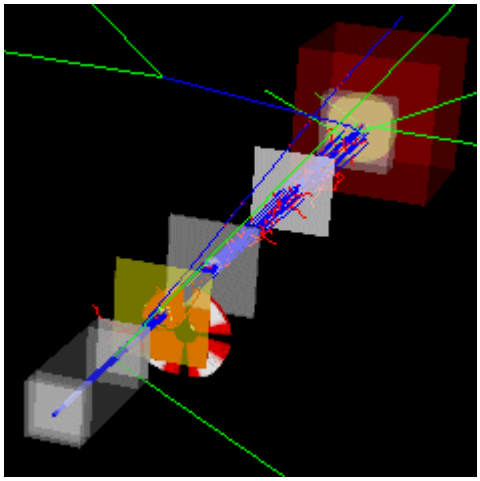
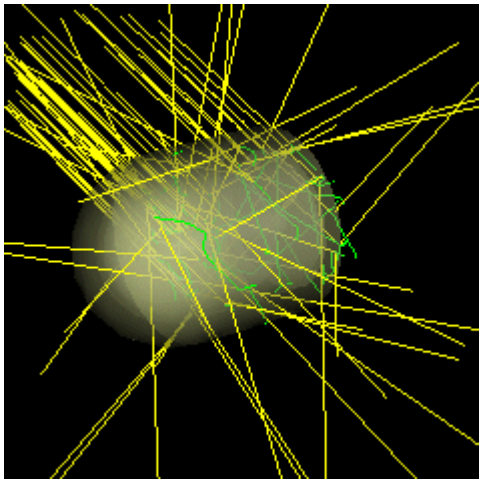
# 16th UK Monte Carlo User Group Meeting (MCNEG 2010)

## 12 - 13 April 2010

## Programme and Abstract Book





**National Physical Laboratory**
**Teddington, Middlesex, UK**

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# MCNEG 2010 MEETING PROGRAMME
# 12 – 13 April 2010

Provisional timetable

## Monday 12 April 2010

09:30 – 10:00 **REGISTRATION AND REFRESHMENTS**

10:00 – 10:15 **Introduction & Welcome to NPL**
*Rebecca Nutbrown, David Shipley and Mark Bailey*

***Session 1*** – ***Protons and light ions:*** Chair: (to be confirmed)

10:15 – 10:45 **Recent and future developments of the FLUKA MC code for ion beam therapy**
*Katia Parodi (Heidelberg Ion Beam Therapy Centre, Heidelberg, Germany)*
***[Invited speaker]***

10:45 – 11:10 **Ion recombination in scanned proton beams using Monte Carlo calculated dose distributions**
*Hugo Palmans (NPL)*

11:10 – 11:40 **REFRESHMENTS**

11:40 – 12:05 **Fluka simulations for characterisation of a laser-driven X-ray beam**
*Francesca Fiorini (University of Birmingham)*

12:05 – 12:30 **Water equivalence of some plastic-water phantoms for clinical proton dosimetry**
*Leena Al-Sulaiti (University of Surrey)*

12:30 – 12:55 **Fluka: Experiences of a new user**
*Lewis MacFarlane (Nuclear Technologies plc, Warrington, UK)*

12:55 – 14:00 **LUNCH**

***Session 2*** – ***Biological, Protection and Environmental:*** Chair: (to be confirmed)

14:00 – 14:45 **Radiation track structure, DNA damage, and risk of exposure to ionizing radiations**
*Professor Hooshang Nikjoo (Karolinska Institute, Stockholm, Sweden)*
**[Invited speaker]**

14:45 – 15:10 **Mathematical calibrations for measurements of radionuclides in people following a radiation incident**
*Arron Shutt (CRCE, HPA, Chilton, Didcot, Oxfordshire, UK)*

15:10 – 15:35 **Determination of the concentration and profile of the activation and fission product gamma-ray emitting radionuclides in a radioactive waste storage vault**
*Ian Adsley (Nuvia Limited, Harwell, Didcot, UK)*

15:35 – 16:15 **REFRESHMENTS: POSTERS**

16:15 – 16:40 **Using MCNP to determine the performance of detectors used for contamination surveys**
*Mike Davies (Nuvia Limited, Harwell, Didcot, UK)*

16:40 – 17:05 **Monte Carlo studies utilising the ICRP adult reference computational phantoms for the assessment of typical normalised organ and effective doses from contemporary computed tomography scanners**
*Jan Jansen (CRCE, HPA, Chilton)*

17:05 – 17:30 **Gamma spectrum unfolding for a NaI monitor of radioactivity in aquatic systems: Evaluation of the Minimum Detectable Activity**
*Jonathan Baré (ULB, Belgium)*

19:00 **MCNEG DINNER (local restaurant)**

## Tuesday 13 April 2010

***Session 3*** – ***Radiotherapy and Imaging:*** Chair: (to be confirmed)

09:30 – 10:00 **The role of Monte Carlo at the Heidelberg Ion Beam Therapy Center**
*Katia Parodi (Heidelberg Ion Beam Therapy Centre, Heidelberg, Germany)*
**[Invited speaker]**

10:00 – 10:25 **A PHITS-based dose calculation engine to evaluate the effect of inhomogeneities in prostate brachytherapy**
*Julien Smeets (ULB, Belgium)*

10:25 – 10:50 **Re-establishing the absorbed dose primary standard for photon beams on the new NPL clinical linac**
*David Shipley (NPL)*

10:50 – 11:20 **REFRESHMENTS**

11:20 – 11:45 **Monte Carlo modelling of the effect of scatter on the CT dose index for cone beam CT**
*Emiliano Spezi (Velindre Cancer Centre, Cardiff)*

11:45 – 12:10 **Matching electron beam parameters calculated using DOSRZnrc with a full BEAMnrc source to the measured output from the new NPL Elekta clinical linac**
*Mark Bailey (NPL)*

12:10 – 12:35 **A non-CAD-based approach to modelling a Linac Treatment Head with the Geant4 Monte Carlo code**
*Daniel O'Brien (Saint Luke's Hospital, Rathgar and University College Dublin, Ireland)*

12:35 – 13:30 **LUNCH**

***Session 4*** – ***Small Fields and Microdosimetry:*** Chair: (to be confirmed)

13:30 – 13:55 **Use and modelling of solid-state dosimeters in small field radiotherapy**
*Richard Hugtenburg (University of Swansea)*

