UPGRADING CEBAF TO 12 GEV*

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Abstract

The Thomas Jefferson National Accelerator Facility (TJNAF) is proposing to upgrade its ~6 GeV cw electron accelerator (CEBAF) to 12 GeV with the purpose of extending its reach in exploring the nature hadronic matter, including the explanation for quark confinement. A plan has been developed that carefully balances cost and risk. TJNAF plans to do the upgrade without change to most of the accelerator components. The core of the upgrade is the addition of ten new 100 MV cryomodules and their supporting rf and cryogenics systems. A new experimental hall, devoted to the quark confinement investigation, will be placed so that the beam transits one of the linacs 6 times (vs 5 times for the other linac). Upgrades to the beam transport system will be required. No new developments in beam diagnostics appear to be required. Beam emittances are degraded by synchrotron radiation but meet the needs of the research program. This paper discusses the issues listed above plus requirements for all systems and developmental opportunities presented by the project.

1 OVERVIEW

1.1 Motivation

CEBAF was built to enable detailed exploration of hadronic matter, i.e. the manifestation of quark degrees of freedom in nuclear systems. Lattice QCD calculations in recent years have given important new insights into the non-asymptotic behavior of quarks. One very exciting development is a description of the potential basis for quark confinement, which has been identified by the US National Academy of Science as one of the ten most significant questions to be answered in physics in this century. The calculations show that the answer to confinement may lie in flux-tubes of gluons between quark pairs and also show that the flux-tubes' degrees of freedom yield exotic meson states. It appears possible to excite these exotic states with a beam of polarized 9 GeV photons and, most importantly, distinguish them from the other states. A high-quality, cw beam of 12 GeV electrons is the ideal way to produce the photons [1]. CEBAF presently has a high-quality cw beam of ~6 GeV is thus an ideal platform upon which to base a facility.

1.2 Base requirements

6 MV of acceleration must be added. A new experimental area (for the exotic meson program) must be added to the present three. It will be on the opposite end of the accelerator from the existing ones; thus the beam that reaches the new end-station will transit one linac one more time than for any of the other end-stations.

12 GeV can be achieved by increasing the linac capabilities or increasing the number of passes. An analysis determined that it would be more cost effective to increase the linac capabilities than to reconfigure (rebuild) the beam transport system for additional passes. Therefore, the present 0.6 GV/linac capability will be upgraded to 1.1 GV/linac. The exotic meson studies need $< 5\ \mu$A; the other programs need much larger beam currents. It was decided to limit the total beam power to the present 1 MW.

The present beam transport system supports 5-pass beam at 6 GeV to each of the existing end-stations. It must be modified to deliver 11 GeV beam to those halls and have added the requisite beam transport to deliver the full 12 GeV beam to the photon radiator target for the new end-station, including an additional recirculation arc.

2 BEAM PHYSICS

2.1 Beam breakup

Beam breakup (BBU) driven by high-order modes (HOM's) in the cavities must always be addressed when using srf cavities even if the beam current in the cavities, < 1 mA in this case, is not exceptional on the scale of storage rings. As was done for 4 GeV CEBAF, the code TDBBU [2] was used to evaluate the situation. A specification of $Q < 2\times10^6$ (versus 1×10^5 for 4 GeV CEBAF) for the HOM's came out of the study. Initial modelling of the new cavities indicate that there should be no problem with BBU for the upgrade.

2.2 Emittance, energy spread, and depolarizaion

Emittance growth from synchrotron radiation of the electrons in dispersive sections of the beam transport did not present a limitation to meeting the 1 nm-rad specification for CEBAF at 4 GeV. For the Upgrade, cost containment drove a desire to forego extensive modifications to the existing optics. Retaining those optics leads to emittances at 11 GeV in the existing end-stations of ε_x=7 nm-rad and ε_y=1 nm-rad. The projected energy spread at 12 GeV is 0.02%, as compared to 0.01% at 6 GeV. The CEBAF User's Group Board of Directors reviewed these values and found them to not limit the proposed research programs. Estimates were made of the cost for modifying the beam transport in order to reduce the dilution of the emittance by

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synchrotron radiation effects. As the estimates were of scale $5M, it was decided to retain the present optics. Potential depolarization of the beam was checked and found to be inconsequential.

