Gradient Maintenance Team - Closeout Doc JLAB-TN-16-038 4Nov2016

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Executive Summary

The Gradient Team has completed a prioritized list of issues and actions needed to optimize the energy reach and 12GeV availability in CEBAF. These tasks address the stakeholders goals detailed in the Team's charter and focus on optimizing gradient, reducing trips, and minimizing recovery time. The team has also begun studying the severity of issues associated with cryomodule field emissions and how it will impact the 12GeV program going forward.

The team scheduled and executed their top prioritized tasks during the summer 2016 SAD. However, the CEBAF accelerator will still have slightly less than the desired 60 MeV of margin at 1050 MeV/linac in FY17 as a result of these changes. The margin is necessary to accommodate ~14MeV for Klystron loss, ~22MeV for field emission increase and ~20-30 MeV to bypass a zone during 30 weeks of operations. At 1090 MeV/linac, 12 GeV, there is presently no margin.

Without additional funding, CEBAF capability will continue to decline at an expected yearly rate of 34MeV/pass for reasons discussed below and in the series of CEBAF Energy Reach tech notes (Freyberger et al). Investment of $4-6M/year is needed to achieve a 12 GeV physics program, with additional investment to make the machine more reliable.

Introduction

The primary issues that must be overcome to achieve 12GeV operations are associated with the C100 acceleration systems. The C100 systems were commissioned to the gradient performance specification values in the tunnel, primarily while in SEL mode. However, current performance in GDR mode, required for operations, is roughly 20% less than commissioning values. Present Operations Drive Highs for the C100's average 86 MeV/module, severely impacting energy reach of the machine. Several issues have prevented C100 operations at the required gradient and trip level.

1. Although meeting the 12 GeV Project's microphonic specification, the unstiffened cavities are susceptible to microphonics coupled from external sources. There are four paths for environmental mechanical vibrations to enter the cavities, beamlines, transfer lines, waveguides and tuners. The tuners underwent vibration response testing in 2011 and tuners after serial number 3 were stiffened during production.
2. The combination of cavity shape and lack of stiffeners result in the sensitivity to pressure variation, Hz per mBar, being one to two orders of magnitude greater in the C100s than in the original cavities.

3. The space frame suspension of the cavity string resonates at 10 and 20 Hz which can be driven to produce error terms beyond the capacity of the klystrons and LLRF to control.
4. Field emission was not modeled until 2012 and this was too late in the design process for changes to be implemented. The present design allows field emission from one cavity to be propagated through the cryomodule. When the cavities are phased to accelerate electrons, the field emission can be accelerated to 10's of MeV and propagated in both up and downstream directions. This has resulted in radiation dose rates which are quite high at both ends of the cryomodules.
5. The heat risers for the C100s are sized for a pressure agreed to during the 12 GeV development. The risers are good for 50 or more watts when operated at the intended design pressure. This is twice the design critical heat flux, the point at which the helium bath return becomes flow limited causing pressure excursions. Operation at higher pressures make the C100s very sensitive to the helium return pressure. This coupled with placement of the C100s at the end of the transfer lines in the linacs, far from the regulation point, and the 5 second delay in switching between electric and rf heat means the critical heat flux can be exceeded inadvertently by an rf and electric ON condition. This can cause an upset condition in the helium bath and prolong the cavity recovery time.

Subsystem Losses/Gains Summer 2016

Warm RF Windows

Coming out of the long shut down during the 12 GeV upgrade, following the conclusion of the 2015 Helium Processing campaign, cavity waveguide window differential thermopile trip points were left at levels which had not been previously evaluated for safe operation of the cryomodules. As a reminder, the interlock serves as protection by comparing the read back of the differential thermopile voltage to a fixed percentage of the saved value of the nominal voltage with RF off at 2K. In the Summer 2016 SAD, all of these cavities were surveyed to ensure accuracy of the stored nominal voltage (those with greater than 5% error were calibrated) and the settings stored in the system at which warnings and faults are issued were returned to known safe values.

