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Publication Date

1969-02-27

Presented at the National Particle Accelerator
Conference, Washington, D. C., March 5-7, 1969

UCRL-18538
Preprint

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February 27, 1969

AEC Contract No. W-7405-eng-48

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UCRL-18538

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MECHANICAL DESIGN OF COMPRESSOR TEST APPARATUS FOR ELECTRON RING ACCELERATOR RESEARCH*

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Summary

The mechanical and vacuum features of the Compressor II apparatus used in the Fall 1968 Electron Ring Accelerator (ERA) experiment are described. Included are the injection beam transport system, the coils and their support structure, the ceramic vacuum chamber and its pumping system, the gas injection system, and diagnostic probes. The coil arrangement for the upcoming Compressor III experimental apparatus is briefly presented.

Introduction

At least two inherently different approaches exist for forming and compressing electron rings: (1) using magnetic fields which vary in space but not in time; (2) using magnetic fields which vary in both space and time. Although the first approach may ultimately prove the more attractive and reliable, at present it is more beset with theoretical and practical difficulties. The second approach is closely allied to existing fast-pulse technology developed, for example, in Project Sherwood. Thus, the ERA Compressor II device was of the fast-pulsed air-core coil variety.

The ERA Compressor II apparatus had components which (1) accepted only the brightest part of an intense beam of electrons and, with precise timing, passed only a small pulse of this current to the compressor, (2) accepted and captured about 50% of this small pulse as three turns at 19 cm radius totaling ~150 A of circulating current, (3) provided a rapidly rising magnetic field to compress this ring from 19 to 3-1/2 cm radius in ~600 μs, at which time the circulating current appears as ~800 A, (4) maintained the magnetic field to hold this ring for observation for 3 to 5 ms, (5) loaded the ring with ions--in this case protons, and (6) provided means to measure and diagnose the activities occurring.

Beam Transport System

The Astron injector[1] produced 3+-MeV electrons and was operated at a rate of about 24 pulses/min. The electron beam was transported to the compressor by the beam-transport system shown on Fig. 1.

A parallel-plate beam chopper[2] in the beam line chopped a 20-ns pulse out of the 250-ns Astron beam and sent it to the compressor. The unchopped part of the 250-ns pulse was deflected upward by a dc bias coil and dissipated in beam dump 1.

The beam was focused with solenoids and steered with four pairs of horizontal and vertical trim coils. Beam current was measured with beam transformers. Beam position could be measured either with pairs of single-loop horizontal or vertical beam-position electrodes, or an image could be viewed directly with an aluminum oxide scintillator viewed remotely with closed-circuit television. An emittance box in the beam line contained a drilled carbon plate attenuator; a 1/4-in.-diam pencil beam collimator; a carbon-plate slit system; and a film holder. The remotely-operated water-cooled aluminum-alloy beam dump 3 blocked the beam from Compressor II during beam tuneup.

The beam line had a graded vacuum from 10^{-6} Torr in the injector emittance box region to $\sim 10^{-8}$ Torr at the Compressor ion pumps. The beam line from the Astron injector to foil valve 1 was made mostly of aluminum alloy and was sealed with Buna-N O-ring gaskets. The vacuum system from foil valve 1 to the compressor was made of stainless steel, sealed with copper gaskets, and used stainless steel bellows to accommodate motion. A 260-liter/s turbomolecular vacuum pump was connected through a liquid nitrogen trap to a position between foil valve 1 and and valve V4. This section of the line also included a titanium sublimation pump, a second aluminum oxide scintillator, and a 50-liter/s ion pump. The first part of the transition line between the 50 liter/s ion pump and the compressor was made of copper to provide eddy-current shielding from the pulsed magnetic fields. The final part was made of low-coercive-force iron with variable-thickness copper plating. This combination shielded the beam entering the compressor and minimized the disturbance to the compressor magnetic field.

