RF System, Dee and Ion Source

Author Mark1 AI instance, driven by Chris Mullins **Date** 2026-09 **Revision** v0 draft

Configuration RF chain and ion source as operated 2021–2025 (last run 2025-02-02); earlier eras described where they explain the record

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. Scope

This note describes the three subsystems that make and accelerate the ions in Mark I: the single dee and its RF drive chain, the matching network at the chamber, and the hydrogen ion source with its gas train. The configuration described is the one that ran from 2021 through the last run on 2025-02-02. Where an earlier arrangement explains something in the run log (the ammo-box matcher, the autotuner, the needle valve, the battery bias string), it is described in its place and dated.

These were the last subsystems built. The magnet, chamber and vacuum system were designed on paper, simulated and machined; the dee and ion source were made in the final push before first beam in 2018, with materials on hand, and never rebuilt. Their shortcuts are documented here with the consequences the log records.

2. The dee

2.1 Construction

The dee is a half-disc of 4 in radius, built as two aluminum sheet faces on a short aluminum ring (Table 1). The faces were cut with tin snips from roughly 3/32 in sheet; the accelerating edge is visibly a little wavy as a result (Figure 1). The edge ring is a 0.5 in tall slice of 4 in radius aluminum pipe. Small side-vented 2-56 screws attach the faces to the ring. The total height, 0.5 in plus two face thicknesses, is about 0.69 in, which leaves about 0.155 in between each face and the grounded lid in the 1.000 in interior of the chamber ring.

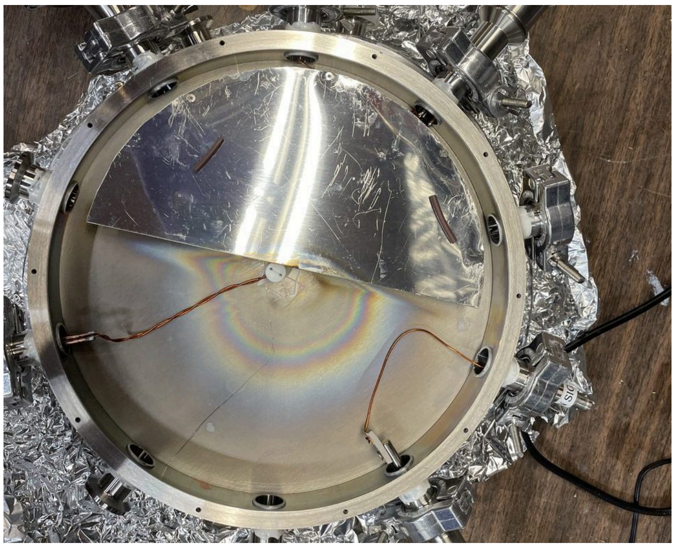

Figure 1. The chamber open from above on 2021-10-24, the day the last spare filament was installed. The aluminum dee occupies the upper half; its straight accelerating edge runs left–right across the center. The ceramic filament button sits at the center just below the edge, with its twisted magnet-wire leads running to the four-pin feedthrough at left. The collector on the linear translator enters from lower right. The concentric interference-color rings on the floor are centered on the filament position. (Media id: Live Photos/IMG_3270.)

Table 1. Dee geometry: design workbook vs as built.

Parameter	Workbook ("Mullins Dee")	As built
Radius	4 in	4 in
Face material	—	aluminum sheet, ~3/32 in, cut with tin snips
Edge ring	—	0.5 in slice of 4 in radius aluminum pipe
Body height	0.4 in (design value)	~0.69 in
Gap, face to each lid	0.16 in	~0.155 in (0.69 in centered in 1.000 in)
Gap, edge to chamber wall	0.3 in	not re-measured

Parameter	Workbook ("Mullins Dee")	As built
Dummy dee	0.4 in gap (design)	never installed; the grounded lids serve
Feed	port 6, 2 kV vacuum feedthrough adapted to an SO-239	same

The dummy dee was dropped early. The 2018 build website lists it as a difference from the design: "The chamber lids are close enough to the main Dee that they can serve as a dummy Dee, since they're also grounded." Nothing later changed that.

2.2 Mounting, and what it cost

The dee is not mounted. It is held in place by the RF feedthrough alone and kept off the chamber floor by small loose pieces of Viton o-ring placed underneath it. Nothing fixes those pieces in position. Assembly means lowering the lidded chamber into the magnet gap carefully enough that the Viton bits do not shift and let the dee touch a lid. This was the last item built before the first run, a deliberate shortcut; it was never upgraded because, once the machine worked, exploring it was more interesting than rebuilding it (builder's review, Aug 2026).

The record shows the cost twice. The 2018 website lists it as difference number three from the design: "The Dee is not fixed in position in the chamber. This makes repeatable experiments more difficult." On 2021-05-09 the log reads: "blew two RF amps, maybe dee touching lid? Re-assembled chamber with viton spacers in better position, new RF amp." It took a new amplifier, "wiggling RF connection to tuning coil, and finding right resonant frequency" to get beam back. A fixed dee mount is the first item on the machine's deferred-maintenance list.

2.3 Capacitance

The design workbook computes the dee capacitance from three parallel-plate terms (Table 2). The same formula was checked against the Rutgers 12-inch dee, for which computed and measured values agree to 0.6 %. Applied to the Mullins dee it gives 74.35 pF; the dee as built measured 100 pF. The 26 pF excess is therefore real and unmodeled: the stem and feedthrough, the fringe field of the straight edge, and the edge-to-wall term at the actual geometry. The workbook records the measurement and moves on; it contains no reconciliation. The matching design used about 112.5 pF for the total system capacitance at 9 MHz, and that is the number the coil was wound to.

