# A SUPERCEBAF Scenario Providing an Incremental Upgrade Path from 12 to 24 GeV

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## Abstract
We describe a machine concept for SUPERCEBAF. It assumes an invasive system upgrade of CEBAF to 12 GeV and provides thereafter incremental upgrades to 24 GeV.

## Introduction
Technical issues for the design of high energy, SRF based CW electron accelerators have been discussed elsewhere [1]. Recent discussions have elucidated various institutional concerns related to implementations of such a machine at Jefferson Lab. The following chronology has been conjectured in these discussions; it implies requirements for the machine concept detailed below.

- CEBAF operation will continue to 2005; machine energy will reach ~7 GeV. This corresponds to an average cryomodule energy gain of 35 MV, and an average linac energy gain of 1.4 GeV per pass.
- Beyond 2003, improved SRF technology is assumed available, providing cryomodules with average energy gain of 80 MV.
- Linac energy reach will be extended from 2003 to 2005 by the replacement of some 35 MV cryomodules by 80 MV modules. This provides ~2 GeV per pass (or higher) as early as 2005. This is not reflected in the machine final energy, which remains transport system limited to 7 GeV.
- CEBAF goes off the air in 2005.
- In 2005-6 a new SUPERCEBAF (Superconducting Upgrade of the Present Electron Recirculator CEBAF) transport system is installed in the existing tunnel, extending machine energy reach from 7 to 12 GeV through utilization of the recently upgraded SRF. It is assumed this transport system is (or can incrementally be made to be) 24 GeV capable.
- In addition to the existing three end stations, SUPERCEBAF serves a fourth end station ("Hall D"), which is intended for very high energy operation. Multiple beams to multiple end stations are retained, with simultaneous, multi-energy service to three of four end stations available.
- From 2006-2015, SUPERCEBAF energy reach is incrementally extended to 24 GeV by replacement of any remaining 35 MV modules by ones providing 80 MV and by installation of 80 MV modules into linac blank spaces.

## Machine Concept - Issues

As noted above, technical issues for such a machine were discussed in detail elsewhere [2]. Key features that enter into the following concept (some of which are addressed in the previous discussions) are as follows.

- *Injection energy* – the following machine concept assumes injection energy in excess of that provided by simple injector energy scaling. This
  - reduces the dynamic range in energy over which the machine operates,
  - limits multi-pass beam envelope mismatch generated by reduced linac focussing on higher passes, and consequently
  - allows use of simpler spreader/recombiner designs (such as asymmetrical chicanes or single-step translations) that may have smaller dynamic acceptance than the staircase presently used in CEBAF.
- *Number of passes* – The existing tunnel provides length for ~50 cryomodule slots. This implies a maximum energy gain (using 80 MV modules) of 4 GeV per pass. The desired 24 GeV final energy thus requires 6 passes. We note that this number is the historical cost optimum for CEBAF. We note that the exact number of cryomodule slots available in each linac, and their precise location, is influenced by other requirements, such as the desire for multi-beam service (see below) or the method used to split beams for recirculation [3].
- *Multi-beam service* – it is assumed that SUPERCEBAF should retain CEBAF multi-beam capability. As this feature was originally implemented for 4 GeV (with assumed upgrade potential to 6 GeV), some challenge may be anticipated in a 24 GeV implementation; rearrangement of available tunnel slot lengths may be needed.
- *High peak current operation* – CEBAF was designed and built to accommodate only low single bunch charge; cavity and vacuum system impedance would result in severe beam quality degradation at high charge per bunch. SUPERCEBAF SRF and vacuum system components should be designed to allow acceleration of high charge-state bunches for novel applications, such as x-ray FELs.
- *Counter-rotating beams* – The present CEBAF cryomodule accelerates/decelerates beam in one direction only (due to cavity-pair spacing in the module). SUPERCEBAF 80 MV modules should allow for use of counter-rotating beams, which, though not present in the following machine concept might arise in future machines and have been noted to be useful in certain FEL applications [4].
- *Component Re-use* – Insofar as possible, CEBAF components should be re-used to build SUPERCEBAF.

## Machine Concept - Details

*Per* the above discussion, at the time of the upgrade CEBAF is assumed to be operating with ~80 MeV injection energy and 7 GeV final energy, using 40 (+2¼ in the injector) 35 MV cryomodules in a 5 pass configuration. The upgrade conceptual requirements to be met are as follows.

- *High injection energy*
- *Component re-use*
- *Multi-beam operation*
- *Incremental Upgrade from 12 to 24 GeV.*

A design scheme meeting these requirements is as follows.

