ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2023-MOPMB070

DEVELOPMENT OF A NON-INTRUSIVE LEAK DETECTION METHOD FOR SRF LINACS

P. Pizzol†, V. Morozov, R. Afanador, J. D. Mammosser, D. Vandygriff
Oak Ridge National Laboratory, Oak Ridge, TN, USA
R. Geng, Jefferson Laboratory, Newport News, VA, USA

Abstract

The SNS accelerator has been vital in delivering high-impact research for the world scientific community since 2006, with an availability of 99%. This high availability rate is crucial to the success of the facility, and after 16 years of operations, the aging of the components could start to impact this parameter. To mitigate this, condition-based maintenance can be applied to areas of the LINAC to reduce or nullify the possibility of unwanted events that may damage the accelerator functionality. In this work, we describe the development of a non-intrusive leak detection methodology that verifies the health condition of the cryomodule isolation gate valve seals. In case of a sudden vacuum leak in a warm section between the cryomodules, these valves act as a final line of defense to protect the SRF cavities from atmosphere gases contamination, hence knowing their sealing integrity condition is paramount. Data taken from the machine during different maintenance periods will be presented, together with the analysis done, to verify the robustness of the numerical method vs. the experimental findings.

INTRODUCTION

Particle accelerators have revolutionized scientific research by enabling the investigation of fundamental particles and their interactions at increasingly higher energies. These sophisticated machines, such as the SNS accelerator, have been crucial in delivering high-impact research to the global scientific community since its inception in 2006.

However, as with any complex technological system, particle accelerators are subject to aging, impacting their performance and reliability over time [1, 2].

The aging of particle accelerators can be attributed to several factors. These machines intense and repetitive operation exposes their components to extreme conditions, including high temperatures, intense electromagnetic fields, and mechanical stresses. These conditions can lead to material fatigue, degradation, and wear, affecting the overall functionality of the accelerator. Furthermore, the accumulation of radiation damage in critical components, such as magnets and vacuum systems, can decrease efficiency and increase failure rates.

Predictive-based maintenance strategies are gaining prominence to mitigate aging's impact on accelerator performance. Traditional maintenance approaches, such as time-based or reactive maintenance, are often inefficient and costly, as they rely on fixed intervals or the occurrence of failures. In contrast, predictive-based maintenance aims to optimize maintenance activities by utilizing real-time data and advanced analytics to predict equipment health and anticipate maintenance needs.

Predictive-based maintenance offers several advantages over traditional approaches [3]. Monitoring the condition of critical components allows for the early detection of potential issues and the implementation of proactive maintenance actions [4]. This approach minimizes the likelihood of unexpected failures, reduces unplanned downtime, and extends the operational lifespan of the accelerator [5-7]. Moreover, predictive-based maintenance can optimize resource allocation by enabling targeted interventions on components that are at higher risk of failure, thus maximizing the efficiency and cost-effectiveness of maintenance activities.

Elastomers used for O-rings in vacuum isolation valves are amongst the more damage-sensitive accelerator components. Isolation valves play a crucial role in preserving the performance of the SRF cavities during maintenance operations or in case of sudden pressure spike events. Radiation encountered during accelerator operation can cause detrimental effects on the o-rings, leading to embrittlement that causes both decay in the seal integrity and the creation of particulate that, if deposited inside the surface of the SRF cavities, can stimulate field emission or arching, damaging the cavities [8-11].

Assessing the quality of these seals is not an easy task: accessing them requires the warm-up to room temperature of the neighbouring cryomodules and the opening of the beamline, potentially exposing the inner SRF surfaces to more contamination than warranted, so unless deemed extremely necessary, it is not a routine maintenance activity.

The need to be able to evaluate the seals without intrusive actions is what has driven our work presented here. Taking advantage of the scheduled SNS maintenance operations, a numerical analysis is being developed to verify if it is possible to predict which o-rings may be underperforming due to radiation damage.

