Jefferson Lab at Higher Energies: Options and Opportunities

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Abstract: Prospects for energy upgrades of the CEBAF accelerator at Jefferson Laboratory are reviewed. The plans begin with the evolutionary upgrade of the maximum energy to 6 GeV, which is already in progress. This would be followed by a construction project to provide energies up to 12 GeV in a remarkably cost-effective manner. A further doubling of the beam energy to 24 GeV is also feasible. The physics that motivates the increase to 12 GeV is reviewed briefly. Then the features of the existing accelerator are outlined with particular emphasis on characteristics of the installed components and the tunnel that impact on possible energy upgrades. Next, the broad approach to increasing the beam energy to 12 GeV, preserving the 100% duty factor and 1 MW beam power of the present accelerator, is outlined. Issues associated with the parallel evolution of the capability of the experimental equipment are reviewed and a "straw man" solution is presented to stimulate discussion. Finally, prospects for a future 24 GeV upgrade are presented briefly.

Introduction

The experimental program that was originally planned for CEBAF has been fully underway for about six months now (since November 1997), with the accelerator delivering beams at or above design specifications and all three halls carrying out experiments[*]. The spectacular performance of CEBAF's superconducting RF cavities has us well on the path toward 6 GeV operation, fully 50% above the design specification, and many experiments have already been approved to take advantage of this capability. The 6 GeV energy upgrade is taking place in an evolutionary manner that is largely transparent to the users of the accelerator.

Despite the exciting prospects of the ongoing physics program, the time is right to begin planning for the longer-term future. This planning effort began seriously with the first user workshop on Jefferson Lab at Higher Energies [1]. It has continued in many subsequent meetings and working groups, and the purpose of this workshop is to bring together in a coherent way the planning for the experimental program at higher beam energies, for the accelerator upgrade itself, and for the experimental equipment required to carry out the science program at the increased beam energies. To help in that process, in this report I outline the physics issues that have pushed the accelerator upgrade energy choice to 12 GeV, discuss the capabilities and limitations of the installed accelerator components that make it clear that 12 GeV is "right" for practical reasons as well as scientific ones, and review the status of discussions about the experimental equipment required to exploit this powerful new accelerator capability. This brief review is intended to set a framework for discussions this week and to stimulate discussion so that we end up with an even better plan and the enthusiasm to work toward its realization as rapidly as possible.

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[*] A post-workshop note: as this article goes to press (October 1998) the equipment in all three halls is operating at or above its design specifications.

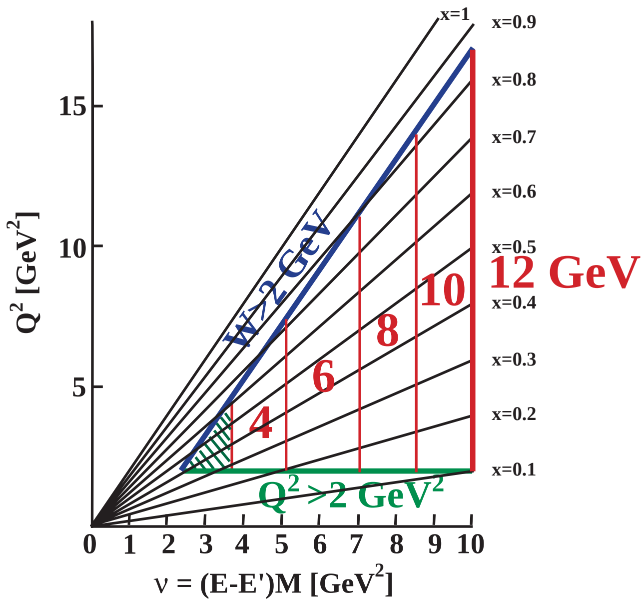
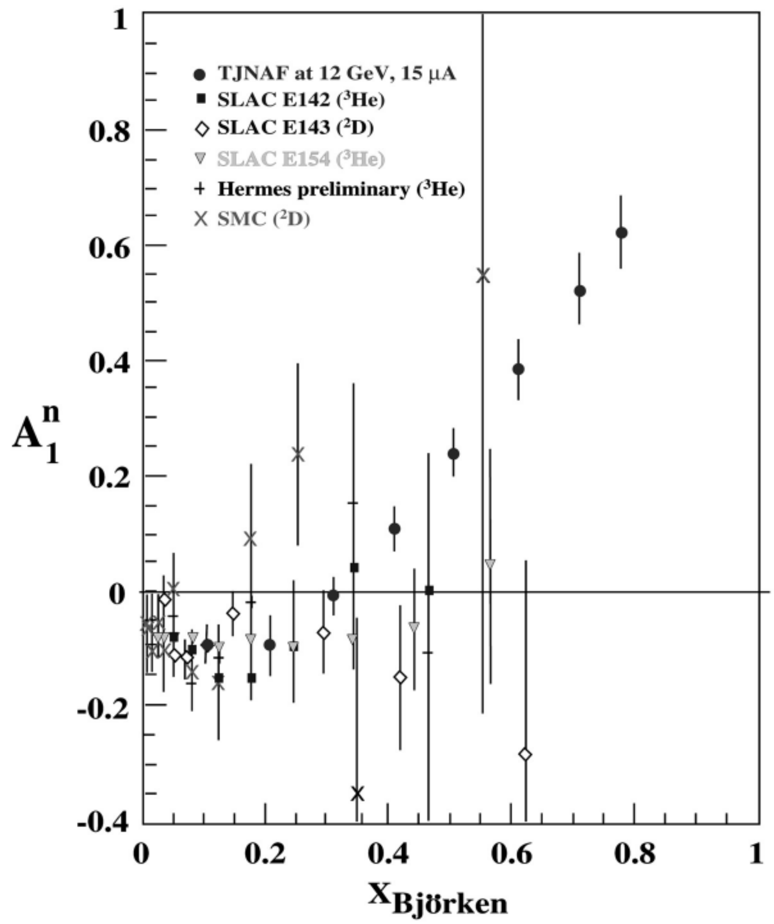


Figure 1: Kinematic regions of electron energy loss, ν, and electron four momentum transfer squared, Q^2, accessible with beam energies between 4 and 12 GeV. The deep inelastic region is defined by Q^2>2 GeV^2, W>2 GeV (where W is the invariant mass), and the scattered electron energy being greater than 10% of the beam energy The diagonal lines radiating from the origin identify constant values of the Bjørken scaling variable, x, and the vertical lines indicate the regime available for various beam energies.

