A dedicated micro-CT beamline for the Australian Synchrotron and the Remote-CT project

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Abstract. A dedicated micro-CT beamline is planned for the Australian Synchrotron which will extend the synchrotron's imaging and tomography capability down to the smaller scale, incorporating phase-contrast and absorption-contrast, and an additional focussing-based mode for high-resolution. The beamline will use multi-layer mirror monochromators for enhanced flux, and will focus particularly on dynamic and high throughput studies in both monochromatic and pink-beam mode. Together with the existing Imaging and Medical beamline, this beamline will produce numerous large datasets of 10 GB or more, providing a significant data-processing challenge. The Remote-CT project addresses this by combining the "MASSIVE" supercomputing GPU cluster with XLI / X-TRACT software, developed at CSIRO. This software has extensive functionality for both processing and simulation of absorption and phase-contrast tomography data and has now been modified for parallel operation on a GPU cluster to take maximum advantage of the speed-up this enables.

1. Introduction
Australia has an active micro-CT community active in lab-based micro-CT [1] and already using overseas synchrotrons such as the APS, SLS and ESRF for conducting micro-CT experiments which cannot be performed in the lab. In many cases this involves in-situ or dynamic experiments. At the Australian Synchrotron the Imaging and Medical Beamline (IMBL), which opens to users in November 2012, will provide a facility targeted primarily at larger-scale imaging and tomography together with radiotherapy. The planned micro-CT beamline is envisaged as a complementary beamline to IMBL, focused on higher-resolution, smaller-scale applications and with a particular emphasis on high-speed CT for dynamic, in-situ and high-throughput applications.

2. A dedicated micro-CT beamline on a bending magnet
The micro-CT beamline will use a bending magnet source with multi-layer broad-band monochromation to maximize monochromatic flux, together with pink/white-beam operation when maximum flux is required for speed. It will have two end stations within one extended hutch and will support in-line and grating-based phase-contrast modes with fields of view ranging from 20mm down to ~1mm with a submicron pixel size and resolution. It will also have a secondary focusing-based mode for higher resolution hard x-ray micro-CT with a resolution of <100nm. The main operational modes and operating parameters of the beamline are summarized in Table 1.

Journal of Physics: Conference Series **463** (2013) 012002 doi:10.1088/1742-6596/463/1/012002

Table 1. Main parameters of the planned micro-CT beamline

Energy Range	8-40keV	
Source type	Bending magnet 6BM1	
Monochromation type	White beam, Pink beam, Multilayer broadband monochromator (bandwidth 2%), Si monochromators (bandwidth 0.02%), possible option of extra broadband multi-layer (bandwidth 8-10%)	
End stations	Station 1 (upstream)	a) Parallel-beam imaging and micro-CT with option of in-line phase contrast. Including high-speed with automated sample exchange. b) Focussing-based high-resolution imaging/MCT mode. (with Stn.2)
	Station 2 (downstream)	a) Grating-based phase-contrast imaging/tomography b) Focussing-based high-resolution imaging/MCT mode. (with Stn.1)
Field of view	Station1	4mm V x up to 2cm H (standard) 50-100microns (focussing mode) (can cover larger areas by stitching)
	Station 2	6 mm V x up to 3cm H (can cover larger areas by stitching)
Pixel size range & max resolution	In-line phase-contrast/absorption contrast	Pixels: 0.2 - 10μm Max resolution: ~0.7μm
	Grating-based phase-contrast	Pixels: 1- 10μm Max resolution: ~4μm
	Focussing-based high-resolution mode	Pixels:20nm Max resolution: (~100nm imaging, ~200nm tomography)
Maximum tomographic data collection speed	Inline phase-contrast/ absorption- contrast	Subsecond in high-speed mode, 5-10min at maximum resolution
	Grating-based phase-contrast	15-45 min
	Focussing-based high-resolution mode	15-30min

As noted above a major focus of this beamline will be on high-speed CT for in-situ/dynamic studies, and for high throughput. This will require high-speed stages and detectors, and robotic sample exchange. In addition it is planned to offer a number of sample environments (heating, cooling, pressure, fluid flow) as standard to facilitate in-situ studies. In developing these aspects of the beamline we are fortunate to be able to draw on the considerable experience at high-speed micro-CT beamlines at SLS, ANKA and ESRF [2].

