Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Pumping Speed Measurements for Non-Evaporable Getter Activation and Saturation Monitoring

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Outline

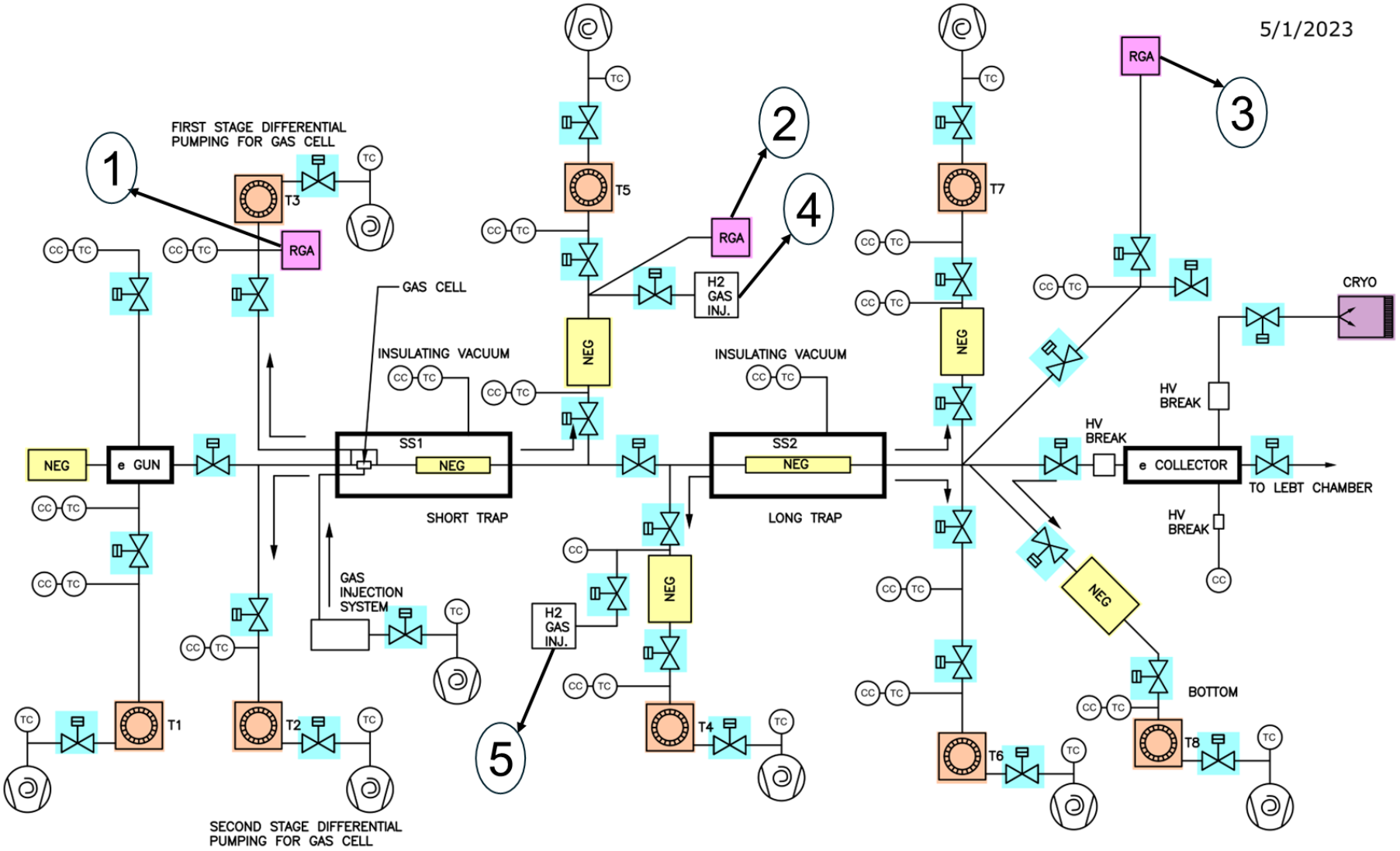
- Extended EBIS vacuum system
- Main features of ZAO non-evaporable getter (NEG)
- Developed method of effective pumping speed measurements
- Application of developed method of effective pumping speed measurements for non-evaporable getter activation and saturation monitoring
- Summary

What is Extended EBIS?

- Extended EBIS (EEBIS) is upgrade for RHIC EBIS to enhance intensity of Au^{32+} ions by 40-50% and to improve capability to generate intense beams of light ions, such as $^{4}He^{2+}$, $^{3}He^{2+}$ and protons
- With a further upgrade, the Extended EBIS will also produce polarized $^{3}He^{2+}$ ions for the future Electron-Ion Collider (EIC).
- Extended EBIS was commissioned and has replaced RHIC EBIS as a main ion injector for both RHIC and National Aeronautics and Space Administration (NASA) Space Radiation Laboratory in the spring of 2023

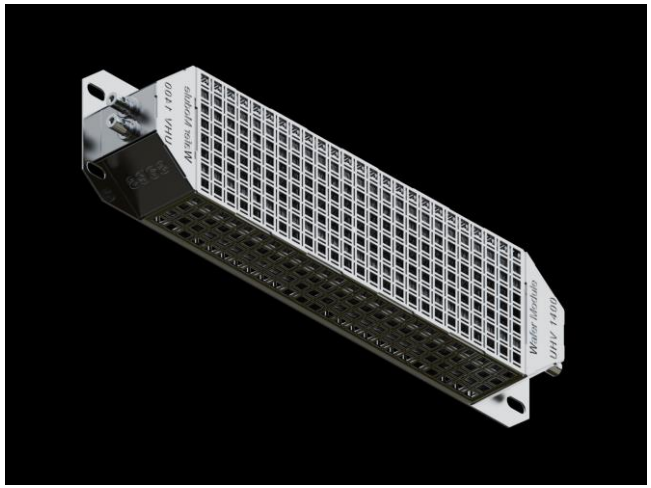
EEBIS During Operation

Extended EBIS Vacuum System

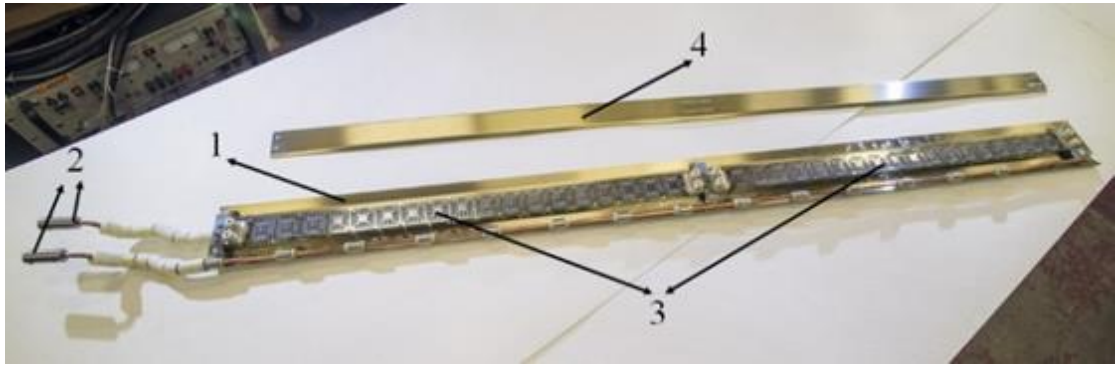


Main Features of EEBIS Vacuum System

- Cryopumps use is avoided in the ionization regions of the EEBIS vacuum system because of their required frequent maintenance and limited capabilities concerning helium pumping
- Two custom linear ZAO NEG units with 1000 l/s and 1500 l/s pumping speed for hydrogen which are placed inside the short and long ion trap vacuum chambers
- Four standard SAES Getter UHV 1400 wafer ZAO NEG modules with 1360 l/s (!) pumping speed for hydrogen are placed within the vacuum chamber connecting arms
- Implementation of *in situ* effective pumping speed measurements to monitor NEG activation and saturation time evolution



UHV 1400 wafer ZAO NEG module



1000 l/s ZAO NEG custom linear unit: 1—mounting cradle, 2—electrical leads to provide heating current, 3—ZAO NEG linear modules, 4—heat shielding top plate.

