Industrial Scale Ion Beam Enhanced Deposition (IBED) Processing System

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Abstract

An industrial scale ion beam enhanced deposition (IBED) system has been specified, designed, constructed, and is now in operation. The system is used to coat a variety of tools and engineered components in a rapid cycle-time, batch-processing mode. The IBED system is capable of depositing a wide range of 1 to 10 micron ($1x10^{-6}$ m) thick metallic, nitride, oxide, and carbide coatings with a high degree of precision and uniformity over a 46 cm (18 inch) diameter zone, at temperatures below 93 °C (200 °F). IBED coatings are produced by vacuum evaporation of metallic species (Cr, Ti, Ni, Al, etc.) with simultaneous bombardment of the evaporated layers with energetic ions (N^+, Ar^+, Kr^+, etc.) in the energy range of 1 keV (1,000 volts) to 100 keV.

Keywords: industrial-scale IBED coating system design

Introduction

Ion beam enhanced deposition (IBED)[1], also termed ion beam assisted deposition (IBAD), is a thin film deposition technique that offers many advantages when used for the deposition of a variety of optical, dielectric, semiconductor, and tribological coatings. The nature of the process allows deposition of coatings having a wide range of metallurgical compositions, and with a high degree of control over coating nanostructure. Film-substrate adhesion is achieved without the external application of heat, and processing temperatures can be held below 93 °C (200 °F) if desired. These process features are important for satisfying specifications required for optical and semiconductor thin film coatings, and can have significant benefits when utilized for the deposition of tribological coatings. In contrast to semiconductor and optical applications where coatings are always thin (sub-micron) and most often deposited on flat substrates, tribological coatings must be thicker (5 – 10 microns) and must be deposited on three-dimensional mechanical components. Therefore, the processing requirements, and the processing equipment used, will be quite different from that used for semiconductor or optical element coating.

A market analysis and a comprehensive engineering design study[2] were both completed, and specifications were developed for an industrial scale IBED coating system designed to deposit tribological coatings on three-dimensional mechanical components. Processing requirements, including part size and volume, coating type and thickness, batch throughput time, and economics were all analyzed before finalizing the system specifications and designs. The industrial scale system was constructed and is now being used to deposit tribological coatings on a variety of different types of manufacturing tooling and engineered components.

The IBED Coating Process

IBED is a physical, non-equilibrium coating process implemented by the simultaneous bombardment of a growing film with an independently controllable beam of energetic particles. The growing film is generated either by vacuum evaporation or ion beam sputtering. The independent beam of particles, termed the augmenting beam, consists primarily of charged atoms (ions) extracted at high energy from a broad beam ion source. Either inert species such as Ne^+, Ar^+, or Kr^+, or reactive species such as N^+ or O^+ can be used. Since the augmenting ion beam is independently controllable, the energy of the ions in the beam can be varied over a wide range and chosen within a very narrow window. This allows the energetics of coating growth to be varied during the coating cycle and allows optimization of coating properties such as interfacial adhesion, density, grain size and morphology, and internal stresses[3,4]. A high vacuum environment is required for propagation of the augmenting ion beam, and also helps limit the arrival rate of contaminant gas species (H_2O, CO_2, etc.) at the surfaces being coated. The wide energy range and controllable flexibility of the IBED process enable the deposition of a variety of highly engineered coatings on a wide range of substrate materials.

IBED Coating Process Implementation

The IBED process[5] is carried out in a high vacuum environment, at pressures of 1×10^{-6} Torr or below. With proper choice of deposition parameters the temperature rise in components being processed can be held below °93 C (200 °F). A general diagram of the implementation of the IBED process is seen in Fig. 1.