Why a 12 GeV Upgrade?

There are many benefits to the nuclear physics program provided by increasing the maximum beam energy to 12 GeV. First, higher energy benefits the kind of experiments we are already doing through enhanced counting rates (at the same momentum transfer) and dramatically improved experiment design flexibility. An example of the latter is the possibility of using coherent bremsstrahlung with CLAS, producing 4 GeV photons with linear polarization and improved signal-to-noise ratios and permitting higher counting rates. Because the upgraded accelerator will retain the full three-beam capability (including the possibility of peeling off a beam after each orbit around the machine), we can deliver, for example, 2.5 and 5 GeV beams, simultaneously with 12 GeV, and continue to satisfy the needs of the present program while we also explore new physics with higher energies. While these gains are quite real and highly desirable, they are probably inadequate to convince the scientific community of the merits of the upgrade.

It is the four key new capabilities that make the scientific case for the upgrade and drive the energy choice: 1) the extension of our physics program to significantly higher momentum transfers, implying finer spatial resolution; 2) broadly enhanced access to the deep inelastic scattering (DIS) regime; 3) access to charm production; and 4) a major new physics initiative in meson spectroscopy. It is the meson spectroscopy initiative that led to the choice of 12 GeV, rather than 8 or 9 GeV, as the desired energy for the upgrade.



$$n\uparrow = ddu \sqrt{\tfrac{1}{6}}\,(\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow - 2\,\uparrow\uparrow\downarrow) \;\Longrightarrow\; A_1^n \rightarrow \begin{cases} 0 & \text{SU(6)} \\ 1 & \text{broken SU(6) and pQCD} \end{cases}$$

Figure 2: The polarized neutron asymmetry measured in deep inelastic scattering of polarized electrons from polarized ^3He. The solid points demonstrate the quality of the data that could be obtained with a 12 GeV beam (Z.-E. Meziani, private communication).

The enhanced access to the DIS regime is shown graphically in Figure 1, which is the latest version of a plot that I first saw presented by Franz Gross back when the community was talking about how CEBAF at 4 GeV, instead of at 2, at least provided access to the corner of the DIS regime. The vertical lines on the plot show where we are today, with a beam energy of 4 GeV, and what happens as the beam energy is raised. By the time 12 GeV beams are available, experiments will have broad access to the deep elastic scattering regime for values of the Bjørken scaling variable, x, out to ~0.8, and dramatically expanded access in terms of the range of energy loss and Q^2 reachable at lower x values.

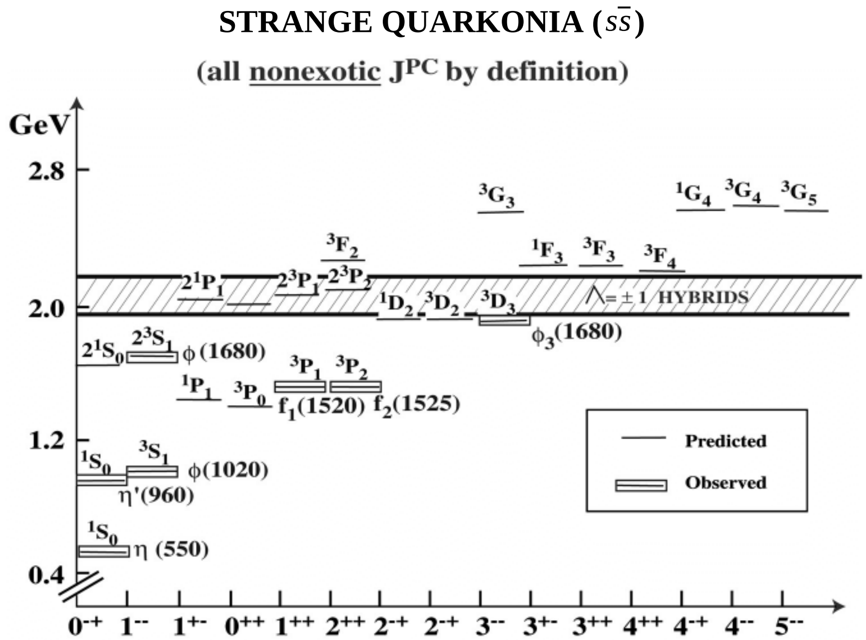


Figure 3: The low-lying portion of the spectrum of all non-exotic states predicted for a strange quark-antiquark pair. The "circled" states have been observed experimentally. (N. Isgur, private communication)

The exact choice of the desired maximum energy needed for DIS studies is somewhat qualitative; higher is generally better (until energy resolution becomes an issue), but how important is the difference between 12 GeV and 10 or 11? Figure 2 shows an example of the kind of experiment we might do, a measurement of the neutron spin structure function with a 12 GeV beam. Models tell us the structure function should go to either 0 or 1 as $x \to 1$, and it would be very interesting to get data in the valence regime ($x \geq 0.3$) to shed light on the proton spin crisis. At 12 GeV we can obtain data with modest (~5%) error bars to $x \approx 0.8$. If the maximum energy available is reduced from 12 GeV to 10 GeV, the error bars get a little bit bigger and the experiment will be limited to somewhat lower x, but we have still tested the theoretical predictions quite well.

In meson spectroscopy, we will have a situation with a 12 GeV electron beam energy that is not very different from where we are now in the N* program at 4 GeV. Figure 3 shows all non-exotic J^{PC} values expected for $s\bar{s}$ mesons. These states are the QCD analog for heavy quarks of positronium in QED. A rational program to understand QCD in the confinement regime would include the study of both quark pairs (the mesons) and quark triplets (the baryons); with CEBAF at 4-6 GeV we are restricted to the study of the triplets. The boxed states in the figure have been observed experimentally and fall roughly where they are expected theoretically. However, as is the case for the proton, a large fraction of the spectrum is missing. Finding these missing states is going to be one of the keys to understanding the $q\bar{q}$ interaction. Completing this spectrum will require that we photoproduce $s\bar{s}$ pairs with masses up to ~ 3 GeV. Photons are the beam of choice to produce the $s\bar{s}$ pairs because, unlike hadron beams, the (flavor-neutral) photon beam has plenty of $s\bar{s}$ pairs.