New ZAO Getter Alloy

- ZAO (Zr-V-Ti-Al) getter became commercially available from SAES Getters in the form of sintered discs about 8 years ago
- According to SAES Getters (Enrico Maccallini's presentation, June 2017, BNL) ZAO demonstrated:

➢Larger sorption capacity for all active gases

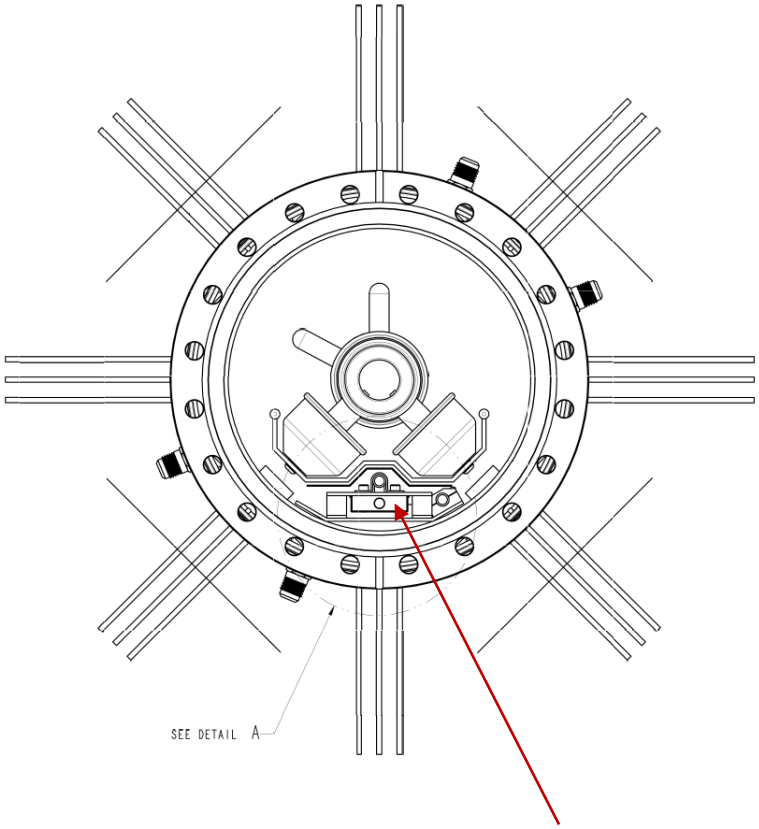
➢Higher pumping speed

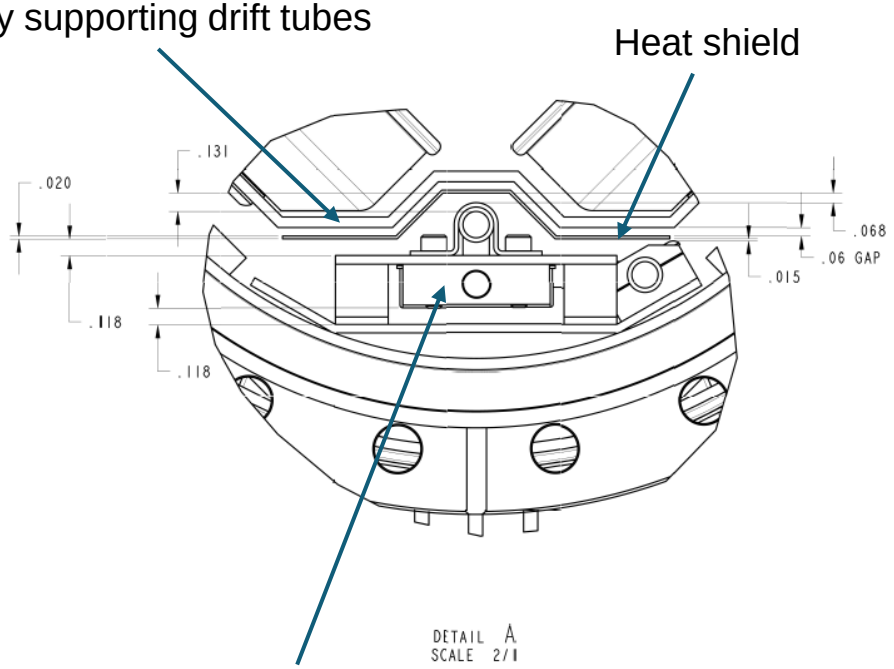
➢Ability to withstand more reactivation cycles

➢Discs are more robust (higher embrittlement limit)

➢Generate much less micro particles

ZAO Linear Module Placement

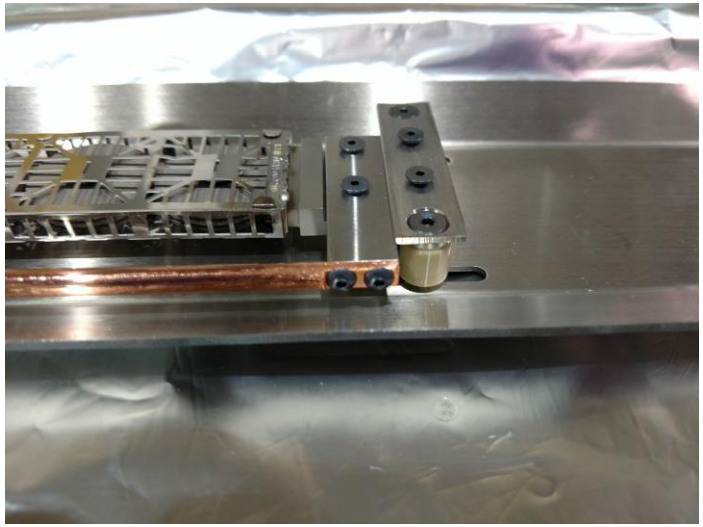


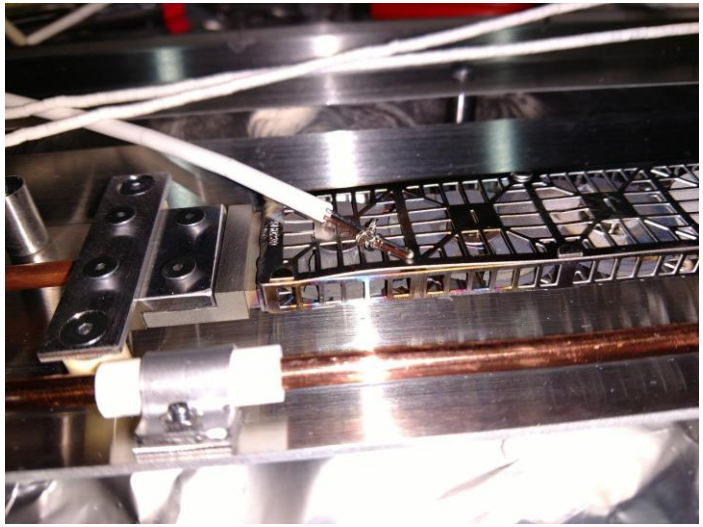


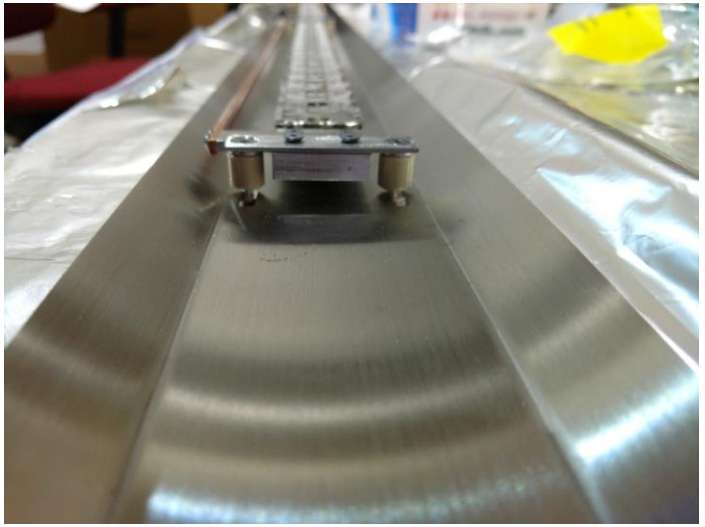
ZAO NEG linear pumping system

ZAO NEG linear pumping system will be placed under tray supporting drift tubes for both “short” and “long” traps.

