CEBAF at 12 and 25 GeV*

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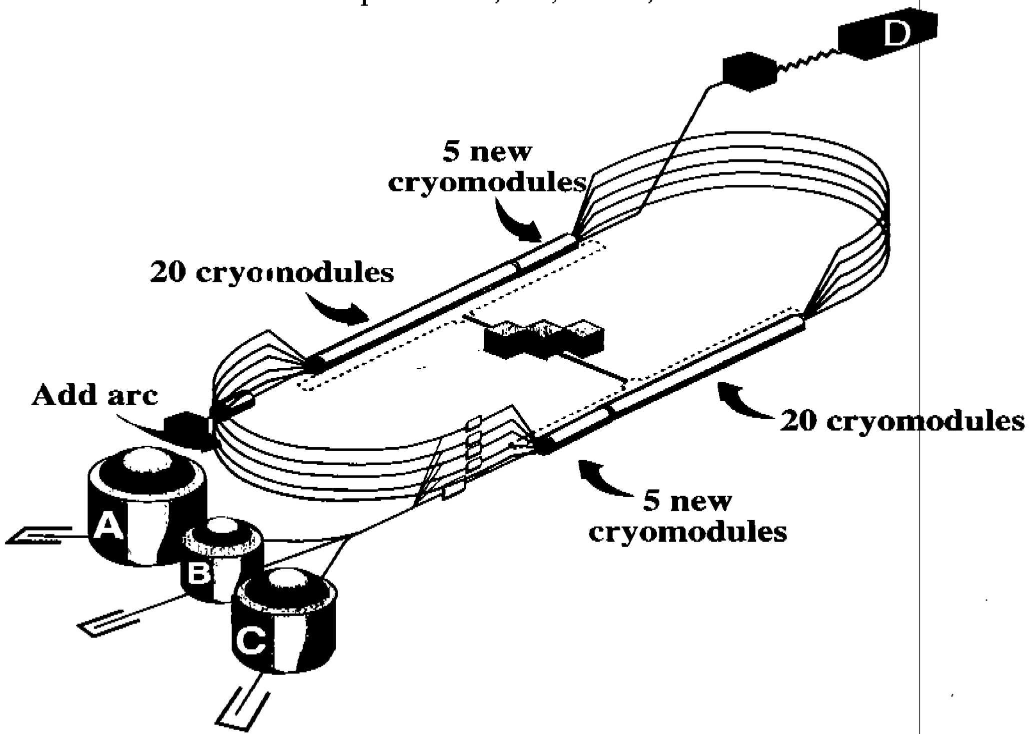

Figure. 1 Illustration of the concept for upgrading CEBAF to 12 GeV

Abstract

The US nuclear physics community has identified an upgrade of CEBAF to 12 GeV as one of its top priorities. The principal motivation is to enable meson spectroscopy with 9 GeV polarized, quasi-monochromatic photons. A plan for implementing the 12 GeV upgrade has been prepared. Subsystem designs are being tested. Additional opportunities to reduce total project costs have been identified and will be pursued. The plan now calls for the addition to CEBAF of 10 new high-performance cryomodules and a new recirculation arc, yielding 12 GeV after 5.5 passes through the accelerator. Formal construction start could be in 2006. The same cryomodule design would subsequently be the building block for an eventual upgrade to 25 GeV.

1 INTRODUCTION

Jefferson Lab is the site of the first large-scale use of SRF technology for particle beam acceleration. At the time of its conception, 5 MV/m was chosen as a prudent performance goal for CEBAF (JLab's main accelerator). That goal was surpassed; beams are being delivered today requiring that the accelerating cavities operate at an average of ~7.5 MV/m. Pulsed systems at JLab and elsewhere have substantially exceeded this value. Parallel developments in cw systems have led to the expectation that substantially higher performance could be expected.

The core mission of Jefferson Lab is research to understand how the nucleon's behavior when interacting with other particles changes from that of an independent entity to that of three interacting quarks. Recent developments in strong-QCD theory have indicated that important understanding of quark-gluon behavior, particularly the nature of quark confinement, could be determined by measuring exotic meson spectra with a beam of polarized 9 GeV photons. This beam could be effectively produced with 12 GeV polarized electrons[1]. Extension of CEBAF's capability to 12 GeV, from its present ~6 GeV, seems the logical route to enabling the community to get this information. The DOE-NSF advisory group NSAC (Nuclear Science Advisory Committee) has recently identified the 12 GeV program as a priority for US nuclear physics efforts in its most recent Long-range Plan. [2]

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A pre-conceptual design [3] has been developed which would enable CEBAF to deliver 12 GeV beam. This design is discussed below, as is its possible extension to higher energies.

