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Construction and Commissioning of the AGS Booster Ultra-High Vacuum System*

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ABSTRACT

The recently completed AGS Booster is a synchrotron for the acceleration of both protons and heavy ions. To minimize the beam loss due to charge exchange of the partially stripped, low ß (= v/c), very heavy ions with the residual gas molecules, ultra high vacuum of 10^{-11} Torr is required for the 200 m Booster ring. An average pressure of mid 10^{-11} Torr has been achieved and maintained after initial insitu bakes and commissioning. In this paper we describe: (1) design and layout of the vacuum systems; (2) material selection and vacuum processing; (3) PC/PLC based bakeout system; (4) operation of vacuum instrumentation over long cable length; (5) results of bakeout and evaluation; and (6) experience gained during construction and commissioning.

I. INTRODUCTION

The recently completed AGS Booster at Brookhaven is a small synchrotron of 200 m in circumference located between the existing 200 MeV Linac, the Tandem Van de Graaff and the Alternating Gradi- ent Synchrotron (AGS). The construction was completed in early June, 1991 with the beam commissioning immediately following. The major objectives of the Booster are:

(1) to increase the proton intensity in the AGS by a factor of four, to $6x10^{13}$ particles per pulse(ppp)

(2) to increase the AGS polarized proton intensity by a factor of twenty, to 10^{12} ppp

*Work performed under the auspices of the US Dept of Energy

(3) to accelerate partially stripped heavy ions up to gold (Au) in the Booster for the AGS and eventually for the Relativistic Heavy Ion Collider currently under construction at Brookhaven.

It is the third objective which puts the most stringent re-quirements on the vacuum system of the Booster ring. In heavy ion accelerators, the cross sections for charge exchange (electron stripping and electron capture) between partially stripped, low β, very heavy ions and the residual gas molecules are usually rather large. They were calculated, as detailed in ref. 1, by using empirical formulae which give the best fit to the measured cross-sections. At the design vacuum of $3x10^{-11}$ Torr (90% H_2 and 10% CO), the integrated beam loss during acceleration cycles is less than one percent for Au^{+33} at $E_{inj.}$ = 1 MeV/amu, which has the largest cross sections of all the ion species to be accelerated in the Booster. At a vacuum of $3x10^{-10}$ Torr (10% H_2 and 90% N_2), the beam loss for Au^{+33} is calculated to be over 30%.

II. VACUUM SYSTEMS

The Booster ring, with a circumference of 201.8 m, has 36 half-cells and 12 quarter-cells. The half-cells consist of dipole, quadrupole and sextupole magnets. The 12 "missing dipoles" down-stream of quarter-cells house the accelerating cavities (RF), kickers and other beam components. The ring, as shown schematically in Fig. 1, is grouped into seven vacuum sectors with each sector isolatable with all-metal gate valves. There are three beam trans-port lines, with a total length over 500 m, for injection of pro-tons and heavy ions, and for extraction to AGS. The transport lines are designed for 10^{-10} - 10^{-9} Torr, which serve as a pressure differential between the 10^{-11} Torr ring and the existing 10^{-8} - 10^{-7} Torr vacuum of Linac and AGS. The design of the Booster vacuum system can be found in ref. 2. Some major components are described below.

A. Vacuum Chamber

A typical half-cell chamber is shown in Fig. 2. It is 4.2 m long, made mostly of Inconel 625 and consists of chambers for dipole, quadrupole, pick-up electrodes (PUEs), sextupole, bellows and a transition with ports connecting to pumps, gauges and rough-ing valve. The dipole chambers are 2.8 m long with an elliptical cross-section of 165 x 70 mm and are curved to a radius of 13.75 m and are 2.8 m in length. To compensate for the chamber eddy current effect during magnet ramping, six pairs of correction coils are mounted on the top and bottom of dipole chamber.

Conflat type flanges with 90° knife edges[3] made of 316LN stainless steel are used throughout the ring vacuum system. To prevent recrystallization[4] of pure copper gaskets after repeated high temperature bakes, all gaskets were made of copper alloyed with 0.1% Ag. Quick disconnect type flanges such as the EVAC[5] and the in-house developed 13 inch "Chain-Clamp" flanges, both featuring 90° Conflat knife edges are used at areas with high expected residual radiation. They were repeatedly baked to 300°C with no creeping or leakage.

The PUE location has to be accurate within 0.1 mm after vacuum firing and repeated insitu bake. This lead to the double gimballed suspension[2] which allows the electrodes to be rigidly supported while being free to move radially and longitudinally during vacuum firing or bakeout. The position accuracies achieved were within $\pm$ 0.1 mm in the transverse directions and less than 1 mrad in rotation.

B. Vacuum Pump

The ring vacuum was achieved by the combination of titanium sublimation pumps and ion pumps. Fifty five titanium cartridges with three filaments each are mounted in the pump bodies. The pump body with a 3000 cm^2 area for sublimed titanium has approximately 1000 *l*/s pumping speed for active gases. The non-getterable gases such as methane and argon are removed by small ion pumps. Ion pumps and non-evaporable getter pumps[6] are used in the beam transport lines. Portable turbo-pump stations were used during roughing down, bakeout and conditioning of the vacuum sectors.

C. Bakeout

The vacuum chambers and the components within were designed to be in situ bakeable to 300°C. Thermocouples (TCs) and custom heating blankets were installed on the chambers before assembling into magnets. Kapton wrapped E-type TCs were used for its low magnetic permeability. The blankets have parallel redundant heating elements, made of multiple strand nickel-copper alloy wires, and fiberglass insulating jackets. The tight space between magnet pole tips and chambers limits the thickness of most blankets to no more than 6 mm. The large heat loss to the magnets due to this thin insulation necessitated the circulating of magnet cooling water during the bake. Heating blankets not confined by space requirement vary from 10 mm to 25 mm in thickness.

