

Shielding Design for the Imaging and Medical Beamline at the Australian Synchrotron

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Abstract

The Imaging and Medical beamline at the Australian Synchrotron will be dedicated to high resolution imaging of cells, tissues, ‘objects’ (tumours, fine structural details in organs and bones), cell tracking using nano-particles and other contrast markers, research in the interaction of radiation with cells - cancer and healthy - to improve radiotherapy prescriptions and treatments and the extension of the above programs to clinical research with patients.

The present paper gives a short introduction to the beamline and describes in more detail the shielding design for this 136 m long beamline.

Details are given on the shielding design of the optics hutch, both for bremsstrahlung (and photoneutrons) and synchrotron radiation, with special attention to bremsstrahlung ray-tracing.

The shielding of the transfer tunnel between the experimental hall and the satellite building, as well as the shielding of the hutches in the satellite building are described. The design uses a combination of lead, concrete and earth shielding.

1. The Imaging and Medical Therapy beamline at the Australian Synchrotron

The imaging and medical therapy beamline will offer high-resolution, phase-contrast x-ray imaging of small animals and a wide range of engineering materials. It will also enable research into new cancer treatments. The beamline will be 136 metres long, with a satellite building which will later include a patient reception area and an animal holding and preparation facility. All experiment enclosures will eventually have near-beam surgery facilities for fast preparation-to-measurement animal transfers. The first phase of this ‘long beamline’ program started commissioning in early 2009, allowing for high resolution phase contrast imaging of large objects.

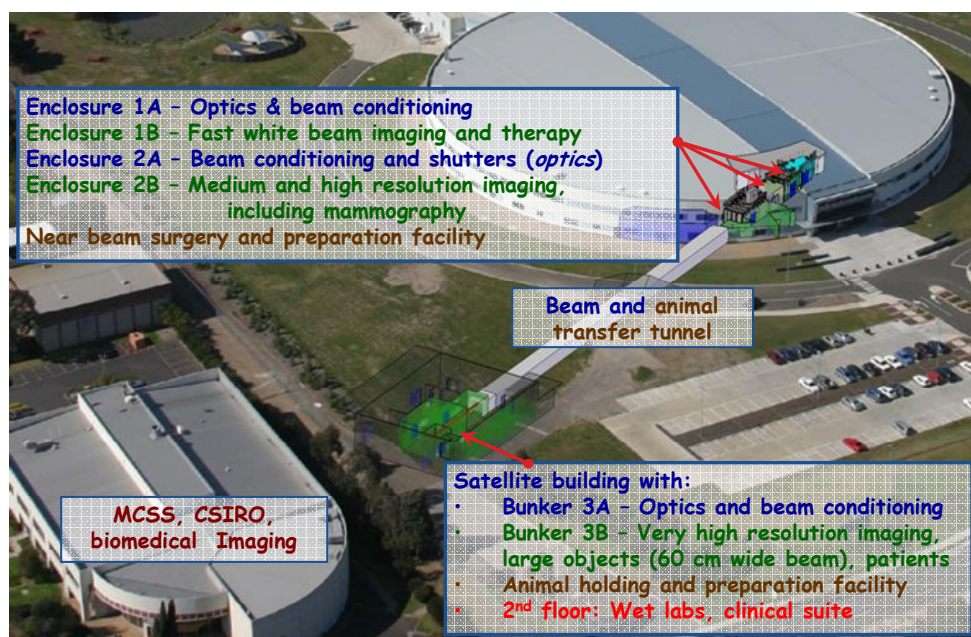


Fig.1 - Layout of the Imaging and Medical Beamline.

Special features of the beamline are:

- phase-contrast and analyser based x-ray imaging, which allows much greater contrast from weakly absorbing materials such as soft tissue than is possible using conventional methods;
- two and three-dimensional imaging at high resolution;
- lower tissue doses than conventional x-ray methods, making longitudinal studies (serial imaging) possible tuneable beam energy, which enables the imaging of specific elements with very high sensitivity, possibly down to submicron scales;
- one of only three beamlines in the world configured for work with a wide range of live animals.

2. Shielding calculations for the optics hutch

The shielding calculations for bremsstrahlung and photo-neutrons were done using the Monte Carlo code *Beamlines* [1]. The following accelerator parameters have been used for the bremsstrahlung calculations.

