

Frame outer height is 21.5 in (15.5 in window plus two 3 in plates); outer width 28 in. The poles attach to the frame with ¾ in threaded rod, 1 in long. Each pole extension is held by eight 8-32 shoulder screws countersunk flush with the face. The as-built pole gap, measured with the extensions on, is 1.421 in — 0.08 in under the 1.5 in design figure — and this is the number the vacuum chamber was later sized to (the chamber stack is 1.400 in, leaving 0.01–0.02 in clearance).

Figures 2 and 3. Left: the machined frame and poles test-fitted, 2017-10-19, standing on cardboard in the shop with the lifting sling at right; both poles are in place, but the 1 in pole extensions were added two days later, so the gap shown is wider than the final 1.42 in. Right: the first efficiency test, 2017-10-21 — the bare frame with about 80 turns of orange extension cord wound around the poles, a bench supply at left and the HT20 gaussmeter (reading zero, supply off) with its probe in the gap. This test produced the "83 %" on the chalkboard.

## 4. Coils

### 4.1 The conductor choice

The coil design was a trade among resistance, supply voltage, size, cost and heat, between magnet wire and ¼ in ACR (air-conditioning and refrigeration) copper tubing. Per pound of copper the tubing was cheaper, and its bore offered a ready path for cooling water. Against it: no insulation, 100 ft rolls (so a 900 ft coil needs joints), and a bulkier coil than wire. Rectangular hollow conductor of the laboratory kind was not available at a sensible price.

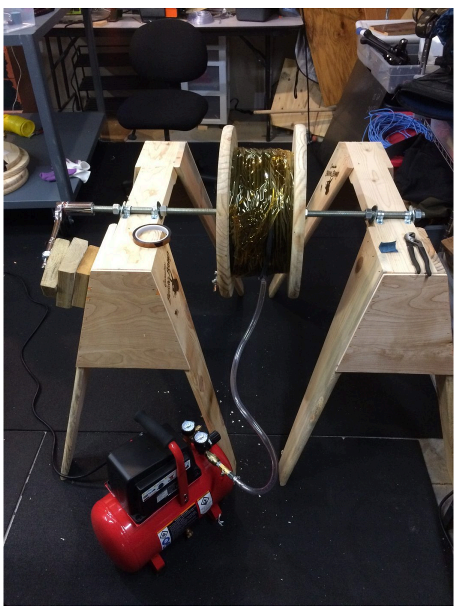
| Coil parameter | Value |
|---|---|
| Coils | 2, series connected, one above and one below the chamber |
| Turns | 269 per coil, 538 total (design goal was 300 per coil) |
| Conductor | ¼ in OD soft copper ACR tubing, ~900 ft per coil, ~1,800 ft total |
| Coil form | 8.25 in ID, to slip over the 8 in poles; each coil 6 in tall with a 5 in radial build (OD about 18.25 in; builder's measurement, Sept 2026) |
| Insulation | Techflex Insultherm 0.263 in fiberglass sleeving; 6 in Kapton tape between layers |
| Joints | 9 × 100 ft sections per coil, silver-soldered couplers |
| Copper weight | 145 lb total |
| Resistance | 0.96 Ω total at 72 °F (measured); ≈1.03 Ω hot |
| Inductance | 72 mH DC; 34 mH at 100 Hz; 14.6 mH at 1 kHz; 0.71 mH at 10 kHz; 0.22 mH at 100 kHz |

The steep fall of inductance with frequency is the signature of eddy currents in the solid (unlaminated) iron; it matters for the back-EMF network (§5) and for how quickly the field can be swept.

### 4.2 Winding method

The sleeving was the hard part: pushing a full 100 ft length of Insultherm over 100 ft of tubing was impractical. The method that worked was to cut it into 25 ft pieces, slide two onto the two ends of a 100 ft roll and work them toward the middle, then add two more from the ends. Each prepared 100 ft section was wound onto a plywood form on a sawhorse stand; the first stand proved unstable on a ladder and was replaced by one with a ratchet to stop unwinding and a turns counter. Each finished layer was wrapped with 6 in wide Kapton tape to hold it in place.

Sections were joined with couplers cut about 1 in long from the next size up, 5/16 in ACR tubing, reamed and gently expanded until they slipped over the ¼ in tubing, then silver-soldered with a torch (Harris Stay-Brite silver solder and flux). After each section was attached, the coil so far was pressure-tested at 100 psi with a shop compressor to confirm the joint was watertight (figure 4).




Figures 4 and 5, both 2017-05-28. Left: the winding stand — a partially wound coil on the plywood form between sawhorses, the compressor at lower left connected by hose for the 100 psi pressure test, a roll of Kapton tape on the stand. Right: a completed joint — the 5/16 in coupler silver-soldered over the ends of two ¼ in tubing sections, with the black fiberglass sleeving pulled back on both sides before it is slid over the joint.

The first coil was completed on 2017-10-22 at 900 ft and 269 turns and set on the frame the same evening; a single-coil test two days later drew 54.7 A at 30 V and reached 0.45 T. The second coil was hoisted onto the frame with a magnetic lifter on 2018-05-12 and the magnet was run to the supply's full 55 V / 55 A the same day (figure 6).

### 4.3 The blocked joint

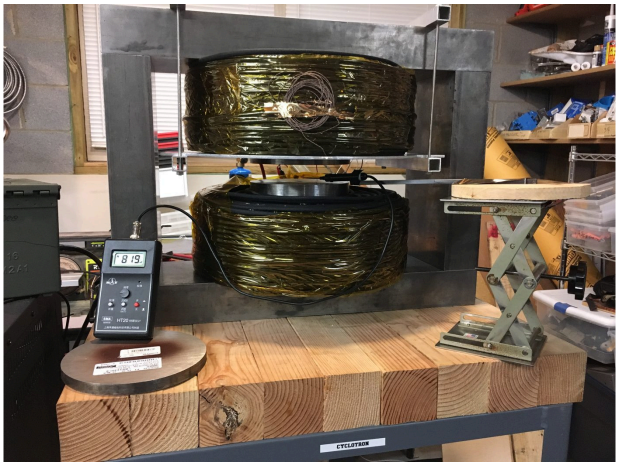
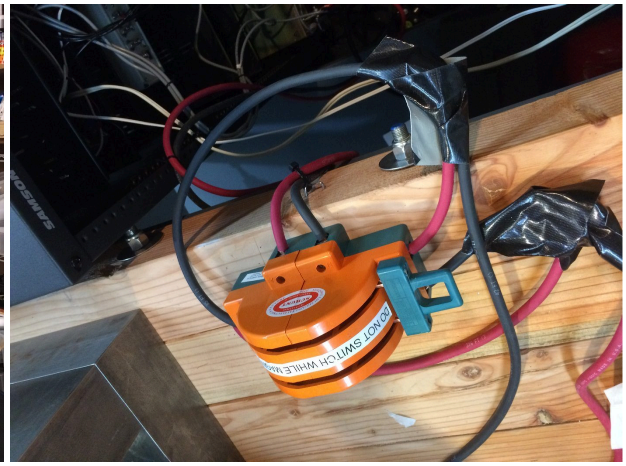
The pressure test proved leak-tightness. It did not prove flow. One coupler in the upper coil is completely blocked: solder fed into the joint filled the ¼ in bore. The lower coil is clear. It was found only after the coil was finished, when flow was tried. Every repair idea considered — locating the joint from outside, cutting into a finished 269-turn coil, bypassing the section — has been judged impractical, and the matter is closed (builder's review, Aug 2026). The lesson is stated plainly in the series' lessons note: a pressure test checks for leaks; a flow test checks for flow; a coil that must carry water needs both, and it needs them before the next turn goes on.

