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ABSTRACT

The Advanced Light Source (ALS), the first US third generation synchrotron radiation source, is currently under construction at the Lawrence Berkeley Laboratory. The low-emittance, 1.5 GeV electron storage ring and the insertion devices are specifically designed to produce high brightness beams in the UV to soft X-Ray range. The planned initial complement of insertion devices includes four 4.6 m long undulators, with period lengths of 3.9 cm, 5.0 cm (2) and 8.0 cm, and a 2.9 m long wiggler of 16 cm period length. Undulator design is well advanced and fabrication has begun on the 5.0 cm and 8.0 cm period length undulators. This paper discusses ALS insertion device requirements; general design philosophy; and design of the magnetic structure, support structure/drive systems, control system and vacuum system.

INTRODUCTION

The Advanced Light Source (ALS), a third generation synchrotron radiation source, is currently under construction at the Lawrence Berkeley Laboratory.[1] This facility consists of a 50 Mev linac, a 1 Hz, 1.5 GeV booster synchrotron and a low-emittance electron storage ring optimized for the use of insertion devices at 1.5 GeV. The use of insertion devices in the low emittance storage ring will produce high brightness beams in the UV to soft X-ray range. Their predicted performance is shown in Fig. 1.[2]

The planned initial complement of insertion devices includes four undulators and a wiggler with the basic parameters given in Table I. To achieve high brightness, the ALS undulator design must meet the stringent requirements in Tables II and III.[3] These requirements are derived from the need for rapid scanning of narrow spectral features and the need to avoid perturbing the electron beam in the storage ring. The wiggler, a high flux device, has reduced spectral requirements but must still meet the storage-ring requirements. The U5.0 Undulator will be used here as an example of a typical ALS insertion device and is shown in Fig. 2 with most major subsystems identified.

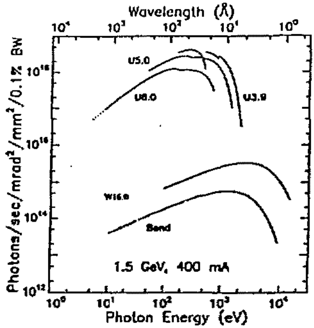

Fig. 1. Spectral brightness as a function of photon energy for the ALS undulators, wiggler and bend magnets. Each undulator curve is the locus of narrow peaks of radiation, tuned by altering the undulator gap, and represents the envelope of the first, third and fifth harmonics.

Table I. Parameters for the planned initial complement of insertion devices for the ALS

Name	Period (cm)	No. of periods	Overall length (m)	Photon energy range (keV)
Undulators				
U8.0	8.0	55	4.6	0.006 - 1.0
U5.0 (2)	5.0	89	4.6	0.052 - 1.5
U3.9	3.9	115	4.6	0.169 - 2.5
Wiggler				
W16.0	16.0	16	2.9	0.5 - 20.0

Table II. ALS undulator specifications based on spectral requirements

Parameter	Value
Useable harmonics	1st, 3rd, & 5th
Brightness requirement	5th harmonic reduction <30%
Spectral broadening requirement	ID broadening ≤ ALS emittance effects
Minimum increment of photon energy	1/10 of 5th bandwidth
Minimum time to go from min. to max. gap (slew)	5 minutes
Maximum photon energy scan rate	1 bandwidth/second

