RF SUPERCONDUCTIVITY AT CEBAF*

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12000 Jefferson Avenue, Newport News, Virginia 23606, U.S.A.
August 14, 1989

INTRODUCTION

The Continuous Electron Beam Accelerator Facility (CEBAF) is a 4 GeV continuous beam electron accelerator being constructed to perform nuclear physics research. The accelerator is being designed and constructed for the United States Department of Energy, Division of Nuclear Physics, by the Southeastern Universities Research Association (SURA). Construction began in February, 1987, and initial operation is scheduled for February, 1994.

The accelerator is 1.4 km in circumference, and has a race-track shape (Fig. 1). The accelerator is of the recirculated linear accelerator type, and employs a total of five passes. The beam is injected by a 45 MeV injector. Two linacs on opposite sides of the racetrack each provide 400 MeV per pass. The beams of various energies are transported by separated arcs at each end of the straight sections to provide the recirculation. There are 4 recirculation arcs at the injector end, and 5 arcs at the other end. The full energy beam is routed by an RF separator to between one and three end stations, as desired, on a bucket-by-bucket basis. The average output beam current is 200 microamperes.

Acceleration is provided by 338 (plus 22 spare) superconducting cavities (Fig. 2). The cavities are five-cell, 1497 MHz units operated at 5 MV/m and a $Q_0 \geq 2.4 \cdot 10^9$ at 2K. The cavities are arranged in pairs (Fig. 3), each of which is enclosed in a helium vessel and suspended inside a vacuum jacket without ends; this unit is called a cryounit (Fig. 4). Four cryounits are connected together by bridging components and fitted with end caps; this unit

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* Work supported by the U. S. Department of Energy, Contract DE-AC05-870R21800.

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is called a cryomodule (Fig. 5). The operating temperature is chosen to provide the minimum capital cost, and also coincidentally provides the minimum operating cost.

PROTOTYPING

The superconducting cavities being used by CEBAF were developed at the Cornell University Laboratory of Nuclear Studies[1] for CESR-II, a proposed e^+e^- storage ring which was not constructed. The concept of a hermetic cavity pair[2] permits two cavities, assembled into a unit, to be tested in a relatively simple vertical cryostat to ensure that their performance is acceptable. After the test, which is conducted with hermetic RF input power windows, beam line gate valves are closed, and the cavity pair is kept under continuous vacuum thereafter to minimize the likelihood of surface contamination. The pair is then outfitted with its tuner and various instrumentation, and installed into its accelerator cryostat. Testing the cavity as a pair effectively makes each cavity's input transmission line part of the resonator, since a shorted superconducting waveguide with integral coax-to-waveguide transition is attached to the cavity's input coupler. Since the input waveguide and its extension is fully superconducting (except for the hermetic window), and since the coax-to-waveguide transmission can be adjusted to have critical coupling to the resonator as a whole, the intrinsic Q of the cavity can be measured directly even though the input Q_{ext} is small compared to Q_0. This property not only permits the Q_0 to be measured in a simple and accurate way, but permits the reference transmission probe to be calibrated accurately.

In order to be able to have the superconducting accelerating cavities for CEBAF produced by industry, personnel from Cornell University and CEBAF undertook an extensive program to transfer the cavity fabrication technology to interested companies. In addition to the original four cavities of the Cornell/CEBAF design fabricated by Cornell, one cavity was built by ATEA (formerly Lemer), three cavities were built and an additional one completed by Babcock and Wilcox, two were built by Dornier, four were built by Interatom, and one cavity was built and an additional one started by TRW. The performance of these cavities is shown in Table I.

Table I. Cavity Test Results

Key: CU = Cornell, IA = Interatom, C = CEBAF, S = single cavity, P = pair. A separate test number indicates a new processing.

Cavity Number	Cavity Manufacturer	Where Process.	Where Tested	Grouping	Test No.	Gradient MV/m	Q_0 x 10^9 (2.0K)
LE5-3	Cornell	CU	CU	S	5	9.2	4.8
LE5-4	Cornell	CU	CU	S	3	7.0	3.4
"	"	CU	CU	S	4	8.0	2.9

Table I. Cavity Test Results (Continued)

Key: CU = Cornell, IA = Interatom, C = CEBAF, S = single cavity, P = pair. A separate test number indicates a new processing.