## 5. Power, protection, reversal and control

| Item | As built |
|---|---|
| Supply | Sorensen DCS 55-55 (0–55 V, 0–55 A), bought used; 2U in the instrument rack |
| Mains | Dedicated 240 VAC branch, 30 A breaker, 30 ft cable to the rack (the 2017 construction spec's "50 A" is wrong; builder's review, Aug 2026) |
| Leads | 6 AWG welding cable soldered directly to the ends of the coil tubing |
| Back-EMF protection | MOV plus clamping diode across the coils, and a series diode, as described in the 2017 construction spec (a 100 V / 100 A Schottky is in the purchase record); not re-inspected since |
| Field reversal | Rotary reversing switch in the coil circuit, labelled "DO NOT SWITCH WHILE MAGNET ON" |
| Current control | Manual front-panel setting, or the supply's analog programming input driven by a function generator (DC level or slow ramp) |

The stored field energy at 0.85 T is roughly 300 J; interrupting 55 A in a 72 mH inductor abruptly would produce a destructive voltage, hence the clamp network and the rule of always ramping the current down, never switching it off.

The reversal switch (figure 7) exists because, at build time, the builders were not confident of predicting on paper which way the protons would bend relative to the collector, and making the polarity switchable was cheap. In practice it was set once and never used; it is still in the circuit in the correct state, and the frame carries a "NORTH, NEG" label recording the polarity. The bottom pole is the magnetic north pole, so the field points up through the gap and protons circulate clockwise as seen from the top lid.

Figures 6 and 7. Left: the completed magnet on its timber deck, 2018-05-12, the day the second coil went on — both Kapton-wrapped coils on the frame, the HT20 gaussmeter reading 819 mT with its probe carried into the gap on a lab jack at right. The tabulated calibration maximum from the same period is 0.851 T at 55 A; the 819 mT here is a single meter photograph, not the settled value. Right: the field-reversal switch, 2017-12-03 — an orange rotary cam switch on the timber deck under the rack, wired with red and black 6 AWG welding cable and labelled "DO NOT SWITCH WHILE MAGNET ON". Set once; never operated in service.

Control in the beam era was almost always by programming voltage; the run log's "mag drive" column records it, and 6.0–6.5 V corresponded to the 570–605 mT band the machine ran in. For a resonance map the function generator's second output supplied a 600 s triangle wave, sweeping the field slowly up and down while the electrometer output was plotted against the ramp on an oscilloscope in X–Y mode (see the instrumentation note). In 2020–21 RF pickup on the programming input made the magnet current unstable above roughly 50 W of RF drive — moving a hand near the cable changed it — and the fix was a 9 V battery and a 10 kΩ potentiometer for fixed-field running, with the generator kept only for sweeps.

## 6. Cooling — designed for water, runs dry

The design assumed water cooling through the conductor itself: house cold water via ½ in PEX, in one end of each coil and out the other, sized in the workbook for 2,200 W at a 44 °C (80 °F) rise — about 0.2 gal/min, a trivial flow at house pressure. (The workbook cell carries an extra factor of 1,000 and prints 0.011 gal/h; the correct figure is ≈0.19 gal/min. The slip is preserved in the workbook and noted here because it propagated into later design thinking; it had no effect on Mark I.)

The 2017 construction spec describes the water connection in the present tense. That describes intent. Because of the blocked joint in the upper coil (§4.3), water cooling was never installed and cannot be installed. The Mark I magnet is, and always has been, air-cooled, and it has a duty-cycle limit.

The build website recorded the practical limit in 2018: "without cooling, coil temperature is too high after 90 minutes". At full excitation the coils dissipate about 3 kW; at the beam-era operating point (~36 A, ≈1.03 Ω) about 1.3 kW. With 145 lb of copper (heat capacity roughly 25 kJ/K) and no forced air, even 1.3 kW heats the coils at a few °C per minute until convective losses catch up. The operating procedure's only thermal rule is the monitored one — keep the coil temperature under 150 °C, preferably under 100 °C — using two K-type thermocouples embedded in the top coil and read on a thermocouple meter (figure 8). The fiberglass sleeving class (~150 °C) sets the ceiling. There is no cooling-water step anywhere in the procedures, which correctly reflects the hardware.