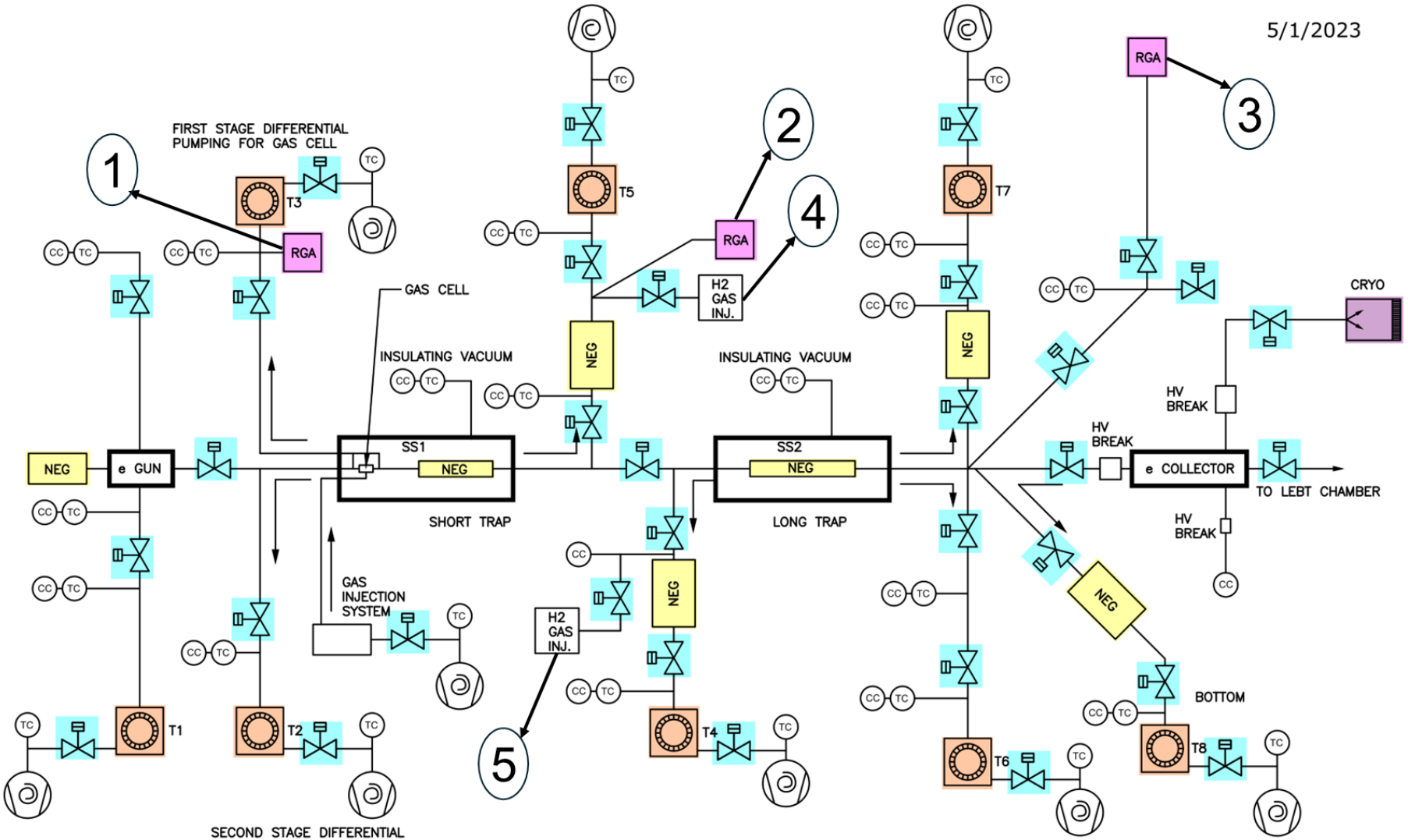
ZAO Linear Module Assembly



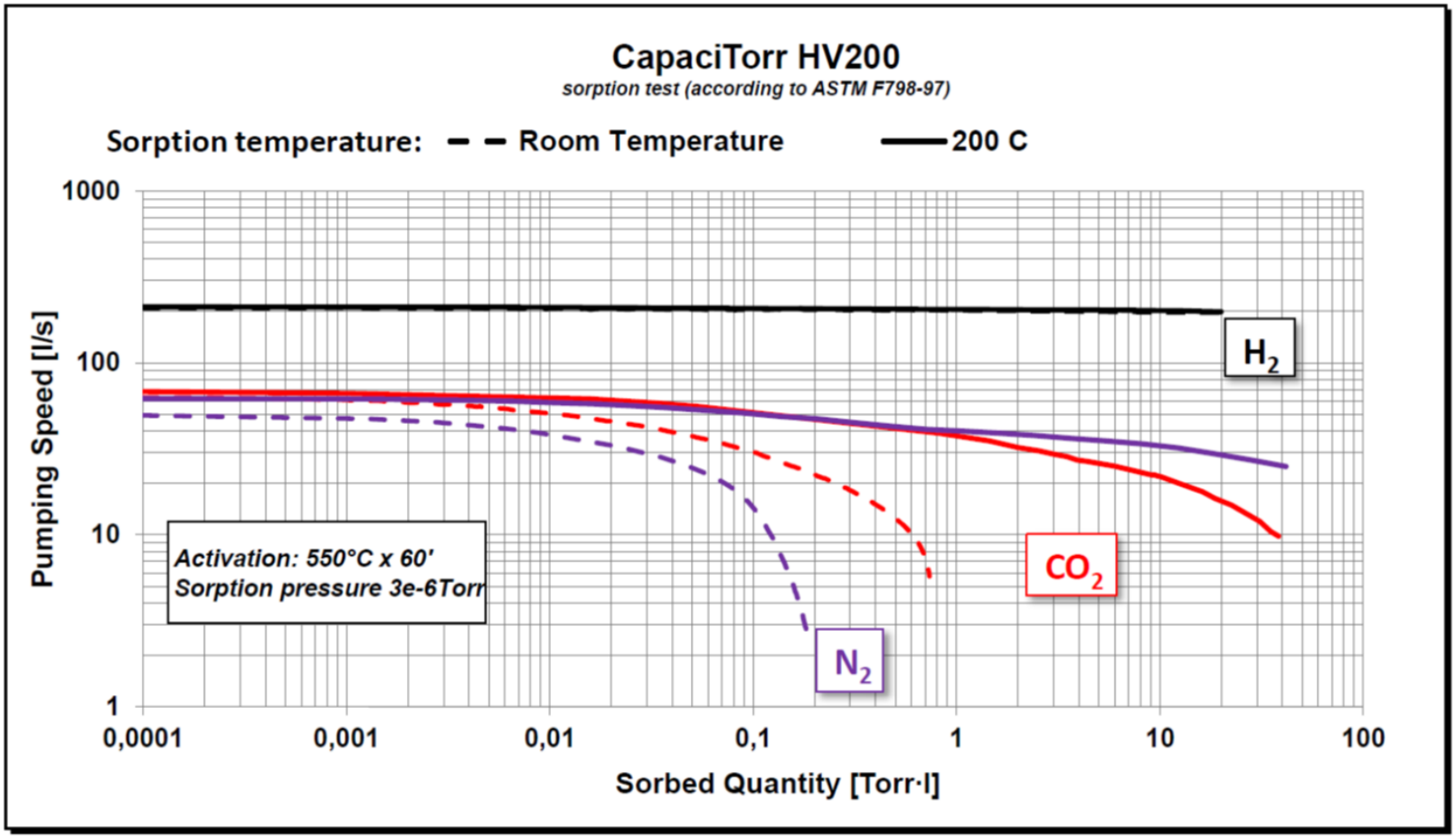




Pulsing Hydrogen into Vacuum Chambers for Pumping Speed Measurements



Why Pulsing Hydrogen and Not Other Specie?



Although using hydrogen raise safety concerns and require administrative approvals, this is the best choice.

How One Can Measure (Effective) Pumping Speed?

