# AP0 Short-term Plan for Lens Operation

**3/29/2019**

## Target Systems Department and Muon Department

This document presents the recommendation for conservative operational lithium lens startup parameters, to preserve the lens life while maintaining an acceptable muon yield for the Muon g-2 experiments.

### Situation

Lithium lens 10mm#10 failed on March 9, 2019, due to a breach in septum. Soon after, this lens was replaced by a new lens 10mm#11, the same type with an internally cooled transformer. At present, the known remaining ready-to-use lens spares are 10mm#8 (with an externally cooled transformer), old style #32 and unit 10mm#1.

With limited ready-to-use lens spares, it is now necessary to run the beam in a conservative mode before further studies can be carried out.

### Criteria and Options

The fact that the rate of lens septum breaches for g-2 operation is much higher than Pbar operation is an indication that the high temperature that the lens has endured for g-2 operation may have contributed to its failure.

The following criteria is considered in evaluating the options.

| Criteria | Description |
|---|---|
| **Temperature risk** | At high temperature, material strength and fatigue life are decreased, leaks may occur at the stop-cock or window seals, material creep, loss of Lithium pre-load, material electric resistivity is increased which in turn will result in higher joule heating, larger differential thermal expansion, cooling pattern may change, material phase change may occur given the Lithium melting temperature of 180.5 °C. |
| **Stress risk** | High stress may cause lens crack or lithium leak, cycling alternating stresses may lead to fatigue failure. |
| **Muon yield** | Running the lens in a conservative mode will result in muon yield reduction, which in turn will require the running time be extended to deliver the same number of muons to the experiment. |
| **Schedule & cost** | If all spare lenses are used up before the required lens pulses are fulfilled for the experiment, it would take a lot effort and time and funds to build new lens. If the running time is extended due to the muon yield reduction, the operation cost / schedule will be increased. |

The evaluation rating scale is defined as “4” being more effective in the preferred way: decrease in temperature or stress. For muon yield, it is rated only as “Compromised” or “No effect”. The options are not mutually exclusive - so they could be operated in concert. The evaluation # is roughly normalized (and then ranked) for the degree of reduction.

| Options | Effect on Temperature | Effect on Stress | Effect on Muon Yield |
|---|---|---|---|
| **Reduce current** | 4 | 4 | Compromised |
| | Heating is roughly proportional to the current squared; stress decrease is roughly proportional to the temperature decrease and alternating temperature range | | |

| | | | |
|---|---|---|---|
| **Reduce number of pulses per cycle** | 3 | 3 | Compromised |
| | Heating is proportional to the number of pulses per cycle; stress decrease is roughly proportional to the temperature decrease. | | |
| **Pulse the lens during Switchyard cycles** | 1 | 2 | No effect |
| | Larger alternating temperature range is eliminated, but the overall heating power is increased by 10%, Fatigue strength is increased, but the pulse count is also increased by 10% | | |
| **Reduce cooling water temperature** | 2 | 1 | No effect |
| | Lens quasi-static temperature is reduced by only a few degrees, but the temperature gradient at lens peak temperature region is increased | | |

## Lens Gradient versus Yield Measurements

The function of the Lithium Lens is to focus the positive secondary particles with an energy near 3.1 GeV from the production target. Reducing the current in the lens causes a reduction in the angular extent of the secondary beam that can be focused and transported through the Muon beamlines. This, in turn, reduces the stored muons in the g-2 Storage Ring and less data for the experiment. The experiment provides a decay positron count that is proportional to the number of stored muons, which was used to measure the impact of reducing the lens current and magnetic field gradient. During a study period on March 22, the lens power supply current was reduced from the nominal 19.5 kA in 1.0 kA steps and the g-2 decay positron count was recorded (the positron count was lower than typical, due to a scaling parameter in the experiment's DAQ). The target to lens distance was adjusted to optimize transmission efficiency for the 19.5 kA and 18.5 kA data points, but was at its physical maximum limit and not optimized for the remaining data points. There is close to a 1:1 relationship between lens current and g-2 decay positrons, but the inability to set the proper focal length causes an increasing second source of inefficiency. As can be seen in the table below, this effect is modest at 17.5 kA, but has become large at 15.5 kA and would be expected to continue growing at lower currents.