The bakeout of each vacuum sector was controlled and monitored with portable PC-based programmable logic controllers (PLC). The blankets and TCs of each half cell were terminated to local con-tactor boxes, which were then connected to PLCs prior to bake. Each PLC cart has modules to monitor up to 150 TCs and control up to 100 corresponding processes, such as heating blankets. The PC downloads and initiates the programmed bake cycles and database to PLCs, and also alarms the operators when abnormal or failure condi-tions occur. With one PC and four PLCs, two thirds of the ring can be baked at one time with each sector having its own programmed bake cycle.

D. Instrumentation

Various vacuum instrumentations are needed to power the pumps, monitor and protect this ultra-high vacuum system. Due to the presence of high radiation levels in the Booster tunnel, all power supplies and controls are located in a separate instrumentation building. This includes power supplies for ion and titanium pumps, controllers for vacuum gauges and valves, and the computer systems. The layout of instrumentation is shown schematically in Fig. 3. The commercial gauge controllers communicate with the device controllers (D/Cs) through RS232 links. The ion pump power supplies and valve controllers are linked to the D/Cs through an IEEE-488 com-patible interface. The D/Cs communicate with the Apollo nodes via station drops. The SCR based titanium pump power supplies are operated manually, since they are energized periodically for only a few minutes.

The titanium pump power supplies degas the titanium filaments during pump-down and bakeout, and sublime titanium onto the pump body surfaces when the need arises. These supplies consist of SCR based controllers which power and regulate the sublimation rate using a constant current mode. The current of SCR controllers is stepped up by transformers located near the cartridges. By cali-brating the gain and offset pots of each SCR controller versus the transformer ratios, current stability of better than $\pm$ 2% is achieved during sublimation at 48 A. The sublimation rate is approximately 1 mg/min. One gram of titanium is available from each filament before it breaks.

The dual ion pump power supplies, using ferroresonant trans-formers, develop potentials up to 5 KV and current up to 200 mA. Both voltage and current are measured for pressure monitoring and for diagnostics. Current down to 10 μA can be reliably measured through the linear and log amplifiers. TTL outputs are available to interlock the sector valves and other equipment.

E. Vacuum Monitoring

The vacuum is monitored by Pirani gauges, ion gauges, ion pump currents and residual gas analyzers (RGAs). The Pirani gauges cover from atmosphere to 1×10^{-4} Torr. The ion pump current can be used to measure pressure down to 10^{-9} Torr. The nude Bayard-Alpert gauges (BAGs) measure vacuum from 10^{-3} Torr down to high 10^{-12} Torr. These BAGs have a thin collector of 0.05 mm diameter. The sensitivities and equivalent x-ray limits of some of these BAGs were measured[7] to be 20 ± 2 Torr^{-1} and $(4 \pm 1) \times 10^{-12}$ Torr, respectively for nitrogen, by comparing with a calibrated[8] extractor gauge and a modulated BAG. The inverted magnetron cold cathode gauges were tested and found to be unreliable at 10^{-11} Torr due to periodical extinguishment of discharge.

The BAGs were mounted near the UHV pump bodies in the standard half-cells and at the center of the beam component boxes. The pressure distribution along the half-cell chambers can be expressed by:

$$P(x) = Po + q * (L/S + L^2/4c - x^2/c)$$

Po is the base pressure of the pump, c the linear conductance of the chamber, q linear outgassing, S the pumping speed and L the distance between pumps. The linear conductance of a half-cell chamber is approximately 1×10^5 *l*.cm/sec. With an estimated pumping speed of 1000 *l*/s at the neck of the pump and 4.2 m between pumps, the average pressure in the half-cell chambers, by integrating the above equation, is approximately 1.3 times of the BAG readings near the neck of the pump. This ratio is not very dependent on the out-gassing rate of the chamber walls and the half-cell chamber pressure turns out to be insignificant in measuring the ring average pressure. The vacuum readings at some beam components, as measured directly by the BAGs, were one or two decades higher than those of half-cell chambers and became the dominant part of the average pressure.

One quadrupole type RGA head was installed in each ring sector. Each head is powered with a portable controller when there is access to the tunnel. With electron multipliers, the RGAs have partial pressure sensitivities down to 10^{-14} Torr level. They were installed as received from manufacture without further calibration and are used to identify qualitatively the composition of residual gas species in the ring vacuum sectors.

Commercial vacuum process controllers (VPCs) are used to power the gauges. The VPCs have process control channels which are assigned either to ion gauges or Pirani gauges. Through these channels, the Pirani gauges interlock the turning-on of the ion gauges, ion pumps and titanium pumps in the same sectors. The ion gauges provide interlocks for sector valves and beam components.

The output voltage from the standard transformers of the VPCs is not sufficient to power the ion gauge filaments over long cable lengths (up to 650'). This is overcome by using AWG #12 wires and transformers with a 40% higher output voltage in the VPC. Fig. 4 gives the measured filament heating power during EB degassing for two cable lengths and for two types of gauge filaments. The standard transformers with 13 volt AC output can only degas thoria-coated iridium filaments over a long cable length. The modified transformers have 19 volt output and allow the degassing of a tungsten filament with up to 35 watts over 500 ft of #12 AWG cables.

