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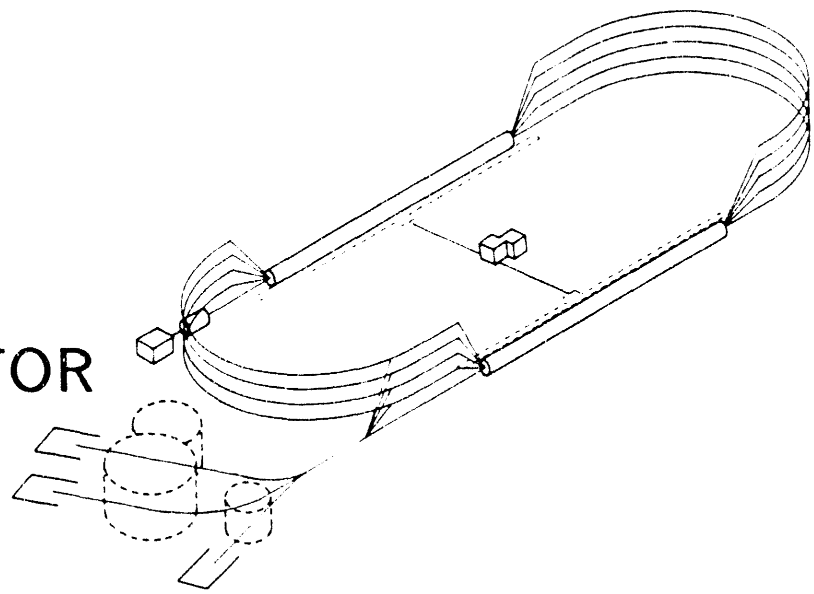

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The Southeastern Universities Research Association (SURA) operates the Continuous Electron Beam Accelerator Facility for the United States Department of Energy under contract DE-AC05-84ER40150.

ALIGNMENT OF CEBAF CRYOMODULES*

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Abstract

CEBAF, the Continuous Electron Beam Accelerator Facility, when completed, will house a 4 GeV recirculating accelerator. Each of the accelerator's two linacs contains 160 superconducting radio frequency (SRF) 1497 MHz niobium cavities [1] in 20 cryomodules. Alignment of the cavities within the cryomodule with respect to beam axis is critical to achieving the optimum accelerator performance. This paper discusses the rationale for the current specification on cavity mechanical alignment: 2 mrad (rms) applied to the 0.5 m active length cavities. We describe the tooling that was developed to achieve the tolerance at the time of cavity pair assembly, to preserve and integrate alignment during cryomodule assembly, and to translate the alignment to appropriate installation in the beam line.

I. INTRODUCTION

The cryomodules for the Continuous Electron Beam Accelerator Facility (CEBAF) located in Newport News, Virginia, will provides a low emittance, 200 μA beam with energies up to 4 GeV for fundamental experimental studies in nuclear physics [2]. The acceleration is achieved from a conventional bunched electron source at 500 keV; a superconducting injector, containing 2 1/4 cryomodules, which provide a nominal energy gain of 45 MeV; and two recirculating linacs containing 20 cryomodules, each linac capable of achieving an energy gain of 400 MeV. After five recirculation passes, the two antiparallel linacs produce a beam of 4 GeV to three end stations.

Exercises conducted during the Front End Test in the spring of 1991 indicated significant transverse beam steering by the accelerating cavities. These effects are attributable to cavity cell orientation and cavity pitch and yaw. Measurements taken at that time indicate that cavity misalignment of 1—2 mrad was not uncommon, and one cavity was reportedly at 6 mrad [3].

