Cryomodule Maintenance Workshop, March 2014

Report/Summary

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Highlights from Individual Lab Reports

KEK/KEK-B

The accelerator operates at an accelerating voltage of 1.1-2 MV per cavity, with cavity Q_0 values of 0.3 – 1.0 x 10^9. Cavity trips due to FE-induced discharges occur at the rate of about 0.5 trips/day for the set of 8 cavities.

As part of routine maintenance, the cryomodules are warmed up to 300K about twice a year – typically have a ~3mo energy-conservation shutdown during the summer months. During the thermal cycle, the tuners are "released" –i.e., detached from the cavity so as not to load the cavity from thermal stresses. Couplers must be re-conditioned at room temperature (using bias HV) before the next cooldown. Cooldown/warmup occurs at a rate of about 3K/hr.

Every ~2 weeks, they cease operations briefly in order to perform cavity conditioning (mitigate FE).

For one cavity in particular, over time they experienced degradation in Q_0 due to FE loading, increase in FE (cavity coupler was removed and gasket replaced – contaminated the cavity). Q_0 values have decreased from ~ $1x10^9$ to ~$3x10^8$. They have recently developed a means to horizontally HPR a cavity in-situ (15min, 7MPa pressure), and this was employed on the cavity in question (and for another that had a He leak and was contaminated during re-assembly). This has led to improved cavity performance (elimination/reduction in FE), and recovery of Q_0 to > $1x10^9$.

ORNL/SNS

Stable operation has been established now for several years, reaching 90% NP availability. The SCL has shown an availability of 99.5% over the last 3 years. Average trip rates now are < 1trip/day, with a < 5min recovery time per trip. During FY12 the primary cause for cavity trips was errant beam, during FY13 it appears to be related to instrument (interlock threshold) settings.

Initially, key factors that affected Linac performance were lower than anticipated gradients in the high β cavities, cavity performance degradation, variability of gradients, and cryomodules requiring repair (leaks). Later, errant beam (beam impacting cavity produces desorption of gases leading to FE/discharge) became the largest contributor to operational trips.

In the case of cavity performance degradation (FE), recovery was achieved by thermal cycling to 300K (with the risk of creating or exacerbating leaks). Since FY07, 34 individual thermal cycle shave been performed, with several cryomodules experiencing 3 or more thermal cycles.

Over time they have observed a "global" decrease in average cryomodule Q_0 from 5 x 10^9 to 3 x10^9; this is attributed to significant increase in FE loading of a few cavities, as opposed to a general degradation.

A number of cryomodules have been repaired since FY07, with the largest fraction of issues being instrumentation failures, followed by tuners (piezo stack and harmonic drive failures) and valve actuators. A total of 10 cryomodules needed to be removed from the tunnel for repair (42%); one is still awaiting removal/repair. This is a "failure rate" of 46% !

Recommendations based on several years of operational experience include caution operation, dedicated diagnostics development/implementation, careful adherence to operating procedures, and strong involvement of subject matter experts during operation/commissioning. Additionally, cryomodule repair capability is essential.

JLab/CEBAF

Major problems with initial cryomodules included tuner feedthrough leaks, helium leaks into insulating vacuum due to corrosion cracking of He piping or In seal failures, and leaks at the poly RF coupler windows. Helium leaks were mitigated by additional (active) pumping on insulating vacuum.

Largest contributor to operational downtime are arc trips due to charging of FPC cold ceramic window.

Rework of a number (10) of cryomodules (C50 program) by light etch (BCP) and HPR of cavities, some mechanical fixes (coupler dog-leg, reduced tuner backlash), and improved assembly environment cleanliness, helped establish robust 6GeV operation. Increase in useful gradient from 5.5 to 12.5 MV/m (limited by klystron power). Still find cryomodule Q's are low – potentially due to magnetizable components in CM or "fast" cooldown leading to trapped flux from thermo-currents.

Over time, there has been a statistically significant reduction in average cavity gradient of about 0.14 ± 0.05 MV/m per year. This is attributed to increase in FE. Some of this increase maybe due to uncontrolled (hurricane) and semi-controlled (CHL maintenance) warmup of cryomodules. This is believed to have led to an increase in ~50 new FE sites, with an average loss of 1-2 MV/m in gradient.

KEK/Tristan

Consists of 16 2-cavity cryomodules operating at 508MHz in CW mode, at a temperature of 4.3K. Cavities are EP'd, H-degassed, rinsed (not HPR), baked at 100°C (In seals), then vertically tested. No re-processing when installed in a CM (N_2 purge).

