EXPERIMENTAL SUPERCONDUCTING ACCELERATOR RING*

(ESCAR)

R. Avery, T. Elioff, A. Garren, W. Gilbert, M. Green, H. Grunder, E. Hartwig, D. Hopkins, G. Lambertson, E. Lofgren, K. Lou, R. Meuser, R. Peters, L. Smith, J. Staples, R. Thomas, R. Wolgast

Lawrence Berkeley Laboratory
Berkeley, California

Introduction

The ESCAR project is an accelerator technology development for which the primary goal is the fabrication and operation of a relatively small proton synchrotron and storage ring employing superconducting magnet elements for the main ring. The purpose is to gather data and experience to insure that the planning and design of future large superconducting synchrotrons and storage rings may proceed in a knowledgeable and responsible manner.

The proposed project will not only provide the experience of fabricating and operating a complete cryogenic magnet system with a significant advancement beyond present experience, but it will also provide a comprehensive accelerator system from which can be learned the realities of the interaction between the cryogenic components and the many other elements of an accelerator. The extent to which these elements (e.g., rf, injection, vacuum, control systems, etc.) are compatible with the cryogenic features of the accelerator, and to which they force modifications of the design, will be determined.

The ESCAR circulating beam will permit experimentation on important aspects of the dynamics of high-current stored proton beams. In this area there are many unresolved issues of importance to future storage rings. The flexibility to carry out a program of beam experiments will be incorporated in the design. Finally, the ESCAR system may indeed prove suitable for an experimental program with high-energy heavy ions, or as a booster-injector for future high-energy proton systems.

Design Goals

The following general parameters express the intended scope of ESCAR.

Maximum Energy -	4.2 GeV
Intensity -	5×10^{12} protons
Pulse Rate -	6/minute
Pressure -	10^{-11} torr
Injection Energy-	50 MeV.

The maximum energy is chosen to permit a realistic test of high-field magnets at a reasonable cost. The intensity evolves from the characteristics of the existing injector, the desire to avoid excessive apertures in the main-ring magnets, and the desire to investigate high-current beam effects. The pulse rate is determined (initially) by power supply and refrigerator capabilities. The magnet system will be capable of faster pulse rates; additional refrigeration capacity can be added if higher pulse rates are desired. Of course, d.c. operation will be provided, and the low pressure expected from cryogenic pumping will permit beam storage times of several hours.

Physical Location

The overall layout with respect to the Bevatron is shown in Fig. 1. ESCAR will utilize the existing 50 MeV linac which is in close proximity. The linac is used also as a proton injector for the Bevatron. A pulsed magnet will direct the 50 MeV beam either to ESCAR or to the Bevatron. ESCAR is located at the rear of the existing Bevatron experimental hall which provides roof coverage, 30-ton-crane facilities, and heavy-duty floor and foundation. Adequate power and water distribution systems are located in tunnels below the experimental hall. No major interference with the Bevatron-Bevalac program is anticipated.

Machine Geometry

An expanded view of the ESCAR system is shown in Fig. 2. The ring, of 15 m average radius, has 4 long straight sections, each 6 meters in length. The lower straight section is occupied by the injection and beam dump system, the right straight section contains the normal accelerating rf system, and the other straight sections are available for experiments, monitoring, and diagnostics. High-frequency cavities which might be used for longitudinal bunch compression are indicated as a future possibility on the left side of the ring.

The magnet layout in a quadrant, or cell, of the lattice is shown schematically in Fig. 3. It is a separated function structure with focusing provided by the groups of 4 quadrupoles. Six dipoles, each $\sim$ 1 meter long, form the 90° arc of each quadrant. This arrangement provides adequate straight sections and a loosely-packed lattice structure which is desired for diagnostics and general flexibility. The betatron functions are shown in Fig. 4, corresponding to betatron tune values of $\nu_x = \nu_y = 3.25$. The structure allows arbitrary values for the transition energy. The nominal value chosen, $\gamma_t \approx 8$, is well above the peak energy--as it would be difficult at best to cross transition with 5×10^{12} protons. The high value of γ_t has been achieved by the action of the strong Q4 lenses that reduce the excursion of off-momentum particles in the curved regions (see Fig. 4). Independent variations of ν_x, ν_y, and γ_t may be obtained by adjustments of the quadrupoles. γ_t can be brought within the machine energy range if experimentation on crossing γ_t is desired. Table I summarizes the nominal value of most of the machine parameters. Other physical paramenters are shown in Fig. 3. Further optimization of these parameters can be expected as the detailed design evolves.

