NOTES ON THE MULLINS MARK I CYCLOTRON

Operator's Manual

Author Mark1 AI instance, driven by Chris Mullins **Date** 2026-09 **Revision** v0 draft
Configuration procedures as of the 2021-10-24 checklist, corrected to the 2025 configuration (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
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 and safety note

This note is the operating manual for the Mark I as it stands. Its core is the startup and shutdown checklist in use since 2021 (the "procedures 2" document, dated 2021-10-24), reproduced step by step in §3 and §5. The checklist was written for the machine as it was that autumn; since then the filament optimum, the bias supply, the mass-flow-controller wiring and one vacuum gate have all moved. Every place the 2021 text is stale is corrected inline, in italics, and the corrections are collected in the errata table of §7. The 2021 text itself is not edited; a reader with the original in hand can follow along line by line.

Two things this note is not. It is not a training document: it assumes the operator built the machine or has been walked through it by someone who did. And it is engineering scope only. The hazard practice below is what the record shows is actually done; it is not a formal safety program, and nothing here is offered as a protocol for anyone else's machine.

Hazard practice on record.

Hazard	What the record shows
Magnet	30 A dedicated 240 V circuit; magnet enabled by its own rack switch behind the keyswitch; coils are air-cooled only, so the checklist's coil-temperature limit (under 150 °C, 100 °C better) and a ~90 min duty limit above ~450 mT are the thermal guard.
RF / HV	~800 V RF on the dee and the open matching coil at the chamber; the amplifier chain is switched from the rack ("RF Power"), and the checklist order puts RF off (generator output 1 disabled) ahead of every chamber-side shutdown step. The filament bias supply (FB 103, 20–250 V) is an electrophoresis supply with a current limit and overcurrent indicator.
Hydrogen	Lecture-bottle-class inventory (102 L cylinder), second-stage delivery at ~10 psi, 1 sccm full-scale flow, open shop volume; tank valve opened at startup and closed at shutdown; line flushed after air exposure.
X-ray	At ~800 V electrode potentials bremsstrahlung is far below the energies of concern. No survey has been made; an X-ray survey of the chamber surfaces is on the deferred-maintenance list and should precede any dee-voltage increase.
Vacuum	The diffusion-pump heater is only switched on once the chamber is below 0.1 torr, and must be cool to the touch before the roughing pump is stopped.
Electrical	Star ground on the rack; all supply commons bonded; the rack is unplugged from 120 V when the machine is idle.

2. Controls and indicators

The machine is two platforms: the 4,000 lb cart carries the magnet, chamber, both pumps and the hydrogen cylinder; the 21U mobile rack carries every instrument and supply. The rack keyswitch is the master, and the switch panel below the gauge meters is where almost every checklist step happens.

