Full-field X-ray Imaging (FXI) Beamline

IRR Functional Description

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1 INTRODUCTION

1.1 Primary Research Capabilities

The FXI beamline will enable 30 nm spatial resolution full-field imaging in the 5-11 keV range using a Transmission X-ray Microscope (TXM). The source for the beamline is the 100 mm period damping wiggler (DW100). Both 2D and 3D (tomography) imaging modalities will be available, as well as nano-XANES. Both absorption and Zernike phase contrast modalities will be available. The field of view will be in the 20-50 micron range. The beamline will focus on high speed imaging that enables visualization of sample dynamics in operando. The beamline will serve a broad interdisciplinary user community that ranges from energy related functional materials and devices, materials science, environmental science, biological sciences and advanced manufacturing.

1.2 Beamline Staff

Lead Beamline Scientist	Wah-Keat Lee	
Authorized Beamline Staff	Mingyuan Ge	Beamline Scientist
Beamline Support Staff	Mike Maklary	Mechanical Technician
	Scott Coburn	Mechanical Engineer
	Huijuan Xu	Controls Engineer (beamline)
	Kazimierz Gofron	Controls Enginner (TXM)

2 BEAMLINE DESIGN AND COMPONENTS

2.1 Beamline Performance Goals

Table 1 summarizes the designed performance of 18-ID. The basic goal of the photon delivery system is to deliver the maximum amount of photons within the required phase-space from the DW100 radiation fan onto the TXM condenser. Within the TXM, the performance is determined by the condenser and the zone plate, both of which are taken from the NSLS X-8C Xradia TXM instrument.

Table 1. 18-ID Design Performance Parameters

Parameter	**Specification/design target**
Insertion device	DW100 damping wiggler
Energy range	5-11 keV
Energy bandwidth	1.4e-4 (Si(111))
Beamline optics design	Collimating mirror-DCM-Toroidal mirror
Secondary source size	~ 0.25 mm x 0.25 mm
TXM condenser	Single bounce capillary
TXM objective	Zone plate
TXM spatial resolution	30 – 60 nm (depends on field of view)
TXM field of view	20-50 microns
Flux over TXM condenser	5.4e13 ph/s/0.01%BW
Expected minimum exposure time per image	< 100 ms

2.2 Beamline Layout

The optical layout of the FXI beamline is shown in Figure 1. The source is the 100 mm period damping wiggler (DW100). A collimating mirror is used to achieve a ~ 10^{-4} energy bandwidth using the Si(111) double crystal monochromator (DCM). This bandwidth is needed for XANES measurements. A toroidal mirror is used to focus the beam (H & V) onto a secondary source aperture (SSA). The DCM and the two mirrors are located in the 18-ID-A hutch (FOE), while the TXM and the SSA are located in 18-ID-B hutch. A shielded beam transport pipe connects the two hutches. The beamline is windowless until just upstream of the SSA where there is a beryllium window that isolates the SSA and TXM from the rest of the beamline upstream. In the B hutch the

diverging beam from the SSA fills the TXM condenser which focuses the beam onto the sample. A zone plate objective is used to make a magnified image of the sample which is subsequently imaged by an area detector.

FXI has been designed to accommodate a future horizontally offset parallel beamline that utilizes a portion of the inboard off-axis DW100 radiation fan. This is why the front-end burn-through device is asymmetrically larger in the horizontal than is currently needed for FXI; which explains the asymmetric incident beam envelope on the FXI fixed mask in the FOE. This future upgrade scenario is not part of this IRR, but is mentioned here to explain the asymmetry in the ray traces.

