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The 12 GeV CEBAF Performance Plan

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Abstract

Effective execution of the 12 GeV CEBAF physics program requires a reliable CEBAF accelerator that delivers beam at design parameters to the experimental end-stations. This document defines the gaps that exist in the present CEBAF accelerator capability and then presents a plan to close these gaps. All aspects of CEBAF operations are analyzed, including staffing. All identified gaps will have an associated plan to close the gaps, which include schedule, staff, and material and supply estimates. The presented plan addresses the identified performance gap in five years so that the majority of the 12 GeV experimental program can be executed at or above the expected performance. Additional plans beyond this initial five year ramp up will address CEBAF maintenance and obsolescence needs for the remaining years of the 12 GeV program.

1 Introduction

The 12 GeV CEBAF experimental physics program has over 75 approved experiments. If CEBAF operates at the optimal level of 37 weeks-per-year, this experimental program will take about 10 years to complete. The experimental backlog and annual accrual rate of newly approved experiments suggests that the 12 GeV CEBAF program will be at least 15 years in duration, so performance gains must be achieved quickly for there to be an impact on the overall effectiveness of the program.

Effective execution of the 12 GeV experimental program is crucial in maintaining CEBAF as the world leader in experimental nuclear physics. This document presents a plan for addressing the known performance gaps as soon as possible, improving CEBAF performance and addressing obsolete systems. The plan places a priority on addressing the performance gaps up front so that the majority the 12 GeV program can benefit from reliable CEBAF operations at design beam parameters. This portion of the plan is called the Accelerator Performance Plan and has a target of five years to complete. This ramp up to reliable CEBAF operations is followed by a ten year period called Accelerator Steady State and

Obsolescence Plans; this document will present plans to address system obsolescence during this period (i.e. obsolete 4 GeV CEBAF systems). Beyond this period, CEBAF efforts will be to complete the remaining 12 GeV program and prepare for the future, as was done during the transition from 6 to 12 GeV CEBAF . Since the future of CEBAF beyond the 12 GeV program is not known, the tasks for this period are presently undefined and will not be discussed in this document. This broad outline for the next 20 years is presented in Fig. 1, along with the high level CEBAF performance goals, linac energy, operating weeks and availability.

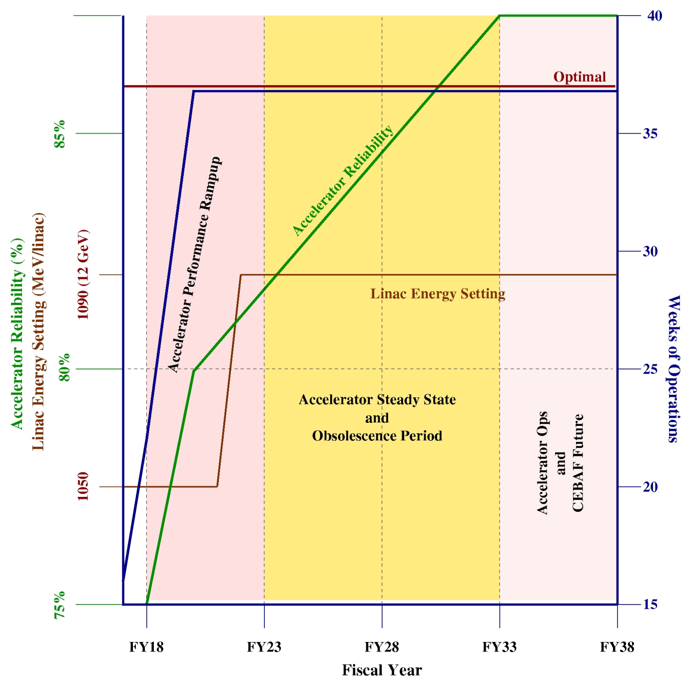

Figure 1: A graphical representation of the 12 GeV era as defined by fiscal years (FY), weeks of operation (right vertical axis), linac energy and reliability for the next 20 years (left vertical axes). The 20 year period is broken up into three periods, the ramp-up to full performance (5y), steady state and obsolescence period (10y), and the preparing for the future beyond 12 GeV (5y). During the steady state period the cyan band represents the goal of supporting between 30→37 weeks of operation per year

The next section defines the 12 GeV CEBAF performance goals on which the gap analysis is based. The performance goals are followed by the gap analysis section that shines light on where the present complex does not meet the performance goals. The gap analysis is segmented into energy reach, system availability, and Operations performance. The plans to address the identified gaps are then presented in the following section. The document finishes with a summary.

2 Performance Goals

A gap analysis compares the present capability of a system and/or organization to performance goals. The performance goals used for this gap analysis are presented in Table 1. Definitions, and in some cases rationale/derivation of the goals in the table, can be found in Appendix A. In broad terms the performance goals are to operate CEBAF at the design energy of 12 GeV (1090 MeV/linac), up to 37 weeks-per-year with 4-hall multiplicity, and availability and reliability exceeding 80%. The gap analysis is described in the following section.

Category	Unit/Metric	Goal
Reliability	%	> 80
Optimal Weeks	weeks-per-year	37
Beam Tuning Hours	h/week	< 8
Peak Hall Multiplicity	Number of halls	4
12 GeV Program Expected Duration	years	20
Linac Design Energy	MeV	1090
Required Linac Energy Margin at start of FY	MeV	> 110
Overall FSD Trip rate	trips/hour	< 15
Overall FSD Trip Downtime	min/hour	< 5
RF Trip rate	trips/hour	< 10
Beam Loss Trip rate	trips/hour	< 5

Table 1: The CEBAF Performance Goals for the 12 GeV CEBAF era.

