Advanced Photon Source Upgrade Project

Final Design Report

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Chapter 3: Front Ends and Insertion Devices

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3-1 Introduction

The Advanced Photon Source (APS) Upgrade Project is a major redesign of the accelerator in the current operating machine. The upgraded APS will be operating at 6 GeV and 200 mA of stored beam with a new low emittance lattice. To fully support the APS Upgrade (APS-U), the front ends and insertion devices (IDs) located inside the storage ring tunnel need to be upgraded. This chapter describes the front ends, IDs, and bending magnet (BM) sources where capabilities must be improved to maximize the potential of the APS Upgrade Project.

Most of the front ends at the APS were designed more than 20 years ago and have been in operation since then. The BM front ends were designed to handle power from the APS operating at 300 mA current at 7 GeV. The ID front ends were originally designed to handle 100 mA of beam from a 2.4-m-long undulator A of period 3.3 cm. Recently, the APS has designed ID front ends capable of handling higher heat loads from two 2.4 m undulator A's in a straight section. The APS Upgrade will require all the original ID front ends to be replaced in order to handle the increased power. In addition, all ID front ends will have next-generation x-ray beam position monitors (XBPM) to provide long-term stability for the beamlines. The current BM front ends will undergo minor modifications and will be reused. Section 3-2 discusses the front end plans for the APS-U.

At the current time, the APS has 34 of the 35 ID ports instrumented with front ends and insertion devices. Of there ID ports seven of then are in canted geometry with two insertion devices installed. In addition 15 sectors have a second insertion device in tandem. Most of the devices were optimized more than 20 years ago for 7-GeV operation, providing full energy tunability in the hard x-ray range. There are some devices with smaller periods and two electromagnetic devices for soft x-ray beamlines. The upgraded APS machine will operate at 6 GeV and will require replacement of most of the IDs. Over the years, user requirements have been refined, and requests for special devices like superconducting undulators have increased. To maximize the brightness and flux for all the beamlines (also part of the APS-U), most of the IDs will be replaced with smaller period devices. Section 3-3 discusses the ID plans for the APS-U.

Currently, there are 23 BM front ends installed, of which only 20 beamlines are in operation. The BM beamlines can use up to 6 mrad in a horizontal fan of radiation. With the multi-bend achromat (MBA) lattice for the APS-U, the BM source is changing. The MBA reverse bend lattice makes the BM source a complex combination of radiation from multiple sources. Section 3-4 will discuss the various options for the existing bending magnet sources.

3-2 Front Ends

Front ends are the sections tangential to the storage ring. Most of the front end components, except for the exit table, are housed inside the storage ring tunnel enclosure. The synchrotron beam extracted from the storage ring must pass through the front ends first. At the APS, there are a total of 40 sectors, 35 of which have beam ports and are capable of extracting a synchrotron beam. Each sector consists of an ID and a BM beam port. An overview of both ID and BM front ends of the APS-U for one sector is shown in Figure 3.1.

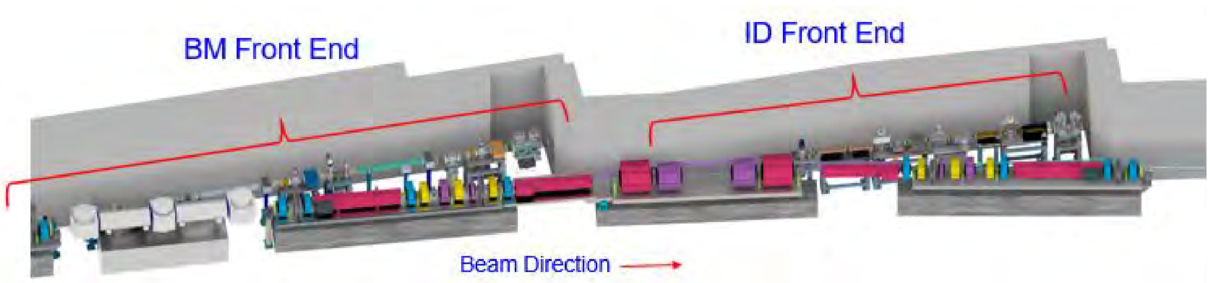

Figure 3.1. Overview of ID and BM front ends in relation to the storage ring components.

The APS Upgrade will build out front ends for the entire 35 ID ports and 20 BM front ends. All existing original ID front ends that were built in the 1990s cannot handle the heat load and will be replaced by new front ends. The ID front ends built in the 2000s can handle the heat load and will be retrofitted to standardize the configuration and to house the next generation XBPMs. A total 20 BM front ends will be retrofitted to be compatible with the new BM source.

The APS Upgrade requires three types of front ends:

1. High Heat Load Front End (HHLFE) for two inline undulators.
2. Canted Undulators Front End (CUFE) for two undulators at 1.0 mrad canting angle between them.
3. Bending Magnet Front End (BMFE) for bending magnet sources.

The configuration of all the front ends for the APS Upgrade has been captured the *APSU Configuration of Insertion Devices and Front Ends document* (ICMS document APSU_2030222).

There are totally 35 Insertion Device ports available for extraction of the ID beams to the experiment hall. All these ports have space for a front end inside the storage ring tunnel. The beam is extracted through an opening in the ratchet wall to the experiment hall. The front end has an exit configuration in the experiment hall outside the storage ring tunnel. The front end exit table is located inside the first optics enclosure for respective beamlines.

Of the two types of ID front ends, based on the configuration requested by the respective beamlines the front end types are selected. In addition beamlines have a choice of either having a Be window or having a windowless configuration. For the case of windowless operations the front end will have a differential pump configuration. In all cases the exit table configuration has a mask with a nominal aperture of 2 mm x 2 mm. For the canted undulator front ends there are two apertures each of 2 mm x 2 mm and separated by 1 mrad between the centers.

Table 3.1 lists specifications and the exit configuration to be used for each beamline front end. Special cases are commented in the table.

Table 3.1. Insertion Device Front End configurations

Location	Configuration	Exit Configuration	Comments
01-ID	High Heat Load	Window	May require 2 mm x 1 mm Exit Mask
02-ID	Canted Undulator	Differential Pump	
03-ID	High Heat Load	Window	Existing 3 mm x 2 mm Be Window
04-ID	High Heat Load	Differential Pump	
05-ID	High Heat Load	Differential Pump	
06-ID	Canted Undulator	Differential Pump	
07-ID	High Heat Load	Differential Pump	
08-ID	High Heat Load	Differential Pump	
09-ID	High Heat Load	Differential Pump	
10-ID	High Heat Load	Window	Existing 3 mm x 2 mm Be Window
11-ID	Canted Undulator	Differential Pump	
12-ID	Canted Undulator	Differential Pump	
13-ID	Canted Undulator	Differential Pump	
14-ID	High Heat Load	Differential Pump	
15-ID	Canted Undulator	Differential Pump	
16-ID	Canted Undulator	Differential Pump	
17-ID	High Heat Load	Window	Existing 3 mm x 2 mm Be Window
18-ID	High Heat Load	Differential Pump	
19-ID	High Heat Load	Differential Pump	
20-ID	High Heat Load	Window	May require 2 mm x1 mm Exit Mask
21-ID	Canted Undulator	Differential Pump	
22-ID	Canted Undulator	Differential Pump	
23-ID	Canted Undulator	Differential Pump	
24-ID	Canted Undulator	Differential Pump	
25-ID	Canted Undulator	Differential Pump	
26-ID	High Heat Load	Differential Pump	
27-ID	High Heat Load	Differential Pump	
28-ID	Canted Undulator	Differential Pump	
29-ID	High Heat Load	Differential Pump	
30-ID	High Heat Load	Window	Will reuse 3 mm x 1 mm Exit Mask
31-ID	Canted Undulator	Window	
32-ID	Canted Undulator	Differential Pump	
33-ID	High Heat Load	Differential Pump	
34-ID	Canted Undulator	Differential Pump	
35-ID	High Heat Load	Window	Will reuse 3mm x 1 mm Exit Mask

There are numerous BM ports where there are no beamlines. For these cases there will be no front end. In such cases the beam extraction port from the storage ring will be capped off with an absorber. The ratchet wall opening in these cases will be plugged with a concrete block and lead. Table 3.2 shows a complete list of various configurations of the 35 BM extraction ports.

Front ends are configured via a complex design of apertures, shielding, control, and interlock system to achieve the following functions.

1. **To ensure personnel safety with the required redundancy and logical control system during commissioning and operation phases, to provide shuttering and, hence, absorb the full power of the beam and/or Bremsstrahlung radiation during injec-**

Table 3.2. Bending Magnet Front End Configurations

Location	Front End Configuration	Exit Configuration	Comments
01-BM	Standard	Window	
02-BM	Standard	Differential Pump	
03-BM	None		SR exit port capped with absorber
04-BM	None		SR exit port capped with absorber
05-BM	Standard	Window	
06-BM	Standard	Window	
07-BM	Standard	Window	
08-BM	Standard	Window	
09-BM	Standard	Differential Pump	
10-BM	Standard	Window	
11-BM	Standard	Window	
12-BM	Standard	Differential Pump	
13-BM	Standard	Window	
14-BM	Standard	Window	
15-BM	None		SR exit port capped with absorber
16-BM	Standard	Window	
17-BM	Standard	Window	
18-BM	None		SR exit port capped with absorber
19-BM	Standard	Window	
20-BM	Standard	Differential Pump	
21-BM	None		SR exit port capped with absorber
22-BM	Standard	Window	
23-BM	Standard	Differential Pump	
24-BM	Standard	Window	
25-BM	None		SR exit port capped with absorber
26-BM	None		SR exit port capped with absorber
27-BM	None		SR exit port capped with absorber
28-BM	None		SR exit port capped with absorber
29-BM	None		SR exit port capped with absorber
30-BM	None		SR exit port capped with absorber
31-BM	None		SR exit port capped with absorber
32-BM	Special		Beamline Size Monitor - No beamline
33-BM	Standard	Window	
34-BM	None		SR exit port capped with absorber
35-BM	Special	Window	Beamline for ASD Diagnostic Group

tion and/or in case of a vacuum failure: This function is carried out by the photon shutter and safety shutters. The photon shutter is used to stop the synchrotron beam and is able to take heat load, hence is water cooled. Safety shutters are used to stop the Bremsstrahlung radiation and must be made with heavy metal such as tungsten to stop hard radiation. Two independently actuated safety shutters are required to ensure redundancy. The function of the photon shutter is to protect the safety shutter from the heat load.

2. **To provide proper collimation so that the beam cannot strike unprotected and uncooled elements within the vacuum envelope even under steering errors:** This function is carried out by various photon masks. The last (downstream) mask (exit mask) defines the synchrotron beam size exiting the front end. The exit aperture can be specified by beamline users.
3. **To confine the Bremsstrahlung radiation angle at the front end exit**: Heavy metal (tungsten or lead) collimators must be positioned strategically in the front end to properly collimate the Bremsstrahlung radiation so the Bremsstrahlung radiation has a defined opening angle at the front end exit. Typically, the Bremsstrahlung radiation exit angle is defined by the aperture of the 1^{st} collimator and the exit collimator. A small Bremsstrahlung exit angle benefits the beamline shielding design.
4. **To provide vacuum protection to the storage ring and maintain the ring vacuum integrity:** The front end must function as a vacuum buffer zone between the beamline vacuum and storage ring vacuum. It must be able to maintain the ultra-high vacuum (UHV) requirements of the storage ring. It must monitor vacuum quality and isolate the storage ring vacuum from the front end and beamline vacuum when necessary. Vacuum pumps, valves, gauges, and exit windows are used to fulfill this function. A UHV valve is required at the upstream end of the front end to isolate the front end from the storage ring when there is a slow vacuum leak or other mechanical problems in the front end. A thermal shutter in front of the vacuum valve is needed to absorb the synchrotron radiation from dipole magnets located on either side of the straight section.
5. **To provide required information on the angular and spatial position of the photon beam in a feedback fashion to the ring in order to maintain a stable beam:** Front ends must be able to house diagnostic components such as x-ray beam position monitors (XBPMs) and beam intensity monitors (IMs) for beam position monitoring. All ID front ends must be equipped with the next generation XBPMs, while BM front ends will use the conventional photo-emission XBPMs.

