ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOMS040

RADIATION SHIELDING DESIGN FOR THE X-BAND LABORATORY FOR RADIO-FREQUENCY TEST FACILITY –X-LAB– AT THE UNIVERSITY OF MELBOURNE

M. Volpi*[1], D. Banon-Caballero[2], M. Boronat[3], N. Catalan-Lasheras[3], R. Dowd[4], R. P. Rassool[1]
S.L. Sheehy[5,1], G. Taylor[1], S.D. Williams[1]

[1]The University of Melbourne, Melbourne, Australia
[2]IFIC, Universidad de Valencia, Valencia, Spain
[3]CERN, Geneva, Switzerland
[4]AS - ANSTO, Clayton, Victoria, Australia
[5]ANSTO, Kirrawee DC New South Wales, Australia

Abstract

Here we report radiation dose estimates calculated for the X-band Laboratory for Accelerators and Beams (X-LAB) under construction at the University of Melbourne (UoM). The lab will host a CERN X-band test stand containing two 12 GHz 6 MW klystron amplifiers. By power combination through hybrid couplers and the use of pulse compressors, up to 50 MW of peak power can be sent to any of to either of the two test slots at pulse repetition rates up to 400 Hz. The test stand is dedicated to RF conditioning and testing CLIC's high gradient accelerating structures beyond 100 MV/m. This paper also gives a brief overview of the general principles of radiation protection legislation; explains radiological quantities and units, including some basic facts about radioactivity and the biological effects of radiation; and gives an overview of the classification of radiological areas at X-LAB, radiation fields at high-energy accelerators, and the radiation monitoring system used at X-LAB. The bunker design to achieve a dose rate less than annual dose limit of 1 mSv is also shown.

INTRODUCTION

The X-LAB is being constructed in an existing radiation shielded bunker located in the basement of the School of Physics at UoM, under refurbishment after previously housing a 35 MeV electron betatron [1] until the late 1980s.

This space will become the first high-power, high-frequency accelerator laboratory in Australia. At the heart of the project is the technology transfer from the Partner Organisation CERN in the form of the multimillion dollar compact X-band accelerator radio frequency (RF) system known as XBOX3 [2, 3]. Refurbishing of the Melbourne University basement is going on, the first high power X-band pulses are planned for the end of 2022.

Conditioning of CLIC structures will take place in the X-LAB high power test stands renamed as Mel-BOX [4] (Fig. 1). Mel-BOX consists of twin low peak power, X-band (11.9942 GHz) 6 MW Toshiba E37113 klystrons and Scandi-Nova K1 modulators. Signals are combined in pairs allowing to sum up power of two klystrons, thus operating at 200 Hz at double power. This together with a pulse compressor on each line allows to reach the power of about 50MW for CLIC's baseline requirements [5] .

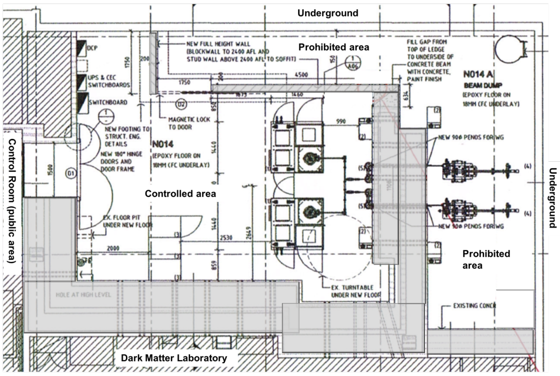

Figure 1: Layout of the new X-LAB and the configuration of the Mel-BOX test stands.

The use of high-gradient RF technology in accelerator facilities has a series of important benefits, such as compactness and cost-efficiency. However, compactness comes at the cost of having very high EM fields inside the RF cavities. High surface electric fields lead to spontaneous emission of electrons from the material surfaces, by means of quantum tunnelling of conducting layer electrons. Furthermore, this emission grows exponentially with field, becoming larger when gradients used get higher. Field emission of electrons is the origin of RF breakdown in high gradient structures' operation, but it can also cause other related problems. Field emitted electrons can be captured by the EM fields and be accelerated throughout the structures, causing the so-called dark currents [6]. If these electrons become energetic enough they can also produce ionising radiation when colliding with material walls. Dark currents can be a source of other issues, such as background noise in Beam Position Monitors (BPMs), transverse kicks of beams, and ionising radiation. To ensure adequate performance of radiation shielding in the X-LAB bunker area, the dark current of two high gradient structures has been used in this study.

