NOTES ON THE MULLINS MARK I CYCLOTRON

Vacuum Chamber, Ports and Vacuum System

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Configuration chamber and vacuum system as built 2017–2018, operated through 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 configuration

This note documents the vacuum envelope of the Mark I — the pancake chamber, its lids, seal and ten ports — and the pumping and gauging behind it. The dee, ion source and collector that live inside are described in their own notes; here they appear only as things that have to fit.

The chamber was machined in December 2017 and closed for the first time in January 2018. It has not been physically altered since: the same ring, the same two lids, the same ten epoxy-bonded flanges. What changed over seven years is what hangs on the ports (the hydrogen inlet went from a needle valve to a mass-flow controller; the beam-pickup feedthrough from a four-pin to a BNC type) and how the pumps are valved (an air-actuated valve in 2018 gave way to hand valves by 2021). The pumps, the three gauges and their calibrations are the 2017 originals, so everything below describes the one configuration that produced every logged run from 2018-12-16 to 2025-02-02. Dimensions are in inches, pressures in torr; every gauge is read as a *voltage* on a rack panel meter, and this note converts those voltages with the same equations the design workbook uses.

2. Design intent

The chamber had to fit inside the 1.42 in pole gap with its lids on, clear an 8 in dee, and carry enough ports for an internal layout that was still being argued about. The choice was a short length of large stainless pipe with flat lids — the Houghton College and Rutgers pattern — and ten small KF16 ports rather than a few large ones (twelve-slot studies on the Rutgers and Houghton models preceded it; one of the ten has been blank ever since). The operating-pressure target came from a mean-free-path calculator in the workbook, which gives 13.5 m at 10^{-4} torr, 135 m at 10^{-5} and 1,350 m at 10^{-6} (3.2×10^{17} molecules per m^3 at 10^{-5} torr).

Two remarks. The calculator uses a molecular radius of 0.72 Å; with the usual kinetic diameter of nitrogen (about 3.7 Å) the molecule–molecule mean free path at 10^{-5} torr is nearer 5 m than 135 m. More to the point, what limits a proton beam is charge exchange and scattering of the fast proton on hydrogen, not the gas-kinetic path; with cross-sections of order 10^{-16}–10^{-15} cm^2 at tens of keV that path is metres to tens of metres at the operating hydrogen pressures — comparable to the total orbit length of a ~100-turn acceleration. This was not analyzed in the design (see open items). The practical rule the builder set in 2017 — 10^{-5} torr before the filament goes on — has stood.

3. The chamber ring

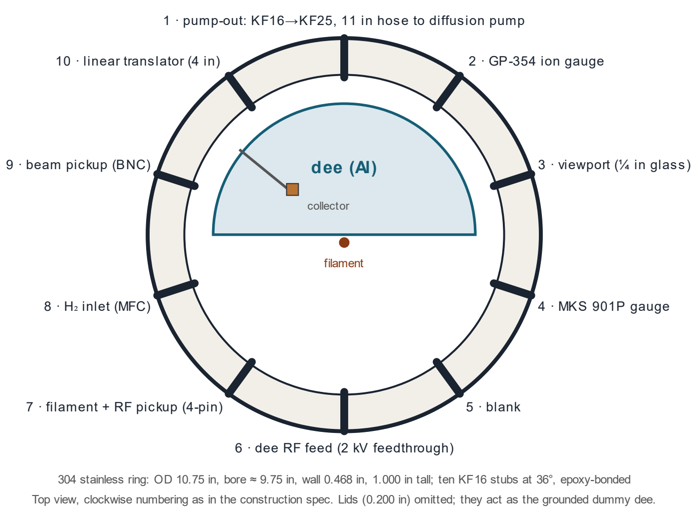

Figure 1. The ten-port chamber in top view, numbered clockwise as in the 2017 construction spec. Port assignments are the as-operated set (§8); port 9 carries a BNC feedthrough, not the four-pin unit the 2017 spec lists.

Item	As built	Source
Stock	10 in schedule 80S 304/304L pipe (TW Metals), $243 for the length bought	purchase list
Outside diameter	10.75 in	all sources

Item	As built	Source
Bore	≈ 9.75 in (see §15 on the "10.25 in" figure)	workbook; builder's review, Aug 2026
Wall	0.468 in	workbook stack-ups
Ring height	1.000 in nominal; not re-measured since machining	workbook `chamber2`
Ports	10 × KF16 blank weld-stub flanges at 36°, epoxy-bonded (§7); 3.259 in of mid-wall arc per port	construction spec, workbook
Port stub on the ring face	0.72 in of the 1.000 in height, leaving 0.14 in above and below	workbook `chamber2`
Lid screw holes	ten 2-56 tapped holes per face on a 10.464 in circle; 0.175 in thread engagement	construction spec, workbook

A 1.000 in slice was parted from the pipe and the ten port holes bored at mid-height, each sized a few thousandths over the flange stub. That tight-clearance boring is, in the builder's judgment, why the epoxied ports have never leaked (§7). Before the stainless ring was cut, a **mock-up chamber was machined from aluminum** (10 in schedule 40 6061 pipe) and fitted with a full set of ports for mechanical trials; it still exists.

