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THE SNS RING VACUUM SYSTEMS *

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Abstract

The Spallation Neutron Source (SNS) ring, which is presently being commissioned at Oak Ridge National Laboratory, is designed to accumulate high-intensity protons. Ultrahigh vacuum of 10-9 torr is required in the accumulator ring to minimize beam-residual gas ionization. To reduce the secondary-electron yield (SEY) and the associated electron-cloud instability, the ring vacuum chambers are coated with titanium nitride (TiN). In order to minimize radiation exposure, quick-disconnect chain clamp flanges are used in some areas where radiation levels are expected to be high. This paper describes the design, fabrication, assembly, and vacuum processing of the ring and beam transport vacuum systems, as well as the associated vacuum instrumentation.

INTRODUCTION

The SNS ring vacuum system consists of the High Energy Beam Transport (HEBT) line, the accumulator ring and the Ring to Target Beam Transport (RTBT) line. The accumulator ring has a circumference of 248 m with four arcs and four straight sections, while the RTBT and HEBT have a total length of ~400m of beam transport lines. An overall layout of the HEBT, ring, and RTBT line is shown in Fig. 1.

The goal of SNS[1] is to provide a short pulse (~0.7 μs) proton beam at 60 Hz with an average beam power of 1.3 MW to a neutron-generating target. To improve reliability and to allow hands-on maintenance, the uncontrolled particle loss in the ring must be less than 10^{-4} or less than 1 nA/m at the design intensity. In the design phase of the vacuum system, beam losses due to H^- stripping, nuclear scattering, multi-Coulomb scattering, and residual gas ionization were evaluated. The vacuum requirements to minimize beam losses for HEBT, the accumulator ring and RTBT are 5 x 10^{-8} torr, 1 x 10^{-9} torr and 10^{-7} torr respectively[2].

The inner surfaces of the 248 m Spallation Neutron Source (SNS) accumulator ring vacuum chambers are coated with ~100 nm of TiN to reduce the SEY of the chamber walls.

SYSTEM DESCRIPTION

HEBT Vacuum

The total length of the HEBT beam line vacuum system is approximately 225 m, including the Linear Accelerator (LINAC) beam dump and injection beam dump extraction lines. The HEBT beam line is divided into three sections, the LINAC to achromat matching section, the achromat arc section and the achromat to accumulator ring matching section. Four electro-pneumatic gate valves isolate the three HEBT sections from each other and the adjacent LINAC and Accumulator Ring. There are also gate valves that isolate the HEBT beam dump lines from the HEBT.

The vacuum requirement for the HEBT beam line is 5 x 10^{-8} torr to minimize the electron stripping of H^- beam by the residual gas and the resulting beam loss and component activation. A total of 18 diode-type 300 l/sec sputter ion pumps are used to maintain operating vacuum in the HEBT. Portable, remote-control interfaced dry turbopump carts are used to rough down the HEBT and are valved out and removed from the system after the ion pumps are conditioned.

The LINAC to achromat matching section and ring injection section were fabricated from 12 cm diameter 316L stainless-steel tubing. There are a total of 26 quadrupole magnet chambers and 26 drift chambers in these two HEBT sections. Several different chamber configurations are needed to accommodate beam instrumentation, vacuum gauging, and vacuum pumping. Quadrupole magnet and drift chambers are typically 1 to 2 m in length. Conflat flanges of 171 mm outside diameter (OD) are used to join most of these beam line chambers. In the collimation regions where higher radiation occurs, quick-disconnect EVAC flanges in conjunction with remote flange assembly fixtures, are used to minimize radiation exposure to workers.

The achromat bend section includes eight bending dipoles and eight quadrupoles magnet chambers. The quadrupole chambers are made from 8 inch diameter 304L tubing and are approximately 1.5 m long. The dipole chambers are nearly 6 meters long and are custom formed elliptical chambers which have a horizontal beam aperture of 20 cm and a vertical centerline aperture of 7.5 cm. Three dipole chambers include an integral Y-section and extraction tube to accommodate LINAC beam dump, momentum dump, and beam-in-gap (BIG) laser. A picture of the dipole chamber for the LINAC dump and BIG is shown in Fig. 2. This bending section by design experiences higher beam loss and, therefore, a higher activation level. Quick-disconnect EVAC flanges with copper gaskets and stainless-steel chain clamps are used in this region to join beam line chambers.

The vacuum windows of the three dump lines in HEBT vary in design depending on the power rating of the dumps. The 7.5 kW Linac dump window is edge-cooled with water. The flight tube downstream of this window to the dump will be filled with helium. The 2 kW momentum dump window is fabricated of stainless steel with a small air gap between the window and the dump. Both windows will be located in the HEBT tunnel. The injection dump located in the injection-dump building will handle up to 200 kW power and is water-cooled. A fast valve provides protection in the event of window failures and isolates the injection beam dump from the HEBT and the ring injection section.

The HEBT vacuum system has been assembled and achieved an average pressure of low 10^{-9} torr during commissioning meeting the design goals.

Accumulator Ring

The accumulator ring, which has a circumference of 248 m, has four arc sections and four long straight sections (a four-fold symmetry)[1]. The vacuum system is divided into eight vacuum sectors, four arc vacuum sectors, and four straight vacuum sectors, isolated with all-metal pneumatic gate valves. The arc vacuum sectors are ~34 m long, consisting of eight half-cell vacuum chambers which are 4 m long and a quarter-cell chamber. A typical half-cell assembly is shown in figure 3. The straight vacuum sectors are ~28 m long, and consist of two quadrupole doublet chambers, as well as individual chambers for injection, collimation, Radio Frequency (RF), instrumentation, and extraction.

A pressure of 10-9 torr is required in the accumulator ring to minimize beam-residual gas ionization and will be maintained by 44 300 l/sec sputter-ion pumps. Turbopump/dry-pump carts will be used for the initial pump down and to supplement the high-vacuum sputter ion pumps. One turbopump cart will be installed at each vacuum section, preferably near high outgassing sources and potential leaks, but away from high radiation areas. Each ring half-cell chamber have extra ports that can be used to add additional pumping for future upgrades. No linearly distributed pumps are needed due to the large aperture and the large conductance of vacuum chambers.

All half-cell and quarter-cell chambers were fabricated from 316L stainless steel, which has excellent mechanical/vacuum properties. 316LN Conflat flanges with 90° knife edges and copper seals are used to join the chambers together.

Fig. 4 shows a standard arc half-cell chamber. The 2 m long dipole chamber has an elliptical inside cross section of 23 cm (H) by 16 cm (V), providing ample aperture for a future upgrade to 2 MW. The chamber is curved with a bend angle of 11.25° and a radius of 730 cm. The top and bottom halves of the dipole chambers were formed by bending each half of the chamber on a bending brake. The two halves were tungsten inert gas (TIG) welded together along the mid plane, forming a straight chamber with an elliptical cross section. The chambers were filled with steel shot packed very tightly during the bending process, which provided support and spread out the stress from bending, preserving the cross section of the chamber. The chambers were bent to the proper angle and radius by drawing the chamber through a bending brake with rollers machined to match the chamber cross section. In order to ensure that the bend angle was in a flat plane, each chamber was checked and straightened in a press, if necessary. To minimize the deflection and to assure the structural stability of the chamber under vacuum load, the dipole chambers were fabricated from 5 mm 316LN stainless-sheet metal.