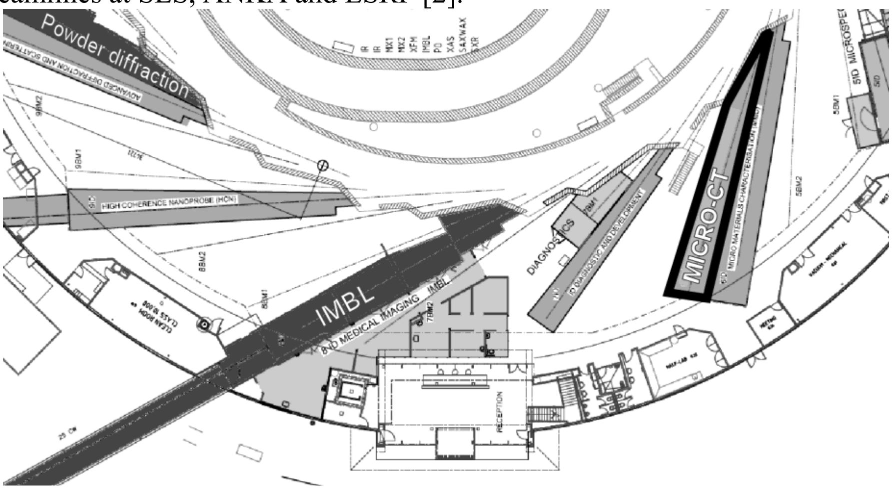

Figure 1. Australian Synchrotron layout showing existing beamlines in black, the micro-CT beamline in grey with a black border and other planned beamlines in grey.

For high-speed micro-CT the aim is to enable data collection within a second or faster if required using pink-beam. This will require high-speed CMOS detectors and reconstruction algorithms able to provide a satisfactory reconstruction with limited numbers of views. This will reduce the volume of data enabling a higher number of continuous scans to be acquired, or else enabling scans to be acquired more rapidly for a given camera speed. Standard air-bearing stages are already available capable of 20 revolutions per second so camera speed and signal-to-noise are the primary limitations. Current state of the art CMOS cameras such as the PCO Dimax enable over 4000 frames per second to be acquired at 1000x1000 resolution, however detectors are rapidly advancing and even faster detectors may become available prior to beamline construction.

High-throughput reconstruction will produce quality data with larger image sizes, and more views than fast CT, at a slower speed perhaps 10-20 minutes per dataset. Automated sample exchange will enable 100 datasets a day to be acquired thus, as with high-speed CT, huge quantities of data will be generated. The following section outlines how we will meet the challenge of processing these quantities of data.

3. The MASSIVE high-performance cluster and the Remote-CT project.

Computational requirements at the Australian Synchrotron are being met by the MASSIVE supercomputer, one of two such machines installed at the Australian Synchrotron and Monash University as part of a Victorian Government funded collaborative project. MASSIVE is a GPU cluster with 42 nodes, each with 2x 6-core X5650 CPUs, 2 nVidia M2070 GPUs and 48GB of RAM. MASSIVE also has a 58TB, GPFS file system capable of 2GB/s sustained write and is connected via a high-performance network (Mellanox IS5200 Infiniband QDR 4X switch).

The existing Imaging and Medical beamline (IMBL) has requirements for high-speed reconstruction of tomographic data up to $(8K)^3$ voxels in size, and both the proposed micro-CT beamline (as outlined above) and IMBL will also be capable of generating many tomographic scans in a relatively short amount of time. The resulting need for high-speed tomographic reconstruction and phase-retrieval is being addressed using X-TRACT software, developed by CSIRO and adapted for parallelized operation on the MASSIVE GPU cluster [3]. Tomographic reconstruction is a readily-parallelizable computational problem and can also benefit greatly from speed-up associated with GPU-based algorithms. Running on the MASSIVE cluster enables X-TRACT to operate in parallel over many CPUs and GPUs, with minimal penalties associated with file input-output (IO) thanks to the high-speed file system.