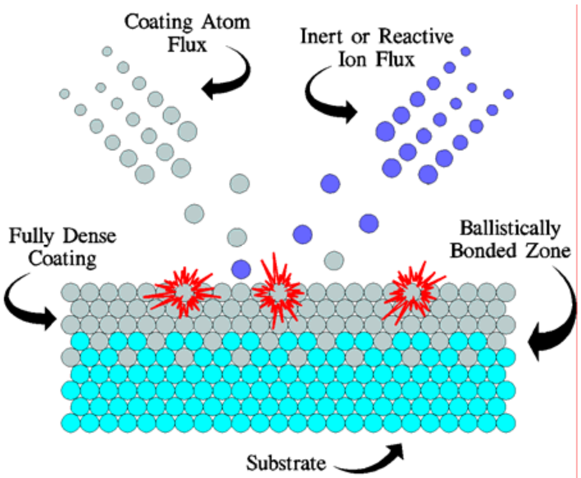


Figure 1: Schematic diagram of the implementation of the IBED process.

The surface to be coated is first illuminated with a flux of high-energy ions that is initially used to remove surface oxides and other contaminants. This flux of ions can consist of inert species such as Ar^+ or Kr^+, or reactive species such as N^+ or O^+, depending upon the chemical composition of the coating to be deposited. This high-energy ion flux is maintained, and once the surface is cleaned, a flux of coating atoms is then directed simultaneously at the surface to be coated. The high-energy ions are used to mix the initial few atomic layers of the coating material into the surface being coated. This forms an alloyed bond layer in the surface that promotes adhesion of the coating and is the mechanism that allows coatings of a variety of materials to be applied to virtually any substrate material without the need of an intermediate bonding layer. Once the alloyed layer is formed properly, the coating is then allowed to grow out from this alloyed layer. The high-energy ion flux is then used to control the morphology of the coating that is being grown from the surface. This allows control over the grain structure of the coating as well as coating density and residual stresses. Coatings in the thickness range of 5-10 microns (0.0002 - 0.0004 inches) can be grown with the technique on most metallic, glass, ceramic, and even plastic surfaces.

IBED Coating Process Geometry

IBED is a dual parameter process in which the reactant fluxes are simultaneously delivered directly to the surface to be coated from two independently controllable sources. Both of the reactant sources are directional in nature and must be located so that they simultaneously illuminate the components to be coated. Figure 2 shows the typical orientation of reactant sources and parts to be coated. The flux of coating atoms is usually produced by thermal evaporation. This dictates that the components to be coated must be mounted above the evaporator and positioned upside down. The augmenting ion flux is produced by a directional broad beam ion source that is aimed at an angle normal to the evaporant flux. The components are mounted to an angling, rotating platen assembly that is used to uniformly expose all surfaces of the components to both reactant fluxes during coating.

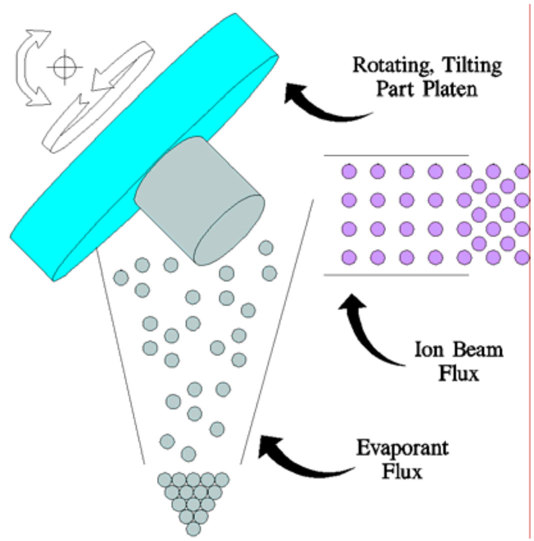
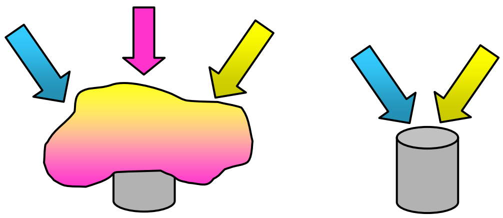


Figure 2: Processing geometry required for the IBED process.