| Lens Current | % Current reduction from 19.5 kA | Focal Length (cm.) | g-2 decay positrons | % reduction from 19.5kA/optimized |
|---|---|---|---|---|
| 19.5 kA | 0 | 30.9 (optimized) | 122.4 | 0 |
| 18.5 kA | 5.1 | 32.5 (optimized) | 116.2 | 5.1 |
| 17.5 kA | 10.3 | 33.5 (maximum) | 107.4 | 12.2 |
| 16.5 kA | 15.4 | 33.5 (maximum) | 99.1 | 18.9 |
| 15.5 kA | 20.5 | 33.5 (maximum) | 76.5 | 32.0 |

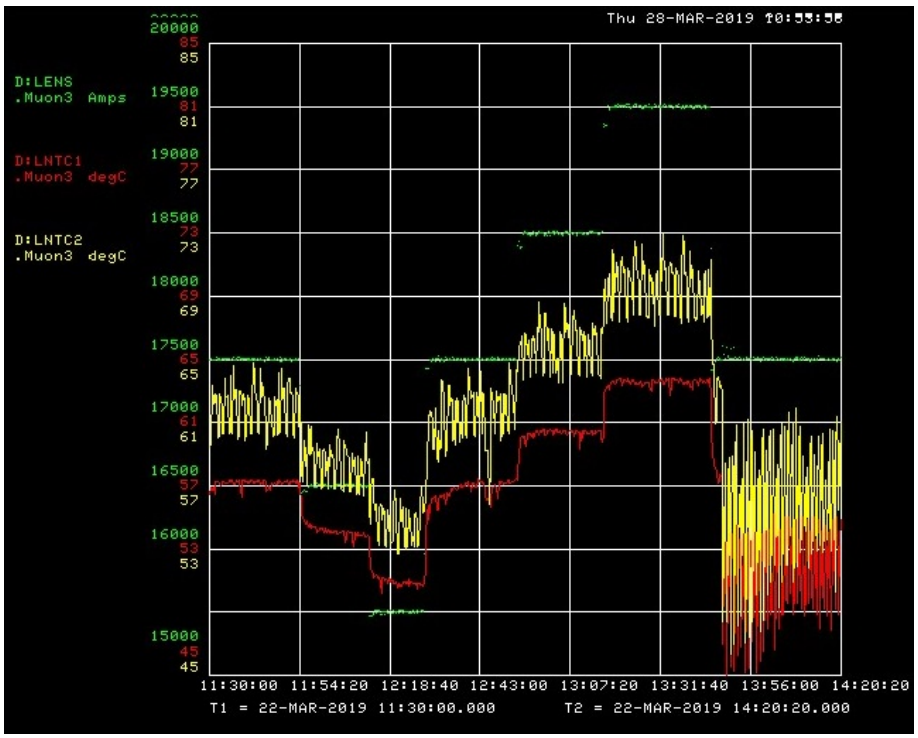
## Recommendation, Temperature Measurements with Beam Operation Modes #1 and #2