At low 10^{-11} Torr vacuum, the gauge collector current is only a few picoamperes, which is susceptible to noise pickup especially over long cable lengths and results in erratic pressure readings. Two prominent sources of noise in accelerator environment are the electro-magnetic interference (EMI) from magnets and power supplies; and the radio-frequency interference (RFI) from accelerating cavities. Tests of noise pickup over long cable runs in the AGS ring, during machine operation, were carried out. The results are summarized in Table 1. Regular RG-59 coax has effective shielding around 90% as compared with that of Beldon 9311 cables. At mid 10^{-11} Torr, the microphonics of RG-59 is usually 100% of the vacuum readings taken with 10 feet of cable. To minimize EMI/RFI, Beldon 9311 cables are used. This cable has microphonics of approx-imately 30% of the vacuum readings at mid 10^{-11} Torr and is accept-able for Booster vacuum operation. This coax features 100% shield coverage, a foil/braid outer shield, a polyethylene dielectric of 26 pf/ft, and good DC performance. The grid and filament wires (4 ea., 12 AWG) are also placed in a single twisted, shielded, low smoke, and radiation retardant jacket.

Table I Noise Pickup of Long Coaxial Cables

Cable Type	Vacuum/Environment*		Microphonics**	
RG 59 A/U, 1000'	$5x10^{-11}$	in Lab	+20%,	-20%
RG 59 A/U, 650'	$5x10^{-11}$	in AGS w/ RF	+200%,	-100%
RG 59 A/U, 650'	$5x10^{-11}$	in AGS w/o RF	+25%,	-25%
RG 59 A/U, 650' triaxial	$3x10^{-11}$	in AGS w/ RF	+30%,	-30%
Beldon 9223, 500'	$4x10^{-11}$	in AGS w/ RF	+100%,	-50%
Beldon 9311, 500'	$5x10^{-11}$	in AGS w/ RF	+30%,	-20%
Beldon 9311, 500'	$2x10^{-11}$	in AGS w/ RF	+50%,	-50%
Beldon 9311, 500'	$2x10^{-11}$	in AGS w/o RF	+30%,	-30%

*vacuum in Torr; AGS = cabling from power supply house to UHV chamber in AGS tunnel; RF = both magnets and cavities ramping

**the percentages of microphonics are derived from the range of vacuum readings divided by the true vacuum readings taken locally with a 10' cable

F. Valve Control and Interlock

The beam vacuum is protected by sector valves, which are interlocked by gauges and ion pumps through process control chan-nels and TTL, respectively. A fault detected by any two out of four ion gauges and ion pumps in the same sector will cause the valves at both ends of the sector to close, thus minimizing the loss of vacuum in adjacent sectors. This voting scheme minimizes false triggering due to noise or malfunctioning of individual devices. A fast closing valve with a closing time of less than 15 msec is in-stalled between the Linac and the Booster to protect the Booster ultrahigh vacuum ring from potential catastrophic failure at Linac. To prevent beam from damaging valves, the valve-closing signals trigger the fast beam interrupt system located at the ion source within 350 μsec. Auxiliary interlock I/Os in the valve controllers also allow for interlocking other valves or equipment.

III. CONSTRUCTION AND COMMISSIONING

A. Vacuum Processing

To reduce outgassing, various degassing treatments were applied to vacuum chambers and beaM components. Before assembly, all chambers and parts were chemically cleaned. The chemical cleaning consisted of vapor degreasing, water rinse, alkaline detergent soak and water rinses. The parts were welded and assembled in a Class 1000 clean room before vacuum firing. The chambers were usually vacuum fired at 950°C for 2 hours at vacuum of low 10^{-5} Torr.

The treatment of beam components, depending on the material involved and the assembly/testing sequence, could be quiet differ-ent. To prevent the trapping of cleaning fluid, ferrites, graphites and other ceramic components are cleaned by vapor degreasing and soaking in a ultrasonic alcohol bath. The nickel-zinc ferrites used in the kicker magnets have outgassing rates of 1×10^{-12} Torr.l/s.cm^2 after vacuum firing at 950°C. However, due to the decomposition of oxides at high temperature which reduced the ferrite impedance, the ferrite was fired at 400°C. The dimensions of some beam components exceeded the capacity of in-house vacuum furnace, therefore, had to be fired separately before assembly. Pressurized steam was also used to clean a few assembled beam components, which were contaminated during assembly. The firing temperatures and cleaning steps for some components are listed in Table II.

Table II Cleaning and Vacuum Firing of Beam Components

MATERIAL	CHEMICAL CLEANING	VACUUM FIRING	
		TEMP (°C)	DURATION (hr.)
Stainless/Inconel	Detergent	950	2
		Or 500	24
Welded Bellows	Alcohol Soak	500	24
Ferrite	Alcohol Soak	400	50
Feedthroughs	Alcohol Soak	500	2
Ceramic w/Brazing	Alcohol Soak	500	2
Graphite	Alcohol Soak	950	2
Copper	Phosphate Dip	500	24

B. Vacuum Evaluation

The assembly and vacuum evaluation of half-cells began in March, 1990, when the first set of production magnets was available. The tunnel was ready for component installation in June, 1990. The assembly and testing of beam components began during the summer of 1990. All ring components were installed by April, 1991. The pump-down and bakeout of the sectors began in Jan., 1991, when all the components in the first sector were installed. The vacuum system was completed in June, 1991.

All the vacuum chambers and the beam components were designed to be bakeable to 300°C. They were baked at 250°C before installation and at 200°C in situ, which was adequate to achieve the de-signed base vacuum.

After cleaning, welding and vacuum firing, eddy current coils, thermocouples and heating blankets were mounted on the half-cell chambers. The chambers were then inserted into the pre-aligned magnets and the PUEs were aligned against the quadrupoles. Of the thirty-six half-cell chambers, two had to be reworked to meet the $\pm$ 1 mrad rotational tolerance of the PUEs. The downstream vacuum flange was welded after PUE alignment and electrical test. The associated vacuum components, pumps, gauges, valve and residual gas analyzer, were then mounted for pump-down and bakeout. The bakeout began on day 1 and terminated on day 3. Degassing, conditioning and turning-on of the pumps followed. Before qualifying for installation, the half-cells, with their associated UHV pumps, had to reach vacuum of $< 1\times10^{-10}$ Torr and be hydrocarbon free. Approximately eighty percent of the chambers reached a vacuum better than 5×10^{-11} Torr one day after bake. Half of the chambers with higher pressure were found to have leaks at the Conflat flange joints. Two chambers had leaks at the welds and were repaired. A half-cell ready for installation is shown in Fig. 5.