II. ALIGNMENT RATIONALE

The original cavity alignment specification was limited to the alignment of the mechanical structure and did not consider the dynamical relevant accelerating field. This specification was in existence at the time of the PCDR [4] and was based on earlier estimates by Leemann and Penner [5]. The model employed for this estimate assumed a uniform accelerating gradient of 5 MV/m over the 0.5 m active length cavity; the transverse beam steering for each cavity was then the cavity pitch or yaw angle caused by misalignment times the ratio of energy gain to the energy in the cavity. The effect of fringe fields was ignored, which resulted in the original tolerance of ± 1 mm from the central orbit. This specification was supported by several simulations—York and Tang [6], and Kewisch et al., [7]—which were consistent with the specifications. During a review of the tolerances it became apparent that the models in question [8] were pessimistic in regard to the effect of cavity misalignment since they ignored effects of cavity fringe fields.

A Mafia study was performed to determine the effect of cavity assembly errors. Because of computer mesh limitations, the grid size was constrained to 2.5 to 5.0 mm, minimum size. The cavity manufacturing and assembly tolerances were routinely 10—20 mils (0.2—0.5mm) or an order of magnitude smaller than the mesh size. These studies, concluded that the most critical assembly error is tilts in the cavity equatorial plane. For assembly errors on the 10—20 mil range, one can then expect pitch and yaw errors equivalent to a few mrad.

III. ALIGNMENT SPECIFICATION

The accelerating field misalignment studies supported the 2 mrad rms tolerance. The simulations were a factor of two too sensitive as they neglected the fringe fields. Similarly the studies were a factor of two too optimistic since they neglected cavity assembly errors. The specification was then set where 2 mrad rms tolerance with a 2 σ cutoff was assigned to cavity assembly, measurement, and fiducialization errors. All of these errors, such as cell tilts, electromagnetic axis determination, fiducial transfers to flanges, etc., are to be limited to this level. The factor of two attributable to fringe fields offsets these effects. The remaining 2 mrad rms error with a 2 σ cutoff is assigned entirely to mechanical alignment of the cavity. An error budget was then set up consisting of three sources: Individual cavity alignment, cavity pair alignment, and cryomodule alignment. The misalignment was defined in terms of net transverse momentum impulse applied to the beam by a single cavity. Reasonable errors were estimated for the three source terms, which resulted in 0.5 mrad level for cavity alignment, 1.25 mrad for cavity pair and 0.1 mrad level for cryomodule net alignment. When added in quadrature this results in less than 2 mrad, which is in the specified range [9].

IV. CEBAF CAVITIES

The design, manufacture [10], test and performance [11] of the CEBAF superconducting radio frequency (SRF)

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cavities are reported elsewhere. Cavities received from Siemens undergo receipt inspection—which includes tuning, mechanical inspection/measurement and initial chemistry. The cavities then undergo final chemistry, are rinsed, and assembled into pairs on the alignment/installation fixture, Figure 1. Cold ceramic windows, pair parts (elbows, beam pipe), HOM loads and dished head assemblies are attached. One of the larger errors associated with the cavity pair alignment was attributable to the end dish assembly as it mounts to the cavity. A special fixture was manufactured to ensure alignment of the beam pipe to cavity centerline. Errors, for a single cavity, after the inclusion of this additional step, translated into an achievable 0.5 mrad level. The pairs are sealed hermetically while in a class 100 clean room to mitigate cavity contamination that can degrade performance. After this the pair is evacuated, mass spectometer leak checked, rotated vertically, transferred to a dewar assembly, tested at 2 K in a vertical dewar, where the performance qualification—Q_0 versus E_{acc}—is accomplished. The pair is then warmed up, transferred back to the alignment fixture and turned over for cryounit assembly. Cavity alignment surveys conducted before and after the vertical tests indicated a repeatability of measurements of better than 1/4 mm total error.