Cavity Number	Cavity Manufacturer	Where Process.	Where Tested	Grouping	Test No.	Gradient MV/m	Q_0 x 10^9 (2.0K)
"	"	C	C	P - A'	6A	9.3	7.0
		Kapton window change					
"	"	C	C	P - A'	6B	9.5	3.3
LE5-5	Cornell	CU	CU	S	1	9.7	>1.9
"	"	CU	CU	S	2	15.3	3.0
		Solvent rinse to remove defect					
"	"	CU	CU	S	4	12.0	4.4
"	"	CU	CU	P - Syst	5	8.6	7.0
LE5-6	"	CU	CU	S	1	5.0	5.5
C-1	Interatom	IA	IA	S	1	6.1	3.3
		Grind defect					
"	"	IA	IA	S	2	6.3	5.5
		Purify, outgas					
"	"	IA	IA	P	3A	12.1	4.8
"	"	IA	C	P	3B	11.7	7.5
"	"	C	C	P - B'	4	8.8	3.3
C-2	Dornier	CU	CU	S	1	8.0	8.4
"	"	CU	CU	P - Syst	2	12.0	7.0
"	"	CU	CU	P - B	3A	10.2	10.8
C-3	Interatom	IA	IA	S	1	6.8	7.0
		Grind defect					
"	"	IA	IA	S	2	7.7	7.5
		Purify, outgas					
"	"	IA	IA	P - C	3A	10.4	7.5
"	"	IA	C	P - C	3B	10.3	3.0
"	"	C	C	P - B'	4	7.4	3.5
C-4	B & W	CU	CU	S	1	6.4	4.5
"	"	CU	CU	P - A	2A	6.7	4.3
		Include ceramic window losses in following Q					
"	"	C	C	P - D'	3	5.2	2.0
C-5	TRW	CU	CU	S	1	7.2	7.0

Table I. Cavity Test Results (Continued)

Key: CU = Cornell, IA = Interatom, C = CEBAF, S = single cavity, P = pair. A separate test number indicates a new processing.

Cavity Number	Cavity Manufacturer	Where Process.	Where Tested	Grouping	Test No.	Gradient MV/m	Q_0 x 10^9 (2.0K)
		Include ceramic window losses in following Q					
"	"	C	C	P - E'	2	7.2	2.4
C-6	B & W	CU	CU	S	1	7.6	6.9
"	"	CU	CU	P - A	2A	7.8	9.1
		Include ceramic window losses in following Q					
"	"	C	C	P - D'	3	7.8	1.2
C-7	TRW + B&W	C	C	S	1	6.7	7.5
"	"	C	C	P - A'	2A	8.6	9.9
		Kapton window change					
"	"	C	C	P - A'	2B	5.0	2.6
C-8	Interatom	IA	IA	P - C'	1A	8.8	6.0
"	"	IA	C	P - C'	1B	7.8	3.5
		Two changes, HOM loads					
"	"	IA	C	P - C'	1C	6.9	3.4
C-9	Interatom	IA	IA	P - C'	1A	9.4	7.0
"	"	IA	C	P - C'	1B	8.7	3.3
		Two changes, HOM loads					
"	"	IA	C	P - C'	1C	8.5	4.5
C-10	Dornier	CU	CU	S	1	7.5	2.2
"	"	CU	CU	P - B	2A	Bad cable; Q O.K.	
C-11	Westinghouse	Hydroforming not successful					
C-12	B & W	C	C	S	1	6.8	2.6
		Include ceramic window losses in following Q					
"	"	C	C	P - E'	2	6.8	3.5
C-13	ATEA	C	C	S	1	6.7	3.0

In addition to the vertical tests of single five-cell cavities and cavity pairs listed above, a number of cryounit tests were performed.

The original cryounit test[1] involving cavities of this design, or course, was the beam test in CESR using two cavities of this design in November, 1984. The results are listed in the table below.

A cryounit of the original CEBAF cryostat design ("A") was tested in February, 1988. This cryounit incorporated B&W cavities 1 and 3, without reprocessing. A vacuum accident during assembly impaired the performance of the cavity closest to the accident. The gradients and Q's obtained are listed in the table below. It was also found that the clearances were such as to make assembly of this cryounit excessively difficult, and there were thermal shorts present, causing the static heat load to be higher than our design value.

A sub-cryomodule ("A+B"), also using the original cryostat design, was tested in May, 1988. The sub-cryomodule test was conducted to find any deficiencies in the method of connecting cryounits together. The "A" cryounit was not disassembled following its previous test, and the "B" cryounit was appended to it. A different vacuum accident during assembly of the "B" cryounit impaired the performance of the cavity nearest to the location of this accident. This test yielded no surprises involving the interconnection of the two cryounits. The static heat load, as would be expected, was still above the design value. The performance of the cavities is listed in the following table.

Following the "A+B" test, the cryomodule design was modified, and the "A" cavity pair was installed, without reprocessing, in a cryostat with a revised vacuum vessel and heat shield. This test, referred to as the "$A^{1/2'}$" test, showed that the static heat leaks associated with the cryostat now conformed to the design values. This test was conducted in January, 1989. The cavity performance values are listed in the table below.

The A' cavity pair, consisting of cavities LE5-4 and C-7, was installed in a cryostat of the completely upgraded design, including the helium vessel. A test of this cryounit, A', was conducted May, 1989. This test yielded static heat leak values of 5.0 watts for the cryounit itself, also in conformance with the design values of 6.6 watts. The performance of the cavities in the cryounit test is listed in the table below. This cryounit will next be tested with the 500 keV injector to produce a 5 MeV beam.