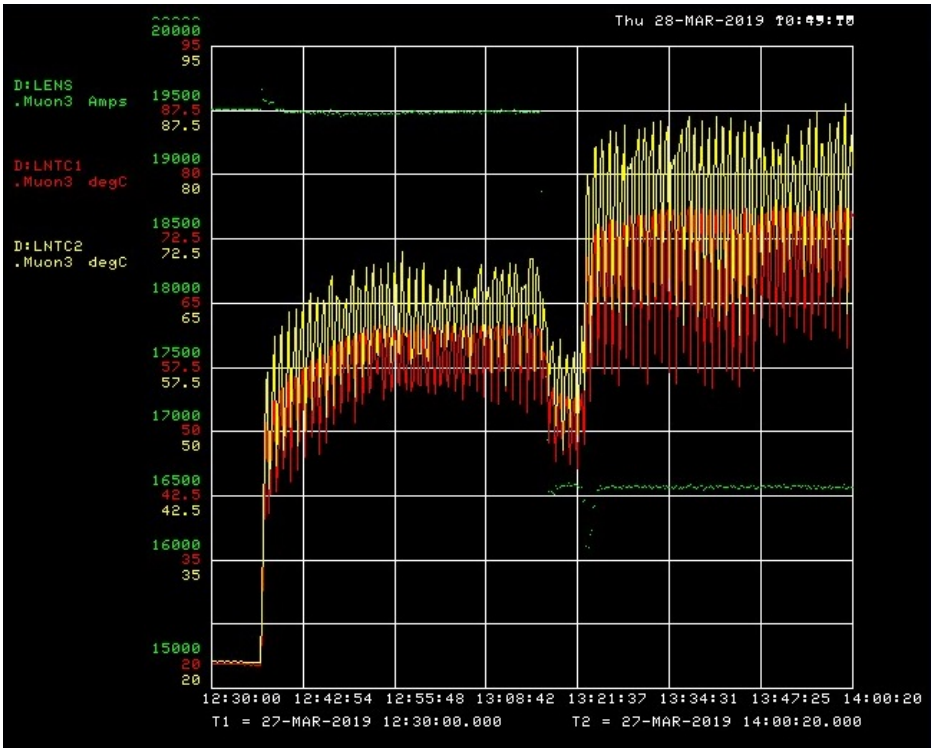
Lens current reduction is more effective in reducing the lens temperature because the heating (and possibly stresses) go as $I^2$. However, as indicated in the beam study, beyond a 15% current reduction, the reduction in muon yield will drop more precipitously due to the focal length mismatch.

Two acceptable safe beam operation modes were proposed for beam startup parameters:

| Operation mode | Current | Number of pulses per cycle | Effect on lens temperature | | |
|---|---|---|---|---|---|
| | | | ΔT drop | Reduction in alternating T range | Peak T |
| **#1** | 19.5 kA | 8 (1.33 s cycle time) | 47.4% | 44% | 73 °C |
| **#2** | 16.5 kA | 16 (1.4 s cycle time) | 28.4% | 28.4% | 88 °C |

Currently there are two thermocouples on the lens body: D:LNTC1 and D:LNTC2. The temperature readings are a few degrees different. Lens temperature plots during beam study period on March 22 in the operation mode #1 (8 pulses per cycle) with different currents (Top) and during the period switching from mode #1 to mode #2 on March 27 (Bottom) are shown below:



## Additional Machine/device Protection (D. S.)

Extra protections are implemented to the lens devices through monitoring.

1. Setting limit to D:LENS - The lens cannot be set higher than a value of 19.5kA. The local controls will inhibit the setting and the set it back to 19.5k if set higher.
2. Analog alarm on D:LENS - added an analog alarm property to the Lens. It will generate an alarm if the reading is higher than 17kA or lower than 15kA.
3. Beam inhibit on D:LNTC1 and D:LNTC2 - if alarm limit is exceeded for lens body temp, the muon beam permit will be lost requiring operators to understand the temperature trip or call an expert before resetting. The power supply will keep pulsing but there is ~ 5% decrease in temperature due to beam heating.
4. Analog limits for D:LNTC1 and D:LNTC2 have been set to 87° C & 94° C respectively for 16 pulse operation with readings at 74° C & 84°C.

**Will add in the next week:**

- Power supply trip on D:LNTC1 and D:LNTC2 – adding an external interlock for the lens body temperature that will trip off the lens power supply in the event the temperature exceeds the set point.