If some small amount of gas is injected into vacuum chamber, the pressure inside the chamber will raise and then after the end of injection pulse will decay exponentially in the certain pressure range according to following equation:

$$P(t) = P(t = 0) \cdot e^{-\frac{S}{V} \cdot t} \qquad (1)$$

where *P(t)* is pressure at the detector location (RGA in our case) at the time *t*,

t = 0 is the time after the end of gas injection pulse when pressure reach maximum value at RGA location,

S is pumping speed at the detector location,

V is effective volume of vacuum chamber.

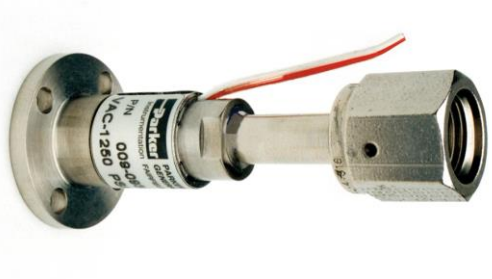
The pressure range where equation (1) is valid is the range from the value of one order of magnitude higher than equilibrium pressure to avoid the influence of outgassing from the walls of vacuum chamber, and up to pressure limit of molecular flow.

In our case that range is from about 10^{-7} Torr up to about 10^{-5} Torr when injecting hydrogen.

Equipment Used for Pumping Speed Measurements

- Both RGAs are Stanford Research Systems (SRS) RGA200 units

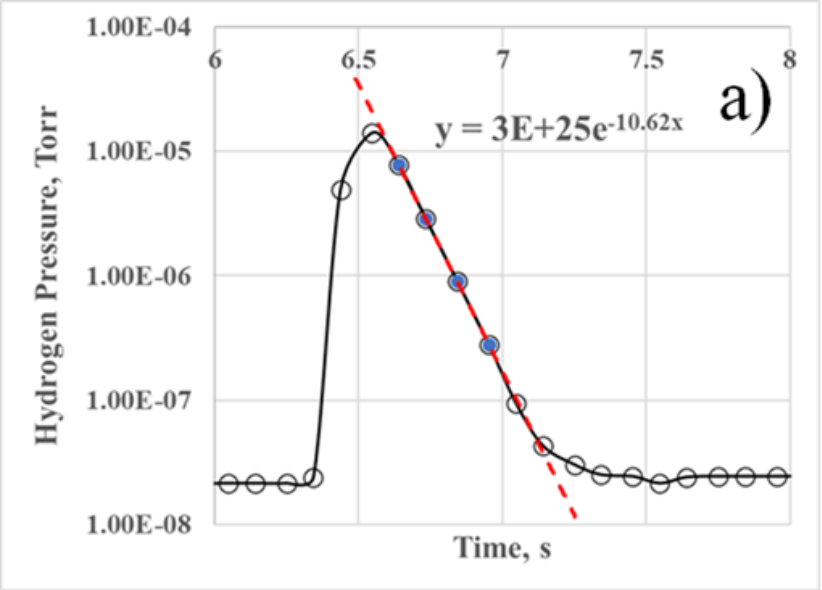
- Both valves are solenoid actuated miniature high speed high vacuum Parker Hannifin (part #:009-1670-900) valves. Their mounting o-ring flanges were modified to mini-conflate flanges to be compatible with EEBIS ultra-high vacuum level and to keep EEBIS equilibrium pressure as low as possible during pumping speed measurements.

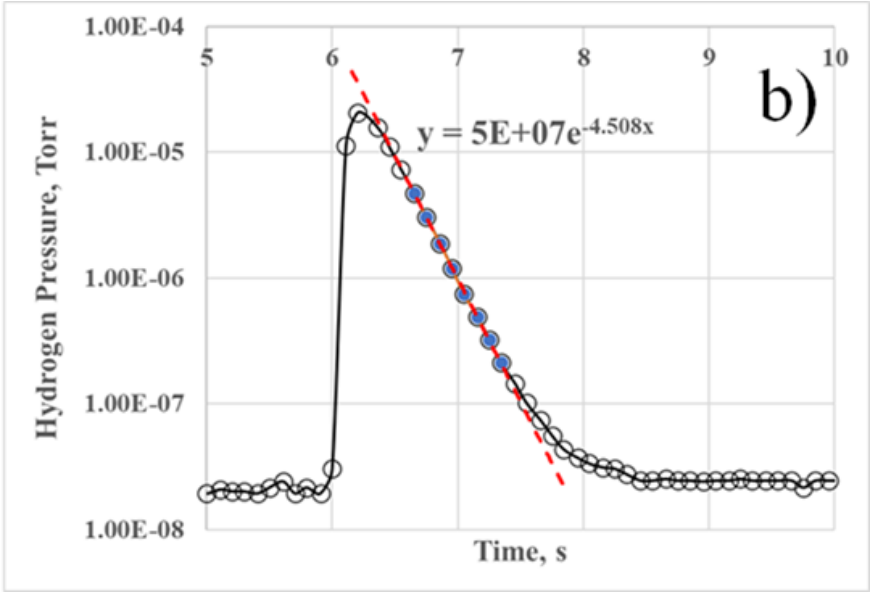


Parameters of Hydrogen Pulsing

- Typical amount of injected gas per single pulse is about 10^{15} atoms
- Typical amplitude of pressure burst is slightly above 10^{-5} Torr, so the whole range of exponential pressure decay can be covered
- Highest RGA recording rate is 8 points per second for RGA model used
- Duration of induced pressure burst is in the range of 0.5 – 1.5 s, so from 4 to 8 points were typically recorded within the right pressure range corresponding to exponential decay
- Estimations show that ZAO NEG pumping speed will not be affected by injection of such small amount of hydrogen atoms up to about 10000 injection cycles
- Typical amount of injection pulses required to complete whole set of pumping speed measurements was about 50 pulses

Pressure Burst Time Dynamics





Time dynamics of hydrogen pressure burst measured by RGA2: a – gate valves 6 and 16 are closed, b – gate valves 6, 8, 9, 10, 11, 12, 15 and 16 are closed: hollow black circles – points recorded by RGA, solid blue circles – selected points which are within pressure exponential decay range, red dash line – exponential fit line for selected points, equations of exponential fit functions are shown as well, effective pumping speeds (*S/V* values (see equation (1)) are 10.62 s^{-1} (a) and 4.508 s^{-1} (b).

How Reproducible Measurements Are?

Table I. Results of effective pumping speed measurements with hydrogen for long trap (LT) with different gate valves open/close configurations: 5 individual measurements for each configuration and average values (all in s^{-1}), all values without brackets were measured right after EEBIS bakeout and consequent activation of all ZAO NEGs, all values within brackets were measured about one month after all ZAO NEGs were activated and exposed to vacuum leak which was later eliminated prior to EEBIS bakeout.

Gate valves (GV) config	1 and 16 GV closed	6 and 16 GV closed	6, 8 and 16 GV closed	6, 8, 12 and 16 GV closed	6, 8, 10, 12 and 16 GV closed	6, 8, 10, 11, 12 and 16 GV closed	6, 8, 9, 10, 11, 12 and 16 GV closed	6, 8, 9, 10, 11, 12, 15 and 16 closed
Measur. 1	11.7	11.2 (4.31)	11.2	11.2 (2.29)	11.0 (1.67)	9.4	4.5	4.5 (1.17)
Measur. 2	11.5	11.5 (4.28)	11.1	11.1 (2.29)	10.5 (1.68)	9.7	4.5	4.5 (1.16)
Measur. 3	11.5	11.0 (4.26)	11.1	11.0 (2.22)	10.5 (1.7)	9.3	4.5	4.5 (1.16)
Measur. 4	11.4	11.0 (4.36)	11.0	11.1 (2.32)	10.8 (1.67)	9.5	4.5	4.5 (1.16)
Measur. 5	11.7	10.9 (4.38)	11.0	11.0 (2.3)	10.9 (1.68)	9.5	4.5	4.5 (1.17)
Average	11.6	11.1 (4.32)	11.1	11.1 (2.28)	10.7 (1.68)	9.5	4.5	4.5 (1.16)

