RF SUPERCONDUCTIVITY AT CEBAF*

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August 19, 1991

INTRODUCTION

This report discusses progress during the past two years at CEBAF. Some descriptive information is repeated here, but more detailed information on prior work can be found in the proceedings of the previous two RF Superconductivity Workshops.[1,2]

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 late 1994.

The accelerator is 1.4 km in circumference, and has a racetrack shape (Fig. 1).

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

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[1] Christoph Leemann, "CEBAF Design Overview and Project Status," Proceedings of the Third Workshop on RF Superconductivity, Argonne, Illinois, 141 (1987).

[2] B. Almeida et al., "RF Superconductivity at CEBAF," Proceedings of the 4th Workshop on RF Superconductivity, Tsukuba, Japan, 1 (1989).

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. Beams can also be extracted on earlier passes.

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 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[3] for CESR-II, a proposed e^+e^- storage ring which was not constructed. The concept of a hermetic cavity pair[4] 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. The probe can also be calibrated accurately if it is known that Q_0^{-1} is negligible compared to Q_L^{-1}.[5]

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

[4] 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).

A cavity pair designated as A' was installed in a cryostat of the final design. This quarter cryomodule was tested in May, 1989, and the gradients, Q_0's, and static heat leaks were all better than their design values. This quarter cryomodule was then combined with the 500 keV injector, and a beam was accelerated to 5 MeV.[6] Near the end of the test, the injector beam melted a hole approximately 1 mm in diameter in a bellows ahead of the quarter cryomodule, admitting approximately an atmosphere-liter of air before the gate valves were closed. After warm up, the Q_0 of the cavity nearest to the leak recovered to approximately $5 \cdot 10^8$, and the gradient was unaffected. The refrigeration available was sufficient that it permitted the test to be completed.

The first full cryomodule was tested in September and October, 1989. The gradients achieved by cavities 1 through 8, respectively, were 6.0, 9.3, 7.2, 8.5, 6.5, 6.9, 8.1, and 8.3 MV/m, averaging 7.6 MV/m, compared to the design specification of 5.0 MV/m. This gradient was substantially identical to the values obtained in vertical pair tests. This is taken to be an indication of the benefit of the hermetic sealing approach. The Q_0 values at 5 MV/m and 2 K were, respectively, 3.6, 2.9, 2.4, 0.18, 3.3, 0.16, 1.9, and $3.7 \cdot 10^9$. This was the first strong evidence of the "Q disease" seen previously at Saclay, DESY, and Wuppertal. The same cryomodule was cooled down a substantial number of additional times, and it was found that, by adhering to a cooldown rate of 50 to 100 K per hour between 200 K and liquid helium temperature, Q_0's which met the design specification were achieved. These cooldown rates are now used routinely.

Other studies[7] show that anodized high-RRR cavities are much less susceptible to the "Q-disease" than unanodized ones. A cavity recently made of reactor grade niobium, unanodized, showed no measurable susceptibility to the "Q-disease."

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.

Measurements have been completed to determine the acceptable differential pressure across a cavity, without inelastically changing the frequency or field pattern of either the cells or the couplers. The safe limit was determined to be 2.7 bar at room temperature, and 6 bar at liquid helium temperature. This is close to the 3 bar which was computed using NASTRAN.

Previous plans to use a pressure compensation bellows between the cavity beam pipe

5 David Farkas, private communication.

6 This test was performed by the Front End Test Group.

7 K. Saito and P. Kneisel, "On the Influence of Cooldown Conditions on the Cavity Performance, CEBAF-TN-90-274 (1990).

and the liquid helium vessel, in order to compensate for the cavity's frequency dependence on external pressure, have been abandoned. It was found that the effective spring constant of the cavity-tuner combination is a significant function of whether the tuner is in compression, in tension, or in neither. The helium pressure stability tolerance has been set at ± 0.1 Torr, and the liquid helium level stability to ± 3 mm. These limits are set to avoid excessive operation of the mechanical tuners.

A hermetic alumina ceramic RF power window has been developed for use at 2 K. 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 had been satisfied at the time of the last workshop, and the cause of the high dissipation was found to be due primarily to a thick metallization to ceramic interface, which has since been corrected. The loss tangent of the ceramic is the second most prominent factor, and this is being addressed by substituting polycrystalline sapphire for the ceramic. The windows have, on occasion, been observed to generate an excessive number of arc trips, and to develop through-leaks in the ceramic. The possibility that these problems are due to charging and arcing of the ceramic is being explored. A conductive anti-multipactor coating, with resistivity of the order of 10^7 ohms per square, in lieu of the present titanium dioxide, is being investigated as a potential solution.

Higher order mode loads which use wedges of an absorptive aluminum nitride - silicon carbide composite were developed. These loads appeared to work very well over a wide frequency range, but it was subsequently discovered that the loads, which are brazed to a flange which attaches to the end of a waveguide, were not really at 2 K when being tested with the waveguide immersed in a 2 K bath. This problem was caused by infrared radiation coming down the waveguide from a room temperature window. The problem was compounded by the discovery that the low temperature sensitivity of the absorber is a function of the pressure at which the ceramic was sintered. An interim solution developed was to add 100 mW heaters to each HOM load; these heaters are coupled to the load and insulated from the bath. Other materials are being explored; aluminum nitride - titanium carbide and aluminum nitride - glassy carbon both appear promising. The specifications on the load performance have also been reduced so that the safety factor on the beam break-up threshold is reduced from the previous factor of 90 to a factor of 30.

CEBAF's cryostats were originally designed so that the helium supply lines and the thermal shields were connected in series from one cryomodule to the next. This design was modified to adopt a parallel configuration, which can be serviced much more easily. In the process, the end can designs were modified so that the measured static heat load of each cryomodule was reduced to the design value of 13 watts. The parallel configuration

functions without problems.

