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Fermi National Accelerator Laboratory



Book of Abstracts

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Session 2b. Induced radioactivity, Convener: Sayed Rokni / 0**The use of ActiWiz in operational radiation protection****Authors:** Christian Theis¹; Helmut Vincke¹¹ CERN**Corresponding Author:** christian.theis@cern.ch

The ActiWiz code has originally been developed at CERN for easy and quick assessment and comparison of the radiological hazard of materials used in the environment of high energy accelerators. Due to its foundations on nuclide production terms recent extensions have been developed to allow for an application also in the field of operational radiation protection.

An isotope build-up and decay engine has been developed to calculate nuclide inventories for arbitrary irradiation- and cooling period patterns. Automatic analysis of the dominating contributors to various quantities like radiotoxicity, clearance levels, photon dose-rate, gamma emission spectra etc. is provided. In addition, shielding of activated equipment, including the treatment of photon dose build-up factors, can be calculated within a few seconds even for nuclide sets with many thousands of gamma lines. The utilized initial nuclear inventories, including radioisotope production terms, can either originate directly from ActiWiz, from Monte Carlo codes like FLUKA, PHITS, MARS, MCNP or gamma spectroscopy measurements.

In this paper an overview of these new features and a benchmark comparison to shielding calculations with FLUKA and the analytic Nucleonica code is given.

Session 1. Source Term and Related Topics, Convener: Hee-Seock Lee / 1**Radiation Skyshine Calculation with MARS15 for the mu2e Experiment at Fermilab****Author:** Anthony Leveling¹¹ Fermilab**Corresponding Author:** leveling@fnal.gov

The Fermilab Antiproton source is to be repurposed to provide an 8 kW proton beam to the mu2e experiment by 1/3 integer, slow resonant extraction. Shielding provided by the existing facility must be supplemented with in-tunnel shielding to limit the radiation effective dose rate above the shield in the AP30 service building. In addition to the nominal radiation shield calculations, radiation skyshine calculations were required to ensure compliance with Fermilab Radiological Controls Manual. A complete model of the slow resonant extraction system including magnets, electrostatic septa, magnetic fields, tunnel enclosure with shield, and a nearby exit stairway are included in the model. The skyshine model extends above the beam enclosure surface to 10 km vertically and 5 km radially.

Poster Session and Reception / 4**Source Term Estimates for the Environmental Impact Analyze of the European Spallation Source Facility_____****Author:** Daniela Ene¹¹ European Spallation Source, ESS-AB, Sweden

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As other accelerator based facilities, the European Spallation Source (ESS) facility will not be a totally isolated system. It will interact with the environment. One can distinguish four types of radiological impacts: i) releases of activated air, ii) discharges of activated water, iii) activation of soil and groundwater, iv) stray radiation in the environment. The Swedish legislation requires a demonstration that the sum of the doses resulting from the exposure of any member of the public to ionizing radiation dose does not exceed the specified limit. A radiological assessment has been produced to provide that demonstration [1]. This evaluation was based upon the actual status of the ESS design as given in the Ref. [2].

This paper reports the source term estimates for the radiological assessment of the dose that would arise: i) from the routine discharge of gaseous and aqueous radioactive waste for ESS facility as well as from ii) the groundwater activation around the linac tunnel and of the beam dump and the target station monolith foundations. Additionally, estimates of the stray radiation effects were done by coupling the results of the deep penetration calculations with analytical formula [3].

The source term for atmospheric releases was separated into two distinct release operations: i) on-line emissions, and ii) emissions resulting from processing. On-line emissions through the stack into the atmosphere were derived from both accelerator tunnel (AT) and target station (TS). For the tunnel the source term was derived from the activation calculations of the air [4] and conservative assumptions upon the ventilation rate. As the Helium cooling loop of the target is a closed circuit the single release source from the target station accounted was the leakage rate of the loop. The main contributions to atmospheric releases arising from processing operations are on-site cementation of tritiated water and the hot cell operations such the cut of the target shaft. The assessment shows that the major contribution to the source term (H-3, Be-7, C-11, N-13, O-15, Ar-41, P-32, P-33, S-35) comes from the linac tunnel. The most important nuclide released from the target station is I-125 while the "post processing" source term given mainly by tungsten dust has negligible effects.

The source term for the migration of activated-groundwater towards the ESS site border (distance 300 m) is driven mainly by H-3 and other radionuclides produced by spallation in the earth around the linac tunnel. Derivation was based on calculations assuming a linac beam loss of 1 W/m, and standard shielding (60 - 80 cm of concrete). The activation of the groundwater underneath the beam dump shielding and the target station was also assessed. As resulted from the bulk shielding calculations for both linac and target station the dose rates on the top of the shields are at the level of 1 microSv/h. Based on this result roughly derivation of the "skyshine" dose from the emitting surface of the shield in a distance corresponding to the site border or more, may be easily achieved. However, more rigorous calculations have to be performed to derive the levels of neutrons escaping outwards through holes or thin parts of the shields.

1. D. Ene, Evaluation of the Environmental impact of the ESS facility, ESS Internal Report, 2013
2. S. Peggs, ESS Technical Design Report, 2013
3. A. H. Sullivan, A Guide to Radiation and Radioactivity and Radioactivity Levels Near High Energy Particle Accelerators, Nuclear Technology Publishing, England, 1992
4. D. Ene Radioprotection studies for ESS superconducting Linac, Progress in Nuclear Science and Technology, Vol. 2, pp.382-388, 2011

Summary:

Radiological studies were performed for the European Spallation Source Facility in order to determine radiological impact to the environment.

Poster Session and Reception / 5

Energy deposition studies for the LBNE beam absorber*

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The Long-Baseline Neutrino Experiment (LBNE) at Fermilab is supposed to provide the world's highest-intensity neutrino beam for the US program in neutrino physics. The corresponding incoming proton beam power can ultimately be as high as 2.3 MW, and the underground beam absorber at the end of the decay channel with related infrastructure is supposed to operate with little or no maintenance for about 20 years. Such a combination of long operation time and high deposited power imposes strict limitations on design of the absorber.

In this paper, we describe results of detailed Monte Carlo energy deposition studies performed for the absorber core and the surrounding shielding with the MARS15 code. The model of the entire facility, that includes the pion-production target, focusing horns, target chase, decay channel, hadron absorber system – all with corresponding radiation shielding – was developed using the recently implemented ROOT-based geometry option in the MARS15 code. This option provides substantial flexibility and automation when developing complex geometry models. Both normal operation and accidental conditions were studied. Various design options were considered, in particular the following: (i) filling the decay pipe with air or helium; (ii) the absorber mask material and shape; (iii) the beam spoiler material and size. Results of detailed thermal calculations with the ANSYS code helped to select the most viable absorber design options.

*Work supported by Fermi Research Alliance, LLC, under contract No. DE-AC02-07CH11359 with the U.S. Department of Energy.

Summary:

Energy deposition studies with the MARS15 code for the Long-Baseline Neutrino Experiment at Fermilab are presented.

Session 5. Status of Codes and Data Bases, Convener: Alfredo Ferrari / 6

Modeling proton-induced reactions at low energies in the MARS15 code*

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Correct predictions of secondary particles, both neutral and charged ones, generated in proton-nucleus interactions below a few tens of MeV is required for various applications. The latter include, e.g., radiation studies for front-end of many proton accelerators, energy deposition studies for detectors, radiation damage calculations, etc. Cascade models of various flavours fail to properly describe this energy region. Therefore, we opted to use the TENDL library developed by the Nuclear Research and Consultancy Group. The evaluated data is provided in the ENDF/B format in the energy range from 1 to 200 MeV, and the library is regularly updated since 2008. In addition, a much more time-consuming approach utilized in a modified code ALICE was also looked at. For both the options, the energy and angle distributions of all secondary particles are described with the Kalbach-Mann systematics. The following secondaries are taken into account: gammas, neutrons, protons, deuterons, tritons, He-3 and He-4. The energy and angular distributions of all generated residual nuclei—including unstable ones—are accounted for as well.

Various comparisons with experimental data for both the options are presented. The corresponding processing and modeling software is written in C++ which provides substantial flexibility with respect to the computer memory used. In addition, the initialization of required evaluated data is performed dynamically whenever the modeling code encounters a nuclide not accounted for yet. The latter feature enables us to significantly reduce the amount of requested memory for extended systems with large number of materials.

*Work supported by Fermi Research Alliance, LLC, under contract No. DE-AC02-07CH11359 with the U.S. Department of Energy.

Summary:

Modeling proton-induced reactions at low energies using TENDL library of evaluated nuclear data is described. Comparisons with experimental data are presented as well.

Poster Session and Reception / 7

Energy Production Demonstrator Model for the GeV-range Megawatt proton beams

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A preliminary study of the Energy Production Demonstrator (EPD) concept, a heavy metal target irradiated by GeV-range intense proton beams and producing more energy than consuming, is carried out. Neutron production and fission are simulated using the MARS15 code for tungsten, natural uranium, lead and thorium target options, along with energy deposition and gain, peak DPA rate, materials testing volume and helium production in the proton energy range of 0.5 to 120 GeV.

Study indicates that the proton energy range of 2 to 4 GeV seems to be the most practical for both the natural uranium EPD and the tungsten testing station that would be the most suitable for proton accelerator facilities. Based on the simulations, conservative estimates not including breeding and fission of plutonium suggest that the proton beam power of 6 MW is appropriate in the first case which can produce more energy than use for accelerator needs. Simulation results reveal that the thorium target is not efficient for the energy production purpose. The ANSYS thermal analysis of the target has also been carried out. An existing prototype of the uranium-based EPD target residing at JINR, Dubna is discussed as a possible candidate for benchmark experiments.

Session 6. Code Benchmarking and Intercomparison, Convener: Robert Grove / 8

Intercomparison of Particle production

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Intercomparison of Particle production

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In accordance with the discussion at SATIF11, we sent the following inter comparison problems of particle production from thick targets to understand the differences of neutron attenuation inside Fe and concrete.

1. Incident particle
Pencil beam of protons with following energy
 - (a) 1 GeV
 - (b) 10 GeV
 - (c) 100 GeV
2. Target materials and their size
Targets geometry is the cylinder.
Source protons incident on the center of the cylinder bottom.
Target detector distance from the center of the cylinder is 500cm.
 - (a) Al : length 40cm, diameter 4.0cm and density 2.7g/cm³
 - (b) Cu : length 16cm, diameter 1.6cm and density 8.63 g/cm³
 - (c) Au : length 10cm, diameter 1.0cm and density 19.3 g/cm³
3. Quantities to be calculated
Neutron spectrum above 20 MeV in n/MeV/sr/proton
at 15, 30, 45, 60, 90, 120, 150 degrees with angular width ± 0.5 degrees.
4. Calculated results must be sent to H. Hirayama at KEK (hideo.hirayama@kek.jp)
with the following data till March 30 of 2014 to prepare the intercomparison.
 - (a) Name of participants and organization
 - (b) Name of computer code used for calculations
 - (c) Name of data base used in the calculation

At SATIF12, we will present comparison between results sent us till the end of March.

Summary:

Present comparison of neutron production by high energy protons between various codes will be presented to understand the differences of neutron attenuation inside Fe and concrete.

Session 6. Code Benchmarking and Intercomparison, Convener: Robert Grove / 9

Code intercomparison and benchmark for muon fluence and absorbed dose induced by 14 and 18 GeV electron beams after massive iron shielding

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In 1974, Nelson, Kase, and Svensson published an experimental investigation on muon shielding around SLAC high energy electron accelerators (NIM 120 (1974) 413). They measured muon fluence and absorbed dose induced by 14 and 18 GeV electron beams hitting a copper/water beamdump and attenuated in a thick steel shielding. In their paper, they compared the results with the theoretical models available at that time.

In order to confront their experimental results with present model calculations, we have used the modern transport Monte Carlo codes MARS15, FLUKA2011 and GEANT4 to model the experimental setup and run simulations. The results are then compared between the codes, and with the SLAC data. Preliminary results from this campaign are reported in the presentation.

Summary:

Results for muon fluence and dose after a thick shielding from the current versions of the MARS15, FLUKA2011 and GEANT4 codes are compared with each other and with SLAC data for 14 and 18 GeV electron beams.

Session 3a. Radiation Shielding, Convener: Hideo Hirayama / 10

Overall assessment of the ESS linac shielding

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European Spallation Source (ESS) will consist of a proton linear accelerator that will accelerate protons up to 2 GeV, a target and a number of neutron instruments. An overall preliminary assessment of the linac shielding is completed. A simplified 3D model is constructed and used for necessary shielding evaluations using MARS Monte Carlo code. Model consists of a linac tunnel and an earth berm around it. Study about the amount of the berm shielding on top of the linac was completed as well as towards the klystron gallery. The klystron gallery building is also part of the model and a number of openings in the bulk shielding are included, such as penetrations for power waveguides, cable penetrations, emergency exits, smoke evacuations, alignment penetrations and a loading bay. Most of the penetrations were designed as chicanes/labyrinths to ensure that they don't contribute to elevated dose rates outside the shielding. A detailed shielding design study is planned at the next stage of the ESS project.

Session 3a. Radiation Shielding, Convener: Hideo Hirayama / 12

Shielding calculations with MCNPX at the European Spallation Source

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The European Spallation Source (ESS) is a collaboration of 17 European partner countries established to project, build and operate the world's most powerful neutron source in Lund, Sweden. The construction of the facility will start in the course of 2014, and ESS is expected to produce the first neutrons in 2019.

Monte Carlo calculations are required to design the appropriate shielding needed to guarantee the radioprotection of the workers and of the public. We will present here the results obtained with the MCNPX radiation transport code for two critical areas of the ESS facility: the front-end building,

and the accelerator-to-target section of the 2 GeV proton linear accelerator.

We have modelled the RFQ, the MEBT and the DTL components of the accelerator, and we have calculated the dose contribution to the rooms adjacent the front-end building, as a function of several shielding solutions. We will discuss the results and present the shielding design in these areas, so to allow unrestricted access during the operation of the accelerator.

We have also modelled the accelerator-to-target section of the accelerator, and we have calculated the dose contribution given by the neutron backshine from the spallation target. These results will be discussed, presenting neutron and gamma doses in the accelerator tunnel.

The exposure limits were set according to international standards, the provisions of Swedish laws, and the indication of the Swedish regulatory authorities. Hence, we will present also the fluence-to-dose conversion factors applied in the shielding calculations at ESS and the relative safety factors.

Session 4. Medical Accelerators, Convener: Vladimir Mares / 13

Neutron Therapy in the 21st Century

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The question of whether or not neutron therapy works has been answered. It is a qualified yes, as is the case with all of radiation therapy. But, neutron therapy has not kept pace with the rest of radiation therapy in terms of beam delivery techniques. Modern photon and proton based external beam radiotherapy routinely implements image-guidance, beam intensity-modulation and 3-dimensional treatment planning. The current iteration of fast neutron radiotherapy does not. Addressing these deficiencies, however, is not a matter of technology or understanding, but resources.

The future of neutron therapy lies in better understanding the interaction processes of radiation with living tissue. A combination of radiobiology and computer simulations is required in order to optimize the use of neutron therapy. The questions that need to be answered are: Can we connect the macroscopic with the microscopic? What is the optimum energy? What is the optimum energy spectrum? Can we map the sensitivity of the various tissues of the human body and use that knowledge to our advantage? And once we gain a better understanding of the above radiobiological issues will we be able to capitalize on this understanding by precisely and accurately delivering fast neutrons in a manner comparable to what is now possible with photons and protons?

This presentation will review the accomplishments to date. It will then lay out the questions that need to be answered for neutron therapy to truly be a 21st Century therapy.

Session 2b. Induced radioactivity, Convener: Sayed Rokni / 14

Activation Products from Copper and Steel Samples Exposed to Showers Produced by 8 GeV Protons Lost at the Fermilab Main Injector Collimation System

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In conjunction with efforts to predict residual radiation levels, measurements of residual radiation were correlated with the time history of losses. Detailed examination suggested that the list of radioactive isotopes used for fitting was incomplete. We will report on activation studies of magnet steel and copper samples which we irradiated adjacent to the Fermilab Main Injector collimation system. Our results identified several additional radioactive isotopes of interest including ones due to small isotopic and small chemical components with disproportionate contributions to the residual radiation. The MARS15 studies using both realistic and simplified models have confirmed our understanding of these measurements. The long half-life isotopes will grow in importance as operation stretches to a second decade and as loss rates rise. These studies allow us to predict limits on these concerns.

Summary:

This presentation will build on the radiation control efforts for the Fermilab Main Injector by examining the activation of materials for the magnet systems which experience activation by 8 GeV beam loss. Activation studies with samples of steel and copper exposed them to the radiation near one of the secondary collimators allow presentation of measured results and comparisons with MARS15 calculations. The cooldown studies at bar-coded residual radiation measurement locations will provide a framework for relating these measurements to the overall effort to quantitatively predict and understand radiation exposures during upgrade and maintenance efforts in the Main Injector tunnel.

Session 5. Status of Codes and Data Bases, Convener: Alfredo Ferrari / 15

Object-Oriented Developments in MARS15 Code*

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The object-oriented modules – recently developed and implemented into the MARS15 code - are described. These include the powerful ROOT-based geometry and visualization; the ROOT-based beam line builder that interfaces the MARS code to the MAD lattice description; integration of MARS and the MAD-X code system; highly-efficient handling of large databases used for DPA, electromagnetic processes and nuclear interactions below a hundred MeV; as well as input data reading and histogramming with the 32-bit limitations removed. Design study examples, that demonstrate the capabilities and flexibility of the new modules, are given: the Fermilab Booster and LBNE experiment, LHC high-luminosity upgrade, and Muon Collider Higgs Factory.

*Work supported by Fermi Research Alliance, LLC, under contract No. DE-AC02-07CH11359 with the U.S. Department of Energy.

Summary:

Motivated by accelerator applications needs, new object-oriented modules were developed in implemented in the MARS15 code. Examples of use and performance of the new modules are given for several accelerator projects.

Session 4. Medical Accelerators, Convener: Vladimir Mares / 16

Accelerators and Advanced Beam Technologies for a National Center for Particle Beam Radiation Therapy Research

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As discussed in the DOE report “Accelerators for America’s Future,” most of the critical R&D in particle-beam therapy can only be conducted at a dedicated accelerator-based medical research facility capable of supplying the full range of ion beams from protons to carbon, oxygen or even neon. Such a facility not only requires beam energies and intensities useful for therapy and imaging but also high beam intensities for advanced radiobiology research and a wide range of Linear Energy Transfer (LET) values. NCI jointly with DOE recently organized a workshop on ion beam therapy where more than 60 experts from diverse fields related to radiation therapy were asked to define research and technical needs for advancing charged particle therapy, producing a detailed final report with requirements for a national center for particle beam radiation therapy research and development. The recommendations of the DOE-NCI workshop report for clinical requirements, in particular high dose deposition rates and motion control, imply beam intensity requirements that take us into uncharted territory for PBRT facilities. This talk addresses the current state of carbon-ion accelerator and beam technologies and the technical and engineering advances required to meet the challenges of a first-in-kind particle research and therapy facility envisioned in the NCI/DOE report.

Summary:

Overview of requirements for a National facility for Particle Beam Therapy Research and current carbon-ion and proton therapy accelerators and beam delivery capabilities.

Session 2b. Induced radioactivity, Convener: Sayed Rokni / 17

Po-production in lead: Calculation and measurement on SINO-samples (PSI)

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The Paul Scherrer Institut operates a MW-class spallation source, SINO, using the 590 MeV proton beam delivered by the ring cyclotron, HIPA. The target of the spallation source consists of a bundle of lead filled metal tubes (cannelloni). Five lead samples were extracted from a rod in the target center close to the beam entry window from SINO target-4, which had been in operation in 2000/2001 and received a total integrated beam charge of about 10 Ah. The lead was radiochemically investigated and the activities of several isotopes could be measured. Special attention was paid to Po as it has α -emitting isotopes with considerable half-lives and the element can show – depending on the experimental conditions - distinct volatility properties. A much larger amount of the Po isotopes ²⁰⁸Po (2.9 y), ²⁰⁹Po (102 y) and ²¹⁰Po (138 d) was found in the samples compared to the prediction obtained with available cross section models in the particle transport code MCNPX. In particular, the amount of ²¹⁰Po measured more than 10 years after the target operation is by far too large to be explained by direct production from Bi impurities in the lead. This implies another reaction mechanism not considered in the standard INC (Intranuclear Cascade) and evaporation models. Therefore, a recently improved INC and evaporation model, the Liège intranuclear-cascade model (named INCL) coupled to the de-excitation model ABLA07 was implemented into MCNPX2.7.0. INCL4.6/ABLA07 is one

of the most accurate models to describe spallation reactions as an inter-comparison done under the auspices of IAEA demonstrated. In this contribution, preliminary results of the nuclide inventory calculated with MCNPX using INCL4.6/ABLA07 and Bertini-Dresner are presented and compared to the experimental data.

Session 2b. Induced radioactivity, Convener: Sayed Rokni / 18

A temporary storage for activated UCx targets at SPES

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SPES (Selective Production of Exotic Species) is a project of the INFN (Istituto Nazionale di Fisica Nucleare) for the production of radioactive ion beams, through direct irradiation of a fissile target with high intensity proton beams.

The irradiation of the uranium carbide target with protons at 40 MeV energy and 200 uA current during an irradiation cycle of two weeks, causes an activity of approximately 10^{14} Bq. Less than 0.5% of the total activity is due to species of half-lives longer than one month. The replacement of the target takes place at each irradiation shift, ideally once per month, taking into account two weeks of irradiation and two weeks for the facility set up. During the first years of operation, a temporary storage will host the exhausted targets.

This work presents the evaluation of the residual dose rate due to the presence of several irradiated targets in order to design the needed shielding for the storage area and to allow the access nearby. The simulations have been performed with the FLUKA Monte Carlo code.

Session 3a. Radiation Shielding, Convener: Hideo Hirayama / 19

Radiation Protection study for the HIE-ISOLDE project at CERN

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The HIE-ISOLDE project will expand the physics program at ISOLDE with the possibility to post-accelerate a large variety of Radioactive Ion Beams to energies well below and significantly above the Coulomb barrier.

While this project contains three major elements: higher energies, improvements in beam quality and higher beam intensities, the most significant improvement is the replacement of the current post-accelerator (REX) by a new superconducting linear accelerator delivering ions of energy up to 10 MeV/u. This energy upgrade leads to new radiological hazards such as neutron emission when the post-accelerated beams at energies above the

Coulomb barrier interact with beam intercepting devices or the vacuum chamber walls in case of beam loss. The new superconducting cavities installed will also be a strong source of X-rays due to electron field emission. FLUKA simulations were performed to assess shielding requirements and the geometry of the tunnel hosting the superconducting cavities as well as to evaluate the maximum neutron dose rates expected in the event of beam losses. Activation of the machine components was

also estimated to determine the future waste classification.

During my presentation, an overview of the HIE-ISOLDE radiation protection study related to the post-accelerator will be given. FLUKA simulations for Xray, neutron emission and activation will be presented. Finally, I will show the technical shielding design chosen and the different mitigation measures taken to deal with the different hazards.

Session 2a. Induced Radioactivity, Convener: Hiroshi Nakashima / 20

Induced radioactivity in accelerator materials and soil-shield samples

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Several samples of materials used for accelerator components and shielding structures were irradiated in the high-energy stray radiation field of the H4IRRAD facility, one of the secondary beam lines (H4) from the SPS at CERN. After irradiation, the induced radioactivity of the samples was measured by gamma spectrometry at various cooling times up to 2 years, allowing identification of isotopes with a wide range of half-lives. The activation of soil-shield samples was also studied in detail. In particular, the mechanism and probability that the radioactivity produced in soil and ground water may transfer from the site of activation to the environment was investigated. Two techniques were used to quantify the amount of radioactivity leaching in the groundwater. Furthermore, the activation experiment was simulated in detail with the FLUKA Monte Carlo code. The isotope production and their specific activities measured in the samples are in good agreement with the FLUKA predictions.

Session 1. Source Term and Related Topics, Convener: Hee-Seock Lee / 21

The CERN High Energy Accelerator Mixed Field (CHARM) facility in the CERN PS East Experimental Area

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The CERN High Energy Accelerator Mixed Field (CHARM) facility is currently constructed in the CERN PS East Experimental Area to study radiation effects on electronic components. The foreseen location has become available due to the decommissioning and subsequent dismantling of the DIRAC experiment and the CHARM facility will share it with a proton irradiation facility that is situated further upstream.

The CHARM facility will receive a primary proton beam from the CERN PS (Proton Synchrotron) at a beam momentum of 24 GeV/c and a maximum average beam intensity of 6.7E10 protons/second with a maximum pulse intensity of 5E11 protons/pulse and a respective pulse length of 350ms. The beam will impinge on one out of a set of dedicated targets to produce the desired radiation fields at several experimental positions. These radiation fields can be adjusted by insertion of up to four

moveable shielding walls, two made out of concrete and two made out of iron. The main purpose of the CHARM facility will be the investigation of the effects of these radiation fields on electronic components in the framework of the Radiation to Electronics (R2E) project.

First, the radiation field requirements on the CHARM facility by the R2E project are discussed. Then, the radiological assessment of the facility is presented, including the shielding design for the prompt radiation, the derived radiation monitoring system and the optimization of the residual radiation. Furthermore, the air activation calculations, the resulting radiological impact from the release of radionuclides to the environment and the derived requirements for the dynamic confinement of the air inside the CHARM facility are illustrated.

The shielding of the CHARM facility will also include the CERN Shielding Benchmark Facility (CSBF) situated laterally above the target. This facility will allow deep-penetration benchmark studies of various shielding materials. The current plans for the construction and the commissioning of the CSBF will be outlined.

Session 2b. Induced radioactivity, Convener: Sayed Rokni / 23

Shielding and activation studies for the ELI-Beamlines project

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ELI-Beamlines is one of the four pillars of the Extreme Light Infrastructure, a European ESFRI Project, for the next generation of high energy and high intensity lasers.

It aims at the development of high-brightness sources of X-rays and at the acceleration of proton, electron, and ion beams, to be used both for pure research and practical applications.

Aiming at a proper radiation protection assessment, for both shielding and activation, extensive FLUKA simulations have been performed, taking into account the laser high repetition rates.

The present work, which is the continuation of the calculations presented at SATIF10, is the first one based on the design of the facility presently being constructed and on the updated experimental setups.

Poster Session and Reception / 25

Shielding Design for the LBNE Decay Pipe

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The Long Baseline Neutrino Experiment (LBNE) is being designed to deliver a high intensity neutrino beam from Fermilab to a detector 1300 km away in South Dakota. The neutrino beam will be

produced

from the decays of pions and kaons generated from a 120 GeV proton beam incident on a 95 cm long graphite target. The pions and kaons will decay in flight in a 200 m decay pipe downstream of two magnetic focusing horns.

The operation of this proposed beamline will generate radionuclides in the soil surrounding the beamline complex which may leach into the groundwater resources. Sufficient shielding will therefore be required to maintain acceptable radionuclide concentrations in the ground water. Presented is an estimate of the minimum decay pipe shielding using MARS. The shielding should have enough thickness to maintain the radionuclide concentrations in the ground water below the regulator limits over a 30 year operation period of the LBNE beamline at 2.3 MW beam power.

Session 6. Code Benchmarking and Intercomparison, Convener: Robert Grove / 26

Benchmarking secondary neutron production with 113-MeV to 800-MeV proton beams using MCNPX 2.7.0, PHITS 2.52 and FLUKA2012 Monte Carlo codes

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The capability to accurately model the production of secondary neutrons from protons interacting with matter is of tremendous importance in Proton Therapy. These neutrons are the major source of secondary doses delivered to a patient during treatment. They also represent the most important contribution to the ambient doses remaining outside the biological shielding. They also constitute an important background for the prompt gamma cameras used in the online monitoring of proton beam range. The IBA Company, world leader in the market of commercial proton therapy system is very active in these different fields and pursues several research projects on these topics.

To validate the Monte Carlo codes used for these studies, we make use of differential neutron production cross sections measured at Los Alamos National Laboratory for 113-MeV to 800-MeV protons impinging on thin and thick targets made of different materials from Beryllium up to Uranium-238. These data are compared to predictions obtained with recent versions of the well-known MC codes MCNPX 2.7.0, PHITS 2.52 and FLUKA 2012.

Comparisons of the total production yields, doubly differential cross sections and angular distributions between measured data and MC expectations will be presented for the different target types, beam energies and nuclear models.

Session 3b. Radiation Shielding, Convener: Vashek Vylet / 27

Design for Radiation Shielding of PAL-XFEL

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The PAL-XFEL is a free electron laser using 10 GeV, 0.2 nC electron beams. The construction started in 2012. In this study, the design for radiation shielding of PAL-XFEL is presented. Beam loss scenario was established, and the bulk shielding was calculated with a consideration of beam loss scenario using SHIELD11 and FLUKA. Several dumps such as the main beam dump, the tune-up dump and spectrometer dumps were designed. To suppress the radiation dose at the experimental area due

to the failure of the main dump magnet, which is the major accidental issue in worldwide free electron laser facilities, the permanent safety magnet, collimators and the safety shutter were applied at the front-end. The preliminary design of front-end components will be present. The neutron skyshine effect of the PAL-XFEL was estimated using new evaluation method using FLUKA and PHITS.

Session 2b. Induced radioactivity, Convener: Sayed Rokni / 28

Benchmarking of Neutron Radiation Effects Facility (NREF) at LENS for Neutron Science Facility (NSF) at the Future Heavy-Ion Accelerator in Korea

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LENS is a novel, long pulsed neutron source located in the Center for Exploration of Energy and Matter (CEEM) of Indiana University and RAON is a heavy-ion accelerator complex that is being constructed in Korea. NREF at LENS utilizes a low energy p-N reaction between Beryllium target and a high-current, variable-pulse-width proton beam to produce Quasi monochromatic high flux neutron beams with the energy up to ~10 MeV while higher energy neutrons are produced in NSF at RAON from the light target such as C and Li by either ~88 MeV protons or ~53 MeV deuteron beams. Because of high neutron fluence at NSF, detailed estimation for prompt radiation and induced activation is important in designing the facility. Simulation results using MCNPX, and PHITS codes are presented to survey and validate the capability of the designed facility with benchmarking of NREF for NSF. Comprehensive comparisons of two facilities and future possibilities of NSF will be discussed.

Session 3a. Radiation Shielding, Convener: Hideo Hiramaya / 29

Evaluation of SNS Beamline Shielding Configurations using MCNPX Accelerated by ADVANTG

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Shielding analyses for the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory pose significant computational challenges, including highly anisotropic high-energy sources, a combination of deep penetration shielding and an unshielded beamline, and a desire to obtain well-converged 'nearly global' solutions for mapping of predicted radiation fields. The majority of these analyses have been performed using MCNPX with limited variance reduction (source biasing and cell-based splitting and Russian roulette) that was largely based on the analyst's insight into the problem specifics. Development of the variance reduction parameters required extensive analyst time, and was often tailored to specific portions of the model phase space.

We previously applied a developmental version of the ADVANTG code to an SNS beamline study to perform a hybrid deterministic/Monte Carlo analysis and showed that we could obtain nearly global

Monte Carlo solutions with essentially uniform relative errors for large-volume mesh tallies with typical spacing of a few centimeters. The use of weight window maps and consistent biased sources produced using the FW-CADIS methodology in ADVANTG allowed us to obtain these solutions using substantially less computer time than the previous cell-based splitting approach. While those results were promising, the process of using the developmental version of ADVANTG was somewhat laborious, requiring user-developed Python scripts to ‘drive’ much of the analysis sequence. In addition, limitations imposed by the size of weight-window files in MCNPX necessitated the use of relatively coarse spatial and energy discretization for the deterministic Denovo calculations that we used to generate the variance reduction parameters. We recently applied the production version of ADVANTG to this beamline analysis, which substantially streamlined the analysis process. In addition, we developed and applied spatial- and energy-collapsing capabilities in ADVANTG. These collapsing options allowed us to eliminate the necessity of applying a priori group collapsing to the HILO2K library, and reduced restrictions on the Denovo spatial mesh. These changes, along with the support for parallel Denovo calculations using the current version of ADVANTG, give us the capability to improve the fidelity of the deterministic portion of the hybrid analysis sequence, obtain improved weight-window maps, and reduce the time required for the analysis sequence.

Summary:

We applied the ADVANTG code in conjunction with MCNPX to perform hybrid deterministic/Monte Carlo shielding analyses for SNS beamline studies. ADVANTG automates the generation of variance reduction parameters for continuous-energy Monte Carlo calculations using the Forward-Weighted Consistent Adjoint Driven Importance Sampling (FW-CADIS) methodology. Our results demonstrate that the use of ADVANTG to accelerate these challenging MCNPX calculations provides ‘nearly global’ Monte Carlo solutions with essentially uniform relative errors. This approach results in substantial savings in computer time and in the time required by analysts to develop efficient variance reduction parameters.

Session 2b. Induced radioactivity, Convener: Sayed Rokni / 30

Beam-loss criteria for heavy ion accelerators

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The activation of the high-energy heavy ion accelerators due to beam-losses is a serious issue for parts of accelerator as collimator systems, magnets, beam-line, fragment separator targets, etc. The beam-losses below 1 W/m are considered as a tolerable for “hands-on” maintenance on proton machines. In our previous studies FLUKA2008 code has been used for establishing a scaling law expanding the existing proton beam-loss tolerance to heavy-ion beams. This scaling law enabled specifying beam-loss criteria for projectile species from proton up to uranium at energies from 200 MeV/u up to 1 GeV/u. FLUKA2008 allowed nucleus-nucleus interactions down to 100 MeV/u only. In this work we revise our previous results and extend them towards lower energies with the help of new FLUKA code version. FLUKA2011 includes a nucleus-nucleus interaction below 100 MeV/u. This research has been done at GSI Darmstadt and is supported by project 05P12RDFN6.

Session 4. Medical Accelerators, Convener: Vladimir Mares / 31

Prospects of Clinical Boron/Gadolinium Neutron Capture Therapy at Fermilab

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The Neutron Therapy Facility (NTF) at Fermilab began treating human patients with fast neutrons in 1976. Fast neutron radiotherapy has continued at the NTF up until 2013 and still is performed at another site in the USA. Another clinical application of neutrons is to combine neutron therapy with a tumor-localizing drug carrying a neutron capture agent such as boron or gadolinium. This is known as boron neutron capture therapy (BNCT) and gadolinium neutron capture therapy (GdNCT). However, after some initial progress, there has been a hiatus in BNCT clinical research in the USA for over a decade, in part perhaps due to the regulatory and security challenges of conducting clinical research and treatment at nuclear reactors after the September 11, 2001 attacks. BNCT research has continued unabated in other countries and preliminary clinical results have been encouraging. As a fully functional and independent clinic, the NTF could be the ideal environment to reinitiate investigations into boron and/or gadolinium neutron capture therapy and boron neutron capture enhanced fast neutron therapy in the USA without the need for a reactor.

The Fermilab p(66)Be(49) fast neutron beam has a mean neutron energy of approximately 25 MeV. The NTF team has created a means of moderating the mean energy down to the energy range appropriate for neutron capture therapy using a beam spoiler made up of titanium and graphite blocks. The moderated beam is enriched in neutrons of epithermal energy making it potentially suitable for BNCT of deep-seated tumors without intraoperative exposure. We have been examining the physical characteristics of this modified beam and actively using it for in vitro radiobiology experiments. In parallel with the physics and radiobiology advancements, in collaboration with several investigators, we have been developing and evaluating various novel boronated compounds (e.g. glutamine derivatives), which may offer improved biodistributions and toxicity profiles over traditional BNCT agents.

Provided the final analysis of the modified beam proves acceptable for clinical applications, we propose addressing two primary malignancies in future clinical trials – malignant brain tumors in human patients (glioblastoma multiforme) and locally advanced bladder cancer in veterinary patients. In this presentation, we will discuss the possibilities and pitfalls of pursuing clinical BNCT and GdNCT at Fermilab.

Summary:

Fermilab could be the ideal facility to resume clinical research into BNCT as well as explore new avenues in GdNCT.

Session 3a. Radiation Shielding, Convener: Hideo Hirayama / 32

Shielding Analysis for the ATLAS Booster Upgrade

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Argonne's ATLAS accelerator facility is a national user facility for low-energy nuclear physics. Ions from protons to uranium are produced by one of two ECR sources, accelerated in the booster linac and the main ATLAS linac, and then directed to one of three experimental areas. ATLAS has just finished upgrading the booster linac to provide a significant increase in current. This paper presents the results of shielding analyses for the booster upgrade. Radiation transport calculations are performed with the radiation transport code MCNPX using neutron and gamma source rates calculated with the fusion-evaporation code NEUGAM. The presentation will address the many constraints that derive from the fact that the upgrades must fit into the existing facility structure and be consistent

with present operating modes. The booster linac shielding is modular and capable of being disassembled to allow for removal of accelerator components in the event maintenance is required. Facility modifications were also made to accommodate future upgrade stages.

Session 3a. Radiation Shielding, Convener: Hideo Hirayama / 33

Towards the next generation RIB facility using the ISOL Method: radiological protection and shielding challenges

Author: Pedro Vaz¹

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Over the last decade, the importance of evolving towards the construction of Radioactive Ion Beam (RIB) facilities gained considerable interest and support from the Nuclear Physics community (at large). Projects like the EURISOL (EUROPEAN ISOTOPE SEPARATION ON-LINE RADIOACTIVE ION BEAM) Design Study paved the way to the investigation of scientific, technological and engineering studies of the next generation facility for the production of RIBs using the ISOL (Isotope Separation On-Line) method, two to three orders of magnitude more intense than the ones currently available at other facilities. At the same time, upgrade studies were undertaken at the existing facilities such as SPIRAL-2 at GANIL and ISOLDE at CERN, among others, in order to fill the gap between the existing facilities and the future EURISOL facility. The HIE-ISOLDE project stands for the ongoing High Intensity and Energy upgrade of the ISOLDE facility at CERN.

Computational studies with the state-of-the-art Monte Carlo codes FLUKA and MCNPX pinpointed severe constraints in the shielding design and in the dose rate assessment of these facilities, due to activation of the structural materials and the high intensity of the proton beams impinging on the spallation targets. These translate in dose-rate values that impose careful shielding assessment and consideration of radiation safety issues, should a technical intervention be needed, in a routine situation/maintenance or following an accident with the need to replace or fix damaged components.

In this paper the dose-rate mapping, activation studies of structural components and the shielding design of the aforementioned installations HIE-ISOLDE and EURISOL will be described. Discrepancies between the Monte Carlo simulation results and the experimental data (measurements) obtained at ISOLDE will be presented and pinpointed. The analysis of eventual limitations in the Monte Carlo modelling and simulation of these complex and sophisticated installations will be performed, from the geometry, materials and available cross-sections data viewpoints.

Summary:

In this paper, radiological protection and shielding issues associated to the next generation or upgrade of existing RIB facilities are discussed, with emphasis in dosimetry (dose-rate distributions), activation of structural components, shielding design and radiation safety issues.

Shortcomings of the Monte Carlo simulations in order to accurately model and predict the aforementioned distributions and to obtain a correct shielding assessment are discussed.

Session 5. Status of Codes and Data Bases, Convener: Alfredo Ferrari / 35**Recent Activities of the OECD/NEA Expert Group on Radiation Transport and Shielding (EGRTS) and Current Status of the Shielding Integral Benchmark Archive and Database (SINBAD)**

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The OECD NEA Working Party on Scientific Issues of Reactor Systems (WPRS) Expert Group on Radiation Transport and Shielding (EGRTS) was started in 2011 under the Nuclear Science Committee (NSC); the 4th meeting was held in February 2014. Among other activities, the EGRTS mandate includes supporting the SATIF community by co-ordinating the organization of and publishing the proceedings for the SATIF-12 Workshop. Another part of the EGRTS mandate is monitoring, steering and supporting continued development of the Shielding Integral Benchmark Archive and Database (SINBAD). This report provides an update on EGRTS activities and on the status of SINBAD.

The SINBAD project began in the 1990s as a cooperative effort of the Organisation for Economic Co-operation and Development Nuclear Energy Agency Data Bank (OECD/NEADB) and the Radiation Safety Information Computational Center (RSICC) at the Oak Ridge National Laboratory (ORNL) in order to preserve and make available information on radiation shielding benchmark experiments. SINBAD currently includes 100 benchmarks including fission reactor shielding, fusion blanket neutronics, and accelerator shielding. Recently, a selection of benchmark experiments were reviewed and revised to verify the completeness and consistency of the benchmark information, in particular concerning experimental sources of uncertainty. This review process will provide users with information on the quality of the experimental information and will be extended to other benchmarks. SINBAD is available from RSICC and from the NEA Data Bank. Since its inception SINBAD has been used by nuclear data evaluators, computer code developers, experiment designers and university professors and students.

Session 6. Code Benchmarking and Intercomparison, Convener: Robert Grove / 36**A Validation of Heavy Ion Capabilities in PHITS via Fragmentation Cross Section Calculations**

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The performance of the Monte Carlo code system PHITS is validated for heavy ion transport capabilities by performing simulations and comparing results against experimental data from heavy ion reactions of benchmark quality. These data are from measurements of isotope yields produced in the fragmentation of a 140 MeV/u ⁴⁸Ca beam on a beryllium target and on a tantalum target. The results of this study show that PHITS performs reliably.

This material is based on work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661

Poster Session and Reception / 37

Comparison between PHITS and LISE++/COSY Calculations in Support of FRIB Dipole Magnet Design

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The Facility for Rare Isotope Beams (FRIB), a project supported by the US DOE Office of Science, is under construction at Michigan State University. The production of rare isotope beams during FRIB operations creates a high radiation environment for the fragment preseparator superconducting magnets. Therefore, detailed studies of the proposed magnet designs and shielding by beam and radiation transport are necessary.

We study the radiation power deposition into the 30 degree bending dipole magnet located in the FRIB fragment preseparator using both the radiation transport code PHITS and the beam physics codes LISE++ and COSY. Preliminary results from these approaches are in reasonable agreement. The results of our calculations are being used by engineers to optimize the magnet design.

This material is based on work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661

Session 3a. Radiation Shielding, Convener: Hideo Hirayama / 38

SNS Shielding Analyses Overview

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The Spallation Neutron Source (SNS) is an accelerator driven neutron scattering facility for materials research, presently operating at 1 MW proton beam power at 1 GeV proton energy on target. Although the facility is completed and in operation, there is still a wide range of demands for shielding analyses. During accelerator operation some parts of the facility are being redesigned and improved, and neutronics optimizations are important part of the process. Linac access way redesign is an ongoing work. Additional facilities for test purposes for accelerator structures being built and require shielding. Recently linac cryomodule RF test facility and a RFQ test stand were constructed. A concept study for standalone electronics irradiation station for single-event effects in avionic and ground based systems is in works to scope out the feasibility and cost. Shielding requirements are a huge player in the construction cost. The neutron scattering instruments USANS and Corelli are will be commissioned soon, which requires extensive work on beam line and instrument enclosure shielding. The neutron imaging instrument VENUS is presently in design; also there shielding is an integral part of the instrument and a large cost factor.. Another large area of neutronics/shielding work is the prediction of isotope composition for spent structures from accelerator and target facilities in order to do waste characterization analyses and to develop proper transport and storage containers such as spent proton beam window and target modules, neutron beam line shutters and neutron beam collimators

Session 2b. Induced radioactivity, Convener: Sayed Rokni / 39**Comparison of Radionuclide Activity in the NuMI Decay Pipe to Results from the MARS Monte Carlo Code****Author:** Diane Reitzner¹¹ *FNAL***Corresponding Author:** reitzner@fnal.gov

The production of tritium is a radiological concern in the operation of accelerators as it has been shown to be relatively mobile; able to move from one medium to another. Tritium produced in shielding could transfer to the environment under the right conditions. Having a reliable inventory on the amount of tritium that will be produced in the shielding is therefore important. The production of radionuclides other than tritium can be used in the estimation on the amount of tritium generated. Presented is a method of inventory of the radionuclide production in the shielding. The activity in samples taken from the NuMI decay pipe shield has been measured and compared to MARS results for the radionuclide distribution and production in a simple model of the NuMI beam line.

Session 2a. Induced Radioactivity, Convener: Hiroshi Nakashima / 40**Evaluation of Radiation Environment at FRIB Linac****Author:** Mikhail Kostin¹**Co-author:** Reginald Ronningen²¹ *Facility for Rare Isotope Beams (FRIB), Michigan State University*² *Facility for Rare Isotope Beams, Michigan State University***Corresponding Author:** kostin@frib.msu.edu

The Facility for Rare Isotope Beams (FRIB) at Michigan State University is a project jointly funded by the US Department of Energy and Michigan State University with the construction scheduled to start in March 2014. This accelerator facility will provide a broad range of ion beams from 18-O to U with a beam power of up to 400 kW and energy of 200 MeV/u for U in its baseline configuration. A possible facility upgrade will include increase of the beam energy up to 400 MeV/u for U and addition of new light ion beams down to 3-He for ISOL operations.

The work presented here is a review of radiation transport calculations aimed to evaluate the radiological environment at the FRIB Linac and adjacent areas. A number of calculations have addressed the impact on environment (activation of soil and ground water, evaluation of radionuclide releases); prompt radiation to the workers and general public due to normal beam losses and beam loss accidents; neutron skyshine; activation of services and various beam elements.

This material is based on work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661

Session 2b. Induced radioactivity, Convener: Sayed Rokni / 41**Thin and Thick Target Activation by 2.25 and 3.36 GeV Electron Beams****Authors:** George Kharashvili¹; Pavel Degtiarenko¹

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Activation of materials impacted by GeV electron beams is of great importance for the purposes of radiation protection as well as future decommissioning. In order to measure thin and thick target activation Al, Pb, Nb, Cu, and stainless steel foils (0.01 – 0.1 mm) were placed upstream and downstream of 1.25-cm thick tungsten alloy blocks and irradiated by 2.25 and 3.36 GeV electron beams. The upstream foils represented thin targets (< 4% r.l.) and the downstream ones – thick targets. Gamma spectroscopy analysis of each foil was then performed using high purity germanium detectors. The setup was modeled using FLUKA Monte Carlo code. Comparison of measured and calculated activities is presented.

Poster Session and Reception / 42

Modified Moliere's Screening Parameter and its Impact on Multiple Coulomb Scattering and Radiation Damage

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The Moliere approximation of elastic Coulomb scattering cross sections plays an important role in accurate description of multiple scattering, non-ionization energy, DPA radiation damage etc. The cross section depends only on a single parameter that describes the atomic screening. Moliere calculated the screening angle for the Tomas-Fermi distribution of electrons in atoms. In this paper, the screening parameter was recalculated using a more accurate atomic form-factor obtained from the self-consistent Dirac-Hartree-Fock-Slater computations. For relativistic particles, the new screening angle can differ from the Moliere approximation by up to 50%. At the same time it is rather close to other independent calculations. At low energies, the new screening angle is different for positrons and electrons. The positron screening parameter is about five times larger than the electron one for heavy nuclei at energies of $\sim Z$ keV. A simple parameterization of the updated atomic screening parameters is proposed. Its impact on particle transport and calculated quantities is discussed.

Session 4. Medical Accelerators, Convener: Vladimir Mares / 43

Future Plan of a Heavy Ion Radiation Therapy and Research Facility in Dallas, Texas

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A heavy ion therapy and research facility is being conceptually designed by the UT Southwestern Medical Center (UTSW) in Dallas, TX, USA. It will be the phase three addition to a total of three phase plan that consists of a proton therapy center (phase 1) and a large conventional (photon) center (phase 2). This unified complex of all currently available modalities for radiation therapy systems will be located at the heart of the Dallas metroplex as an integral part of the UTSW medical complex located only a couple of minutes drive from Dallas downtown. The proton center construction

started in late 2013 and is expected to treat the first patient in early 2017. The proton center will have a Varian Cyclotron system with four full gantries and one fixed beam room. The second phase includes seven conventional linear accelerators for patient care installed in the first stage and additional six conventional linacs installed in the second stage. The conventional phase is currently in architectural design and the first patient is expected to be treated late 2016. The heavy ion center is envisioned to have an accelerator accelerating ions up to 40Ar^{18+} to energies about 360 MeV/nucleon. It will have three clinical treatment rooms and one non-clinical, research bunker with a fixed (non-gantry type) beam. The clinical treatment rooms will have pencil beam scanning capability. The proposed medical complex will serve as a national research and resource center where leading clinical, radiobiological and physics research proposals will be executed. An introduction of the hosting institution and the status of the facility will be presented.

Session 6. Code Benchmarking and Intercomparison, Convener: Robert Grove / 44

Shielding benchmarks for Geant4 version 10

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Geant4 is a toolkit for the simulation of the passage of particles through matter. To show its capability in the shielding area, we have submitted Geant4 results for the "Inter comparison Problems of Neutron Attenuation" to SATIF organizers since 2006. Version 10 is the latest and major update of Geant4 and is publicly available since December 2013. Because it is a major update, there are many new features, among which are the multi-threading migration and new physics models for users of shielding applications. The former impacts computing performance and the latter affects physics performance. In this presentation, we briefly explain the benefit of multi-threading and features of the new and improved physics models. We will also show new results of benchmarks proposed by the SATIF organizers, using several physics models and cross sections offered by Geant4.

Session 1. Source Term and Related Topics, Convener: Hee-Seock Lee / 45

Fast Neutron Measurements at the Booster Neutron Beamline for Future Coherent Elastic Neutrino-Nucleus Scattering (CENNS) Experiment at Fermilab

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Low energy neutrinos ($E < 50$ MeV) have a predicted, but unobserved, coherent elastic scattering channel on nuclei. Coherent neutrino scattering has important physics reach for supernovae, standard model tests, and nuclear physics. The CENNS collaboration will deploy a liquid argon detector in a far off-axis configuration at the Booster Neutrino Beam (BNB) in order to produce a flux of low-energy neutrinos from decay-at-rest pions. A major concern for the first measurement of CENNS is beam-correlated fluxes of neutrinos that give the same signal as coherently scattered neutrinos. To understand these fluxes, the Indiana-built SciBath detector was deployed to measure fast neutron fluxes 20 m from the BNB target in the MI-12 target building. The SciBath detector is a novel 80 liter liquid scintillator detector read out by a three dimensional grid of 768 wavelength-shifting fibers. The fiber readout allows SciBath to measure neutral particle fluxes by tracking the recoiling charged particles with uniform efficiency in all directions. In this talk, I describe the SciBath detector and summarize our measurement of the flux of 10 to 200 MeV neutrons at the BNB. I will also highlight

additional neutron measurements that are planned for this Fall at the BNB with the SciBath detector with a new prototype shielding configuration.

Poster Session and Reception / 46

Contribution of the Direct Electronuclear Processes to Thin Target Activation

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Contribution of the direct inelastic interactions of electrons with nuclei to the neutron production and to the material activation radiation source terms may become significant or even critical in certain conditions at high energy electron accelerators. Impact of these processes may be considered negligible in descriptions and simulations of fully developed electromagnetic or hadronic particle cascades in thick targets and beam dumps. However, in the cases of electron beam interactions in targets thinner than few percent of a radiation length, the direct electronuclear processes become dominant. At Jefferson Lab's CEBAF accelerator these processes are often responsible for the significant portion of the radiation source terms in the experimental Halls. New experimental data on thin nuclear target activation by the few-GeV electron beams, obtained at JLab recently, help to evaluate the contribution of the direct electronuclear processes to the thin target activation. A model description of the process based on the Equivalent Photon Approximation method, the corresponding Monte Carlo simulation algorithm, and the (limited and simplified) method of implementing these processes in the FLUKA code are presented.

Session 3b. Radiation Shielding, Convener: Vashek Vylet / 60

Radiation safety design of Super KEKB factory

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The super KEKB factory, which will start at early 2015, is a electron-positron collider that is designed to derive $80 \times 10^{34} \text{ 1/cm}^2/\text{s}$ luminosity, 40 times greater than former one, KEKB factory, for investigation of CP violation and new physics beyond the Standard Model. The facility consists of 7 GeV electron / 3.5 GeV positron LINAC, 1.1 GeV positron damping ring, beam transport, and 7 GeV electron / 4 GeV positron collider. To fulfill the luminosity, the collider will be operated with small beam-size with a large crossing angle at the interaction point. According to particle tracking simulation, beam losses under this condition will reach to 35 times more than previous. Leakage radiation and induced activity are estimated through empirical equations and detailed Monte-Carlo simulation MARS15 for interaction region, halo collimators, emergency pathways, ducts, forward direction tunnels and positron production target, to optimize shielding design. Examples of shielding strategy are discussed to reduce both leakage dose and induced activity for several parts of the facility.

Poster Session and Reception / 62

Studies supporting the derivation of the radioactive waste for European Spallation Source target station

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European Spallation Source (ESS) is next generation research facility for dynamics and material structure studies. It is common European project taking place in Lund, Sweden. Spallation reaction will be produced in helium cooled tungsten target by pulsed (50 Hz pulse length 2.8 ms) proton beam. Protons will be driven by linear accelerator (Linac) with maximum energy of 2 GeV and average power of 5 MW. Produced neutrons will be moderated and then guided through beamlines to 22 research instruments.

Radioactive waste will be produced as the result of interactions of primary and secondary particles induced by spallation reactions in ESS target station.

The main goal of this work is to perform shielding and activation calculations for the ESS target station in order to derive the radioactive waste and to estimate the source term for environmental impact analysis. Estimation of radioactive waste is mandatory for radiological safety during radioactive waste handling, management and transportation.

The geometry of the target station used in calculations was taken from TDR [1]. Model contains: target, moderator, reflector assembly (TMRA) and the shielding monolith. In this stage a bulk shielding was considered. Calculations were done with Monte Carlo programs MCNPX 2.6.0 and FLUKA. MCNPX used CEM3k nuclear reaction model and was coupled with CINDER'90 for activation calculations. Three main calculations were carried out, using various geometry models for the shielding monolith: lateral to, above and below TMRA. In this respect biasing techniques and sufficient shielding were used to include back-scattered neutron influence.

The obtained results include: i) neutron and photon dose equivalent rate around the target shielding to estimate accessible areas during operation; ii) average dose rate at target station building roof for further skyshine estimation; iii) activity levels of the shielding monolith for radioactive waste derivation and iv) soil activation for the estimation of the source term to be used for environmental impact analysis. It was concluded from this analysis that the thicknesses of the shielding are sufficient to comply with the criteria targeted by ESS.

[1] S. Peggs, R. Kreier, ESS Technical Design Report, ESS-doc-274, (2013)

Session 5. Status of Codes and Data Bases, Convener: Alfredo Ferrari / 63

New Developments in FLUKA

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The FLUKA code is the tool used at CERN and elsewhere for a variety of tasks, ranging from beam-machine interactions, to shielding, radioprotection, dosimetry, experiment analysis and medical applications. The code is undergoing continuous developments in order to cope with new problems and challenges. The latest developments both in the physics models and the ancillary tools will be discussed and presented with particular emphasis on very high energy applications, including recent improvements to DPMJET-3, and medical applications.

Session 1. Source Term and Related Topics, Convener: Hee-Seock Lee / 64

Measurement of pulsed ionizing radiation at DESY

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At DESY sources of pulsed ionizing radiation include rf-driven electron accelerators and in the near future laser driven plasma accelerators. Pulsed neutron and photon doses are measured using the LB 6419 probe from Berthold Technologies. Operational experience has been gained over the last 6 years with the current number of devices reaching more than 100. In this talk, quantities suitable to characterize detector response to pulsed radiation will be discussed. A simple condition is derived for the conditions in which a pulsed time structure of radiation has to be taken into account.

Session 1. Source Term and Related Topics, Convener: Hee-Seock Lee / 65

Measurements of Laser Induced Ionizing Radiation Doses at SLAC

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Interaction of high intensity, short pulse laser beam on matter generates plasma in which electrons can be generated and accelerated to high energies (10s of keV to MeV) which in turn interact with target material generating ionizing radiation hazards. The radiation field and the dose level depend on the laser irradiance (laser energy, pulse length and spot size on target) and the target materials. The radiation field is primarily comprised of bremsstrahlung X-rays at lower irradiances, but will include neutrons at higher intensities.

With the rise in the number of high-intensity (multi-terawatt and petawatt) lasers in R&D facilities, for example in conjunction with both 3rd and 4th generation light sources, characterization of the radiation source terms, understanding of radiological hazards, and development of appropriate measures to ensure personnel safety are needed.

A systematic study of measurements of photon and neutron radiation doses generated from laser-plasma interaction has been underway at SLAC National Accelerator Laboratory using the the short pulse laser (800 nm, 40 fs, up to 1 J and 25 TW) at LCLS MEC. Results from the most recent measurements with the laser-optic-target system (peak intensity 2.4×10^{18} W/cm²) will be presented and compared with the calculations based on analytical models. Shielding and interlocked controls to mitigate the ionizing radiation hazards will also be discussed.

Summary:

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Session 3a. Radiation Shielding, Convener: Hideo Hirayama / 66

CONSIDERATION OF PARTICLE CHARGE AT SHIELDING ANALYSIS OF HEAVY ION ACCELERATOR

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A shielding analysis was carried out for 90 degrees bending section of heavy ion accelerator of RISP (Rare Isotope Science Project). A projectile beam is 18.5 MeV/u, 9.5 pμA U-238 with charges of 33+(50%) and 34+(50%). A thin carbon stripper is placed to generate higher positive charged U beam at the front of the 90 degrees bending section. The bending section consists of many quadrupole magnets, two dipole magnets and two two-cell type superconducting RF cavities. The charge state with maximum intensity was found as 79+ using LISE code. We used two Monte Carlo codes, FLUKA and PHITS for this shielding analysis. Both codes have a subroutine of particle transport in a magnetic field but don't have a subroutine to treat multi-charged particle except of fully-ionized particle like U92+. Therefore, we applied simple technique to consider the relationship of charge-magnetic field and charge-energy of U beam. Finally, much precise results like the dose distribution depending on particle charge was produced and the effect of this approach is discussed in this paper with benchmarking results of U-beam induced reactions.

Session 1. Source Term and Related Topics, Convener: Hee-Seock Lee / 67

Estimation of environmental effect due to radioactive material released from the Hadron Experimental Facility of J-PARC

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Due to a malfunction of magnets for slow beam extraction of the 50 GeV synchrotron of the Japan Proton Accelerator Research Complex (J-PARC), intense proton beam beyond a designed value was instantaneously delivered to a gold target in the Hadron experimental hall (HD hall). Part of the gold target was melted and evaporated, and the radioactive material dispersed from the gold target, leaked into the environment outside of the radiation controlled area of the HD hall. In order to estimate environmental effect, the total amount of radioactive materials released from the HD hall was calculated, by combining a simulation with measured data on the airborne sample collected in the HD hall and data of area monitors in the HD hall. The radiation dose of the site boundary at the location closest to the HD hall was also estimated.

Summary:

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Radiation Field Calculations Around the Spallation Target and the Reactor Core for the MYRRHA ADS Design

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The MYRRHA facility at SCK-CEN in Mol (Belgium), which should enter the construction phase in 2015, aims to demonstrate efficient transmutation of high level waste and associated Accelerator-Driven Systems (ADS) technology. The system is based on a lead-bismuth eutectic (LBE) cooled reactor, working both in critical and in sub-critical operation modes. The neutrons needed to sustain fission in the sub-critical mode are produced via spallation processes by a 600 MeV, <4 mA proton beam, which is provided by a linear accelerator and hits a LBE spallation target located inside the reactor core. In order to assess the main shielding problems, a method based on the combined use of the two Monte Carlo codes MCNPX and FLUKA has been developed, with the goal to perform detailed analyses of both the radiation fields due to the system in operation, and the coupled residual radiation due to the activated materials. The results of this simulation work are presented, with the implications on the design solutions.

Summary:

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Source Term Determination for Shielding Assessment of High-Power Laser-Plasma Experiments

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In an increasing number of experiments, high-power, high-intensity lasers hit targets and create plasma. The laser-plasma interaction will produce hot electrons with a Maxwellian energy spectrum and an electron temperature ranging from about 10 keV to 10 MeV for irradiance between 10^{16} and 10^{21} W/cm². The electrons interact in turn with the target, producing bremsstrahlung and possibly photoneutrons, resulting in a radiation field that must be contained by shielding. Since the physics of plasmas is very different from that of the common phases of matter, the shielding design cannot be carried out with only conventional tools.

Different, complementary approaches are possible: to use analytical formulas, to experimentally evaluate source terms to be used as input to established Monte Carlo codes, or to interface those codes with specialized Particle-In-Cell programs, which describe the generation and transport of particles in plasma.

At the Helmholtz-Beamline, which will operate as laser facility at the European XFEL, the shielding design of the High Energy Density (HED) Physics Instrument has been evaluated by using analytical calculations, cross-checked with measurements at the DRACO laser at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR). On the other hand an extensive experimental campaign is planned at SLAC, where dedicated radiation measurements will be performed at the Matter in Extreme Conditions (MEC) short-pulse laser facility.

Summary:

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Session 4. Medical Accelerators, Convener: Vladimir Mares / 72

Measurement of stray neutron radiation within a proton therapy facility

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Proton therapy is an advanced radiation treatment that destroys cancer cells with high accuracy. Proton treatment beams can be fine-tuned to deposit most of their energy at a specific depth within the patient, keeping irradiation of adjacent organs and healthy tissue to a minimum. However, proton interactions with materials in the beam line and with patient's tissue create secondary neutrons with energies from thermal to several tens or hundreds of MeV. These secondary neutrons may increase the risk of a second cancer significantly, and should be taken seriously.

Dosimetry measurements around medical proton accelerators are very complex due to heterogeneous radiation fields, for this reason the use of well proved and well known measurement systems is necessary. In 2013, organised by EURADOS Working Group 9 (Radiation Protection Dosimetry in Medicine) a large set of intercomparison measurement was carried out in the IBA (230 MeV) active-scanning proton beam therapy facility in Trento, Italy. Several types of active detectors and dosimeters were used: Bonner Sphere Spectrometers (BSS), HAWK TEPC, several REM-counters such as WENDI-II, Berthold, RadEye, NM2B, and new HMGU electronic dosimeters. The proton

beam was directed into a water phantom (30 x 30 x 60 cm³) with a 1 liter (10 x 10 x 10 cm³) target volume, simulating the patient. The isocenter of the beam was in depth of 15 cm inside the water phantom. