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Argonne National Laboratory

ARGONNE CYCLOTRON--HELIUM-3 CONVERSION

by

W. J. Ramler, R. Benaroya,
G. W. Parker, and J. Aron

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Chemistry Division

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ARGONNE CYCLOTRON--HELIUM-3 CONVERSION

by

W. J. Ramler, R. Benaroya,
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The Argonne 60-inch cyclotron¹ has been operating since 1952 with projectiles limited to a charge-to-mass (Q/M) ratio of $1/2$, i.e., D^+ , H_2^+ , $^4He^{2+}$, and $^6Li^{3+}$. The cyclotron was modified to permit acceleration of $^3He^{2+}$ ions. Required modifications were accomplished in the period from May to August, 1964. In the following these modifications, along with the 3He gas-recovery system and resulting accelerator operation, are discussed.

I. ACCELERATOR MODIFICATIONS

Given the problem of converting an existing constant-frequency cyclotron to acceleration of many kinds of particles with very limited funds and allowable down time, one is immediately confronted with a fundamental decision: should the conversion encompass a variable-frequency rf system and a variable magnetic field, or should the upgrading be limited to increasing the flexibility of just one component, i.e., either the rf or the magnetic field? It was decided to install electric trim coils to shape the magnetic field and leave the rf system unchanged.

To understand the basis of this decision, the possible operating parameters of the machine are listed in Table I.

TABLE I. Cyclotron Parameters

Q/M	Particle	B_{center} (kG)	f (Mc/s)	T (MeV/nucleon)	Comments
$1/2$	D^+ , $^4He^{2+}$...	14.88	11.20	10.8	Normal operation; 374 kG-in.
$2/3$	$^3He^{2+}$	14.88	14.96	19.3	B held constant; f increased
$2/3$	$^3He^{2+}$	11.20	11.26	10.9	f held constant; B decreased
$3/7$	$^7Li^{3+}$	14.88	9.64	8.0	D held constant; f decreased
$3/7$	$^7Li^{3+}$	16.97	11.00	10.4	B increased; f changed within limits of existing system

Variation of the trimmer capacitor in the existing rf system provides a frequency range of about 11.00 to 11.50 Mc/s. For operation with ${}^7\text{Li}^{3+}$, a frequency of 11.00 Mc/s was assumed to decrease the required magnetic field.

Rf modifications were considered for both the 14.96 and 9.64 Mc/s operations, but the overall problem including phase slip was formidable. It was decided that the system shorting bar would have to be rebuilt and the interior surfaces of the existing vacuum cavity would have to be re-worked. Since these changes required an accelerator down time in excess of three months and an estimated expenditure in excess of \$59,000 (allowable funds), it was decided to limit machine changes to the addition of magnetic-field trim coils to the acceleration of both ${}^3\text{He}^{2+}$ and ${}^7\text{Li}^{3+}$ at a frequency of about 11 Mc/s.

A. Magnetic-field Contours

The radial field shape for the 14.88-kG center field, i.e., for operation with particles of $Q/M = 1/2$ at 11.20 Mc/s, is given by Fig. 1. This figure also sets forth the uncorrected shape of the field when the center level is lowered to 11.20 kG (for ${}^3\text{He}^{2+}$) or raised to 16.97 kG (for ${}^7\text{Li}^{3+}$).

Fig. 1. Magnetic-field Contours. Accelerator operation for projectiles with $Q/M = 1/2$ is achieved with the B_c contour of 14.88 kG. The other contours (uncorrected) result when the field level is lowered to 11.20 kG (${}^3\text{He}^{2+}$) or raised to 16.97 kG (${}^7\text{Li}^{3+}$).

These uncorrected field contours provided the necessary data to establish the design requirements for the electric trim coils. Since the cyclotron is quite successful in the acceleration and extraction of high beam currents (300 μA of D^+ , 170 μA of ${}^4\text{He}^{2+}$) it was decided to correct the 11.20 and 16.97 kG fields in such a manner that the radial pattern of the field index n would remain unchanged.

Calculations showed that 3 circular trim coils located on the top and bottom rf liners (pole-tip side) and positioned at mean radii of 5.95 (2 turns--200 A max), 14.55 (3 turns--300 A max), and 24.7 in. (12 turns--500 A max) would provide the necessary field correction for the operating range from 11.2 to 16.97 kG.

Since a model magnet was not available, all field calculations were checked by mounting full-scale trim coils in the magnet gap of the cyclotron. These measurements required a total accelerator down time of four weeks. Model measurements and calculations were in good agreement.

B. Construction of Rf Liners

Construction of the rf liners and trim coils was guided by the requirements established by the calculations and the magnet model endeavors.