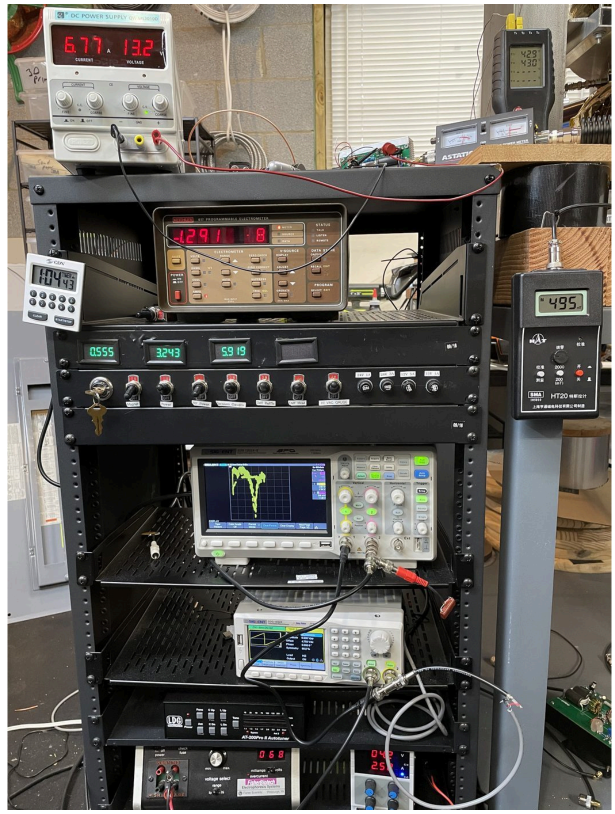

Figure 1 (left). The rack front on 2025-02-02, the last run. Top shelf: the RF final's DC supply (reading 2.51 A / 25.1 V), the Astatic PDC2 SWR/power meter and the thermocouple thermometer for the amplifier FETs. In the rack, top to bottom: Keithley 617 electrometer (reading in the 10^{-10} A range), the three green gauge meters (0.520 / 1.598 / 5.379 V), the keyswitch and toggle panel, the Siglent SDS1202X-E scope in XY mode, the Siglent SDG1032X generator, the LDG autotuner (still mounted, no longer in the RF chain), the FB 103 bias supply beside the small filament supply (2.35 A), and the Sorensen DCS 55-55 at the bottom. The HT20 gaussmeter hangs on the cart post at right. **Figure 2 (right).** The control panel during the 2021-03-06 run. Gauge meters read 0.555 / 3.243 / 5.919 V (foreline ≈ 0.025 torr; the middle gauge was noted as out of calibration in that day's log; high gauge 8×10^{-5} torr N_2-equivalent with hydrogen flowing). Key in the keyswitch; toggles labelled Magnet · Power · RF Power · Vacuum Gauges · Diff Baffle · Diff Heat · Hi Vac Gauge; fused rail indicators 24 V 1 A · 28 V 3 A · 12 V 5 A · 15 V 1 A. HT20 at 495 mT; electrometer at -1.29×10^{-8} A; run timer at 1:04:43; the resonance trace is on the scope below.

Switch panel (left to right), from the rack wiring table in the design workbook and the panel labels.

Control	What it does
Keyswitch	Enables the switched 120 V receptacle that feeds everything below
Magnet	Magnet-enable: permits the Sorensen DCS 55-55 to be energized
Power	Turns on all the small DC supplies (24 V, 28 V, 12 V, 15 V rails)
RF Power	28 V DC to the RF power amplifier (the 12 V feed to the former autotuner rode on this switch too)
Vacuum Gauges	24 V DC to the three gauge modules
Diff Baffle	12 V DC to the diffusion-pump inlet-baffle Peltier cooler

Control	What it does
Diff Heat	Enables the variac that feeds the diffusion-pump heater (normally set ~75 %, ≈90 VAC to the heater)
Hi Vac Gauge	Powers the Granville-Phillips 354 Micro-Ion module
Four fuse holders	24 V/1 A gauges · 28 V/3 A RF final · 12 V/5 A baffle, panel meters · 15 V/1 A RF preamp

Indicators. Three green panel meters show the three gauges as *voltages* (left: GP-275 foreline; center: MKS 901P chamber "middle"; right: GP-354 "high"). The fourth display position is unused. Every vacuum checkpoint in the checklist is a voltage on one of these meters; §3 gives the pressure each one means and Figure 3 plots the conversions. The gaussmeter is a hand-held HT20 with its probe in the gap; the electrometer is a Keithley 617 whose 2 V analog output drives the scope's Y axis.

Off-rack controls. Two hand valves on the cart: the roughing-pump vent ("small knurled handle") and the chamber/foreline valve ("large black plastic handle") between the roughing pump and the diffusion pump. There is no large gate valve; the diffusion pump is always open to the chamber. The diffusion-pump fan plugs into a white extension cord. The hydrogen cylinder valve and its two-stage regulator are on the cart front. The mass-flow controller (Horiba/STEC SEC-7320M, 1 sccm full scale) takes a 0–5 V setpoint and has a valve-override lead (green) whose state is a checklist item (see the correction at step 7). The magnet field-reversal knife switch on the cart deck is in circuit, in the correct position, and never operated.