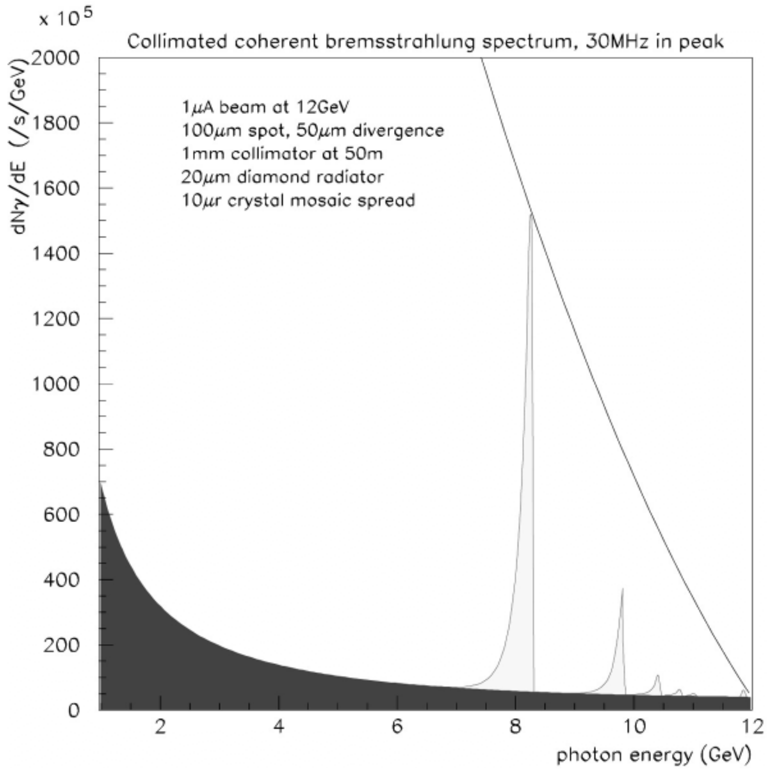


Figure 4: The photon spectrum obtained via coherent bremsstrahlung from an oriented diamond crystal radiator using a 12 GeV electron beam. (R. T. Jones, private communication)

The kinematics of photoproduction implies that we need ~9 GeV photon beams to do this job, and because we need linear polarization as well, we would like to produce these beams with coherent bremsstrahlung. Figure 4 shows an example of a coherent bremsstrahlung spectrum obtained using a 12 GeV electron beam. The "spikes" in the spectrum are from coherent bremsstrahlung, and it is in these spikes that the linear polarization is significant. (For the spike at 8 GeV the polarization for this crystal orientation is about 50%.) The energy of the spike can be moved by rocking the crystal axis relative to the beam directions. The spike gets narrower (and the associated polarization larger) as the energy of the coherent peak is moved to a smaller fraction of the electron beam energy.

A typical compromise between photon energy, energy resolution, and polarization needs is to orient the crystal so that the spike occurs at ~$\frac{1}{4}$ the electron beam energy. However, since we will be tagging the photon beam, energy resolution is less of an issue, and we can afford to move the energy of the spike to ~$\frac{3}{4}$ of the electron beam energy, where it broadens and the linear polarization is reduced somewhat, but the beam quality is still acceptable. Design considerations for the kind of photon beams needed to do meson spectroscopy lead to the goal of 12 GeV for the maximum machine energy.

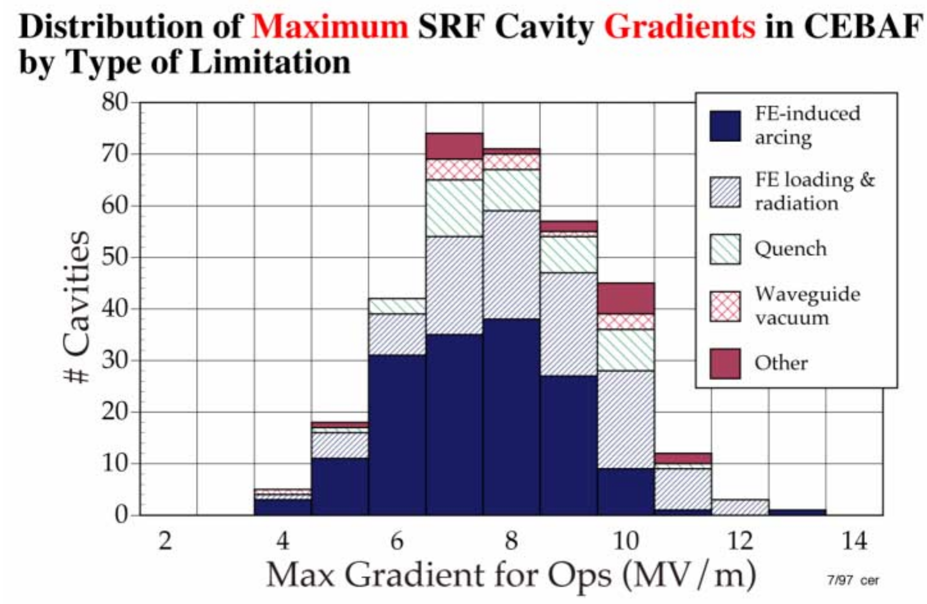


Figure 5: The maximum accelerating gradient possible for the 338 superconducting cavities in the 42_ cryomodules installed in the CEBAF accelerator. The shading on the vertical bars identifies the process that limits the gradient to the value shown. (C. Reece, private communication)

The Accelerator Upgrade, Phase I (4→6 GeV)

Next I want to discuss the present status of the accelerator, our plans for the near term future, and how it can evolve to higher energies in a way that is rational and has a minimal impact on the ongoing physics program. The first phase of the upgrade results from the performance of the superconducting cavities. Figure 5 shows the maximum gradient for the installed superconducting cavities and identifies the sources of the gradient limitations. Running CEBAF at 4 GeV requires a gradient of 5 MV/m. In addition, an “overhead” of about 10% in gradient capability is required for reliable operation. The average of this distribution is at about 7.8 MV/m and the ratio of 7.8 to 5 explains why the machine will be able to run at 6 GeV soon. As can be seen from the figure, field emission induced arcing is the main phenomenon that limits the available gradient.

We have begun a program of “in situ” helium processing to enhance cryomodule performance so that we can get from 4 GeV to 6 GeV with high beam availability. To helium process a cavity we bleed a little bit of helium into the cavity and run the RF field up until field emission occurs. The helium gets ionized in the regions where the field emission occurs (e.g., where there is a surface defect in the niobium). The helium ion goes backwards in the RF field, bombarding the surface in the region of the defect until the field emission goes down. As a result the available accelerating gradient goes up. This is a classical trick that has been used in linacs since the early days when the cavities were copper; it works well for SRF cavities as well.

