ORNL-3325
UC-20 – Controlled Thermonuclear Processes
TID-4500 (20th ed., Rev.)

ENGINEERING FEATURES OF DCX-2

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THERMONUCLEAR DIVISION

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ABSTRACT

The DCX-2 is a large, complex experimental apparatus. Its aim is the generation of a hot, dense plasma by the injection and dissociation of 600-kev hydrogen molecular ions in a magnetic-mirror field. For facilitating this process, the molecular ions are given a long path in the machine, and the ion-pumping action of the plasma is used to maintain the vacuum. The major component systems of the apparatus are the ion source and accelerator, high-voltage power supply, magnet system, beam-injection duct, vacuum system, and dissociating arc. This report describes the design, construction, and performance of each component system, the constructional features not peculiar to any one component, and the instruments and techniques available for plasma study.

INTRODUCTION

The DCX-2 apparatus admirably demonstrates the complexity which results when an idea for an experiment is translated into an apparatus. The initial concept contains only the following points: A beam of 600-kev hydrogen molecular ions is injected into and dissociated in a magnetic-mirror machine so as to form a hot, dense plasma. For facilitating this process, the molecular ions are given a long path in the machine, and the ion-pumping action of the plasma is used to maintain the vacuum. Finally, eventual experiments with a reacting deuterium-tritium plasma are contemplated.

The resulting apparatus is shown in Figs. 1 and 2 and is described in detail in the sections to follow. The physical background and related calculations are given in refs 1 and 2. The apparatus is sufficiently complex that there is considerable interrelationship between the various components. This produced numerous occasions of interlocking design considerations, perhaps more than will be evident from the following description.

DCX-2 first took form as the result of design studies which began in the spring of 1959.[3] A proposal[4] containing a fairly complete system design was submitted to the AEC on March 4, 1960,

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*Now at Jet Propulsion Laboratory, Pasadena, Calif.

[1]P. R. Bell *et al., The DCX-2 Program of Plasma Accumulation by High Energy Injection,* presented at the Conference on Plasma Physics and Controlled Nuclear Fusion Research (IAEA), Salzburg, Austria, Sept. 4–9, 1961 (paper No. CN-10/190).

[2]W. F. Gauster *et al., Calculations of Ion Trajectories and Magnetic Fields for the Magnetic Trapping of High Energy Particles,* presented at the Conference on Plasma Physics and Controlled Nuclear Fusion Research (IAEA), Salzburg, Austria, Sept. 4–9, 1961 (paper No. CN-10/191).

[3]A Livermore group conducted a study which resulted in a quite similar design [F. C. Gilbert *et al., High-Energy Molecular Ion Injection Into a Mirror Machine,* UCRL-5827 (Feb. 1960)].

[4]P. R. Bell *et al., Proposal for a Thermonuclear Experiment Involving Injection of Molecular Ions at 600 kev, Dissociation by Multiple Passes Through an Arc, and Exponentiation Upon the Resulting Trapped Atomic Ion Population,* ORNL CF-60-1-73 (Mar. 4, 1960).

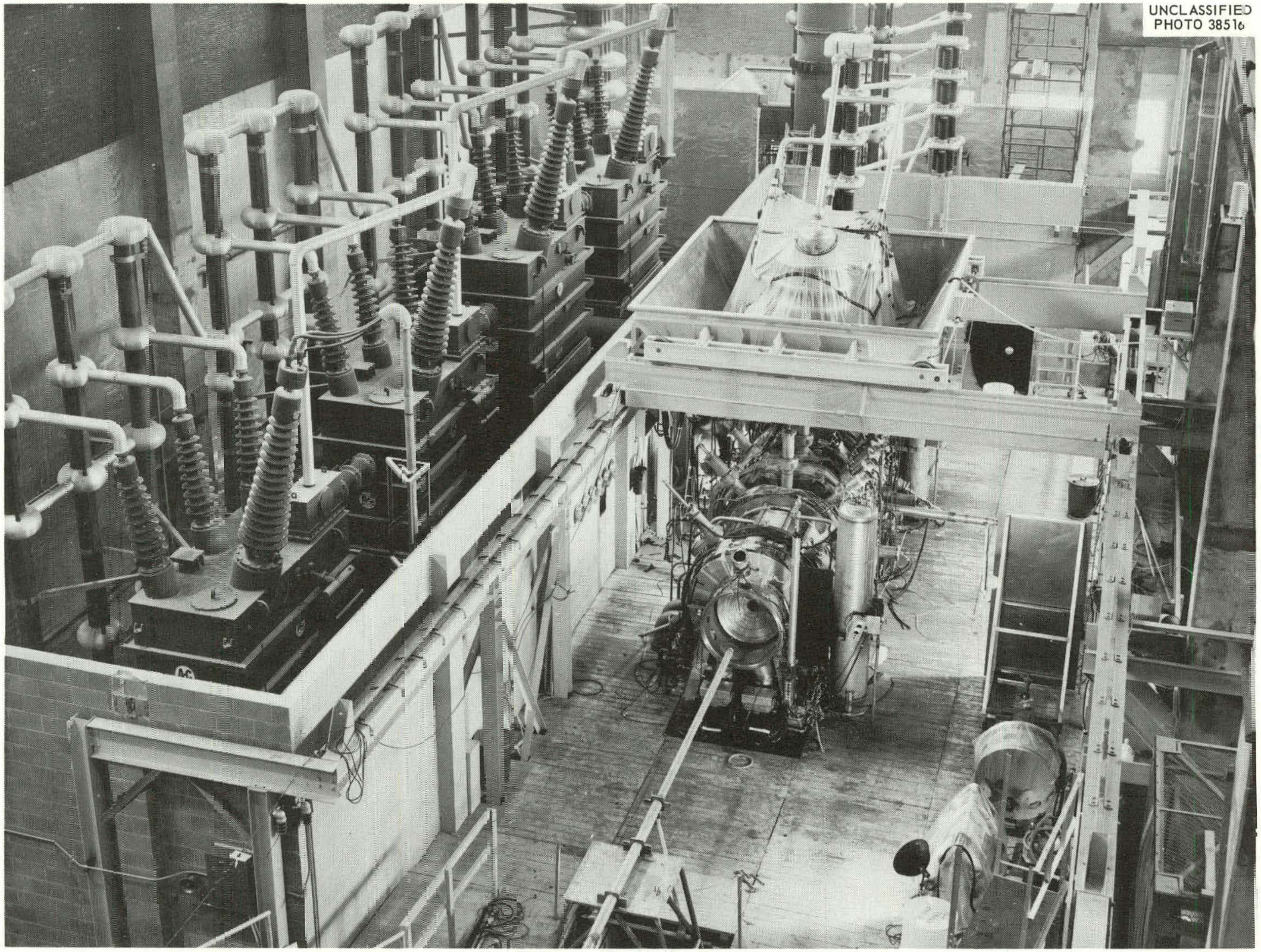

Fig. 1. DCX-2 and High-Voltage Supply.

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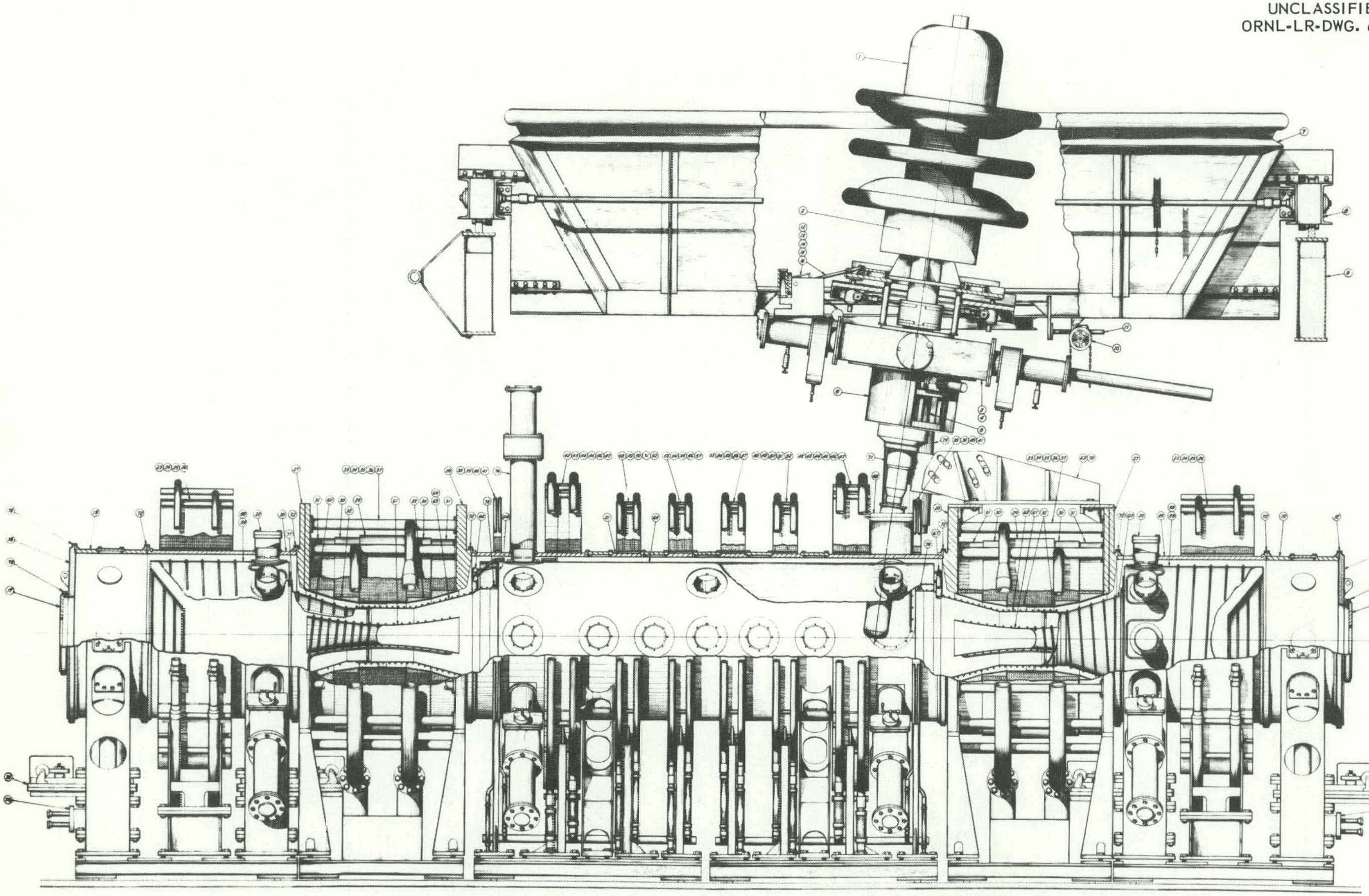