3 Gap Analysis

In the following sections, the gap analysis is performed on several aspects of CEBAF operations. The gap is defined with respect to the goals in Table 1. There are three subsections: availability, energy reach and operations performance. Identified gaps need to be addressed by a performance plan found in the next section.

The performance of 12 GeV CEBAF to date has been a struggle punctuated with many noteworthy accomplishments. The hardship summary of commissioning and initial 12 GeV operations consists of:

- Frequent (one almost every run period) failure of critical systems that result in CEBAF not able to support the scheduled program resulting in a change of program and/or in schedule.
- CEBAF energy 4% below the design energy with the energy reach declining.
- Reduced weeks of operations, mainly driven by funding issues. Present staffing levels are insufficient to support reliable CEBAF operations.

The gap in CEBAF performance is not insurmountable nor large enough to warrant a halt in 12 GeV operations, but the gaps are significant enough to place the effective execution of the 12 GeV experimental program at risk. The plans presented following this gap analysis section are meant to mitigate this risk.

3.1 Availability Gap Analysis

DOE's minimum goal for facility reliability is 80%, see Appendix A for details on facility reliability. After accounting for trip related downtime, the CEBAF system availability goal becomes 87.3%. CEBAF operation in the 12 GeV era has not met this goal. In addition, the overall reliability does not take into account capability limitations caused by hardware failures that have resulted in a programmatic change (one hall operation, change in energy,...)

or schedule changes (abrupt termination of physics operations). The availability gap analysis presented here is the gap between the CEBAF systems ability to support the scheduled program: 4-hall operations at the scheduled energy with overall system availability greater than 87.3%.

12 GeV CEBAF beam operations commenced in January 2014 and since then there have been ~70 weeks of operations with ~35 weeks at 1050 MeV/linac or greater (1090 MeV/linac is the design energy). System outages or downtimes, have been recorded throughout this period, with notable improvements in the accuracy of the outage assessment tool as time progressed. CEBAF availability goals have not been achieved in the 12 GeV era and more striking is that the program and/or schedule had to be changed essentially every run period due to a major system failure which compromised CEBAF capability to support the program. Presently the gap between CEBAF availability and the availability goal is approximately -5 to -10%; accounting for programmatic/scheduling changes due to system failure would make this gap significantly larger.

Linac availability performance due to RF trips will be discussed in the energy reach section. A succinct summary for this section is that when the linac energy is set with sufficient margin, the impact on beam availability due to trips is within the performance goal. Presently this means the linac energy is set at 4% below the design energy.

The availability gap is observed to be from two main sources, single point of failures and system end-of-life. And in some cases the harsh combination of an end-of-life single point of failure, i.e. the cryogenic 2 K coldbox, has interrupted beam operations. High availability systems are achieved through either redundant components or spare replacements ready to be placed in service in the case of failure.

The performance plan, presented later in this document, will list the critical spare parts required to mitigate the known single points of failure. The list of single points of failure that have impacted the 12 GeV era to date include:

1. Spring 2014, ZA magnet coil and vacuum failure; 3 week interruption to replace damaged coil and repair the vacuum chamber. This failure consumed the existing spare coil; the next failure will take much longer for repair and recovery, on the order of half a year.

2. Spring 2015, Cold Compressor 4 (CC4) failure in 2 K cold-box, SC1. No spare at JLab. SNS cold compressor spare consumed in the repair of SC1.

3. Fall 2015, Failed magnet YR coil on 3-pass extraction line. Limited Hall-A to passes 1,2,4 & 5. Repaired during shutdown, consumed one of the YR coil spares. This magnet was an original 4 GeV CEBAF magnet, that was not refurbished as part of the 12 GeV upgrade.

4. Fall 2016, Arc7 box supply failure, no spare, program changed to single hall operation until supply repaired.

5. Fall 2016, 5th pass separator vacuum leak, program change required, could not support 5th pass beam to Hall-A simultaneously with 5.5 pass beam to Hall-D.

6. Spring 2017, Cold Compressor 5 (CC5) failure in 2 K cold-box, SC1. Failure was due to a failed connection on the vacuum side of the cold-compressor. Root cause investigation is on-going. SC1→CC5 has been repaired.

The availability performance of CEBAF to date has also been impacted by end-of-life components from the original 4 GeV CEBAF . The original 4 GeV CEBAF systems include: 80% of the linacs (C20/C50 modules and warm girders), East arc diagnostics, RF separation systems, vacuum, CHL1, 2 K cold-boxes (SC1 and SC2) and the end-station refrigerator (ESR).

End-of-life issues identified and corrected in the first years of 12 GeV beam operations include linac bellows, valve position switches and C20 RF windows. End-of-life issues identified and remain to be addressed include 2 K cold-box(SC1 and SC2), C20/C50 O-ring seals and injector warm RF LCW cooling systems. There are the additional unknown unknowns that require continuous tracking of system performance for identification of trends and development of corrective actions and application of sufficient funding, aka contingency, to address new issues as they are identified.

In summary, the gap in system availability is predominantly due to single point failures of systems with insufficient spare coverage or redundancy. Beam availability degradation, but not program/schedule changes, has been from end-of-life systems. The C20/C50 end-of-life issues can be partially mitigated by operating with sufficient gradient margin to absorb a failed cavity or even a whole cryomodule. This will be discussed in the next section.