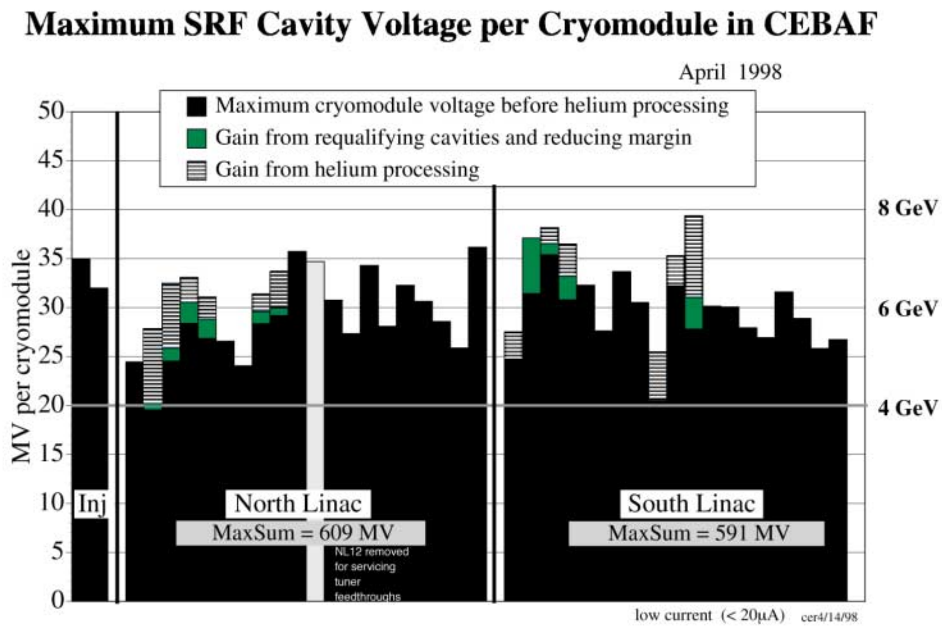


Figure 6: The maximum energy gain for each of the 42 full cryomodules installed in the CEBAF accelerator. The shaded areas on the tops of the vertical bars indicate the gains from careful adjustments of the operating parameters of the cavity control systems, and the gain from helium processing of some of the cavities. (C. Reece, private communication)

Figure 6 shows the available energy gain per cryomodule for the installed cavities; 20 MV/cryomodule is the gain necessary for operating CEBAF at 4 GeV. The black portion of each bar shows the energy gain available following the initial installation of the cavities; the gray portion shows the gain obtained by looking very carefully at the operating limits on each cavity; and the striped region shows the gain we made last summer when we processed 12 of these cryomodules with helium. This processing added 60 MeV/pass, or 300 MeV to the maximum energy of the accelerator. This summer we're planning to process a dozen more cryomodules. By the time we have run through all $42\frac{1}{4}$ cryomodules, we expect an additional 125 MV/pass to be available. The helium processing has also reduced the window arcing.

Another way of attacking the window arcing limit, which is being developed as part of the FEL program, is to relocate the window so it can no longer see the ionization produced by the beam in the very, very good, but still imperfect, vacuum on the axis of the superconducting cavities. Figure 7a shows the present geometry; you can see that it’s not very difficult for stray electrons to go from the linac axis to the ceramic window. The window can then charge up and arc. When this happens we turn the RF off so that we don’t burn a hole through the window (and allow the charge to drain off the window before we turn the RF back on). Figure 7b shows the new RF waveguide geometry, in which a modest bend is introduced. This has the obvious benefit of moving the window well away from the beam, requiring the electrons to scatter at least twice to reach the windows. We anticipate that this new geometry will substantially reduce window arcing.

Figure 7a

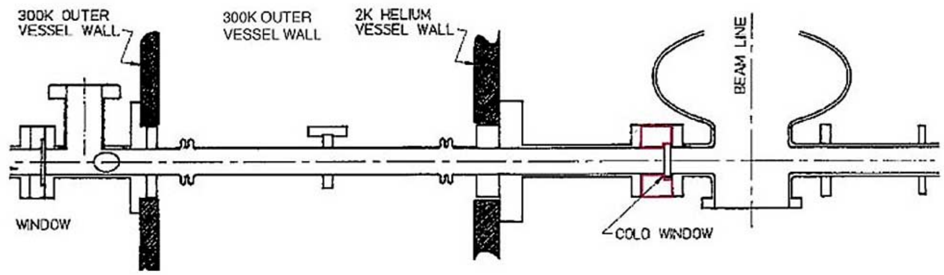


Figure 7b

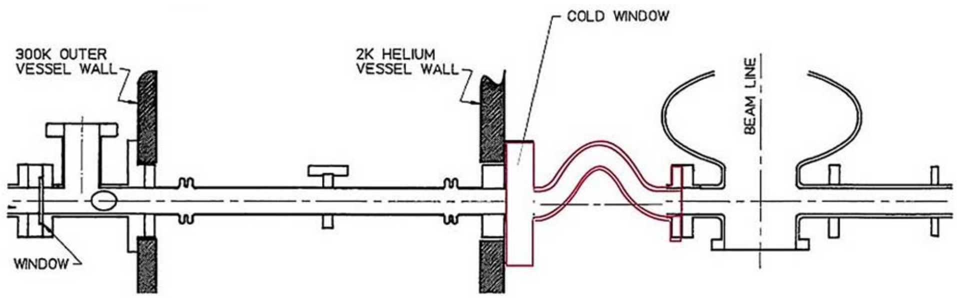


Figure 7: The geometry of the RF power feed and window for the present CEBAF cryomodules (a) and the improved geometry under consideration for the next generation cryomodules (b). (J. Delayen, private communication)

The Accelerator Upgrade, Phase II (6→12 GeV)

Cryomodule Performance

Helium processing provides a clear path to 6 GeV, but it's not going to get us to 12. One key effort in that direction is what we refer to as the "80 MV cryomodule" program. It includes a series of steps that will move the cryomodules from where they are now, solidly supporting a 6 GeV machine, to the enhanced performance that would support a cost-optimized 12 GeV machine. Work is proceeding on two fronts. First we are investigating a switch from 5 to 7 cell cavities; this would provide increased RF electrical length within the physical length of the existing cryostat, thereby providing 7/5 times the accelerating capability with no increase in the gradient. Second, we want to increase the Q of the cavities. As we begin to attack the 12 GeV problem, we've come to appreciate that if we really want to optimize the performance of the accelerator at higher energies we must work on the gradient, the length, and the Q.