Two 0.5-mil-thick mylar foils were used to protect the compressor vacuum during the early part of the experiment but caused the beam to scatter badly. Later foil 2 was removed entirely, and foil 1 was replaced with a nitrocellulose foil of about 71 μg/cm^2 thickness (10 to 20 μin.). The nitrocellulose foil (model airplane "microfilm")

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*Work performed under auspices of U. S. Atomic Energy Commission.

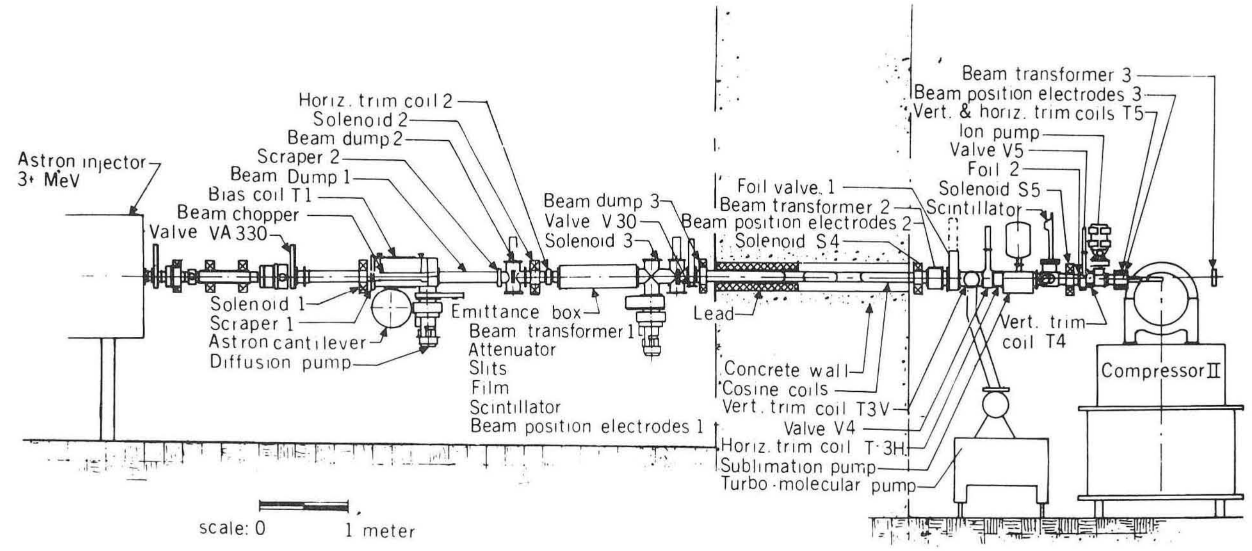

Fig. 1. Beam transport system.

caused some beam scattering but was acceptable.

Coils

The "magnetic bottle" which guides and compresses the electron ring was generated from three pairs of air-core coils, as shown in Fig. 2. Coil and power supply characteristics are given in Table I. Coil set 1 was fired first, and when the field reached about 900 G, the electron beam was injected at a radius of ~19 cm. When the current reached a maximum after one-quarter cycle, the energizing capacitors were crowbarred (short-circuited) so the current remained during the sequential pulsing of the other two coil sets. Coil sets 2 and 3 were successively fired and crowbarred to achieve maximum ring compression. A "flattop" pulse transformer and rectifier assembly[3] maintained the peak current in coil set 3 for 3 to 5 ms. During flattopping, the average power input was 5 MW.

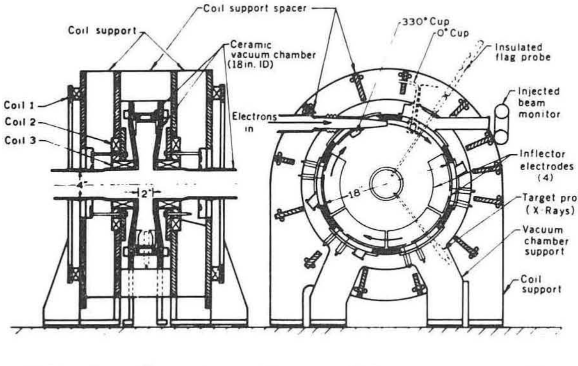

Fig. 2. Cross sections of Compressor II.

