C75 Project and Implementation Review – Final Report

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The C75 project represents a change in the CEBAF gradient maintenance program, requires significant lab resources and its success is a critical aspect of the CEBAF Performance Plan (CPP, JLAB-TN-17-022) as well as the Nuclear Physics 12 GeV program. The C75 project draws on the direct NP resources of the Accelerator and Engineering division, as well as indirect resources to support procurement for the project and any required changes in the power and cooling infrastructure.

At this time, the "C75 Project" is not yet an approved project at Jefferson Lab, with defined scope, resources, and schedule. It presently consists of a set of evolving plans not yet formally baselined or resourced.

The Director of Accelerator Operations invited a review committee to consider the present state of analysis and readiness to proceed with project implementation. The committee membership consisted of JLab staff members: Matthew Bickley, Rong-Li Geng, Sarin Philip, Ken Baggett, Joseph Preble, and Charles Reece, chair.

The review committee was asked to consider five charge elements. On February 15, 2018, twelve talks were presented to the review committee these and other background documents form the basis of the review. (https://www.jlab.org/indico/event/251/) This report provides the committee's responses to the charge elements.

Charge 1

Does the proposed C75 system meet the requirements as defined in the CEBAF Performance Plan?

Yes.

The CPP requires new accelerating voltage added to CEBAF on a particular timescale. Implementation of C75 zones on the proposed schedule would fulfill that requirement.

Will the C75 module, RF controls and power deliver an integrated gradient of 70 MeV in GDR mode?

Yes.

For the C75 system, the design target is 80.6 MeV, the specification is 75 MeV, and the operational requirement per the CPP is 70 MeV. The generous design margin results in a robust solution. The most significant performance risk appears to be related to avoiding field emission effects, since the peak surface electric field is 50 MV/m at design target; this is significantly higher than the achieved average value of 32 MV/m in C50 or C100 cavities, and 25% higher than the surface fields for LCLS-II cavities at their design target of 21 MV/m accelerating gradient.

Will the tunnel installation and commissioning of up to two C75 systems per FY allow for 37 weeks of CEBAF operation?

Yes, when called for.

The CPP states that 37 weeks of operations will allow for 1 module swap and that the number of run weeks needs to be reduced to 35 weeks to support 2 module swaps (CPP, pg 8).

The level of coordination and intensity of parallel activities that would be required for installation and commissioning of two zones per year would be challenging. The CPP calls for 37 weeks only beginning in 2023, after full energy reach is achieved with appropriate margin.

Recommendation

1. Staffing resources should be carefully evaluated to ensure parallel efforts for installation are realistic with the current staff or a plan for additional staff should be developed and approved.

Is the system design robust, reliable and maintainable? Is the proposed system consistent with a 20+ year 12 GeV CEBAF program?

Conditional Yes.

While the system design appears to be robust relative to the required performance, its reliability and maintainability will be similar to the present C50 zones, better than the C20's. Both are heavily dependent upon JLab's institutional technical expertise in controlling field emission for the entire life cycle of each cryomodule and rely on subcomponents circa 1991. LLRF maintainability of the proposed system will be the best available.

Observations:

- C75 preliminary design review was conducted on January 21, 2016. Out of three charge questions, the review committee responded three charge questions with one YES and two CONDITIONAL YES. The written report of that review was made available to this present C75 project and implementation review committee.
- The CEBAF accelerator performance plan (CPP) was published as a JLAB Tech note in June 2017.
- CPP defines gaps in CEBAF accelerator capability for supporting 12 GeV era physics and presents a plan to close gaps for the 15-year period from June 2017 to June 2032.
- The 5-year period from June 2017 to June 2022 closes the CEBAF performance gaps while the 10-year period from June 2022 to June 2032 addresses system obsolescence, i.e. obsolete 4 GeV CEBAF systems.

