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IRPS Bulletin

Newsletter of the International Radiation Physics Society

14th International Symposium Radiation Physics - Cordoba, Argentina

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IRPS Council and Editorial Board 2019

From the Editors

Dear Colleagues,

Welcome to the very first issue with the new editorial team and the first of 2019. As 2018 was an election year, we have a report from the outgoing president, Professor Chris Chantler and a first report from the new President of the Society, Professor David Bradley. In addition we have a conference report from the Society's International Symposium on Radiation Physics (ISRP-14), held in Cordoba, Argentina, in October, 2018, a report from the 12th Egyptian Radiation Physics and Protection Conference, by Mohamed Gomaa, IRPS vice president for Africa and Middle East, and two articles from our members, one by Ming Tsuey Chew on radiobiology research with heavy ions at Chiba in China, and one by Dudley Creagh on the history of synchrotron radiation science in Australia.

We would also like to introduce ourselves and make a special plea for material for forthcoming bulletins. Richard Hugtenburg is an Associate Professor of Medical Physics at Swansea University (UK), while Katie Ley and Maria Pinilla are both currently pursuing PhDs. Katie is at the University of Surrey (UK) and is investigating the development of silica beads as dosimeters and Maria in the Department of Mechanical and Nuclear Engineering, Kansas State University (USA) is studying the replacement of dangerous radiological sources in oil well logging. Several of us are indeed young, and we are all energetic, but we rely on submissions from members to keep the bulletin fresh and interesting. Please send your submissions to any or either of us. Our coordinates are on page 2.

We wish you a happy and productive 2019!

Richard, Katie, and Maria, Editors

From the President

As the incoming President of IRPS, first allow me to introduce myself, also giving an opportunity to reflect on a little bit of history of the Society. Believing myself to be one of the longest standing members of IRPS, with some associated ability to record a little of the background, I have enjoyed an association with what was to become the Society since March 1982 when I attended ISRP-2 in Penang (you can do the calculation to obtain a fair estimation of my age). The only two other living members of the Society that I know to have had a longer association with the grouping than myself would be Professors Richard Pratt (University of Pittsburgh) and Suprakash Roy (erstwhile Head of Physics at the Bose Institute, Kolkata), both of whom participated in ISRP-1 (Kolkata). The Proceedings of that meeting appeared as NBS Special Publication 461 (I invite you to Google 'National Bureau of Standards Special Publication 461, International Symposium on Radiation Physics' in order to find a record of this). I am really happy to own a hardcopy of that Proceedings, indeed I have a hard copy of every single Proceedings, up to ISRP-13, with ISRP-14 now in the midst of the refereeing process, more of which below).

I want to talk about the passion that comes with being involved in research, not just in as far as it refers to my own personal case but surely that which was born in all of us in wanting a creative outlet from within which we might contribute meaningfully. I also want to make an appeal for all of us to remain faithful to that passion and to fight against jaded work, one all too clearly projected oh so strongly into manuscripts. Often, somewhere along the way, the various pressures raining down on us can be seen to take over, not least the institutional demands we are all aware of, sensing many of us to have lost direction, producing turgid manuscripts that frankly no-one wishes to referee or indeed publish. Going back to my early 20s, I recall the thrill of being accepted into academia as a junior scientist, albeit with naivety abounding. To participate in ISRP-2 was part of that same sense of the thrilling, the contents of that meeting and also of the contents recorded in the Proceedings of ISRP-1 creating a sense of adventure of which I wanted so badly to be a part. Indeed I was so thrilled that ever since that time I have remained totally hooked into wanting to be a part of the arena of radiation physics research (an area some might like to call Nuclear and Applied Nuclear Physics, although equally imperfect since a great deal of what we do concerns atomic phenomena, not just inner-shell either – perhaps we could invite members to write in to let us know what they might suggest to be an appropriate encompassing moniker for what we do). As an aside, the constitution of the IRPS defines Radiation Physics as "the branch of science which deals with the physical aspects of interactions of ionizing radiations (both electromagnetic and particulate) with matter."

Subsequent to the 1985 ISRP-3 (held in Ferrara and sadly the only other of the ISRPs that I did not manage to attend) I was to join with Professor Pratt (RHP) and John Hubbell in writing the constitution of this Society, also for the first decade or so of its existence (IRPS born 29 September 1985) joining with RHP in editing of IRPS-News, the forerunner of the present Bulletin (Dudley Creagh taking over in the mid 80s and making it so much better – indeed Dudley has been the dominant force in the Bulletin ever since).

Attending ISRP-2 inspired me to join in research with Professor Ananda Mohan Ghose (joint proposer of the Society with John Hubbell, also becoming my PhD supervisor for the period 1982 – 1985, with much input from RHP). The wonderful thing that evolved from the various relationships was the opportunity to become a member of the University of Pittsburgh Atomic Physics Theory group, an amazing privilege for an experimentalist and one that further opened my eyes to what I could reasonably call my own personal Encyclopedia of Ignorance. I recall some really sage advice from RHP in response to my comment that the work that he was suggesting for me sounded difficult. It was a simple and direct response, couched in just five words; 'Well don't do it then'. I have since had the opportunity to use the same five words on others and wow does it hit the target. You get what I mean and the direction in which this advice is going and yes I openly admit to living in the same non stone-proof glasshouse that all of us occupy. So let me once again appeal to all of us to remember how we typically came to be part of academia, the passions that need to be aroused in engaging in meaningful research and the recollection that reward rarely comes from lack of effort (not just in doing the work but also in writing about it in great and convincing style).

Finally, I skip forward to the present and to what is approaching a university career of some 37 years duration (currently within the tail of the $e^{(1-x)}$ function). I share with you yet another key underpinning part of the IRPS Constitution: "The primary objective of the Society is to promote the global exchange and integration of scientific information pertaining to the interdisciplinary subject of radiation physics", including "the promotion of (i) theoretical and experimental research in radiation physics, (ii) investigation of physical aspects of interactions of radiations with living systems, (iii) education in radiation physics, (iv) utilization of radiations for peaceful purposes". Towards this end and together with the series of triennial conferences that the Society sponsors (the ISRP series, the series International Topical Meeting on Industrial Radiation and Radioisotope Measurement Applications, IRRMA, and the series International Conference on Dosimetry and its Applications, ICDA) IRPS publishes the IRPS Bulletin. Indeed everyone is welcome to put material forward, to be considered for inclusion within the Bulletin. Let us also look forward to meeting at the various conferences the Society sponsors, all of us putting forward our very best work, worthy of consideration for inclusion in the various Proceedings and publishable therefore in high quality journals.

David A. Bradley

Reflections from the Immediate Past President

It has been a great three years for the Society and for our Conferences, mixed perhaps with apparent chaos in international affairs. I look forward to the next three years, for the former will continue in strength, under the new leadership of Prof David Bradley.

The Major conferences of the International Symposium of Radiation Physics [Cordoba], ICDA3 [Surrey] and IRRMA [Chicago] went extremely well ard were a credit to the Society, Membership, and all attendees and organisers. I thank everyone for their hard work in putting exciting programmes together. The Special Issues, the Proceedings and Forum issues including ForumBA, ICDA3 and IRRMA have all come out very well I think and I congratulate all contributors and the Guest Editors. Processing of the ISRP Cordoba meeting Special Issue are proceeding well and at a good pace. I note that the IXAS meeting in Poland last year is also being published in Radiation Physics and Chemistry and augurs strong impact and citations for the Journal. We remain a first quartile journal, which is of importance in some regions for submissions, and that is in part up to you, all members and contributors, for submitting and maintaining a high standard (and also for reviewing, editing and rejecting to strengthen that standard!).

At Cordoba we gained some 40 new members, which is an exciting and healthy growth which should continue with each year and each Conference.

We thank the team of Larry Hudson and Ron Tosh for carrying the flag with our Bulletin over many years now, and having just now passed that duty in transition to Richard Hugtenburg, Katie Ley and Maria Pinilla. The new team has the great energy and vigour to carry us through many years and with the encouragement of members and Council, and interesting contributing articles, we will do just that.

During the last three year we have set up a new website, so that currently we have two websites in parallel. This is excellent and we owe a great debt to Shirley and Dudley for managing the website and distributing the Bulletin. This will continue in the near future and I hope that we can maintain and update the websites for all current and future events (that is a little message to myself!).

David has welcomed the new Councillors and I echo that Welcome. Every new, renewed and Continuing Councillor is fully deserving and we hope fully active and engaged. We need your help for the health of the Society and the activities. We thank the incoming new Membership Officer Eric Shirley and all the past Councillors who are in ‘recess’ at the moment. We need you more and not less!

Relating to my personal journey with the Society, I give Special Thanks to the late John Hubbell, and to Dudley Creagh and Shirley McKeown to whom I owe and we owe a great debt. John and Dudley have both mentored me, and I would like to think that one of the key and most important purposes of the Society is the encouragement and mentoring of developing scientists the world over. If they have done this for me, if you have done this for me, and you have, then I thank you and I celebrate the success of the Society. In that case, which is true, it is then incumbent upon me to encourage, mentor and aid the development of other (young) scientists. Mentoring includes professional, emotional and moral aspects, and I would hope that the Society has helped in all these areas.

I have many friends in the Society at all levels and would like to thank them all for this stage of the journey. I thank Jorge for the minutes and David for taking the helm, and Isabel and Pedro in particular for the coming ICDA-3 in Portugal but for much more.

Even though it is discussed elsewhere, I also look forward with excitement to the coming meetings over the coming three years:

- ICDA-3 (2019, Lisbon, Portugal) P. Vaz, I. Lopes
- IRRMA-11 (2020, Moscow, Russia) S. Dabagov
- ISRP-15 (2021, Malaysia) D. Bradley, Iqbal Saripan

With the exciting program coming, I hope that we all can be as fully involved in the Society to everyone’s betterment!

Very best wishes,
Chris T. Chantler

14th International Symposium on Radiation Physics

October 7-11, 2018 - Córdoba, Argentina

What it left in science and hope

By: Marcelo Rubio

The fervor and the intensity of life during the days of the 14th International Symposium on Radiation Physics, gives rise to the analysis herein of what it left us regarding science and technology. Multiple contacts were formed between colleagues and the participants from **32** countries of the **five** continents during the conference are now becoming new joint projects, and most of them were born within ISRP-14. We have had, in Córdoba, part of the most select human resource applied to the study of radiation and its interaction with matter from all over the world. Anyone who attended the symposium could share their insights with scientists from high-end international institutions such as NIST, INFN or Kyoto University *(just to mention some of them at the risk of injustice, among several dozen other institutions present*).

Winner of the Didier Isabelle Award for best oral presentation by a student was Debora de Paiva Magalhaes (Laboratório Nacional de Luz Síncrotron, Brazil)

Thus, how relevant and ephemeral, in turn, were the cold hard numbers of ISRP-14, already expressed as: **281** scientific abstracts, **34** plenary speakers, with an enormous vocation to tell us which level (aspect) of science they currently pursue. In addition, the corridors were full of active minds in their own traditional clothes and with their customs of origin. Hiking through the colonial spanish style Argentine Pavilion allowed us to listen to so many different languages and accents from over 30 countries, that were unified in English when it came to communicating with each other.

Winner of the best Poster Prize Jose Vedelago (Instituto de Física Enrique Gaviola, Argentina)

In these days of a hot January in Argentina, I am writing to tell you that the editors assigned by **Radiation Physics and Chemistry** are coordinating the evaluation of **157** manuscripts submitted for publication in the Special Issue dedicated to ISRP-14.

It is Cordoban people doing science in this Mediterranean Argentina who appreciate the effort made by every participant who, under economic hard times for science, managed to obtain the resources needed to travel. To all of them, the greatest gratitude from those who organized this symposium. The year **2018** was an exceptional year to bring to our city the radiation physics scientific world. We have accumulated more than a hundred formal messages of thanks for the organization and reception we provided. In short, it was only because we tried to be warm hosts, attentive at all times to the needs of our guests; to make them feel good with what we have, which is not little.

But, let us see what was left; a task not easy to synthesize, because it was a large task, varied, complex, specific, and difficult to apprehend in this instance.

Applications of radiation physics to Health

Fundamental physical processes of radiation intervened in determining, with high-accuracy radiative techniques; why dementia is related to a fragment of metal binding to an amyloid β protein.

