NOTES ON THE MULLINS MARK I CYCLOTRON

Performance Record 2018–2025

Author Mark1 AI instance, driven by Chris Mullins **Date** 2026-09 **Revision** v0 draft
Configuration all logged runs 2018-12-16 → 2025-02-02 (176 rows, 44 dates)

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 1×10^{-5} torr (5.0 V on the ion gauge)
Ion source	Tungsten filament (ES-020) in hydrogen at ~10^{-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. What this note is

This is the performance record of the Mark I cyclotron as it actually exists: a spreadsheet run log kept from the first logged run on 2018-12-16 to the last on 2025-02-02, plus the earlier claims on the build website from May–December 2018, before the log was started. The log has 176 rows on 44 run dates. Each row is one operating point at which a resonance sweep was made and the peak collector current written down.

This note is written the way a reader who wants to repeat or improve on the machine would want it written: what was measured, with what instrument, under what convention, and what was never measured at all. Where the log and the website disagree, **the log is authoritative**; the website was written first, from memory and enthusiasm, and was never updated after 2018.

The short version. Over seven years the machine repeatedly produced nA-scale, background-subtracted collector-current peaks at the magnetic field predicted for hydrogen-ion cyclotron resonance at the dee frequency, with the odd sub-harmonic peaks (B/3, B/5) in their predicted places. That is the evidence that it accelerates. What the record does *not* contain is a species

measurement, an energy measurement, or a calibrated dee voltage. Section 12 says what a future measurement campaign would add.

2. The log as an instrument

The log is one Excel sheet with 36 named columns (currents, field, collector position, RF settings, source and gas settings, three vacuum gauges, computed orbit quantities, and notes). The columns that matter for this note, and how each number was obtained, are in Table 1. The notes column is the machine's engineering diary; the entries most useful to a builder are collected in Section 10.

Table 1. Log columns and their provenance.

Column	How the number was obtained	Status
Beam current, background current	Keithley 617 electrometer reading at the resonance peak, and beside the peak, on the same sweep	Sign convention changed mid-2020 (see below)
Mag field (mT)	HT20 Hall gaussmeter, probe at a fixed point near pole centre, read with RF off	Centre-point reading; no field map; probe relocated toward the pole edge 2021-10-30
Linear pos (in)	Collector translator scale; 0.5 in on the scale = collector at r = 3.8 in	Mechanical, repeatable
RF freq (MHz)	Function-generator setting, peaked for maximum dee pickup	Reliable to the last digit shown
MFC, fil. I, fil. bias, beam bias	Front-panel settings of the hydrogen mass-flow controller, filament supply, filament bias and collector bias	Settings, not measurements
radius, keV, turns, path length	Computed from B, the collector radius and the dee-voltage entry, uniform-field formula	Computed, not measured
resonance, B/3, B/5	Precomputed H^+ resonance field at the entered frequency and its odd sub-harmonics	Computed; the identification basis for every peak
Dee voltage	First appears 2020-05-25 as 800; subsequent values 801–809 are a drag-fill artifact; the RF pickup reading was a peaking indicator only	Nominal only (Section 6)
notes	Free text	The diary

How a row was made. The dee frequency is set and left fixed. The magnet current is ramped slowly by a triangle wave (600 s period in 2018; a 240 s sweep was found necessary in April 2020 to see narrow features) from the function generator's second channel into the magnet supply's analogue input. The oscilloscope runs in XY infinite-persistence mode, with the ramp voltage on X and the electrometer's analogue output on Y, so that after one ramp the screen holds a graph of collector current against field. A peak at the predicted field is the resonance; its height, and the level beside it, are read from the electrometer and written into the row. Figures 4–7 show what this looks like on the rack.

The sign convention and the mid-2020 collector fix. Rows from 2018 to early 2020 log positive currents; from 2020-06-28 onward they are consistently negative. The change is not cosmetic. The builder confirmed in his 2026 review that the switch happened when the collector was correctly biased; before that, secondary-electron emission from the unbiased plate added to the reading, so the early absolute currents are inflated by an unknown factor. The early "background" values are also the electrometer floor rather than a same-configuration background, so signal-to-background ratios do not compare across the boundary. The machine was peaking at the right fields throughout; it is the *current scale* that changed.

3. Before the log: the 2018 website claims

The build website's "It works!" page, written in May 2018, describes the first resonances: a 170–450 mT magnet sweep at a fixed dee frequency of 3.258 MHz, with peaks at 214 mT identified as H^+ and 427 mT as H_2^+, plus smaller peaks attributed to harmonics of trace gases, mostly nitrogen. A second sweep from 0 to 178 mT showed the odd sub-harmonics of the 214 mT peak (B/3 = 71 mT, B/5 = 43 mT) "for H^+ and H_2^+, as well as N^+". The predicted fields check: at 3.258 MHz the fundamental for H^+ is 213.7 mT and for H_2^+ 427.4 mT.

This half-field era is worth noting for a reason that becomes important later: at 3.26 MHz the H^+ and H_2^+ fundamentals both fit inside the magnet's 851 mT maximum and appear as *separate* peaks, which is the closest thing to a species discrimination the record contains. At the ~9 MHz operating point used from 2019 on, they do not (Section 5).

