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THE AGS BOOSTER VACUUM SYSTEMS*

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ABSTRACT

The AGS Booster is a synchrotron for the acceleration of both protons and heavy ions. The design pressure of low 10^{-11} mbar is required to minimize beam loss of the partially stripped heavy ions. To remove contaminants and to reduce outgassing, the vacuum chambers and the components located in them will be chemically cleaned, vacuum fired, baked then treated with nitric oxide. The vacuum sectors will be insitu baked to a minimum of 200°C and pumped by the combination of sputter ion pumps and titanium sublimation pumps. This paper describes the design and the processing of this ultra high vacuum system, and the performance of some half-cell vacuum chambers.

1. INTRODUCTION

The Alternating Gradient Synchrotron (AGS) Booster,[1] currently under construction 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 AGS. The major objectives of the Booster are:

(1) to increase the proton intensity in the AGS by a factor of 4 to 6×10^{13} protons per pulse.
(2) to increase the AGS polarized proton intensity by a factor of twenty to 10^{12} protons per pulse.
(3) to accelerate heavy ions up to gold in the Booster for AGS.

It is the third objective which puts the most stringent requirements on the vacuum system of the Booster ring. In heavy ion accelerators such as Booster, the cross sections for charge exchange (electron stripping and electron capture) between the partially stripped, low β, high Z heavy ions and the residual gas molecules could be rather large. To avoid beam loss due to charge exchange between the heavy ions and the residual gas molecules, an ultra high vacuum of 10^{-11} mbar (3-4 orders of magnitude better than that for proton operation) is required.

The capture and stripping cross sections for heavy ions can be expressed as

$$\delta_c \propto \beta^k \times q^m \times Z_t^n$$

$$\delta_s \propto \beta^k \times q^m \times Z_t^n \times Z_p^r$$

with β equals to v/c; q the projectile charge state; Z_p the atomic number of the projectile; and Z_t the equivalent atomic number of residual gas.

For capture, the values of k vary between -6 and -12; of m ≥ 2; and of $n \leq 1$. For stripping, the values of k fall between -1 and -2; of m -3 to -4; of

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n < 2; and of r 2 to 2.5. The capture cross section is significant at low energy and drops off rapidly during the acceleration cycles, while the stripping cross sections decrease slowly with increasing β and become the dominant beam loss process at higher energy.

The charge exchange cross sections can be calculated by using the empirical formulae which give the best fit to the experimentally measured cross sections. Using the scaling rules proposed by A.S. Schlachter[2] for capture cross sections, and the modified Bohr-Lindhard formulae[3] for stripping, the total cross sections and beam loss during Booster acceleration cycles can be estimated. The results[4] for Au^{+33}, which will be the worst case for Booster, are summarized in Fig. 1. At the designed vacuum of 3×10^{-11} mbar, the integrated beam loss will be less than one percent.

2. VACUUM SYSTEMS

The designed vacuum levels for the ring and the injection/ extraction lines are 3×10^{-11} mbar and 10^{-10} - 10^{-9} mbar, respectively. The good vacuum for the beam transport lines will serve as pressure differentials between the 10^{-11} mbar ring vacuum from the existing 10^{-8} - 10^{-7} mbar vacuum of Linac and AGS. Figure 2 shows the layouts of the Booster facility and the AGS complex.

2.1 RING VACUUM CHAMBERS

The Booster ring is divided into 48 half cells. Thirty six standard half cells contain dipole, quadrupole and sextupole magnets. The twelve half cells with "missing dipoles" house the accelerating cavities, injection/extraction magnets and other beam components. It is logical to divide the vacuum chambers into 48 groups to coincide with these half cells. The half-cell chambers are grouped into 7 vacuum sectors isolatable by all metal gate valves. The standard half cell chambers shown in Fig. 3 are 4.2 m long and made mostly of Inconel 625. This material was selected for its good mechanical, electrical and vacuum properties. The dipole chambers having an elliptical cross section of 70 mm x 165 mm and are 2.8 m in length. These chambers are curved with a bending radius of 13.75 m. Top and bottom halves of the dipole chambers are formed from a curved die, welded together then sized to the required dimensions. Six pairs of correction coils are mounted on the top and bottom of the dipole chambers for self correction of the eddy current field. These correction coils are necessary during rapid cycling (7.5 Hz) proton acceleration, in which the magnets will be ramped at 8 Tesla per second.

The remainder of the half cell consists of chambers for quadrupole, pick-up electrodes (PUEs), sextupole, bellows and the transition with ports flanged to UHV pumps. Worth mentioning is the construction of the PUEs. The location of the PUEs has to be accurate within 0.1 mm after vacuum firing at 950°C and repeated insitu bake at 200°C. This leads to the double gimballed design[5] as shown in Fig. 4. The vacuum envelopes are machined from heavy wall tubing. To minimum stress, electric discharge machining is used to split the detector plates. The detector plates are then fastened through four inner ceramic posts to the calibration ring, which in turn is supported by the posts in the vacuum envelope. Due to symmetry, all expansion is radial and the parts return to the original location after vacuum firing and bake.