4. Lids and fasteners

Item	As built
Lid stock	304 stainless sheet, 11 × 11 in, **0.200 in** thick (two lids)
Screws	2-56 × 3/8 in flat-head socket, silver-plated (FA-206-NA); ten per lid, countersunk; 2.1 in·lb, 0.050 in hex
Dee screws (inside)	2-56 × ¼ in side-vented (FA-204-SV), to avoid trapped volumes
Assembled height	0.200 + 1.000 + 0.200 = **1.400 in** in a 1.421 in measured pole gap: ~0.01–0.02 in total clearance

The BOM still reads "3/16 in" for the lids because that was the shopping language when candidate sheets were priced; the as-built stack-up in the workbook (0.200 in per lid, giving a −0.011 in margin against the measured gap with tolerance included) is only consistent with 0.200 in, and the builder confirmed it in 2026. The lids do double duty: electrically they are the grounded "dummy dee" facing the live dee, so their flatness under vacuum load matters to the RF gap (§6).

5. The O-ring gland

Each lid carries a −273 Viton (FKM, 75 durometer) O-ring — section 0.139 in, inside diameter 9.734 in — in a rectangular groove machined into the lid face: **0.140 in wide × 0.080 in deep**, 0.02 in corner radius, on a 10.00 in groove diameter.

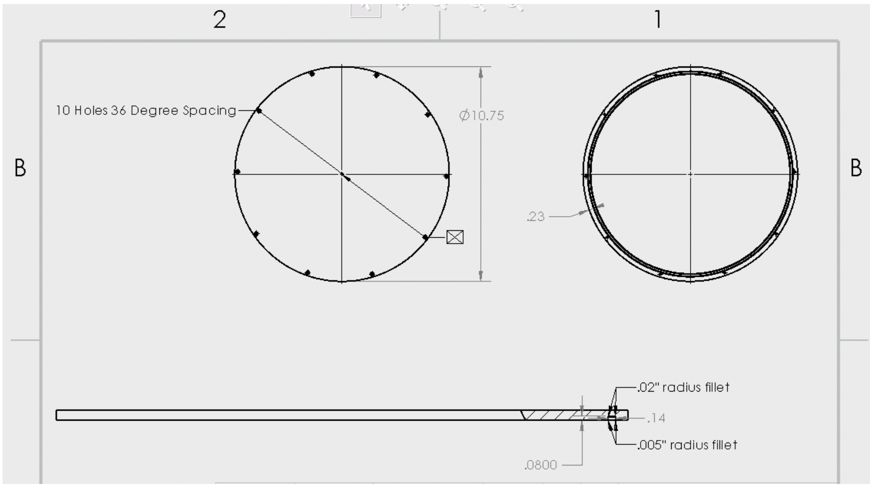

Figure 2. The lid fabrication drawing (SolidWorks, December 2017): ten holes at 36°, 10.75 in outside diameter, and the gland section at right — 0.14 in wide, 0.0800 in deep, 0.02 in and 0.005 in fillets. The drawing settles the width/depth orientation the prose sources swapped (§15).

The derivation in the workbook went through several candidates, judged by groove fill (O-ring section area ÷ groove area):

Candidate	Groove W × D (in)	Groove area (in²)	O-ring area (in²)	Fill	Note
−262	0.103 × 0.081	0.00834	0.00759	0.91	"Houghton gland"; too full
−377 (10 in ID)	0.244 × 0.162	0.0395	0.0173	0.44	bought, then superseded
−273, handbook ideal	0.158 × 0.101	0.0160	0.00759	0.48	27 % squeeze
−273, as built	**0.140 × 0.080**	**0.0112**	**0.00759**	**0.68**	**42.4 % squeeze**

Stretch on the 10.00 in groove is (10.00 − 9.734)/9.734 = 2.7 %; axial squeeze is 1 − 0.080/0.139 = 42 %. That squeeze is high by handbook standards (the Parker face-seal chart the builder used suggests 20–30 %), but because the lids pull down metal-to-metal on the ring face the compression is fixed by groove depth and cannot be over-driven by the screws, and 68 % fill leaves room for the rubber to move. An earlier scheme cut 0.101 in grooves into the *ring* faces; the final design moved them to the lids. Two −273 rings ($12.56 the pair) have served since 2018; no seal has been replaced.

6. Lid deflection under vacuum — predicted and measured

The workbook treats each lid as a simply-supported circular plate of radius $a = 5$ in, thickness $t = 0.200$ in, under $q = 14$ psi, with $E = 1.9\times10^{11}$ Pa and $\nu = 0.27$ for 304 stainless:

$\delta_{center} = 0.696 \cdot q \cdot a^4 / (E \cdot t^3) =$ **0.0276 in**

(0.696 is the Roark coefficient for $\nu = 0.3$; the construction spec rounds to "0.03 in"; fully clamped edges would give 0.019 in). The measurement was made in April 2018 with the chamber on the bench pumped to 180 µm — already the full atmospheric load — using a steel rule across the lid, a depth gauge at the center, and feeler gauges in the lid-to-ring gap at the edge.

Quantity	Front lid	Back lid
Center reading, atmosphere → 180 µm	11 → 44 mil	— → 33 mil
Center deflection	**33 mil**	**33 mil**
Lid-to-ring edge gap, atmosphere → 180 µm	15 → 16 mil	—

Measured 0.033 in against predicted 0.028 in: plate theory held to about 20 %, and in the expected direction — the lid is effectively supported nearer the 10.46 in bolt circle than the 9.75 in bore edge, and deflection scales as a^4, so a 5.2 in effective radius accounts for the difference. The practical consequence is that under vacuum each lid bows about 0.03 in *toward* the dee at the center, closing roughly a fifth of the nominal ~0.155 in lid-to-dee gap there (the RF note treats what that does to dee capacitance).