The semi-rigid coaxial cables used to bring the RF reference probe signals out of the cryostat proved to be another source of trouble. The center conductors "walked" with thermal cycling, leading to a loss of the RF connection. Attempts to stabilize the cables by thermally cycling them many times did not work, and attempts to solve the problem using type N connectors in place of SMA connectors (to take advantage of the longer center pin) did not work. The problem has been solved by using a semi-rigid coaxial cable in which the thermal expansion coefficient of the dielectric is matched to that of the conductor.

Many of the gate valves being used to provide hermeticity for the cavity pairs developed through-leaks after a number of thermal cycles. This problem has been solved by changing to a gate valve in which the sealing force is applied by a screw, rather than by an over-center cam.

Some of the high RRR Nb was found to have a yield strength of 6,000 to 7,000 psi, which is well below the specified minimum of 11,000 psi. It was determined, however, that the yield strength of the Nb increased to 20,000 psi during the process of deep drawing the cell cups.

The specification of the maximum differential pressure on the cavities has required that burst disks be replaced with parallel plate relief valves to obtain more precisely controllable relief thresholds. A small relief vents into a pumped vacuum line, and a larger one vents to atmosphere.

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.

Several of the items which had been identified for further development at the time of the last workshop have been deleted from the list because it was determined that the development was not likely to be cost justified. Items which have been deleted include niobium coated copper elbows and lead-tin plated waveguides.

Fundamental power couplers forged and machined from solid niobium halves, rather than being beam welded together from sheet metal with reinforcing ribs, were developed. They exhibited the same plastic deformation differential pressure as the ribbed couplers, and exhibited twice the elastic deformation per unit of differential pressure as the ribbed couplers. It also appeared that they would not result in any savings, so they were not

incorporated into the production design.

Kalrez® O-rings were studied as an alternative to Viton® O-rings for the gate valves. The Kalrez® exhibited much lower absorption and outgassing rates than the Viton®, but exhibited much higher helium diffusion rates. The original Viton® O-rings continue to be used for this reason.

Calculations on the radiation damage to the warm Teflon windows show that they will lose less than 10% of their tensile strength due to radiation during the lifetime of the accelerator. However, they are somewhat permeable to gases, and this may make use of ceramic windows desirable. The location of the windows is such that they can be retro-fitted easily during an accelerator warm-up.

Lifetime studies on the mechanical tuners revealed that the wobble-plate, bellows sealed rotary feedthroughs had a marginal lifetime. A change in process by the manufacturer corrected the problem.

FACILITIES

CEBAF's facilities for working with superconducting accelerating cavities and cryomodules are listed in Table I.

Table I. Cavity and Cryomodule 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	C	C	C
Coord. meas.	Check cavity dimensions	C	C	C
Inspection	Inspect cavities visually	C	C	C
Tuning	Check incoming cavities Retune old cavities	C	C	C
Grinding	Grind internal defects	C	C	C
Chemistry	Process cavities	C	C	C
Clean Room	Clean pair assembly	C	C	C
Vertical Attach.	Attach pairs to top plate	C	C	C
Vert. Pair Test				
Test Area	Radiation Shield cryostat	C	C	C
Top Plate	Pair support	N/A	C	C
Cryogenics	Cool pair	C	C	C
Control Room	Control testing	C	C	C
Clean holding room	Clean pair storage	C	C	C

Table I. Cavity and Cryomodule Facilities (Continued)

Parts storage	Pair parts storage	C	C	C
Parts receiving	Cryostat parts receiving and storage	C	C	C
Cryounit assembly	4 cryounit assembly bays	C	C	C
Cryomodule ass'y	Cryomodule assembly area	C	C	C
Cryomodule test				
Test cave	Radiation shielding	C	C	C
Cryogenics	Cool cryomodule	C	C	C
Control room	Control cryomodule test	C	C	C
Fabrication				
Shear	Nb cutting	C	C	C
Press	Nb deep drawing	C	C	C
CNC Mill	Nb machining	C	C	C
EBW	Beam welding Nb	C	C	C
Chemistry				
Chemistry lab	Nb cleaning, parts	C	C	C
Pure water system	Nb rinsing, parts	C	C	C
Clean Work				
Clean Room	Cavity assembly	C	C	C
Attachment Room	Top plate attachment	C	C	C
Coating Room	SC and anti-MP coatings	C	P	T
Clean Chem Bench	Chem bench, clean air	C	C	C
UHV Furnace	Cavity firing	C	P	N
SIMS (surplus)	Nb surface analysis	C	P	N
SEM	Nb surface analysis	C	C	C
Scanning Auger	Nb surface analysis	C	P	N
Testing				
4 shielded cryostats	Single 5-cell tests	C	P	P
2 unshielded cryo.	RRR tests, etc.	C	P	P
Control room	Test controls	C	P	P
Cryogenics	Cryostat cooling	C	C	C
Other				
Light shop	Minor parts	C	C	C
RF & Therm. lab	Special bench measurement	C	C	C
Brazing furnace	Parts brazing	C	C	C
Nb furnace	Nb purification/brazing	C	C	C

DESIGN STATUS

The design of the cavities, cavity pairs, cryounits, and cryomodules is complete. These designs may undergo minor changes during production, as discussed above. The design of the warm beam pipe regions between the cryomodules has also been completed. VAT® valves, with the elastomer bonded to the edge of the gate, are being used for the remotely operable valves between cryomodules. They are particularly suitable for the slow valves because they can be pneumatically operated without the high acceleration and velocities characteristic of pneumatically operated over-center-cam type valves; such acceleration and high velocity is believed to be capable of throwing particles down the beam pipe, with the associated risk of contaminating cavities. The same valves can be operated at high speed, as required every 4 cryomodules to limit the extent of damage due to an abrupt vacuum accident.

The interlocks to be used to prevent or limit equipment damage have been determined in detail, and are being implemented.

PRODUCTION

The production procedure 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 was 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.

Cavities are being received from Interatom at the rate of 12 per month, with the deliveries being on schedule. To date, 137 Interatom cavities have been received. An additional 16 cavities were made in conjunction with job shops to accelerate the schedule prior to release of the Interatom contract.

Contracts for all other major parts have been placed, and the parts are being received. This includes niobium sheet, liquid helium vessels, cryostats, bridging components, end cans, cryomodule support stands, thermal transition fundamental power waveguides, top hats, and tuners.

One and a quarter cryomodules had been installed in the tunnel during September, 1990. The full cryomodule was replaced in March, 1991, due to a leak. In April, 1991, the one and a quarter cryomodules installed at that point were used[8] to accelerate a beam to 25 MeV, the design value. In June, 1991, the second injector cryomodule and the first north linac cryomodule were installed. The 2.25 cryomodules in the injector were then used[9] to accelerate the beam to the design value of 45 MeV. Studies on this system are

[8] Ibid., Ref. 6.

[9] Ibid., Ref. 6.

continuing, and a local recirculation experiment is being implemented to study beam break-up and to gain operating experience with multiple passes.

The cavity pair and cryomodule production teams have demonstrated the capability to assemble, test, and install more than 1.5 cryomodules per month. The production is temporarily halted while the higher order mode load and window problems described above are being corrected. It is believed that the indium seal leak and higher-order-mode load problems are solved, but the window arcing and through-leak problem is still a concern.

The gradients and Q_0's of Interatom cavities tested to date (and not limited by extraneous factors) in vertical pair tests is shown in Figure 6. 60 out of 62 of the tests conducted to date have yielded results which passed (i.e., met or exceeded specifications). Of the results which passed, the average gradient is 9.22 MV/m, and the average Q_0 at 5 MV/m and 2 K is $7.41 \cdot 10^9$.

The achieved gradients and Q_0's of cavities installed in the tunnel is shown in Figure 7. Most of the Q_0's are as measured in the tunnel, but 8 are as measured prior to installation. The Q_0's measured in the Test Cave prior to installation tend to be low because of residual magnetic fields in the concrete reinforcing bar from the NASA SREL synchrocyclotron which was originally installed in that location. The double magnetic shielding on the cryomodules is adequate for the earth's magnetic field, but not for the much higher field found in the Test Cave. Helmholtz coils have recently been installed to buck the remnant fields. Two of the gradients are limited by a helium leak into the waveguide vacuum between the cold and warm RF windows. The average gradient is 7.56 MV/m, and the average Q_0 at 5 MV/m and 2 K is $3.86 \cdot 10^9$.

A maximum operating gradient is specified at a value below the maximum achievable gradient. This is done to provide reliable operation and avoid radiation damage to the cavity surface. The value is normally set at 90% of the break-down field, or at the point at which field emission increases losses by $Q_0^{-1} = 10^{-10}$, whichever is lower. It is sometimes set at an even lower value for conservatism, or because the break-down field was not determined. The presently specified maximum operating gradients, and the associated Q_0's at 5 MV/m, are shown in Figure 8. The average gradient is 6.34 MV/m, and the average Q_0 at 5 MV/m and 2 K is $3.55 \cdot 10^9$.

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 20 GeV. If, at a later time, the technology can be improved so that a gradient of 20 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 20 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 a factor of 9; reducing the duty cycle to 10%, with no improvement in Q_0, 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 Department at CEBAF.

The gradient improvements needed for an upgrade of CEBAF would be directly relevant to TESLA.