Table 2. Dee capacitance derivation (design workbook, sheet "RF matching").

Term	Basis	Value
One face to one lid	$\frac{1}{2}\pi r^2 \cdot \varepsilon_0$ / 0.16 in, r = 4 in	35.29 pF
Both faces	× 2	70.58 pF
Edge to chamber wall	0.3 in gap	3.76 pF
Computed total		**74.35 pF**
Check: Rutgers dee, same formula	computed 77.64 pF vs measured 78.1 pF	0.6 %

Term	Basis	Value
Measured, Mullins dee		**100 pF**
Used for matching	measured plus feed strays, 9 MHz	~112.5 pF

A modern LCR-meter measurement of the dee in place has not been made. It would settle the 26 pF term and is a prerequisite for the planned higher-power RF work.

3. The RF chain

3.1 Signal path as operated 2021–2025

Figure 2 shows the chain in order, from the function generator to the dee, as confirmed by the builder in 2026; Figure 3 shows the chain on the bench, and Table 3 lists the stages.

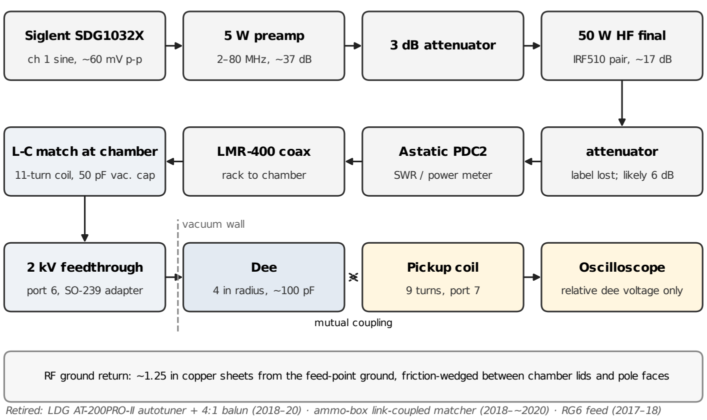

Figure 2. The RF chain as operated 2021–2025. Power flows left to right along the top row, right to left along the middle row, and into the chamber at the lower left. The pickup coil is inductively coupled to the dee and gives a relative dee-voltage reading only. Retired stages are listed at the bottom.

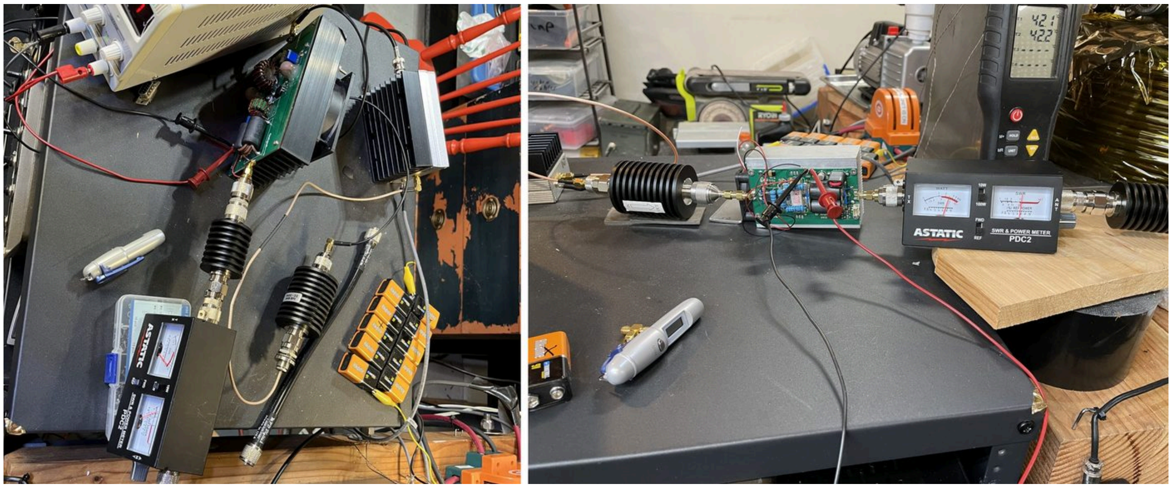

Figure 3. Left: the RF chain on the rack bench, 2025-02-02 — the 50 W IRF510 amplifier board with fan and heatsink at top, a finned attenuator in line to the Astatic PDC2 SWR/power meter at lower left, a second finned attenuator on a pigtail, the thermocouple thermometer used to watch FET temperature, and the string of 9 V bias cells at right (media id: Live Photos/IMG_9641). Right: a replacement 50 W amplifier board under test on 2021-03-06, driving a finned dummy load through the PDC2; the thermometer reads 42.1 and 42.2 °C on the two FET channels. The log for that day: "new rf amp, 10W drive", later "30W RF out, decent beam shape, 75C" (media id: Live Photos/IMG_2511).

Table 3. RF chain stages.