Conflat type flanges made of 316LN stainless steel are used through out the ring vacuum system. To prevent knife-edge rounding after vacuum firing and high temperature bake, these flanges have a 90° knife edge. Copper gaskets with 0.1% Ag are used to prevent leaks caused by the recrystallization of pure copper after repeated high temperature bakes. High-strength bolts and nuts are used on the Conflat flanges. They are silver plated (~0.01 mm thick) to eliminate both the problem of galling and the contamination hazard caused by the high temperature thread lubricant. In a few locations of potentially high beam loss (therefore, high residue radiation) , conical flanges with Conflat knife edge and quick release chain clamps will be used. This type of flanges has been tested and found to remain leak tight after repeated bake to 300°C.

2.2 VACUUM PUMPS

The designed ring vacuum will be achieved by the combination of the titanium sublimation pumps and ion pumps. Titanium cartridges with three filaments each will be mounted in the UHV pump bodies. Each pump body has over 3000 cm^2 area for the sublimed titanium and pumping speeds of over 1000 ℓ/s for hydrogen and carbon monoxide. The total pumping speed in the ring is over 50,000 ℓ/s for active gases. The non-getterable gases such as methane and argon will be removed by diode type ion pumps of 20 ℓ/s and 100 ℓ/s. Total available pumping speed for inert gas is estimated to be over 400 l/s at 10^{-11} mbar.

2.3 BEAM TRANSPORT LINES

Three transport lines with a total length of 350 m are built to connect the Booster ring with the existing Linac, Tandem and AGS. The vacuum pipes of the transport lines are made of mostly 304L stainless steel. They will be baked insitu to 150°C and pumped by the combination of ion pumps and non-evaporable getter(NEG) pumps. The low temperature NEG St707 strips from SAES Getters, which were successfully implemented in HITL vacuum system[6] will be used wherever possible in these transport lines.

2.4 VACUUM INSTRUMENTATION AND CONTROL

Due to the presence of high radiation levels in the Booster tunnel, all the power supplies and controls are located in the instrumentation building. They include the power supplies for ion pumps and titanium pumps, controllers for vacuum gauges, valves and bakeout system, and the Apollo computer systems. The layout of a typical vacuum sector is depicted in Fig. 5. The gauge controllers will 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 IEEE-488 compatible Datacon interface cards. The D/Cs communicates with the Apollo system via a station drop. The titanium pump power supplies and the bakeout controls will be used occasionally. They will be interfaced and controlled by a PC which could be linked to the Apollo network.

Titanium Pump Power Supply: The titanium pump power supplies will degass the titanium filaments during pumpdown and bakeout, and sublime the titanium to the UHV bodies when the needs arise. These supplies consist of SCR based controllers which power and regulate the sublimation rate through the constant current mode. The filament current will be stepped up by transformers located in the tunnel near the cartridges. At 48 A filament current, the sublimation rate, depending on the age of the filaments, will be approximately 1 mg/min. Approximately one gram of titanium can be sublimed from each filament by using this constant current mode.

Ion Pump Power Supply: The power supplies using ferroresonant transformers develop potentials up to 5 KV and are current limited to 200 mA. Both voltage and current are measured for pressure monitoring and for diagnostics. Current down to 1 μA can be reliably measured through the linear and log amplifiers. The measured current and voltage are converted to frequencies and fed to Datacon interface cards for computer monitoring and display. Opto coupling is used for ground isolation in outputting the interlock and status signals for valve control and other equipment.

Vacuum Monitoring: The vacuum will be monitored by nude Bayard-Alpert type ion gauges and ion pump currents. The ion gauges have a thin collector of 0.05 mm diameter and an X-ray limit of 6×10^{-12} mbar.[7] Commercially available vacuum process controllers will be used to power, monitor and interlock these gauges. To overcome losses over the long cable run(up to 200 m), large gage wires and bigger transformers are needed to power the filaments. To minimize interference caused by electromagnetic and radiofrequency noise, the ion collector cables will be 100% shielded and the grid/filament wires will be placed in a single twisted and shielded jacket. Ferrite attenuator beads will be utilized where needed. Process control outputs from each ion gauge will be utilized for sector valve interlock. A residual gas analyzer will be installed at each vacuum sector to measure the gas composition of the beam vacuum and for trouble shooting.

Valve Control and Interlock: The beam vacuum is protected by sector valves. A fault detected by one ion pump or two ion gauges in the same sector will cause the valves to close, thus minimizing the loss of vacuum in adjacent sectors. This voting scheme will eliminate the false triggering due to noise or malfunctioning of individual controllers. Auxiliary interlock I/O in the valve controllers also allow for the cross coupling and interlock of other valves or equipments.

3. VACUUM PROCESSING

Several degassing treatments will be applied to reduce the outgassings of the vacuum chambers and the components located inside them.

Before assembly, the components are usually chemically cleaned, welded and then vacuum fired. The chemical cleaning consists of the standard ultrasonic degreasing with perchloroethylene, followed by a rinse with detergent and water. To minimize contamination, the assembly and welding is done in a class 1000 clean room. Vacuum firing is done at the in-house vacuum furnace. The furnace has a 5 m long by 0.5 m diameter hot zone and is capable of low 10^{-5} mbar at over 1000°C. Whenever, the complete chambers can not fit in the furnace, the parts will be vacuum fired before final welding and assembly. The eddy current correction coils, the thermocouples (TCs) and the heating blankets are then mounted on the chambers before inserting them into the magnets. E type TCs are utilized because of its nonmagnetic property and are used to control the heating blankets which have redundant heating elements. The available space between the magnets and the chambers for blankets and TCs is less than 6 mm. At 200°C, the heat load due to this small gap is over one kilowatts per meter.