13:55 – 14:20 **A model calculation for proton and neutral hydrogen interactions in water: The classical-trajectory Monte Carlo approach**
*Thiansin Liamsuwan (Karolinska Institute, Stockholm, Sweden)*

14:20 – 14:45 **MCNEG AGM**

15:00 **END OF MCNEG 2010**

**Recent and future developments of the FLUKA MC code for ion beam therapy**

Katia Parodi (on behalf of the FLUKA Collaboration)

***(Invited speaker)***

*Heidelberg Ion Beam Therapy Centre, Heidelberg, Germany*

## ABSTRACT

Nowadays, Monte Carlo (MC) methods are commonly recognized as powerful computational tools for detailed and realistic description of radiation transport and interaction with matter. Although the intensive computational time requirements still prevent inverse dose optimisation and daily application in clinical routine of ion beam therapy, MC methods are increasingly being utilised at several institutions for a wide range of activities spanning from beam characterisation to quality assurance and dosimetric calculations.

The suitability of a MC code for application to ion beam therapy demands a reliable description of the electromagnetic and nuclear processes, which are responsible for the favourable energy deposition but also the alteration/degradation of the primary radiation field with the penetration in tissue. Especially in case of ions heavier than protons, an accurate simulation of the mixed radiation field components is extremely important for correctly performing not only physical but also biology-based dose calculations. In addition, accurate prediction of emerging secondary radiation is of utmost importance in emerging areas of research aiming to in-vivo treatment verification.

This talk will address the specific case of the general-purpose particle and interaction code FLUKA, presenting its current status with special focus on the recent model developments, which are of relevance in the energy range of therapeutic interest. Moreover, it will review examples of validation and application at several experimental sites as well as ion therapy facilities with passive and active beam delivery systems, indicating that the code already represents a valuable choice for supporting a large variety of applications in ion beam therapy. Further ongoing activities are aimed to extend the collection of nucleus-nucleus cross-section data to better validate and eventually improve the models of the FLUKA code for more sensitive dedicated applications, such as imaging of secondary emerging radiation and radiobiological calculations.

## Ion recombination in scanned proton beams using Monte Carlo calculated dose distributions

Hugo Palmans

*Radiation Dosimetry Group, National Physical Laboratory, UK*

## ABSTRACT

It has been shown before that in range modulated scattered proton beams, a correct treatment of the recombination in ionisation chambers requires accounting with the time-dependent structure of the ionisation current [1]. In scanned proton beams, the possible instantaneously partial or inhomogeneous exposure of the ionisation chamber cavity constitutes an additional complication. A theoretical treatment of scanned beams has been previously proposed [2]. However, this model only considers the time dependent current as a function of lateral distance to the beam and treats the ion chamber as a point. For photon beams, a model for the integration of the recombination correction of a time-dependent and inhomogeneous dose distribution over the cavity volume was developed for pulsed beams [3].

In the present work, the effect of a proton spot sweeping over the length of a cylindrical air cavity with dimensions corresponding to the size of a Farmer type chamber was investigated using Monte Carlo calculated dose distributions. The transport of primary protons was simulated using PTRAN while electron transport was tracked using EGSnrc, and this for two proton beam energies: 60 MeV and 250 MeV. The model presented in ref. [3] was modified for a (quasi) continuous proton beam extracted from a cyclotron and an air cavity with dimensions similar to those of a Farmer type ionisation chamber.

The results show that for a narrow beam hitting the centre of the cavity, the volume recombination is lower in a proton beam with a realistic Gaussian lateral distribution than one with a rectangular distribution with the same integral dose. The volume recombination increases by about 20% when a Gaussian proton beam hits the top or bottom of the cavity and than drops to zero when the beam spot moves out of the cavity. Secondary electron transport has an impact on the result that is, however, limited to a few percent.

## REFERENCES

[1] H. Palmans, R. Thomas and A.Kacperek, “Ion recombination correction in the Clatterbridge Centre of Oncology clinical proton beam,” Phys Med Biol. 51:903-917 (2006)

[2] J. W. Boag, “The recombination correction for an ionisation chamber exposed to pulsed radiation in a 'swept beam' technique. I. Theory,” Phys. Med. Biol. 27:201-211 (1982)

[3] H. Palmans, R. A. S. Thomas, S. Duane, E. Sterpin and S. Vynckier, “Ion recombination for ionization chamber dosimetry in a helical tomotherapy unit,” Med. Phys. *In press* (2010)

## Fluka simulations for characterization of a laser driven X-ray beam

Francesca Fiorini[1], Rob Clarke[2], David Neely[2], Stuart Green[3]

*[1] University of Birmingham, Medical Physics Group, School of Physics and Astronomy, Birmingham*
*[2] Central Laser Facility, Rutherford Appleton Laboratory, Didcot, Oxfordshire*
*[3] Medical Physics, University Hospital Birmingham, Birmingham*

## ABSTRACT

The Laser Induced Beams of Radiation and their Applications (LIBRA) is a British consortium which aims to develop a new type of ion source by shining an ultra intense laser beam onto a small target of metal, plastic, liquid or gas. The laser□s energy causes intense high energy ionising radiation to be ejected from the surface of the target and the type of radiation emitted depends on the dimensions and composition of the target.

There are many potential applications for the particles produced in these experiments, but the most important from the practical point of view are the promising medical applications, including laser-plasma driven ion beams for radiotherapy and laser-plasma driven X-rays for medical imaging usable during an ion therapy session to check the therapy progress in time.

The X-ray beam is produced by the fast electrons in the target material, which are generated during the laser-target interaction. In this work, our primary interest lies in studying how the X-ray spectrum changes in dependence of the target material and thickness when the electron beam interacts with it.

At present, simulation programs capable of simulating exactly what happens in matter when the laser hits a target are few. Some of them are not useable for all laser parameters and/or can only simulate some particular reactions.

The simulations presented in this work have been done using Fluka (FLUctuating KAskad), a Monte Carlo code for calculations of particle transport and interaction with matter. Given its aims, Fluka is not meant to simulate reactions produced by lasers, but in good approximation it can simulate the electron interactions which produce the photon beam.