Stage	Unit	Notes
Source	Siglent SDG1032X, channel 1	~60 mV p-p drive in the procedures, 130–140 mV in 2025; channel 2 drives the magnet-field ramp
Preamp	2–80 MHz 5 W HF preamp (eBay, $56)	nominal 37 dB; 15 V/2 A rail
Pad	3 dB attenuator	between preamp and final (log, 2020-07-03 onward)
Final	2–30 MHz 50 W HF linear amplifier, IRF510 pair (eBay, $115–120)	~17 dB; 28 V/6 A rack rail (25 V bench supply in photos)
Pad	attenuator, label lost	most likely the 6 dB unit ("3dB atten between preamp and amp, 6db after amp", log 2021-10-24); a home-made 1 dB T-pad is the other candidate
Meter	Astatic PDC2 SWR/power meter ($23)	10 W / 100 W scales; the "W on SWR meter" figures in the log
Feed	LMR-400 coax	replaced the RG6 of the 2017 construction spec
Match	11-turn coil + 50 pF vacuum variable capacitor	at the chamber, port 6 (Section 4)
Feedthrough	2 kV ceramic vacuum feedthrough, adapted to SO-239	port 6
Pickup	9-turn coil inside the chamber, port 7 feedthrough	to the oscilloscope; relative only (Section 5)

The LDG AT-200PRO-II autotuner and its 4:1 balun (2017; the "RF autotuner" on the 12 V rail in the construction spec) sat in the chain in the early years and are no longer used. Workbook bench data describe the stages as bought: preamp about 48 dB small-signal, compressing to 37.8 dB at 6 W out; preamp plus final 59–60 dB, 55 W at −13 dBm drive (141.6 mV p-p), compressing toward 90 W; harmonics −25 to −12 dBc. Into the real dee the chain ran at 20–40 W for most of the beam era and about 60 W in 2025. A 1 kW BLF188XR amplifier was priced ($790) but never bought; the planned higher-power path is a 100–500 W LDMOS amplifier.

3.2 The IRF510 problem

The 50 W final uses a pair of IRF510 MOSFETs, a switching part pressed into HF linear service in a widely copied amateur design, and it does not tolerate a mismatched load. The 2018 website states it as difference number two from the design: "The 50W RF amp does not tolerate unmatched loads. After a few minutes, the two power transistors fail and must be replaced. For now, the 5W pre-amp is sufficient for operation." The log records the toll through the beam era (Table 4). The builder's estimate in 2026 is that ten to fifteen IRF510 pairs were consumed over the life of the machine, which makes it the most-replaced component on the cyclotron; two complete 50 W amplifier boards were bought in addition to loose FETs. FET temperatures were logged at 85–110 °C in 2020, "190F on IRF511" in May 2021 and 88 °C in December 2022; they are read with a small hand-held infrared thermometer. The 50 W amplifier is still in the chain as of 2025 but is not driven to its rating: the logged drive levels correspond to a few watts to a few tens of watts at the dee, well short of 50 W.

Table 4. RF amplifier failures in the run log.

Date	Entry
2019-01-13/20	"did not work, new RF setup" — three sessions of RF rework before the 587 mT / 9.27 MHz resonance of 2019-01-26
2021-01-10	"amp dies after a minute or so at 450 mV drive"; magnet supply unstable above ~350 mV / 50 W
2021-05-09	"blew two RF amps, maybe dee touching lid?" (Section 2.2)
2021-05-15	"removed 3dB attenuator on rf out, bad connection somewhere"
2022-08-14	"RF amp failed within a few minutes after cyclotron working"

The failures cluster around load faults (an open or short at the dee, a bad connector) rather than steady operation at rated power; the amplifier ran for hours at 20–40 W without dying. The machine has no forward/reflected-power interlock; the SWR meter was read by eye. Protection circuitry, or a final that survives an open load, is the obvious upgrade.

3.3 What the RF power ladder taught

Through 2020 and 2021 the log records deliberate drive and attenuator experiments (Table 5). Together they say that beam current responds weakly to RF power once on resonance, that there is a minimum drive below which there is no beam at all, and that raising drive shifts the whole resonance sweep rather than sharpening the peak. No quantitative model of the last effect was made.

Table 5. RF power ladder entries (MFC and filament settings varied between rows; compare within a date).

Date	Chain configuration (from the log)	Drive → power	Observation
2020-07-03	3 dB pad between stages, no output pad, preamp at 13.3 V	120 mV = 10 W, 350 mV = 50 W into dummy load	"not much increase in beam from 180, 280, or 380 mv drive, much lower at 80mv"
2020-07-04	same	150 → 200 mV	"increase in RF drive mostly just shifted entire sweep rather than just the peak, 200mv is good compromise"
2020-07-18	same	160 mV = 20 W, 169 mV = 22 W, 190 mV = 40 W	"22W RF output, just 10% or so boost with 40W out"; 2:1 SWR at 20 W
2021-01-10	same, magnet on battery drive	300–450 mV	"beam current steadily increasing with RF drive, shape broad but good, amp dies after a minute or so at 450 mV"
2021-05-09	new amplifier	70 mV = 20 W (~15 W DC input); 191 mV = 40 W	"below about 70 mv drive, no output at all"
2021-10-24	3 dB pad between stages, 6 dB pad after final	60 mV = 2 W; 160 mV = 19 W	2 W: "good peak"; 19 W: "wider peak"

The interference side matters as much. RF drive above roughly 50–160 mV (depending on the day) upset the Sorensen magnet supply's analog programming input, so from 2021 the magnet was ramped from a 9 V battery and a 10 kΩ potentiometer instead of the function generator. RF also reads into the HT20 gaussmeter (every logged field value was taken with RF off) and raises the electrometer background through the pickup.

3.4 Frequency and field operating points

Table 6 and Figure 4 give the machine's operating points. The 12.57 MHz / 0.824 T design point was never used; the 3.258 MHz half-field runs of 2018 found the first resonances; the machine then settled at 8.8–9.1 MHz and 570–600 mT for the whole beam era, and came back at 9.353 MHz in 2025.

Table 6. Operating points.

