THE CEBAF SUPERCONDUCTING ACCELERATOR–AN OVERVIEW*

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Abstract

The CEBAF accelerator is a CW linac based on RF superconductivity and making use of multiple recirculation. Its major components are a 50 MeV injector, two linac segments of 0.5 GeV energy gain each, and recirculator arcs connecting the two linac segments. Each linac segment consists of 25 cryomodules, separated by warm sections with quadrupoles, steering magnets, and beam diagnostics. Each cryomodule contains 8, 1500 MHz, 5-cell, Cornell type cavities with waveguide couplers for fundamental power and HOM damping, each cavity being powered by its own klystron. Recirculator arcs are vertically stacked, large radius, strong focusing beam lines that minimize synchrotron radiation effects. A high quality ($\Delta E/E \sim 10^{-4}, \epsilon \sim 10^{-9}$ m) beam of 200μA, 100% duty factor, with 0.5 GeV $\leq$ E $\leq$ 4.0 GeV will be generated.

Introduction and Overview

Scientific Background

CEBAF is a high energy, high duty factor, high current (4 GeV, 100 %, 200 μA) electron accelerator for nuclear physics. The need for such a facility has first been clearly stated in 1979, has been endorsed on several occasions since, and represents today nuclear physics' highest priority in terms of new facilities acquisitions. In the broadest terms, the scientific mission are experiments leading to an understanding of the nucleus in terms of quarks and QCD. The envisaged experiments determine the stated performance objectives of the accelerator. The energy range, 0.5 GeV to 4.0 GeV is determined by the goal of establishing overlap with existing facilities on the low side, at the high end by the minimum energy required to achieve the spatial resolution judged necessary to meet the general mission's goals. As will be shown below, the present design has the capability to exceed this energy. The need for a high duty factor beam, ("continuous" beam) simply stems from the fact that coincidence experiments will constitute an essential fraction of the envisaged program. The relatively high average current of 200 μA ensures adequate event rates for the processes of interest that typically have low cross sections, and allows the simultaneous operation of three experimental stations. Beyond those basic beam parameters, good beam quality, particularly a relative momentum spread of the order of 10^{-4} are desirable because complexity of design and cost of high resolution spectrometers is reduced by such features. Construction begin is planned for fiscal year 1987, the start of physics experiments in fiscal year 1992.

Technology Base

The most straight-forward approach to generate the beam described above is a continuous wave (CW) device. Such an approach is feasible today, both technically as well as in terms of capital and operational costs. The key elements are the use of RF superconductivity (SRF) and beam recirculation, i.e., the multiple passage of the beam through the same accelerating structure. In the energy range of interest, room temperature cavity based systems encounter difficulties because the necessary large number of recirculations, as in microtron like machines, severely impact the achievable beam quality. The use of SRF, allowing a low number of recirculations (3 to 5), is therefore essential.

The status of SRF technology is described elsewhere, a recent update being presented at this conference.[1] The breakthroughs that make this a practical solution occurred recently, mostly since 1983, and may be summarized as follows:

- Optimization of shape and coupling.
  - Serious multipacting prevented by elliptical and spherical cavity shapes.
  - RF-coupling and HOM damping at beam pipe avoid cell penetrations and their deleterious effects.
- Better superconductor quality may reduce number of defects, and stabilizes the remaining ones through better thermal conductivity.
- Better manufacturing techniques include reduced electron beam weld defects, improved cleanliness in assembly, identification of defects through surface inspection and thermometry, and improved chemical procedures.
- Essential to the use in storage ring and recirculated linacs is heavy damping of higher modes.

Accelerator Description

Conceptual Description

Figure 1 illustrates the CEBAF accelerator concept. Two sections of linac, 240 m long and providing 0.5 GeV energy gain each, are located in the two straight sections of the racetrack shaped layout of the accelerator. Transport lines, consisting of sections called "spreaders," recirculation arcs, and "recombiners" connect the two linac segments. While beams of different energies occupy the same physical locations in the linac sections, they are by necessity separated in the beam transport lines of which there are four connecting segment 1 to segment 2, for four-pass recirculating, and 3 connecting segment 2 back to segment 1.

