MASTER

UCRL-70026
Preprint

COPY PRICES

CONF-661016-1

H.C. \$ 1.00; MW .50

OCT 10 1966

UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Livermore, California

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission," includes any employee or contractor of the Commission, or employee of such contractor, to the extent that disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

MECHANICAL DESIGN OF THE BASEBALL COIL AND PLASMA-TRAPPING CHAMBER

Robert E. Bathgate
William S. Neef, Jr.

September 23, 1966

RELEASED FOR ANNOUNCEMENT

IN NUCLEAR SCIENCE ABSTRACTS

This manuscript was prepared for presentation at the Symposium on Engineering Problems of Controlled Thermonuclear Research, Gatlinburg, Tenn., October 3-6, 1966; and for publication in the Proceedings of the meeting.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

MECHANICAL DESIGN OF THE BASEBALL COIL AND PLASMA-TRAPPING CHAMBER*

Robert E. Bathgate and William S. Neef, Jr.

University of California, Lawrence Radiation Laboratory
Livermore, California

BACKGROUND INFORMATION

In a previous report¹ the basic mechanical design requirements for the Alice neutral injection plasma containment experiment at Lawrence Radiation Laboratory were reviewed. Some preliminary design steps toward a new magnet configuration had been taken. The magnetic field to be produced was a non-zero "minimum B" (potential well) and the conductor geometry led to the obvious name, "baseball coil."

A method of inexpensively constructing such a magnet was successfully developed, and two magnets have been built. Cryogenic vacuum-pumping techniques have developed rapidly, and a bakeable plasma-trapping chamber with its pumping system was designed to utilize the unique "baseball" field geometry and employ cryo-pumping to achieve base pressure of 10^{-11} torr and even lower.

This paper reviews some of the basic calculations and design decisions for this major mechanical revision in the Alice experiment. It also contains a discussion of a structural failure encountered during magnet operation, and corrective measures which were taken.

*This work was performed under the auspices of the U.S. Atomic Energy Commission.

THE BASEBALL MAGNET

The magnetic field produced by the "baseball" magnet has several unique properties, which are shown in Fig. 1. In addition to magnetic lines of force, the surfaces of constant "minimum B" are shown and the potential well is easily observed. This plot was obtained from the computer program MAFCO² developed by Perkins and Brown at LRL. It can be seen that useful field gradients exist as far as 30 cm from the center of a 1-meter, mean diameter coil.

One compromise with physics requirements was necessary. Lorentz trapping considerations show the optimum beam injection angle to be about 45°. This is demonstrated by Pittenger and Moir.³ If this angle were used, the beam exiting from the trapping region would collide with the conductor bundle. To permit the beam to enter the burial chamber, the injection angle was changed to 57°, which is not optimum but still is adequate from an ion-trapping consideration.

The magnetic field strength desired was about 7000 G in the "well," with a mirror ratio of 3:1. Matching considerations with available power supplies gave 400 turns of 0.340 square hollow conductor with 5000 A in each turn. Analysis of the forces on this magnet was a complex problem which was greatly aided by use of the MAFCO computer code. The code cannot calculate a field vector on a current-carrying conductor. The coil was approximated by subdividing the mean coil filament into 72 straight line segments. By eliminating one segment, the field at the center of that segment due to all remaining 71 segments could be obtained. With B_x , B_y , and B_z known at that point, the vector cross product with current at that point gives the three components of force per unit length of conductor. Figure 2 shows one-fourth of the baseball coil and the forces obtained at full field strength.

The baseball seam geometry can be ideally described as the intersection line between a spherical surface and the surface of a hyperbolic paraboloid. The compound curvature of such a line makes fabrication of that shape very difficult. It was suspected that a good approximation would be four plane arcs of length π radians, tipped toward the axis at their centers and joined at their ends by straight-line segments. This was tested by computer code and gave a very satisfactory magnetic field shape. The field of Fig. 1 was developed by using such an approximation while dividing the conductor bundle into nine current filaments to give a better representation of the real magnet, as opposed to a single-current filament on a 1-meter sphere. The winding fixture for this magnet was very simple (see Fig.3). It had to disassemble in such a way that after the coil was completely wound the fixture could be removed piece by piece from the "inside" of the coil. The fabrication cost of coil and winding fixture, excluding the cost of the copper, was \$8600. This compares very favorably with the cost of simple water-cooled solenoids of comparable weight.

COIL-RESTRAINING STRUCTURE

The interaction of the coil field and the current in the coil tends to force the coil into a circular hoop. These forces are proportional to the square of the current and can get very high, depending on coil geometry and field.