The same page records the state of the machine at the time: no dummy dee (the grounded lids serve), the 50 W amplifier failing into unmatched loads so the 5 W pre-amplifier was used, "1300 Volts of RF on the Dee" as an estimate, the dee not fixed in position, and no coil water cooling, limiting operation above 450 mT to about 90 minutes. The 1300 V figure is an early estimate from the same uncalibrated pickup; the later chain estimate is ~800 V and neither number is a measurement.

The homepage headline, never updated after 2018, reads: *"Best so far: Proton energy: 164 keV, Proton Beam current: 3.2 nA achieved at 582 mT, 8.87 MHz."* The field and frequency are consistent with H^+ at k = 1 (8.87 MHz predicts 581.8 mT). The run itself is not in the log, which starts four months later, so neither the current nor the energy can be checked; the current is from the pre-bias-fix era and therefore inflated by an unknown factor. Under the log's own formula, 582 mT at the usual r = 3.8 in collector position gives 151 keV; 164 keV corresponds to r ≈ 3.96 in, so the collector position for that run was presumably different, but it was not recorded. We treat the headline as an unverifiable claim and the log's 2023-10-14 run as the best beam on record.

4. Era timeline

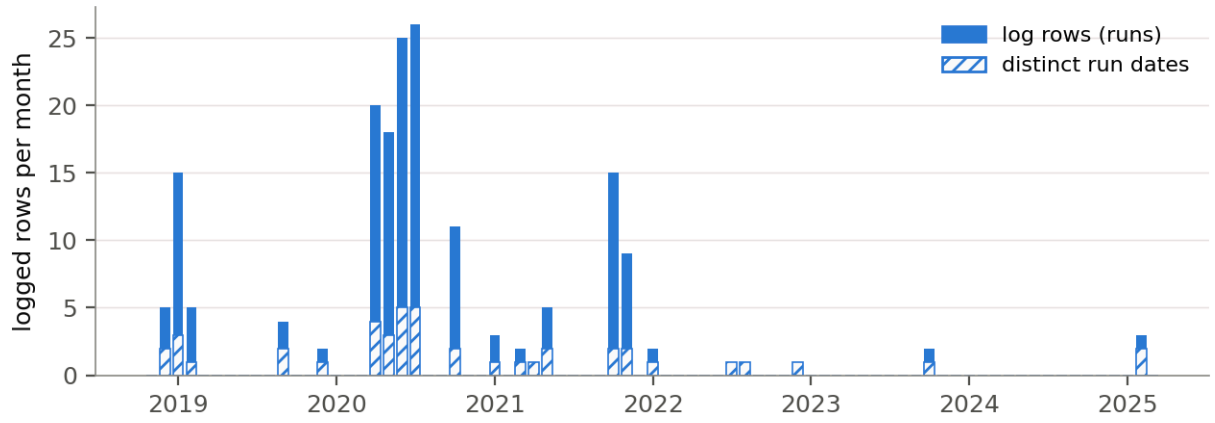

Figure 1. Logged rows per month (solid) and distinct run dates per month (hatched), 2018-12 to 2025-02. The 2020 lockdown year holds 100 of the 176 rows.

Table 2. Eras of the logged record. Row and date counts are from the log itself.

Era	Dates (rows)	Operating point	What happened
Pre-log, May–Dec 2018	—	3.258 MHz half-field → 8.87 MHz / 582 mT	First resonances (website); "164 keV / 3.2 nA" headline, unlogged
First logged runs, Dec 2018	2 (5)	6.0–6.15 MHz, 392–408 mT	H^+ at ~400 mT; 4.4 nA (positive era) at MFC 0.85, "0.30 on MFC more reasonable"
RF rework and reach for energy, 2019	7 (26)	6.6 → 9.27 → 10.26 → 11.48 MHz / 754 mT	Three "did not work, new RF setup" sessions; new coil; highest-energy point ever (254 keV computed) at small currents; "RF is interfering with HT20 field meter — must measure B with RF off"; new H_2 tank; ammo-box RF
The systematic year, 2020	19 (100)	settling on 570–603 mT / 8.8–9.1 MHz	Filament-bias shifts the resonance field (April); 240 s slow-sweep discovery; RF power ladders 5–50 W; filament bias optimum 61–62 V; collector bias converges on 89.7 V (July); MFC current-vs-shape trade mapped
Peak currents and RF fragility, 2021	9 (35)	570–598 mT / 8.7–9.1 MHz	Magnet supply upset by RF → battery-and-pot magnet drive; two RF amplifiers blown, dee touching lid suspected; new 1 sccm MFC; last spare filament installed (October); the −1.2 µA "not repeatable" row
Occasional operation, 2022–23	5 (7)	8.9–9.03 MHz	Probe-tip break, new probe; another amplifier failure; **2023-10-14 best credible beam**
Recommissioning, Feb 2025	2 (3)	9.353 MHz	Reassembled after months open to air; beam within two bench days; dead 9 V bias batteries replaced by a bench supply