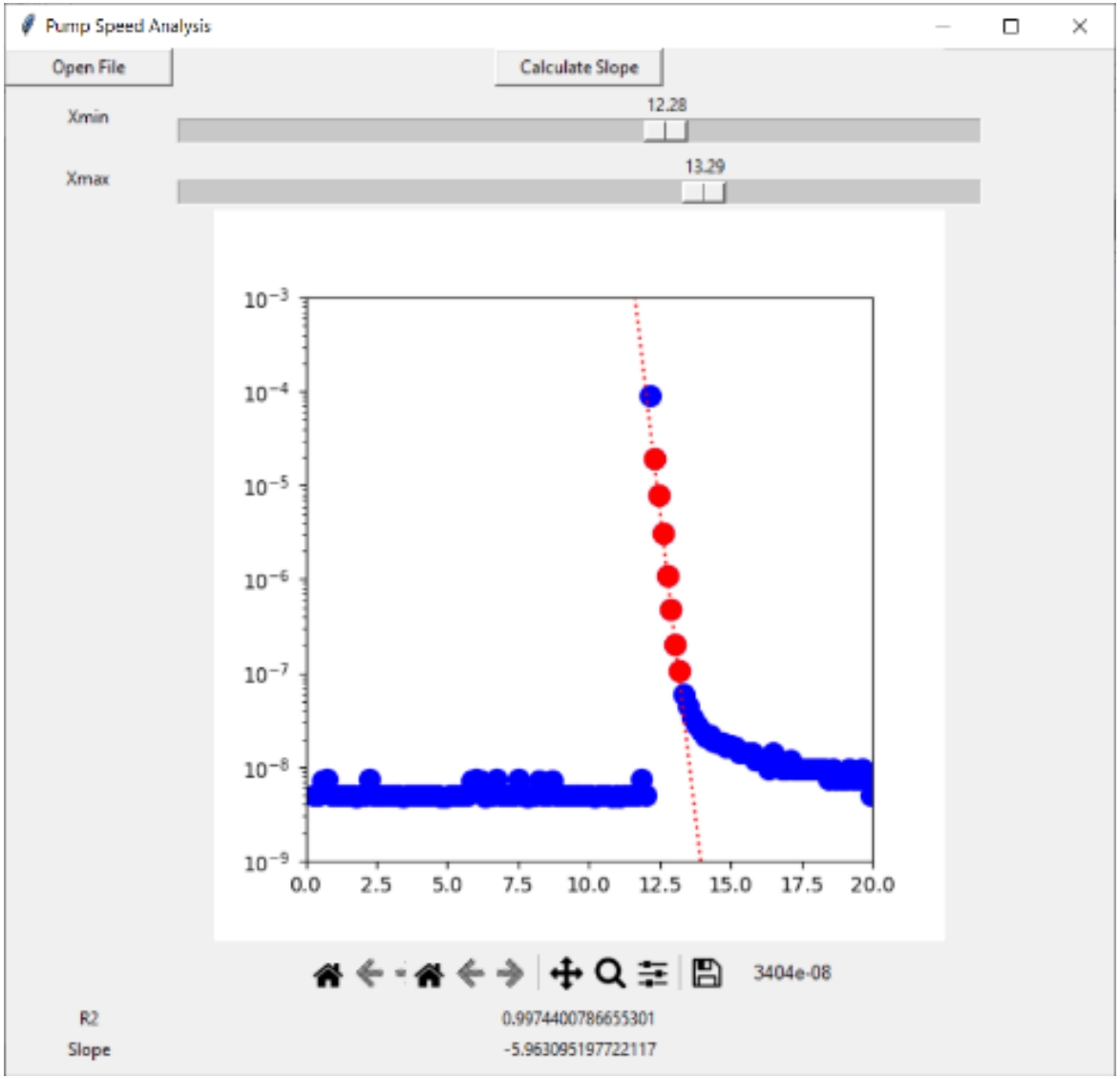
Answer – quite reproducible (within +/- 2%).

Code for On-line Effective Pumping Speed Calculations

A code was created to allow fast on-line calculations of effective pumping speed:

- Written in python utilizing NumPy and Matplotlib.
- Download and plot pressure data files as saved from the SRS RGA App.
- Pressure burst decay in the defined by user pressure range is approximated by exponential function and the linear slope of this line determines effective pumping speed.
- User can select the range of x values (times) to be included in the slope calculation and visually confirm that the correct time region is processed.
- Software calculates the slope and associated coefficient of determination R^2 of the line to be used to calculate effective pumping speed.
- The closer R^2 to 1 is, the better experimental points are approximated by exponential function.
- Effective pumping speed is extracted from saved pressure data file within 1 minute by using this code.

Code Visual Interface



NEG Status Monitoring by Effective Pumping Speed Measurements

- Vacuum conductance between “short” trap (ST) and “long” trap (LT) is limited, so pumping speed is measured separately for ST and LT
- Partial bake out and first activation of all EEBIS NEGs at source operational location was done on April 2, 2023
- Being under time pressure to provide first set of beams for NASA Space Radiation Laboratory, we didn’t measure initial pumping speeds right after NEGs activation
- First effective pumping speed measurements were done on May 18, 2023, and 3 times after that (June 13, December 11, December 21, 2023)

“Long” Trap Results

Gate valves (GV) configuration	1 and 16 GV are closed	6 and 16 GV are closed	6, 8 and 16 GV are closed	6, 8, 12 and 16 GV are closed	6, 8, 10, 12 and 16 GV are closed	6, 8, 10, 11, 12 and 16 GV are closed	6, 8, 9, 10, 11, 12 and 16 GV are closed	6, 8, 9, 10, 11, 12, 15 and 16 GV are closed
Measurement 1	11.7/11.0	11.2/11.0/4.31	11.2/9.4	11.2/9.6/2.29	11.0/9.2/1.67	9.4/7.7	4.5/3.2	4.5/3.1/1.17
Measurement 2	11.5/10.9	11.5/10.8/4.28	11.1/9.7	11.1/9.4/2.29	10.5/9.5/1.68	9.7/7.8	4.5/3.1	4.5/3.1/1.16
Measurement 3	11.5/10.4	11.0/10.9/4.26	11.1/9.9	11.0/9.7/2.22	10.5/9.5/1.7	9.3/7.7	4.5/3.1	4.5/3.1/1.16
Measurement 4	11.4/10.5	11.0/10.8/4.36	11.0/9.9	11.1/9.6/2.32	10.8/9.5/1.67	9.5/7.5	4.5/3.1	4.5/3.0/1.16
Measurement 5	11.7/11.0	10.9/11.2/4.38	11.0/9.5	11.0/9.7/2.3	10.9/9.5/1.68	9.5/7.6	4.5/3.1	4.5/3.0/1.17
Average	**11.6/10.8**	**11.1/10.9/4.32**	**11.1/9.7**	**11.1/9.6/2.28**	**10.7/9.4/1.68**	**9.5/7.7**	**4.5/3.1**	**4.5/3.1/1.16**

Black font – June 13, 2023, **right after all NEGs activation**

Red font – December 11, 2023, **after 6 months of Extended EBIS operation**

Blue font – May 18, 2023, **no full baking of EEBIS, NEGs were severely affected by vacuum leak** (NEGs activation was done on April 2, 2023).

“Short” Trap Results

Gate valves (GV) configuration	1 and 16 GV are closed	1 and 6 GV are closed	1, 2 and 6 GV are closed	1, 2, 3 and 6 GV are closed	1, 2, 3, 4 and 6 GV are closed	1, 2, 3, 4, 5 and 6 GV are closed
Measurement 1	22.9/9.0	22.7/8.8	21.6/8.8	21.6/8.8	44.5/35.9	43.1/35.3
Measurement 2	24.1/9.0	20.7/8.9	21.8/8.8	20.3/8.8	42.8/36.1	41.3/35.5
Measurement 3	26.3/9.0	23.4/8.4	21.3/8.8	21.0/8.8	44.5/35.7	40.0/35.6
Measurement 4	22.5/9.0	24.0/9.0	23.3/8.8	22.8/8.8	44.5/36.0	43.7/35.7
Measurement 5	24.1/9.0	23.6/8.9	21.2/8.8	21.0/8.8	44.2/35.5	44.1/35.7
Average	**24.0/9.0**	**22.9/8.8**	**21.8/8.8**	**21.3/8.8**	**44.1/35.8**	**42.4/35.6**

