Final Report

High Coherence Nanoprobe (HCN)
Beamline Scoping Group (BSG)

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Executive Summary

The capabilities provided by the proposed beamline, a high coherence nanoprobe capable of nearly simultaneous collection of images from x-ray fluorescence and diffractive modalities at high spatial resolution combined with spectroscopic capability, will generate world-leading scientific outcomes across a number of fields, including existing as well as emerging research strengths in the Australian community. The primary scientific focus will be on biological and biomedical applications, however the instrument should retain capability for environmental, geological and materials science applications.

This document updates scientific focus areas and goals for the beamline in the context of the entire facility, outlines the capabilities required to generate internationally competitive outcomes in those areas, and addresses technical and design considerations pertinent to successful and expedient construction and commissioning.

In brief, the beamline should be capable of imaging trace levels of elements heavier than phosphorus in micron-scale thickness samples maintained at cryogenic temperatures. Using a focal spot size down to 50 nm, areas up to 100 μm on a side should be imaged in 1-24 hours. The coherence characteristics of the focussed beam, which will provide coherence spatial lengths of > 200 μm, should allow diffractive imaging of structure in the same samples with minimal or no reconfiguration of the instrument. The beamline should be optimised for high-sensitivity mapping studies over the full energy range of 2-20 keV by using a selection of high-efficiency beamline and endstation optics. Highly monochromatic x-rays are also required over the full energy range – optimised over the 5-13 keV range – for spectroscopic measurements. By extending the energy range down to 2 keV we will capitalise of the peak brilliance of the AS. A low-energy coherence-optimised capacity will capitalise on local (Australian) expertise in coherent diffractive imaging and will speed development of complementary imaging modalities that will add significantly to the value of the AS and the HCN facility. The energy range should extend to 20 keV to enable studies of second-row transition elements and platinum-group elements, of interest in the mining industry.

Background and motivation

The Australian scientific community has benefitted from quality access to several hard and soft x-ray microscopy beamlines over the last decade and produced a significant body of high-impact research outcomes as a result. Hard X-ray experiments were initially conducted at the APS beamlines 2-ID-D and E, which provide high fluxes into beamspots from approximately 0.2-1 μm, along with XANES capability at D station. Softer X-ray (1-4 keV) imaging and spectroscopy on phosphorus and sulfur in biological samples was conducted at the 2-ID-B branchline, at a spatial resolution as low as 50 nm. In parallel, Australia has developed world-leading expertise in the area of coherent diffractive imaging (CDI), pioneered at the ARC Centre of Excellence for Coherent X-ray Science, where developments in the technique are now leading to new understanding of biological structure at the nanoscale. Access to the 2-ID-B beamline has been instrumental to that development.

The sensitivity of the hard X-ray lines is such that first transition series metals can be detected at concentrations as low as 10 ng/cm^2 or better, which allows their localisation to be determined in single cultured mammalian cells, for example. The bulk of work has been conducted in step-scanning mode with thinner samples up to 100 μm in one dimension, although recent development of fast detection (electronics) and fly-scanning approaches allows much larger areas of thicker samples (e.g. tissue sections 10 or more μm thick) to be imaged, of the order of several millimetres, with submicron resolution. During the same period a number of groups used other international facilities for hard x-ray scanning microscopy experiments, but in general these had lower sensitivities and either examined larger samples or samples with greater amounts of the elements of interest. In some cases these beamlines allowed more advanced experiments such as spectromicroscopy (XANES stacking) or cryogenic tomographic imaging.

The dual microprobe/nanoprobe XFM beamline at the AS now provides much of this capability at the micron length scale within Australia. Successful implementation of KB mirror focussing in combination with the 384-element annular Maia fluorescence detector have allowed the microprobe to overcome a source/flux disadvantage compared to the APS lines to provide world leading micron-scale rapid imaging capability for large area samples. Overcoming source characteristic disadvantages for the ZP focussed nanoprobe system is an ongoing challenge; however, sensitivity within an order of magnitude of 2-ID-E has been achieved within a limited incident energy range using a beamspot of approximately 0.4 μm.

Internationally, continued development of synchrotron facilities has lead to scoping, design and initial commissioning of several hard x-ray nanoprobe beamlines with focussing targets to as low as 1 nm. These developments are driven by a desire to understand structural and chemical phenomena in biological, materials and environmental sciences at a spatial scale that has not previously been possible – i.e. below 100 nm.

The international community recognises the potential benefits in this field from combining multiple imaging modalities at these length scales to provide complementary structural, compositional and chemical information simultaneously. The X-ray (spectro)microscopy user base in Australia combined with existing expertise in X-ray imaging modalities positions the AS to lead world progress in this area, however the source characteristics of the AS ring dictate that we should not compete in a race for smallest spot size or photon flux, but instead in the area of scientific outcomes for target scientific areas.

Scientific Focus Areas and Overlap with Existing Research Strengths

The original science case II document for the HCN outlined a number of research projects that would be possible for the new facility. These are collected into focus areas here for alignment with national research priorities, and to assist in defining capability requirements for the HCN.

Biological and Biomedical Research – The increased resolution XRF and CDI imaging that will be possible on the HCN will allow 2D and 3D imaging of sub-cellular organelles in cultured cells and sectioned hard and soft tissues, and imaging of single bacterial cells at a level of detail that is currently possible for mammalian cells. This new capability will have a significant impact on understanding of fundamental biological processes that involve cellular architectural reorganisations and ion homeodynamics at that length scale. The same can be said for the understanding of disease processes and their treatment, for example, in oxidative stress conditions and neurodegenerative pathology where metal-ion dysregulation is heavily implicated, or in infectious diseases where bacterial virulence may be linked to nanometre-scale structural changes or host/pathogen competition for nutrients. Research outcomes in this area are clearly aligned with the National Research Priority “Promoting and Maintaining Good Health” and there is a large base of research expertise in Australia, both in the broader area as well as in the application of X-ray imaging and spectroscopy to the area.

Biological research will likely comprise the major component of research effort at the facility, based on current demand for microprobe experiments at the AS and other facilities along with interest expressed by the community for enhanced capabilities to be provided by the HCN. Biological samples pose perhaps the greatest technical challenges for the beamline in terms of sensitivity requirements and retention of sample integrity, both during sample preparation and data collection.

Techniques:	mapping, XANES, CDI
Resolution:	50 – 500 nm
Sensitivity:	Extremely high
Energy range:	2 – 20 keV

Environmental and Agricultural Sciences – A key area of expertise in the Australian community in environmental sciences is that of the soil-plant interface, especially with respect to transport and fate of nutrients, supplements, contaminants and infectious agents. Nanoscale information on, for example, micronutrients such as zinc, environmental contaminants such as arsenic or metal nanoparticles, or microbial pathogens leading to improved control over such processes has the potential to improve crop yields, limit water usage and improve public health. These processes, and the associated chemistry, have been demonstrated to be sensitive to sample preparation, so imaging and spectroscopy of intact specimens is crucial. Sensitivity requirements for imaging and spectroscopy in this area are generally less stringent than those for biological specimens due to higher concentrations of elements of interest, however some cases will certainly benefit from improved sensitivity. In general, plant microstructures will be more robust and defined than for

mammalian, or to a lesser extent, bacterial specimens, meaning that they are more amenable to 3D imaging.
Research in this area is clearly aligned with the National Research Priorities "An Environmentally Sustainable Australia" and "Promoting and Maintaining Good Health".