The importance of working on both of these quantities is evident from the equation describing RF power requirements for a linac:

$$P_{RF} \doteq P_{Beam} + DE^2/RL,$$

where P_{RF} is the total RF power required, D is the duty factor of the linac, E is the total energy gain in the linac, L is the active length of the linac, R is the shunt impedance of the linac, and

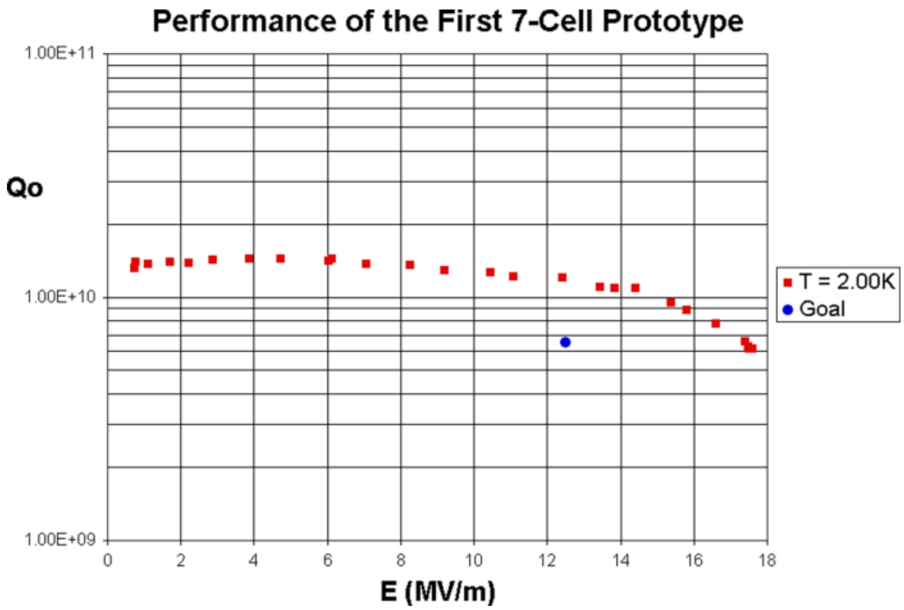


Figure 8: The performance of the first 7-cell prototype superconducting cavity. The measured Q_0 for the cavity is plotted as a function of the accelerating gradient. The large dot at E_{acc}=12.5 MV/m and $Q_0=6.5\times10^9$ corresponds to the design goal for the cavity. (J. Delayen, private communication)

P_{beam} is the beam power ($P_{beam} = E \cdot I$, where I is the beam current). This equation has two terms: the power put into the beam, and the power required to maintain the accelerating fields in the linac. In copper accelerators, the second term is huge, and the first is typically modest or, at best, equal. In contrast, for superconducting linacs the second term is very small and the power put into the beam dominates. However, the linac is at 2 K and removal of the power dissipated at 2 K is tougher than removal of power at room temperature (by roughly a factor of 1000). As this equation clearly shows, if the length of the linac is increased or its shunt impedance raised, we can reach higher duty factor for a given power dissipation.

For the 12 GeV upgrade we currently plan to begin by adding 25% more cryomodules to each linac, filling in the empty space at the end of each linac left by the original 4→5 pass design change; this increases L by 25%. We also plan to increase the electrical length of the new cryomodules by 40% by switching from 5 to 7 cells; this increases the total electrical length of the linac by another 10%. Finally, we intend to double the Q of the cavities in the new cryomodules (the shunt impedance, R, is proportional to the square root of Q).

The 80 MV cryomodule program also includes the new window coupler design, improved assembly techniques (the entire assembly will be done in a clean room), heat treatment of the cavities (to increase the quench limit), and diagnostics to identify and remove defects in the material. Figure 8 shows the results obtained from our first, 7-cell cavity tests; the cavity Q_0 is plotted as a function of the accelerating gradient for a temperature of 2K. The goal is a Q_0 of 6.5×10^9 at an accelerating gradient of 12.5 MV/m (the heavy dot on the figure). Clearly this first cavity exceeds the program goals, a very promising beginning.

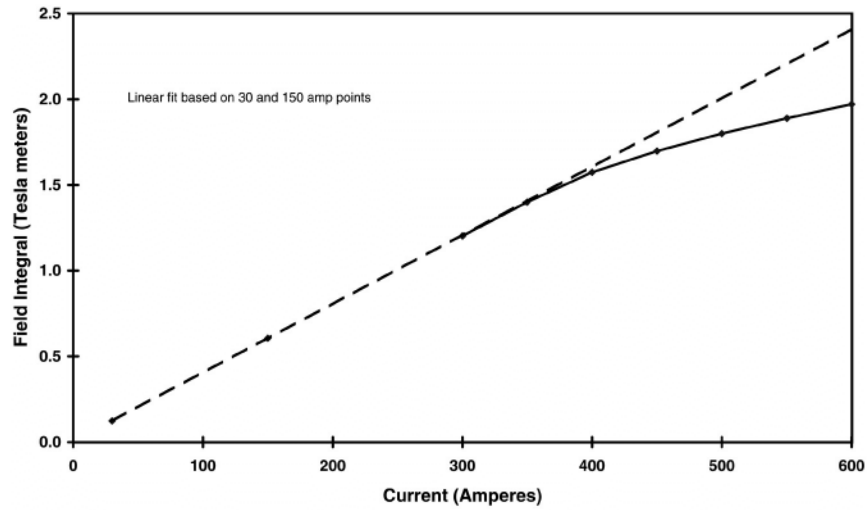


Figure 9: The measured field integral as a function of the excitation current for the standard CEBAF arc dipole magnets. The dashed line is a linear fit to the two lowest data points. (J. Karn, private communication)

Other Limitations

It is useful to review the limitations of other elements of the present accelerator as this explains many aspects of the planned upgrade. The first limit comes from the spreader/recombiners. The spreaders separate the beam orbits after each linac, and stack them vertically to send them around the arc where the (mirror image) recombiners merge them for acceleration in the next linac. The first septum magnet in the two spreaders (and the last in the two recombiners) limits operation to about 6 GeV. By replacing these four magnets, and doing some additional work, we could probably raise the maximum energy of the present recirculation system to as high as 7.5 GeV.