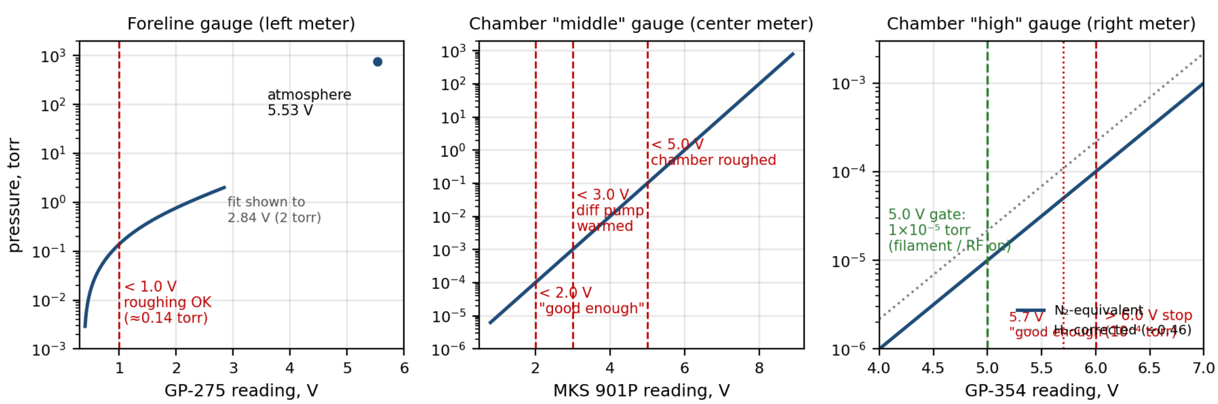

Figure 3. Meter voltage to pressure for the three gauges, using the conversion laws in the design workbook (GP-275: polynomial fit from the gauge manual, plotted to 2.84 V; MKS 901P: P = 10^(V−6) torr; GP-354: P = 10^(V−10) torr nitrogen-equivalent, with the ÷0.46 hydrogen correction dotted). The checklist checkpoints are marked; the 5.0 V line on the high gauge is the real go/no-go gate (§3, the wait line after step 21).

3. Startup checklist

Numbered as in the 2021 document. *Italic lines are corrections and conversions added in 2026; they are not part of the 2021 text.* "Stop" means what it says: the checklist was written with abort points, and every one of them has been used.

Pre-vacuum

1. Make sure the roughing-pump vent valve (small knurled handle) and the chamber valve (large black plastic handle) are both closed.
2. Make sure all rack switches are off.
3. Turn on the rack keyswitch.
4. Turn on the rack main power switch.
5. Turn on the diffusion baffle switch.
6. Plug in the diffusion-pump fan (white extension cord).
7. Make sure MFC flow is off (green wire connected to black). *Correction: the MFC is wired per the workbook's wiring sheet — red = +15 V (DB-9 pin 3), black = −15 V (pin 5), green = valve open/close override (pin 1). There is no white wire. The checklist reads green-tied-to-black as "flow off"; the wiring sheet labels the same connection "purge" (valve forced fully open) and "normal" as green not connected. Both agree that green floating = normal setpoint control. Which state green-to-black actually produces on this controller is to be confirmed at the bench before the next revision (§7, E3). In a 2021 photograph the installed MFC carries a hand-written "Closed / no flow" tag for the off state.*
8. Turn on rack vacuum-gauge power — the gauges should read about 5.5, 8.2 and 10.6 V. *At atmosphere: 5.53 V on the GP-275 is 755 torr at the shop's altitude; the 901P compresses near atmosphere (its law would give 8.9 V); the 354 reads above 10 V whenever it is off or over-range.*
9. Turn on the roughing vacuum pump (check the oil level first).
10. Wait 10 seconds.
11. Check the roughing-pump gauge (first meter on the left): it should read under 1.0 V. If not, briefly open and close the small vent valve. Do not proceed until this gauge reads under 1.0 V. *1.0 V on the GP-275 ≈ 0.14 torr (140 µm). The pump's measured ultimate is 0.87 V ≈ 98 µm, so the meter settles in the 0.4–0.6 V range (3–30 µm) once the foreline is clean.*
12. Open the chamber valve. The rough gauge should read under 1.0 V and the middle gauge under 5.0 V within a few minutes. If not, close the chamber valve and go back to the foreline steps. Do not proceed until the gauges are under 1.0 V and 5.0 V. *5.0 V on the 901P = 0.1 torr. The 2021 text says "go to step 8"; in its own numbering that is the gauge-power step — the intent is steps 9–11.*
13. Turn on the electrometer, scope, function generator and magnet power supply.
14. Dial the filament-current knob to zero (it should already be there) and turn the filament supply on.
15. If the chamber or the hydrogen copper lines have been exposed to air since the last use, or it has been more than a week, the copper lines need to be flushed with hydrogen to purge air. "See separate hydrogen flushing procedure." *That separate procedure was never written. The practice, as far as the record shows it: with the chamber pumping, the MFC valve is forced fully open (the override lead) so hydrogen sweeps the copper line into the chamber, then the override is released. The log records one such purge on 2021-05-15 ("after 1.5 hour pumpdown after exposure to air, new MFC, H2 line purge"). Durations and regulator settings are not recorded; writing this step down is the cheapest improvement this checklist can get (§7, E5).*

After the middle gauge reads below 5 V

16. Turn on the diffusion-pump heater. *Variac normally at ~75 % (≈90 V AC to the heater). The SI100 is charged with Dow Corning DC-704.*
17. Start a 10-minute timer.
18. Open the hydrogen tank valve.