Comparison with Conventional PVD

Tribological coatings such as titanium nitride and chromium nitride are usually deposited by glow-discharge, physical vapor deposition (PVD) processes such as activated reactive evaporation, cathodic arc sputtering, or magnetron sputtering[6]. In these processes coating reactants are transported to, and combined together in a glow-discharge carrier gas plasma. The reactions that occur when the reactants are combined in the glow-discharge carrier gas are driven primarily by the energetics of the glow-discharge. Therefore the metallurgical, morphological, and mechanical properties of the coatings deposited are determined by the thermodynamic environment in the glow-discharge. Once submerged in the glow-discharge the reactants cannot be controlled individually, and optimizing one coating feature such as grain size may have to be done at the expense of another feature such as density or adhesion.

The IBED process differs from the PVD process in that the reactants are not first reacted in a glow-discharge but are delivered individually directly to the surface to be coated as seen in Fig. 3. In addition, the energy of reaction is supplied by kinetic energy provided to one of the reactants. This provides more control over the reaction process and therefore more flexibility in the final morphology of the coating. Sacrificing one coating feature in order to optimize another is not necessary, which allows deposition of tribological coatings that perform better than the equivalent PVD-deposited coating. The major differences between the IBED and PVD processes are summarized in Table 1.



PVD
Reactants Delivered
to Carrier Gas
Plasma
(10^{-3} Torr)

IBED
Reactants Delivered
Directly to Surface
(10^{-6} Torr)

Figure 3: Reactant delivery differences: PVD versus IBED.

Table 1 IBED and PVD Process Comparison

PVD	**IBED**
Reactant Delivery	
Into plasma atmosphere surrounding parts	Simultaneous, directly to surface of parts
Reaction Chemistry	
Thermally driven by plasma temperature	Kinetically driven by kinetic energy of ions
Reaction Atmosphere (Pressure)	
10^{-3} Torr with high partial pressures of (H_2, H_2O, O_2, CO_2)	10-6 Torr with low partial pressures of (H_2, H_2O, O_2, CO_2)
Reaction Vessel Temperature	
> 400 °C	< 93 °C
Coating Morphology	
Crystalline, grains 1 –50 micron dimensions	Semi-amorphous, grains sub-micron dimensions
Coating Adhesion	
Thermal diffusion driven, interlayer needed	Ballistically alloyed, no interlayer needed

Attractive Features of The IBED Process

The nature of the IBED process provides many features that make it attractive for use as a process to deposit tribological coatings on mechanical components.

Low Temperature

Processing temperatures below 93 °C allow deposition of hardcoatings on a wide variety of temperature-sensitive metals and non-metals. Finished precision components can be treated without the risk of thermally induced dimensional distortion or bulk softening of the base material.

High Vacuum Operation

The requirement for operation at high vacuum reduces partial pressures of contaminating species such as H_2, O_2, H_2O, and CO_2 which during deposition can influence coating composition and morphology and therefore degrade coating quality.

High Degree of Control of Reactants

Only two parameters must be monitored and controlled during IBED coating, and they are independent of each other. The evaporant flux rate and the augmenting ion beam flux rate can each be independently varied over a wide range thereby allowing a wide range of metallurgical compositions in the deposited coating. Accurate, real-time monitoring of both flux rates can be achieved with conventional measurement technology.

Versatility

A variety of reactants can be used as feedstocks in the same processing system without the need to change any system hardware. Thus a wide range of metallic, metallic nitride, carbide, and oxide coatings can be deposited on a variety of substrate materials, all with the same processing system.

Uniformity

The IBED process is a line-of-sight deposition process that requires three-dimensional components be manipulated to maintain proper angles relative to the reactant flux flows. The continuous part motion relative to the reactant fluxes results in deposition of coatings having very uniform thickness over the entire treated surface because all surfaces are exposed to the reactant fluxes from all angular orientations.