- The machine will be upgraded to a 6 pass, 12 GeV machine by replacing some 35 MV cryomodules with 80 MV cryomodules. The single-pass linac energy gain will therefore be 2 GeV following the invasive upgrade, 4 GeV in the "final" configuration.
- To ensure multi-beam operation is feasible, the 5 South Linac dead spaces will be absorbed into the transport system, and used for additional extraction region slot length.
- To allow maximum available acceleration slot length, the east extraction region will be absorbed into the North Linac, allowing 5 additional North Linac zones.

*This scenario thus asymmetrizes North and South Linac energy gains, and assumes all end stations remain located at the West End of the machine. Alternative end-station distributions (with halls at the East End of the machine) can be conjectured; such scenarios may introduce difficulty in retaining multi-beam service at very high energy.*

- The distribution of installed 80 MV modules will be chosen so as to allow energy-doubling the South Linac by replacing the remaining 35 MV modules, and energy doubling the North Linac by replacing the remaining 35 MV modules and installing 10 80 MV modules in the 10 available dead spaces.
- The first suite of replaced 35 MV modules will be used to construct a 1 GeV recirculating pre-accelerator. This can be energy doubled (along with the rest of the machine) either by an upgrade using the remaining 35 MV modules (when they are replaced), by replacing 35 MV modules with 80 MV modules at a future date, or by changing the recirculation scheme.
- CEBAF magnets will be re-used for the pre-accelerator and for the low energy passes of SUPERCEBAF.

Only two problems have to be worked out – how many 80 MV modules are needed (and where they go), and how the CEBAF magnets are redistributed in the low passes of the new transport system. Trivial details (such as the actual 6 pass transport system design that handles a ~20 GeV beam without degradation due to quantum excitation) are left to the reader.

With regard to the modules, we note that if N (S) of 20 35 MV modules are replaced by N (S) 80 MV modules, the North (South) linac energy gain will be simply (20-N) x 35 + N x 80 MeV [(20-S) x 35 + S x 80 MeV]. Following the upgrade to full energy, the North (South) linac energy gain will be (including 10 modules for the dead spaces) 20 x 80 + 10 x 80 MeV (20 x 80 MeV). The final upgrade doubles the energy, so N and S are specified as follows:

$$2[(20-N) \times 35 + N \times 80 \text{ MeV}]= 20 \times 80 + 10 \times 80 \text{ MeV}$$

$$2[((20-S) \times 35 + S \times 80 \text{ MeV}]=20 \times 80 \text{ MeV}$$

Thus, N=11 and S=2, meaning the North linac is initially upgraded to ~1.2 GeV and the South to 0.8 GeV, with final upgrades to 2.4 and 1.6 GeV. The energy upgrade can be accomplished entirely incrementally, with new modules (and, perhaps, transport system power supplies) being installed as procurement money becomes available from 2006 through 2015.

The initial 12 GeV project yields 13 35 MV modules that can be used in a pre-accelerator. Noting the CEBAF injector will, at that time, have 2¼ 35 MV modules giving about 80 MeV energy, we can postulate a 2-pass pre-accelerator (built out of spare CEBAF parts; see the discussion below) using the 13 35 MV modules to give about 1 GeV total injection energy. The configuration can be chosen in various ways. Some of these follow.

- 13 (12 or 14) modules in single-pass split linacs with 13 (12 or 14) total dead spaces that can be used to incrementally upgrade the pre-accelerator using 35 MV modules liberated during the SUPERCEBAF 12 to 24 GeV upgrade. This allows the injection energy to be incrementally upgraded to track the main machine energy without purchase of new modules
- 13 modules in a 2 pass single (or split) linac without dead spaces, that would be upgraded to track SUPERCEBAF upgrades using new 80 MV modules.

This scenario chooses the former option inasmuch as it appears to have significant cost advantage. Though the required tunnel is roughly twice as long, the total tunnel length is clearly of order less than 1 km (four times the length of 26 modules), which, at 5000$/m, gives a total tunnel cost of ~5 M$.

This is roughly the cost of a two 80 MV modules with RF. Upgrading pre-accelerator energy by installing new 80 MV modules is thus not a winner!

Regarding CEBAF component re-use, we note that the arc dipole magnet distribution in a 7 GeV CEBAF is as given in Table 1. Table 2 provides a potential redistribution of these magnets into a SUPERCEBAF transport system. Note that the magnet peak fields will remain essentially the same in the new system. Similar considerations may be made for other dipoles and various classes of quadrupoles.

