Instrumentation and the Resonance-Mapping Method

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Configuration instrumentation as operated 2020–2025 (cup bias corrected mid-2020; last run 2025-02-02)

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
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 covers

Mark I has one internal collector, one electrometer, one Hall probe, one oscilloscope and a spreadsheet. Everything the machine is known to have done was established with those five things and one method: sweep the magnetic field slowly at fixed RF frequency and draw collector current against field on a persistence display, so that cyclotron resonances appear as peaks at the fields the mass-to-charge ratios predict.

This note describes the instruments as actually wired (including the improvised parts), the field-sweep method in enough detail to reproduce it, the interference problems that shaped operating practice, the run log as the machine's integrating instrument, the raw captures that exist, and, briefly, rack power and grounding. The configuration is the mature one, from the mid-2020 collector-bias correction to the last run on 2025-02-02; where 2018–2019 differed, the difference is stated.

2. The chain at a glance

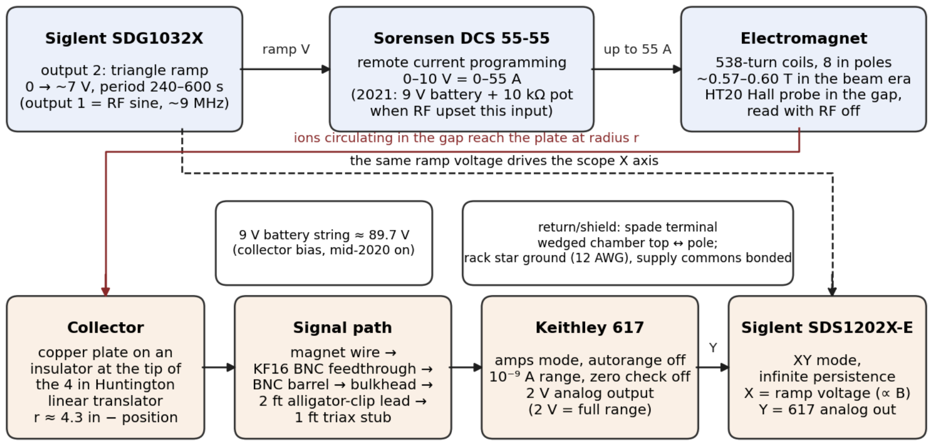

Figure 1. The measurement and field-sweep chain as operated 2020–2025. Top row: the function generator's second output ramps the magnet supply through its remote current-programming input. Bottom row: collector plate to electrometer to oscilloscope. The same ramp voltage drives the scope's X axis, so the persistence display draws collector current against field.

Table 1 lists the instruments, with the prices the design workbook's purchase sheet records; all of them together cost less than the magnet steel.

Instrument	Model	Role	Bought
Electrometer	Keithley 617 programmable electrometer	Collector current; 2 V analog output to the scope	eBay, $600
Oscilloscope	Siglent SDS1202X-E, 200 MHz, 2 ch	XY infinite-persistence display of current vs field	$379
Function generator	Siglent SDG1032X, 2 ch	Output 1: RF drive (sine, ~9 MHz). Output 2: field ramp (triangle, minutes-long period)	$359
Tesla meter	HT20 digital Hall-effect meter (eBay listing "Huntoon HT-20"), 200 / 2000 mT ranges, hand-held, 9 V battery	Center field, probe in the gap, read with RF off	eBay, $111
Linear translator	Huntington Labs VF-107 linear-motion feedthrough, 4 in travel, on port 10	Sets the collector radius	eBay, $150
Signal feedthrough	KF16 BNC vacuum feedthrough	Collector signal out of the chamber	eBay, $37
RF power meter	Astatic 302-PDC2 SWR / power meter, 100 W	Forward power between the amplifier and the matching network	$23
Panel meters	Three DROK 5-digit DC voltmeters on the rack's 12 V rail	Display the three vacuum-gauge output voltages	$34

Instrument	Model	Role	Bought
Bias source	String of 9 V alkaline cells on top of the rack	Collector bias, 89.7 V as measured (at times also filament bias)	—
Thermometers	Two K-type thermocouples embedded in the top magnet coil, read on a thermocouple meter; a small hand-held infrared thermometer for the RF final transistors	Coil temperature (limit 150 °C, 100 °C preferred); FET temperature	—
Timer	Kitchen countdown timer clipped to the rack	Pump-down waits, the 90-minute air-cooled coil duty limit	—

Table 1. The measuring instruments. The magnet supply (Sorensen DCS 55-55) and the RF chain belong to other notes but appear in the sweep method below.