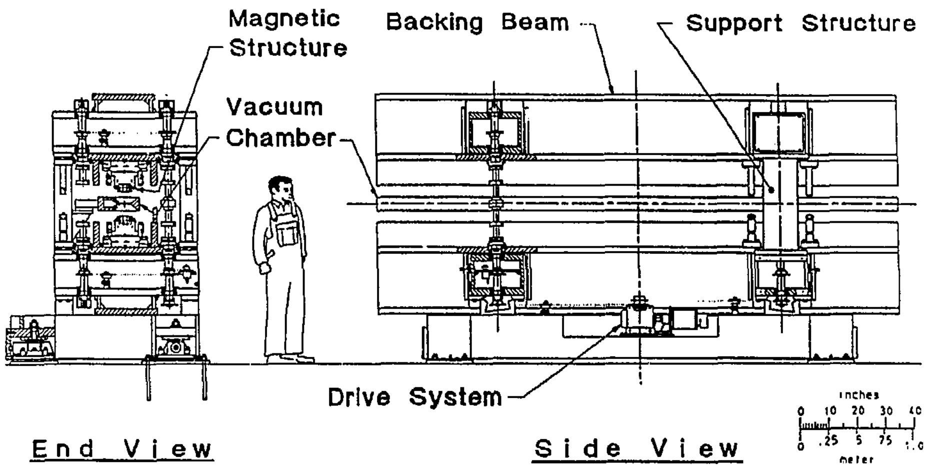

Fig. 2 U5.0 Undulator Design.

The engineering parameters, shown in Table IV for the U5.0 Undulator, are derived from the basic parameter, spectral and storage-ring requirements. The insertion device conceptual designs are nearly complete, and the detail design is well advanced. Component purchase and fabrication has started on the U5.0 and U8.0 Undulators.

Table III. ALS insertion device specifications based on storage ring requirements

Parameter	Limit
$\int B_y\, dl$	100 G cm
$\iint B_y\, ds\, dl$	100 G cm^2
$\int B_x\, d\, l$	500 G cm
Integrated quadrupole	50 G
Integrated skew quadrupole	50 G
Integrated sextupole	50 G/cm
Integrated octupole	1 G/cm^2
Required vacuum	10^{-9} Torr

Table IV. U5.0 Undulator engineering design parameters

Parameter	Limit
Maximum peak field (@ 1.4 cm magnetic gap)	0.89 T
Effective peak field (@ 1.4 cm magnetic gap)	0.837
Period length	5 cm
Number of periods	89
Number of full field poles	179
Entrance sequence	0,-1/2,+1,-1
Overall length	455.8 cm
Pole width	8 cm
Pole height	6 cm
Pole thickness	0.8 cm
Number of blocks per half-period (one side of pole)	6
End correction range (B_y)	1,500 G cm
End correction range (B_x)	None
Steering coils (short)	~ 5 λ long
Dipole trim coils (long)	To 4.5 m
Steering and trim field strength	± 5 G
Systematic gap variation	58 µm

DESIGN PHILOSOPHY

The approach taken for the initial complement of ALS insertion devices has been to develop a generic design with the objective of reducing engineering, fabrication, and maintainance costs.

The following commonality exists between the various planned devices:

Magnetic Structure:

- Scaled undulator magnetic configurations.
- Similar backing beams for the undulators.
- Wiggler backing beams two-thirds the length of the undulator backing beams.

Support Structure/Drive Systems:

- Identical support structures for the undulators.
- Support structure shortened for the wiggler.
- Identical drive systems for all devices.

Control System:

- Identical control systems for all devices.

Vacuum System:

- Similar vacuum chamber configurations for the undulators.
- Wiggler vacuum chamber similar to the undulator vacuum chamber.
- Identical pumping systems for the undulators.
- Similar pumping system for the wiggler.

Design, fabrication, testing and installation of the ALS insertion devices takes advantage of the LBL experience with the BL VI and BL X Wigglers that are now operational at SSRL.[4,5]

MAGNETIC STRUCTURE

The magnetic structure provides the required magnetic fields and includes the periodic magnetic structure, end magnetic structures, backing beams and if required auxiliary tuning coils.

The ALS insertion devices incorporate hybrid magnetic configurations consisting of Nd-Fe-B magnetic blocks and vanadium permendur poles. The hybrid design was chosen because there are several advantages over the pure current sheet equivalent material (CSEM) design:

- Fields are dominated by the characteristics of the poles, which can be made very uniform both in size and magnetic performance.
- Errors in magnetic moments of the blocks can be averaged by sorting the blocks for the poles.
- Errors in total magnetic moment of all the blocks of a pole have little effect on the electron beam or the photon spectrum because they contribute equally to adjacent poles and produce no electron steering.
- A higher peak field is achievable. (This is most important for the wiggler.)