2 GENERAL DESCRIPTION

CEBAF presently delivers beams of up to ~6 GeV energy. Reaching 12 GeV requires doubling the existing 6 GV of acceleration. CEBAF is a recirculating linac. Full beam energy is achieved by repeatedly using the accelerating fields in the linacs; this is accomplished by transporting the beam from one linac to the other and back, repeating the process up to five times. Consequently the additional 6 GV of acceleration need not be installed as new cryomodules whose voltages add to 6 GV. It does mean, however, that the beam transport system must be upgraded to handle twice the present energy.

An important detail of the accelerator is that there are 5 empty "zones" at the downstream end of each linac; these "zones" were left empty when the accelerator was cost-optimized from 4-pass to 5-pass after the civil construction had begun. It has been realized [4] that installing cryomodules with ~100 MV capability in these locations would lead to linacs of 1.1 GV each; 5-passes through both linacs would then produce an 11 GeV beam. Further, placing a new hall, Hall D, at the end of the initial linac would permit an additional transit of that linac, thereby producing a beam of ~12 GeV. This choice has the important consequence of preserving the opportunity for continuing and extending the nuclear physics programs in the three existing halls.

The following parameters were adopted:

Table 1. Base parameters for Upgrade

Parameter	Value
Maximum beam energy	12 GeV
Maximum beam power (cw)	1 MW
Number of passes for max energy	5.5
# of new cryomodules in linacs	5 per linac
Equiv voltage of new cryomodules	98 MV

One obvious change to the CEBAF configuration is the requirement that beam be delivered to the initial linac for a 6th acceleration pass. The beam transport system for this must be added. The existing beam transport system for CEBAF was not designed for 12 GeV, thus it must undergo changes to provide the requisite bending and focussing fields. Those changes are described in the section below on beam transport . Ideas for the 98 MV cryomodules are described in the section on acceleration.

3 BEAM TRANSPORT

The simplest approach, and the most expensive, would be to replace the entire beam transport system with magnets with having twice the bending power. A more cost-effective solution would be to leave all the magnets in place and simply install larger power supplies; unfortunately, many of the magnets would be deep into saturation and waste power. An even more cost effective solution, and the one chosen, is to push the magnets to the edge of saturation wherever possible and to solve the saturation problem where it exists.

The most important place to solve the saturation problem is in the arc dipoles, as they constitute the bulk of the power consumption in the beam transport system. A quite effective solution was hit upon stemming from the fact that the dipoles presently have "C" shapes. It was found that it is possible to turn them into "H" magnets, and thereby halve the fields intensity in the return iron, by adding a "C" shaped iron piece to the existing magnet bodies. This addition can be done without disassembling the magnets.

New dipoles were designed for the new arc 10, i.e. the transport system that delivers the beam to the initial linac for its final acceleration. These magnets will be "H" in configuration.

The spreaders and recombiners (sections of the beam transport system which separate the co-linear beams after they exit the linacs or combine them before re-injection into the linacs) are quite congested regions. The dipoles in these areas will receive individual examination as to the most effective solution to generating the required fields.

Evaluation of the quadrupoles showed that all are "well" until ~7 GeV. Samples of the several design types in use have been tested to 70% above the design fields. Even though saturation is seen, field quality remains acceptable. Thus, larger power supplies will take them to near 12 GeV; this is sufficient because the upgraded portion of the existing machine will be operating at the equivalent of 11 GeV. In some cases, additional field beyond the simple scaling is needed. For these few locations, new magnets will be designed and built.

4 ACCELERATION

4.1 Upgrade activities to date

During the past several years, cavity and cryomodule designs have been developed for use in upgrades to CEBAF and the JLab FEL.[5] Two of these cryomodules (Mk II) are to be completed in 2002, one for CEBAF and one for the FEL IR upgrade. Key subsystems are presently in fabrication and testing.