Table I.
Coil and coil power-supply design characteristics

		Coil set 1	Coil set 2	Coil set 3
1.	Mean radius (cm)	32-1/4	14	7.1
2.	Mean spacing (cm)	48	21	15.2
3.	Square conductor size (in.)	0.255	0.340	0.340
4.	Number of turns/coil	12	12	12
5.	Cooling circuits/coil	4	2	2
6.	Typical driving voltage for 2 coils in series (kV)	22	12	7
7.	Max current/turn (A)	6300	5300	30 000
8.	Current rise time (μs)	130	180	260
9.	Size of capacitor bank power coils (μF)	43.8	78.1	780
10.	Peak magnetic field (kG)	1.6	6.4	20
	at electron-ring radius (cm)	~14	~7	~3.2

Coil set 1 was initially fabricated by placing the bare, formed copper into a mold. Insulation spacing of 0.1 in. was obtained by "egg-crating" with glass cloth pads every 6 or 7 in. The assembly was then vacuum-impregnated with epoxy. When individual coils were tested by discharging the capacitor bank through them at voltages up to 16 kV, they catastrophically failed--a somewhat noisy process. This difficulty was corrected by hand-winding new conductor with 3/4-lapped No. 53 Mylar tape before potting. No subsequent failures were experienced. It is uncertain whether the additional electrical insulation or the mechanical cushioning provided by the eight layers of tape and adhesive between conductors was the real corrective agent.

Coil sets 2 and 3 were fabricated in molds which were fully packed with glass cloth and roving before the structure was vacuum-impregnated with epoxy. All coils were wound as a series of rings with sharp, specifically positioned offsets between turns rather than being wound as helices. They easily passed 10-kV (coils 2) and 6-kV (coils 3) proof tests. To minimize stray field disturbance coaxial leads were used on coils 2 and 3.

Design currents of 30 kA/conductor in coil set 3 would produce hoop tensions which the copper conductor could not carry by itself. Development tests showed that copper stresses above 10 000 psi produced unacceptable stretching of the conductor. Coil set 3 was therefore designed with split stainless steel rings surrounding the copper. These rings, 1/16 by 3/16 in. in section, were spaced apart by 1/16-in. epoxy glass rings, and then vacuum potted. This outside surface and the mounting flange were made by wet layup of glass tape and epoxy. In this manner copper stresses were kept to ~ 8800 psi. The copper carried approximately 60% of the hoop load, the stainless steel rings about 38%, and epoxy-glass laminate about 2%. It was estimated that at 50 000 A the stainless steel rings would yield, initiating a progressive failure. Hoop stresses in coil sets 1 and 2 were well below yield levels.

Coil-Support Structure

Because of the rapidly-changing magnetic field, the coil-support structure was fabricated from NEMA G-10 fiberglass-epoxy laminate. Rigidity under the axial attractive loads was essential. Two 3/4-in.-thick G-10 sheets were separated by 12 bonded ribs giving a 5-in.-thick diaphragm structural element. One such structure was provided on each side of the vacuum chamber. Axial forces were carried across the vacuum chamber by 12 separate G-10 spacer struts. Thus, each coil support was the reaction member for the other. Axial loads reach ~9000 lb peak at full excitation of coil set 2 and ~13 000 lb peak after full excitation of coil set 3. As is usual when minimum deflection is the design criteria, flexure stresses are very small, ~1000 psi.