* Work supported by the U.S. Atomic Energy Commission.

Table I

Design Momentum	P	5 GeV/c
Kinetic Energy	T	4.2 GeV
Dipole Field	B_o	4.6 T
Quadrupole Gradients:	dB/dr	
Q1		12 T/m
Q2		-13 T/m
Q3		-15 T/m
Q4		18 T/m
Aperture Radius (dipoles & quads)	A_r	8.2 cm
Number of Cells	N	4
Betatron Tunes	$\nu_x = \nu_y$	3.25
Transition Energy	γ_t	7.8
Beta Function (maxima)	$\hat{\beta}_x$	16.4 m
	$\hat{\beta}_y$	20.2 m
Dispersion (maximum)	$\hat{\eta}_x$	3.3 m
Injection (vertical stacking)		
Energy	E_{inj}	50 MeV
Linac Emittance	ε_L	2π cm-mrad
Linac Current	I_L	100 mA
Number of Injected Turns	n	∿20
Captured Intensity	N_p	5×10^{12} protons
Stacked Emittances	ε_H	2π cm-mrad
	ε_V	16π cm-mrad

Injection and Ejection

To obtain the intensity of 5×10^{12} protons, one must use multiturn injection and stack about 12 effective turns, of which about 70% will be captured by the accelerating rf. The stacking will be done in vertical betatron space using programmed kicker-magnets. If needed for additional intensity and to make the beam cross-section more round, the beam from the linac may be split vertically and recombined radially before injection to reduce the vertical emittance.

For an experimental accelerator, it is particularly desirable to minimize radioactivation by the accelerated beam. Normal operation will include deceleration of the beam and controlled internal dumping at an energy below 150 MeV. The primary goal of the project and studies of single-particle dynamics can be done with an intensity reduced to 10^{11} or less protons. For emergency beam dumping at high intensity, a pulsed magnetic ejector is planned.

Accelerating Radiofrequency System

For the greatest flexibility in beam experiments, the particles shall be accelerated in one bunch at the first-harmonic frequency. After acceleration, if desired, the beam can be more tightly bunched or divided into a few bunches by a second, higher-frequency system. It is possible that a single drift tube may serve for both frequencies; that is, it will act as an accelerating drift tube at the fundamental frequency and also act as a half-wave resonator at a higher harmonic; e.g., the 10th or 11th. For experiments with extremely short bunched beams, it will be possible to add other high-frequency cavities.

Magnets and Cryosystem

The magnets and associated equipment are central to the ESCAR experiment and will include many features appropriate to a full-scale high-energy ring. Although certain adaptations to the magnets are required by the smaller scale of ESCAR, the experience gained with the complete system will be directly applicable to future systems. Hence, the magnet system must not be regarded as an exact prototype but a realistic test of the technology.

The preliminary design for the dipole magnets is illustrated in Fig. 5. The quadrupoles will have a similar structure. Each dipole is ∿1 meter long, with a design field of 4.6 T. The magnet design[1] incorporates intrinsically stable, fine filament, NbTi superconductor that is well cooled with liquid helium and rigidly supported. The high-vacuum region is enclosed by a cold beam tube upon which the multi-layered coil is wound. Circular symmetry is used in all inner regions to yield the best possible structural and magnetic properties.

The cold-bore system will be continuous through each quadrant of the ring containing 6 dipoles and 8 quadrupoles. Helium at 4.4°K is introduced at the quadrant entrance magnet, flows through the quadrant elements, and then flows back, at reduced pressure and temperature in the outer annular region of the cryostats, as in a counter-flow heat exchanger[2]. This system is surrounded by evacuated super-insulation and an 80° temperature shield. The magnet iron at room temperature surrounds the cryostat. The cryostats of three dipoles will be welded together, forming a single unit to be assembled into the main ring. Two such units are required in each quadrant. In addition, there will be two straight cryostats, each containing 4 quadrupoles to complete each quadrant.