- CEBAF performance goals defined in CPP:
  - Energy reach: 1090 MeV/linac (Injector energy 123 MeV)
  - System reliability: > 80%
  - Operations performance: 37 weeks-per-year with 4-hall multiplicity
- Performance plan
  - First priority is to improve CEBAF availability.
  - Full design energy will be reached in 5 years by FY22.
  - The energy reach gap at the end of FY22, assuming no performance plan in place, will be 100 MeV/linac + 5*17 MeV/linac = -185 MeV/linac.
    - The CPP addressed closing this gap via rebuilding or new cryomodules in amount of
      - 15 C50 module rebuilds, or
      - 8 C75 module zone upgrades, or
      - 6 full new C100 modules zones
  - Analysis of cost per MV of energy for these three potential cryomodule upgrade paths found that the C75 concept provided the most economical solution.
  - C75 cryomodules will have
      - New higher-gradient cavities (~19 MV/m)
      - High power klystrons (8 kW)
      - Digital controls
- C75 design and prototype
  - The C75 program was proposed in 2015 as the least invasive, least expensive modification to a C20 cryomodule by replacing the old Original CEBAF fine grain cavity cells with new large grain cells exhibiting a High Current cell profile (JLab prototyped design), while recycling as much of the cavity and cryomodule components as practically possible such as the FPC and HOM endgroups, helium tanks, cold RF windows, mechanical tuner components, and HOM 2 K waveguide absorbers, while replacement loads have been identified for the latter if needed.
  - The energy gain of 75 MeV equates to an accelerating field of nominally 19.07 MV/m per cavity, which also requires an upgrade of the original 5 kW to 8 kW RF system zones.
  - The associated dynamic heat load expected for C75 cryomodules at the specified cavity Q_0-value of 8e9 at 2.07 K is within the cryomodule heat load capacity and deemed supportable by the central helium liquefier plants.
  - External Q specification for the various cavities operating in CEBAF
      - C20: 6.6E6+/-20%
      - C50: 8E6 +/-25%
      - C100: 3.2E7 +/-20%
  - Q_{ext} = 2.0E7 ± 15% for C75 cavity.
  - 30 Hz peak microphonics detuning is specified for C75 cavity in operation.
  - Maximum beam loading for 12 GeV CEBAF: 460 µA.
  - New 8 kW klystron is proposed for C75 zones, allowing regulation of peak microphonics detuning of 35 Hz.
  - C75 cavity length (flange to flange) is ≈4.5 mm longer compared to C20/C50 cavities. This difference is considered of no consequence.

  - The cost of medium-purity ingot Nb discs is about a factor of three lower than that of typical high-purity fine-grain sheets.
  - Magnetic shield around cavities inside the liquid helium vessel was implemented for all cavities in cryomodule C50-13.
  - By November 2017 cryomodule C50-13 including two C75 prototype cavities was commissioned in the CEBAF tunnel.
    - No issues were found when operating the mechanical tuners of the C75 cavities with the modified cell holders. This validates that the mechanical stiffness of the C75 cavities is comparable to that of C50 cavities after adding stiffening rings and agrees with earlier bench tests for a C75 prototype and a C50 cavity with and without the cavity magnetic shield installed.
    - Furthermore, microphonic measurements for C50-13 cavities have shown that the peak detuning levels (6σ) in C75 prototype cavities in reworked C20 cryomodule were below the specified allowance of 30 Hz during the measurement period.

Comments:

- Installed C100 cavities have demonstrated acceleration gradient capability significantly higher than the actually used gradients for physics runs. FSD trip rate has a heavy impact to the usable gradient and the CEBAF energy reach. The integrated system is not sufficiently stable at the higher gradients. The root cause of RF related FSD and its gradient dependence are not well established. An improved understanding of the RF related FSD may result in a path to modifications which significantly increase the accelerator energy reach in a cost-effective manner, taking increased advantage of the installed cryomodules.
- The gradient loss "rate" of C50 and C100 cryomodules is yet undetermined and should be evaluated and compared to the established rate of loss for the C20 cryomodules. This is needed to verify that the CPP energy reach plan will achieve its goals.
- An analysis of historic severe gradient loss in cryomodules that necessitated total replacement of the units would identify failure patterns. The CPP should include a statement on the performance impact of a prompt loss of a C20, C50 or C100 cryomodule and make clear the inventory available for response.
- Any end-of-life issues for the C20 cryomodules should be identified, with an eye toward performance degradation preceding end-of-life that serve as early indicators. Lessons learned should be folded into future C50 rework and C75 development.
- In the CPP, the margin in energy gain varies significantly for a C20/C50/C75/new C100 zones. Has JLab SRF/CEBAF operation established a credible design criterion for choosing the margin in cavity operation gradient for beam acceleration and driving the cryomodule and cavity design using this margin?
- The cost per MV of energy has been used to compare various gradient maintenance/recovery options. C75 is favored for its lowest cost per MV. Cost factor was a driver in making the C75 choice among other approaches. The mitigation of particular risk factors and administrative requirements flowing from this design should continue to be pursued aggressively to avoid delays in project implementation. Examples:

    - Mitigation of performance-limiting field emission contamination.
    - Uncertainties in integrated system reliability with new high power RF and new LLRF.
    - For potential propagation to other applications, the pressure code compliance due to use of large-grain niobium cavity and fulfilling code stamp requirements.
- Q_{ext} for C75 cavities are chosen with relevant factors carefully considered.
- HOM impedance calculations are systematic and thorough, allowing one to verify that the C75 specification is comfortably within requirements for 12 GeV operations. QA checks during production testing are able to confirm realization of design properties.
- Availability of appropriate ingot niobium disks at the cost of 1/3 of the high purity fine-grain sheets for 64 5-cell cavities needed for eight C75 cryomodules should be confirmed early.
- C75 cryomodules are operated at gradients significantly higher than C20 cryomodules. Full voltage operational testing of its prototype cavities meeting C75 project specification in C50-13 have not yet been carried out due to lack of RF control dynamic range.
- E_{pk} =46.7 MV/m for C75 cavities at specification. This can be compared with E_{pk} =41.7 MV/m for C100 cavities at their E_{acc} =19.2 MV/m specification, and E_{pk} =32.4 MV/m at E_{acc} =16.2 MV/m for LCLS-II. The C75 cavities will be more vulnerable to particulate contamination on the beamline than either C50, C100, or LCLS-II cavities under specified operating conditions.
- FE onset specification for E_{pk} =48 MV/m (E_{acc} =19.5 MV/m) for C75 cavities is aggressive as the actually achieved E_{pk} has been around 32 MV/m for major large-scale SRF projects carried out at JLab, including SNS, C50, C100 cavities. On-going effort for LCLS-II helps JLab in developing and practicing improved procedures for SRF handling and assembly, but the LCLS-II requirements are less than for C75. Major efforts and initiatives are required to control field emission reliably at E_{pk} level specified for C75.
- There appears to be no present attention given to meaningful C100 rework planning. Once design uncertainties are resolved, the cost-effectiveness of this may compare well with C75 zones.

Recommendations:

1. Take full advantage of the recent and continuing cryomodule work for LCLS-II; document the best practice in field emitter control in cavity string and cryomodule assembly. Translate and apply these standards, and better, in C75 work.
2. Continue/launch programs in parallel with C75 project to attack aggressively the field emission problem including its control and mitigation for the entire life cycle of a cryomodule.
3. Systematically review the recycled cryomodule components for their compatibility with cryomodule maintainability and 20+ year 12 GeV CEBAF program.
4. Maintain vigilance; aspire to zero tolerance for particulates; accept the opportunity to establish world leadership addressing this challenge.

Charge 2.

Is the C75 system specification document complete?

An integrated specification document for a C75 system, which includes SRF cryomodules, RF power and controls, cryogenics, beamline vacuum, and electronics interface for controls does not exist at the project level. Each sub-system has specifications that align with accelerator needs and appear to be well defined. A single reference document that collates specifications from each of the sub-systems will be useful in meeting the design goals of the first C-75 module within the very stringent time constraints. Completion of such a document would allow increased confidence in the overall system integration.

Are the cavity<->RF controls/power interface parameters clearly defined

The cavity to RF controls/power interface parameters are defined in terms of existing systems. The reference specification document, that clearly states any change in parameters, should be created by the project in order to mitigate pressure on design time, installation schedules and commissioning time. Parameters that are not affected should be defined as “No changes”.

C-75 Cavity to Cryogenics Interface:

- Temperature, pressure, de-tuning, impedance, window losses, cryogenic load, cryogenic flow appear to be clearly specified in “C75 Cavity Design Parameters and RF specification” table.

Comments:

- JT valve controls, cryogenic temperature gradient in Linac were not addressed

Cavity to Vacuum pumps:

- New “NEG” pumps and ion pumps are defined

Comments:

- Vacuum pump interface to controls and instrumentation were not defined in the presentation
- C-75 Module to beamline vacuum interface not addressed (Fast valves, mechanical etc)

RF power to cavity:

- High-voltage power supply input and output specifications are well defined
- Klystron power and cooling specification is defined
- Circulator power and cooling is defined

Comments:

- High-power Waveguide stub tuners need to be fully specified

Recommendation:

1. Hardware specifications and costs to meet LCW requirements for C-75 high-power RF needs to be finalized and agreed to by facilities, RF engineering, and project.

RF controls to cavity:

- Analog RF controls have been verified in operation at 1L13
- RF Digital controls using C100 based hardware has been verified in VTA
- Controls bandwidth, Lorentz detuning, impedances and stability requirements appear to be well defined

Comments:

- Digital RF controls are required for full gradient/power operation.
- Stepper motor to cavity tuner control interface should be specified.