After 10 minutes

19. The middle gauge should read below 3 V. If so, proceed. If not, the vacuum system is not working — stop. *3.0 V on the 901P = 1×10^{-3} torr.*
20. Turn on the high-vacuum gauge. The reading should briefly go to 10 V, then drop under 7 V. If not, the vacuum system is not working — stop. *7 V on the 354 = 1×10^{-3} torr.*
21. Turn on the high-vacuum gauge bias-current switch. Wait 2 minutes. If the gauge turns off (meter goes back to 10 V), repeat, waiting a minute or two. *The rack panel has one "Hi Vac Gauge" toggle; the second switch the checklist refers to is not on the panel — the Micro-Ion module at the chamber has its own front control. Confirm which is meant when the checklist is revised (§7, E9).*

Wait until the vacuum is at least 5.5 V on the high gauge (1×10^{-5} torr) before proceeding. This may take another 30 minutes. (Unnumbered in the 2021 text.)

Correction: the two halves of this line disagree — 5.5 V on the 354 is 3.2×10^{-5} torr, and 1×10^{-5} torr is 5.0 V. The builder confirmed in 2026 that the gate actually used is 5.0 V ≈ 1×10^{-5} torr ("that's what I look for on the meter"). The pressure in the parenthetical was right; the voltage is the stale half. Fresh pumpdowns in the operating configuration reach 4.7–5.0 V (5–10×10^{-6} torr) in one to three hours; after a long open period it can take much longer (the 2025 recommissioning needed "hours of vacuum pumping").

22. Turn off electrometer autoranging, switch to amps, switch to the −9 range, and turn off zero-check. *Keithley 617: amps mode, 10^{-9} A range, zero-check off during runs. The 2018 procedure used the −6 range; −9 is the beam-era setting.*
23. Slowly adjust the filament current to 2.7 A, taking at least 30 seconds and pausing 10 seconds at 0.5 A. The voltage at 2.7 A should be about 3.3 V. *Correction: 2.7 A is the 2018–2019 optimum, on the earlier filament. Keep the ramp discipline but stop at the beam-era optimum: 2.35–2.47 A (2023–2025; "2.35 A is optimal fil current", log 2025-02-02). The optimum drifts with each filament and with MFC setting; approach from below and watch the electrometer. Above ~2.5 A on the current filament the beam falls off and the peak widens. Note also the 2021-10-30 event: a filament touching the chamber floor made the RF misbehave above 2 A.*
24. Adjust RF generator output 1 to the resonance frequency (e.g. 9 MHz), 60 mV peak-to-peak, and turn output 1 on. *Beam-era practice: 100–200 mV p-p drive (110–160 mV typical; 130–140 mV in 2025). Below about 70 mV there is no dee voltage at all; above ~200 mV returns diminish and the amplifier heats (FETs logged at 85–110 °C). 60 mV was the preamp-only era. Frequency and field go together: for protons B(mT) ≈ 65.6 × f(MHz), so 9.033 MHz needs 593 mT; the log precomputes B, B/3 and B/5 for each run.*