Every beam component for the ring was evaluated for UHV before installation. Among the twenty beam components tested, ten had reached vacuum of 10^{-11} Torr one day after bake. Two kickers had to be rebaked at higher temperature(300°C) for several days to remove hydrocarbon contamination introduced during the assembly. Others had high hydrogen outgassing originating from parts that were not vacuum fired.

The in situ bakes of vacuum sectors, similar to half-cell bakeouts, also spanned three days. The beam transport line sectors were baked at 100 - 150°C, while the ring sectors were baked at 200°C. A vacuum of 10^{-10} - 10^{-9} Torr was reached in the lines, depending on bake temperature and available pumping speed. Among the seven ring sectors, three reached the designed vacuum of low 10^{-11} Torr one day after bake. One sector had hydrocarbon contamination and had to be rebaked at 250°C for five days. After initial bakes, the ion gauge readings in two-thirds of the ring were at 1 x 10^{-11} Torr (the readout limit of our VPCs) and an average vacuum of high 10^{-11} Torr was reached. Using RGAs, sources of local pressure bumps were identified as either high hydrogen outgassing at ferrite kickers or small leaks. We expect to reach the designed vacuum of 3 x 10^{-11} Torr when the kicker magnets are rebaked and the leaks are repaired. The RGAs allowed us to identify the leaks even at low 10^{-11} Torr level. This is evident as shown in Fig. 6, where the presence of argon peak (m/e=40) in sector C indicates a leak which was subsequently located at a bellows weld.

IV. CONCLUSION

With proper selection of material (metal and ceramic), degassing treatment and in situ bake, a vacuum of 10^{-11} Torr was achieved over the 200 m Booster ring. The selection of inconel 625 and stainless steel 316LN as chamber and flange material allow us to avoid chromium carbide precipitation during welding and vacuum firing. Carbide precipitation is susceptible to corrosion[4,9] especially under radiation environment. No knife-edge rounding was observed after 950°C vacuum firing, attributed to the 90° knife-edge design[3]. The commercial and the home-made quick disconnect flanges worked well after repeated thermal cyclings.

The use of PC/PLC based bakeout control system assists in monitoring and controlling the bakeouts of several sectors with minimum operator intervention. The SCR power supplies were found to be accurate within $\pm$ 1 A when subliming titanium through 500 feet of cable. The operation of ion gauges over long cable length was more complex than expected. The AWG #12 wires used to power gauge filaments and modified transformers compensated for the voltage loss in the cables. The triac firing cycles of filaments had to be shielded from the collectors. The noise pickup of the collector cables was minimized by using fully shielded low capacitance cable. However occasional oscillations in the gauge readouts during acceleration cycles limit their accuracy to around 50% at low 10^{-11} Torr. The use of RGAs as a diagnostic tool at ultra high vacuum levels proves to be very powerful in qualitatively identifying the sources of residual gas.

The tight space between the magnets and chambers, and the expected residual radiation will make the maintenance and upgrade of this vacuum system rather difficult. The bakeout system is necessary to reduce thermal outgassing and will also allow us to treat areas with contamination. The cost of the bakeout system, including blankets, TCs, contactor boxes, PLCs, PC and labor, is much higher than originally estimated and is approximately 30% of the total vacuum system cost. The procurement of custom blankets to fit chambers and beam components of various shapes and dimensions was especially costly and time consuming.

FIGURE CAPTION

Fig. 1. Booster Ring Vacuum Layout.

Fig. 2. Schematics of Half-cell Vacuum Chamber; the heating blankets are not shown.

Fig. 3. Layout of the vacuum instrumentation and control.

Fig. 4. Filament Heating Power Versus Degassing Power Over Long Cable Length. The Emission Was 1 mA at Zero Degassing Power.

Fig. 5. Completed Half-cell Before Installation.

Fig. 6. Residual Gas Spectra of Vacuum Sectors at 10^{-11} Torr (a) without detectable leak; and (b) with 10^{-10} Torr.*l*/sec leak at bellows. The leak is evident by the presence of argon at m/e=40.