Recommendation:

2. Heater control interface/specification between RF controls and Cryogenics needs to be addressed

Charge 3:

Are the resource requirements for the C75 system comprehensive and appropriately defined?

- **SRF resources**
- **Eng. resources**
- **Facilities resources**
- **Operations resources (Software, commissioning support,…)**

Findings:

- The SRF production labor and procurement requirements for the C75 system are both complete and well-defined for the project. Using the C50-11 project as a starting point for these resources estimates lends credibility given the similarity between the two projects.
- The technique development and any implicit retraining or retooling associated with solving the field emission inducing particulate issue described under Charge 1 was not included in the presented resource requirements.

- The engineering labor and procurements associated with the new low-level RF system are clearly stated and appear justified.
- The resources required from the facilities management division are well understood. The costs are outside the scope of the C75 project, but the committee was told that the required accelerator site improvements have already been incorporated into the long-range plan for the division.
- The operations resources required for the C75 project were not addressed during the review.

Comments:

- Two aspects should be added to make the SRF resource estimate complete. First, the plan should include an explicit summary of the new investments required to support field emission-free operational performance of C75 cavity pairs. Second, the plan should include additional technical oversight for the first cryomodule by knowledgeable scientists and engineers, since it should be expected that more analytical and problem-solving engagement will be required for the first article of the series.
- The low-level RF plan laid out in this review was not the same as the plan developed for the C75 preliminary design review, held in January of 2016. The committee believes that the low-level RF group in the engineering division will be severely challenged to meet the milestones laid out in the CPP, given the development effort that will be required and the staff currently available. A resource-loaded schedule would help clarify what skills are most constrained and when those constraints are expected to impact the C75 schedule.
- The creation of a complete services requirements document would help ensure that the necessary facilities improvements will be implemented when operationally needed.
- If a new digital low-level RF system is not available and the first C75 is controlled with the existing CAMAC-based analog RF system, it was made clear that the zone will be limited to ~60 MV, providing 10 MV energy gain less than required in the CEBAF Performance Plan at that point in time. Implementing control with the digital RF system in use for the C100 zones would make this additional voltage available.
- No overall resource-loaded schedule was presented. The committee is thus unable to judge whether the schedule presented is consistent with available resources at JLab.

Recommendation:

1. Develop a resource-loaded schedule for implementing control of the first C75 zone with the existing C100 low-level RF system. This would be a contingency plan for the first C75 zone if development time for the new LLRF is not compatible with initial commissioning of that zone.
2. Add the resource requirements to address recommendations in Charge 1 and 5.

Charge 4

Have the project risks been identified and addressed?

A good start has been made on identifying risks and risk mitigations for the project. To this point the risk assessment is qualitative and highlights areas for concern. There is benefit to a risk assessment that identifies quantitative impacts and mitigations to help guide the use of project resources (time, people, and dollars) to the best effect.

An example is,

- *Description* - The unique program that recovers end groups from existing SRF cavities for use in the vendor fabrication of new cavities may impact the performance of the delivered cavities.
- *Impact* - Reduced energy gain from the cryomodule (5-15 MeV).
- *Risk level* – Medium
- *Mitigation* - Fabricate SRF cavities in house as a parallel supply of cavities.
- *Cost* - XX$$
- *Mitigated Risk Level* - Low

Recommendation:

1. Build a quantitative risk assessment, then reevaluate whether adequate resources are identified and assigned to adequately address the most significant risks.

Charge 5

Is the presented project organization and management appropriate?

The accelerator project organization for the C75 project was presented. Randy Michaud was presented as the primary project manager for the CPP project with all roll up sub-projects of the CPP assigned to him. A high-level WBS for the CPP-Energy Reach (1.04.8.006) has been created and sub-projects all have named project managers.

Comment:

- The C75 project is currently a "No Fund" project. This means any work currently done to move the R&D effort forward has been absorbed under some other project funding as an improvement to other lab funded efforts (i.e. C50-13, etc.). This lack of funding and coordinated oversight may result in design silos as the SRF/RF/Facilities/Cryo groups struggle to move C75 forward. Immediate funding is needed to control this aspect of the C75 project.
- Responsibility for system integration is unclear. This is true both for detailed design integration and performance optimization during implementation.

- In JLab's typical task multiplexing environment there is risk of time/attention over commitment of key individuals, including sub-project managers.