---

* m.volpi@unimelb.edu.au

DARK CURRENT AND RADIATION IN HIGH-GRADIENT RF STRUCTURES

The dark current is the main radiation source of the X-LAB, understanding the process is fundamental to design an appropriate shielding. During high-power operation of CLIC structures the incident, transmitted and reflected RF powers are measured, together with dark current in the downstream and upstream Faraday (FD) cups. Downstream refers to the direction of RF power propagation. And in the case of CLIC structures, which are forward travelling wave, it also refers to phase travel direction. Dark current signals appear only in the peak power region where the E field is high enough for field emission of electrons to take place.

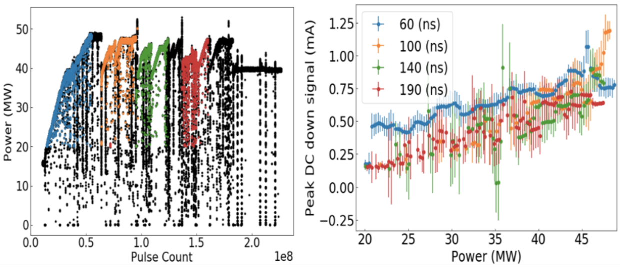

Figure 2: Structure conditioning plot on the left, relative downstream dark current measurements at various flat top pulse width on the right. Dark current radiation consistently goes down during conditioning.

Analysis of the conditioning data from the T24 CLIC prototype structure tested at CERN is shown in Fig. 2. RF power is presented, marking different pulse lengths with different colours. Following that, the peak dark current as a function of the input RF power is shown, where the conditioning ramps for different pulse lengths are overlapped. It can be seen how the pulses of later stages of conditioning (red) present lower dark currents at same power levels than those of earlier stages (blue). Another important point is the dependence with RF power, which is linear instead of exponential, as one would expect from the Fowler-Nordheim [7] equation of field emission. This happens because, in long term operation, the exponential growth as a function of power is compensated by a decay with the number of pulses, because breakdown occurrences change the emitters' location and intensity.

TD24 structure particle simulations are done making use of CST's Particle In Cell (PIC) solver. EM fields resulting from eigenmode solver are imported in the first cell. CST allows to place electron field emission property in a selected area, the iris surface is chosen because it has the highest E field. Dark current magnitude is obtained placing PIC 2D monitors, as if they were FD cup measuring current on selected planes. To calculate the radioactive emission outside the structure, the energy profile of the electrons inside the structure has been obtained (Fig. 3). The maximum energy observed is downstream up to 18 MeV, although this energy depends of the type of the structure and the applied gradient (100MV/m). Electrons are able to reach 20 MeV downstream with a positive frequency shift due to the tuning of the pulse compressors [2].

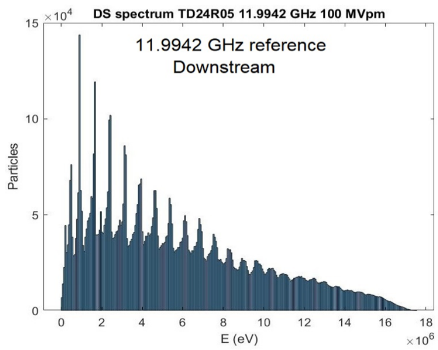

Figure 3: Energy spectrum of electrons reaching downstream Faraday cups in CST periodic simulation of the TD24.

INTERLOCK SYSTEM AND SIMULATION

The X-LAB (Fig. 1) area consists of a control room (public area), a bunker (controlled area) and a beam line (prohibited area) of 60, 50 and 25 m^2 respectively. These zones must be physically delimited so that access is monitored and controlled, a dosimeter to access to the controlled area and prohibited area will be mandatory.

In the first phase of operation, the X-LAB will be used for high power RF testing, producing dark current but without an accelerated beam, which planned for the next stage of implementation. Standard radiation safety requirements apply, including the following controls:

- Radiation monitors will be placed both inside and outside the bunker and run for twenty four hours a day, the modulators interlocked if the radiation levels are too high.
- Temperature, pressure, reflected power and more threshold interlocks shutdown RF power, meaning that the experiment stops, under certain circumstances a manual reactivation is required.
- Interlocks on the beam line door stop modulator pulsing if opened.