Pairs B', C', D', and E' have been processed, assembled, and tested vertically. They have been installed in their respective cryostats, and the resulting cryounits have been assembled into a complete cryomodule. This cryomodule was completed on July 27, 1989, and its cooldown is scheduled to start September 2, 1989. Assuming that the cryomodule test is successful and that the 5 MeV test is successful, the injector, quarter cryomodule, and full cryomodule will be moved into the tunnel for the "front end test" to be conducted in 1990.

Test results on Cornell/CEBAF cavities tested in accelerator cryostats to date are summarized in Table II.

Table II. Cavity Test Results in Cryounits

Key: CU = Cornell, IA = Interatom, C = CEBAF. A separate test number indicates a new processing.

Cavity Number	Cavity Manufacturer	Where Processed	Test Number	Pair No.	Gradient MV/m	Q_0 x 10^9
LE5-4	Cornell	CU	5	CESR	6.5	3.5
"	"	C	6C	A'	7.9	3.3
LE5-5	Cornell	CU	3	CESR	2.4(Dust)	3.5
		Installation vacuum accident:				
C-2	Dornier	CU	3B	(A+)B	9.5	11.5
		Installation vacuum accident:				
C-4	B & W	CU	2B	A	6.8	1.4
"	"	CU	2C	A(+B)	7.4	3.0
		Installation vacuum accident:				
C-6	B & W	CU	2B	A	10.	0.25
"	"	CU	2C	A(+B)	6.7	0.17
"	"	CU	2D	$A^{1/2'}$	7.6	0.3
C-7	TRW+B&W	C	2C	A'	3.5(MP)	2.4
		Installation vacuum accident:				
C-10	Dornier	CU	2B	(A+)B	-	0.002

PROBLEMS AND THEIR SOLUTION

A variety of problems have been solved during the prototyping activities at CEBAF. Most of these were known in advance, but a few were unexpected. The various problems and their solutions are discussed below.

Due to the high Q_{ext} value with which superconducting cavities are operated, microphonics are an inherent problem. This is particularly true in accelerators such as CEBAF where the energy is controlled by the accelerating gradient rather than by the field in the magnets, and where an extremely small emittance is desired[3]. Microphonics can be reduced by supporting the equator of each cell rigidly relative to other equators (as was done in the HEPL accelerator); this solution has the disadvantage of interfering with the use of rotating thermometry to find defects. Use of cell walls much thicker than CEBAF's 3.3 mm also reduces microphonic effects, but is very expensive. CEBAF's design goal is to keep the tuning angle of the cavities within ± 20° at a Q_{ext} value of $6.6 \cdot 10^6$. Under this condition, the amplitude and phase of the fields in the cavity can be controlled adequately by the control circuit. In order to keep the tuning angle of the cavities within ± 20°, a general guideline has been established that the peak velocity of any object in contact with the cryomodule should be kept below 10 microns per second.

An unexpected phenomenon observed was that of ponderomotive oscillations. These were observed while operating in a mode employing fixed source frequency and fixed incident power. They had not been observed previously, because a frequency locked voltage controlled oscillator was used. When using fixed frequency and when the field in the cavity is regulated (rather than the incident power), the oscillations are also absent with a substantial safety margin; this is the normal operating mode in the accelerator, so the existence of ponderomotive oscillations is not a problem in this situation. The oscillations involve transverse mechanical oscillations of the cavity and breaking of the up-down (or left-right) symmetry that would otherwise make frequency shifts as a function of transverse deflection a second-order effect. The symmetry breaking appears to result from dimensional deviations from cylindrical symmetry within the cells.

The pressure differential which the cavities can tolerate without appreciable inelastic deformation was measured some time ago to be >1.67 bar. Analytic calculations using NASTRAN show the yield pressure to be 3 bar. Further measurements are being done to find the experimental limit and compare it to the NASTRAN value.

Another observed phenomenon which had not been anticipated was splitting of the fundamental mode into a 2-member passband. This phenomenon is caused by electric coupling between the two cavities in a pair. The magnitude of the splitting is $6 \cdot 10^{-7}$, expressed as a fraction of the fundamental frequency. Although this is small as an absolute number, the high Q_{ext} value makes it objectionably large. This problem had not been observed during the beam test at Cornell in 1984 because the physical arrangement of the two cavities was different and because the beam test at Cornell was conducted with a lower Q_{ext} value. Solutions to the problem include designing the amplitude and phase control circuitry so that it tolerates the coupling, moving the cavities farther apart, or reducing the diameter of the niobium beam pipe connecting the two cavities. Since the beam pipe was 7.0 cm in diameter and needed to be no larger than 3.8 cm, it was reduced to the smaller value. This provided 70 dB attenuation of the signal in a second cavity induced by a field in the first cavity, effectively eliminating the problem.

The bandwidth of the cavities with the design Q_{ext} value is 227 Hz. The design also calls for use of only a mechanical tuner, so the question arises as to whether or not the mechanical tuner has a resolution good enough to keep the tuning angle within the ± 20° specification. The resolution of the tuner has been measured to be better than 10Hz, which is well within this requirement.