To reduce wall impedance, there are tapered transitions on each end of the dipole chamber one to the round quadrupole pipe and one to the end flange. The quadrupole pipes have an inside diameter (I.D.) of either 19 cm or 25 cm. The remainder of the half-cell chamber consists of a beam-position monitor (BPM), a cross for mounting pumps and vacuum gauges, and a bellows. To minimize the radiation-induced stress corrosion, the thin wall bellows were fabricated from Inconnel 625. The pump ports has a 203 mm Conflat flange with an RF screen installed with >80% transparency for evacuation.

A welding fixture 9as shown in Fig. 5) was used to align and clamp the parts together during the TIG welding of all half-cell, quarter-cell, and straight section chambers. The fixture was precision surveyed and ensured all the BPM's, pump crosses, dipole chambers, and tubes were aligned with respect to the quadrupole magnet pole tips with overall precision to ±.1 mm. The alignment was of particular importance for long chambers (such as the quad doublets and half-cell chambers) and prevented any interference with magnet pole tips. All piece parts to the chambers were either chemically cleaned in an ultrasonic bath with detergent followed by a deionzed water rinse or steam cleaned, depending on the size of the part. After the piece parts to each chamber were clamped into the welding fixture the end flanges of each chamber were welded first. Each chamber was then set up with an argon purge to prevent oxidation of the inside of the chamber walls in areas of butt welds when parts were joined together. After the chambers were welded, they were helium leak-checked and then vacuum fired at 450^{o} C for 48 hours in an in-house vacuum furnace.

Special chambers such as doublet chambers (Fig. 6) and chambers for collimators, RF cavities, and injection and extraction equipment are all located in the straight sections. The doublet chambers consist of a quadrupole pipe, BPM, cross for mounting pumps and gauges, bellows, and flanges. Tapered transitions were also used to adapt to different pipe sizes and to reduce the wall impedance.

In several locations with potentially high background radiation, such as the injection, extraction, and collimator regions, quick-disconnect type flanges and seals are used, which will minimize the radiation exposure during machine maintenance periods and repairs. Extensive testing of several types of EVAC flanges and chain clamps was performed in order to find the most reliable type of flange that could be assembled quickly in high-radiation areas. The three types of flanges tested were International Standards Organization (ISO), Conflat (CF) and CFX. These flanges are machined with a 20° taper and use a segmented chain clamp with two bolts for tightening the joint. The chain clamp makes contact on the 20° taper. These flanges are much faster to assemble than a standard Conflat flange which has many bolts. The test result indicated that the EVAC CFX flange and chain clamp[3] with copper CFX seals were the best choice on flanges up to 250 mm in diameter. On flanges with larger diameters than 250mm, custom flanges machined with a 20° taper and an o-ring groove to accept Helicoflex Delta seals were used with EVAC chain clamps and were found to be faster and more reliable than the standard CFX seals in these larger sizes.

The ring vacuum system has been commissioned and achieved the design vacuum pressure of 10^{-9} torr in the ring arcs and most straight sections. In the extraction straight section, the average pressure is 10^{-7} torr due to the fact that this area was not baked *insitu*. This area is expected to achieve 10^{-9} torr after being baked at 200° C for 48 hours.

RTBT Vacuum

The total length of the RTBT beam line vacuum system is approximately 165 m including the extraction beam dump line. A pressure of $\sim 10^{-7}$ torr is required for the RTBT section adjacent to the ring extraction section and $\sim 10^{-6}$ torr near the target area. A total of 13 diode 300 l/sec sputter ion pumps are used to maintain operating vacuum in the RTBT. Portable, dry turbopump carts are used to rough down the RTBT from atmosphere and valved out and removed from the system after the ion pumps are conditioned. The RTBT vacuum chambers have a 20 cm aperture except for the last 30 m of RTBT inside the target building, which has a 36 cm aperture. No vacuum pumps are installed near the target due to the intense radiation and the lack of access. Remote-operable quick-disconnect type flange assemblies are designed and employed for the quadrupole doublet chambers adjacent to the Target. The welding fixture used for the accumulator ring chambers was modified and surveyed and used for alignment during welding of all RTBT chambers. A fast valve was installed to protect the RTBT vacuum from catastrophic failure of the target window.

The RTBT vacuum system is still in the installation phase at the present time and therefore pressure readings are not available for the system. However, since the vacuum requirement for this section are not very stringent, no problems achieving the design pressure are anticipated.

TiN Coating Of Ring Vacuum Chambers

The inner surfaces of the 248 m Spallation Neutron Source (SNS) accumulator ring vacuum chambers are coated with ~100 nm of titanium nitride (TiN). This is to minimize the secondary-electron yield (SEY) from the chamber wall, and thus avoid the so-called e-p instability caused by electron multipacting as observed in a few high-intensity hadron and positron storage rings. A total of 135 vacuum chambers with a total length of over 300 m, including some spare chambers, were coated. These chambers ranged from 20 to 36 cm in diameter and from <0.5 m to 5 m in length. The coating is deposited by means of reactive DC magnetron sputtering using a cylindrical cathode with internal permanent magnets. This cathode configuration generates a deposition rate sufficient to meet the required production schedule and produces stoichiometric films with good adhesion, low SEY, and acceptable outgassing. Moreover, the cathode magnet configuration allows for simple changes in length and has been adapted to coat the wide variety of chambers and components contained within the arcs, injection, extraction, collimation, and RF straight sections.

Cathode Configurations

Reactive DC magnetron sputtering, with its high deposition rate, was chosen over diode sputtering to facilitate the coating of these vacuum chambers[4]. The cathode configuration used is similar to the one reported by Hosokawa *et al* [5]. A schematic of this cathode, which shows the magnetic field and resulting electron-trapping mechanism, is shown in Figure 7. To produce this configuration, permanent magnets (*Alnico*) were installed within the Ti cathode with alternating poles, as shown in Fig. 8. A deposition rate of ~100 nm/hr at a cathode power density of 0.6 watts/cm^2 was achieved during development with a 20 cm diameter chamber. For production coating, discharge power was varied linearly with the chamber length (i.e., magnet string length) and the deposition time varied with the diameter. Increasing the power density above 1 watt/cm^2 level would cause heat damage to the titanium nitrogen distribution tube, which was not well thermal anchored with the water cooled cathode. Without that concern, much higher deposition rates could be achieved.

This magnetron cathode could be easily adapted to a wide range of chamber sizes and geometries. Adjustments in length could be made by simply adding or removing magnets. There were four major configurations required to coat all the SNS ring chambers: arc half-cell chambers; straight section metal chambers; injection ceramic chambers; and extraction ferrite kicker modules. In all configurations, the cathode was isolated from the chamber using ceramic breaks. Bellows were also used for alignment and centering of the cathode. Cathode deflection was reduced by applying an upward bending moment to the cathode through special fixtures.

Arc Half-Cell Chambers

Due to the half-cell chamber geometry, which had a curved dipole section, a cathode was constructed with a sagitta equal to the dipole section. Due to the difference in nitrogen consumption rates resulting from the difference in cathode-to-chamber spacing between the dipole half and quadrupole half, independent flow control was required. A schematic of the coating setup for arc half-cell chambers is shown in Figure 9.

Straight Section Metal Chambers

The coating of straight chambers was similar to that of the half-cell chambers. In the case of short chambers sharing like flanges, the chambers could be joined together by the flanges and coated in batches. The cathode used to coat the 5 m injection and RF doublet chambers, was made from thick wall 1.25 inch diameter schedule 40 Ti pipe. This stiffer cathode reduced the deflection by a factor of 2. Special collars were fabricated to transfer the increased bending moment stress applied to the ceramic break end cuffs when leveling the cathode. Two independent nitrogen tubes were also used to help control the process.