Existing Technology

Assembly of IBED coating systems requires vacuum chamber technology, ion beam technology, vacuum evaporation technology, and process monitoring and control technology, all of which is already developed and in the marketplace. No new technologies need to be developed in order to build industrial-scale IBED processing systems.

Scalability

Since the IBED process is an athermal process, the complexity of designing process chambers that maintain a uniform temperature distribution over large volumes is eliminated. Very large chambers can be constructed capable of holding large parts or large volumes of smaller parts. Likewise multiple, commercially available evporators and broad beam ion sources can be positioned to treat large areas in single pump-down cycles.

Industrial Scale IBED System

The industrial scale IBED system currently in operation was designed and specified primarily to deposit tribological hardcoatings on precision machined parts and manufacturing tooling. System designs and specifications were developed based on a detailed analysis of the needs for tribological coatings on tools and components found in a variety of market sectors including the automotive, truck, aircraft, aerospace, medical, and general machinery. System designs and specifications were defined based on a set of key IBED system design criteria established by the analysis.

IBED System Design Criteria

Part Performance Requirements

Wear resistance and corrosion resistance requirements encountered in the various market sectors were tabulated and related to the thickness of hardcoatings that would be required to meet those requirements. Current and future specifications for component performance were evaluated.

Part Geometry

The general sizes, weights, and shapes of components that require tribological coatings were studied and categorized in order to specify a process chamber size large enough to accommodate a variety of components. Typical dimensional tolerances and surface finish specifications required for precision engineered components and tools were also evaluated.

Substrate Materials

Engineered components and manufacturing tooling are manufactured from a range of both ferrous and non-ferrous alloys. The process and processing system is specified to allow deposition of hardcoatings on the full range of alloys.

Temperature Limitations

The processing system is specified to limit the temperature rise in processed parts to below 200 ° F (93 °C).

Competitive Processes

Competing processes, already well established in the marketplace including electroplating (Cr and Ni), hardcoat anodizing, and PVD coating were studied. Features (and limitations) of each process, as well as the engineering properties of the coatings deposited were tabulated. A series of market niches were mapped where coatings deposited with the IBED process have distinct technical and performance advantages.

Feedstock materials

Availability and cost of feedstock materials including a wide variety of metals (Ti, Cr, Al, Si, V, Zr) and gases (N_2, O_2, Ar, Kr) at the purity levels required were tabulated and analyzed.

Environmental and OSHA

Since no toxic materials are required as feedstocks for, and no waste products are produced by the process, no special design criteria were needed in order to comply with environmental regulations. Electrical safety considerations include the need for high voltage power supplies (up to 100,000 volts DC) required for the high energy ion source, and high current power supplies (15 kilowatts) required for the electron gun evaporator.

System Economics

A model for the economics of system operation was completed which included a detailed analysis of expected capital costs and hourly operating costs. Expenditure flows for design and construction were estimated. Revenues were projected based on system productivity and a return on investment analysis was completed.

IBED System Specifications

The specifications for the industrial scale IBED processing system are outlined in Tables 2 through 6. Included are specifications for the IBED process, processing system capacity and throughput, the hardware configuration, the part-processing envelope, and system operation and control. An IBED processing system with the specifications developed will have the capabilities and capacities needed for industrial viability for a variety of market applications.

Table 2 IBED Process Specifications

Process	
Specification	**Description**
Coatings	Metals, nitrides, oxides, carbides
Ion Beam Species	Gases (Ne, Ar, Kr, N_2, O_2, CO_2)
Ion Beam Energy Range	1 keV – 100 keV
Evaporative Flux	Multiple metal species

Table 3 IBED System Capacity and Throughput

Part Capacity and Throughput	
Specification	**Description**
Processed Part Size	45.7 cm dia. X 20.3 cm
Processed Part Weight	227 kg
Processed Part Manipulation	Rotation up to 100 RPM, angles through 360 degrees
Process Temperature	< 93 °C (200 °F), water cooled part platen
Coating Time (Cr_2N, 3 micron thick)	45 minutes
Cycle Time (air to air) for a 3 micron coating	60 minutes

Table 4 IBED System Hardware Configuration

System Hardware Configuration	
Specification	**Description**
Vacuum Chamber System	Multiple chambers with isolation valves
Part Processing Chamber Size	1m Dia. X 1.5 m Long
Ion Beam Exit Grid to Part Platen Distance	152 cm (60 inches)
Evaporator Hearth to Part Platen Distance	102 cm (40 inches)
Baseline Operating Pressure	10^{-6} Torr
Vacuum Pumping	Oil Diffusion, multiple distributed pump stacks

Table 5 IBED System Processing Envelope

Processing Envelope	
Specification	**Description**
Part Platen	45.7 cm diameter
Ion Beam Flux	±5% over 45.7 cm
Evaporator Flux	±5% over 45.7 cm

Table 6 IBED System Operation and Control

Operation and Control	
Specification	**Description**
Vacuum System	Automatic (PLC)
Ion Source	Manual
E-gun Evaporator	Manual

System Design and Implementation

The basic block diagram of the IBED processing system designed to meet the specifications required for industrial viability is diagrammed and described in Fig. 4. Four 304 stainless steel vacuum chambers are coupled together in a "T" configuration. The central chamber houses the water-cooled part manipulator and a cryocoil[7], which is used for high speed pumping of remnant water vapor. The high energy and low energy ion sources are housed in the chambers directly to the left and right of the central processing chamber respectively. The electron gun evaporator is housed in the chamber directly beneath the processing chamber. The four vacuum chambers are separated by individual gate valves so that the central processing chamber can be cycled to atmospheric pressure while maintaining the other three chambers at high vacuum. The vacuum system is operated automatically by a dedicated programmable logic controller (PLC)[8]. The operator interface to the PLC is provided by RS View® (Allen-Bradley Company) process control software resident in a personal computer (PC) operating in a Windows® (Microsoft Corporation) environment. A second Windows® based PC supports a residual gas analyzer[9] that monitors the vacuum state in the central processing chamber. The low energy ion source[10] and electron-gun evaporator[11] controls are operated manually. The electron-gun evaporator can be fitted with either a continuous carousel or a four pocket hearth. Film deposition rate and thickness is monitored by a quartz crystal deposition controller[12].

The operator interface screen provided by the RS View® software is seen in Fig. 5. The vacuum state of all chambers and the position of all valves are displayed in color, and all key vacuum pressures, water cooling flow rates, pump temperatures, and pneumatic valve states are indicated on the display screen. The part platen tilt angle and rotation rate are set by pop-up windows displayed on the operator control screen. Likewise the electron gun evaporator hearth rotation rate and shutter position are set by pop-up windows displayed on the operator screen.

The IBED processing system hardware is seen in Fig. 6. The system is sited in a temperature-controlled room with finished walls and a drop ceiling. The operator control panel, power distribution panel and water and compressed air manifolds are also located in the processing system room, but are not shown. Ancillary equipment including the water chiller and air compressor are both located in an adjacent equipment room.

Summary and Conclusions

The industrial scale IBED processing system was constructed as specified and designed. All design objectives were met and the system is currently in operation. Deposition process protocols have been developed for hardcoatings including titanium nitride, chromium nitride, and silicon nitride. These coatings are now being applied to a variety of engineered components and manufacturing tooling on a quick turnaround service basis. The viability of the IBED process and processing system as an industrial-scale, low-temperature, precision coating process has been confirmed.

Acknowledgements

The market analysis, the engineering specifications for the IBED processing system, and the extensive business plans and designs for the construction and operation of the system were reviewed and refined with the expert assistance of Mr. John Slane, Manager of Research for Worthington Industries, Inc., 905 Dearborn Drive, Columbus, OH 43085.

The digital process control system was designed and constructed under contract with River Consulting, Inc., 3000 Corporate Exchange Drive, Columbus, OH, 43231, managed by Mr. Bryan Tucker, Electrical Project Engineer.

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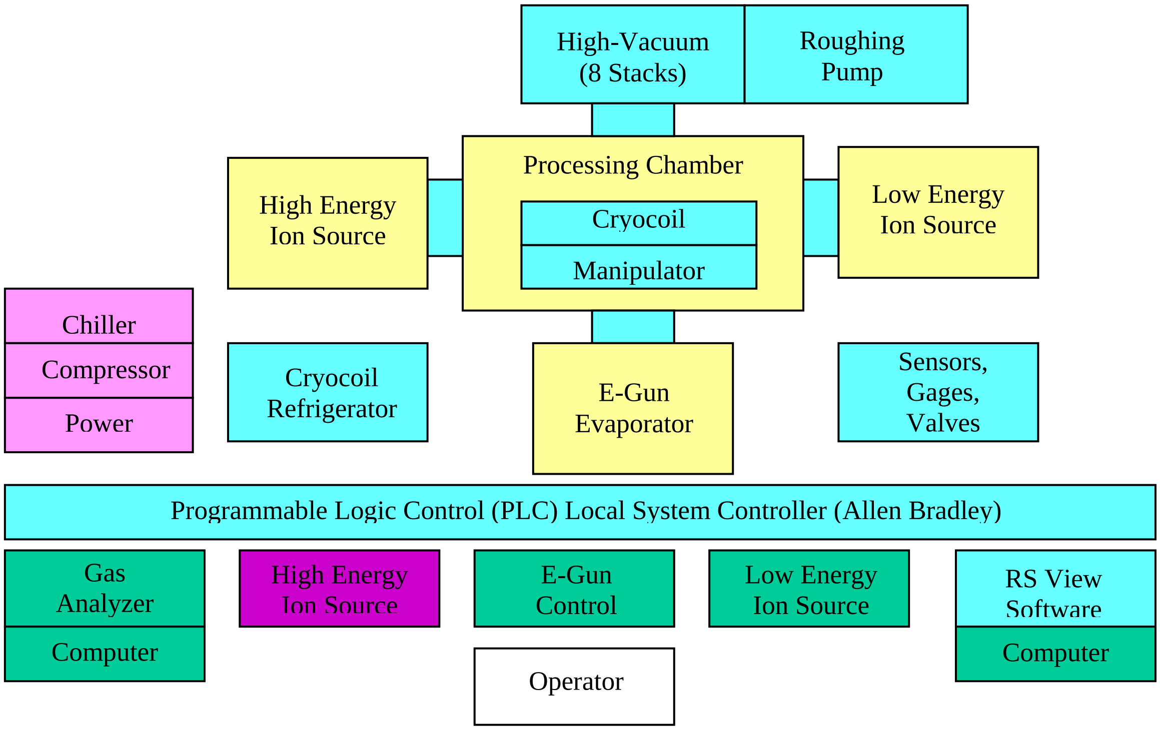

***Figure 4:* General IBED system configuration and block diagram. The operator controls the vacuum system through the RS View software. Pumpdown sequences for the processing chamber roughing pump and all eight high vacuum pumping stacks are all controlled automatically by the PLC. A refrigerated water unit supplies chilled water to cool the oil-diffusion pumps and the part platen. An air compressor supplies compressed air for opearation of pneumatic valves. The low energy ion source and electron-gun evaporator are controlled manually through the individual controls provided with each unit.**