The estimation of radiation dose in the underground bunker area has been performed with FLUKA Monte Carlo software [8]. The simulation includes: a detailed bunker geometry (beam dumping including existing air holes in concrete, air condition pipes, emergency exit), two high gradient structures (TD24), upstream and downstream FD cups and the lead shielding around the downstream FD cups where a radiation peak is expected. In this particular configuration the "targets" are the steel plates of the downstream FD cups used to measure the dark current. The lead shield consist of a lead boxe 20cm tick around each downstream FD cup and two lead wall on the sides of the two test stands as shown on Fig. 4

A 20 MeV downstream electron beam, 1 MeV upstream electron beam and 0.5 MeV from the side of the structure

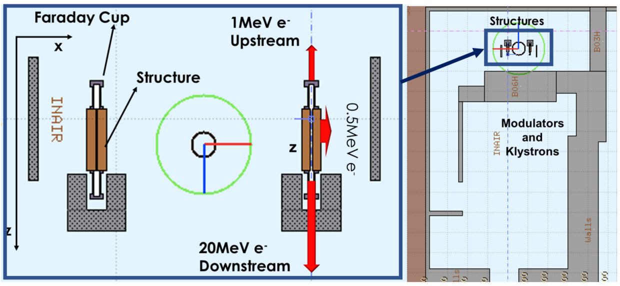

Figure 4: FLUKA simulation, structures shield (left) and X-LAB area (right).

are been simulated in each structure (Fig. 4). Since the dark current decreases during conditioning an average value of 0.5 mA and a 100 ns flat top pulse was chosen for the simulation, the maximum repetition rate of 200Hz for each test stand is also applied.

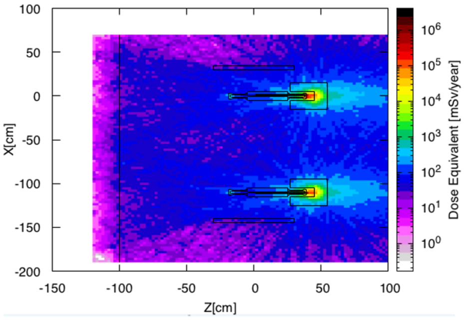

Figure 5: Annual DOSE-EQ estimation around the structures (beam line area).

The equivalent dose (DOSE-EQ) addresses the impact that the type of radiation has on tissue, and is defined as the absorbed radiation dose in an organ or tissue corrected by a radiation weighting factor. Using the above energy profile, the annual dose that would be expected in the different points of the underground laboratory has been estimated (Figs. 5 and 6). The annual dose limit at the University of Melbourne is 1 mSv, this calculation assume that a person will work 50 weeks a year, 40h/week, weekly dose rate cannot exceed 20 uSv/week over 50 weeks. As expected, the peak radiation dose is around the downstream FD cups (Fig. 5), a dose of a few hundreds mSv/h as been also measured and simulated at CERN inside X-band facilities and similar high gradient structures [5].

Figures 6 and 7 show the DOSE-EQ of the top view (XZ) and the front view (YX) before and after applied the annual threshold of 1mSv/year. As shown in Fig. 7, no radiation above the annual limits is anticipated outside the beamline area, thus the radiation shielding design is sufficient for operation. As expected the the less shielded zone is the ceiling of the beam line area in which an existing ladder is installed as an emergency exit (YX Fig. 6). The garden on top of the laboratory and the emergency exit room will be monitored with radiation monitors connected to the interlock system.

Another X-ray source are the two high power klystrons, the impact of the electrons in the collector produce photons by bremsstrahlung. Klystrons are self-shielded by the company and they will be also monitored. The annual dose of two klystrons measured at CERN is below the University limit, that secure the access to the controlled (bunker) area during the operation of the Mel-BOX.