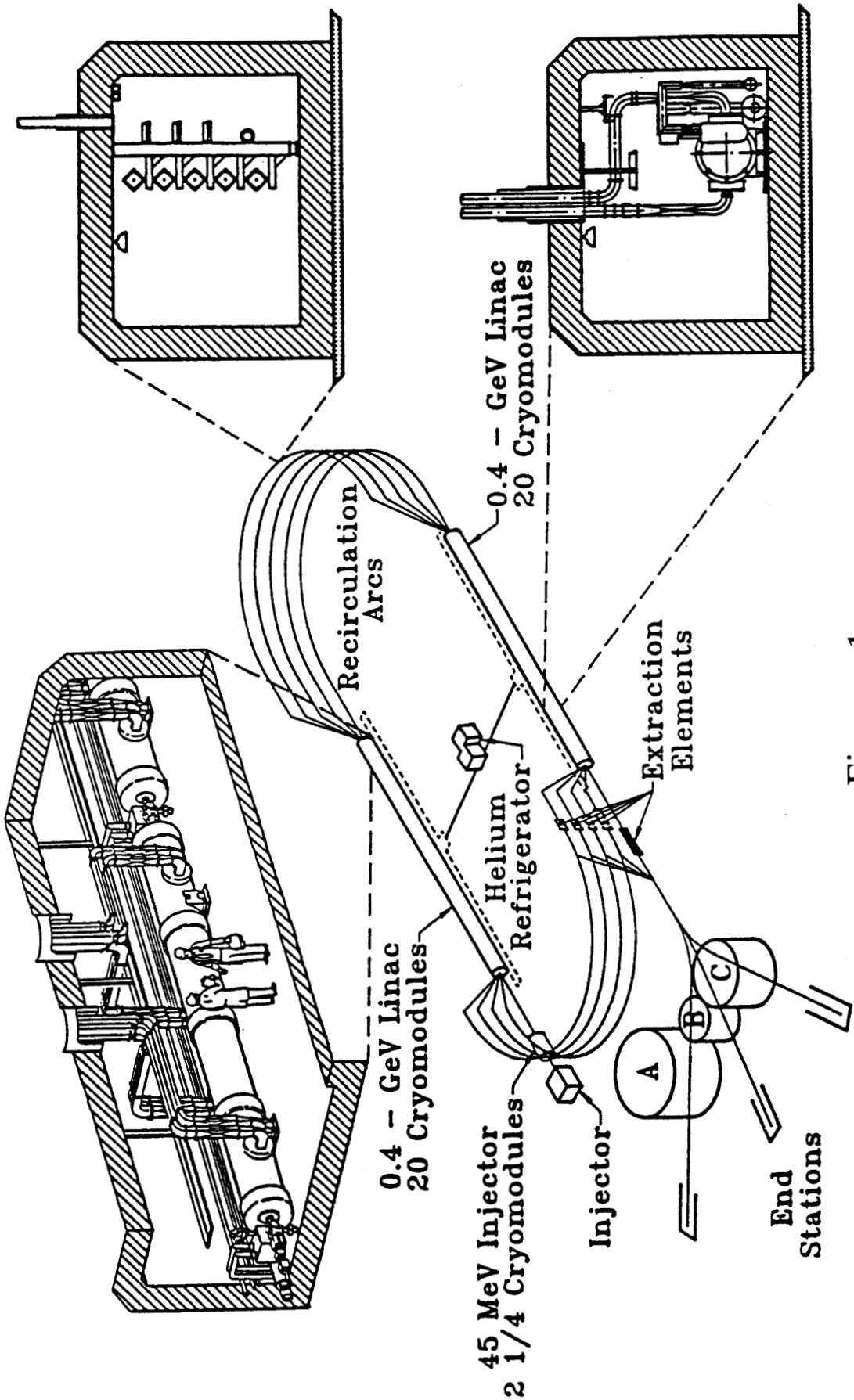

MACHINE CONFIGURATION
CEBAF
Recirculation Arcs
0.4 – GeV Linac 20 Cryomodules
0.4 – GeV Linac 20 Cryomodules
Helium Refrigerator