Using hot electron spectra, estimated through other simulation programs, the photon beams created in several targets have been investigated.

Even if the electron-matter reactions are well simulated by Fluka, there are other reactions which are not implemented in the simulations.

With the upcoming experiments planned at the Rutherford-Appleton Laboratory it will be possible to understand to what extent the approximations used in this work are valid, and whether it is possible to use Fluka as a simulation code for predicting X-ray emission from high intensity laser-target interactions.

**Water equivalence of some plastic-water phantoms for clinical proton dosimetry**

Leena Al-Sulaiti [1,2], David Shipley [2], Russell Thomas [2], Andrzej Kacperek [3], Hugo Palmans [2]

[1] *Physics Department, University of Surrey, Guildford, UK*
[2] *Radiation Dosimetry Group, National Physical Laboratory, Teddington, UK*
[3] *Douglas Cyclotron, Clatterbridge Centre of Oncology, Wirral, UK*

## ABSTRACT

Several studies of water equivalence for plastic-water phantoms have been reported on photon and electron beams, but none in clinical proton beams. In a proton beam, the non-elastic nuclear interactions in water are different from those in plastic-water phantoms due to their different elemental compositions.

In this work, the water equivalence of plastic water (PW), plastic water diagnostic therapy (PWDT) and WT1 phantoms was studied for clinical proton energies (60 MeV and 200 MeV). The difference in energy loss ratios arises from the difference in stopping powers for water and plastic water phantoms was investigated. Also the fluence correction factor due to the non-elastic nuclear interaction for these materials at water equivalent depths was studied. This was performed using analytical model calculations and Monte Carlo simulations using MCPNX 2.5.0 and FLUKA 2008.3. MCNPX simulations showed that the contribution of the fluence correction factor was less than 0.3% for PW and less than 1% for both WT1 and PWDT up to the entire penetration depth of 200 MeV protons, while for 60 MeV protons it was negligible. Analytical calculations are consistent with these results. Preliminary results of FLUKA simulations will be presented.

## FLUKA: Experiences of a New User

Lewis MacFarlane

*Nuclear Technologies plc, Warrington, UK*

## ABSTRACT

FLUKA is a Monte Carlo particle transport code that has been specifically developed for applications in high energy physics.

I come from a background of using Monte Carlo codes (amongst others) for radiation transport calculations relating to shielding design and dose uptake assessments, primarily in support of the commercial nuclear industry in the UK. However, a move into consultancy has encouraged me to build upon my skills and more recent work has included consideration of the termination of high-energy charged particle beams and shielding against the subsequent spallation, through both beam dump design and structural shielding.

This is one of the many situations for which FLUKA has been developed. Subsequently I would like to talk about my experience of learning how to use FLUKA: First impressions, advantages, disadvantages (when compared to other codes) and pitfalls that I have encountered, with a focus on current and future projects.

**Radiation track structure, DNA damage, and risk of exposure to ionising radiations**

Hooshang Nikjoo

***(invited speaker)***

*Radiation Biophysics Group, Department of Oncology-Pathology, Karolinska Institutet, Stockholm, Sweden*

## ABSTRACT

A premise of research in radiation biology, and in radiation biophysics in particular, is to understand the mechanism and consequences of damage, and quantify the emerging risk involved as a function of dose, dose rate and quality of ionising radiation. After half a century of rapid advances, much information has become available from experimental work, epidemiological studies and advances in genome research. However, there still remains a lack of coherent description of mutagenic processes, pathways to neoplastic changes and cancer induction, and of models to quantify accurately the risk to humans from acute and protracted exposures to ionising radiations.

The genomic analysis and re-analysis of human cancers shows many genes are involved in most of them. More than one thousand somatic mutations have been identified in over two hundred cancers. All of these highlight a complex picture, the resolution of which calls for a combination of theoretical predictions and experimental confirmation. Traditionally, track structure simulations at a molecular level have been applied to scrutinise aspects of radiation damage in biological molecules based upon fundamental physical and chemical principles to generate hypotheses which are testable experimentally. To this end, track structure has provided a basis for understanding the mechanism of dose effect relationships. In particular, it has enabled predictions of frequencies of different types of DNA damage in terms of complexity and source of damage.

This presentation will outline the latest progress in the physics and simulation of radiation tracks in medium of the cell; the formation of simple and complex DNA damage; and briefly describe the relevance of the approach to the estimation of carcinogenesis and genetic risks of ionising radiation.

**Mathematical calibrations for measurements of radionuclides in people following a radiation incident**

Arron Shutt and Arthur Smalley

*Intakes of Radionuclides Group, Dose Assessments Department, Health Protection Agency, CRCE, Chilton, Didcot, UK, OX11 0RQ*

## ABSTRACT

There is a continuing threat to the general public from radiological incidents. Such incidents could occur as a result of the deliberate release of radioactive material from a radionuclide dispersal device (RDD). Assessment of the radiation doses to exposed people would in most circumstances be performed by making measurements of the amount of the radionuclide in the body. Currently, body-monitoring calibrations for such measurements are made using a physical model of the body (a "phantom") containing a known amount of radioactive material. Such phantoms are almost always constructed for measurements on adult males.

However, in an RDD incident, men, women and children of different ages and different body sizes could be exposed. Using a calibration phantom with different physical attributes to the person being measured could give rise to errors in the measured activity. Furthermore, calibrations with physical phantoms may not have been performed for the radionuclides that might be encountered. Radionuclides that are inhaled may be distributed non-uniformly in the respiratory tract which may affect the detector efficiency for lung calibrations. Commercially available phantoms used for efficiency calibrations typically use a uniform radionuclide distribution. Phantoms designed to be used in a supine position, do not always provide reliable calibrations for measurements on people made in a seated geometry, which presents problems for emergency monitoring applications. Mathematical phantoms can be applied to overcome all of these limitations.

A research project (VOXPOP) is under way to develop mathematical phantoms and mathematical detector systems for use with particle transport codes such as MCNPX. Research is currently being carried out to produce more realistic phantoms that represent the range of subject sizes and consider exposure parameter values such as the nature of the intake and the measurement time after intake. These factors affect the activity measurements carried out on affected persons. The research is applicable to both hand-held detectors used for screening measurements, and dedicated body-monitoring systems.