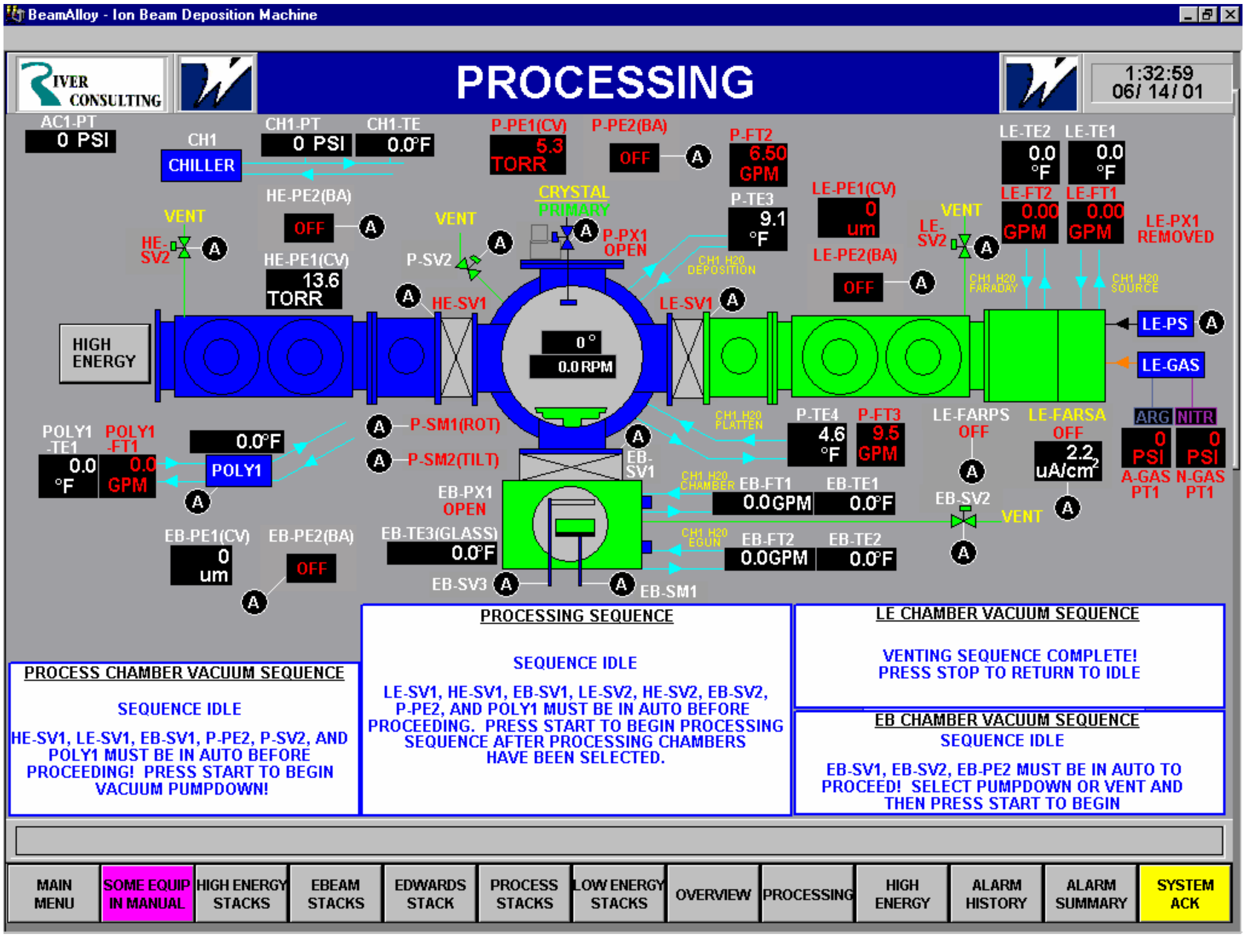

Figure 5: The operator interface screen seen as generated by the RS View® software. The software provides descriptions of the status of all of the processing subsystems throughout the deposition process along with alarm conditions. A series of additional screens can be displayed by choosing them from the toolbar at the bottom of the Processing screen. These screens display conditions in all the vacuum subsystems. Pop-up screens (not shown) display controls for additional PLC-controlled functions including part platen tilt angle, part platen rotation rate, electron-gun evaporator hearth rotation rate, and evaporator shutter position.