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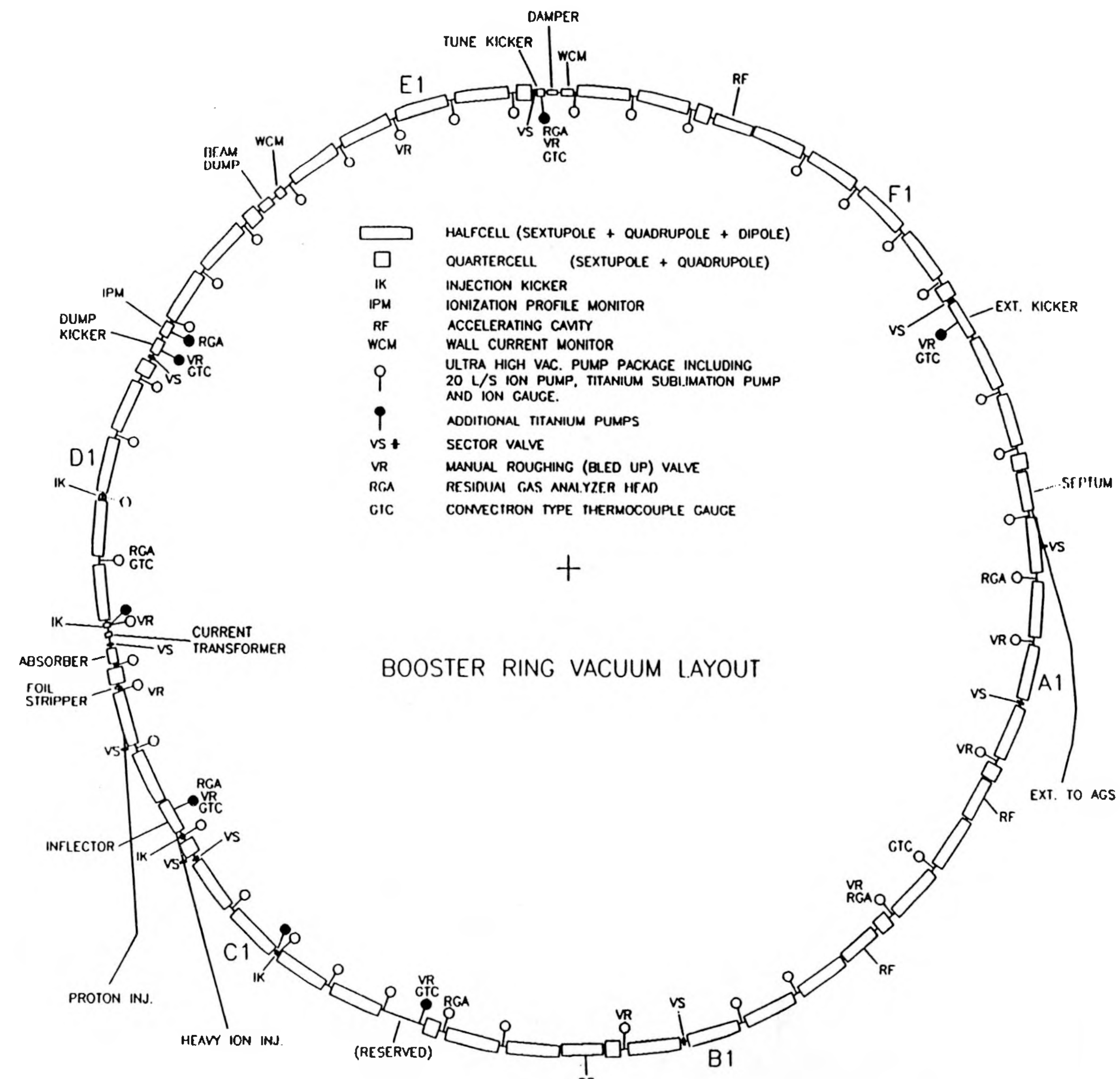