In operation, main problem is cavity trips due to synchrotron radiation on cavity liberating adsorbed gases (Hydrogen). Thermal cycle to ~50K used to reduce trip rate.

Not much performance degradation seen in cryomodule operation; main degradation occurs between vertical test and cryomodule assembly. Suspect that N_2 purging enhances SEY of surface leading to enhanced MP, and possible contamination from Indium seal removal/replacement. Recommend using Argon for purging instead of N_2, and bakeout of cavities at ~100°C in –situ.

INFN-LNL/ALPI

Unlike previously discussed high-β cryomodules, the INFN (and ATLAS, ISAC-II) cryomodules often employ a common-vacuum arrangement between beam line and insulating vacuum.

Cavities are operated at that gradient which leads to a maximum power dissipation of 7W in the He bath.

Cavity performance degradation is observed due primarily to increases in FE which lead to a decrease in Q_0. This is typically mitigated with RF and He processing/conditioning. Multipacting can also (re-)occur (potentially due to mis-steered bema liberating adsorbed gases?) and is conditioned away using RF with strongly overcoupled input coupler (they have variable couplers on all cavities/cryomodules, with significant range in coupling). They can condition Nb QWRs with up to 1kW in CW and pulsed mode (controlled automatically). At most 2-3 days are needed.

In some cases tuner hysteresis has increased, presumably due to wear in or loosening of components. Typical mitigation is to run at lower gradient or increase bandwidth.

Other issues have been mechanical/cryo related, such as leaks in cryo valves, thermal shield cooling leaks to vacuum, Viton seals failing in beamline valves, leading to 2-3 cryostats per year requiring maintenance/repair. There have also been some failures primarily in the cryo systems (not cryomodule related, but affecting cryomodule operation).

ANL/ATLAS

Early modules were not assembled in a clean room (similar to INFN practice) and had common BL/insulating vacuum, but later modules were assembled in cleanroom and had separate BL/insulating vacuum spaces.

Cooldown is typically “fast” to about 50K, then slower to 4K. 1.5 days overall.

ATLAS has run for about $1x10^5$ hours – of this about 2.1% were used to work on SC cavities/system. Scheduled maintenance over winter for 2-3 weeks; cryomodules removed as needed otherwise.

Any pumpdown/purge of cavity spaces is controlled using a mass flow controller to limit pressure change rates to 50mBar-l/sec. Typically, this yields 8hrs for cooldown of the 72MHz cryomodule. (This is also the practice followed at FNAL for e.g., preparing cavities for VTA, HTS testing, etc.)

Pneumatic tuner is reliable – only failure modes could be over-pressurization of bellows – mitigate w/pressure regulator. Dichronite coating of some hardware may reduce friction/binding.

Cold traps (LN_2 cooled) are installed surrounding all CMs to adsorb H_2O, gases, particulates, etc., from the warm beamline sections.

Some cavities (split-ring) have had performance recovered after removal and HPR.

So far no real permanent performance degradation from FE, FE onset is typically 9 MV/m, above operating gradient of 8 MV/m. Performance improvement typically from RF processing. If needed, MP conditioning takes ~minutes to hours. Couplers have been trouble-free.

TRIUMF/ISAC-II

Numerous issues were observed during the long time operation of the accelerator, including Q degradation after cavities installed in CM, Q disease (cavities not H-degased), trapped flux in cavities (magnetization of components in CM), some He leaks, feedthrough failures, etc.

Initial Q/gradient degradation in CM thought to be due to dirty assembly – mitigated by N_2 purge during assembly. Gradient loss between cavity test and CM ops about 4-5 MV/m (E_{pk}).

Cavities show a strong low level/low field MP (kV/m). Use variable coupler for conditioning, takes up to several hours. After cavity turn off/trip MP could re-establish, needs to be conditioned. Typical conditioning time reported to be ~15min(!).

Some cavities very susceptible to Q disease – even as little as 1hr when 150 > T > 50K. Mitigation – fast cooldown (1/2 hour in that temp regime). Otherwise need to warm to 200K. Try to always keep cavities < 40K even if cryo system failure.

Degaussing cycles are used if cavities have increased in temp above T_c but solenoid still on or has remnant fields. Degaussing includes solenoid bipolar cycling and warmup of cavities & solenoid above T_c.

Have been other failures – He leaks due to Indium seals (esp after thermal cycling), mechanical failures of tuners and dampers. Also some RF breakdown in couplers/cables.

Suggest to minimize thermal cycling, seen as significant contributing factor to CM problems.