For undulators, the objective of the magnetic design is to develop a magnetically well behaved structure which yields a high value of B_{eff} for mid-plane fields. B_{eff} is given by

$$B_{eff}^2 = \sum_{i=0}^{\infty} \left(\frac{B_{2i+1}}{2i+1}\right)^2 \quad (1)$$

where B_1 is the amplitude of the fundamental, B_3 is the amplitude of the third harmonic, etc.

The magnetic configuration is based on 2-D modeling with the computer code PANDIRA and a 3-D Hybrid theory for hybrid CSEM insertion devices.[6,7] To verify the magnetic design for U5.0, a model was built and tested under a variety of conditions.[8]

The undulator performance criteria is met by tolerances based on the hybrid CSEM insertion device theory. The tolerances established for U5.0 are given as an example in Table V.[9]

Table V. U5.0 Magnetic Structure tolerances

Error Type	Total Tolerance	Error (%)
Spacing CSEM to pole	102 µm	0.08
Pole thickness	50 µm	0.03
Vertical pole motion (gap)	22 µm	0.05
Pole width	100 µm	0.03
Surface easy axis orientation	±2.3 degrees	0.16
	Total:	0.19

Figs. 3 and 4 show the U5.0 magnetic structure which includes:

- Half-period pole assemblies, that consist of an aluminum keeper, a vanadium permendur pole (8 cm wide X 6 cm high X 0.80 cm thick) pinned into the keeper and six Nd-Fe-B blocks (3.5 cm square X 1.7 cm thick in the magnetization direction) bonded into the assembly.[10] This design allows for accurate vertical and longitudinal pole tip placement.
- Assembly sections; that consists of a pole mount fabricated from 5083-H321 aluminum onto which 35 half-period pole assemblies are mounted and accurately positioned.
- Backing beams that are 4.5 m long, stress relieved steel structures, with 81 cm depth and 89 cm width, each beam provides magnetic shielding and holds five assembly sections and two end sections.[11]
- Dipole and steering coils if needed.

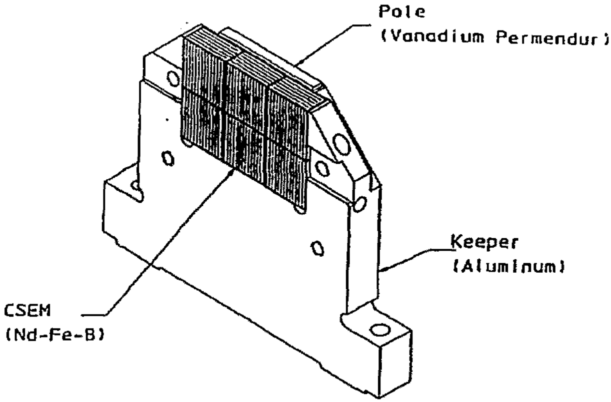

Fig. 3. U5.0 half-period pole assembly

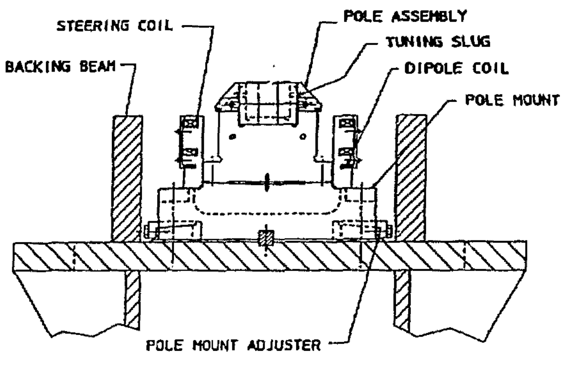

Fig. 4. U5.0 magnetic structure assembly section

The upper and lower backing beams are tied together with low reluctance NiFe hinges to reduce the effect of environmental fields on the electron beam trajectory.[12]

To avoid steering the beam as it travels through the insertion device, it is necessary to control the configuration of the fields at the ends. Fig. 5 shows a schematic of the end magnetic structure that utilizes a system of Nd-Fe-B rotors to fine-tune the fields at the ends of the insertion device. There are four rotors at each end, and a small quantity of Nd-Fe-B at each rotor location. Gap-dependent errors at the ends are small, thus the objective is to determine a single set of orientations for the rotors that minimizes the steering errors introduced by the end magnetic fields over the entire range of gaps.

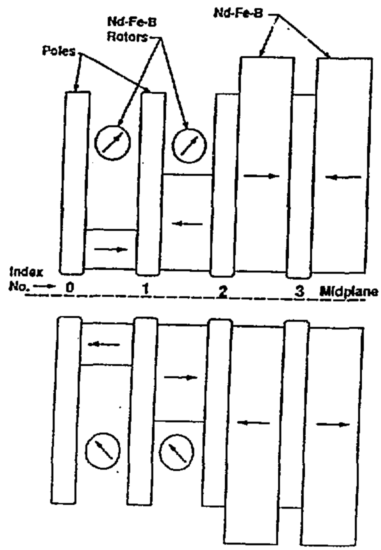

Fig. 5. End rotator configuration.

SUPPORT/DRIVE SYSTEMS

The support/drive systems include the support structure that provides the framework for holding the magnetic structure and the drive system that opens and closes the magnetic gap. Requirements for the support structure shown in Figs. 2 and 6 include the following:

- Support a maximum magnetic load of 84,000 lb. (The loading of a 5 m long insertion device with 10 cm wide poles operating at 1.85 Tesla.)
- Maintain a magnetic gap variation of 46 μm at the smallest gap (14 mm). (U5.0 Undulator requirement is 58 μm.)
- Meet the ALS storage ring, tunnel and adjacent beamlines space requirements.
- Accommodate the vacuum system and its support structure.
- Be capable of being installed, aligned and serviced in the storage ring.

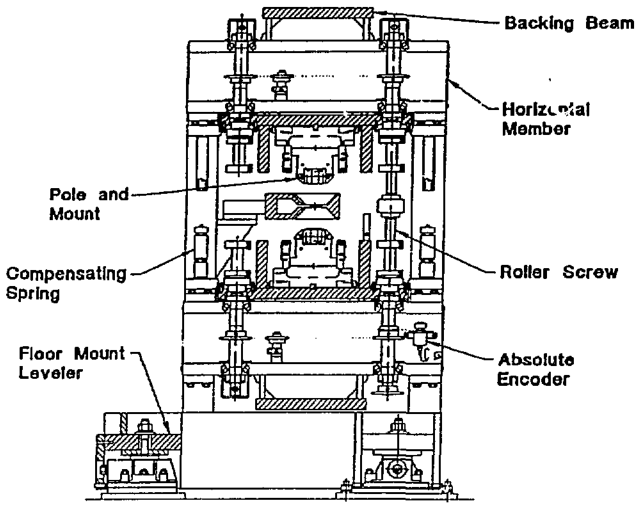

Fig. 6. Undulator end view.

Both 4-Post and C-Frame structures were considered. The 4-Post configuration was selected for the following reasons:

- Greater tunnel aisle clearance.
- Less gap deflection due to a more rigid structure.
- No pole rotation because of symmetrical support loading.
- Better access for assembly and maintenance of components.

The principal advantage of the C-Frame structure is that it would be open on one side allowing magnetic measurements with an external measurement system and the possibility of insertion device installation with the vacuum chamber in place in the storage ring.

As shown in Figs. 2 and 6, the support structure is of rigid construction consisting of a base onto which two lower horizontal members are mounted. Four vertical posts are in turn attached to the lower horizontal members and the two upper horizontal members are attached to the tops of these posts. The horizontal beams pass thru the webs of the backing beams to limit the overall height of the support structure to less than the 8 ft tunnel height. The base is a welded assembly containing a platform for the gear reduction unit and motor. Three y-axis leveling mounts, which include x-axis and z-axis adjustments, provide a kinematic support system. This arrangement provides a satisfactory range of adjustments for all six degrees of freedom for installation and alignment. The support structure is modular with bolted and pinned members, which simplifies fabrication, installation, calibration and servicing. All subassemblies are individually stress-relieved before final machining to minimize warpage.

A magnetic-load compensating spring system is provided to buck the gap-dependent magnetic load.[13] For the U5.0 Undulator, the eight spring assemblies consist of two helical compression springs in series selected to match the gap dependent magnetic load to within 20%. The compensating spring system provides the following benefits:

- Reduced system friction which gives better positional response from the drive system over the life of the device.
- Minimum required motor load holding torque at any magnet gap, which gives stationary stability when the null position is reached. Motor current can be turned off or reduced to minimize motor heating.
- Elimination of "lifting" when the magnetic load exceeds the gravitational weight of the lower backing beam.
- Reduced structure load, which gives better gap reproducibility.

The drive system requirements are set by the spectral requirements and include:

- Capability of opening the magnetic gap with an 84,000 lb magnetic load.
- A step resolution of 1 µm (based on increments of 1/10 of the 5th harmonic for a U3.65 undulator.)
- A maximum scanning speed of 2.3 mm/s (based on a scan rate of 1 bandwidth/s for a 11-cm-period device).

- A magnetic gap range of 1.4 cm to 21.6 cm.
- Opening or closing time must be five minutes or less.
- Gap position determined by an absolute encoder.

Changing the magnet gap in an insertion device requires moving the backing beams. This is accomplished by rotating the 2 mm pitch Transrol roller screws that are mounted to the horizontal beams and support the backing beams. Specifically, the four right-handed roller screws attached to the upper backing beam and four left-handed roller screws attached to the lower backing beam are connected by a shaft coupling and combine to provide equal and opposite vertical motion when rotated. Gap motion begins at the rotation of a stepper motor which is transmitted thru a gear box and a series of sprocket wheels and roller chains to the roller screws. An absolute rotary encoder is coupled to a Transrol roller screw shaft to read the absolute position of the magnet gap.

The drive system has been sized for the maximum possible ALS insertion device magnetic load. Though one revolution of the roller screws changes the gap by 4 mm, the minimum incremental gap motion is 0.1 micron. This is possible because the 200 steps/revolution stepper motor has a 10 micro-step/step capability through the control electronics and the motor rotation is reduced a factor of 30 through the gear reduction unit. At the 2000 step/revolution operation, the motor can easily be driven at a velocity to move the gap from full closed to full open in 1 1/2 minutes. The rotary-encoder selected is a Compumotor AR-23, which has a resolution of 16,384 counts/revolution and is mounted with a step-up ratio of 4.75. This arrangement allows resolution of a gap variation of less than 0.1 µm.

Analysis of the proposed system shows that stick-slip will give a gap uncertainty of less than 0.4 µm.[14] Unidirectional scanning and control of the undulator gap are required because backlash is estimated at 87 µm in gap motion. Scan-to-scan gap reproducibility for unidirectional scanning is estimated to be less than 8 µm.

Drive system protection guidelines include:

- Travel limits set by the closed-loop control system stored in the control program.
- Micro-switches hard-wired to the control system for minimum and maximum gap positions.
- Mechanical stops for minimum and maximum gap positions.
- Full-torque stepper-motor stall capability.
- Mechanical drive components designed to handle full stepper motor torque.
- Full load current sensing (control system will shut down current after a preset time interval).

Insertion device temperature control is important. A vertical temperature gradient of greater than 0.1 degree C in the undulator backing beams produces excessive spectral broadening. Hence, each undulator will have an enclosure, and the temperature in the enclosure will be maintained by circulating the air with muffin fans.

CONTROL SYSTEM

The insertion device control systems are designed to provide sufficient position accuracy, resolution, velocity and range information for the motors and encoders for all anticipated insertion devices. In addition, the control system must control and monitor the dipole and steering correction power supplies, as well as controlling gap-dependent rotator positioning, if required. The insertion device control systems are to be integrated into the overall accelerator computor control system.

The insertion device gap must be controlled (via request to the accelerator control system) and monitored by the experimenter using the generated synchrotron radiation. During development, the insertion device is to be capable of being manipulated through the control system by a local computer, so that the necessary control and monitoring algorithms can be determined.

The control system block diagram is shown in Fig. 7. A Compumotor system has been selected for the gap control and is currently undergoing tests. One scheme proposed for the control system is to use five intelligent local controllers (ILCs). One ILC coordinates the activities of the other four and communicates with either the accelerator control system database or an IBM-PC. The ILCs controlling the rotators and power supplies would contain the compensation data tables that give the rotator positions and the coil settings required for each magnet gap.

Provisions for interfacing limit switches are included in the indexer as well as the ability to compensate for backlash and to program acceleration and deceleration curves. The indexer can be programmed to microstep the motor with as many as 25,000 steps per revolution.

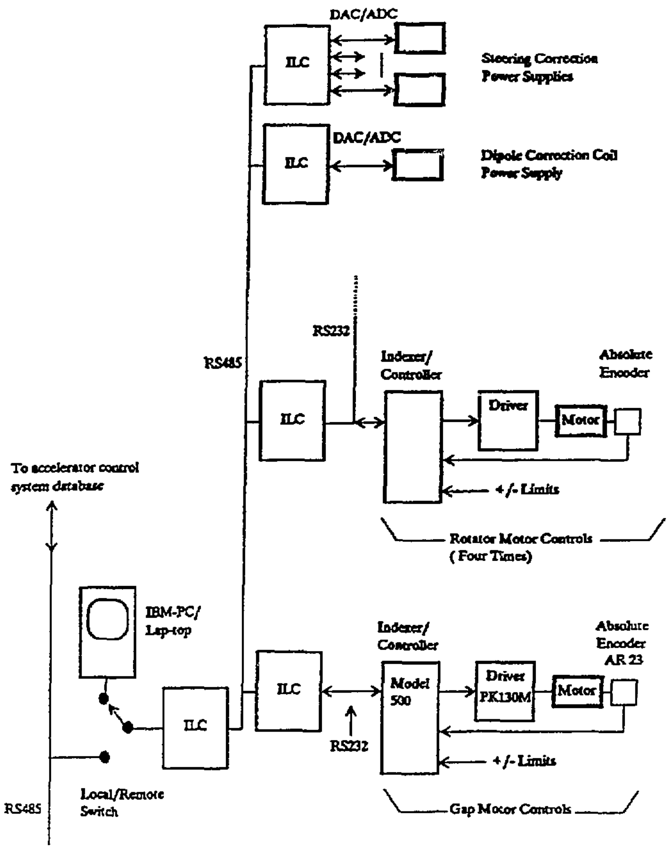

Fig. 7. Insertion device control system.

The objective of the vacuum system is to provide a 10^{-9} Torr vacuum at the insertion device beam aperture. Fig. 8 shows a plan view of an undulator vacuum system. Two vacuum chambers are required for ALS operation, one for commissioning and one for dedicated operation.[15] The commissioning chamber has an elliptical beam aperture of dimensions 1.8 cm vertical x 6.0 cm horizontal. The chamber for dedicated operation, which replaces the commissioning chamber, has a rectangular beam aperture of dimensions 1.0 cm vertical x 6.0 cm horizontal.