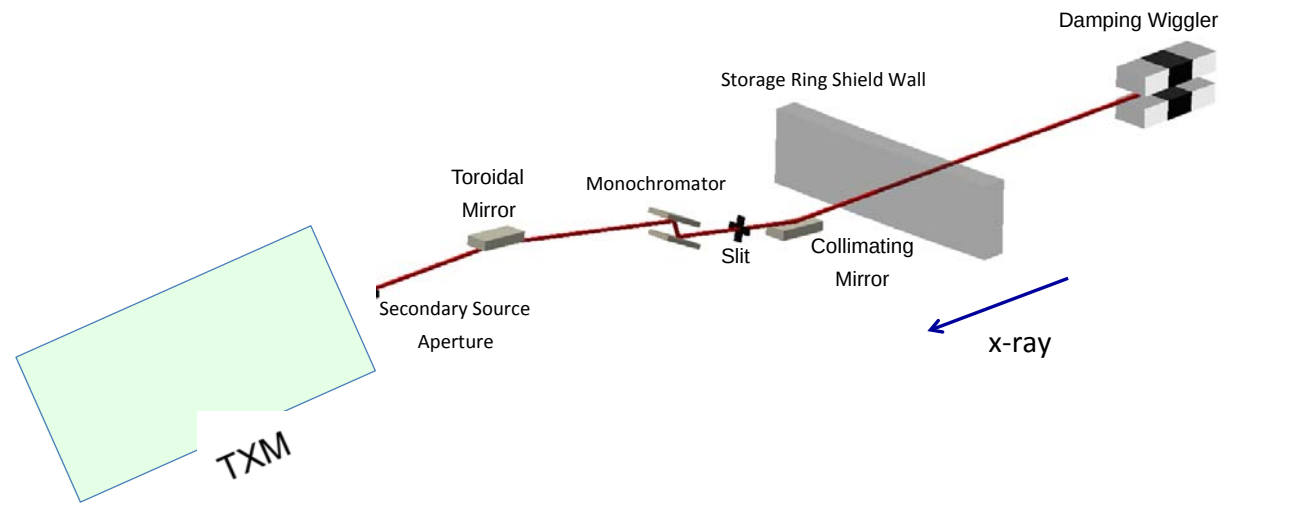

Figure 1: Beamline layout

2.2.1 Source

The TXM phase space requirements are well matched by the NSLS-II 100 mm period damping wiggler (DW100). The TXM requires about 100 um-mrad phase space in both directions, which is well matched by a 0.2 mrad x 0.2 mrad acceptance from the DW100 on-axis radiation fan. The TXM does not require source coherence. The required energy range is also well suited to the spectral output of the DW100.

2.2.2 Optics and Diagnostics

The overall layout of the FXI beamline is shown in Figure 1 and described above. Specifications of the mirrors and monochromator are tabulated below.

Collimating mirror:

Optical length	1450 mm
Substrate	Single crystal silicon
Coating	Bare silicon, Cr and Rh
Shape	Flat bent to ~ 13.4 km tangential radius
Bender	Piezo-electric transducer (PZT)
Cooling	Top side contact cooled
Maximum incident power	1.9 kW
Operational incidence angle	4.4 mrad, reflect up
Motions	5 linear motorized stages to achieve roll, pitch, yaw, X and Y

Monochromator:

Type	Double crystal, fixed exit
Cooling	Indirect LN2. LN2 pump located on mezzanine above the FOE.
Maximum incident power	1 kW
Offset	25 mm (up)
Energy range	4-20 keV (larger than TXM range)
Crystals	Si(111)
Motions	9 actuators. Overall X, Y, pitch, roll and yaw Fine pitch and roll on second crystal Translation on second crystal for fixed exit

Toroidal mirror:

Optical length	1450 mm
Substrate	Single crystal silicon
Coating	Rh
Shape	Flat bent to ~ 10.8 km tangential radius
Bender	Piezo-electric transducer (PZT)
Cooling	None
Maximum incident power	< 0.1 W
Operational incidence angle	4.4 mrad, reflect down
Motions	5 linear motorized stages to achieve roll, pitch, yaw, X and Y

Diagnostics:

For beam diagnostics, FXI has several in-line retractable fluorescent screens that can visualize the white beam, the pink beam from the collimating mirror, the monochromatic beam after the DCM, and the reflected beam from the toroidal mirror.