5. Operating points, species and harmonics

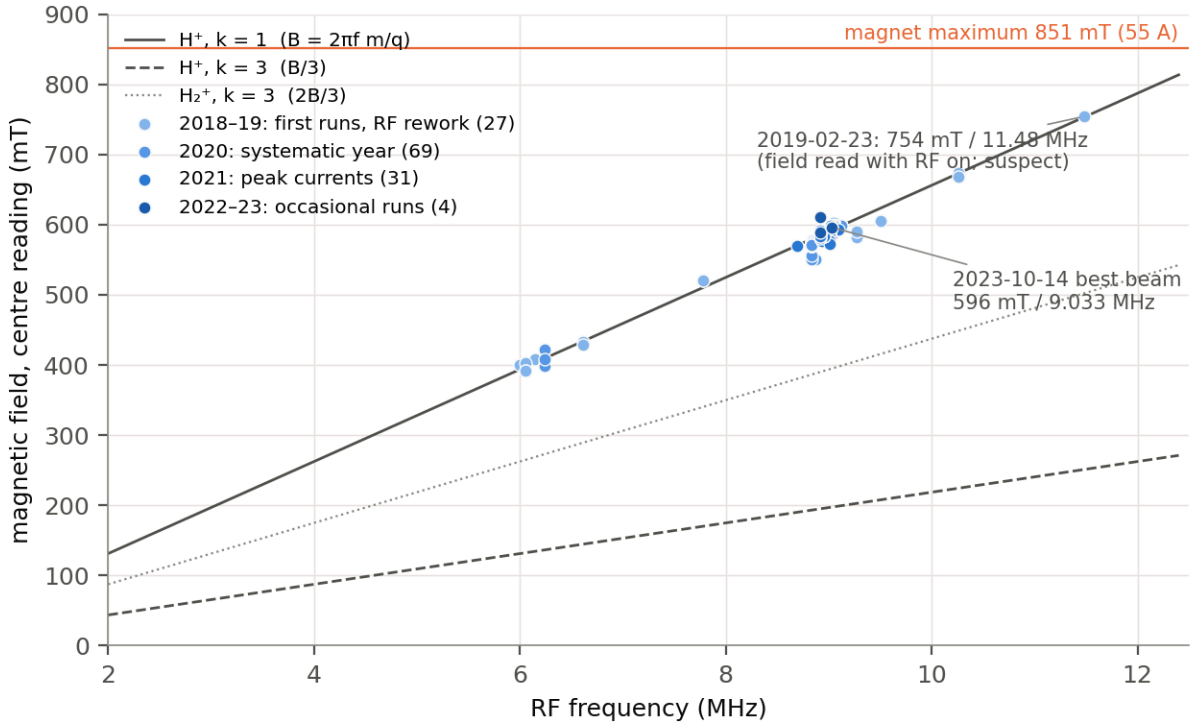

Figure 2. Every logged row with both a field and a frequency (131 rows), coloured by era, against the H^+ fundamental line $B = 2\pi f \cdot m/q$, the H^+ k = 3 line (B/3) and the H_2^+ k = 3 line. The 2025 rows have no field reading (probe status unknown that weekend) and are absent. The 2019-02-23 points at 754 mT were read with RF on, the day the RF-gaussmeter interference was discovered, and are partially suspect.

Every logged operating point sits on the H^+ k = 1 line to within the gaussmeter's scatter. That is what the operating method guarantees, since the frequency was set first and the field swept to find the peak; the figure is a consistency check on the identification, not an independent measurement. Sub-harmonic peaks were seen and noted in the diary ("can also see 198 mT resonance", 2020-10-16; "b/3 almost as large", 2020-06-28), which is why the log carries the B/3 and B/5 columns. Only odd harmonics appear: with one dee and grounded lids the ion crosses two accelerating gaps per turn, and even multiples of the orbital frequency give no net energy gain.

Table 3. Where the resonances fall at the 2023 best-beam frequency, 9.033 MHz. Resonance field for an ion of mass m at harmonic k is $B = 2\pi(f/k)\cdot m/q$. Masses from the log's `particles` sheet (H^+, H_2^+, N^+, O^+, H_2O^+); H_3^+ added here. Magnet maximum 851 mT.

Ion	k = 1	k = 3	k = 5	Nearest odd harmonic inside 851 mT
H^+	**593 mT**	198 mT	119 mT	k = 1 at 593 mT
H_2^+	1185 mT (out of reach)	395 mT	237 mT	k = 3 at 395 mT
H_3^+	1778 mT (out of reach)	**593 mT**	356 mT	k = 3 at 593 mT — coincides with H^+ k = 1
N^+	8235 mT	2745 mT	1647 mT	k = 11 at 749 mT, k = 13 at 633 mT, k = 15 at 549 mT

Ion	k = 1	k = 3	k = 5	Nearest odd harmonic inside 851 mT
O^+	9412 mT	3137 mT	1882 mT	k = 13 at 724 mT, k = 15 at 627 mT, k = 17 at 554 mT
H_2O^+	10588 mT	3529 mT	2118 mT	k = 13 at 814 mT, k = 15 at 706 mT, k = 17 at 623 mT

The table makes the central caveat concrete. At 9 MHz the main peak at 593 mT is where H^+ resonates on the fundamental *and* where H_3^+ resonates on its third harmonic. A resonance sweep at fixed frequency cannot tell them apart, and a hydrogen filament discharge at 10^{-5} torr produces H_3^+ readily. The heavy residual-gas ions would need harmonics of order 11–17, whose acceleration is very inefficient, and no peaks at those fields were reported in the ~9 MHz era. The defensible identification is therefore *hydrogen ions*, not *protons*.