<i>Electron energy</i>	<i>3 GeV</i>
<i>Stored beam current</i>	<i>400 mA</i>
<i>Length straight section</i>	<i>7.6 m</i>
<i>Average pressure in the straight section</i>	<i>$2. \times 10^{-9}$ mbar</i>

Table 1 - Accelerator parameters used for the gas-bremsstrahlung shielding calculations.

The shielding calculations were carried out for a value for the stored beam of 400 mA, i.e. twice the nominal current, to be coherent with the general shielding guidance report of S. Costantin [2]. With respect to this report, the value for the pressure has been increased from 1 ntorr to 2×10^{-9} mbar. The latter value seems more realistic than the value of 1 ntorr for a current of 400 mA. The residual gas composition shown in table 1 is used, based on RGA measurements in the proximity of crotch-absorbers at the ESRF.

<i>Molecule</i>	<i>Relative pressure (%)</i>	<i>Partial pressure (mbar)</i>
<i>H₂</i>	<i>71</i>	<i>1.42×10^{-9}</i>
<i>CO</i>	<i>20</i>	<i>0.4×10^{-9}</i>
<i>CO₂</i>	<i>4</i>	<i>0.8×10^{-10}</i>
<i>CH₄</i>	<i>2</i>	<i>0.4×10^{-10}</i>
<i>H₂O</i>	<i>3</i>	<i>0.6×10^{-10}</i>

Table 2 - Residual gas composition used for the calculations. The partial pressures in the third column correspond to a total pressure of 2×10^{-9} mbar.

At the time of the shielding calculations, the details of the optical elements were not yet known. The calculations have been carried out using typical optical elements (detailed 3D simulations of existing ESRF components). The configuration consisted of a pair of slits followed by a double crystal monochromator. This layout is shown schematically in figure 2.

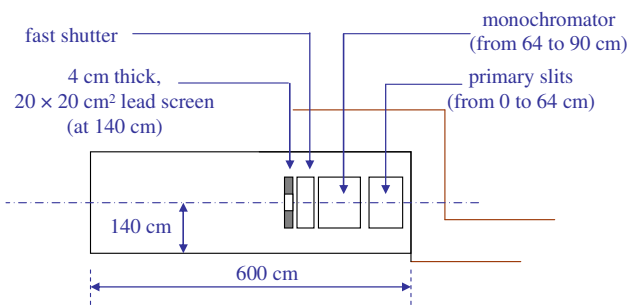


Fig.2 - Schematic layout of the white beam hutch used for the Monte-Carlo calculations for scattered bremsstrahlung and photo-neutron shielding.

Figure 3 shows, as an example, the photon ambient dose equivalent rates behind the optics hutch side wall, as a function of the distance along the hutch, for different lead thicknesses of the hutch side wall and the total ambient dose equivalent rates behind a 25 mm lead wall. The results show that a 25 mm sidewall will keep

dose rates below the 0.5 $\mu\text{Sv/h}$ limit for non-exposed workers up to an average pressure in the straight section of $8 \cdot 10^{-9}$ mbar (at 400 mA).