Injection into the device is performed with a 50 MeV beam from a linac consisting of room temperature structures up to 1 MeV, and the same SRF cavities, as used in the main linac segments, to accelerate from 1 MeV to 50 MeV.

Extraction is achieved by means of RF separators in a way that makes it possible to serve simultaneously all three end stations with beams of the same or up to three different, although correlated energies.

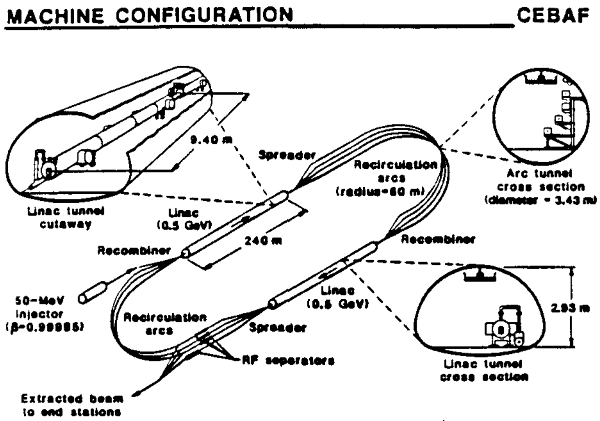


Figure 1. CEBAF accelerator schematic.

Key Issues and Design Choices

The preservation of beam quality and the assurance of beam stability are the most outstanding beam dynamics questions for a machine of the type described. Important design choices involve operating frequency, the basic choice of a cavity design and judiciously chosen design values of gradients and Q-values. All of the latter are obviously tightly connected with the task of effective and successful technology transfer to industry, and have strong cost impact. High reliability and protection against damaging beam loss is equally important.

Many aspects of design are pertinent to the issue of beam quality and will be described below or in other contributions.[2] The most fundamental concern, and one that directly impacts the accelerator layout, is to hold the effects of quantum excitation in the recirculation arcs at a tolerable level. A sufficiently large bending radius is the only means to control growth of momentum spread σ_E, while both radius of curvature and strong focusing help in minimizing the growth in horizontal emittance. The present design achieves these goals with a relatively loosely packed, separated function lattice that results in an average radius of curvature of 80m. It has been shown[2] that within the planned enclosure an alternate lattice design will fit that would meet our criteria for energies up to ~16 GeV, i.e., an energy that would appear achievable at a time when multicell cavities achieve the gradients that are observed today in the best single cell results.

With regard to beam stability it can be argued that at the projected current levels, and with the planned cavities, the only beam current limitation of importance could arise from multipass regenerative beam breakup that has, e.g., limited the Stanford SCA to currents of tens of microamperes.[3] The phenonmenology of this instability is easily understood: a bunch passing through a cavity off axis will excite higher order modes (HOM's) that are transversely deflecting. If a bunch, kicked by a preexisting field corresponding to one of these HOM's, returns with a betatron and RF phase that adds to the HOM field, the potential for instability is given; steady state is maintained if the bunch excitation compensates for the losses that occur during the revolution time due to the finite Q of the mode in question, and at higher currents instability sets in. Key ingredients to analyze this phenomenon are knowledge of HOM frequencies, corresponding impedances and Q values, cavity to cavity frequency spread and the spatial arrangement and transverse beam optics of the accelerator. Analytic estimates, lumping all cavities in a single location and assuming maximum conspiracy in the choice of the transverse matrix elements result in a worst case threshold estimate that still exceeds the design current by nearly an order of magnitude.[4,5]