Techniques:	mapping, XANES
Resolution:	50 – 500 nm
Sensitivity:	High
Energy range:	2 – 20 keV

Geological Sciences – Compositional and chemical detail in geological samples can vary across several orders of magnitude and Australian researchers have pioneered rapid X-ray fluorescence imaging of that detail in the sub-micron to cm length scale, particularly along with the development of the Maia detector system. Extending the length scale capability for XRF imaging into the 50-200 nm range, coupled with the potential for XANES-stack chemically-specific imaging, will generate knowledge in the fundamental geochemistry of ore deposition, provide new information on the evolution of life through examination of microfossils, and drive improvements in mineral processing through better understanding of surface and grain boundary structure in mineral deposits. The potential for new information from diffractive imaging of geological samples is perhaps underestimated at present and this may be a fertile area for development.

Given Australia's reliance on primary industry, and particularly mining exports, research in this area is clearly aligned with the "Frontier Technologies for Building and Transforming Australian Industries" National Research Priority.

Techniques:	mapping, XANES
Resolution:	50 – 500 nm
Sensitivity:	Modest
Energy range:	2 – 20 keV

Nanotechnology and Materials Sciences – Demand for XFM beamtime from the materials science community has been limited to this point in time, mainly due to insufficient resolution of the XFM KB mirror system and scan rate limitations of the ZP nanoprobe. The extremely high resolution of the HCN, combined with fast, efficient Maia detector will overcome these limitations and will enable detailed materials-based investigations. Developments in semiconductor polymer blends, OLEDs and solar cells are generating devices that have intrinsically nanoscale dimensions. In tandem with fluorescence mapping and spectroscopy, 3D diffractive imaging at the ~10 nm length scale will function beyond the resolution capability of 2D electron or atom probe techniques providing insight into the nanoscale structures of integrated circuits, semiconductor devices, and nanoparticle-based catalysts. The HCN facility will compliment micron scale XFM/XRD studies anticipated with MMC and XFM beamlines.

The proximity of the Melbourne Centre for Nanofabrication should drive demand in this area and significant industry interaction could be expected once feasibility of imaging modalities is demonstrated. Research in this area is aligned with the "Frontier Technologies for Building and Transforming Australian Industries" National Research Priority.

Techniques:	mapping, XANES, CDI
Resolution:	50 – 500 nm
Sensitivity:	Modest
Energy range:	2 – 20 keV

Coherent Diffractive Imaging Method Development – In addition to applications of CDI described above, there is significant scope for development of diffractive imaging methodologies. Small beam sizes and high coherence provide the ideal conditions for method development and testing. The ability to move towards higher intensity by decreasing the spatial and / or temporal coherence of the illumination then allows methods to develop to more generalised illumination conditions greatly increasing the applicability of the technique. Significant science capability would be achieved by realising simultaneous, fully complementary fluorescence and diffractive imaging at biologically-relevant energies (10 keV) on a routine basis. A series of high profile studies in the area of CDI have been carried out at beamline 2-ID-B (1-4 keV) at the APS using Fresnel zone plate optics (FZP). Initial development will occur where coherent flux is optimised-at the lowest possible energy, 2 keV (see table 2 for calculation of coherence length and coherent flux as a function of energy) and using zone plate optics to create a diverging wavefront at the sample.

Techniques:	CDI
Resolution:	5 – 10 nm
Coherence length:	>200 µm at 10 keV (Zone plate optic must be coherently illuminated)
Coherent flux:	as much as possible – most CDI experiments are flux limited
Energy range:	2 – 10 keV

Evidence for Demand

The primary indicator of likely demand for the HCN facility is the oversubscription rate for the XFM beamline in both nanoprobe and especially microprobe. Much of the science that is conducted at XFM can be expanded by studying smaller areas of interest- previously identified at the micron length scale at XFM - at higher resolution. The fact that the number of proposals seeking time on the microprobe (KB/Maia) system is greater than those seeking time on the XFM nanoprobe should not be taken to mean that demand for smaller length scales is weak. Instead, it indicates that the HCN must implement the advantages of the XFM microprobe, viz. adequate flux for the scientific problems at hand coupled with rapid detection which allows imaging of larger areas at high resolution. It is expected that the demand for time for experiments in different disciplines will be similar to that for XFM, with cryo-capability likely to attract a greater proportion of biological applications and high-resolution imaging opening up demand from the nanoparticle and materials science communities.

A number of ISAP proposals in the past two years have requested capabilities beyond those of XFM; these are predominantly either diffractive imaging experiments (7 in 2009-2011) or XRF experiments requiring submicron resolution at incident energies above 10 keV (5 in 2009-2011). The CDI experiments (4 in the first half of 2011 alone) have been performed at APS 2-ID-B at low energies using the endstation that will be relocated to the AS SXR beamline. Similar demand for CDI is expected for HCN where the spatial coherence at higher energies should be very good; this has not been evident so far as this capability is not currently available at higher energies. Limited ISAP demand has been demonstrated for cryo-capability so far (1 in last cycle), but again this is because this is developmental at this stage and not generally accessible.

Technique	Visits in 2009 – 2011
CDI	7
XFM – higher resolution & / or energy	5
XFM – cryo	1
XFM – low E XANES	1
XFM – fluorescence tomography	2

Experimental Capabilities Required to Deliver Science Outcomes

A major component of HCN will be rapid XRF mapping of cryogenics samples in 2D from ~1 to 100 μm on a side, with an incident beam around 10 keV in energy and a beamspot ranging from ~50 nm in some experiments up to 500 nm in others. In mature phase this will be coupled with CDI in either full field or scanning modes. It should be feasible to map samples of this type using both scanning XFM and Scanning Diffraction X-ray Microscopy (SDXM) simultaneously. Switching from XRF to full-field CDI should be possible simply by moving the sample downstream of the focal plane, and with no other reconfiguration of the beamline. Routine swapping between the geometry for CDI and for STXM has been successfully demonstrated at 2-ID-B. In addition to the SDXM capability, differential phase contrast images simultaneously with XRF data should also be possible.

Energy range - For these rapid-imaging experiments, the beamline should be optimised to provide high-flux focussed beam in the energy range from 2 to 15-20 keV and, crucially, to collect the maximum amount of fluorescence using the most advanced detector technology available at the time.

