Australian Synchrotron Development Plan
Project Submission Form

Section A: Summary and Proponent Details

Project Title

Ultrafast scanning upgrade for fast tomography and high-throughput chemical imaging (MFU)

Spokesperson

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Executive Summary (approx. 100 words)

Upgrades to the monochromator and scanning stages would simultaneously increase the specimen throughput at XFM – relieving user demand – and enhance capabilities. Specifically, they will enable fast fluorescence tomography of biological specimens and will capitalize on the ultrafast acquisition potential with the current and future generations of the Maia detector.

Demonstrations of the prototype Maia96 have stunned the World's scanning-x-ray community and on biological specimens have clearly shown the measurements are flux limited.

The upgrade will install a double multilayer monochromator delivering an increase of 20-50 in focused flux on sample and fast scanning tomography stages for the KB mirror microprobe.

Other proponents (add more rows if necessary)

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Australian Synchrotron

Section B: Detailed Description

Attach a document using the following headings (max 10 pages):

B1: Description of Proposed Beamline/Development Project

B1.1 Introduction

The hard x-ray micro and nanoprobes at the x-ray fluorescence microscopy beamline provide sub-micron spatial resolution across an energy range of 4–25 keV. The scanning x-ray microprobes provide high resolution elemental mapping for μ-XRF and μ-XANES for elemental and chemical microanalysis. The XFM beamline commenced user operation in early 2009 and accommodates a diverse range of environmental, biological and materials science applications and is currently one of the most over-subscribed beamlines with extremely high demand for x-ray fluorescence elemental mapping. The 384-element Maia fluorescence detector developed by BNL and CSIRO featuring a large solid-angle planar silicon array enables count rates up to 10^7 events/sec. A Silicon Drift-Diode upgrade to this detector expected to be realized within the next 3-5 years will enable measurement of count rates well in excess of 10^8 cts/sec.

Upgrades to the optics and scanning stages described in this proposal would simultaneously increase the specimen throughput at the XFM beamline – thus relieving user demand – and enhance capabilities. These enhanced capabilities are required to capitalize on the ultrafast capabilities of the current and future generations of the Maia 384 detector, which is presently unique to the Australian Synchrotron.

For many applications in scanning fluorescence imaging it is desirable to trade incident energy resolution for increased flux. The in-vacuum undulator source provides an opportunity to use the natural energy width of the harmonics as monochromatic sources. The high harmonics combined with the spatial filtering of the microprobe acceptance have energy widths of ~0.23%. In order to transmit this entire energy width, a double multilayer monochromator (DMM) would be incorporated with a bandpass of $\sim 10^{-2}$. The estimated **increase in flux is 20-50 times** that obtained using an existing double crystal monochromator.

B1.2 Motivation for upgrades

Increased focused flux on sample

Demonstrations of the Maia-96 have stunned the scanning-x-ray community, and are clearly a world-first for the Australian Synchrotron. However, these demonstrations were made predominantly on geological samples, with high concentrations (often ppm to %-level) and thus count rates. Measurements made on biological specimens have clearly shown that more signal is required, that the measurement is flux limited. Installation of a Double Multilayer Mirror (DMM) as outlined in this proposal will result in a dramatic reduction of the time required to measure biological specimens. As approximately 50% of scanning time is devoted to biological specimens, the DMM upgrade would translate directly into servicing of more users in each proposal round.

High-throughput, large-area imaging

It is a simple fact that fast scans require fast stages. Present scanning of geological specimens is limited by the ultimate speed of the existing stages, 20 mm/sec. An increase to 3 m/sec with 5g acceleration is perfectly achievable using commercially-available stages. This would enable high-throughput mapping of literally hundreds of specimens in a short time, as is often warranted in more statistical studies, or large-area mapping of elemental distributions in large-area objects such as brain tissue sections and artwork. Fast scanning capabilities would realise fluorescence tomography and large-area mapping on practical time scales.