3.2 Energy Reach Gap Analysis

The CEBAF accelerator meets the experimental requirements for the beam emittance, energy spread and beam size. The only beam parameter not presently met is beam energy. This section presents the gap in the CEBAF energy reach.

The energy reach goal of each linac is the energy required to deliver 12 GeV beam to Hall-D, (1090 MeV/linac) with sufficient margin (110 MeV/linac) for high availability, which adds to a requirement 1200 MeV/linac or greater. The energy margin allows for operations to absorb the failure of a cavity or even a whole cryomodule and achieve the availability goal. The most recent CEBAF operations (FY17) were performed with an estimated energy reach of 1100 MeV/linac. The present energy reach gap is -100 MeV/linac.

$$\text{Linac Energy Margin} = 1100\text{MeV/linac} - 1200\text{MeV/linac} = -100\text{MeV/linac}$$

In summary, at present, in order to deliver beam with the availability and energy goal an additional 100 MeV of integrated energy gain is needed in each linac.

3.2.1 Annual Energy Reach Losses and Gains

The energy reach gap is growing at an average rate of -4.5 MeV/linac/year. The annual loss due to new field emitters and operational losses is estimated to be about -17 MeV/linac/year. [1] This loss is partially mitigated by the on-going C50 program which

[1] The annual gradient loss estimate is documented in JLAB–TN–14–024 [1]. New CEBAF tunnel SRF beamline vacuum and operations valve actuation procedures have recently been put in place to reduce the

What	Unit	Gap
Energy Reach circa 2017-May	MeV/linac	-100
Average Energy Reach Gap change cavity based with one rebuilt C50/year: Δ(C50 – New Field Emitters)	MeV/linac/year	-4.5
Energy Reach Gap change due to klystron Loss (10 per year)	MeV/linac/year	$<$ -17

Table 2: Tabulation of the CEBAF energy reach gap.

presently replaces the poorest performing C20 module in CEBAF at a rate of one per year. One C50/year in CEBAF trims the degradation in the energy reach from -17 MeV/linac/year to -4.5 MeV/linac/year. The status-quo of performing one C20→C50 refurbishment per year results in an annual loss of energy of -4.5 MeV/linac/year (on average).

The RF power source, klystrons, have a limited lifetime. The historical failure rate for C20/C50 klystrons is 0.28 klystrons/week-of-operations. Optimal operations, 37 weeks/year, will result in about 10 failed klystrons-per-year in CEBAF . The loss of gradient associated with 5 failed klystrons/linac is estimated to be, at worst, an increase in the energy reach gap of -17 MeV/linac, comparable to the degradation due to annual new field emitters. Presently there are no new spare klystrons. The definition of failure used here is that the klystron can no longer deliver the gradient that the cavity is capable of supporting. The klystron may be able to deliver a lower gradient, so that the loss of gradient (energy gain) is less than if the cavity is turned off (aka by-passed). There are over 50 compromised klystrons presently in use in CEBAF .

Table 2 tabulates the gap in the CEBAF energy reach, **-100 MeV/linac**, the estimate of gradient loss due to new field emitters (-17 MeV/linac/year) is partially mitigated with one C50/year refurbishment program down to **-4.5 MeV/linac/year**, and the potential degradation due to the lack of spare klystrons, **-17 MeV/linac/year**.

3.3 Operations Gap Analysis

The performance goals on the amount of beam tuning, hall multiplicity and ability to support optimal weeks of operations in a year are analyzed in this section.

3.3.1 Beam Tuning Gap Analysis

In addition to system downtime, the experimentalists cannot productively use the electron beam if it is unavailable due to beam tuning. This beam tuning may be due to a problem in the accelerator proper or in one of the transport lines to the other end-stations. Historically (aka 4-6 GeV era) beam tuning has been one of the largest contributors to Beam Not Available for use (BNA) to the halls. For initial years of the 12 GeV era, system failure dominated the downtime statistics. In the Spring 2017 run beam tuning rose to second place in the list of downtime causes. This rise is attributed to the improved hardware reliability and

onset of new field emission sites. More data is required to assess the impact of these new procedures on gradient degradation [2, 3].

the complex nature of the run: a dynamic mix of configuration changes, two simultaneous high current halls, and three hall operation. Most of the tuning was hall related as the configuration was frequently changing and required optimization (aka tuning). The total time spent restoring and tuning the beam in FY17 was 358 h, well in excess of the total time scheduled for this activity, 256 h.[2] The gap, -102 h of excessive beam tuning in a short run period, will grow as the program becomes more complex; simultaneous four hall operations, high bunch charge, high power (∼1 MW) beams, and demanding (beam parameters more stringent than nominal requirements) experiments (parity violation).

3.4 Supporting Optimal Weeks

The gap in CEBAF's ability to operate for 37 weeks per year has two components. The first is the Operator/Crew Chief staffing level and the second is the ability to perform the required maintenance and shutdown activities in the scheduled shutdowns.

3.4.1 Operator/Crew Chief Staffing

Present Operations and Technical support staffing levels are insufficient for reliable operations. To date CEBAF 12 GeV running weeks-per-year have been less than 20 weeks-per-year. Instances of beam termination due to insufficient MCC staff resources (Operators and Crew Chiefs) have occurred during recent beam operations. An increase in operating weeks without an increase in staffing will result in beam availability degradation due to insufficient MCC staffing as required by the Accelerator Operations Directive (AOD) and Accelerator Safety Envelope (ASE).