Two ways out are visible in the record itself. First, at the 2018 half-field frequency the H^+ and H_2^+ fundamentals were resolved as separate peaks at 214 and 427 mT. Second, at any frequency at or below about 4.3 MHz all three hydrogen-ion fundamentals (H^+ 282 mT, H_2^+ 564 mT, H_3^+ 846 mT at 4.3 MHz) fit inside the magnet's range, so a single slow sweep would show the species ladder directly. Neither was done as a controlled species measurement at the time; Section 12 returns to it.

6. The dee-voltage column

The `Dee voltage` column first appears on 2020-05-25 as 800. On 2020-05-31 it runs 801, 802, 803, 804, 805, then 800, 800; on 2021-10-24 it runs 801 to 808, incrementing by exactly one per row; from 2021-10-30 onward every row reads 809, including the 2023 best beam. Ten "measurements" incrementing by 1 V are the signature of a spreadsheet drag-fill on a nominal 800 V estimate, and the builder confirmed this in his 2026 review. The pickup coil was only ever a peaking tool, so **no absolute dee-voltage measurement exists for this machine**; the record supports "~800 V nominal, uncalibrated" and nothing more precise. The computed `turns`, `revolutions` and `travel time` columns, which divide the energy by the per-turn gain, inherit this uncertainty in full. Readers who have seen "809 V" quoted for the Mark I should treat that number as this artifact.

7. Notable runs and the collector-current record

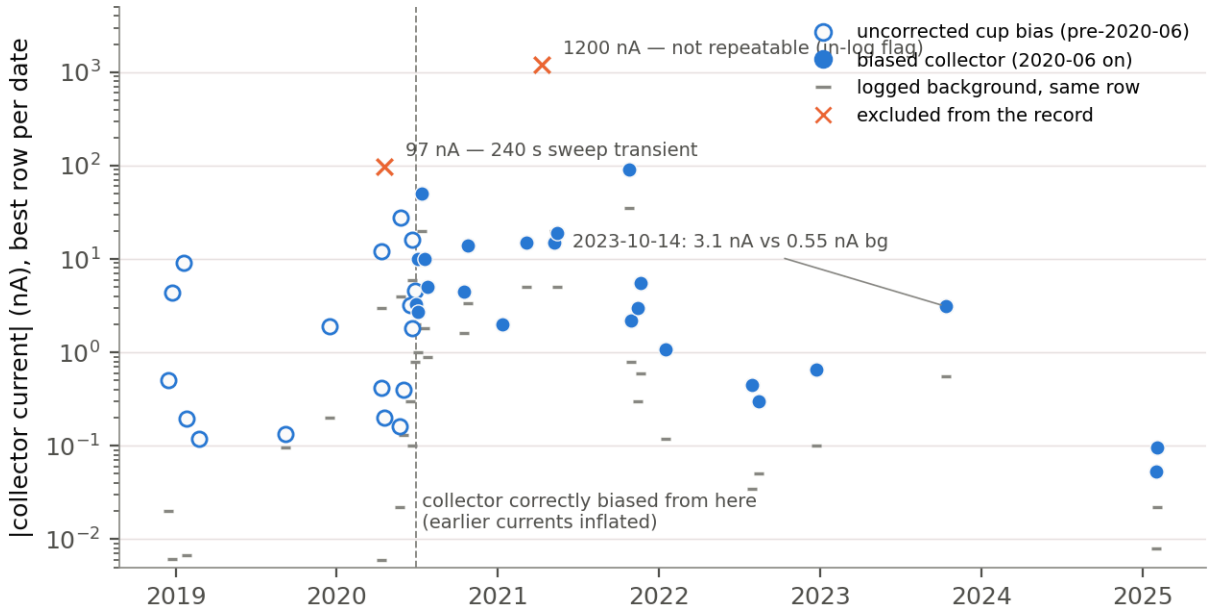

Figure 3. Largest |collector current| logged on each of the 42 dates with a current entry (log scale), with the same row's logged background as a grey tick. Open markers are from before the collector was correctly biased (dashed line, 2020-06-28) and are inflated by secondary-electron emission; the two crossed points are excluded by the log's own annotations.

Table 4. Runs a reader should know about. Currents as logged; energies in the log's uniform-field convention, with the profile-corrected value in parentheses where the collector was at r = 3.8 in.