The next limit comes from the arc magnets. Figure 9 shows the field integral of an arc dipole as a function of the coil current; a field integral of 20 Tesla - meters is needed for 10 GeV. The figure shows that the magnets can reach 10 GeV by tripling the excitation current, but they are 20% into saturation. However, Figure 10 shows that the field uniformity remains excellent even at these high excitations. The existing magnets are suitable for bending 10 GeV beams around the arcs by running three times the current through them.

As has been appreciated here for many years, a limit of the beam recirculator approach embodied in the CEBAF “geometry” arises from emittance growth due to quantum fluctuations in the synchrotron radiation [2]. The arcs were made quite large to minimize this problem, and thus provide a machine footprint permitting future upgrades. Figure 11 shows the results of a calculation by Dave Douglas [3] of the beam’s transverse and longitudinal emittance as a function of the beam energy. The present machine (at 4 GeV) has a transverse emittance of < 1 nm - rad and an energy spread σ_E/E of .0001. As can be seen from the figure, 12 GeV will present no problem in this regard, as the beam emittance stays at values compatible with the accelerator transport system aperture of ~ 1 cm.

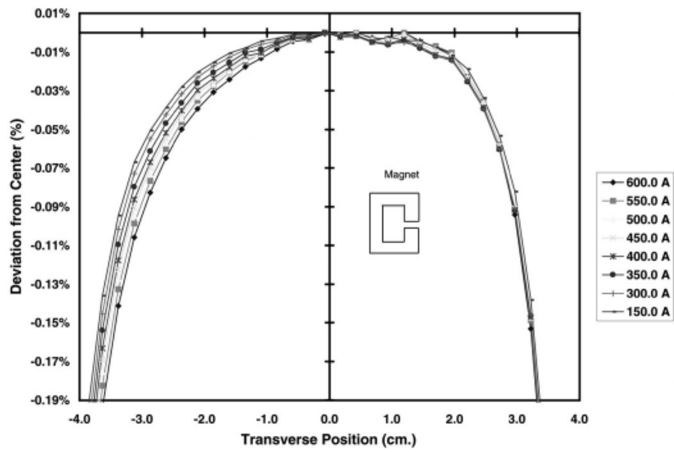


Figure 10: The deviations (in percent) of the measured field integrals as a function of the transverse displacement from the center of the dipole. (J. Karn, private communication)

Figure 11a

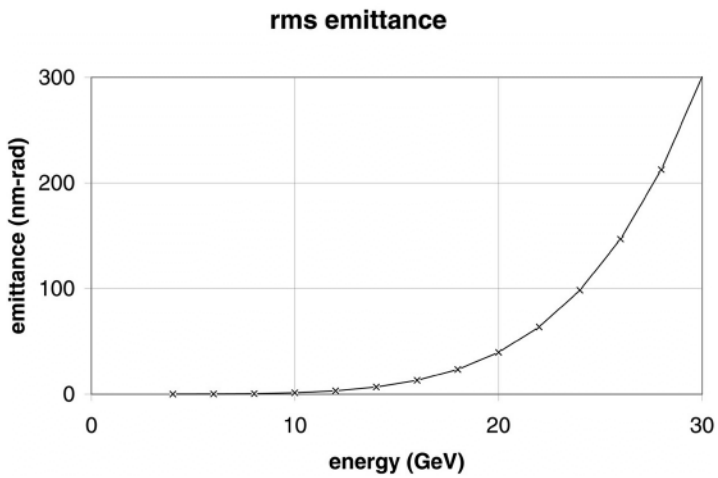


Figure 11b

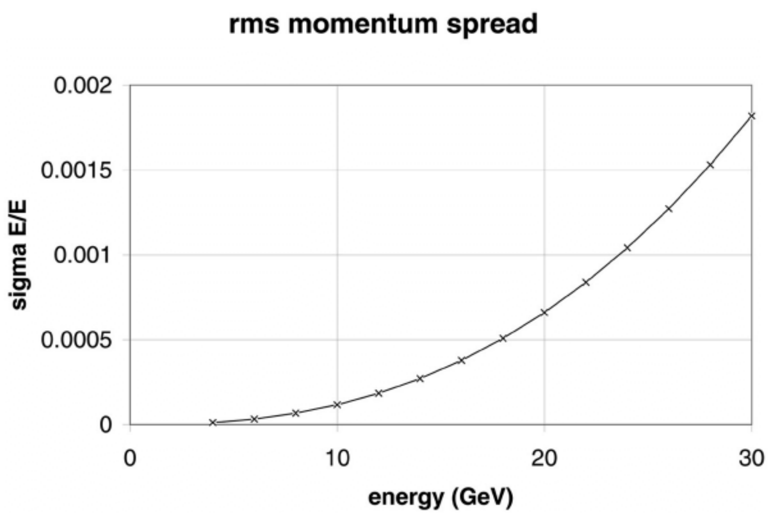


Figure 11: The transverse (a) and longitudinal (b) emittance calculated for the CEBAF beam as a function of the final beam energy for the present recirculation arc system. (D. Douglas, private communication)

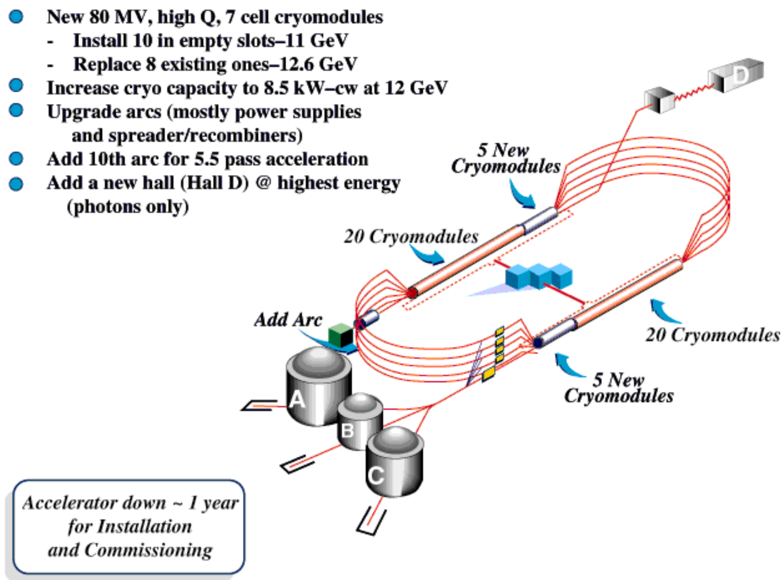


Figure 12: The layout of the present CEBAF accelerator identifying the main features of the proposed upgrade to 12 GeV.