Regarding the treatment of cancer with particulate radiation or photons, new spatial high-resolution dosimeters were presented, constructed of Ge-doped optical fibers, which make it possible to guide the patient's treatment in real-time.

Quantum metrology

At a time when CEPROCOR (*My scientific institution in Córdoba*) installed an ambitious program of reference standards and materials (CEPROMAT), we had an incredible vision within ISRP-14 from NIST, with quantum metrology. That is, using radiation measurement of very high accuracy to trace the basic units of the International System to the universal quantum constants.

New spectrometers and radiation sources

On one hand, giants with huge feet were well planted, such as SIRIUS, the fourth generation synchrotron of Campinas in Brazil. One of the first of three in the world, where CEPROCOR already has a space earned on its CARNAÚBA beamline through the merit of researchers from the center that contributed with projects in agro-environmental sciences, approved and considered for their instrumental development.

On the other hand, competing in innovation with the large facilities, small x-ray sources and detectors assembled as compact x-ray spectrometers were demonstrated. From Kyoto there came the use of high resolution 3D printers for the design and construction of new portable spectrometer prototypes. From INFN, Italy, new projects for proton accelerators 70 cm long were proposed. Imagine the in situ applications that could be developed by joining small accelerators with portable spectrometers especially designed for each application by 3D printing!

Joining radiation physics with universal art

Virtual or real museums? The challenge of preserving the cultural heritage of humanity. What do we do to protect them with the passing of decades and centuries? Do we restore them? Or do we digitize them? From the perspective of radiation as a powerful tool to characterize, diagnose, preserve and cure samples of universal culture; ISRP-14 provided innovative methods to continue walking with them and see them intact with exact restoration processes. From here, the digitization of universal works of art still has no place.

What about Argentina at ISRP-14?

Among the **34** plenary speakers of ISRP-14, seven were Argentinians, with several Cordobans among them. Their contributions were highlighted as works as well as the rest of the invited speakers, and they left high the level of our formation, schools and scientific aptitude. There were also many oral contributions and national posters, which had the attention of all of the public present in the galleries of *Patio de las Palmeras*; one of them, from FAMAF, won the 2nd prize of the International Radiation Physics Society. The first prize was for a young researcher from Brazil. It is difficult to select any work, but when it comes to disseminating science, I suggest reading the first-rate work of our geologist colleagues of CICTERRA in the use of high-definition radiation and spectrometers for the mineralogical characterization on the nanometric scale. Our old National University of Córdoba, with one of its oldest careers, staying alive at a global level.

The greatest gratitude to all participants at ISRP-14, to our beloved International Radiation Physics Society for promoting the accomplishments in Argentina of the fourteenth scientific event of its historic Symposia series. I want to thank all national and foreign institutions that gave their endorsement and support to ISRP-14. And, finally, which was needed from the very beginning, to thank the ISRP-14 administrative staff and all members from the different organization committees that made it possible to provide a worthy format for this event.

The Cordoba meeting showed that hope is the permanent flame of the science engine, and it remains intact in each one of the scientists who day by day define, construct and defend what we currently call radiation physics.

The 12th Egyptian Radiation Physics and Protection Conference

Mohamed Gomaa - IRPS vice president for Africa and Middle East

Radiation physicists and radiation protection experts gathered for the 12th Radiation Physics and Protection conference which was held from 27 - 29 October, 2018 in Cairo, Egypt. The conference took place at the main Building of Egyptian Atomic Energy Authority, Nasr City, Cairo.

Historically, 11 previous conferences were held from the year 1992 until 2012. Several of these conferences were held in the following Egyptian cities (Qena, Assiut, Menia, Beni Suwf, Alexandria, Ismailia) with the aim of establishing good cooperation between universities and nuclear centers.

Conference Opening Ceremony

The conference activities included 15 scientific sessions, two invited talks and one round table.

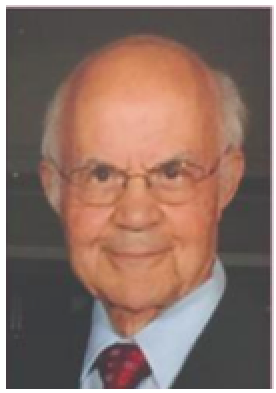
Among radiation physics topics were radiation sources and detectors, theoretical physics, environmental Physics and medical Physics. Among Radiation Protection topics, operational radiation protection, safety of research and power reactors, decontamination after accidents and regulations were discussed.

Conference Photo

The invited talks included brief talks about the UNSCEAR, IRPA and the IRPAFEA congresses.

The conference youth award was presented to Mr Mohamed Helmy (a demonstrator at Assiut University) for his excellent presentation of his paper in the field of environmental physics. Great effort was made by Mr Ibrahim Duhaini from Lebanon (currently Treasurer of IPMP) to cover various topics of Medical Physics including training and safety of a medical facility and NIR. Furthermore, Dr Amgad Shokr from IAEA presented an invited talk in the field of research reactor safety.

Participants from several universities, and nuclear and atomic authorizes as well as from several ministries participated in the conference. The conference activities also included scientific exhibitions and the conference was sponsored through donations from companies and personal funds, as well through locally supported IAEA radiation protection projects


The Conferences Sponsors: The late Prof. Dr Anas El Naggar. Dr Galal El-Sayyad (AMALE International). The late Dr Hussein Abou-Leila (SATCO fund).

Greetings from Mohamad Gomaa

Photon to Particle Radiation for Radiotherapy

Ming Tsuey Chew
Centre for Biomedical Physics
School of Healthcare and Medical Sciences
Sunway University, Malaysia

The principle of radiation therapy is to deposit enough energy through the ionization of atoms to damage and inactivate or kill tumour cells but to spare normal tissues or organs surrounding the tumour. Ideally, the higher the delivered energy to the tumour tissue, the higher the probability that the tumour will be fatally damaged. Hence, radiation types that can localize the deposited energy within the tumour and within a well-defined volume would greatly benefit radiotherapy.

Radiation is the emission of energy in the form of waves or particles from an atom or nucleus. The two main forms of radiation are particulate radiation which is directly ionizing and electromagnetic radiation which is indirectly ionizing. Particulate radiation consists of atomic or subatomic particles (such as electrons, neutrons, protons and heavy charged ions) which carry energy in the form of kinetic energy of mass in motion, while, the energy from electromagnetic radiation is carried by oscillating electrical and magnetic fields travelling through space at the speed of light.

Radiation therapy

Radiation therapy is based on the use of direct or indirect ionizing radiation (Hall and Giaccia 2012). Directly ionizing radiation has sufficient kinetic energy to disrupt the atomic structure of the absorber through which they pass directly and produce chemical and biological changes. Ionizing radiation can remove tightly bound electrons from their atomic orbits, causing the atom to become charged or ionized. The atom can then react with neighbouring atoms, forming new chemical bonds. The energy released by one ionizing event is, on average, 33 eV which could easily break a strong chemical bond, for example, a C=C bond with an associated energy of 4.9 eV (Hall and Giaccia 2012). The charged atom can interact with several atoms or molecules, which in turn, lose kinetic energy with each successive interaction until all energy has been absorbed by the material. Charged particle radiations are directly ionizing radiations. Directly ionizing radiation causes direct and indirect actions in cell damage by radiation. Charged particle radiation induces approximately 70% direct action and 30% in-direct action damages on cells, while, photon radiation induces 30% direct action and 70% in-direct action damages.

In direct action of directly ionizing radiation, the radiation interacts directly with the critical target in the cell; the atoms of the target itself may be ionized or excited through Coulomb interactions, leading to disruptions of the atomic structure, producing chemical and biological changes. Densely ionising radiation of charged particles with high linear energy transfer (LET) produces direct action damage that are more severe such as clustered damage as compared to sparsely ionizing radiation (Ward 1985; Schipler and Iliakis 2013). As LET increases, the clustered damages also increase as shown in Figure 1.

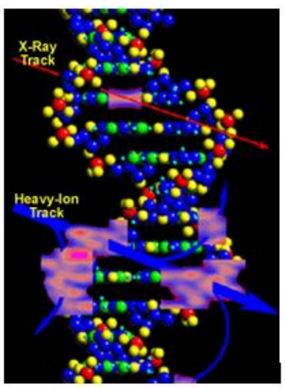


Figure 1. Heavy ions track is more damaging to DNA molecule than X-ray Adapted from: https://srag.jsc.nasa.gov/SpaceRadiation/Why/Why.cfm

Conversely, in indirect action, the radiation interacts with other molecules and atoms within the cell to produce free radicals (mainly water, as approximately 80% of a cell is composed of water), which are able to diffuse into the cell and damage the critical region within the cell. Indirect actions damage critical site by reactive species produced by ionization in water which creates free radical that damage the target. Examples of radicals are reactive free radicals such as H_2O^+ (water ion) and $^{\bullet}OH$ (Hydroxyl radical), which are able to damage the DNA of the cell. These free radicals damage the cell by breaking the chemical bonds and producing chemical changes via their 'unpaired valence electrons' which are highly chemically reactive. These hydroxyl free radicals has the ability to diffuse in tissue about twice the diameter of a DNA double helix and causes approximately two third of all biological damage (Hall and Giaccia 2012).

Indirect ionization process occurs when non-charged 'particles' such as photons or neutrons interact with atoms and molecules resulting in the release of charged particles (such as electrons) that interact with atoms and molecules by direct ionization mechanism. These non-charged particles do not produce chemical or biological damage themselves but when they are absorbed in the material through which they pass, they give up their energy to produce fast moving charged 'particles' (electrons) that in turn are able to produce damage. Photons have to first undergo interactions to produce free electrons, which are then ionize. There are four basic photon interactions with matters namely; photoelectric effect, Compton's effect and pair production that produces a high energy electron. Rayleigh or coherent scattering is a type of scattering that occurs between a photon and an atom where, essentially, no loss of energy occurred; but only a slight deflection of the incident photon (Cherry, Sorenson, and Phelps 2003).

Radiation damage

Radiation of cells induces several basic types of response from the cells such as oxidative stress, activating and inactivating of different signalling pathways, DNA damage such as base loss, base modification, dimer, single and double strand breaks (DSB); and cell cycle delay response of the cells will then modify the effects of irradiation and affect the radio sensitivity status (Hall and Giaccia 2012). Radiation can result in DNA damage in the tumour cells that could be repaired without error by the tumour cells, incorrect DNA repair resulting in genetic aberrations or tumour cell death, or significant DNA damage that could not be repaired. In essence, Homologous Recombination repair (HRR) requires an undamaged DNA strand as a template to repair without error by the damaged cells, which primarily occurs in the late S/G_2 phase. On the other hand, Non Homologous end-joining (NHEJ) occurs primarily during G1 phase of the cycle, do not required a template and they are error prone repair (Hall and Giaccia 2012). Tumour cells that have the capacity to repair the DNA damage induced by the radiation are said to be radio-resistant.

Radiobiology of radiotherapy

The goal of radiation is to kill all tumour cells without incurring serious damage to the normal surrounding tissues. To achieve this goal, fractionation radiotherapy was implemented to spare normal tissues surrounding the tumour as one single high dose could be detrimental not only to tumour but also to normal tissues. At the same time, it also allows tumour cells to reassort or redistribute into the mitotic phase which is radio-sensitive. Sparsely ionizing radiations fractionated radiotherapy are limited by the 5 Rs of radiobiology (Steel, McMillan, and Peacock 1989; Hall and Giaccia 2012). The 5 Rs by Steel, McMillan and Peacock (Steel, McMillan, and Peacock 1989) is an extension of the 4 R's by Wither (Withers 1975) where the additional 'R' represent cells from different types of tumour have different inherent radiosensitivity. The 5 'Rs' are Reoxygenation, Redistribution, Repopulation, Radiosensitivity and Repair, (Steel, McMillan, and Peacock 1989). These 5 Rs determine the effectiveness of the fractionation. Fractions increases damage to a tumour because of Reoxygenation and Reassortment of cells into radiosensitive phases of the cycle.