Era	RF frequency	Field	Notes
Design (2017)	12.57 MHz	0.824 T	never operated
2018 half-field	3.258 MHz	170–450 mT sweeps	H^+ at 214 mT, H_2^+ at 427 mT, B/3 and B/5 harmonics; the website's video era

Era	RF frequency	Field	Notes
2018 full-field	8.87 MHz	582 mT	website headline; predates the log
2018-12 – 2019-12	6.0–11.5 MHz	400–754 mT	early chain variants ("new RF setup", "new coil", "ammo box RF"); the 2019-02-23 field values are partly suspect, the RF–gaussmeter interference having been discovered that day
2020	6.24 MHz (April), then 8.83–9.12 MHz	~400, then 570–600 mT	the systematic year
2021–2023	8.69–9.09 MHz	570–611 mT	best beam 2023-10-14 at 9.033 MHz / 596 mT
2025-02	9.353 MHz	not logged	~60 W RF, 130–140 mV drive

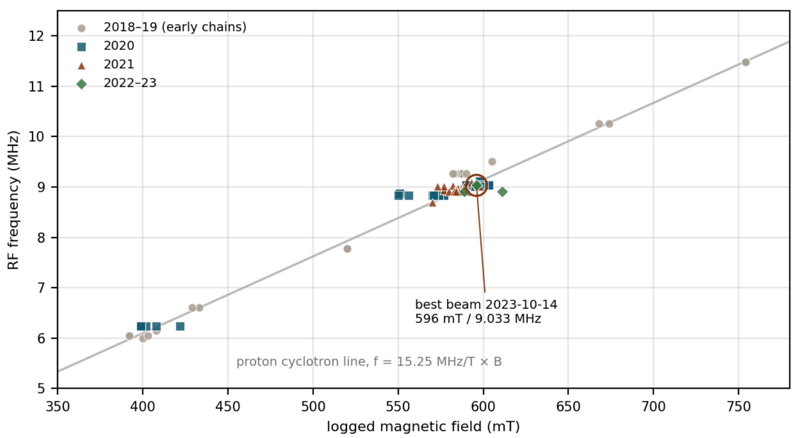

Figure 4. Every run-log row with both a field and a frequency recorded (131 rows), against the proton cyclotron line f = 15.25 MHz/T × B. The points cluster on the line, as a working machine's should; scatter across it reflects the day-to-day gaussmeter and probe-position issues discussed in the Performance note, not a change in physics. Workbook cross-check: 590 mT ↔ 9.001 MHz.

4. The matching network

4.1 Evolution

The RF match has had three forms (Table 7). The current one, an air-core coil with a vacuum variable capacitor mounted directly at the chamber feedthrough, is the simplest of the three and has been in place since at least April 2021 by photograph and since April 2020 by the log note "tuned inductor, no ammo box."

Table 7. Matching network eras.

Era	Arrangement	Evidence
2018 – ~2020	LDG AT-200PRO-II autotuner (with 4:1 balun) feeding a link-coupled air-core transformer in an RF-tight ammo box	website; construction spec; workbook coil designs; log 2019-12-15 "ammo box RF, broad peak"
2020-04-19 →	"tuned inductor, no ammo box"; "RF preamp connected directly to matching coil"	log
2021-04-11 → 2025	11-turn bare copper tubing coil and glass-envelope vacuum variable capacitor at port 6	photographs (Figure 5); builder's review

The ammo-box matcher was designed in the workbook from 1/8 in ACR copper tubing: an inner coil of 13 turns, 1 in radius, 8 in long (1.90 μH by Wheeler's formula), link-coupled from an outer 3-turn coil of 1.75 in radius; for 9 MHz and 112.5 pF the workbook computes 2.78 μH and notes a measured 2.43 μH. A second coil served the 3.5 MHz half-field runs. It was developed on the bench against a polycarbonate "simulated chamber" capacitor (387 pF), on which the website shows 1.38 kV peak-to-peak at 11 MHz.

4.2 The current matcher

The coil is 11 turns of bare copper refrigeration tubing wound immediately at the capacitor. The capacitor is a glass-envelope vacuum variable of Russian manufacture labeled 50 pF; whether that is the maximum of its range was not recorded. The assembly hangs from the port-6 feedthrough and is propped on a styrofoam block and a plastic stand. Tuning is by the capacitor and by the function generator frequency; the resonance is found by peaking the DC current drawn by the final and the pickup voltage, then fine-tuned on beam.