3-2.1 High Heat Load Front End

The HHLFE must be able to handle heat load from a 6-GeV ring operating at 200 mA with two inline undulators at minimum gap. The front end must handle a total power limit of 21 kW and peak power density of 590 kW/mrad^2. The HHLFE front end is based on an existing HHLFE design currently in operation for numerous masks and shutters, hence the criterion for the maximum power and power density is based on the existing design limits. The existing HHLFE heat load limit will be used for the design to give extra margin to allow for different types of undulators, such as superconducting undulators (SCUs). Table 3.3 summarizes the HHLFE design heat-load limits.

Table 3.3. HHLFE heat load limit

Type of front end	HHLFE
Limit on total power (kW)	21
Limit on peak power density (kW/mrad^2)	590

3-2.1.1 Front End Layout Changes

The HHL front end currently designed for the APS Upgrade will be used and installed in the current APS storage ring. This front end design is based on 28ID HHLFE. The HHLFE to be installed for APS-U is shown in Figure 3.2.

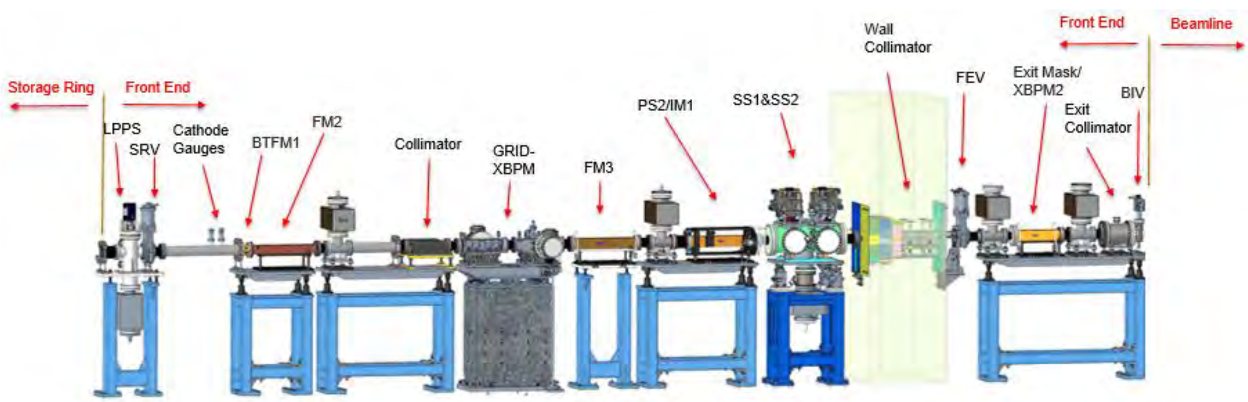

Figure 3.2. Layout of High Heat Load Front End for APS-U.

Listed below are the major changes from the existing APS HHLFE's:

- A clearing magnet has been added to deflect and dump the electron beam in the case where there is mis-steering or a failure during swap out injection. The clearing magnet will cause the electron beam trajectory to change such that the resultant path, as indicated by ray tracing, goes into a shielding structure and remains within the bulk shielded volume. This is a new requirement exclusively for the APS Upgrade. In current APS operation, electron trace studies have been performed for each front end to ensure that no electrons can enter from the storage ring and pass through the front end during top-up injection. Due to the large number of magnets and the complex nature of the lattice in the APS-U, the simulations are complex and would likely involve numerous interlocks to achieve safety. As an alternative, a passively safe method involving the addition of a clearing magnet will be included. The clearing magnet must be designed using permanent magnets and be located in the extraction port just upstream of the LPPS to reduce the size and prevent scattered electrons from reflecting into the experimental enclosures when the safety shutter is open.

- The existing storage ring isolation valve between the front end and the storage ring is removed. The same role is now played by the valve just downstream of the LPPS. This change improves the safety of the SR operations because the LPPS now protects the front end valve (which will be henceforth called the Storage Ring Valve (SRV)). The SRV can now be closed and yet protected by the LPPS, which is made to stop the dipole radiation.
- A passively safe sacrificial device called the Burn Through Fixed Mask 1 (BTFM1) is installed in the front end upstream of fixed mask 2 which will provide for all cases of possible mis-steered ID beam. The worst case ID beam is determined by using the ID vacuum chamber walls as the source (in the event of BPLD failure) and limited by the downstream storage ring absorbers. The BTFM1 must also be able to block the residual bending magnet radiation created by the dipole magnets, similar to the existing pre-mask in the current machine. Two cold cathode gauges will be added just upstream of BTFM1 and tied into the Front End Equipment Protection System to immediately close the LPPS in the case of a vacuum breach during mis-steering.
- The fast valve located midway in the front end has been eliminated. This once again has been done for operational convenience as it helps remove the false trips. Similarly, the VAT chassis to operate this valve has also been eliminated.
- The safety shutter used in this front end is the original v1.2 front end safety shutter. However the pneumatics and the guide systems have been upgraded. Also the switches have been modified for changes in PSS and ACIS logic at a later date. Two closed switches have been added to the SS1 and SS2 for ACIS monitoring.
- The location of the GRID XBPM has been shifted more downstream to avoid potential interferences with the SR plinth for the APSU.
- The vacuum system in the front end has been standardized using the same pump sizes and new controllers which will be compatible with future front end installations. The location of the pumps are now on top of the vacuum system to allow for potential access under support tables in the area between the front end and the SR.
- The exit collimator aperture has been narrowed down to 5mm x 5mm as it is located immediately downstream of the 2mm x 2mm exit aperture mask. The reduction in the size of the aperture is to allow for the beamlines to manage the bremsstrahlung when small offset monochromators are used.

3-2.1.2 Next-Generation XBPMs

The x-ray beam position monitors (XBPM) of the white x-ray beam are important for undulator x-ray beam stability. The HHL front end will use the next generation XBPM as part of the front end. The new HHLFE designed for the APS Upgrade has the revised next gen XBPM (XBPM1) located further downstream compared to the design used for the existing HHL front end with Next Gen XBPM (27-ID and 35-ID) under current operation. This shift was to accommodate the space requirement on the APS Upgrade machine. Figure 3.3 is the 3D model of the GRID XBPM designed for the HHL front end.

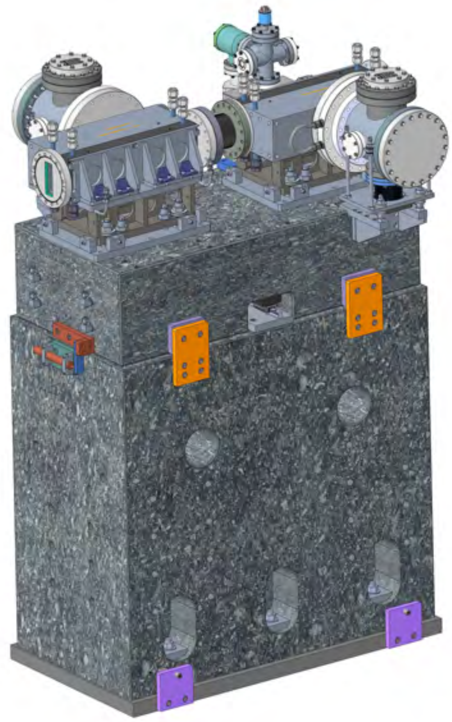

Figure 3.3. Model of the GRID XBPM for the HHL front end.

The front end has an intensity monitor (IM1) integrated into the photon shutter and a second XBPM(XBPM2) integrated into the exit mask. The three components, namely XBPM1, IM, and the XBPM2, work together as the next generation XBPM system.

Table 3.4 lists common requirements for XBPM1 in HHLFE. These requirements are derived from the beam stability requirements specified in the Preliminary Design Report for the APS Upgrade and are tighter than the current APS machine and hence will be used for this front end. Table 3.5 lists the power load requirements for XBPM1 in HHLFE. These requirements are derived from the nominal undulator sources under consideration for the APS upgrade.

Table 3.4. Requirement of XBPM1 in HHLFE

	Horizontal	Vertical
Minimum range	± 200 µm	± 100 µm
Minimum aperture	± 0.04 mrad	± 0.02 mrad
Resolution (DC – 7 days)	12 µm	10 µm
AC (0.01 – 1000 Hz)	3.7 µm	2.4 µm
Raw gap dependence offset	< 30 µm*	< 30 µm*

* Before software compensation.

The second XBPM (XBPM2) monitors relative beam position changes outside of the feedback loop. Its resolution requirements are similar to XBPM1 except the gap dependence requirements, since it sees only clipped x-ray beam and is expected to have strong gap dependence.

The intensity monitor (IM1) is an alignment aid for setting up XBPM1. It needs to resolve intensity

Table 3.5. Power load requirement of XBPM1 in HHLFE

Front end	HHLFE
Sets of XBPM	One
Maximum power per beam	20 kW
Maximum power density	200 W/mm^2
Nominal undulator source	U27.5-K2.4-4.8m
Nominal electron beam	7 GeV / 200 mA

changes at 0.2% or better with a bandwidth of 1 Hz over the entire dynamic range of 200 W – 2 kW beam power on the photon shutter.

3-2.1.3 Front End Exit Configuration

The APS-U HHLFE's will have either a Beamline Isolation Valve (BIV) or exit windows and will interface with the beamline with a 2.75 CF flange connection. If the front end is a windowless configuration, a differential pump will be built into the front end. The exit mask aperture for the beamline is 2(H)mm x 2(V)mm. The aperture in the tungsten exit collimator will be 5(H)mm x 5(V)mm.

3-2.1.4 Reference Documents

The front end design for the HHL for APS-U was reviewed by an external review committee. It was also presented to BSDRSC. Most of the support documentation for the front end exists in the CAD repository or in ICMS. The documentation list of reference materials is show in Table 3.6.

Table 3.6. List of reference documents for HHLFE

Document Title	**ICMS / Drawing Number**
HHLFE Functional Requirements Document	APSU_190893
HHLFE Interface Control Document	APSU_190889
FEEPS Interface Control Document	APS_190964
FEEPS for Low Power Photon Shutter	APS_1444651
Clearing Magnet Engineering Specification Document	APSU_190903
Low Power Photon Shutter Engineering Specification Document	APSU_190895
Burn Through Fixed Mask 1 Engineering Specification Document	APSU_2029843
Fixed Mask 2 Engineering Specification Document	APSU_190892
First Lead Collimator Engineering Specification Document	APSU_190898
GRID Mask 1 and 2 Engineering Specification Document	APSU_190902
Fixed Mask 3 Engineering Specification Document	APSU_190893
Photon Shutter 2 Engineering Specification Document	APSU_190896
Safety Shutter Engineering Specification Document	APSU_190899
Wall Collimator Engineering Specification Document	APSU_190900
Exit Mask Engineering Specification Document	APSU_190894
Exit Collimator Engineering Specification Document	APSU_190901
Final Design Review 1	APSU_1699214
BSDRSC Review 1	APS_1707238
Final Design Review 2	APSU_2030620
BSDRSC Review 2	APS_2019471
Approval for removal of Fast valve	APS_1703776
Source definition for APS-U insertion devices and bending magnet beamlines	APSU_2032015
Use of burn through device in APS-U insertion device front ends	APSU_2028668
Thermal Analysis of High Heat Load Front End for APSU 28ID and MBA	APS_2016883
Thermal Analysis of LPPS for HHLFE	APSU_2017449
HHLFE Layout Drawing	A098-LO3000
HHLFE Ray Trace Drawing	A098-RT3000
HHLFE Component Reference Table	APSU_2030048
Low Power Photon Shutter 1 Drawing	U1520203-100000-02
Burn Through Fixed Mask 1 Drawing	A098-M60100-01
Fixed Mask 2 Drawing	A098-M20100-00
First Lead Collimator Drawing	U2520103-100000-00
Grid Mask 1 and 2 Drawings	U2520106-110000-00
Fixed Mask 3 Drawing	U2520102-300000-00
Photon Shutter 2 Drawing	U2520102-700000-01
Safety Shutter Drawing	U2520103-500000-00
Wall Collimator Drawing	U1520205-300000-00
Exit Mask Drawing	U2520102-410000-00
Exit Collimator Drawing	U2520103-300000-00

3-2.2 Canted Undulator Front End

The CFE must be able to handle heat load from a 6 GeV ring operating at 200 mA with two canted undulators at 1.0 mrad angle at the minimum gap. The front end must handle a total power limit of 2 x 10 kW of total power and 280 kW/mrad^2 peak power density. The CFE front end is based on an existing CFE design currently in operation for numerous masks and shutters, hence the criterion for the maximum power and power density is based on the existing design limits. The existing CFE heat load limit will be used for the design to give extra margin to allow for different types of undulators, such as superconducting undulators (SCUs). Table 3.7 summarizes the CFE design heat-load limits.

