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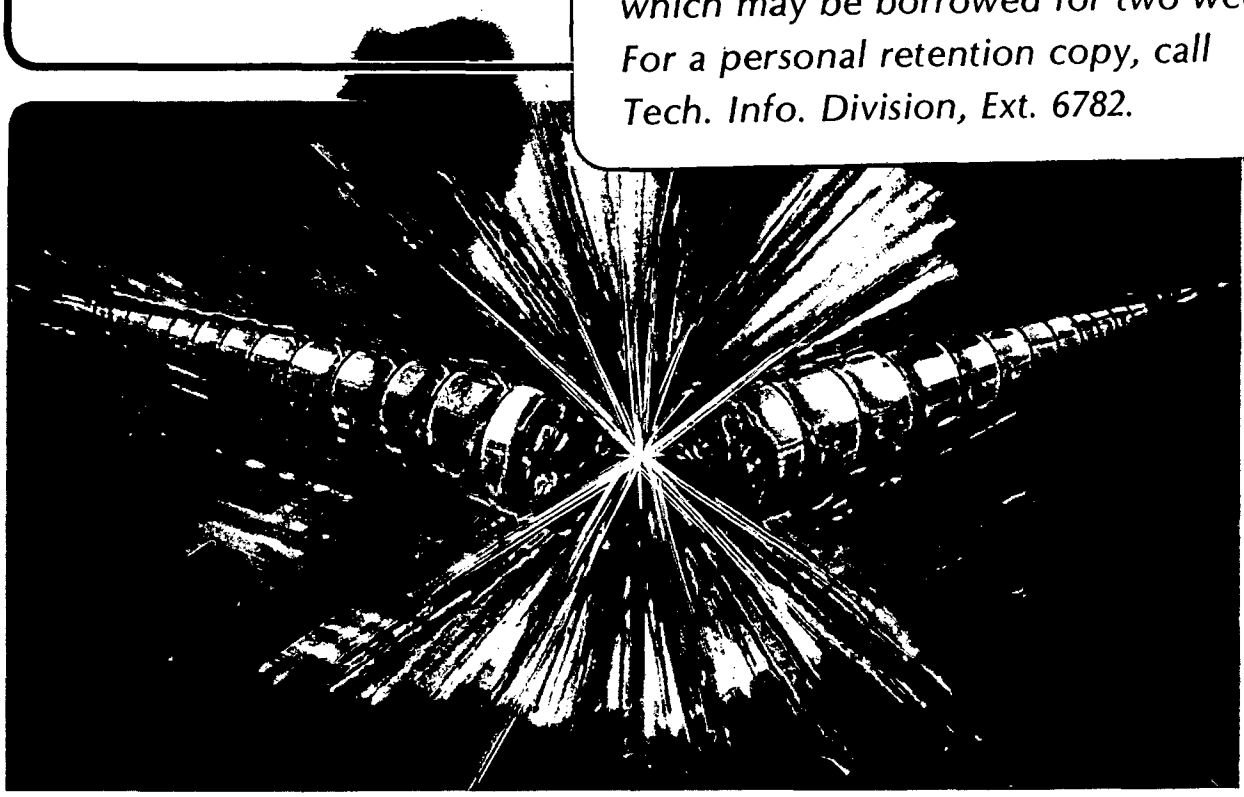

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VACUUM SYSTEM DESIGN FOR A NEUTRAL BEAM INJECTION SYSTEM*

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ABSTRACT

A conceptual design study of neutral beamlines to deliver up to 25 Mwatts of 160 keV neutral deuterium to the proposed West German tokamak, ZEPHYR, was performed at LBL.[1] The study included predicted vacuum behavior of a neutral beamline module, proposed cryopanel design, and a suggested topology for the cryogenic flow distribution system. The cryopanel features an all tubular structure, designed for maximum mechanical flexibility without the use of the bellows in the flow volume. The structure will be insensitive to thermal shock and can withstand large pressure excursions. The distribution system is designed for forced flow cryogenic fluid delivery in two circuits, each feeding three neutral beamlines in hydraulic series. The requirements for balancing a large number of parallel circuits and for long transfer lines are thus avoided by this simple distribution system. Although the plans for ZEPHYR construction were cancelled, the vacuum calculations, the cryopanel and distribution system design are relevant for the future design of neutral beamlines required for plasma heating of the next generation of magnetic fusion devices.

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INTRODUCTION

The vacuum system design for a Neutral Beam Injection System (NBIS) to provide heating for a fusion reactor is multifaceted challenge. Tradeoffs occur at all levels, from the setting of the fundamental Physics parameters, to the design of the mechanical systems for low initial cost and ease of operation and/or maintenance.

This paper describes the design process followed by the Lawrence Berkeley Laboratory (LBL) staff in the course of developing a conceptual design for a NBIS for ZEPHYR. The discussion concentrates on the vacuum and cryogenics aspects of the design, but considers other mechanical components when they couple tightly to the design parameters of the vacuum and cryogenic hardware. Finally, the design is a direct descendent of the Doublet III Injector (designed and fabricated at LBL) and the TFTR Injector (designed at LLL, fabricated and operated at LBL), and benefits from the fabrication, assembly and operating experience accumulated at LBL.