Extraction Elements
45 MeV Injector 2 1/4 Cryomodules
Injector
A
B
C
End Stations

Figure 1

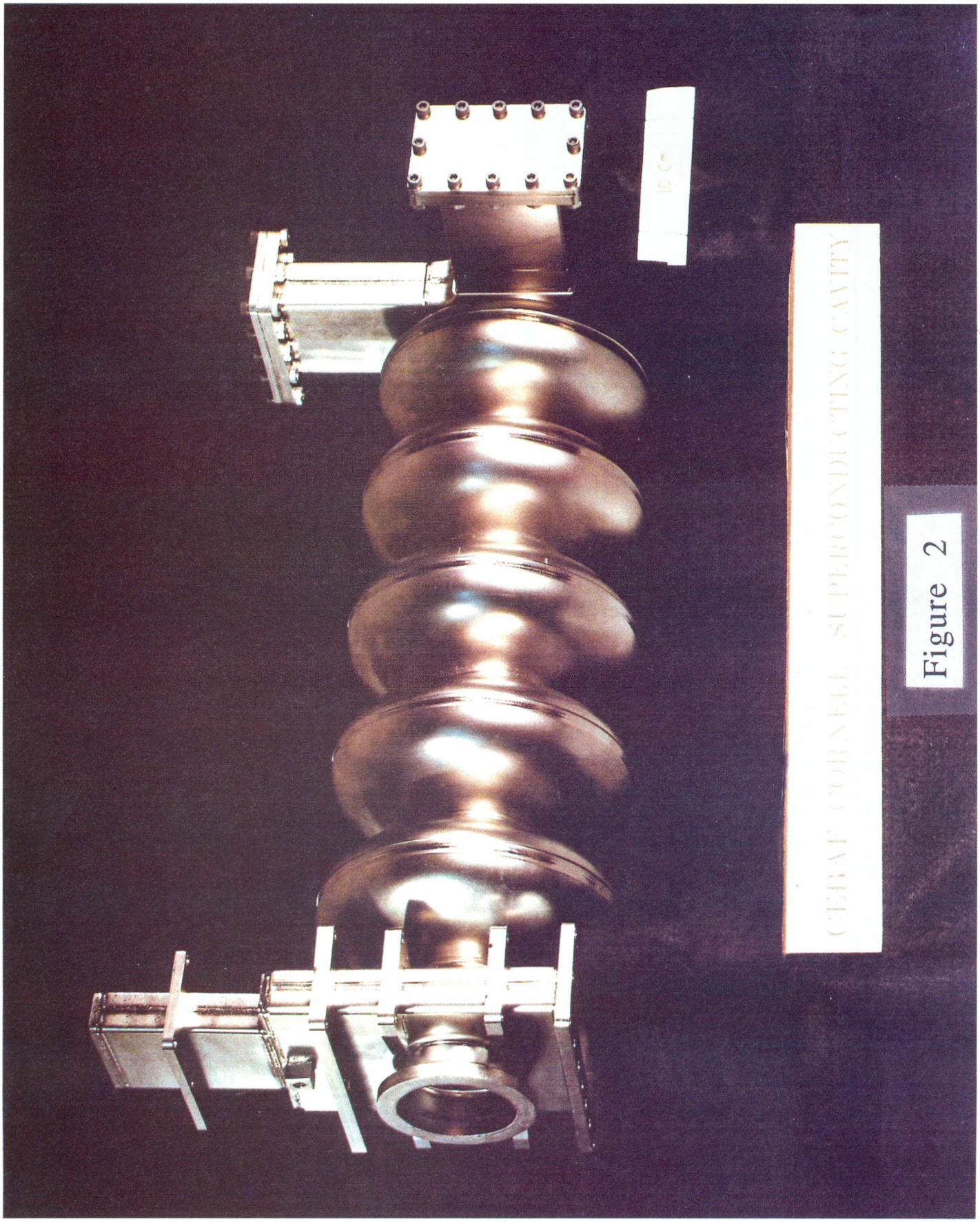
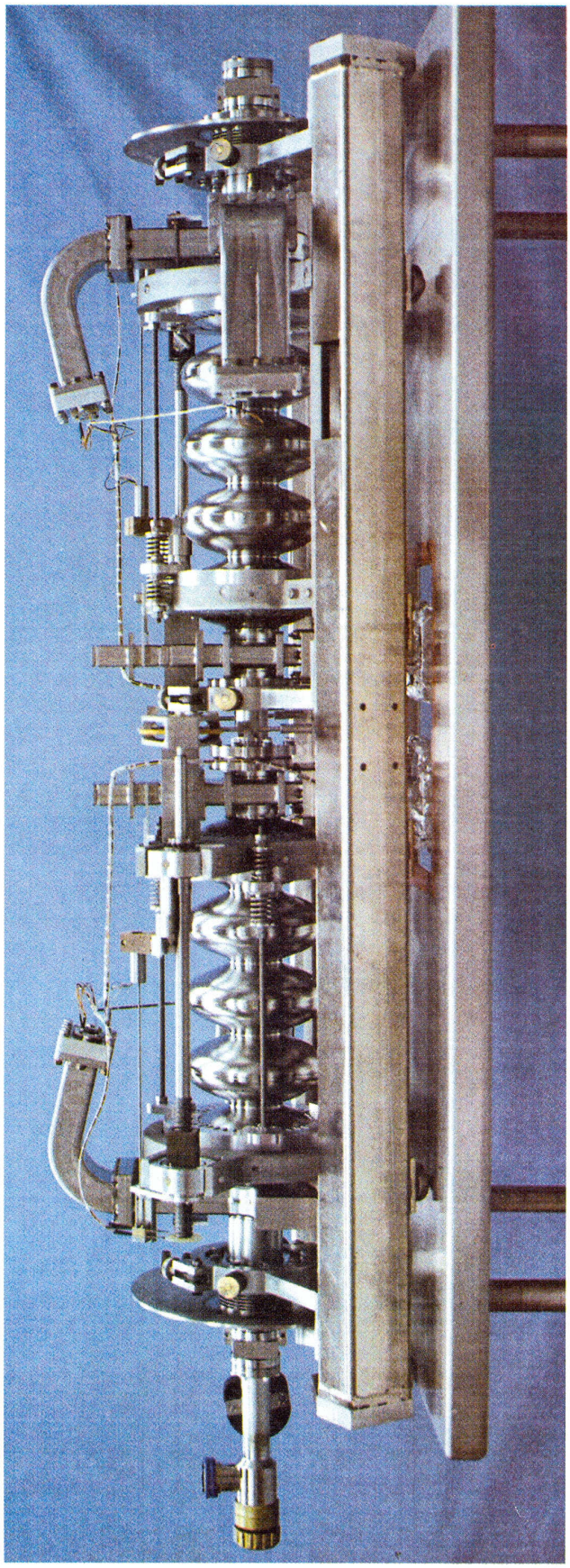


