System requirement specification for replacement cryomodules for CEBAF linac
Jay Benesch
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Abstract

This specification was inspired by the mention by Mike Maier at the Operations Staytreat in July 2017 that he was surprised that JLab did not do systems engineering. Having two years experience in this at GE, I decided to write a sample specification informed by my 24 years supporting the SRF department's product in Operations. The numbered items comprise the specification. The lettered items are justification or explanation. In an organization with formal systems engineering, these would be removed after negotiations with stakeholders resulted in a final specification.

Mr. Maier reviewed the November 3 draft of this specification and provided the comments below in an email. Readers will judge how well I've fulfilled them.

Jay,

Good start on a accelerator cryomodule requirement.

Having written and having responded to a bunch of requirements over the years I have developed five rules for what I think work well.

These are:

1. The requirements should be unambiguous. That is, if any part of the requirement is subject to interpretation, then any interpretation of that part must be acceptable. A good requirement is one that can be successfully implemented by any developer skilled in the requisite technology and a perfect requirement is one that can be successfully implemented by any developer independent of their skill in the requisite technology.

2. The requirement should be complete. That is, the end item should be fully capable if built only to the requirement. If some feature or capability is essential, it must be in the requirement.

3. The requirement must be verifiable. That is, each requirement needs to be provable, if a requirement can't be proven, then it is either not essential or poorly written.

4. The requirement must be self-consistent. That is, no part of the requirement should contradict another part.

5. The requirement should be solution independent. That is, the best requirements just speak to desired features or capabilities without overconstraining the design. I think this is one of the most important (and often violated) requirement rules. For example, the Range Safety organization at the space center for many years required that every rocket have two independent tracking sources. The intent was to never not have at least one tracking source during powered flight. But this dictated a solution and was contested by new entrants (like SpaceX) who argued they could fly safely with one source as long as they could demonstrate that single source met the 30X10^-6 casualty requirement imposed on them by statue.

I think we should be encouraging this sort of practice, it would bring much needed rigor to the design, development, and eventual operation of a world-class accelerator.

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1. Cryomodules shall be fabricated of all new material.
   a. Justification: The change in overhead rates in FY18 altered the labor/material cost balance. Purchases now see 9% overhead while labor is 124%. This 115% difference means that the more-than-doubling of labor required for refurbishing an existing module exceeds the cost of building a module with new material. No radioactive material precautions need be taken with new material.
   b. Justification: Four of the twelve refurbished C50 modules in the tunnel have supplemental vacuum pumps on the insulation vacuum (one third). Modules were selected for refurbishment based on low gradient sum, not leaks. Only seven of the remaining twenty-nine original modules have leaks (one fourth). It may be that handling during refurbishment cracked welds or brazes or that radiation-hardened elastomers were not replaced due to inaccessibility. *One of the C100 modules has already developed a leak too.*
   c. Justification: private communications from SRF personnel indicate that visibly worn parts are being re-used for C50 refurbishment because they are grandfathered under JLab's pressure vessel code application; the responsible engineer states exact replacements would not be. Another subject matter expert disputes this interpretation. Root cause of (b)?

2. No chlorine-bearing cutting or forming fluids shall be used on carbon or stainless steel parts, especially bellows. This requirement shall be included in all procurements except fasteners.

Cavity/cryounit specifications

3. Cavity pairs may be of five cells (four pair per module) or nine cells (three pair per module). If the transverse E field from the fundamental power couple cannot be reduced sufficiently in the latter case to ~1% of original CEBAF design, the modules will be produced in pairs having six cavities each facing wall and aisle. If there are eight cavities per module, four to wall and four to aisle unless transverse E field is ~1% of that in original CEBAF FPCs.

4. Bolt patterns for rectangular indium wire seal flanges shall be patterned after those on gate valve bonnet seals (no holes in corners) and modeled in a mechanical finite element code to determine flange thickness and torque so deflection in flange is less than 1% of as-supplied wire diameter along wire path. Roughness and flatness specification on sealing surfaces shall also be 1% of as-supplied wire diameter. If thicker flanges can, at fixed deflection, reduce the number of bolts and therefore chance for particulate generation during assembly, do so. Consideration should be given to replacing individual nuts with U's with threaded hole pattern to reduce flange deflection. BeCu Belleville washers under bolt heads.

5. Helium vessels will be similar to those used in the original CEBAF modules, not the C100s. Large LHe volume required.

6. 44 mbar He pressure at return end can exit shall be assumed in all design calculations.
   a. When running on one CHL there is a 2 mbar pressure difference between the centers of the linacs where the large return lines exit to the CHL and feedback pressure sensors are placed.
   b. There is a (modeled) pressure difference of 3.2 mbar from the injector to the NL sensor at 200 g/s.

c. The CHLs are limited to ~39 mbar by stress on and therefore rotation rate of CC4.
d. 44 mbar design spec ensures that new cryomodules can be operated anywhere in the tunnel.