The magnet coils will be water cooled during bakeout to protect the coil insulation from excessive heat.

Each half-cell chamber will be baked individually to ensure both vacuum reliability and the achievement of the designed vacuum level. During the bake, the assembly will also be treated with nitric oxide (NO) gas[8,9] which breaks down and removes any hydrocarbon contamination. The NO treatment is done by bleeding the NO gas into the chamber at mid 10^{-5} mbar pressure for several hours. After installation, the whole vacuum sector will be baked insitu. The vacuum chambers and components within are designed to be bakeable up to 300°C. In practice, they will be baked insitu at 200°C which was found to be quite adequate for achieving the designed vacuum. High outgassing beam components such as the ferrite kickers, and septums will be baked at 300°C. The bakeout will be carried out using a commercially available PC-based system with programmable local controllers (PLCs). These PLCs will be wheeled to the vacuum sectors prior to the bake. The system will initiate and maintain control over the programmed bake cycles, and alarm the operators when abnormal or failure conditions occur.

Portable turbopump stations will be utilized during system pump down, bakeout and conditioning. They consist of a Balzers turbopump package, the necessary valves, Pirani and ion gauges, and a control chassis. The stations monitor the pump down and bakeout and will terminate the bake in the events of component failure, avoiding damage and contamination to the beam vacuum. The pump stations will be monitored by the Booster computers through RS232 drops in the tunnel.

4. PERFORMANCE OF VACUUM HALF CELLS

Up to this date, several halfcell chambers have been constructed, assembled and evaluated. Outgassing levels of low 10^{-13} mbar. $\ell/s.cm^2$ were routinely achieved for stainless and inconel chambers after vacuum firing and 200°C bake. The average pressure inside the standard halfcell chambers, based on this outgassing rate, will be less than $1x10^{-11}$ mbar. The major pressure contribution in the ring will be from the beam components, such as the ferrite kicker magnets. Outgassing rates of less than $1x10^{-12}$ mbar.$\ell/s.cm^2$ have been achieved in our tests for ferrite blocks and graphite blocks after chemical cleaning, vacuum firing and insitu bake.

The effectiveness of NO in removing hydrocarbon from the vacuum system has been successfully tested in the half cell chambers.[9] Fig. 6 shows the residual gas spectra of the halfcell chamber at 200°C before and after the NO treatment. The difference in total pressure was very small, however, the levels of carbonic peaks without NO treatment were more than one decade higher than those with the treatment. This treatment will be used for on-line cleaning of Booster vacuum half cells. The pump down of a prototype half cell chamber is shown in Fig. 7. One week after the 200°C bake, a base pressure of $1x10^{-11}$ mbar was reached with no measurable hydrocarbon down to 10^{-13} mbar levels.

FIGURE CAPTIONS

Fig. 1. (a) The charge exchange cross sections for Au^{+33}; and
(b) the estimated beam loss due to charge exchange for Au^{+33} during booster acceleration cycle.

Fig. 2. The layout of the Booster ring and the AGS accelerator complex.

Fig. 3. The standard halfcell vacuum chamber for Booster ring.

Fig. 4. The cross sectional view of the Booster pick-up electrodes(PUE).

Fig. 5. The vacuum instrumentation and control for a typical vacuum sector.

Fig. 6. Residual gas spectra of the half cell vacuum chamber
(a) before nitric oxide treatment; and (b) after nitric oxide treatment.

Fig. 7. The pumpdown curve of the prototype half cell vacuum chamber.