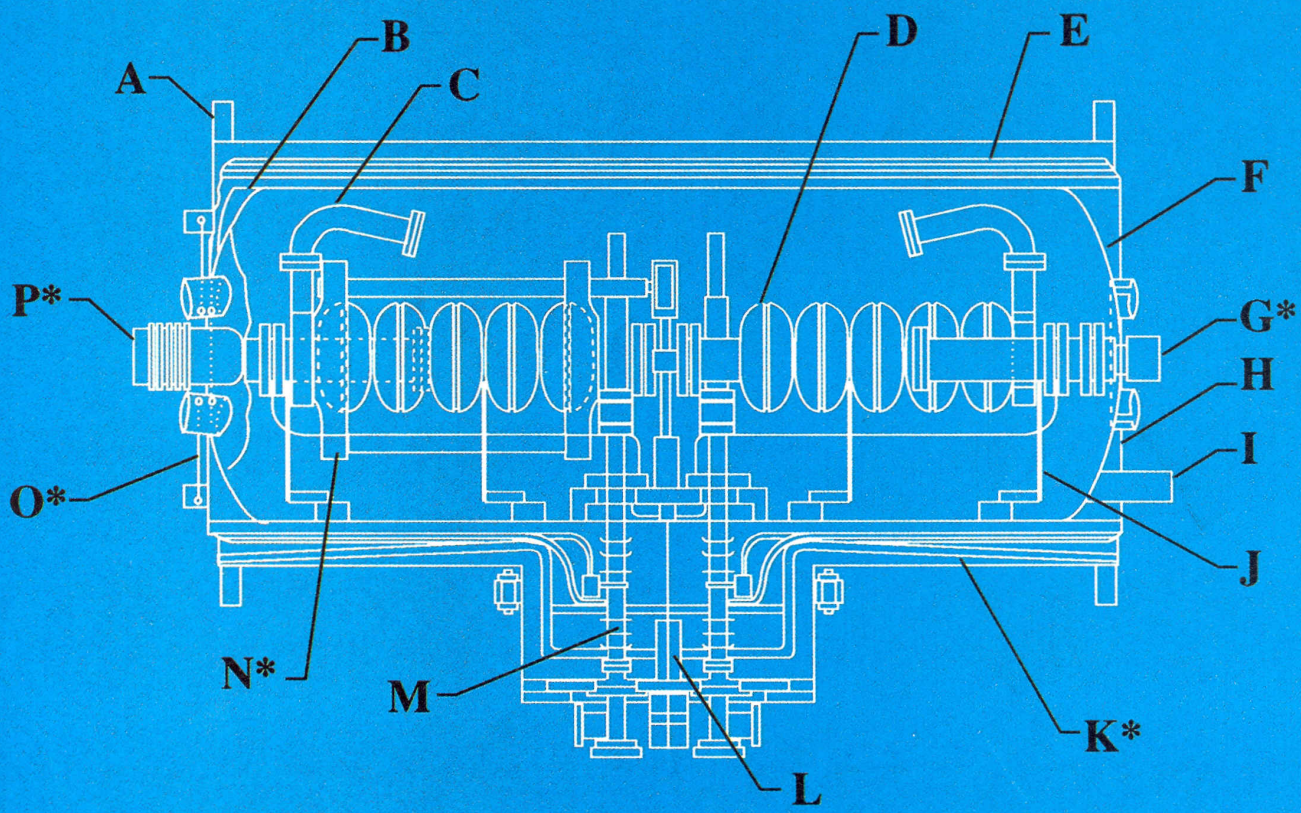
Figure 2



CEBAF SUPERCONDUCTING CAVITY PAIR

Figure 3

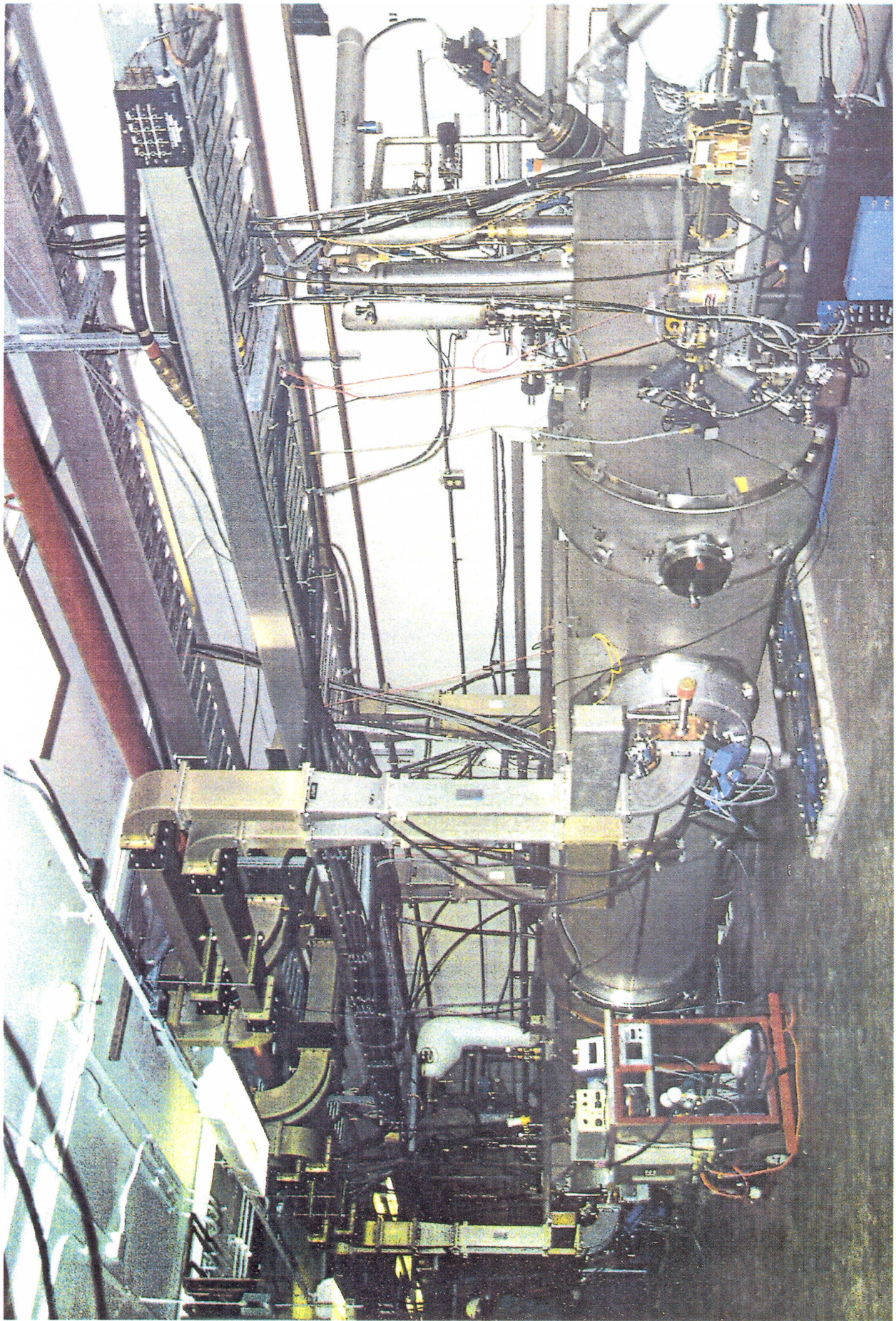
TOP VIEW OF CRYOUNIT CEBAF



A. Vacuum Shell Flange
B. Magnetic Shield & 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. 2K Helium Return

*Asterisked items shown only once to simplify illustration.