7. Magnetic shields within the helium vessel, if used, shall be ≥3 cm from cavity equators and perforated with 5 mm holes covering about 5% of the area to create short paths for heat transfer from the cavity vicinity to the main LHe reservoir.
   a. Steve van Sciver's textbook assumptions are unlikely to reflect the geometry here so simply following the text is a concern. Ask him. If he says the slots as now designed suffice, OK
   b. TN 17-043 Opera magnetic analysis https://jlabdoc.jlab.org/docushare/dsweb/Get/Document-143478/17-043.pdf

8. Cavities which produce less than 14 MV/m at 0.1 W field emission in vertical test will be reworked.
   a. Calculated by assuming beta of 100 in field emission and 20 MV/m maxium. $0.1*100*(20/14)^{2.5} = 24.4$W

9. Input Qs of the cavities seen by the RF system shall be such that bandwidth shall be at least 100 Hz as-fabricated. Recommended bandwidth range 100-150 Hz.
   a. Three-stub tuners in RF racks above grade may be used to reduce bandwidth. They have not in CEBAF experience been able to increase bandwidth, hence absolute 100 Hz lower limit on sheet metal fabrication.

10. The first vacuum window in the input waveguide shall NOT have line of sight to the beam axis so as to reduce charging by field-emitted electrons.
    a. This may be accomplished via, e.g., dogleg waveguide as in the C50s or a 90° bend in the waveguide as in Wiseman's original C100 design.

11. Cavity pressure sensitivity shall be less than 400 Hz/mbar. O*riginal CEBAF specification was 525 Hz/mbar.*
    a. In the 30 minutes beginning 1000 on 2/16/17, pressure at NL tee varied 0.03682-0.03689 bar, mean 0.03685 bar, sigma 12 μbar (~5 Hz at spec). *Interval chosen arbitrarily.*
    b. In the 30 minutes beginning 1000 on 2/16/17, pressure at SL tee varied 0.03744-0.03758 bar, mean 0.03750, sigma 28 μbar (~11 Hz at spec). There was a 150 μbar excursion 1046-1048 that morning (~60 Hz).
    c. specification 11 is derived from observed historical pressure variation and the input bandwidth in specification 9. See (41) for comment on microphonics.

12. Cavity frequency change as a function of Lorentz force shall be less than 4 $Hz/(MV/m)^2$, 1024 Hz at 16 MV/m. Less is better. *Original low level RF controls will need to be replaced.*

13. Cavity frequency shall be greater than 1497 MHz unrestrained at 2.1K (44 mbar) so tuners are always in compression. 1497.15 MHz upper bound desirable.

14. Cavity pairs which do not pass the integrated superfluid leak test devised by G. Myneni at the 10^{-13} torr-liter/sec level will be reworked.

15. Tuners shall be of the original CEBAF style but use all non-magnetic components including gear boxes (e.g. BeCu used in mines) and rotary feedthroughs to room temperature.

16. Cavity pairs shall be tested in vertical dewar with tuners and any magnetic shielding installed.

17. Tuner function shall be tested before cryounits are welded shut.

18. Cryounit assembly, including cavities, tuners and magnetic shielding, shall not have mechanical normal modes less than 100 Hz so as not to be excited by pulsed beam at 60 Hz. Demonstrate by CAD analysis including LHe and prototype testing with hammer and accelerometer.

19. HOM (higher order mode) loads shall be of the Campisi type, installed in waveguides beyond cutoff for the fundamental. HOM waveguides shall be located at "45º" points, aka NE, SE, NW and SW on compass rose, not vertically and horizontally, to eliminate RF skew quadrupole component in original CEBAF design. The normal RF quadrupole resulting should be calculated so it can be incorporated in the normal linac optics.
    a. It is likely that the carbon material used in the original loads was over-specified. Common soot or crushed anthracite may suffice. Original German source retired two decades ago. Again, proper bolt circles shall be used on the flanges.
    b. Coaxial HOM couplers are problematic due to the balance needed among adequate coupling to higher order but not fundamental modes and not intercepting the beam. Loads in waveguides beyond cutoff do not have this problem. For CEBAF to 1 mA in linac, heat load to 2K bath from Campisi-type loads is not an issue and the damping is at least an order of magnitude better than C100 coaxial HOM couplers.

20. Temperature measurement diodes shall be placed on the beam pipes between pairs and at the interface between cryounits and end cans (six total). Other temperature sensors as helpful for cooldown may also be installed.

21. At least two liquid level sensors shall be installed in each cryomodule. These shall be tested in a small dewar before installation to insure that there are no thermal shorts greater than 0.25% in the range 75-100%.

22. Field probe effective Q shall be such that power output to RF feedthrough on the outside of the cryostat (300K) is 140 to 330 mW at 20 MV/m and 90 to 220 mW at 16 MV/m.