The upper bound to the incident energy range using the high-flux 2D imaging mode can be set by considering science requirements. For biological samples, K fluorescence detection should be considered routine between phosphorus and selenium as this range encompasses the biological endogenous elements barring Mo and I. Exogenous elements (as well as I) of pharmaceutical or toxicological interest that are not included in this range can be mapped by detecting K fluorescence up to Ru and perhaps up to Cd with lower sensitivity/resolution. Elements heavier than Cd can be mapped using L fluorescence as these peaks do not interfere with K fluorescence from the abundant biological elements up to Ca. For non-biological samples, matrices are usually somewhat less complicated so spectral interference on L lines from heavy elements is less of an issue. In geological samples, K fluorescence from abundant Fe will overlap with some lanthanides of potential industrial interest; however, consideration of extending the energy range to cover the K edge for these elements is unreasonable. Considerable minerals insight is obtained from Zr, Y, and Sr, suggesting a minimum of 20 keV as an upper limit.

Flux requirements - A useful guideline for flux through the focal spot across this energy range is the flux provided by the 2-ID-E and D beamlines at the APS. These have consistently provided high impact publications over the last ten years with the sensitivity that that flux provides. As such, the HCN should provide flux that is intermediate between the total fluxes provided by 2-ID-E and the higher flux 2-ID-D.

The comparatively weaker source characteristics of the AS ring compared to the APS mean that the HCN must take several steps to achieve internationally competitive sensitivity for 2D mapping experiments. The three most significant of these are the use of KB mirrors for the microfocussing optics, a double multilayer monochromator and the continued development of world-leading fluorescence detector technology. Together the DMM/KB combination will increase flux in the focal spot by between 2-3 orders of magnitude compared to a DCM/zone plate implementation as used on the APS beamlines (see Table 1).

The lower brilliance of the AS also has major implications for CDI. The limited availability of coherent flux is often regarded as a significant barrier to achieving higher resolution in diffractive imaging, hence it is essential that the HCN beamline covers the 2-4 keV range, for which flux at the AS is optimised. The Australian team pioneering CDI have made significant progress in relaxing the coherence requirements for CDI and thus providing greater useable flux onto the sample. For example very recently CDI has been demonstrated from a wide-bandwidth incident beam provided by a DMM. However these methods are still at the proof-of-principle stage and require further development for routine implementation.

There is no theoretical barrier to CDI being implemented with KB mirrors; however this is yet to be demonstrated experimentally and remains a developmental goal for the HCN. In the first instance therefore we will implement CDI using the well-established method relying on FZP to produce a divergent wavefield at the sample.

Cryoprotection - Focussing the flux of 2-ID-E or D through a spot that is as much as 10 times smaller than theirs means an increase in flux density of 1-2 orders of magnitude with a concomitant increase in radiation dose and associated damage to the sample. The APS lines are already operating at or near doses that result in structural damage to biological samples maintained at room temperature (to say nothing of chemical damage!). As a result it is vital that the HCN has a cryogenic environment for samples undergoing measurement to minimise photodamage.

A cryogenic sample environment means that suitable ancillary equipment must be available to appropriately vitrify hydrated samples and that appropriate cryotransfer facilities are also available. Automated vacuum transfer of multiple specimens into the nanoprobe is required for proper thermal equilibration. In-vacuum robotics are required for specimen mounting and demounting without disruption to the chamber. Rapid freezing is important to limit ice-crystal formation which will disrupt structure on the length scale that is to be interrogated at the beamline. A number of pieces of equipment are likely to be required, such as plunge-freezer, vitrobot, freeze substitution, sample transfer interlock system, cryogenic optical microscope etc, however choices of equipment for these purposes, beyond indicative costings, can and should be delayed until nearer to beamline commissioning and learning lessons from implementations at other facilities (e.g. APS bionanoprobe).

Stability - The beamline must reference the sample position to that of the final focussing optics to a stability of <5 nm/hr. This is necessary for CDI techniques, where measurements requiring of order 1-hr will reach to 5-nm resolution. The LaTrobe Fresnel Imaging ENDstation (FRIEND) has taught us that instability is by far the most significant limitation to progress in CDI. A high-coherence facility with high stability would certainly be very attractive for this extremely productive community.

Experience and engineering effort from other facilities allows us to estimate other stability parameters. The endstation needs to be referenced to a SSA with a motion of less than about 1 micron per day. Thermal stability within the endstation should be around 0.1°C; outside the station this should be of order 1°C. As explained, these figures are indicative only, being wholly derived from other facilities' PDRs. A more detailed study is clearly required.

Detectors - Development of the next generation Maia detector system, "BioMaia", should parallel the beamline design and build. A switch to Si-drift technology will allow detection of the biologically important low Z elements down to phosphorus and improved energy resolution will deliver better detection limits for those elements especially. Because sample sizes on HCN will be much smaller than on the XFM microprobe, the advantage of the backscatter geometry annular Maia is not so clear. As such, the beamline should be able to accommodate a Maia detector in both backscatter geometry and at 90˚ (perhaps two detectors – one at 90˚ and one at 270˚). The Maia may not be ready at the beginning of user operations and an appropriate interim solution would be either a single- or four-element Si-drift Vortex detector with fast readout backend electronics.

CDI requires large imaging detectors with small pixels and extremely high dynamic range. In addition, minimising readout time is also a high priority as this directly influences the stability requirements for the sample and maximises the use of beamtime. Presently no one detector satisfies all requirements, but it is anticipated that a leader will emerge over the next 5 years. Present options include Medipix and Pilatus for high dynamic range, high quantum efficiency, and good energy discrimination; however, CCDs offer over an order of magnitude improved linear resolution. Hybrid Pixel Array Detectors (PADs) bridge this parameter space, and will be an attractive option for CDI.

Advanced Experimental Modes - Beyond straightforward 2D elemental mapping, experiments will require XANES capability, either for spectroscopy on single spots identified by elemental mapping, or in chemically-specific XANES stack imaging at multiple incident energies. Clearly these must utilise a DCM and cope with the associated loss of flux from the DMM, but will benefit from the achromatic nature of KB focussing. Consideration should be given to implementing a fast slewing mode on the DCM to allow QEXAFS as this may limit dose and hence radiation damage to the sample.

A cryogenic environment is vital to maintain chemical integrity in samples subjected to the dose from the HCN. A DCM that can provide suitable flux over an energy range from 2 keV to something over 20 keV would enable such studies on a wide variety of systems and should be strongly considered in the final design.

While not all experiments will include spectroscopic or spectromicroscopic measurements, the increase in scientific impact provided by that spatially-resolved chemical information should not be underestimated and the capability must be implemented at the HCN. The ability to provide fully position-referenced XANES at below 100 nm, using the system as-demonstrated on the XFM nanoprobe, would be a world-leading capability with very strong likelihood of delivering significant scientific outcomes in several disciplines.

A capacity to perform tomographic measurements should be incorporated in the form of high stability rotational stages that are compatible with the cryogenic sample environment. X-ray fluorescence tomography is a local strength at the AS, and promises 3D resolution at extremely high sensitivity.

At present diffractive imaging requires zone-plate focussing optics, as opposed to KB mirrors, and coupled with the DCM. Although this will result in significantly lower flux, there may also be a number of XRF experiments for which sensitivity requirements are less stringent but may justify needing a smaller spotsize that generates higher resolution. The microfocussing optics arrangement at HCN should be compatible with the implementation of a number of zone plate options to provide focussed beam in the energy range 2-12 keV. XANES capability with the ZP option can then be implemented with runout tracking as demonstrated at XFM nanoprobe but with higher sensitivity and resolution.