Reoxygenation - oxygen plays an important role in radiation as it enhances radiation effect; known as the Oxygen Enhancement Ratio (OER). Oxygen is required in photon radiation to help fix the radiation damage as describe by Hall and Giaccia (Hall and Giaccia 2012). The high energy electrons formed in the body through interaction with photon radiation when impinge upon the water molecules which are abundant in the body, hydroxyl radicals are formed. These radicals are highly unstable and extremely reactive (chemically) and could damage DNA. However, these damages are repairable and the damaged DNA can be restored and cell kill prevented. This kind of damage which is common in photon radiation makes radiotherapy less effective. But, if the radical reacts with oxygen prior to the collision, it form a new type of radical called a 'peroxy radical' that is difficult and impossible to repair chemically, consequently 'fixing' DNA into a permanent irreparable state (Grimes and Partridge 2015). This is the basis of the importance of oxygen in radiotherapy. Gray et al. were the first to demonstrate that oxygen plays an important role on biological response by affecting the chemical changes produced directly in the cells by radiations (Gray et al. 1953). Re-oxygenation has accounted for the success of fractionated radiotherapy of hypoxic tumour cells; when a radiations tumour has shrunk and re-oxygenation of tumour occurs (Withers 1975) due to reopening of temporarily occluded blood vessels; and also resorption of dead cells which lead to decreased distance from capillaries to tumour cells (thus improving oxygen supply). Most malignant tumours contain a proportion of hypoxic cells and glioblastoma is known for its necrotic and hypoxic features (Amberger-Murphy 2009). Tumours that are hypoxic (low oxygen level) are radio-resistant to photon radiation and they require higher dosage of radiation to inactivate them. The OER is a measure of tumour sensitivity to radiation in the presence or absence of oxygen. It is usually expressed as the ratio of radiation dose required to produce a given effect in the absence of oxygen to the dose required to produce the same effect in one atmosphere of air (Hall and Giaccia 2012).

Redistribution also known as Reassortment refers to radiation-induced cell cycle effects (Withers 1975). The cell cycle is divided into four phases that is G_1, S, and G_2 and mitosis. In interphase (G_1, S, and G_2), the cell grows, duplicates its DNA content and prepare for mitosis. Mitosis involves the process of nuclear division and cytokinesis, resulting into two genetically identical daughter cells. G_0 phase is where cell stop dividing. Cells have different radiation sensitivities at different phase of the cell cycle; the most radiation sensitivity is late G_2/M phase of the cell cycle and S phase is the most resistant (Tobias 1985). S is the synthesis phase where damage repair can occur and any damaged induced can be repaired. G_2 is the gap phase between Synthesis and Mitosis. Radiation induces slowing of cell cycle progression by molecular checkpoint genes that tend to block irradiated cells in the G_2 phase (Hall and Giaccia 2012; Yamada and Puck 1961). Tumour cells are more sensitive in G_2/M phases of the cell cycle than G_1/S and when they are blocked in G_2/M due to a functional G2 checkpoint after exposure to radiation, they are more susceptible to the subsequent irradiation. Moreover, tumour cells have shorter cell cycle times in comparison with normal tissues. In contrast, normal cells are mostly in G0/G1 due to G1 checkpoint and are thus less susceptible to this type of sensitization (Ng et al. 2013). Fractionation in radiotherapy permits tumour cells to reassort themselves into a more sensitive phases of the cell cycle to allow effective killing (results in therapeutic gain) and favour survival of normal late responding tissues (Withers 1975; Hall and Giaccia 2012).

Repopulation, another name for Regeneration ~ fractionation radiotherapy allows normal tissues to repopulate which is important to reduce overkill and severe side effects for radio-sensitive tissues such as the skin or mucosa and surrounding normal tissues. For the early reacting normal tissues, fractionation interval brings about increase in radiation tolerance with increasing overall treatment time. When the interval time between two dose fractions exceeds the cell cycle, there will be an increase in the number of cells surviving due to cell proliferation. Just as normal cells can proliferate, tumour cells can also react with an increase rate of repopulation. At the same time as tumour shrinks post treatment, surviving tumour cells proliferate at an accelerated rate, and this counteracts the cell killing effect of radiotherapy. Repopulation time of tumour cells varies during radiotherapy (Withers 1975). Repopulation has a negative effect on fractionated doses.

Radio-sensitivity - different types of cells exhibit different intrinsic radio-sensitivity which is unique to the individual cell (Steel, McMillan, and Peacock 1989).
Radiation repair is the ability of cells to repair sublethal damage (Withers 1975; Elkind and Sutton 1959) and potential lethal damage (Phillips and Tolmach 1966).

Radiation Repair
All cells have the ability to repair radiation induced DNA damage depending on the doses. Although, it is essential to allow normal tissues to repair all repairable radiation damage, the tumour cells can also be repaired. Withers describes the repair of sublethal injury in normal and neoplastic cells (Withers 1975). In mammalian cells, the three radiation damage categories produced by ionizing radiations as describe by Hall *et al.* (Hall and Giaccia 2012; Hall and Kraljevic 1976) are: Lethal damage which are irreversible and irreparable and that leads to cell death; Sublethal damage (Elkind and Sutton 1959), damage that could be repaired in hours, usually considered to be completed within 24 hours; unless sublethal damage are added within this time which could interact to form lethal damage; and potentially lethal damage (PLD), that was first described by Phillips and Tolmach (Phillips and Tolmach 1966) is a component of radiation damage that can be modified by post-irradiation environmental conditions, such as allowing the radiated cells to remain in a non-dividing state. Under normal circumstances without interference post irradiation, PLD causes cell death but changing cellular growth conditions and the microenvironment of cells influences PLDR. Hence, PLDR (Weichselbaum 1986; Weichselbaum, Schmit, and Little 1982; Weichselbaum et al. 1984; Weichselbaum, Dahlberg, and Little 1985; Weichselbaum and Beckett 1987; Guichard et al. 1984; Weichselbaum et al. 1986) indirectly affect the radiosensitivity of cells and the radiocurability of tumours. These 4 and 5 Rs constraints the effectiveness of radiotherapy for tumours (Withers 1975; Steel, McMillan, and Peacock 1989; Hall and Giaccia 2012; Elkind and Sutton 1959; Phillips and Tolmach 1966).

Benefits of particle radiation therapy
Photons have low LET. In contrast, charged ions like protons, neutrons, α particle, ^{4}He-ion, ^{12}C-ion, ^{20}Ne-ion, ^{28}Si-ion, ^{56}Fe; and other are densely ionizing radiation with high LET. These high LET charged particles have more potential in killing tumour cells due to the increased ionization density. In addition, photons deposit energy in a highly dispersed mode, displaying a very broad energy distribution in tissue with the peak dose located relatively close to the surface charged ion interact with matter and

deposit energy differently (Allen et al. 2011). With photons, the absorbed dose by the body shows an exponential decrease in radiation dose with increasing tissue depth. In contrast, charged ions deposit minimal energy at the body’s surface, when the velocity is high, and deposit most of their energy just before they come to rest in tissue; this release of energy is termed the Bragg peak (Bragg 1906). Moreover, due to the large mass of ions; it travel in straight paths with a relatively well defined stopping range and the pattern of energy deposition is characterized by a dense core of ionization that is localised along the path of the ion (Allen et al. 2011). Together with the Bragg peak of ion that exhibit an inverse dose profile, where an increase of energy deposition with penetration depth and the dense core of ionization, this provide an excellent dose distribution in patients (Wilson 1946). As mentioned earlier, charged ions has increase in ionization density (high LET) and the DNA damage is more complex, which are difficult to repair and leads to increase relative biological effectiveness (RBE) which ultimately results in increase in RBE. Furthermore, majority of DNA damage by low or high LET is understood to arise indirectly through production of reactive oxygen species (ROS) and required oxygen to fix DNA damages (Allen et al. 2011). High LET radiation is known to reduce the requirement of oxygen with hypoxic cells being more sensitive to this type of radiations (Tobias et al. 1982). This reduction in the OER is of importance in treatment of hypoxic tumours which are radio-resistance. The reduced in OER by high LET could be due to the more clustered DNA damage induced which are difficult to repair by the cellular DNA repair systems (Hada and Georgakilas 2008). Furthermore, the cell cycle dependence of cell inactivation, is also reduced with high LET, near the Bragg peak region, it is less affected by variation in cell cycle-related radio-sensitivity and the damage caused is lethal to the cell (Orecchia et al. 2004; Durante and Loeffler 2009). Charged ion radiations are less affected by the 5 Rs of photon irradiation.

Particle radiation demonstrate precisely these characteristics with its pristine and sharp Bragg peak. The Bragg peak of ions provides the quality of the sharp lateral margin; has excellent precision at targeting of tumours by depositing maximum energy at the tumour and minimizing dose to critical organs at risk. The highest damage is achieved at the end of the range which is most suitable for small tumours located close to radiation sensitive organs in the body (Durante and Loeffler 2009). Moreover, the spread out Bragg peaks could encompass the tumour accurately with precise imaging.

Charged ion radiotherapy was first proposed by Robert Wilson in his seminal paper ‘Radiological Use of Fast Protons’ (Wilson 1946). Charged ion/particle therapy is also called ‘Hadron therapy’ which refers to the particles ability to participate in nuclear interactions in addition to atomic interactions based on charge (Allen et al. 2011). The first clinical centre proton therapy was at Harvard proton based therapy. Charged ions has the potential for treatments of radio-resistant tumours because of its high relative biological effectiveness (RBE), its Bragg peak that gives the ability to deliver its' maximum dose to the tumour cells and sparing of the healthy tissue of the body. The RBE of charged ion is important as it is used to calculate gray equivalent dose (GyE) in clinical practice. Charged ion radiotherapy has the potential to treat tumours that are radio-resistant and are located near to critical organs/tissues (Durante and Loeffler 2009). For example, glioblastoma is a primary tumour of the brain that are resistant to conventional radiotherapy and aggressive multi-modalities treatments with frequent post-treatments local relapses.

Additionally, ions have the quality of a sharp lateral margin (µm); depth dose depending on ions and energy of ions and excellent precision at targeting of a tumour as it uses the benefit of the SOBP energy deposition properties to minimize the maximum dose to critical body structures (Durante and Loeffler 2009). It is most suitable for small tumours located close to radiation-sensitive organs in the body. Most of the energy is deposited in the last final millimetres of their trajectory (when the speed slows). The initial energy (speed) of the charged ion determines how deep in the body the Bragg peak will form. The intensity of the beam determines the dose that will be deposited to the tissues. By adjusting the energy of the charged particles and by adjusting the intensity of the beam, pre-specified doses can be delivered anywhere in the patient's body with high precision. To irradiate a whole tumour area, multiple Bragg peaks (SOBP) of different energies and intensities are combined (Trikalinos et al.). As with photon therapy, the biological effects of charged particle beams increase with absorbed dose.

Charged ions interact with tissues to cause complex damage to the target, the same amount of radiation can have more pronounced biologic effects. Moreover, high LET radiation causes clustered DNA damage which Ward coined as locally multiple damaged sites (LMDS), also known as clustered damage which are not easy to repair to the original structure (Ward 1985; Hall and Giaccia 2012) as shown in Figure 1.

Charged ion radiotherapy potentially possesses physical and biological advantages over photons (megavoltage X-rays). The physical benefits of heavy charged ions provided by the Bragg peak allow precise delivery of high radiation doses to tumours while minimizing destructive irradiation to normal tissues and also critical organs at risk. Furthermore, its depth-dose distributions can be modulated/shaped to cover tumours of different shapes (SOBP); and the increase in ion density (LET) (Gray 1946) also makes it a more superior modality of radiation compared to photons.

The biological damages increases with LET until the optimum LET that is about 100 – 200 keV/µm (Hall and Giaccia 2012). Hall and Giaccia describe the reason for this optimum LET in producing a biologic effect is because at this density 100 keV/µm, the average separation between ionizing events just about coincides with the diameter of the DNA double helix (20 Å = 2 nm). Since DNA of the nucleus is the main target of radiation, this density has the highest probability of causing a DSB by the passage of a single charged particle. In contrast, high LET, like 200 keV/µm which is much more densely ionizing; the ionizing events are too close together and easily produce DSB but the extra energy is 'wasted' (as the cell can only be killed once) (Hall and Giaccia 2012). Moreover, the authors also describe the RBE of this densely ionizing glioblastoma cell line irradiated with various particles and LET as compared to X-rays).