The cavities for these two cryomodules are of a hybrid design. They use the same cell shapes as the initial CEBAF cavities (Mk I) but have two additional cells per cavity. The $\lambda/2$ stub input coupler is replaced by a $\lambda/4$ stub to eliminate the field asymmetry that gives rise to a transverse "coupler kick" and to reduce the tight mechanical tolerances required to establish the desired external Q (Q_{ext}) of the coupler to the cavity. The waveguide HOM couplers of the Mk I cavity have been replaced with an adaptation of the DESY couplers developed for TESLA use. Sixteen of these cavities are presently in fabrication at JLab. The performance specification for the cavities in the Mk II cryomodules is average E_{acc}=12.2 MV/m, with a Q_0 of $> 6\times10^9$.

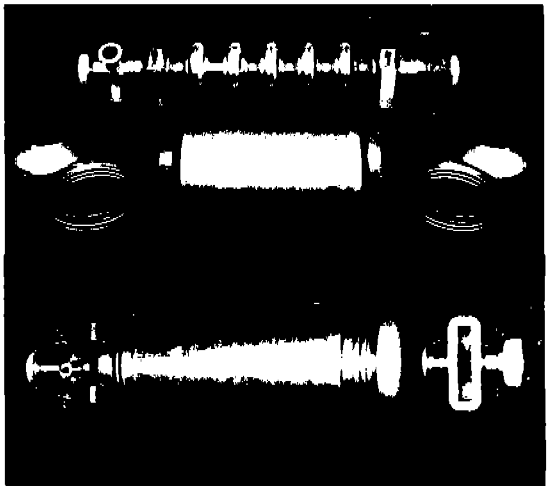

Figure 2. CEBAF Mk II upgrade cavity

The first space frame in which the eight seven-cell cavities are to be mounted is presently being evaluated. (See Figure 3.)

Figure 3. Upgrade cryomodule space frame and vacuum vessel.

The new tuner for the upgrade exceeded the specification for resolution during its initial evaluation using the Horizontal Test Bed (HTB).[6] The tuner, which uses a concentric linear motion scissor-jack mechanism to place all bearing parts external to the vacuum vessel, met the necessary resolution of < 2 Hz using only the mechanical tuner. [7] Since control of microphonics is crucial in this application, the cavity microphonic response to tuner actuation was monitored and found to be less than 0.3 Hz peak. The piezoelectric fine tuner also met or exceeded all specifications. The frequency response of the whole system, including the tuner, was also evaluated for possible dynamic applications such as active vibration cancellation.

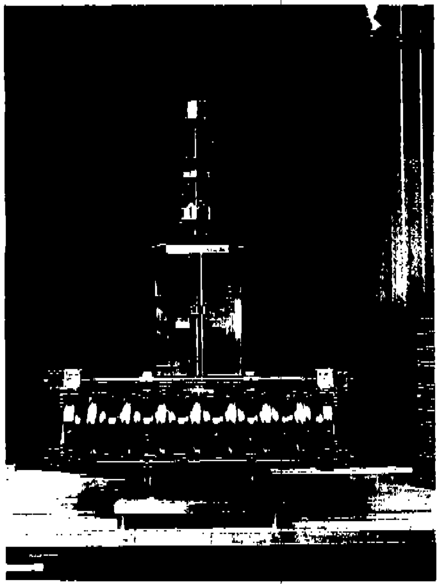

Figure 4. Prototype tuner for CEBAF upgrade.

Initial tests of microphonic sensitivities of the upgrade cavities were also carried out on the HTB. Although the mechanical suspension was different than that of upgrade cryomodules, opportunity was taken to characterize the rf resonance response of the cavity/cryostat system to background vibration, swept frequency, pulsed rf, and external mechanical impulse.[8] The dominant excitation from background was an ambient vibration at 54.7 Hz. The most significant mechanical vibration mode of the structure was observed at 33.7 Hz. The net microphonic detuning in the HTB was 2.5 Hz rms, which is below the design limit of 3.5 Hz rms. Similar tests will be made on the upgrade cryomodules during the next year.

4.2 New options for CEBAF upgrade

It would take 16 new cryomodules with the performance specification of the Mk II style to obtain 12 GeV with 5.5 passes through CEBAF.[3] Ten of these cryomodules would fill presently empty slots, while six would replace the weakest of the Mk I cryomodules. The maximum beam current of the 12 GeV design is 465 µA. A presumption in past plans was that the present CEBAF klystron design could be pushed to 8 kW by raising the gun voltage. Events of the past year demonstrated that this is not an option, and the development of a new klystron is being pursued.

Removal of this constraint on the 12 GeV design allows further optimization of the cavities to reduce overall project costs. Exploiting current design and fabrication methods, we intend to develop a Mk III cavity for CEBAF that will increase the shunt impedance and geometry factor while obtaining state-of-the-art SRF performance.