While the beamline should be designed to be compatible with both focussing optics (e.g. using an SSA), the final choice of any optics (i.e. actual KB or Montel mirrors) should be delayed for as long as possible to allow access to the latest technology.

The likely optical design of the beamline will discard a significant proportion of the beam at a secondary source aperture. Some consideration should be given to the possibility of a parasitic pick-off beamline that utilises some of this discarded beam. One suggestion is to move the current nanoprobe instrument from XFM to generate a room temperature facility that could cover the 0.2-1 µm length scale for XRF/DPC imaging, with additional capability for spectroscopic and tomographic measurements. XFM could then be upgraded and dedicated to KB/Maia experiments at > 400 nm resolution.

Complementarities with Existing and Future Capability at AS

HCN will be the flagship high-resolution hard X-ray imaging beamline at the AS. It will cover length scales from those currently possible at XFM to the smallest sensibly possible at the AS with a sensitivity that can answer significant scientific questions. Other beamlines such as XAS, MEX and MMC may provide additional XRF imaging capabilites at the >10 micron length scale.

Spectroscopic capability should certainly be available at HCN from ~4 to over 20 keV, with some trade-off for sensitivity or resolution above 13 keV. This will complement the soft X-ray imaging and spectroscopy capability of the CDI/STXM endstation. It is desirable to cover the capability gap in the tender energy range (2-4 keV), and so serious consideration should be given to the cost / benefit analysis on this capability. The current state-of-the art for CDI necessitates that the energy range of the beamline include X-ray energies down to 2 keV, and there are a number of cases where spectroscopic capability in this range would generate scientific impact, particularly around phosphorus and sulfur in biological, environmental, and mineral systems.

Executive Summary – Beamline Design

Nanoprobe beamlines have recently converged to a single optical design principle. The trend was set with the design of the APS HXN in around 2005, and has continued through the AS XFM beamline, Soleil's Nanoscopium, NSLS-II's HXN, and others. The design incorporates a predominantly horizontal optical layout to improve stability with focussing to a secondary source located downstream of the monochromator. We can therefore say with a high degree of certainty that this design principle will also be used for the HCN, with design particulars chosen to optimise performance in response to the source brilliance and the science goals.

The following represents our present best guess at the optical layout of the beamline. This design is based on a very similar nanoprobe at a similar, medium-energy 3rd-generation synchrotron source: the Nanoscopium beamline at Synchrotron Soleil, France. However, we cannot directly copy the design of Nanoscopium because Soleil's brilliance is some 20 times that or the Australian Synchrotron. An MoU between the AS and Soleil is being prepared by HoS Andrew Peele. We have been in close contact with Andrea Somogyi (Principal Scientist of Nanoscopium), and she has indicated that she is prepared to make the design available to us once the MoU has been ratified.

In order to mitigate the low brilliance of the AS source, we will need to find ways to conserve flux. Strategies include (1) use of a DMM instead of a DCM for monochromation; with ~20-fold increased bandpass; (2) use of a mirror-based focussing system instead of a zone-plate based focussing system, with >10-fold increased efficiency and acceptance, and; (3) optimisation of detection efficiency by customised detector design, especially the Maia.

HCN beamline design report

The High-Coherence Nanoprobe facility will present a number of design challenges for the Australian Synchrotron. Similar facilities around the world are most often flux limited; even at the (present) flagship beamline at the APS – the CNM – dwell times of order 3-8 seconds per 30-nm pixel are common. Long dwell times place significant limitations on the area of an image that can be investigated, which in turn limits the utility of the instrument. With this limitation in mind, we therefore recommend that careful attention be given to all aspects of the design to achieve whatever gains are possible; getting this right is directly connected to the long-term performance of the instrument and its ability to serve Australian Science.

International review of the design

The machine brilliance is the single most important parameter determining the performance of a microprobe instrument. Clever beamline design can do nothing to improve the *geometric* fundamentals of the beam as produced in the source. The maximum, diffraction-limited monochromatic focussed flux is directly proportional to the brilliance of the source. Table 1 indicates that that the geometrical properties of our source will limit us to approximately 1/300th of the flux of major international competitors such as the HXN of the NSLS-II, and 1/20th of that of the APS and Soleil beamlines. However, strategic reduction in other beam properties (perhaps by increasing the bandpass of the monochromator; factor of 20 gain), use of optical components with higher efficiency (mirrors vs ZPs; factor of 10 gain), adoption of next-generation insertion device technology (super-conducting undulators can provide a factor of 4 gain in brilliance, with desirable tuning curves)), or the use of higher efficiency detectors (Maia; factor of 10 gain) can address the reduced machine performance to provide a flexible and versatile instrument. These components are therefore factored into this preliminary design, and result in a very attractive specification.

Beamline	Ring energy [GeV]	ID	Target energy [keV]	Target resol.	Target flux	Brilliance at 10 keV [ph/s/mm^2/mrad^2]	relative brilliance	Monochromator throughput [dE/E * efficiency]	Nanoprobe focussing efficiency	detector solid angle [str]	max relative sensitivity	Special features
NSLSII - HXN	3	IVU20				6.E+20	300	1.0E-04	0.10	0.25	1.5E+15	
NSLSII - SXM	3	IVU21	2-15	100nm		6.E+20	300	1.0E-04	0.90	0.25	1.4E+16	
Soleil – Nanoscopium	2.75	U20	5-20	30nm – 1um	1.4e10 @ 5keV, dE/E=1e-4, into 110nm focus	4.E+19	20	1.0E-02	0.90	1.00	3.6E+17	
APS – CNM – HXN	7					5.E+19	25	1.0E-04	0.1	0.25	1.3E+14	
APS - BNP	7		5-20	30nm map;			0	1.0E-04	0.1	0.25	0.0E+00	In vac, Cryo, tomo, DPC
APS – 2IDD	7	Und A 3.3	5-32	100nm		4.E+19	20	1.0E-04	0.1	0.25	1.0E+14	
APS – 2IDE	7	Und A 5.5	7-10.5	250nm	1e9 @ 10keV	4.E+19	20	1.0E-04	0.1	0.25	1.0E+14	parasitic
Petra - P06							0				0.0E+00	
AS HCN	3	3mIVU	2-20	50nm – 1um		2.E+18	1	1.0E-02	0.9	2.00	3.6E+16	

Table 1: Source properties for global Nanoprobe facilities. As a guide, the sensitivity (ng/cm^2) is proportional to the product of the brilliance, the monochromator throughput, the focussing efficiency, and the detector solid angle. The numbers here are indicative, and a more detailed study is demanded; however, it is clear that the appropriate selection of monochromation, focussing system, and detector implementation can completely overcome the modest performance of the AS machine.