23. Minco foil electric heaters sufficient for 100W each shall be placed in each cryounit.

24. Tube diameters between cavities and cryounits shall be set with the need to minimize propagation of field-emitted electrons through more than one cavity. See also (36).

25. If the inter-cryounit piping and end cans can be designed to support the cooldown rates found by FNAL to help exclude flux, do so. Unlikely given LHe volumes, but ....

Cryostat and cryomodule specifications

26. Emissivity control, either one layer of superinsulation or aluminized mylar tape, shall be applied to the OD of the helium vessel and the ID of the 50K shield. No superinsulation shall be installed between them. For the ID of the 50K shield, 0.01" thick aluminized mylar is springy enough to make good thermal contact and is easily installed; tape at ends to secure.

27. Outside the 50K shield, single sided aluminized mylar with dimples multi-layer insulation shall be applied to manufacturer's specification.
    a. No interlayer material shall be used as all adsorb large amounts of water.
    b. See FNAL TN 1618, J.D. Gonczy, W.N. Boroski and R. C. Niemann, Thermal Performance Measurements of a MLI System for the SSC Part II- Laboratory Results. September 1989

28. Static heat leak shall be less than 30 W to 2K and 150 W to 50K. Dynamic heat load shall be less than 200 W to 2K. Internal LHe/GHe piping shall be sized for 300W to 2K to allow for degradation over time.

29. Helium vessel supports from the 300K vacuum shell shall minimize transmission of vibrations less than 100 Hz and 980-1040 Hz (TwisTorr frequency 1010 Hz). Alternatives with internal damping (to the narrow stainless rods used in original CEBAF design) should be considered.
    a. These could include wire rope or continuous filament-wound straps connected via clevices.

30. 300K to 2K waveguide vacuum need not be fully isolated from insulation vacuum at the ultra-high vacuum level if waveguide is isolated from beam line vacuum by a cold window. Whatever is used has to withstand 1 atmosphere differential pressure in both directions because pumpdown sequence can't be guaranteed.
    a. Alternatively, low-conductance tubes joining WG and insulation vacuum, perhaps inside the 50K shield, shall bridge the two vacuum volumes to ensure differential pressure does not exceed the WG material strength limits.
    b. Composite materials with inside coating of 10-12 microns of copper or aluminum which have thermal contraction reasonably matched to stainless steel and are compliant for bending as cryounit assembly shrinks towards the center should be considered. Glass-loaded Ultem, used for RHIC magnet supports, is one possibility. E-glass epoxy is another. Aluminized mylar held in waveguide shape with an external alumina frame and epoxied to 2K and 50K stations is a third.

31. If the waveguide vacuum is isolated at the percent level or better from insulation vacuum, differential pumping shall be supplied by a temporary (tooling) system during cooldown. After cooldown only a particulate-free vacuum gauge shall be used to monitor waveguide vacuum. Waveguide vacuum gauges shall be one per cavity, not paired as in original CEBAF modules, so fault source can be determined and mitigation attempted.

32. Ion pumps shall not be used.
    a. sputtering from ion pumps on the beam line has been shown to introduce particulate into cavities, likely causing degradation due to field emission.
    b. NEG pumps, cryo pumps or turbo pumps with remote electronics may be used.

33. Vacuum interlocks shall be set no lower than 5E-7 torr
    a. Tests to determine at what pressure (as measured at room temperature) RF discharges occur in cold RF structures should be undertaken to determine if this value can be raised. It is known from CEBAF experience that this value is sufficiently low; how much higher it can go has not been tested.

34. Warm RF windows shall be brazed into rectangular CF flanges so the temperature constraint on the window is at least 200C. Or the temperature limit of the material used to satisfy (28).
    a. While rectangular CF flanges are expensive and may be larger than typical waveguide

flanges, this eliminates the need for a warm window temperature sensor and interlock.

b. While multi-physics modeling is probably capable of handling everything including convective air and conductive cooling, prototyping the assembly from klystron to stub tuner through to cavity is faster and likely cheaper.

35. Vacuum vessels may be made of carbon steel if provisions are made for in-tunnel demagnetization. Conductor used for demagnetization shall be installed on each cryomodule and remain with the cryomodule so systems may be demagnetized at installation and whenever a cryomodule is warmed to 300K for other reasons.

36. Cryomodules shall produce at least 64 MeV (eight five-cell) or 85 MeV (six nine-cell) energy gain in CEBAF tunnel with field emission less than 100 R/hr (~10^5 hours of superinsulation life) just outside the beam lines at the ends of the module and circumferentially. Cryomodules should not be tested before tunnel installation. All cryomodule testing after initial frequency tuning shall be accomplished via EPICS controls so data may be archived. Only testing which is required for CEBAF Operations or which is timely enough to feed back to manufacturing process improvement shall occur.