**Determination of the concentration and profile of the activation and fission product gamma-ray emitting radionuclides in a radioactive waste storage vault**

Yegneniy Tur[1], Alexander Klepikov[2], Ian Adsley[3]

[1] National Nuclear Center, Kurchatov City, Kazakhstan
[2] *Nuclear Technology Safety Center, Almaty, Kazakhstan*
[3] *Nuvia Limited, Harwell, Didcot, UK*

## ABSTRACT

This study concerns the investigation of active materials deposited in a radioactive waste storage vault at an experimental reactor. The reactor was used for the assessment of various fast neutron reactor fuel types and sections of spent fuel assemblies were examined in a heavily shielded, lead windowed, hot cell using remote cutting and handling equipment. Some βγ-active materials, such as the fuel element handling heads, coolant inlet and wrapper sections, were removed and deliberately dropped through a penetration in the floor of the hot cell into a shielded vault beneath. This material was principally stainless steel with the main gamma-ray activity coming from $^{60}$Co. In addition, it was suspected that small amounts of particulate fuel could also have been released into the hot cell cavity and found their way into the vault – the main gamma-ray emitting radionuclide in this case being the $^{137m}$Ba daughter of $^{137}$Cs.

As part of its monitoring activities, the IAEA requested an assessment of the amount of nuclear material which could have found its way into the waste vault. Although the amounts of nuclear material in this case were suspected to be low, a project funded by the Department of Energy and Climate Change as part of the UK Global Threat Reduction Programme was initiated to assess the activity of material in the vault.

The method adopted combined a remote video/dose rate survey and direct sampling with a matching theoretical assessment to determine expected dose rates. The survey was undertaken by making three penetrations into the vault through the bioshield. This enabled the introduction of a lighting system, a camera and a manipulator into the vault. The camera and lighting system enabled a video to be taken to identify the position and type of the waste components. A dose-rate meter was fixed onto the manipulator and this was used to provide a partial 3D survey of the dose-rate field within the vault. Finally, a sampler was fixed to the manipulator to obtain samples of the dust/residues on the floor of the vault and from liquid residues in a waste container placed under the hot cell access penetration.

Using the information gained from the video survey, sampling and the measured 3D dose rate field, MCNP models were constructed to simulate the source term distributions within the vault. The results of these are presented together with estimates of the uncertainties of the models.

## Using MCNP to determine the performance of detectors used for contamination surveys

Mike Davies

*Nuvia Limited, Harwell, Didcot, Oxfordshire, UK*

## ABSTRACT

Surveys of land potentially contaminated with radioactive materials have some particular problems. The nature of possible contamination is often unclear. While the group of radionuclides may be reasonably well understood from the processes that are known to have occurred on the site (radium luminising, nuclear fuel reearch, nuclear power production, nuclear weapon research) the actual contamination profile is rarely known due to a lack of accurate historical records. To make things worse, the processes that occurred on the site may have changed, often over decades.

Thus, when designing a survey for a site, it is often important to be able to evaluate several different contamination 'scenarios' and survey practices, such as walkover or static surveys. Where gamma radiation detectors are viable, MCNP provides the ability to rapidly evaluate scenarios and thus allow the choice of an appropriate detector and survey practice. When MCNP models are validated using small-scale laboratory experiments, they provide a critical part of the characterisation and calibration process for the chosen detector, often providing the key information for calculation of Minimum Detectable Activity.

This talk describes the types of detector that have been modelled with MCNP and the application of the detectors for environmental surveys. The contamination scenarios are also discussed, notably those where 'particles' of radioactive material are present on beaches at Dounreay and Sellafield.

**Monte Carlo studies utilising the ICRP adult reference computational phantoms for the assessment of typical normalised organ and effective doses from contemporary computed tomography scanners**

Jan T.M. Jansen and Paul C. Shrimpton

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## ABSTRACT

The new adult male and adult female computational reference phantoms, as defined in ICRP Publication 110 [1], have been implemented in MCNPX format for Monte Carlo simulations at HPA. For verification purposes, organ doses derived for a broad parallel beam of mono-energetic photons impinging AP on the phantoms have been compared with data published by ICRP in relation to similar simulations using EGSnrc, Geant4 and MCNPX versions 2.3.0 and 2.5.0. In most cases, the current calculations for MCNPX version 2.6.0 [2] lie in between results for EGSnrc and Geant4, but surprisingly do not closely reproduce the published data for MCNPX. This latter discrepancy is most probably due to the use of different cross section libraries or different fluence to dose functions.

MCNPX has also been used to calculate normalised organ doses for the Siemens Definition 64 multi-slice computed tomography (CT) scanner. The study has been performed with both a revised mathematical adult hermaphrodite phantom (HPA18+), based on the phantom developed by Cristy and Eckerman [3] with modified thyroid and neck, added oesophagus and the additional risk and remainder organs specified in ICRP Publication 103 [4], and also the voxel ICRP phantoms Adult Male [1] (AM) and Adult Female [1] (AF).

Values of normalised effective dose E103 tend to be somewhat higher when averaged between the AM and AF phantoms compared with results for HPA18+. This is largely due to the differences in size between the phantoms; AM and HPA18+ are of similar size, whereas AF is smaller, which results in higher normalised organ doses and therefore also a higher sex-averaged effective dose.

ICRP Publication 110 does not provide specific fluence to dose functions in relation to bone. Therefore red bone marrow dose has been calculated with the inclusion of King and Spiers [5] enhancement factors appropriate for low photon energies, whereas for the endosteal cells (previously called bone surface), average skeleton dose has been used. The distribution of red bone marrow cells throughout the various bones is according to Cristy [6] for the HPA18+ phantom and ICRP-110 [1] for the voxel phantoms. For the endosteal cells, the distribution is proportional to the mass of each part of the skeleton for HPA18+ and according to ICRP [1] for the reference voxel phantoms. In addition, bones are homogeneous in the HPA18+ phantom, whereas for the voxel phantoms, cortical, spongiosa, medullary cavities and cartilage are identified separately. As a result, endosteal cell doses are lower for the voxel phantoms than the HPA18+ phantom. However, the red bone marrow doses are comparable.