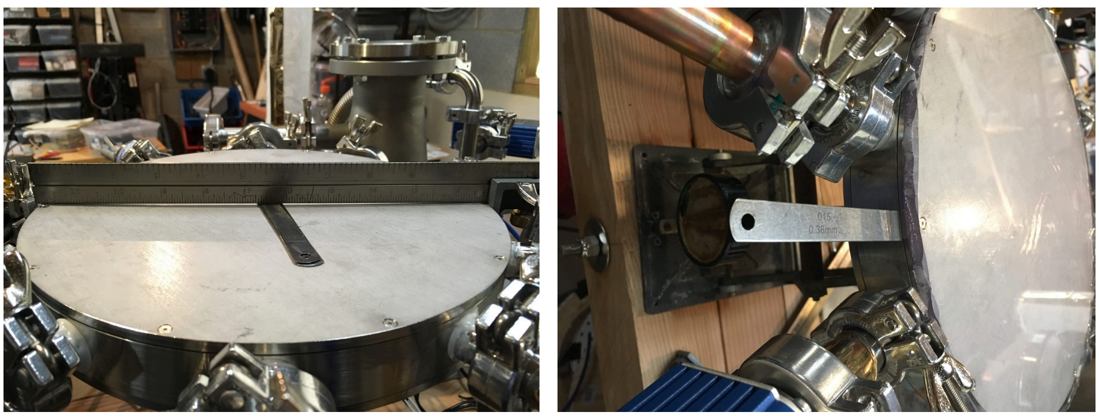

Figure 3. 2018-04-14, the deflection measurement. Left: the chamber on the bench under vacuum with a steel rule spanning the lid and a depth gauge at the center; behind it the SI100 with its ISO100→ISO63 adapter, KF25 side port and the flexible hose to the chamber. Right: a 0.015 in feeler gauge in the gap between lid edge and ring face at atmosphere; the gap grew to 0.016 in under vacuum. Port numbers ("6", "9") are scribed on the ring beside the flanges.

7. The epoxy-bonded ports — and the lesson

The ten KF16 ports are not welded. They are commercial blank weld-stub flanges (HFS, 304 stainless, about $10 each) set into the bored holes and bonded with **Loctite Hysol 1C** epoxy: 100 : 44 resin : hardener by weight (a 79.3 g : 34 g batch was weighed; working batches of 7.5 g + 3.3 g), cured 3 hours at 150 °F, one flange at a time. The same epoxy fixes the KF16 adapter into the rough pump's inlet.

After eight years and a good deal of handling — the chamber has been lifted in and out of the gap, opened for filament changes, left open to air for months, and clamped and unclamped hundreds of times — **no epoxy joint has ever leaked or failed.** The builder attributes this to two things. First, the thin bond line the tight machining produced: the epoxy fills a few mils of gap perfectly and is never asked to bridge a void. Second, preparation: clean materials, and the full cure period observed before the joint was handled — hurried along with a hair dryer, one port at a time (the build website has a photograph of exactly that). That conditional is the lesson. Epoxied KF ports are a legitimate technique at this scale *when the machining gives the adhesive almost nothing to fill*; with loose holes the same recipe would be a different experiment. The corollary is a temperature ceiling: the chamber can be warmed for outgassing but is not a bakeable ultra-high-vacuum vessel — and in any case cannot be baked in place (§13).

8. Port map, feedthroughs and their history

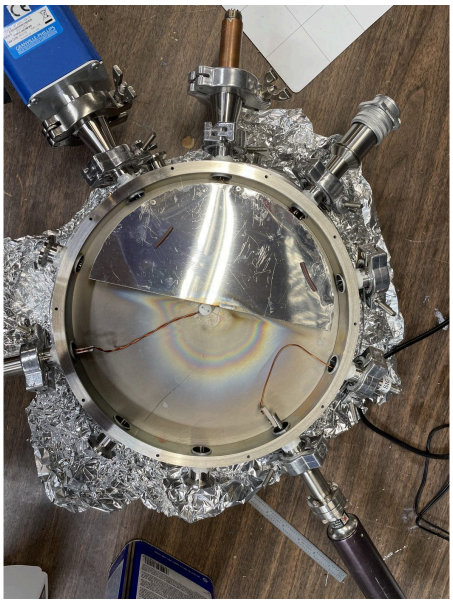

Figure 4. 2021-10-24: the chamber open from above for a filament change, resting on foil on the bench. All ten ports are visible around the ring; the aluminum dee occupies the upper half, the filament sits at center with its twisted leads running to the four-pin feedthrough at left, heat-tint rings mark the floor, the GP-354 module is at top left and the linear translator enters at bottom right.