3 ACCELERATION

Note: The details of the acceleration systems (cryo-modules, rf, and cryogenics) are described in detail in ref. [3]. The following is a summary of that information. It should be remembered that the existing systems will be used without modification.

3.1 SRF

The additional 0.5 GV/linac will be achieved by adding 5 new cryomodules (total of 10 needed for both linacs) each providing 100 MV. Each cryomodule will have eight 7-cell cavities. The cavities have a performance specification of $Q_0 = 8x10^9$ at 19.2 MV/m. While only 17.5 MV/m is required for the cryomodule to reach 100 MV, the specification was set at 19.2 MV/m to overcome the real possibility that some cavities might be off-line. The Q_0 specification was set by the requirement to fit within the projected cryogenics plant's capacity (see below). Key to meeting this performance are: 1) use of electropolishing techniques for the interior of the cavities, 2) a new cavity shape with better R/Q than was used for 4 GeV CEBAF, 3) changes in cryomodule design details aimed at excluding particulate-producing components, 4) changes in assembly procedures in order to better preclude contamination of cavities, and 5) development of in-situ cavity processing in order to deal with any particulates that may be problematic. In addition, the tuner resolution has been improved versus that of the existing cryomodules, this being motivated by a desire to minimize the rf power required for keeping detuned cavities on-phase.

Prototype 7-cell cavities have exceeded the performance specification when electropolishing has been used. The first of the cryomodules with 7-cell cavities is presently under construction with another to be built in 2003. These cryomodules have a performance goal of 70 MV and are interim steps toward 100 MV. New cell-shape options will be prototyped in 2003. The prototype 100 MV cryomodule is expected to completed in 2004.

3.2 Cryogenics

The present 2K helium plant is now operating at its full capacity. In anticipation of the Upgrade project, JLab acquired the former MFTF-B helium plant from LLNL, which has a capacity of >10 kW at 4K. We also have a redundant ("hot spare") 2K coldbox. With a reconditioned MFTF-B plant, the potential addition of an 80K exchanger, and utilization of the "spare" 2K coldbox, we will have a 2K plant with maximum capacity of ~5 kW at 2K. After allowance for system control headroom, there would be ~300W available for each of the new cryomodules, 250W of which would be available for dynamic load. At 19.2 MV/m, 250W translates to the $Q_0 = 8x10^9$ mentioned earlier.

3.3 RF

Each new cavity will be energized by its own klystron. A budget was developed for the saturated output power for the klystrons based on the following criteria: 1) ≤450 μA of beam transiting the cavity (limited by 1MW total beam power limit), 2) Q_{ext} is off-optimum by ≤ 30%, 3) maximum detuning ≤ 25 Hz of which 4 Hz is 2x the tuner resolution and 21 Hz is 6x the σ of the measured microphonics spectrum on existing cavities, 4) some cavities will be able to operate at 21 MV/m (10% above the mean of the population) and stay within the cryogenic limits, and 5) add 10% so that the klystron will still have gain. The result of the calculation was 12.5 kW. 13 kW has been chosen as the design specification so as to add headroom. Furthermore, we want a power conversion efficiency > 50%. No such klystrons exist commercially and would need to be developed. Discussions have begun with firms regarding potential manufacturing.

A new rf control module must also be developed. We anticipate using digital technology [4]. Preconceptual work is presently underway in collaboration with Cornell and DESY. Important control issues that must be addressed are:

- The electro-magnetic field pressure at 19.2 MV/m and the optimum Q_{ext} for the new cryomodules are sufficiently large that the detuning curve is multi-valued. If a cavity with a multi-valued detuning curve trips off, it must be retuned to the zero-field resonant frequency before it can be energized if the control system uses a generator-driven resonance loop; this process can be time consuming and, thus, detrimental to beam availability. Two potential solutions are under consideration: 1) a self-excited resonance control loop which inherently overcomes this limitation and 2) utilization of a piezo-electric component in the tuner.
- ~1/3 of the 13 kW is reserved for the effects of microphonics-induced detuning of the cavity. There are two solutions under consideration: 1) a new control algorithm has been developed [5] that uses a field modulation to damp the microphonics and 2) the piezo-electric component of the tuner could be used to keep the cavity on resonance. Use of piezo's has some risk as it has not been demonstrated that they are rugged enough for long-term use in this way. The electronic approach does not suffer from this disadvantage; however, it has not been demonstrated on a real cavity.