## References

[1] International Commission on Radiological Protection. *Ann ICRP* 39, 2, 1–165 (2009)
[2] D. B. Pelowitz, ed., *MCNPX User's Manual, Version 2.6.0*. LA-CP-07-1473, LANL, Los Alamos (NM) 2008
[3] M Cristy and KF Eckerman. *Specific absorbed Fractions of energy at various Ages from internal photon Sources. I. Method.* ORNL/TM8381/V1, ORNL, Oak Ridge (TN) (1987)
[4] International Commission on Radiological Protection. *Ann ICRP* 37, 1–332 (2007)
[5] King and Spiers. *Brit J Radiol*, 58, 345-356 (1985)
[6] Cristy. *Phys Med Biol*, 26, 389-400 (1981)

**Gamma spectrum unfolding for a NaI monitor of radioactivity in aquatic systems: evaluation of the Minimum Detectable Activity**

Jonathan Baré [1,2], A. Dubus [2], J.-C. Dehaes [2], F. Tondeur [1]

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*[2] Service de Métrologie Nucléaire CP165/84, Université Libre de Bruxelles, 50 Avenue F. D. Roosevelt, B-1050 Brussels, Belgique*

## ABSTRACT

Spectrum unfolding is a powerful method that may enhance clearly the readability of experimental energy spectra obtained by detectors of poor resolution, like scintillators. This technique can be implemented when the angular distribution of the radiation fluence is known. In the case of the NaI(Tl) based device developed by the Institut National des Radio-Eléments (IRE, Belgium) for monitoring the radioactivity in aquatic systems, the source may be considered as an infinite homogeneous medium surrounding the monitor, with constant density.

This work is dedicated to the experimental evaluation of the Minimum Detectable Activity (MDA) after deconvolution, for some radioactive isotopes such as $^{137}$Cs or $^{88}$Y. The experimental γ-spectra have been measured at the IRE, in a 20m³ seawater tank. The GRAVEL algorithm (UMG 3.3 package) is used for unfolding the spectra, on the basis of a response matrix obtained with MCNP5.1.40. The activities are directly calculated from the peaks in the unfolded spectra. An empiric method is used to evaluate the confidence interval associated with each result. It is shown that the MDA is significantly reduced by this treatment.

## The role of Monte Carlo at the Heidelberg Ion Beam Therapy Center

Katia Parodi[1,2], A. Mairani[1,3§], I. Rinaldi[3,1], D. Unholtz[1,2] and F. Sommerer[2,1]

***(Invited speaker)***

[1] *Heidelberg Ion Beam Therapy Centre, Heidelberg, Germany*
[2] *University Clinic of Heidelberg, Heidelberg, Germany*
[3] *German Cancer Research Centre, Heidelberg, Germany*

## ABSTRACT

The new hospital-based Heidelberg Ion Beam Therapy Centre (HIT) in Heidelberg, Germany, offers high precision radiotherapy treatments with different ion species (initially protons and carbon ions, later on also oxygen and helium ions) and the state-of-the-art, intensity-controlled raster-scanning beam delivery technique. Clinical exploitation of the utmost dose conformality offered by scanned ion beams demands accurate determination and characterisation of the individual pencil-like beams building up the treatment field. At present, treatment planning systems (TPS) for ion therapy rely on fast performing analytical pencil-beam algorithms. However, Monte Carlo (MC) transport codes offer more powerful and flexible computational tools for detailed description of ion beam interactions in the beam-line and the target, including the complex and heterogeneous patient tissue. At HIT, MC calculations for protons and carbon ions based on the FLUKA code have been extensively performed for manifold activities related to beam modelling, treatment planning and quality assurance.

This talk will review the main accomplishments such as the determination of the beam parameters (focus and energy) of the accelerator library as well as the TPS basic input data (depth-dose and fragment spectra for $^{12}C$), which have been in clinical use since treatments began in November 2009. Moreover, it will address the application of MC to forward recalculations of treatment plans in water and in the patient to support validation and further improvements of TPS. Finally, it will give an overview on ongoing research activities on the application of MC to support and investigate in-vivo treatment verification techniques.

§ Current affiliation: INFN Italy

## A PHITS-based dose calculation engine to evaluate the effect of inhomogeneities in prostate brachytherapy

Julien Smeets[1], Jean-Claude Dehaes[1], Stéphane Simon[2]

[1] *Department of Nuclear Metrology, Université Libre de Bruxelles, Brussels, Belgium*
[2] *Department of Radiophysics, Bordet Institute, Université Libre de Bruxelles, Brussels, Belgium*

### ABSTRACT

Monte Carlo simulations have been developed to estimate the effect of localized calcifications on the dose distribution of $^{125}$I prostate brachytherapy. The calculations are based on the PHITS code and benefit from its high precision voxel scoring capabilities. The PHITS code was benchmarked for brachytherapy and the presence of spherical calcifications was simulated in an idealized prostate. Results suggest that the effect of a single localized calcification on the dose distribution could be rather small.

### PURPOSE

During routine treatment of prostate cancer by brachytherapy with $^{125}$I seeds, the treatment planning software calculates the dose distribution by superposing the contributions of all the sources by means of their TG43 calibration parameters. This calculation neglects the possible presence of heterogeneities like calcifications that strongly absorb low energy photons and could affect the dose distribution [2]. In this study, the effect of a single homogeneous spherical calcification [4] is evaluated and compared with other effects.

### METHODS

The Monte Carlo program *PelMod* has been developed to calculate the dose distribution in the prostate using PHITS (Particle and Heavy Ion Transport code System) version 2.15a [3]. The sources are precisely modelled and arranged in a water medium where the dose is calculated with a mesh tally on a 1 mm³ voxel matrix. When voxels are partially filled by a source or a calcification, the dose is only scored in the fraction filled by water [1]. Different corrections were implemented and their effect was evaluated.

The source *STM1251* (*Bard*®) is used and its TG43 dosimetric parameters were evaluated with PHITS, benchmarked with MCNPX (version 2.5.0), and compared with previous studies to validate our model and the use of PHITS for brachytherapy.

Calculations are based on an idealized pelvis model whose geometry was introduced in the *Variseed 7.2* software (*Varian*®) to optimize the position of the seeds. The dose distribution calculated by *Variseed* is compared with different Monte Carlo models to observe the effect of the source anisotropy, of the interseed attenuation and of a localized calcification.