V. CEBAF CRYOUNITS

Assembly of cryounits [12], each consisting of a cavity pair housed in a helium vessel within an insulated dewar, is accomplished outside of the clean room. Tuners, fundamental power coupler extensions (FPC's) and electrical wiring are installed while the pair is mounted on the fixture. The pair is inserted into the helium vessel, Figure 2, which is supported on a hydraulic adjustable stand. Alignment is maintained by sliding the fixture on bearings riding on Thompson rods through the open vessel. The FPC's are connected to the vessel; wiring is brought out through feed throughs; titanium cavity supports, which match the Niobium thermal expansion, are added, and the alignment and installation fixture is removed. The cavity pair alignment is now preserved by the helium vessel. After leak check of the connections, closure heads are added at both ends, allowing the beam pipe to exit the vessel and thereby providing a fiducial, and the heads are welded up. After leak check of the welded vessel, the magnetic shielding, Multi-Layer Insulation (MLI) thermal shield, and additional MLI are added, and the unit is inserted into the vacuum vessel equipped with additional magnetic shielding. The vacuum vessel is supported on a fixture which allows the beam axis to be preserved through a pair of Thompson rods and bearings, Figure 3. Nitronic rods are installed which support and axially restrain the helium vessel inside the vacuum vessel. Adjustment of the rods aligns the mounted pair inside the cryounit. A top hat assembly, including a pair of waveguides for RF, wiring connections, thermal and magnetic insulation and the top hat cover, completes the installation. Alignment has now been transferred outside of the vessel to the two beam line flanges and alignment is maintained by the fixturing of the Thompson rails and bearings.

VI. CEBAF CRYOMODULES

A cryomodule consists of four cryounits, each of which contains a cavity pair, two end cans and five sets of bridging components. In the cryomodule assembly area, a precision assembly bench, consisting of steel "I" beams equipped with Thompson rails, allows the alignment built into the cryounit to be transferred to the module, Figure 4. Initially, a return end can is installed on the rail , then the four cryounits followed by the supply end can. Connections between cryounits are completed under a laminar flow hood, and consist of beam pipes, three helium connections, and thermal and magnetic shielding covered by the bridging cylinder. Access to the beam pipe flange within the vessel is achieved through a port at the midplane on each side of the bridging rings. Special tooling equipped with an optical cross hair is installed on each of the beam pipe flanges which project out to the module midplane. When the assembly bench was installed, four granite blocks were installed at the ends on either side. Scope mounts were set up at one end and targets placed at the other. A rough alignment of the cryounits is performed initially as they are installed. After assembly the bridging rings are welded. Initially we were concerned, as we were for the welding on the helium vessel, that alignment would be compromised. Although we do see movement when welding the helium vessel, the bridging ring welds do not affect alignment. The moment of inertia of the vacuum vessel is large; hence there is little deflection of the cavities. Despite this, final alignment is completed while the welded module is supported at the quarter points, thereby cancelling out this effect. By sighting down both sides simultaneously both the x and the y components can be corrected. Typically alignment of the module is better than a 1/4 mm, which when added with the cryounit errors comes in at the 1.25 mrad level.

VII. CEBAF INSTALLATION

Following the alignment of the cryounits into a cryomodule, a series of external reference points are placed on the outside of the vacuum vessel. These fiducials, which are used to place the cryomodule in its proper position in the tunnel, are surveyed with a theodolite-based industrial measurement system [13]. This procedure, through a rigorous three-dimensional survey and least-squares adjustment, transfers the transverse and angular orientation of the cryomodule centerline as defined by the granite monuments to the reference points. The ideal coordinates in the overall machine coordinate system can then be calculated by knowing the cryomodule's design position on the beam line and the measured target offsets.

Transfer of the cryomodule to the tunnel is accomplished on a specially equipped air ride trailer. Tunnel alignment consists of two steps, both of which utilize a reference control network which defines the machine's position in the tunnel.

This network was measured using standard high-precision surveying techniques developed for particle accelerators [14,15]. The first alignment step, which employs optical tooling techniques, "rough" aligns (<1.0 mm) the cryomodule and its adjacent components for vacuum interconnections. The second step aligns the cryomodule to 0.1 mrad relative to the control network and the design beam line. The beam pipe girders are connected to the module after the second alignment to preclude rotation of the beam line bellows. A third alignment is done to account for tunnel settling.