3 BEAMLINE SAFETY

3.1 Radiation Enclosures

The design of all radiation shielding (hutches and radiation safety components) for the FXI beamline follow set guidelines to reduce radiation levels external to the beamline enclosures during normal operation to levels that are consistent with NSLS-II policy: that dose levels in continuously occupied areas are < 0.05 mrem/hr at 1 foot distance and < 0.5 mrem/hr on contact. Shielding of hutches is as follows:

Hutch 18-ID-A (lead and steel hutch):

- Lateral wall: 18 mm lead
- Downstream wall: 50 mm lead
- Roof: 4 mm lead

Beam Transport System between A and B hutches:

- Pipes: 6 mm lead wrapped around stainless steel vacuum pipe
- Enclosures for ion pumps and flanges: >6 mm lead

Hutch 18-ID-B (lead and steel hutches):

- Lateral wall: 4 mm steel
- Downstream wall: 4 mm steel
- Roof: 3 mm steel
- Beam stop: 20 mm lead

A photon shutter of standard NSLS-II design (25 x 40 mm aperture) is installed near the downstream end of the 18-ID-A hutch. Beam transport pipe penetrations out of the A hutch and into the B hutch are fitted with guillotines and lead collars. Figure 2 shows a schematic of the radiation enclosures.

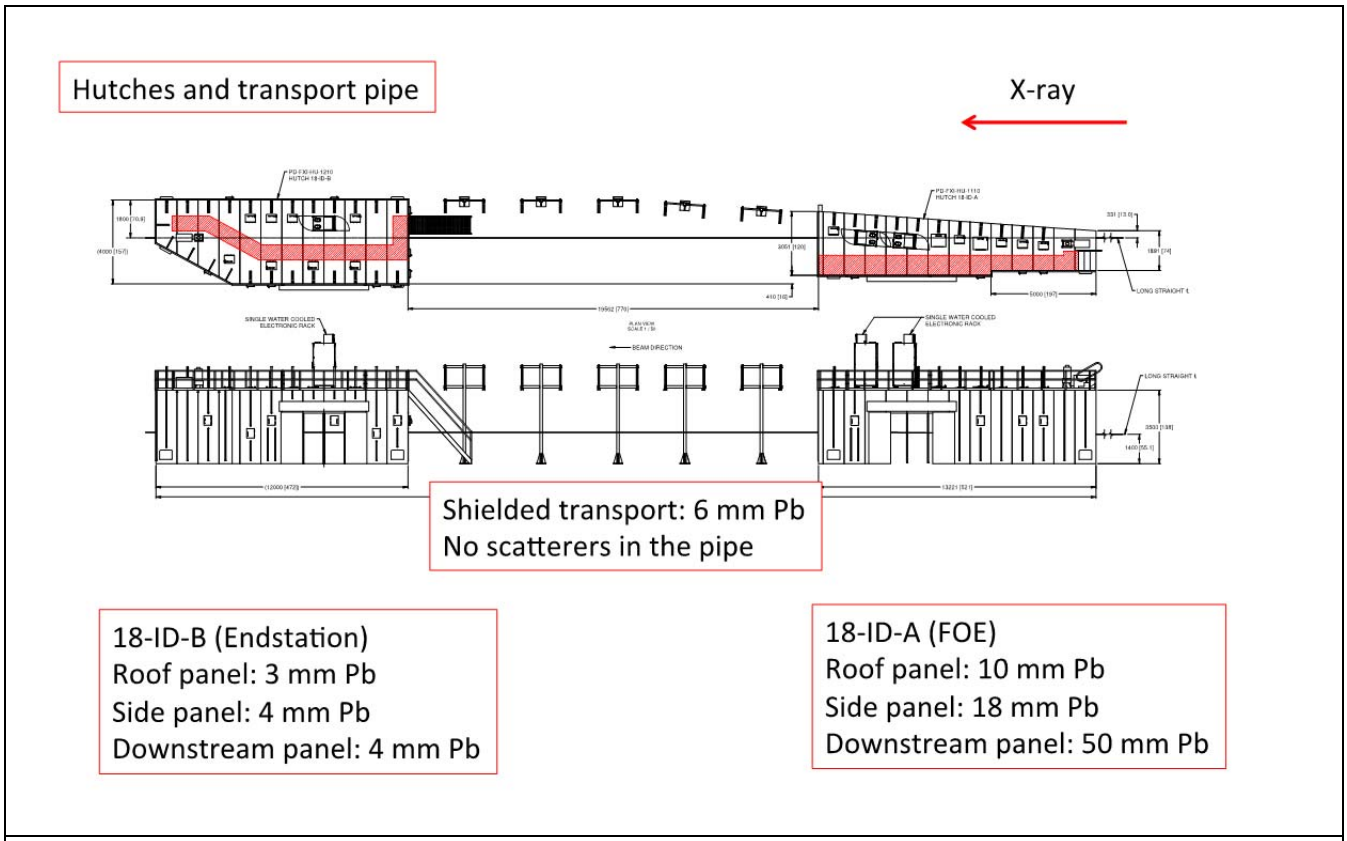

Figure 2: Schematic of the hutches and beam transport pipe

3.2 Radiation Safety Components and Configuration Control

Radiation safety components ensure that all radiation (synchrotron, primary and secondary Bremsstrahlung) are safely contained inside shielded enclosures and shielded transport pipes. These components can be classified into two categories: (a) radiation safety related thermal components and (b) radiation shielding components. The former is usually made from a copper alloy and its function is to ensure that the downstream radiation shielding components (usually Pb or W) are not damaged by the power of the beam.

The radiation safety components in the Front End (not shown) include burn-through devices and standard lead Bremsstrahlung collimators. In the FOE, there are 3 water cooled radiation safety thermal management components: the fixed mask, the white beam stop/pink beam mask and the pink beam stop. Inside the FOE, the incident primary Bremsstrahlung fan is collimated by the Bremsstrahlung Collimator and is stopped by the Primary Bremsstrahlung Stop. There are 5 secondary Bremsstrahlung shields (SBS-0 to SBS-IV) that capture any scattered Bremsstrahlung from the collimating mirror or fixed mask. Figure 3 shows the radiation safety components in the FOE. Refer to the raytracing drawings and the 18-ID radiation safety component checklist for more information.