Table 1: CEBAF arc dipole distribution

| Arc | # dipoles | Dipole length (m) | Arc Energy (GeV) |
|---|---|---|---|
| 1 | 16 | 1 | 0.7 |
| 2 | 16 | 2 | 1.4 |
| 3 | 32 | 1 | 2.1 |
| 4 | 32 | 2 | 2.8 |
| 5 | 32 | 2 | 3.5 |
| 6 | 32 | 2 | 4.2 |
| 7 | 32 | 3 | 4.9 |
| 8 | 32 | 3 | 5.6 |
| 9 | 32 | 3 | 6.3 |

Table 2: SUPERCEBAF arc dipole distribution – 12 GeV

| Location | # dipoles | Dipole length (m) | Arc Energy (GeV, for 12 GeV) | Arc Energy (GeV, for 24 GeV) |
|---|---|---|---|---|
| Pre-accelerator arcs | | | | |
| 1 | 16 | 1 | 0.25 | 0.5 |
| 2 | 16 | 2 | 0.50 | 1.0 |
| 3 | 32 | 1 | 0.75 | 1.5 |
| SUPECEBAF arcs | | | | |
| 1 | 32 | 2 | 2.2 | 4.4 |
| 2 | 32 | 3 | 3.0 | 6.0 |
| 3 | 64 | 2 | 4.2 | 8.4 |
| 4 | 64 | 3 | 5.0 | 10.0 |
| 5-11 | New design | | | |

All that said, the 12 GeV machine concept is shown in Figure 1, its 24 GeV final form in Figure 2. The 12 GeV system consists of an 80 MeV injector, a 1 GeV pre-accelerator, and a 12 GeV main linac. The 80 MeV injector is that used in the pre-upgrade 7 GeV linac. The 1 GeV pre-accelerator comprises two split linacs, three recirculation arcs, and an initial complement of 12 to 14 35 MV modules recovered from CEBAF during the upgrade. The pre-accelerator also has 12 to 14 dead spaces, into which additional 35 MV modules will be inserted as they become available during energy upgrades of SUPERCEBAF. The main accelerator consists of a 1.2 GeV North Linac (with 9 35 MV modules, 11 80 MV modules, and 10 dead spaces), a 0.8 GeV South Linac (with 18 35 MV and 2 80 MV modules), and a 6 pass recirculator comprising 11 arcs. All machines can be incrementally upgraded by replacing 35 MV modules with the 80 MV version (and putting up to ~13 35 MV modules so obtained into the pre-accelerator) or by installing 80 MV modules in the North Linac dead spaces. Final energy of the first upgrade is ~13 GeV; that of the second ~26 GeV.