Testing the cavities after these changes found a net loss of 18 MeV, 16 MeV in NL and 2 MeV in SL. Some of these losses could be mitigated by selectively turning down the set points of the affected ceramic windows encountering CWWT faults. Cavities could be tested using calibrated IR cameras or bolometers in the RF sweeps to determine what the most appropriate, but aggressive, settings for window interlock settings should be. Previously gathered window test stand qualification data, possible future destructive window testing, and a survey of the available literature on the subject could all be employed in this analysis as well.

Observed loss: 18 MeV/pass

300K cycles

Controlled 300K cycles cause an average loss in cavity gradient at fixed performance of 0.45 MV/m. (Uncontrolled, aka – Isabel; 0.7 MV/m). Seven modules remaining in service were warmed to 300K during the summer: 1L08, 1L11, 1L13, 1L23, 1L25, 1L26 and 2L08. It should be stressed that these losses are based on empirical statistical models and individual specific cases may perform differently.

Expected loss: 7 MeV/pass

Klystrons
The final seven 5.5 kW spares were swapped for poorest tubes. There remain 39 poor tubes in the machine. No fully functional spares remain and the expected lead time for replacements is 9 to 12 months. No 8 kW tubes left available to C50 and C75 upgrade CMs.

Expected Gain: 2MeV/pass

C50-12 Replacement
Using the improved techniques developed during the refurbishment of C50-11. The new cryomodule has been installed and gradient improvement will be determined in the coming month. There is a tuner problem in cavity 3 which could be corrected to regain 7 MeV/pass.

Expected Gain: ~30MeV/pass

Helium Processing
Changes made to the helium processing techniques tested during the summer down in zone 1L23 have shown significant improvement in reducing the onset of field emissions and a modest, 4MeV for entire zone, improvement for gradient. The initial results of the processing show that beamline radiation levels at full gradient, are about half.

Expected Gain: 4 MeV/zone, 47% reduction in beamline radiation at full gradient in 1L23

Microphonics
Tom Powers leads a data-driven study of microphonics. Working with Mechanical Engineering and others, several approaches to mitigation of C100 microphonics have been tried. Initial results from the latest damping struts suggest a possible 30-40% improvement in RMS microphonic content. Improvement to gradient and trip rates will need to be quantified once CEBAF returns to the nominal 12GeV CHL configuration.

Expected Gain: 12MeV/pass (3 modules with ~2-10 MV/m improvement, ~6MV/m * 3 = 18MV/m = 12MeV/pass)

Sum Energy Delta: -18+-7+2+30+4+12 = +23 MeV/pass

Short term mitigations

The following tasks have been executed over the summer down to mitigate the unexpected performance limitations.

LLRF
The LLRF group has updated their software over forty times since the first C100 was delivered. Recovery time after a fault has fallen to a minute, about a 30x reduction. The one-minute recovery time allows for ~80% availability at a trip rate of 10 trip/hours. Work continues. This effort has mitigated some of the effects of the issues cited above. Further mitigation efforts include:

- C100 Auto-recovery: Before a cavity trips it is placed into SEL mode and the beam is turned off (FSD). When the cavity has recovered it is automatically returned to GDR (locked condition) and the operator is notified so they can turn beam back on. The operation staff would never have to recover a C100, only observe when it is ready to run beam. Currently in progress.

- Piezo Tuner: The first four C100s are known to be more susceptible to microphonics. Since these may be produced by the tuner motor's vibrations, it is planned to use the piezo tuners on these C100s in FY17
- Eight Channel Heater: A plan is in place to have individual cavity heaters on all C100s by February 1, 2017.
  Expected Gain: 20-35% improved availability, no gradient

Stub tuners
All the C100s have stub tuners. They could be used to lower the input Q, increasing the effective bandwidth seen by the klystron and possibly reducing trip rates due to microphonics. This has not been done successfully so some R&D might be required.

Many C20s cavities lack stub tuners. After helium processing klystron voltages were turned up to allow the full use of the best cavity in each zone. If stub tuners were retrofitted in all locations, a few MeV now inaccessible would be made available and the voltage could be reduced in about a third of the zones, reducing the power bill and preserving klystron service life. Twenty stub tuners are in hand; 4 person-weeks are required for installation. The parts removed can be reworked and the iterative process completed opportunistically.