Fig. 2. Cutaway Pictorial Drawing of the DCX-2 Apparatus.

and reviewed at a meeting of personnel from the major Project Sherwood sites on March 22, 1960. Approval for its construction was granted in August 1960, at which time a rather complete conceptual design was submitted for detailed engineering. Except for the accelerator, magnet, and injector duct (snout), the engineering was accomplished by the Y-12 Engineering Division under the technical supervision of members of the Thermonuclear Division. Such supervision extended, where possible, only to those aspects of the design that were intimately connected with the prospective experiments. The Division's Accelerator Group developed and tested the accelerator and ion source. The Engineering Sciences and Engineering Services Groups of the Division designed the magnet coils and the snout. The H. K. Ferguson Company installed most of the apparatus and related utilities. Construction of vacuum, magnet, and accelerator components was completed in the fall of 1961. The injector duct was completed a few months later, and the first beam was introduced into the machine on January 24, 1962.

DCX-2 cost 2 million dollars, including certain operating costs of the Division during construction and preliminary operation, but not including the purchase of the generators or the high-voltage power supply.

June 1962 marks the transition between the shakedown and serious plasma experiments. The shakedown experiments have not only shown that all the components appear to work as designed but have already yielded some interesting and highly suggestive plasma phenomena.

The authors are greatly indebted to the members of the various groups who participated in the design and construction of DCX-2, and to many interested consultants and members of the Division for helpful discussions and advice. At the end of this report, the acknowledgments are collected by section. In addition, we wish to extend our special thanks to A. Simon, whose original analysis played a major role in designing the machine; to T. K. Fowler, for continued theoretical assistance and guidance; and to A. H. Snell and E. D. Shipley for unfailing encouragement and support.

ION SOURCE AND ACCELERATOR SYSTEM

Several hundred milliamperes of injected molecular ions may be required to produce burnout and the resulting high-density high-energy plasma hoped for in DCX-2. Because of the requirement of a long path and the limitations imposed by the size of the injection duct, the injector must produce this current in an intense well-organized beam. Since such a beam had not been produced anywhere, an accelerator-development program was necessary. This program has been successful.

Space-charge forces are responsible for the major difficulties encountered in making a high-intensity beam. These forces are most troublesome in places where the ions are traveling slowly. For this reason, it was decided to accelerate the beam to full energy as quickly as possible and to forego focusing and mass separation at low energy. Acceleration takes place in four equal voltage increments over a total distance of about 15 in. (Fig. 3.) The only lens at present is a magnetic solenoid (6-in. aperture and up to 2×10^5 ampere turns) immediately below the accelerator tube and 100 in. above the point of entry into the DCX-2 field.

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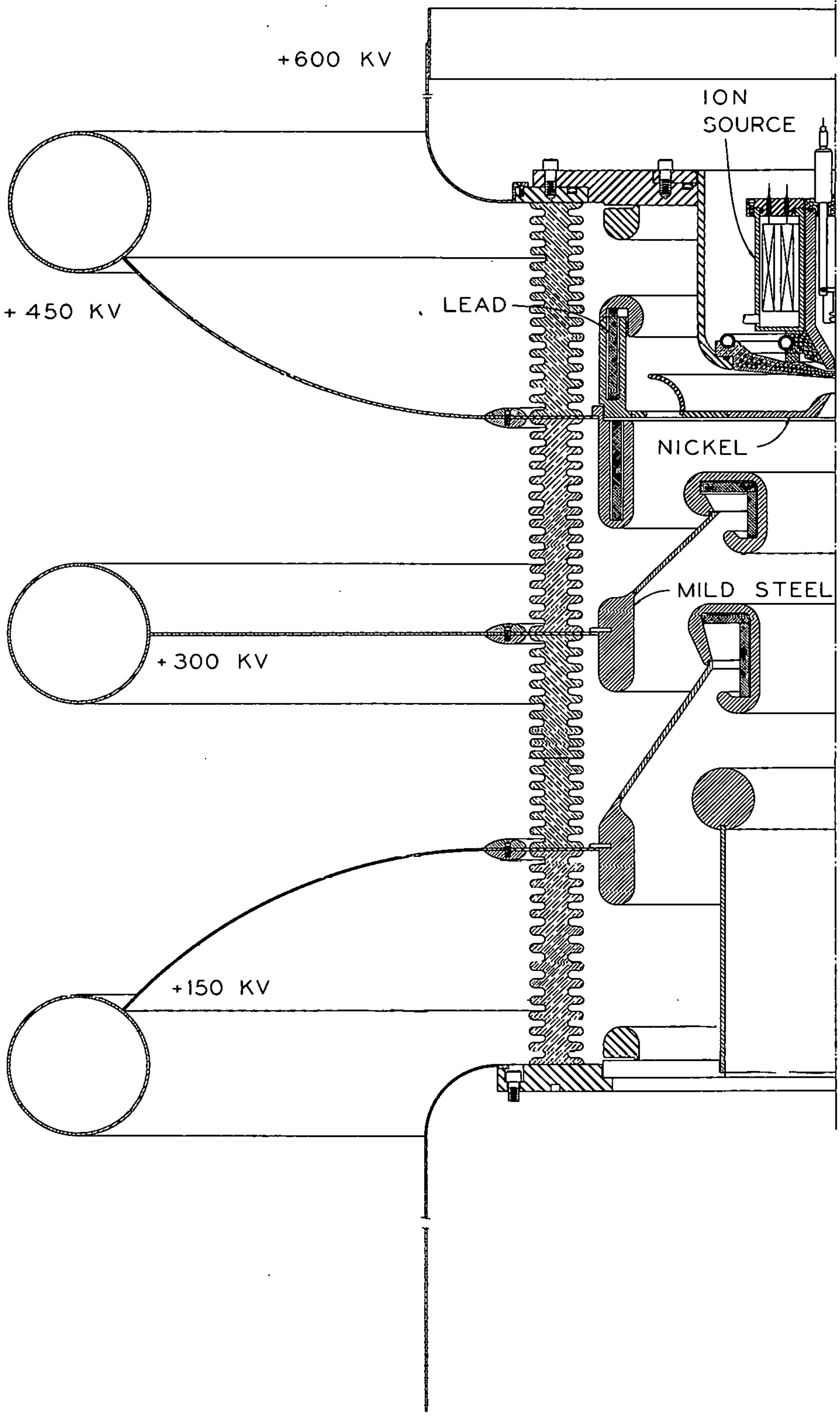

Fig. 3. Accelerator Tube.

The beam below the lens is neutralized by trapped electrons. Thus, the ion trajectories, being unaffected by space-charge forces, are straight lines. The ion source produces not only the desired molecular ions but also protons and H_3^+ ions. A typical set of beam trajectories is shown in Fig. 4. Since the focal length of the solenoid is proportional to ion mass, the three components emerge from the lens at different angles. It is possible to insert another lens at 50 in. which, with the removal of the neutralizing electrons, will permit greater control of the divergence angle of the beam at the channel exit.

The ion source is the duoplasmatron of von Ardenne,[5] modified to withstand dc operation at more than twice the previous maximum allowable arc current. Studies were made in order to determine the influence of source parameters on ion species produced. By variation of these parameters it is possible to make H^+, H_2^+, or H_3^+ predominate. A source with a 0.2-in. exit aperture produced[6] 350 ma at 70 kv. The maximum current limitation is understood, and it scales as expected with the $\frac{3}{2}$ power of the extraction voltage, indicating the availability of more than an ampere in the injector with extraction at 150 kv.

A current of 210 ma at 615 kev has been produced by the injector, with an estimated 60% consisting of H_2^+ ions. At the time of test, current was limited to this value by external voltage breakdown resulting from x-ray ionization of the air. More recently, lead shielding was added inside the tube, which should reduce greatly the external x-ray flux. Careful electrode design resulted in a reduction of voltage-cleanup time to less than 15 min.

The design of the tube is such that no appreciable ion current strikes the electrodes, and the electron loading results only from ionization of residual gas above the lens. Electron loading and attendant x-ray production are reduced by the very high gas efficiency of the source (greater than 90% at design current) and by the large conductance for gas flow in the tube.

A program is under way for a detailed study of "quality" (product of focused-spot size and convergence angle) in these intense beams. All that can be said at present is that, by visual observation and the use of probes swept through the beam, a 100-ma H_2^+ component has been seen to converge to a diameter of less than 0.5 in. about 80 in. below the lens. Under these conditions the source-spot magnification was 1.6, the effective source diameter was about 0.14 in., and the diameter of the beam in the lens was 3.9 in. The smallest crossover diameter expected, therefore, is 0.22 in.

The system was designed originally with two lenses to permit an unneutralized beam of 400 ma to be passed through the injection channel. First tests of a solenoid-lens-focused system showed, however, that neutralization was automatically produced at the lowest pressure available (2×10^{-6} mm Hg) unless electrons were extracted intentionally by externally applied voltages. Consequently, only one lens is installed on DCX-2.