PHYSICS SPECIFICATIONS AND CONSTRAINTS

The ZEPHYR specifications called for six neutral beamlines, each beamline delivering 50 amps of deuterium neutrals at 160 keV. At this energy the efficiency of a gas neutralizer for D^+ is poor, requires a "thick" neutralizer, and results in a large flux of charged particles delivered to the beam dump. The source divergence required a long wide neutralizer operating at low pressure or a short narrow neutralizer operating at high pressure. The gas load for the various sizes was a rather flat function of the geometry, and the selected neutralizer/source design was predicted to deliver a gas load of 60 t-l/sec of deuterium. The gas load predicted from the remaining charged pacticles added another 10 t-l/sec at the beam dump location. Miscellaneous beam losses at the collimators in

the beam delivery aperture added a gas load of 1 t-l/sec at the "downstream" end of the beamline. An additional (often overlooked) constraint are the eddy currents generated by the high magnetic field in the immediate vicinity of the tokamak reactor. This required the design of elements, sensitive to eddy current heating, which minimize large continuous areas or loops.

BEAMLINE DESIGN

Figs. 1 and 2 show the relative locations of the beamline components in the NBIS, and indicate the scale of the device. The vacuum objective in laying out and locating the various beamline components was to reduce the integrated pressure x distance value beyond the end of the neutralizer. The $\int pdl$ between the end of the neutralizer and the exit of the magnet represents "controlled" losses. The neutrals ionized in this region will be swept out of the beamline and only results in performance inefficiences. The $\int pdl$ beyond the end of the magnet results in undesired ionized particles aimed toward the reactor plasma. A reflection magnet geometry was chosen for ion removal so as to remove the gas source (the beam dump) away from the neutral drift line. The three gap analyzing magnet is located and mounted so that it acts to reduce the gas flow from the neutralizer to the downstream beamline. Five cryopanel modules with total pumping area of 50 m^2 (4.4×10^6 l/sec total D_2 pumping speed) are mounted along the lateral walls and across the center of the beamline. The center cryopanel pumps from both sides and also acts as a septum, further reducing downstream gas flow. The refrigeration load for this cryopanel system is estimated (in equivalent cryogen consumption) at 100 l/hour LHe, and 260 l/hour LN_2. However, recent measurements at the Neutral Beam Test Facility (NBSTF) indicate that the actual loads may be only 35 to 40% of these figures.

PRESSURE DISTRIBUTION CALCULATION

The pressure distribution calculations follow the method used by Feist[2] and Kamperschroer[3] using the classical conductance formula between adjacent volumes. These conductances are computed and arranged in a matrix which reflects the coupling between volumes, and the matrix is inverted to solve for the pressure distribution.[4]

$$[C]\,(p) = (q)$$

$[C]$ = conductance matrix
(p) = pressure vector
(q) = gas load vector

"Streaming" is a possibility in the direction of the beam thru the analyzer magnet. Corrections for the conductances due to streaming are possible. However, the pressure distribution results presented here are not corrected for gas streaming because the exponent which characterizes the Cosine distribution is not well known for the source/neutralizer systems proposed.

The results of the pressure distribution calculation are shown in Figs. 3 and 4. The reionization losses between the neutralizer and the analyzing magnet exit is predicted to be 5.5%, which shows up as slightly more gas generated at the beam dump, and requires additional cooling over an extended area. (The distribution and thus the orbits of the ions created in the magnetic field are difficult to predict.) The reionization losses beyond the magnet is predicted to be a tolerable 1.5%.

CRYOPANEL DESIGN

The cryopanel design is a rather conventional LN_2 cooled chevron panel shielding a flat surface cooled with helium at ~4.2° K. The chevron geometry was chosen rather then the "one bounce" geometries adopted by JET[5] and fabricated for Doublet III[6] (sufficient room was available for the

cryopanel area required, and the higher specific pumping speeds of the one-bounce systems were not required).

The cryogenic flow circuit for both LHe and LN_2 cooled panels are tubular and require pumped feeds for the cryogenic fluids. The tubular construction has several advantages which more than compensate for the apparent simplicity of the free convective flow system used in the TFTR cryopanal design.

1. Tubular construction is inherently light and strong and can take advantage of automated welding tools for fast, reliable joining.
2. The mechanical flexibility of tubular structures allows one to avoid the use of bellows in the flow lines. The high pressure capabilities of bellows often constitutes an arbitrarily low pressure limit for the cold circuitry, and requires the design of relief valves into the cryopanel module. This mechanical flexibility also allows the design of a structure which is immune to thermal shock. Warmup and cooldown times are not limited by the cryopanel design. Expensive temperature monitoring and control schemes and devices to measure and control the transient behavior of the cryopanels can be eliminated.
3. Flexibility permits relatively relaxed mechanical tolerances.
4. The fluid inventory for a tubular system is small since the large flow cross-sections required for free convective circuits are not required. This small inventory can be vented safely in the case of an up to air accident or routine maintenance. Also, gas recovery systems can be sized for the fluid inventory of the refrigerater and distribution circuitry, and can ignore the small amount of

fluid stored in the NBIS, thus reducing the facilities cost for the reactor.

5. The tubular structure can be designed "linearily" to reduce to a minimum linkages with the reactor pulsed fringe field. Thus for the higher field, next generation tokamak reactors, the problems associated with the eddy current heat loads on the cryogenic systems can be minimized.

The proposed geometry of the LHe and LN_2 panels are shown in Figs. 5 and 6. The flow circuitry, and the construction schemes used to maintain the mechanical flexibility of these structures are best seen in these figures.