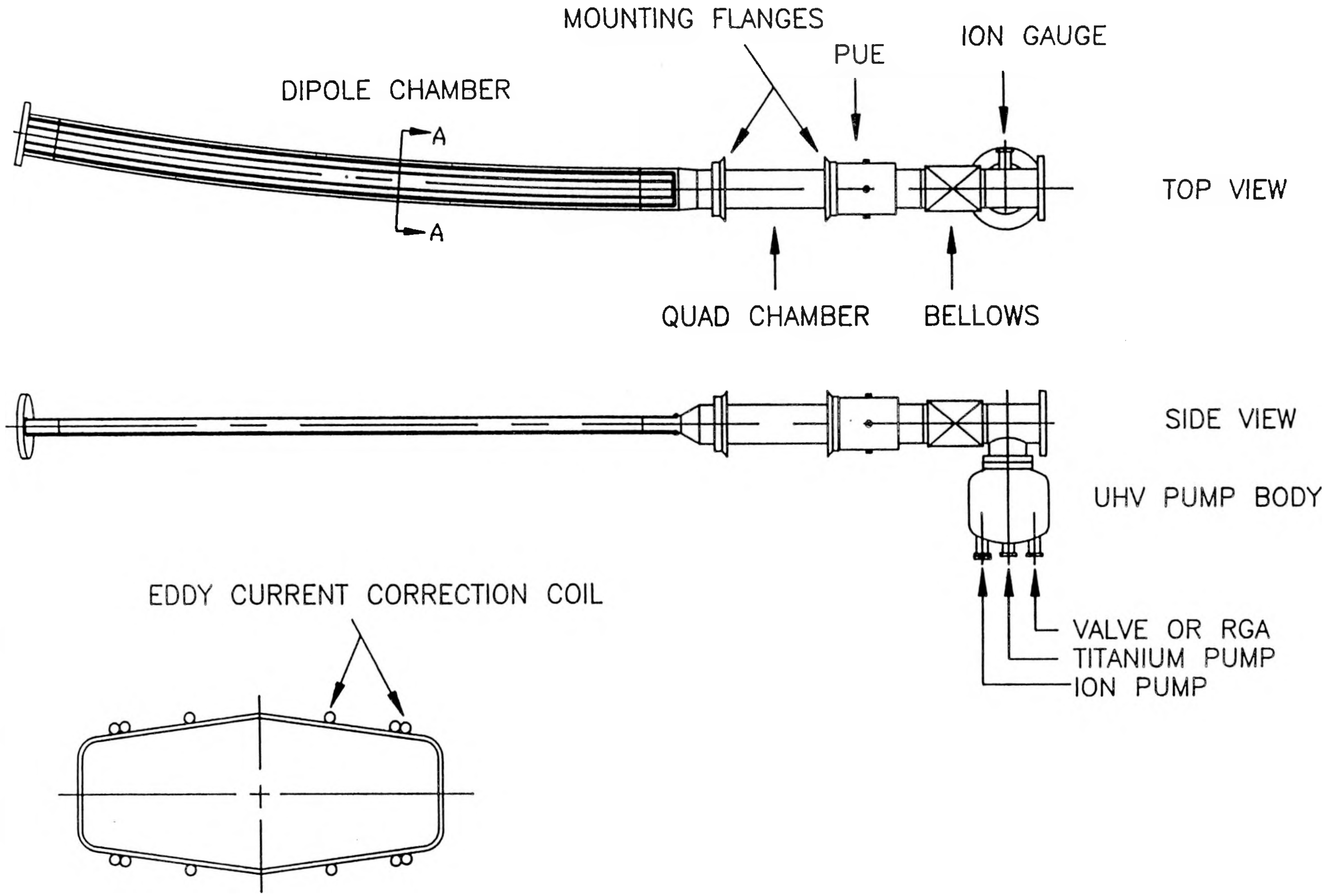
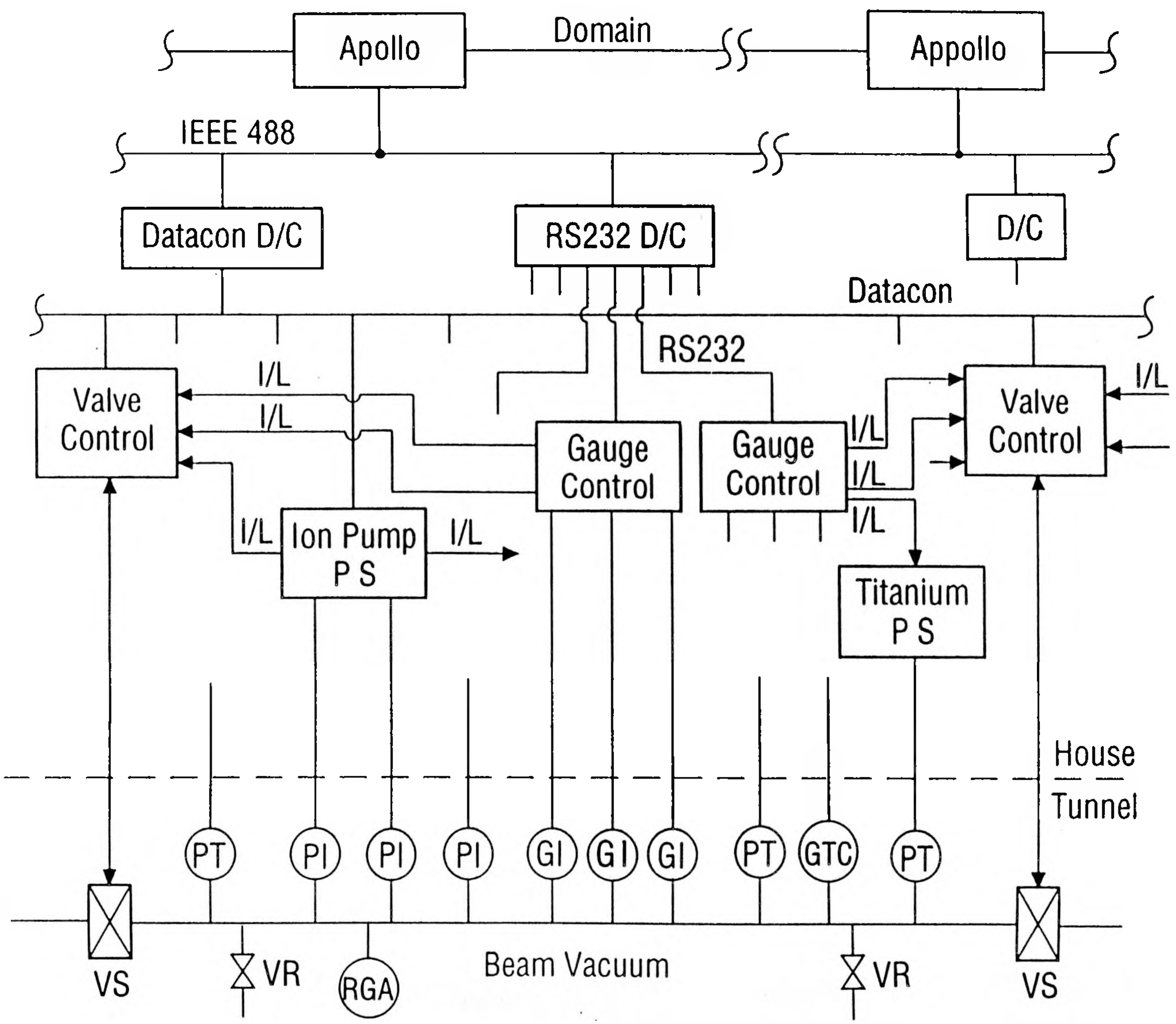