3. The beam collector

The "Faraday cup" is not a cup. It is a small flat copper plate mounted on a white insulator block at the tip of the linear translator's arm, connected by a length of enamelled magnet wire to the center pin of the KF16 BNC feedthrough on the chamber wall (Figure 2, left). It is an open plate with no enclosure and no suppressor electrode, which is why the bias story in §4 matters so much. The builder confirmed the geometry from photographs in 2026. The first collector, used for the 2018 filament-emission tests, was a 6 AWG battery-cable crimp lug — a "pseudo-Faraday cup" in the website's words; the plate replaced it before the mature era, on a date the log does not record.

Position convention. The translator's micrometer reading is logged as `linear pos`, in inches. The log's `radius` column converts it as

> $r \approx 4.3$ in – linear pos,

so that the standard setting of 0.5 in puts the plate at r = 3.8 in, 0.2 in inside the 4 in pole radius. Table 2 lists every position used in the 176 logged runs. Three-quarters of all rows were taken at r = 3.80–3.85 in; the rest are radius scans (2018-12-24, 2019-01-20, 2020-05-25, 2021-10-30) in which the plate was pulled inward to see where the current stopped.

Logged position (in)	Radius (in)	Rows	Logged position (in)	Radius (in)	Rows
0.45	3.85	12	1.5	2.8	3
0.48	3.82	17	2.0	2.3	1
0.50	3.80	93	2.3	2.0	1
0.75	3.55	1	2.7	1.6	7
1.0	3.3	4	2.8	1.5	2
1.3	3.0	28	3.1	1.2	2

Logged position (in)	Radius (in)	Rows	Logged position (in)	Radius (in)	Rows
			3.3	1.0	4

Table 2. Collector positions in the run log (175 rows carry a position). Radius = 4.3 in – position, the log's own convention.

The design workbook's linear-scan sheet, from the April 2020 sessions at 6.4 MHz, uses a different offset (radius = 3.75 in – position). The 0.55 in difference is unexplained; the log's convention is the later and consistently applied one, and the one the energy figures in this series use. Radius is the only geometric input to the computed energy, $E = (qBr)^2/2m$, so the offset matters: at the standard setting the two conventions differ by about 25 % in energy. This uncertainty sits on top of the field-profile convention discussed in the performance note.

The radius scans are recorded as notes rather than curves: "not much beam change from 0.5 to 2.0 on linear positioner" (2020-07-03), "no change in beam current from 0.5 to 1.0 linear position, 1.5 in is higher" (2021-10-30). A plate that intercepts everything outside its own radius reads a nearly flat current over most of such a scan; a shielded, radius-selective probe was never fitted.

4. Collector bias, and the lesson in it

The collector is biased so that secondary electrons knocked out of the plate by incoming ions are pulled back instead of leaving. On an open plate without a suppressor this is the only thing between the reading and a large error: every escaping secondary electron counts as one more positive charge arriving.

Source. The bias comes from a string of 9 V alkaline cells on top of the rack. The Keithley 617 has its own voltage source, but in 2018 it added noise to the current reading (build website), so batteries were adopted and never replaced. The 2018 bench test used twenty cells (Figure 2, right); the working string behind the logged 89.7 V is about ten. On 2025-02-01, after months open to air, the log records "all 9V batteries were dead"; a Fisher FB103 electrophoresis supply was pressed into service the next day.

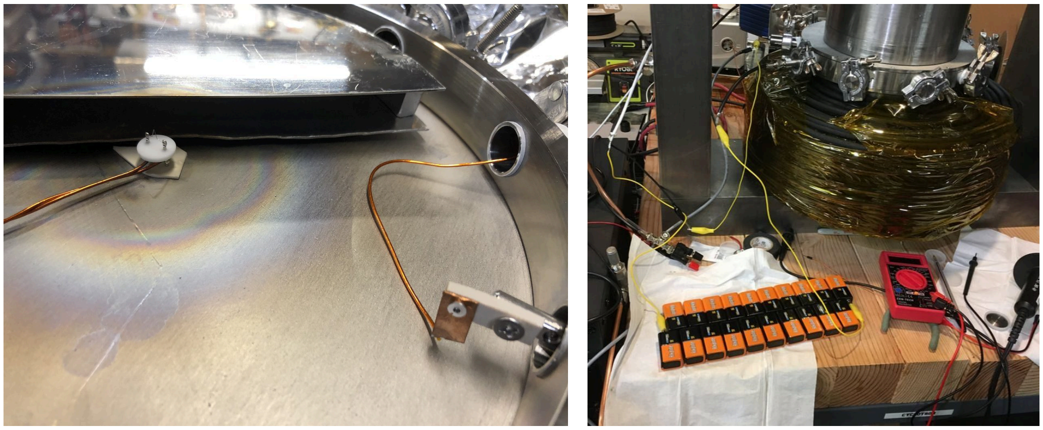

Figure 2. Left: chamber interior, 2020-06-15, lids off. At right in the frame, the collector — a flat copper plate on a white insulator block at the tip of the linear-translator arm, its magnet wire running to the BNC feedthrough in the port above; at left, the ES-020 filament on its ceramic button base, sitting loose on an insulator sheet; the aluminium dee at top left; heat-tint rings on the chamber floor. Right: January 2018, from the build website — testing collector bias from a string of twenty 9 V cells on the cart top beside the lower coil, multimeter at right. The working string in the beam era was shorter (89.7 V as measured).