Injection Kicker Ceramic Chambers

In the SNS accumulator ring, ceramic vacuum chambers are used for the eight injection kickers to avoid shielding of a fast-changing kicker field and to minimize eddy-current heating. The inner surface of the ceramic chambers was coated with Cu (to reduce the beam-coupling impedance and provide passage for beam image current), and a TiN over layer (to reduce secondary electron yield).

The coating of the injection kicker ceramic chambers posed a unique set of problems[6]. Because the ceramic chambers could not couple the discharge to the cathode, a stainless-steel anode screen was placed between the cathode and ceramic chamber. The screen allowed uniform discharge along the cathode, but created a non-uniform coating due to shadowing. This shadowing was a form of destructive interference between the discharge ring spacing on the cathode and the screen. Several tests were conducted with various screen sizes. Counter intuitively, a smaller screen size yielded the best result.

The coating system isolated the metal flanges of the ceramic chamber with additional ceramic breaks so *in-situ* resistance measurements could be taken during the coating.

Extraction Kicker Modules

The extraction kicker modules were fabricated with ferrite blocks with copper conductors. The ferrite surfaces facing the beam have high SEY and must be coated with TiN. To minimize the eddy current loops on the ferrite surface due to the conductive TiN film, the coating was laid down in small longitudinal strips isolated from each other[6]. Customized masks were used to produce longitudinal coating strips of 1 cm x 5 cm with ~1 mm separation among the strips.

An estimate of the coating uniformity was made based on a cosine approximation. The results raised concern that the uniformity of the TiN coating on the vertical ferrite walls would vary as much as eightfold. However, measurements showed a fourfold difference in thickness from the midplane to the corner.

SEY And Outgassing

The measured SEY of coated chambers was found to be dependent on surface roughness[7]. A rougher surface yields lower SEY values. Testing revealed that the surface roughness of the coating could be increased when produced at higher sputtering pressures. However, these coatings were found to have a higher outgassing rate than coatings produced at lower pressure[8]. For SNS chambers, low SEY was of primary importance. Consequently, rougher coating surfaces were produced at higher sputtering pressures (i.e., ~5 mtorr), which yielded SEY values in the 1.6 to 1.8 range, as shown in Figure 10. SEY values in this range are sufficient to suppress electron cloud build-up in the accumulator ring[9]. Although the coatings produced had elevated outgassing, rates, the design vacuum of 10^{-9} torr has been achieved in the ring arcs and most straight sections.

VACUUM INSTRUMENTATION AND CONTROL

The vacuum system instrumentation includes gauges and controls for valves, ion-pumps, and turbomolecular pumps. All vacuum system devices, valves, gauges, ion pumps, and turbomolecular pumps, are operated via programmable logic controllers (PLC). Three types of valves are used: sector gate valves, pump isolation valves, and fast valves. The sector and isolation valves have +24 Vdc solenoids with both open and closed limit switch position indicators.

Ion-pumps are used to maintain high vacuum in the accumulator ring and transport lines. The ion pump current, which is proportional to pressure, will give a detailed pressure profile around the ring and transport lines. The ion pump controllers operate two ion pumps simultaneously and independently and have a normally open relay contact set point for each of the two outputs. These set points are used in the Programmable Logic Controller (PLC) logic that controls sector valves. Turbomolecular pump stations are used to pump the beam line from atmospheric pressure to high vacuum. Remote operation of the turbos will be accomplished through remote control of analog inputs and discrete inputs and outputs. Analog pressure readings from the turbo stations are used in the isolation valve-control logic.

Convection-enhanced Pirani gauges are used to monitor the rough vacuum; high vacuum levels are measured with inverted magnetron gauges. The gauge controllers supply one normally open relay contact per gauge, used for sector valve and isolation valve control. RS-485 remote serial communication is used to obtain controller status, ion pump current, voltage readings, and pump and gauge pressures.

Programmable logic controllers are used to monitor gauge and pump interlocks and control valves. The primary function of the PLC is to provide control of the sector valves that sectionalize the vacuum systems. The valve control logic is designed to be fail-safe. A sector valve will close in case of a) vacuum conditions deteriorating to a specified limit, b) power loss, and c) operator input from the support building or remote terminal. The vacuum PLCs provide interlock and beam permit outputs and receive interlock inputs from other subsystems (e.g., RF, machine protection, and target systems). The control of the HEBT, ring, and RTBT vacuum systems is distributed among a network of PLCs linked by Ethernet/Internet Protocol (IP) networks. A vacuum system instrument and control schematic is shown in Fig. 11.

A VersaModule Eurocard (VME) input/output Controller (IOC) provides the gateway between the global- control system and the vacuum-instrumentation system. The IOC provides supervisory controls to the vacuum subsystems, interfaces with other subsystems, and acts as a gateway to operator interface machines[10]. The IOC hosts the RS-485 serial communication networks for the ion pump and gauge controllers and communicates with the PLC through an Ethernet/IP interface. The Experimental Physics and Industrial Control System (EPICS) is used to provide the graphical user interface for operation of the vacuum systems via the IOC. An EPICS display manager is used for monitoring and controlling vacuum devices.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Figure 1. Layout of the SNS ring, HEBT, and RTBT lines.

Figure 2. HEBT Linac dump and BIG dipole chamber.

Figure 3. Typical half-cell assembly with vacuum chamber and associated magnets.

Figure 4. Typical half-cell vacuum chamber assembly.

Figure 5. Fixture used to align chambers during welding.

Figure 6. Extraction quadrupole doublet chamber assembly.

Figure 7. Schematic of the long cylindrical cathode with internal magnets.

Figure 8. BNL cathode showing permanent magnet string above, to be inserted within Ti cathode (shown with nitrogen gas distribution tube) below.

Figure 9. Schematic of magnetron-sputtering setup for arc half-cell chambers. The lower portion shows the central cathode support. (IMG: inverted magnetron gauge, RGA: residual gas analyzer, MFC: mass flow controller)

Fig 10. SEY as a function of incidence electron energy for bare and TiN-coated stainless-steel coated at high and low pressure.

Figure 11. SNS vacuum instrumentation and control schematic.