BOOSTER RING VACUUM LAYOUT



CROSS SECTION A-A
DIPOLE VACUUM CHAMBER

AGS BOOSTER
TYPICAL HALFCELL VACUUM CHAMBER



Apollo
Domain
Appollo
IEEE 488
Datacon D/C
RS232 D/C
D/C
Datacon
RS232
I/L
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I/L
I/L
I/L
I/L
Valve Control
Gauge Control
Gauge Control
Valve Control
Ion Pump P S
Titanium P S
House
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PI
PI
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GI
GI
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VS
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RGA
Beam Vacuum
VR
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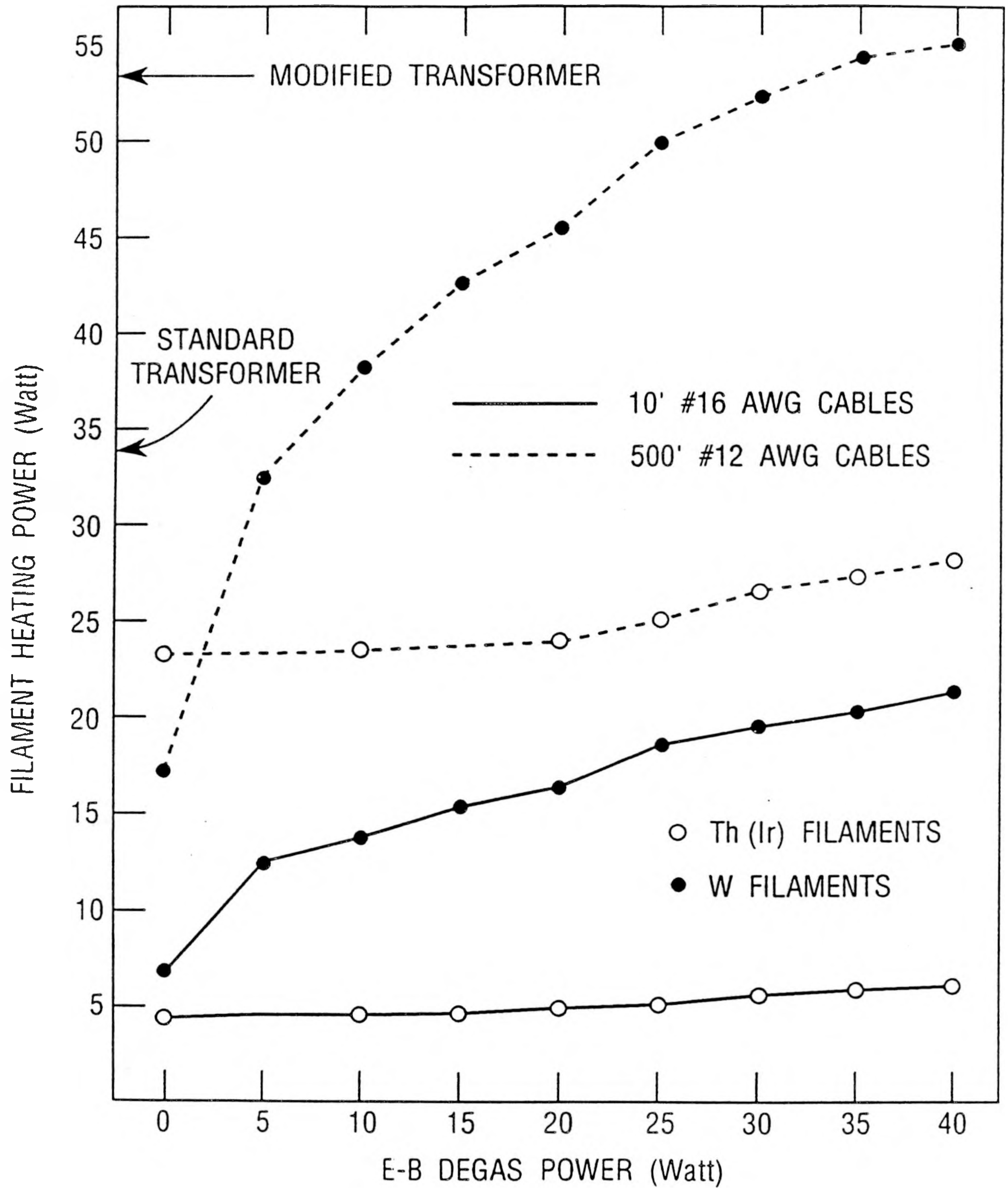