The maximum required quadrupole gradient is 20 T/m. The quadrupoles will be separately controlled to vary focusing conditions. Initially the magnets will have a 5 second rise time to full field, as determined by the capacities of the power supply and the refrigeration system. Shorter rise times as low as one second are possible and will not complicate the magnet fabrication or the conductor requirements. Without flattop the pulse rate will be six per minute, or the power supply can hold full current continuously for studies with coasting beam.

In the straight sections, it is planned to maintain the beam tube at ∿4.4°K, except where a warm section is required for special equipment. The magnets may remain cold while straight sections are warmed and opened. The refrigeration capacity required is 1500 watts. The choice of the optimum refrigerator system is presently under investigation.

Vacuum

The vacuum system will be designed for 10^{-11} torr. It is believed that this can be economically obtained via distributed cryopumps at 4.4°K. This is the operating temperature of the superconducting magnets and provides practically unlimited pumping capacity for all gases except helium and hydrogen. Hydrogen can be pumped effectively by bare-surface cryopumps up to a coverage of eight-tenths of a monolayer. The only helium gas loads which could arise come from leaks from the refrigeration system. Helium is pumped by bare-surface cryopumps at a pressure of 10^{-11} torr to only 1/1000 of a monolayer before saturation. Because of the large area of cold surface available, about 200 minimum detectable leaks can be pumped effectively for a number of weeks.

The straight sections contain the accelerating cavities, the injection and extraction systems, and diagnostic equipment. These elements will present additional gas loads for which the geometry and size of the cryopumps must be designed. Distributed cryopumping will be used where possible. The hydrogen and helium pumping capacity of the straight section cryopumps can be increased as required by operation at a lower temperature, by a permanent electro-deposit of porous silver, or by a replaceable condensation deposit of CO_2. The CO_2 deposit could be especially useful in the valved cryopumps used for finish roughing and conditioning. These pumps could be operated steadily to remove small helium leak loads. Gas loads that could enter from the straight sections into magnet sections will be intercepted by short lengths of tubular cryopumps that are easily cycled.

While a cold bore through most of the system provides excellent cryopumping, the surfaces surrounding a high-intensity beam are a concern with respect to gas desorption, the electrical impedances presented to the beam, and the potential need for ion-clearing electrodes. Consequently, various liners for the bore are being considered.[3] Fig. 6 illustrates some examples. These vacuum system questions are an important part of the ESCAR mission. The cold-bore system visualized here would greatly simplify the design and reduce costs[4] of future large proton storage rings.

Accelerator Research

In addition to the primary goal of obtaining a workable superconducting accelerator system, it is expected that ESCAR can be effectively utilized to investigate phenomena related to high-current stored proton beams. Some of the present design considerations for high-energy colliding beam devices are making new demands, for example, on beam densities, magnet tolerances, and rf systems. ESCAR should be able to provide additional information with regard to some of the beam effects in question. The relatively long straight sections would permit the addition of special diagnostic components, low-β insertions, or rf systems to accomplish strong bunching, as required, for example, in the PEP device[5].

In the 1973 PEP Summer Study, a number of problems were discussed for which various existing and proposed devices would provide important contributions toward future proton storage rings. Listed below are suggested studies[6] for ESCAR:

- Methods for achieving ultra-short bunches. Can high-frequency passive cavities be used for self-bunching?
- Bunch stability: coupling of the beam to cryogenic surroundings, bunch-broadening phenomena (transverse and longitudinal), multibunch effects, rf noise, intrabeam scattering.
- Beam-vacuum interaction. What are the differences with bunched and unbunched beams?
- Investigation of cold-bore vs. warm-bore vacuum systems.
- Investigation of new diagnostics for beam measurements in a cryogenic environment.
- Investigation of methods for correction elements; i.e., superconducting or conventional, lumped or distributed?
- Determination of radiation damage effects and fatigue effects on superconducting elements. Also beam-heating effects.

Some of the above examples are a logical part of the primary ESCAR goal, such as the feasibility of the cold-bore vacuum system. It is expected, however, that many other phenomena will arise and require investigation when a real circulating high-peak current beam is at hand.

Other Research Potential

Aside from the potential value for experiments in beam effects, ESCAR could provide unique physics research facilities for ultra-heavy ions. In Fig. 1, it is seen that it would be relatively easy to inject ions as heavy as Uranium from the SuperHILAC, whose output-beam line is near the 50 MeV linac which serves as the ESCAR proton injector. Due to the excellent ESCAR vacuum system, the unstripped SuperHILAC output could be accelerated in ESCAR to $\sim$300 MeV/nucleon, which is nearly two orders of magnitude more energetic than any existing system. Partially stripped outputs could reach more than 1200 MeV/nucleon. Apart from obvious uses in nuclear science and in biomedical studies, the interest in such energies has been heightened by recent theories[7] which indicate the possibility of new superheavy states of nuclear matter which might be achieved by heavy ion collision at these energies.