Requirements of the physics experiment placed a number of restrictions on the restraining structure design. The more basic of these are as follows:

- 1) Accessibility to the high vacuum inner chamber for assembly of the chamber, and installation of diagnostics equipment.

- 2) Non-magnetic materials to keep from perturbing the trapping field.
- 3) High strength at near liquid nitrogen (LN) temperature.

Force analysis on the coil showed that there were large forces tending to push the four lobes of the coil away from each other and a large tensile or "hoop" load in the coil conductors. The tensile load was on the order of 300 kips, and the net force tending to spread the lobes apart was approximately 250 kips. These forces are for 2,000,000-A turns, a central field of 7000 G, and a mirror ratio of 3.

It was felt that the restraining structure should be self-contained, rather than bringing in supports from the insulation chamber or other points.

With these conditions placed on the design there seemed to be only one practical solution; this was to tie the two sets of lobes together with tension members. Also, some method of taking up part of the tension in the coil was necessary, since the stress in the copper was close to its yield strength. The only problem remaining was how to attach the tension members to the coil and take some of the bending stress out of the coil.

The idea of putting four crescent-shaped troughs on the outside edges of the four coil lobes permitted attachment points for the tie rods or tension members. This also permitted the structure to take up some of the coil tension.

The coil crescents were cast from an austenitic stainless steel (14 Ni, 18 Cr). The design is such that all four castings are identical, and these are then machined differently to meet the requirements on each lobe.

Weldments were considered for the job but because of the large cross-sections involved and the amount of welding required, castings seemed more practical.

The castings were potted onto the coil with epoxy resin and glass cloth. The i.d. of the castings were made slightly oversized to allow for variations in the coil. The "potting" permitted generous coil fabrication tolerances and some surface roughness. It also allowed wider tolerances in machining the large castings. By "potting" the coil and castings together, a uniform load distribution was made between them. The coil and its restraining structure, being one integral unit, could be mounted independent of the high-vacuum chamber. The coil and high-vacuum chamber were mounted on a framework which could be put into the environmental chamber as a unit (see Fig. 4). By mounting the coil and vacuum chamber independently, each could be adjusted independently of the other. Because of the problems of manufacturing the coil and its mating parts, as much room for adjustment as possible was built into the design.

Spherical seats were used on the tie-rod nuts to take care of any misalignment between the four castings.

Since the first force calculations on the coil were somewhat crude and the results were somewhat uncertain, several of the tie-rods and some critical casting areas were instrumented with resistance strain gages. These were monitored during coil pulses. The coil forces were, in all cases, slightly lower than had been predicted.

THE TRAPPING CHAMBER

To have the largest possible volume available for plasma within the "baseball" magnet, the vacuum chamber was constructed of four major pieces (see Fig. 5). The possibility of winding the coil directly on a spherical chamber was seriously studied, but was rejected because a coil malfunction would call for replacement of an expensive chamber as well as the magnet

(this later proved to be a good decision since such an accident did occur and the chamber was only slightly damaged). The bell-shaped parts had to be placed within the coil first and the center section with beam and diagnostic ports then slipped in between. Seals for the entire ultrahigh vacuum system are aluminum foil, and a flange design originated at LRL is used. The largest seals are 23 in. in diameter. All joints were easily assembled and proved very reliable over several months operating time.

The large shapes forming the chamber were made from ring forgings of large cross section. This is a departure from our usual welded construction. They were simple to machine, and offered an ideal grain-flow pattern and wall thickness. Wall porosity can be a severe problem when an attempt is made to attain very low pressures.

Recent data indicate a gradual transformation to martensitic structure in type 304 stainless steel at cryogenic temperatures. After many hours at 80°K, permeability as high as 4.0 at 200 Oe magnetizing force has been measured. Type 316 stainless steel exhibits excellent stability in the austenitic state, and is also plentiful in all forms at reasonable price. That alloy was used for all portions of the trapping chamber which operate at cryogenic temperatures.

Diagnostics on the plasma is accomplished by several fast-atom gridded detectors, RF antennae, capacitance pickups, and a scanning solid-state detector. The latter device can be aimed inside the chamber. Several other fixed solid-state detectors were used. Moveable "eyelids" actuated by an electrically heated bimetallic strip are used to prevent evaporation of active metal on sensitive detector surfaces during periods of "getter" pumping.

The "gettering" is done by a retractable evaporator filament assembly. Bellows seals permit the large motion required of these devices.