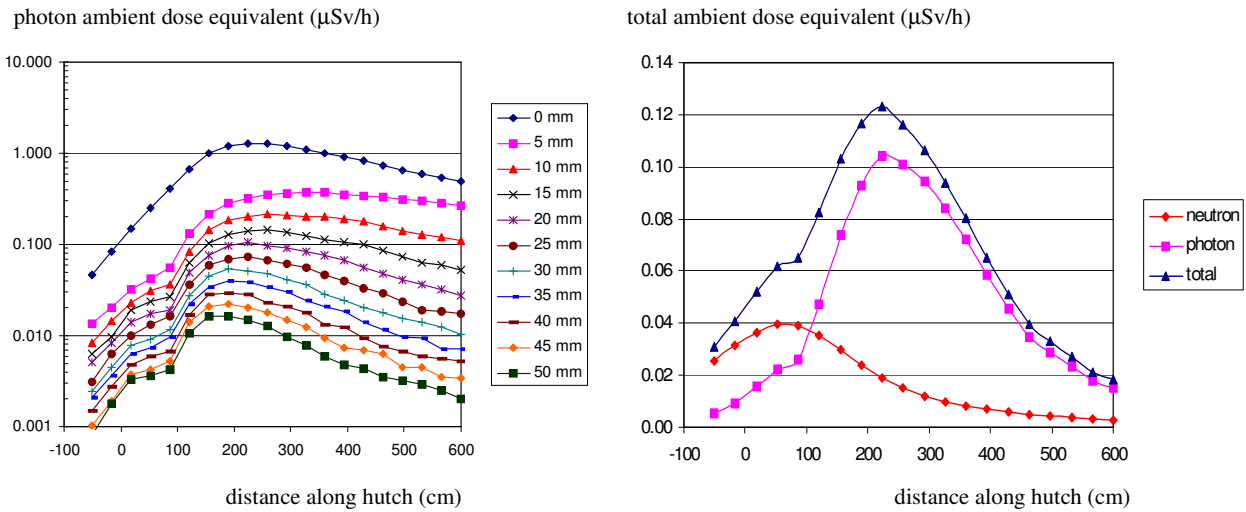


Fig.3 - Photon ambient dose equivalent rates behind the optics hutch side wall, as a function of the distance along the hutch, for different lead thicknesses of the hutch side wall (left); total ambient dose equivalent rates behind a 25 mm lead wall (right).

For the back wall, a lead thickness of 5 cm, with an extra 5 cm of lead in an $80 \times 80 \text{ cm}^2$ area around the beam axis was obtained.

The shielding calculations for the synchrotron radiation were carried out using the characteristics of the final wiggler (see table 3). The results for the side wall are shown in figure 4. One sees that the thickness defined for the bremsstrahlung shielding provides adequate shielding also for the synchrotron radiation.

Electron energy	3 GeV
Stored beam current	400 mA
Insertion device	Length: 1.5 m Period: 48 mm Bmax: 4.17 T ($E_C = 25 \text{ keV}$)
Front end	4 mrad full horizontal angle

Table 3 - Accelerator parameters used for the synchrotron radiation shielding calculations.

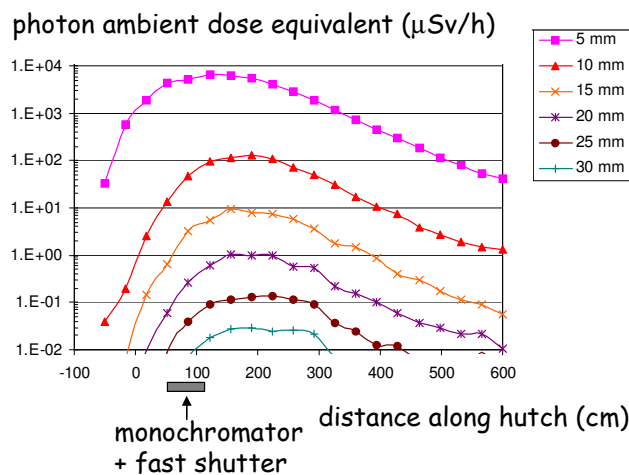


Fig.4 - Photon ambient dose equivalent rates behind the optics hutch side wall, as a function of the distance along the hutch, for different lead thicknesses of the hutch side wall.

3. Bremsstrahlung ray-tracing

Space in the optics hutch is limited. Monte Carlo calculations have been performed to optimise the required bremsstrahlung collimation inside the hutch. Two copper masks are installed in the front end. The first one, placed at 7.4 m from the centre of the straight section, has a full horizontal opening of 3.35 mm and a full vertical opening of 52.7 mm. The second one, placed at 11.9 m from the centre of the straight section, has a full horizontal opening of 6.4 mm and a full vertical opening of 49.5 mm. This defines an effective collimation of $\pm 0.23 \text{ mrad}_V$ and $\pm 2.08 \text{ mrad}_H$. At the end of the hutch a 20 cm thick tungsten beamstop is installed, 15 cm wide and 8 cm high, placed at 18.85 m from the source point. It provides both horizontally and vertically, a 1.5 cm overlap with the $15 \text{ cm}_H \times 5 \text{ cm}_V$ rectangular beampipe. The calculations showed that the dimensions of the safety shutter installed at the end of the optics hutch are sufficient to correctly shield under all possible misalignment conditions of the electron beam, without need of further bremsstrahlung collimators. This is illustrated in figure 5 which shows the bremsstrahlung dose rates behind the optics back wall, for three configuration, a perfect aligned electron beam in the straight section, a beam with a 2.63 mrad horizontal misalignment (trajectory from -1 cm to + 1 cm in the 7.6 m long straight section) and a beam with a 3.95 horizontal misalignment respectively. One sees clearly the effect of the copper masks resulting in a net dose decrease for misalignment angles above 3 mrad.