Port	Connection as operated	Hardware	Changes since 2017
1	Pump-out	KF16→KF25 adapter, 11 in KF25 stainless hose to the diffusion-pump inlet adapter	shorter KF25 tube fitted 2018-12-24 (run log)
2	High-vacuum gauge	Granville-Phillips 354 Micro-Ion, on a KF25→KF16 reducer	—
3	Blank (viewport intended)	KF16 blank. A viewport was planned here and 1 in BK7 glass discs were bought for it, but it was never made; there is no optical viewport on the machine	—
4	Rough/medium gauge	MKS 901P loadlock transducer	—
5	Blank	KF16 blank	never used; believed still blank

Port	Connection as operated	Hardware	Changes since 2017
6	Dee RF feed	2 kV single-pole HV feedthrough (KF25 part), adapted to an SO-239	coax changed with each RF generation
7	Filament + RF pickup coil	4-pin ceramic KF16 feedthrough (two pins each)	—
8	Hydrogen inlet	KF16→Swagelok ¼ in copper	needle valve (2017–18) → UNIT MFC (Dec 2018) → Horiba 1 sccm MFC (May 2021)
9	Beam pickup	KF16 BNC feedthrough → BNC barrel → triax stub → Keithley 617	2017 spec lists a 4-pin unit here; superseded (builder's review, Aug 2026)
10	Linear translator	Huntington VF-107-4, 4 in travel, carrying the collector	—

The assignment table went through four generations in the workbook — twelve-slot "Rutgers" and "Houghton" study columns, a "Simon" column, and the ten-port "new" column that was built. An interim snapshot marks port 3 "skip" (the viewport came later) and port 9 "crimp", from the era when the beam pickup was a crimp lug rather than a collector plate.

9. Fitting everything in

Inside the 1.000 in ring the workbook budgets, lid to lid: dee plate 0.04 + gap 0.10 + dee interior 0.50 + gap 0.10 + dee plate 0.04 = 0.78 in, leaving 0.22 in of slack. The dee as built is about 0.69 in tall, centered, with roughly 0.155 in to each lid; the ion source's ceramic base and the collector on the translator arm share the same interior at the mid-plane. There are no internal liners or shields. Outside, the 1.400 in stack sits in the 1.421 in gap with so little clearance that the lids are in effect pole-face material, which is why ring height and lid thickness were treated as magnet dimensions in the design.

10. The vacuum system

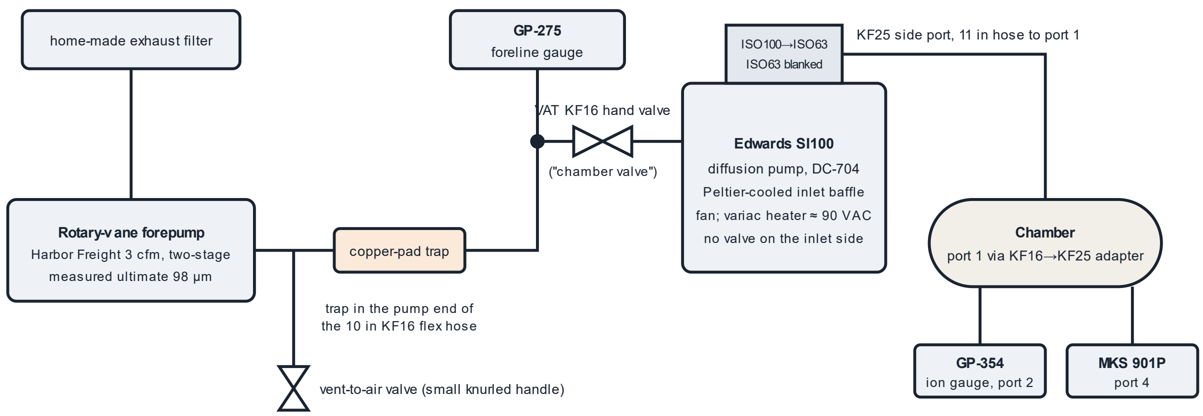

Figure 5. The two-pump system as built. The forepump backs the diffusion pump through a hand valve; the diffusion pump's ISO100 inlet is adapted down to a KF25 side port and an 11 in hose to chamber port 1. There is no valve between the diffusion pump and the chamber.

Component	Make / model	Cost	Notes
Forepump	Harbor Freight "Pittsburgh" 3 cfm two-stage rotary vane	$150	nameplate 22.5 µm; measured 98 µm
Forepump inlet	3/8 in male BSP → KF16 adapter, epoxied (Hysol 1C)	$15–20	replaces the refrigeration-service brass inlet
Foreline	10 in KF16 stainless flex hose, elbow, tee	$60	copper scouring pad in the pump end of the hose as trap; GP-275 on the tee
Valves	VAT series 265 KF16 hand valve ("chamber valve"); KF16 vent valve	$30 + $42	between forepump and diffusion pump; on the roughing side
Diffusion pump	Edwards SI100, s/n P35642, made Sept 1995	$379 (surplus)	60 L/s air; cleaned and rebuilt June 2017
Pump fluid	Dow Corning DC-704 silicone, 20 mL charge	$72	not changed in the last several years
Inlet adapter	ISO100→ISO63 with KF25 side port; ISO63 face blanked	$167	the KF25 side port is the only path to the chamber
Chamber hose	11 in KF25 stainless flex, KF16→KF25 at port 1	—	shortened Dec 2018
Gauges	GP-275 (foreline), MKS 901P (port 4), GP-354 (port 2)	$37, $35, $175	all surplus; §11
Bakeout tape	BriskHeat HSTAT101010, 1 in × 120 in, 720 W	$165	learning-era use only (§13)
BOM subtotal, vacuum system		**$1,024**	

Foreline. The forepump is the ordinary refrigeration-service pump with its brass inlet block removed and a BSP→KF16 adapter screwed and epoxied in its place (Figure 6). Its measured ultimate, 0.87 V on the GP-275, converts to **98 µm** — four times the nameplate but well below the 0.19 torr the SI100's foreline tolerates. A home-made exhaust filter, built to a published design for these pumps, sits on the outlet. The trap is a copper "Chore Boy" scouring pad ($3.55) packed into the pump end of the flex hose; a Leybold RST16KF trap was bought and never installed. The forepump oil level is a startup check and on the operator's watch list.