Recommendations:

1. Create a clear set of gateway milestones that float in schedule with available resources.
2. Assign project funds to the project as a whole or define and fund the initial aspects of the project that need early oversight.
3. Confirm that management responsibilities are assigned to individuals with sufficient availability to provide the needed technical and budgetary oversight and communication in the context of other duties.

<u>What additional controls if any should be implemented?</u>

Comment:

- This is a large complicated project that involves several groups across divisions at JLab. Systems engineering needs to be incorporated into the C75 project because of the complexity of the project, the number of groups, cross division collaboration, and other issues detailed earlier in this document.
- As addressed in the response to Charge 2, an integrated system specification document is required. Subsequent to that, a systems engineering document set is needed to capture engineering implementation choices.
- The systems engineering document should describe and mitigate risks (referencing the risk assessment document) associated with several aspects of the design and implementation. The document must identify areas with potential gaps and overlaps between groups as well as specification details, schedule and any iterative improvements that may be required during manufacturing, testing and installation. It should serve as the shared communication tool to also minimize risk of misidentified expectations at interaction points in the C75 system design and schedule.

Recommendation:

4. Create a system engineer position, reporting to the CPP Project manager and/or director, to guide the interdivisional and interdepartmental C75 systems engineering document development and its maintenance through the project.

Appendix

Summary of Findings of Context for CEBAF Energy Improvement Options at the time of the C75 Project Review

- The operational performance of the accelerator portion of the 12 GeV upgrade fails to meet expectations for energy reach, putting the 12 GeV physics program in jeopardy.
- Three types of credible opportunities exist to add the needed energy reach to CEBAF.
  A. Upgrade present "C20" zones to add significant voltage.
  B. Upgrade present "C100" zones to add significant voltage.
  C. Replace existing "C20" zones with new "C100" zones to add significant voltage.
- The challenge of (A) is to obtain maximum voltage with minimum new procurements and additional labor or engineering support.
  - Constrain to rework of original cryomodules with improved cavities, existing tooling.
  - The voltage gain from incremental "C20" >> C50 is diminishing over time as the weakest modules are reworked and appears inadequate to obtain the target energy reach and headroom.
  - Constrain to proven 8 kW output from existing klystron design.
  - Result is the C75 concept
- All available technology developments have been folded into C75 cryomodule plans, where possible.
- For the C75 concept (A), the choice of cell shape was primarily driven by HOM concerns, secondarily by efficiency and surface fields. (Chosen HC shape meets the original CEBAF BBU spec, is 9.5% more efficient than OC with 4.5% lower Epk , but 13% higher Epk than C100 LL)
- Specific design choices in C75 were made conservatively from accelerator physics perspective, focusing on beam stability assurance and microphonics control to maximize voltage with available RF power, not peak surface fields.
- C75 design choice to use large grain Nb material capitalizes on previous SRF cost minimization development efforts. (C75 disks are ¼ the cost of LCLS-II spec material)
- The LLRF system needs for CEBAF are general.
  - A new system is required to address obsolescence of C20 RF zones.
  - A new system is required to obtain 75 MV from any upgraded zone.
  - The C100 LLRF design, while sound, is 10 years old, already on track for early obsolescence.
- The LLRF team proposes a general solution for CEBAF needs,
  - Involves a new modular digital LLRF system that exploits all community developments to date.
  - Significantly improves CEBAF beam energy stability

  - Tracks for long-term maintainability with single system for all of CEBAF
  - C75 zones would be the first application
  - All zones need to be digital eventually to support efficient injection into JLEIC.
- The challenge of (B) ("C100R") is to
  - Meaningfully characterize the reasons that the C100 CMs fall short of realizing their 108 MV design capability,
  - Develop corrections to those issues
  - Implement the corrections and any other accessible improvements via rework of existing cryomodules/controls to gain significant CEBAF energy reach.
- Known issues to be addressed in a C100R effort
  - Beamline contamination control – objective is field-emission-free operation to 20 MV/m in CEBAF, for 10 years. (Similar to C75, but likely easier)
  - Improved microphonic management, especially in #1-4.
  - Improved heatload management
    - FE-free
    - Cavity-specific heater compensation
    - Improved Q_0 during rework cycle (1.5 – 2.0 e10 via N-doping?), cut heatload by 50%?
- There exists at present no plan or budget for a C100R effort; no major procurement costs are foreseen (undetermined at this time).
- The challenge of (C) is major new procurement costs, compounded by the current lack of clarity from (B) regarding appropriate system changes to yield satisfying performance.
- Other paths were considered (see 2015 Staytreat), e.g. J100, but not pursued due to perceived cost, risk or need for engineering support.