## Future Plans

The current operating modes will be revisited with further structural analysis to be performed in the near future. We hope we can go to a less conservative mode with further study.

| Rev. | Date | Originated By | Checked By | Approved By |
|---|---|---|---|---|
| - | March 29, 2019 | Kris Anderson / Yun He / Patrick Hurh / Jim Morgan / Dean Still | Bob Zwaska | |

## Appendix I: Rough Estimate of Required Pulses for g-2 Experiment (K. A.)

Pulsing the lens at the g-2 rep rate of 11.4 Hz, it is equivalent to 1 M pulses per day at 100% duty cycle. Assuming 75% yearly duty cycle x 365 days x 1M = 270,308M pulses per year (~ 270M pulses per year).

The Muon g-2 project is estimated to run for at least 2 years. Therefore, we require 540M lens pulses to achieve the baseline projections. Considering g-2 operation, 10mm#4 acquired 29M g-2 pulses (plus 12.4M Pbar pulses) and 10mm#10 acquired 131.75M g-2 pulses (80M test stand cycles, not quite production timing + 51.75M operational cycles). Considering the g-2 pulse train operation, these previous two lenses provided about 15% of the required g-2 project baseline requirements.

*Summary: the remaining stable of lenses need to supply at least 459.25M pulses going forward.*

## Appendix II: Lens Runs for Muon g-2 vs. Pbar Operations

Even though peak current and gradient are reduced by a factor of ~3 for g-2 operation, the pulse rate is increased by a factor of 25 compared to Pbar operation.

| | Pbar Operation | Muon g-2 Operation |
|---|---|---|
| **Gradient / Current** | 670 (T/m) / 62 kA | 230 (T/m) / 19.25 kA |
| **Rep rate** | 0.45 Hz | 11.4 Hz |
| **Pulses per day** | 39,270 | 986,700 |
| **Lens septum breach incident** | 1 out of 7 of the 10mm lens | 2 out of 2 of the 10mm lens |
| **Lens measured peak temperature** | 63 °C | 102 °C |

## Appendix III: Lens Failure Modes (P. H.)

No autopsy has been conducted to determine the failure of 10mm#4 and 10mm#10 (the lenses are too radioactive for any autopsy procedures which are also viewed as difficult and challenging).

For Pbar running, old style steel body lenses had many septum breaches. Increasing Lithium pre-load helped that. 10mm lens was designed for maintaining high pre-load in the high current density region.

Being exposed to millions of cycles at high temperature, the following lens failure modes are possible:

| Failure Modes | Description |
|---|---|
| **Lost Lithium pre-load** | • Li leak in the Be window or stop-cock seals resulting in loss of required Li pressure<br>• Ti stud relaxing / creeping allowing window seals to lose compression resulting in lower Li pressure |
| **Li-Ti separation** | • Magnetic pinching forces on Li separate the Li from the Ti septum tube causing a void and resulting cavitation-like damage to the septum<br>• Caused by Li pre-load being too low or a localized region of lower Li pressure caused by deformation of the Li out of the conductor volume<br>• Thought to be the primary mode of failure for septum breaches<br>• High temperature of Li could aggravate the condition and/or invalidate simulation results<br>• Note that Li melting temperature is 180.5 °C. |
| **Fatigue strength limit** | • Likely lower at high temperature<br>• FEA simulations may have underestimated temperature (we are measuring higher temperature than simulated, temperature dependent resistivity was only incorporated for the first pulse of joule heat generation) |
| **Crack** | Crack initiated during previous operation (p-bar or test stand) propagated to failure under the cyclic conditions of g-2 operation |

## Appendix IV: Some Factors to Consider for Determining the "Safe" Level Operation (K. A.)

The FEA analysis suggests that the resultant stress cycles are relatively low and fatigue life experienced in the lens under Muon g-2 operation should achieve $>10^8$ cycles. Given the recent failures it seems the possibility exists that the FEA results might not capture the present failure mode (e.g., lithium creep and separation from Ti septum, perhaps in the end region where geometry is more complicated). Other effects such as elevated temperature operation of 10-2-3 Ti, local hot spots from uneven flow or cavitation at the turnaround geometry is also not captured in the analysis. Even a simple scaling exercise extrapolating from $10^7$ to $10^8$ cycles suggests reductions of stress on order 6-8% would be sufficient for an order of magnitude increase in fatigue life.