B1.3 Design and details

Design concept - DMM

The XFM DCM has been designed with the capacity to hold the first multilayer, and sufficient space has been reserved for an additional chamber to hold the second multilayer and a long (1.0 m) linear stage. A conceptual design of an integrated DCM has been produced by IDT – the company that constructed the XFM beamline including the DCM. The design has significant cost benefits over separate DCM and DMM design with efficient use of the first crystal holder, Bragg axis and the DCM cryogenic cooling.

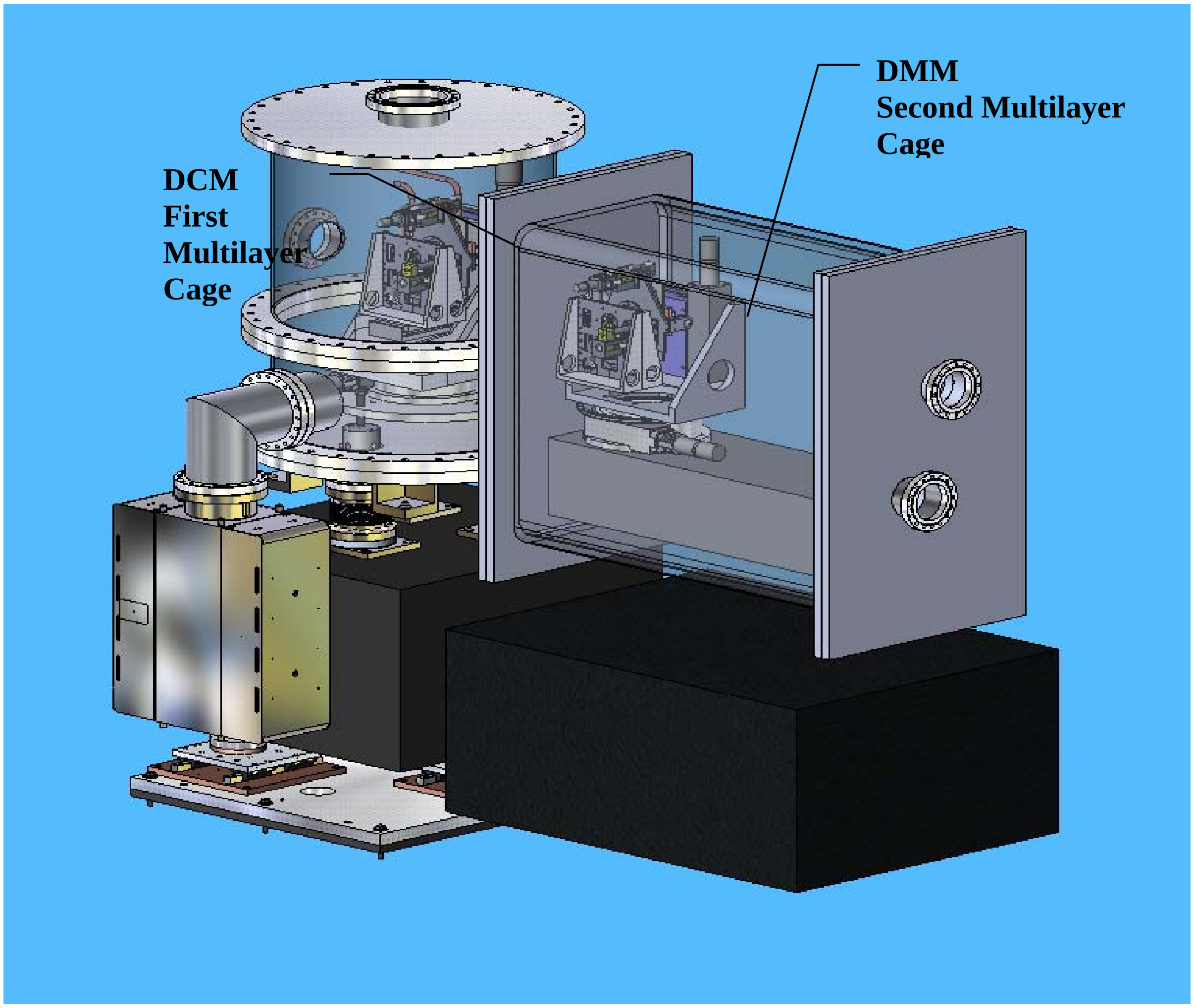

Figure 1. *Conceptual design of the integrated DCM and DMM.*

Design concept – Fast scanning stages for high-throughput, large-area, and tomography