Table 3.7. CUFE heat load limit

Type of front end	CUFE
Limit on total power (kW)	2x10
Limit on peak power density (kW/mrad^2)	280

3-2.2.1 Front End Layout Changes

The CUFE currently designed for the APS Upgrade will be used and installed in the current APS storage ring. Towards this, Figure 3.4 shows the design of the CUFE front end for APS Upgrade with the modifications for the current APS. Some modifications have been made to the CUFE to be compatible with APS-U CUFE.

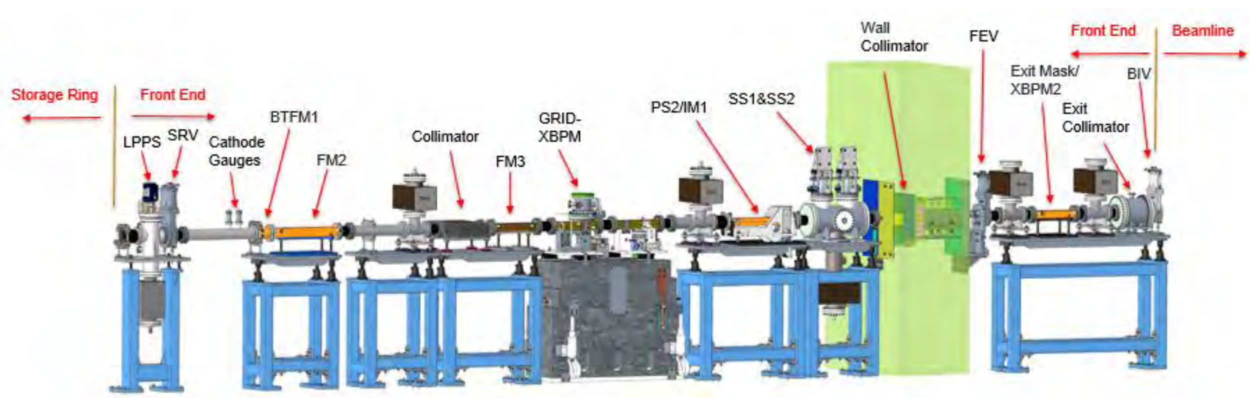

Figure 3.4. Layout of Canted Undulator Front End for APS-U.

Listed below are the major changes between the two versions:

- A clearing magnet has been added to deflect and dump the electron beam in the case where there is mis-steering or a failure during swap out injection. The clearing magnet will cause the electron beam trajectory to change such that the resultant path, as indicated by ray tracing, goes into a shielding structure and remains within the bulk shielded volume. This is a new requirement exclusively for the APS Upgrade. In current APS operation, electron trace studies have been performed for each front end to ensure that no electrons can enter from the storage ring and pass through the front end during top-up injection. Due to the large number of magnets and the complex nature of the lattice in the APS-U, the simulations are complex and would likely involve numerous interlocks to achieve safety. As an alternative, a passively safe method involving the addition of a clearing magnet will be included. The clearing magnet must be designed using permanent magnets and be located in the extraction port just upstream of the LPPS to reduce the size and prevent scattered electrons from reflecting into the experimental enclosures when the safety shutter is open.

- The existing storage ring isolation valve between the front end and the storage ring is removed. The same role is now played by the valve just downstream of the LPPS. This change improves the safety of the SR operations because the LPPS now protects the front end valve (which will be henceforth called the Storage Ring Valve (SRV)). The SRV can now be closed and yet protected by the LPPS, which is made to stop the dipole radiation.
- A passively safe sacrificial device called the Burn Through Fixed Mask 1 (BTFM1) is installed in the front end upstream of fixed mask 2 which will provide for all cases of possible mis-steered ID beam. The worst case ID beam is determined by using the ID vacuum chamber walls as the source (in the event of BPLD failure) and limited by the downstream storage ring absorbers. The BTFM1 must also be able to block the residual bending magnet radiation created by the dipole magnets, similar to the existing pre-mask in the current machine. Two cold cathode gauges will be added just upstream of BTFM1 and tied into the Front End Equipment Protection System to immediately close the LPPS in the case of a vacuum breach during mis-steering.
- The fast valve located midway in the front end has been eliminated. This once again has been done for operational convenience as it helps remove the false trips. Similarly, the VAT chassis to operate this valve has also been eliminated.
- The safety shutter has been upgraded. The switches have been modified for changes in PSS and ACIS logic at a later date. Two closed switches have been added to the SS1 and SS2 for ACIS monitoring.
- A grazing incidence beam position monitor (GRID XBPM) and XBPM2 has been added to have a more reliable beam steering feedback method in APSU. These BPM's are fluorescence based vs. photo-emission based as in the previous machine. XBPM2 is now also incorporated into the exit mask design.
- The vacuum system in the front end has been standardized using the same pump sizes and new controllers which will be compatible with future front end installations. The location of the pumps are now on top of the vacuum system to allow for potential access under support tables in the area between the front end and the SR.
- The exit collimator aperture has been narrowed down to 5mm x 5mm as it is located immediately downstream of the 2mm x 2mm exit aperture mask. The reduction in the size of the aperture is to allow for the beamlines to manage the bremsstrahlung when small offset monochromators are used.

3-2.2.2 Next-Generation XBPMs

The x-ray beam position monitors (XBPM) of the white x-ray beam are important for undulator x-ray beam steering and position. The CUFE will use the next generation XBPM as part of the front end.

The front end has a first and second XBPM(XBPM1 and XBPM2). XBPM2 is integrated into the exit mask. The two components work together as the next generation XBPM system. Figure 3.5 is the 3D model of the GRID XBPM designed for the CU front end.

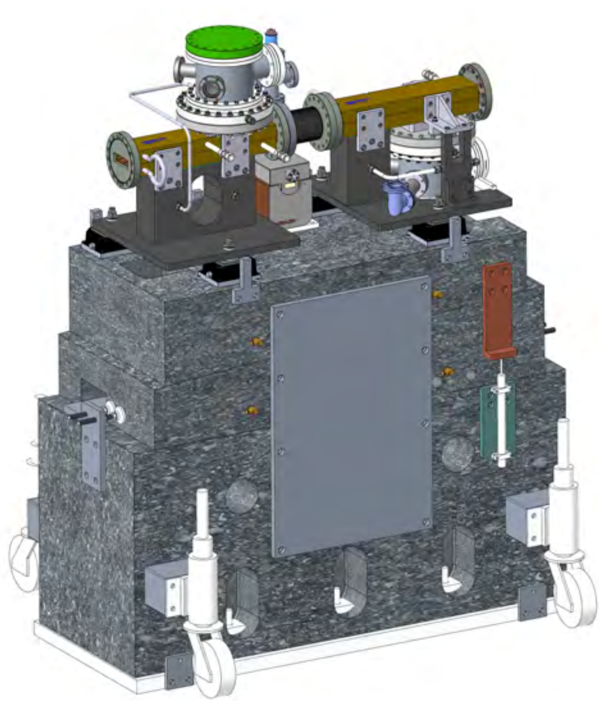

Figure 3.5. Model of the GRID XBPM for the CU front end.

Table 3.8 lists common requirements for XBPM1 in CUFE. These requirements are derived from the beam stability requirements specified in the Preliminary Design Report (CDR) for the APS Upgrade and are tighter than the current APS machine and hence will be used for this front end. Table 3.9 lists the power load requirements for XBPM1 in CUFE(see thermal analysis located at ICMS# APSU_2025902). These requirements are derived from the nominal undulator sources under consideration for the APS and APS upgrade.

Table 3.8. Requirement of XBPM1 in CUFE

	Horizontal	Vertical
Minimum range	± 200 µm	± 100 µm
Minimum aperture	± 0.04 mrad	± 0.02 mrad
Resolution (DC – 7 days)	12 µm	10 µm
AC (0.01 – 1000 Hz)	3.7 Îijm	2.4 µm
Raw gap dependence offset	< 30 µm*	< 30 µm*

* Before software compensation.

The second XBPM (XBPM2) monitors relative beam position changes outside of the feedback loop. Its resolution requirements are similar to XBPM1 except the gap dependence requirements, since it sees only clipped x-ray beam and is expected to have strong gap dependence.

Table 3.9. Power load requirement of XBPM1 in CUFE

Front end	CUFE
Sets of XBPM	Two
Maximum power per beam	10.5 kW
Maximum power density (upstream mask at 19.4 m)	418.4 W/mm^2
Nominal undulator source	SCU
Nominal electron beam	7 GeV / 200 mA

3-2.2.3 Front End Exit Configuration

The APS-U CUFE's will have either a Beamline Isolation Valve (BIV) or exit windows and will interface with the beamline with a 2.75 CF flange connection. If the front end is a windowless configuration, a differential pump will be built into the front end. The exit mask aperture for the beamline is two 2(H)mm x 2(V)mm separated by 1 mrad horizontally. The aperture in the tungsten exit collimator will be two 5(H)mm x 5(V)mm separated by 1 mrad horizontally .

3-2.2.4 Reference Documents

The front end design for the CU for APS-U was reviewed by external review committee. It was also presented to BSDRSC. Most of the support documentation for the front end exists in the CAD repository or in ICMS. The documentation list of reference materials is shown in Table 3.10.

Table 3.10. List of reference documents for CUFE

Document Title	ICMS / Drawing Number
CFE Functional Requirements Document	APSU_190885
CFE Interface Control Document	APSU_190890
FEEPS Interface Control Document	APS_190964
FEEPS for Low Power Photon Shutter	APS_1444651
Clearing Magnet Engineering Specification Document	APSU_190919
Low Power Photon Shutter Engineering Specification Document	APSU_190908
Burn Through Fixed Mask 1 Engineering Specification Document	APSU_2029844
Fixed Mask 2 Engineering Specification Document	APSU_190905
First Lead Collimator Engineering Specification Document	APSU_190912
GRID Mask 1 and 2 Engineering Specification Document	APSU_190916
Fixed Mask 3 Engineering Specification Document	APSU_190906
Photon Shutter 2 Engineering Specification Document	APSU_190910
Safety Shutter Engineering Specification Document	APSU_190913
Wall Collimator Engineering Specification Document	APSU_190914
Exit Mask Engineering Specification Document	APSU_190907
Exit Collimator Engineering Specification Document	APSU_190915
Technical Design Review	APSU_2019969
BSDRSC Review 1	APS_2021371
Final Design Review	APSU_2030620
BSDRSC Review 2	APS_2031437
Source definition for APS-U insertion devices and bending magnet beamlines	APSU_2032015
Thermal Analysis of Canted Undulator Front End for APSU MBA and 25ID	APSU_2019373
Use of burn through device in APS-U insertion device front ends	APSU_2028668
Approval for removal of Fast valve	APS_1703776
CFE Layout Drawing	A099-LO1000
CFE Ray Trace Drawing	A099-RT1000
CFE Component Reference Table	APSU_2030217
Low Power Photon Shutter 1 Drawing	U1520203-100000-02
Burn Through Fixed Mask 1 Drawing	A099-M60100-01
Fixed Mask 2 Drawing	A099-M20100-00
First Lead Collimator Drawing	4102030110-100000-02
Grid Mask 1 and 2 Drawings	A099-B10300-00 A099-B20300-00
Fixed Mask 3 Drawing	U2520202-300100-00
Photon Shutter 2 Drawing	A099-P20100-01
Safety Shutter Drawing	4102030106-500000-07
Wall Collimator Drawing	4102030113-100000-03
Exit Mask Drawing	A099-M40100-00
Exit Collimator Drawing	A099-K30100-00

3-2.3 Bending Magnet Front End

The Bending Magnet Front End must be able to handle heat load from bending magnet source of a 6 GeV ring at 200 mA. The APS-U bending magnet source will be a combination of M3, M4, and Q8 as shown in Figure 3.6. The original BM front end was designed for the APS 7-GeV BM source at 300 mA. Because the power and power density of the APS-U, which is a combination of M3, M4, and Q8 magnets at 200 mA, is less than that of the original BM front end design limit, the heat load limit for the original front end will be used for the APS-U. Therefore, the existing masks and photon shutters that are being re-used will have no heat load issues. The comparison of the BM sources for the current 7 GeV at 300 mA versus APS-U 6 GeV at 200 mA is shown in Table 3.11. Compared to the current lattice, the planned centerline of the BM is ~42 mm inboard compared to the current APS. The centerline of the BM front end may still change pending on the exact source point, however, the BM front end is not sensitive to the shift of the centerline of the front end as long as it is not shifted further inboard due to space interference to undulators, girders, and walls.