Expected Gain: 2-5MeV/pass, power savings payback in two years

RF vs electric heat algorithm
Super-MOPS with sufficient power capacity to balance increased C50 rf heat loads could be available by February and could be installed zone by zone once software is available. The effectiveness of the upgrade will only be realized once this algorithm is completed and software is available.

Expected Gain: ~22MeV/pass in C50 zones

Microphonics
Application of damping hardware to the other seven cryomodules can be implemented once the current design and analysis processes are completed.

Expected Gain: 29 MeV/pass (7 modules with ~2-10 MV/m improvement, ~6MV/m*7 = 42 MV/m = 29 MeV/pass)

Better vacuum technique and Magnetic Hygiene
The latest refurbished module has been installed in NL12. The adjacent girders were found to contain many particles when removed. They have been cleaned and returned to the tunnel using better vacuum technique than was standard during original installation. Improved vacuum techniques and magnetic hygiene have been implemented and will be used moving forward. Resulting improvements will be analyzed in FY17.

No gradient gain, maybe less field emission.

Lead collars
RadCon has proposed working with ME to design lead collars which could be placed around the exit and entrance flanges of C100s to absorb the gammas from field emission. These would localize girder activation. Design should consider tools needed for removal with torso distance 50-100 cm. Might explore reuse of existing lead from site for this purpose.

No gradient gain, but reliability of warm girder components would improve.

C100 Fault Logger
LLRF and Ops High Level Apps (HLA) expect to have a beta version of C100 fault loggers and viewers available early September and released by October 1. There are 37 distinct faults displayable in the C100 viewer vs 12 in the C20/C50 viewer. This will help LLRF and Ops focus on the issues which lead to the greatest loss of beam time for physics. Prototype is done and distributed for comment.

No gradient gain, but would allow informed decisions on where to throw resources to reduce lost beam time.

Operating pressure vs C100 gradients
The C100 modules are more sensitive to LHe pressure due to heat riser geometry. The C100 modules were installed in the empty zones at the end of each linac rather than the center (lowest pressure) or front (best optics) to reduce 12 GeV project cost. This results in performance tradeoffs between the cryo plant reliability and operational performance and availability. Parasitic tests will be run in Fall 2016 to better understand the effect so as to make an informed decision on operating pressure. Lower operating pressure increases stress on the cold compressors quite non-linearly and so increases the chance of a second failure.

Short term mitigation benefits:

Expected Gradient Gain: ~54MeV = ~3MeV (stub tuners), +22MeV/pass (heat) + 29MeV (7 modules microphonic mitigation)
Recovery Time: 15x faster
Radiation Hardening: some protection to warm region girders

The harvest is past, the summer is ended; and we are not saved. (Jeremiah 8:20)

Medium term mitigation

Increase Q0
FNAL has developed a procedure for in-situ cryomodule demagnetization for LCLS-II. Magnetic material in the old tuners cuts the Q0 a factor of two as discovered by Rongli Geng. Adapting the FNAL procedure to in-tunnel demagnetization at 25K would increase gradient at which field emission heating limits each cavity as baseline would be higher. The C50 modules are the only candidates as C20 cavities are all limited by field emission induced window arcs.
This process could also benefit the cryogenic load on CHL. Analysis should be done now to determine good candidate cryomodules which are limited by field emission heating and are likely to have embedded magnetic materials.

Expected Gain: ~30MeV

Change insulation vacuum pumps
There are about ten turbo pump cubes in the tunnel pumping on insulation vacuum at any one time. One to two of these fail a year due to radiation damage which requires a tunnel access for repair. A radiation hardened replacement unit with increased pumping speed, which can be controlled by EPICS, has been procured and will be evaluated this fall.

Expected Recovery Time Improvement: ~15 beam hours/year

Vacuum instrumentation
C100 insulating vacuum gauges failed quickly due to radiation and need to be replaced. Improved vacuum instrumentation is needed in the linacs. Consider replacing all linac ion pumps with NEG pumps and rad hard gauges. Failure of these systems has required personnel to access the area after beam operations to check the pump/pressure. An improved system will align with JLab's ALARA system.