The 12 GeV Upgrade Plan

The overall plan for the facility upgrade is shown in the cartoon in Figure 12. It begins with the addition of five new cryomodules at the end of each linac. We may also upgrade some of the cryomodules already installed in the linacs for the higher energy gain capability and improved Q of the new modules. Next we increase the cryo plant capability to 8.5 kW to support CW operation at 12 GeV. Third, we upgrade the arcs (mostly new power supplies and some reworking of the spreader/recombiner). Finally, we add one more arc (so that the accelerator becomes a $5\frac{1}{2}$ pass recirculator for the highest possible energy), and build a new hall (Hall D) at the opposite end of the accelerator from the present halls. The new hall will be for photons only.

We anticipate the transformation of CEBAF to 12 GeV capability will require the accelerator to be shut down for about 1 year; that period should be adequate for both work that needs to be done in the tunnel and re-commissioning the upgraded accelerator. This relatively short shutdown is possible because much of the work that needs to be done for the upgrade can be accomplished in parallel with normal accelerator operations.

Building Hall D has several advantages. First, by having a fourth hall we can increase the average hall multiplicity from two to three, a 50% increase in the physics output. (We are presently limited to a multiplicity of two by the installation effort required to support typical CEBAF experiments; on average one hall is undergoing significant modification.) Second, adding the last half orbit permits us to reach 12 GeV while continuing to use most of the components in the present accelerator, particularly the dipole elements in the arcs and in the transport lines to the present halls. In the past, when we talked about the upgrade, we often talked about a maximum energy of “8 to 10 GeV.” When we looked hard at the basic accelerator elements, we found that the maximum value (for a 5-pass machine) is ~ 11 GeV. With the addition of Hall D we can get to 12 GeV with the addition of one more linac pass (half an orbit). The third big advantage is that by building the new hall at the opposite end of the accelerator, we can start work on the hall as soon as funds are available. Hall construction and the installation and preliminary testing of the detector can be done while we run the present experimental program, allowing this major new detector to be ready to run at the time the accelerator comes back up after the upgrade.

<u>Characteristics of CEBAF at 12 GeV</u>

The beam characteristics of the upgraded accelerator are impressive, and include 100% duty factor, 1 MW of beam power, and multiple beam capability. In the upgrade scheme shown in Figure 12, Hall D must get the highest energy available; the present plan has no RF separators for “peeling off” lower energy beams for this hall. We could add a second set of RF separators (similar to those now used for pass 1 through 4 extraction to the existing end stations) to permit lower energies in Hall D, but it isn't clear that it would be worth the expense. An additional constraint of the new recirculation scheme is that Halls A, B, and C each receive unique energies. We will no longer have the capability of running the three existing halls at the top energy because the RF separator that currently provides that capability will be used in the new scheme to send beam to Hall D. To make the constraints concrete, consider the following example. If we ran the accelerator at 1.1 GeV per linac we can choose to send beams to three of the halls; Hall D could be at 12.1 GeV, and Halls A, B, and C could each choose one of the available energies of 2.2, 4.4, 6.6, 8.8 and 11 GeV.

Experimental Equipment for CEBAF at 12 GeV

Next I want to discuss the end stations briefly. One of the keys to the success of the present facility is the thoughtful effort that went into planning the end station capabilities. The complementary capabilities of the halls maximize the research capability of the facility. We must repeat that effort for the 12 GeV upgrade. The upgrade is being discussed as a construction project with an $80 M price tag, roughly half for the accelerator and half for the experimental areas. We also have on-going annual equipment upgrade funding. As we move toward 12 GeV, we should preferentially apply these funds to devices that will be useable at higher energies as opposed to devices that might be useable now but would not work at higher energies. We are working with the Hall D group to investigate high energy physics funding support for a major new detector for meson spectroscopy, the basic device that would go into Hall D. Finally, we of course welcome foreign collaboration in all aspects of the project.

In the following I present a “straw man” for how the facility might evolve to stimulate discussion at the workshop this week. This is my personal summary of what’s been percolating in the halls, with no small amount of input from both the user community and the laboratory staff.

<u>Hall A</u>
We have a huge investment in this hall, which is equipped with a pair of spectrometers with excellent momentum and angular resolution. Futhermore, the physics program that motivated this hall is highly likely to be worth continuing long into the future (I note in this regard that Hall A has the largest backlog). Therefore we keep Hall A as the place where we retain a focus on high precision experiments requiring resolution on the nuclear physics energy scale. We will

add ancillary detectors to complement the spectrometers and expand the reach of the physics program, devices such as scintillator hodoscopes for hadron correlation studies and a photon calorimeter for real and virtual Compton scattering experiments. Also, under consideration is a next-generation hypernuclear spectroscopy system in which a small, short, high-resolution spectrometer could be coupled with the splitter already under construction. Details are provided in Kees de Jager's contribution to these proceedings.

Hall B

My guess is that even in 2003 the CLAS collaboration will still have plenty of physics on its plate. Therefore, I anticipate evolutionary improvements in Hall B aimed at realizing the ultimate potential of the CLAS superconducting toroidal coil geometry. Maintaining CLAS's capability to identify exclusive final states will require a strategy change as the beam energy is increased; missing mass techniques will no longer work because we will run out of resolution. We will have to enhance the detection capabilities so that the detector can "see" everything. The basic strategy under consideration (discussed in B. Mecking's contribution to these proceedings) includes the addition of full coverage tracking to the inner detector and the addition of calorimeter elements inside the coils to complement the outer calorimeters.

Hall C

The focus of Hall C will remain high luminosity, high Q^2 physics and one-of-a-kind experimental setups. To retain this capability at the higher beam energies, we will use the HMS as the lower energy hadron detector and build a "Super HMS" matched to the 12 GeV electron beam. This new spectrometer pair can do the high Q^2 physics at the high luminosities that a megawatt of 12 GeV beam could provide. Details are given in R. Carlini's contribution to these proceedings.

Hall D

As discussed above, Hall D will be a new, photon-only hall, added at the opposite end of the site to get $5\frac{1}{2}$ passes of acceleration for the highest possible beam energy. The Hall D detector will be optimized for meson spectroscopy, and have characteristics (both neutral sensitivity and small forward angle detection) that are complementary to the CLAS. It will also have a tagged, coherent bremsstrahlung facility to be able to exploit that detector. Details are provided in A. Dzierba's contribution to these proceedings.