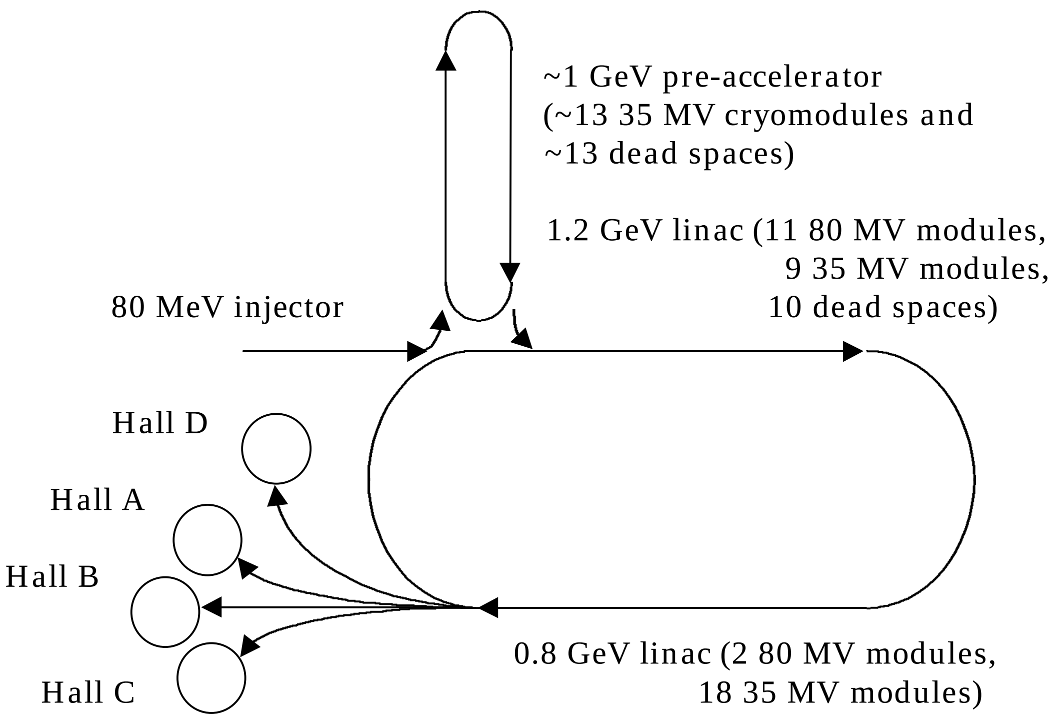


Figure 1: 12 (13, actually) GeV SUPERCEBAF configuration. Injector assumed to be 2¼ 35 MeV modules, single pass. Transport system is either immediately 24 (26, actually) GeV capable, or incrementally upgradeable (through, *e.g.*, power supply modification) to 24 (26) GeV.

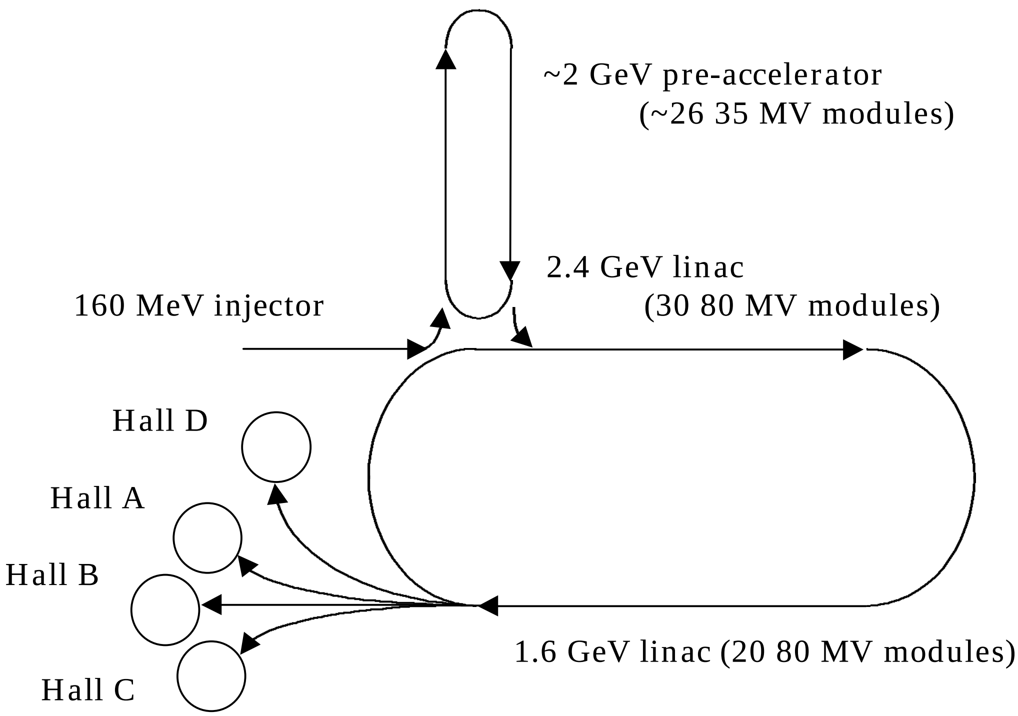


Figure 2: 24 (26, actually) GeV SUPERCEBAF configuration. Injector is assumed to be either 2¼ 80 MeV modules, single pass, or 2 passes in a machine with 2¼ 35 MeV modules.

## Acknowledgments

The concepts detailed in this note draw heavily upon discussions during meetings of the Accelerator Design Department. All members of this group have contributed significantly to ideas used in the above design concept, as have Leigh Harwood, Paul Rutt, and Christoph Leemann. I thank them all and acknowledge their very useful input.

## References

[1] D. Douglas, "Lattice Design Principles for a Recirculated, High Energy, SRF Electron Accelerator", in Proc. 1993 IEEE PAC Conf., Washington, D.C. (May 1993); D. Douglas, "Quantum Excitation Estimates for CEBAF Energy Upgrades", JLAB-TN-97-038, 15 October 1997.

[2] *Ibid*.

[3] See, *e.g.*, the first of References [1].

[4] See, e.g., the discussion at http://www.cebaf.gov/~douglas/FEL/guide/application.html#pottop.