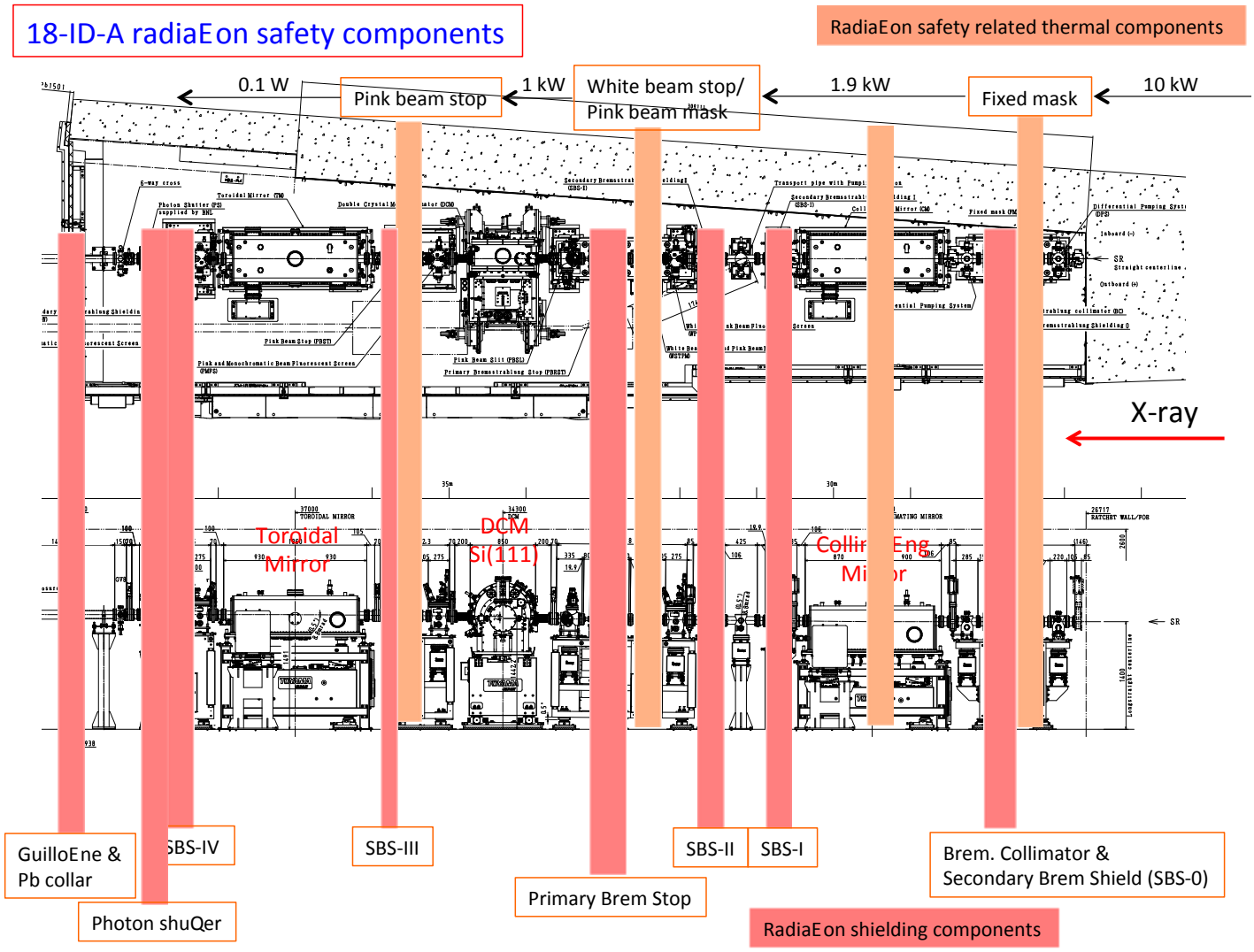

Figure 3: Schematic of all the radiation safety components in the FOE (not including the hutch labyrinths and guillotines). Estimates of the incident and exit power on the thermal components are also shown.

3.2.1 Thermal Management

The maximum power entering the FOE is about 10 kW. This is defined by the PPS-credited front-end burn-through device. In the FOE, this beam is captured by the fixed mask. The maximum power transmitted through the fixed mask aperture is about 1.9 kW. The white beam stop/pink beam mask stops the white beam while enabling the pink beam (reflected by the collimating mirror) to be transmitted to the DCM. The maximum power of the pink beam is about 1 kW. The pink beam is stopped by the pink beam stop downstream of the DCM. These three radiation safety related thermal components (fixed mask, white beam stop/pink beam mask and pink beam stop) are water cooled in series and have redundant flow sensors as required by the PPS.

Hard stops are installed on the collimating mirror vertical stages to ensure that the reflected pink beam, which can be up to 1 kW, is safely captured by either the white beam stop/pink beam mask or the pink beam stop. As such, we consider the hard stops to be radiation safety components related to thermal management and place them under configuration control. The hard stops are installed 'outside' the normal motion limit switches; i.e; the limit switches will stop the motion before hitting the hard stops.

3.2.2 Bremsstrahlung Management

Primary Bremsstrahlung radiation entering the FOE is collimated by the Bremsstrahlung Collimator and subsequently fully stopped in the FOE at the Primary Bremsstrahlung Stop.

Secondary bremsstrahlung radiation shielding design is based on the recommendations of LT-C-ESH-STD-001 and verified by FLUKA simulations. A series of secondary Bremsstrahlung shields (SBS-0 to SBS-IV) ensure that all secondary Bremsstrahlung is safely contained within the FOE.

3.2.3 Configuration Control

All radiation safety components are under configuration control, in accordance with the *NSLS-II Radiation Safety Component Configuration Management* procedure (PS-C-ASD-PRC-055).