3.4.2 Shutdown Tasks: CEBAF Maintenance

The gap analysis in this section analyzes the annual CEBAF maintenance requirements against the performance goal of 37 weeks of operation per year. The typical amount of shutdown tasks performed each year on CEBAF include:[3]

PSS Certifications DOE requires at least one PSS certification per year, CEBAF performs two as required by the FSAD/ASE. Each PSS certification cycle consumes about 3 weeks of time. For most of that period the PSS is unavailable for use, so other tasks that require power or beam permit cannot take place.

Winter Break @ 4K In order to reduce the chance of an uncontrolled transition to 4K (cold-box trip/malfunction) the two 2K cold-boxes are turned off prior to the Winter break. Both CHLs remain operational and maintain 4K cryogens throughout the break.

Cryogenic Maintenance The Summer shutdown is sufficiently short, so that transitioning to one CHL and warming the other CHL to room temperature for maintenance will only occur when there is identified maintenance to be performed. Instead the Summer

[2] FY17 Joule report

[3] The highlevel task layout and Gannt charts for a year with 37 weeks of beam operation can be found at: http://opsweb.acc.jlab.org/TJ3/CEBAF_PerformancePlan/37weeks

plans will likely include a partial warm up (to 80 K) of one CHL/2K cold-box system. At least One CHL and cold-box must be configured to maintain CEBAF at 2K (or 4K) during the summer shutdown.

Refurbished Cryomodule At least one refurbished cryomodule is installed and commissioned per year.

SRF maintenance This has included tasks such as Helium processing, warm window replacement, stuck tuner repair and other sundry tasks to recover any lost cavities/gradient during the shutdown. SRF maintenance requires CEBAF @2K to parameterize cavity/module performance post maintenance work.

CEBAF Maintenance Technical groups use the summer to address issues identified during beam operations and prepare for the next run period.

Analysis of time available for these tasks in an optimal year results in the following:

Cryogenic Maintenance It is estimated that there will be about 41 days in the Summer available for cryogenic maintenance.

- This amount of time is too short for regeneration of the Carbon beds (required roughly every 7 years/CHL).
- This amount of time is too short for a complete warm up of a CHL/2K cold-box. Maintenance on these system will have an impact on the optimal weeks in years when that maintenance is required.

Cryomodule Swap One cryomodule swap exhausts the Summer shutdown.

- There is no contingency remaining in the Summer shutdown to absorb delays in the cryomodule swap.
- Cannot perform more than one cryomodule swap per year.
- Other SRF maintenance activities, i.e. Helium processing, will be severely constrained.

Winter Break During this short break the only tasks that can be accomplished is the PSS certification.

The lack of contingency in the shutdown schedules suggests that there will be severe schedule pressure resulting in a highly likelihood of a delayed start to the run. Until the performance plan, described later in this document, is completed it is recommended that the optimal weeks-per-year be set at 35 weeks-per-year.[4] A year with 35 weeks of beam operation increases the summer shutdown so that the period for cryogenic maintenance is increased to 55 days (from 41 days in the 37 week scenario) and allows for two cryomodule swaps to be completed before the RF soak period. During years when the expected cryogenic tasks will exceed 55 days, the optimal weeks should be reduced accordingly (for example, new 2K cold-box or ESR commissioning).

[4] The highlevel task layout and Gannt charts for a year with 35 weeks of beam operation can be found at: `http://opsweb.acc.jlab.org/TJ3/CEBAF_PerformancePlan/35weeks`

Summary: Optimal Weeks Gap In summary, supporting 37 weeks of beam operations is not viable at present due to staffing and the limited amount of time for the necessary maintenance.

3.5 Supporting 4-Hall Multiplicity

The desire to maximize the Physics throughput of 12 GeV CEBAF, leads to the desire to operate with 4-halls simultaneously. There are two gaps associated with 4-hall multiplicity.

The first gap is technical in nature; the present end station refrigerator has insufficient capacity to support the cryogenic loads of Halls B, C, and the proposed `MOLLER` and SOLID experiments in Hall-A simultaneously and subsequently imposes scheduling and/or multiplicity constraints.[5] [6] Measurements of the A,B,C end-station load in Spring 2017 have confirmed the assessment in the DRRC report.

4-hall operations will strain the Operations and technical support staffing due to the increased complexity of 4-hall operations. The Fall 2017 program will provide some data on how the present staff levels impact 4-hall operations.

3.6 12 GeV 20 year program: The Obsolescence Gap

This section analyzes the performance goal of a 20 year 12 GeV program. At the end of the 12 GeV program, 20 years from now (FY38), elements of original CEBAF will be 45 years old. Systems were not designed with this lifetime in mind. This section examines every aspect of the CEBAF accelerator and identifies systems that will become obsolete during 12 GeV operations. The definition of obsolete used for this analysis is:

1. Spare parts are no longer available at a reasonable cost/timeframe.
2. System has reached its end-of-life.
3. System will likely be destroyed (break) due to CEBAF environment (for example, radiation damage).
4. System maintenance costs become prohibitive.

Systems that suffer on one or more the obsolescence issues will not perform up to specifications and will likely impact CEBAF reliability. Failure to address obsolescence places 12 GeV CEBAF reliability performance in jeopardy.

Every CEBAF system has an obsolescence gap, some were identified during the final years of the 6 GeV era but were not addressed due to funding issues. The annual CEBAF Run the Machine budget (1.04.02) process prioritizes the annual procurements to address the FY beam operations as the highest priority and obsolescence at a lower priority. Unfortunately

[5] From the 2010 Director's Review of Cryogenic Capacity report: Committee Recommendations: Secure funding and finalize plans for installation of the ESR#2 refrigerator to make it available for the proposed Hall A research program in the 12 GeV era (e.g. Moller and/or SOLID experiments).