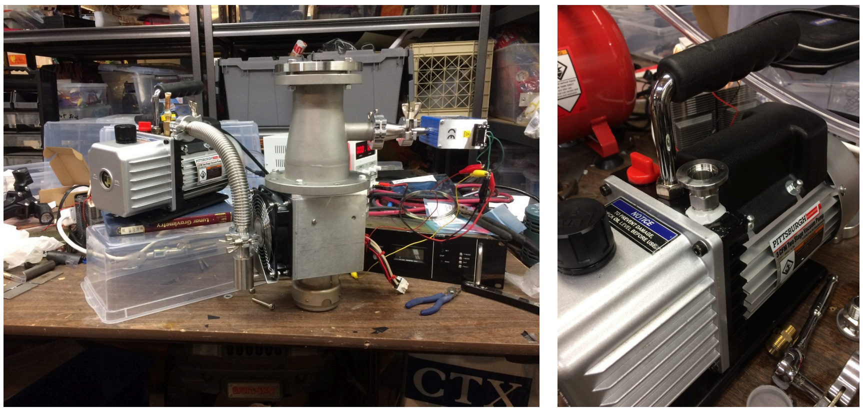

Figure 6. Left, 2017-06-22: system test with both pumps on the bench — forepump at left with its KF16 inlet adapter and flex hose, the SI100 at center with its cooling fan and the ISO100→ISO63 adapter on top, the blue GP-354 module on the KF25 side port through a reducer, and a panel meter reading the gauge. Right, 2017-07-15: the forepump with the epoxied 3/8 in BSP→ KF16 adapter in place of the original brass service inlet; the cured epoxy fillet is visible at the adapter's base. A small air compressor stands behind it; the 2018 procedures used a compressed-air-actuated valve, later replaced by hand valves.

Diffusion pump. The SI100 is a small (4.2 kg) air-cooled silicone-oil pump with a Peltier-cooled inlet baffle. Its nameplate reads: heater 90 V, 250 W; power required 220–240 W; Peltier 5–8 VDC, 8–12 W; fan 115 V, 12 W; fluid charge 20 mL. It runs from a custom supply box — 120 VAC to the fan, DC to the Peltier, a variac to the heater. The builder's normal heater setting is "about 75 %" of the 120 V input, i.e. ≈ **90 VAC, the nameplate heater voltage**. The construction spec gives the Peltier supply as 12 VDC from the rack; whether a regulator brings that down to the nameplate 5–8 V is not recorded. The pump was bought surplus, stripped, cleaned and rebuilt in June 2017 before first use; the oil was last changed at an unrecorded date some years ago.

The workbook's one performance prediction is a compression-ratio estimate: $10^{4.8}$ from a 0.19 torr foreline gives an inlet pressure of **3.0×10^{-6} torr**. The best pressure ever recorded on the complete, clean, empty chamber was **3.4×10^{-6} torr** (§12). The system reached the pump's theoretical floor: when clean it is compression-limited, not leak-limited — the strongest statement the record makes about the tightness of an epoxied, O-ring-sealed chamber with ten ports.

Valves, and what was not built. The high-vacuum path is short: SI100 inlet → ISO100→ISO63 adapter → KF25 side port → 11 in hose → port 1. There is **no gate valve**; an ISO100 gate valve ($240) was bought and never installed, so the chamber is always at the diffusion pump's pressure once the pump is hot. The consequence is procedural: shutdown waits twenty minutes for the heater to cool before the forepump is valved off, and the chamber is never vented warm. On the roughing side are the VAT isolation valve (the procedures' "chamber valve", large black handle) and a vent valve (small knurled handle); the 2018 procedures used a compressed-air-actuated valve here, driven from a small shop compressor. A Pfeiffer TPU-062 turbopump (theoretical 10^{-8} torr) was evaluated and never bought; that figure has no connection to this machine. No conductance calculation was ever done, so the restriction of the KF25 hose and KF16 port between pump and chamber is unquantified — a plausible reason the operating chamber sits an order of magnitude above the pump's floor.