Densely ionizing radiation produces higher RBE because it causes greater biological damage to the tumour cells compared to the equivalent less dense ionizing radiation exposure. In general, the RBE increases with the LET and is ion-dependent to reach a maximum RBE of around 100 – 200 keV/µm; is dependent on the level of cell kill, and then

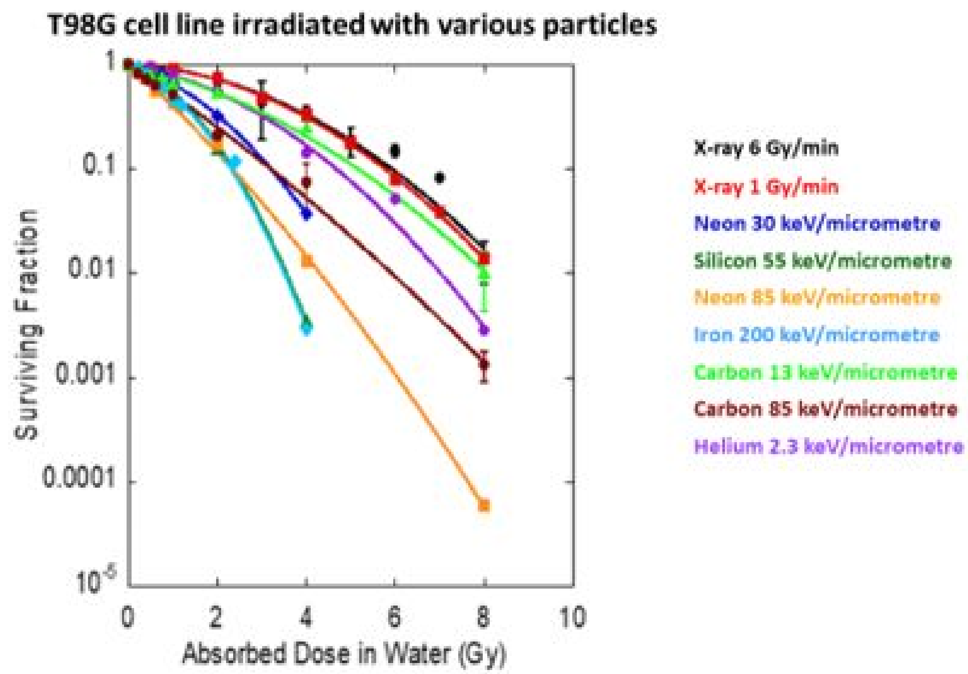


Figure 2. T98G surviving fractions irradiated with different charged particles and different LET as compared to X-rays (observe the low dose surviving fractions)

radiation is lower than the optimal LET radiation as RBE is the ratio of doses producing equal biologic effect, hence, this densely radiation has a lower RBE. The more densely ionizing radiation is just as effective per track, but less effective per unit (Hall and Giaccia 2012) as shown in Figure 2 (T98G a decreases because of overkill (Skarsgard 1998). Thus, the RBE of LET above the optimal LET radiation will be lower. These highly densely ionizing radiations (> 200 keV/µm) is just as effective per track, but is just less effective per unit dose.

Of interest is that, an increase in RBE in itself is of no therapeutic advantage unless there is a wide therapeutic window/index between RBE of tumour and normal tissues (Hall and Giaccia 2012; Joiner, van der Kogel, and Steel 2009). Also, of importance is the peak to plateau biological effective dose ratio as it can spare the normal tissue before hitting the tumour (Skarsgard 1998)

References

Allen, Christopher, Thomas B. Borak, Hirohiko Tsujii, and Jac A. Nickoloff. 2011. 'Heavy charged particle radiobiology: Using enhanced biological effectiveness and improved beam focusing to advance cancer therapy', *Mutat Res Fund Mol Mech Mut*, 711:150-57.

Amberger-Murphy, Verena. 2009. 'Hypoxia helps glioma to fight therapy', *Curr Cancer Drug Targets*, 9:381-90.

Bragg, WH. 1906. 'On the Ionization of Various Gases by the α Particles of Radium-No 2', *Proc Phys Soc London*, 20:523.

Cherry, SR, JA Sorenson, and ME Phelps. 2003. *Physics in Nuclear Medicine, ; 2003*.

Durante, M., and J.S. Loeffler. 2009. 'Charged particles in radiation oncology', *Nature Rev Clin Oncol*, 7:37-43.

Elkind, MM, and Harriet Sutton. 1959. 'X-Ray Damage and Recovery in Mammalian Cells in Culture', *Nature*, 184:1293-95.

Gray, L. H., A. D. Conger, M. Ebert, S. Hornsey, and O. C. A. Scott. 1953. 'The Concentration of Oxygen Dissolved in Tissues at the Time of Irradiation as a Factor in Radiotherapy', *Br J Radiol*, 26:638-48.

Gray, LH. 1946. 'Comparative studies of the biological effects of X rays, neutrons and other ionizing radiations', *Br Med Bull*, 4:11-18.

Grimes, David Robert, and Mike Partridge. 2015. 'A mechanistic investigation of the oxygen fixation hypothesis and oxygen enhancement ratio', *Biomed Phys Eng Express*, 1:045209.

Guichard, M., RR Weichselbaum, JB Little, and EP Malaise. 1984. 'Potentially lethal damage repair as a possible determinant of human tumour radiosensitivity', *Radiother Oncol*, 1:263-69.

Hada, M., and A.G. Georgakilas. 2008. 'Formation of clustered DNA damage after high-LET irradiation: a review', *J Radiat Res*, 49:203-10.

Hall, Eric J, and Amato J Giaccia. 2012. *Radiobiology for the Radiologist* (Lippincott Williams & Wilkins).

Hall, Eric J, and Ursula Kraljevic. 1976. 'Repair of Potentially Lethal Radiation Damage: Comparison of Neutron and X-Ray RBE and Implications for Radiation Therapy 1', *Radiology*, 121:731-35.

Joiner, MICHAEL C, ALBERT J van der Kogel, and G GORDON Steel. 2009. 'Introduction: the significance of radiobiology and radiotherapy for cancer treatment', *Basic Clinical Radiobiology Fourth Edition, Hodder Arnold Publication, London*: 1-10.

Ng, Wooi-Loon, Qian Huang, Xinjian Liu, Mary Zimmerman, Fang Li, and Chuan-Yuan Li. 2013. 'Molecular mechanisms involved in tumor repopulation after radiotherapy', *Transl Cancer Res*, 2:442.

Orecchia, R., M. Krengli, B. A. Jereczek-Fossa, S. Franzetti, and J. P. Gerard. 2004. 'Clinical and research validity of hadrontherapy with ion beams', *Crit Rev Oncol Hematol*, 51:81-90.

Phillips, RA, and LJ Tolmach. 1966. 'Repair of potentially lethal damage in X-irradiated HeLa cells', *Radiat Res*, 29:413-32.

Schipler, Agnes, and George Iliakis. 2013. 'DNA double-strand–break complexity levels and their possible contributions to the probability for error-prone processing and repair pathway choice', *Nucleic Acids Res*, 41:7589-605.
Skarsgard, LD. 1998. 'Radiobiology with heavy charged particles: a historical review', *Physica Medica*, 14:1-19.
Steel, G Gordon, Trevor J McMillan, and JH Peacock. 1989. 'The 5Rs of radiobiology', *Int J Radiat Biol*, 56:1045-48.
Tobias, CA, EA Blakely, EL Alpen, JR Castro, EJ Ainsworth, SB Curtis, FQH Ngo, A Rodriguez, RJ Roots, and T Tenfordf. 1982. 'Molecular and cellular radiobiology of heavy ions', *Int J Radiat Oncol Biol Phys*, 8:2109-20.
Tobias, Cornelius A. 1985. 'The future of heavy-ion science in biology and medicine', *Radiat Res*, 103:1-33.
Trikalinos, Thomas A, Teruhiko Terasawa, Stanley Ip, Gowri Raman, and Joseph Lau. 'Particle beam radiation therapies for cancer'.
Ward, JF. 1985. 'Biochemistry of DNA lesions', *Radiat Res*, 104:S103-S11.
Weichselbaum, R., W. Dahlberg, JB Little, TJ Ervin, D. Miller, S. Hellman, and JG Rheinwald. 1984. 'Cellular X-ray repair parameters of early passage squamous cell carcinoma lines derived from patients with known responses to radiotherapy', *Br J Cancer*, 49:595.
Weichselbaum, Ralph R. 1986. 'Radioresistant and repair proficient cells may determine radiocurability in human tumors', *Int J Radiat Oncol Biol Phys*, 12:637-39.
Weichselbaum, Ralph R, and Michael Beckett. 1987. 'The maximum recovery potential of human tumor cells may predict clinical outcome in radiotherapy', *Int J Radiat Oncol Biol Phys*, 13:709-13.
Weichselbaum, Ralph R, William Dahlberg, Michael Beckett, Theodore Karrison, Daniel Miller, John Clark, and Thomas J Ervin. 1986. 'Radiation-resistant and repair-proficient human tumor cells may be associated with radiotherapy failure in head-and neck-cancer patients', *Proc Natl Acad Sc*, 83:2684-88.
Weichselbaum, Ralph R, William Dahlberg, and John B Little. 1985. 'Inherently radioresistant cells exist in some human tumors', *Proc Natl Acad Sc*, 82:4732-35.
Weichselbaum, RR, A. Schmit, and JB Little. 1982. 'Cellular repair factors influencing radiocurability of human malignant tumours', *Br J Cancer*, 45:10-16.
Wilson, R.R. 1946. 'Radiological Use of Fast Protons', *Radiology*, 47:487-91.
Withers, H Rodney. 1975. 'The four R's of radiotherapy', *Adv Radiat Biol*, 5:241-71.
Yamada, Masa-atsu, and Theodore T Puck. 1961. 'Action of radiation on mammalian cells, IV. Reversible mitotic lag in the S3 HeLa cell produced by low doses of X-rays', *Proc Natl Acad Sc*, 47:1181-91.

DIY Meets Bespoke in Synchrotron Radiation Science: The Australian Experience

Dudley Creagh
University of Canberra BRUCE ACT 2617 Australia

Abstract
This article chronicles the history of the growth of synchrotron radiation science in Australia, culminating in the establishment of the Australian synchrotron in Melbourne. It commences with the establishment of the Australian National Beamline Facility (ANBF) as Beamline 20B at the Photon Factory KEK Tsukuba Japan, transitions through the creation of the Australian Synchrotron Research Program (ASRP) and changes again to the building of the Australian Synchrotron (AS). These entities overlap one another chronologically; the ANBF remained in operation from its beginning in 1991 until seven years after first light was produced in the AS in 2007. These developments in Australian synchrotron radiation science are as viewed through the lens of my personal involvement and experiences.

The Beginning
Synchrotron radiation science is just over thirty years old. In the decade 1980 to 1989 the use of synchrotron radiation for what we would consider to be “scientific purposes” was in its infancy. In fact synchrotron radiation was regarded as unwanted energy loss by the scientists running the large particle accelerators which were searching for mesons, baryons and the “grand unified theory”.

You could count the number of Australian scientists with any experience in this field on the fingers of one hand. I was attending the 1984 Congress of the International Union of Crystallography (IUCr) in Hamburg having just finished an experiment at the synchrotron at DESY when Stephen Wilkins brought Jimpei Harada, a prominent Japanese crystallographer to meet me. I was at that time Chairman of the Commission on Crystallographic Apparatus of the IUCr. Jimpei brought a message from the Director of the newly commissioned Japanese synchrotron source, the Photon Factory; “would Australia be interested in building a beamline at the Photon Factory?”

This was a wonderful opportunity for Australian scientists, but could we? Our user base was <5. We explained that we did not have a formal body interested in synchrotron radiation science but we would work to set one up….and yes, we **were** interested in the proposition.

When Stephen Wilkins and I returned to Australia we commenced lobbying for Australian involvement at the Photon Factory. Others were interested, and the Australian Synchrotron Beam Users Group was formed to assist in the lobbying process. I was its President and Stephen was its Secretary. We spoke at every conference we were able to attend, lobbied politicians, spoke with senior public servants, lobbied the scientific academies (the Australia Academy of Science (AAS) and Australian Science and Technology Council (ASTEC)): the list of people we talked to seemed endless. (Creagh, Wilkins, 1994).

Eventually, in 1987, we received government funding from the Department of Industry Technology and Commerce (DITAC) to hold a workshop in Melbourne. This was attended by nearly 100 scientists and was opened by the Minister for Science and Technology.

The AAS (Hans Freeman) and ASTEC (Don Niklin) both held investigations culminating in July 1989 in the release of an AAS report to the Prime Minister: *Small Country-Big Science: Australian Participation in Major International Accelerator and Beam Facilities*. The Photon Factory proposal was to receive \$2.7M over three years. An Australian Government minister assured us funding was included in the 1990 budget, but it was removed from the budget papers.

