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The Imaging and Medical Beam Line at the Australian Synchrotron

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Abstract. As a result of the enthusiastic support from the Australian biomedical, medical and clinical communities, the Australian Synchrotron is constructing a world-class facility for medical research, the 'Imaging and Medical Beamline'. The IMBL began phased commissioning in late 2008 and is scheduled to commence the first clinical research programs with patients in 2011. It will provide unrivalled x-ray facilities for imaging and radiotherapy for a wide range of research applications in diseases, treatments and understanding of physiological processes. The main clinical research drivers are currently high resolution and sensitivity cardiac and breast imaging, cell tracking applied to regenerative and stem cell medicine and cancer therapies. The beam line has a maximum source to sample distance of 136m and will deliver a 60cm by 4cm x-ray beam – monochromatic and white – to a three storey satellite building fully equipped for pre-clinical and clinical research. Currently operating with a 1.4 Tesla multi-pole wiggler, it will upgrade to a 4.2 Tesla device which requires the ability to handle up to 21kW of x-ray power at any point along the beam line. The applications envisaged for this facility include imaging thick objects encompassing materials, humans and animals. Imaging can be performed in the range 15-150keV. Radiotherapy research typically requires energies between 30 and 120 keV, for both monochromatic and broad beam.

Keywords: Radiotherapy research facility, x-ray imaging research facility, synchrotron radiotherapy, synchrotron x-ray imaging,
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INTRODUCTION

The committees involved in planning the Australian Synchrotron made the decision in 2005 to include an imaging and radiotherapy research facility in its first suite of 9 beam lines.

The imaging and medical therapy beam line (IMBL) is aimed at supporting a number of research areas in biomedical and materials science in which Australian scientists excel.

A major focus of the IMBL program will be the development of phase contrast imaging techniques for both biomedicine and materials research. Techniques supported in the early operation of the beam line will include phase contrast enhanced x-ray projection radiography and tomography, as well as microbeam and monochromatic beam radiation therapy. The beam line was designed to deliver beams of photons with an energy range extending from 15 keV to 150 keV.

A primary science area supported by the IMBL is radiotherapy. In a survey of potential Users some 23% will be working on radiobiology and related research. For a large fraction of this research a broad spectrum of radiation is required. Furthermore, dose rates need to be high but variable. The ability to deliver 1,000 gray / second to the sample was requested. Animal trials with microbeam radiotherapy typically require beams with a spectrum extending from 30 to around 120 keV and with very low divergence. Depending on the results of this pre-clinical radiotherapy work, clinical trials might then be requested. In this case it will be possible to retrofit a human patient stage into an appropriate section of the IMBL.

The IMBL is a unique beam line. As such it has none of the advantages that other beam lines have of

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being able to purchase off-the-shelf turn-key systems. All the beam line items are being obtained separately and brought together by the team at the synchrotron. Despite the necessarily long planning and procurement process, such is the desire to start work with IMBL that a loan of a suitable magnet was negotiated with the Advanced Photon Source (APS) at the Argonne National Lab in the USA. A type A wiggler was offered, the offer accepted and the device delivered in 2007. The device is currently installed on section 8ID of the storage ring. Borrowing this device has allowed the IMBL to start operation far sooner than if a new device was specified and procured. For the next 18 months the APS wiggler will be the source of photons for the IMBL. A superconducting multipole Wiggler has now been specified and tenders are about to be requested.

The beam line achieved first light in December 2008. A report on the first images taken with the beam has been published in the Journal of Synchrotron Radiation (1). Radiotherapy research programs have also started. Reports at this conference, and subsequent publications, reveal the exciting developments enabled by the IMBL.

To support the local needs of IMBL researchers, ancillary experiment areas and clinical facilities are being constructed around the beam line over the next few months. Having IMBL supported by this infrastructure, and with extant local expertise in x-ray imaging and radiotherapy, will position the IMBL suite within the top synchrotron facilities in biomedical imaging and therapy research world-wide.