Bisognano[5] and Gluckstern[6] have performed more realistic calculations along two distinctly different paths that yield the same numerical predictions. One approach is based on simulation, realistically modeling all 400 cavities and the beam transport optics, and is based on a modification of a SLAC code by R. Helm. The other approach is based on the fact that finding the complex frequencies that correspond to the zeros of the determinant of a 2(n-1) dimensional matrix solves the problem for an n-pass configuration, irrespective of the number of cavities involved. The matrix elements are relatively lengthy, trancendental expressions but numerical searches for the zeros have been successfully demonstrated. We summarize the results of these investigations by quoting from Bisognano[5] the determined threshold values at 4 GeV that exceed specifications by more than 2 orders of magnitude.

Table 1
Computer Simulation Estimates of Beam Breakup Thresholds

	1888 MHz	1969 MHz	2086 MHz	2110 MHz
I_{th}	21 mA	18 mA	56 mA	26 mA

The above analysis was only possible after a cavity design had been adopted. The choice of the Cornell 5-cell, 1500 cavity with waveguide, beam pipe couplers for fundamental power and HOM damping was based on the advanced state of this design that virtually eliminated the need for further lab scale R&D, the need to demonstrate a feasible overall accelerator design on a very short time scale, the proximity of the Cornell group, and the appropriateness of the frequency. Frequencies below ~900 MHz would have violated the CW beam concept, implying undesirably high microbunch charges from the experimenter's point of view, while very high frequencies become undesirable because transverse impedances will scale as the third power of the frequency, given similar shapes. Based on the experience at Cornell and worldwide a design gradient of 5 MeV/m and a design residual Q of $3 \cdot 10^9$ was postulated. Industrial prototyping is in progress and the successful results and will be reported below and in a separate contribution to this conference.[7]

The parameters of the CEBAF accelerator are summarized in Table 2, Figure 2 shows a cavity prototype.

Detailed Description of Machine Sectors

Injector

The injector has the task of providing beam with a nominal energy of 50 MeV, a norminal 1500 MHz bunch structure and the capability of modulating bunch to bunch intensity with periodicity three, i.e., matching the requirement of serving three end users with beams of different intensity.

The injector consists of a warm section providing beam of 0.95 MeV, followed by a section of superconducting linac consisting of 18 SRF cavities contained in the sequence 2+8+8 in three separate cryogenic modules. The only difference from the main linac segments to be described below is the one module containing only 2 cavities.

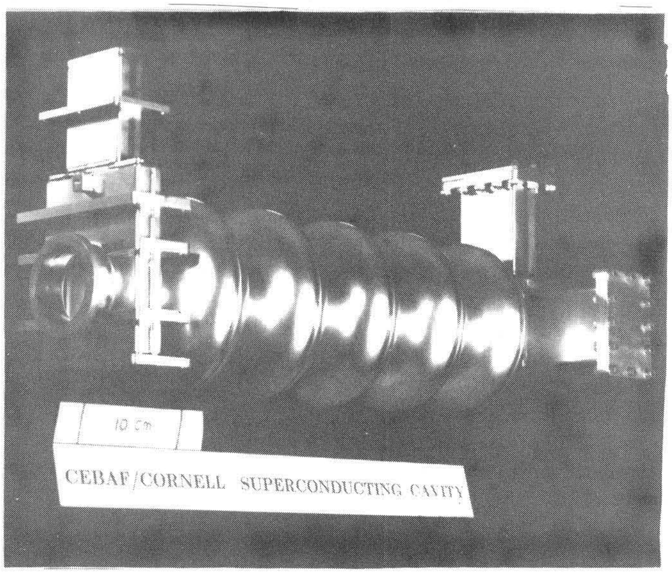


Figure 2. CEBAF/Cornell cavity.