The frequency sensitivity of the cavities, with mechanical tuner mounted, is approximately 60 Hz/Torr. The helium pressure is expected to vary by ± 0.5 Torr. In order to avoid using up too much of the ± 20° tuning angle tolerance due to this effect, reduction of the effect is desirable. It has been recognized that this can be accomplished by connecting the beam pipe to the helium vessel using a bellows of appropriate diameter. This causes the tension on the beam pipe to vary in such a way as to counteract the frequency effect of the direct helium pressure on the cavity. This technique has been demonstrated to work, and statistics are being collected on the reproducibility of the compensation from one cavity to another.

The hermetic windows originally used on the cavities were made of Kapton, which was captured between two niobium waveguide flanges by an indium seal which wrapped around the edge of the Kapton. Although this design works, it has a number of significant disadvantages. One is that the double indium layer is subject to cold flow, and, unless adequate force is maintained on the flange joint, the Kapton can pull out of the indium during assembly (there is a pressure differential across the window during assembly, but not during operation). Other disadvantages are that the Kapton is slightly permeable to gases and is capable of absorbing water vapor; these effects can cause deterioration of the cavity vacuum. In response to these problems, a hermetic alumina ceramic window has been developed. This window has to simultaneously satisfy a large number of requirements: the VSWR must be very low at the operating frequency, it must be reasonably low at other frequencies, the window must be leak tight to both the outside and against through-leaks, the window must not multipactor, the window assembly must tolerate temperature cycling without developing leaks, the window assembly must tolerate slight flexing of its surrounding niobium waveguide without cracking, the window must not be a source of dust or excessive gas, and the power lost by the window must be small compared to the allowed cavity dissipation of 5.5 watts. All of the requirements except the last have been satisfied, and causes of and cures for the remaining problem are actively being explored.

As higher order modes (HOM's) go up in frequency, the density of cavity modes per unit frequency interval increases. Somewhere in the vicinity of three to four times the fundamental frequency, it becomes impractical using presently available techniques to either calculate or to measure the properties of these modes. The problem is further aggravated by the ability of the modes to propagate through beam pipes, coupling more than one cavity together. As shown previously[4], modes in this frequency regime can be controlled if an adequate number of propagating transmission line modes are available to them all the way from the cavity to an effective absorber. HOM loads which are marginally adequate for CEBAF's requirements have been developed. These loads employ two metallized ceramic cards suspended at angles inside a shorted stainless steel waveguide. Even more effective loads, which absorb all propagating transmission line modes at all frequencies, are being developed.

The magnetic shielding of the cryostat employs two layers of shielding, and achieves the design objective of ≤ 5 milligauss at the cavity location on cooldown. Previously, a 1-layer shield achieved only 50 milligauss.

Assembly clearance was a problem with the original cryostat design. This has been addressed by reducing the HOM elbow radius by 0.375" to provide adequate clearance for inserting the cavity pairs into the helium vessel, and by increasing the vacuum vessel diameter by 3" to facilitate assembly, reduce the likelihood of direct thermal shorts, and reduce the compression of the multi-layer insulation (MLI) blankets.[5]

Another problem with the original cryostat design was that of controlling the location of the waveguide feed-through plate with sufficient accuracy. Efforts to first machine and then weld this plate resulted in excessive tolerances. Efforts to make the feed-through location bellows adjustable were abandoned as being too complicated, requiring too much assembly effort, and being more susceptible to microphonic transmission. A boring mill suitable for machining the feed-through plate to the proper dimension, after welding this plate into the helium vessel, solved the problem.

Obtaining access to the mechanical tuner drive, for connection to the bellows-sealed rotary feed-through, was solved by redesigning the coupler for easier connection from the end of the helium vessel.

Welded vacuum bridging components have been substituted for the previous bolted ones. This has the advantage of making cryostat manufacture and cryostat assembly easier and less expensive, but has the disadvantage that it makes cryostat disassembly more difficult. The components are designed to be re-useable. During assembly of the cryomodule, it was verified that the differential weld shrinkage effects are tolerable.

Solid state cryogenic pressure measurement sensors are being explored as alternatives to standard pressure transducers at the ends of pressure sampling tubes.

The liquid helium level in the cryomodule is designed to be part way up in the pipes connecting the liquid helium vessels together near their top. This level is to be measured and regulated. Studies on liquid helium level sensors using superconducting wires indicate that there are some temperature ranges where the sensors have no hysteresis-free operating range in electric current. Differential pressure transducers have been successfully used to measure the liquid helium level at all temperatures of possible interest. Suitability of these devices for use in CEBAF is under consideration.

CEBAF was originally designed to have the shields and 2.2K supercritical helium supplies connected in series from one cryomodule to the next. This design had been adopted to minimize cost. However, it was recently recognized what a major problem this would represent for initial commissioning of the accelerator, for subsequent removal of cryomodules for repairs, and for diagnosis of the sources of leaks and thermal shorts involving these circuits. A change request has been approved to use parallel circuits instead, which effectively makes each cryomodule cryogenically independent.