25. Check the high-vacuum gauge. The reading has probably risen to 5.5 V from filament and dee outgassing. If it goes above 6.0 V there is a problem — stop. *5.5 V = 3.2×10⁻⁵ torr; 6.0 V = 1×10⁻⁴ torr.*
26. For best vacuum, wait 30 minutes or longer for outgassing to settle. If the middle gauge is under 2 V and the high gauge under 5.7 V, the vacuum is good enough, though lower is better. *2 V on the 901P = 1×10^{-4} torr; 5.7 V on the 354 = 5×10^{-5} torr. Beam-era runs typically show 1.8×10^{-5} torr with no hydrogen and 5–8×10^{-5} torr (nitrogen-equivalent) with hydrogen flowing.*
27. Make sure the hydrogen pressure is OK: first stage over 100 psi (max 1700 psi), second stage between 8 and 12 psi. If not, something is wrong — stop. *The cylinder today is the 102 L UHP Matheson tank with CGA-350 fittings; the regulator and second-stage setpoint on it are not written down. The MFC was calibrated at 10 and 13 psi inlet, and the 2018-era regulator was a 0–10 psig unit, so "8–12 psi" is the practical band.*
28. Turn on the MFC — the green wire disconnected from white and black. Set the MFC setpoint between 0 and 5 V; 5 V = 1 sccm hydrogen. *No white wire (step 7). The controller has a dead zone below ~0.07–0.15 V: kick the setpoint to at least 0.2 V to start flow, then set the working value. Working setpoints in the log run 0.05–2.6 V; see §4 for the shape-versus-current trade.*
29. Turn on the magnet rack switch.
30. Turn on magnet current, either manually at the power supply or with the function generator's DC output or ramp waveform. *The generator's output 2 drives the Sorensen's analog programming input. The log's "mag drive" column is that voltage: 6.1–6.7 V for 570–600 mT. Measure the field with the RF off — the HT20 reads wrong with RF on. Check the HT20's 9 V battery: a low cell once read 700 mT for 577 mT.*
31. Use the electrometer with manual magnet adjustment, or the scope to graph scans with the function generator sweeping the field. *See §4.*
32. Keep watching for signs of trouble: vacuum gauges, filament current, electrometer output, gaussmeter, roughing-pump oil level, coil temperature (keep under 150 °C; 100 °C is better). *The coils are permanently air-cooled — there is no cooling-water step to add, and none was ever omitted. Plan on about 90 minutes of running at high field before the coils are too hot; a thermocouple on the coil surface is the only temperature indication.*

4. Beam tuning and the sweep

Figure 4 (left). Frame from a video of the rack during the 2020-05-31 run: the scope in XY infinite-persistence mode has drawn a single clean resonance peak (X = magnet ramp voltage, Y = electrometer output); the Keithley 617 reads -7.6×10^{-11} A at that instant; the generator below it shows the triangle ramp on output 2. Every logged row for this date records beam current 0.0 — the trace holds what the numbers do not. **Figure 5 (right).** Chamber side on 2025-02-02: the Granville-Phillips Micro-Ion module (blue) on its chamber port, the matching coil and glass vacuum capacitor at left on their foam block, the mass-flow controller with its readout on the timber deck at right, and the ¼ in copper hydrogen line with Swagelok fittings. Under the cart, a small compressor — presumably left from the 2018 air-actuated valve arrangement that the hand valves replaced.

4.1 The sweep. The measurement that defines this machine is the swept-field resonance scan. The RF frequency is fixed. The generator's output 2 produces a slow triangle ramp into the magnet supply's analog input; the scope in XY mode with infinite persistence plots ramp voltage (∝ B) on X against the electrometer's 2 V analog output on Y. A beam shows as a spike at the field where the ion's cyclotron frequency matches the RF. The first sweeps in 2018 used a 600 s period over 170–450 mT at 3.258 MHz; the beam era sweeps a narrow window around the proton resonance near 590 mT. A 240 s sweep proved necessary to see short pulses ("faster sweeps hid pulse", 2020-04-18). The gaussmeter and electrometer faces are read in real time alongside the trace, and the field value that goes in the log is read with the RF off.

4.2 Reading a sweep. Three things to look for. The main peak at B = 65.6 mT/MHz × f. The odd-harmonic sub-peaks at B/3 and B/5 (198 and 119 mT at 9.033 MHz), which the log precomputes and which were observed routinely ("can also see 198 mT resonance"). And the shape: a narrow, symmetric spike is a "good beam shape"; broad, choppy or double peaks are the signature of too much gas or too much filament. A flat trace means no dee voltage or the wrong frequency — "easy to miss resonance ... tough to distinguish" (2021-05-09), so the first thing to check when nothing appears is the RF connection at the matching coil and the frequency. Signal is always paired with a same-configuration background row (RF off or off-resonance); the best on record is 5.6× background. What the peak identifies is a positive hydrogen-ion resonance: H^+ at the fundamental and H_3^+ at the third harmonic sit at the same field, so the species is not separated by this measurement alone.