BEAM LINE DESCRIPTION

The IMBL is situated on insertion device segment 10ID, in the North West quadrant of the storage ring. The source for the IMBL is currently a multipole 'wiggler A' on loan from the APS in the U.S.A (2). This device is a 28 pole structure with an 8.5 cm period and a total length of 2.4 metres. The pole gap is variable between 11 mm and 150 mm. At a gap of 55 mm the field is 0.24 T giving a deflection parameter K of 1.9. At this gap the critical energy is 1.4 keV. The apparent source size for imaging from the device has been measured. At a gap of 55 mm with a field of approximately 0.24 T the source size is 361 μm horizontal and 19.2 μm vertical.

Situated along the beam line are 6 radiation enclosures. These comprise three pairs of optics and experiment hutches. All hutches are designed to accept the full x-ray spectrum from a superconducting wiggler device which we are in the process of procuring. Two pairs of enclosures are situated within the walls of the main synchrotron building. The third pair are situated outside the main building and are supplied with photons by a beam line extension through the wall of the storage ring building. The IMBL Satellite Building contains the two radiation enclosures as well as extensive support facilities. The experiment hutch in the Satellite Building is serviced with a beam of radiation which has propagated 136 meters from the source to the sample position. The beam therefore has a high degree of phase coherence and a relatively large width. The hutch is designed to deliver a beam at sample of 600 mm horizontal by 50 mm vertical at 40 keV from the superconducting source. This device is described in the next section. It will deliver a total of 21 kW of power to the beam line. Modifying and controlling this large photon flux is an engineering challenge which the IMBL team is currently tackling.

The Satellite Building houses infrastructure to provide our biomedical experimenters with access to essential facilities that are required for their research. A human patient area has been built on one side of the building with provision for a reception desk and waiting room, examination and preparations rooms. This area will offer ergonomic design and an ambience expected by patients from a clinical medical facility. On the other side of the building is an area equipped for non human biomedical imaging. This is equipped with short term laboratory animal handling, preparation and recovery rooms.

Broadly speaking the IMBL will be used for two research areas. The first are novel forms of radiation therapy, the other for leading edge x-ray imaging. The first experiment hutch (1B) is designed to be the primary radiotherapy research facility. Intense beams will be available in this hutch to deliver the very high dose rates required for some of the radiotherapy research projects such as micro beam radiation therapy (3). A bright monochromatic beam will also be available in this hutch derived from a double Laue monochromator situated in the optics hutch 1A. Monochromatic radiotherapy research such as photon activation therapy (PAT) (4) and stereotactic radiation therapy (SSRT) (5) will be carried out in hutch 1B.

Monochromatic and broad band imaging on objects up to 100 mm in diameter will take place in imaging hutch 2B. It is expected that a significant program of small animal radiography will take place here. The beam at the sample position in 2B is an ideal size and intensity for this type of research. Phase contrast imaging is supported on all IMBL imaging stations. The size of the source limits propagation based phase contrast to the hutches farthest from the source (2B and 3B). We also own a diffraction enhanced imaging (DEI) system which will be made available to those that want to use this technique. Both organic and inorganic material 3-D imaging will be carried out in station 2B. The areas outside the stations within the main building are designed to include storage and sample preparation areas. The layout includes rooms for consultation, preparation and reporting for possible future clinical programs, as well as the beam line control.

The large beam available in station 3B is well suited for human chest imaging. It is this hutch which is likely to become the primary clinical facility on the IMBL. Station 3B will also be used for larger animal imaging. It is anticipated that animals as large as sheep will be imaged using the equipment in this station. The optics station 3A will house a specialist monochromator for edge subtraction imaging (dichromography). Dichromography can provide rapid, low dose, and high contrast images through the use of contrast agents.