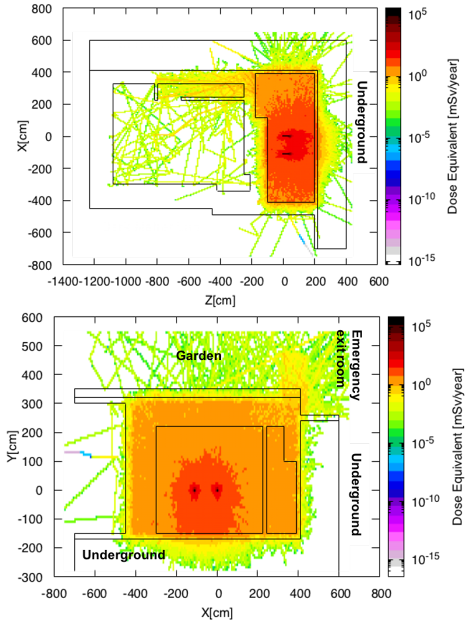

Figure 6: Top (XZ) and front (YX) estimations of the equivalent dose inside the X-LAB.

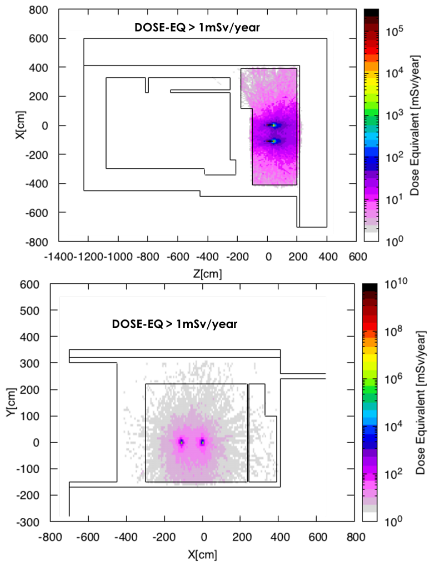

Figure 7: X-LAB equivalent dose above the annual limit of 1mSv/year.

CONCLUSION

The current radiation shielding design is easily adequate for radiation protection, along with interlock and radiation monitoring systems. This serves to bring the underground accelerator laboratory up to 21st century radiation safety protocols to secure the future of the X-LAB research programme.

REFERENCES

[1] S.F. Macintyre and R.J.W. Selleck, *A short history of the University of Melbourne*, Melbourne University Press, 2003. `https://physics.unimelb.edu.au/about/history`

[2] N. Catalan Lasheras *et al.*, “Construction and commissioning Xbox3: a very high capacity X-band test stand”, in *Proc. of IEEE Power Modulator and High Voltage Conference*, San Francisco, USA, 2016.

[3] X. W. Wu *et al.*, “High-Gradient Breakdown Studies of an X-Band Accelerating Structure Operated in the Reversed Taper Direction”, in *Proc. IPAC’21*, Campinas, Brazil, May 2021, pp. 1543–1546. `doi:10.18429/JACoW-IPAC2021-TUPAB076`

[4] M. Volpi *et al.*, “The Southern Hemisphere’s First X-Band Radio-Frequency Test Facility at the University of Melbourne”, in *Proc. IPAC’21*, Campinas, Brazil, May 2021, pp. 3588–3591. `doi:10.18429/JACoW-IPAC2021-WEPAB374`

[5] “A Multi-TeV linear collider based on CLIC technology: CLIC Conceptual Design Report”, edited by M. Aicheler, P. Burrows, M. Draper, T. Garvey, P. Lebrun, K. Peach, N. Phinney, H. Schmickler, D. Schulte and N. Toge, CERN-2012-007. `doi:10.5170/CERN-2012-007`

[6] D. Banon-Caballero *et al.*, “Dark Current Analysis at CERN’s X-band Facility”, in *Proc. IPAC’19*, Melbourne, Australia, May 2019, pp. 2944–2947. `doi:10.18429/JACoW-IPAC2019-WEPRB059`

[7] P.H. Cutler *et al.*, “Theory of electron emission in high fields from atomically sharp emitters: Validity of the Fowler-Nordheim equation”, *Progress in Surface Science*, vol. 42, pp. 169-185, 1993. `doi:10.1016/0079-6816(93)90068-7`

[8] T.T. Böhlen *et al.*, “The FLUKA Code: Developments and Challenges for High Energy and Medical Applications”, *Nuclear Data Sheets*, vol. 120, pp. 211-214, 2014. `doi:10.1016/j.nds.2014.07.049`