Figure 4



CEBAF CRYOMODULE IN TUNNEL
Figure 5

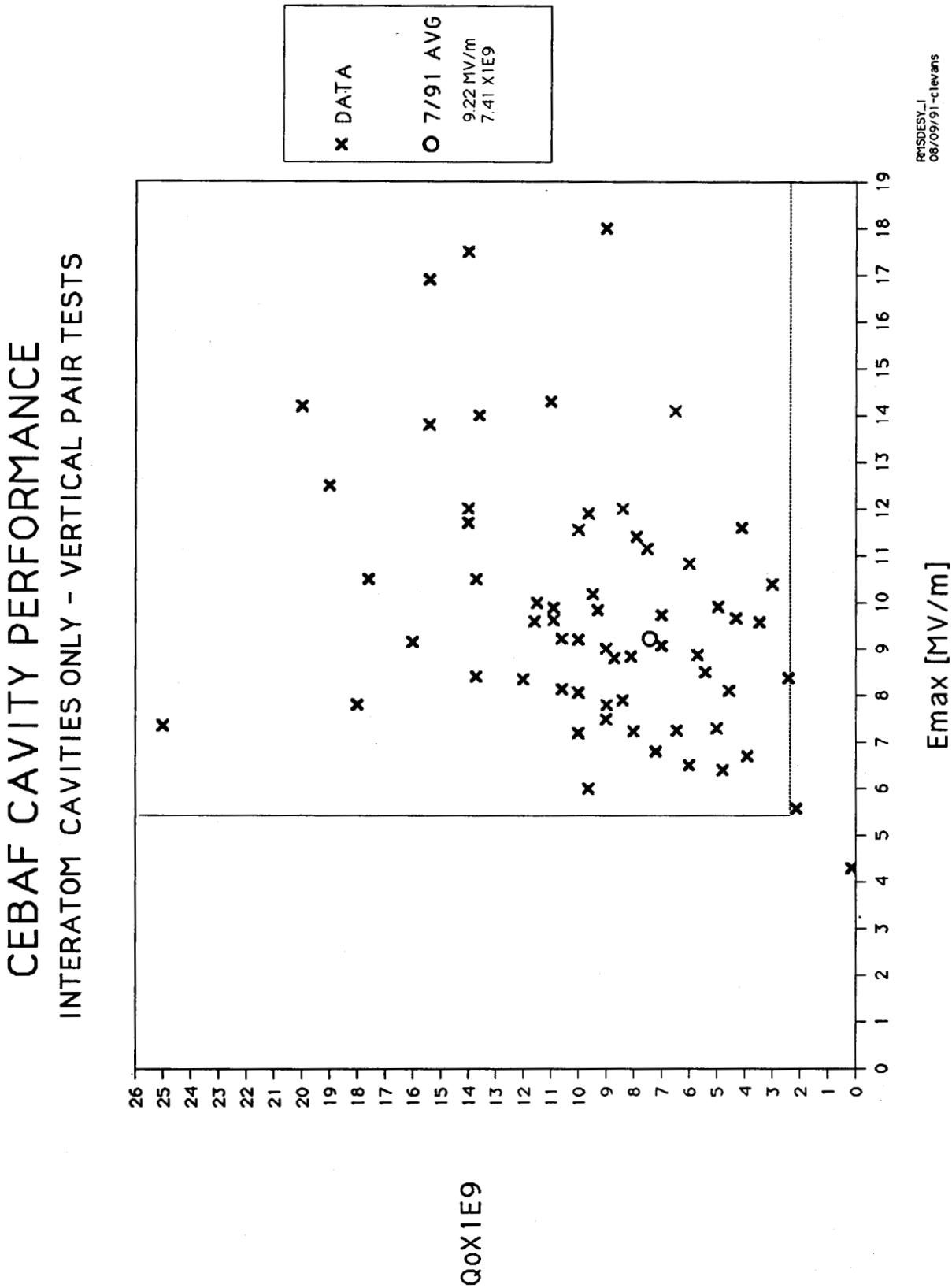
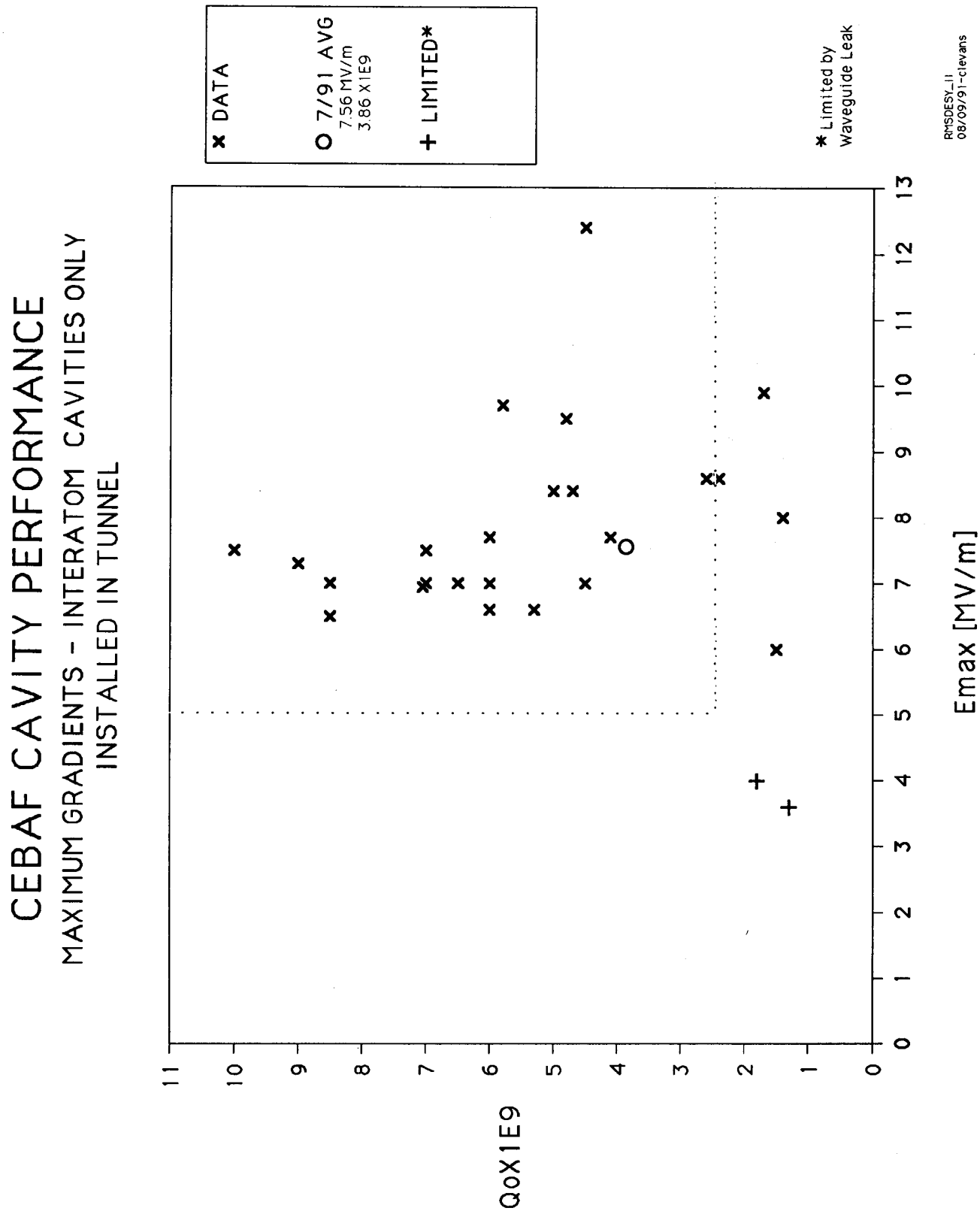