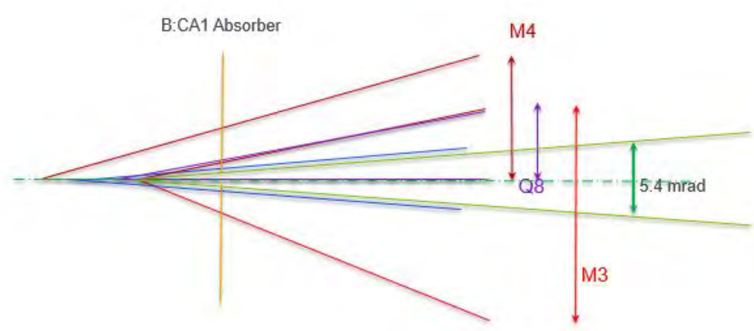

Figure 3.6. Horizontal fan of radiation from different dipoles for bending magnet beamlines.

3-2.3.1 Front End Layout Changes

APS currently has two different type of BM front ends; 20 original style and 3 modified original style. For the APS Upgrade, only the 20 BM modified original style front ends will be installed. Most of the components will be reused, however the locations will be adjusted to resolve clearance issues. The layout changes are addressed here.

A layout of the APS original BM Front End is shown in Figure 3.7 and the Bending Magnet Front End for the APS-U is shown in Figure 3.8 to illustrate the upgrade requirements.

Listed below are the major changes from the existing APS BMFE's:

- A clearing magnet has been added to deflect and dump the electron beam in the case where there is mis-steering or a failure during swap out injection. The clearing magnet will cause the electron beam trajectory to change such that the resultant path, as indicated by ray tracing, goes into a shielding structure and remains within the bulk shielded volume. This is a new requirement exclusively for the APS Upgrade. In current APS operation, electron trace

Table 3.11. BMFE heat load limit

Parameters	**APS Design**			APSU	
Machine energy	7 GeV	6 GeV	6 GeV	6 GeV	6 GeV
Ring current	300 mA	200 mA	200 mA	200 mA	200 mA
BM Source	BM Dipole	M4* Upstream	M3* downstream	Q8*	M4+M3+Q8 (outboard) M3 (inboard)
Critical Energy (Kev)	19.6	15.872	16.232	4.357	N/A
Peak field (Tesla)	0.6	0.663	0.678	0.182	N/A
Total power per mrad horizontal fan (W)	260.5				239
Total power entering front end (W)	1860 (total: 7.1 mrad)	315	322	86	1045 total (723 outboard 322 inboard)
Peak power density ($kW/mrad^2$)	2.342	0.937	0.958	0.256	2.151

* The values shown for APSU magnet strengths are much higher than current design for worst case power calculations.

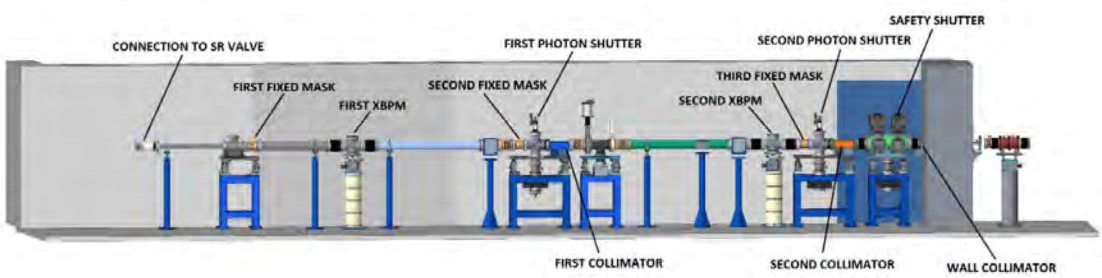

Figure 3.7. Layout of Original APS Bending Magnet Front End in current APS.

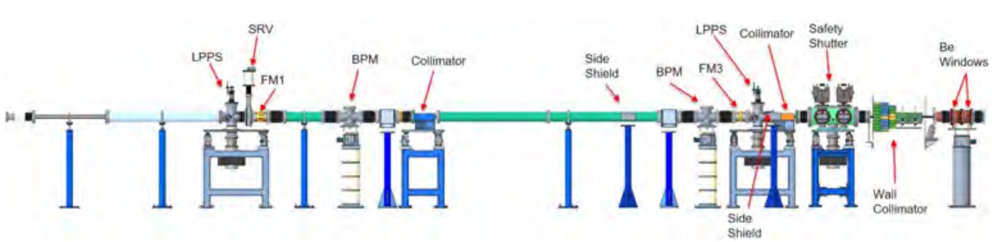

Figure 3.8. Layout of modified APSU Bending Magnet Front End to be installed in APSU.

studies have been performed for each front end to ensure that no electrons can enter from the storage ring and pass through the front end during top-up injection. Due to the large number of magnets and the complex nature of the lattice in the APS-U, the simulations are complex and would likely involve numerous interlocks to achieve safety. As an alternative, a passively safe method involving the addition of a clearing magnet will be included. The clearing magnet must be designed using permanent magnets and be located in the extraction port just upstream of the LPPS to reduce the size and prevent scattered electrons from reflecting into the experimental enclosures when the safety shutter is open.

- The existing storage ring isolation valve between the front end and the storage ring is removed. The same role is now played by the valve just downstream of PS1. This change improves the safety of the SR operations because PS1 now protects the front end valve (which will be henceforth called the Storage Ring Valve (SRV)). The SRV can now be closed and yet protected by PS1, which is made to stop the dipole radiation.
- The fast valve located midway in the front end has been eliminated. This once again has been done for operational convenience as it helps remove the false trips. Similarly, the VAT chassis to operate this valve has also been eliminated.
- The safety shutter used in this front end is the original front end safety shutter. However the pneumatics and the guide systems have been upgraded. Also the switches will be modified for changes in PSS and ACIS logic at a later date. Two closed switches have been added to the SS1 and SS2 for ACIS monitoring.
- The location of the BPM1 has been shifted more downstream to avoid potential interferences with the SR plinth for the APSU.

3-2.3.2 Front End Exit Configuration

The normal APS-U BMFE's will be two Be Windows each of 250 µm thick Be. The exit is a 10.0 CF flange connection. For special cases where a Differential pump is needed the Be windows will be replaced by a differential pump with a smaller aperture mask and will terminate with a Beamline Isolation Valve (BIV).

3-2.3.3 Bending Magnet XBPM

The first-generation XBPMs in the APS were based on photoemission from blades insulated from the ground. Figure 3.9 shows the copper holder of the blades, which is mounted on a water-cooled platform. Since the BM radiation has a stable spatial spectral distribution and is the only beam in the front end, the photoemission XBPM works well for the vertical beam angle measurements. We plan to reuse these XBPMs in the APS-U BM front ends. No major redesign has been planned.

A relatively minor change will be made to the BM XBPM for the APS Upgrade due to the presence of multiple synchrotron radiation sources in the BM port: M4, Q8, and M3. While all these sources can be seen on the outboard side of the BM axis, only M3 is visible on the inboard side. It is thus desirable to position the XBPM blade on the inboard side of the BM port axis, either through modification of the blade mount or a simple displacement of the XBPM chamber.

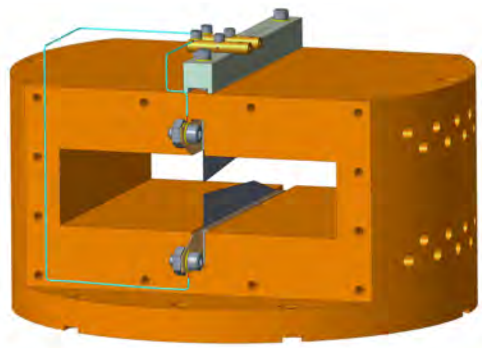

Figure 3.9. Photoemission blade holder of the BM front end XBPM.

3-2.3.4 Reference Documents

The front end design for the BM for APS-U was reviewed by an external review committee. Most of the changes on the BM front end are reconfiguration of components to eliminate the interference between the straight section and the BM FE. Most of the support documentation for the front end exists in the CAD repository or in ICMS. The documentation list of reference materials is given below:

Table 3.12. List of reference documents for BM FE

Document Title	ICMS / Drawing Number
BMFE Functional Requirements Document	APSU_190886
BMFE Interface Control Document	APSU_190891
Final Design Review	APSU_2030620
Source definition for APS-U insertion devices and bending magnet beamlines	APSU_2032015
(FEEPS) Interface Control Document	APSU_190964
Clearing Magnet Engineering Specification Document	APSU_190921
Fixed Mask 1 Engineering Specification Document	APSU_190920
Thermal Analysis of First Fixed Mask for APS-U Bending Magnet Front End	APS_2030220
BMFE Layout Drawing	A100-LO0300
BMFE Ray Trace Drawing	A100-LO0300
BMFE Component Reference Table	APSU_2030264
Photon Shutter 1 and 2 Drawing	4102020103-240000-00
Fixed Mask 1 Drawing	A100-M10100
Beam Position Monitor 1 Drawing	410202-220000-03
Lead Collimator 1 Drawing	4102020102-210000-04
Beam Position Monitor 2 Drawing	410202-270000-04
Fixed Mask 3 Drawing	4102020101-230000-01
Photon Shutter 2 Drawing	4102020103-240000-00
Lead Collimator 2 Drawing	4102020102-220000-04
Safety Shutter Drawing	410202-290000-02
Wall Collimator Drawing	4102020113-100000-01
Be Window 1 and 2 Drawing	4102020106-200000-01
Approval for removal of Fast valve	APS_1703776

3-3 Insertion Devices

Optimized insertion devices (IDs) are key elements for the Advanced Photon Source (APS) for high brightness photon beams. IDs are periodic magnetic devices that bend/oscillate the high-energy electron beam to produce radiation. Third-generation light sources, like the APS, were designed and optimized to take full advantage of radiation from IDs located in long straight sections of the storage ring. The ID performance, and most notably the brightness, is being enhanced several orders of magnitude with the APS upgrade. IDs can be designed to oscillate the electron beam in a plane, which produces linearly polarized light, but can also be designed to oscillate the electron beam in a circular or elliptical path, which produces circularly or elliptically polarized light. The magnetic field can be created by permanent magnets or electromagnets, including superconducting electromagnets. In the case of a permanent magnet (PM) insertion device, the field can be changed by varying the gap between two opposing magnet arrays; this then varies the energy of the emitted radiation. To provide very precise control of the radiation energy (harmonic energy) and its bandwidth, the magnet gap and gap taper must be controlled and repeatable to better than 10 µm. In electromagnetic (EM) IDs and Super Conducting Undulators (SCU) the field can be varied by varying the current in the magnet coils. Both types of IDs need to be able to be turned off, either by opening the gap sufficiently on PM devices or by turning off the current in the magnet coils of EM devices.

Regardless of ID type, the period length is chosen to optimize the x-ray spectral output over a user-selected energy range taking into account the electron beam energy and the expected magnetic field strength that can be achieved. The maximum magnetic field strength can be increased by decreasing the gap between opposing magnet arrays of the IDs, subject to limitations imposed by the requirements for the stored electron beam, i.e., acceptable beam lifetime, injection efficiency, etc., and limitations due to heat load constraints of front end components. Therefore, the design of the IDVCs must demonstrate a balance between ID performance and storage ring performance. The primary IDVC will be compatible with i) dual in-line undulators, ii) canted undulators, and iii) revolver undulators. For APS Upgrade there is a vacuum envelop which separates the ID magnets from the storage ring vacuum system. This is also true for the SCU where the ID vacuum chamber resides inside the cryostat. All vacuum chambers come with small apertures and ante-chambers for NEG pumping. Even for SCUs the IDVC is inside the cryostat and will be cryopumped and is different from the cryostat vacuum where the SCU magnet reside.

The configuration of all the Insertion Devices selection for the APS Upgrade has been captured the *APSU Configuration of Insertion Devices and Front Ends document* (ICMS document APSU_2030222). The functional requirements for all the insertion devices are captured in *Insertion Devices Functional Requirements Document* (ICMS document APSU_1688663).

Table 3.13 shows a comprehensive list of source selections sector by sector planned for the APS-U. The configuration and period lengths have been identified along with the geometry for each sector (canted sectors in blue).

All the functional requirements, interfaces and engineering specifications are captured in different documents. Table 3.14 is a list of all reference documents pertaining to insertion devices for APSU.

Table 3.13. Insertion device selections sector by sector.

Location	Configuration	Upstream Device	Downstream Device	Additional Magnets
01-ID	Dual inline long cryostat	SCU 1.65	SCU 1.65	Correctors inside long cryostat
02-ID	Canted	Planar 2.8	Planar 2.8	Canting magnets, corrector
03-ID	Dual inline	Planar 2.5	Planar 2.5	Phase shifter/corrector
04-ID	Dual inline	Planar 3.0	Planar 3.0	Phase shifter/corrector
05-ID	Single		Planar 3.3	
06-ID	Canted	Planar 2.7	SCU 1.8	Canting magnets, corrector
07-ID	Single		Planar 2.8	
08-ID	Dual inline	Rev 2.5/2.1	Rev 2.5/2.1	Phase shifter/corrector
09-ID	Dual inline	Planar 2.1	Rev 2.5/2.1	Phase shifter/corrector
10-ID	Single		Planar 3.3	
11-ID	Canted long cryostat	SCU 1.65	SCU 1.65	Canting magnets, center canting magnet/corrector inside cryostat
12-ID	Canted	Planar 2.8	Planar 2.8	Canting magnets, corrector
13-ID	Canted	Planar 3.3	Planar 2.7	Canting magnets, corrector
14-ID	Dual Inline	Planar 2.1	Planar 2.1	Phase shifter/corrector
15-ID	Canted		Planar 2.8	Canting magnets, corrector
16-ID	Canted	Planar 2.7	Planar 2.5	Canting magnets, corrector
17-ID	Single		Planar 3.3	
18-ID	Single		Planar 3.3	
19-ID	Dual Inline	Rev 2.5/2.1	Rev 2.5/2.1	Phase shifter/corrector
20-ID	Dual inline long cryostat	SCU 1.65	SCU 1.65	Correctors inside long cryostat
21-ID	Canted	Planar 3.0	Planar 2.1	Canting magnets, corrector
22-ID	Canted		Planar 3.3	Canting magnets, corrector
23-ID	Canted	Planar 3.3	Planar 3.0	Canting magnets, corrector
24-ID	Canted	Planar 3.0	Planar 2.1	Canting magnets, corrector
25-ID	Canted	Planar 2.8	Planar 2.8	Canting magnets, corrector
26-ID	Dual Inline	Planar 2.8	Planar 2.8	Phase shifter/corrector
27-ID	Dual Inline	Planar 2.7	Planar 2.7	Phase shifter/corrector
28-ID	Canted long cryostat	SCU 1.85	SCU 1.85	Canting magnets,center canting magnet/corrector inside cryostat
29-ID	Full Length	IEX12.5		
30-ID	Dual Inline	Planar 1.35	Planar 1.35	Phase shifter/corrector
31-ID	Canted	Planar 3.3	Planar 3.3	Canting magnets, corrector
32-ID	Canted	Planar 1.35	Planar 2.8	Canting magnets, corrector
33-ID	Dual Inline	Rev 2.5/2.1	Rev 2.5/2.1	Phase shifter/corrector
34-ID	Canted	Planar 2.8	Rev 2.5/2.1	Canting magnets, corrector
35-ID	Single		Rev 2.3/1.35	

Table 3.14. Design and specification documents for Insertion Devices

Document	ICMS Content ID
General	
Insertion Devices Functional Requirements Document	apsu_1688663
APS-U Configuration of Insertion Devices and Front Ends (ICD)	apsu_2030222
APS-U Planar Undulator Physics Requirements Document	aps_2022617
Engineering Specification Documents (ESDs)	
Planar Permanent Magnet Undulators-2.1-cm Period Magnetic Structures ESD	apsu_2029851
Planar Permanent Magnet Undulators-2.5-cm Period Magnetic Structures ESD	apsu_2029850
ESD-Planar Permanent Magnet Undulators- 2.8-cm Period Magnetic Structures	apsu_2019573
Planar Permanent Magnet Undulators - Canting Magnet Assemblies ESD	apsu_2030031
Planar Permanent Magnet Insertion Device Straight Section Vacuum Chamber ESD	apsu_190928
Planar Superconducting Undulators ESD	apsu_190927
Interface Control Documents (ICDs)	
Permanent Magnet Undulator ICD	apsu_190923
Insertion Device Vacuum System Scope and Interface Control Document	apsu_190925
Planar Superconducting Undulator ICD	apsu_190924

3-3.1 Storage Ring Requirements

The storage ring requirements of the IDs installed in the APS-U storage ring are documented in detail in the APS-U Planar Undulator Physics Requirements Document [1]. All HPMU and SCU requirements derived therein are summarized in the ID FReD (ICMS document APSU_1688663).

There are two important changes from the past:

1) Global orbit errors
   A recent study of ID perturbations has resulted in improved field integral error specifications. The main results are that the residual global-orbit error (with orbit corrections running) depends on the time-rate of change of the ID field integrals and not the absolute values of the field integrals.
2) Local orbit errors
   Even though the global orbit correction system compensates for the perturbations produced by an ID outside the ID straight section from which it originates, there remain local orbit errors due to first- and second-integral field errors when the ID changes its gap or current. The orbit correction may not have enough correctors to attenuate the orbit errors inside the changing device or in the neighboring device in the same straight section (for two IDs in the same straight section in canted geometry). The absolute field integral errors are now described in terms of the entrance and exit "kick" angles of the electron beam instead of the first and second field integrals.

The requirements for global orbit stability are summarized in Table 3.15 in terms of the rate of change of the first and second field integrals.

Even when the global orbit correction system compensates for the perturbations produced by an ID outside the ID straight section from which it originates, there remain local orbit errors due to

Table 3.15. Requirements for the rate of change of the first and second field integrals for one ID. The ID should satisfy the square root quantity or the limits of the individual I_1 and I_2.

Field Integral Rates of Change	Requirement [1)]
$\left(I_{1,x}^2 + I_{2,x}^2/\beta_y\right)^{1/2}$	840 µT m/s
$I_{1,x}$	600 µT m/s
$I_{2,x}$	1800 µT m^2/s
$\left(I_{1,y}^2 + I_{2,y}^2/\beta_x\right)^{1/2}$	1500 µT m/s
$I_{1,y}$	1060 µT m/s
$I_{2,y}$	5700 µT m^2/s

[1)] 1 µTm = 1 G-cm; 1 µTm [2)] = 100 G-cm^2

first- and second-integral field errors when the ID changes its gap or current. Limits are given in terms of the entrance and exit kick angles $\theta_{1,\mathrm{u}}$ and $\theta_{2,\mathrm{u}}$ (where u = x,y).

Table 3.16 shows the case of a single device, either 2.4-m-long or 5.0-m-long, installed in a straight section.Table 3.17 shows the case for two independent IDs installed in a straight section.

Table 3.16. Entrance $\theta_{1,u}$ and exit $\theta_{2,u}$ angle requirements for a single ID (either 2.4-m-long or 5.0-m-long ID) installed in a straight section.

Entrance/Exit Angle ($\theta_{1,\mathrm{u}} = \theta_{2,\mathrm{u}} = \theta_\mathrm{u}$)	Usable Gap/Current Range (µrad)	Full Gap/Current Range (µrad)
Horizontal θ_x	±5	±10
Vertical θ_y	±2.5	±5

Table 3.17. Entrance and exit angle requirements for two independent IDs installed in a straight section.

Entrance/Exit Angle ($\theta_{1,\mathrm{u}} = \theta_{2,\mathrm{u}} = \theta_\mathrm{u}$)	Experiment Gap/Current Range (µrad)	Usable Gap/Current Range (µrad)	Full Gap/Current Range (µrad)
Horizontal θ_x	±3.9	±5	TBD
Vertical θ_y	±1.25	±2.5	TBD

The normal and skew integrated quadrupole limits are shown in Table 3.18.

The limits for the multipole field integrals are listed in Table 3.19.

3-3.2 Overview of Insertion Device Straight Sections

The insertion device straight section length in the MBA lattice remains the same as in the current APS lattice, nominally accommodating 4.8 meters of undulators. As in the current APS, a typical straight section would include two undulators, each 2.4 meters long. Dual, canted undulators will also be feasible, each with a nominal undulator magnet structure length of 2.1 meters. The undulators are out-of-vacuum, allowing the vacuum system to remain in place when an undulator is removed or installed.

Table 3.18. ID normal and skew quadrupole limits.

Quantity	Limit	Driving Requirement
Quadrupole	±50 G	Tune stability
Skew Quadrupole	±50 G	Coupling stability

Table 3.19. ID higher-order normal and skew multipole limits.

Quantity	Limit	Driving Requirement
Sextupole	±200 G/cm	Nonlinear beam dynamics
Skew Sextupole	±100 G/cm	Nonlinear beam dynamics
Octupole	±300 G/cm	Nonlinear beam dynamics
Skew Octupole	±50 G/cm	Nonlinear beam dynamics

Figure 3.10 shows the available space and typical distances of the straight sections. Figure 3.11 shows a layout of two insertion devices in canted geometry with three canting magnets and a corrector in the middle.

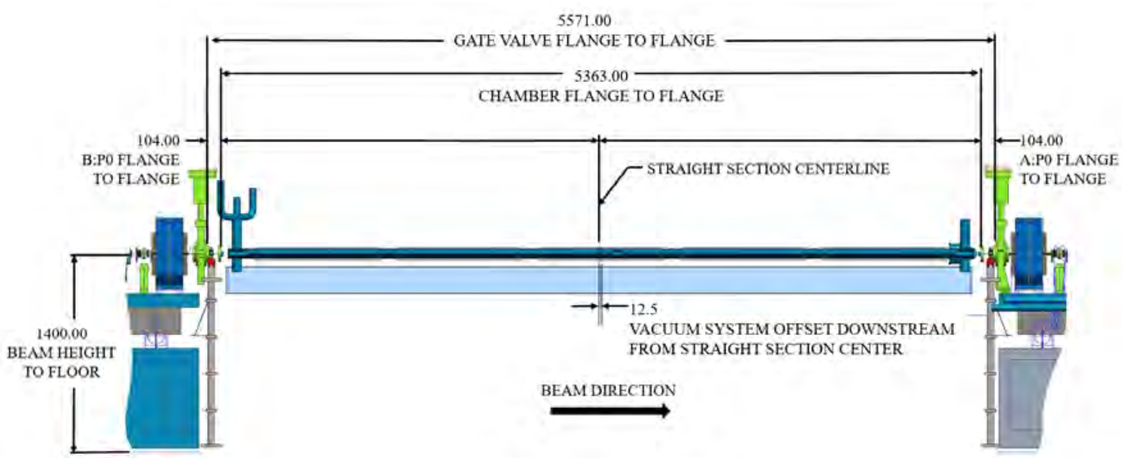

Figure 3.10. Available space for IDs in APS-U straight sections

Table 3.20 summarizes different ID configurations and required components for the APS-U.

3-3.3 Permanent Magnet Undulators

Table 3.21 summarizes the global ID specifications applicable to HPMUs installed in the APS-U storage ring.

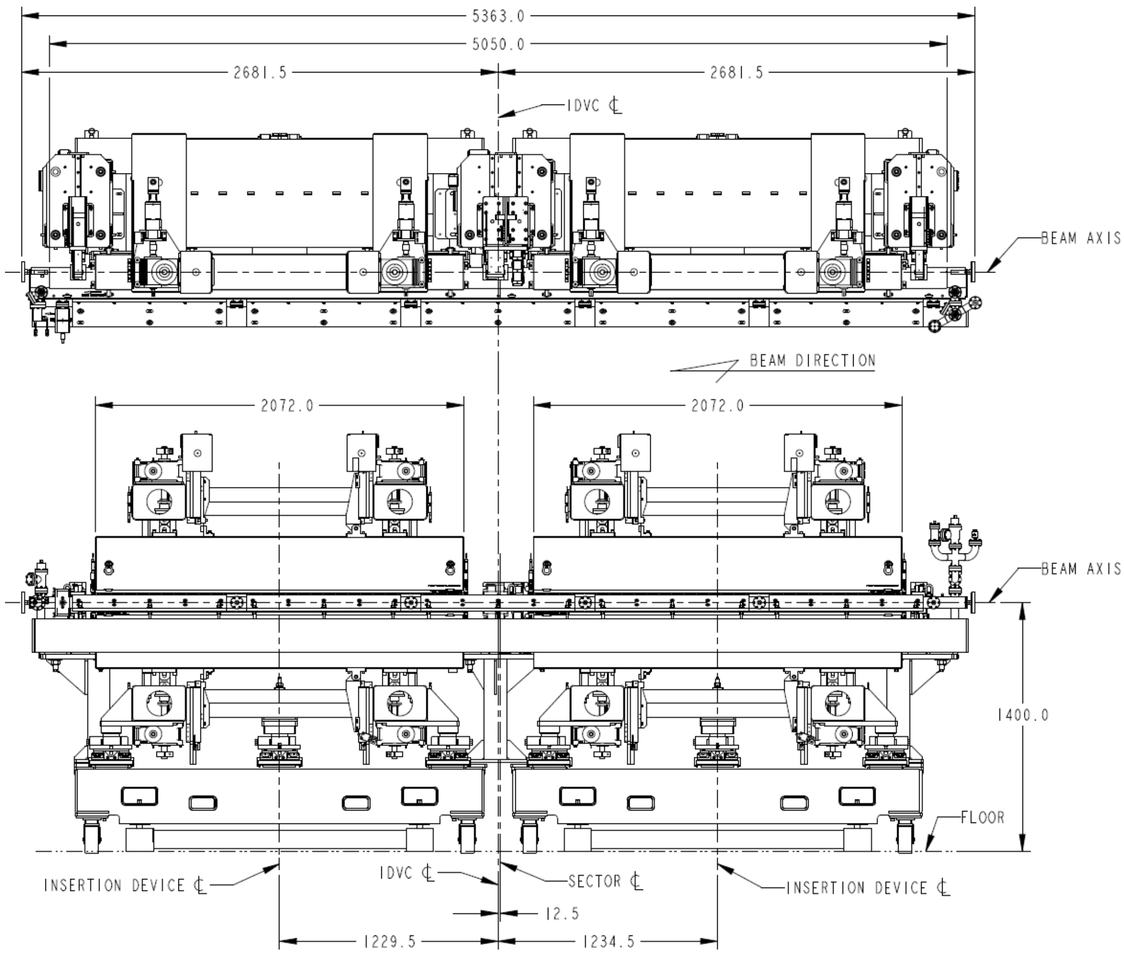

Figure 3.11. Plan (top) and elevation (bottom) views of the straight section for ID canted geometry. The straight section consists of two 2.1-m-long HPMUs, 0.5-mrad canting magnets at the upstream and downstream ends, and a corrector and a central 1-mrad canting magnet in the middle. The length of the IDVC (flange to flange is 5363 mm) and the length of the machined nose of the IDVC is 5050 mm.

Table 3.20. ID configurations with required main components.

Parameter	**Value**	**Unit**	**Comments**
Canted IDs			
Length	2.1	m	Approximate (two independent IDs)
Canting magnets	0.5/1.0/0.5	mrad	Upstream/Center/Middle; Electromagnetic
Corrector magnet in the middle	Yes	-	Electromagnetic
One ID			
Length	2.4	m	Located in either upstream or downstream half
Corrector magnet in the middle	TBD	-	Electromagnetic (only considered when undulator is in downstream half)
Two IDs			
Length	2.4	m	Approximate
Corrector magnet in the middle	Yes	-	Electromagnetic
Phase shifter in the middle	Yes/No	-	Yes for HPMUs and No for SCUs. Permanent magnet or electromagnet downstream of the corrector magnet

Table 3.21. Insertion device global specifications for planar HPMUs.

Parameter	**Value**	**Unit**
Number of ID straights	35	
Insertion device maximum length	4.8	m
Vertical magnetic gap	≥8.5	mm
ID chamber vertical aperture	≥6.3	mm
Maximum (horizontal) canting angle	1	mrad
Vacuum chamber straightness in plane with small magnetic gap	50	µm
ID rms phase error for any operational gap [1)]	~3	degree

[1] Target value for all IDs. May be relaxed for select IDs not operating at high harmonic energies.

3-3.3.1 Planar Undulators with One Magnet Structure

These undulators will be similar to the one shown in Figure 3.12 (left). A gap separation mechanism (GSM) precisely positions two vertically-opposed magnet arrays while balancing the strong attractive forces between them. Each array uses hundreds of strong, rare earth permanent magnets together with hundreds of vanadium permendur poles, as shown in the Figure 3.12 (right). The poles redirect and concentrate the horizontal magnetic flux across the gap to create a spatially alternating vertical magnetic field in the gap. The design for the magnet arrays will be based on current APS designs, but will be smaller in cross section because the required horizontal size (x-axis size) of the field can be smaller for the MBA lattice. About one third of the existing magnet arrays at the APS will be reused, but most will be replaced with shorter magnetic periods. An improved modular magnet structure design will be used (based on the design currently in use at the APS) which allows undulators to be assembled full-length or to be shortened if necessary to allow space for the canting magnets in dual canted undulator sectors or for a phase shifter and corrector between tandem undulators.

The majority of undulators will reuse gap separation mechanisms (GSMs) that are currently in use at the APS. There are two main types of GSMs: one uses two drive motors and the other uses four. The 2-motor GSMs are an older, now obsolete, design from STI Optronics and all are ~20 years old. However, they will have been serviced at the time of removal and will be serviceable for 10 – 20 years beyond the APS upgrade. Plans are to reuse only ~60% of these and to retain the rest as spares. The 4-motor GSMs (see Figure 3.13 left) were first installed at the APS over 15 years ago but most are much newer or have been upgraded more recently. The 4-motor GSM design is still in use for new undulators at the APS. Most, if not all, of those available, will be reused for the upgrade. The 2-motor GSM has a higher load capacity than the 4-motor GSM, which may be useful to exploit on some of the longer-period undulators.

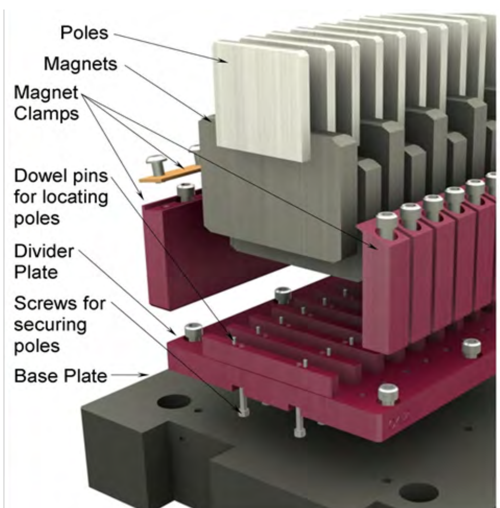

Figure 3.12. Planar undulator (left). Modular undulator magnetic structure used at the present-day APS (right).

3-3.3.2 Revolver Undulators

Revolver undulators are an evolution of planar undulators and provide the benefit of two different undulator periods in the space of a single undulator. Figure 3.13 (left) shows the top and bottom magnet structures in mid revolution and (right) is a model of the same device. The two undulator magnet structures are mounted at 90°to each other on a common "strongback." A revolver mechanism precisely revolves the strongback to select the active magnet structure. Two such revolver strongback assemblies are mounted to a common gap separation mechanism. Several layers of safeguards are in place to ensure that the gap is opened before rotation takes place and that the revolved position is correct before the gap can be closed again. The gap separation mechanism is the same as the 4-motor version used for undulators with only one magnet structure.

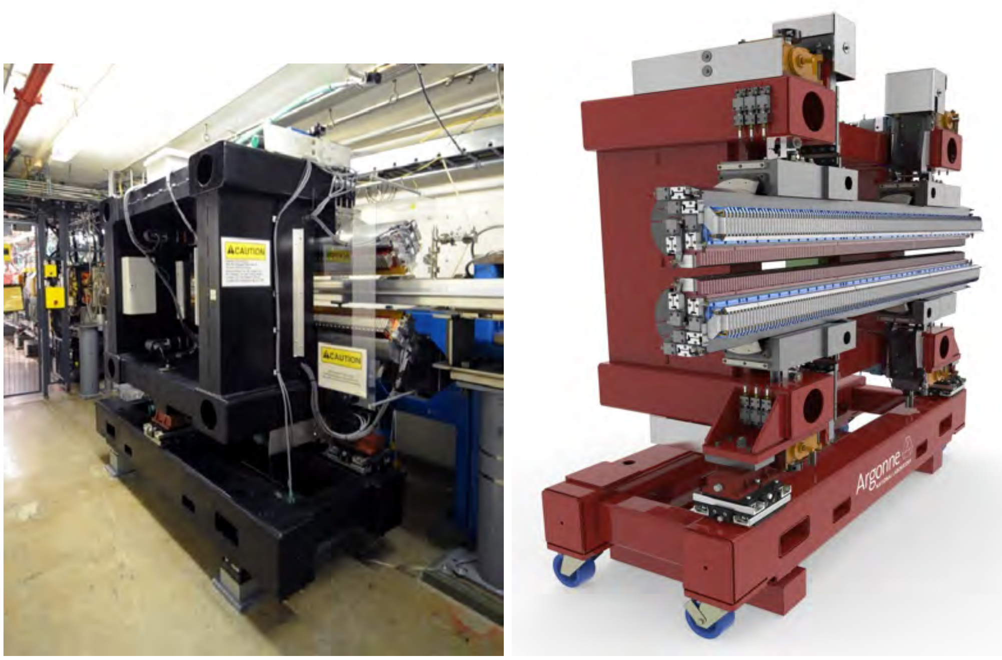

Figure 3.13. Revolver undulator installed (left) and a model of a revolver undulator (right).

3-3.3.3 Gap Separation Drive System Specifications

Table 3.22 summarizes parameters of the HPMU drive system applicable to both single-structure undulators and revolver undulators.

3-3.3.4 Permanent Magnet Material and Design

All current APS planar devices are hybrid devices with magnets and poles. For APSU for the newly designed devices the same principle will be used. Permanent magnets shall be made of NdFeB with heavy rare earth elements added via a grain boundary diffusion (GBD) process or some other technique to enhance the coercivity at the magnet surfaces for new magnets. This enhanced coercivity reduces the risk of radiation-induced demagnetization of the magnets. The grain-boundary diffusion and coercivity enhancement only reach a limited distance into the magnet;

Table 3.22. Parameters for planar HPMU drive system applicable to both single-structure and revolver undulators.

Parameter	Value	Unit
Minimum gap (normal operation)	8.5	mm
Minimum gap (absolute operational limit)	8.2	mm
Gap taper (maximum)	5.0	mm
Maximum gap	125 - 180	mm
Gap resolution	0.5	µm
Gap repeatability (unidirectional)	<3	µm
Gap stability (open loop control)	<5	µm
Rate of gap change	1	mm/s

beyond that depth, the magnet properties are those of the base grade. The pole material shall be made of vanadium permendur. Table 3.23 lists magnet and pole specifications for the APS-U for all newly designed devices.

Table 3.23. Permanent magnet and pole specifications for APS-U.

Parameter	Value	Unit	Comments
NdFeB Magnet coercivity (H_{cJ})	≥21	kOe	At 20°C. Near surfaces (≤3 mm) H_{cJ} ≥28 kOe with grain boundary diffusion enhancement.
Poles	Vanadium Permendur		VAC Vacoflux 50 or equivalent

3-3.3.5 Canting Magnets

When a sector is configured in a canted geometry, the two ID lengths will be reduced from their nominal length of 2.4 m to accommodate canting magnets. For the MBA lattice it is planned that 0.5 mrad canting magnets will be required at the upstream and downstream ends and a 1 mrad canting magnet will be required between the two undulators. This geometry is similar to current configurations and defined in the engineering specification document. Figure 3.14 shows the center canting magnet installed in current APS and the planned installation for APSU

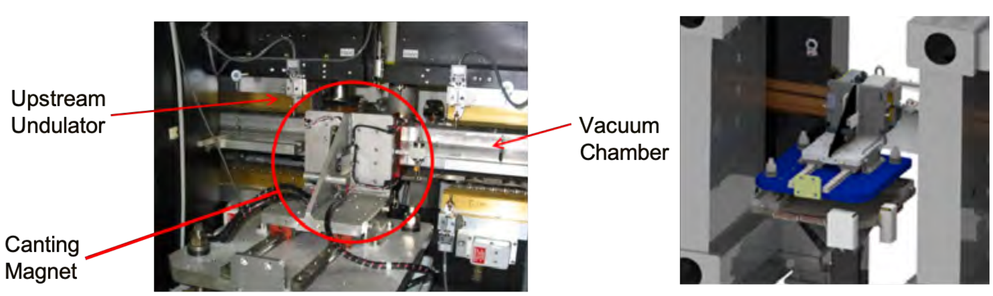

Figure 3.14. Center canting magnet assembly: The image on the left is in current APS and the figure on the right is the same canting magnet but with the APS-U undulators with super-strongbacks.

3-3.3.6 Phase Shifters

For the small-emittance MBA lattice, optimal photon intensity from two in-line undulators will require that proper phasing between the photon and electron beams be preserved from one undulator to the other. The necessary phase relationship will vary with the undulator gap, so an active adjustment of the phasing between the undulators is needed. It will be accomplished with a variable-field mini-wiggler based on either electromagnets or permanent magnets. The electromagnetic phase shifter could have a fixed gap but would require power supplies with associated controls and possibly cooling. A permanent-magnet phase shifter would require a variable gap with the associated gap controllers. Another possibility, which would be a new design concept at APS, is to provide a means of shifting the position of one of the undulators in the z direction. This last option would provide only a limited range of phase shift.

3-3.4 Superconducting Undulators

The technology of superconducting undulators was developed at the APS over the last decade [2, 3, 4]. A superconducting undulator (SCU) employs a set of superconducting coils to generate a periodic magnetic field. Due to the high current-carrying capacity of superconductors, superconducting undulators outperform all other undulator technologies in terms of peak magnetic field for a given period length and magnetic gap. There are three SCUs currently in operation at the APS – two planar devices and a helical device. For the APS-U, the SCUs are the preferred choice of undulators for beamlines requiring x-rays at 60 keV and beyond.

The current scope of superconducting undulators for the APS-U include eight devices assembled in pairs in four long cryostats as shown in in Table 3.24. The APS-U project will capitalize on the existing infrastructure and experience of the team.

Table 3.24. Scope of APS-U superconducting undulators

Period length (mm)	Magnetic length (m)	Configuration	Quantity of cryostats
16.5	1.9	Two in line	2
16.5	1.5	Two canted	1
18.5	1.2	Two canted	1

Table 3.25 summarizes global ID specifications applicable to SCUs installed in the APS-U storage ring.

Table 3.25. Global specifications for SCUs.

Parameter	**Value**	**Unit**
Cryostat maximum length	4.8	m
Insertion device maximum length	1.9	m
Vertical magnetic gap	8.0	mm
ID chamber vertical aperture	6.3 +0.1/-0.3	mm
Vacuum chamber straightness in plane with small magnetic gap	± 50	Îijm
ID rms phase error for any operational current	˜5	degree

3-3.4.1 Vacuum Chambers for Planar SCUs

The IDVCs for the planar SCUs shall satisfy the following constraints:

- System needs to fit within the confines of the straight section and not interfere with the outboard bending magnet front end, upstream and downstream Doublet L-Bend Multiplet (DLM) plinths, or the upstream and downstream vacuum and magnet equipment outside of the isolation gate valves.
- Minimize the amount of synchrotron radiation deposited on the SCU vacuum chamber wall and ensure that the downstream vacuum system is masked from upstream bending magnet radiation for a distance of 1.2 m.
- Ensure photon absorbers can safely mitigate the upstream bending magnet heat load.
- Ensure that if the cryostat insulating vacuum fails the chamber would not plastically deform.
- Maximize vacuum chamber wall continuity and minimize steps within the vacuum system to reduce wakefield heating.
- Minimize the vacuum chamber wall thickness to allow as small a magnetic gap as possible.
- Ensure sufficient vacuum pumping to meet beam lifetime requirements.

3-3.4.2 Superconducting Magnet

A superconducting undulator magnet consists of two magnet cores separated by a magnetic gap where a beam chamber is accommodated, as shown on a cut through view of the cryostat in Figure 3.15. A set of multiple racetrack coils are formed when a NbTi superconducting wire is wound into the core groves seen on a view of a single core, Figure 3.16. The current is flowing in opposite directions in the adjacent coil packs, therefore generating an alternating field profile along the beam axis. In this scheme, the superconducting wire makes an 180-degree turn on the back side of the core around a pin (seen in Figure 3.16) after being wound into a groove. The number of wire turns in a winding pack depends on the undulator period length and the groove dimensions. The core and the superconducting wire is cooled to the temperature of 4.2 K with liquid helium passing through a channel in the core, also seen in Figure 3.15.

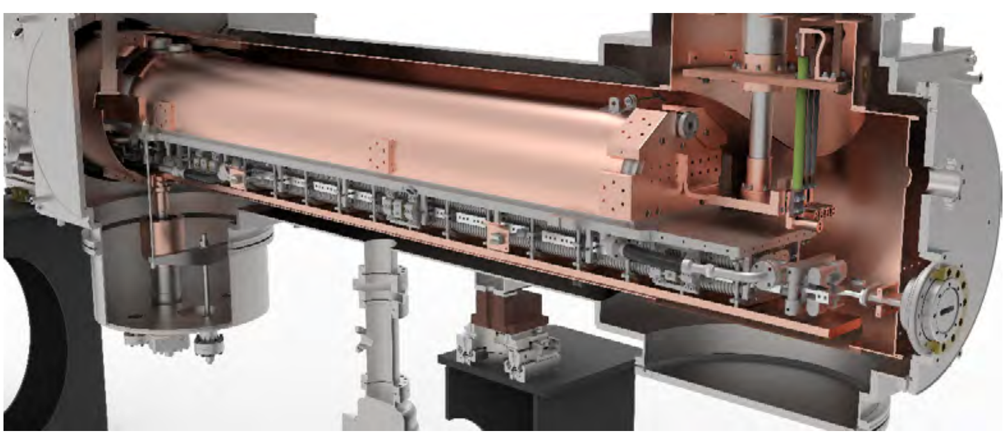

Figure 3.15. Exploded view of the SCU Cryostat

It has been learned during SCU development program at the APS that the quality of the magnetic field, i.e. repeatability of the peak magnetic field from one undulator period to another along the full

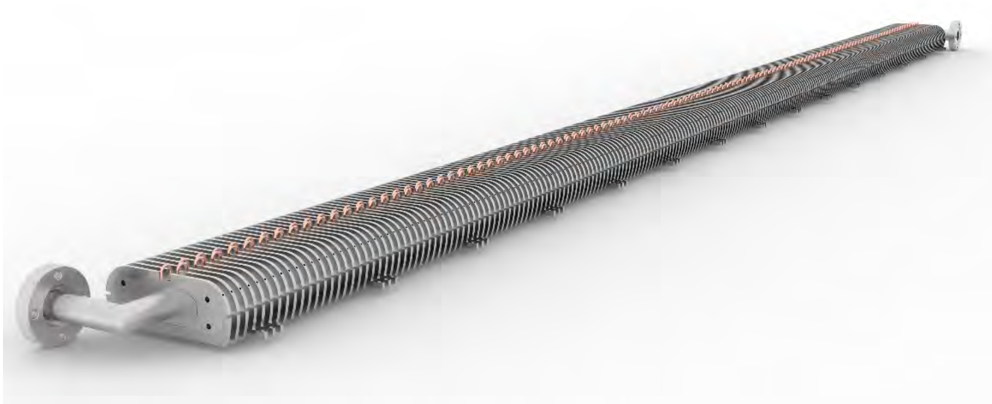

Figure 3.16. Design of a 1.9m long core for SCU coil winding

device, strongly depends on the precision of grooves in the magnet core, quality of winding, and the uniformity of the magnetic gap. The high quality of APS SCU winding is already demonstrated in a 1.5-m long magnet that was built within LCLS R&D program [5] and achieved a phase error of less than 5°RMS. The SCU cores are typically machined to high precision with the coil winding groove dimensions within typically 15 µm RMS. Also, a system of mechanical clamps (seen in Figure 3.15) which allows adjustment of the magnetic gap to a value defined by the gap spacers machined to a 10 µm tolerance, assures the precision of the magnetic gap.

3-3.4.3 Cryostat

For the APS-U, a 4.8-m long SCU cryostat is designed. The cryostat design concept has been tested in a 2-m long cryostat developed for helical SCU which is currently in operation at the APS [6]. The single long cryostat will hold two sets of magnets either in a tandem or in a canted geometry. In this cryostat, the 4.2-K cold mass is cooled by five 2-W 4-K cryocoolers, while the beam chamber is cooled below 20 K with one 20-K cryocooler.

A 3D rendering of the long cryostat in the APS-U straight section is shown in Figure 3.17. More details of the designs and the requirements are captured in various documents are shown in Table 3.26.

Table 3.26. Design and specification documents for Super Conducting Undulator

Document Name	ICMS Tag
Physics Requirement Document	APS_2022617
ID Functional Requirement Document	APSU_1688663
IDVC Interface Control Document	APSU_190925
SCU Engineering Specification Document	APSU_190927

Figure 3.17. 3D rendering of the long cryostat in the APS-U straight section

3-3.5 Insertion Device Vacuum Chamber

The vacuum chamber shall be produced from a 6063-T5 alloy aluminum extrusion. The planar ID vacuum chamber's interior elliptical profile, shown in Figure 3.18 where it is labeled "beam aperture', is critical to undulator operation and function. Vacuum chamber height, straightness, and wall thickness are key parameters that must be controlled during the manufacturing process. The cavity at the transition location needs to allow for vacuum pumping (upstream and downstream) and for photon absorber placement (downstream only).

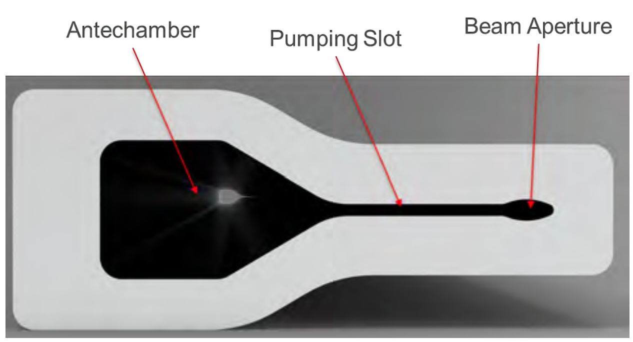

Figure 3.18. Cross section of insertion device vacuum chamber extrusion

The key undulator vacuum chamber specifications are summarized in Table 3.27.

Detailed Design requirements and specifications for the Insertion Device Vacuum Chamber (IDVC) can be found in the following documents shown in Table 3.28:

The ID vacuum system (IDVS) is situated between the up and downstream P0 BPMs (see Figure 3.18). The longitudinal distance the IDVS needs to span between P0 BPMs is nominally 5.363 meters. The P0 BPM vacuum aperture matches the storage ring 22 mm diameter round aperture. The IDVS transitions from the SR aperture down to a nominal 6.3 mm (H) x 16 mm (L) elliptical

Table 3.27. Key undulator vacuum chamber specifications.

Parameter	**Value**	**Unit**
Material	6063-T5 Aluminum	-
Beam aperture	$6.3\left[\begin{smallmatrix}+0.1\\-0.3\end{smallmatrix}\right]$ x 16.0	mm
Upstream/downstream transition aperture	22 ∅ round (SR) to 6.3 x 16 elliptical aperture (IDVC)	mm
Upstream/downstream transition length (z-axis)	$\geq$100	mm
Minimum pumping channel L/H ratio	12 to 1	-
Welded flange to flange length	5363.0	mm
Wall Thickness	$0.6\left[\begin{smallmatrix}+0.13\\-0.0\end{smallmatrix}\right]$	mm
Minimum Nose Thickness	7.2	mm
Maximum Nose Thickness	7.86	mm

Table 3.28. Design and specification documents for Insertion Device Vacuum Chamber

Document Name	ICMS Tag
Physics Requirement Document	APS_2022617
ID Functional Requirement Document	APSU_1688663
IDVC Interface Control Document	APSU_190925
IDVC Engineering Specification Document	APSU_190928
Space Requirements for ID Assembly and Testing	APSU_2015673

aperture. The purpose of the reduced aperture height is to allow the ID magnetic gap to close as close to the stored beam as possible. The IDVS has been designed for use in the IEX, Revolver, and inline or canted HPMU layouts. Figure 3.19 and Figure 3.20 shows the completed IDVC design and support. A complete description of the design is captured in *Insertion Device Vacuum System Design* report (APS_2021737).