Black font – June 13, 2023, **right after all NEGs activation**

Red font – December 11, 2023, **after 6 months of Extended EBIS operation**

Checking Effect of Leaking E-gun Chamber Gate Valve

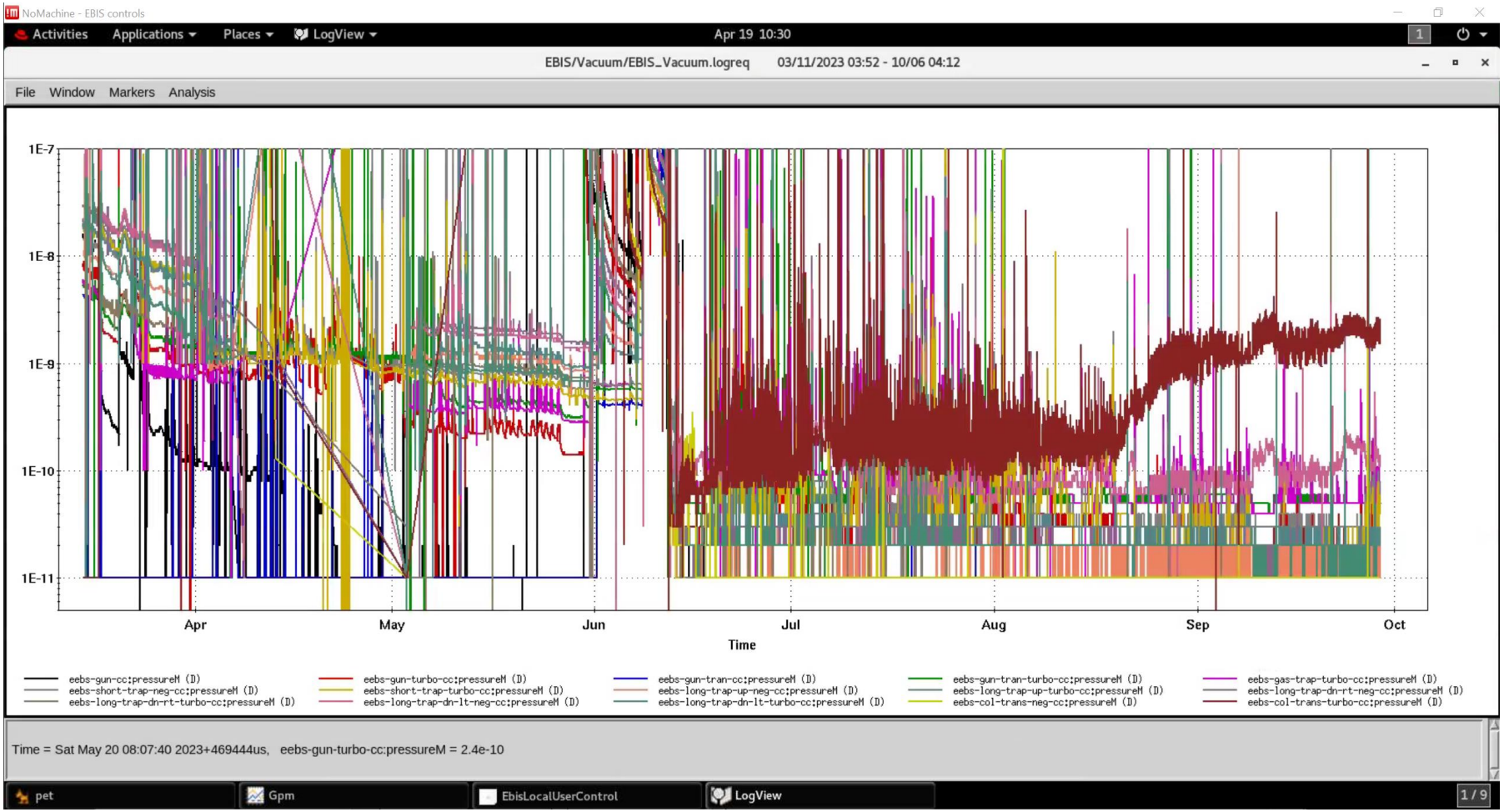
Gate valves (GV) configuration	1 and 16 GV are closed	1 and 6 GV are closed	1, 2 and 6 GV are closed	1, 2, 3 and 6 GV are closed	1, 2, 3, 4 and 6 GV are closed	1, 2, 3, 4, 5 and 6 GV are closed
Measurement 1	9.2/9.0	9.0/8.8	8.9/8.8	8.7/8.8	36.5/35.9	37.5/35.3
Measurement 2	9.1/9.0	9.0/8.9	8.8/8.8	9.0/8.8	36.5/36.1	37.5/35.5
Measurement 3	9.0/9.0	9.0/8.4	8.9/8.8	8.9/8.8	37.2/35.7	36.3/35.6
Measurement 4	9.1/9.0	8.8/9.0	9.0/8.8	8.9/8.8	37.3/36.0	36.8/35.7
Measurement 5	9.1/9.0	8.8/8.9	8.9/8.8	8.6/8.8	37.8/35.5	37.4/35.7
Average	**9.1/9.0**	**8.9/8.8**	**8.9/8.8**	**8.8/8.8**	**37.1/35.8**	**37.1/35.6**

Black font – ST pumping speed measurements on **December 21, 2023 (after e-gun cathode replacement)**

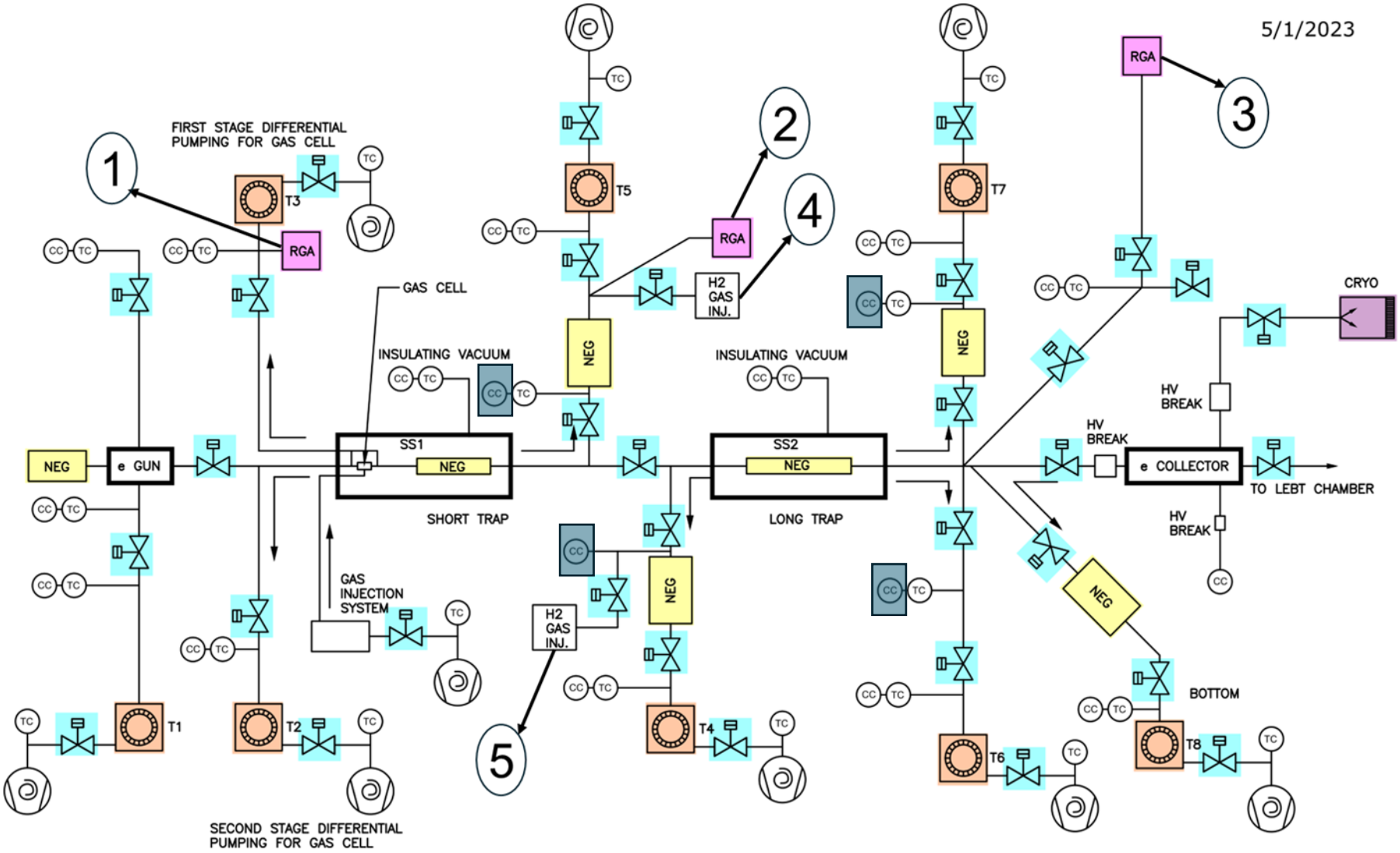
Red font – ST pumping speed measurements on **December 11, 2023 (before e-gun cathode replacement)**

It was confirmed that leaking valve didn't affect pumping status of all NEGs.