FURTHER DEVELOPMENT

Further development related to construction will be conducted for a limited number of reasons: (1) to solve new problems which may be discovered; (2) to reduce the uncertainty concerning a course of action which has been selected; (3) to improve the technical performance of a marginally useable approach which has been adopted; and (4) to reduce construction costs. For the fourth category to make sense, the cost of developing an alternative must be offset by the probability that the development will be successful, that it can be phased into construction without delaying construction, that the amount of construction remaining is sufficient, that the alternative will actually result in a cost reduction, and that any incompatibility in spare parts that would result is warranted.

In addition to the few items described in the previous section that are still being developed, one item that has been selected for development is copper HOM elbows. If copper elbows, with or without part of the copper being coated with a superconductor, can be substituted for niobium elbows, substantial savings are expected.

Another item selected for development is cavity couplers of the same interior geometry that is presently in use, but each coupler being made of two forged niobium halves rather than various welded pieces of sheet metal with reinforcing ribs. The primary object is cost savings, with better dimensional control a secondary consideration.

Copper input power waveguide extensions, coated with superconductor, is another area selected for exploration. These extensions are presently made of solid niobium; the objective is cost savings.

Exploration of gate valve sealing materials other than Viton is of interest to reduce the outgassing rate.

Warm ceramic windows are to be developed following successful development of cold ones. The object of this development is to replace the present Teflon warm windows, which are subject to radiation damage.

Tuner life studies are to be performed to find out how frequently the mechanical tuners can be safely operated. It is presently anticipated that they need not be operated more than a few times a day, but further knowledge of their tolerance to movement is an important piece of information.

FACILITIES

CEBAF's facilities for working with superconducting accelerating cavities and cryomodules are separated into two distinct categories: on-line facilities are used in a production-line mode, and all cavities received are subject to passing through these facilities; off-line facilities are facilities to be used for identifying, diagnosing, and finding solutions to various types of problems which may arise, both during construction and during operation. The on-line facilities will also be used for reprocessing cavities which fail during operation.

The on-line facilities are listed in Table III.

Table III. On-Line Facilities

Key: N = Not started; P = Partially complete; C = complete; T = temporary substitute

Name	Function	Civil Constr. Status	Equip-ment Status	Commis-sioned
Leak checking	Check incoming cavities	P	P	T
Coord. meas.	Check cavity dimensions	P	P	T
Inspection	Inspect cavities visually	C	P	T
Tuning	Check incoming cavities Retune old cavities	C	P	T
Grinding	Grind internal defects	C	P	No
Chemistry	Process cavities	P	P	T
Clean Room	Clean pair assembly	C	P	Yes
Vertical Attach.	Attach pairs to top plate	P	P	T
Vert. Pair Test				
Test Area	Shield cryostat	P	P	T
Top Plate	Pair support	N/A	Y	Yes
Cryogenics	Cool pair	P	P	T
Control Room	Control testing	C	P	T
Clean holding room	Clean pair storage	P	P	T
Parts storage	Pair parts storage	P	P	T
Parts receiving	Cryostat parts receiving and storage	C	C	Yes
Cryounit assembly	4 cryounit assembly bays	C	P	T
Cryomodule ass'y	Cryomodule assembly area	C	P	Yes
Cryomodule test				
Test cave	Radiation shielding	C	P	T
Cryogenics	Cool cryomodule	C	P	T
Control room	Control cryomodule test	C	P	T

The off-line facilities are listed in Table IV.

Table IV. Off-Line Facilities

Key: N = Not started; P = Partially complete; C = complete; T = temporary substitute

Category / Name	Function	Civil Constr. Status	Equip-ment Status	Commis-sioned
Fabrication				
Shear	Nb cutting	C	C	Yes
Press	Nb deep drawing	C	C	Yes
CNC Mill	Nb machining	P	C	Yes
EBW	Beam welding Nb	P	P	No
Chemistry				
Chemistry lab	Nb cleaning	P	P	Yes
Pure water system	Nb rinsing	C	C	Yes
Clean Work				
Clean Room	Cavity assembly	P	P	No
Attachment Room	Top plate attachment	P	P	T
Coating Room	SC and anti-MP coatings	P	P	T
Clean Chem Bench	Chem bench, clean air	P	N	No
UHV Furnace	Cavity firing	P	P	No
SIMS (surplus)	Nb surface analysis	P	P	No
SEM	Nb surface analysis	P	P	No
Scanning Auger	Nb surface analysis	P	N	No
Testing				
4 shielded cryostats	Single 5-cell tests	P	P	T
2 unshielded cryo.	RRR tests, etc.	P	P	T
Control room	Test controls	C	P	T
Cryogenics	Cryostat cooling	P	P	T
Other				
Light shop	Minor parts	C	C	Yes
RF & Therm. lab	Special bench measurement	C	C	Yes
Brazing furnace	Parts brazing	C	C	Yes
Nb furnace	Nb purification	C	P	No

DESIGN STATUS

The design of the cavities is complete. The design of the pair parts is complete, with the exception that the diameter of the bellows between the beam pipe and the helium vessel may be adjusted slightly for further optimization; in addition, the cold ceramic window geometry is unlikely to change, but a change in ceramic composition or metallization technique may be necessary.