Another possibility is the use of ESCAR as a booster injector for future proton storage rings. The ESCAR parameters are well matched to the proton injector requirements of PEP Stage II. In any case, its components could provide a compact injector for a future high-energy storage ring.

Schedule and Plans

The nominal parameters and systems outlined above are presently being investigated in detail. A preliminary engineering design for all system components is planned for completion in July 1974. Final design and fabrication of components can begin at that time, coincident with the beginning of FY 75. Based on expected funding levels, 2.5 years are projected to fabricate ESCAR and begin operational testing.

The AEC has appointed an ESCAR advisory board having members from other accelerator laboratories. It is intended that this group help guide the scientific planning of the project. It is recognized that the primary goal of ESCAR is to gain information on superconducting accelerator design and system operation. For this purpose alone, the entire project could be considered as an experiment that would end with successful operation as an accelerator and storage ring. But it is also apparent that the ring has potential value as a tool for experiments in beam effects and controls, as well as for physics research.

At this time, when funding is limited and progress requires the extrapolation of our understanding to ever more complex and costly machines, it seems that ESCAR will be a very appropriate and productive experiment in accelerator science.

References

1. W. Gilbert, R. Meuser, and F. Toby, Proceedings of the International Conference on Magnet Technology, BNL, Upton, N.Y., September 19-22, 1972.
2. Refrigeration System for the NAL Energy Doubler, Cryogenic Consultants Incorporated, April 26, 1973 (Unpublished).
3. Superconducting Accelerator Miniproject (Concept & Intent), LBL Accelerator Study Group, Proposal #1, Sept.1973.
4. J. R. J. Bennett, Hot or Cold Bore for a Superconducting EPIC Ring, Rutherford Internal Report EPIC/MC/42.
5. L. Smith, The Proton-Electron-Positron Project, Proceedings of the 9th International Conference on High Energy Accelerators, Stanford, May 2-7, 1974.
6. 1973 PEP Summer Study Report, LBL-SLAC Study Group, PEP Note #66, March 1974.
7. T.D. Lee and G. C. Wick, Physical Review D, April 15, 1974.
8. This method is related to that utilized by V. V. Vladimirskii and E. K. Tarasov, "Problems of Cyclic Accelerators," USSR Academy of Sciences, Moscow, 1955.