CRYOGENIC CIRCUITRY

Upto six NBIS must be fed with LN_2 and LHe. The topology of the system makes individual parallel feed to all the units impractical because of the excessive transfer line lengths required and the valves needed for flow control and isolation. It was proposed that the cryogenic feed be divided between two circuits, each feeding three NBIS from the central liquid helium refrigerator and LN_2 supply dewar, as shown in Fig. 7. The three NBIS are fed in series, with the boil-off gas being collected in return manifolds. Because of the series-feed arrangement, the flow through an individual NBIS may be up to three times greater than needed for its load. However, the pressure drop is proportional to m^2/d^5, where m is the mass flow rate and d is the tube diameter; thus, increasing the flow cross-section diameters by 60% will more then compensate for the increased pressure drop due to trebling the mass flow rate. For similar reasons, the individual cryopanels on each beam line are also fed in series. Valving makes possible the bypassing of individual beam lines and/or cryopanels.

CLOSURE

At the time of the study, the ground rules were that the design use the existing experience accumulated from the TFTR and Doublet III NBIS design, fabrication, assembly and operating experience, and extrapolate as little as possible from existing technologies developed in these efforts. However, one should not ignore the possibilities and design options which may be available by considering more recent operating data or more exotic design concepts.

Beam loss data from NBSTF indicate that the residual gas in the beamline has an average temperature of approximately 100° K.[7] This is not surprising since the inside wall of the beamline is virtually covered with LN_2 cooled chevrons, and the probability of gas striking a warm component (magnet or beam dump) is estimated at less than 30%. The neutralizer is essentially a room temperature pipe filled with gas. Since the charge exchange probability is higher for lower temperature gas, the present design achieves the opposite effect of that desired for a system designed for most efficient gas utilization. The idea of achieving the desired neutralizer target thickness by cooling the neutralizer to 80° K has been briefly considered. This would significantly reduce the gas load and allow for a reduced area of cryopanel. However, the problems associated with secondary beam collisions and the resulting gas desorption from a cold wall plus heat loads radiating from the hot plasma have not been adequately studied or modeled.

Another idea briefly considered was to construct the neutralizer as an LN_2 cooled chevron, shielding a superconductor cooled to 4.2° K.[8] With proper design, the neutralizer structure can support a large pressure gradient (making a thick target with low total gas flow to the NBIS) and

also act as a magnetic shield excluding the pulsed tokamak magnetic field from the charged particle orbit.

Replacing the cryopanels with zirconium-aluminium getter pumps is another option which will require further investigation. The resulting elimination of the cryogenic supply system infrastructure is an attractive potential simplification and could result in significant initial and operating cost savings.

ACKNOWLEDGEMENTS

The opportunity to generate a "real" design based on the requirements and constraints appropriate to a serious tokamak reactor design was invaluable. For this opportunity, I thank the ZEPHYR staff in West Germany, and in particular Jost Feist who was luckily in the midst of a long term assignment from IPP to LBL. The staff at LBL was headed by Bill Cooper, under whose scientific guidance the engineering requirements were clearly stated. Further scientific support and the effort required to pull together a final design report and proposal were provided by David Goldberg. Ken Lou provided the real life experience from the TFTR construction effort to add economic and manufacturing reality to the conceptual designs.

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FIGURE CAPTIONS

Fig. 1 Plan View of a Neutral Beamline.

Fig. 2 Elevation View of a Neutral Beamline.

Fig. 3 Pressure Distribution along the Beamline

Fig. 4 Pressure Line-Integral Calculated from the Duct Entrance.

Fig. 5 77° K Liquid-Nitrogen-Cooled Chevron Shields.

Fig. 6 4.2° K Helium-Cooled Cryopanel Surface.

Fig. 7 Liquid Helium Distribution System.