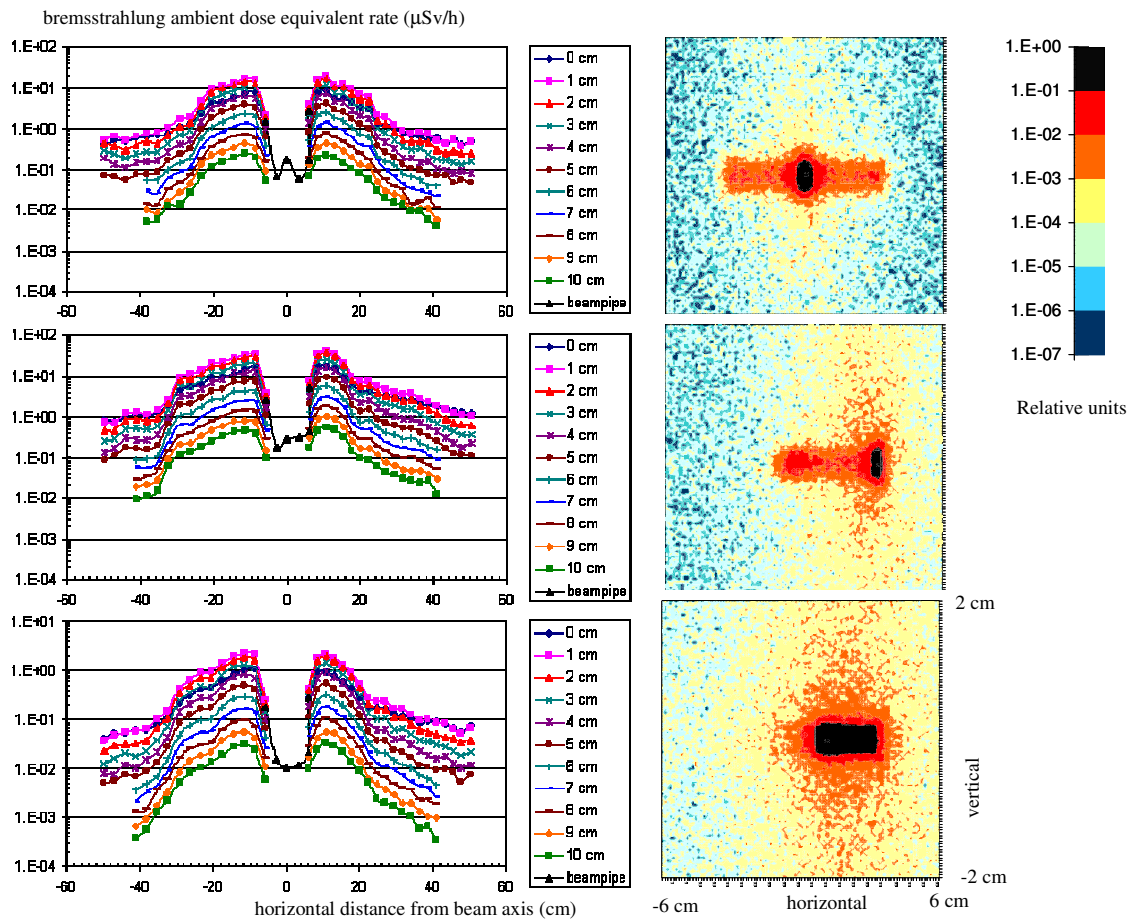


Fig.5 - Left: Bremsstrahlung ambient dose equivalent rate behind the optics hutch back wall, as a function of the horizontal distance from the beam axis (vertical scoring height = $\pm 2 \text{ cm}$ around beam height) - Right: relative dose distribution in a $12 \text{ cm}_H \times 4 \text{ cm}_V$ area centred around the beam axis. Top: nominal orbit; middle: orbit horizontally misaligned by 2.631 mrad; bottom: orbit horizontally misaligned by 3.947 mrad.

4. Shielding for the tunnel and the satellite building

A combination of lead, concrete and earth is used for the shielding of the hutches inside the satellite building and for the tunnel between the latter and the experimental hall. A concrete density of 2.4 g/cm^3 is used, while a soil density of 1.8 g/cm^3 is assumed, with the elemental composition shown in table 4.

The results of the optics hutch showed that similar lead thicknesses are required to shield against gas-bremsstrahlung and synchrotron radiation. When using a combination of lead, concrete and earth the thickness requirements will be determined by synchrotron radiation. All calculations are carried out using a low-Z grazing incidence scatterer. Figure 6 illustrates the results of the shielding calculations for the side wall of the 3A optics hutch (distance from beam axis = 200 cm), showing that a 4 mm lead lining on the 44 cm concrete wall is sufficient.

Element	Relative weight (percentage)
Oxygen	47.33
Sodium	2.84
Magnesium	2.11
Aluminum	8.24
Silicon	28.1
Potassium	2.64
Calcium	3.65
Iron	5.09

Table 4 - The elemental composition for soil used in the calculations

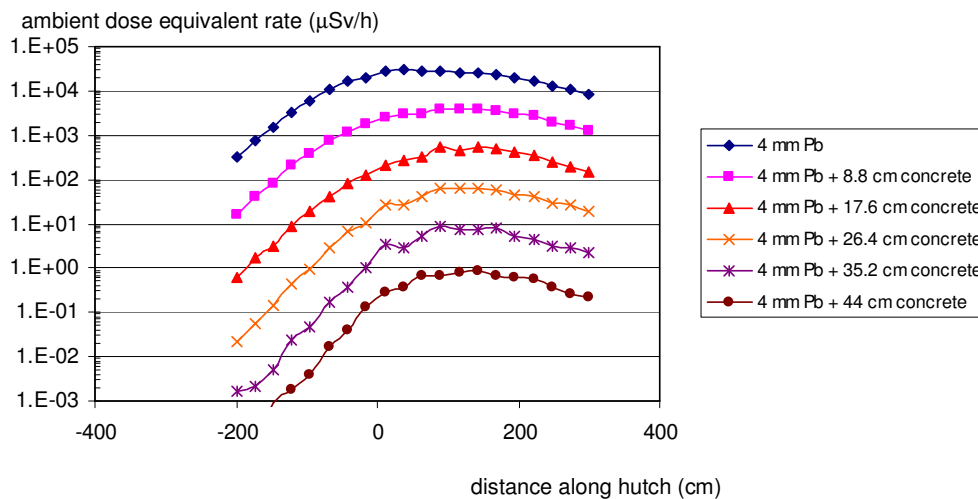


Fig.6 - Ambient dose equivalent rates behind the 3A hutch side wall, as a function of the distance along the hutch (0 cm corresponds to position of scatterer), for different concrete wall thicknesses.

The relative inefficiency of the concrete as shielding material for X-rays is illustrated in figure 7 showing the results for the lead door in the side wall of the 3A optics hutch (distance from beam axis is 244 cm), showing the superior shielding efficiency of the 24 mm thick lead door, compared to the 44 cm thick, lead lined, concrete wall.

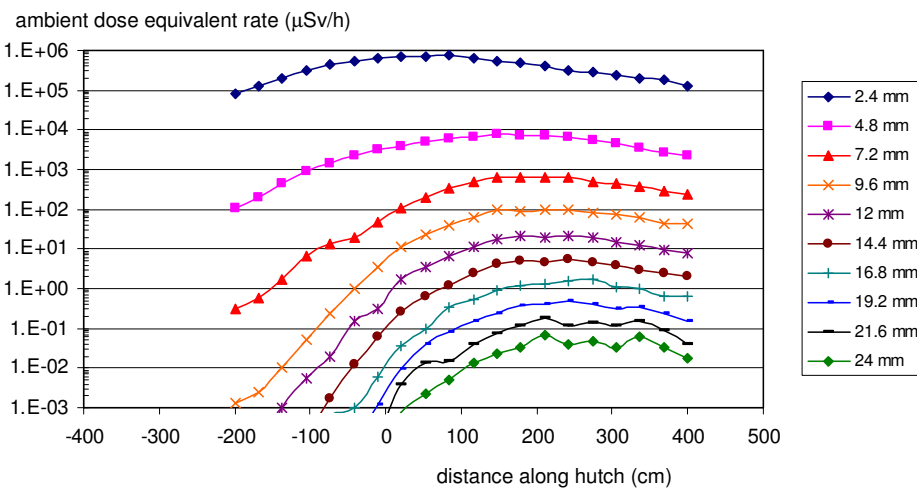


Fig.7 - Ambient dose equivalent rates behind the 3A hutch lead door, as a function of the distance long the hutch (0 cm corresponds to position of scatterer), for different lead thicknesses.