CEBAF Beyond 12 GeV

What next? (Not that 12 GeV shouldn't keep us happy for a while!) 24 GeV is a technically feasible, scientifically exciting, realistic long-range goal. The higher energy is well matched to completing the lab's scientific goal of understanding the QCD basis of strongly interacting matter. Basically this accelerator has capabilities that correspond to the European ELFE proposal [4]. I note with amusement that 12 GeV is what the French academy told the Saclay physicists back in 1989 was the "right" energy for the next electron machine [5]. The Saclay physicists looked hard at the issues in collaboration with many other European physicists, and came to the conclusion that 12 GeV was indeed interesting, but that raising the energy to 30 GeV provided even more physics possibilities. In reality, a 24 GeV beam can do essentially all the physics that has been discussed for 30 GeV, and has the important advantage (here) of fitting within the existing tunnel. An upgrade that required a new tunnel would be really expensive.

The principal constraint on the maximum beam energy that can be accommodated in the present CEBAF tunnel is the emittance growth that results from quantum fluctuations in synchrotron radiation emitted as the beams pass through the recirculation arcs. The longitudinal and transverse emittance growths are proportional to γ^7/ρ^2 and γ^5/ρ^2 respectively, where γ is the standard relativistic factor (E/mc^2) and ρ is the bending radius of the beam [2]. As can be seen from the calculation of these effects for the present arc configuration shown in Figure 11a, the beam will fill the ~1 cm aperture available by an energy of about 20 GeV (when the transverse emittance exceeds ~50 nm-rad).

This problem might appear to be intractable, but relief can be found once you realize that the relevant bending radius is the actual bending radius of the beam in the dipoles, not the physical radius of the arc. The ratio of the radius of the arc tunnel to the radius of the beam curvature in the dipoles is ~3 in the present CEBAF recirculator for the highest energy arc (and even higher for the lower energy arcs). Dave Douglas has done a proof of principle design of an arc lattice [3] that shows we could reach an energy of order 24 GeV by decreasing this ratio for the three highest energy arcs. His calculation of the emittance growth for this arc configuration is shown in Figure 13; by making these arc modifications we can reach a beam energy of ~25 GeV before the beam fills the available aperture (see Figure 13a). Figure 13b shows that the energy spread remains acceptable in this configuration.

Calculations by Christoph Leemann and others suggest that with an improved recirculation arc system (possibly adding a sixth orbit) and the CHL improvements planned for 12 GeV, we could provide a 1 MW, high duty factor (~40%) 24 GeV electron beam for a total cost of order $200M. We could even have 100% duty factor for energies up to about 21 GeV.

Summary

Now is the time to start thinking seriously about the future. I have presented an outline of our draft plan. It begins with evolutionary upgrades to an energy of 6 GeV that will be transparent to CEBAF's users. The second phase, raising the energy to 12 GeV, will require a one-year shutdown that will be used mainly to rebuild the arcs and recommission the accelerator. We would like to start the construction project in 2003, in which case the shutdown would occur roughly in 2006. Before any of this can happen we need to plan the end station equipment and refine the scientific case for the experimental program, because we must convince the larger science community of the merits of the upgrade and its science. Last, but not least, the combination of the SRF technology and the present tunnel will take us another factor of two down the road, raising the maximum energy to ~ 24 GeV. The sum of these possibilities provides Jefferson Lab with an incredibly exciting and promising future.

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Figure 13a

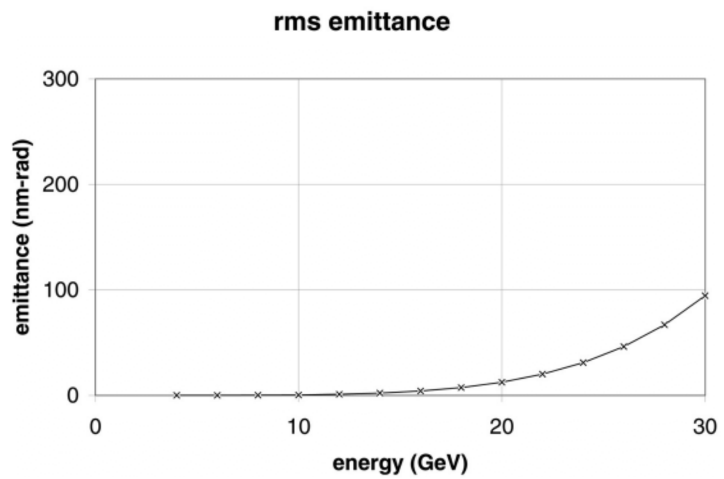

Figure 13b

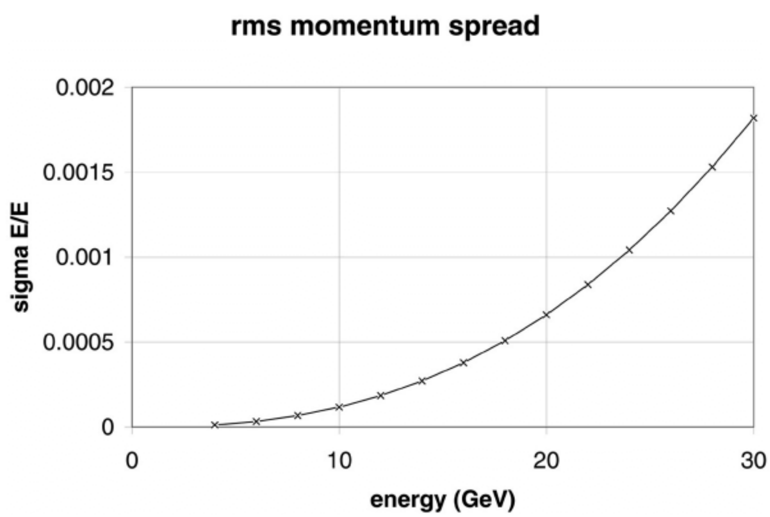

Figure 13: The transverse (a) and longitudinal (b) emittance calculated for the CEBAF beam as a function of the final beam energy for a revised recirculation system in which the total length of the dipole bending field is increased in the three highest energy arcs (increasing the bending radius in the dipoles) and some additional focusing is provided. This result should be compared with the calculation for the present arcs in Figure 11. (D. Douglas, private communication)

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