Improved Instrumentation will minimize radiation exposure to personnel during repairs/investigations in the tunnel.

Radiation damage and sensors
RadCon dosimeters documented high radiation levels at the ends of C100 modules, of order 5 kRad/hr, with 14 kRad/hr in one location. Circumferentially placed sensors saw ~500 Rad/hr. With ~5400 hours of operation annually, the integrated dose along the beamline is 27 MRad/yr and 2.7 MRad/yr circumferentially. Aluminized mylar, aka superinsulation, suffers severe mechanical degradation at an integrated dose of 100 MRad. Teflon, aka wire insulation, is more susceptible.

Use of Helium processing to increase the field emission onset point for specific C100 cavities and selective reduction of the Emax setting for others based on a field emission model may allow the C100s to operate at increased gradient for a few more years.

Implementing a monitoring technique, such as an adaptation of that used at CERN, would allow the radiation dose to be integrated and C100 gradients to be set to maximize integrated gradient while minimizing ambient dose rates. If a C100 CM does need to be removed for internal material damage other modifications should be considered at that time.

Klystrons

A klystron replenishment program is necessary for sustained 12GeV operations. The program should provide funds to purchase twenty 8 kW klystrons/year and refurbish (yield 40%) poor tubes until all of the out of spec tubes have been replaced. Since all C50 and C75 cryomodules use 8 kW klystrons and we have no in-spec tubes left, any upgrade program must include klystron procurements. Implementing a replacement program now will maintain or improve gradients while protecting the lab against a collective end of life failure event. Replaced, non-optimal klystrons can become part of a spares inventory to use if failure rates increase. Continue until sufficient spares are on hand to deal with end of life issues of the tubes that date from 2000+.

The 13 kW C100 klystrons go non-linear around 11 kW. This limits the maximum level of microphonics which can be handled within the phase/amplitude specification. Consideration should be given to higher power (15 kW?) replacements, which would fit in the same external solenoid. These could be developed and purchased as the existing tubes fail. This would also allow the C100s to drive more beam current as the C100 microphonics issues are addressed.

Helium processing

Continue to refine the helium processing procedure. This will also mitigate some of the field emission problems in the C100 modules. Applying this selectively to a portion of the machine every year should mitigate the steady reduction of 0.5 MV/m per cavity discussed in the Freyberger series of TNs cited above.

Long term mitigation

Incorporate lessons learned into current and future cryomodule design. Design new cavities to minimize the number of field emitted electrons which can be accelerated by multiple cavities.

Procure a new 2K cold box. Use the less energy efficient of the old ones for spare parts. This is needed to allow operation of C100 modules at the highest gradients possible without endangering the cryo plant reliability.

Required Procurements

The Gradient Team suggests the following procurements to recover the 12GeV program.

$1.2 M/yr klystrons (20-30 klystrons) Need 8 kW tubes for C50/75 CMs; none available except LERF
$0.3 M/yr HeP+demag
$0.1M C100 Microphonics mitigation in eight zones
$2.4 M/yr *3 yrs cold box
$2-4M/yr C50s / C75s until cold box finishes, then more

This list does not include a repair/replacement program for field emission/radiation damage in and around the C100s. Radiation data has now been collected and a plan should be developed and in place to address imminent failures when they occur.

Summary

Several strategies have been developed and implemented to improve the gradient in CEBAF during the summer 2016 SAD. Based on observed C100 performance, these improvements will not provide the required margin for a 12GeV CEBAF at the nominal 1090MeV/linac. At best, these improvements, along with a C50 refurbishment program, may allow CEBAF to operate at 12GeV for periods with reduced reliability. Changing the C50 refurbishment to a yearly C75/C100 upgrade program improves this scenario. An optimized helium processing program also provides a path for meeting CEBAF 12GeV energy requirements.

The Gradient Team task list was developed to guide immediate efforts and detail needed improvements going forward. The task list has been delivered to the stakeholders for review and the team has acted on the guidance provided. Specific tasks have been delegated to groups and many are either completed or are in process. The stakeholders may wish to consider handing off the remaining tasks to the long range performance improvement team for oversight going forward or reassessing the tactical goals of the gradient team.