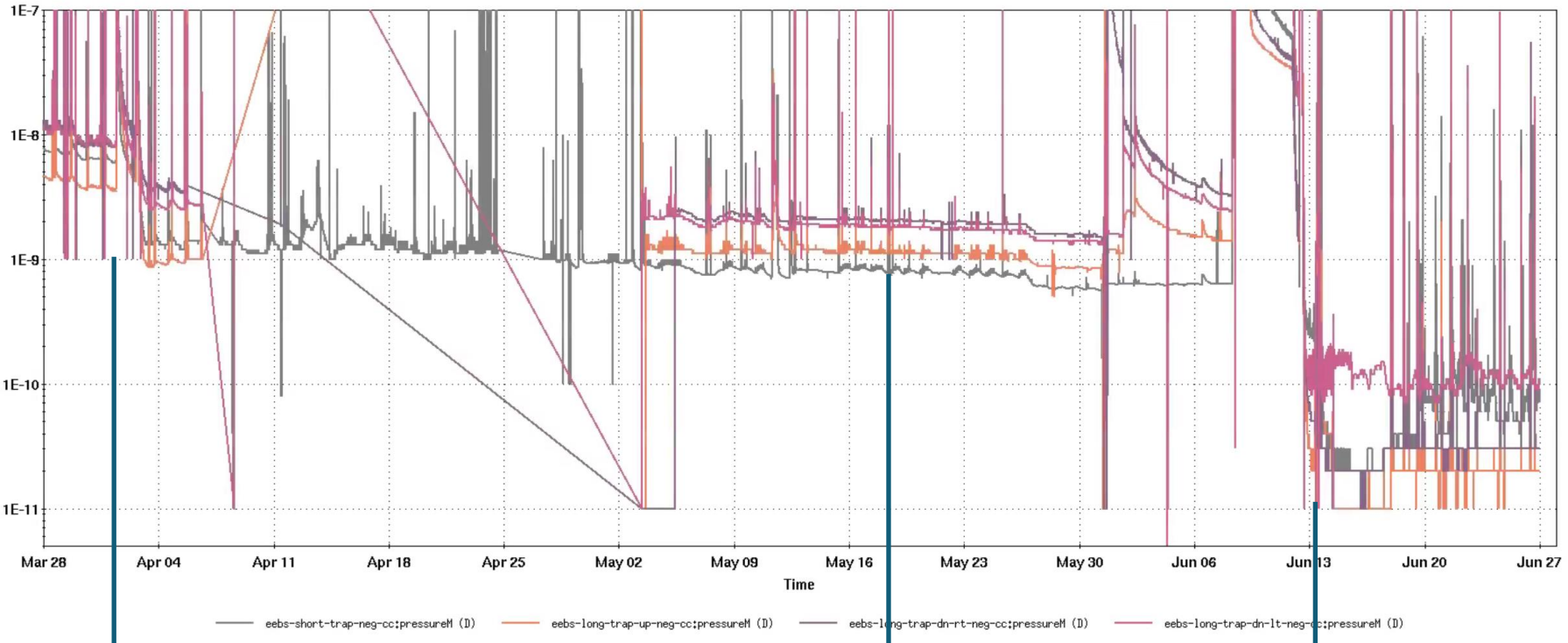
Can One Monitor NEG Status by Readings of Vacuum Gauges?



Choice of Gauges to Look at



Gauge Pressure Readings and Events (March-June, 2023)



May 18 – 1-st pumping speed measurements,
NEGs were found saturated

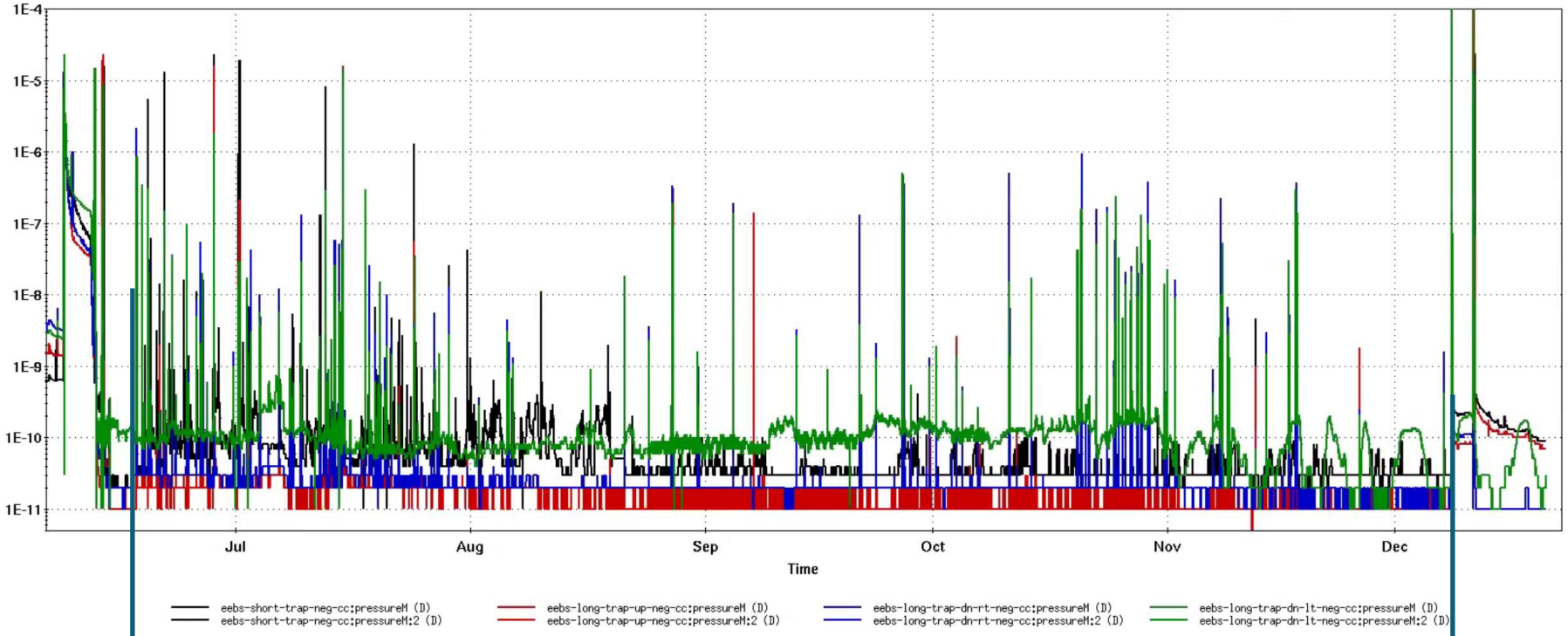
June 13 – 2-md pumping speed measurements,
right after full bake-out, all NEGs activated

Apr 2 – partial bake-out, all NEGs activated

Q: Can we see from gauge readings that NEGs were severe saturated between Apr 2 and May 18?

A: No, gauge pressure readings were not raising, but steadily improving.