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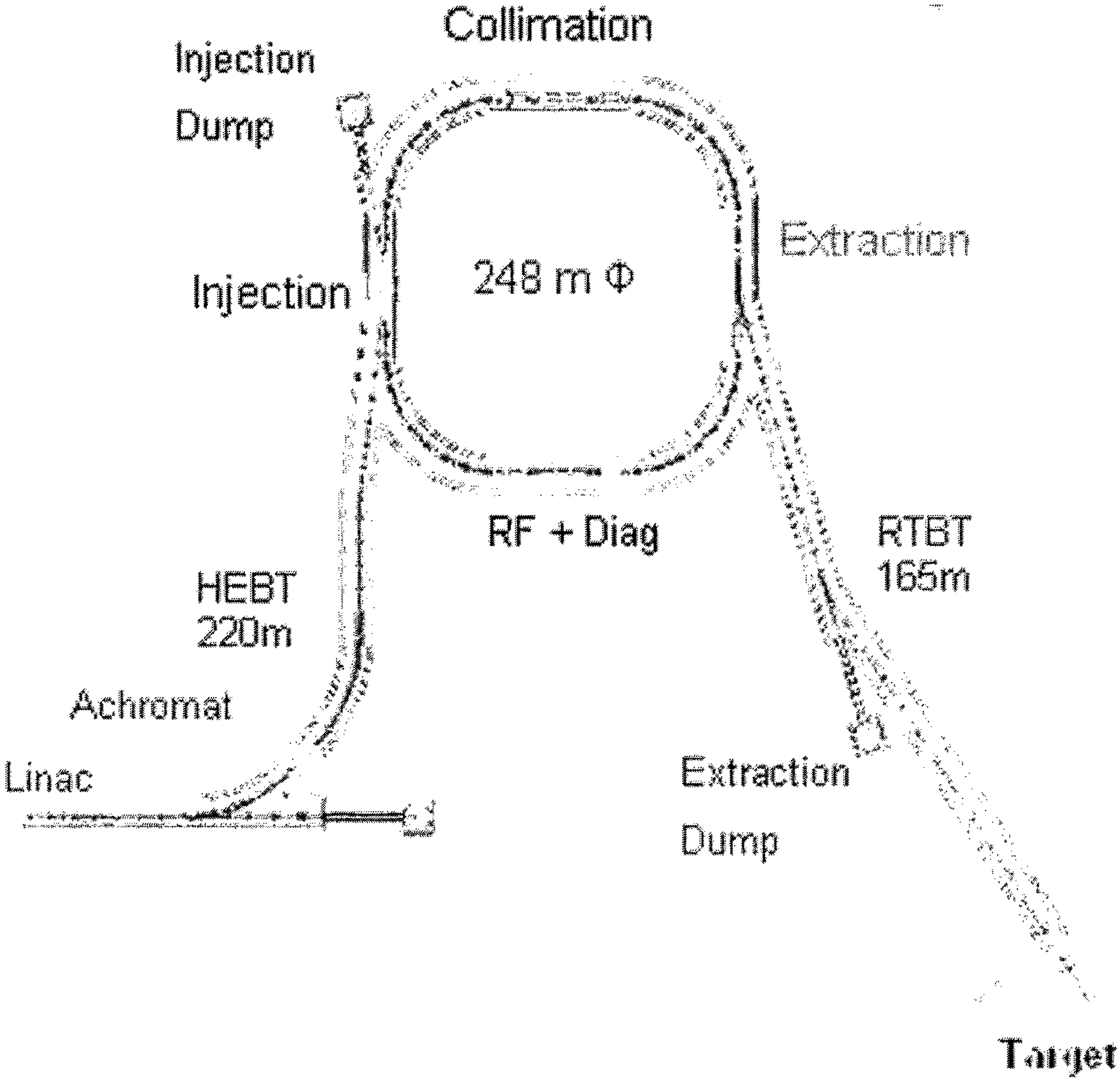

Figure 1. Layout of the SNS ring, HEBT, and RTBT lines.

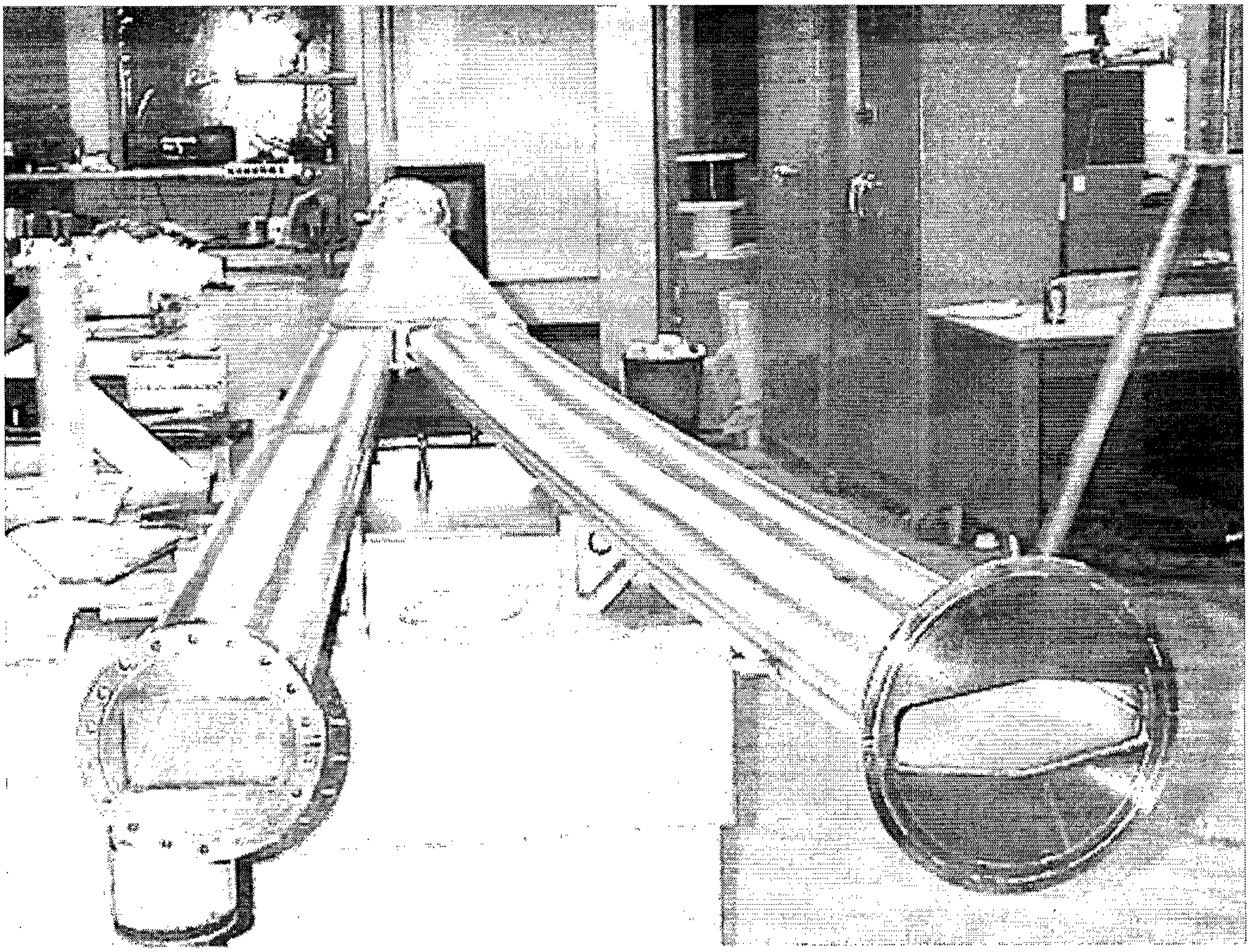

Figure 2. HEBT LINAC dump and BIG dipole chamber.