Date	Result	Context and caveats
2018-12-24	+4.4 nA at 392 mT / 6.05 MHz, MFC 0.85, collector at r = 1 in	First strong logged peak. Pre-bias-fix era: magnitude inflated; resonance real. A video of the rack during this run exists (Figure 4).
2019-02-23	754 mT / 11.48 MHz, 254 keV computed (208 profile-corrected); 0.016–0.10 nA	Highest-energy configuration ever run, on a new coil. The field was read with RF on, the day the RF–gaussmeter interference was discovered, so the field value is partially suspect.
2020-04-18	97 nA "pulse" on a 240 s sweep	"Faster sweeps hid pulse." The next row, at an impossible 21.4 MHz, is self-labelled "actually probably bogus". Treated as a sweep transient, not a beam record.
2020-06-28	First negative-polarity rows, −0.04 to −3.3 nA, 574 mT / 8.835 MHz	Collector bias 9 V; "61V was best filament bias, sweep good shape". The start of the credible current scale.
2020-10-25	−13 nA vs −3 nA at MFC 0.33, "decent beam shape"; −14 nA at MFC 0.6, "not great beam shape"	The high-current end of the current-versus-shape trade at 598 mT / 9.02–9.045 MHz, 160 keV (131).
2021-04-10	−1.2 µA vs −0.14 µA	Logged with the note "not repeatable". Excluded from the record.

Date	Result	Context and caveats
2021-10-24	−90 nA vs −35 nA at 3.1 A filament, "wider peak"	Highest filament current tried; wide peak; new filament that day with "bad vacuum due to long chamber downtime". A shape caveat, not a clean record.
2023-10-14	**−3.1 nA vs −0.55 nA background (5.6×)**, 596 mT / 9.033 MHz, MFC 2, r = 3.8 in; 158.7 keV computed (≈130)	**Best credible beam.** Mature methodology: biased collector, explicit background, settled operating point. Collector bias was 18 V that day rather than the usual 89.7 V; the builder does not recall why.
2025-02-02	−97 pA vs −22 pA (4.4×), 9.353 MHz	Recommissioning proof of life after months open to air; weaker but unambiguous. Field not logged.

The record's largest currents are not its best evidence. The −90 nA and −13 nA rows come with "wider peak" and "not great beam shape" in the diary, and the diary is consistent from 2020 on that raising the hydrogen flow raises the peak current while broadening and degrading the peak (Section 10). The 2023-10-14 run is the best beam on record because it combines a clean, explicitly background-subtracted peak with the settled operating point, not because it is the largest number.

8. What the record establishes, and what it does not

Established. The credible record is *recurrent, nA-scale, background-subtracted, resonance-locked* collector-current peaks. Concretely: peaks at the field predicted for hydrogen-ion resonance at the set frequency, on 42 dates over seven years across several rebuilds of the RF chain, with the odd sub-harmonics in their predicted places, that disappear when the RF is detuned (the 2021-05-09 diary: "if no rf or resonance, flat output from sweep on electrometer"). From mid-2020 the polarity and collector bias are settled, backgrounds are logged beside every peak, and the diary flags its own artifacts (the μA outlier, the "bogus" 21.4 MHz row, "tesla meter broken", "not sure about calibration").

The phrasing used in this series when citing the documented record is **"positive hydrogen-ion cyclotron resonances consistent with acceleration"** and **"nA-scale collector-current excursions"**. That is conservative language about what the *log* supports on its own; it is not a claim that the beam is something other than protons. The reasons, and what the builder adds from the undocumented record, follow.

Not established.

- *Species, formally.* Every logged identification is a field-versus-frequency match plus background subtraction, and H_3^+ on k = 3 is co-resonant with H^+ on k = 1 (Table 3), so the log by itself cannot separate them. The builder's view is that the record beyond the log settles it in practice: many more phone videos of resonance sweeps exist than are cited here, and species-ladder sweeps at low frequency, where the H^+, H_2^+ and H_3^+ fundamentals fall at separate fields, have been made several times and show more protons than H_3^+. Those sweeps were not written down; recording them is on the builder's list (Section 12). Until then, "hydrogen-ion acceleration, predominantly protons" is the defensible statement of the documented record.

- *Energy*. No energy was ever measured. Every keV figure is computed from the field and the collector radius (Section 9). Nothing in the record — no range-foil, no stopping measurement, no time-of-flight — tests whether the ions reaching the collector at r = 3.8 in have the full computed energy or arrived some other way.
- *Dee voltage*. Nominal only (Section 6). The turn count and the per-turn gain are unknown.
- *Absolute current before mid-2020*. Inflated by an unknown factor; ratios across the boundary do not compare.
- *Controls*. The historical peaks were not taken with a systematic RF-off / gas-off / off-resonance control set on the same sweep, and no raw sweep trace was saved as data. Five phone captures of the oscilloscope screen exist (Figures 4–7 are four of them); they are illustrations, not data files.