Table 2

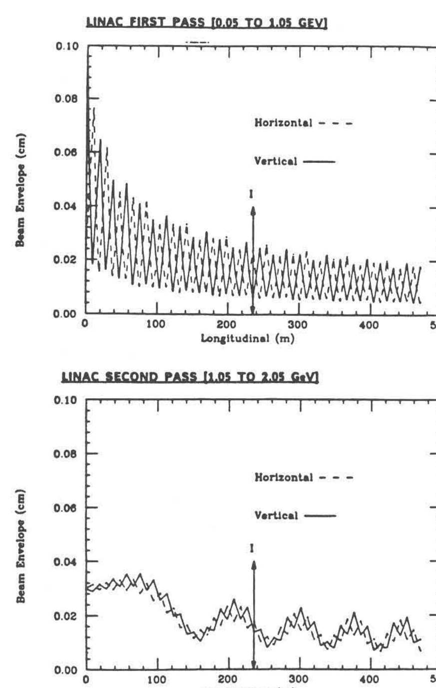
CEBAF SRF CW Linac Design Parameter List

Beam characteristics	
Electron energy E [GeV]	0.5 ≲ E ≲ 4.0
Average current [μA]	200
Transverse emittance (95%, 1 GeV) [m]	2 x 10-9
Energy spread [95%]	1 x 10-4
Duty factor	100%
Simultaneous beams	3
Simultaneous energies	≲ 3
Linac Parameters	
Concept	Superconducting CW recirculating linac
Number of passes	4
Number of linac segments	2
Segment length [m]	235
Maximum energy gain per pass [GeV]	1.0
Recirculation time per pass [μS]	4.2
Focusing	FODO
Phase advance per cell (pass 1)	120°
Half-cell length [m]	9.4
Number of cavities per half-cell	8
Number of half-cells per segment	25
Vacuum (before cooldown) [torr]	10-9
Cavity parameters	
Type	Superconducting
Frequency [MHz]	1500
Electric length [m]	0.5
Shunt impedance (r/Q) [ohm/m]	960.0
Design gradient [MV/m]	5.0
Design residual Q	3 x 10^9
Typical HOM $Q_{external}$	10^3 to 10^5
Clear aperture [mm]	70
Transverse HOM Z^*/Q [ohms/m^3]	≲ 16.4 x10^4
RF system	
Number of klystrons	418
Klystron RF power coupled to beam [kW]	2.0
Injector parameters	
Gun energy (MeV)	0.10
Injection energy [MeV]	50
Average current [μA]	200
Transverse emittance (at 0.1 MeV) [mm-mr]	1
Longitudinal emittance [keV-degrees]	< 15π
Bunch length [degrees]	< 1.5
Pulse capability [μs]	0.05 to 10
Recirculation arcs	
Number	7
Magnetic radii [m]	11.5 to 28.6
Phase advance per period	2π(5/4)
Periods per arc	4

The room temperature section consists of an electron gun in Pierce geometry capable of providing a 2mA DC beam with an emittance of 10^{-6}m at 0.1 MeV, about an order of magnitude better than the design goal of $\sim 2 \cdot 10^{-9}$m at 1 GeV. The gun will have the capabilities for fast pulsed operation, mostly for tune-up and diagnostic purposes. Two cavities and an adjustable 3-slit aperture system provide chopping and intensity control. The slits can be adjusted from 0° to 60° bunch length for each of three succeeding bunches. Both cavities are excited at $f_o/2$ and $f_o/3$ in two orthogonal directions, the first cavity providing the sweep pattern over the 3-slit aperture, the second serving to eliminate the introduced transverse momentum. A buncher cavity operating nominally at 1500 MHz reduces the bunch length to below 10°. Two 5-cell cavities, graded in β, and each driven by the same type of klystron as used in the main linac capture the beam and accelerate it to 0.95 MeV with an energy spread of 16 keV and a bunch length of 1.7°. The whole room temperature section relies strongly on the NBS/NPL/LANL design[8], and the whole injector has been extensively modeled with PARMELA.