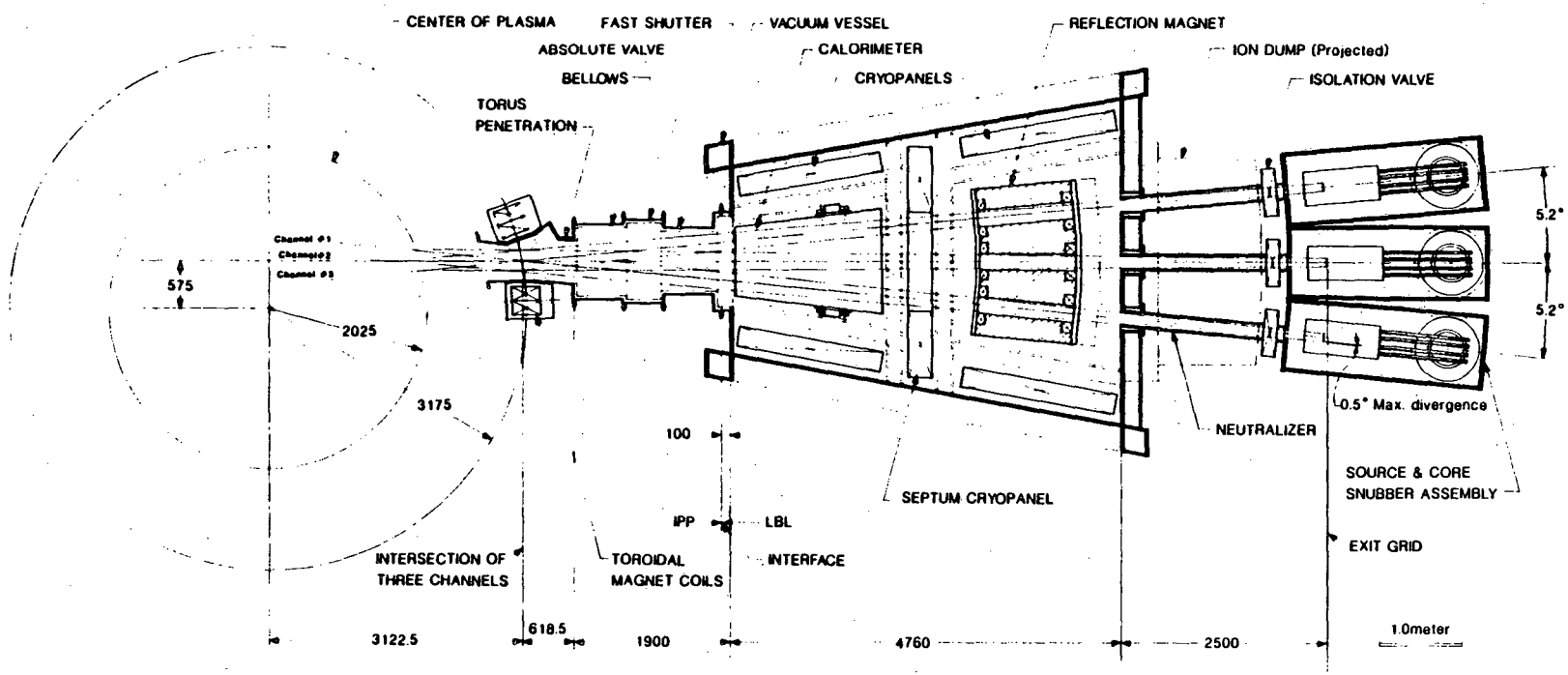

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Fig. 1