The shielding requirements for the tunnel are determined by backscattered radiation from the 3A optics hutch and from air scatter inside the beam tube. Since backscattering occurs permanently, dose rates from this source must be kept below 0.5 $\mu\text{Sv/h}$. Air scatter will only occur accidentally and from the shielding calculations a maximum closing time of the beam shutter in case of a vacuum problem is obtained (interlocked to the personnel safety system).

Figure 8 shows the ambient dose equivalent rates behind the tunnel outboard side wall (distance from beam axis = 170 cm). No extra earth shielding over the 20 cm thick concrete wall is required for distances more than 40 m from the 3A hutch wall. A 4 mm lead cladding of the tube over the last 20 m upstream of the 3A hutch wall is foreseen.

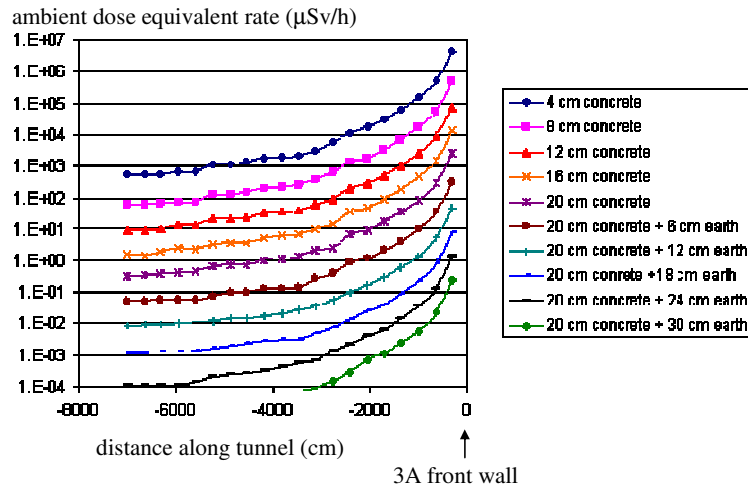


Fig.8 - Ambient dose equivalent rates behind tunnel outboard side wall, as a function of the distance from the 3A hutch outer face of upstream wall.

Finally, figure 9 shows the dose rate behind the outboard tunnel wall, as a function of the concrete thickness and the additional earth thickness. No extra earth shielding is present for the first part of the tunnel, near the experimental hall. The results of figure 8 show that in the case of a sudden vacuum loss an integrated dose of about 20 μSv is obtained for a shutter closure time of 1 s.

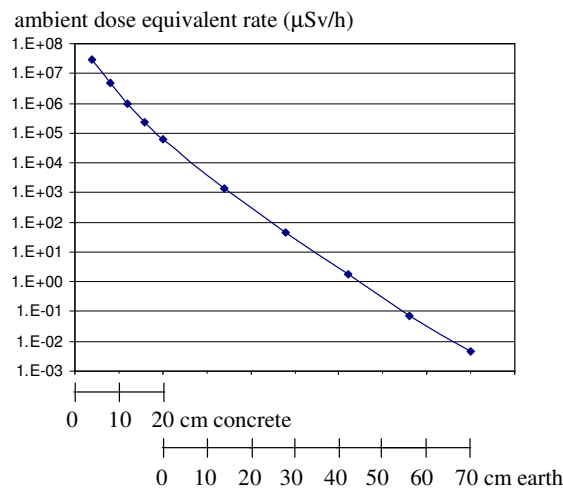


Fig.9 - Ambient dose equivalent rates due to air scatter (atmospheric pressure) behind tunnel outboard side wall, as a function of the concrete + earth thickness.

References

- [1] P. Berkvens, R. Kersevan and P. Colomp, Shielding assessment of the optics hutches of the ESRF beamlines, proceedings of Radsynch07 workshop, 2008.
- [2] S. Costantin, "Guidance for beamline shielding at the Australian Synchrotron" ASP-RADS-BLS-0001, revision 0 (March 2006).