Linac

The total accelerating structure comprises 400 cavities and is arranged in the form of two separate linac sections, each approximately 240 m long. The linacs are built in a modular fashion consisting of cryogenic modules separated by warm sections that contain quadrupoles, steering magnets, beam diagnostics and vacuum equipment. The focusing sequence and strength corresponds to a 120° phase advance FODO structure for the first pass through the accelerator, later passes at higher energy obviously have weaker focusing, particularly in the "low energy end," i.e., the first linac close to the injector. The sequence of beam envelopes through the accelerator, Figure 3, shows the regular pattern on the first pass as well as the decreased but still adequate focusing for higher energy passes.



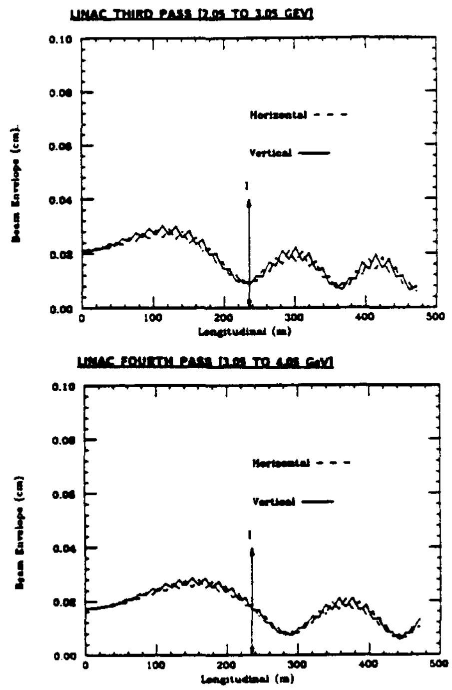


Figure 3. Beam envelope traces through four linac passes. An identity transformation is substituted for the beam transport section between linac 1 and linac 2.

Each cryogenic module, Figure 4, is made up from four cryo-units, cryostats containing two 5-cell cavities, representing the smallest self-contained building block of the accelerating structure. Figure 2 depicts the cavity and Table 2 summarizes its key parameters. The design of the cryostat, and issues pertaining to the cryostat-cavity assembly and their solution are discussed by Biallas.[9] As is evident from Figure 4, the orientation of the fundamental power couplers alternate from cavity pair to cavity pair in a left-right-right-left pattern.

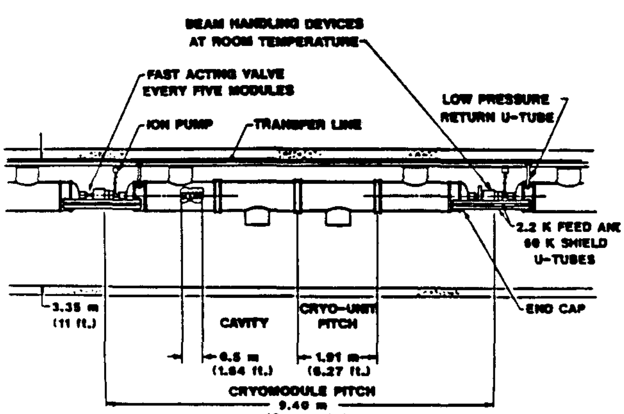


Figure 4. CEBAF cryogenic module.

This arrangement ensures that the very small beam emittance is not degraded by the head to tail variation in the transverse deflections that are inexorably associated with the field asymmetry across the aperture at the power coupler end. With all cavities powered equally the compensation is essentially perfect, but as illustrated in Figure 5 very good results are obtained even if a standard deviation of 1 MeV in energy gain per cavity is allowed.[10] Even this effect can be reduced by individual adjustments of the cavity gradients on the few percent level.[11]