The cryounit design is complete. A bellows has been incorporated in the waveguide between the vacuum vessel and the helium vessel, thereby eliminating the need for a bellows between the waveguide and the vacuum vessel. This reduces the susceptibility of the cavities to microphonics coupled through the waveguides.

The cryomodule design is nearly complete.

The design of the warm beam pipe regions between cryomodules is conceptually complete, and a detailed design is being developed. The fast valves, located every fifth cryomodule for disaster control, are still in development.

PRODUCTION

The production plan is to have the cavities and cryostats made by industry, and to perform the processing, clean assembly, pair testing, cryounit assembly, cryomodule assembly, cryomodule testing, and cryomodule installation in house. This plan has been adopted because of the difficulty of shipping the delicate units, the lack of a broad industrial base for performing the in-house steps, the expense of developing and maintaining a broad industrial base, and the intrinsic need to maintain the technology base at CEBAF for maintenance of the accelerator.

The production plan calls for delivery of 2 cavities a month starting 6 months after placement of the cavity order, and continuing for 8 months. After these 16 cavities had been delivered, the delivery rate would increase to 12 cavities a month and remain there until a total of 360 cavities had been delivered. The order for the cavities was placed with Interatom on May 2, 1989. Although CEBAF had indicated that it would prefer to deal with two cavity manufacturers, the substantial additional cost of doing so was not justified. Performance of the contract was stopped following B&W's protest to the General Accounting Office on May 12, 1989, and is awaiting resolution. All other parts are to be acquired at a rate consistent with the cavity receipt rate.

The initial niobium contracts have been placed, and additional ones are in the procurement process. Pair parts contracts have been placed for initial quantities. The helium vessel, vacuum vessel, and waveguide assembly packages are in the procurement process. Initial end cap packages of the revised design are also in the procurement process.

UPGRADE POTENTIAL

The design of CEBAF's tunnel was frozen prior to changing the design from four passes to five passes, thereby leaving ten cryomodule slots empty. The gross radius of the arcs was chosen so that, by adding more dipoles and increasing quadrupole strengths, an acceptable emittance could be obtained at energies up to 16 GeV. If, at a later time, the technology can be improved so that a gradient of 16 MV per meter can be obtained, and if the existing cavities are upgraded, the empty cryomodule slots filled, and the extra magnets added, CEBAF's energy can be increased to 16 GeV. Depending on the degree to which the Q_0 of the cavities can also be improved, the refrigerator capacity would need to be increased less than or equal to a factor of 7; reducing the duty cycle would be another alternative, and use of a superconductor with a higher transition temperature than Nb could be beneficial. Performance of R&D to make such an upgrade possible is an objective of the SRF Division at CEBAF, but time to begin working on such R&D is realistically at least a year away.

It is also the opinion of many people at CEBAF that use of pulsed superconducting cavities at gradients around 30 MV/m is at least as promising an approach to TeV linear colliders as any other approach currently being pursued. While such an accelerator would not be built at CEBAF, we consider its pursuit a worthwhile objective.

References

1. This work was supported by the National Science Foundation, with supplementary support under the U.S.-Japan Agreement.

2. P. Kneisel, "Test of Superconducting Accelerator Structures in a Closed Vacuum System," Proceedings of the 1987 IEEE Particle Accelerator Conference, IEEE 87CH2387-9, 1893 (1987).

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5. W. Schneider, this workshop.