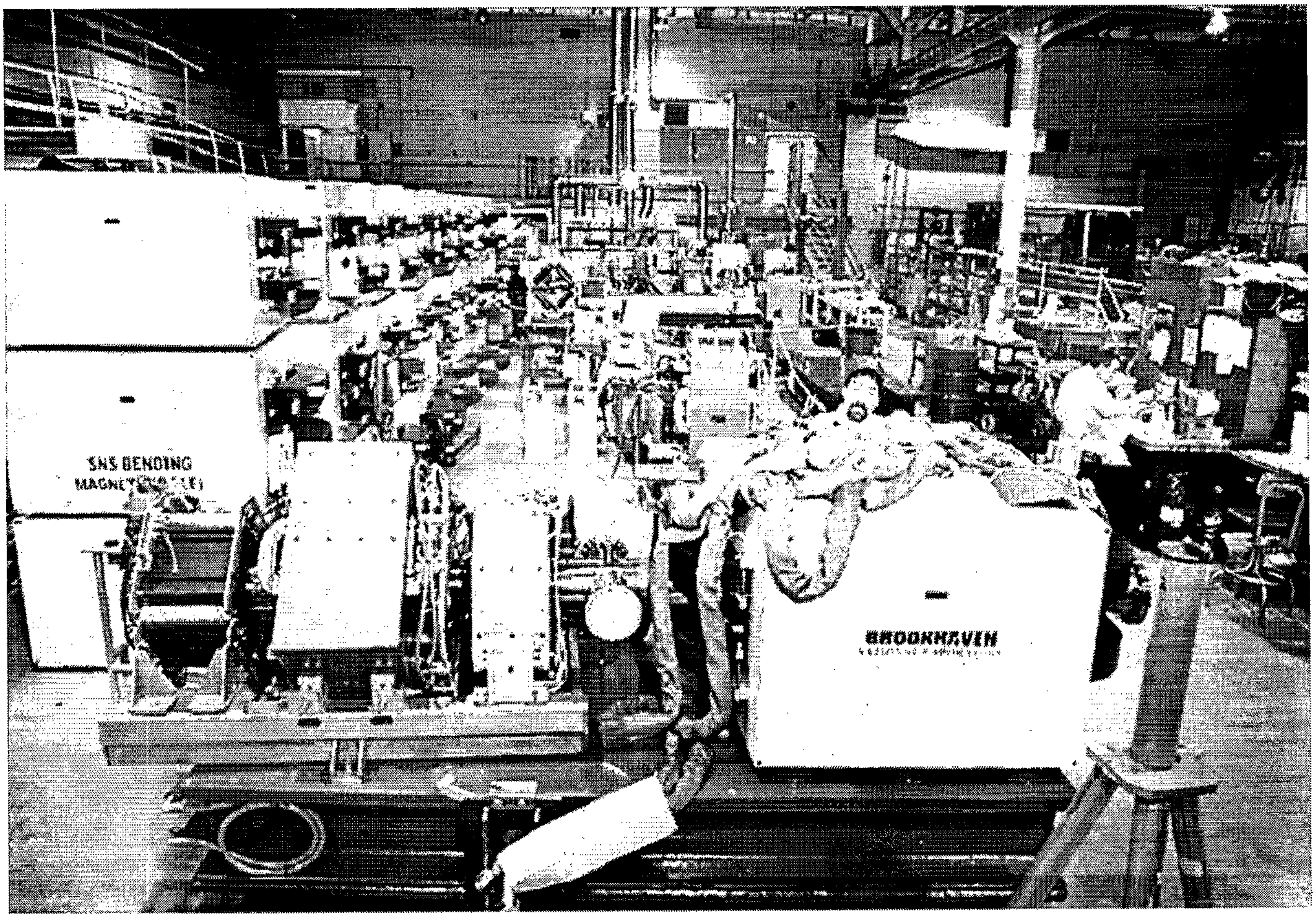

Figure 3. Typical half-cell assembly with vacuum chamber and associated magnets.

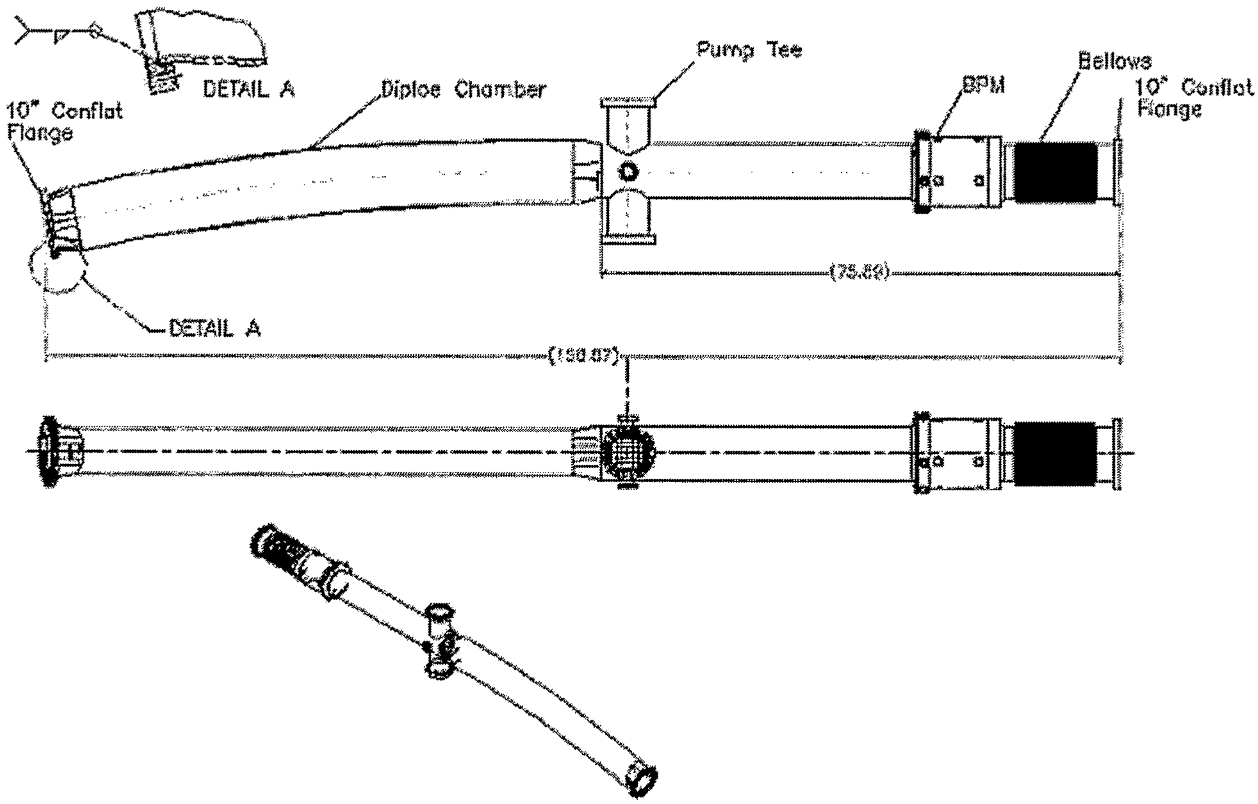

Figure 4. Typical half-cell vacuum-chamber assembly.