Gauge Pressure Readings and Events (June-Dec, 2023)



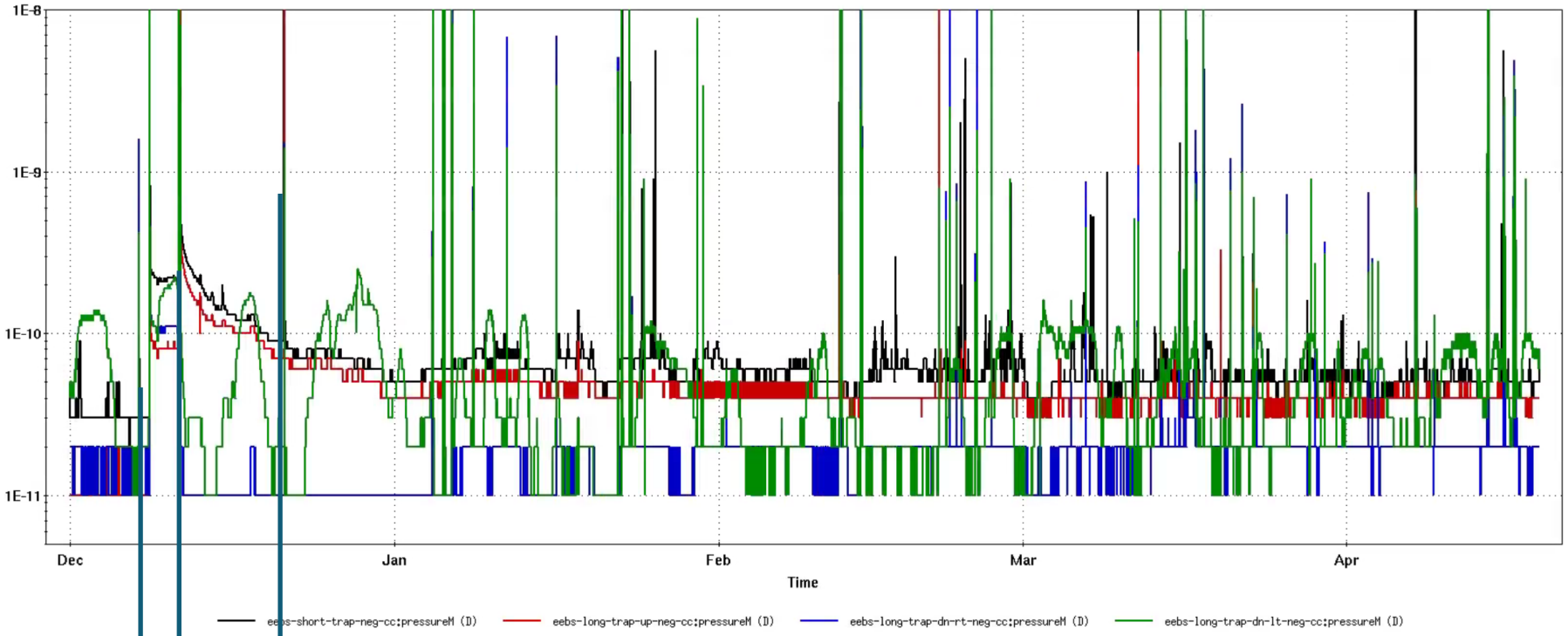
Dec 11 – 3-rd pumping speed measurements, after 6 months of EEBIS operation (NEGs partially saturated)

June 13 – 2-nd pumping speed measurements, right after full bake-out, all NEGs activated

Q: Can we see from gauge readings that NEGs were severe saturated between Apr 2 and May 18?

A: No, gauge pressure readings were not raising.

Gauge Pressure Readings and Events (Dec 2023-Apr 2024)

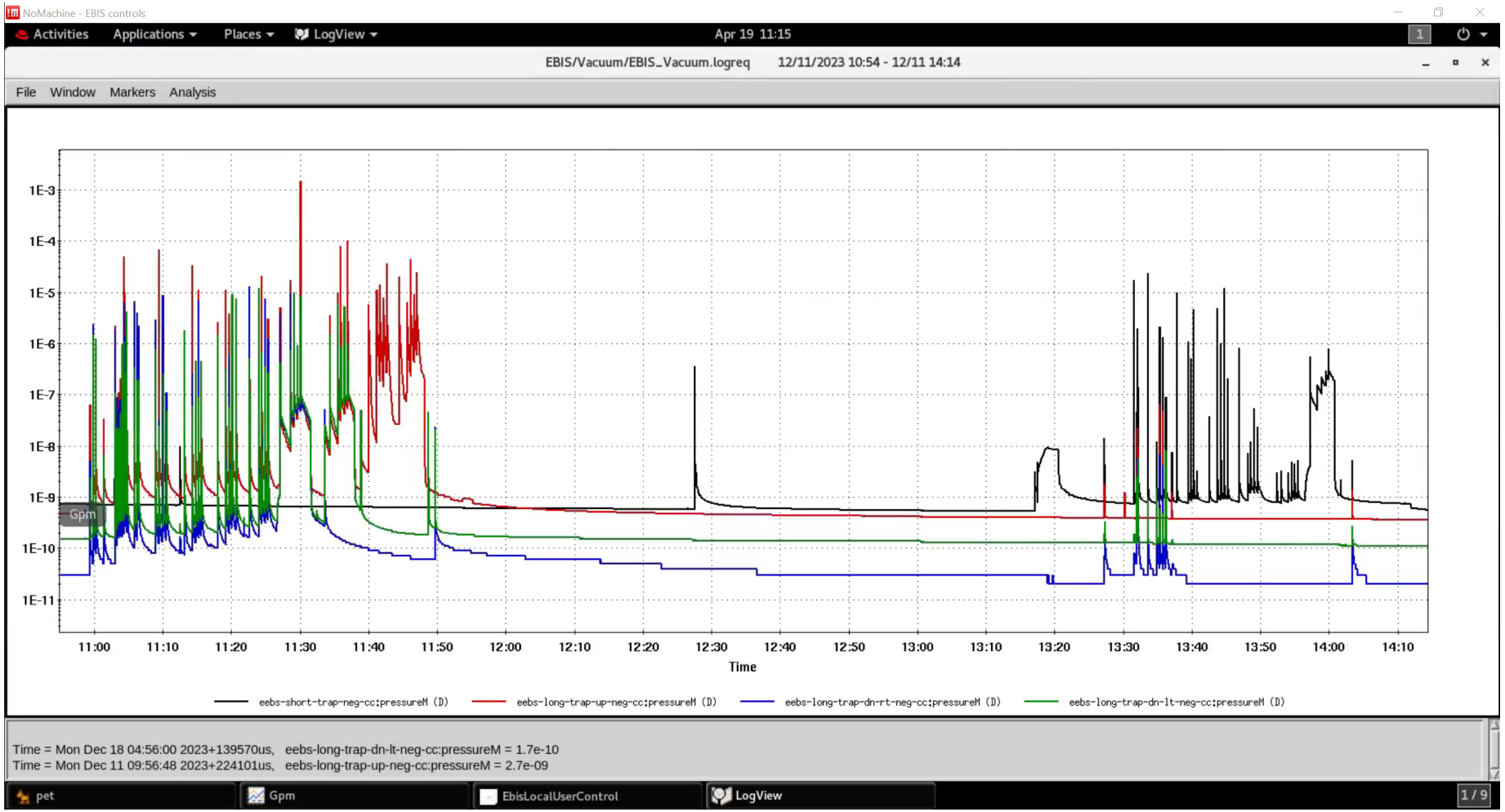


Dec 21 – 4-th pumping speed measurements to see if leaking e-gun gate valve affected ST NEGs during cathode replacement

Dec 15 – e-gun cathode replaced

Dec 11 – 3-rd pumping speed measurements, after 6 months of EEBIS operation (NEGs was found partially saturated)

Gauge Readings During Pumping Speed Measurements



Summary

- In many applications it is impossible to realize what is the current pumping speed of NEG-based pumps and when their re-activation is required
- Method of in situ effective pumping speed measurements has been developed and applied to Extended EBIS vacuum system
- If hydrogen is used as injected gas into vacuum chamber, operational parameters of ZAO NEG-based pumps are not affected up to about 10000 measurements
- On-line analyzing software was developed allowing calculation of effective pumping speed within about 1 minute using recorded RGA file
- Developed method allows monitoring of NEG-based pump pumping speed and confirmation of NEG parameters after activation or re-activation
- Having initial pumping speeds recorded allow us to define time intervals required for NEG-based pumps re-activation and to monitor their status over many years of Extended EBIS operation.