MSU/ReA3

During initial operations, found that coupler needed additional cooling to allow cavities to run at higher gradients (>18MV/m). Now can run stably at 30MV/m

Warm sections (diagnostic boxes) are enclosed by portable-style clean rooms, pumps in diagnostic boxes maintain vacuum at $P < 1 \times 10^{-8}$ torr. Procedures developed for operation w/beamline open copied from SRF cleanroom procedures. There are many diagnostic elements in the ReA beamline; some of these are movable and candidates for particulate generation.

Until recently FE onset/levels have been stable and unremarkable, and MP not a concern (after initial extensive conditioning during commissioning). Recent increase in FE levels, earlier onset, primarily in end cavities. Also recurrence of strong MP barrier in one end cavity (upstream end). Pulsed and CW RF conditioning, and partial (40-50K, below Q-disease region) warmup, did not improve MP. Only improvements seen after a full (300K) warmup. So most likely MP returned due to contamination of higher-temp condensates (N_2, H_2O, CO_2, etc.) and full warmup was needed.

<u>General Observations & Summary</u>

Following the presentations from the active accelerator installations, and descriptions of the FRIB basic cryomodule design, ancillary systems, and Linac layout, there ensued a discussion regarding maintenance and repair strategies. There were a number of common themes or valuable points that arose from the presentations and discussion, to wit :

- When MP returned, RF conditioning seemed to alleviate it and typical conditioning times were minutes to several hours - rarely were “days” required to condition MP.
- MP conditioning was facilitated by using a variable coupler, especially one with a wide range of Q_{e1}.

- Field emission increase was by far the primary cause of Q degradation or operating gradient loss, and was usually alleviated by RF conditioning and/or a thermal cycle.
- Loss of diagnostics/instrumentation was also common, and accounted for a large number of repairs. Implement redundancy where sensors are critical, if possible, or replacement from "outside" (e.g., warm tuner motors).
- Leaks from He circuits to the insulating vacuum space were not uncommon – the standard mitigation was to actively pump the insulating vacuum spaces.
- While thermal cycles were used often to improve cavity FE/MP performance, it was still recognized as a "last resort" due to the very real possibility of establishing or exacerbating leaks, so thermal cycles should be avoided if at all possible.
- These thermal cycles were also used to mitigate migration of gases from warm beamline components that migrate to the cavity surfaces via cryo pumping. There did not appear to be consensus as to the "effective length" of this migration "mean-free-path" or whether it included particulates, but most agreed that since thermal cycling has shown improvement the effects must be real. Inclusion of cold traps in the warm beamline sections before cryomodules seemed to be recognized as a positive suggestion.
- Diagnostics on couplers are vitally important to understand if couplers are experiencing MP or breakdown. Typically larger coaxial couplers utilized vacuum gauges, arc detectors, and e-probes, while smaller couplers (e.g., ANL) utilize thermometry.
- Some installations actively pump (ion pump) the beamline vacuum, others use a TMP and isolate the pump during cooldown. No consensus. Choice may depend on the achievable vacuum level by the pump – a TMP will not reach the same vacuum level as a cryo-pumping cavity, therefore backstreaming must be avoided by isolating the pump. Not clear if same applies to ion pumps which can achieve 1×10^{-10} pressure level, on par with that achieved by cavity cryo-pumping. Perhaps the real question to ask is what is the benefit of an ion pump if you cryo pump the cavities? A TMP that can be valves off will be better suited for pumping down the beamline (or maintaining vacuum) as it warms up during a thermal cycle (ion pumps are notoriously poor at pumping high gas loads), and can achieve a good enough vacuum in the beamline before cryo-pumping starts at cooldown.
- There did not seem to be strong evidence for an active preventative maintenance program. Instead, accelerator downtimes were utilized to repair or address known issues or attempts to recoup performance. Except in the case where there was a known faulty or defective component (SNS HOM FTs) and a campaign to replace them as circumstances allowed was pursued.
- It was mentioned that, especially early on in a facilities lifetime, re-surveying beamline components is important due to shifts of components as the facility foundation settles (new construction) or additional components are added, loading the neighboring surface.
- Though it was very successful at JLab, He processing was not mentioned much or widely adopted as a cavity performance repair technique. Ditto plasma cleaning.
- The recent plan to adopt an isolation valve on the FRIB CM beamline to isolate the ion gauge for repair/removal, was generally supported by those in attendance.
- Having the ability to repair cryomodules "on site" was seen as a vital requirement to ensure continued operability of the accelerator, as evidenced by cryomodule repair activities taking place at every installation discussed. Preferably repairs take place outside of the accelerator tunnel, for obvious reasons.