11. Gauges and their calibration

Three gauges, powered from a 24 V/2 A rack supply, drive panel meters that display the gauge output *voltage*. Every procedures checkpoint, every pressure column in the run log and every number in this note passes through the workbook's conversions:

Gauge	Location	Range used	Conversion (V → torr, nitrogen-equivalent)
Granville-Phillips 275 Convectron	foreline tee	0.375–5.66 V	0.375–2.842 V: $P = -0.02585 + 0.03767\,V + 0.04563\,V^2 + 0.1151\,V^3 - 0.04158\,V^4 + 0.008737\,V^5$ · 2.842–4.945 V: $P = (0.1031 - 0.02322\,V + 0.07229\,V^2)/(1 - 0.3986\,V + 0.07438\,V^2 - 0.006866\,V^3)$ · 4.945–5.659 V: $P = (100.624 - 20.5623\,V)/(1 - 0.37679\,V + 0.0348656\,V^2)$
MKS 901P	chamber port 4 ("middle")	1–9 V	P = 10^(V − 6)
Granville-Phillips 354 Micro-Ion	chamber port 2 ("high")	2–8 V	P = 10^(V − 10); **hydrogen correction P_{H_2} = P_indicated / 0.46**; reads 10 V when off or over-range

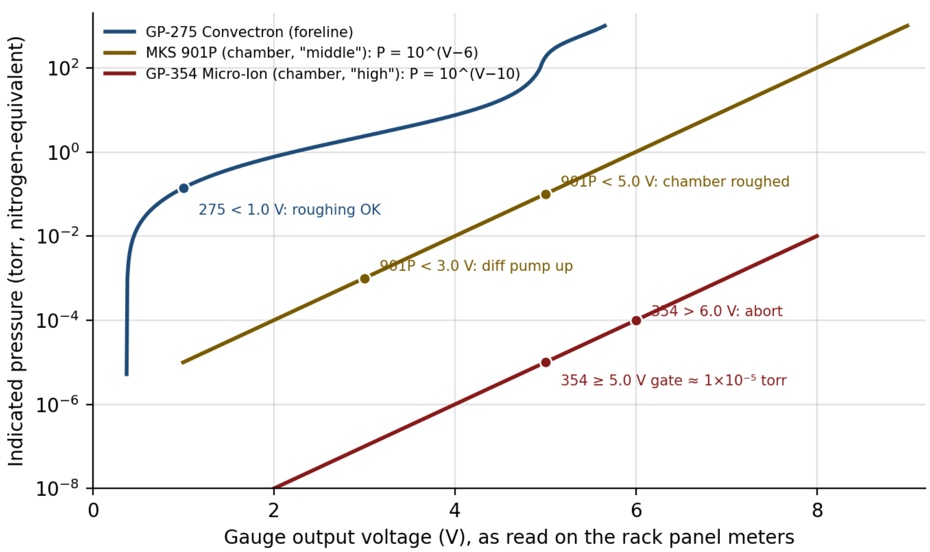

Figure 7. The three gauge conversions, with the operating checkpoints from the procedures marked. The GP-275 curve is the manufacturer's nitrogen fit as coded in the workbook; the 901P and 354 are decade-per-volt logarithmic outputs.

- At atmosphere the meters read about 5.5, 8.2 and 10.6 V (275, 901P, 354-off). The workbook interpolates the local atmosphere at 1,200 ft as 754.6 torr = 5.5298 V on the 275; the fit gives 751 torr there. The 901P's 8.2 V is below the 8.88 V its law predicts for 760 torr — it compresses near full scale; harmless.
- Two build-website captions test the fits: "0.591 V = 32 micron foreline" reproduces as 0.0317 torr; "4.351 V = 2.2×10^{-6} torr chamber" as 2.24×10^{-6}.
- The 0.46 factor is the standard ion-gauge relative sensitivity for H_2. The log's pressure columns are *indicated* values, so with hydrogen flowing the true hydrogen pressure is about 2.2× the logged number.
- The 901P drifted — "probably needs re-zero" (2020-10-25), "probably wrong" (2021-01-10), "out of cal" (2021-11-13) — and was recalibrated on 2021-11-21. It is a process gauge; the GP-354 carried the decisions.

12. Pressure records

Base pressures (2017–2018 learning era). Taken while learning the system, some after bakeouts; the best the vessel has done. Durations are the pump-down times noted with each reading; dates were not recorded.

Configuration (as labeled)	GP-354	torr
Pumps only, no chamber	4.258 V	**1.8×10^{-6}**
Best, complete chamber, empty	**4.533 V**	**3.4×10^{-6}**
With test dee, 1 hour	4.658 V	4.6×10^{-6}
Working chamber, all ports, no dummy dee, 3 hours	4.759 V	5.7×10^{-6}
With filament and collector, 50 min / 1.5 h / 2 h	4.927 / 4.986 / 4.723 V	8.5 / 9.7 / 5.3×10^{-6}
Working chamber after a running session	5.306 V	2.0×10^{-5}
Website: "high vacuum: 3.912 V" (test setup, after bakeout)	3.912 V	8.2×10^{-7}

The construction spec closes with a note dated 2017-12-10, "best vacuum with needle valve: 1.069, 1.754, 5.198, 30 minutes" — foreline ≈ 0.15 torr, middle 5.7×10^{-5}, chamber 1.6×10^{-5} torr with hydrogen admitted: the first operating-condition pressure on record.

Operating checkpoints (procedures, 2021), converted.

Checkpoint	Gauge and voltage	Pressure
Forepump ready; OK to open the chamber valve	275 < 1.0 V	< 0.14 torr
Chamber roughed	901P < 5.0 V	< 0.1 torr
Diffusion pump warmed (10 min after heater on)	901P < 3.0 V	< 10^{-3} torr; if not, "vacuum system is not working — stop"
Ready for filament and RF	**354 at 5.0 V**	**1×10^{-5} torr** (typically 30 min more)

Checkpoint	Gauge and voltage	Pressure
Outgassing after filament + RF on	354 rises toward 5.5 V; abort above 6.0 V	3×10^{-5} typical; > 10^{-4} stop
"Good enough" to run	901P < 2 V and 354 < 5.7 V	< 10^{-4} and < 5×10^{-5} torr; "lower is better"

The written procedure says "at least 5.5 V (1E-5 torr)", which is internally inconsistent (5.5 V is 3.2×10^{-5} torr). The builder confirmed in 2026 that the gate he actually looks for is **5.0 V**: the pressure in parentheses was right and the voltage was stale. A future revision should change the voltage, not the pressure.