On 15 August 1990 Professor Don Aitken, Vice Chancellor of the University of Canberra, Chairman of the ARC, formed a consortium comprising; the Australian Nuclear Science and Technology Organization (Ansto), the Commonwealth Scientific and Industrial Organization (CSIRO), the Department of Industry Technology and Commerce (DITAC), the Australian Defence Force Academy (ADFA/UNSW), the Australian National University (ANU), and the AAS to build an Australian Beamline at the Photon Factory. We received \$3.3M over three years to build the Australian National Beamline Facility (ANBF) as Beamline 20B of the Photon Factory. It should be noted that only two Australian universities (UNSW and ANU) were interested in investing in the project.

David Cook (ANSTO) was the chairman of the ANBF. As chairman of the Technical Committee I was responsible for all infrastructure matters, designing and constructing the beamline and its monochromators, and interfaces with the diffractometer and the control and acquisition systems. As well I liaised with Stephen Wilkins (CSIRO) who was responsible for the production of the unique vacuum X-ray diffractometer, BIGDIFF. John White (RSC-ANU) headed the Program and Review Committee. ANSTO was responsible for finance and staffing, the hiring and management of staff, and the provision of IT and control systems for the overall system.

There were meetings in Australia and Japan concerning the form the beamline and its components (beamline, monochromator, diffractometer) might take. At that time it was not easy to buy equipment “off the shelf” from a catalogue. And if the available equipment was too expensive or did not meet the required specifications you had to **do it yourself** (**DIY**).

Staff was recruited. Richard Garrett came from the NSLS Brookhaven as project scientist, and beamline staff were appointed, namely David Cookson, who was a research manager at Kodak and Garry Foran, a PhD student from the Department of Chemistry, Sydney University. The fact that Garry spoke and wrote Japanese fluently was of immeasurable value to us. His contribution to the success of the entire project must not to be underestimated. Richard Garrett was responsible for the design and implementation of the control systems and both he and Gary Foran helped build the equipment at CSIRO and ADFA.

What we were supposed to achieve in three years was to build a world class x-ray beamline and diffractometer (Cookson *et al*, 1992), provide the facilities necessary to support research staff in a foreign country and to provide accommodation in which visiting researchers could relax during the course of their experiments, which ran effectively 24/7. And at the end of 3 years world-class experiments must have been performed at the beamline. It was a stated requirement that the user community had to grow considerably.

Building complex equipment is difficult when you live at the opposite side of the earth from the component manufacturers. The ordering and delivery processes were lengthy so we concentrated on what might get us “on line” experimentally in the quickest time. The decision was made to build the infrastructure (container house to provide recreation facilities for the ANBF staff and ADFA technical staff, experimental hutch to house the diffractometer, the coupling to the storage ring, and the radiation protection systems) first.

Whilst work was being done in Japan the construction of the beamline was being undertaken in the ADFA workshops. One ADFA team was building the white beam beamline including the connection to the beam exit port from the storage ring, the slit system, vacuum pumps, all the safety interlocks in the experimental hutch. A second team was building the monochromator. When the white beam beamline was constructed we were able to undertake experiments which used the full extent of the radiated spectrum available from the bending magnet from the storage ring (4 to 10 keV).

White beam experiments (incident beam energy range 4 to 10 keV)

Immediately as the white beam beamline was reached in Japan and re-assembled we commenced experiments using equipment from my ADFA laboratory, which was located on an experimental table loaned by our ever-helpful Japanese colleagues. Experiments such as *Laue diffraction from single crystals* and *Energy dispersive x-ray diffraction* (EDXRD) were possible.

In the *Laue diffraction* case each diffracted beam image (they were typically 4mm x 2mm) contained information on dislocations, stacking faults, and the like, present in the crystal which provided insights into some of the magnetic structure of samarium. (Creagh and Foran, 1993).
EDXRD was used to study the crystallography and composition of materials. In one experiment we studied the change of structure of $MgSiO_3$ with pressure in a high-pressure cell (Creagh and Liu, 1993).

The monochromator
The monochromator system was a cylindrical vacuum vessel ($<10^{-13}$ Bar) located with its axis accurately located in parallel to the centre of the primary beam slit. The monochromator crystal was sited on a precision Huber large goniometer and located such that the surface of the monochromator crystal lay on this axis. The monochromator crystal was a channel-cut [111] hyper-pure silicon crystal produced by Michael Hart, 1996. This was designed to eliminate the harmonics which occur when a white beam is diffracted by adjusting the position of the second reflecting surface of the channel-cut crystal (Creagh, 1992).

The elimination of harmonics from the incident beam is important in all experiments for which a single photon energy is required. One of the analytical techniques for which this requirement is particularly stringent is X-ray Absorption Fine Structure (XAFS) (Creagh, 1992).

Because of this XAFS & XANES were used to test the performance of the monochromator using standard metal and non-metallic foils/objects. Tests which are critical are: energy calibration, energy resolution (the rocking curves have a finite width), harmonic rejection, accuracy of return to zero (hysteresis in scanning). More will be said about this later.

The versatile vacuum X-ray diffractometer: BIGDIFF
BIGDIFF was constructed by CSIRO technicians according to a design by Stephen Wilkins, myself, and others.

Shown in Fig.1 are the vacuum vessel, the Huber dual axis diffractometer base with motor-encoders on both axes (note that the axis of the diffractometer had to be located exactly on the axis of the film cassette (573mm radius)), specimen spinning stage (optional), the imaging plate holder. Of course, there are precision mounting rails, feed-throughs for electrical cables and so on.

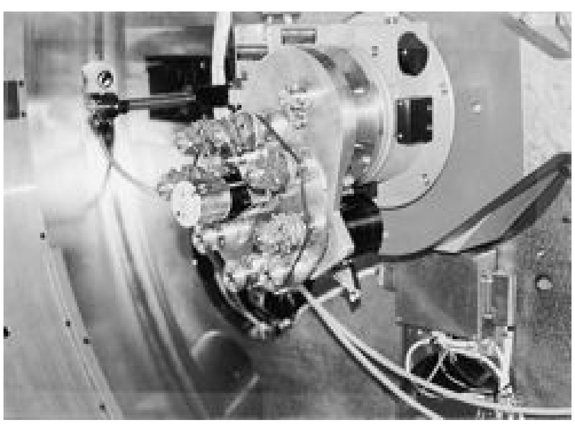
Fig 1. Inside view of BIGDIFF with David Cookson making preliminary adjustments.

What cannot be seen is the fact that the IP holder could be translated parallel to the diffractometer axis and when required, linked to the θ-rotation. The removable Weissenberg slits are not mounted: one side of the slit is mounted on the body of BIGDIFF and the other is mounted on the door. Another feature which is not visible is an exit port which enables the incident beam to pass through BIGDIFF. This exit port enabled experiments mounted on an experimental table behind BIGDIFF to be performed.

The different uses to which BIGDIFF could be used were;: a *Debye powder diffraction* camera with a sample spinner and imaging plate detection, a *single crystal* θ−2θ *diffractometer* using a single detector on the 2θ arm, a *single crystal system* using single detector on the 2θ arm (θ fixed, 2θ moveable), a *single crystal system with a diffracted beam monochromator (ω-axis)* and detector mounted on the 2θ axis (Triple Axis Mode) [7], and a *Weissenberg camera* with the slit in position, θ rotated through about 15^{o} and simultaneous translation of the film cassette coupled to the θ rotation. The exit port enabled the incident beam to pass through BIGDIFF when required, to enable experiments (usually XAFS) to be undertaken behind BIGDIFF.

Conventional powder diffraction

It became apparent that the pump-down time (15-20 minutes) for the diffractometer limited the rate at which spectra from a set of samples could be acquired. Could we overcome this problem? Yes. In a powder XRF system the specimen is spun to minimize the effect of that specimens with irregular grain size and specimens with preferred orientation have on the uniformity of the Debye rings. The Weissenberg slits were to be used to define the diametric section of the Debye cones, with imaging plate images similar to those obtained by standard Debye cameras.



An eight-position spinning specimen stage was devised by Fred Johnson (Creagh *et al*, 1998) to extend the number of spectra which could be taken before the vacuum had to be broken. One of the goniometer heads carries a standard specimen allowing the imaging plate to be calibrated for both intensity and angular position. The other seven goniometer heads carry the samples to be analyzed. One sample is exposed to the radiation, and the IP carrier is moved, a procedure which is repeated for the remaining seven samples.

Fig.2. 8-position spinning sample changer

The spectra shown in Fig. 3 are from research by Maria Kubik *et al* [10] on the pink and red ochres used in traditional Aboriginal bark paintings, taken using BIGDIFF with the 8-position stage in position.

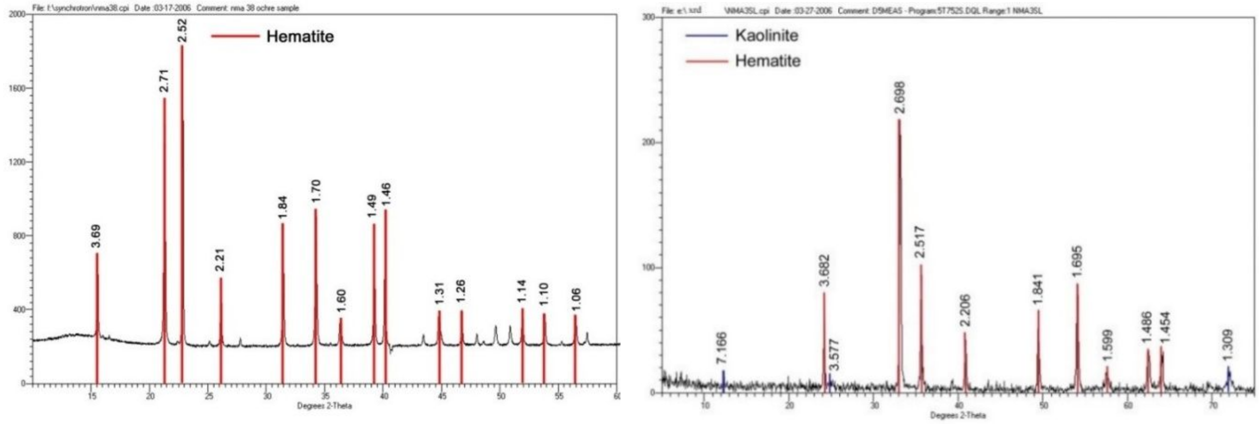


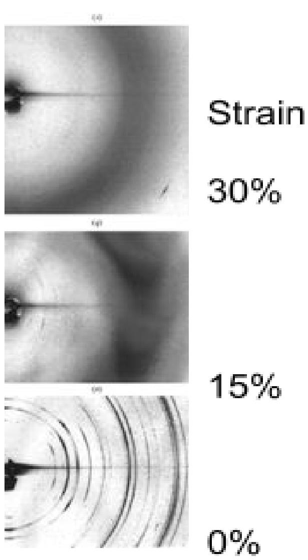
Fig. 3. Powder xrd patterns for ochres taken from two different historical Aboriginal mine sites.

Triple Axis Diffraction (TAD)

The inbuilt Huber θ-2θ X-ray diffractometer with a diffracted beam monochromator and detector mounted on the 2θ arm enabled TAD measurements of surface stress in epitaxially grown semiconductor layers: *e.g.*, GaAlAs deposited epitaxially on a GaAs wafer (Usher and Creagh, 1994), and Nikulin *et al.*, 1995. In the latter experiment stripes of B^+ were implanted into the [111] surface of a silicon wafer, and the effect implantation had on the [111] rocking curve was used as a measure of the surfaces induced by the implantation.

Tensometry

A number of engineers asked us “can you do tensometry at the Photon Factory?” We did not have a tensometer. So we built a prototype tensometer. Again DIY was necessary.

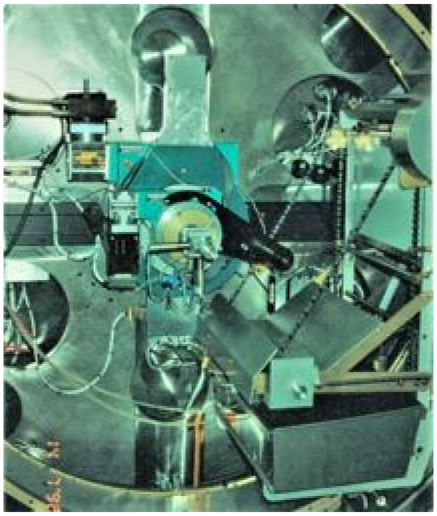


◄ **Fig.4.** SAXS images using a tensometer in BIGDIFF.