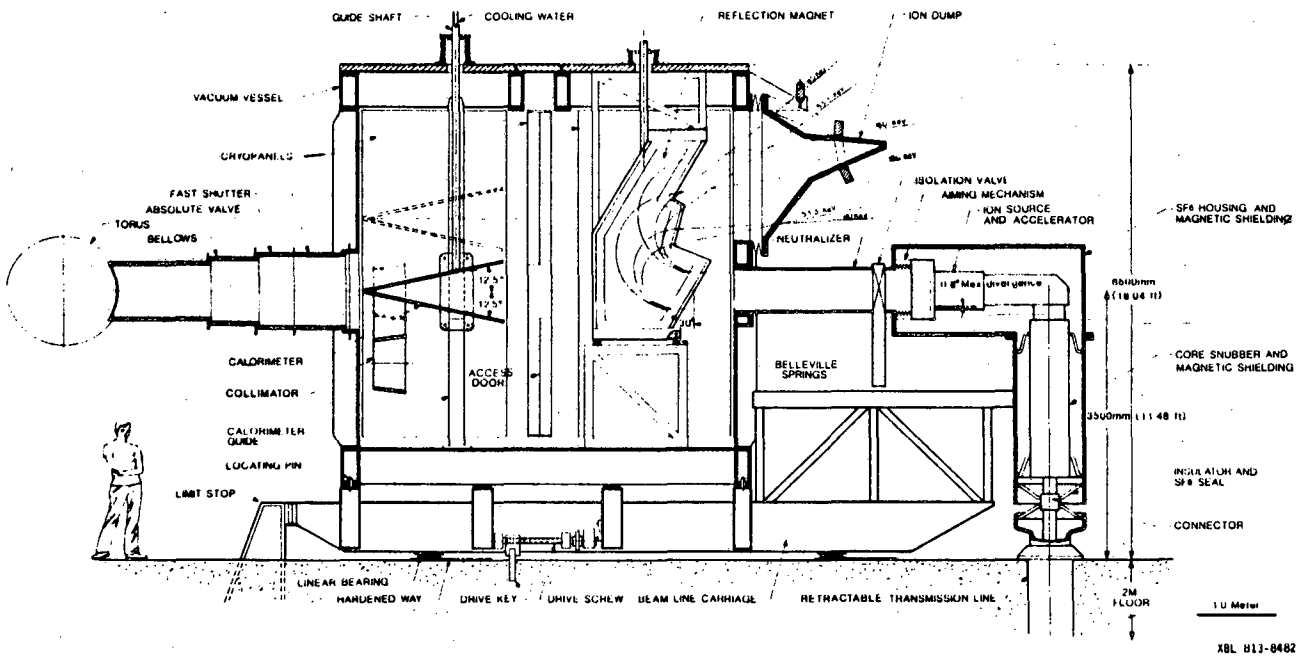
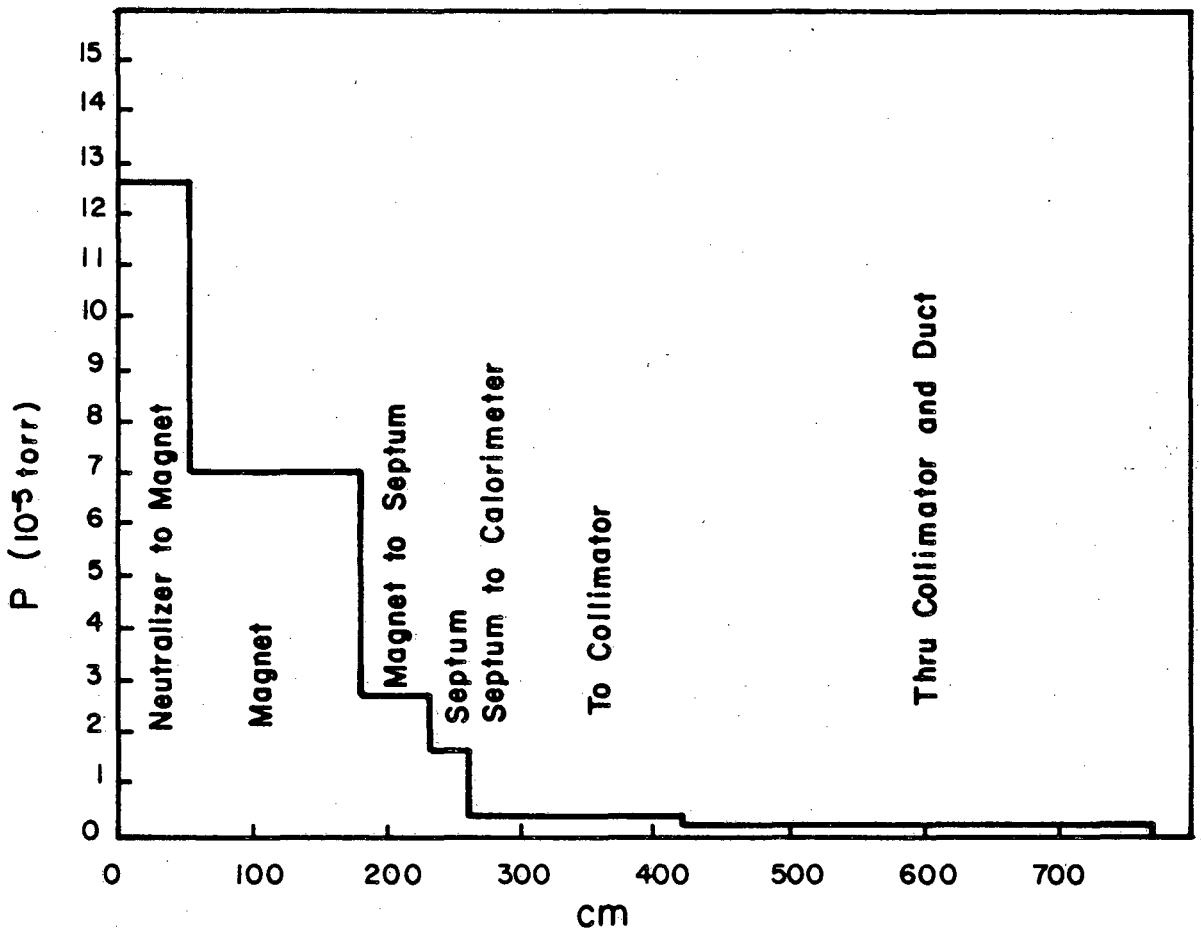