Clearances between the coil-support structure and the ceramic vacuum chamber are quite small, ~0.1 in. Behavior of the coil structure was proven before the vacuum chamber was installed. Coils 2 and 3 were mounted and excited to 33 000 and 10 000 A respectively. Structure deflection was measured by adding a tube extension to one coil support, and providing a pretensioned, 40-in.-long, 3/8-in.-diam acrylic rod on the centerline. Wire strain gages were bonded to the outboard end of the rod. As the coil structure deflected the rod lost some of its pretension, and the cycle of strain change was displayed on an oscilloscope. Deflections under maximum excitation were ~0.010 in./side, which is about 1/3 of the calculated static deflection. Slightly more than 1.5 ms were required to reach the maximum mechanical deflection. The second cycle of vibration was approximately one half the amplitude of the first, indicating high damping--an advantage of the G-10 material. At maximum excitation there was no doubt the apparatus was operating as the hammer-blow loading gave ample acoustical response!

Vacuum Chamber

The vacuum chamber was designed so that changes could be made to internal components. This accessibility was provided by a gasketed design utilizing Viton O-ring seals. Eddy currents from the changing magnetic field would be intolerable unless a nonconducting material were employed. For example, ~450-A peak would circulate in a 0.001-in. stainless steel foil 2 cm wide and 14 cm in diameter placed on the inner wall of the vacuum chamber. A brisk construction schedule implied straightforward fabrication from materials of known characteristics, consequently, 85% alumina ceramic was selected.

The chamber (Figs. 3, 4, and 5) consisted of a central ceramic ring 3-1/2 in. wide by 18-in. ID, and two 5/8-in.-thick conical cover plates on each side with 4-in.-diam by 8-in.-long tabulations. Gasket grooves for 18.5-in.-diam Viton O-ring were ground into the end faces of the ring. The ring had six oval ports spaced around its periphery. The ports were closed with 1/8-in.-thick stainless steel curved cover plates carrying a Viton O-ring. These curved covers mounted the inflectors, the "Gozinta" and the "Gozouta" snouts and various probes and windows. The inside faces of the ceramic parts were vacuum-coated with a 500-Å thickness of nickel to drain electric charge.

Vacuum System

The compressor vacuum system is pumped with two 500-liter/s ion pumps. The system is roughed with an aspirator plus two cryosorption pumps. The volume of the compressor and the two ion pumps is 70 liters and the internal surface is about 3 m^2, excluding the beam transport system. A base pressure $\leq 10^{-8}$ Torr was