Fig. 4 shows the diffraction patterns for polyurethane: unstressed, intermediate stressed, fully extended. (Creagh *et al.*, 1998). In later experiments we used a properly made tensometer, and an Imaging Plate changer designed by Ian Gentle (Foran *et al.,* 1998) (Fig.5).

The system was designed for exchanging imaging plates within BIGDIFF for his Grazing Incidence X-ray Diffraction experiments. Because we did not have to break the vacuum between plate exposures throughput was significantly improved.

This imaging system was later to be used for many other experiments: time resolved xrd, studies of crystallographic structure with temperature, Diffraction Anomalous Fine Structure, and Small Angle Scattering.



A second monochromator, so-called “sagittal focusing” system was built to enable the synchrotron radiation to be focused onto samples in BIGDIFF. This monochromator had a water-cooled [111] silicon block (Hart, 1996) as its first reflecting surface and a separated [111] silicon reflecting crystal. This was mounted on a separate θ-axis and the angle could be adjusted to reflect the incident beam parallel to the beam entering the monochromator. Its surface could be bent into a cylindrical shape thereby focusing the beam in the horizontal plane. (Creagh and Kennedy, 1997, Creagh *et al*, 1998). The monochromator had potential for use for studying small single crystals, in high resolution powder diffraction, such as the high temperatures studies of phase changes in materials.

Fig.5 Imaging plate changer (Foran *et al* [12])

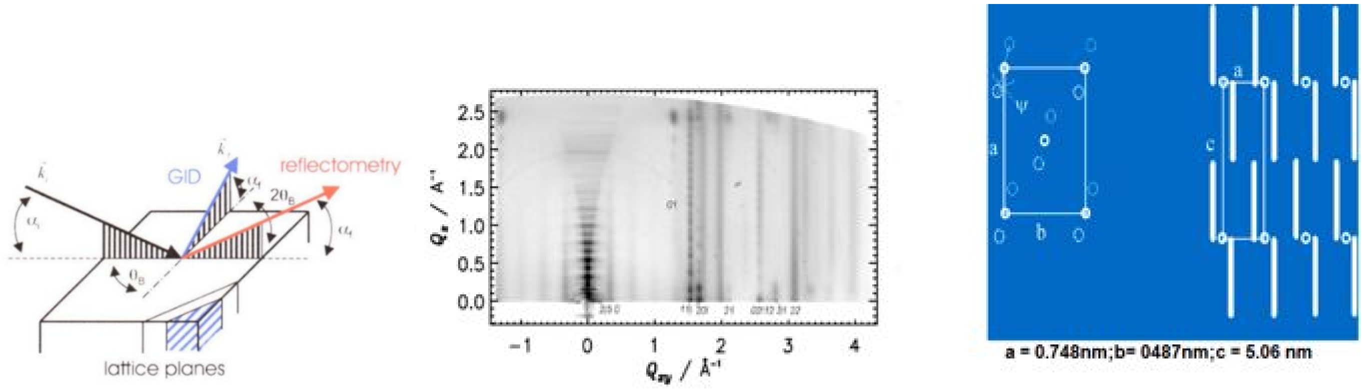
High Temperature Powder Diffraction

A number of scientists fabricated high temperature furnaces in their own workshops and brought them to BIGDIFF to study compositional and structural changes in materials with temperature. The earliest experiment was conducted by Kennedy *et al*, 2001 on the Perovskite materials $Sr_{1-x}Ba_xZrO_3$. His was the first of many such experiments performed at BIGDIFF.

X-ray Reflectivity and Grazing Incidence Diffraction

In the 1990s my Cultural Heritage Research group was interested in the use of self-organized waxy substances as a means of protecting metal surfaces on statues, motor vehicles, *etc* from corrosion. We used the techniques of X-ray Reflectivity (XRR) and Grazing Incidence Diffraction for these studies, initially using a liquid-air reflectometer I designed for John White in 1993.

Fig. 6a shows schematic drawings illustrating the XRR and GID processes. They show what happens when radiation interacts with a surface in the close to the angle of total external reflection. Research at the Photon Factory by Ian Gentle’s Group was related to the self-ordering on substrates of long chain fatty-acids. Shown in Fig.6b is the GID pattern for stearic acid (C_{18}) deposited on dilute $CdCl_2$ using the Langmuir- Blodgett process. Thirty-one layers were deposited on a silicon substrate. As well, the crystal structure was shown by Peng *et al*, 2000 to be Body Centred Tetragonal (a = 0.748nm, b = 0.487nm, c = 5.06nm). Note that the Q = 0 layer-line shows intensity variations characteristic to the interference related Keissig fringes (Holt *et al*, 1998) observed in the purely X-ray Reflective case.



(a) **(b)** **(c)**

Fig.6 (a) Schematic diagram illustrating the processes of XRR and GID.

(b) GID image for stearic acid deposited on dilute $CdCl_2$:(31 layers on a silicon substrate). Peng *et al*, 2000.

(c) Crystallographic representation of the layer structure

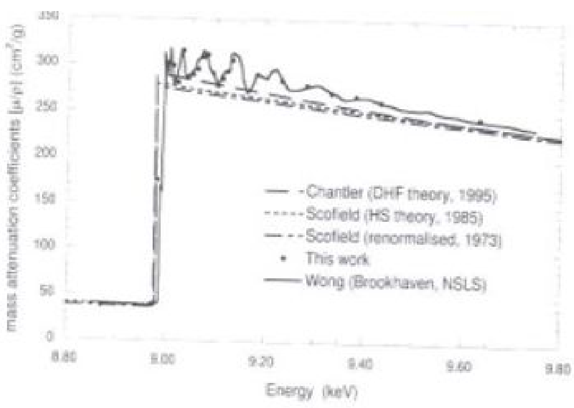
To give another example of the use of these techniques in a different research field, Brown *et al.*, 1999 used XRR to study the effect of capping of a multiple quantum well and quantum well devices. This type of research is important in the microelectronic fabrication industry.

X-ray Absorption, XAFS

In 1977 the I was asked by the IUCr to undertake a project to determine what technique would produce the most reliable measurements of the X-ray absorption coefficients (and by extension: the dispersion corrections, f’ and f”). Details are to be found in Creagh, 1999. Nine quite different configurations were used by the international laboratories which participated in the project. The configuration commonly used by XAFS researchers is one of these.

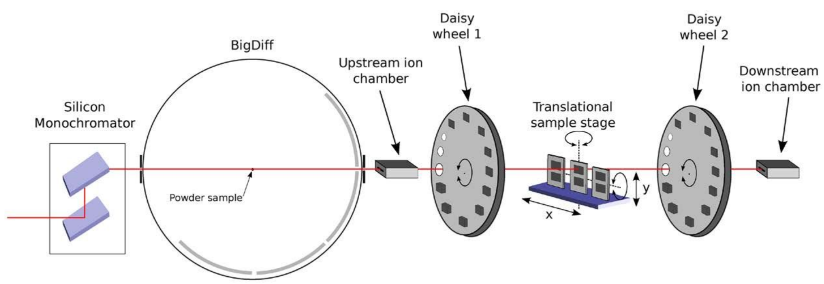
The outcome of this project was that, although highly-skilled scientists produced data which were highly reproducible within their own research laboratory, the actual measured results were often quite dissimilar from data measured elsewhere on the standard samples supplied to them.

Another significant problem existed because the current theories were being compared with imprecise data. An example of this is shown in Fig.7 for copper, perhaps the most measured of all elements because it is used in most XAFS test kits. Note that the shape of the XAFS curve is the same for all carefully performed experiments. What is different is the actual measured value of the mass attenuation coefficients.



◀**Fig.7** XAFS spectra for copper and a comparison of how closely the theoretical values match the experimental values.

It is important to have systems for measuring X-ray absorption coefficients of sufficient precision to enable testing of the credibility of theoretical predictions. Chris Chantler *et al*, 2012 devised such a technique; the X-ray Extended Range Technique (XERT) (Fig.8).



◀**Fig.8.** Schematic diagram of the XERT technique.

The XERT technique accurately measures the X-ray wavelength using a standard crystal, usually silicon. This is very important measurement because accurate knowledge of the photon energy is necessary, especially in the region of the absorption edge and for the interpretation of the results of experiments investigating the X-ray Absorption Near Edge Structure (XANES) of materials. Daisy wheel 1 contains absorbers to enable the intensity of the incident beam I_0 to be varied. This enables the detectors to be calibrated over a wide intensity range. The linearity of the counts-versus-incident intensity response of the detectors over a wide energy range is very important since the detected intensity I is related to I_o by the relation $\ln(I_0/I) = \mu_l\, t$, where μ_l is the linear absorption coefficient.

The key to obtaining precise data is the attention paid to identifying sources of error in every facet of the experiment and the subsequent error analysis thereof.

Quite apart from the ability to provide data of sufficient precision to challenge the existing theories the procedure has demonstrated in research on ferrocene and decamethyl-ferrocene which gave results at least as accurate as those determined by standard crystallographic techniques (Bourke *et al*, 2016). The technique has recently been used for definitive studied into peptides associated with Alzheimer's disease (Strelsov *et al*, 2018).

The number of experiments performed at the ANBF increased from 4 in 1992 to 52 in 1996. At that stage it was becoming a significant contributor to the Photon Factory's publication list. BL20B was recognized by the Australian Research Council as a valuable research asset and regularly granted funds for the upgrading of its the solid state detectors, cryostats and the like. The ANBF ceased operation in February 2013 when the XAFS beamline at the Australian Synchrotron became operational.

Throughout its existence the ANBF was a **DIY** laboratory; most of the experiments were undertaken with equipment which could not be bought “off the shelf”.

Timelines

I have followed the ANBF development from 1991 to 2013 because the ANBF continued in operation through the stewardship of both the ASRP and the Australian Synchrotron.

Going back in time: the funding for the ANBF was due to run out at the end of 1996. The ANBF Committee asked for and received further financial support to the Australian Major National Research Facilities Committee (MNRF). The ASRP received a total funding of $12.2M over 5 years which funded the ANBF and as well funded a program enabling access by Australian scientists to the Advanced Photon Source (APS) at Argonne (USA). It was stipulated that ASRP should set aside $100,000 for a feasibility study to establish an Australian synchrotron.

The ASRP was managed by ANSTO and John Boldeman was made its first director in 1996. Richard Garrett became director in 2001 and continued in that role until the ASRP was incorporated in the Australian Synchrotron’s operations in 2008.

The initial board of the ASRP was later expanded to include representatives from the Universities of Sydney, Melbourne and Queensland, Monash University, and the CSIRO. Each of these institutions had chosen to invest funds in the ASRP.

Four specialist committees were established to oversee the ASRP activities; the Specialist Committee for the Photon Factory (Dudley Creagh), the Specialist Committee for BioCARS at the APS, the Specialist Committee for ChemMatCARS at the APS, and the Specialist Committee for SRI-CAT (later renamed XOR) at the APS. All the APS Committees were supervised by Hans Freeman.
Important staff changes occurred in 2001 when David Cookson went from the Photon Factory to the APS and James Hester joined the ANBF. Cathy Harland joined the ANBF in 2003. At the request of Robert Lamb, later to become the first Director of the Australian Synchrotron, Richard Garrett set up a VUV facility for Australian scientists at the NSRRC in Taiwan to increase the range of techniques available to Australian scientists. Anton Stampfl was appointed to be the person responsible for this facility.

By the time it finished operation, the ASRP the scientific community grown significantly to comprise more than 300 experienced users. In 2007 alone there were 161 refereed publications.

More significantly, beamline scientists had been trained through a Fellowship Scheme. Some of these scientists are key staff members at the AS today: David Paterson, Kia Wallwork, Nigel Kirby, and Stephen Mudie.

The new synchrotron

By 1999 there was significant agitation within the Australian scientific community for the creation of an Australian Synchrotron. In particular John Boldeman sought support for the creation of a 3 GeV storage ring—Boomerang. This was very similar in lattice design to that of the 2.6 GeV ANKA storage ring at Kalrsruhre, designed by Dieter Einfeld.