Hutch by hutch details

1A /1B

1A

Purpose	Beam conditioning and optics and enclosure
Distance from source	Nominal 16 m
Usable beam width	74 mm
SCW Flux at 40keV	1.05×10^{13} ph/s/0.1%bw/mm^2
Conditioning	High heat-load slits, filters, photon stop and shutter
Optics	Double bent-Laue crystal monochromator for CT (vertical geometry)

1B

Purpose	Microbeam radiotherapy and high speed micro CT
Distance from source	Nominal sample at 23 m
Usable beam width	106 mm
SCW Flux at 40keV	3.37×10^{12} ph/s/0.1%bw/mm^2
Instrumentation	Slits and micro-beam slit system for MRT Optics, sample and detector systems on corresponding support tables
Therapy activities	Microbeam radiotherapy
Imaging activities	Small area, low resolution 2D imaging. Initially equipped for analyser based imaging (DEI). Small area, semi-quantitative fan-beam 3D tomography

The optics hutch 1A will house the high load white beam conditioning optics. The white beam horizontal and vertical slits are water cooled and designed to handle 21 kW of power.

Following the slits are a set of broad band filters allowing tailoring of the white beam spectral shape. The filter assembly comprises 5 vertically mounted filter paddles, each paddle housing three water cooled in-vacuum filter foils. Currently the paddles are populated with beryllium, carbon (graphite), aluminium, and copper foils with a variety of thicknesses.

A fast shutter will be included in this hutch in the near future. This will have a minimum exposure time of 50 milliseconds. The shutter is designed for accurate and rapid exposures in radiotherapy research. The photon safety shutter and vacuum valves are the last beam line components in 1A before the beam enters hutch 1B.

The flange on the end of the vacuum tube into hutch 1B incorporates a polished beryllium window allowing the beam into the experiment hutch. The vacuum window is protected against oxidation with a helium filled space, separated from air by a Kapton foil. At this point the beam is in air and can be used for radiotherapy experiments. Hutch 1B houses three versatile remotely controlled experiment tables. One table closest to the upstream hutch wall is used for mounting motion control equipment for radiotherapy experiments. The optical assembly for analyser based phase contrast imaging (DEI) is mounted behind the first table. The DEI apparatus was kindly gifted to the IMBL when it became surplus to requirements from the SRS synchrotron in the UK. The system consists of a large vibration stabilised frame with tandem optical axes separated by 1.1 metres. Each axis is designed to carry a channel cut silicon crystal. The second experiment table sits between the monochromator and the analyser crystal cages in this DEI frame, and is used for sample positioning. The final downstream table in hutch 1B carries the imaging detector. All IMBL tables have vertical motion over a range of 350 mm. The top of the table is comprised of a vibration isolated optical bread board and is used to carry a variety of motion control and other equipment.

At the back wall of hutch 1B is a large radiation shield block which can be slid into place in order to safely isolate these hutches from the downstream stations.

2A/2B

2A

Purpose	Beam conditioning and optics and enclosure
Distance from source	Nominal 28.5 m
Usable beam width	131 mm
SCW Flux at 40keV	2.64×10^{12} ph/s/0.1%bw/mm^2
Conditioning	Slits, photon stops and shutters for white (on-axis) and monochromatic beam.
Optics	Bent Laue monochromator (single crystal), vertical geometry, K-edge capable.

2B

Purpose	High resolution, small and medium size object imaging. Possibly clinical mammography.
Distance from source	Nominal sample at 38 m
Usable beam width	175 mm
SCW Flux at 40keV	1.24×10^{12} ph/s/0.1%bw/mm^2
Instrumentation	Optics, sample and detector systems on corresponding support tables (initially shared with 1B) Analyser setup on custom-table
Therapy activities	Tomotherapy. Photo-activation therapy
Imaging activities	K-edge subtraction imaging. Phase contrast using secondary focus. Analyser based imaging. Small animal imaging. Possible human and large animal radiography and phase contrast mammography

The detailed plans for the second pair of hutches 2A and 2B are currently being considered. For the next 12 months the optics hutch will carry a beam transport pipe which will allow the beam from 1B to enter experiment hutch 2B. Imaging samples which are situated on the specimen table in 1B with a detector in 2B provides a maximum of 17 meters propagation for propagation phase contrast imaging (PBI) studies. In early experiments hutch 2B will contain a table to carry the x-ray imaging detector. The table can be moved on central rails the full length of the hutch to accurately vary the object to image distance.