An additional phenomenon, not yet understood, is the failure of these intense neutralized

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[5]Manfred von Ardenne, *Tabellen der Elektronenphysik, Ionenphysik, und Übermikroskopie*, Band I, VEB Deutscher Verlag der Wissenschaften, Berlin, 1956.

[6]G. G. Kelley, N. H. Lazar, and O. B. Morgan, *Nucl. Instr. Methods* **10**, 263–71 (1961).

beams to produce ion optical crossovers which are symmetric in the direction of flow. Apparently a violent scattering takes place at high current densities, making it appear that the beam vanishes below a crossover. This phenomenon has a profound effect on the design of ion optical systems for intense beams.

A pumping manifold is provided between the lens and the shielded duct to remove the gas from the unwanted components of the beam (H^+ and H_3^+) after they have struck the walls of the channel. Two filaments evaporate titanium onto the surface of a copper liner. A shield prevents titanium atoms from entering the beam. A liquid-nitrogen-trapped 10-in. oil diffusion pump keeps the residual gas pressure at about 5×10^{-8} mm Hg. The low pressure in the manifold (about 3×10^{-6} mm Hg at an ion current of 100 ma) and the low conductance of the channel result in a negligible gas flow into the plasma region. Mutually perpendicular pairs of coils in the manifold are provided to compensate for stray field penetration and slight misalignment.

An additional factor which had to be considered in the design of the injector is the stray field from DCX-2, which is of the order of 100 gauss at the accelerator. The use of ferromagnetic electrodes and of additional cylindrical shields along the path of the beam reduced the field to the acceptable value shown in Fig. 5.

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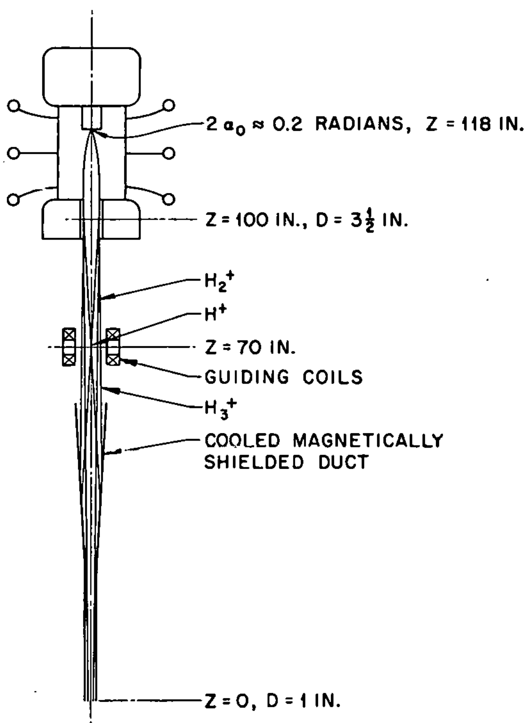

Fig. 4. Beam Envelopes.

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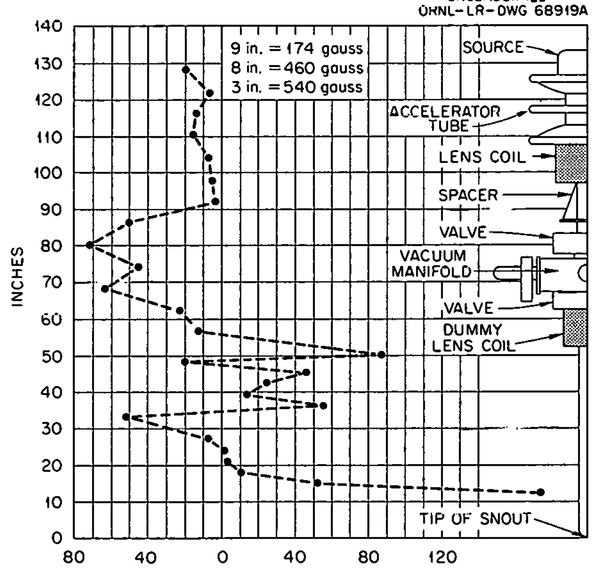

Fig. 5. Transverse Magnetic Field Along the Path of the Beam.

The angle of injection of ions into the plasma region is an important parameter determining path length. The accelerator is mounted on a platform which may be tilted about an axis passing through the point of entry into the main vacuum tank, translated along the axis of the machine, and raised and lowered by means of jack screws. This structure, surrounded by a tub lined with 10 tons of lead for x-ray shielding, is mounted on a bridge crane and may be moved completely clear of the main vacuum tank.

Power supplies and beam-pulsing equipment are mounted on a platform on top of the 600-kv isolation transformer. Meters are read in the control room by a closed-circuit TV system, and the source is controlled by pneumatically operated Variacs. The source is pulsed by gating the arc current through a parallel array of vacuum tubes. A crater lamp transmitter, at ground level, and a photomultiplier receiver permit gating the beam on or off in less than 2 μsec.

HIGH-VOLTAGE POWER SUPPLY

The high-voltage power supply, built by Allis-Chalmers Manufacturing Company, is rated at 600 kv and 1 amp and is designed to withstand repeated short circuits. It is a four-stage cascade arrangement of silicon rectifier bridges with staggered Y and Δ transformer connections to give a ripple frequency of 720 cps. The internal supply impedance is about 5×10^4 ohms with a 0.0125-μf filter, followed by an additional 1.4×10^4 ohms. The voltage may be controlled by coarse and fine steps in increments of 2300 v.

Protection of the supply and load is accomplished in the following ways:

- Overload protection on the ac primary
- Differential-current comparison of power-supply output and input currents
- Operator-adjustable load overcurrent level
- Differential comparison between output voltage and current in the voltage divider supplying the accelerator tube (to detect electrode-electrode discharges)

MAGNET SYSTEM

Present Configuration

DCX-2 has a magnetic-mirror configuration provided by a pair of mirror coils and five pairs of supplementary coils. Flexibility has been a watchword throughout the design of the machine, and the present coil arrangement, while exceedingly specialized, can be modified drastically as the experimental requirements evolve. The mirror ratio, 3.3, was set as high as was practical in order to facilitate the plasma's ion-pumping action and with an eye toward eventual reacting-plasma experiments.

In the present configuration, mirror coils are 4 m apart, and the central chamber is 1 m in diameter. The useful magnetic volume is thus about 3 m^3. The scale of the machine was set by a compromise among the following requirements:

- Larmor diameter (of 300-kev protons) small compared with characteristic length over which the field changes significantly (an empirical rule is that the orbit circumference be less than 1/7 the distance between the mirrors)

- Need to contain alpha particles from D-T reactions and desire to permit injection of 900-kev D_3^+
- Available power, 21 Mw
- Minimum plasma volume per unit length (this scales the amount of H_2^+ beam necessary for burn-out)
- Desired H_2^+ path length in excess of 10 m

The resulting scale was such as to yield quite modest power densities in the various coils. It was thus decided to make the design as conservative and trouble-free as possible and to use hollow copper conductors of rectangular cross section. The coils consist of spirally wound pancakes stacked together. The mirror-coil support spool was made a section of the wall of the vacuum chamber. The other coils have no supplementary support pieces. Many of the construction features are shown in Fig. 6.

Requirements

In the initial experiment a long molecular-ion path, or alternatively a large number of passes through a dissociating arc, is achieved by injecting the ions into a helical orbit with very fine pitch. The beam is injected through a magnetically shielded channel near one of the mirrors. After traveling the length of the machine and reflecting from the opposite mirror, the undissociated particles return and strike a target on the injection duct. The injector is inclined along the axis of the machine at such an angle that injected ions will just miss the duct housing after their first revolution in the magnetic field. The injection point is in a region of slightly reduced field, and the orbit pitch becomes finer as the ions move into the uniform field which extends over the central region of the machine.

Orbit calculations led to the requirement that the field on axis be uniform to within a few parts in 10^4 over a length of about 1 m. The on-axis field at a point opposite the injection point had to be reduced from this central-field value by 1.26%. The actual field requirements are based on a proper averaging over the particle orbit; for design purposes they have been translated into equivalent field variations on the machine axis.

In order to give maximum access for experiments the additional requirement that gaps between coils be at least 7 in. was imposed.

Presuming successful operation of the apparatus with hydrogen, it is desired that it be useful without appreciable modification for generating reacting thermonuclear plasmas of deuterium and tritium. Thus, an additional magnet-circuit requirement was that the coils could be reconnected with twice their initial resistance in order to operate at double voltage and double power. Thus, the 12-kilogauss field corresponding to operation with hydrogen requires 10.5 Mw, and the reconnection (see Fig. 7) makes available a 17-kilogauss field requiring 21 Mw for deuterium operation. Of course there may be reasons other than deuterium