One potential improved cavity design has been proposed by Barni et al. [9] With it one can construct a 12 GeV CEBAF design that might be realized with only ten new cryomodules, using 13 kW klystrons. [see 12 GeV paper] This design assumes an average cavity gradient of 19.2 MV/m. An even more ambitious design goal is to realize 25 MV/m in the 0.7 m cavities, while dissipating only 33 W at 2.1 K, using the same klystron. Such a goal could only be realized by reliably eliminating field emission sources from the cavity, maintaining surface resistances of ~25 nΩ, and implementing an agile rf system capable of handling the Lorentz-force detuning and microphonics.

Performance approaching this level has already been observed. Electro-polishing of cavities has demonstrated the potential elimination of field-emission as a problem. A cavity using the original CEBAF cell shape was chemically processed, tested, electro-polished, and retested. The results are shown in Figure 4.

An even more ambitious design goal is to realize 25 MV/m in the 0.7 m cavities, while dissipating only 33 W at 2.1 K, using the same klystron. Such a goal could only be realized with the effective elimination of field emission sources from the cavity preparation process, reliably obtaining surface resistances of ~25 nohm, and an agile rf system capable of handling the Lorentz-force detuning and microphonics.

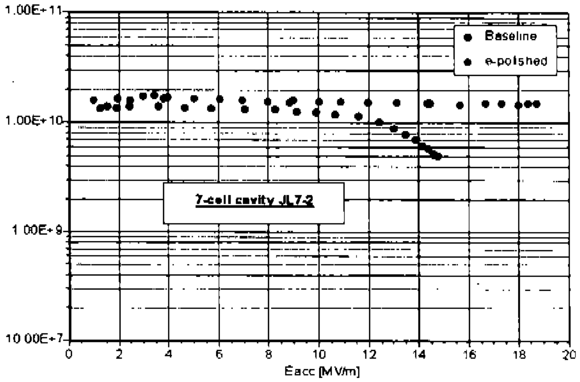

Figure 4 Performance of a cavity that was chemically processed (blue) and electro-polished (red)

5 RF

As was mentioned in the previous section, 13 kW klystrons are called for in the present plan. No such klystrons exist commercially at the present time and would need to be developed.

There are two control issues for the rf system, both associated with detuning.

Lorentz detuning

The optimum Q_{ext} for the system will be ~$2x10^7$, resulting in a rather narrow detuning curve. The field pressure on a cavity operating at 19 MV/m distorts the cavity shape enough to tip the peak of the resonance curve and make the detuning curve multi-valued, as shown in Figure 5. In these circumstances, the Lorentz-force tune shift is approximately sixteen times the resonance bandwidth. This condition is particularly problematic in a pulsed machine. Even if CEBAF remains a cw accelerator, a distorted detuning curve is a problem: cavities sometimes trip off and the beam delivery would have to be suspended while the cavity is retuned, energized, and ramped back to the operating field; this results in undesirable down-time. If the rf system is designed to accommodate this detuning, perhaps with a self-excited loop approach or with piezo-electric actuators, then the recovery would be much quicker than in a generator-driven approach

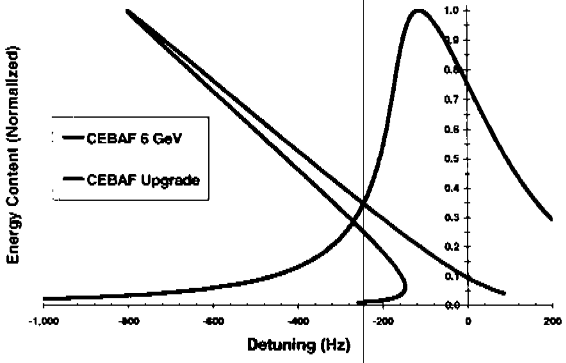

Figure 5. Detuning curve for existing cavities (blue) and new cavities (red).

Microphonics

A bit more than half of the required rf power is reserved for driving a detuned cavity. It was assumed that there may be 25 Hz of detuning: 21 Hz of microphonics (6x3.5 Hz rms) and 4 Hz of static tuning error (the tuner is to have a 2 Hz resolution). If a method for reducing the microphonics were to be developed, that power would be available for driving the beam. One solution that has been proposed [10] is to modulate the cavity field to damp the effects of the microphonics. This approach needs development but could have a major pay-off for this and other machines that are on the horizon.