### CONCLUSIONS

The PHITS code turns out to be an interesting tool for brachytherapy. Results of *PelMod* indicate that *Variseed* slightly overestimates the dose distribution in the prostate as expected. Most of the difference is due to the value of the dose rate constant that acts as a scaling factor on the dose distribution. The dose rate constant calculated with PHITS, although identical with the WAFAC value resulting from the detailed simulation of Kirov et al. [5], is 3.7% smaller than the TG43 consensus value used in *Variseed*. When both *PelMod* and *Variseed* use the TG43 value and treat a homogeneous prostate, *Variseed* gives values only 1% higher than *PelMod* for the V100 and D90 dosimetric indicators. The interseed effect, when considered by *PelMod*, is responsible for an additional 1-2% deviation and a 5 mm wide calcification has a smaller effect.

## ACKNOWLEDGEMENTS

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**Re-establishing the absorbed dose primary standard for photon beams on the new NPL Clinical Linac**

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## ABSTRACT

A new state-of-the-art clinical linac facility has recently been opened at the National Physical Laboratory (NPL) in addition to the existing research linac facility, whose linac is now over 40 years old. The new machine is an Elekta Synergy Digital Linac with iViewGT portal and XVI 3D x-ray volumetric imaging, MOSAIQ management system and Pinnacle treatment planning system. The NPL machine can be configured to deliver seven x-ray beam energies (instead of the usual maximum of three in any one hospital machine). This feature, together with the ability to provide up to ten electron beam energies, will enable NPL to provide absorbed dose calibrations for the full range of energies currently in therapeutic use in the UK.

The NPL is responsible for maintaining the UK primary standards of absorbed dose to water in both high-energy photon and electron beams. For photons, the primary standard is a graphite calorimeter [1] that directly measures absorbed dose to graphite, that is, the energy deposited in a small graphite core at the centre of the calorimeter, in $^{60}$Co gamma ray and MV X-ray beams, divided by the mass of the core. Reference standard ionisation chambers placed in a graphite phantom are then calibrated against the primary standard in terms of absorbed dose to graphite. These calibrations are then converted to absorbed dose to water through the application of the photon fluence scaling theorem [2,6]. Hospital secondary standard instruments are then calibrated against these reference standards at either 5cm or 7cm depth in a water phantom.

Monte Carlo modelling is required at various points in the realisation of absorbed dose to water at depth in a water phantom from measurements with the primary standard calorimeter, in particular:

- corrections to account for the presence of non-graphite materials and air / vacuum gaps in the calorimeter,
- water-to-graphite dose ratios in the phantoms and associated corrections for the photon fluence scaling theorem,
- corrections for the different geometrical configuration of the calorimeter (cylinder shaped) and graphite chamber phantom (box shaped).

In addition and prior to the calculation of these values, validated Monte Carlo models of the linac source are also required for each X-ray energy.

In this work, the usercodes DOSXYZnrc and DOSRZnrc from the EGSnrc code system (release V4-r2-2-5) [3], together with the associated package BEAMnrc (release 2007) [4], were used to build the linac source models and to determine the required corrections for re-establishing the existing UK primary standard of absorbed dose in the new X-ray beams. Simulations were run on the NPL distributed computing grid that utilises the idle time of over 350 networked computers across the NPL site.

For the seven energies (and after fine tuning each linac source), calculated depth-dose curves agreed with plotting tank measurement to better than 1% beyond the dose maximum ($d_{max}$) for both 10x10 cm$^2$ and 30x30 cm$^2$ fields. Similarly, the calculated dose profiles agreed with measurement over the central region and 'horns' to within 1-2% at $d_{max}$ and at various depths in the phantom although some small discrepancies in the regions beyond the penumbra have been observed (and are currently being investigated). These small discrepancies, however, are unlikely to have any significant effect on the dose values on axis under reference conditions that is of interest here. Penumbral widths of the profiles agree with measurements to within 0.5mm.

With these fine-tuned sources under reference conditions, the presence of gaps (and non-graphite materials) in the primary standard calorimeter were found to reduce the dose the calorimeter core by typically 0.62% for 4MV X-rays and 0.24% for 25 MV X-rays. These corrections are consistent with earlier experimental investigations of this correction carried out on the existing NPL research linac using similar X-ray beams having comparable quality indices (or tissue-phantom ratios) [5].

Water-to-graphite dose ratios in scaled phantoms required for the photon fluence scaling measurements were found to be mostly independent of source-chamber distance for a given energy (apart from distances very close to the source where back-scatter becomes an issue in the measurements). These ratios at a source-chamber distance of 100cm varied from 1.081 for 4MV X-rays to 1.115 for 25MV X-rays and again were consistent with previous values determined on the existing research linac [6].

Finally, changes in the scatter dose component due to the different geometrical configurations of the primary standard calorimeter and graphite phantom were calculated and found to be less than 0.1-0.2% and predominately due to increased backscatter from extra material present at the back of the phantom. These calculations were in good agreement with comparable scatter measurements in the new beams. In all cases, the statistical (Type A) uncertainty in the quoted corrections and dose ratios are typically 0.1% (SDOM) or better.

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**Monte Carlo modelling of the effect of scatter on the CT Dose Index for Cone Beam CT**

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## ABSTRACT

The Computed Tomography Dose Index (CTDI) is an international standard radiation exposure index used in X-ray computed tomography and is reported by the CT manufacturers to express the dose given to patients on each CT examination. The CTDI was developed for conventional CT scanners when the width of the fan beam was small compared to the length of the detector. Since the introduction of Cone Beam CT (CBCT) and multi-slice CT scanners, which use a broader X-ray beam, the CTDI has been considered for revision [1].

The CBCT machine used in this work is the X-ray Volume Imaging (XVI) unit mounted on an Elekta Synergy linear accelerator (Elekta, Crawley, UK). The Elekta XVI tube can produce X-ray beams with peak accelerating voltage between 70 and 150 kV. A selection of ten collimator cassettes is provided for kV image acquisition with a blank or with a bowtie filter. We used the EGSnrc/BEAMnrc Monte Carlo (MC) code [2-3] to model the Elekta XVI unit. An extensive dosimetric validation of the MC model has been previously reported [4-6].