The sources are loose about that run: the 2025-02-02 row records 89.7 V collector bias "using FB103 instead of 9V batteries", while the builder's 2026 review has the FB103 taking over the *filament* bias with the collector bias still on batteries. The builder adds that the choice between batteries and the FB103 for bias has gone back and forth over the years, so the log's supply wording should be read loosely; which supply biased the collector on the final run is not settled.

History. Table 3 shows the bias by year: a single cell in 2018, mostly no bias through mid-2020, a stepped study through 9, 27 and 54 V, then 89.7 V from July 2020 through 2022. The two rows of the best-beam day, 2023-10-14, record 18 V, for reasons the log does not give.

Year	Bias settings logged (V) and row counts
2018	8.85–8.9 (5 rows: one 9 V cell)
2019	0 (19) · ±8.9 (5) · not recorded (2)
2020	0 (40) · 9 (7) · 27 (7) · 54 (2) · **89.7 (27, from July)** · not recorded (17)
2021	89.7 (34) · 0 (1: "tried with no faraday cup bias, not any better")
2022	89.7 (5)
2023	18 (2, the best-beam day)
2025	0 (1, batteries dead) · 89.7 (2)

Table 3. Collector bias in the run log.

The sign change. Rows before mid-2020 log *positive* collector currents; rows from July 2020 on log *negative* ones. The switch coincides with the bias being applied correctly. The builder's 2026 reading is that the early positive currents were inflated by secondary-electron emission: the cyclotron was resonating at the right fields throughout, but the early absolute currents are not to be trusted, and the early "background" values are electrometer floor rather than same-configuration background, so signal-to-background ratios cannot be compared across the boundary. This is the single most important caveat on the Mark I current record, and it is why the series quotes "nA-scale collector-current excursions" rather than beam currents for the early era.

There is no separate shielding around the collector; what the builder has sometimes called the "pseudo-Faraday cage" is this biased copper plate itself.

5. The electrometer and its cable

The Keithley 617 is operated as the procedures list it: autoranging off, amps function, 10^{-9} A range, zero-check off during a run. (The 2018 procedures used the 10^{-6} range, in the days of microamp filament-emission tests.) Its rear-panel 2 V analog output — 2 V at full scale on whatever range is selected, per the manual — drives the scope's Y input. Bench resolution in 2018 was 0.1 pA with a noise floor near 0.01 pA (build website); in the beam era the readings of interest were nanoamps against tens-of-picoamp backgrounds on the 10^{-8} to 10^{-10} A ranges.

The path from plate to instrument, recorded here as the builder gave it in 2026 because it is the part of the machine most in need of improvement:

1. copper plate → enamelled magnet wire (inside the chamber);
2. → KF16 BNC vacuum feedthrough, wire on the center pin;
3. → female BNC on the flange → BNC barrel → BNC female bulkhead solder connector;
4. → a cheap **2 ft alligator-clip lead**, clipped to the center conductor of
5. → a **1 ft triaxial stub** with a triax connector into the 617's input;
6. shield and return: a second alligator lead to a short ground wire ending in a crimped spade terminal **pushed between the chamber top and the pole piece** — a friction-fit ground, and the local return for the collector current.

The construction spec's description ("4-pin vacuum feedthrough to triax cable, feeding to coulometer", port 9) is the plan; the BNC feedthrough and the clip leads are what was built, and the 4-pin feedthrough on port 7 serves the filament and the RF pickup instead. This chain was assembled quickly in the last weeks before first beam and never revisited because the cyclotron worked. Its documented cost is in the log: "level jumped around a bit" (2020-06-28), "beam starting to get jump in level, presumably due to gas flow variations" (2020-07-04), "frequent step baseline curve changes" (2020-07-11). The clip-lead segment is a plausible contributor to those steps; so are gas-flow variations, as the operator suspected at the time. The chain cannot be calibrated as it stands, and every current figure in this series — including the 0.1 pA bench resolution and the 5.6× best-beam ratio — passed through it. A future measurement campaign should replace items 4–6 with a proper triax run and a bolted ground before claiming a calibrated current.

Two self-flagged electrometer artifacts stay in the log and out of the performance summaries: a −1.2 µA reading on 2021-04-10 ("not repeatable") and a 21.4 MHz row on 2020-04-18 ("actually probably bogus").