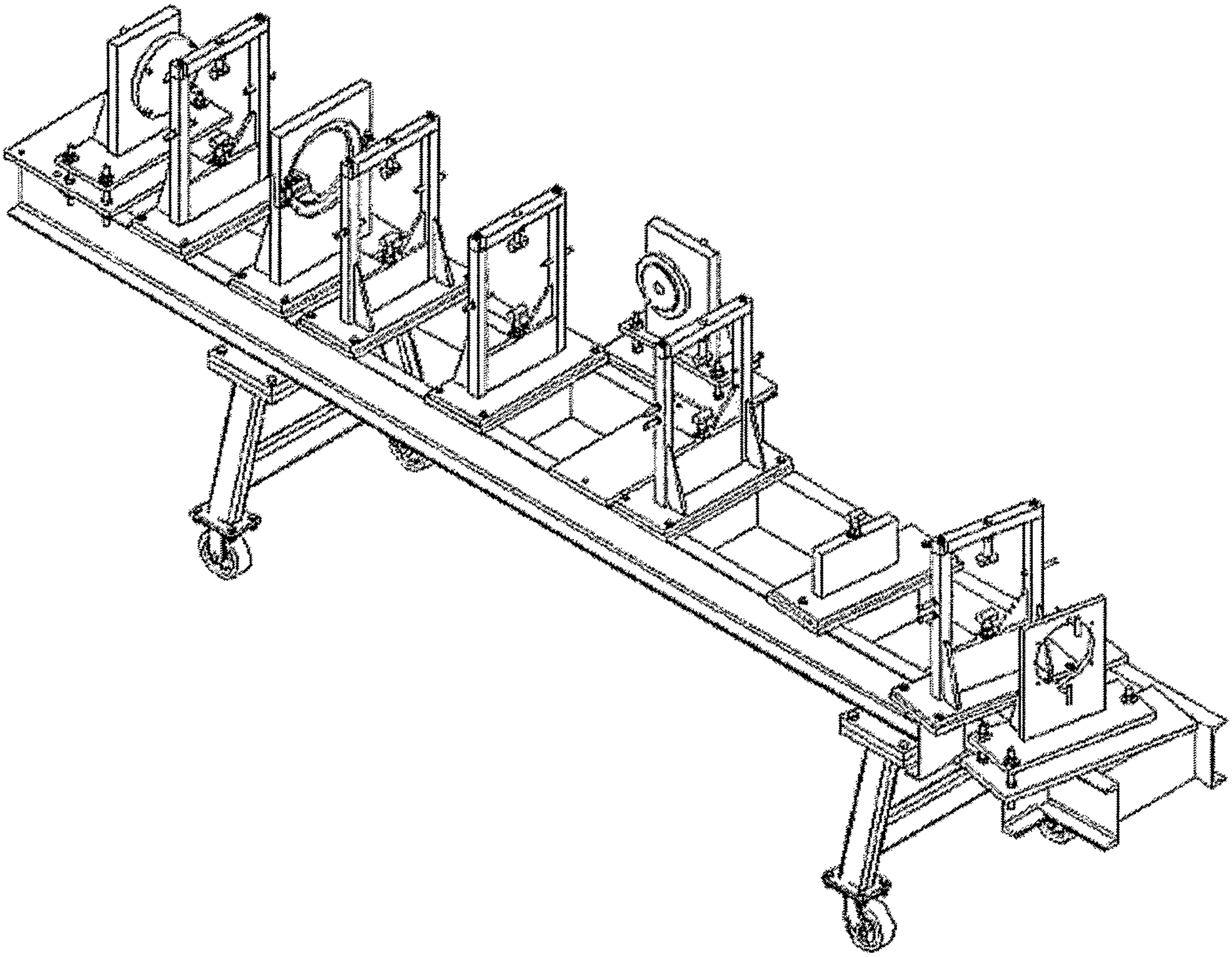

Figure 5. Fixture used to align chambers during welding.

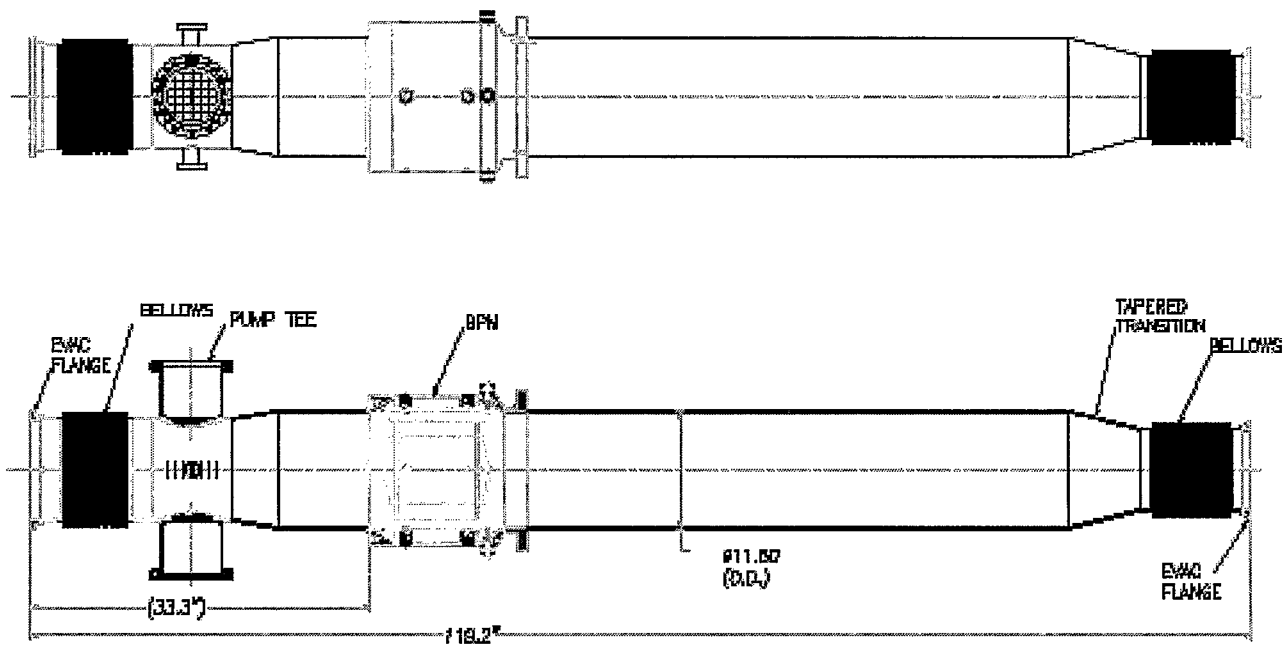

Figure 6: Extraction quadrupole doublet chamber assembly.

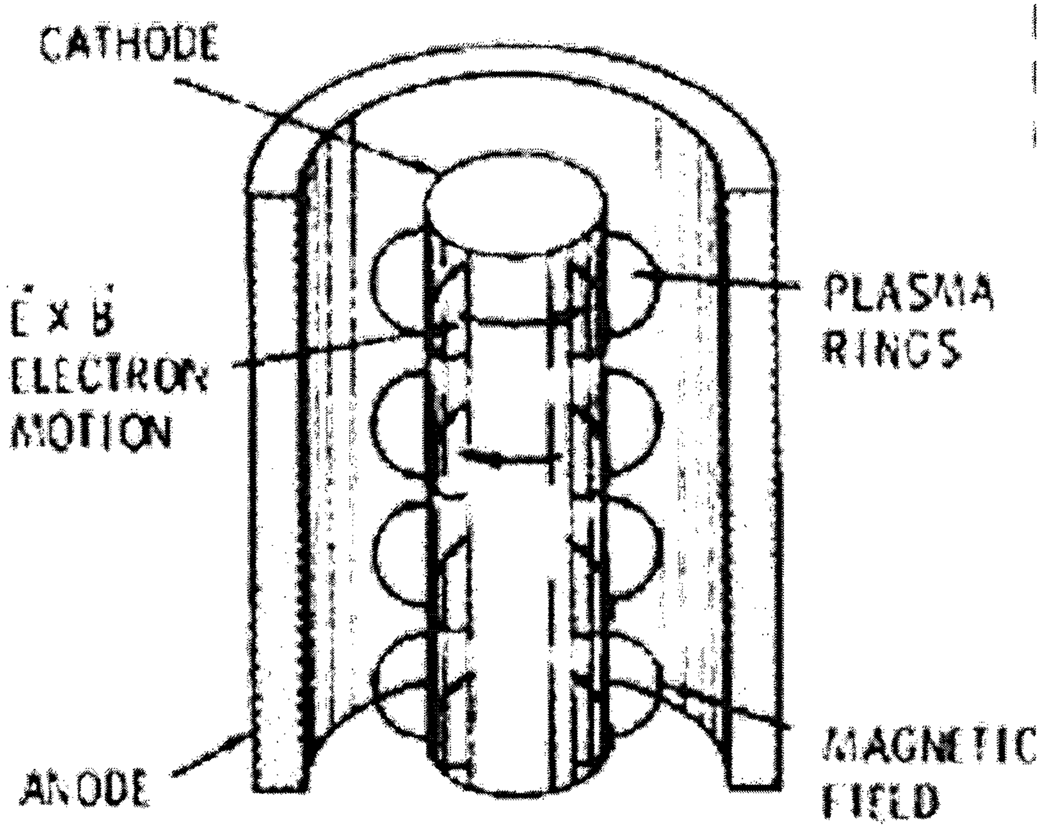

Figure 7. Schematic of the long cylindrical cathode with internal magnets.