EXPERIMENTAL SETUP

LINAC Side

We took advantage of the first day of maintenance to perform our study. The methodology was kept the same as the study conducted in August 2022. The vacuum isolation valves that separate the cryomodules from the warm sections between them were closed simultaneously at 8:00 AM. Subsequently, the LINAC SRF cavities temper-

ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2023-MOPMB070

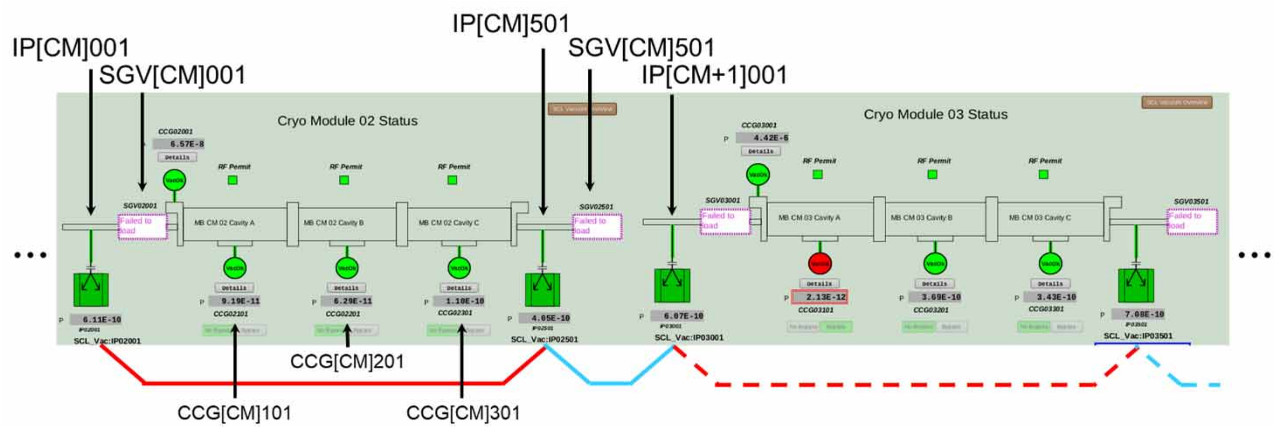

Figure 1: Diagram of cryomodule with Cold Cathode Gauges (CCG) and Ion Pumps (IP) highlighted.

ature was raised from 2 K to 4 K, increasing the cryomodules pressure. The cold cathode gauges situated next to each RF coupler, pressure readout and the ion pump current positioned at the end of each cryomodule were monitored and recorded (see Fig. 1). The warm section pressure was monitored only via ion pump current due to the lack of other pressure gauges. The vacuum isolation valves were opened after 2 hours – at 10:00 AM.

Numerical Analysis

The Pearson correlation coefficient was used as a parameter to analyze the data obtained from the cryomodules warm-up. As previously mentioned, we chose to compare the ion pump pressure readouts to verify any cross-talk between the cryomodules and the warm sections. The cold cathode gauges data were primarily used to verify the cryomodules ion pump pressure readouts. Unfortunately, their unreliability at very low pressures prevented us from using their data meaningfully.

The pressure signals from the ion pumps tend to be quite noisy, so the data were binned in 60 seconds intervals to clean them up. The interval of interest was then chosen as 7:30 AM – 11:30 AM to ensure we could capture the pressure values before the closing and after the reopening of the isolation valves as an ulterior verification of the valves movement. The valves were not reopened at 10:00 AM in a couple of cases, but that did not affect our data collection.

Additional data analysis was performed to improve the significance of the signal. A 45 min window was identified around the time when the pressure was rising in each cryomodule. The R coefficient was then calculated for each pressure point within this window. Pressure data within 15 min prior to each point was used to obtain R at that point. To enance the signal, R was normalized by the maximum relative pressure changes of the two correlated signals during each 15 min correlation period. Thus, below we use a normalized correlation coefficient $\tilde{R}$ defined as $\tilde{R} = R \cdot (\Delta p_1^{max}/\langle p_1\rangle) \cdot (\Delta p_2^{max}/\langle p_2\rangle)$. A Python code was written to calculate the average $\langle\tilde{R}\rangle$ and variation $\Delta\tilde{R}$ of $\tilde{R}$ over the 45 min period of pressure change in each cryomodule. This analysis was completed for all combinations of adjacent cryomodules and warm sections with one or two exceptions where the pressure data were not available.

RESULTS

The results obtained during this study were compared with the previous shutdown study, and both correlation summary plots are shown in Fig. 2. In the ideal case, assuming the same experimental conditions, the average R values extrapolated from the August 22 experiment should match the values obtained during the current study. An increase in correlation between a cryomodule and an adjacent warm section from the older study to the current one, though, could indicate the appearance or the increase in the cross-talk between the two, therefore, the presence of a leak in the valve.