VIII. LINAC RESULTS

A limit on the alignment error of the end cavity of the North Linac can be set by the fact that no observable beam spot growth occurs when a 120 MeV beam is energy modulated by a 0.5 MeV using this cavity. The observed down stream steering was ≤ 1/4 mm which implied ≤ 3 mrad misalignment angle which is consistent with the specification.

IX. ACKNOWLEDGEMENTS

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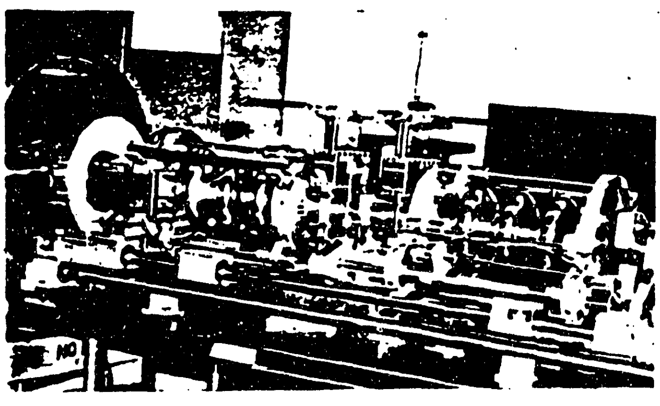

Figure 1. Alignment/installation fixture.

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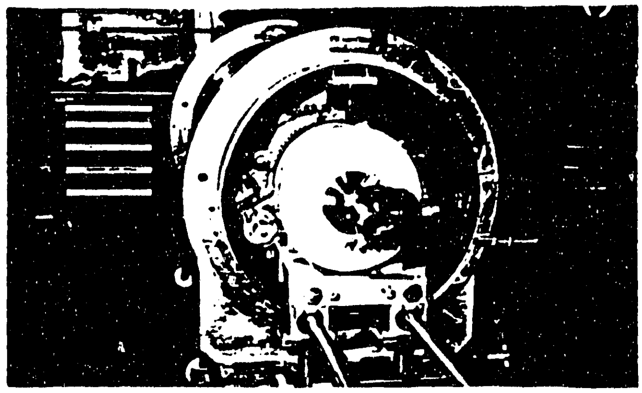

Figure 2. Insertion of cavity pair into helium vessel.

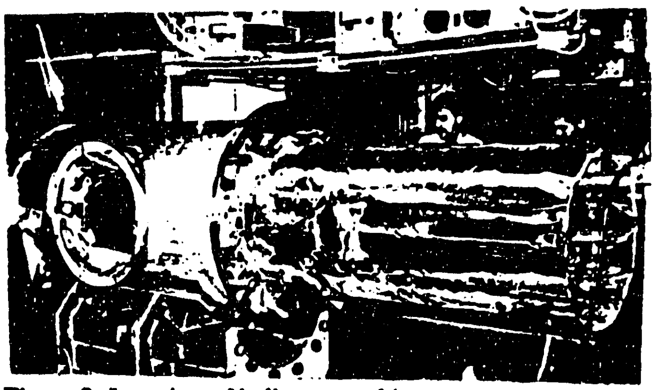

Figure 3. Insertion of helium vessel into vacuum vessel.

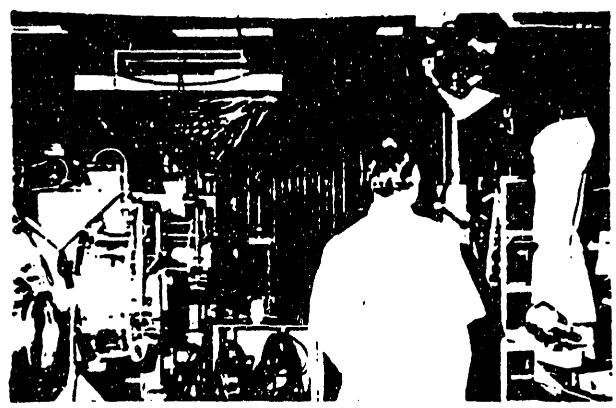

Figure 4. Cryomodule fiducialization.

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