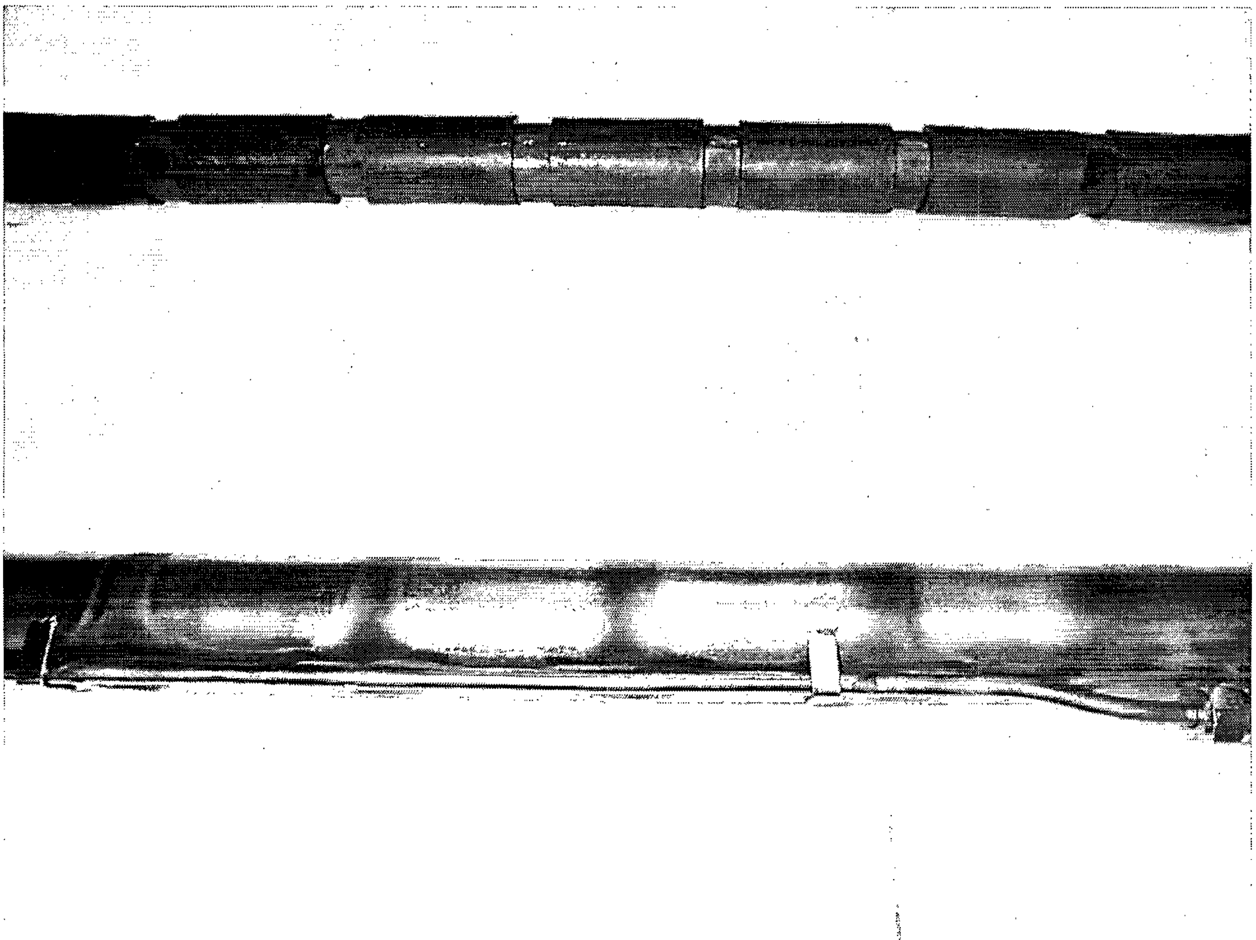

Figure 8. BNL cathode showing permanent magnet string above to be inserted within Ti cathode (shown with nitrogen gas distribution tube) below.

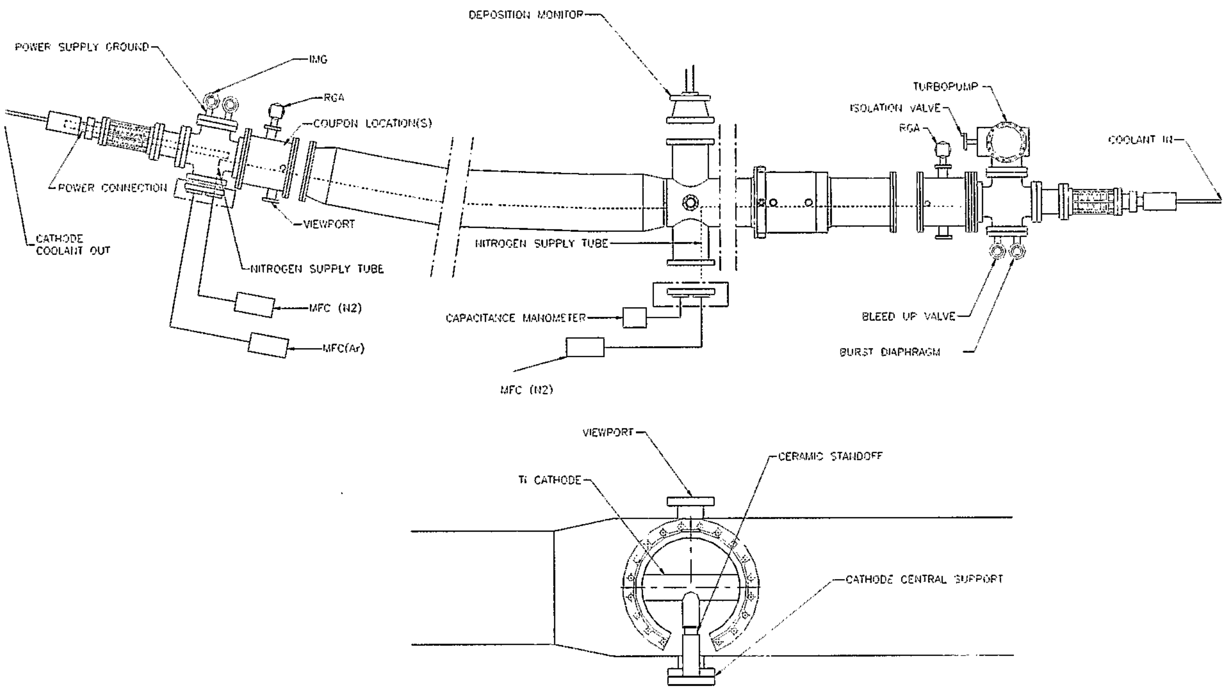

Figure 9. Schematic of magnetron sputtering setup for arc half-cell chambers. The lower portion shows the central cathode support. (IMG: inverted magnetron gauge, RGA: residual gas analyzer, MFC: mass flow controller)