Early in 2001, the Federal Government announced a new MNRF program as part of its "*Backing Australia's Ability*" Science and Technology Policy, and urged three State governments to submit bids to build the Australian Synchrotron. Victoria, Queensland and New South Wales made submissions.

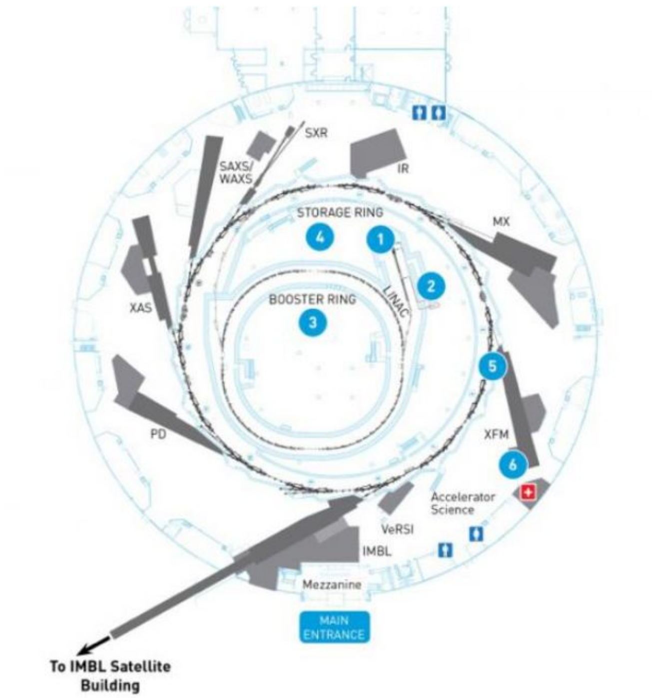
Before the MNRF process was completed in June 2001, because of the perceived crucial importance of the project to Victoria, the Premier of Victoria, Steve Bracks, and the Minister for Innovation and the Treasurer, John Brumby, announced that Victoria would proceed independently of the MNRF process. The amount allocated for the project was $178M. As well a separate budget of $2.9M per year over five years was allocated to ensure that the project obtained the best international and national advice, and to build the national and regional partnership.

John Boldeman was made the Foundation Technical Director and Advisory Committees were created the: International Machine Advisory Committee (IMAC) (Chairman—Alan Jackson), International Science Advisory Committee (ISAC), and the National Science Advisory Committee (NSAC). The Chairman of these committees was Frank Larkins.

I was a member of NSAC. Within NSAC groups were to be created to work on the development of the proposed beamlines: *powder diffraction* (Brendan Kennedy); *Small Angle Scattering/Wide Angle Scattering* (Ian Gentle); *X-ray Absorption Spectroscopy/XAFS* (Mark Ridgway); *Infrared and Vibrational Spectroscopy* (Dudley Creagh); *X-ray and Medical Imaging* (Stephen Wilkins); *X-ray Lithography* (Errol Harvey); *Soft X-ray Spectroscopy* (Robert Leckey); and *micro-spectroscopy* (David Cohen).

The Australian Synchrotron

Work on the Australian Synchrotron commenced in 2001 and first light was achieved in June 2006. Fig.9 shows a schematic view of the AS and its initial tranche of beamlines.



◄**Fig 9** AS and beamlines

The circumference of the storage ring is 216 m. Electrons accelerated to an energy of 100 Mev by a linear accelerator are diverted into a booster synchrotron which rapidly increases the energy of the electron bunches to 3 GeV. These electrons are then diverted into the storage ring. During operation the intensity of the beam decreases due to collisions with gas molecules in the high vacuum system (10^{13} Bar) and interaction with the bending magnets used to bend the electron beam into a circular orbit. Electrons are released from the booster synchrotron to "top up" the circulating current (200 mA). Without topping up the beam would decay to half its initial value in 20 hours. For further details see Creagh, 2007, 2019. The (almost) circular ring is made up of 14 almost identical sectors comprising a straight section and two bending magnets as well as quadrupole and sextupole magnets for beam steering and beam conditioning. Insertion devices (undulators and wigglers) can be inserted in the straight sections to change the shape of the brightness versus emitted energy curves to suit the requirements of different experiments. (Creagh, 2017, 2019)

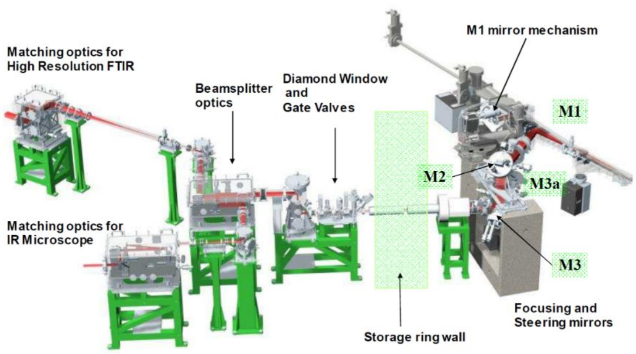
As can be seen in Fig.9, there are nine beamlines with different characteristics and instrumentation chosen the allow the possibility of undertaking experiments in a very diverse range scientific fields. See the ANSTO website (http//www.ansto.gov.au) for the characteristics of the beamlines and the range of accessories available at each beamline. I will concentrate on the development of the IR and Vibrational Spectroscopy Beamline for which I was responsible.

The Infrared Beamline

We were allowed only a very short timeline for consultation, design, and producing a report on which the tender schedule was based.

The IR Beamline Advisory Panel (IRBAP) met for the first time in July 2002. The Australian members were Bill Van Bronswijk, Don McNaughton, Robert Armstrong, and Peter Fredricks. The international members were Michael Martin (Berkeley), Michael Moser (Singapore Synchrotron) and Paul Dumas (Synchrotron Soleil). The design of the beamline was completed in 2004. It has a number of unique features and was unlike IR beamlines elsewhere (Creagh *et al*, 2007).

The first mirror is sited inside the vacuum vessel of the storage is deflected downwards and then horizontally to pass through the shield wall of the ring passing through a polycrystalline window before being returned to bench height and the entrance slits of the analytical instruments (Fig. 10).



◄**Fig.10** Schematic diagram of the IR beamline with the shield walls and experimental hutch removed

The radiation emitted by the electrons as they traverse the bending magnet has two components with different characteristics, one caused by the uniform field of the bending magnet and the other due to the gradient in magnetic field which occurs at the entrance of the bending magnet (Fig.11).

Fig. 11. **Left:** Schematic diagram illustrating the formation of bending magnet radiation. **Right**: The image of the radiations at the first mirror.

These components were be separated with mirrors and used to illuminate two different beamlines feeding to different instruments; a Bruker IR-VIS FTIR microscope, and a Bruker high-resolution THz FTIR spectrometer. As well, we could split one of these beams to illuminate a focal plane array spectrometer; three experimental opportunities for almost the price of one!

Many factors affect the performance of IR beamlines not the least of which are; instabilities in the circulating electron beam caused by insertion devices and other electromagnetic devices, the effects of vibrations and heating of the first mirror (which is inside the storage ring and very close to the electron beam), the length of the beam path from this mirror to the instruments (1:1 optics has to be achieved), and mechanical vibrations in all the elements of the beam transport system.

The DIY component of the design lies in the unique method of extraction of the radiation from the storage ring and the means used to separate the bending magnet and edge radiations was crucial to the creation of what has proved to be highly stable and reliable in operation. This required a complete redesign of the vacuum vessel to enable the extraction of the beam from the storage ring, and the detailed design of the water-cooled first mirror which is inserted into the vacuum vessel. This was done by Jonathon McKinlay.

When the tenders for the beamline, the Bruker IR Microscope and accessories, and the Bruker High Resolution spectrometer had been accepted in 2006, Mark Tobin was recruited from the Diamond Synchrotron to be the Principal Beamline Scientist and to take responsibility for the installation and commissioning of the IR Facility.

Experiments after first light

With the operation of the IR Beamline in the safe hands of Mark Tobin. I was free to give priority to my work on Border Security for the Australian Government. (Creagh, 2011). Members of my Cultural Heritage research group continued to follow their research interests. Alana Treasure (Australian War Memorial) continued her research into the mechanisms underlying the degradation of iron gall inks on parchment and paper. This work involved the use of the Bruker micro-spectrometer with its ATR objective and the X-ray Fluorescence Microscope (XFM) (Treasure *et al*, 2012).

Since 2013 David Thurrowgood (Queen Victoria Museum and Gallery) has been collaborating with Daryl Howard and David Paterson (AS staff-XFM beamline) on a variety of projects. One notable experiment was able not only to detect the presence of a portrait which was overpainted with a painting of a vase of flowers, but also to colour the portrait using pigment tones taken from the pallet of the artist (Degas) (Fig. 12). This was the “lost” portrait of Emma Dogbigni (Thurrowgood *et al*, 2016)

◄**Fig. 12**. Portrait of Emma Dogbigni (Degas concealed under the another painting)

In a collaboration with Tamar Davidowitz (the Rijksmuseum) a detailed study of the Dutch National Treasure, the Dirk Hartog plate, has been made using the xfm facility. Daryl Howard, David

Thurrowgood, David Hallam (RTait and Associates), Ian McLeod, and I used the XFMs Maia detector to map the elemental composition of the pewter plate in an effort to determine how best to prevent further corrosion and rectify past treatments by earlier conservators (Davidowitz *et al*, 2019). Fig. 13 shows a photograph of a monitor screen of the plate mapped in PbL fluorescence radiation. Part of the message written by Dirk Hartog in 1617 can be seen. As well, a photograph of the plate taken to highlight its fragility.

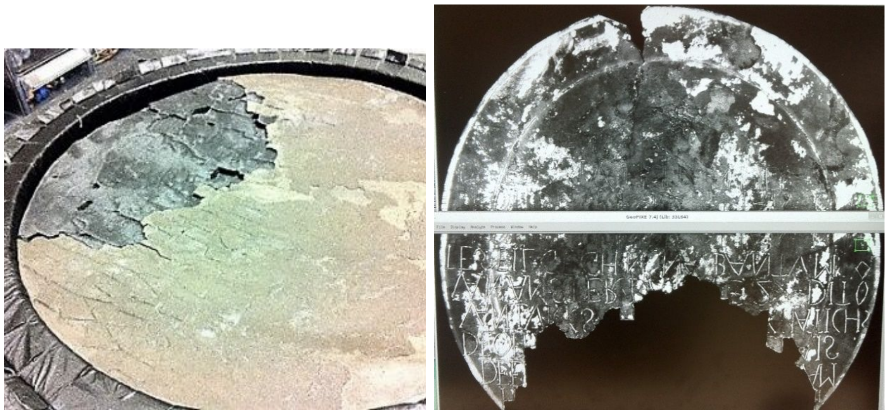


Fig.13a. Left: A screen image of the Dirk Hartog plate, imaged with PbL fluorescence radiation. **Right:** Photograph of the Hartog plate in its protective mount.

Future Development of the Australian Synchrotron (2015-2025)

The funding of the ANBF, the ASRP, and the Australian Synchrotron was uncertain for many years. But in 2015 the Australian Government made a National Innovation and Science statement in which $520M was set aside to enable stable funding for Major National Facilities like the Australian Synchrotron for the next 10 years. As well as providing funds for maintenance and operation, $82M was allocated to provide for the construction of an additional 7 beamlines which are intended to augment and expand the analytical capabilities of the AS.

These are the so-called BR—GHT beamlines. Beamlines are to be provided for: *high energy X-ray diffraction and scattering* (to be used for studies in materials science, engineering and chemistry); *Biological-Small Angle X-ray Scattering* (studies in structural biology); *Micro-Computed Biology* (studies in health, food, archaeology, palaeontology, geology); *Medium Energy XAS* (biology, agriculture, the environment, soil science); *High Performance Macromolecular Crystallography* (structural biology); *High coherence Nano-probe* (high resolution microspectroscopy, elemental mapping, coherent diffraction imaging); *Micro-Materials Characterization* (materials science, engineering, geology, environmental science).

Each of the beamlines take about 5 years to bring into service, so it is expected that by 2020 17 beamlines will be operating at the Australian Synchrotron.

The future does look BRIGHT for the Australian Synchrotron and synchrotron radiation science in Australia.