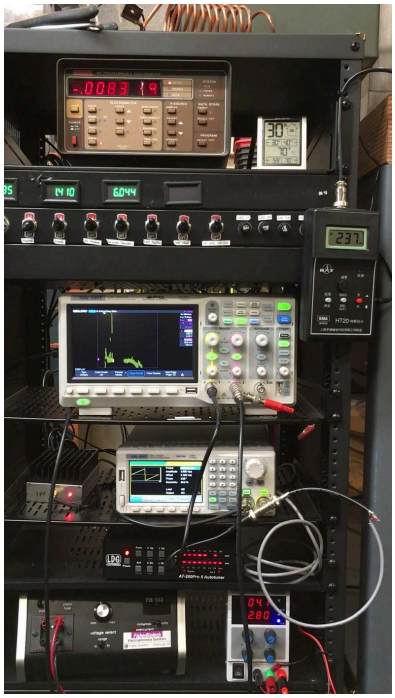

Figure 4 (left). Video frame, 2018-12-24, during a sweep. Top: Keithley 617 electrometer on its 10^{-9} A range. Right: HT20 gaussmeter reading 237 mT as the ramp passes through. Centre: Siglent oscilloscope in XY infinite persistence, the current-versus-field trace building from left; below it the function generator showing the triangle ramp. The three green panel meters are the vacuum-gauge readouts. First logged era, unbiased collector. **Figure 5 (right).** Video frame, 2020-05-31: a single clean peak on the persistence trace, electrometer reading −0.076 nA at the moment of the frame, countdown timer running. The log rows for this date carry no field value (the gaussmeter had failed on 05-25) and peak currents of 0.07–0.4 nA at 8.85 MHz; the trace shows the peak shape the numbers do not.

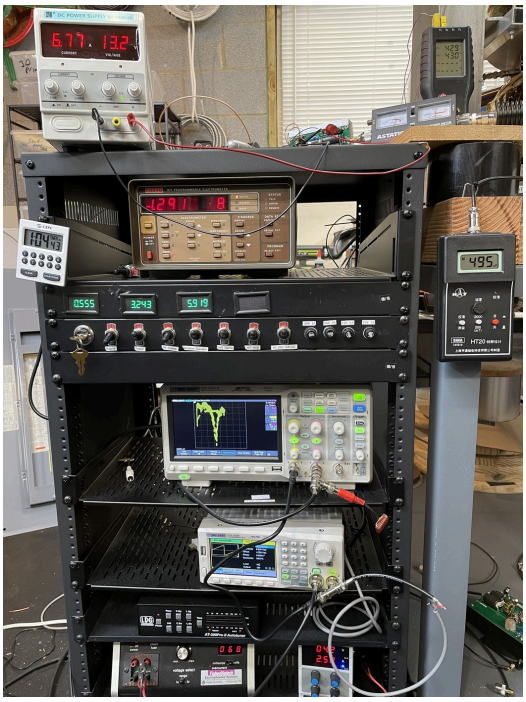

Figure 6 (left). 2021-03-06, the day the new RF amplifier went in: gaussmeter reading 623 mT near the top of the ramp, the resonance trace on the scope, electrometer in the 10^{-8} A range, timer at 1:04. The amplifier board and the Astatic SWR/power meter are on the bench at right, thermocouples at 42 °C. The log: "30W RF out, decent beam shape, 75C", −15 nA vs −5 nA at 587 mT / 8.981 MHz. **Figure 7 (right).** Same session, thirty seconds earlier: a twin-peak trace, gaussmeter reading 495 mT at the moment of the frame (the ramp is a triangle wave, so the instantaneous reading is not the peak field), electrometer -1.29×10^{-8} A. Peak structure of this kind was noted throughout the diary but never recorded as data.

9. Computed energy and the convention that matters

The log's keV column is $E = (qBr)^2/2m$ with r the collector radius and B the *logged* field — the centre-point gaussmeter reading. That is a uniform-field convention: it assumes the field at the collector radius equals the field at the centre. It does not. The design workbook's own FEMM radial profile for the as-built magnet gives $B(3.8\text{ in})/B(0) \approx 0.90$ at 55 A, and the energy goes as B^2, so the kinematically correct energy at the collector is about 0.81–0.82 of the logged value.