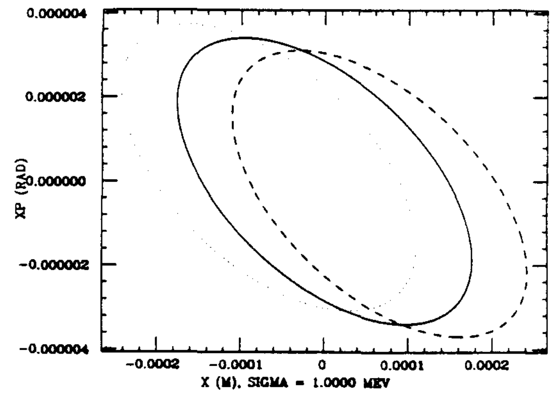


Figure 5. Uncorrected differential head to tail deflections after four passes with 400 cavities with $G = 5MV/m, \sigma_G = 1MV/m$. Ellipses correspond to $\epsilon = 5 \cdot 10^{-10}m$ and head, center, and tail of bunch, respectively.

The latter observations are important because each cavity is powered by its own klystron. This results in increased system availability and provides an extra margin of safety for reaching or even exceeding design energy. We can expect a spread of several MeV/m between different cavities, and the planned system allows maximum utilization of the available cavity capabilities. The demands on the control of the RF system are quite demanding: amplitude must be controlled within 10^{-4}, phase within 1°, and this in a severely beam loaded situation. A contribution by J. Fugitt[12] to this conference describes the RF-system design.

Beam Transport

Under this heading we subsume all the beam transport elements not contained within the linac sections proper. The key requirements are to provide matching in all three phase planes from linac section to linac section, isochronicity (or sufficiently small deviations from it), total circumference lengths of exact multiples of the RF wave length, and minimal degradation of beam quality due to synchrotron radiation effects.

The transport systems from linac section 1 to section 2 contain the same basic components as those connecting section 2 back to section 1, if we abstract from the fact that the corresponding energies are different and that we deal with four beam lines in the first case, and only 3 in the second. Starting at the exit of a linac we first encounter the vertical spreader, an achromatic bend, followed by a matching section containing extraction elements (after section 2) or the space to implement them at a later stage (section 1). The 180° bend is then executed by the recirculation arcs proper, which in turn are followed by a (shorter) matching section and another achromatic vertical bend, the recombiner.

These arrangements are depicted in Figure 6. One of the central concerns in the design of the arcs was minimization of beam degradation and a solution that could be implemented with uncomplicated magnets. The present design foresees arcs composed of four periods each, with a total phase advance of $5 \times 2\pi$ in both planes. Each period is an isochronous second order achromat. Basically the same quadrupole arrangements are employed in all beam lines but the number of dipoles is reduced for the lower energy lines. Magnetic radii thus fall between 11 m and 29 m. Table 3 summarizes key parameters of the recirculation arcs.

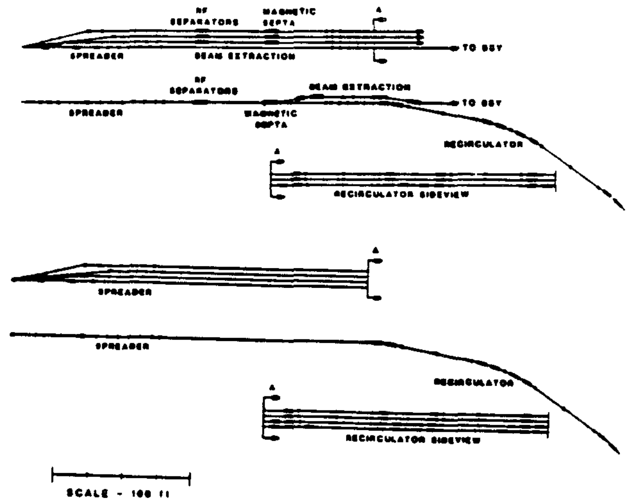


Figure 6. Details of beam transport following linac 1 and linac 2, respectively.