MACHINE CONFIGURATION

CEBAF

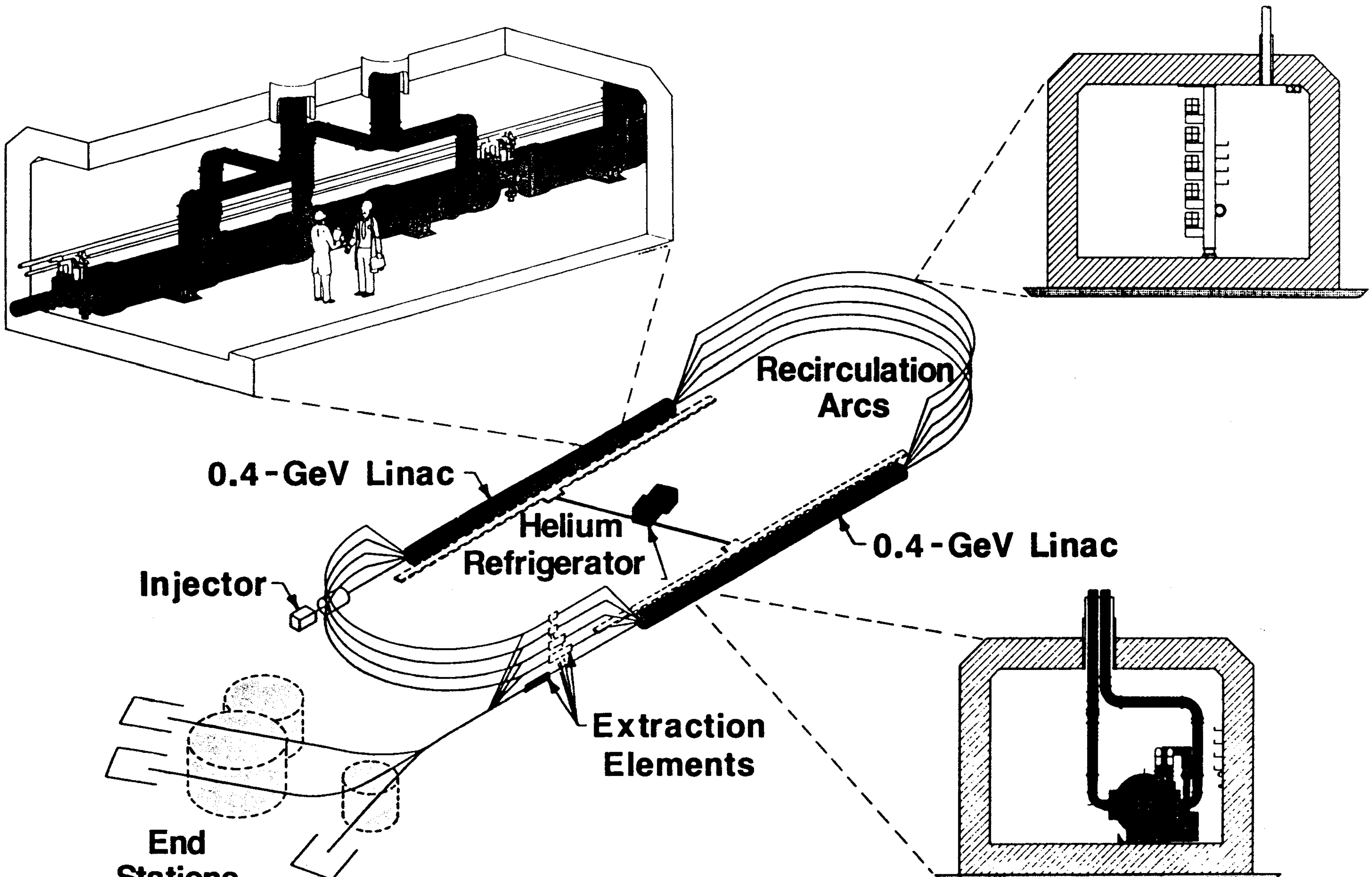


Fig. 1 Race-track shape

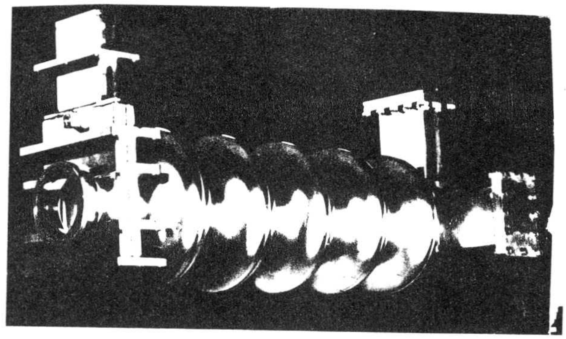


Fig. 2 Superconducting cavities

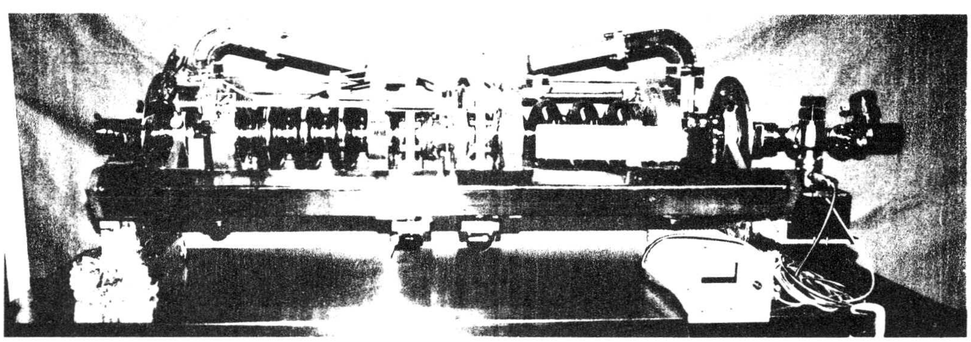
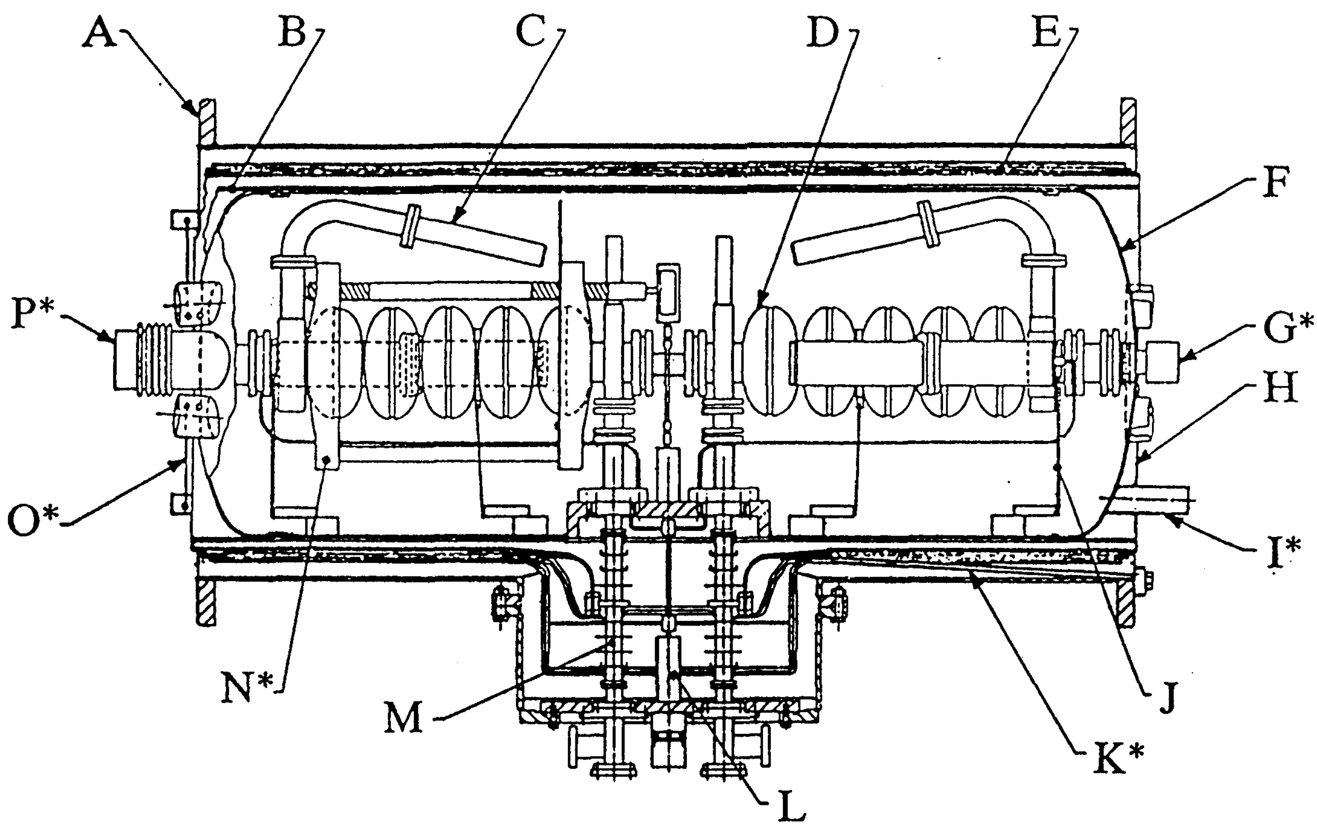


Fig. 3 Pairs

TOP VIEW OF CRYOUNIT CEBAF



A. Vacuum Shell Flange
B. Magnetic Shield and Inner Superinsulation
C. HOM Load
D. Cavity
E. Shield Superinsulation