Figure 2 illustrates the relationship of the trim coils and liners to the magnet gap. New rf liners were necessitated by the deterioration of the original pair. The following design requirements were established:

1. trim coils to be a rigid part of the pole-tip side of each liner;
2. thickness of each liner to be a maximum of $1/2$ in. so that the rf system and the $2\frac{1}{2}$ dee-to-ground clearance is unchanged;
3. trim-coil conductors to have a maximum cross section of 0.20×0.20 in.;
4. liners to be operated in a vacuum of about 1×10^{-6} Torr;
5. liners to be constructed of OFHC copper without any brazed or soldered joints facing a dee;
6. adequate cooling to remove the rf heat losses;
7. the face toward the "dees" to be flat and smooth with a finish of approximately $15 \mu\text{in.}$;
8. all water and electrical connections to be located in an accessible region of the acceleration chamber.

The original liners (1952 to 1964) were constructed of $1/8$ in. thick OFHC copper plate. Cooling was provided by a zig-zag pattern of $3/8$ in. OD copper tubing, soft soldered to the plate. This type of construction had disadvantages such as the difficulty of soldering the cooling lines to the plate, yet maintaining a flat surface, and the difficulty of using the plate as a mounting base for the trim coils.

Other methods were considered. The one adopted consisted of a two-plate design (see Fig. 3) with one section $1/4$ in. thick, machined grooved for water channels, and the second plate a $1/8$ in. thick cover silver brazed to its mate.

Fig. 2. Modified Magnet Pole Gap

Fig. 3. Rf Liner and Trim Coils

The base plate for each liner was constructed of OFHC copper, with an overall size of 5 ft x 6 ft x 1/4 in. thick. Four continuous and independent circuitous water channel grooves, 0.375 in. wide x 0.140 in. deep, were machined into one side of the plate. A water-tight cover was provided by silver brazing a 1/8 in. thick OFHC copper plate to this base. Groove pattern and locations are illustrated in Fig. 4. Silver brazing of this

assembly was accomplished by placing both plates into a stainless steel container of about 5 x 6 ft in plan dimension. A $1\frac{1}{4}$ in. thick steel plate, smooth and flat, was first placed into the container to act as a heat homogenizer. This was then covered with a 0.030 in. thick fiberglass cloth, followed by the $1/8$ in. copper cover, sheets of BT alloy (72% Ag-28% Cu, 0.0015 in. thick and $2\frac{3}{4}$ in. wide) without any edge overlap, and then the $1/4$ in. copper liner base. Alignment was achieved by inserting a pin through a center reference hole in each plate. Upon alignment, a $1/4$ in. hole was drilled in a region remote from the cooling channels and a copper pin was inserted to prevent plate rotation. To complete the package, a fiberglass cloth was placed over this plate and a $1/16$ in. thick stainless steel cover was welded to the container. Throughout assembly, all parts were thoroughly cleaned with acetone and alcohol, and all workers wore clean, lint-free gloves.

Fig. 4. Water Groove Pattern of Rf Liner

The first liner assembly was brazed in a gas-fired furnace, the only type in the Chicago area that was sufficiently large to handle the container. Prior to raising the temperature, the container was evacuated to 5×10^{-3} Torr and then the temperature was slowly raised to 1550°F, maintained for 2 hr, and then slowly cooled for 12 hr to room temperature.

After cooling, the container top was opened and the liner assembly removed. To facilitate the handling and to maintain the flatness of the liner, it was placed on a specially prepared hold-down skid. The next operation consisted of enlarging the outside openings of the internal cooling grooves to an oval cross section of $3/16 \times 9/16$ in. A $3/8$ in. copper tube was shaped to fit into each opening and then it was heli-arc'd (Sil Fos) into place.

Application of an air blow to each cooling channel indicated blockage; subsequent radiography showed the extent of the obstructions. The resultant study predicated that the obstructions occurred because of the capillary action generated by temperature gradients in the plate. It was thought that these gradients were developed by the gas jets of the furnace.

In proceeding with the brazing of the second liner assembly, the technique previously used was modified by placing a 1 in. thick steel plate on the top (outside) of the container to serve as an additional heat homogenizer. Also, the thickness of the BT alloy was decreased from 0.0015 to 0.0010 in. The brazing results were better, but small channel obstructions still occurred. After radiography, channel clearance was achieved by using a vertical mill to cut through the $1/8$ in. plate to remove the excess solder existing in a water channel. To facilitate the sealing of the cut and to maintain a flat and smooth surface, each hole area, 2 total, was shouldered recessed. A copper cover was inserted into the recess and heli-arc'd (Everdur) sealed.

Upon completion of the gas-furnace brazing of the second liner, with the first being considered a failure, it was decided to use an electric-type furnace. Such a furnace with forced-air circulation was located in Paducah (AEC), Kentucky. The third assembly was processed as before, the only change being the furnace. Even though subsequent radiographs indicated some very minor channel filling, the overall effort was successful.

Prior to the final machining, each unit was spectrometer leak checked by "bagging" the assembly in a helium atmosphere and vacuum pumping the internal water channels. These tests indicated that the assemblies were free of leaks from the channels to the outside surfaces. Inter-channel leakage was also checked by pumping on a channel and helium pressurizing the adjacent path; each assembly was tight.

Upon completion of these tests, the required grooves for trim-coil placement, 0.062 in. deep, were milled into the pole-tip side of the assembly. This machining included the required clearance for the original Rose Rings (positions unchanged), the recesses required for the conductor crossings, the necessary mounting holes and a surface finish of $15 \mu\text{in.}$

Final shop tests consisted of repeating the spectrometer leak checks and thermally cycling the assembly. Cycling was accomplished by

distributing live steam over the outside surfaces for a period of about 4 min, then removing the steam, and covering these surfaces with 60°F water for about the same time period. Each liner received 15 complete temperature cycles before the final vacuum leak test. Both assemblies passed these tests without any difficulty.

It is to be noted, that calculations were made to determine the maximum deflection of the liners when in place. The considered forces were gravitational and electromagnetic with the maximum deflection calculated to be about 0.04 in. at the 18 in. radius. During the design, this did not appear to be a severe problem, and subsequent accelerator operation supported this conclusion.

C. Construction of Trim Coils

As previously stated, three coils are required per pole with mean radii of 5.95 (2 turns), 14.55 (3 turns) and 24.70 in. (12 turns). All coil conductors are nominally 3/16 in. square (extruded by Anaconda American Brass Co.) without insulation and have an internal hole diameter of 1/8 in. Insulation was applied by the Anaconda Wire & Cable Co. and consists of 0.013 in. thick double Silotex Dacron, thus increasing the overall conductor size to 0.200 in.

The outer coil was connected in three portions, a design necessitated by the excessive coolant pressure required for a single continuous coil. These three coil segments are parallel connected for cooling and series connected for power. The other two trim coils are continuous in construction and each has a single cooling loop. All coils were designed for a maximum water temperature rise of 50°C for an operating current of 550 A and a coolant pressure drop of 220 psi.

Both liners were shipped to a commercial coil winder for the winding and installation of the trim coils. Prior to mounting, each coil was formed, epoxied, and baked to form a rigid structure. Two epoxy coats were applied for a total buildup of about 0.010 in. Air baking was performed at 120°C for 24 hr.

In preparation for coil mounting, each liner surface was sanded and washed with alcohol. These surfaces and those of the coils were meticulously cleaned. Then the grooves and adjacent surface areas were epoxy coated, and the coils were immediately inserted into the grooves and again epoxied, the coating extending over to the bare surface of the liner. The assembly was air baked at 120°C for 24 hr. After cool down, the overall coating and baking process was repeated. The total thickness of the completed coil coating was about 0.020 in.

The epoxy² was composed of the following:

1. Shell Epon 828 Epoxy	100 parts by weight
2. Nadic Anhydride Hardener	90 parts by weight
3. Propylene Glycol P400 Flexibilizer	20 parts by weight
4. Argus Chemical DB VIII Catalyst	5 parts by weight

Materials 1 and 3, and 2 and 4, were mixed together to form two material groups, 1-3 and 2-4. In the use of this material, it is to be noted that the final mixing of these two groups must not be done more than 24 hr prior to use and that the resultant strength of the epoxy bond is dependent upon clean joints; hence, utmost care must be exercised in maintaining cleanliness.

The choice of epoxy was made on the basis of its mechanical characteristics and its ability to withstand radiation. Shear tests were made with sample conductors mounted on flat plates. When the above procedures were followed, the strength of a bond was about 670 psi at 100°C.

120-8311

Fig. 5. Liner-Trim Coil Assembly. Liner mounted on special hold-down "skid."

Established³ radiation data indicates that this epoxy will withstand a total dose of 10^9 Rads without appreciable deterioration of its bonding strength. For its use in the cyclotron, calculations indicated that about 160 yr of three-shift operation will be required to give a total dose of 10^9 Rads to the epoxy when operating with an external deuteron beam of $200 \mu\text{A}$, 21.6 MeV impinging upon a copper target. For the described design, radiation-damage effects should not be a problem.

Photographs of a completed liner are given by Figs. 5 and 6.

120-8313

Fig. 6. Trim-coil Crossovers and Leads

D. Electrical Tests of Trim Coils

Both trim-coil assemblies were load tested prior to and after installation in the acceleration chamber. A summary of these test data are given in Table II.

TABLE II. Test Data for Trim Coils

Inlet Water Temp: 30.4°C
 Inlet Water Pressure: 245 psi
 Outlet Water Temp; No Coils Excited: 34.5°C

	Coil or Coil Section	Current (A)	Voltage (V)	Outlet Water Temp (°C)	ΔT (°C)	R (Ω)	Comments
1	25 in. Total Top-Bottom	260.0	41.65	-	-	0.160	
2	25 in. Top--All Sections A ₁ -C ₂	260.0	20.84	-	-	0.0801	
2A	25 in. Bottom-- All Sections A ₁ -C ₂	260.0	20.80	-	-	0.0800	
3	25 in. Top Section C ₂ -C ₁	260.0	7.28	44.5	10	0.0280	R ₂₅ Trim Coil Contains 3 Coil Sections; See Fig. 7.
3A	25 in. Bottom Section C ₂ -C ₁	260.0	7.32	45.0	10.5	0.0282	
4	25 in. Top Section B ₂ -B ₁	260.0	6.67	43.0	8.5	0.0256	
4A	25 in. Bottom Section B ₂ -B ₁	260.0	6.66	42.5	8.0	0.0256	
5	25 in. Top Section A ₁ -A ₂	260.0	6.86	42.5	8.0	0.0264	
5A	25 in. Bottom Section A ₁ -A ₂	260.0	6.80	42.5	8.0	0.0261	
6	15 in. Total Top-Bottom	175.0	4.71	-	-	0.0269	
7	15 in. Top D ₁ -D ₂	175.0	2.28	35.5	1.0	0.0130	
7A	15 in. Bottom D ₁ -D ₂	175.0	2.30	36.0	1.5	0.0131	
8	6 in. Total Top-Bottom	300.0	4.10	-	-	0.0137	
9	6 in. Top E ₁ -E ₂	300.0	2.05	36.0	1.5	0.00684	
9A	6 in. Bottom E ₁ -E ₂	300.0	2.01	36.0	1.5	0.00671

R_{25} = 24.7 INCHES - MEAN RADIUS ; 12 TURN TOTAL ; 3 WINDING SECTIONS @ 4 TURNS ; MAX. OF 550 AMPERES.

R_{15} = 14.55 INCHES - MEAN RADIUS ; 3 TURN TOTAL ; MAX. OF 650 AMPERES.

R_6 = 5.95 INCHES - MEAN RADIUS ; 2 TURN TOTAL ; MAX. OF 650 AMPERES.

Fig. 7. Schematic of Trim Coils

E. Liner Installation

The cyclotron was shut down on April 1, 1964, allowed to cool, and then the dee structure and accelerator chamber were removed from the magnet gap. The liner installation was completed and the system readied for magnetic field tests on May 11, 1964.

Removal of the acceleration chamber facilitated the installation of the liners. Figure 8 shows the top liner prior to being positioned in the chamber. Figure 9 illustrates the top liner in the acceleration chamber,

120-8383

Fig. 8. Top Rf Liner Ready for Assembly

120-8386

Fig. 9. Top Rf Liner in the Acceleration Chamber

and the position of the electrical and water connections. In these two photographs, one can see the periphery and center disc spacers which are $1/2$ and 3 in. in diameter, respectively. Each disc is $3/16$ in. thick and contains a central hole of $1/4$ in. ID for the insertion of a $1/4$ in. hold-down screw. All spacers were baked into position with epoxy. Each liner was fastened to the 5 in. thick lids by means of $1/4$ in. machine screws.

Electrical and water connections to the trim coils was accomplished by the use of vacuum feedthrough bushings, as illustrated by Fig. 10A. A total of twenty bushings were required with all units being mounted on one common base (Type 304 stainless steel) which served as one vertical closure plate of the acceleration chamber.

A common water header at 250 psi pressure is used to supply cooling to each trim coil or trim-coil section. Electrical isolation is provided by rubber hoses on both the input and output cooling lines. The output water from each loop is directed into a Hayes, Shure Flow Model 2600, flow interlock. Soldered to the ends of each coil lead is a copper block (see Fig. 11) which serves as a connector for both electrical and water services, and also provides a means of measuring the outlet water temperatures. Interconnection of the matching coils of the top and bottom liners is accomplished with 4/0 welding cable.

All liner cooling is supplied by a common header at 80 psi, the output from each of the 8 circuits (4 per liner) being monitored by a Hayes Shure Flow interlock. A typical feedthrough bushing is shown in Fig. 10B.

Individual power supplies are used to energize each trim-coil set. The R_{25} and R_{15} sets are powered by Navy surplus MG units with a d.c. output rating of 110 V and 545 Amp. The long-term current regulation for each supply is 0.1%. Regulators of each supply are such that the current can be smoothly reversed. The R_6 set is powered by a solid-state supply rated at 6 V d.c. and 500 A. A regulator is not used and current variations are within 2% for a given setting.

The main cyclotron magnet has a long-term current stability of 100 ppm, and its center field coil constant is 42 G/A at 11.20 kG. This constant is about 0.92 G/A for both R_{25} coils, 0.23 for R_{15} , and 0.15 for R_6 . For the stated regulations, the effective field stability at 11.20 kG for each coil set as referenced to the main coil is about 20 ppm for R_{25} , 50 ppm for R_{15} and 70 ppm for R_6 .

Fig. 10. Feedthrough Bushings

A. Trim-coil feedthrough bushings with the following materials of construction:

- Item (a) Stainless Steel 304
- (b) Stainless Steel 304
- (c) Stainless Steel 310
- (d) Nickel-Iron Alloy (42% Ni-58% Fe)
- (e) Copper

B. Liner feedthrough with the following materials of construction:

- Item (a) Stainless Steel 304
- (b) Stainless Steel 304
- (c) 3/8-in.-OD Copper Tube

Fig. 11. Electrical and Water Connector for Trim Coils

F. Magnetic-field Measurements

Field tests were initiated May 11, 1964 and at first were limited to the determination of the magnetic and mechanical median plane and the measurement of the radial field contour at two azimuthal positions spaced 180° apart. Measurements were performed with the acceleration chamber at atmospheric pressure.

Nuclear magnetic resonance (NMR) equipment obtained from the original cyclotron field controller was used to measure the field perpendicular to the median plane. These endeavors established the existence of a 5/64 in. displacement between the mechanical and magnetic planes. This discrepancy was corrected by vertical positioning of the chamber until both planes were coincident.

Radial field contours were obtained by using an existing ballistic galvanometer (G.E. Model 32C249G73). At two azimuthal positions, 180° apart, the measured fields and required trim-coil currents agreed with calculations, and the accelerator was then readied for vacuum pumpdown.

On June 8, 1964, the accelerator was energized and deuterons ($B_c = 14.88$ kG) were immediately accelerated and extracted. All machine parameters were normal, except for a low extraction efficiency (10%). Many days later, subsequent beam-probe checks indicated the existence of a radial beam oscillation. At this time, it was decided that azimuthal field-measuring equipment had to be constructed immediately and that measurements had to be obtained with the acceleration chamber evacuated. To facilitate the task, instrumentation was developed around the existing ballistic galvanometer.

Azimuthal field measurements initiated August 19, 1964 immediately indicated the magnitude of the problem. With the trim coils de-energized, a first harmonic field dip of 45 G existed at a radius of 26 in.; this extended inwards into about 5 in. where the magnitude was about 5 G. In addition, a second field distortion was detected in the radial region from 20 to 26 in. At 26 in., a field variation of about 8 G occurred every 90° .

Subsequent mechanical checks indicated two faults. A 0.020-in. vertical motion occurred for both lids when the magnetic field was applied (chamber evacuated), and secondly, a lid scalloping effect existed with a minimum gap occurring at the positions of four mechanical support jacks. These jacks are spaced 90° apart and are located between each lid and pole tip. The scalloping effect accounted for the observed rhythmic field variation of 8 G. Increasing the number of jacks to 8, located at 45° intervals, reduced this variation to less than 4 G at the 26 in. radius.

The 0.020 in. lid shift was of concern because of the "working" effects that could possibly occur with time. The lids rest on a flat rubber gasket located in a circular channel of the acceleration chamber. A vacuum seal is obtained by numerous mechanical latches that force the lid down onto the gasket. When the field was applied, the force of attraction stressed these latches and allowed the lids to move towards the poles of the magnet; vacuum seal was not disrupted. This difficulty was overcome by tightening the 8 jacks with the chamber evacuated and the magnet de-energized; resulting lid motion was limited to <0.001 in. for the maximum operating fields. This correction did not eliminate the field dip of 45 G.

The cause of the main field distortion was related to the new 304 stainless steel plate used for mounting the feed-through bushings for both trim coils. This plate is one vertical side of the acceleration chamber and is located at a radius of about 37 in. Samples of the plate material were analyzed and found to be magnetic. It was concluded that the machining operations had created this magnetic state. Since the feed-through bushing seals had already been made, it was decided not to change the plate, but to correct the field dip by introducing iron shims in the region, both top and bottom, between each lid and pole tip. These shims, 4 in. in width and $1/32$ in. thick, were empirically located at a mean radius of 28 in. and were centered

about the line connecting the center of the plate and that of the cyclotron. When the field trimming was completed and the acceleration chamber

TABLE III. Maximum Azimuthal Field Variation

R (in.)	B _C = 14.88 kG (G)	B _C = 11.20 kG (G)
5	<1	<1
10	<1	<1
15	3	2
20	7	4
22	9	4
23	9	4
24	9	4
25	9	4
26	16	9

evacuated, the maximum azimuthal field variation was about 9 G at R = 25 in. for a 14.88 kG field (see Table III).

Coil-lead effects were determined by exciting all three trim coils at their required operating currents (R₆-175 A; R₁₅-175 A; R₂₅-260 A) with the main magnet de-energized. The measured effect was <0.9 G. Refer to Fig. 6 for an explanation of the positioning of the trim-coil leads.

G. Contour Measurements

Radial field contours were established by both NMR techniques and the use of a ballistic galvanometer. The NMR probe is about

0.5 cm long with an OD of 0.5 cm and contains a 1.0M aqueous solution of MnSO₄. In general, the probe was used to establish the absolute value of the center field B_C (R = 0) and the galvanometer with a flux coil of 845 turns, resistance of 154.5 ohms, and 0.59 in. OD was used to measure the field change vs radius as referenced to the center field B_C.

The field corrections provided by the trim coils were predicated by the criteria of maintaining the same value of the field index n as a function of radius for 11.20, 14.88, and 16.97 kG operation. Since

$$n = - \frac{R}{B} \frac{dB}{dR},$$

we have

$$\frac{n_1}{n_2} = \frac{B_2(dB/dR)_1}{B_1(dB/dR)_2} = 1$$

and

$$B_1/B_2 = \frac{(dB/dR)_1}{(dB/dR)_2},$$

or for the same but small incremental change in radius

$$\frac{B_1}{B_2} \approx \frac{\Delta B_1}{\Delta B_2}$$

If B_1 and B_2 are to be proportional for any given radius, then for the 11.2 kG contour

$$\frac{\Delta B_1}{\Delta B_2} = \frac{14.88}{11.20} = 1.327,$$

and for the 16.9 kG contour

$$\frac{\Delta B_1}{\Delta B_2} = \frac{14.88}{16.97} = 0.877.$$

With these constants, the ballistic galvanometer and associated instrumentation can be readily adapted to produce normalized field-contour data for quick and precise comparison. For example, the flux-coil carriage is indexed to fixed radial intervals of one inch. The indexing device triggers a light source from which a signal is directed into a phototube of the galvanometer circuit. The reference light "pips" are then transcribed onto the chart of the recording fluxmeter. The flux change between "pips" represents a $\Delta B/\Delta R$ measurement.

Now, the deflection of the ballistic galvanometer is given by

$$d = \frac{\Delta B}{k[1 + (R_c/R_s)]},$$

where k is the sensitivity of the galvanometer, R_c is resistance of the flux coil, and R_s is the shunt resistance placed across the galvanometer. To compare and match the B_2 contour directly to that of B_1 , one has

$$\frac{d_1}{d_2} = \frac{\Delta B_1 [1 + (R_c/R_s)]_2}{\Delta B_2 [1 + (R_c/R_s)]_1} = 1. \quad (1)$$

For ^3He and ^7Li , $\Delta B_1/\Delta B_2 = 1.327$ and 0.877 , respectively, and only the value of $(R_s)_2$ need be adjusted to satisfy the condition of Eq. (1). This normalizing process is independent of the galvanometer constant k , and with the proper setting of $(R_s)_2$, field contours can be visually compared with the standard 14.88 kG contour, and changes in the trim-coil currents can be made and quickly evaluated.

Field contours of each trim coil are given by Fig. 12. These data illustrate the permeability change of the magnet iron for the required operating levels and the relating effect on each trim-coil contour. Within the error of measurement, the R_6 contour is essentially unchanged for either 11.20 or 16.97 kG field levels.

Fig. 12. Field Contours of Trim Coils

The 11.20 kG contour (see Fig. 1) is corrected by the addition of the resultant fields of all 3 coils. Correction of the 16.97 kG contour is achieved by reversing the fields of the coils so that the effect is one of subtraction. In Fig. 13, the normalized corrected 11.20 and 16.97 kG contours and associated field-index values are compared with the accepted 14.88 kG contour.

To assist in the expedient establishment of the main central field B_C with the required set of trim-coil currents, a relation was established between the field between the lid and pole tip at $R = 26.5$ in. vs the B_C as measured by the NMR probe. In practice, the trim coils are first set to their proper values and then the current of the main magnet coils is raised until the NMR reading (at $R = 26.5$ in.) is of the correct value to give the desired center field. Throughout the operation of the cyclotron, the NMR signal as viewed by an oscilloscope gives a visual indication of field stability.

Fig. 13

Corrected Field Contours. Trim coil currents are as follows:

$B_C = 11.20$ kG	$B_C = 16.97$ kG
$R_6 = +175$ A	$R_6 = (-)75$ A
$R_{15} = +175$ A	$R_{15} = (-)250$ A
$R_{25} = +260$ A	$R_{25} = (-)515$ A

II. ^3He OPERATION

Within minutes after the establishment of the magnet-field contours of Fig. 13, an extracted $^3\text{He}^{2+}$ beam of several microamperes was obtained. Subsequent operation has achieved extracted beams in excess of $100\ \mu\text{A}$ with a deflector extraction efficiency of 35 to 45%. The measured energy of the beam was 32.4 MeV. With B_c increased to 11.55 kG, and the field trimmed accordingly, a projectile energy of 34.6 MeV has been obtained.

III. SYSTEM FOR RECOVERY OF ^3He GAS

The high cost of ^3He gas necessitates the use of a system to recover any gas not accelerated or trapped in the cyclotron and to provide its purification for reuse in the ion source. When the system construction was initiated, the cost of ^3He gas, \$1.50/cc at STP, was such as to dictate stringent design requirements, such as the minimization of the volumes associated with the pumps, valves, traps, and associated tubing. The present cost of ^3He , \$0.10/cc at STP, is sufficiently low so that a simpler and more flexible design might be employed. But even so, a recovery method is required because the cyclotron source requires a gas flow ranging from 5 to 10 cc/min, thus representing an additional operating cost of \$30 to \$60/hr.

On the basis of present costs, the recovery system to be described is overdesigned. But even so, a description is included for completeness and to establish operating feasibility. The design of this system was based upon the previous work of others.⁴⁻⁷

The complete unit is mounted on a cart and provides for a closed cyclotron pumping loop. The contained pumps replace the normal mechanical pump (Kinney--Model 8810) used with the two 16-in. oil diffusion pumps (DPI--MCF 5000) of the cyclotron. Any recoverable gas at the output of the diffusion pumps is circulated through the cart, repurified, and is available for use in the ion source.

The functions of the cart are almost fully automatic, thereby facilitating continuous accelerator operation with a fairly constant pressure at the input to the needle valve of the ion source.

A. Pumping System

A blower-type pump serves as the main backing for the existing cyclotron diffusion pumps. Its output is connected to one of two alternative gas paths; each path includes a backing pump for the blower and an associated oil trap. Either gas path may be serviced while the other is in operation. The pumped gas is directed into one of two alternative activated-charcoal traps cooled with liquid nitrogen. The purified gas is then

available for direct use in the ion source. The use of two purification traps in the system permits one to be reactivated while the second performs its recovery function.

The total gas inleak into the cyclotron tank (85×10^3 liters) is about 1 cc/min STP of air and 5 to 10 cc/min STP of ion-source gas. The 1 cc/min inleak is composed of approximately 0.3 cc/min from the cyclotron vacuum envelope plus 0.7 cc/min from the external beam-transport system. The tank must function at about 5×10^{-6} Torr, with the gas flow at the output of the diffusion pumps being about 8.5 liters/sec at 1.5×10^{-2} Torr. This load is handled by a Heraeus Model VPR-150 blower with a pumping speed of about 25 liters/sec at this forepressure. In turn, this is backed by an Edwards Model ED-150 compound mechanical pump. The Heraeus VPR-150 is inherently leak-tight and did not require any modifications. The Edwards pump is a replacement for a Heraeus Model E-12 which was originally installed in the system. It must be noted that this Model E-12 was plagued with constant shaft-seal leaks and it was next to impossible to obtain spare parts. For 18 months of regular service, both the VPR-150 and the ED-150 pumps have given excellent performance.

B. Valving and Gas Flow

A system of manual and solenoid operated valves (see Fig. 14) is provided to accomplish the following:

1. System isolation from the cyclotron. The cart input valve S-1 is cross-interlocked with the main cyclotron fore-valve S-2 to prevent simultaneous pumping by both the cart and the cyclotron backing pump. Excessive diffusion-pump forepressure, 1.5×10^{-2} Torr, due to either an air leak or gas burst in the cyclotron tank will automatically close the cart input valve S-1, output valve S-3, and open the fore-valve S-2 to the cyclotron forepumps.
2. Individual component isolation for control of gas flow through the chosen backing pump, No. 1 or 2, and charcoal trap, No. 1 or 2, as well as selective pumping by the auxiliary pump for cleanup purposes.
3. Transfer of excessive gas (pressure buildup) from the input or output of the charcoal traps by means of pressure-relief valves (PRV) to one of two storage tanks from which the gas can later be recovered. The PRV valves are adjustable over a nominal pressure range from 3 to 15 psig, and the setting is dictated by the ion-source requirements.
4. Supply fresh gas during the operation of the cyclotron.

Fig. 14. Recovery System for ^3He

A typical path for gas flow would be through valve S-1, the blower pump (VPR-150), valve V1, backing pump (ED-150) No. 1, valves V3 and V5, charcoal trap No. 1, valves V6 and S-3, cyclotron needle valve, and finally the ion source. Alternative backing pump and charcoal trap flow paths may be substituted as previously mentioned.

At each pertinent point in the flow path there are located either Bourdon or thermocouple-type pressure gauges for local indications. In addition, the input and output pressures of the cart are remotely monitored by a thermocouple gauge and pressure transducer (Bourne Model 426), respectively.

C. Traps

Each path for gas flow contains two traps. The first is located at the discharge side of the ED-150 pump to collect the backstreaming oil. Purification of the gas is accomplished by the second unit, which consists of activated charcoal cooled with liquid nitrogen.