GUIDE SHAFT
COOLING WATER
REFLECTION MAGNET
ION DUMP
VACUUM VESSEL
CRYOPANELS
FAST SHUTTER
ABSOLUTE VALVE
TORUS
BELLOWS
ISOLATION VALVE
AIMING MECHANISM
ION SOURCE
AND ACCELERATOR
NEUTRALIZER
SF6 HOUSING AND
MAGNETIC SHIELDING
CORE SNUBBER AND
MAGNETIC SHIELDING
CALORIMETER
COLLIMATOR
CALORIMETER
GUIDE
LOCATING PIN
LIMIT STOP
ACCESS
DOOR
BELLEVILLE
SPRINGS
INSULATOR AND
SF6 SEAL
CONNECTOR
LINEAR BEARING
HARDENED WAY
DRIVE KEY
DRIVE SCREW
BEAM LINE CARRIAGE
RETRACTABLE TRANSMISSION LINE
2M
FLOOR
1.0 Meter
XBL 813-8482

Fig. 2



Pressure distribution along beamline

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Fig. 3

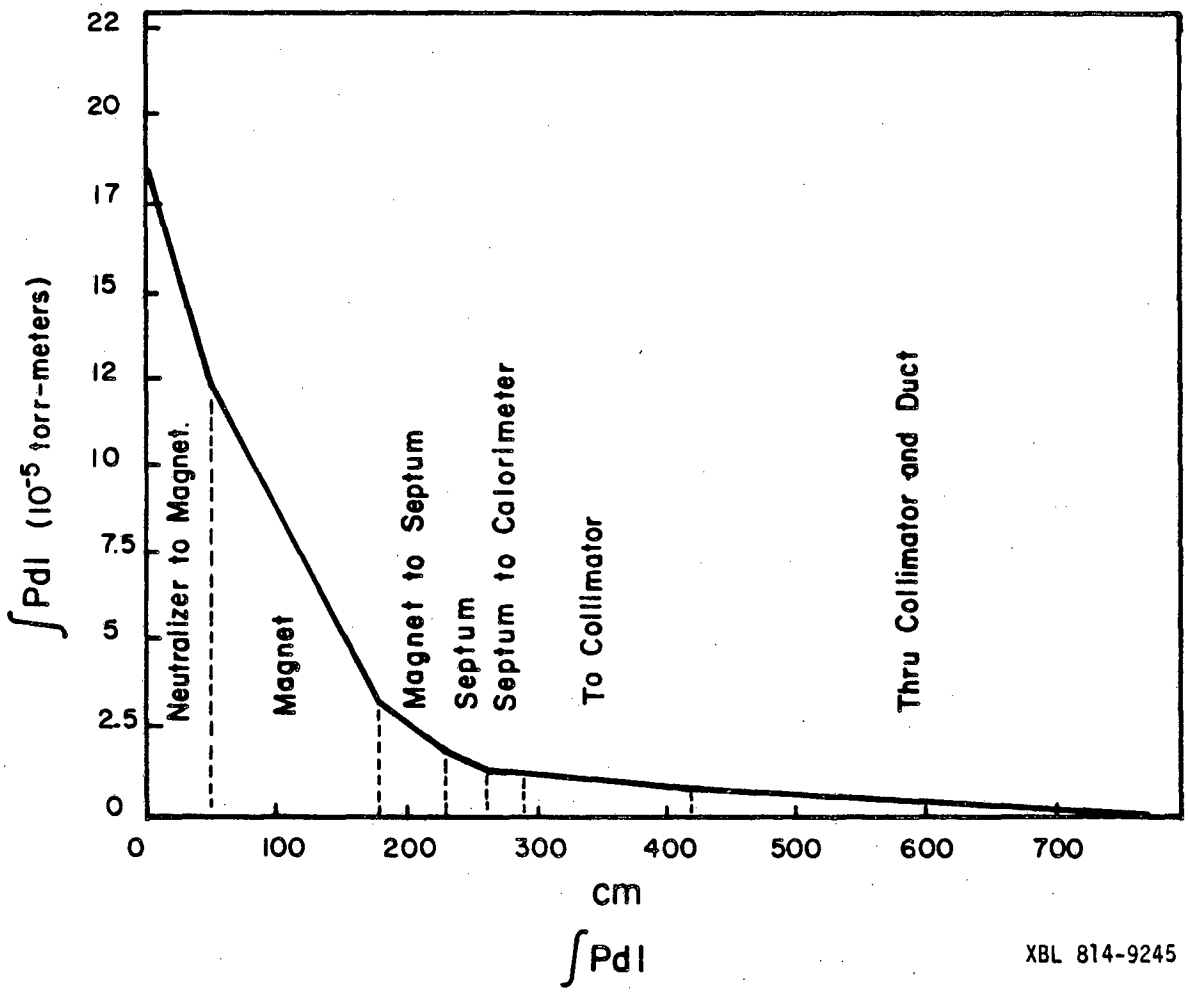
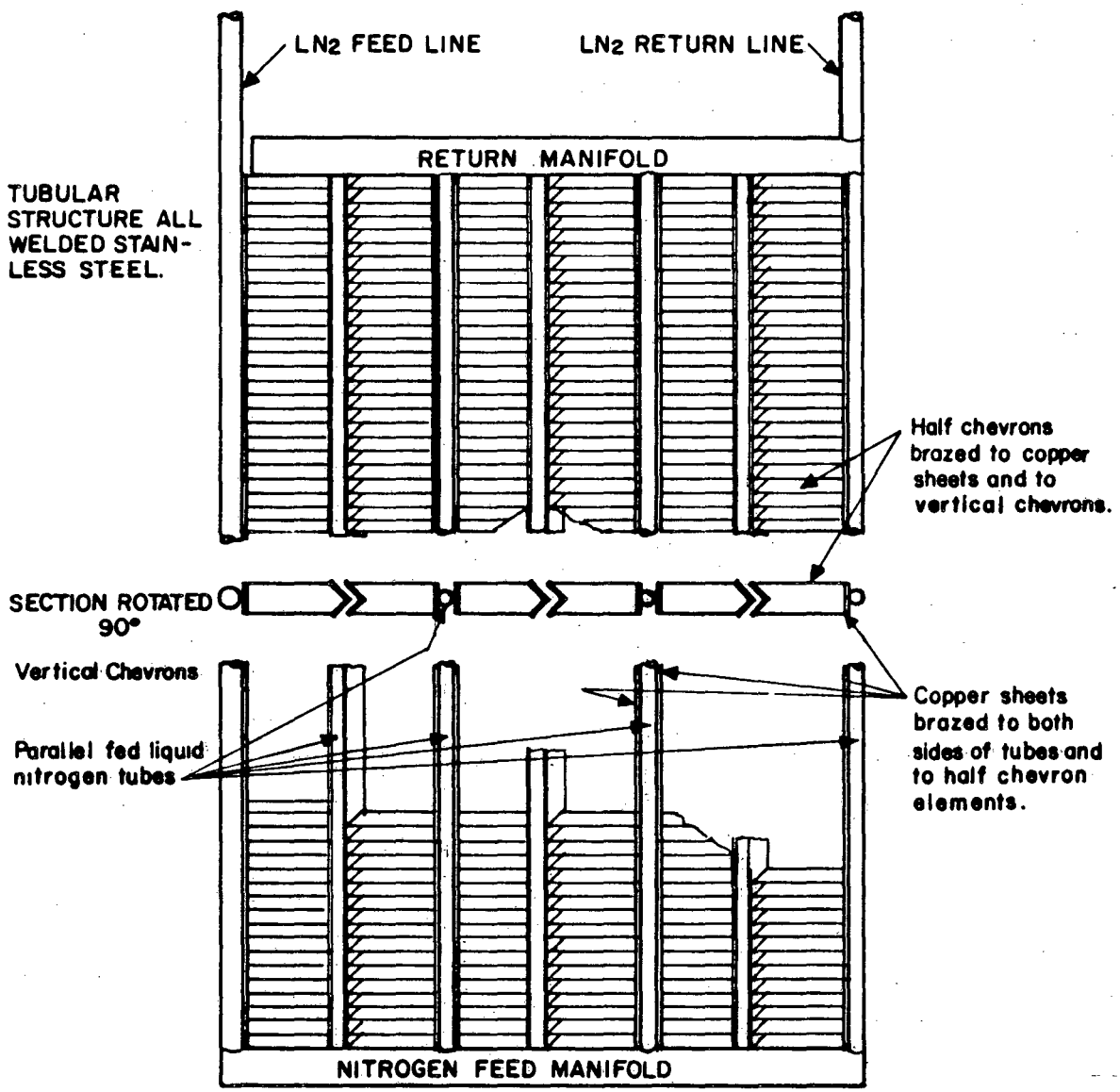