3A/3B

3A

Purpose	Beam conditioning and optics and enclosure
Distance from source	Nominal 140 m
Usable beam width	560 mm
SCW Flux at 40keV	9.28×10^{10} ph/s/0.1%bw/mm^2
Conditioning	Slits, photon stops, shutters, filters
Optics	Bent Laue monochromator for dichromography
Later developments	Multilayer monochromator and focusing components

3B

Purpose	Very high resolution large object imaging. 3-D imaging (CT) and monochromatic beam therapies.
Distance from source	Nominal sample at 150 m
Usable beam width	600 mm
SCW Flux at 40keV	8.09×10^{10} ph/s/0.1%bw/mm^2
Instrumentation	Sample and detector systems with corresponding support. Analyser setup on custom-table. Human patient handling.
Therapy activities	Photo-activation therapy. Possible tomotherapy.
Imaging activities	Imaging of large objects using high coherence & high resolution. Quantitative CT and micro-CT (PB-PCI). Analyser based imaging. Edge subtraction imaging. Human and large animal CT

The space available for the hutches and surrounding infrastructure outside the synchrotron building made it possible to design radiation enclosures in a radically different way. The stations are enclosed using concrete rather than lead and steel as with the other IMBL hutches. This gave significant cost savings and a larger area in the experiment hutches. The optics hutch 3A is 10 meters long by 4 metres wide. The experiment hutch 3B is even larger, being designed to hold a large amount of patient and materials handling. The hutch internal dimensions are 10 metres long by 6.3 metres wide.

FIGURE 1 Aerial view of the Australian Synchrotron seen from the North West, showing the plans for the extended IMBL overlaid.

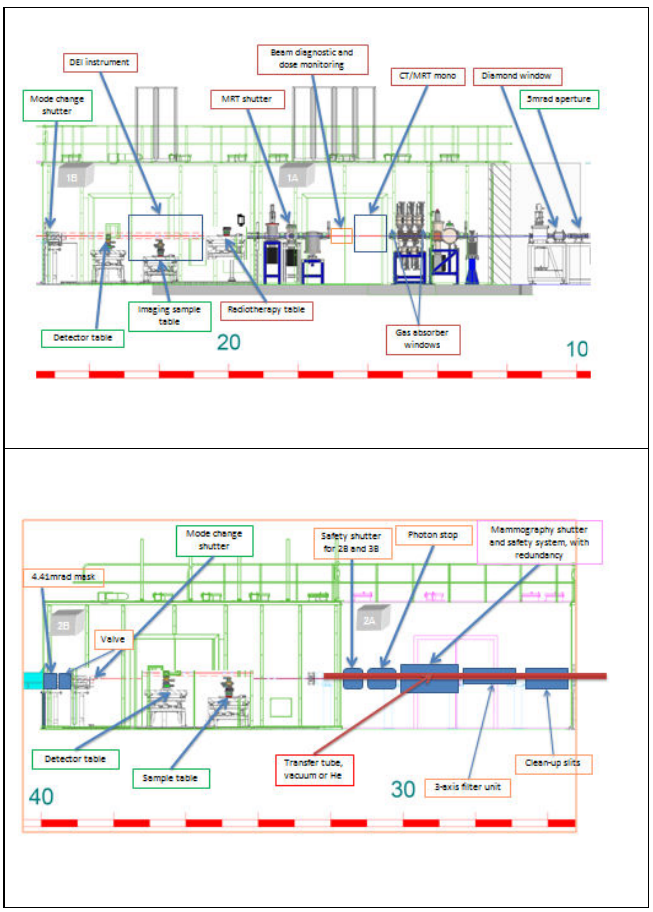

FIGURE2 Schematics showing the components in the hutches interior to the synchrotron building. The top figure shows the hutches closest to the source 1A and 1B. The lower figure shows the small beam imaging hutches 2A and 2B.