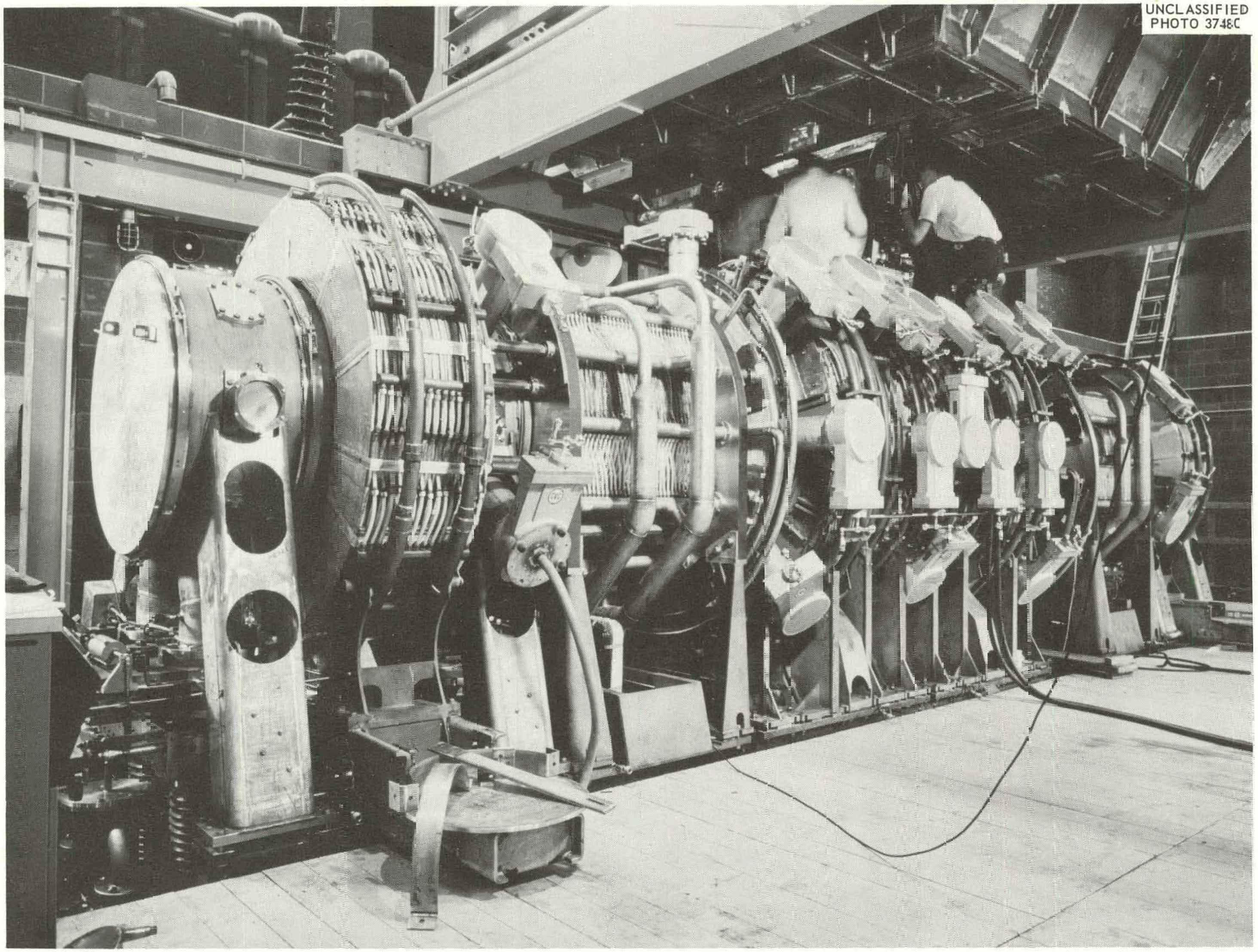

Fig. 6. DCX-2, Showing Coils.

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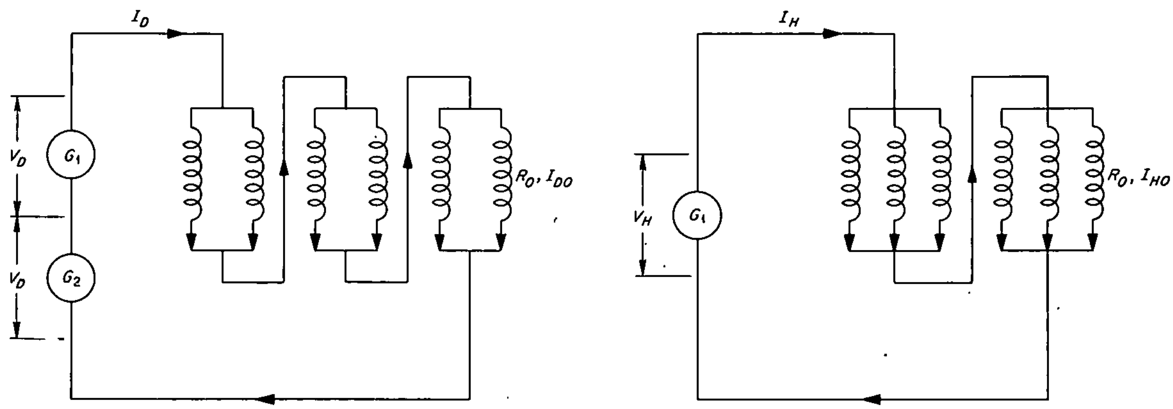

$$R_D = \tfrac{3}{2} R_O$$
$$I_D = 2\,V_D/R_D = \tfrac{4}{3}\,V_D/R_O$$
$$I_{DO} = I_D/2 = \tfrac{2}{3}\,V_D/R_O$$
$$2P_D = 2V_D \times I_D = \tfrac{8}{3}\,V_D^2/R_O$$

"*D*-OPERATION"

$$I_{DO}/I_{HO} = \sqrt{2} = \frac{\tfrac{2}{3}\,V_D/R_O}{\tfrac{1}{2}\,V_H/R_O} = \tfrac{4}{3}\,V_D/V_H$$
$$V_D/V_H = \tfrac{3}{4}\sqrt{2} = 1.061$$
$$I_D/I_H = \frac{2\sqrt{2}}{3} = 0.943$$
$$P_D = V_D I_D = V_H I_H = P_H$$

$$R_H = \tfrac{2}{3} R_O$$
$$I_H = V_H/R_H = \tfrac{3}{2}\,V_H/R_O$$
$$I_{HO} = I_H/3 = \tfrac{1}{2}\,V_H/R_O$$
$$P_H = V_H \times I_H = \tfrac{3}{2}\,V_H^2/R_O$$

"*H*-OPERATION"

Fig. 7. Coil Connections for Deuterium and Hydrogen Operation.

operation for going to the higher field. Finally, calculations indicate that the generator thermal time constants permit operation for brief periods at 42 Mw, giving a 24-kilogauss central and an 80-kilogauss mirror field.

The installed synchronous-motor-generator complement consists of four 3-Mw, two 2.5-Mw, and two 1.75-Mw sets. For hydrogen operation the mirror coils will be fed by two series-connected 3-Mw (8600 amp at 350 v) sets. Three pairs of coils between the mirrors (inboard boosters) will be supplied by one 2.5-Mw set and the pair outside the mirrors by the other 2.5-Mw set. (The outboard coils actually require only 1.75 Mw for hydrogen operation.) A fifth pair of coils, one in each region of field dip between the mirror coil and the adjacent inboard booster, requires only 0.25 Mw and is fed by a supplementary generator.

The requirement that the three pairs of inboard booster coils, which play a critical role in achieving the desired high degree of field uniformity, be fed by one generator imposed a strong constraint on the coil design. Maintenance of the proper current in the injector-snout coil required that it be connected in the same series circuit. Finally, careful attention was given to pairing the various coil-connecting leads so that they would produce essentially no stray field.

Design

The synthesis of a set of coils to meet these very stringent criteria was carried out by the Engineering Sciences Group with the computational help of Mozelle Rankin and G. R. North. The calculations are described in ref 2. For each assumed coil configuration a set of current densities which would give an "optimal field" was calculated. For design purposes this optimal field was defined as one which minimized the field's rms deviation from its average over a certain axial length. Configuration adjustments were made in a direction to bring the respective current densities in line with what could be achieved by the proposed power-supply system.

In the course of the work it was found that the three pairs of inboard booster coils could be given approximately the same current density and radial dimensions if one pair was approximately 50% wider than the other two. A second-order approximation to uniformity was obtained by adjustment of the outer diameters of the three pairs of coils. A final adjustment was made by supplying resistive shunts for each coil section which divert up to 5% of the current. In order to provide operational fine control on the field shape, there was connected to the central section of each coil a low-voltage rectifier supply, which could add as much as 80 amp in that section. The shunt resistors were all set so that the expected current from each low-voltage supply lay in its midrange.

Adjustment of the field dip is achieved mainly by varying the current in the dip coils. To each current in the dip coils there corresponds a new set of currents in the other three pairs of inboard coils which will produce an optimal uniform field region. The relationship is linear, and the system has therefore been designed to provide automatic variation of the currents in the fine-control power supplies as the dip-coil current is varied.

Transistorized feedback networks are used on each generator to provide current stability to within one part in 10^4. These are also used as current-control networks. Generator currents can be adjusted individually or collectively.

Details of Construction

The coils are made of OFHC copper, with stringent finish and dimensional tolerances. The insulation is 0.002-in. Mylar tape with 0.0015-in. thermosetting adhesive on one side. It is wound half-lapped on individual conductors. The coils in the first set were taped lengthwise as they were being wound. Difficulty with wrinkling on the inside turns led to the development of a novel taping machine for spiral application of the tape at a point between the supply drums and the winding mandrel.

Two of the coils were wound in the electrical shop of the Y-12 Plant. The remainder were wound by the General Electric Company, Schenectady, to the Division's design specifications. Their total weight is about 33 tons.

In order to make the length of each water-cooling passage less than the conductor length in a pancake, each pancake is made up of seven conductors. This "seven-in-hand winding" arrangement gives, for each pancake, seven parallel water paths and one series electrical connection. In the coil design, this permitted adjusting the outer diameter of each coil in increments of one turn except where this led to a multiple of seven turns.

An existing closed-circuit demineralized-cooling-water supply delivers water at 200-psi differential pressure. Total flow capability of the system is 11,400 gpm.

In order to provide protection against the absence of water flow in one of the 908 water paths, a thermal switch set to open at 95°C is mounted on the exit side of each path. The action of such a switch turns off the magnet power supply and turns on a light on an indicator panel. Because of the coil inductance, it is necessary to provide protection against very large voltage surges in the event of internal current disturbances. Therefore, across each coil section is a nonlinear (Thyrite) resistor whose current-voltage characteristic is exceedingly steep, limiting the voltage to 150 v. The Thyrite resistors also protect the coils against overvoltage during shutdown.

In addition, there are three 10-turn coils wrapped around the mirror and inboard coils, which sense any rapid field changes (spits). The output of these pickup coils is summed and monitored and can be used to shut off the generators when the signals exceed a certain amplitude.