In this investigation we studied with MC the effect that phantom length and radius have on CTDI value for 10 different volume view presets (vvp). Both CTDI head and body phantom were modelled. Five phantom lengths were considered: 15, 24, 30, 33 and 39 cm (where 15 cm is the length of the standard phantom in current use). The irradiation of each phantom was simulated and the dependence with phantom length of the dose scored at centre and periphery of the phantoms was assessed. On the basis of the simulation results, the CTDI phantom geometry was optimized for CBCT dose measurements. The selection of the optimal phantom length was based on the size of the dose profile as well as the CTDI value; at least the 10% level in the dose profile should be measurable and the CTDI value should be measured with all the scatter contribution taken into account.

The effect of CTDI variation with respect to phantom length is shown in *Figure 1* for the body phantom and vvp3 (kVp=120, mA=40, ms=40, collimator=M20, filter=bow-tie). Similar results were obtained with the head phantom and other presets. The increase in CTDI due to the phantom length reaches a plateau at ~30 cm. This is because as the phantom length increases, the additional scattered radiation is also self-absorbed by the phantom with increased efficacy. *Figure 2* depicts the MC simulated profiles for a given preset and different phantom sizes. It can be seen that 10% level in the dose profile can only be measured when the phantom length is ≥ 39 cm. The length of the phantom that has been chosen as a replacement of the standard 15 cm for measurements of CTDI is 40 cm.

After the optimised phantom was manufactured, verification measurements of $CTDI_{100}$, weighted $CTDI_{100}$, dose and sensitivity profiles (according to the requirements of the relevant IEC compliance standard [7]) were performed on the standard set of phantom (head and body) and on the new phantom design for all the 10 XVI vvps. Data analysis was carried out with the Computational Environment for Radiotherapy Research (CERR) and in-house built software [8-9] in the Matlab platform (The MathWorks, Inc. USA).

Excellent agreement was found between calculated and measured CTDI values and dose profiles. The proposed approach represents a useful application of MC modelling in a rapidly evolving field such as Image Guided Radiotherapy and presents the basis for a computer-based investigation of the most appropriate quantitative parameters in modern computed tomography.

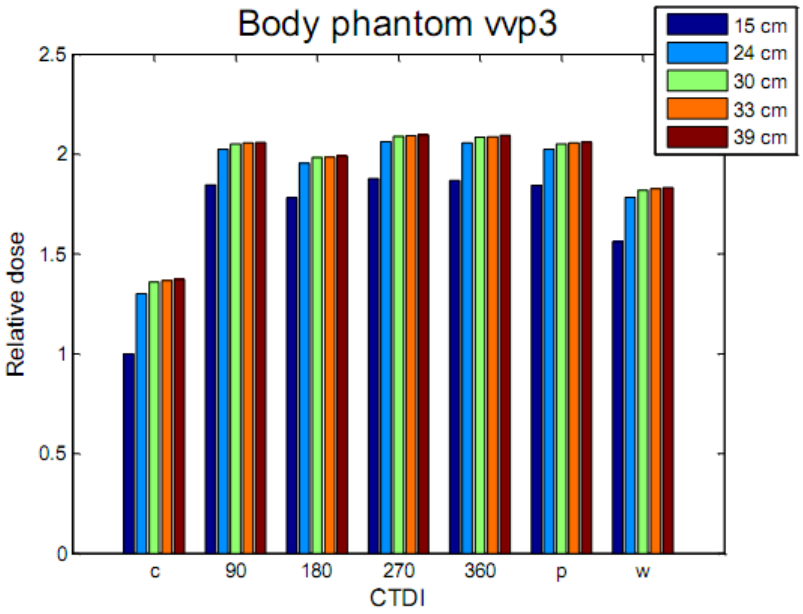


**Figure 1** CTDI value dependence on phantom length for volume view preset 3 and body phantom. The values for CTDI centre (c), peripherals (90, 180, 270, 360 and p) and weighted (w) are reported.

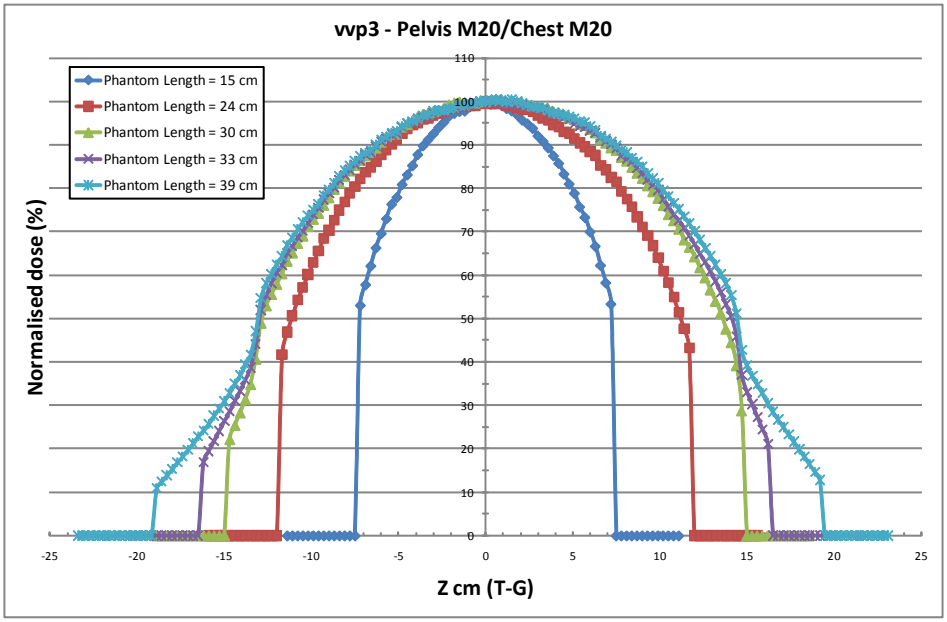


**Figure 2** MC simulated dose profiles along the central axis of the CTDI phantom at source to axis distance of 100 cm for the Pelvis M20/Chest M20 preset (vvp3) and a set of different Body Phantom lengths.