Table 3

Table 3: Beam Line Lattice Properties

Lattice Property	0.5-2.0 GeV Lines	2.5 GeV Line	3.0-3.5 GeV Lines
# Dipoles	16	32	40
Orbit Radius in Dipoles (m)	11.46	22.92	28.65
Dipole Magnetic Length (m)	2.25	2.25	2.25
# Quadrupoles	32	32	32
Min. Quad Focal Length (m)	4.56	4.30	4.36
Phase Advances $\psi_{x,y}$	$2\pi \times 5$	$2\pi \times 5$	$2\pi \times 5$
Matched β_x, β_y (m)	35.,3.5	35.,3.5	35.,3.5
$\langle \mathcal{H} \rangle$ (m)	.114	.167	.269
x,y Natural Chromaticities	-7.6,-8.11	-8.66,-7.76	-9.28,-7.92
# Sexupoles	8	8	8
Peak Sextupole $(B''l/B\rho)$ (m^2)	1.51	1.14	1.24

The design of these arcs is described in detail by Douglas[2]. The key features are:

- Alignment, field quality and energizing tolerances within current practice result in negligible beam quality degradation and/or are sufficiently well compensated by the planned set of beam monitors and correction magnets.
- The induced momentum spread σ_E/E is only $1.2 \cdot 10^{-5}$ to be compared with the undisturbed value of $2.5 \cdot 10^{-5}$, indeed negligible in quadratic addition. The resulting emittance growth is completely negligible at $\Delta\epsilon \simeq 3.4 \cdot 10^{-11} m$ compared to the expected $\epsilon \simeq 5 \cdot 10^{-10} m$ at 4 GeV.
- The resulting average arc radius of 80 m will accommodate alternate lattices for higher energies that would result in similar performance at up to four times higher energies.

We finally discuss the extraction process. RF-separators, i.e., cavities excited in a deflecting mode are used to achieve extraction on a bunch by bunch basis. An obvious but practically undesirable frequency is 500 MHz for the task at hand, namely to affect three interspersed sequences of bunches differently. In fact any frequency $f = \ell/3 \cdot f_0 = \ell \cdot 500 MHz$, where ℓ is not an integral multiple of 3 will do, and the design choice is $5/3 \cdot 1500 MHz = 2500 MHz$. Three RF separators are installed in the extraction/matching straight sections following the spreader downstream of linac segment 2. If an RF separator is not energized all bunches continue for another pass through the accelerator. If extraction is desired the separator is energized and deflects, if properly phased, every third bunch maximally outward across a thin magnetic septum that completes the extraction process while all other bunches are deflected inwards receiving a kick of only half the maximum strength whose effect is compensated by a static magnet further downstream. After four passes all remaining beam exits without further manipulations. A vertical recombiner brings the beams back into the horizontal plane. The extraction channels are tuned such that at this point the beams are slightly divergent such that, some distance downstream, they can be separated by magnetic septa. This is obviously only achieved if each beam is extracted at a different energy. For the case where more than one beam is extracted at the same (full four pass) energy, a fourth separator is located following the last recombiner element. This separator is phased such that the relative kick strength is +1, 0, -1, +1, ... to distribute the beams to the three end stations.

Key issues in the design of this extraction system are the choice of technology, SRF versus conventional, and the minimization of emittance growth due to differential head to tail deflection. The present design achieves extraction with negligible emittance growth at deflection angles of the order of 10^{-4}, and with these modest kick requirements room temperature deflectors appear to be the simpler and more cost effective solution.

Overview over Other Systems

Vacuum

Vacuum requirements as set by beam loss criteria are modest. The arcs and other beam transport lines are pumped by discrete ion pumps and at a pressure of $2 \cdot 10^{-7}$ Torr total beam loss is at the very most a few 10^{-6} for four full passes. This pressure is initially exceeded due to the desorption of gas by synchrotron radiation[13] but is reached after only four days of operation during which beam loss will not exceed the 10 to 20w level if full beam power is used. More stringent requirements are established by the need to protect and keep clean the cavity surfaces. Fast gate valves placed between every fifth cryomodule will limit damage in the case of a sudden vacuum accident. The warm sections between cryomodeles will be treated such that a pressure $< 10^{-9}$ Torr is reached with the end valves to the cryomodules closed. At the ends of both linacs an additional length of beam pipe will be kept at 2K.