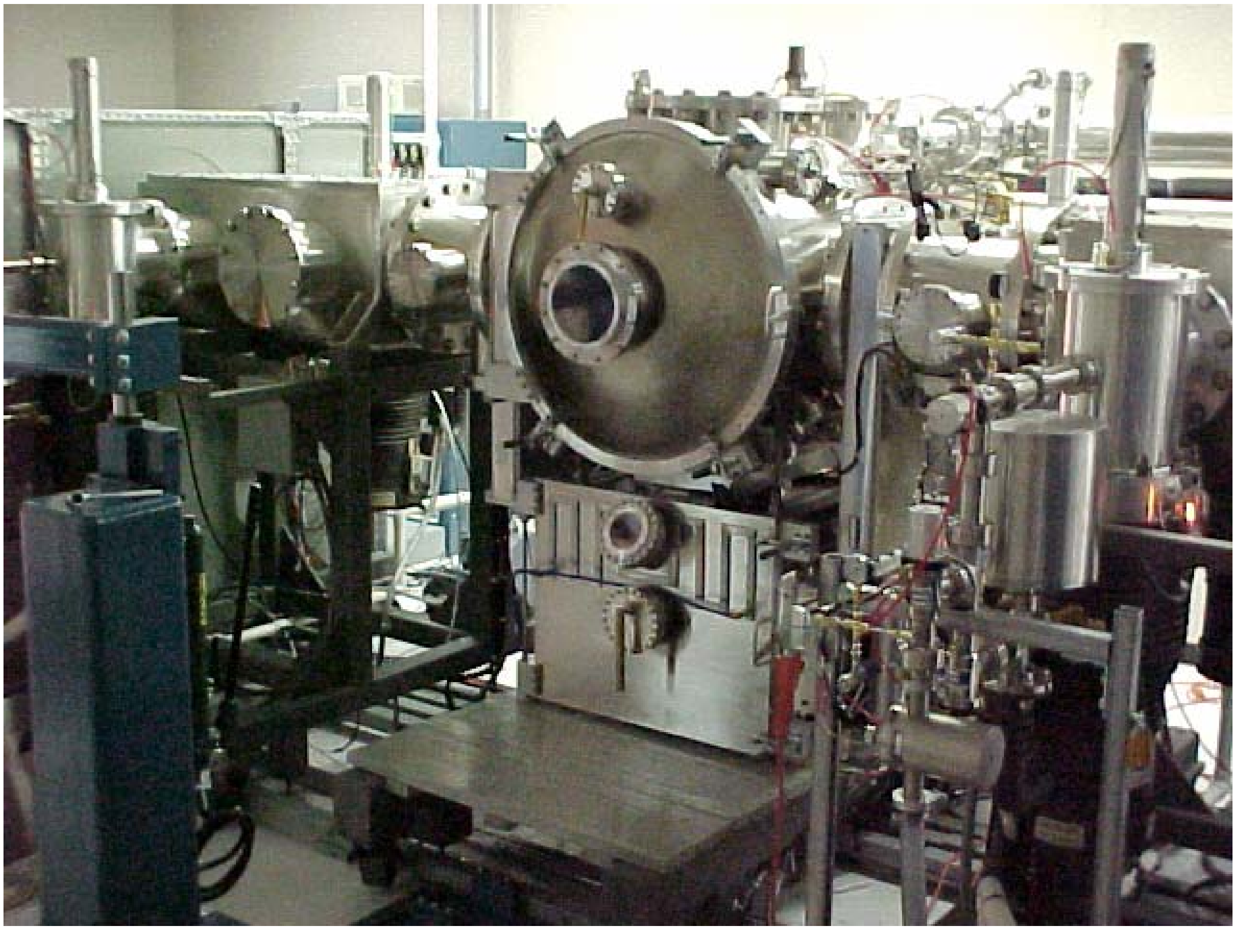

Figure 6: The industrial scale IBED processing system hardware.