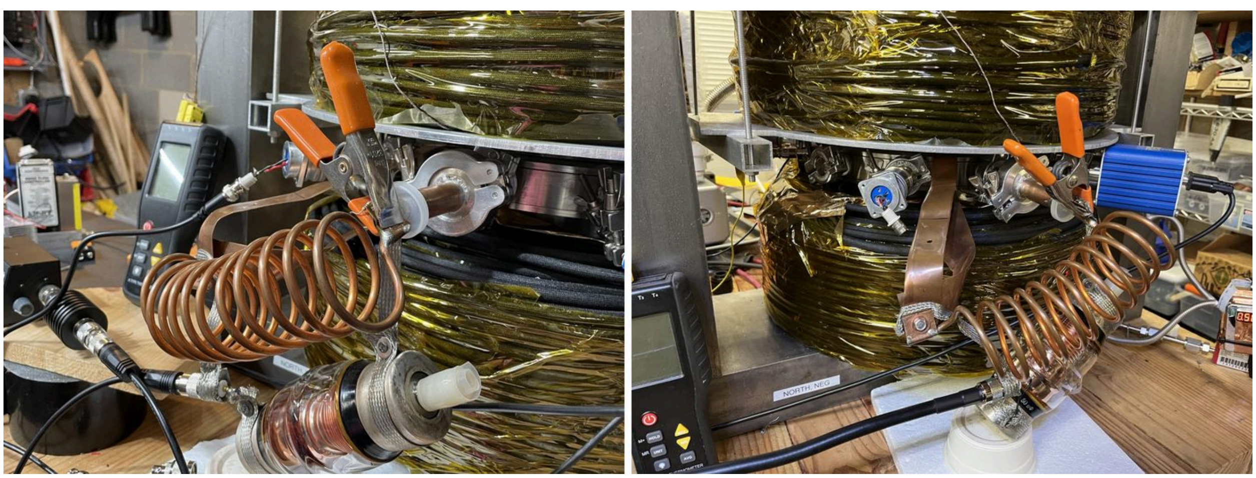

Figure 5. The matcher at port 6. Left, 2021-04-11: the bare copper tubing coil (the builder counts 11 turns) wound at the glass vacuum capacitor, whose concentric copper-cylinder electrodes show through the envelope at lower right; tinned braid runs to the copper ground strap, which disappears upward between the chamber lid and the pole; a spring clamp holds the strap to the feedthrough flange; the older UNIT mass-flow controller and the HT20 gaussmeter are in the background (media id: Live Photos/IMG_2658). Right, 2025-02-02, from the other side: the capacitor's label reads "50 пФ" (50 pF, Russian surplus); the wide flat copper ground sheet runs from the feed-point braid up between the lower lid and the lower pole face; the LMR-400 feed enters at lower left on a styrofoam block; the four-pin filament/pickup feedthrough is at upper left, and "NORTH, NEG" is the pole-polarity label (media id: Live Photos/IMG_9642).

The RF ground return deserves attention from anyone copying it. From the ground point at the feed, flat copper sheets about 1.25 in wide run to the chamber and are wedged by friction between the chamber lids and the pole faces. There is no bolted RF ground. It has worked at 60 W. Its resistance has never been measured, and it should be, before the planned amplifier upgrade.

4.3 Q on record

Three Q measurements exist, at three different frequencies and configurations (Table 8). They are not in conflict; they describe a low-Q system whose losses are distributed through the chain rather than concentrated in the coil's DC resistance, and they carry a lesson for any successor RF design: budget for a loaded Q of 500 or more.

Table 8. Loaded Q measurements (design workbook).

Configuration	Frequency	Measurement	Q
Operating configuration, with tuner	~9 MHz		**34.1**
With matching, half-field era	3.258 MHz	f½ = 3.313 MHz	29.7
Early bench test	19.1 MHz	f½ = 17.56 MHz; 14.8 V p-p → 0.7 V p-p	6.2

5. Dee voltage and the pickup coil

The only in-chamber RF diagnostic is a small pickup coil on two pins of the port-7 four-pin feedthrough: 9 turns, 0.2 in outside diameter, 0.475 in long, 0.097 µH and Q 7.7 at 100 kHz in free air, rising to 2.1 µH when installed because of mutual coupling to the dee. The workbook records a ratio of 1120 and a scale factor for the scope, with a worked example of 0.072 V pickup corresponding to 1,440 V on the dee.

That example is where the historical dee-voltage numbers come from, and the builder's 2026 review is unambiguous: the pickup was a peaking and tuning tool. An attempt to measure the true peak dee voltage with a high-voltage probe did not yield a calibration. Every dee-voltage figure ever quoted for this machine (1,300 V on the 2018 website with the 5 W preamp alone, "over 2 kV" on the RF page, 1,440 V in the workbook example, 800–809 V in the log) is relative or estimated; the 801–809 V values in the log's "Dee voltage" column are a spreadsheet drag-fill artifact. The honest statement is "~800 V nominal, uncalibrated," and an absolute calibration is the first deliverable of the planned higher-power RF work. The 2018 website's expectation that 50 W would raise the dee voltage by √10 over 5 W is right in form; what the log found (Section 3.3) is that beam current did not follow.

6. The ion source

6.1 Filament

The ion source is a bare tungsten hairpin filament, a Kimball Physics ES-020 cathode on a white ceramic two-pin button, at the center of the chamber just inside the dee's accelerating edge.

Electrons from the filament, accelerated by a negative bias of a few tens of volts, ionize hydrogen at about 10^{-5} torr; the ions are picked up by the dee field at the center. There is no source housing, chimney, puller or extraction geometry.

The filaments were bought as two 10-packs ($212 and $213), about $20 each; roughly twenty were bought in total. Spares remain on hand, together with raw tungsten wire for making more. The log entry of 2021-10-24, "new filament (last one)," refers to the stock at that time. That entry and Figure 1 date and picture the filament now in the machine.

6.2 Mounting, and what it cost

The ceramic button rests on a thin flat insulator sheet on the chamber floor. It is not fixed down. The only thing holding it in position is the solid magnet wire that carries the filament current (Figure 6). Like the dee, this was a first-run shortcut never revisited. The failure mode is a short from the filament to the chamber floor if the assembly is jostled, and the log records it on 2021-10-30, six days after the filament change: "had to open chamber, shorting across filament, causing RF to misbehave when filament current > 2A. With this rebuild, max beam current at 2.31A filament." The concentric heat-tint rings on the chamber floor are centered on the filament position and are the source's physical signature; their exact origin (tungsten evaporation, pump-oil film, occasional arcing) is uncertain, and they have been cleaned off once or twice over the years.