Therefore, it seems that determining a "safe" initial operating limit based on temperature scaling might be more prudent. If one assumes an ambient temperature of 300K, Ryan Schultz's paper and FEA predicts a corner region Li temperature for Pbar operation at 670 T/m of 355K or a $\Delta$T of 55K. For Muon g-2 running an equivalent analysis predicts an end region Li temperature of 375K or a $\Delta$T of 75K. This scaling would suggest a temperature reduction of 27%, or a current reduction of about 15% from the baseline 19.5 kA.

We could consider running at this "safe" mode for some number of pulses (40M -50M?) with a couple of gradual ramps at intervals (e.g., 3% increases) to gain a larger operational history vs. operational current to guide how we might employ future running limits to manage our existing inventory or spare lenses.

## Appendix V: Effect on Muon Yield from Lens Current Reduction (J. M.)

Ad described earlier, reducing the lens current linearly reduces the focusing strength, which reduces the muons per cycle delivered to the g-2 Experiment. The lens to target distance can be adjusted to provide the proper focal

length for the secondary beam, but reaches its maximum range around an 8% reduction in lens current. With a greater reduction in lens current, muon yield will be reduced by both lower focusing strength and lower than optimum focal length. The practical implication of this is that there is a point when the loss in yield per pulse offsets the gains from 16 cycle operation. For instance, at an operating current of 15.5 kA, the yield per pulse (from the gradient versus yield table) is reduced 32%. In this example, the total stored muons when going from 8 to 16 pulses and reducing the lens gradient from 19.5 kA to 15.5 kA would be a factor of only 1.29 [(16 cycles/8 cycles) * .68 yield * (1.33s/1.4s) = 1.19]. In this example, nearly twice the number of beam cycles will be required to deliver the same number of muons to the experiment. The benefits from reducing the current should be weighed against the adverse effects to the lens, lens transformer, target, pulsed magnet and other pulsed devices in the accelerators and experiment due to the increased pulse count.

## Appendix VI: Lithium Lens History (J. M. / P. H. / K. A.)

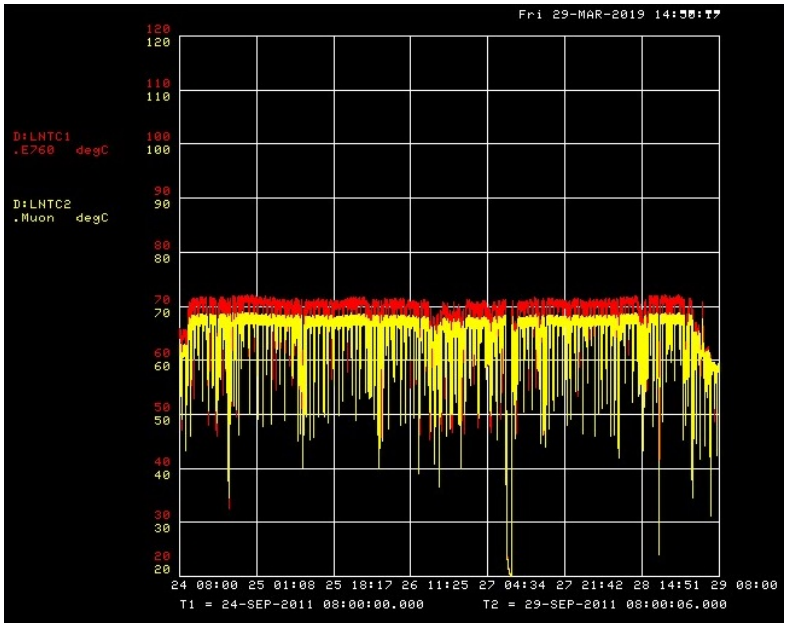
Modern High Gradient lenses are titanium and Diffusion-bonded, old style lenses are welded titanium with a steel body. Modern transformers are internally cooled, old style transformers are externally cooled