While several of these storage rings share major characteristics with the AS, Soleil's Nanoscopium has the closest correspondences to our source properties and design goals. Here we roughly base our design on that of Soleil's Nanoscopium, but take inspiration also from the NSLS-II HXN [1], NSLS-II SRX [2], Diamond's I-18 [3], the APS HXN [4], and the NSLS-II XFM [5].

Facility review of the design

What is required from the beamline is a facility that (1) builds on and complements current strengths, and; (2) does not try to do everything. Current local capabilities relevant to this proposal are:

XFM fast mapping with Maia
~2 μm resolution, possibly upgradeable to ~0.5 μm – see below for detailed discussion

XAS EXAFS and XANES spectroscopy, 5-50 keV

MEXAS EXAFS and XANES spectroscopy, 2-15 keV

MMC 1-5 μm; 5-60 keV; SXFM; XANES; EXAFS, and; DAXM / microdiffraction. With the planned CDI implementation, the HCN will be compatible with a simple extremely high-resolution microdiffraction setup to provide a resolution well beyond the MMC capability.

While the HCN must situate itself strategically with respect to all AS beamlines, there is no doubt that the greatest overlap is with the XFM beamline. Here we consider the immediate future (10-yr timescale) of the XFM beamline, with reference to likely upgrades and future capability.

Immediate future of the XFM beamline

The XFM beamline is extremely successful, in great part due to good design, the established community, and the ability to capitalise on the capabilities of the Maia detector (enabling XANES imaging, large-area scanning, and tomography). The beamline covers and energy range of ~4.2-25 keV, and design has been optimised for the use of a KB mirror system with ~2 μm FWHM resolution. The Nanoprobe device is used only occasionally, only because the astigmatic source does not couple efficiently with this instrument. XRF mapping, XANES, and tomography are routine at the beamline. The Maia detector is used for ~80% of experiments.

Three upgrades are anticipated at the XFM beamline: (1) installation of a DMM to improve focussed flux; (2) optimised large-area fast scanning stages with tomography capability, and (3) reconciliation of the focussing optic, leading to an upgrade of the KB mirrors to a system that reaches down to perhaps around 400 nm resolution. At present we believe that the design of this beamline will not permit significantly higher resolution than this due to the location of the SSA and the length of the experimental hutch.

While an upgrade of XFM to 400 nm resolution would be a significant extension of the capabilities of the beamline, there is a lot of science that would benefit from 50-400 nm resolution and which could be performed locally. The HCN beamline will address this science and – with the high coherence of the design – will capitalise on a capability within the Australian X-ray community of Coherent Diffractive Imaging.

Science Objectives and the design

The case for the beamline clearly describes a number of science targets. Each target corresponds to one or more key performance capabilities. These are described below.

Beamline design

1. focussed spot size / spatial resolution
2. beam intensity (also referred to as 'sensitivity', and related to 'minimum dwell time')
3. energy range for spectroscopy
4. bandwidth for mapping and spectroscopy ($\Delta E/E$ for Si 111 ~ 10^{-4}; $\Delta E/E$ for IVU + DMM ~ 10^{-2})
5. beam coherence for CDI

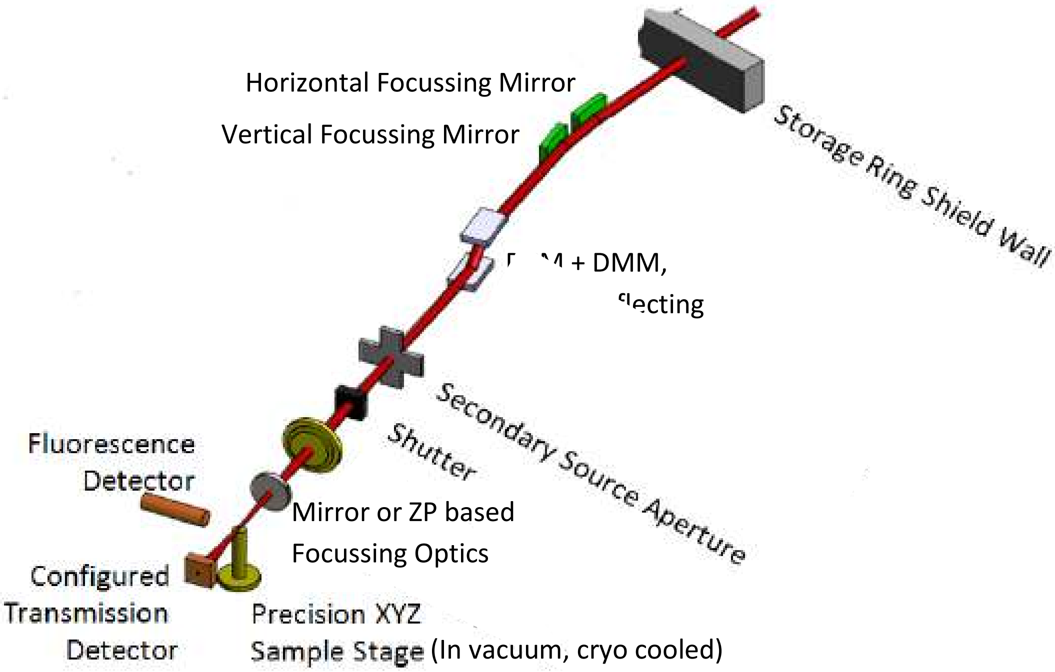
6. [SHOULD CONSIDER COST / BENEFIT OF] beam polarisation and polarisation time structure, kHz domain (crystal polariser inserted into the beam)
7. [SHOULD CONSIDER COST / BENEFIT OF] temporal structure, kHz domain (beam chopper)

Instrumentation design

8. cryogenic specimen environment
9. temperature controlled environment (eg., -100 to + 300 deg C)
10. tomography (specimen rotation)
11. CDI – cameral length. Camera lengths presently in use at APS-2-ID-B are around 70 focal lengths (the relevant parameter for CDI). For the same sampling, this corresponds to around 5 m at 10 keV (assuming a camera with the same pixel size) or 30 m with a current-generation Pilatus. Future x-ray area detectors will certainly reduce this requirement. These figures are preliminary and should be refined further.
12. CDI – compatibility of focussing optics with CDI and flavours

With tailored design, the HCN could just about compete in any one of these areas, but definitely not in all areas simultaneously. The HCN will not be world-leading in terms of spatial resolution, due to limitations of the source. However, the HCN could adopt a unique blend of capabilities and thus become world leading in one or more areas of importance to the Australian XFM / CDI user communities.

Overview of the Beamline Design



Storage ring

The horizontal emittance η_x of the electron beam is a limiting factor to the focussed flux density. A 10% reduction in the emittance results in a direct 10% increase to the focussed flux, and so improves the value of the facility by 10%. Further, the large η_x necessitates the use of beamline optics with large acceptances, which ultimately result in increased cost and reduced quality.

Insertion device

For imaging at the highest sensitivity we will require an insertion device with the highest available brilliance. The likely first choice for this is a 3-m-long in-vacuum undulator with suitably chosen period, subject to design requirements and constraints. In particular, the length may need to be reduced so as to decrease the minimum gap, giving a lower fundamental energy. Alternately, the design team should review improvements to insertion device technology, in particular with regard to Cryo-cooled insertion devices. Smaller period devices can be used to reduce the energy gap between the fundamental and the third order. An alternate would be to have two IVUs of different periodicity so as to cover the gaps in the IVU spectrum.