Pressures during logged runs, 2018–2025.

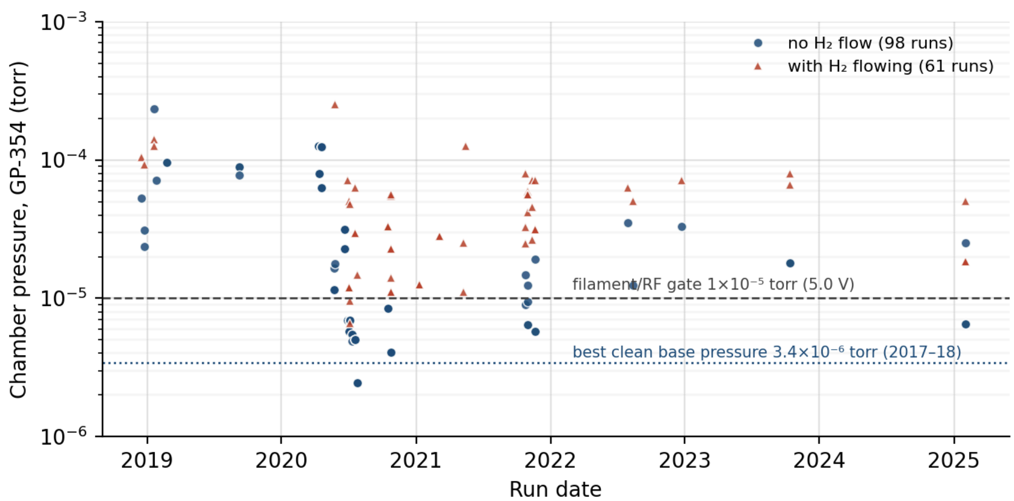

Figure 8. Chamber pressure (GP-354, converted) for every logged run that recorded it: 98 readings without hydrogen and 61 with hydrogen flowing. One off-scale reading from 2018-12-24 lies above the plot. Values are nitrogen-equivalent; divide by 0.46 for true hydrogen pressure when gas is flowing.

Year	Runs, no H_2	Median, no H_2 (torr)	Runs, with H_2	Median, with H_2 (torr)
2018 (Dec)	3	3.1×10^{-5}	3	1.0×10^{-4}
2019	7	8.9×10^{-5}	2	1.3×10^{-4}
2020	71	7.0×10^{-6}	28	1.9×10^{-5}
2021	9	9.0×10^{-6}	20	3.2×10^{-5}
2022–2023	5	$1.8–3.3\times10^{-5}$	5	$6.3–7.3\times10^{-5}$
2025 (Feb)	3	6.6×10^{-6}	3	1.8×10^{-5}
All runs	**98**	**1.0×10^{-5}**	**61**	**3.3×10^{-5}**

In the systematic 2020 campaign, when the machine ran most weekends and stayed pumped, the chamber sat below 10^{-5} torr before gas was admitted; in the occasional-use years it started sessions in the low 10^{-5} range after long idle periods; and after the 2024 months open to air it needed "hours of vacuum pumping" (log, 2025-02-02) to get from 2.5×10^{-5} back to 6.6×10^{-6}. With hydrogen flowing at beam-producing settings the indicated pressure was $2–8\times10^{-5}$ torr ($4–17\times10^{-5}$ torr of actual hydrogen). The best beam on record (2023-10-14) was taken at 1.8×10^{-5} torr no-H_2 and $6.6–7.9\times10^{-5}$ torr with hydrogen.

When the machine is powered down the chamber is left under vacuum with the valve closed. Its pressure then creeps back toward atmospheric over two to three weeks; this leak-up has not been formally characterized. In practice, with weekend-only operation and the pumps off during the week, the chamber is still well below atmosphere at the next start and recovery to the operating gate is quick.

13. Bakeout and contamination hygiene

Bakeout belongs to the learning era only. In 2017 the test assembly was wrapped in the 1 in BriskHeat tape and taken above 100 °C to find the system's floor (the 8.2×10^{-7} torr website figure and the base-pressure table came out of that work). Once the chamber went into the magnet, baking stopped, for a structural reason: **the chamber cannot be baked in place** — there is no way to heat it between the poles without cooking the coils, and taking it out means venting it. The tape has not been used in years. The 2025-02-01 log line "chamber not fully baked" refers to outgassing time under vacuum after the long air exposure, not to the heat tape.

Two hygiene practices are on record. A small contamination experiment in the workbook: after 25 minutes of pumping, a "sticky bolt" left in the chamber held it at $1.4–2.4\times10^{-5}$ torr against $1.8–1.9\times10^{-5}$ torr with a clean bolt or an empty chamber — early, measured evidence for the cleanliness discipline in the procedures. And the hydrogen lines are flushed with hydrogen whenever they have been opened to air or idle for more than a week; the procedures refer to "a separate hydrogen flushing procedure" that was never written down.