4.3 The knobs and their documented optima.

Knob	Beam-era setting	What the log taught
Filament current	**2.35–2.47 A** (2023–25); 2.37–2.51 A(2020–21); 2.7–2.8 A (2018–19)	Sensitive and filament-dependent; "steep drop-off below 2.5 A" on the old filament, 2.31 Aafter the 2021 rebuild; optimum depends somewhat on MFC setting
Filament bias (negative, logged as magnitude)	**~40 V** (2025, FB 103); 43.8 V (2021–23); 61–62 V (2020)	More is not better; some days "best beam at fil bias = 0"; bias shifts the resonance field (higher bias → lower field, Apr 2020); bias makes beam less sensitive to filament current
MFC setpoint	**0.05–0.33 V** for best shape; 0.5–2 V for more current; the 2023 best beam ran 2.0 and 0.2	Current keeps rising to 2–5 V but "beam wider, uglier"; big excursions hysteretic ("took a while for low vac to return"); residual H_2 can sustain beam with the MFC off
RF drive (generator output 1)	**110–160 mV p-p**; 130–140 mV in 2025	Nothing below ~70 mV; "200 mV is a good compromise"; more drive "mostly just shifted the entire sweep"; FET temperature is the limit
Collector ("beam") bias	**89.7 V** standard from mid-2020 (9 V battery string)	8.9 V in 2018; 18 V on the 2023 best-beam day (unexplained); "no faraday cup bias — not any better"
Collector position	**0.5 in** on the translator (r = 3.8 in)	Radius scans 0.5–3.8 in are how energy is computed
Field	**570–596 mT** at 8.9–9.05 MHz	Set by where the RF chain puts voltage on the dee, not by the iron (0.851 T available)

4.4 Cross-interference to expect. RF into the HT20 gaussmeter (read B with RF off; a 20 % high reading was traced to this in 2020). RF pickup raising the 617's background. RF into the Sorensen's analog input, making the magnet current unstable above ~50 mV drive — the workaround was a 9 V battery and a 10 kΩ pot as the magnet drive, and "magnet drive varies with hand placement". Ground noise from the generator into the magnet drive above ~90 mV RF. The electrometer's baseline drifts and steps; the alligator-clip segment of the collector lead is a plausible contributor. None of these are fixed; they are managed.

5. Shutdown checklist

Numbered as in the 2021 document; corrections in italics.

1. Ensure the magnet is de-energized — ramp down with the function generator, or turn the manual Sorensen current knob to zero. Turn off function generator output 2.
2. Power off the Sorensen supply.
3. Turn hydrogen off — connect the white wire to black. *No white wire: put the MFC into its off state (the green override lead, step 7 of startup) and, if in doubt, set the setpoint to zero.*
4. Turn off RF — disable function generator output 1.
5. Ramp the filament current down to zero over 20 seconds.
6. Turn off any filament bias. *Either the FB 103 or a 9 V battery string — the builder has alternated between them over the years; the FB 103 was in use in Feb 2025. The collector bias string is a separate battery pack and is simply disconnected.*
7. Turn off the filament power supply.
8. Turn off the diffusion heat switch.
9. Start a timer; wait 20 minutes.

While waiting

- Turn off the scope and function generator.
- Turn off the gaussmeter ("Tesla meter").
- Turn off the electrometer.
- Turn off the high-vacuum gauge.

After 20 minutes

10. Verify that the diffusion-pump heater is cool to the touch.
11. Close the chamber vacuum valve.
12. Turn off the roughing pump while briefly opening, then closing, the roughing-pump vent valve.
13. Unplug the diffusion fan (white extension cord).
14. Turn off the diffusion baffle switch.
15. Turn off main rack power.
16. Turn the rack keyswitch off.
17. Close the hydrogen tank valve. *Builder's practice not in the 2021 text: the rack is then unplugged from 120 V. The chamber stays under its static vacuum with the valve closed; the diffusion pump is left open to it.*

6. Routine maintenance

Figure 6 (left). Magnet, chamber and diffusion pump on 2024-08-03 (photographed while the machine was open to air between the 2023 and 2025 runs). The Edwards SI100 with its nameplate at right, the KF25 hose from its inlet-adapter side port to the chamber, the ISO63 face blanked on top; the MKS 901P transducer on its chamber port; the coil ends with the welding-cable leads soldered on. **Figure 7 (right).** Same day: the Harbor Freight 3 cfm roughing pump on its tray on the cart deck with the home-made exhaust filter (white cylinder) and the KF16 flex hose to the foreline tee; the orange knife switch in the magnet circuit is the never-used field-reversal switch, labelled with a warning about switching while the magnet is on; a 9 V battery string (bias supply) at lower right.