IVU should be capable of sub-μm motions at each end with taper and gap under beamline control. Modes: step scanning with frequencies up to 10 Hz, and continuous scanning should be possible for fly-scanning spectroscopy. Within its internal safety limitations the device should be capable of being master or slave to another device. Backlash corrections should be beamline configurable. Signals from two encoders (gap at each end) should be available to the beamline.

Depending on the energy - gap - length interrelationship, it may be worth considering the use of two IVU devices in the one straight (Such a configuration has been adopted at APS sector 26-ID). This would allow full power at minimum gap using one device, and the use of both devices at other gap settings. The minimum gap device may need to be located around the minimum of the beta-function so as to reach smaller gap, and this may require it to be situated at the centre of the straight. However, it may be appropriate to investigate asymmetric beta functions if there is no loss of performance.

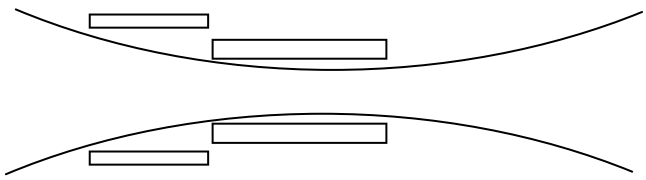


Figure: Symmetric beta-function waist in a straight section with two IVUs at minimum gap. The IVU at the centre of the straight has a smaller minimum gap than the other, located at one end of the straight.

The HCN has a demonstrable and pressing need for a superconducting undulator, with brilliance gains of order 4 times, and the possibility of gapless transition from 1st to 3rd harmonics. However, this technology is young, and so it is proposed that the beamline design consider compatibility with likely future devices, and consider this to be a future upgrade for the beamline.

We are aware that machine physics has some plans to develop a superconducting undulator. If that project goes ahead then there would be significant institutional advantage if that device were designed towards the requirements of the HCN.

Front-end

X-ray beam position monitors should be installed, as these provide proper independent diagnostic for the x-ray beam quality. Fixed mask and white-beam slits (WBS) are required. In general it is useful to get the WBS as close to the source as possible. A study should be undertaken to determine whether it is worthwhile putting these inside the ratchet wall.

Conditioning optics

Two fixed-curvature horizontally-deflecting mirrors should be considered, to focus the beam at the SSA. The location of these should be dictated by a ray-tracing study of the beamline optics. The horizontally-focussing mirror (HFM) – which is likely to be first – will need to be cooled to withstand the high power load from the IVU. This mirror will also act as the harmonic rejection mirror, which will influence the angle of the mirror to the beam. The mirror will need multiple stripes for harmonic rejection. The VFM may be located some distance downstream of the HFM, as required to optimise the transfer of flux to the secondary source aperture.

It is reasonable to consider whether the HFM should be of fixed or adjustable curvature, as the optical tolerances on this mirror are not as tight as for the VFM. Such a solution will be adopted at the HXN of the NSLS-II project. Note that Soleil has selected fixed curvature mirrors.

Monochromation

A double-crystal monochromator (DCM) design should be considered for spectroscopy experiments. However, this device should be interchangeable with a double-multilayer mirror (DMM) whose bandpass can be matched to that of the IVU for higher flux. These devices should both work with the same beam offset for simplicity of use. It is acceptable for these to be located at different z positions.

If it remains within scope to deliver photons with energy down to 2 keV then it may be necessary to use a vertically-deflecting DCM; if the minimum energy is around 4 keV then a horizontally-deflecting geometry DCM may be preferred. For reference, the NSLS-II SRX beamline upgrade [2] aims to run from 2-15 keV with crystal optics.

Energy [keV]	Si <111> angle [deg]	Comment	peak reflectivity - V defl	peak reflectivity - H defl
2	81.4		20.8%	18.1%
2.145	67.2	P-XANES	25.0%	25.0%
2.472	53.1	S-XANES	36.0%	1.4%
2.796	45.0	Polarisation zero for H deflection	44.9%	0.0%
3	41.2		47.6%	0.4%
4	29.6		64.0%	32.5%
5	23.3		74.0%	59.3%
6	19.2		81.0%	72.3%
8	14.3		88.4%	84.6%
10	11.4			
15	7.6			
20	5.7			
25	4.5			

Table: SI <111> DCM geometry and peak reflectivities for the energy range from 2 – 20 keV. Peak reflectivities estimated using XOP 2.3 XINPRO indicate that horizontally deflecting monochromator will not cover the entire energy range in a continuous manner due to the polarisation zero at 45 degrees Bragg angle.

Secondary source

The secondary-source aperture (SSA) defines the beam for the purposes of the imaging optics, and allows the scientist a simple trade-off between focussed intensity and focussed spot size. The function of these is well documented in the literature, and they: define and filter the source; hide beam instabilities and intensity variations. As the SSA is imaged into the focus by the imaging optics we require stability of these slits of around s/10, where s is the minimum size of the slits for diffraction-limited imaging of the imaging optics. An estimate of a likely value for the minimum size of the SSA is 10 μm * 10 μm, as a specimen imaged with this setting will receive a small x-ray flux.

The HCN will benefit significantly from a windowless design. The natural vacuum stricture that is formed by the SSA makes it a natural location for differential pumping and fast vacuum valves.

> The Soleil facility is much larger than the AS, and so their SSA can be accommodated onto the experimental floor. It is likely that this is not possible at the AS, and so an intermediate station must be considered. The SSA needs to be spatially referenced to the endstation to better than ~1 μm / hr in transverse directions.
>
> A significant amount of flux is discarded at the plane of the SSA. It is definitely worth considering the possibility of a future branch-line that could pick off some fraction of the focussed intensity for another microprobe facility. This could be achieved using a crystal to diffract intensity from the beam (though this would not be compatible with XANES spectroscopy at either station, and so the branch would need to stop running while the main line was doing spectroscopy) or by some other mechanism.

End-station(s)

The stability requirement for the end station is very high. It must be stable wrt the SSA to around 1 μm, and will accommodate equipment with extremely high local stability requirements. Temperature control will likely be required to be better than around 0.1 deg C in the endstation, with ~1 deg C required for the building. It is beyond the scope of this document to go into these studies, but several examples exist, particularly the PDRs for the NSLS2 HXN and the Soleil Nanoscopium.

There would be significant flux advantages to be obtained from the use of mirror-based optics (JTEC?). It may be that two systems should be considered; probably only one needs to be equipped with cryo-capabilities. It would be most excellent if both could be operated independently, but it is difficult to see how this could be achieved.

The capabilities of the Maia detector system offer significant new opportunities for x-ray fluorescence microscopy. This should be considered in the selection and design of end-station instrumentation.

Coherent diffractive imaging can be performed using a scan through the focus (Thibault, Science) or by placing a specimen some distance downstream of the focus to introduce wave-front curvature (Williams, Nature). Both of these techniques will benefit from a long camera length, of order 8 m.