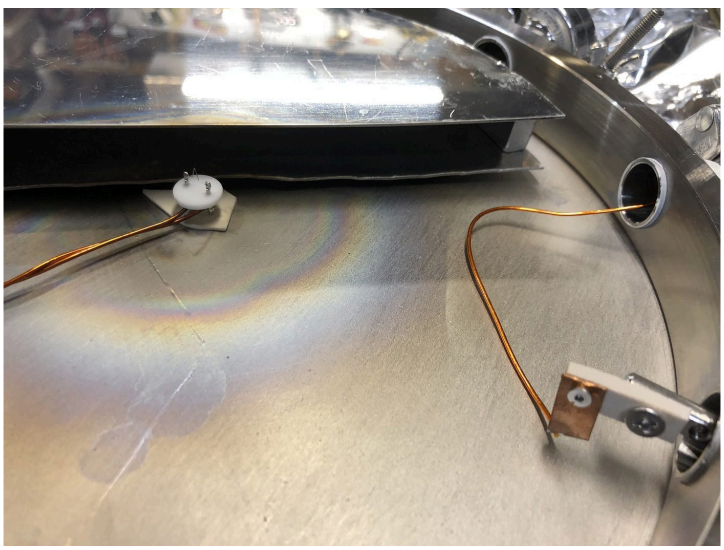

Figure 6. Chamber interior, 2020-06-15. Left: the ES-020 filament on its white ceramic two-pin button, resting on a small insulator sheet on the floor beneath the dee's accelerating edge; the twisted magnet-wire leads run off to the left. Right: the collector, a small copper plate on a white insulator block at the end of the linear-translator arm, wired by a single magnet wire to its feedthrough. The dee, with its slightly uneven tin-snipped edge, is above; the heat-tint rings on the floor are centered on the filament. (Media id: Photos/IMG_1501.)

6.3 Emission data

The filament was characterized on the bench in 2018 with the collector as anode (workbook sheet "electron beam"; Figure 7). At 101 V bias and 5×10^{-6} torr, collected electron current stays in the nanoamp range up to 1.8 A of filament current and then turns on sharply: 0.08 µA at 1.9 A, 0.32 µA at 2.0 A, 1.5 µA at 2.1 A, 8.2 µA at 2.6 A. At a fixed 2.25 A the current was swept against bias from a string of 9 V batteries: 1.2 µA at 67 V rising to 54 µA at 192 V. The sheet tabulates this against V^1.5 as a Child–Langmuir check; the data rise as about V^3.6, so the collection is not a simple space-charge-limited diode. The website's headline from the same tests was 77 µA at 2.2 A.

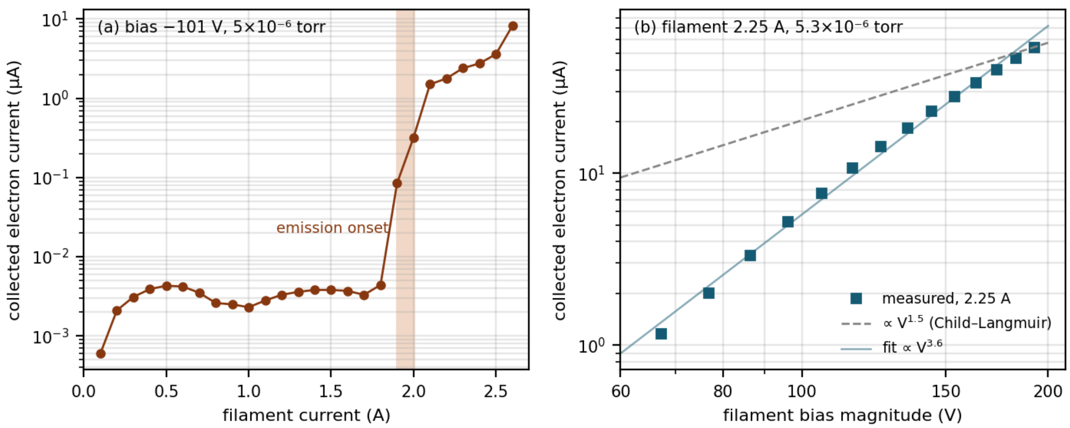

Figure 7. Filament bench data from the design workbook, 2018. (a) Collected electron current against filament current at −101 V bias, showing the sharp onset between 1.8 and 2.0 A. (b) Collected current against bias magnitude at 2.25 A, with the V^1.5 Child–Langmuir slope the workbook tabulated against and a power-law fit to the data.

6.4 Operating settings and the filament supply

The filament runs from a constant-current DC supply. The procedures ramp it over at least 30 s to 2.7 A, pausing 10 s at 0.5 A, and expect about 3.3 V across it at 2.7 A (about 1.2 Ω hot; the workbook's lead-drop calculation had assumed 0.67 Ω). Leads are 22 AWG through the feedthrough (0.048 V drop at 3 A by the workbook). The operating optimum drifted with each filament and rebuild: 2.7–2.8 A in 2018–19, 2.37–2.51 A in 2020–21 ("steep drop-off below 2.5A"; "2.31A" after the 2021-10-30 rebuild), and 2.35–2.47 A in 2023–25. The log calls it "very sensitive" and notes that the optimum "seems somewhat dependent on MFC setting." The 2018 emission onset at 1.9–2.0 A is consistent with all of this: the machine has always run just above the knee of the emission curve.

6.5 Filament bias: four supplies and a tuning discovery

Table 9. Filament bias supplies.

Era	Supply	Bias
2017–18 bench tests	electrophoresis supply	−200 to −300 V
2018–19	string of twenty 9 V batteries (9.6 V each measured)	up to −192 V; adopted because the Keithley 617's internal source added noise
2020–2023	batteries in smaller strings ("six 9V", 2021-11-27), alternating at times with the FB 103	the log's "fil. bias" column: 0 to −97 V, mostly 0 or −40 to −62 V

Era	Supply	Bias
Feb 2025	Fisher Scientific FB 103 electrophoresis supply (20–250 V, $55)	−40 V; in use when every 9 V cell was found dead on 2025-02-01

The builder notes that the choice between battery strings and the FB 103 for filament bias has gone back and forth over the years; the table gives the dominant supply of each era. The sign convention, confirmed by the builder in 2026, is that the log records the magnitude of a negative filament bias. The supply history is also the history of a finding: more bias is not better. The bench tests ran at −200 to −300 V. On the working machine the optimum was −61 to −62 V in 2020 ("62V filament bias is optimal (bias gnd to filament gnd)", 2020-07-25), −43.8 V through 2021–2023, and −40 V in 2025 ("40 is optimal fil bias, 2.35A optimal fil current", 2025-02-02). On several days the note is "best beam at fil bias=0," and on 2020-10-25: "not much difference with 0-62V bias voltage, worse > 62V."