3.1. X-TRACT software and the Remote-CT project

X-TRACT is a Microsoft Windows application which has been under development in CSIRO for a number of years. It incorporates tools for tomographic reconstruction, phase-retrieval, simulation of phase-contrast/tomographic data, and a large number of general image processing tools which can be accessed and combined into scripts using the X-TRACT Image Calculator.

The Remote-CT project has extensively modified X-TRACT to run in parallel on MASSIVE for high-speed operation with large datasets, and to be accessed remotely over the network. A fully-featured PC version of X-TRACT on a user's computer can be used as a stand-alone application, but it can also operate as a remote client for the server version of X-TRACT running on the cluster. The user only needs to tick a check box for 'remote mode' in the dialog they are using and X-TRACT will 'see' and operate on the cluster file system, dispatching the tasks to the X-TRACT server running on MASSIVE. Currently MASSIVE has dual-booting Windows/Linux nodes to accommodate X-TRACT but a Linux port of the X-TRACT server is currently underway.

The IMBL is connected to MASSIVE via a dedicated optic-fibre link to ensure rapid transfer of data to the cluster. A similar linkage is envisaged for the micro-CT beamline. X-TRACT has been in operation on IMBL for a number of months during commissioning and will be available to users for the start of the user program in late 2012. Users will be able to continue working on their data using the cluster in remote mode after they finish their experiments.

3.1.1. Processing speed-up on MASSIVE

The majority of tasks involved in image processing, phase-retrieval and tomographic reconstruction are 'embarassingly parallel' in that many tasks are carried out file by file and as such can be distributed over many worker threads in order to speed up processing of the full dataset. Initially the time taken goes in inverse proportion to the number of worker threads used, however, for some cluster architectures the file IO starts to limit the increase in speed available by recruiting increasing numbers of worker-threads. In the case of the MASSIVE cluster, however, the high-speed file-system mitigates this problem enabling larger numbers of threads to be used to speed up a task without significant penalty from file IO. This can be seen in Figure 2 which shows a comparison of reconstruction speeds versus number of workers for X-TRACT implemented on the CSIRO GPU cluster and on the MASSIVE cluster. Due to the latter's high-performance IO system, reconstruction time continues to reduce as more workers are used, whereas for the CSIRO cluster reconstruction time levels off for 50 or more workers.

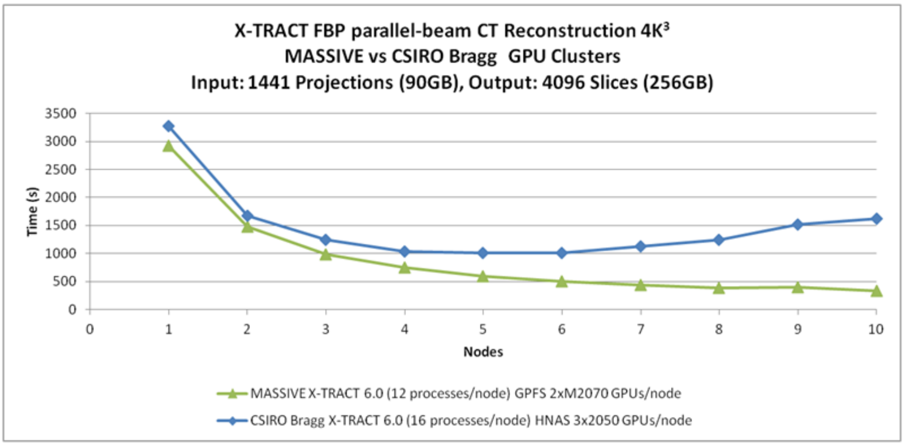

Figure 2 – 4K dataset reconstruction time in seconds vs number of worker threads for the CSIRO GPU cluster and the high-speed IO MASSIVE cluster

4. Conclusions

The micro-CT beamline combined with the IMBL and the supporting high-performance computing facilities will provide high-quality and rapid CT for investigation of dynamic processes and a wide range of samples, with reconstruction tools commensurate with the speed of data collection. Future computational challenges lie in addressing the need for rapid segmentation and analysis of the datasets in order to extract the maximum value from them on a manageable timescale.

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