Endstation requirements

Computing

- High speed computing for on-line data analysis
- Multiple terminals (4?) for data analysis; potentially access to a small cluster
- Remote access through scheduled (bookable) sessions

Specimen preparation

- High pressure / rapid plunge freezer
- Plunge freezer
- Cryo microtome
- Cryo-optical microscope
- Freeze-drying apparatus
- Freeze substitution apparatus
- Tissue culture facilities
- Cell culture facilities
- Small wet area for animal sacrifice and crude operation; long working distance zoomable stereo microscope for operations.
- High resolution fluorescence microscope with digitally encoded stages; with mechanism for mounting specimens on their beamline mounts for pre-registration.
- LN2 facilities for cryo specimen storage

Nanoprobe capabilities

- Multiple specimen loading cryo transfer robot
- Cryo stage
- (likely) in-vacuum operation with automatic cryo sample transfer system
- ZP – ultimate resolution mapping – is fluoro tomo feasible on this system?
- KB - tomo capable, 50+ nm resolution

Summary of major differences with the Soleil facility & other considerations

1. The brilliance of our IVU is likely to be a factor of 20 lower than that at Soleil.
2. The available length in our straight section is longer (3.5 m). Soleil has a canted undulator straight.
3. We probably cannot fit the SSA onto the experimental floor.
4. Our total length is slightly shorter than theirs (130 m vs 150 m)
5. CDI, SXDM, and FCDI require a camera to be installed downstream of the focussing system. This may require us to build a long end station. Camera handling and flight tubes will be required, with a preference for mainly in-vacuum, windowless design.

6. Windowless design is preferred wherever possible. Differential pumping to be employed at a number of locations along the beamline. Fast shutters and valves required to protect sensitive components such as mirrors and DCM.
7. End-station focussing optics require development. Fortunately the BNP and Soleil should be on-line by then and so we will be able to capitalise on their design efforts.

Endstation Instrumentation

The high intensity density at the specimen suggests that in-vacuum cryogenic sample stages will be required to preserve specimen structure. Such a system has been developed for the BioNanoProbe (BNP) beamline at LS-CAT of the APS, and this could form the basis for the design of a similar system for the AS. We have had a tour of the BNP endstation device (supplied by Xradia; details can be provided). That system cost around $3.3M USD. It is estimated that a similar system would have a similar cost for the HCN

The engine of the SXFM is the focussing optics, the specimen manipulation and environment, and the detectors. Below are some initial estimated costings for various devices.

Zone-plate cryonanoprobe [Xradia; APS BioNanoProbe]

Design specifications [extract of email from Xradia]:

- Energy range 5-30 keV (upper end limited by zone plates)
- Various zone plates covering resolution from 30 to a few hundred nm
- Six axis laser interferometer (currently only four integrated in feedback loop)
- Piezo scanning on top of coarse axis, 5 nm positioning accuracy (basically same stage stack as your system)
- 4-element Vortex detector with amplifier / DXP
- Quadrant photodiode (IRD) with current amplifiers
- Transmission scintillator camera for alignment
- On axis VLM (10x)
- Cartridge-based cryo system
    - Cryogenic sample holder on sample stage stack
    - Rotatable ~+/-90 degrees
    - 110 K target temperature
    - Sample cartridges can hold standard TEM grids or Si3N4 windows (could be modified for different sample holders)
    - Robotic sample exchange system
        - Offline workstation to load grids / windows on cartridges
        - Cartridges are mounted on “shuttle” (cartridge carrier for up to four cartridges)
        - Transfer chamber provided to move shuttle to microscope and into vacuum chamber
        - Robot can mount cartridges (up to four on the shuttle) onto sample stage one by one
- Complete automated vacuum system
- EPICS based control system
    - VME / VxWorks (same as APS)
    - Delta Tau motion controllers
    - Struck multi-channel scaler

- IP330 A2D
- Windows PC to host IOC for fluorescence detector
- Step and fly scanning using scan record (we put a lot of work into implementing fly scanning using Delta Tau and EPICS)
- Basic instrument control interface
- Visualization through MAPS (Stefan takes care of that)

The Xradia system is a wheel-in wheel-out device, and so could be interchanged with a KB system or other developmental systems.

The system as delivered would run around US$ 3.3M. The system has been delivered to APS 21-ID, is currently set up outside the hutch for further testing and will move into the hutch during the fall shutdown. First x-rays probably in November.

Kirkpatrick-Baez mirror [JTEC; Soleil Nanoscopium]

Estimated specifications and price [extract of email from JTEC]

OPTICS: 200 mm long, useful area of 190 mm x 10 mm or more, shape error (PV)= 1 nm guaranteed.

slope error [urad]	roughness [nm rms]	price [M JPY]	price [K AUD]
<0.1	0.2	22	270
0.2	0.2	18	220

MIRROR MANIPULATION SYSTEM: JM2000, Nano-focusing system with purge (extra for vacuum) - 22,000,000JPY-25,000,000JPY (~$270K - $310K AUD)

Note that the JTEC mirror manipulation system is extremely basic; it is not vacuum compatible, does not include any sample handling or manipulation infrastructure, and does not have active feedback on the mirrors, etc. Therefore it cannot be compared with the Xradia system in any manner.

Detectors

Required detectors include:

- I_0 or monitor detector. Although ion chambers are commonly used for this, the all vacuum design of the beamline will require a different solution. It is likely that a highly-polished, thin diamond detector could be used for this purpose.
- Transmission detector. A quad diode would be suitable.
- DPC / phase contrast configured detector with fast in-built pre-amplification.
- In-line microscope, with resolution down to 1-2 um, and field of view of between 200 and 2000 um.
- XRF detector, likely quad diode Vortex detector. Consider also a Bruker quad SDD with annular geometry and a Maia detector, geometry to be developed.
- Large, fast, high-resolution area detector (camera) for CDI.

The Maia detector system is a jewel in the crown of XFM. Full and proper integration of this system with the HCN could continue to revolutionise the art of x-ray fluorescence mapping and spectroscopy, and this opportunity must be pursued as actively as possible. Copied below are some observations from CSIRO Maia project leader Dr Chris Ryan, clearly indicating a willingness to optimise such a system in collaboration with the Australian Synchrotron.

> “The HCN Maia detector may go down the path of our nuclear microprobe version, which is in vacuum and has the facility for moving it in and out on a welded bellows. An indicative cost estimate is around $0.5M. Depending on timing, the HCN Maia may be a quite new beast based on SDD technology. The basic cost would be similar though, I would expect.
>
> “A bigger issue, according to Martin, is the limited detector access in the present Xradia model for the APS bionanoprobe. There is a big cooling shroud around the sample, which limits detector access to about 15 mm from the beam spot, and only at 90 degrees. We probably should not get too uptight about these restrictions at this stage, and assume that a large degree of collaboration between the AS, Xradia and CSIRO would be needed to refine this model for our range of applications. A new SDD based Maia designed to fit these constraints may be the best approach to optimize all aspects simultaneously (sample movement/tomo, cooling, detector solid-angle). We should budget for this custom design work, say $100k.
>
> “But we probably need to be mindful of the interplay between shroud dimensions and maximum sample movement/size. The shroud rules out unlimited sample movement. Indeed, it's probably not something we should contemplate on the HCN, assuming that micron resolution preliminary work may have already been done at XFM, or elsewhere using electrons, etc. and we now zoom in on small samples akin to the 2-ID-D/E stalks. In the final analysis, we may even go for less movement/range than the ~1"on the Bionanoprobe.

Outstanding Design Considerations

Energy Range / Insertion Device / Monochromation

There are clear science drivers to reach all energies within the proposed 2-20 keV range. However, *continuous access* across the 2-4 keV range poses some challenges for the beamline design, particularly with regards to insertion device parameter selection and DCM design. Access to 2 keV also suggests all-in-vacuum endstation apparatus; however, this is also indicated by the cryo capability and so does not impose an additional constraint.

As a result of these difficulties in design, there is no question that a detailed cost / benefit analysis needs to be performed on the 2-4 keV low-energy requirement. Solutions to the above design challenges include:

IVU design	- use of or future upgrade to a superconducting undulator with K~2.3 - cryo-cooled undulator - tolerate an energy gap in the low energy range (i.e., 1.5 < k < 2), but still have access to low energy beam for studies requiring ultimate coherence.
DCM design	- horizontal deflecting (with 100% polarisation loss at 45 degrees), with (discontinuous) access down to lowest energy for studies requiring ultimate coherence. - vertical deflecting monochromator, with careful attention to much more stringent stability requirements when this geometry is used.

Endstation focussing optics

Fresnel CDI has not yet been demonstrated with mirror-based optics; however, the high focussing efficiency of these optics is required for fluorescence sensitivity. Conversely, Fresnel CDI is very well established for ZP focussing optics.

One approach to this situation is to realise that some degree of endstation interchange ability would be useful, with both mirror and ZP optics available. The ZP instrument that is presently located at XFM could be relocated to the HCN endstation (a vacuum vessel may need to be built for this device, if true 5 nm stability is required). The state-of-the-art Xradia in-vacuum cryo scanning device that is presently being commissioned at the BNP beamline of the APS comes on a moveable kinematic frame that can be removed and reinstalled in a matter of hours, with repeatability of order 10 µm. It is proposed that the HCN should use two such devices, and consider rapid changeover between instruments as a way of mitigating the cost of equipment failure; as a way of diversifying the science that can be done with the beamline; and to enable developmental work with other endstations with relatively minimal disturbance to the local science programme.

Beam-splitting: Parasitic, pick-off, or branch-line

Realisation of an extremely small focus requires many photons to be discarded. A branch line can use these photons *without cost to the main beamline*. Several branch lines around the world have scientific output that matches or exceeds that of their parent line (eg 2-ID-E). The HCN should consider either building a branch line in the first deployment or at least remaining fully compatible with a branch line in the near future.

Timeline for design and construction

The projected timescale for delivery of beamlines for science case two is 3 years for the first round / 'easy' beamlines (often bend magnet sources) and 4 years for IVU beamlines. It is recommended that these timelines be compared with estimates from other facilities; perhaps by contacting the lead scientists of those beamlines. At a minimum, 12 months of effort for two scientists and a team of engineers should be considered reasonable effort for design optimisation.

Beamline length

The length of the HCN beamline is a significant contributor to its cost. In particular, positioning the midstation and endstation off the existing technical floor increases the cost of those stations. It is therefore wise to undertake a full analysis of the design to determine the degree of benefit derived from this choice. Unfortunately, this assessment cannot be performed at this stage of the design.

The FWHM coherence length L_C of the illumination at some distance L from an ideally incoherent source of size S is given by $L_C = 0.44\, L\, \lambda / S$. The coherent flux F_C is related to the on-axis source brilliance B by: $F_C = B\, (\lambda / 2)^2$.

Energy [keV]	Wavelength [nm]	Brilliance [ph/s/0.1%bw/ um^2/ur^2]	F_C [ph/s]	L_C at 20m from 50um source [mm]
2	6.2	1.5E+19	1.4E+20	1.1
4	3.1	6.0E+18	1.4E+19	0.5
10	1.24	2.5E+18	9.6E+17	0.2

Table 2: The expected coherence properties as a function of energy, with one order of magnitude greater coherent flux at 2 keV than at 4 keV. This gain is highly attractive for CDI experiments.

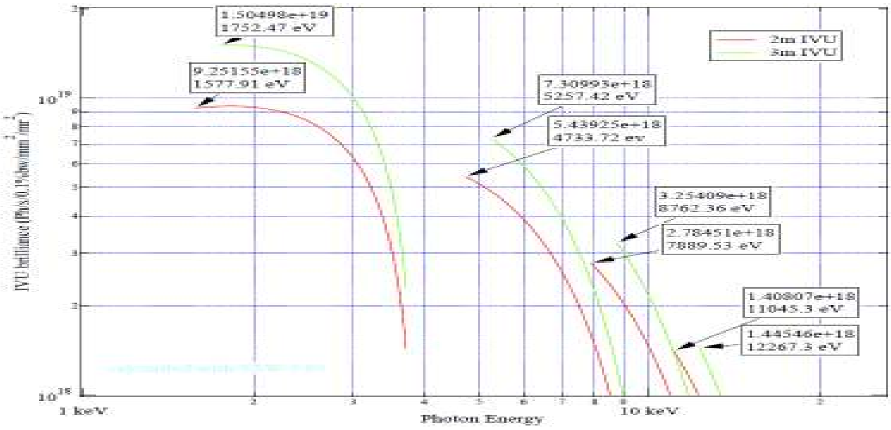


Figure 2: Brilliance of existing AS IVUs, calculated by David Wang, AS.

Reference Documentation

[1] NSLS-II Project: Preliminary design report for the Hard X-ray Nanoprobe (HXN) beamline (First draft, September 2010) - very thorough analysis of the design for the HXN beamline.

[2] NSLS-II Project: Preliminary design report for the Submicron Resolution X-ray Spectroscopy (SRX) beamline at NSLS-II (Issued, September 2010) – both beamlines described in this report are relevant to the HCN; in particular, the ZP branch line which has an energy range of 2-15 keV.

[3] Mosselmans et al, I18 – the microfocus spectroscopy beamline at the Diamond Light Source, J Synch Radiat, **16** 818 (2009). – 2-20 keV microprobe with Si (111) in vertical deflection, 3 µm resolution. Note that “vertical resolution is limited by DCM motion”… micro-EXAFS is possible.

[4] Preliminary design report for the Nanoprobe beamline at the Advanced Photon Source, February 13, 2004. – good source of design considerations.

[5] NSLS-II Beamline Development Proposal: X-ray Fluorescence Microprobe (XFM): A three-pole wiggler X-ray fluorescence microprobe beamline for characterization of materials in an "*as-is*" state. Rev 3/10 (2010).