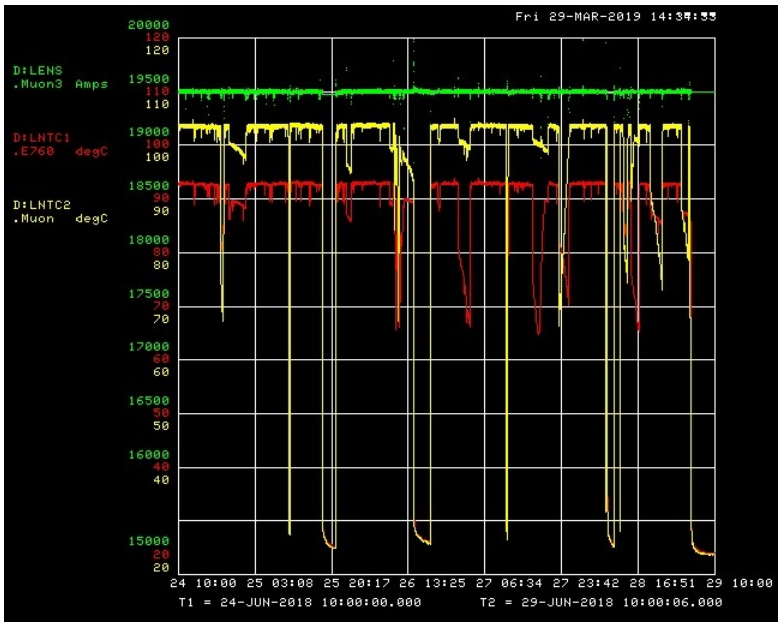
| **Lens** | **Pulses (Million)** | | **Style** | | **Description** |
|---|---|---|---|---|---|
| | **Pbar** | **Muon** | **Lens** | **Transformer** | |
| **10mm#10** | | 80+51.75 | Diffusion-bonded | internally cooled | Septum breach |
| **10mm#4** | 13.1 | 29 | Diffusion-bonded | externally cooled | Septum breach |
| **10mm#11** | 0.2 | | Diffusion-bonded | internally cooled | |
| **10mm#8** | 0.3 | | Diffusion-bonded | externally cooled | was tested in multiple transformers. |
| **10mm#7** | 11.8 | | | | transformer ground fault, picture show a spot on the window the same size as the beam. Run at 2300 volts |
| **10mm#6** | 0.74 | | | | Septum breach |
| **10mm#5** | 5.4 | | | | water leak on VCR fitting |
| **10mm#3** | 1.8 | | Diffusion-bonded | internally cooled | failed stripline, briefly back in service again Late summer 2008, had transformer fault/VCR leak. Hipotted OK later, but failed Hi-pot in Nov. 2018 |
| **10mm#2** | 5.2 | | Diffusion-bonded | externally cooled | moved to a different transformer as hot Job after original transformer failed in service, also removed another time to repair loose tie rod. |
| **10mm#1** | 6.2 | | Diffusion-bonded | externally cooled | moved to different transformer as hot job after original transformer failed in service. Hi-potted Ok in Dec. 2018 |
| **32** | 1.0 | | Old style | externally cooled | was working when replaced with diffusion-bonded lens |
| **30** | 6.1 | | Old style | externally cooled | has sputtered target material on beryllium end cap |
| **28** | 8.7 | | | | transformer or water line issues |
| **23** | 9.4 | | Old style | externally cooled | transformer failed in service, repaired |
| **4** | 0.6 | | Early old style | no cooling | |
| **8mm#2** | smaller diameter lithium conductor but diffusion-bonded), was never used operationally because there were signs of lithium extruding from the end. It's transformer was used to fix 10mm-2, but the lens might have some life left in it. | | | | |
| **Suitable spares** | 1. 10mm#8, new lens; might be considered for internally cooled transformer update;<br>2. #32, Original type lens; was operational when replaced with diffusion bonded style lens; might consider installing as-is to determine if there is some mode | | | | |