Fig. 1
ESCAR Location

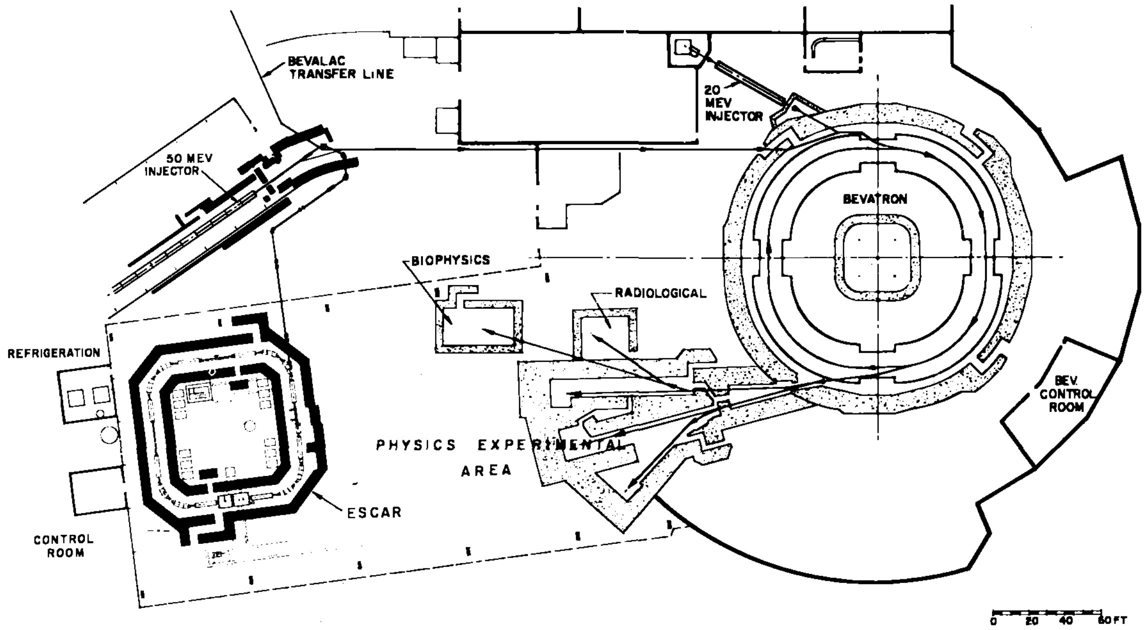
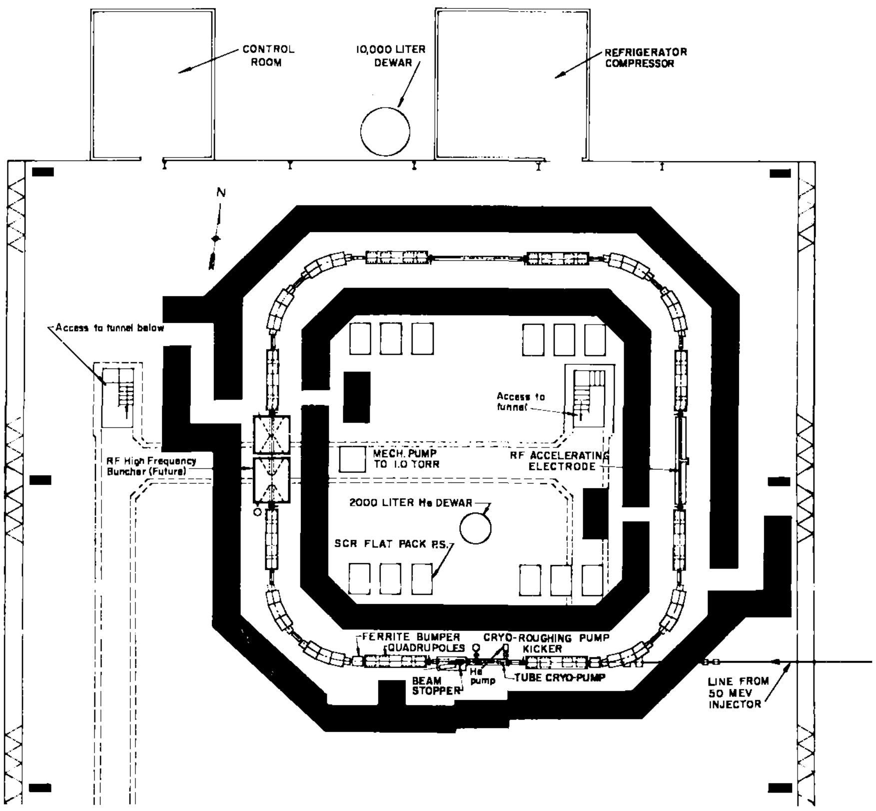