F. Helium Vessel
G. Flange Surface on Isolation Valve
H. 40 to 50 K Radiation Shield
I. Shield Helium Supply Line
J. Outboard Cavity Support
K. Axial Support
L. Rotary Feedthrough
M. Fundamental Power Waveguide
N. Tuning Mechanism
O. Helium Vessel Support Rod
P. 2 K Helium Return

*Asterisked items shown only once to simplify illustration.

Fig. 4 Cryounit

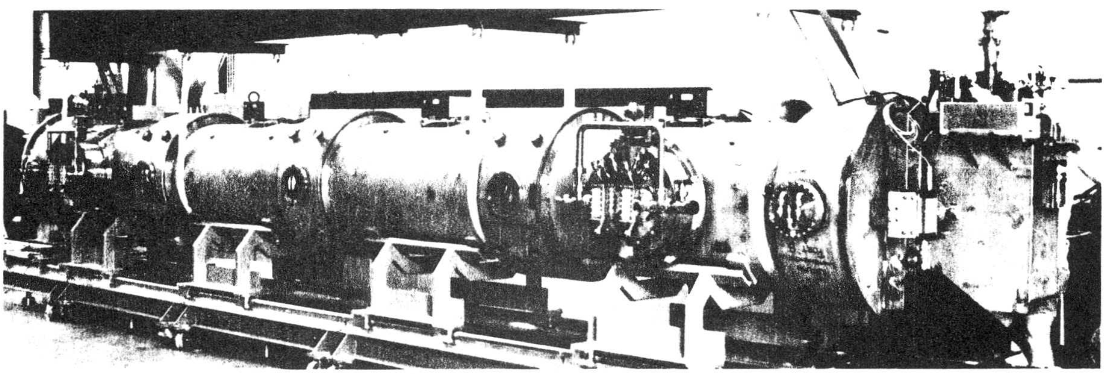


Fig. 5 Cryomodule