| | |
|---|---|
| | of failure in diffusion bonded lenses that is not well understood (note- no diffusion bonded lenses that failed as a result of septum breach has been autopsied);<br>3. 10mm#1, used, passed Hi-Pot in Nov. 2018 |
| **Potential spares** | 10mm#2, 10mm#3, 10mm#5, 10mm#7, #28, 8mm#2 |
| **Bonded, ready for machining** | 10mm9, 10mm12, 10mm13, 19mm14 |

## Appendix VII: Lens Temperatures Studies

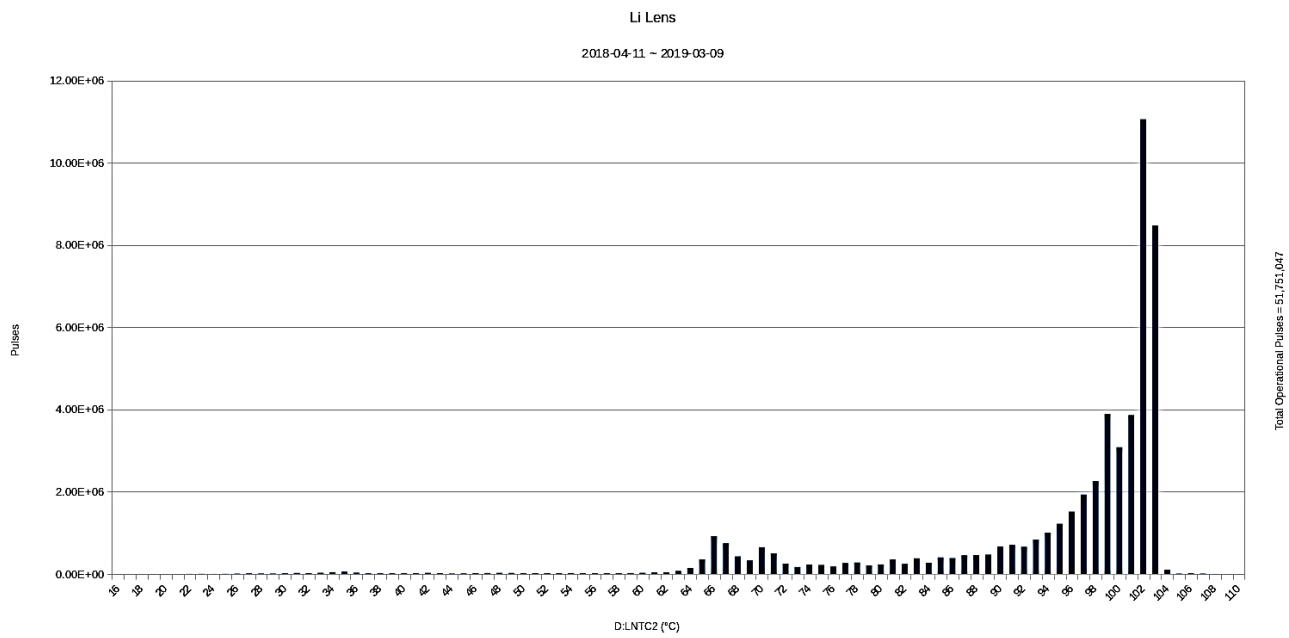
Below are lens historical temperatures plots per Pbar operation (Top) vs. g-2 operation (Bottom), each for a 5-day period. They show that the lens has been running most of time at about 102 °C for g-2 operation whereas it was about 70 °C for Pbar operation.



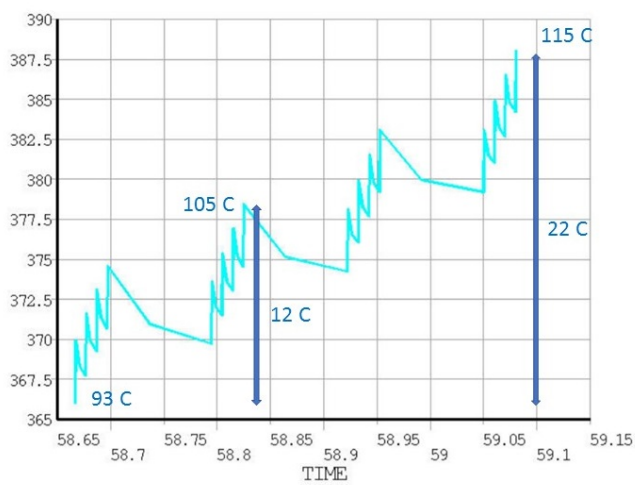



The temperature in the high current density region is estimated to be 20 °C higher than the spot where the thermocouple is located. Beam heating is << the current (~4%).

The histogram of 10mm#10's operational pulses at different temperatures shows that it spent most of its operational life at high temperature.



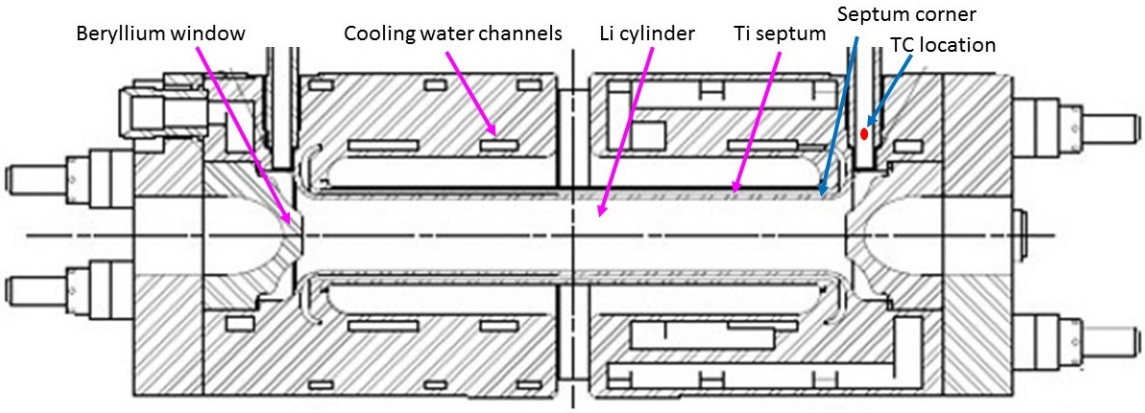

If we run 8 pulses instead of 16 pulses, the dynamic temperature rise during each cycle will be reduced by 4/9.




## Appendix VIII: Lens Structure

The lithium (Li) lens provides the focus of pions downstream of the target. It is contained within a toroidal transformer, both are cooled with closed loop RAW. The lens' magnetic field is generated by passing high current through the stripline to the 8-turn transformer and then to the central conductor Li cylinder. Pions passing through this cylinder will see an inward focusing kick back toward the center of the cylinder proportional to the magnetic field strength.

Surrounding the Li cylinder is a jacket of titanium (Ti) alloy (Ti-10V-2Fe-3Al) called the Septum. The Septum's purpose is to contain the Li against various thermal and magnetic forces while allowing cooling by an annular water passage. The ends of the Li cylinder are bound by end windows made of beryllium (Be). A critical process in the lens fabrication is Li filling, in which the Li is melted and forced into the lens inner cavity under pressure and allowed to solidify. During this filling process, pressure is continued to be applied, with the final pressure of solid Li to be about 3800 psi. This pre-load is needed to prevent Li from separating from Ti septum under the magnetic pinching force during the current pulsing.




When the lens is tripped off on high conductivity in the return water, it is indicative of a septum breach in which water comes into contact with lithium metal which forms lithium hydroxide solution.