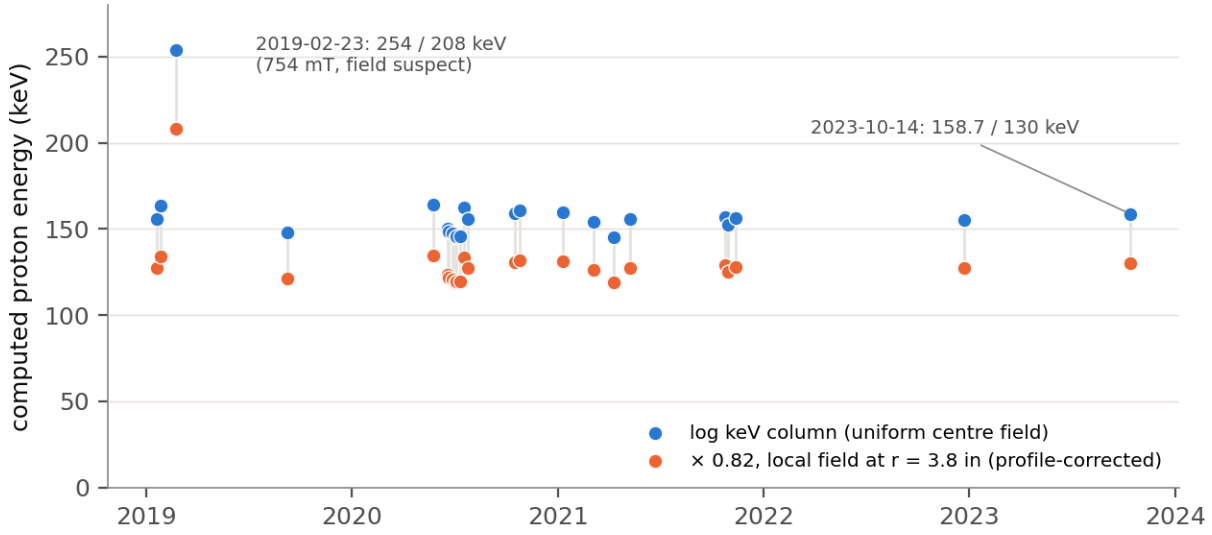

Figure 8. Largest computed energy per run date for rows with the collector at r ≥ 3.8 in: the log's uniform-field keV column (blue) and the same value × 0.82 for the local field at the collector (orange). The convention alone moves every figure by about 18 %. The 2020-05-25 point (164 keV) was taken with the gaussmeter broken and the field estimated.

For the 2023-10-14 run this gives 158.7 keV uniform-field and ≈130 keV profile-corrected. The canonical phrasing for this machine is therefore **"~150 keV-class computed (158.7 keV uniform-field / ≈130 keV profile-corrected)"**; the bare 158.7 keV should not be quoted. The same applies to every other point in Figure 8, including the 254 keV (≈208 keV) of 2019-02-23.

Two residual uncertainties pull in opposite directions and are not resolved. The FEMM profile was computed at 55 A, while the beam era ran at about 36 A where the steel is less saturated; the roll-off is mostly geometric, so the factor is probably similar but has not been recomputed at the operating current. And on 2021-10-30 the Hall probe was "moved further towards edge of pole piece", so from then on the logged field may itself read below the centre value, partly offsetting the correction. An external reviewer in 2026 arrived at ~132 keV for the 2023 run independently, which agrees in direction and magnitude.

None of this is a measurement. The computed energy is what an ion of the assumed species would have if it followed a full-radius orbit in the assumed field.

10. Operating knowledge from the diary

The 2020–2021 diary is a record of parameter studies made one knob at a time. Table 5 collects the durable findings; the operator's manual note carries the procedure.

Table 5. Operating knowledge recovered from the log notes.

Knob	Finding	Where in the log
Filament current	Optimum drifted with each filament and rebuild: 2.7–2.8 A (2018–19) → 2.37–2.51 A (2020–21) → 2.35–2.47 A (2023–25); "steep drop-off below 2.5A" on the old filament; "somewhat dependent on MFC setting".	2020-06 → 2025-02

Knob	Finding	Where in the log
Filament bias	More is not better. Optimum 61–62 V (2020), 43.8 V (2021–23), 40 V (2025); "best beam at fil bias=0" on some days. Bias *shifts the resonance field*: lower bias moves the peak up in field, higher bias moves it down.	2020-04-18, 2020-06-28, 2020-07-25, 2021-11-13, 2025-02-02
Hydrogen flow (MFC)	The master trade-off. Best peak *shape* at 0.05–0.33; peak current keeps rising to MFC 2–5 but "beam wider, uglier". Large excursions leave hysteresis ("took a while for low vac to return"). Residual hydrogen in the lines sustains a peak with the MFC off.	2020-07-04, 2020-07-25, 2020-10-25, 2021-10-24
RF drive	Diminishing returns: "22W RF, just 10% or so boost with 40W out"; more drive "mostly just shifted entire sweep rather than just the peak". A minimum drive exists below which there is "no output at all". Transistor temperatures of 85–110 °C were routine.	2020-06-28, 2020-07-04, 2020-07-18, 2021-05-09
Collector bias	8.9 V (2018) → 9 / 27 / 54 V steps → 89.7 V standard from 2020-07-04; "no faraday cup bias — not any better" (2021-11-21); 18 V on the 2023 best-beam day, unexplained.	2020-07, 2021-11-21, 2023-10-14
Sweep rate	A240 s ramp revealed structure that faster sweeps hid.	2020-04-18
Collector radius	Little change in peak current between 0.5 and 1.0 in on the translator; higher at 1.5 in on one day.	2020-07-03, 2021-10-30
Cross-interference	RF upsets the gaussmeter (read B with RF off); RF pickup raises the 617 background; RF above ~50 W destabilises the magnet supply's analogue input (fix: 9 V battery and 10 kΩ pot as magnet drive); ground noise from the function generator.	2019-02-23, 2020-04-19, 2021-01-10, 2021-11-13
Finding resonance	"Easy to miss resonance … flat output from sweep on electrometer — tough to distinguish. Check rf power and current draw." "Found RF freq by peaking DC current after close resonance."	2021-05-09, 2021-11-13

11. Failures and maintenance in the log

Table 6. Failure and maintenance events recorded in the diary.