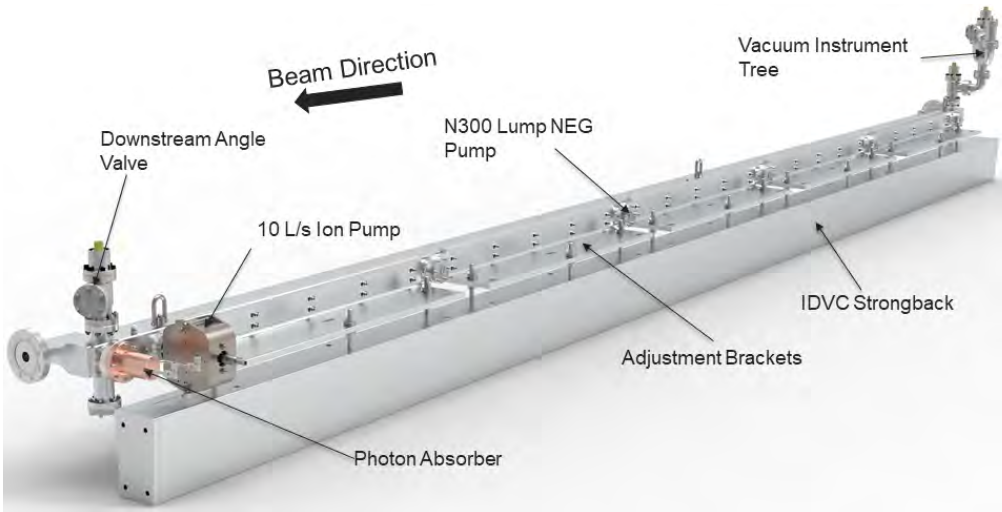

Figure 3.19. Planar Insertion Device Vacuum Chamber Assembly outboard view

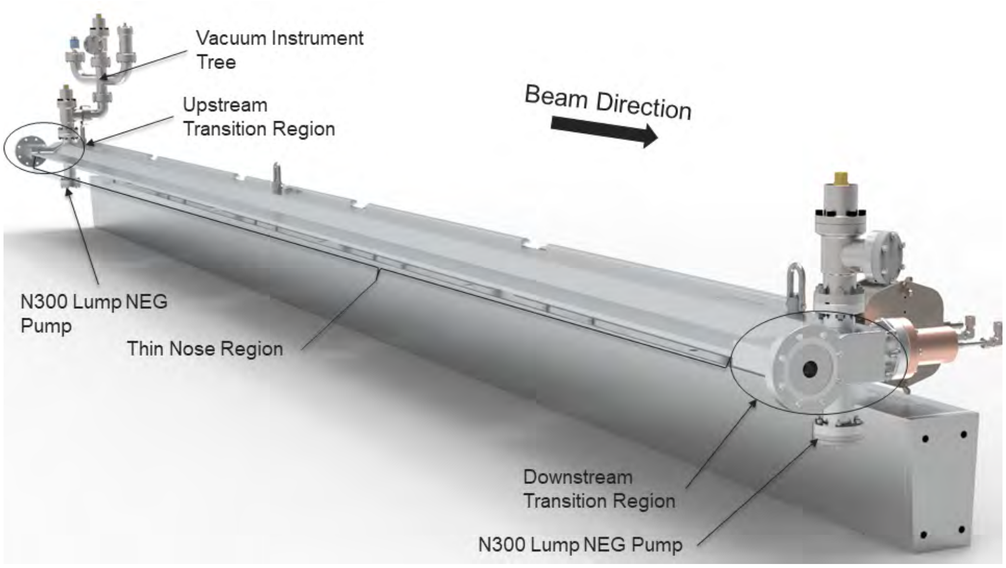

Figure 3.20. Planar Insertion Device Vacuum Chamber Assembly inboard view

3-4 Bending Magnet Sources

The current APS has 20 Bending Magnet (BM) beamlines in operation. The beamlines are provided with a 6 mrad horizontal fan of radiation from one of the two dipole magnets per sector. The current storage ring has two dipoles per sector and only one of the dipole sources is used for BM beamlines. The other dipole just downstream of the ID straight section is not used. The separation between the ID and the BM source is currently set to 5.0625°. All beamlines have been built with this geometry.

The APS-U is a MBA lattice and has 7 bending magnets per sector. The lattice has been optimized to keep the ID beamline tangent line the same to avoid having to realign all the ID beamlines. However by keeping the separation between the ID and BM line the same, the new source point for the BM beamlines lies 42.3 mm inboard of the current location. The center of BM source point is located 5.36 mrad into B:M3 magnet. Figure 3.21 is an elevation view of the FODO section of the lattice showing the location of the BM source point. In addition, the source point has also shifted upstream by 1.826 m relative to the current APS BM beamline source. More details are availble in the source defintion document (APSU_2032015) and the BM front end FReD (APSU_190886).

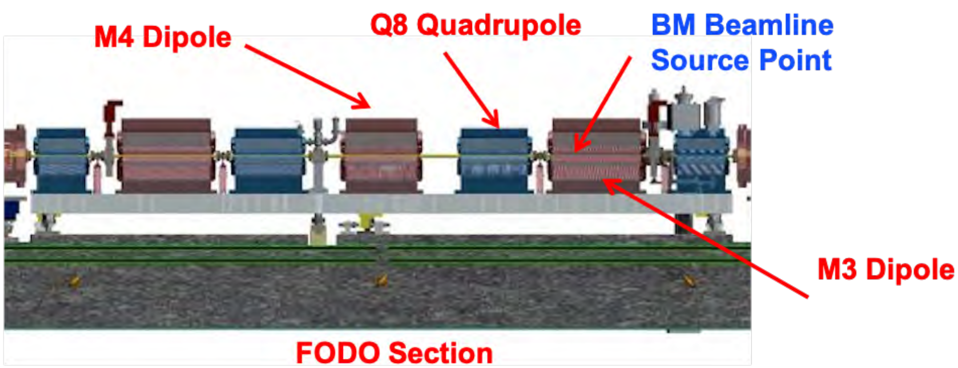

Figure 3.21. An elevation view of the BM source location in the FODO section.

In the APS-U lattice, as designed, the BM beamlines will receive a combination of radiation from the M4 and M3 transverse gradient dipoles. In addition, the reverse bend lattice makes it more complex as the quadrupole Q8 between the M4 and M3 magnet provides a 5.36 mrad of reverse bend. The net result for the beamline will be a combination of all these dipole sources.

All the existing BM front ends will be reused with realignment for the new shifted centerline. The radiation fan delivered to the beamlines is determined by the masks in the front end and will be limited to about 5.4 mrad due to the shift of the new source upstream by 1.826 m, while providing the same spatial fan of radiation as delivered to the beamlines currently. Most beamlines are using only about a 1 mrad fan of radiation. Figure 3.22 is a visualization of the horizontal fans of radiation overlapping. We are anticipating that most beamlines which use about 1 mrad fan will be realigned to use the clean M3 source on the inboard side.

A comparison of the various sources are shown in Table Table 3.29. The APS BM is shown in the table for 7 GeV and 100 mA while the other sources are for 6 GeV at 200 mA. The horizontal fan in the table is what is received by the beamline based on the front end configuration. The power per

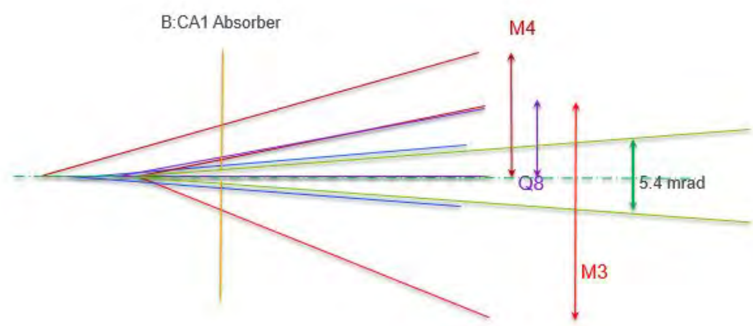

Figure 3.22. A schematic view of the radiation fans on the BM source centerline.

mrad is for the horizontal fan of 1 mrad at 25 m from the source for the current configuration. For the APS-U, the increased source distance has been compensated. Figure 3.23 is the comparison of the spectral flux at current 25 m point of the beamline for an aperture of 25 mm horizontal by 2 mm vertical.

Table 3.29. Comparision of the different BM beamline sources

Source	Field [T]	Critical Energy [keV]	Horizontal Fan [mrad]	Power/mrad [W]
APS BM	0.599	19.519	6	87
M3	0.653	15.633	5.4	119
M4	0.609	14.58	2.7	111
Q8	0.186	4.453	2.7	34
M3+M4+Q8	-	-	2.7	257

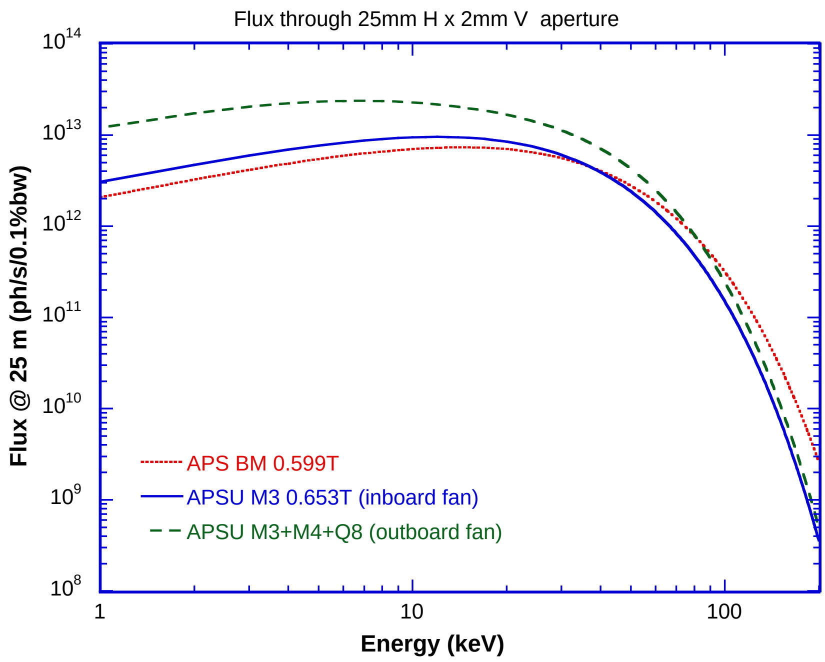

Figure 3.23. Calculated spectral flux at current 25 m point through an aperture of 25 mm horizontal and 2 mm vertical. The inboard M3 dipole radiation (blue curve), and the combined outboard radiation from M3, M4, and Q8 (green curve) for a beam energy of 6.0 GeV and a current of 200 mA are shown. The performance of the current APS BM for a beam energy of 7.0 GeV and a current of 100 mA (red curve) is shown for comparison.

References

[1] V. Sajaev, L. Emery, and A. Xiao, Argonne National Laboratory, unpublished information, 2018.

[2] Efim Gluskin. Development and performance of superconducting undulators at the advanced photon source. *Synchrotron Radiation News*, 28(3):4–8, 2015.

[3] Y Ivanyushenkov, K Harkay, M Abliz, L Boon, M Borland, D Capatina, J Collins, G Decker, R Dejus, J Dooling, et al. Development and operating experience of a short-period supercon-ducting undulator at the advanced photon source. *Physical Review Special Topics-Accelerators and Beams*, 18(4):040703, 2015.

[4] Y Ivanyushenkov, K Harkay, M Borland, R Dejus, J Dooling, C Doose, L Emery, J Fuerst, J Gagliano, Q Hasse, et al. Development and operating experience of a 1.1-m-long superconducting undulator at the advanced photon source. *Physical Review Accelerators and Beams*, 20(10):100701, 2017.

[5] P Emma, N Holtkamp, H Nuhn, D Arbelaez, J Corlett, S Myers, S Prestemon, R Schlueter, C Doose, J Fuerst, et al. A plan for the development of superconducting undulator prototypes for lcls-ii and future fels. In *FEL 2014 Conference Proceedings, Basel, Switzerland*, 2014.

[6] J Fuerst, Q Hasse, Y Ivanyushenkov, M Kasa, and Y Shiroyanagi. A second-generation superconducting undulator cryostat for the aps. In *IOP Conference Series: Materials Science and Engineering*, volume 278, page 012176. IOP Publishing, 2017.