The log also records the physics behind the sensitivity, from 2020-04-18: "lower filament bias shifts resonance mag field up in tesla" and "higher filament bias shifts resonance mag field down," the H^+ resonance at 6.237 MHz moving between 408 and 422 mT with bias. The bias sets the potential at the center where ions are born, and so their starting energy and phase relative to the dee. On 2021-11-13: a negative bias of 10–40 V made beam current "less dependent on filament drive"; maximum current came at zero or negative bias; positive bias, "especially when > 40V," reduced it. No model of these effects was made.

7. Hydrogen delivery

7.1 Supply

Table 10. Hydrogen supply.

Era	Cylinder	Fitting	Regulator
2017 – 2019	56 L UHP lecture bottle (Matheson, $174)	CGA-170 with Teflon washers	2210-series miniature dual-stage brass, 0–10 psig second stage, 1/8 in FNPT ($331)
2019-09 –	102 L UHP cylinder ("new H2 tank", log 2019-09-07); the cylinder in the machine is a Matheson one, though the purchase record lists Roberts Oxygen ($280)	CGA-350 stainless fittings	the regulator serving the CGA-350 cylinder and its setpoint were not recorded in the as-built review

Lines are ¼ in copper up to the chamber, with Swagelok fittings and a KF16-to-Swagelok adapter at port 8; the cylinder is strapped to a leg of the cart. The construction spec and website set the second stage at 10 psig; the procedures say 8–12 psi; the MFC calibrations were taken at 10 and 13 psi inlet; one results block says "low reg 3 psi." The pressure varied by era and the discrepancy is not resolved here.

7.2 Flow control: three eras

1. **Parker needle valve, 2017–18.** A 4A-NML-V-SS-K ¼ in metering valve with a 10-turn knob (Cv 0.030 at 9 turns, 0.0025 at 1 turn), used at a quarter turn or less; it raised chamber pressure to about 5×10^{-4} torr from a base of 10^{-5} torr. The best-vacuum note of 2017-12-10 was "with needle valve."
2. **UNIT UFC-1101 mass-flow controller, from about December 2018.** A surplus unit with a card-edge connector, built up on a small chassis. The "MFC" column in the log begins here.
3. **Horiba/STEC SEC-7320M, 1 sccm full scale, from 2021-05-15.** Setpoint 0–5 V for 0–1 sccm. It is the controller in the machine now, with a digital voltmeter on its chassis reading the setpoint (Figure 8).

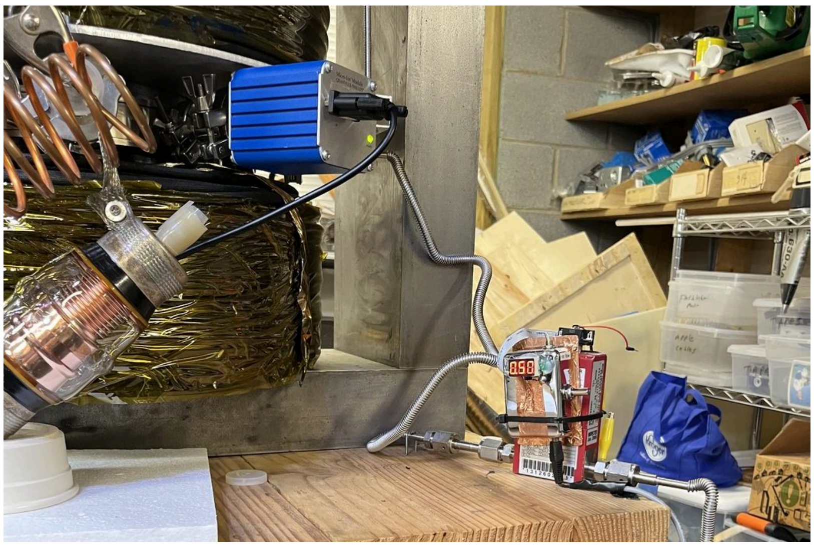

Figure 8. The SEC-7320M mass-flow controller in the hydrogen line on 2025-02-02, its chassis wrapped in copper tape, with the digital setpoint readout, inline between the stainless flex line from the regulator and the copper run to port 8. The vacuum capacitor and coil of the matcher are at upper left, the ion-gauge module above. (Media id: Live Photos/IMG_9655.)

Table 11. SEC-7320M wiring as used (design workbook, sheet "MFC wiring").

DB-9 pin	Function	Wire
1	valve open/close override	green
2	flow output, 0–5 V	
3	+15 V	red
4	power and signal common	
5	−15 V	black
6	setpoint input, 0.1–5 V	
7, 8	signal common	

Operating convention: black not connected to green is normal flow control; black tied to green overrides the valve (the "flow off" step of the startup checklist and the purge setting). The procedures document's wire-color text ("green wire should be disconnected from white and black") predates this unit; there is no white wire, and the wiring sheet is the authoritative record.