An electron gun to trace certain field lines in the plasma volume is available. Also a lithium gun, adjustable in position, can be used to measure plasma potential. The "baseball" containment geometry offers many possible instrumentation mounting points, and we availed ourselves of all.

THE PUMPING SYSTEM

It was felt that achievement of base pressures in the 10^{-12} torr range could be achieved in this system. The Alice mirror experiment had achieved base pressures as low as 8×10^{-11} torr upon a few occasions under conditions not nearly so ideal. This system was designed to permit the trapping chamber to be cooled to LN temperature. A liquid helium (LHe) temperature zeolite pump manufactured by the Linde Division of Union Carbide Corporation was also incorporated in the design.

The following four different forms of pumping, all shown in Fig. 6, are used at appropriate pressure levels:

- 1) A single 4-in. oil diffusion pump with a LN temperature, 2-bounce, elbow trap serves to bring the system from roughing pressure to the 10^{-7} torr range. This trap has a flapper which serves as a bakeable valve to shut off the pump when desired.
- 2) A triode ion pump is used to further reduce system pressure to 10^{-9} torr.
- 3) At this point, molybdenum is evaporated on all interior surfaces of the system. Those vacuum walls which are not directly LN-cooled are provided with internal copper liners

through which LN circulates. This "getter" pumping from three/separate filaments brings the system to pressures approaching 10^{-11} torr.

- 4) To activate the helium cryopump, it is filled with LHe and then the helium container is vacuum-pumped to drop its temperature to about 2.5°K.

Figure 7 shows the pumping system ready for test before being coupled to the "baseball" trapping chamber. After its first assembly and bakeout, this system attained 4×10^{-11} torr. We feel that additional baking and experience with this complex system will enable us to achieve pressures in 10^{-12} range or better. Aluminum foil seals are used throughout. A newly designed 12-in. bakeable valve has proved satisfactory on this system.

The largest possible pumping aperture was used to couple this system to the trapping chamber. A 16-in.-diam tubulation, with bellows for ease of alignment, accomplishes this.

THE ENVIRONMENTAL CHAMBER

Thermal insulation of large LN-cooled trapping magnets was never satisfactorily accomplished on previous versions of Alice. Thermal lagging was a difficult and expensive operation. Condensed water and ice were continual problems, causing everything from bellows failures in the vacuum system to wet, slippery floors. Provision of a vacuum insulation "can" around the plasma-trapping chamber and "baseball" coil has solved all of these problems. Figure 4 shows the trapping chamber and coil on its support frame. This frame rolls easily into the environmental chamber and provides independent position adjustment for both the plasma chamber and the "baseball" coil. Two heavy end-plates close the two chamber ends. They are

retained by toggle clamps, and seal loading is accomplished by atmospheric pressure. One end provides for certain diagnostic device lead-outs. The other cover plate passes the 16-in. tube which connects the trapping chamber to the pumping system. This method of assembly has been simple, and alignment of the chamber has been no more difficult than with previous designs.

The following advantages are offered by the chamber:

- 1) Vacuum thermal insulation is provided for magnet and trapping chamber (both of which are at about 80°K).
- 2) A guard vacuum is provided around many aluminum foil gaskets in a critical location.
- 3) Almost all condensation of moisture on apparatus is eliminated.
- 4) A barrier is provided to stop fragments from a catastrophic bolt failure, thus preventing possible injury to personnel or damage to equipment.

A particularly successful design has evolved for a cryogenic vacuum-tube fitting. LN is distributed to 10 parallel cooling channels in the coil inside the environmental chamber. This fitting is of type 304 stainless steel and has an aluminum foil seal. It is composed of three simply machined elements plus a ring of household aluminum foil. Twenty-five of these joints were made inside the environmental chamber with no leakage into the vacuum. The main LN feeder lines into the chamber have 1-in. aluminum foil bolted flanges, and these have proved completely reliable for flowing nitrogen at 100 psi in a vacuum environment. Figure 8 is a view of the internal plumbing and wiring, taken before the end of the chamber was closed.

RESTRAINING STRUCTURE FAILURE

Although the coil forces were less than calculated, the coil restraining structure failed at 84% of full current, or 71% of full load.

The material used for the tie-rods was beryllium copper, 1/2 hard and heat-treated to 170,000 psi yield and 195,000 psi ultimate. These broke at a nominal stress of 38,000 psi.

After considerable investigation it was determined that the cause of failure was low-cycle fatigue, aggravated by a high stress concentrator at the thread root. The coil had been pulsed 109 times, with 46 pulses above 60% of rated current. All failures were at the thread root area, and on five out of nine rods both ends were broken.