22
20
17
15
12
10
7.5
5
2.5
0
∫Pdl (10⁻⁵ torr-meters)
Neutralizer to Magnet.
Magnet
Magnet to Septum
Septum
Septum to Calorimeter
To Collimator
Thru Collimator and Duct
0
100
200
300
400
500
600
700
cm
∫Pdl
XBL 814-9245

Fig. 4



77° K Liquid-Nitrogen-Cooled Chevron Shields

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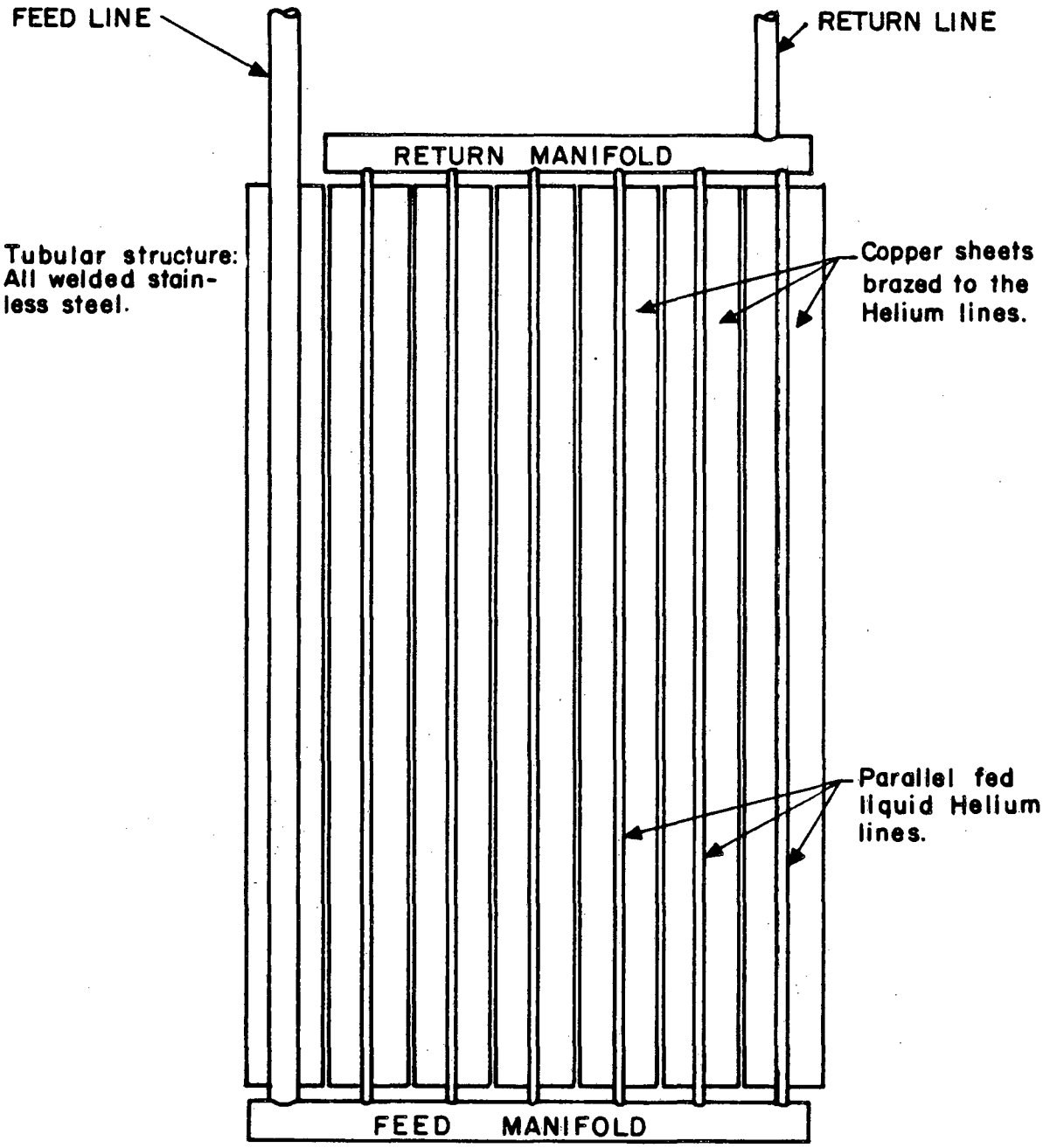
Fig. 5



4.2° K Helium-cooled Cryopanel Surface.