CEBAF CAVITY PERFORMANCE
INTERATOM CAVITIES ONLY - VERTICAL PAIR TESTS
DATA
7/91 AVG
9.22 MV/m
7.41 X1E9
RMSDESY_I
08/09/91-clevans
Emax [MV/m]
QoX1E9

Figure 6


CEBAF CAVITY PERFORMANCE
MAXIMUM GRADIENTS - INTERATOM CAVITIES ONLY
INSTALLED IN TUNNEL
× DATA
O 7/91 AVG
7.56 MV/m
3.86 X1E9
+ LIMITED*
* Limited by
Waveguide Leak
RMSDESY_II
08/09/91-clevans
Q0X1E9
Emax [MV/m]
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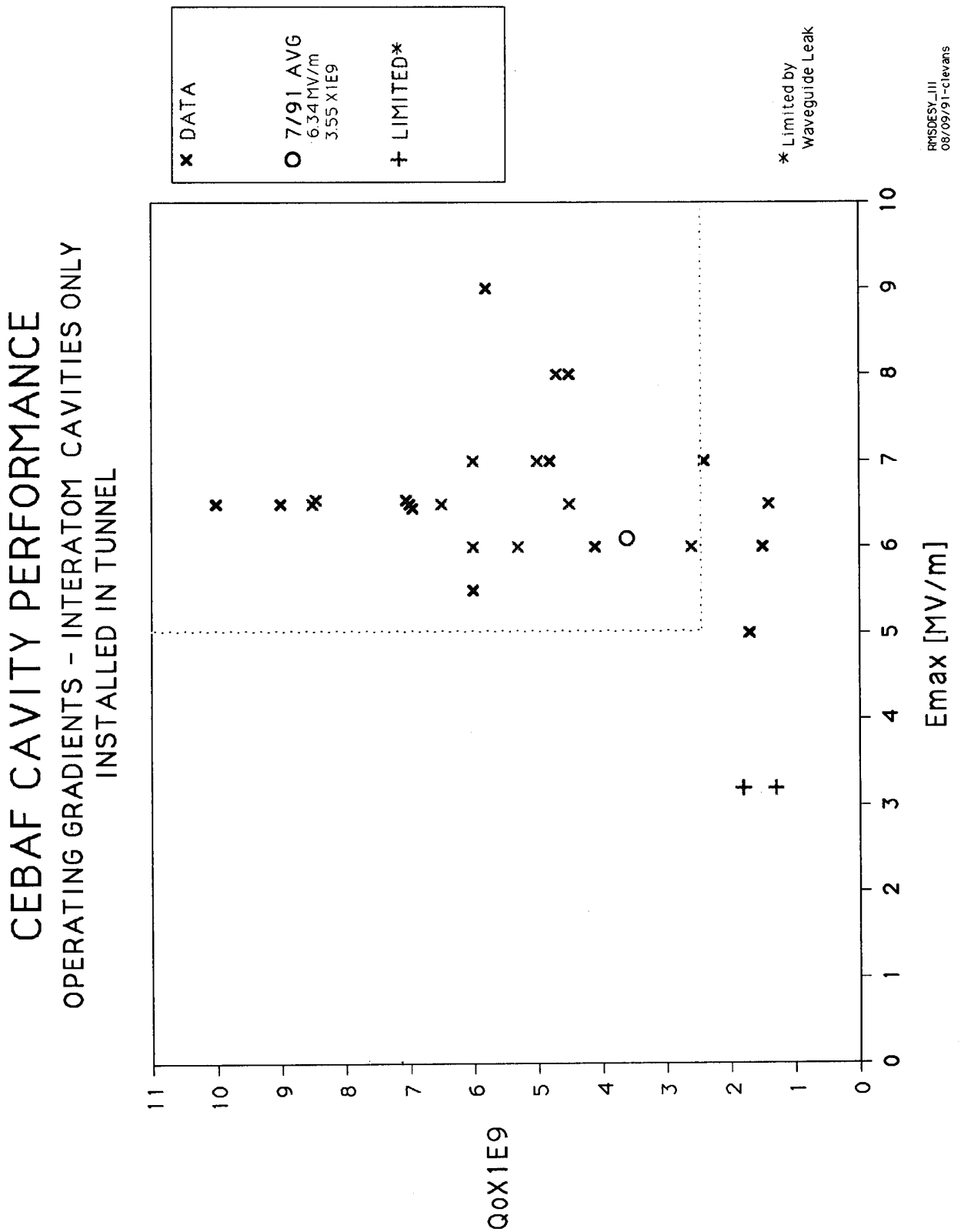
13

Figure 7



Note: Gradients are set at 90% of breakdown or field emission threshold.

Figure 8