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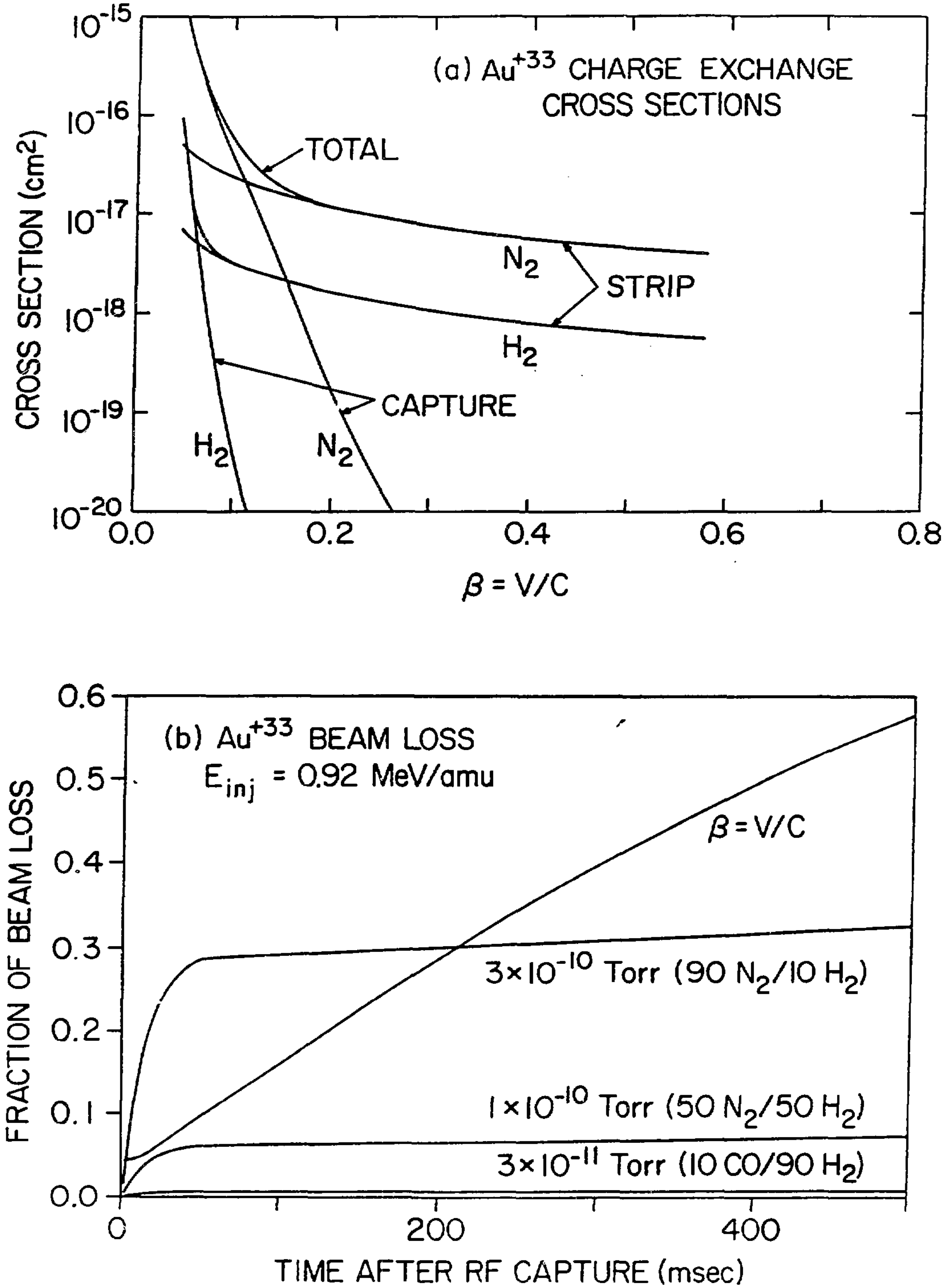
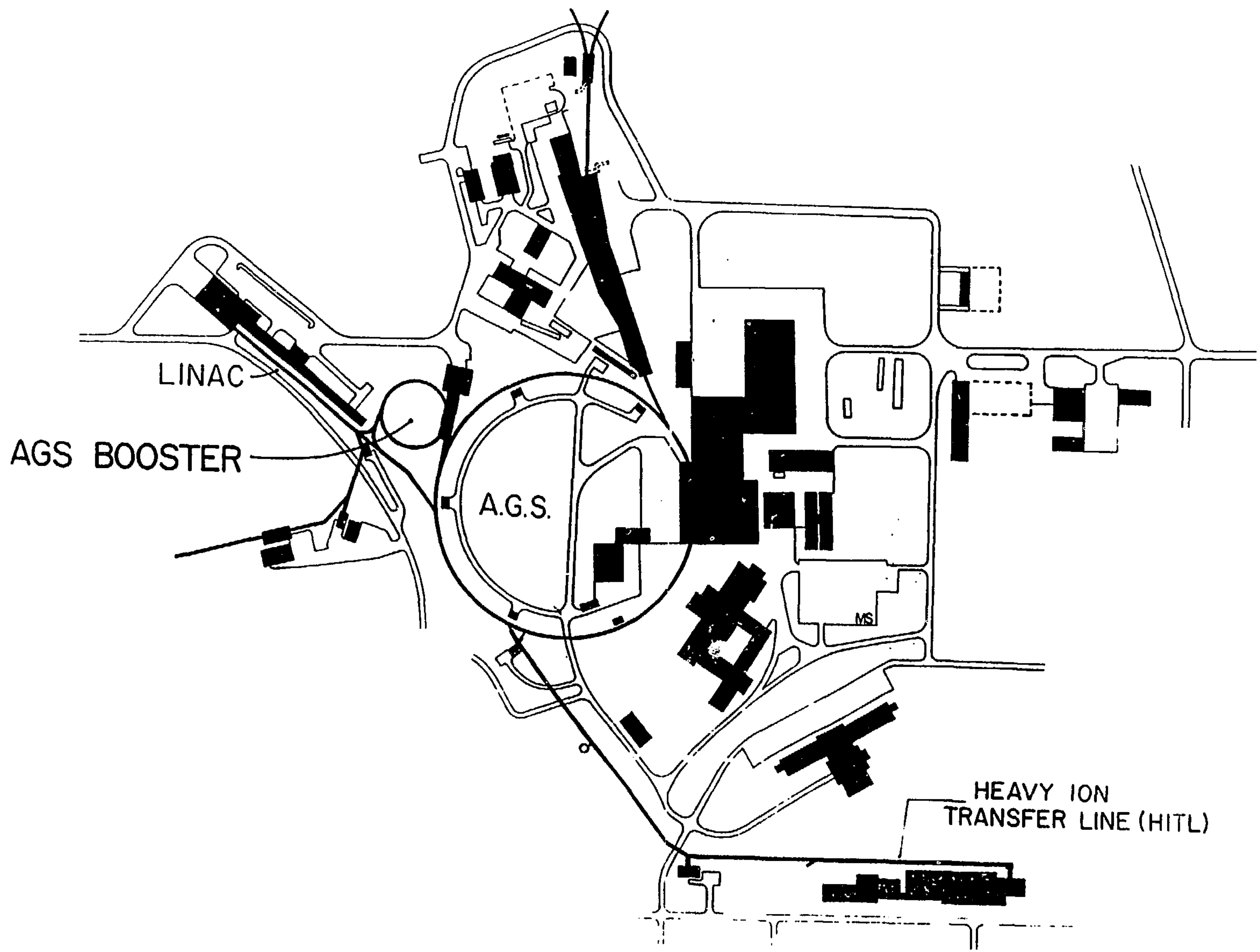