6. Measuring the field

The meter. The center field is read with a hand-held HT20 digital tesla meter — a low-cost Hall-effect instrument with 200 and 2000 mT ranges, powered by a 9 V cell — whose probe sits in the gap. It hangs on the rack frame during runs (Figure 5). There is no field map: every field in the log is a single Hall reading, and the magnet's B(I) calibration in the design workbook is a set of such readings at the pole center.

Read it with RF off. The first coil-and-RF configuration change, in February 2019, produced the entry that became a standing rule: "new coil, RF is interfering with HT20 field meter — must measure B field with RF off" (five rows, 2019-02-23). The error is not even of constant sign: "reading 20% high" (2020-04-19, RF on), "lower than actual" (2020-07-18). The practice thereafter was to set the field, read the meter with the RF output disabled, then enable the RF; the log's precomputed resonance fields (§9) give a second check.

Where the probe sits. The probe is nominally at the center of the gap between the top pole and the chamber lid, but it is pushed in blind: the shaft, which is a thin printed-circuit strip, may not lie exactly tangent and so may not be centered, and it is not quite long enough to reach the center of a 4 in-radius pole in any case. The state of the vacuum (lid deflection makes the fit possible under vacuum; at atmosphere the tip is trapped), pre-existing kinks in the shaft, and the day's angle all add placement variation. Several HT20 meters and several probes have been used over the years, because the probe tip is eventually damaged by being forced into and out of that gap. A groove machined into the top lid to give the probe a channel is on the builder's list; it would improve repeatability and end the damage.

Probe history. Table 4 gathers the meter's history from the log notes. The present probe's calibration was never checked against a reference.

Date	Entry
2019-02-23	RF interferes with the HT20; rule adopted to read B with RF off
2020-04-19	Meter reading 20 % high with RF on
2020-05-25 → June	"tesla meter broken, field strength is estimate" (six rows over several weeks; the 2020-05-31 rows carry no field at all)
2021-05-15	Meter "not trustworthy": read ~700 mT at full drive where ~519 was expected; cause was a low 9 V cell in the meter (6 V); with a new cell, 577 mT
2021-10-30	Probe "moved further towards edge of pole piece" (the logged field from here on may sit slightly below the true center value)
2022-07-30	Probe tip broken; no field measurement that day
2022-08-14	New probe, "not sure about calibration"
2022-12-23	"new field probe OK"
2025-02-01/02	Field logged as "?" on both recommissioning days

Table 4. The tesla meter and probe in the run log.

The set-point is a voltage. In practice the field was set by the programming voltage sent to the magnet supply, logged as `mag drive`, and the meter read afterwards. The Sorensen DCS 55-55's remote current-programming input takes 0–10 V for 0–55 A (manual, figure 3-4), so the best-beam setting of 6.26 V commands about 34 A. Figure 3 plots every log row carrying both quantities against the workbook's 2018 Hall calibration mapped through that scale. The points follow the calibration but sit about 3–4 % above it (median ratio 1.035, range 0.98–1.10); programming-input scale, hysteresis (about 1.4 A loop width at 0.4 T in the workbook) and probe placement could each account for a few percent. The offset was never run down; beam-era fields quoted in this series are the meter readings.

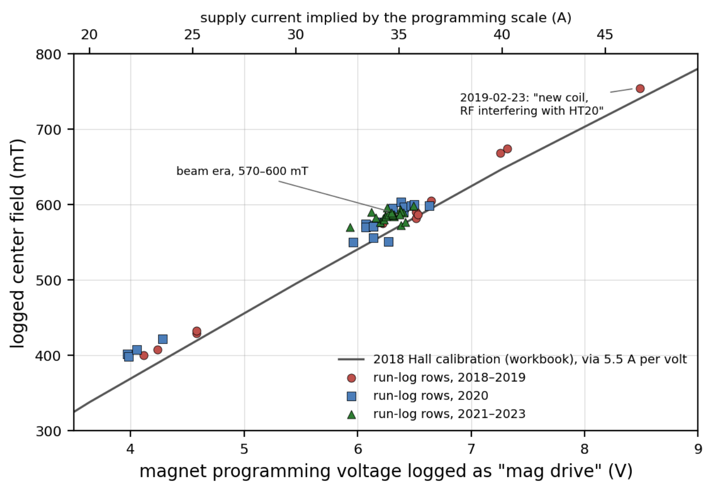

Figure 3. Every run-log row carrying both a magnet programming voltage and a field reading (54 distinct pairs, 2018–2023), against the design workbook's 2018 Hall calibration mapped through the supply's 0–10 V = 0–55 A programming scale. The high 2019 points are the "new coil, RF interfering with HT20" session.