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Fig. 6

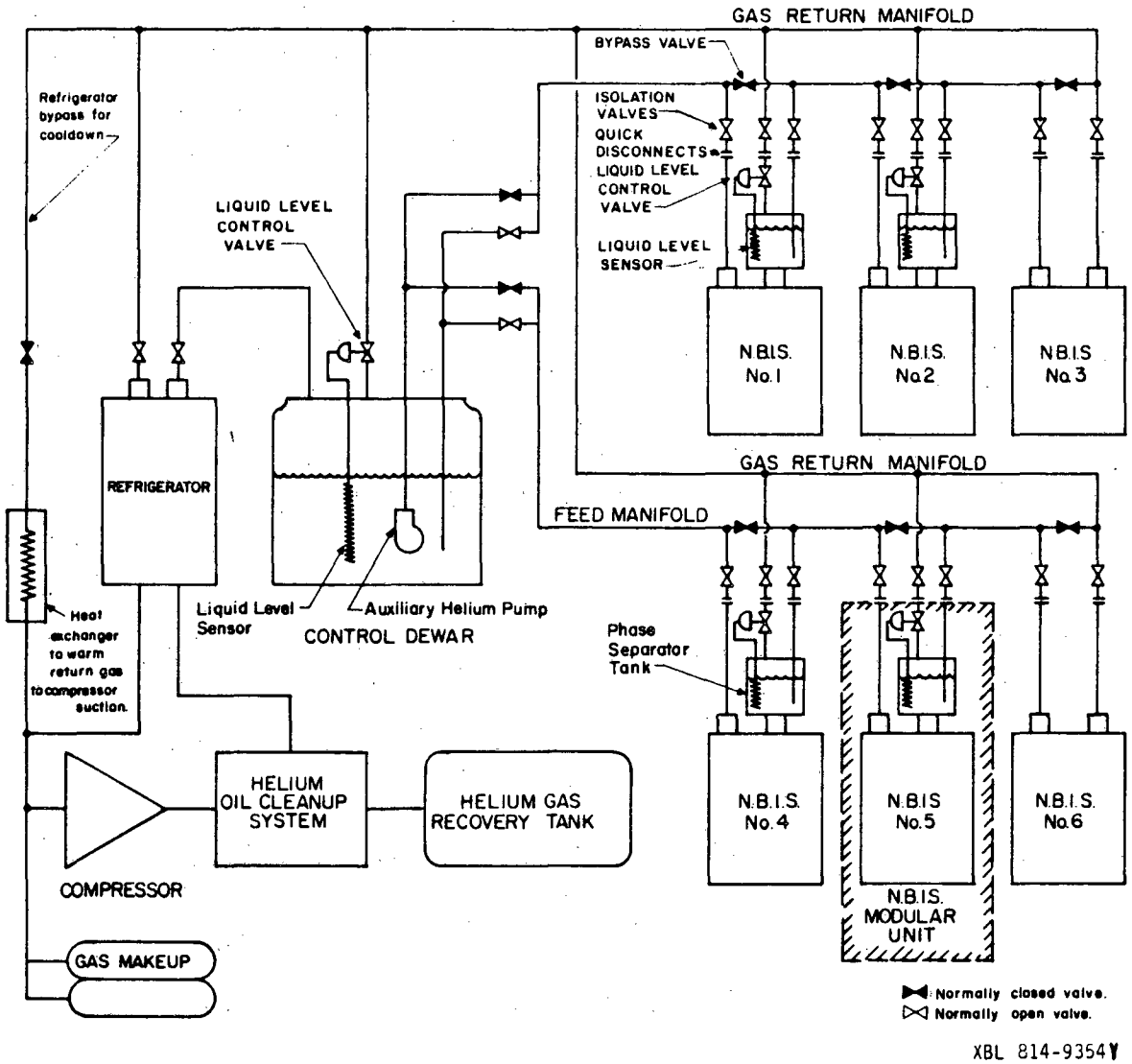
GAS RETURN MANIFOLD
BYPASS VALVE
ISOLATION VALVES
QUICK DISCONNECTS
LIQUID LEVEL CONTROL VALVE
LIQUID LEVEL SENSOR
Refrigerator bypass for cooldown
LIQUID LEVEL CONTROL VALVE
N.B.I.S. No.1
N.B.I.S. No.2
N.B.I.S No.3
REFRIGERATOR
GAS RETURN MANIFOLD
FEED MANIFOLD
Heat exchanger to warm return gas to compressor suction.
Liquid Level Sensor
Auxiliary Helium Pump
CONTROL DEWAR
Phase Separator Tank
HELIUM OIL CLEANUP SYSTEM
HELIUM GAS RECOVERY TANK
N.B.I.S. No.4
N.B.I.S No.5
N.B.I.S. No.6
N.B.I.S. MODULAR UNIT
COMPRESSOR
GAS MAKEUP
Normally closed valve.
Normally open valve.
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Fig. 7

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