[6] 2017-May: `MOLLER` received CD0 in FY16 and the optimistic timeline for `MOLLER` scheduling is FY23 (this is the authors WAG, needs to be confirmed).

the funding situation during the initial 12 GeV operations has resulted in a very near term focus. Annual funds are not available to address the known pending obsolescence issues.

The details of the identified obsolete systems and estimates on replacing these systems are found in the Obsolescence Plan section.

4 Performance Plans

In the following sections performance plans to address the gaps found in the previous section are presented. The proposed timeline, found in the accompanying spreadsheet [8], places an emphasis on improving CEBAF availability first, as the impact to the physics program of CEBAF downhard is much more severe than beam operations 4% below design energy. The energy reach plan, while not the highest priority, will achieve full design energy operations within five years (FY22). It is assumed that in this same five year period CEBAF operating weeks grows from the 16 weeks in FY17 to around 30 weeks by FY22 and can support up to 37 weeks-per-year beyond FY23. Implications on CEBAF resources of this increase in operating weeks is also presented in this section. The plans to deal with system obsolescence ramp up following FY22 and continue to to FY33.

The dollar values in this section represent FY17 direct dollars. When determining total cost overhead must be applied. When estimating the cost for future implementation, inflation must be applied.

4.1 Availability Performance Plans

The plan to close the gap in CEBAF availability within five years addresses the lack of critical spares for the accelerator and cryogenic systems. In some cases the critical system, i.e. 2 K cold-box, is obsolete and the solution requires a complete replacement. Operations and Cryogenics have developed a critical spares list that will mitigate the impact of several single point failure modes. Each critical spare is evaluated in terms of the likelihood, schedule, and capability impact. Validation of this method has been through the observed failure of the 2nd and 3rd highest combined risk items on the list. Similar lists have been created for Cryogenic systems and similar alignment of failures with the identified critical spares provides confidence in the methodology used.

Beyond the critical spares, the plan addresses end-of-life, obsolete or soon to be obsolete systems. This obsolescence plan is expected to continue while the 12 GeV program is the top priority of the laboratory.

4.2 Accelerator Systems Availability Performance Plan

The accelerator plan to achieve greater than 87% availability is to fund the critical spares list as soon as possible, phased replacement of end-of-life and obsolete systems, continued tracking of system performance, identify new end-of-life issues, and continuously (weekly, monthly, quarterly and annually) reassess the priorities.

4.2.1 Critical Spares Plan

The accelerator and cryogenic critical spares lists are found in the accompany spreadsheet [6]. The total cost estimate for these critical spares is $1.3M ($0.5M) for the accelerator (cryogenic) systems and the plan proposes a two (three) year allocation of funding for these critical spares.

In addition there will be a need to build a spare $\frac{1}{4}$ cryomodule for the injector once the injector upgrade has been completed. This is included in the plan for FY23-24.

4.2.2 Immediate Needs and Obsolescence Plan

The harsh budget climates of the last half dozen years has resulted in a depleted pool of consumable spares. The LERF systems have been cannibalized in order to maintain CEBAF operations. Each system owner reviewed the present capability to support the near term program and developed an *immediate needs* list. This list is a combination of consumable replenishment and high priority obsolescence items. Looking beyond the near term and staging CEBAF to support the 12GeV program and beyond, a *obsolescence lists* were developed.

CEBAF obsolescence planning started at the end of the 6 GeV era with the "Baseline Improved Accelerator" plan. The plan presented here include some remaining items from that plan as well as items from a recent review of CEBAF systems with a 20 year view. The plan identifies CAMAC, PLCs and other currently or soon to be obsolete systems for upgrades. Additionally the plan includes annually processing of warm girders in the linacs and upgrading the vacuum systems in these regions to mitigate accumulation of new field emitter sites. The plans do not eliminate all CAMAC or other obsolete systems, but will free up enough functioning spares to support the remaining aging systems. Details can be found in the associated *immediate needs and obsolescence* spread sheet[7].

Control System Software Obsolescence Plan The CEBAF accelerator control system software is EPICS based with the majority of the IOCs (Input Output Controllers) running proprietary VxWorks operating system. The decision to use this configuration for the control system was made in 1994 and it is time to assess the modern and future control system architectures. Additional proprietary software is used in the large database applications which use a Oracle database. The Control System Software Obsolescence plan includes a review of the future options for accelerator control system operating systems and databases, migration plan development, if deemed necessary, and migration of the all CEBAF systems to the next generation by FY28. The goal of this effort will be to have a modern control system, software and hardware, ready to the last half of 12GeV CEBAF era and beyond. To support this effort while simultaneously supporting 30+ weeks of 4-hall operations, additional computer staff resources are needed.

4.3 Cryogenic Availability Performance Plan

CEBAF cannot execute the 12 GeV program without reliable cryogenic operations. Cryogenics has had the largest impact on CEBAF availability in the 12 GeV era. Details of the cryogenic availability plan are not presented here. The summary from the operations perspective is that the end-of-life SC1 will be replaced with a new 2K cold-box. The parts of the decommissioned SC1 cold-box will serve as spares to the active SC2 cold-box. It is estimated that the new 2K cold-box may be completed by FY21, until then 12 GeV operations (as well as the SNS operations) are at risk.