7.3 Measured MFC behavior

Both controllers were calibrated as setpoint voltage against chamber pressure on the ion gauge (Figure 9). Both show a dead zone: no flow at all below about 0.07–0.15 V, and flow does not start unless the setpoint is first raised to at least 0.2 V. The older unit passed several times more gas at the same setpoint and its readings wandered above 1.5 V, with a roughly 10 s period. The new unit's sweep at 13 psi inlet runs from 1.6×10^{-5} torr at 0 V (hydrogen-corrected gauge reading, after purge) to 1.0×10^{-3} torr at 5 V. No voltage-to-sccm table exists beyond the 1 sccm full-scale rating.

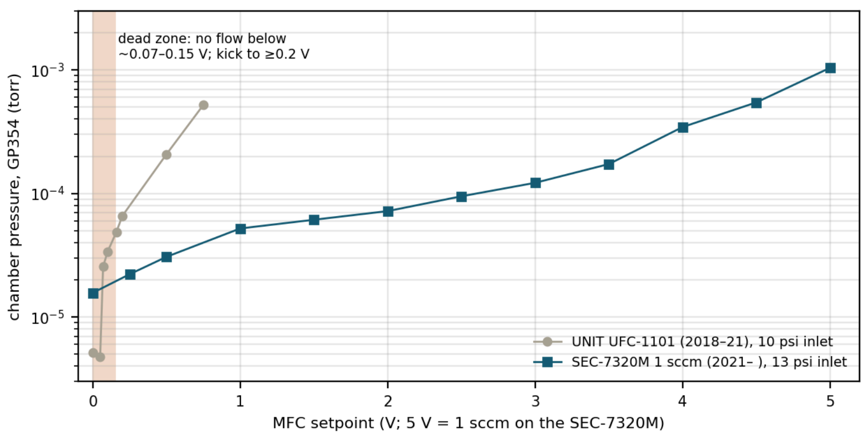

Figure 9. Mass-flow-controller setpoint against chamber pressure for the two controllers (design workbook, sheet "MFC flow"; ion-gauge readings, hydrogen-corrected where gas was flowing). The shaded band is the dead zone. The UNIT unit's series stops at 0.75 V because above that only the rough gauge read.

In operation the MFC setpoint is the master knob, and the log's finding is a tradeoff: the best resonance *shape* comes at 0.05–0.33 V; current keeps rising to 2–5 V but the peak gets "wider, uglier" and eventually disappears into background. After a large excursion upward, "it took a while for low vac to return." Residual hydrogen in the lines has sustained beam with the controller off. The 2023 best beam ran at 2.0 and 0.2 V on the new unit.

7.4 Hydrogen flush

After the chamber or the copper lines have been exposed to air, or after more than a week idle, the lines are flushed with hydrogen before use. The startup checklist refers to a separate written flush procedure; that document was never written, and the practice exists only as the builder's habit. Writing it down is on the list for the Operator's Manual note.

8. Sources and their disagreements

- **Dee voltage.** The website (1,300 V; "over 2 kV"), the workbook worked example (1,440 V) and the log column (800–809 V) disagree. All are uncalibrated pickup readings or estimates; the log values are the consistent relative record and the 801–809 V sequence is a drag-fill artifact (builder's review, Aug 2026).
- **Dee height.** The workbook's 0.4 in body was a design value; the chamber sheets budgeted 0.72–0.78 in; the as-built stack is 0.5 in plus two ~3/32 in faces ≈ 0.69 in (builder's review, Aug 2026).
- **Second-stage regulator pressure.** 10 psig (website, construction spec), 8–12 psi (procedures), 10 and 13 psi (MFC calibrations), 3 psi (one results block). Not resolved.
- **Odd records.** The 102 L cylinder is Matheson's though the purchase record says Roberts Oxygen; one results sheet records "FB103 bias 287", above the FB 103's 250 V range (a transcription slip).
- **Capacitance reconciliation.** An earlier internal review claimed the workbook reconciles 74 → 100 pF through edge and lid terms. It does not; those terms are already inside the 74.35 pF figure.

9. Open items

Things a future measurement or a short bench session would settle:

- Dee capacitance in place with an LCR meter (the 26 pF question).
- An absolute dee-voltage calibration: a calibrated capacitive divider or HV probe at the feedthrough, referenced to the pickup reading. Every energy and dee-voltage statement about this machine waits on it.
- The DC resistance of the friction-fit copper-sheet RF ground, before any higher-power amplifier is connected.
- Whether the vacuum capacitor's 50 pF label is its maximum, and the full L and C of the current match at 9 MHz.
- The regulator and second-stage setpoint actually in use on the CGA-350 cylinder; a setpoint-to-sccm calibration of the SEC-7320M.
- A fixed dee mount and a fixed filament mount, which would remove the two failure modes the log records.

Sources

- Run log (`cyclotron_log.xlsx`, sheet "log"), 2018-12-16 through 2025-02-02: RF, MFC and filament columns and notes.
- Design workbook (`cyclotron9.xlsx`): sheets "RF", "RF matching", "Specs", "H2", "MFC flow", "MFC wiring", "electron beam", "chamber", "purchases", "BOM".

- Construction spec (`Cyclotron_construction.docx`, 2017–18); operating procedures (`Cyclotron_procedures2.docx`); build website (mullinscyclotron.weebly.com): "HV RF System", "Hydrogen Delivery", "Filament and Meter Tests", "It works!".
- Builder's review, Aug 2026: dee construction and mounting, chain composition, matcher and ground, pickup status, IRF510 count, filament stock and mounting, cylinder and MFC wiring.
- Photographs (iPhone camera-roll export, EXIF dates): media ids Live Photos/IMG_3270, Photos/IMG_1501, Live Photos/IMG_9641, Live Photos/IMG_2511, Live Photos/IMG_2658, Live Photos/IMG_9642, Live Photos/IMG_9655.