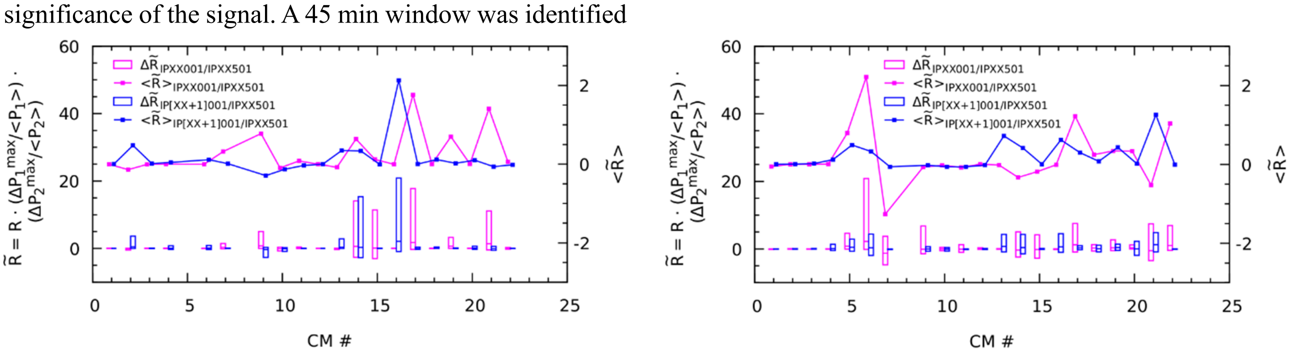

Figure 2: Average $\langle\tilde{R}\rangle$ and variation $\Delta\tilde{R}$ of $\tilde{R}$ for cryomodules and upstream (purple) and (downstream) warm sections. On the left the results from August 2022, on the right the results from March 2023.

ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2023-MOPMB070

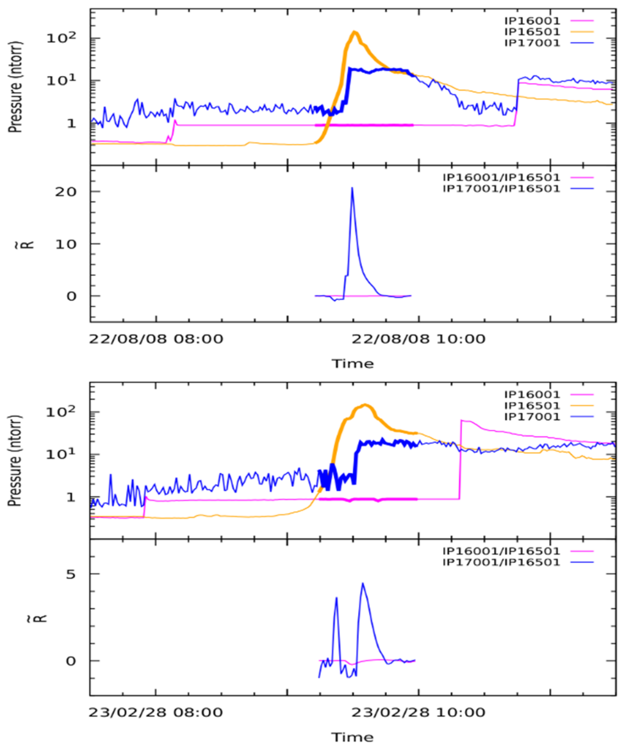

Figure 3: Pressure trends and $\tilde{R}$ values for cryomodule 16. Top August 2022, bottom February 2023.

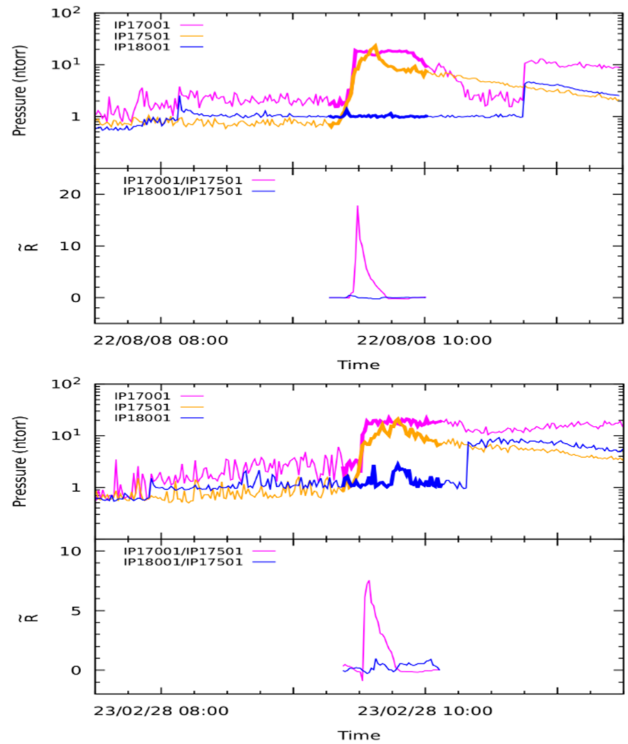

Figure 4: Pressure trends and $\tilde{R}$ values for cryomodule 17. Top August 2022, bottom February 2023.