3.3 Area Radiation Monitors (ARMs)

Radiation levels in the area will be actively monitored through an area radiation monitor (ARM) installed on the outboard wall at the upstream end of the FOE. The monitor will be certified in accordance with the procedure PS-C-ASD-PRC-008, *NSLS-II Area Radiation Monitor PPS Test.*

3.4 Oxygen Sensors

The DCM uses liquid nitrogen (LN2) to cool the two crystals. This creates a potential oxygen deficiency hazard (ODH) which is mitigated by the installation of oxygen sensors inside the FOE. This system has been certified in accordance with procedure PS-C-XFD-PRC-005, *Beamline Enclosures ODH Monitoring and Alarm System Certification and Inspection*.

3.5 Personnel Protection system (PPS)

The PPS controls access to the hutches through the interlock system and beamline-specific search and secure procedure, to ensure personnel safety during normal operation of the beamline. In addition, the the water flow through the radiation safety related thermal components and the two user labyrinths in the 18-ID-B are also PPS interlocked.

3.6 Hazard Identification and Mitigation

The FXI beamline is similar to other beamlines already in operation at NSLS-II with respect to any hazards that might be encountered.A USI evaluation has been conducted and it was determined that the anticipated activities at the beamline do not violate the existing SAD and ASE. All relevant NSLS-II procedures and safety practices were followed during the design and construction of the beamline to mitigate the hazards identified in these documents.

4 INSTRUMENT READINESS

4.1 Survey and Alignment

The beamline components are installed according to the specifications and respective final designs. Installation of the components is verified and documented by travelers with input from the NSLS-II Survey Group working closely with the beamline staff.

4.2 Utilities

The following services/capabilities are deployed at the beamline:

- Electrical power distribution to all electrical power outlets, light fixtures, fans, etc., in the hutches and along the beamline
- Distribution of deionized water
- Distribution of process chilled water
- LN2 distribution to the LN2 cryocooler on the mezzanine
- Compressed air
- Dry nitrogen gas
- Network connectivity
- Cabling and piping support for all utilities, including EPS and PPS

4.3 Vacuum System and Pressure Safety

FXI does not have a vacuum window between the FOE and the front-end. The FXI beamline will be under vacuum from the front-end all the way to B station, where there is a beryllium window. A differential pump system is installed at the upstream end of the FOE as transition to the front-end and accelerator vacuum. Although the FXI beamline vacuum is specified as $5x10^{-8}$ mbar or better at all locations under vacuum, the vacuum pressure just downstream of GV2 (upstream section of the differential pump system) is expected to be 10^{-9} - 10^{-10} mbar range. The accelerator vacuum is also protected by a fast valve located in the Front End, with a fast value sensor located just downstream of the DCM.

The end beryllium window, which terminates beamline vacuum at the upstream end of Hutch B has been pressure-tested to 1.5 atm differential. A vacuum failure in a given beamline vacuum section results in the closing of the Front End photon shutter and the closing of the adjacent gate valves. When venting any of these beamline vacuum sections to dry nitrogen gas, a pressure relief valve with a very low relieving pressure (1/3 psi) will be used to prevent any internal overpressure condition.

Downstream of the beryllium window, in the B hutch, all equipment will be operated either in air or under a very low constant He flow environment. Equipment under He environment have pressure relief valves that are set to 1/3 psi above atmosphere.

All vacuum vessels containing water or LN2 are equipped with burst disks.

4.4 Controls

All motorized components have been tested by the Controls Group and documented in the travelers. Controls System Studio (CSS) screens have been prepared to access the motors on the components. The individual motors are also accessible using standard EPICS Extensible Display Manager (EDM) screens.

4.5 Equipment Protection System (EPS)

The EPS at the FXI beamline performs the following functions:

- Vacuum pressure monitoring and interlock for required vacuum sections of the beamline
- Temperature monitoring and interlock for non-safety-related components, including the collimating (white beam) mirror and monochromator
- Water flow monitoring and interlock for cooling of the collimating mirror, retractable diagnostic screens and monochromator
- Monitor oxygen levels of equipment that is under He environment
- Monitor status of the LN2 pump
- Experimental Physics and Industrial Control System (EPICS) interface for components that require I/Os installed on the EPS Programmable Logic Controller (PLC), including the readout of thermocouples, control of venting, evacuation valves, and pumps