An overcurrent relay is activated at currents 50% in excess of normal. It switches into the coil circuit a resistor with twice the coil resistance. All other emergency shutdowns drop the generator current by removing the field excitation.

Connections between the generators and magnets are provided by 1,000,000-circular-mil stranded cables encased in rubber jackets with demineralized water cooling. Each such cable has a conservative rating of 4500 amp. Jumpers and distribution leads are made of 0.375-in.-square hollow copper conductors.

The magnetic forces acting on the mirror coils are taken up by the central section of the vacuum tank. Adjustable mechanical stanchions support the supplementary coils against the axial forces acting upon them. These forces range up to 98 tons under normal operating conditions and up to 350 tons under certain fault conditions. The inboard booster coils, which were found to be somewhat compressible, required tie bars to preload them against "breathing" during operational cycles. Further construction details are given by Potts and Gauster.[7]

Performance

So far the coils have operated without any failure requiring a major shutdown. During testing and subsequent operation the following faults have been found and repaired:

- Several leaks in the welded joints which electrically connect individual water paths
- Shorts at terminal points (repaired without removing the coils)
- Internal shorts in the mirror coils which have not yet been repaired. These caused a loss of a small fraction of the total ampere turns, and operation is proceeding with symmetrically located turns shorted externally

[7] J. F. Potts, Jr., and W. F. Gauster, *Current Engineering Status of the ORNL Experimental Devices for CTR*, presented at the Fourth Symposium on Engineering Problems in Controlled Thermonuclear Research, Fontenay-aux-Roses, France, Apr. 17–20, 1962.

The most crucial tests of the magnet system were those in which the adjustment for uniform field was attempted. The culmination of this effort was the achievement, over a 1.2-m length, of a 3-gauss peak-to-peak field ripple out of 12 kilogauss. Although further tuning may lead to an even higher degree of homogeneity, the above figure is regarded as eminently acceptable.

BEAM-INJECTION DUCT

The magnetically shielded duct (snout) through which the molecular-ion beam is injected has the rather severe requirement that it shield the internal channel from an external magnetic field of 12 kilogauss while disturbing the external, very uniform field to a negligible degree. The internal field may exceed 75 gauss only over short distances. Orbit calculations on trapped protons show that the external disturbance should be less than $\frac{1}{2}\%$ of the field beyond a few centimeters from the surface of the snout. The snout must have an internal open channel at least $1\frac{1}{2}$ in. in diameter to admit the beam and must have an outside diameter as small as possible for three reasons: (1) The injected H_2^+ beam must miss the tip of the snout on its first turn. The inclination of the snout axis, the shape of the dip, and the orbit diameter all enter into the extent to which the beam moves axially in its first orbit. Although the snout inclination can be compensated for by a deeper dip, the beam divergence is amplified more by the deeper dip, resulting in a decrease of the average path length. (2) A fraction of the atomic ions produced by dissociation will eventually strike the snout; the smaller the snout diameter, the smaller is the fraction of protons lost to it. (3) The snout must be inserted between the coils producing the main field and must be slightly adjustable in angle and position. The allowable gap in the coils producing the uniform field is quite limited. Considerations driving the snout to larger diameter are the limited saturation flux of the best available ferromagnetic material (Hiperco) and the limited current-carrying capacity of the conductors carrying the compensating current.

Figure 8 is a diagrammatic cross section of the snout body. The basic design concept dates back several years.[8] The principal elements are the roughly cylindrical Hiperco shield and a corrector coil (a series of conductors on the exterior of the Hiperco) designed to produce a uniform internal magnetic field. The Hiperco and the coil together reduce the flux in the central hole while producing equal and opposite two-dimensional dipole external-field disturbances. The tipping of the snout with respect to the magnetic field produces a longitudinal magnetization which must be canceled by a helical coil. (The radial component of the field near the main coils must also be canceled.) An extra-high-permeability magnetic shield is provided in the central hole by a Hipernik sleeve separated from the Hiperco body by a magnetically insulating gap filled with a high-velocity water stream which is part of the cooling circuit.

One of the necessary complexities of the snout is the provision for the safe stopping of the H^+ and H_3^+ components of the beam leaving the accelerator. These components are largely removed

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[8] F. C. Gilbert, *A Beam Injector*, UCRL-5698 (Nov. 1959).

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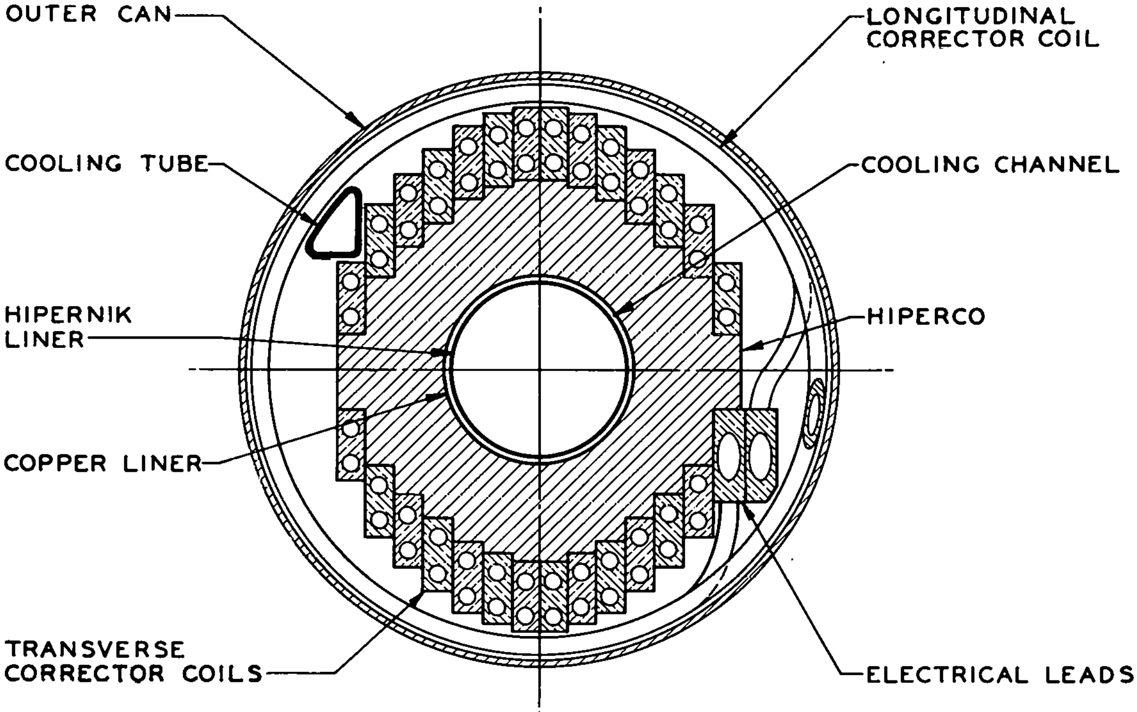

Fig. 8. DCX-2 Snout, Cross Section.

in the snout before the beam enters the machine, since they are focused differently by the solenoidal focusing coil below the accelerator. Figure 9 is a diagram of the snout with focus conditions adjusted for H_2^+ injection. Above the snout entrance the H^+ component crosses over, the H_2^+ component is converging slowly, and the H_3^+ component is diverging. The H^+ and H_3^+ components are absorbed largely by the upper and lower cones, which are cooled by a high-velocity water stream; the cylindrical section of the snout must absorb the entire (and somewhat larger) H_2^+ beam in case of an accidental misfocus or deflection of the beam. Any component of the beam could be as large as 200 kw under expected conditions, and the total may be greater than 300 kw. Under the usual conditions, all the H_2^+ enters the machine and less than 100 kw (H^+ and H_3^+) is lost in the snout. Even with the longest path expected, however, very little of the beam is dissociated, and the beam will return to a target wrapped around the tip of the snout, where its power must be absorbed without harm. The target is a group of 1-cm-diam copper tubes with internal spiral strips to produce a rapidly rotating water flow. Fortunately the beam spreads uniformly around the cylinder represented by its spiral orbit, reducing the beam concentration.

The required exactness of adjustment of the snout-coil currents relative to the main field is secured by connecting all the inboard coils in series with the transverse and longitudinal coils of the snout. Adjustment is provided by shunts across each snout coil so that the ratio of fields

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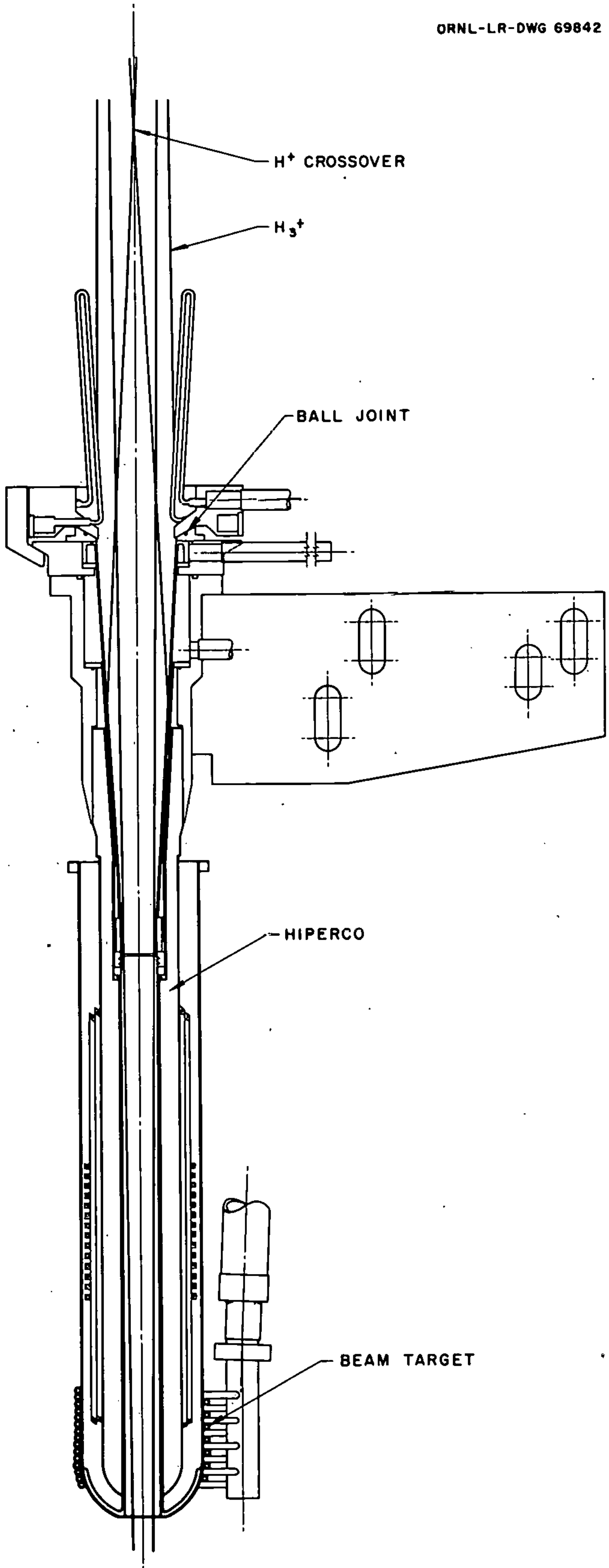