MODIFIED TRANSFORMER
STANDARD TRANSFORMER
10' #16 AWG CABLES
500' #12 AWG CABLES
Th (Ir) FILAMENTS
W FILAMENTS
FILAMENT HEATING POWER (Watt)
E-B DEGAS POWER (Watt)
55
50
45
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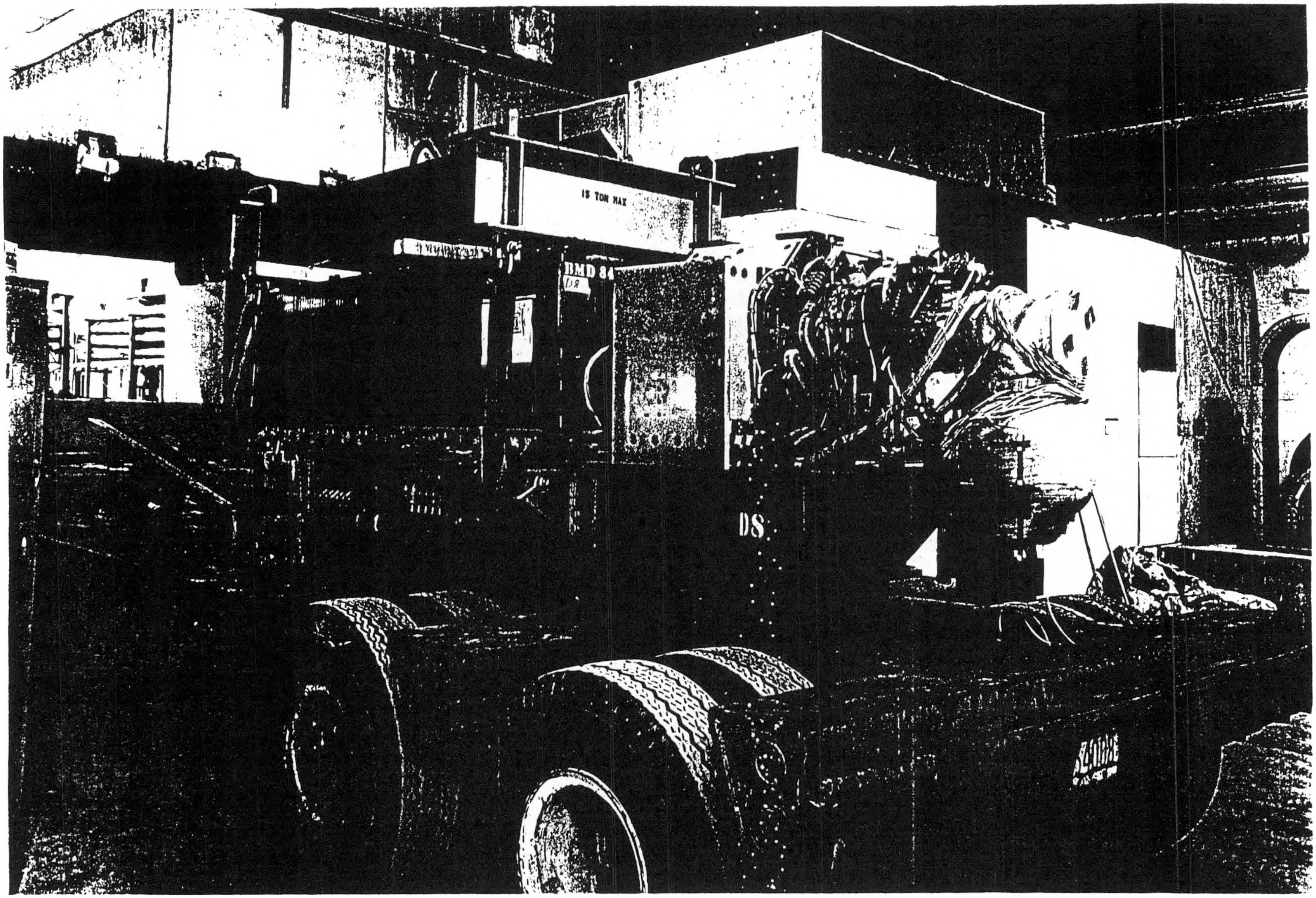
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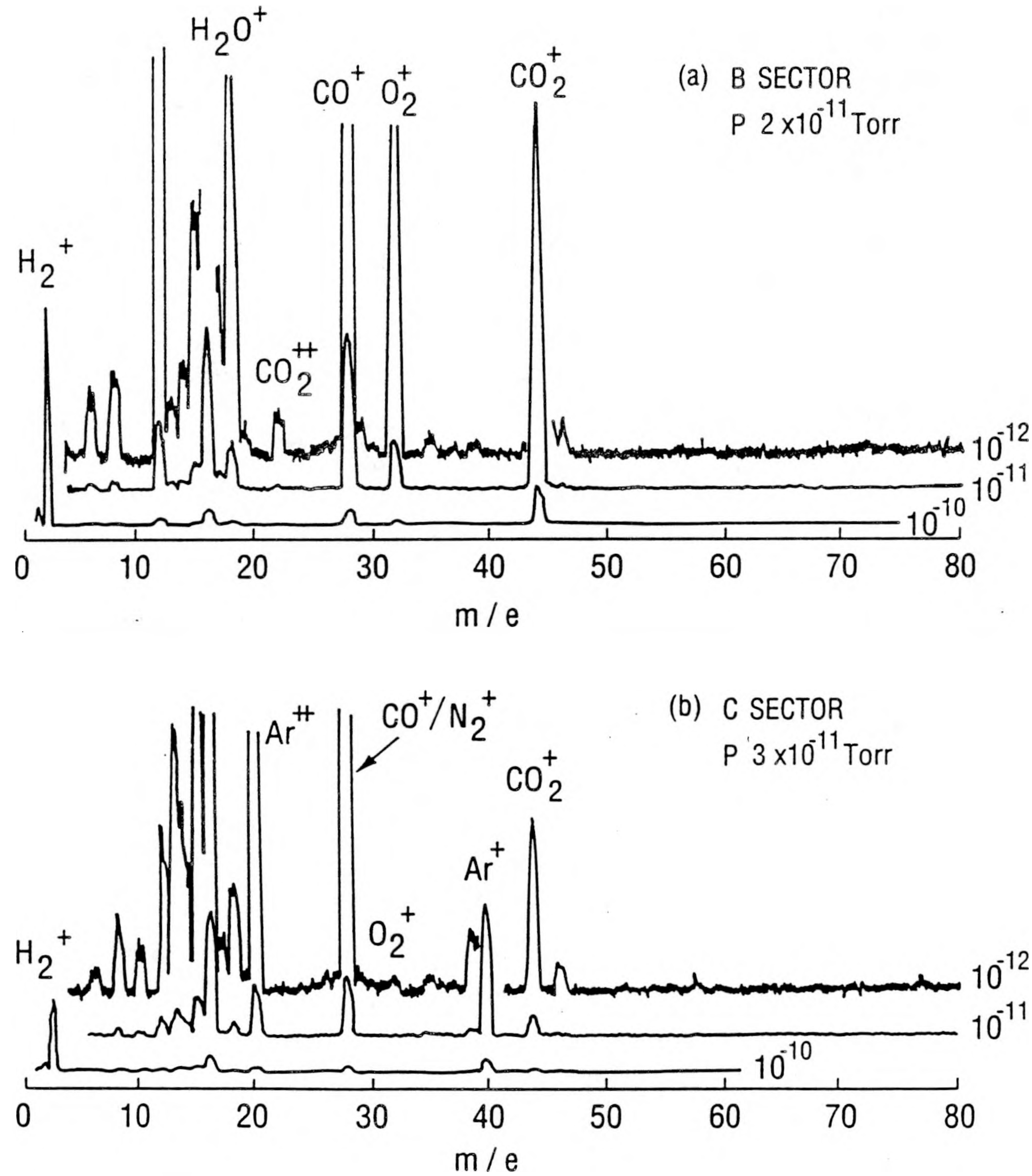
BMD 84
DS



(a) B SECTOR
P 2 x10-11 Torr
H2+
H2O+
CO+
O2+
CO2+
CO2++
10-12
10-11
10-10
0 10 20 30 40 50 60 70 80
m / e
(b) C SECTOR
P 3 x10-11 Torr
H2+
Ar++
CO+/N2+
O2+
Ar+
CO2+
10-12
10-11
10-10
0 10 20 30 40 50 60 70 80
m / e