Fig. 2
Ring Geometry



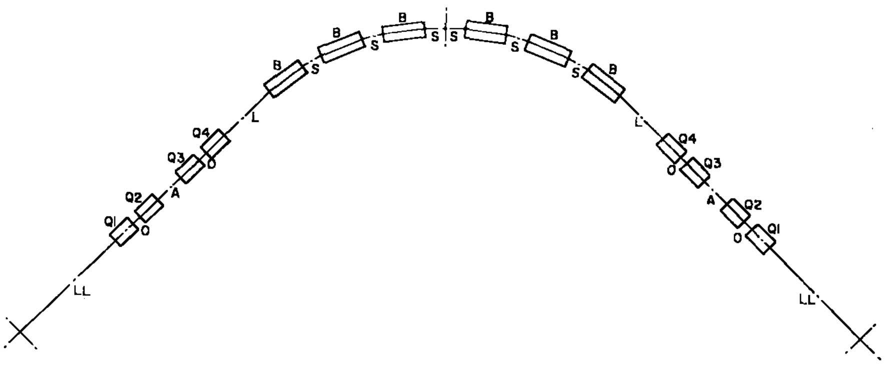
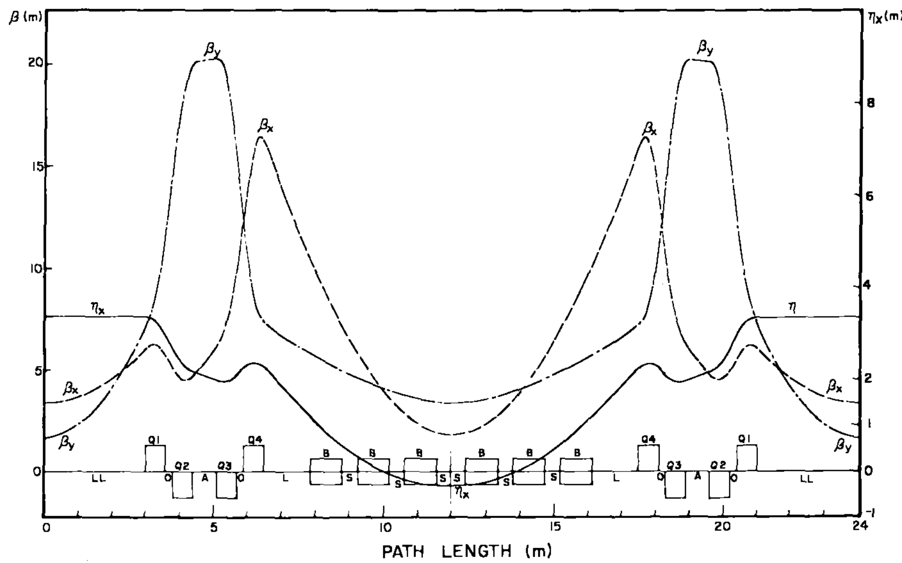


Fig. 3 - ESCAR Quadrant Schematic

Radius (Circ./2π)	R	15.29	m	Drift Lengths (Effective):		
Magnetic Radius	ρ	3.6287	m		LL	3.00 m
Cell Length	Lc	24.0	m		O	0.20 m
Quadrupole Effective Length	ℓ_Q	0.6	m		A	0.70 m
Dipole Effective Length	ℓ_B	0.95	m		L	1.36 m
					S	0.43 m

Fig. 4 Betatron Functions



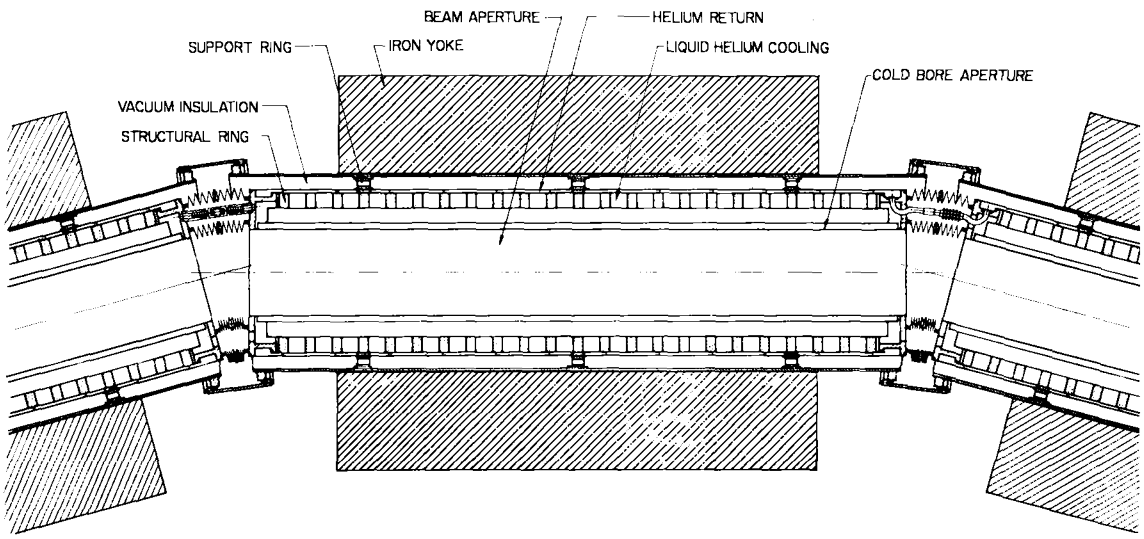


Fig. 5 - Dipole Magnet Structure