DESCRIPTION OF BEAM LINE OPTICAL ELEMENTS

Double Laue Monochromator

This monochromator concept is based on the CT monochromators developed at the ESRF for the medical beamline ID17.

One of these uses a Z-motion to move the first crystal in and out of the white beam. Further information can be found in the paper by Suortti et al (6).

The New Superconducting Multipole Wiggler (SCMPW)

The IMBL science program calls for high flux in the 100 to 120 keV X-ray range. The key parameter for the design of the SCMPW is therefore the critical energy (E_c), chosen as 25 keV. This in turn dictates an ideal value of 4.17 Tesla for the peak magnetic field (B_0). The shortest period, with a low deflection parameter (K) will produce the highest X-ray brightness but will increase the design challenge because of the compact magnetic poles and the size of the device resulting from the large number of poles.

The main design drivers behind our SCMPW are:

1. A **high field** to give a critical energy of 25keV;
2. A **high flux** by having a large number of periods;
3. A **high brightness** by using a short period length to keep K low.

We have requested tenders for a short period (48 mm to 52 mm) structure. There are some concerns about the long term performance of such a device. The main question asked of the supplier will be: Are the small radius bends in the coils a weak point which may cause a degradation of the field / wiggler performance in time?

In addition to the main array of full size poles, pairs of fractional poles should be added inside the cryogenic vessel for electron beam orbit maintenance, for example 2 x ½ or 2 x ¼ and 2 x ¾. These shall enable the correction of the first field integral.

The storage ring and suggested SCMPW parameters are given in the table below.

Parameter	Requirement
Storage ring energy	3 Gev
Storage ring current	200 mA
Magnet Peak Field, B_0	≥ 4.17 Tesla [nominal field at 4.2 K or higher temperature]
Critical Energy, E_C	25 keV
Period Length, λ_0	desired: 48 mm – 52 mm, preferred: ≤ 56 mm
Number of full field periods	31(1)
Number of poles	62
Cool-down / warm-up time	≤ 72 hours
Deflection Parameter, K	18.7 – 21.8 [absolute upper limit is 23.4 with λ_0 = 60]
Horizontal / Vertical Aperture	≥ 60 / ≥ 10 mm
Operating Time Between Service	1 year
Time between LHe fill up	> 3 months: prefer zero consumption

(1) This number was chosen to give a total emitted x-ray power of ~30 kW at the storage ring operating conditions.

THE IMBL BIOMEDICAL SUPPORT CENTRE

The Australian Synchrotron is situated in an area of Melbourne close to both Universities and a significant number of medical and other research institutes. The IMBL was quickly seen by our local clinical researchers as a tool which can be used to synergise x-ray imaging and radiotherapy with existing and planned biomedical research. There are several groups in the vicinity with world class expertise in x-ray imaging. With the help of these physicists and the need for novel imaging capabilities from the biomedical community, a beam line was designed which could deliver large and coherent x-ray beams to the sample. This required a long beam line and a significant amount of real estate around it. The result is the IMBL hutches 3A/3B, surrounded by a building containing limited facilities but which suited the original beam line budget.

To aid in the development of a superior IMBL a significant grant was awarded by the National Health and Medical Research Council and the Victorian Government in April 2009. The award was made to provide the station building with a second storey which would include laboratories and clinical support rooms for human imaging and therapy research.

Details of the development are currently being finalised. In the area outside the hutches on the animal side will be four animal holding rooms and a surgery. Two lifts separately service the animal and human patient areas. These will transport both human and animal patients from ground level reception areas down one level to emerge opposite the entrances to the hutches. On the human patient side a reception area and preparation room has been designed. The main support centre facility control room will be next to this.

The second storey will provide ample consultation, reporting and other imaging areas, as well as meeting rooms on the clinical side. A molecular laboratory, tissue culture laboratory, a general purpose wet laboratory and animal surgery room are planned for the animal side.

The building next door to the Australian Synchrotron on Blackburn Road, and very close to the IMBL satellite building, is home to a consortium of x-ray imaging experts. The Advanced Imaging Laboratory houses groups from Monash University and CSIRO.

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