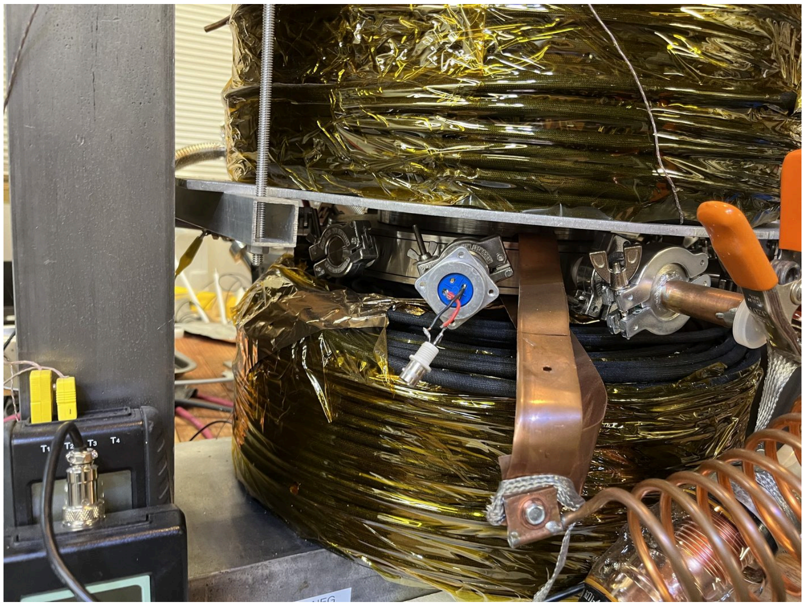



Figure 8. The magnet as it stands, 2024-08-03: the lower Kapton-wrapped coil, the chamber edge with KF16 flanges and a four-pin feedthrough in the gap above it, the copper RF ground strap, and at lower left the four-channel thermocouple meter (T1–T4) with yellow thermocouple plugs — the coil-temperature monitor that substitutes for cooling.

## 7. Measured performance

### 7.1 Field versus current, three ways

The 2018 calibration (figure 9) compares three things at each current: the ideal-gap formula $B = \mu_0 NI/g$ with the 1.5 in design gap, the two-dimensional FEMM model (§8), and the field measured with the HT20 Hall probe at the center of the empty gap.

| Current (A) | Formula (T) | FEMM (T) | Measured (T) | Measured / formula |
|---|---|---|---|---|
| 5 | 0.089 | 0.083 | 0.080 | 0.90 |
| 10 | 0.177 | 0.167 | 0.168 | 0.95 |
| 15 | 0.266 | 0.252 | 0.255 | 0.96 |
| 20 | 0.355 | 0.336 | 0.338 | 0.95 |
| 25 | 0.444 | 0.421 | 0.418 | 0.94 |
| 30 | 0.532 | 0.504 | 0.495 | 0.93 |
| 35 | 0.621 | 0.584 | 0.572 | 0.92 |
| 40 | 0.710 | 0.662 | 0.647 | 0.91 |

| Current (A) | Formula (T) | FEMM (T) | Measured (T) | Measured / formula |
|---|---|---|---|---|
| 45 | 0.799 | 0.736 | 0.720 | 0.90 |
| 50 | 0.887 | 0.803 | 0.787 | 0.89 |
| 55 | 0.976 | 0.860 | **0.851** | 0.87 |
| 100 (FEMM only) | 1.774 | 1.165 | — | (FEMM 0.66) |

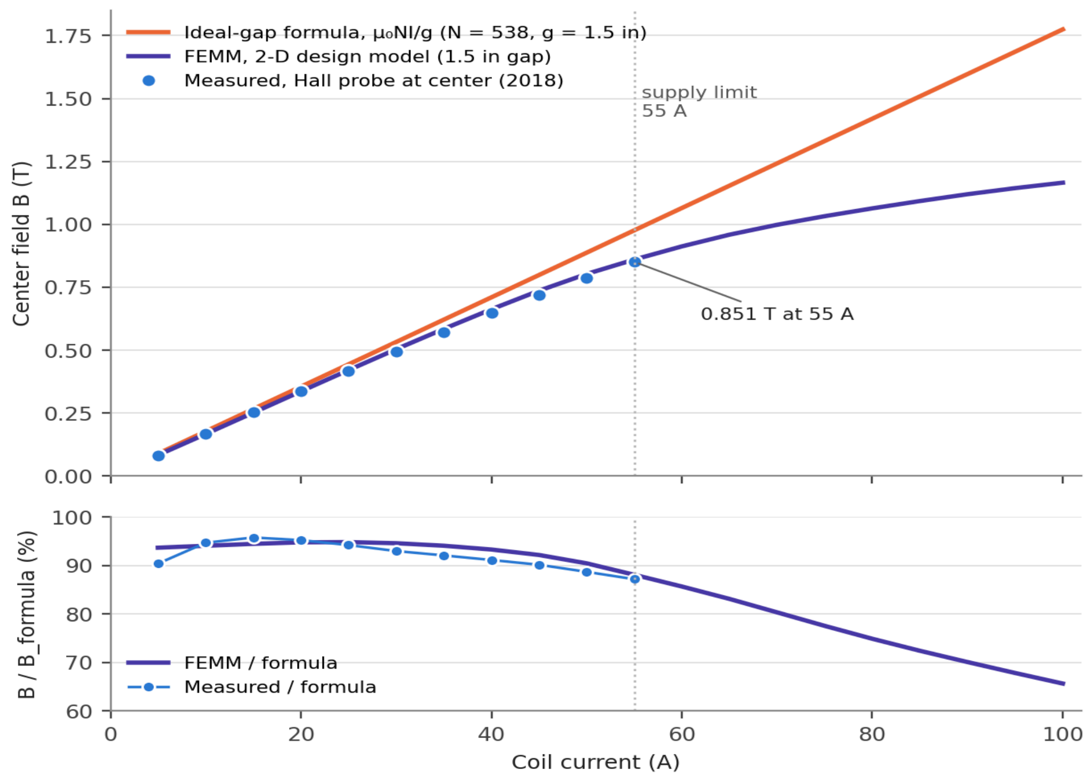



Figure 9. Center field versus coil current from the design workbook: the ideal-gap formula, the 2018 FEMM model, and the Hall-probe measurements to the supply's 55 A limit (top); the same data as a fraction of the formula value (bottom). The FEMM curve is extended to 100 A to show where saturation would take the magnet if a larger supply were fitted.

Three points are worth drawing out.

- **The shortfall from the ideal formula is layered, not just "saturation".** Even at 10–20 A the measured field is 5 % below the formula: finite iron permeability, return-path and joint reluctance, and fringing at the gap edge, all present at any current. FEMM captures most of it (0.94–0.95 at low current); the remaining 1–2 % is joint reluctance and real-material differences. True yoke saturation is the component that grows above ~40 A and takes the ratio to 0.87 at 55 A.
- **The as-built gap is 1.42 in; formula and FEMM both use 1.5 in.** A 5 % smaller gap should give slightly more field for the same ampere-turns, so figure 9 is not quite like-for-like (see Open items).

- **0.851 T at 55 A is the maximum on record.** The build website's summary page says 0.850 T; one gallery caption says 819 mT (figure 6). The 0.851 T value is the tabulated calibration row and is the one to quote.

At the 46 A design current the magnet gives ~0.73 T, not the 0.824 T of the formula; it takes 55 A (29,600 A-turns) to pass the design field. The formula was 13 % optimistic at the top of the range — normal for an unlaminated H-frame near 0.85 T, and anticipated by the 55 A supply choice.

### 7.2 Hysteresis

Every calibration row was taken twice, with the current descending and then ascending. The loop is narrow but real:

| Field (T) | Amps, descending | Amps, ascending | Loop width (A) | A/T at this field |
|---|---|---|---|---|
| 0.05 | 4.4 | 5.6 | 1.2 | 100 |
| 0.10 | 10.5 | 11.6 | 1.1 | 110 |
| 0.15 | 15.8 | 17.3 | 1.5 | 110 |
| 0.20 | 21.5 | 23.2 | 1.7 | 112 |
| 0.25 | 27.6 | 29.2 | 1.6 | 114 |
| 0.30 | 33.7 | 35.4 | 1.7 | 115 |
| 0.35 | 40.2 | 41.7 | 1.5 | 117 |
| 0.40 | 46.7 | 48.1 | 1.4 | 119 |
| 0.45 | 54.1 | 54.6 | 0.5 | 121 |

Roughly 1.5 A of loop width, or about 25 mT at fixed current, over most of the range. It is why the procedures always read the field, never the current, and why sweeps were run as slow triangles so that the up and down traces could be compared.

The workbook also carries a "calculated T" column that reproduces the Hall data to within a few percent using N = 239 and a 1.42 in gap. That 239 is an effective-ampere-turn fudge factor, not a turn count; the coils have 538 turns.

### 7.3 Dynamics and remanence

A step-response test in the workbook, logged at one-second intervals, shows the field settling within 1–2 s of a current step at the supply — the supply's own ramp rate rather than the electrical time constant ($L/R \approx 72$ mH / 1 Ω ≈ 70 ms). A step to 28.5 A settled at ~453 mT and one to 11.4 A at ~194 mT (15.9–17 mT/A, consistent with §7.1 within probe placement); one meter sample of 819 mT during the larger step was an instrument transient. On shutoff the field decays in about 2 s to a remanent 15–19 mT, which is what the gaussmeter reads on the unenergized magnet — small, but the reason the log's low-field readings never reach zero.

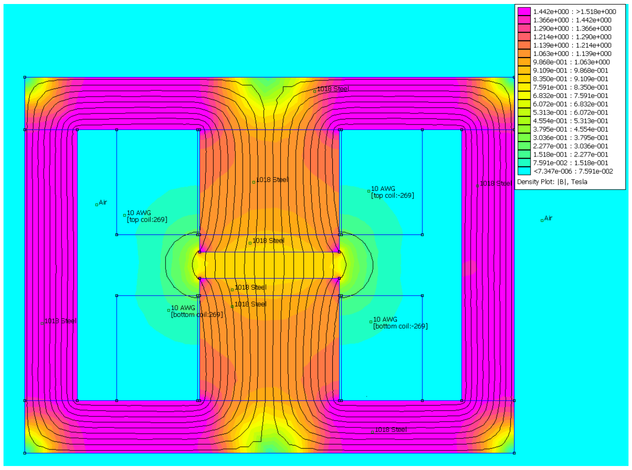
### 7.4 The Hall probe and its position

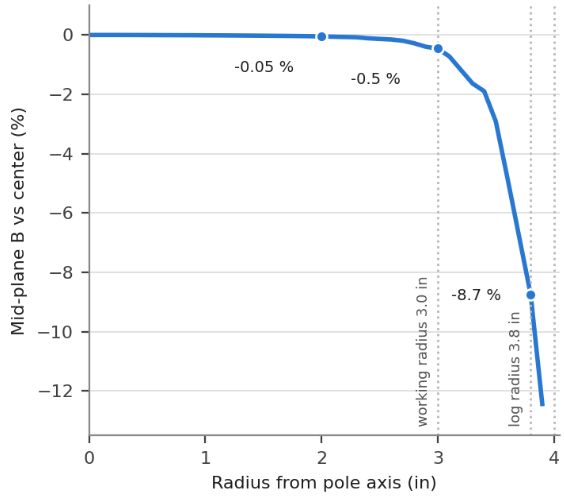
All field numbers here and in the run log come from hand-held Huntoon HT20 Hall-effect gaussmeters — several meters and several probes over the years, the first bought used for about $110 — and their history matters to anyone reading the log. With the RF on it reads wrongly (noted 2019-02; "measure B with RF off" is in the procedures), and in 2020-04 it was reading ~20 % high from RF on the probe cable. It was broken for the 2020-05 sessions, whose logged fields are estimates. A low 9 V battery spoiled one session in 2021-05. The probe tip broke in 2022-07; a replacement probe of uncertain calibration went on in 2022-08 and was recorded as "new field probe OK" in 2022-12.

Where the probe sits during a run is known only loosely. The 2018 calibration was made at the center of the empty gap. During runs the probe is pushed in blind between the top pole and the chamber lid, nominally to the center, but its thin printed-circuit shaft may not lie tangent, it is not quite long enough to reach the center of a 4 in-radius pole, and lid deflection, kinks in the shaft and the day's angle all move it; the log notes it being placed "further towards the edge of the pole piece" in October 2021. The tip is eventually damaged by being forced into and out of the gap (under vacuum the lid deflection makes room; at atmosphere the tip is trapped), which is why several meters and probes have been used. A groove in the top lid to guide the probe is on the builder's list. No transfer between that position and the center calibration was ever measured, and no field map of any kind exists. The mT values in the log are therefore the reading at the probe's position on that day, with the probe and meter in whatever state the list above gives. They are entirely adequate for locating and reproducing resonances, which is what they were used for; they are not an absolute center-field measurement.

## 8. The FEMM model and field flatness

The 2018 design model is a two-dimensional planar FEMM problem, 8 in deep: the H-frame as 3 in members, 28 in wide by 21.5 in tall; 7 in pole stacks (pole plus extension) with a 1.5 in gap; each coil a 269-turn circuit in the 4.125–8.75 in radial band; 1018 steel with the built-in B–H curve. Model and sweep scripts are in the simulation-models note. Figure 10 is the flux-density plot at 55 A and figure 11 its radial profile.






Figures 10 and 11. Left: design-phase FEMM result, 2018 — flux density magnitude and flux lines for the two-coil H-frame at 55 A (planar model, 1.5 in gap); the return legs and pole roots are in the 1.1–1.4 T band, the gap at 0.86 T. (The "10 AWG" label is the coil block's material name in the model, not the conductor used.) Right: the same model's mid-plane field along a radius at 55 A, relative to the center value; marked are the 3 in design working radius, the 3.8 in radius used in the log's energy column, and the 4 in pole edge.

The model puts the frame legs at 1.1–1.4 T at full current, which is why the B(I) curve rolls over, and the top and bottom pole faces within 0.03 % of each other. What it says that no measurement has checked is the radial profile (figure 11). Along the mid-plane the field is flat to ±0.1 % out to r = 2 in, down 0.5 % at the 3 in design working radius, down about 9 % at r = 3.8 in (the radius the log uses for its energy computations) and down 12 % at r = 3.9 in, the last computed point before the 4 in pole edge. This falloff is what makes the log's uniform-center-field energy convention optimistic by 18–19 % at r = 3.8 in, and it is also the source of the weak vertical focusing a classical cyclotron needs near full radius. Whether the real magnet matches is the first thing a Hall scan would settle.

## 9. Operating reality

The magnet can reach 0.85 T. The cyclotron never used it. Every logged run from mid-2019 onward sits in a narrow band:

| Year | Runs with a logged field | Field range (mT) | Median (mT) |
|---|---|---|---|
| 2018 | 5 | 392–408 | 400 |
| 2019 | 22 | 429–754 | 587 |
| 2020 | 69 | 399–603 | 574 |
| 2021 | 31 | 570–598 | 587 |
| 2022–23 | 4 | 589–611 | 596 |

The operating point was set by the RF system, not the iron: the ~9 MHz at which the amplifier chain could put usable voltage on the dee fixes the proton resonance at about 590 mT, and the magnet was simply run there — about 36 A, or two-thirds of its capability. The runs at ~400 mT (December 2018 to April 2020) were proton resonances at ~6 MHz, the frequency the first RF chain ran at; the 2019 excursion to 754 mT was a run at 11.5 MHz. From mid-2020 the chain ran at ~9 MHz and the field followed it to ~590 mT. The best beam on record, −3.1 nA on 2023-10-14, was at 596 mT and 9.033 MHz.

At 36 A the magnet is comfortably linear (measured/formula ≈ 0.92) and dissipates about 1.3 kW, under half the rate for which the 90-minute limit was quoted. The iron has headroom the RF cannot use.

## 10. Mounting

The magnet stands on a 30 in × 48 in welded steel service cart rated for 4,000 lb (Durham HET-3048), decked completely with 4 × 4 timbers bolted through with four ¾ in stainless threaded rods. The timber spreads roughly 900 lb over the cart top and keeps the cart's steel a few inches from the magnet so it does not join the return path. The magnet simply rests on the timbers and has not moved since the second coil went on; the pumps and hydrogen bottle share the cart, the instrument rack is separate. Total weight is 757 lb iron plus 145 lb copper, about 902 lb; the workbook's "923.5 lb with water" includes 21 lb of coil water never filled.

## 11. Cost

Magnet-category purchases from the workbook's bill of materials (full accounting in the BOM note):

| Item | Cost |
|---|---|
| Frame plate, 3 × 8 in 1018, four pieces (Metals Supermarket; an earlier quote was $1,030 incl. shipping) | $1,418 |
| Machining (BRMW) | $629 |
| Poles and pole extensions (MSC) | $788 |
| Shoulder screws and ½ in locating pins | $124 |
| ¼ in ACR tubing, 20 × 100 ft rolls (ICS) | $964 |
| Fiberglass sleeving, 7 × 250 ft (Digi-Key) | $559 |
| Kapton tape | $23 |
| Coil support plates, 6061 aluminum, 2 × 18 × 24 × 0.19 in | $133 |
| Sorensen DCS 55-55 (used, eBay) | $513 |
| 6 AWG welding cable and lugs | $39 |
| **Magnet category, BOM subtotal** | **$5,191** |

Booked under other categories: the 4,000 lb cart, timbers and hardware (≈ $610), the HT20 gaussmeter (≈ $111, used), the magnetic lifter used to install the coils (≈ $96), silver solder and flux (≈ $62), and the 5/16 in coupler stock (≈ $33).

## Sources

Design workbook `cyclotron9.xlsx` (sheets Specs, iron, sim, curve, water cooling, power, magnet time constant, BOM, purchases) · construction specification, December 2017 · operating procedures, 2021 · build website mullinscyclotron.weebly.com, pages "Electromagnet" and "Magnet Coils" (frozen May 2018), with the downloadable FEMM model `mcm_2coil.fem` · run log `cyclotron_log.xlsx`, 2018-12 to 2025-02 · steel quotes (2017) and the coupler shop instruction (2018) · the builder's camera roll, dated by EXIF · builder's review, August 2026.

## Open items

- A coil-resistance measurement, cold and after a 90-minute run, would settle the "0.97 Ω at 150 °F" vs "0.96 Ω at 72 °F" labelling conflict between the construction spec and the workbook, and give a real hot-coil temperature.
- The identity and calibration of the gaussmeter probe now on the machine (the 2022 replacement) has not been re-verified; nor has the back-EMF network been inspected since 2018.
- An azimuthal Hall scan at fixed radius and a radial scan along the mid-plane would be the first measured field-map data for this magnet and the first test of the FEMM profile (figure 11); a FEMM re-run at the as-built 1.42 in gap with the extensions and chamber lids in the model would make figure 9 like-for-like.