6 OTHER SYSTEMS

Clearly the new cryomodules will increase the load on the cryogenics system. With a Q_0 of $8x10^9$ (chosen as a prudent goal relative to the observed $1.8x10^{10}$) at 19 MV/m and 75 W of static heat load, each cryomodule will add 300 W (250W of which is dynamic load) of load to the system. The 10 new modules, with operating overhead, then represent a near doubling of the heat load. To provide the additional capacity, the central liquifier will need to be doubled. This can be done cost effectively by utilizing the existing spare 2K cold box and adding to it the necessary >4K systems.

The larger magnet power supplies, additional rf power, larger helium plant, and addition of Hall D will all require expansion of the facility's ac power and LCW system.

7 COSTS

The pre-conceptual work has progressed sufficiently to make a cost estimate. The estimated cost to design and build the accelerator modifications is ~\$60M (FY01\$; includes contingency) with about ~40% going to new cryomodules and rf. There are additional R&D and commissioning costs, but these have not yet been reviewed in detail. The cost to implement the plans for the experimental systems is ~\$90M (in FY01\$; includes contingency), with a bit less than half of that being for Hall D. The \$150M represent ~20% of the original cost of CEBAF and it's experimental suite after correcting for inflation. Doubling the energy and expanding the experimental equipment suite, and thereby perhaps explaining quark confinement, thus seems quite cost effective.

8 BEYOND 12 GEV

An obvious question is "What can be achieved if the existing cryomodules are replaced?" Twenty-five of the new cryomodules would provide an additional ~2.5 GV in each linac. Five "passes" through both linacs would then result in a beam with ~25 GeV of energy. An accelerator of this energy has been proposed previously at CERN, but is presently not an approved project.

Considerable additional cryogenics capacity would have to be added. Ten of the new cryomodules, operating at 19 MV/m, consume the equivalent of a plant equivalent of the existing 5 kW (at 2 K) CEBAF central helium liquifier. Adding 40 more, and removing the old ones, would result in the need for an additional 4 plants beyond the two needed for 12 GeV.

The topology of beam recirculation would likely change from the one presently used. A combination of horizontal and vertical separation of the recirculation arcs would be needed. It is also likely that superconducting magnets would be used when the beam exceeds 12 GeV, i.e. in the later stages of acceleration, as room temperature dipoles would occupy about half of the pathlength and would consume considerable power. These superconducting magnets would also require additional cryogenics capacity, beyond that mentioned above.

Other details of the layout of the complex would potentially remain unchanged. The injector would need only have its two cryomodules replaced. Halls A, B, C, and D could be reused. Additional experimental halls could potentially be added alongside Hall D.

With the upgrade of CEBAF envisioned to be complete near the end of this decade, several years of exploitation of the new capabilities might be expected. Thus, 25 GeV beams might be on the horizon at Jefferson Lab in the second half of the next decade. We also note that considering the progress in SRF technology in the past 15 years, one could project substantial improvement in cavity performance by 2015. Thus, our vision for a 25 GeV accelerator in the present tunnel is undoubtedly conservative from a technological perspective. Cavities have already been produced at DESY that perform at 30 MV/m, which, if used in all 52 cryomodules, would produce a beam with >35 GeV. Further scaling is left to the optimistically enthusiastic reader. Alternatively, if microphonics can be controlled and beam power is limited to 1 MW, gradients of ~35 MV/m could be supported with the planned 13 kW klystrons. Only 14 of these cryomodules would be needed per linac to deliver the 25 GeV beam.

9 SUMMARY

Exciting understandings of the nature of the nucleonic/sub-nucleonic nature of matter are projected coming from research using 12 GeV cw electron beams. Development of SRF technology since the construction of CEBAF has reached a point that increasing CEBAF's energy, already 50% more than the original construction goal of 4 GeV, to 12 GeV is relatively straight-forward and inexpensive. The enhancement to the systems would include: adding 10 new 98 MV cryomodules and associated rf systems, doubling the present cryogenics plant, and increasing the fields in the beam transport system by installing larger power supplies and replacing a handful of the present magnets. The hadronic matter research program could potentially begin as soon as 2009.

Replacing the existing cryomodules and revamping the beam transport system could transform the 12 GeV machine into a 25 GeV machine. This might be done when the important research at 12 GeV has been thoroughly mined, perhaps circa 2020. SRF developments in the mean time could potentially boost that capability further.

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