While in a few cases, there is a distinct increase in correlation between the two tests (cryomodule 6 and 13), this correlation is not evident in the $\tilde{R}$-value analysis. After our numerical analysis, for example, the correlation between the two tests of cryomodule 16 and warm section 17 seems to decrease, suggesting diminished cross-talk and, therefore, the diminishing of a leak. Now although this is possible, it is unlikely.

By looking at the raw data, then, as shown in Figs. 3 and 4, a different conclusion can be reached. In both experiments, the cryomodule pressure (the orange line, IP16501) climbed at almost the same rate and to nearly the same absolute pressure values, ruling out a different gas load in the cryomodule at the time of testing that could have impacted the valves seals differently.

The same can be said about cryomodule 17 (IP17501), which is directly downstream of warm section 17.

The pressure plots also show that the pressure rise in warm section 17 almost overlaps with the increase in cryomodule 17. The pressure increase in cryomodule 16 precedes warm section 17 by almost 15 minutes, as visible in Fig. 3. This fact is reflected in the value of $\tilde{R}$: the increase in pressure in both cryomodules and the warm section creates high correlation factors (both data set increase at the same rate), but the timing of the events highlights that one correlation is more significant than the other for our analysis.

CONCLUSION

In this work, we presented the progress on the non-intrusive leak detection method. The comparison between the results taken in two separate maintenance periods suggests that the data analysis is promising but not perfected yet.

Further tweaking of the parameters considered (number of steps, time window, the interval of study) is undergoing to help us differentiate the different events and link $\tilde{R}$ values to potentially leaking seals.

REFERENCES

[1] L. Hardy, "Accelerator reliability-availability," in *Proc. EPAC'02*, Paris, France, Jun. 2002, paper WEXLA001.

[2] C. Sinnis, "The Future of LANSCE [Slides]," LANL, NM, USA, LA-UR-20-20854, Jan. 2020.

[3] H. M. Hashemian, "State-of-the-art predictive maintenance techniques," *IEEE Trans. Instrum. Meas.*, vol. 60, pp. 226–236, 2010. doi:10.1109/TIM.2009.2036347

[4] M. Pech *et al.*, "Predictive maintenance and intelligent sensors in smart factory," *Sensors,* vol. 21, p. 1470, 2021. doi:10.3390/s21041470

[5] C. Able *et al.*, "SU-E-T-205: MLC predictive maintenance using statistical process control analysis," *Med. Phys.,* vol. 39, p. 3750–3750, 2012. doi:10.1118/1.4735265

[6] C. M. Able *et al.*, "A model for preemptive maintenance of medical linear accelerators—predictive maintenance," *Radiat. Oncol.,* vol. 11, pp. 1–9, 2016. doi:10.1186/s13014-016-0602-1

ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2023-MOPMB070

[7] A. Grünhagen *et al.*, "Predictive Maintenance for the Optical Synchronization System of the European XFEL: A Systematic Literature Survey," in *Proc. BTW 2023,* 2023. doi:10.18420/BTW2023-70

[8] K. Tsumaki *et al.*, "Radiation damage to accelerator components of SPring-8 storage ring," *Radiat. Meas.,* vol. 41, pp. S265–S270, 2006. doi:10.1016/j.radmeas.2007.01.024

[9] A. Zenoni *et al.*, "Radiation resistance of elastomeric O-rings in mixed neutron and gamma fields: Testing methodology and experimental results," *Rev. Sci. Instrum.,* vol. 88, p. 113304, 2017. doi:10.1063/1.5011035

[10] G. Lee, "Radiation resistance of elastomers," *IEEE Trans. Nucl. Sci.,* vol. 32, pp. 3806–3808, 1985. doi:10.1109/TNS.1985.4334510

[11] M. Ferrari *et al.*, "Neutron Radiation Effects on Lubricants and O-Rings for Target and Accelerator Applications," *Mater. Sci. Forum*, vol. 1024, pp. 127–133, 2021. doi:10.4028/www.scientific.net/MSF.1024.127