37. It is suggested that a fiber-based radiation sensor be placed within the vacuum vessel.

38. A pressure sensor which is reproducible to 0.0001 bar and accurate to 0.0002 bar shall be connected via a valve and tee to the output gaseous helium port on the return end can. The valve and tee are to allow annual re-calibration on an in-house test stand; material activation will preclude outside calibration. The tee will have a second valve to allow the isolated volume to be pumped out after gauge recalibration and re-installation.

39. Consider installing a BA gauge or Pirani/Penning gauge combination to monitor the insulating vacuum. A gauge which reads below 1E-4 torr must be installed. Gauges must allow for electronics to be placed at least 20m from gauge head, i.e. upstairs in the linac service building.

40. Elastomer o-ring use shall be minimized
    a. due to radiation hardening causing leaks.

RF power source

41. RF power within linear response shall be sufficient to deal with three-sigma pressure variation with 1 mA in the cavity at 20 MV/m, ~33 Hz zero to peak. Per Marhauser et al. C75 specification, three sigma of microphonics is 12.6 Hz, to be added in quadrature, and 15 Hz absolute detuning allowance is needed. Thus RF power should allow 50 Hz detuning at 1E7 external Q. The “13 kW” klystrons would suffice for the five-cell cavities. 20+ kW would be needed for the nine-cell, but only two-thirds as many. Klystrons or IOTs, minimizing total cost including engineering/development by vendor. [Environmental assessment allows for 1 MW <u>each</u> to halls A and C. FONSI wording clean up by a request to ORO and memo to file.]

42. Power distribution: it was pointed out by an RF technician during the response to the 11/25 power incident that the power distribution system may not suffice for the C75 program, much less the modules specified here. The 12 GeV distribution upgrade simply replaced aluminum cables with copper, gaining 62%. No conductor area was added. Power panels (4160V) and breakers were not replaced in the old zones. Evaluate. No cost included in guesstimate.

Pressure vessel code

This is not an area in which I have expertise. Over 30 years ago while at GE I was involved in a failed attempt to pay ASME to write a code subsection specifically for cryogenic vessels. ASME refused and continues to refuse. GE designed first to JSA and TUV-Rhineland cryogenic specifications and then did calculations to get ASME stamps under allowed variations. Something of the sort should be applied. The code used by DESY for XFEL should also be examined for utility here.

a. graphite burst disks are preferred to spring-loaded relief plates with elastomer o-rings for reliability and because radiation hardening allows for leaks in the latter over time.

Quantity

43. Material shall be purchased for 24 modules if the five-cell option is chosen, yielding 768 MeV per linac. This will allow the C100s and the seven worse performers among the C25/C50 population to be replaced. The remaining 13 older modules will have to provide 33.25 MeV each to total 1200 MeV/linac. If the nine-cell option is chosen, material for 16 modules shall be purchased if they have to installed in pairs due to FPC kick. Eight per linac yields 680 MeV with 520/17 = 30.6 MeV each needed from the 17 old modules per linac. Material for two spares of either type should also be purchased but need not be assembled.

44. RF tubes sufficient to power 110% of the new cavities shall be purchased per specification 41.
    a. This should provide sufficient spares to deal with infant mortality and replacement time for later failures. If there is contingency remaining after full installation, 25% spares.

Inconsistencies

45. Perceived or actual inconsistencies among these specifications shall be presented, with calculations backed by whatever data exists, to the Director of Accelerator Operations for resolution.

Cost guesstimate

46. $2.25M materials loaded per module irrespective of number of cells. Klystron and LLRF costs will be higher for nine cell option, perhaps $1M/zone vs $0.8M/zone for five cell.

47. Labor: ~100 person-years were required to build the 40 original CEBAF modules in two years, say 2.5 person-years/module or $600K/module with current labor and overhead cost. About the same labor is being expended on the 20 LCLS-II modules over two years, so 5 person-years/module with a more involved cavity process. Cryounits are easier to build and merge than a unitary LCLS-II module. Say 4 person-years per module specified above. Minimum staffing to cover all functions is about 32 or $7.2M/year. At eight modules/year, $900K/module. At six modules/year, $1.2M/module. Assume six/year, 5.33 person-years/module.

48. Nine cell option at six/year: $11.5M materials and $7.2M labor = $18.7M/year. 2.5 years to finish 16. $51.3M before contingency including two sets spare material. Add $2.7M development and engineering, $54M. RF $1M*16+spares, $18M. $72M total. With one-fourth contingency, $90M.

49. Five cell option at six/year: $18.7M/year as above but 4 years to finish 24. $79.3M before contingency including two sets spare material. Add $1.7M development and engineering as much has been done, $81M. RF $0.8M*24+spares, $21M. $102M total. With one-fourth contingency, $128M.