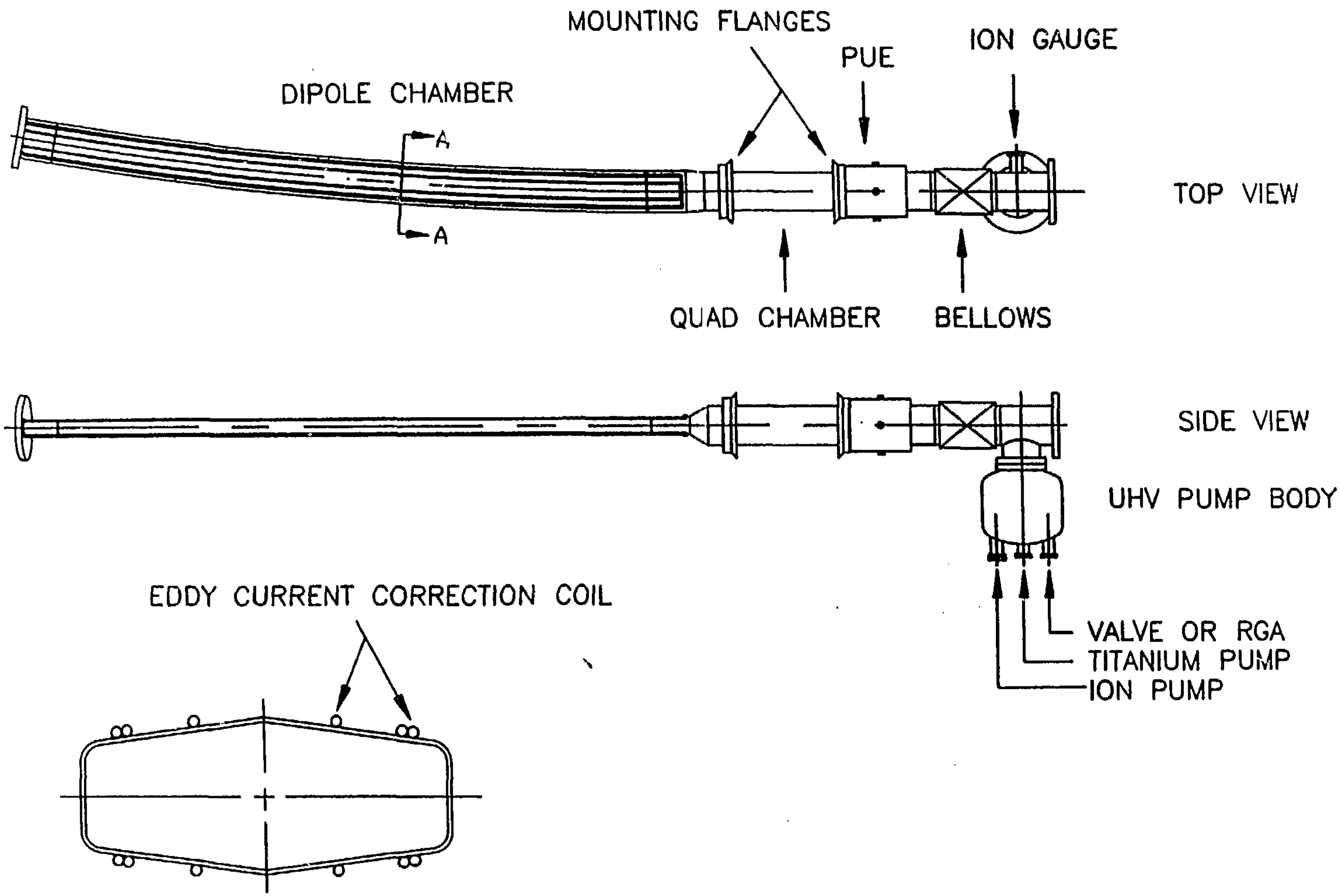
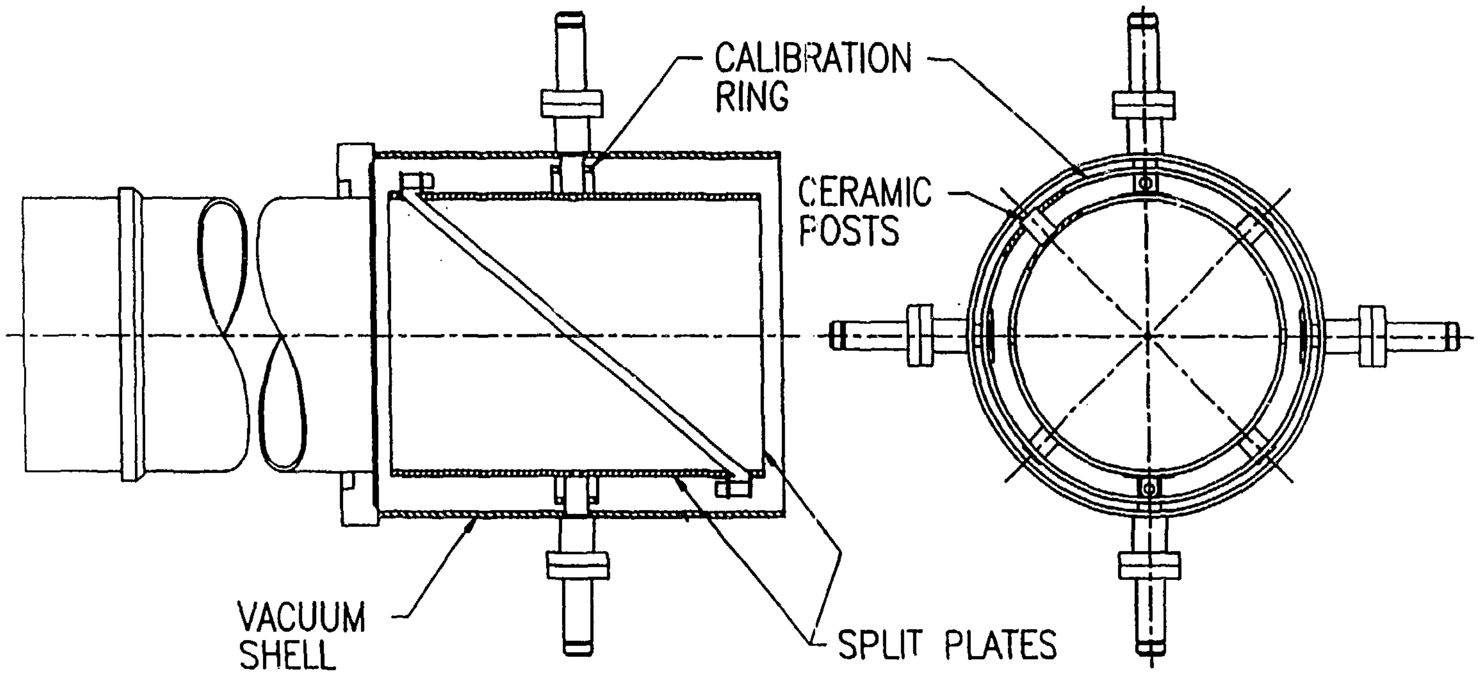