I&C and Correction Systems

The CEBAF accelerator will be extensively instrumented and equipped with a commensurate set of correction elements. Essentially at every quadrupole a beam position and beam current monitor will be installed. These will be based on cavities resonant at 3000 MHz oscillating in the TM_{110} and TM_{010}

modes, respectively, and providing X, Y position and current information. With every quad location in the linacs an X and Y steering dipole will be associated, while in the beam transport lines steering dipoles will act only in the quad's focusing plane. Beam profile monitors for the beams of only a few 100μm width are being evaluated, with synchrotron radiation devices and "flying wires" being the leading candidates.

The key features of the control system will be heavy emphasis on hardware versus software, the extensive use of distributed intelligence, and the general orientation towards the user and operator, and his evolving needs and demands.

Cryogenic System

A sizeable cooling system is required to operate the superconducting accelerator.[14] After lengthy and careful analysis 2.0K has emerged as an optimum temperature with regard to technical complexity, capital and operating costs. The system's cooling requirements are summarized in Table 4.

Table 4

Cooling Requirements

	He temp (k)	Calculated load	Refrig. capacity	(%)	Pres. (atm)
Linac cavities	2.0	3200 W	4,800 W	(150)	0.031
Linac heat shields	40.-52.	8000 W	12,000 W	(150)	3.0
End Sta. liquefac.	4.4	154 l/hr	260 l/hr	(169)	1.2

The distribution system is designed with a flow safety factor of 200, and quite generally design features were employed that would allow upgrades by the simple addition of compressors, expanders, and cold compressor capacity. The latter are at the forefront of helium refrigeration technology and have become operational as the result of intensive development by both U.S. and European manufacturers. They are central to the operation allowing on one hand 2.0K at 0.031 atm and positive pressure (1.05 atm) in the ambient suction piping and compressors.

Status and Outlook

The present CEBAF design is the result of an effort that started with a review of the applicable technology base beginning in June 1985, and concluding in August 1985 that a complete redesign based on SRF was the most appropriate and effective approach. This new design has passed the review process required for a 1987 construction start, culminating in a Conceptual Design Report (CDR) that established in February 1986 a baseline for technical features, cost and schedule. The design is currently being defined and optimized with all major areas undergoing through scrutiny for opportunities for improvements. The single most important activity is the development of industrially fabricated cavities and cryostats. This program is well on schedule and results of early prototypes[7], Figure 7, corroborate the conservative nature of the key design parameters: E$\geq$ 5 MeV/m, $Q_\circ \geq 3 \cdot 10^9$.

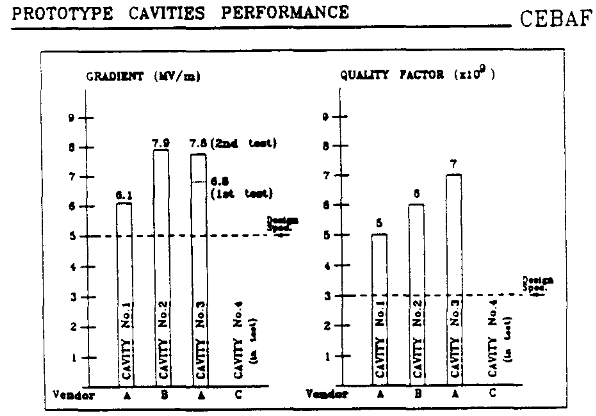


Figure 7. Results of first industrially fabricated CEBAF cavities. Design gradients and Q-values (5.0 MeV/m, $3 \cdot 10^9$) are substantially exceeded.

Acknowledgements

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