The cryogenic performance plan includes:

- Funding the cryogenic critical spares list, as captured in the critical spares section.
- Construction of a new 2 K cold-box to replace the end-of-life, obsolete, SC1 cold-box.
  - This will free up 5 cold compressors to serve as spares to SC2 (and SNS) which will continue to operate.
  - Spare parts for the new 2 K cold-box must be included in the plan
- Construction of a new end-station refrigerator to replace the ESR which has insufficient capacity to support the 12 GeV program, specifically 4-hall multiplicity [4].
- A new Hall-D refrigerator (HDR).

New End-Station Refrigerator is needed to support simultaneous 4-hall operations when the `MOLLER` and SOLID experiments in Hall-A are in operations (or other high cryogenic load experiments). This is sketched in the plan for completion by FY23, but needs to be merged with the experimental plans.

The Hall-D refrigerator (HDR) is a small resuscitated 4K refrigerator. This refrigerator has been identified as obsolete and should be replaced.

4.4 Energy Reach Performance Plan

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**. Closing this gap would require about 15 C50 module rebuilds, 8 C75 module or 6 C100 modules for three years. The above estimates assume the existing CEBAF module to be replaced is producing about 25 MeV of energy gain and that the C50/C75/C100 total operational energy gain is 50/70/85 MeV respectively.

Analysis of cost per MV of energy for three competing cryomodule upgrade paths found that the C75 concept provided the most gradient for the least number of dollars.[7] Additional factors against a C50 refurbishment plan is that the required number of modules per year, 3 C50/year, to close the gap would be a challenge to fit in an optimal year schedule and the low Q_0 of the C50 cavities would add significantly to the cryogenic heat load. The higher Q_0 of the C75 compared to refurbished C50 cavities help mitigate the RF heat load increase of the higher gradients.

[7] See the slides on the preliminary C75 design review: `https://www.jlab.org/indico/event/137/`

	FY	Proposed Linac Energy Setting for FY	Linac Margin	Rebuilt cryomodules completed in FY
Date		(MeV/Linac)	(MeV/linac)	
2016-10-01	FY17	1050	55	C50-13
2017-10-01	FY18	1050	50	C75-1
2018-10-01	FY19	1050	56	C75-2
2019-10-01	FY20	1050	62	C75-3,C75-4
2020-10-01	FY21	1050	90	C75-5, C75-6
2021-10-01	FY22	1090	78	C75-7, C75-8
2022-10-01	FY23	1090	106	C100-Refurb-0
2023-10-01	FY24	1090	89	C75-9
2024-10-01	FY25	1090	95	C100-Refurb-1

Table 3: The C75 based Energy Reach Cavity Based Performance Plan. This plan establishes CEBAF as 12 GeV capable in FY22, maybe as soon as FY21.

4.4.1 Performance plan to eliminate the Energy Reach gap (C75)

The proposed performance plan is to upgrade **eight** of the poorest performing C20 cryomodules with new high-gradient cavities, high power klystrons and digital controls resulting in a module with design energy gain near 75 MeV/module. Assuming 70 MeV of operational energy gain yields a gain of 70-25=45 MeV-per-C75 replacement. New LLRF digital controls and klystrons capable of controlling and powering the high-gradient C75 cavities are required and included in the plan. The klystrons will be accounted for in the klystron performance plan at the end of this section. Table 3 has the details of the proposed C75 rebuild plan as well as the transition to energy maintenance beyond FY22.

4.4.2 Performance plan to maintain Energy Reach beyond FY22

C75 Upgrades The energy reach gap should be eliminated by the start of FY22, earlier if the annual gradient loss is mitigated or eliminated, by the improved vacuum and valve procedures recently put in place [2, 3]. [8] The annual gradient and the estimated energy reach should be evaluated annually and the energy reach performance plan should be adjusted to maintain the capability of CEBAF to deliver design energy beams with sufficient margin. Present values suggest that the C20->C75 upgrades will be needed beyond FY22 at a rate of one C75 every 1.3 years. The transition to the energy reach maintenance phase of the C75 upgrades starts with the C75-9 module.

C100 Refurbishment The lifetime of the C100 cryomodules is not known. The field emitted radiation is sufficient that degradation of plastics and even ceramics is expected before the end of the 12 GeV era, (see George K. presentation at the 2016 Operations StayTreat [5]).

[8] In parallel with beam operations and performance plan, research on the source of new field emitter and the annual gradient loss is on-going. Work in this area has resulted in new vacuum procedures for in-tunnel cryomodule work to maintain clean SRF environment as well as new vacuum pump technologies for the SRF beamline.

	New Klystrons	
FY	6.5 kW	13 kW
FY17	0	0
FY18	20	2
FY19	20	2
FY20	20	2
FY21	20	2
FY22	20	2
FY23	10	2
FY24	10	2
FY25	10	2

Table 4: The Klystron Performance Plan. 20 6.5 kW klystrons in FY18 - FY 22 are needed for the C75 program and for CEBAF spares.

If there has not been a catastrophic failure of a C100 by FY24, the weakest C100 will be replaced by the F100 from the LERF and refurbished. If there has been a catastrophic failure of a C100, this plan will start at that moment with the failed cryomodule removal and installation of the F100 from the LERF. The amount of work needed to refurbish or repair a C100 is unknown, so the effort needed to refurbish a C20 module is used for estimates. This C100 refurbishment plan will alternate years with the C75 Upgrades.[9]

Klystron Performance Plan As stated in the gap analysis the klystron status is quite dire and if not corrected could lead to additional, unwanted gradient loss. To re-cap the situation, there are presently no new spare 6.5 kW klystrons. Over 50 6.5 kW klystrons in operation show signs of end-of-life. Klystrons installed in the LERF RF zones will be used to populate the C50-13 zone installed in the Summer 2017. The expected klystron failure rate is 10 klystrons/optimal-year, based on 4-6GeV era data. The klystron performance plan proposed here consists of a ramp up period that will be in place during the same period as the C75 refurbishment plan which will support the C75 plan with new klystrons as well as provide CEBAF with spares. In this initial ramp-up period, the number of klystrons purchased is 20 klystrons/year for five years. After this 5 year period, the annual rate is reduced to 10 klystrons/year. The klystron failure rate and spare accumulation should be evaluated annually and appropriately adjusted once a three year stockpile of new or qualified good klystrons has been accumulated.