Fig. 9. DCX-2 Snout, Longitudinal View.

will remain constant once set. The snout-coil currents are, therefore, 7000 amp for hydrogen operation. The current density in the copper near the snout tip, because the tip is necessarily small, rises to 13,000 amp/cm^2, and the total snout-coil power is about 350 kw.

Although the lack of distortion of the machine field means that there should be no force upon the snout, there are very large internal forces, since the conductors carrying 7000 amp are immersed in a field of 12,000 gauss. In addition, provision must be made for accidents such as an accidental shutdown of the generator supplying the snout and inboard coils with a failure of the automatic trip for the mirror-coil generator, or a short circuit of some of the snout coils. An extremely strong, but adjustable, mounting attached to the mirror-coil container (the origin of the principal fault force) is provided to support the maximum fault force.

The necessary mechanical alignment of the snout axis with the axis of the emerging accelerator beam is provided by the beam-alignment coils (see "Accelerator System") and the ball joint at the top of the snout.

VACUUM SYSTEM

Pumping Concept

The design of the vacuum system in DCX-2 is based on the assumption that the major source of gas will be the undissociated component of the injected molecular ions, which recombines with electrons at the target on the snout. This gas load is produced only when a plasma is being formed. Advantage is taken of the favorable ratio of ionization to charge-exchange cross section of the trapped protons, in order to make use of the ion-pumping action of the plasma ("plasma pumping"). In this process, the neutral atoms (mostly hydrogen) are ionized in the plasma; the ions so produced are trapped on magnetic field lines, along which they rapidly move out through the mirror coils into the end liner regions. There they are neutralized and pumped by titanium films evaporated onto the walls for this purpose. Because of the high pumping speed of the titanium and the random direction of the atoms after recombination, only a small fraction of those ions which were trapped on field lines manage to return through the mirrors into the central liner region containing the hot plasma. Pumping by the plasma at speeds up to 10^6 liters/sec may reasonably be expected.

Description

These considerations led to the configuration shown in Fig. 10. The outer tank wall bears the atmospheric forces and is made of ~1-in.-thick stainless steel. This tank also serves as a rough vacuum container ($p \approx 10^{-6}$ mm Hg), permitting the use of organic O-rings for seals to atmospheric pressure. Inside the tank is a copper liner approximately 1 m in diameter. The liner is made by welding together several panels of Roll-Bond, a metallurgically bonded copper sheet made by Olin Mathieson Chemical Corp., East Alton, Illinois. Details of fabrication are given in ref 7. Water-cooling passages tailored to accommodate the heat load in the various regions are formed by

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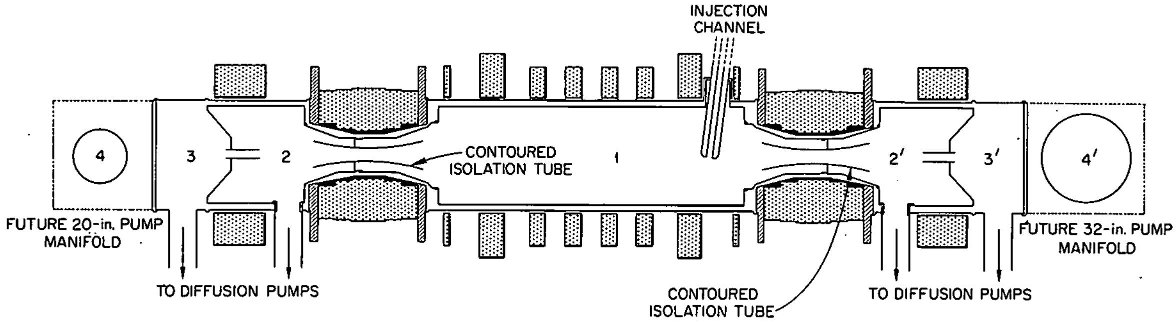

Fig. 10. DCX-2 Vacuum System.

hydrostatic inflation of the thinner, outer copper sheet to a predetermined pattern (Fig. 11). Cooling of the liner is essential, because of the power load of the 300-kev neutral flux produced by charge exchange of the trapped protons with residual background-gas molecules. No conventional or absorption pumping is used in the main liner, because of the expected high speed of ion pumping by the plasma.

Connection between central and outer liner regions is made by means of contoured tubes, which were designed to follow the magnetic field lines just outside the trapped plasma so as not to interfere with plasma pumping. This shape ensures that the conductance for returning neutral gas is low enough to permit the absorption of the ion-pumped gas in the outer vacuum region at pumping speeds of $\sim 2 \times 10^4$ liters/sec. The titanium used for this purpose is continously evaporated from two heated filaments at each end of the machine at the rate of ~ 4 g/hr. The area available for titanium deposition is approximately 3×10^4 cm^2 in each end liner region. Using the conservative rule of thumb of 1 liter sec^{-1} cm^{-2}, the pumping speed at room temperature at each end should easily handle 0.04 mm-liter/sec (half the gas load produced by the 500-ma beam) at a pressure of 2×10^{-6} mm Hg. In addition, at each end of the machine, two 10-in. diffusion pumps are used to establish a base pressure low enough that the titanium pumps are effective and to assist in the pumping of those gases not absorbed efficiently by titanium films. Four other 10-in. diffusion pumps evacuate the outer vacuum region.

The valving in the manifolds of the forepump system was designed to permit any of the three Roots blowers, backed by 5-hp Kinney mechanical pumps, to be used either as a roughing pump or as a forepump backing the diffusion pumps. The valves are pneumatically driven and operated from the vacuum display panel in the control room (Fig. 12).

Each diffusion pump has a water-cooled cap which fits snugly over the top jet of the pump to reduce streaming of oil back into the high vacuum from evaporation of oil droplets on the lip of the top umbrella. Chevron-type baffles cooled with liquid nitrogen further trap volatile fractions from the pumps. Liquid-nitrogen traps have also been installed in the forepump lines to condense cracked diffusion-pump oil, which is inefficiently handled by the forepumps. Just enough liquid nitrogen is stored in the baffles and traps to maintain their temperature. This reduces the area