7. The resonance-mapping method

This is the measurement that established that the machine works. The method is adapted from the Rutgers 12-inch cyclotron's pen-plotter field-sweep display; the specific source will be cited in a later revision.

Set-up.

1. RF frequency fixed on the function generator's output 1 (3.258 MHz in the first months of 2018; 6.0–6.6 MHz in the winter of 2018–19 and April 2020; 8.8–9.4 MHz in the mature era). The dee is matched and the RF left on.
2. Output 2 of the same generator produces a triangle wave of very long period — 600 s in the 2018 website sweeps, 240 s in April 2020 — with offset and amplitude chosen so that the ramp runs from near zero to the programming voltage of the field of interest (about 7 V for 600 mT), into the magnet supply's remote current-programming input. The magnet's time constant (about 70 ms) and the supply's settling (1–2 s) are negligible on this timescale.

3. The oscilloscope is put in XY mode with infinite persistence. Its X input is the ramp voltage, proportional to field. Its Y input is the electrometer's 2 V analog output, proportional to collector current on the selected range.
4. Ramp up, ramp down, and let the display accumulate. A resonance is a peak that re-draws in the same place on every pass; noise and baseline steps do not. Field and current are read live from the tesla meter and the electrometer while the trace forms.

What the screen shows. With the dee at fixed frequency f, ions of mass m and charge q are accelerated only when the field satisfies $B = 2\pi f \cdot m/q$. As the ramp carries the field through that value the collector current rises and falls, and the persistence display turns this into a peak at the corresponding X position. Ions also see the RF at odd sub-multiples of the resonant field — at B/3 an ion makes three turns per RF cycle and still crosses the gap at the right phase — so each species produces a family of peaks at B, B/3, B/5, B/7 ..., which is why the log carries precomputed columns for B, B/3 and B/5 (§9). Figure 4 is the website's 2018 scan of the low-field region at 3.258 MHz, and Table 5 gives the identifications the workbook's results sheet made for that first campaign.

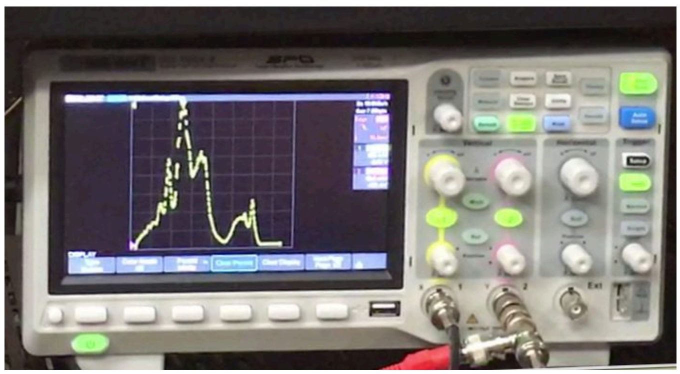

Figure 4. Scope screenshot from the build website, early 2018: persistence trace of a field sweep from 0 to about 178 mT with the dee at 3.258 MHz. The peaks are odd sub-harmonics of the H^+ (214 mT) and H_2^+ (427 mT) fundamentals; assignments in Table 5. Vertical scale is collector current on the 2018 (unbiased, inflated) chain.

Observed (mT)	Assignment	Predicted (mT)	Note in the sheet
31	H^+, B/7	30.5	
35	H_2^+, B/11	38.8	
42	H^+, B/5	42.7	
50	H_2^+, B/9	47.5	
60–65	H_2^+, B/7	61.0	"strong"
71	H^+, B/3	71.2	"inflection"
82–88	H_2^+, B/5	85.5	"big lump"
146	H_2^+, B/3	142.4	"strong"
206	H^+, fundamental	213.7	"strong"
402, 430	H_2^+, fundamental	427.3	

Table 5. Peak identifications from the 2018 scans at 3.258 MHz (design workbook, results sheet). Observed positions are the meter readings noted at the time; predictions use the sheet's mass table. Currents are omitted: that era's chain was unbiased.

Every strong feature lands within a few millitesla of an odd sub-harmonic of one of the two hydrogen fundamentals. This is a resonance identification, not a mass spectrum: H^+ on its fundamental and H_3^+ on its third sub-harmonic fall at the same field, which is why this series says "hydrogen-ion resonances consistent with acceleration" rather than "protons detected".

The trace flips over in mid-2020. Because the 617's analog output follows the sign of the current, the peaks point *up* in the 2018 and May 2020 traces, when the log recorded positive currents, and *down* from 2021 on, when correctly biased collection produced negative currents. Figure 5 shows both.