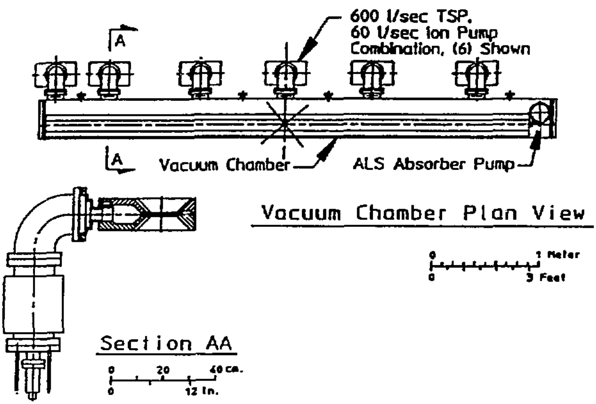

Fig. 8. Undulator vacuum system layout.

The 5.1 m long undulator vacuum chambers will be made of two pieces of machined 5083-H321 aluminum alloy. These two-piece welded chambers are similar to the ALS storage ring sector chambers that are currently under construction. Both the commissioning and dedicated chambers have a total horizontal aperture of 21.8 cm, the inner 6.0 cm provides the circulating beam aperture and the outer aperture allows the bending-magnet synchrotron radiation to pass through the chamber. The radiation is then absorbed by the photon stop located at the exit end of the chamber. Both chambers have an antechamber along the complete length as part of the outer aperture to improve vacuum by an increased conductance. External surfaces of the chambers have pockets machined into them for the magnet poles. The shape allows a minimum magnetic gap of 2.2 cm for commissioning and 1.4 cm for dedicated operation. The undulator vacuum chamber has 6 side ports and one top and bottom port near the exit end of the chamber for vacuum pumps. Several smaller ports are provided for a roughing system, ion gauges and a RGA head. The upstream end of the chamber includes a flange for insertion of NEG pumping strips and for a viewport for remote visual inspection of the aperture.

The vacuum system consisting of six combination 600 l/s titanium sublimation and 60 l/s ion pumps (which give a net pumping speed of 173 l/s each at the antechamber) and an ALS absorber pump of 1450 l/s capacity has a total antechamber pumping speed of 2500 l/s.[16] The pressure distribution at the beam aperture was estimated after 40 Ampere hours of accumulated electron beam operation assuming a thermal outgassing rate of 10^{-11} Torr l/s cm^2, a molecular production rate, due to photon induced desorbtion, of 10^{-5} molecules/photon (for photons of energies greater than 10 eV) and 1.9 GeV - 400 mA storage ring operation.[17] The average pressure distribution is 3 X 10^{-10} Torr, as shown in Fig. 9. If two NEG strips, 3 cm wide by 450 cm long are inserted into the chamber and activated, the pressure will drop to 1 X 10^{-10} Torr in the beam aperture.[18]

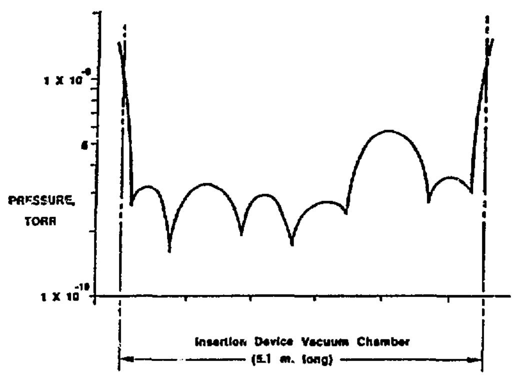

Fig. 9. Insertion device chamber pressure distribution.

The ion pumps will be driven and monitored by ion pump controllers. The titanium sublimation pump filaments will be powered by a single power supply multiplexed to the six pumps. Insertion device vacuum chamber pressure will be monitored in two ways. Ion pump current will be converted to approximate pressure in the local display and accurate pressure measurements will be accomplished at one or two locations with nude ion gauges and an ion gauge controller.

The vacuum chamber and associated pumping system will be supported from the top of the insertion device support structure. Struts will be used for the chamber and spring loaded hangers used for the pumps.

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