In addition to the 6.5 kW klystrons, 13 kW klystrons are used by the C100 cavities. There is also a spare gap identified for the 13 kW klystrons. Operational data on the C100 klystrons is relatively limited: to date there has been about 30 weeks of 12 GeV operation and two failures. The expected failure rate based on the initial data is about 1 klystron/year and there are presently two 13 kW klystron spares on the shelf. The 13 kW klystron performance plan calls for the purchase of two klystrons/year until a full zone (8) of spares are on the shelf (approximately eight years).

[9] Once the C100 refurbishment process has started the LERF will not have a C100 style cryomodule. Unless a spare is produced.

The proposed klystron plan is captured in Table 4.

4.5 Supporting Optimal Weeks

4.5.1 Operations Staffing Performance Plan

Present operator staffing is insufficient to support reliable beam operations. The Operator group (which includes Operators and Crew Chiefs) is 4 staff below the 6 GeV operations levels. The ability to staff MCC at required levels with the present staff depends on the operators health, training schedule and vacation schedule. In order to remove these uncontrollable constraints the operator staffing needs to be increased to allow for more scheduling flexibility.

In addition to the control room staff, the small group size requires all members of the Operator Group to be part of shift rotation. During 6 GeV operations 3-4 senior members of the operator group (Group leader, the deputy, plus one or two crew chiefs) were off shift rotation. This allowed for these senior experienced operators to review the beam performance, provide quality checks of beam delivery to the end-stations and mentor the operators and crew chiefs on a daily basis. This oversight is crucial in achieving the beam tuning goal. This group of off-shift operators/crew-chiefs were also expected to step in the case an operator/crew chief was not able to stand shifts due to illness, travel or training.

An increase of five in the Operator group staffing would restore the Operator group to the 6 GeV levels which supported 30+ weeks-per-year and 3-Hall operation. This additional staffing would also accommodate the more complex 4-Hall, 12 GeV program.

The Operations programming staff is also below its 6 GeV staffing level. Additional programming staff is needed to support 12 GeV operations; one more end-station, accelerator controls group continue to support more groups at JLab (LERF, Test-lab(SRF), UITF, 4-halls...). Based on this increased demand for Operations programming staff, the complexity of the 12 GeV program, its performance goals, and supporting accelerator controls obsolescence plan an increase of programming staff of 3 above is present levels is needed.

The Operability group tracks CEBAF system hardware performance. The need for a statistician to join the operability group will be crucial for identifying end-of-life systems as CEBAF ages.

4.5.2 Shutdown Tasks: CEBAF Maintenance Performance Plan

To support 37 weeks of operations the maintenance schedule needs to be compressed/reduced. This can be accomplished by the following steps:

- Execute the PSS related obsolescence tasks at a high priority and evaluate if the MTBF supports transitioning to one PSS certification per year.

- Construct spare warm beam tubes for between cryomodules (both C20/C50 and C100 tubes). Process and assemble these spare tubes so that they are ready for installation when the warm girder to dis-assembled and the dirty beam tubes are removed from the tunnel. This will eliminate the delay in having to wait for the removed warm girder to be dis-assembled, processed and assembled.

- Evaluate the need to transition to 4K over the Winter break. Eliminating this 2K→4K→2K cycle allow a few more days of beam operations right up to the break as well as support more maintenance tasks during the relatively short winter break.

These modifications will allow for 37 weeks of beam operation and the full compliment of maintenance tasks to be performed, including up to two cryomodule swaps in year.

5 Summary

Gap analysis of 12 GeV CEBAF performance has been completed. Several gaps have been documented and mitigation plans proposed. More details on the proposed plan including a proposed schedule and cost estimates can be found on accompanying spreadsheet [8].

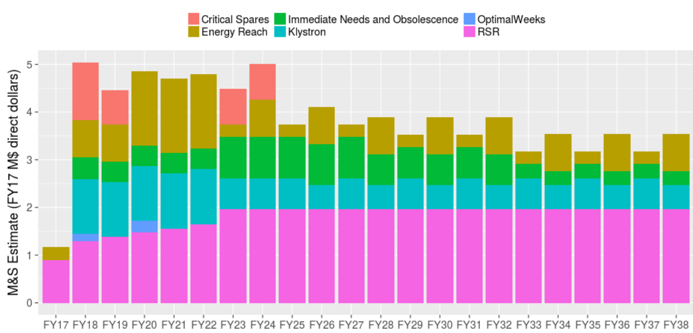

Figure 2: The material and supplies estimate for CEBAF Performance Plan. Values are in FY17 direct dollars, total cost requires the application of the appropriate inflation and overhead rates.

The estimated material cost, excluding cryogenic 2K cold-box and end-station refrigerator, is shown in Figure 2. Included in the cost estimate is the base level of funding needed to support the weeks of operations, this is list by its Annual Workplan identifier, *RSR*.