4 BEAM TRANSPORT

4.1 Upgrading existing beamlines

The existing beam transport system consists of ~400 dipoles (B*L≥0.2T-m) and ~700 quads. One approach is to replace the entire beam transport system with magnets designed for twice the present bending power. Another is to leave all the magnets in place and simply install larger power supplies; many of the magnets would be far into saturation thus greatly increasing the size of the required power supplies and "waste" power during beam delivery. A third approach is to push the magnets to the edge of saturation wherever possible and to solve the saturation problem where it exists by modifications to the magnets. This last is the plan as it seems most cost effective.

For the majority of the dipoles, i.e. those in the nine 180° arcs and in the beamlines to the existing end-stations, the present "C" shape will be changed to "H" profiles by augmenting the magnets with bolted-on iron. Modeling and prototyping have shown that the saturation is only a few percent with the additional iron, while it would exceed 50% if the iron were not added.

The dipoles in the spreaders and recombiners (S/R), i.e. the 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 so closely spaced that the bolt-on iron option is often not viable. All these dipoles have 200 W electronic "shunts" that trim the field for steering purposes. A combination of three approaches will be used:

- Reduce the flux, and thus the saturation, by reshaping the poles
- Add coil packs (to compensate for the saturation) and increased capability electronic shunts to compensate for the effects of the added coil packs at low fields where there is minimal saturation (exact parameters for the upgraded "shunts" have not been developed, but the units will likely have ~1 kW capability).
- Add iron, but in lesser amounts than in the 180° arcs.

For some magnets, no combination of the three options will work; those magnets will be replaced with new ones.

The present suite of quadrupoles includes only four basic designs eventhough the beam energy increases by 100x during the recirculation process; the result is that a given design is typically operating far below its maximum capability. The fields required for the upgrade exceed the capabilities of the present magnets for only ~10% of the population. Tests were performed that showed satisfactory field quality if the units were pushed to the required field levels. The plan now is to replace the power supplies on that 10% and run them well in excess of their original design specification; the remainder will be left "as is".

The dipole strings are energized by 32 power supplies varying in size up to 750 kW. All but nine will be reused for the upgrade. Those nine will be replaced with larger units that are anticipated to use one or more of a common power "pack" (the number being variable so as to meet the specific needs of the application) feeding a current regulating unit.

4.2 New beamlines

A new recirculation arc, i.e. Arc 10, is needed so that the beam re-enters the north linac for its final acceleration before going to Hall D. Both Arc 10 and the beamline to Hall D must be built using new components. Thirty-two 4 m "H-style" dipoles will be used for Arc 10 and four of the same magnets will be used for the Hall D beamline. ~40 new quadrupoles will be built using a new design that is matched to the needs of these two beamlines.

4.3 Diagnostics

We presently anticipate no need to develop any new beam diagnostic instrumentation for this project. For the existing beamlines, no changes whatsoever are planned. New units of existing designs will be used for Arc 10 and for the beamline to Hall D. We need not add electronics for the beam position monitors in Arc 10 since they can be multiplexed onto the same electronics that presently monitor the existing arcs on that end of the accelerator.

5 PROJECT STATUS

The 12 GeV Upgrade received the endorsement of the US Nuclear Science Advisory Committee in its 2002 Long Range Plan. With this endorsement, JLab is seeking primary funding for the project from the US Department of Energy (DOE). The Mission Need Statement (MNS) has been prepared by DOE's Division of Nuclear Physics and forwarded to the DOE Office of Science for a decision on Approval of Mission Need (Critical Decision 0). The projected cost for the total project (accelerator and experimental systems) is $170-250M; this cost range will be refined as the project scope and specific system cost estimates are refined in the preparation of the Conceptual Design Report. The MNS includes a schedule that has completion of conceptual design in 2003, post-conceptual engineering work beginning in FY04 (with concurrent R&D), construction beginning in FY07, and project completion in FY10.

6 SUMMARY

Lattice QCD calculations have indicated that exciting new understandings of hadronic matter and perhaps the nature of quark confinement can be investigated with the availability of a 12 GeV cw electron beam. JLab has developed a cost-effective plan that builds on it existing infrastructure to deliver the 12 GeV beam and, furthermore, extend srf and rf technology. The project is under review by the US Department of Energy.

7 REFERENCE

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