14. Leaks, failures and vacuum-related maintenance, 2017–2025

Date	Event	Vacuum consequence
2017-06 / 07	SI100 rebuilt; forepump inlet converted to KF16	measured forepump ultimate 98 µm
2018-04	Lid deflection measured (33 mil)	no leak; edge gap 15 → 16 mil
2018-12-24	Shorter KF25 tube between chamber and diffusion pump	—
2020-07-25	After running the MFC high, "took a while for low vac to return"	hydrogen loading of the walls
2020-10 → 2021-11	MKS 901P read wrong; recalibrated 2021-11-21	gauge, not vacuum
2021-10-24	"Bad vacuum due to long chamber downtime and filament change"	1.5×10^{-5} no-H_2, 7.9×10^{-5} with H_2 at session start
2021-10-30	Chamber opened to clear a filament-to-floor short	the loose ion source, not the vacuum

Date	Event	Vacuum consequence
2023–2024	Chamber open to air for months during the magnet loan (magnet stayed in place)	—
2025-02-01/02	Reassembled "after months open to air"; "after hours of vacuum pumping"	$2.5\times10^{-5} \rightarrow 6.6\times10^{-6}$ torr; beam recovered on day two
2017–2025	Epoxied flanges, O-ring seals	**no leak, no failure, no seal replacement on record**

There is no leak-hunting episode anywhere in the log. Every "bad vacuum" entry traces to time open to air or filament outgassing, and cleared with pumping time.

15. Sources and their disagreements

Item	Construction spec / website	Workbook and as-built	Resolution
Ring inside diameter	"10.25 in"	OD 10.75 − 2 × 0.468 = 9.75 in; 10.25 in is labeled "center D" (mid-wall)	bore ≈ 9.75 in
Gland dimensions	"depth 0.140, width 0.080" (spec); reversed on the site	width 0.140 × depth 0.080; the 42 % squeeze and the fab drawing agree	width 0.140 in, depth 0.080 in
Lid thickness	BOM "3/16 in"	stack-up 0.200 in, margin −0.011 in vs 1.421 in gap	0.200 in
"Total chamber height 1.42 in"	spec	assembled stack 1.400 in; 1.421 in is the pole gap	1.400 in; ring height not re-measured
O-ring	BOM lists a −377	final BOM: two −273	−273 as built
Port 9	4-pin feedthrough to triax	KF16 BNC feedthrough	BNC (spec superseded)
Filament/RF gate	procedures "5.5 V (1E-5 torr)"	5.5 V = 3.2×10^{-5} torr; 1×10^{-5} = 5.0 V	5.0 V in practice
Gate valve, Leybold trap	in the purchase list	not in the plumbing walk	never installed
Peltier supply	spec: 12 VDC	nameplate: 5–8 VDC	unresolved
Mean free path at 10^{-5} torr	workbook 135 m	standard kinetic diameter gives ~5 m	design conclusion unaffected (§2)

16. Open items

- **Ring height** — measure at the next chamber opening; 1.000 in is the drawing value.

- **Pump-down curve** — no dated pressure-versus-time record exists for the operating configuration; one clean curve from atmosphere to the 5.0 V gate would fix the configuration record for future beam-evidence work.
- **Hydrogen flush procedure** — write it down.
- **Conductance** — estimate or measure the KF25/KF16 restriction between the SI100 and the chamber, the likely reason the operating chamber sits an order of magnitude above the pump's floor.
- **Proton-loss path length** — estimate charge-exchange and scattering loss over the ~40 m orbit path at operating hydrogen pressures: the missing link between the pressure record and the nanoampere currents.
- **Peltier supply voltage; port 5** — confirm what the baffle cooler receives and that port 5 is still blank (believed so; not verified against the machine since the 2021 photographs).
- **Leak-up rate** — the 2–3 week creep to atmosphere with the valve closed has never been measured; one logged curve would characterize the seals.

Sources

- Construction specification (`Cyclotron_construction.docx`, December 2017); operating procedures (`Cyclotron_procedures2.docx`, October 2021).
- Design workbook `cyclotron9.xlsx`: sheets `chamber`, `chamber2`, `gland`, `deflection`, `vacuum`, `vacuum gauge`, `conductance`, `baking tape`, `Specs`, `BOM`, `purchases`.
- Run log `cyclotron_log.xlsx`, sheet `log`: gauge columns and notes, 176 runs, 2018-12-16 to 2025-02-02.
- Build website (mullinscyclotron.weebly.com), Chamber and Vacuum System pages; SolidWorks chamber and lid drawings (December 2017); deflection-study photographs (April 2018).
- Manuals in the archive: Edwards SI100; Granville-Phillips 275 and 354; MKS 901P; Harbor Freight pump; Loctite Hysol 1C; VAT valve. O-ring references: Parker O-Ring Handbook (face-seal section, design chart 4-3), semiconductor gland handbook, vacuum-sealing application note.
- Builder's review, August 2026: bore, lid thickness, epoxy-flange history, valve set, trap, variac setting, oil, bakeout practice, the 5.0 V gate, port 9.
- Photographs from the builder's camera-roll archive, dated by EXIF: IMG_6749, IMG_6916, IMG_3270, IMG_8435, and the deflection-study frame `lid_gap.jpg`. The SI100 nameplate data are read from IMG_6691.