The oil trap is a simple assembly in which the gas output from the ED-150 is directed through a group of 18 parallel-path copper tubes, of 1/16 in. ID and 3 in. long, with water circulated about these collectors. An 18 mesh bronze diffusing screen, several layers thick, is located at both the input and output of the assembly.

The charcoal trap is cooled with liquid nitrogen. Its effectiveness as a collector for oxygen, nitrogen, hydrogen, and hydrocarbons at atmospheric pressure is well known. The trap consists of a stainless steel chamber containing approximately 100 cc of Columbia activated charcoal. The input and output gas line seals are water cooled to prevent their being damaged during trap bakeout. An external Nichrome heater surrounds the chamber and is capable of raising its temperature during bakeout to about

600°C. A nickel radiation shield is utilized between the heater and the surrounding liquid nitrogen Dewar.

TABLE IV. Typical ^3He Analysis
(Mound Laboratory)

Date	$^3\text{He} + ^4\text{He}$ (%)	^3He (%)	H_2 (%)	H_2O (%)	N_2 (%)
4/64	99.79	99.57	0.03	0.09	0.09
9/64	99.96	99.29	0.01	-	0.03
2/65	99.95	99.80	-	0.06	0.14
4/65	99.76	99.59	0.14	-	0.09
12/65	99.98	99.73	-	-	0.02

D. Performance

The initial gas charge for the entire system is about $2\frac{1}{2}$ liters. Table IV shows typical gas analyses obtained from the supplier, Mound Laboratory.

Tritium content $< 1 \times 10^{-9}\%$.

Required set-up time will vary from $1\frac{1}{2}$ to 2 hr

dependent upon the previous history of operation. The flow of gas into the ion source is remotely monitored by a Hastings-Raydist Model LF-10 flow transducer. Flow adjustment is achieved by the use of a remotely driven Vactronic bellow-sealed needle valve as well as by the control of the cart's output pressure, which does not exceed 4 psig.

Since the initial operation of the system in 1964, about 1000 hr of ^3He acceleration has been compiled. Initial difficulties were numerous, such as leaks in the E-12 pumps, and excessive consumption of liquid nitrogen. These faults have been corrected, and presently the system performs satisfactorily. External beam currents of $100 \mu\text{A}$ can be achieved readily.

E. A Suggested Alternative Recovery System

Since the initiation of the construction of the recovery system described above, there have appeared on the commercial market certain components that suggest a simpler and less expensive design. A conceptual layout of this system is set forth by Fig. 15. Two prime components are required, a helium diffusion cell and a high-pressure compressor. The diffusion cell (Electron Technology Inc., Model ET1-SLM-1), which is capable of purifying helium to an extremely high degree (impurities < 1 ppm), is now available. The cell requires input pressures of 200 psig or greater, and this would be provided by a clean, high-pressure diaphragm compressor (Pressure Products Industries, Inc.--Series 1000).

Fig. 15. Conceptual Design of a ^3He -recovery System

The cyclotron diffusion pumps would be backed by a blower-forepump combination as used in the present system. The output of the forepump would charge a small helium-tight gasometer, of the type used in liquid-helium cryostat recovery systems. Upper and lower limit switches on the gasometer would control the operation of the compressor and associated valves. The high-pressure gas would then be used to fill "contaminated gas" storage cylinders for later purification. At some convenient time, the high-pressure gas would be fed into the helium diffusion cell, the output of which is either stored in "purified" gas cylinders or fed directly through a regulator to the ion source. A simple auxiliary vacuum pumping system would be provided for initial system cleanup. A compressor bypass valve is needed to charge the evacuated "contaminated gas" cylinders to atmospheric pressure directly from the gasometer. This feature insures proper operation of the compressor.

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REFERENCES

1. W. J. Ramler and G. W. Parker, The Argonne 60-inch Cyclotron, ANL-5907 (Feb. 1959).
2. Obtained from F. Markley of ANL.
3. R. J. B. Hadden and W. Spittle, The Effects of Proton and Neutron Irradiations on an Epoxy Resin Vacuum Chamber Proposed for the Harwell 7 GeV Proton Synchrotron, AERE A/R 2690, Harwell, Berkshire (1959).
4. D. N. Kundu, T. W. Donaven, M. L. Pool and J. K. Long, Nuclear Reactions with 21-MeV ^3He in a Cyclotron, Phys. Rev. 89, 1200 (1953).
5. K. E. A. Effat, J. H. Fremlin, A Circulating System for ^3He , J. Sci. Instr. 32, 363 (1955).
6. J. Ise, Jr., R. V. Pyle, D. A. Hicks and R. M. Main, The Production of 340 MeV Deuterons by ^3He Stripping, Rev. Sci. Instr. 25, 437 (1954).
7. H. E. Wegner and W. S. Hall, ^3He Recirculation and Purification System for a Cyclotron Ion Source, Rev. Sci. Instr. 29, 1100 (1958).