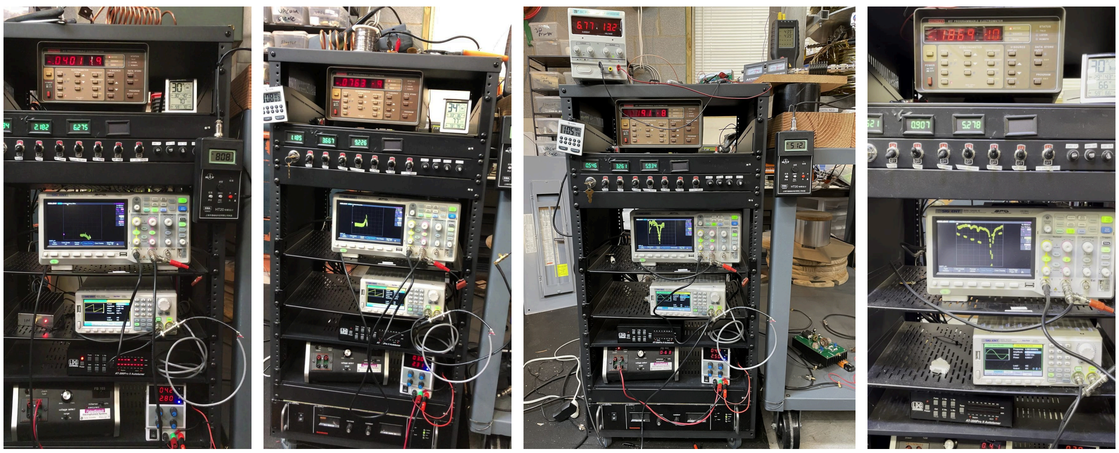

Figure 5. The rack during four sweeps, left to right. (a) 2018-12-24, video frame: Keithley 617 on its 10^{-9} A range, switch panel and gauge meters, the HT20 tesla meter hanging at right (808 mT at this instant; at that day's 6 MHz the H_2^+ fundamental falls near 800 mT), the scope in XY persistence with a short trace forming, the SDG1032X showing the triangle ramp, the LDG autotuner (since removed), FB103 and filament supply (2.80 A). (b) 2020-05-31, video frame: a clean single upward peak; the log rows for that day record positive currents of 0.07–0.4 nA with no collector bias and no field reading — the tesla meter was broken that week — so the trace is the session's only field-axis record. (c) 2021-03-06: the mature configuration, RF amplifier bench supply (6.77 A, 13.2 V) and Astatic SWR meter on top, HT20 at 512 mT, a downward twin-peaked trace, Sorensen DCS 55-55 at the bottom, the new RF amplifier board on the bench at right; log 587 mT, 8.981 MHz, −2.2 and −15 nA rows. (d) 2025-02-02, frame from a 124 s video of the last logged run: 617 reading about −19 pA on its 10^{-10} A range, a downward resonance dip, the generator showing output 1 at 9.353 MHz sine with output 2 (the ramp) on.

Operating knowledge the method produced, from the notes column:

- *Sweep speed*. "Used 240 second sweep — faster sweeps hid pulse" (2020-04-18). The electrometer settles in seconds on its low ranges; a fast ramp carries a narrow peak past it too quickly.
- *Finding the resonance at all*. "Easy to miss resonance; if no RF or resonance, flat output from sweep on electrometer — tough to distinguish" (2021-05-09). Remedy (2021-11-13): "found RF freq by peaking DC current after close resonance" — set the field near the expected value, tune frequency for maximum current, then sweep.
- *Sub-harmonics as a check*. "Can also see 198 mT resonance" and "b/3 almost as large" (2020) — the B/3 peak of the ~590 mT operating point, at the field the log's precomputed column

predicts.
- *Shape versus height*. The MFC setting trades peak current against peak shape (best shape at 0.05–0.33, more current but a "wider, uglier" peak at 2–5); filament bias shifts the resonance field slightly (April 2020), a plasma-potential effect the display made visible.

8. Interference: the catalog

Small-signal work next to a 50 W transmitter and a 2 kW magnet supply is dominated by cross-coupling. Table 6 collects the entries. Three of them changed how the machine was run: the RF-off rule for the field reading; the 2021 replacement of the generator's ramp with a 9 V battery and a 10 kΩ potentiometer as the magnet-supply programming source whenever RF power was high; and the attenuator and matching changes that kept RF pickup out of the electrometer.