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**Fitting measured depth-dose curves on the new NPL Clinical Linac with realistic electron beam spectra using EGSnrc user codes DOSRZnrc, SPRRZnrc and DOSXYZnrc, with a full BEAMnrc source**

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## ABSTRACT

In addition to the seven photon beam qualities available on the new Elekta Synergy Digital Linac installed at NPL, there are ten available electron beam qualities, up to nine of which will be in common use. During commissioning exercises, depth-ionisation measurements were made using a Scanditronix NACP-02 parallel-plate ionisation chamber, and prior to calculating gap corrections for primary standard calorimetry and wall perturbation factors for hospital ionisation chamber calibration services, validated Monte Carlo models of the electron beam source are required for each electron beam quality. EGSnrc [1] -based calculations using DOSRZnrc and DOSXYZnrc, with water-air stopping power ratios calculated using SPRRZnrc, all with a full BEAMnrc [2] source, were used for these calculations.

It is important to compare these results with those obtained using the current IPEM electron radiotherapy dosimetry code of practice [3] since the equations presented in the code of practice were obtained using Monte Carlo calculations using EGS4-based codes in 1995 [4,5]. EGSnrc contains more complete physics particularly in relativistic spin interactions and in the Bhabha and Møller cross-sections for electron and positron scattering.

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## A non-CAD-based approach to modelling a Linac Treatment Head with the Geant4 Monte Carlo code

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## ABSTRACT

The accuracy of Monte Carlo calculations depends heavily on an accurate geometrical model. The choice of Monte Carlo software is thus influenced by which packages allow a complex geometry to be described easily. BEAMnrc is an attractive and popular choice for radiotherapy simulations as it is specifically designed for such purposes and significantly simplifies the process of describing a LINAC treatment head [1]. However, this simplification reduces its flexibility to produce arbitrarily complicated shapes. For this, a more general purpose Monte Carlo package is more suitable and one that has gained some attention lately is Geant4 [2] [3] [4] [5]. Geant4 allows for geometries composed of combinations of primitive shapes (such as cuboids, spheres, cylinders etc.) or complicated tessellated solids [7].

Due to the complex nature of a LINAC treatment head, some are inclined to use CAD software to generate the geometry input [5] [6]. Using CAD software is a commercial solution and the ouput is generally composed of tessellated solids (depending on the CAD software used). A more efficient design would be a combination of tessellated solids with primitive solids in areas where the geometry is sufficiently simple since primitive solids can take advantage of the symmetries in their shape to optimise computations. More significantly, areas of the geometry that are curved, such as the multileaf collimators (MLCs), are approximated by triangular and rectangular facets when described by a tessellated solid [5] [6]. By using primitive solids, curved faces can be described precisely in Geant4. In fact, even complicated shapes can be constructed from a combination of primitive solids. As part of a PhD project being undertaken at Saint Luke's Hospital in Dublin, a Monte Carlo model of an Elekta Synergy Linac has been developed based on specifications provided by the manufacturers. This model has been constructed almost entirely of primitive shapes without compromising the manufacturers specifications and demonstrates an alternative to CAD based geometry definition.

This model was described by hard-coding the geometry directly into the Geant4 application, however the geometry can be imported at runtime if described in a GDML file [8]. GDML (Geometry Description Markup Language) is an XML file specification developed by CERN as an application independent format for describing detectors for physics based simulations. This is what CAD files are exported to for use in Geant4, however because they are written in XML format they are human readable and therefore they can be written directly by the user. This has the advantage of not having to use C++ or interact with the Geant4 API to define the geometry and also allows it to be changed without recompiling the code. Also, as GDML is designed to be application independent, a geometry defined by a GDML could in principle be used with other Monte Carlo codes [8], eliminating the need to redefine the geometry again and reducing the potential for differences in cross-platform geometries introduced by human error. Support for GDML has yet to be implemented by Monte Carlo codes other than Geant4 [5], however with sufficient support this could change or even be implemented by third parties. This would allow for precise cross platform geometries to be developed without the need for CAD software.

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## Use and modelling of solid-state dosimeters in small field radiotherapy

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## ABSTRACT

The dosimetry of small field radiotherapy, where the range of secondary charged particles is significant in comparison to the size of the field, presents a number of challenges and has led to errors in the calibration of radiotherapy beams. This work has examined the use of solid-state detectors, including diamond and silicon strip detectors, utilising Monte Carlo modelling in order to predict radiation profiles of small fields and detector response. The influence of the size of the detector and changing charge particle spectra, due to a lack of electronic equilibrium, on detector response have been examined suggesting that additional stopping power-related corrections of the order of 0.5% are required at small field limits. It has been shown that the perturbing effects of non-tissue equivalent systems such as silicon are greatly reduced when utilising thinned structures of < 50 micron thickness. However, Monte Carlo calculations of the energy absorbed in micron-dimensions from linac-based beams require large amounts of computing time, demanding that parallel computing techniques have been used throughout.

**A model calculation for proton and neutral hydrogen interactions in water: The Classical Trajectory Monte Carlo approach**

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## ABSTRACT

We present a model calculation for the interactions of protons and neutral hydrogen atoms from 1 keV/u – 1 MeV/u in water. Interaction cross-sections for low- and intermediate-energy ions provide a detailed description of radiation interactions at and beyond the Bragg peak of ion beams, where the stopping power of ions reaches a maximum. At this energy region, projectile and target nucleus simultaneously influence electron emission from the primary beam, leading to significant a contribution from charge transfer to the energy loss processes of ions. Charge transfer also gives rise to the contamination clothed ions in the initial bare ion beam. To accurately model the interactions of ions at and beyond the Bragg peak, the two-centre effect and the interactions of bare and dressed ions need to be included.

In this work, the interaction cross sections for protons and neutral hydrogen atoms were calculated using the Classical Trajectory Monte Carlo (CTMC) method, taking into account the interactions of projectile, target, and (projectile- or target-) electron simultaneously. The binding of electron to target (or projectile) is governed by a model potential and a quantum mechanical energy state. The results are presented as total, singly, and doubly differential cross sections for ionisation and electron capture (electron loss) for protons (neutral hydrogen atoms). The calculated stopping cross sections are compared with literature values, for a consistency-check of the equilibrium charge state of the proton beam and the energy transfer model. The model calculations can be extended to other ions such as carbon, which is of particular interest for radiation therapy and biophysical modelling including microdosimetry.