The scanning stages required for fast, large-area scanning and tomography will have extremely demanding requirements and will require significant engineering time to develop final design. Preliminary designs comprise two long-range stages for x-y raster scanning (with the horizontal axis fast and high-acceleration), a small z stage for focussing, a tip-tilt stage to ensure that the rotation axis is perpendicular to the beam axis, an accurate rotation stage, and a pair of x-z stages to align the specimen with the rotation axis. These interior stages might also be fast to enable extremely fast combined-motion scanning (this mode might be the fastest as it involves the least payload on the scanned axes).

Details

1. DMM including vacuum chamber, second multilayer cage, goniometer and long travel range. $500K
2. Multilayer substrates and their coatings. The multilayer pairs would have stripes suitable for high energy (10^{-2} bandpass), and several stripes optimised for particular 'intermediate' energies (~10^{-3} bandpass). ~$100K
3. Fast scanning stages for fluorescence tomography on the KB mirror microprobe. $115K.
4. Additional electronics required to support fast scanning $50K
5. Ancillaries for intermediate energy studies would include energy dispersive detectors optimised for low energy and a helium environment sample chamber. ~$50K.

The total cost would be ~$815K

B2: Applications and Potential Outcomes to Australian Scientific Community

B2.1 Fast scanning fluorescence for high definition elemental mapping

The DMM would provide more than an order of magnitude increase in flux and coupled with fast fluorescence Maia detection scheme allow scanning rates to increase by 2-3 orders of magnitude. It is clear that upgrades to the specimen stages are necessary, and – in combination with the DMM upgrade - would dramatically improve throughput. These upgrades would enable mega-pixel elemental maps in an hour on **dilute** samples, primarily biological, although most investigations will also benefit through increased sensitivity and reduced minimum detection limits. The current investigations at XFM have demonstrated the incredible potential of high definition elemental images predominantly on geological samples with relatively high concentrations (100s of ppm). These upgrades would enable studies to be extended to dilute samples.

B2.2 Fluorescence tomography

Scanning fluorescence x-ray microscopy provides a wealth of information about elemental distributions in all kinds of specimens. The high penetration of x-rays simplifies specimen preparation and thereby reduces measurement artifacts. However, this high penetration means that elemental distributions are imaged in projection which can lead to confused interpretation of elemental maps, which in turn means more measurements and longer beamline-to-press timelines. An application of tomographic imaging is illuminated by a recent investigation by de Jonge et. al into the biology of diatoms.

With 18 to 20 billion metric tons of organic carbon produced by diatoms through photosynthesis each year, their effect on global carbon cycling is predicted to be of similar magnitude as all rain forests combined. Based on large scale iron fertilization experiments, iron has been found to be a key element regulating primary productivity in major regions of the global ocean. Diatoms frequently dominate marine phytoplankton blooms initiated by iron fertilization, and their success is therefore predicted to be highly dependent on their iron uptake and storage mechanisms. Below we show the tomographic reconstruction of one of these diatoms, measured using scanning fluorescence x-ray micro-tomography at the APS. The Fe distribution is quite apparent as a series of rings around the circumference of the shell. High-magnification inspection of the tomographic data has revealed that the Fe is localised within the inside layer of the shell, which could be due to the Fe-rich environment of this diatom or because it is preparing for cell division.

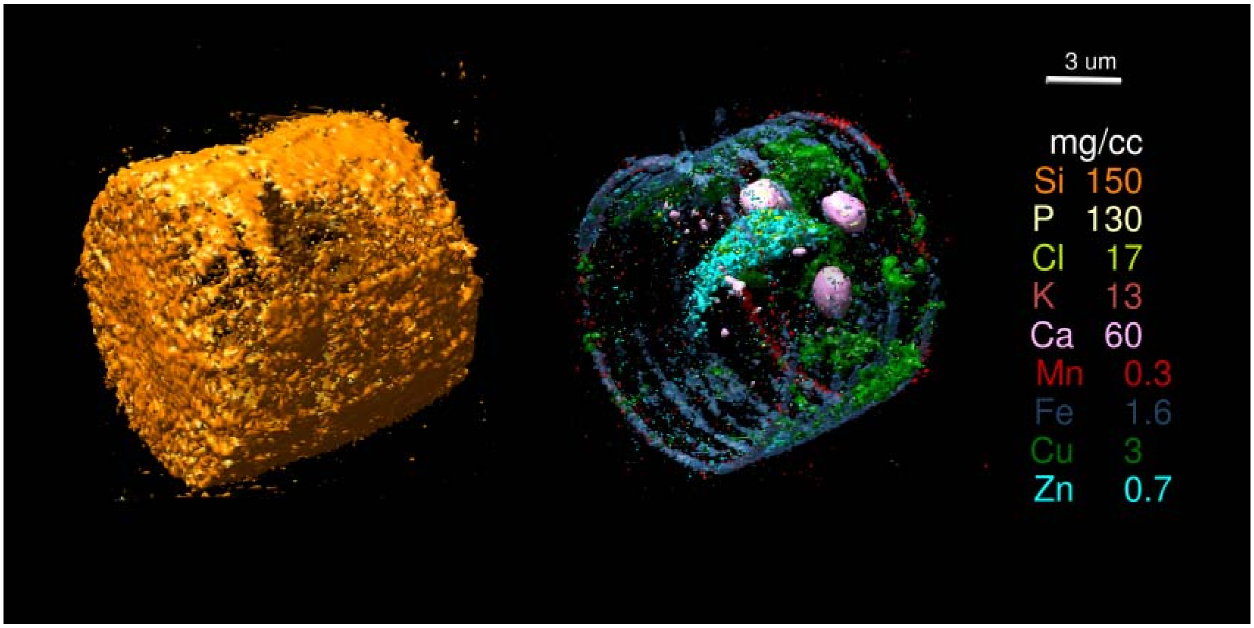

Figure 2. *Quantitative Fluorescence tomography of C. Meninghiania with an estimated spatial resolution of 300 nm.*

Interest in fluorescence tomography has recently been rekindled by the dramatic improvement in the speed of fluorescence detectors. In order to implement fluorescence tomography we need to exploit the ultrafast acquisition capabilities of the Maia detection scheme with fast scanning stages. de Jonge has already performed two experiments at the APS to implement fluorescence tomography, and these are attracting great interest from the fluorescence community worldwide. Capitalising on de Jonge’s expertise, local implementation will be straightforward and such capabilities will be user-ready within a very short timeframe.

B2.3 micro-XANES imaging

The potential of “fluorescence XANES stack” imaging or micro-XANES chemical imaging has been demonstrated with geological samples using the Maia96 and the current XFM scanning stages. This technique acquires fast 2D elemental maps at each incident energy step in a near edge scan. Results were most recently presented at SRI09 by international collaborators M. Rivers, T. Lanzirotti, and P. Eng. These investigations have shown that for major elements, e.g. Fe, faster scan stages are required to take full advantage of rapid acquisition rates and achieve practical experimental times. Chemical state mapping overcomes the time constraints and statistical uncertainty in “spot XANES” examinations of heterogeneous samples. The capabilities delivered by this upgrade will enable chemical state mapping of modest concentration samples in realistic time frames, a unique capability at X-ray microprobe beamlines.

B3: Match to Selection Criteria
These criteria can be found in the guidelines.

B4: Potential Users
Does the project address a clearly identified need in the community? The need may be actual or potential.