Date	Logged symptom	Response
2019-02-23	RF interferes with the HT20 tesla meter	Read the field with RF off (standing rule)
2020-04-19	Tesla meter reading 20 % high under RF; "mag drive RF interference"	Noted
2020-04-19	RF preamp connected straight to the matching coil: "RF pickup raising 617 background current"	Attenuation restored in the chain
2020-06-28	1 dB output attenuator removed: RF interfering with the tesla meter again	—
2020-07-18	Above ~160 mV drive, "intermittent Sorensen output faults"; meter reads lower than actual under RF	Drive limited
2021-01-10	Magnet unstable above 50 mV RF drive; "switched to battery and pot for magnet"; still unstable above 350 mV / 50 W	Battery + potentiometer programming source at high RF power
2021-03-06	"Magnet drive varies with hand placement — RF pickup"	—
2021-05-15	Tesla meter wildly off: low 9 V cell in the meter	Cell replaced
2021-10-30	Supply "getting RF interference at higher powers"; "switch to battery drive for magnet to increase RF power"	Battery drive
2021-11-13	"Ground noise from Siglent causing mag drive trouble above 90 mV RF drive"	9 V battery for magnet drive
2020-06/07	Baseline "jumped around", "frequent step baseline curve changes" on the 617	Attributed at the time to gas-flow variation; the clip-lead chain is the other suspect

Table 6. Instrument cross-interference in the run log.

The battery-and-potentiometer workaround removes the ramp: runs made with it were tuned by hand at fixed field and have no persistence trace, and the log does not always say which drive a row used.

9. The run log as an instrument

Every run was hand-logged in a spreadsheet with 36 named columns, one row per setting change, 176 rows on 44 dates; nothing was logged automatically. This series treats the log as the primary instrument — it outranks the website where they disagree (builder's rule, 2026) — and its notes column as the machine's engineering diary. Table 7 groups the columns.

Group	Columns
Identity	date; notes (free text, 117 of 176 rows)
Beam	beam current (A); background current (A)
Field and geometry	mag field (mT); linear pos (in); mag drive (V)
RF	RF freq (MHz); RF drive (mV p-p at the generator); RF pickup
Source	MFC setting; filament current (A); filament bias (V); beam (collector) bias (V)
Vacuum	VG1, VG2, VG3 without hydrogen; VG1, VG2, VG3 with hydrogen; "vac, no H_2" and "vac, H_2" in torr
Computed	radius (in); keV; power (μW); turns; path length; speed; revolutions; travel time (μs)
Resonance bookkeeping	"resonance, B/3, B/5" (three precomputed fields for the row's frequency, e.g. "593, 198, 119"); particle; mass; charge
Nominal	Dee voltage (the 800 V placeholder; see the calibration box)

Table 7. The run log's columns. A "log sorted" sheet holds the same rows sorted by setting, and a "particles" sheet holds the mass table behind the resonance columns.

Three habits are worth copying: the precomputed resonance columns made sub-harmonic peaks expected features rather than surprises; background rows — same configuration, beam-defining parameter removed — were logged explicitly from mid-2020, which is what makes the 2023 ratio of 5.6 quotable; and artifacts were flagged in place ("not repeatable", "probably bogus", "field strength is estimate") rather than deleted.

Two are cautionary. The Dee-voltage column carries a nominal value that a spreadsheet drag-fill turned into "801, 802 ... 809 V" entries that look like measurements and are not. And the current columns are spot readings from the electrometer display, not the trace: for 2020-05-31 the log has seven rows of currents but no field, while the video of the session (Figure 5b) shows a clean peak with its field axis. Where a trace exists it holds information the columns do not.

10. Raw captures on record

Table 8 inventories everything that exists below the level of a logged number. None of it meets the standard a future beam-evidence packet would need — instrument identities, calibration status, RF-off / gas-off / off-resonance controls, uncertainty — and historical material cannot be upgraded after the fact.

Date	Item	What it shows	Log context
early 2018	Video on the build website (170 → 450 mT, 3.258 MHz, 600 s ramp)	H^+ at 214 mT and H_2^+ at 427 mT on the persistence display, meters live	Pre-log era
early 2018	Scope screenshot on the build website (0–178 mT)	Sub-harmonic family, Figure 4	Pre-log era
2018-12-24	Phone video, 144 s	Rack, meters and trace forming (Figure 5a)	392–403 mT, 6.0 MHz, 8.9 V bias, +0.04 to +4.4 nA
2020-05-31	Phone video, 13 s	Clean upward peak (Figure 5b)	+0.07 to +0.4 nA, 8.846 MHz, no bias, no field logged
2020-06-21	Three phone videos, 21–35 s	Display during sweeps	556–573 mT, 8.835 MHz
2021-03-06	Three live photos and two videos, 17 s each	Downward traces; meter frames at 495, 512 and 623 mT (Figure 5c)	587 mT, 8.981 MHz, −2.2 and −15 nA; new RF amplifier
2025-02-02	Two phone videos, 37 s and 124 s, and a live photo	Downward dip, generator at 9.353 MHz (Figure 5d); switch panel (Figure 6)	−0.06 to −0.10 nA; recommissioning
undated	Scope waveform file SDS00001 (.csv, .dat, .png)	The only raw waveform in the archive: a two-channel time-base capture at 2 ms/div, one peaked trace a few milliseconds wide — not a field sweep. Scope clock never set (files dated 1980)	Run and signal not identifiable

Table 8. Raw captures. Phone media are identified by date; the archive's media index holds the file identities.

11. Rack power and grounding

The instruments and supplies live in a 21-unit mobile 19 in rack (Figure 6), the magnet, pumps and hydrogen cylinder on the 4,000 lb cart; the layout has barely changed since 2017.

Figure 6. The rack on 2025-02-02. Top: the three gauge voltmeters (0.526, 0.906 and 5.389 V: roughing, mid-range and high-vacuum gauge outputs), the keyswitch, seven labelled toggles (Magnet, Power, RF Power, Vacuum Gauges, Diff Baffle, Diff Heat, Hi Vac Gauge) and the four fused DC-rail holders at right. Below: the SDS1202X-E, the SDG1032X, the LDG autotuner, the FB103 supply and the filament supply (2.35 A).

Power. The magnet supply has its own 240 V circuit through a 30 ft cable; the construction spec and website say a 50 A plug and breaker, and the builder confirmed in 2026 that the breaker is 30 A. Everything else runs from a surge-protecting strip on the side of the rack: the workbook budgets about 1.1 kW / 9.4 A of 120 V load, and the log recorded a measured 712 W "not including magnet" on 2021-11-13. There is no UPS; the rack is unplugged from the wall when idle. Four fused DC rails feed the low-voltage loads (Table 9). A keyswitch gates the main power switch; the procedures switch on in the order keyswitch, main, baffle, gauges, pumps, and off in reverse.

Rail	Loads	Fuse
24 V, 2 A	The three vacuum gauges	1 A
28 V, 6 A	RF power amplifier	3 A
12 V, 30 A	Diffusion-pump Peltier baffle, rack panel meters (and, historically, the RF autotuner)	5 A
15 V, 2 A	RF preamplifier	1 A

Table 9. DC rails in the rack (construction spec). The fuse values have not been re-verified since the RF rebuild of 2024–25.

Grounding. The rack frame goes to earth through a 12 AWG conductor terminated at a star ground point on the rack. Separate ground wires run from that point to the cart and to every piece of rack equipment, and all four DC supply commons are bonded together. The one deliberate exception is the collector return, grounded locally at the chamber through the spade terminal of §5. Whether the star point is fully intact after the 2024–25 RF dismantle and rebuild has not been checked.

Sources

- The run log (`cyclotron_log.xlsx`, sheet `log`, 176 rows to 2025-02-02; sheets `log sorted`, `particles`, and the 2018 `results` sheets) — every dated quotation and count above.
- The design workbook `cyclotron9.xlsx` — purchase and bill-of-materials sheets (instrument identities and prices); `sim` and `Specs` sheets (Hall calibration, hysteresis); the linear-scan results sheet.
- The construction specification (`Cyclotron_construction.docx`) — port assignments as planned, rack, rails, grounding.
- The operating procedures (`Cyclotron_procedures2.docx`) — electrometer settings, switch order, monitored quantities.
- The build website (mullinscyclotron.weebly.com): "It works!", "Filament and Electrometer Testing", "Rack and Cart Design" — the 2018 method description, the 20-cell bias test, the 0.1 pA / 0.01 pA figures, the scan screenshot and sweep video.
- Instrument manuals on file: Keithley 617 (2 V analog output), Sorensen DCS series (remote current programming, 0–10 V), Siglent SDS1000X-E and SDG1000X.
- The builder's review, August 2026 — collector geometry, the signal path and its ground, the bias string, scope identity, the mid-2020 sign change, the 30 A breaker, the idle-unplugged practice.
- The photo and video record, 2018–2025 (frames reproduced only after viewing), and the scope capture file SDS00001.

Open items

1. **A calibrated current chain.** Replace the alligator-clip lead and the friction-fit spade ground with a continuous triax run and a bolted return, then re-measure the baseline-step behaviour. Until then no absolute collector current on this machine is better than an order-of-unity estimate.
2. **The collector's true radius.** Measure the plate position against the chamber center at the next opening and settle the 4.3 in versus 3.75 in offset; the computed energies depend on it quadratically.
3. **The tesla meter and probe.** Check the present probe against a reference, record which probe is installed, and measure the field at the plate radius.
4. **The programming-voltage offset.** Resolve why logged fields sit 3–4 % above the 2018 calibration at the same programming voltage (scale, hysteresis or probe placement).
5. **Which supply biased the collector on 2025-02-02**, and a written note of the bias source on every future row.
6. **Time-stamped captures.** Set the scope's clock, save the XY display and both waveforms for every sweep, with RF-off, gas-off and off-resonance controls.