In terms of beamline design and construction the situation will be more bespoke than DIY; modules will be bought from catalogues and interconnected to achieve the required functionality. Entire beamlines might be ordered, delivered to site and commissioned purely on the basis of specifications contained in a tender document.

Acknowledgements

Many have contributed to the development of synchrotron radiation science in Australia. Those who have made significant contributions have been cited in the text using their given names as well as their family names. The contributions made by the workshop staff of the ADFA Physics Department, the CSIRO Division of Materials, and the University of Queensland Chemistry Department are of great significance to the development of the synchrotron radiation science in Australia. The project could not have succeeded without their contributions.

Nor could the project have succeeded without the assistance of our Japanese friends and colleagues. Notable amongst them are Jimpei Harada, Juinici Chikawa, Masami Ando, Tadashi Matsushita, Hiro Oyanagi, Ohsamu Shimomura, Hiroshi Kawata, Hiro Hashezumi, and Soichi Wakatsuki.

None of what has been achieved, or will be achieved, could have happened without the support of the Australian Government, State Governments, Ansto, CSIRO, and the 40-or-so Australian and New Zealand universities which now contribute to the program.

References

Australian Synchrotron: https://www.ansto.gov.au/research/facilities/australian-synchrotron/overview

Australian Synchrotron-Bright: https://www.ansto.gov.au/research/facilities/australian-synchrotron/Bright

Bourke, JD, Aslam, MT, Rae, NA, Tran, CQ, Chantler, CT. 2016. *Conformation analysis of Ferrocene and Decamethyl Ferrocene via Full Potential Modelling of XANES and XAFS.* J Phys Chem Letters, 2792-2796.

Brown, AS, Holt, SA, Creagh, DC. (1999). *Reflectivity and Grazing Incidence X ray Diffraction Studies of the Influence of capping and annealing on well shapes in Single Quantum Well Devices*. J. Colloids and Surfaces A, **155**, 85-91

Chantler, CT, Islam, MT, Rae, NT, Tran, CQ, Glover, GL, Barnea, Z. 2012. *New consistency tests for high accuracy measurements of X-ray mass attenuation coefficients by the X-ray extended-range technique.* Acta Cryst A 688, 188-195.

Cookson, DJ., Garrett, RF, Foran, GJ., Creagh, DC, Wilkins, SW. 1992. *The Australian National Beamline at the Photon Factory. Japanese J. Synchrotron Radiation*, **6**, 1, 127-130.

Creagh, DC. 1992. *X-ray absorption.* In International Tables for Crystallography, Volume C 2 Ed.. Section 4.2.3. Ed. E. Prince. International Union of Crystallography. Kluwer: Dordrecht. pp 210-220.

Creagh, DC. 2007.. *Synchrotron radiation and its use in art, archaeometry, and cultural heritage* . In Physical Principles in Art, Archaeometry and Cultural Heritage Vol.2. Creagh, D.C., Bradley, D.A. (Eds.). Elsevier Science B.V. Amsterdam.

Creagh, DC. 2011. *Technology for border security*. In Handbook of Particle Detection and Imaging. Eds. C. Gruppen, I. Buvat, D. MacGregor. Springer Verlag, Berlin. Ch. 35 (12 October 2011) ISBN978364213270

Creagh, DC. 2019. *Monochromators*. In International Tables for Crystallography. Chapter 4.2.5. Ed. TR Welberry. Vol C. IUCr, Chester UK.

Creagh, DC. 2019. *Sources of Ionizing radiation*. In International Tables for Crystallography. Chapter 4.2.1. Ed. TR Welberry. Vol C. IUCr, Chester UK.

Creagh, DC, Foran, GJ. 1993. *Laue diffraction imaging from a single crystal of samarium.* In Experimental Report: Access to Major Facilities Program 1993. Vol.2. Ed. M. Edmondson. Australian Nuclear Science and Technology Organization. Sydney.

Creagh, DC, Liu, L-G. 1993. *White beam energy dispersive X-ray diffraction and fluorescence at the Australian National Beamline Facility.* In Experimental Report 1993: Access to Major Facilities Program. Vol.2. Ed. M. Edmondson. Australian Nuclear Science and Technology Organization. Sydney.

Creagh, DC, Wlikins, SW. 1994. *The Australian National Beamline at the Photon Factory: a brief personal history*. Australian and New Zealand Physicist, **31**, 13-18.

Creagh, DC, Kennedy, BJ. 1997. *A study of the effect of sagittal focusing on the resolution of the powder diffractometer at BL20B (BIGDIFF).* In Experimental Report1997: Access to Major Facilities Program. Vol.2. Ed. M. Edmondson. Australian Nuclear Science and Technology Organization. Sydney.

Creagh, DC., O'Neill, PM, Mills, RJ, Holt, SA. 1998. *The tensometry of carbon fibres and elastomers at the diffractometer at BL20B of the Photon Factory*. J. Synchrotron Radiation, 5, 3, 958-961

Creagh, DC, Foran, GJ, Cookson, DJ, Garrett, RF, Johnson, F. 1998. *An eight position capillary spinning stage for the diffractometer at BL20B of the Photon Factory*. J.Synchrotron Radiation, 5, 823-825.

Creagh, DC., Tobin, M, McKinlay, J., Dumas, P. 2007. *An Australian Beamline for the Australian Synchrotron*. J. Synchrotron Instrum. 40, 615-619.

Davidowitz, T, Thurrowgood, D, Howard, D, MacLeod, I, Creagh, D, Hallam, D. 2019. *Understanding the Hartog Plate: A Comprehensive Examination of Australia's First European Object.* In ICOMCC Conference. Metal 2019. Neuchatel Switzerland, 2-6 September 2019. Accepted for publication.

Foran, GJ, Gentle, IR, Peng, J-B, Barnes, GT, Garrett, RF, Creagh, DC.,1998. *Time resolved Grazing Incidence Diffraction studies of this films using an imaging plate camera and focusing monochromator.* J.Synchrotron Rad. **5**, 2, 107-111.

Hart, M. 1996. *X-ray and Neutron Design Principles.* In X-ray and Neutron Dynamical Diffraction. Eds. A, Authier *et al*. Plenum New York. Chapter 10.

Holt, SA., Creagh, DC, Hutchinson, WD. 1998. X-ray reflectivity studies of mono- and bilayers of manganese stearate on silicon substrates. Appl.Rad. Isot., **54**, 4-6, 543-546.

Kennedy, B, Howard, C, Thorogood, G, Hester, J. 2001. The influence of composition on temperature and phases of $Sn_{1-x}Ba_xZrO_3$. Solid State Chem. 161, 106-112.
Nikulin, A, Stevenson, AW, Hashizume, H, Wilkins, SW, Cookson, DJ, Foran. 1995. *High resolution triple crystal diffraction study of B^+ implanted Si [111].* Rev Sci Instr, 66, 2, 1483-1488.
Peng, J-B, Barnes, GT, Gentle, IG, Foran, GJ. 2000. *Superstructures and correlated metal ion layers in Langmuir-Blodgett films of cadmium soaps observed with grazing incidence X-ray diffraction*. J Phys Chem B 104, 5553-5561.
Strelsov, VA, Ekanayake, RSK, Drew, SC, Chantler, CT. 2018. *Structural Insight into Redox Dynamics of Copper Bound N-truncated Amyloid-b Peptides from in situ X-ray Absorption Spectroscopy*. Inorganic Chem.,57, 1142-11435.
Thurrowgood, D, Paterson, D, de Jonge, M, Kirkham, R, Thurrowgood, S, Howard, DL. 2016. A hidden portrait by Edgar Degas. Nature Scientific Reports. www.nature,com/articles.rep29594. 4 August 2016.
Treasure, A, Creagh, DC., Whitely, C, Howard, D, de Jonge, M, 2012. *SR-mXRF in the analysis of iron gall ink on parchment.* In Proceedings of the European Conference on X-ray Spectrometry. Eds. C.Streli, M.Mantler. Vienna, Austria. 18-22 June 2012. **Poster Session** 1. Art and Cultural Heritage, 12.
Usher, B, Creagh, D 1995. *Measurement of the surface stresses in GaAlAs layers epitaxially grown on a GaAs substrate at the Australian National Beamline Facility.* In Experimental Report 1995: Access to Major Facilities Program. Vol.2. Ed. M. Edmondson. Australian Nuclear Science and Technology Organization. Sydney.

This paper is a summary of an address by Emeritus Professor Dudley Creagh given on the occasion of his receipt of the Inaugural Australian Synchrotron Lifetime Contribution Award at the Australian Synchrotron Users Meeting on 26 November 2018.

Recent Advancements in Neutron Physics

A Special Issue for the Journal of Nuclear Physics, Material Sciences, Radiation and Applications, Chitkara University

The neutron was discovered by Sir James Chadwick (20 October 1891) in the year 1932, which is a carrier of the nuclear chain reaction when used in the peaceful application of nuclear energy. Nuclear energy is becoming an important need in today's rapidly developing world. Peaceful applications of nuclear energy involve radiation protection against ionizing radiation in the nuclear fuel cycle and medical purposes, using engineering, science and technology. The present volume is therefore dedicated to Sir James Chadwick.

In order to give a special tribute to Sir Chadwick for the discovery of the neutron, we invite researchers and academics to contribute their research works that will stimulate understanding of recent advancements in neutron physics. Potential topics include, but are not limited to:

- Neutron Reactor and Accelerator Physics
- Neutron Shielding Materials
- Neutron Detector and Dosimetric Materials
- Neutron in Medical Imaging, Radiotherapy and Medical Physics
- Monte Carlo Simulation applications for Neutron Interaction
- Radiation Protection against Neutron

The papers will be considered in three categories; as a full research paper, a technical note or a review paper. Before submission authors should carefully read over the journal's Author Guidelines, which are located at https://jnp.chitkara.edu.in/index.php. Prospective authors should submit an electronic copy of their complete manuscript through the journal Manuscript Tracking System at https://jnp.chitkara.edu.in/paper_submission.php.

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May 27-31, 2019	**3rd International Conference on Dosimetry and its Applications (ICDA-3)** *Congress Centre of Instituto Superior Técnico, Lisbon* *http://www.ctn.tecnico.ulisboa.pt/icda-3/*
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International Radiation Physics Society

The primary objective of the International Radiation Physics Society (IRPS) is to promote the global exchange and integration of scientific information pertaining to the interdisciplinary subject of radiation physics, including the promotion of (i) theoretical and experimental research in radiation physics, (ii) investigation of physical aspects of interactions of radiations with living systems, (iii) education in radiation physics, and (iv) utilization of radiations for peaceful purposes.

The Constitution of the IRPS defines Radiation Physics as "the branch of science which deals with the physical aspects of interactions of radiations (both electromagnetic and particulate) with matter." It thus differs in emphasis both from atomic and nuclear physics and from radiation biology and medicine, instead focusing on the radiations.

The International Radiation Physics Society (IRPS) was founded in 1985 in Ferrara, Italy at the 3rd International Symposium on Radiation Physics (ISRP-3, 1985), following Symposia in Calcutta, India (ISRP-1, 1974) and in Penang, Malaysia (ISRP-2, 1982). Further Symposia have been held in Sao Paulo, Brazil (ISRP-4, 1988), Dubrovnik, Croatia (ISRP-5, 1991) Rabat, Morocco (1SRP-6, 1994), Jaipur, India (ISRP-7, 1997), Prague, Czech Republic (ISRP-8, 2000), Cape Town, South Africa (ISRP-9, 2003), Coimbra, Portugal (ISRP-10, 2006), Australia (ISRP-11, 2009), Rio de Janeiro, Brazil (ISRP-12, 2012), Beijing, P.R.China (ISRP-13, 2015), and Córdoba, Argentina (ISRP-14, 2018).

The IRPS also sponsors regional Radiation Physics Symposia.

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6. Please list any national or international organization(s) involved in one or more branches of Radiation Physics, of which you are a member, also your status (e.g., student member, member, fellow, emeritus):

7. The IRPS has no entrance fee requirement, only triennial (3-year) membership dues. In view of the IRPS unusually low-cost dues, the one-year dues option has been eliminated (by Council action October 1996), commencing January 1, 1997. Also, dues periods will henceforth be by calendar years, to allow annual dues notices. For new members joining prior to July 1 in a given year, their memberships will be considered to be effective January 1 of that year, otherwise January 1 of the following year. For current members, their dues anniversary dates have been similarly shifted to January 1.

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