The plans also identified additional staffing needed to support an optimal program (37 weeks-per-year, 4-hall multiplicity). The labor estimate associated with C75 cryomodule upgrades, C100 refurbishment and LLRF digital upgrades can be found in the associated spreadsheet.

This document did not identify funding sources or tag pieces as possible Accelerator Improvement Projects (AIP). That effort is left to the implementation phase. All the plans listed in this document are in addition to the annual funding required for CEBAF operations (WBS 1.04.02, aka RSR) and the on-going AIP projects.

A Definitions

This appendix defines some of the terms used to measure CEBAF performance. Some of these metrics are defined precisely by Department of Energy (DOE) and are repeated here for completeness. Included in these definitions are the performance goals for 12 GeV CEBAF .

A.1 DOE Metric: Reliability

JLab transmits the *Joule Report* to DOE quarterly. This report includes a table on CEBAF beam hours which are then reduced to a value called reliability. The DOE definition of reliability presented in the Joule report is as follows:

$$\text{Reliability} = 100 \times \frac{\text{Research} + \text{BeamStudies} + \text{TuningRestore}}{\text{Research} + \text{BeamStudies} + \text{TuningRestore} + \text{UnscheduledFailures}}$$

In broad terms the reliability is the ability of CEBAF to support the program (research, beam studies, tuning and restoration). The reliability goals are set for the next five years during the annual budget briefing (nominally in Jan/Feb of each year) to DOE. The minimum reliability goal is 80%. There remains a question of whether the frequent short beam interruptions (see fast shutdown trip rate section below), should be included in the Unscheduled Down hours. For the purposes of this report, they are included as this is consistent with the recent Joule Report transmissions.

A.2 System Availability

The term availability is used throughout this document to describe the system performance:

$$\text{Availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTBR}} \leq \text{Reliability}$$

.

If availability meets the reliability target for all times, than the reliability goal will be met within the schedule period. This distinction is made since the system availability data does not account for the program schedule.

The overall CEBAF reliability goal of 80% includes the downtime associated with FSD trips. The nominal FSD trip rate accumulates about 5 min/h of downtime/h or 91.7% availability. Taking this into account, the non-trip related system availability must be greater than $A_{system} \geq 87.3\% = \frac{80.0\%}{91.7\%}$. System availability is tracked by the operations Downtime Manager which classifies downtimes into 14 high level categories. The top level goal of each system is allocated by the Director of Operations.

A.3 DOE Metric: Optimal Weeks of Operation

In addition to reliability goals, the lab annual briefing includes a value for the optimal weeks of operation for the facility. This is the maximum number of weeks that CEBAF could operate in a year with sufficient funding. The optimal weeks take into account the minimal number of weeks required for maintenance, holidays and planned upgrades. The CEBAF optimal running is 37 week-per-year.

A.4 Peak Hall Multiplicity

CEBAF is near completion of an upgrade to support all four end-stations simultaneously. This upgrade will be complete and fully commissioned in Fall 2017. The sum of the end-stations receiving beam is denoted as the hall multiplicity. For 6 GeV CEBAF the peak hall multiplicity was three and an average hall multiplicity of about 2.5 was achieved. The average is typically less than the peak due to scheduling constraints. For 12 GeV CEBAF the peak multiplicity goal is four.

A.5 CEBAF Design Energy

The 12 GeV CEBAF design called for a beam energy of 12.06 GeV delivered to Hall-D. This is the electron beam energy after 5.5 passes of energy gain. This energy gain corresponds to a linac energy gain of 1090 MeV/linac. For the purposes of this report the energy gain per linac, 1090 MeV/linac, is used as the CEBAF design energy for convenience in analyzing linac performance and plan development. This defines the total injector energy to be 123 MeV.

A.6 Linac Energy Reach

The term Linac Energy Reach is an estimate of the maximum energy gain possible in a linac (MeV/linac) that would result in 10 RF related trips/h and provide no gradient margin to accommodate real-time loss of gradient. Beam operations for Physics at the Linac Energy Reach value is not recommended (see FY16 operations).

A.7 Linac Energy Setting and Margin

The term linac energy setting refers to the integrated energy gain in MeV/linac of the North or South linacs, and combined with the Linac Energy Reach, the Linac Energy Margin can be extracted:

$$\text{Linac Energy Margin} = \text{Linac Energy Reach} - \text{Linac Energy Setting}$$

The goal for the Linac Energy Margin is +110 MeV/linac at the start of each Fiscal Year[10]

A.8 Fast Shutdown (FSD) Trip rate

CEBAF beam delivery is interrupted when the hardware detects an off-normal condition. The fast shutdown (FSD) system terminates beam and beam resumes when normal conditions are restored. This interruption is defined to be less than five minutes in duration and often between 0.25 to 1 minute. Experimental blank off around these FSD trips are often greater than the trip duration. The sources of FSD interruptions can be broadly cast into two categories, RF related and beam loss.

Operations strives to keep the FSD rate at a minimum. The present requirement is that the hourly averaged FSD trip rate should be less than 15 trips/h with brief (less than one-shift in one week period) excursions above 15 trips/h. The FSD trip rate goal is also set at < 5 min/h for setting reliability goals. Further partitioning of the FSD trip rate can be found in Table 1

The trip rate is mentioned here as it is used to determine the linac energy reach and has a role in overall CEBAF availability.

[10] The Linac Energy Margin is evaluated for the start of the FY assuming that there will not be extended downs for major repairs and with a goal of ending the FY operations with 100 MeV/linac of margin. See private communication, CEBAF _eReach_Fall2016.pdf, from Freyberger to Gradient Team.

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