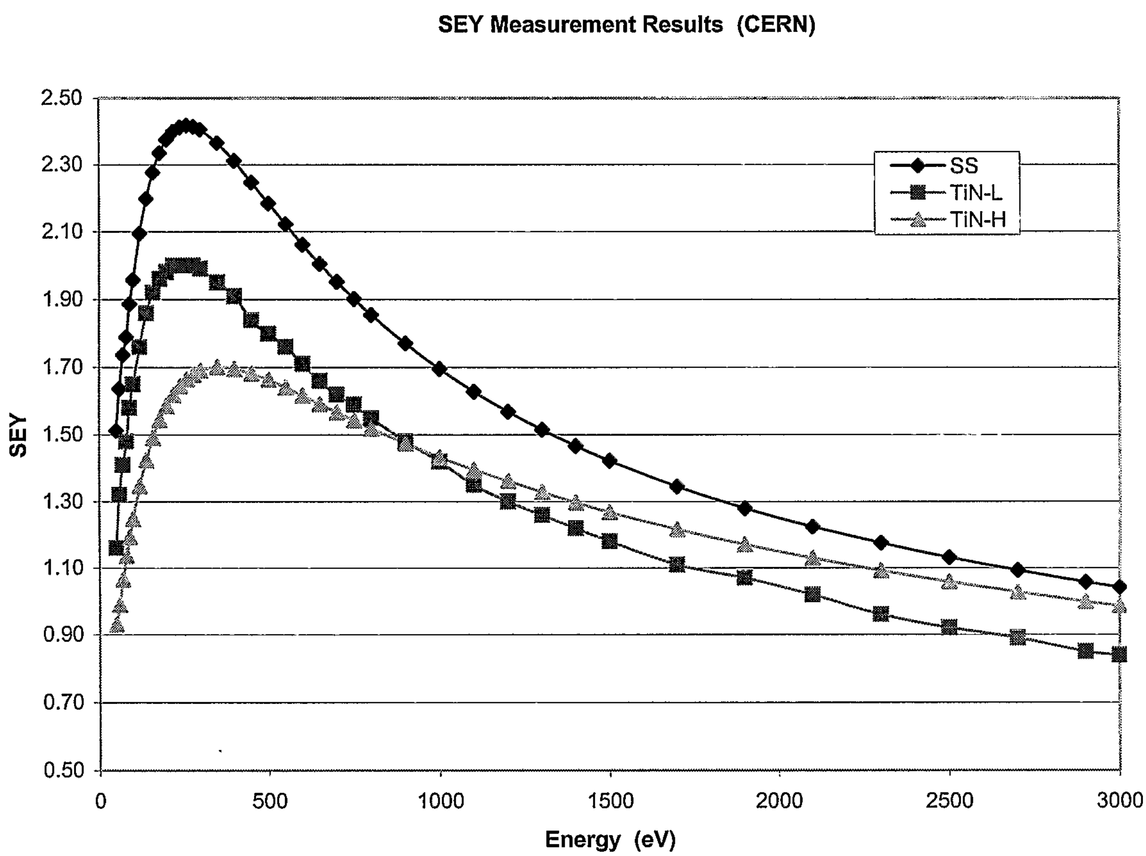

Fig 10. SEY as a function of incidence electron energy for bare and TiN-coated stainless steel coated at high and low pressure.

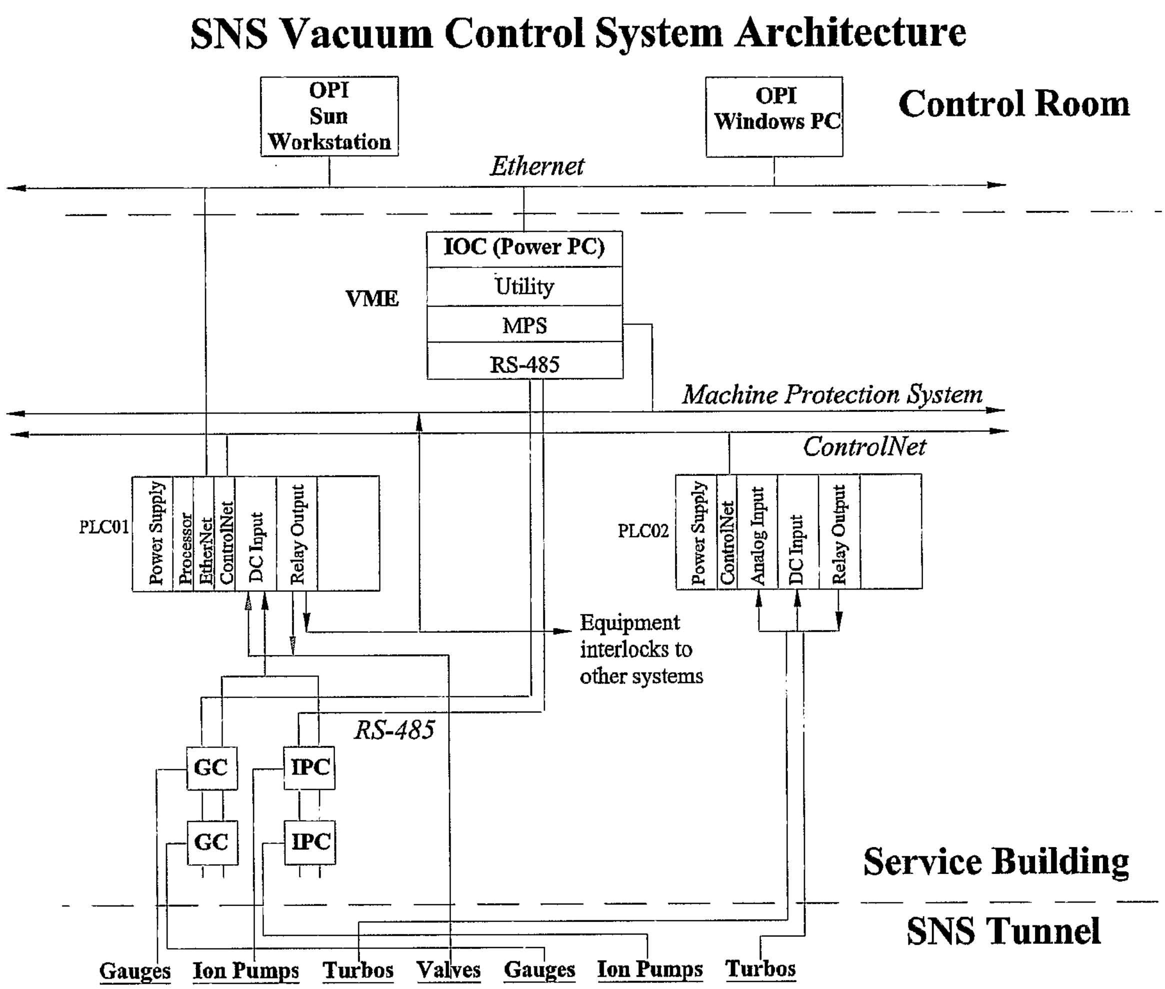

Figure 11: SNS Vacuum instrumentation and control schematic.