(a) Au+33 CHARGE EXCHANGE CROSS SECTIONS
CROSS SECTION (cm2)
TOTAL
N2
STRIP
H2
CAPTURE
H2
N2
β = V/C
(b) Au+33 BEAM LOSS
Einj = 0.92 MeV/amu
FRACTION OF BEAM LOSS
β = V/C
3×10-10 Torr (90 N2/10 H2)
1×10-10 Torr (50 N2/50 H2)
3×10-11 Torr (10 CO/90 H2)
TIME AFTER RF CAPTURE (msec)

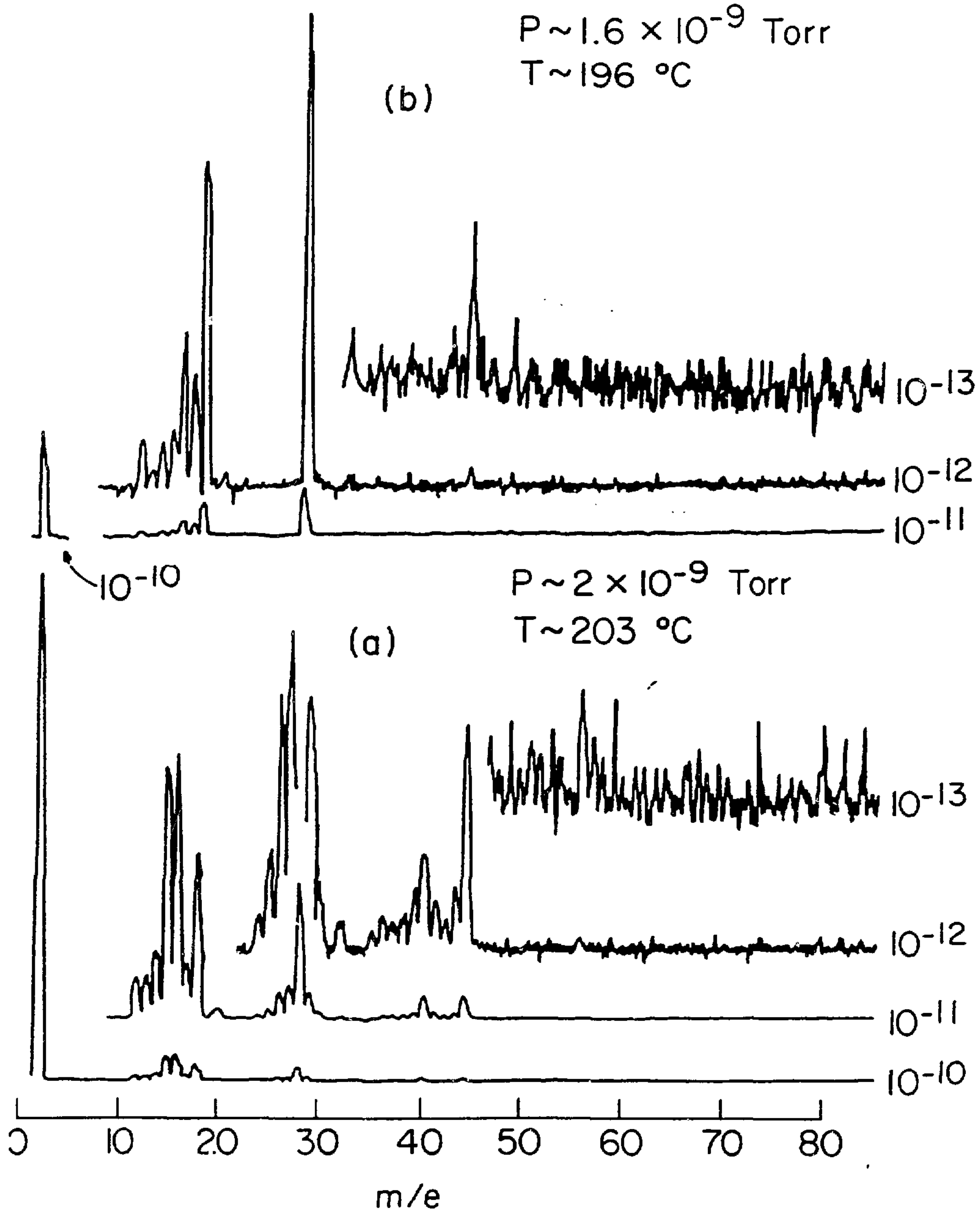

LINAC
AGS BOOSTER
A.G.S.
MS
HEAVY ION
TRANSFER LINE (HITL)