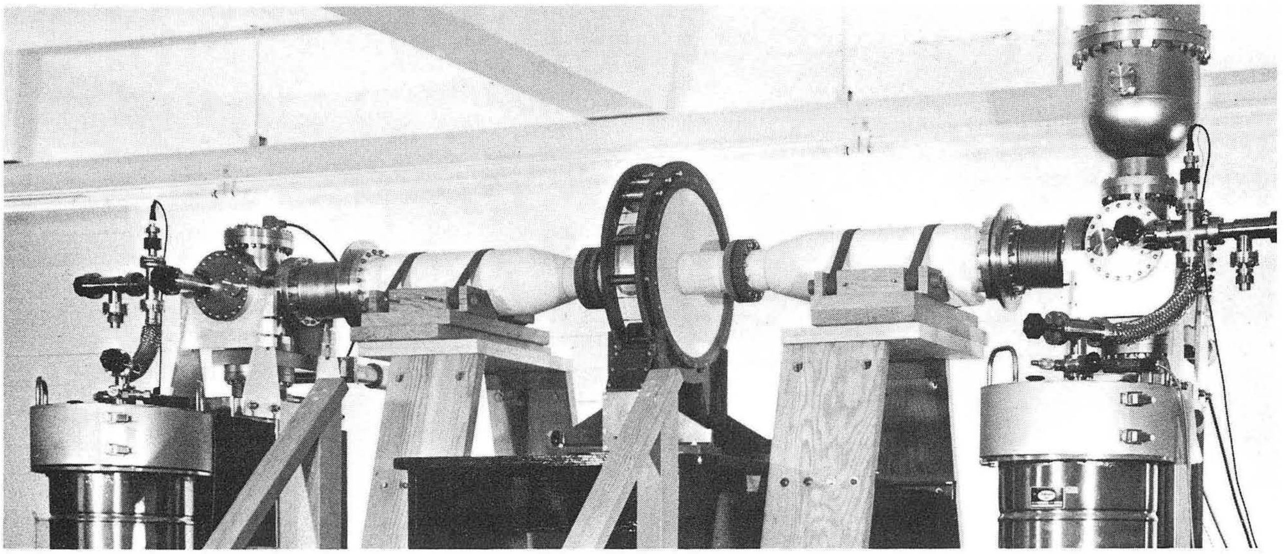

Fig. 3. Compressor II vacuum system during test.

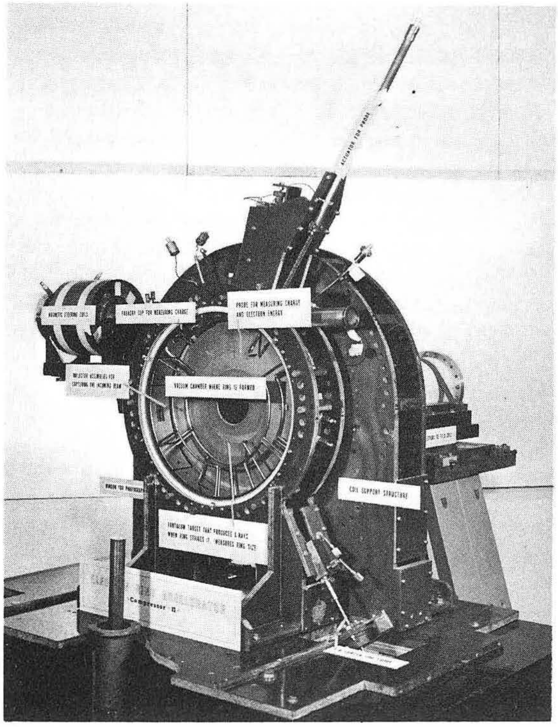

Fig. 4. Compressor II showing interior components.

desired in the compressor region to avoid populating the electron ring with unwanted residual gas ions. Pumpdown times from atmosphere of ~2 days were attained. Air was the main constituent to be pumped at first, but subsequently nitrogen was the principal gas after the system had been let up to pure dry nitrogen. Hydrogen from the puff valve was present during operation.

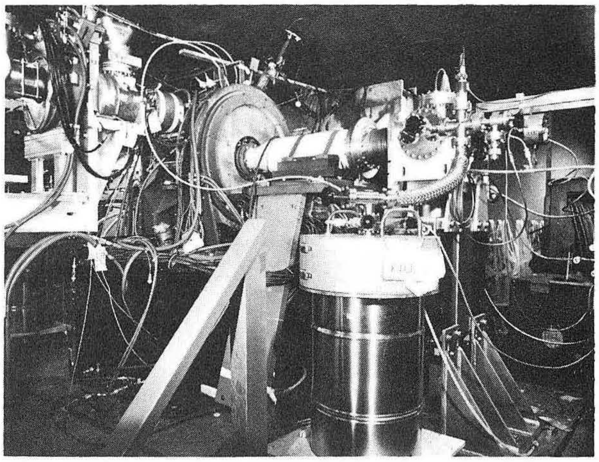

Fig. 5. Installation of Compressor II at Livermore, Fall 1968.

In the hard vacuum region stainless parts were Diversey cleaned, copper parts were ultrasonically cleaned in alcohol, and ceramic parts were wiped with alcohol. The lack of time precluded sufficient bakeout or pumpdown time. There is some question regarding outgassing from the agents used to clean the ceramic. It is suggested that ceramic parts be baked after cleaning at the factory and shipped under dry nitrogen. It is difficult to obtain high-integrity reliable seals between dry Viton and alumina ceramic, especially when seals are attempted on curved surfaces.