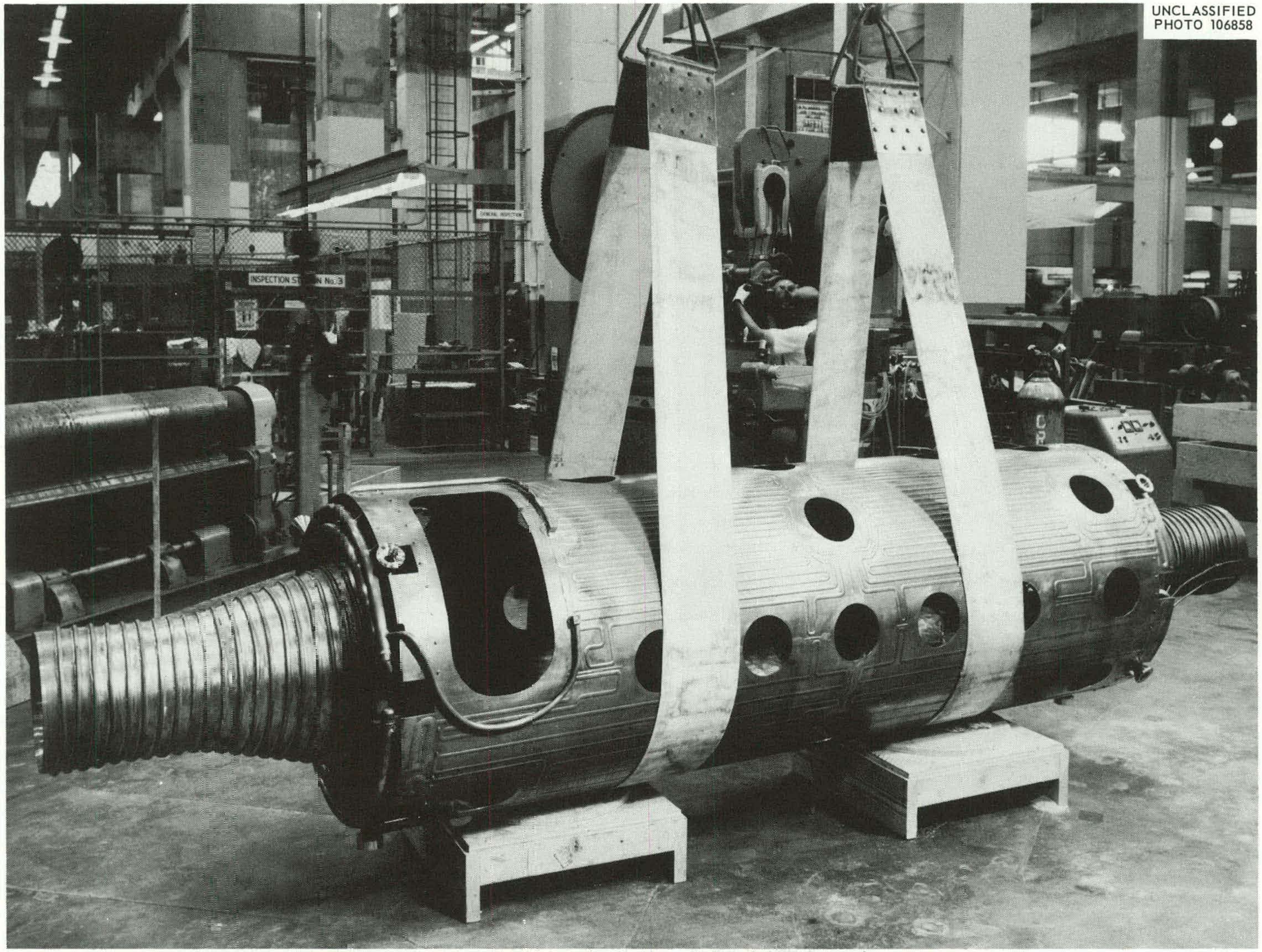

Fig. 11. DCX-2 Liner.

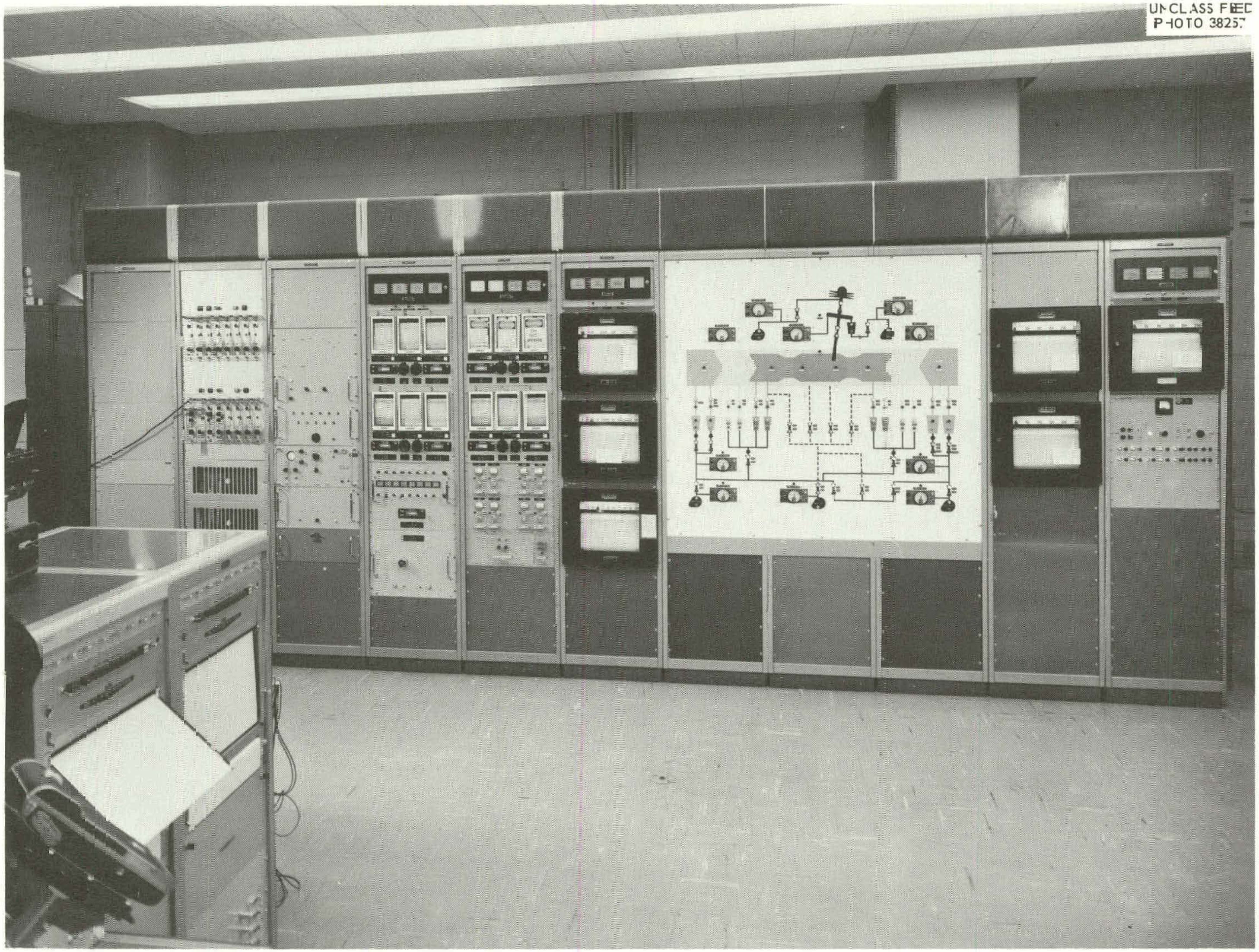

Fig. 12. DCX-2 Control Room, Showing Graphic Vacuum Control Panel.

of exposed cold surfaces and, thereby, the nitrogen-use rate. These relatively small volumes are gravity-fed from insulated storage tanks through heat-shielded vacuum-insulated lines. The capacity of each tank (110 gal) was chosen to permit storage of enough liquid nitrogen to last 24 hr.

Liner Bakeout

To ensure the validity of the basic assumption that the injected ions are the source of all the gas in the machine, baking of the liner at $\sim 400°C$ is necessary. An argon arc is run on the axis of the machine, and the radiated power (mostly in the form of ultraviolet light) is sufficient to elevate the temperature when the water cooling of the liner is turned off. The arc, ~ 7 m long, is run at 150 amp and 275 v. The radiated power was measured as ~ 100 w/in. (approximately 10 to 20 kw into the liner). After the water was turned off, a temperature rise of 3.35°C/min was observed until the liner temperature reached 75°C. Higher temperatures were not attempted in the experiment, since the cooling gas was not yet installed.

Nitrogen gas is circulated through some of the water passages in the machine to cool the liner after baking, to purge the cooling channels during baking, and to control the temperature of areas closest to the arc.

ARCS: EVOLUTION AND STATUS

The course of the DCX-2 arc-development program has reflected very strongly the changing design requirements imposed by theoretical advances. The initial DCX-2 proposal, which was guided by the desire to use existing types of components throughout, was based on the use of a high-vacuum carbon arc. Despite the large charge-exchange losses of such an arc, it was shown that its use could significantly reduce the molecular-ion current required for burnout.

The actual arc development was divided into two programs, one directed toward a deuterium arc[9] and the other toward a highly ionized lithium arc.[10] Each of these devices was modeled conceptually after the carbon arc. They were expected to produce much less severe charge-exchange losses, because of the use of only fully, or nearly fully, stripped ions. In order to accommodate a deuterium arc, which operated on about 5 cm^3/sec of deuterium gas at atmosphere pressure, the DCX-2 vacuum system was designed to include two 32-in. pumps, a 20-in. pump, and two additional differential-pumping regions using titanium pumps.

As the design proceeded, there grew a proper appreciation of the effects of energy losses incurred by protons in passing through such arcs. Because of the extremely steep charge-exchange cross section, very modest energy losses can move protons into an energy region in which they

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[9] R. A. Gibbons and R. J. Mackin, Jr., *Development and Study of a Highly Ionized Steady-State Deuterium Plasma,* presented at the Fifth International Conference on Ionization Phenomena in Gases, Munich, Germany, Aug. 28–Sept. 1, 1961.

[10] J. E. Francis *et al., Thermonuclear Div. Progr. Rept. Oct. 31, 1961*, ORNL-3239, p 49.

will be lost rapidly. This had been considered earlier and passed over without proper evaluation. At any rate, the new insight made it appear as though either of the arcs under development with a density around 10^{14} ions/cm^3 would be a net liability if used in DCX-2. The design of the extra vacuum components proceeded to completion, but they will not be installed until a need for them is apparent.

At this stage it appeared that a desirable arc density would lie between 10^{11} and 10^{12} ions/cm^3. The lithium-arc program shifted its emphasis to the "backstream plasma" which was found to drift past a properly designed arc cathode. This plasma appeared to have a proper density and could be made to contain highly stripped lithium ions. (This approach could also be used for a deuterium plasma if one were willing to tolerate the pumping inconvenience.) A lithium "backstream" arc has been operated in the machine.

The deuterium arc work was diverted to the development of a non-self-sustaining arc of adjustable density whose electrons were supplied by a resistance-heated cathode. This work has led to plasma densities in the desired range, with the possible additional advantage of an electron temperature high enough (300 to 500 ev) that energy-loss effects are reduced.

Theory has now passed through another convolution. With the energy transfer between trapped protons and background electrons considered in the most accurate way now possible (a self-consistent Fokker-Planck treatment), the S curves which describe the current-density relationship have become more nearly vertical near the upper critical current. This implies that no appreciable help is to be gained from the use of any arc unless it contributes significantly to the removal of the background gas. Since this requires a pumping speed comparable to a half-million liters per second (the plasma pumping speed), one is led to the old "arc wall" concept, in which the plasma is essentially surrounded by an arc hot enough and dense enough to be opaque to neutral molecules. This represents a more ambitious project than seems indicated by the problem.

CONSTRUCTIONAL FEATURES OF DCX-2

Sectional Construction

The DCX-2 is a large (~ 30 ft long), complex, and heavy (~53 tons) system of tanks, coils, and instruments. In order to have adequate access to the inside of the machine for installation of instruments too large to be inserted into instrument ports, or for cleaning or repair of the vacuum liner, as well as for the repair or replacement of the field coils, the machine was built in six separable major sections. Separation is easy enough that any two adjacent sections can be parted, minor changes made, and the system reclosed in less than 8 hr.