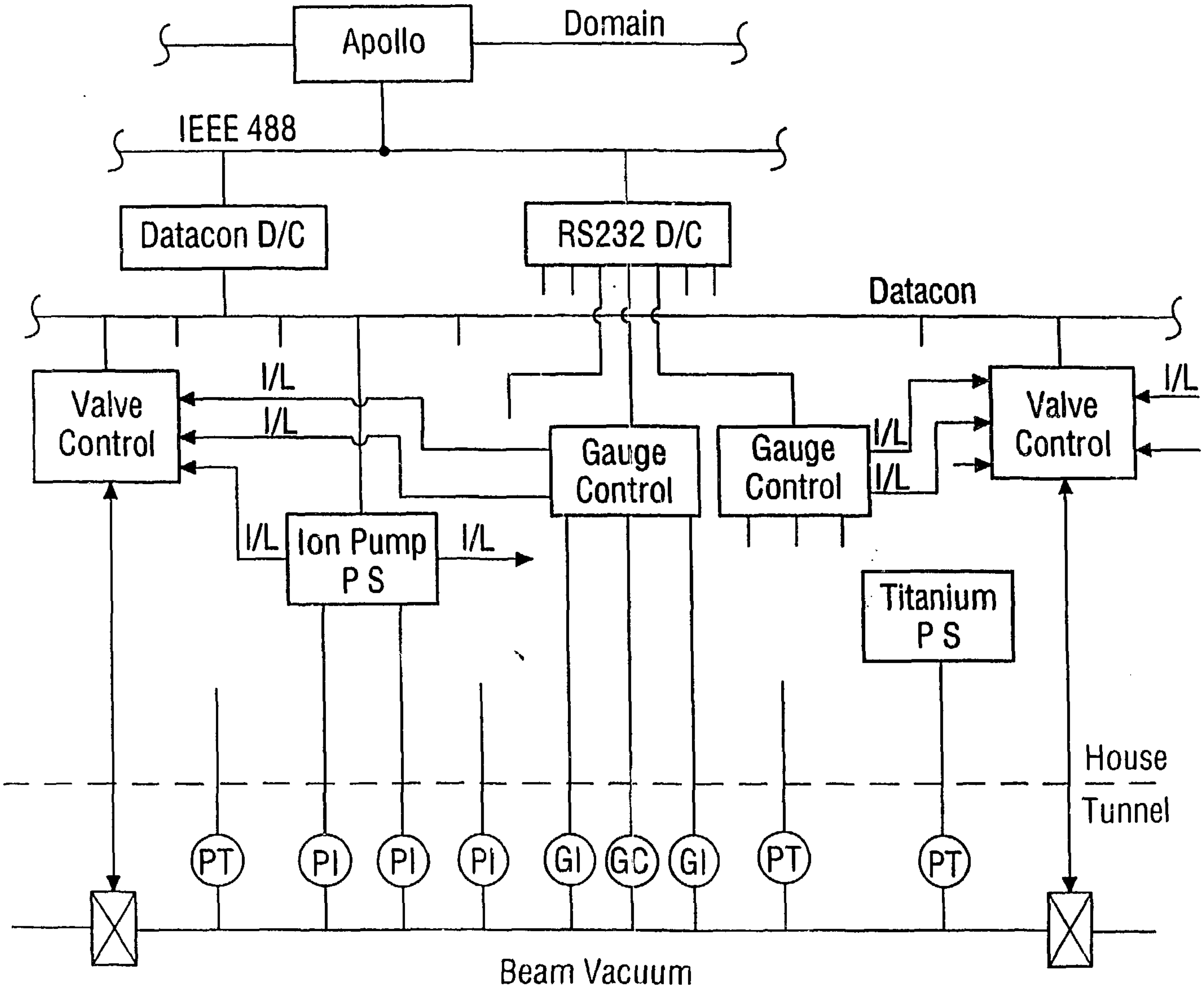


CROSS SECTION A–A
DIPOLE VACUUM CHAMBER

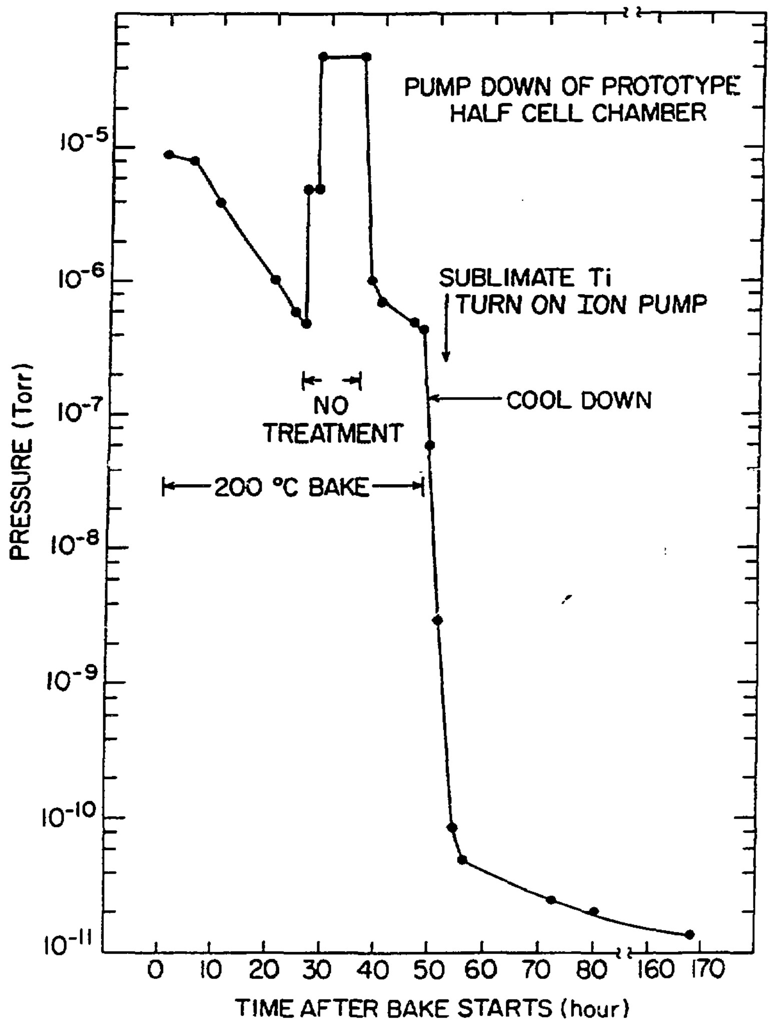
AGS BOOSTER
TYPICAL HALFCELL VACUUM CHAMBER


CALIBRATION
RING
CERAMIC
POSTS
VACUUM
SHELL
SPLIT PLATES


P ~ 1.6 × 10-9 Torr
T ~ 196 °C
(b)
10-13
10-12
10-11
10-10
P ~ 2 × 10-9 Torr
T ~ 203 °C
(a)
10-13
10-12
10-11
10-10
0
10
20
30
40
50
60
70
80
m/e



Apollo
Domain
IEEE 488
Datacon D/C
RS232 D/C
Datacon
Valve Control
I/L
I/L
I/L
Ion Pump P S
I/L
Gauge Control
Gauge Control
I/L
I/L
Valve Control
I/L
Titanium P S
House
Tunnel
PT
PI
PI
PI
GI
GC
GI
PT
PT
Beam Vacuum


PUMP DOWN OF PROTOTYPE HALF CELL CHAMBER
PRESSURE (Torr)
10-5
10-6
10-7
10-8
10-9
10-10
10-11
SUBLIMATE Ti
TURN ON ION PUMP
COOL DOWN
NO TREATMENT
200 °C BAKE
0 10 20 30 40 50 60 70 80 160 170
TIME AFTER BAKE STARTS (hour)