Item	Practice on record	Interval / status
Roughing-pump oil	Level checked at every startup (step 9) and watched during runs (step 32); copper scouring-pad trap in the foreline hose; home-made exhaust filter	No oil-change record exists; measured ultimate 98 µm vs 22.5 µm nameplate
Diffusion-pump oil	DC-704; pump was cleaned and rebuilt in 2017	Not changed in the last few years; last change date unrecorded
Vacuum gauges	The 901P has needed re-zeroing/recalibration several times (2020-10, 2021-03, 2021-11)	Recalibrated 2021-11-21; check against the 354 when readings drift
Filament	Kimball ES-020, changed by opening the chamber; the button base rests loose on an insulator sheet and is held only by its own supply wire, so reassembly must not jostle it	Installed 2021-10-24 ("last one" at the time); spares now on hand plus tungsten wire to make more; ~20 bought over the life of the machine
Dee	Free-floating on loose Viton pieces; on reassembly position the pieces so the dee cannot touch a lid	Repositioned 2021-05-09 after two blown amplifiers
RF amplifier FETs (IRF510)	The consumable of this machine: 10–15 pairs replaced; fail on unmatched load within minutes	Keep spares; watch FET temperature
Batteries	Collector-bias string (~10 × 9 V), HT20 gaussmeter cell, magnet-drive battery when used	All bias batteries were found dead on 2025-02-01; check before each session
Hydrogen line	Flush after air exposure or >1 week idle (startup step 15)	Procedure unwritten; see §3

Item	Practice on record	Interval / status
Idle vacuum	The chamber is left under vacuum with the valve closed when the machine is powered down; pressure creeps back to atmospheric over 2–3 weeks (not formally characterized)	With weekend-only operation and the pumps off during the week, recovery to the operating gate is quick
Coil temperature	Two K-type thermocouples embedded in the top coil, read on a thermocouple meter; RF FETs checked with a hand-held infrared thermometer	Limit 150 °C, 100 °C preferred; ~90 min duty at high field
Bakeout	BriskHeat tape used only during the 2017 vacuum-learning phase; the chamber cannot be baked between the poles	Not current practice; after a long open period, hours of pumping instead
Grounds	RF ground straps wedged between lids and pole faces; collector ground a spade terminal wedged between chamber top and pole	Friction fits; inspect after any chamber move

7. Known errata against the 2021 checklist

#	2021 text	Correction	Basis
E1	"at least 5.5 V on high gauge (1E-5 torr)" (wait line after step 21)	Gate is **5.0 V ≈ 1×10^{-5} torr**; 5.5 V would be 3.2×10^{-5} torr	Gauge law (workbook); builder's review, Aug 2026
E2	Filament to 2.7 A, ~3.3 V (step 23)	Beam-era optimum **2.35–2.47 A**; ramp discipline unchanged	Run log 2020–2025
E3	MFC wires green / white / black (steps 7, 28; shutdown 3)	**No white wire.** Red = +15 V, black = −15 V, green = valve override; the "flow off" vs "purge" meaning of green-to-black conflicts between checklist and wiring sheet — confirm at the bench	Workbook wiring sheet; builder's review, Aug 2026
E4	RF 60 mV p-p (step 24)	100–200 mV p-p in the beam era; nothing below ~70 mV	Run log
E5	"See separate hydrogen flushing procedure" (step 15)	No such document exists; practice described in §3 as far as recorded — to be written	Builder's review, Aug 2026
E6	"go to step 8" (step 12)	Intent is the foreline re-check, steps 9–11	Reading of the text
E7	Second-stage 8–12 psi; first stage max 1700 psi (step 27)	Cylinder is now the 102 L CGA-350 Matheson tank; regulator and setpoint on it unrecorded	Purchases record; builder's review
E8	Filament bias — none specified	~40 V negative from the FB 103 (2025); 43.8 V batteries (2021–23)	Run log
E9	"high vacuum gauge bias current switch" (step 21)	Not a rack-panel switch; identify the control (module front) in the next revision	Panel labels vs text

#	2021 text	Correction	Basis
E10	(absent) coil cooling	Correctly absent: the coils are air-cooled and cannot be water-cooled (blocked joint); the 150 °C / 100 °C limits and ~90 min duty are the guard	Builder's review, Aug 2026
E11	(absent) idle state	Rack unplugged from 120 V when not in use — builder's standing practice	Builder's review, Aug 2026
E12	"Tesla meter"	HT20 gaussmeter; check its battery at startup (low cell gave a false field in 2021)	Run log 2021-05-15
E13	(absent) collector bias	89.7 V from the battery string; connect before the sweep, check the cells	Run log

8. Troubleshooting from the failure catalog

Every entry below happened at least once and is dated in the run log.

Symptom	Found to be	What was done
Flat electrometer trace, no peak anywhere in the sweep	No dee voltage (bad RF connection at the tuning coil) or wrong frequency; RF drive below ~70 mV	Wiggle/redo the coil connection; re-find resonance; raise drive (2021-05-09)
RF amplifier dies minutes after beam appears	Unmatched load — dee touching a lid (2021-05-09); FET overheating; IRF510 fragility in general (2020, 2022-08-14)	Open chamber, reposition Viton pieces; replace FET pair; watch temperature
RF "misbehaves" once filament exceeds ~2 A	Filament shorting to the chamber floor (2021-10-30)	Open chamber, reseat filament; new optimum 2.31 A after rebuild
Magnet current wanders, changes with hand position	RF pickup into the supply's analog input; generator ground noise (2021-01-10, 2021-03-06, 2021-11-13)	Battery + 10 kΩ pot as magnet drive; keep RF drive moderate
Gaussmeter reads high / implausible	RF on during the reading (2019-02-23, 2020-04-19); low HT20 battery (2021-05-15); broken probe tip (2022-07-30)	Read with RF off; new battery; new probe (calibration uncertain, "OK" by 2022-12)
Middle gauge disagrees with the others	901P out of zero (2020-10-25, 2021-03-06, 2021-11-13)	Re-zero / recalibrate (done 2021-11-21)
Beam level jumps by tens of percent over seconds	Gas-flow variation (2020-07-04); jumpy current 0.72–0.85 nA (2021-11-13); 617 baseline steps	Lower MFC setpoint; log the artifact; be suspicious of the alligator-clip lead
Peak broad, "ugly", or double	Too much gas (MFC ≥ 0.2–0.85 V, 2020-10-16) or too much filament (3.1 A, 2021-10-24)	Back off MFC; filament toward 2.4 A
Vacuum will not come down after a long idle	Chamber outgassing after downtime / filament change (2021-10-24); months open to air (2025-02-01)	Hours of pumping; hydrogen flush of the line; no bakeout possible

Symptom	Found to be	What was done
No bias voltage at all	All 9 V cells dead (2025-02-01)	FB 103 for filament bias; fresh cells for the collector string
Beam worse after a high-MFC excursion	Hysteresis; low vacuum slow to return (2020-07-25)	Wait; avoid large setpoint excursions mid-session
Middle gauge not below 3 V ten minutes after heater on	"Vacuum system is not working — stop"	Check valve positions, foreline gauge, oil level, heater variac
Peak present but at the "wrong" field	Filament bias shifts the resonance (2020-04-18); H_3^+/H^+ ambiguity	Record bias with every field; treat identification as hydrogen-ion resonance

Sources

The 2021 operating checklist (Cyclotron procedures 2, 2021-10-24) and its 2018 predecessor · the run log (176 runs, 2018-12-16 to 2025-02-02; notes column read in full) · the design workbook `cyclotron9.xlsx`, sheets `vacuum gauge` (conversion laws, base-pressure record), `MFC wiring`, `MFC flow`, `rack`, `power`, `H2` · the construction spec (2017-12) · the build website (rack-and-cart, vacuum-system and "it works" pages, frozen 2018) · the builder's review rounds of August 2026, cited inline · the photo record (iPhone export; frames IMG_9648, IMG_2513, IMG_1450, IMG_9655, IMG_4478, IMG_4480, all viewed).

Open items

- The MFC override lead: does green-to-black close the valve (checklist) or open it (wiring sheet)? One bench check settles E3 and lets the flush step be written.
- Write the hydrogen-flush procedure down: duration, regulator pressure, gauge readings to expect.
- Identify the "bias current switch" of step 21 and label it.
- Record the regulator model and second-stage setpoint on the CGA-350 cylinder.
- A dated pumpdown curve (three gauges vs time) from a routine start would put numbers on "another 30 minutes" and "hours of pumping".
- Coil temperature: what the embedded top-coil thermocouples read at the 90-minute point is not recorded.
- The IRF510 spare count and the roughing-pump oil-change date are not written anywhere.