Date	Event
2019-01-13 / 01-20	"Did not work, new RF setup" — three sessions of RF rework before the 2019 configuration ran
2020-05-25	Gaussmeter broken; field values estimated for the following weeks
2021-01-10	Magnet supply unstable above ~50 W RF; battery-drive workaround adopted
2021-05-09	Two RF amplifiers blown, "maybe dee touching lid?"; chamber reassembled "with viton spacers in better position", new amplifier; "likely blew rf amps from open or short"
2021-05-15	Gaussmeter reading untrustworthy — low 9 V battery (6 V); correct after replacement
2021-10-24	New filament, "last one" at the time (spares and tungsten wire to make more exist now, per the builder's 2026 review); "bad vacuum due to long chamber downtime and filament change"

Date	Event
2021-10-30	Chamber opened: short across the filament fixed; Hall probe repositioned toward the pole edge
2022-07-30	Broken field-probe tip; no field measurement
2022-08-14	New probe, "not sure about calibration"; RF amplifier failed minutes after the machine was working
2022-12-23	"New field probe OK"
2025-02-01	All 9 V bias batteries dead; chamber "not fully baked" after months open to air; RF "dismantled and rebuilt"

The magnet, chamber and vacuum system never appear in the failure table; the RF amplifier, the filament and the small instrumentation batteries carry the whole burden. After the magnet was loaned in place for an unrelated test in 2023–24 and the machine sat open to air for months, it produced a resonance again within two bench days in February 2025.

12. What a future measurement campaign would add

The record above is good enough to say the machine works and to operate it repeatably. It is not good enough to publish a beam-current or beam-energy number without qualifiers, because the qualifiers are about what was not measured. A short campaign on the existing hardware would close most of the gap. In order of value:

1. **Controlled sweeps saved as data.** The same slow field sweep at fixed frequency, recorded from the electrometer's analogue output as a time series, four ways: normal; RF off; hydrogen off; RF detuned well off resonance. The peak should survive only the first. Each file to carry the instrument identities, ranges and settings, and the gaussmeter reading taken with RF off. This is the standard the historical record defines but does not meet.
2. **Species ladder at low frequency.** One slow sweep at $f \le 4.3$ MHz, where the H^+, H_2^+ and H_3^+ fundamentals all fall inside 851 mT (282, 564 and 846 mT at 4.3 MHz), to see which hydrogen ions the source delivers and in what proportion. The 2018 sweep at 3.258 MHz did this by accident; doing it deliberately, with the controls above, would settle the H^+/H_3^+ question for the ~9 MHz peak. The builder has made such ladder sweeps several times without recording them; the task is to capture one as data.
3. **Dee-voltage calibration.** A capacitive divider or a calibrated pickup against a known RF voltage, so that the turn count and per-turn gain become numbers rather than a nominal 800 V. This is also the prerequisite for the planned higher-power RF amplifier.
4. **A radial scan with the existing translator**, peak current against collector radius in fine steps with all else fixed, which the diary touched (2020-07-03, 2021-10-30) but never completed.
5. **An energy measurement**, even a crude one: a stopping foil or a retarding grid in front of the collector would test the computed 130–160 keV directly. Nothing of the kind has been attempted.

6. **A field map**, or at least a radial profile at the operating current with the Hall probe, to replace the FEMM-derived 0.82 factor with a measured one.

Until these exist, the honest summary of this machine's performance is the one in the box on the first page.

Sources

- The run log, `cyclotron_log.xlsx` (sheets `log`, `log sorted`, `particles`), 176 rows on 44 dates, 2018-12-16 to 2025-02-02. Every number and quotation in Sections 2, 4–7, 10 and 11 is from it.
- The build website (mullinscyclotron.weebly.com), "It works!" and home pages, May–December 2018, for the pre-log claims in Section 3.
- The design workbook `cyclotron9.xlsx`, FEMM radial-profile sheet, for the 0.90 field ratio at r = 3.8 in used in Section 9.
- The builder's review, August 2026, for the collector-bias explanation, the dee-voltage-column confirmation, the filament-spares status, the magnet-loan-in-place statement, and the unexplained 18 V bias on 2023-10-14.
- Phone photographs and videos of the rack during runs, 2018-12-24, 2020-05-31 and 2021-03-06 (media ids IMG_9526, IMG_1450, IMG_2512, IMG_2513), for Figures 4–7.
- An independent external review of the machine's numbers, 2026, for the ≈132 keV profile-corrected estimate cited in Section 9.

Open items

- Which hydrogen ion dominates the 593 mT peak at 9 MHz — the builder's undocumented low-frequency ladders say protons; a recorded ladder would make it citable.
- The actual energy of ions reaching the collector at r = 3.8 in (no measurement exists).
- The dee voltage (no calibration exists; "~800 V" is a chain estimate).
- The radial field profile at the operating current (the 0.82 correction is from a 55 A FEMM model).
- Why the collector bias was 18 V on the best-beam day.
- The calibration of the field probe fitted in August 2022 against the original.