Five of the major sections, constituting the magnet and vacuum systems, are mounted on two flat horizontal tracks by means of flat shoes with openings, in such a manner that they become hydraulic bearings when supplied with oil at a few hundred pounds per square inch. The end sections are connected to the mirror coils and the mirror coils to the central tank by O-ring-sealed joints with clamp rings. This permits the system to be parted at any point and the sections to be pushed apart with negligible effort. The other major section, the accelerator and its shield, is supported on a bridge crane that permits the adjustment of accelerator position and its complete removal from the top of the machine.

The diffusion-pump system is supplied with valves and small temporary forepumps, so that the system can be separated without shutting down the pumps and waiting for cooling and startup. Access to the plasma region and the end liner sections is provided by 67 6-in.-diam ports with air locks. These ports permit the insertion of instruments or new titanium evaporators without letting the system down to air. Whenever a port is unoccupied, a plug is inserted to retain the isolation between the liner and the outer vacuum.

A recent shutdown illustrates the built-in ease of maintenance and modification. During the shutdown, all the liners were removed, cleaned, and leak-checked, the main tank was cleaned, and several new components and pieces of experimental gear were installed. This took only two weeks.

Flexibility

Considerable flexibility is retained in the construction, so that the magnetic configuration can be varied without rebuilding more than the central tank (a relatively inexpensive item). It is possible that a modified field shape will be needed to reduce instabilities if they occur.

Minimization of Magnetic Effects on Instruments

The extended-leakage magnetic field of the machine requires the location of much of the control room at a considerable distance from the machine, since much of the control and diagnostic equipment requires that the ambient field be less than 20 gauss. The control room is connected with the working platform of the machine by a ramp for easy access. The control and instrumentation cableways were laid out with some care to minimize pickup of false signals by ground loops and to protect against induction surges from 600-kv spark-over, or from a scram of the 20-Mw magnet system. A satisfactorily low level of pickup in instruments and telephone communication among the operating crew was achieved, despite the complications introduced by multichannel recording of experimental data.

DIAGNOSTIC INSTRUMENTS

Since there are many ports in the vacuum tank which permit access to the liner region, many diagnostic tools may be used simultaneously to observe time-correlated parameters of the plasma. A list of the types of instruments available and in the design stage follows.

Instruments on Hand

Foil Neutral Detectors

Function: Detection of fast neutral atoms produced by proton charge exchange or H_2^+ dissociation.

Operation: Neutrals pass through thin nickel foil, which strips off their electrons, and are collected in a Faraday cup. Foil thickness ranges down to 10 μin., giving a threshold of 50 kev. This is a modified DCX-1 probe design.

Purpose: Determination of the space and time distributions of emerging fast neutrals. For time distributions, fast gating of the ion beam is provided. Used for optimizing H_2^+ orbit, investigation of particle-loss mechanisms, and measurement of fast-ion density.

Neutral-Particle Energy Spectrometer

Function: Measurements of the energy distribution of emerging fast neutral atoms.

Operation: Semiconductor surface-barrier proportional counter feeds into 256-channel pulse-height analyzer. Resolution is 30 kev.

Purpose: Correlation of energy dispersion and energy loss with other system parameters. Ultimately, comparison with predictions of various velocity-space instability theories.

Fast Ion Gage

Function: Determination of time dependence of gas pressure in plasma region.

Operation: Ionization gage with large connecting tubulation; output is fed into a fast electrometer amplifier. Gage time constant is estimated to be 6 msec.

Purpose: Correlation with emerging fast-neutral currents for determination of the time dependence of plasma density during beam-gating experiments; measurement (via time constant) of the rate of ion pumping by the plasma; possibly detection of the existence of gross instabilities which release large amounts of plasma.

End Probe

Function: Determination of parameters of plasma which drifts through mirrors.

Operation: Probe characteristics (plots of current vs applied voltage) give cold-ion density, electron energy distribution and "temperature," and plasma potential.

Purpose: Evaluation of secondary plasma parameters which strongly affect the fast-proton density produced by a given input ion current; measurement of ion-pumping rate.

Beam Calorimeter: (a) Unbroken-Up-Beam Target; (b) Unfocused-Beam Target; (c) Liner

Function: Determination of currents in various beam components from the power which they deposit in appropriate targets.

Operation: Measurement of flow and temperature increment of cooling water.

Purpose: Beam-current measurements under circumstances where background plasma makes direct-current measurements unreliable; particle-accountability experiments; indications of system malfunction or misalignment.

Pressure Gages: (a) Plasma Region; (b) End Liner

Function: Determination of gas pressure in various regions of vacuum system.

Operation: Measurement with ionization gages.

Purpose: Measurement (via pressure comparison) of the rate of ion pumping by the plasma; evaluation and monitoring of the performance of titanium pumps; indication of system outgassing.

Electric and Magnetic Probes

Function: Measurement of the strengths of oscillating electric and magnetic fields outside the hot plasma.

Operation: Antenna signals are amplified and displayed on a panoramic receiver or an oscilloscope.

Purpose: Indication of the effects of organized particle motion within the plasma; observation of the onset of instabilities; possibly, elucidation of instability mechanism, normal modes, or other characteristics.

Periscope

Function: Observation of all parts of the plasma region.

Operation: Optical periscope (60° field, unity magnification) is mounted on a central observation port.

Purpose: Assistance in ion-beam alignment; visual observation of plasma.

Photomultiplier

Function: Measurement of time and space dependence of light intensity in the plasma.

Operation: Photomultiplier is arranged to detect image produced by a lens of long focal length; output is amplified and fed to an oscilloscope or a panoramic receiver.

Purpose: Detection of organized ion motion or "clumping."

Microwave Interferometer

Function: Determination of density of plasma electrons.

Operation: Measurement of phase shift of X-band (later Kα-band) microwaves passing through plasma yields dielectric constant and thus electron density.

Purpose: Direct determination of time dependence of plasma density (especially during beam-gating experiments); correlation with fast-ion density measurements to indicate slow-ion density.

Fast-Neutral Calorimeters

Function: Measurement of axial distribution of emerging fast neutrals resulting from H_2^+ dissociation.

Operation: Multiple calorimeter elements at 4-in. intervals along tank wall; outputs are displayed on an oscilloscope by means of a scanning switch.

Purpose: Observation of effects of ion-beam and field-alignment procedure.

Instruments Being Designed

Diamagnetic Pickup Loop

Function: Determination of changes in magnetic flux in region occupied by the plasma.

Operation: Flux changes during beam-gating experiment (or other plasma-density variation) induce signals in loop.

Purpose: Determination of plasma pressure in terms of magnetic field lines excluded from plasma region; correlation with other data to give density or temperature.

Slow-Ion Spectrometer

Function: Measurement of the energies of "slow" ions emerging through the mirrors.

Operation: Measurements with a magnetically shielded spherical electrostatic analyzer with swept voltage.

Purpose: Determination of plasma potential and its space and time variations.

Langmuir Probes

Function: Determination of parameters of secondary plasma.

Operation: Probe characteristics (plots of current vs applied voltage) give cold-ion density, electron energy distribution and "temperature," and plasma potential.

Purpose: Determination of distribution and flow of cold plasma; indication of flow of cold ions for improving design of ion-pumping system; study of effects of plasma potential.

Mass Spectrometer

Function: Measurement of partial pressures of the various components of gas before and during operation.

Operation: Measurements with a commercial mass analyzer; laboratory design of an improved (time-of-flight) model to operate in DCX-2 magnetic field and give faster response is in progress.

Purpose: Indication of outgassing effects; determination of fraction of free hydrogen atoms in the vacuum chamber in the presence of plasma.

End Plates

Function: Determination and attempted control of parameters of secondary plasma.

Operation: Connected as gridded probes, these will measure electron and ion flow independently; correlated calorimetric measurements will give energy information and thus measure either electron "temperature" or plasma potential.

Purpose: To supersede end probes (listed above) now in DCX-2. An additional purpose is possible plasma stabilization by operation at high voltage (about 10 to 30 kv).

X-Ray Spectrometer

Function: Measurement of bremsstrahlung spectrum.

Operation: Thin scintillating crystal and photomultiplier feed into 256-channel analyzer.

Purpose: Determination of energy distribution of electrons in range above a few kiloelectron volts.

X-Band Microwave Radiometer

Function: Measurement of thermal radiation in 10-kMc range.

Operation: Comparison of radiation from plasma with that of a room-temperature resistor, using a microwave receiver.

Purpose: Measurement of electron temperature.

Data Recording

The readout of the data from the various instruments must be sufficiently simplified that correlations will not be lost in reams of chart paper. Therefore, a 16-channel American Optical Company recorder in which each channel output may be separately controlled was obtained. The chart speed may be 0.1, 1, 2.5, 5, 10, 25, 10, 100, 250, or 500 mm/sec. The overall rise time (of pen and amplifier) for a square-wave input is ~2 msec. The chart is automatically accelerated to speed before each experiment begins and then returned to a low speed at a predetermined time. Side marking pens are coded to designate each experiment, so that correlation with any oscilloscope pictures (similarly coded) taken simultaneously is automatically made.

For information which is faster than can be handled by the 16-channel recorder, two data-recording procedures are possible. Several oscilloscopes are available for photographing any of these signals. In addition, a tape recorder with a 10-μsec rise time, on which 14 channels of information may be stored at high speed and then automatically played back at a slower speed into the 16-channel recorder, will be used.

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An apparatus of the size and complexity of the DCX-2 could not have been built without the skill and ingenuity of many people. We are pleased to take this opportunity to acknowledge, however inadequately, the assistance of those who contributed most directly to the design and construction. A few of the names follow:

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