Although beryllium copper does not become more brittle at low temperatures, the heat treatment on the tie-rods gave only 2 to 3% elongation. This, compounded with the use of American standard threads instead of Whitworth threads and cycled loading, caused the rods to fail.

The energy contained in the coil at 100% rated current is approximately 2.5 MJ. Thus this system is potentially dangerous, should a coil failure occur. The environmental tank which surrounds the coil was shown to be a very effective barrier for loose nuts and tie-rod ends during the failure. This tank is made of 1/2-in.-thick stainless steel, and completely contained the failure. It is still in use, and no repair on it was necessary.

The present design incorporates a heat-treatable, non-magnetic steel (A-286) with rolled threads. A special nut design is also used which distributes the loads more evenly along the first few engaged threads. The yield strength of this material is 85,000 psi minimum, but it has 15% elongation and good fatigue and impact strength. In addition, more rods have been added to lower the load per rod.

FUTURE DEVELOPMENTS

As we were trapping the beam with the first LN-cooled "baseball" coil, a superconducting version of the "baseball" was constructed on a 10-in. -diam sphere. It operated very reliably for many hours in the superconducting state.

The advantages of a cw trapping magnet with a cw beam source for neutral injection plasma experiments do not need further elaboration here. We are currently planning a superconducting magnet approximately 1-1/2 meters in mean diameter. It will be used with the present Alice beam line. A second beam, crossing the existing one, may be feasible to add to this improvement of our present experimental apparatus. Data acquired during months of pulsed operation in our present Alice facility could be obtained in days or even hours if the magnet were superconducting.

The symmetry of the "baseball" seam and the properties of the magnetic field produced lead to the ultimate goal of four injected neutral beams. This will require an experimental facility far advanced from the present Alice machine and its building.

Our physics group has requested advanced planning and study on a 3-meter mean diameter superconducting "baseball" magnet with four beam sources and four burial chambers. Some feeling for the magnitude of the problems may be gleaned from the estimated magnet weight of 50 tons. Coil forces of the order of 1 million pounds per linear inch must be constrained when the central field is 20 kG. All of the associated structure will be cooled to 4.2°K, and certain pumping surfaces near the plasma will use subcooled helium in the 2-2.5°K range.

The target base pressure for this Alice II Experiment is 10^{-13} torr, and the trapping chamber itself will be a huge pump with both 80°K and

2.5°K cryo-surfaces.

Fiscal 1970 is the target date for completion of this facility.

REFERENCES

- ¹W.S. Neef, Lawrence Radiation Laboratory (Livermore), Rept. UCRL-12325, Jan. 14, 1965.
- ²W. A. Perkins and J. C. Brown, Lawrence Radiation Laboratory (Livermore), Rept. UCRL-7744, March 3, 1964.
- ³R. W. Moir and L. C. Pittenger, Lawrence Radiation Laboratory (Livermore), Rept. UCID-4750, Aug. 10, 1964.

FIGURE CAPTIONS

- Fig. 1. 66° baseball magnet field geometry.
- Fig. 2. Force on one-quarter of "baseball" magnet.
- Fig. 3. Winding fixture for "baseball" magnet.
- Fig. 4. Trapping chamber and coil prior to assembly into environmental chamber.
- Fig. 5. "Baseball" plasma-trapping chamber.
- Fig. 6. Schematic plan view of "baseball" vacuum systems.
- Fig. 7. Plasma pumping system.
- Fig. 8. Liquid nitrogen plumbing.

IBI AT CENTER = 9.7 KG
 $NI = 2 \times 10^6$ AMP TURNS

66° BASEBALL MAGNET FIELD GEOMETRY

FIGURE I.

FIG. 2
FORCE ON ONE-QUARTER
OF "BASEBALL" MAGNET

400 Turns Square Hollow
Copper Conductor

FIG. 3

WINDING FIXTURE
for "BASEBALL" MAGNET

Fig. 4 - Bathgate

FIG.5

"BASEBALL" PLASMA TRAPPING CHAMBER

Fig. 6 - Bathgate

Fig. 7 - Bathgate

Fig. 8 - Bathgate

DISTRIBUTION

LRL Internal Distribution

No. Copies

Michael M. May

Dr. C.M. Van Atta

2

Wallace Decker

William Watson

Tomas Batzer

Robert E. Bathgate

13

William S. Neef, Jr.

12

R. K. Wakerling, Berkeley

2

TID File

30

External Distribution

Division of Technical Information Extension, Oak Ridge, Tenn.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

VM/ss