Valves were bellows-sealed stainless in the hard region. In the whole experiment about 50 stainless steel bellows were employed for vibration isolation, thermal expansions, adjustments, and probes. Bakeable pyrex windows were adversely affected by radiation and were barely satisfactory for this short experiment. Sapphire windows are suggested for future experiments. Varian's Bayard-Alpert-type ion gauges were installed where they would not interfere with the experiment or be unduly affected by pulsed fields.

Gas Injection and Diagnostic Probes

The electron ring was loaded with protons derived from hydrogen gas, which was injected by a "puff valve," a novel device initially developed for Project Sherwood. A shock wave was induced in a long rod by a magnetic hammer. When the shock wave reached the valve end near the median plane, the valve was unseated a few thousandths of an inch for a few microseconds. Hydrogen entered the chamber during this period.

Instrumentation included means to monitor the incoming injected beam without the magnetic field. A graphite-electrode Faraday cup monitored the beam immediately after it entered the field (the "0° cup") and after it had completed about 1 turn (the "330° cup"). Two insulated tantalum flags could be remotely positioned to any radius. Two axial probes were introduced down the vacuum pumping manifold. One of these, the "rising-stem probe," remotely positioned a tantalum target to most any radial or azimuthal position within the chamber. A second capacitor pickup probe monitored charge in the electron ring. The function and performance of these devices are described by Keefe.[4]

Upcoming Experiment

Our next ERA experimental apparatus, designated Compressor III and shown in Fig. 6, is now being designed and fabricated. In addition to studies of electron-ring compression and ion loading, it permits extraction of the loaded electron ring from the magnetic bottle into a modest length ($\sim$60 cm) region of magnetic acceleration ($B_r \sim 5$ gauss) producing, hopefully, protons of at least 10 MeV energy. Many components from the earlier experiments are being reused. The Astron accelerator has been relocated and will again be used as the injector.

The prominent new feature of Compressor III is coil set 3, which consists of a 14-cm solenoid on one side of the median plane and a 100-cm solenoid on the other. Both are air-core double-layer solenoids, with the longer solenoid having slightly greater pitch to preserve median-plane symmetry during compression while both are carrying equal currents ($\sim$45 kA peak). To achieve extraction (spillout), the current in the shorter solenoid is increased to $\sim$105 kA while that in the longer is reduced to $\sim$30 kA corresponding to field strengths of approximately 50 and 20 kG respectively. Stainless steel reinforcing helices carry most of the large hoop forces due to the 50-kG fields. The solenoids are trifilar wound to provide suitable impedance to the power supplies and to provide three-fold azimuthal symmetry which reduces the possibility of exciting unwanted particle resonances. The magnetic precision of the long solenoid is of the order of 1 gauss in 20 000 and is achieved by placing the conductors in precisely machined helical grooves in a fiberglass-epoxy coil bobbin.

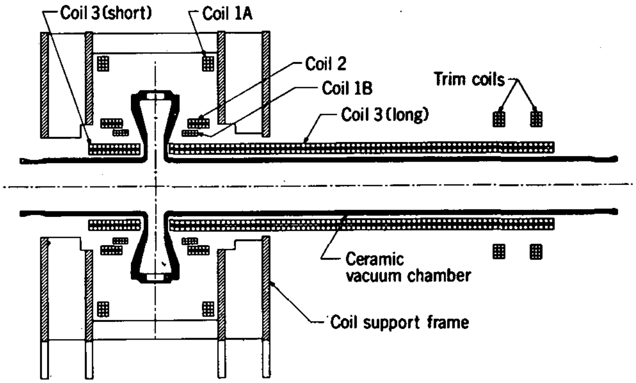

Fig. 6. Longitudinal section of Compressor III.

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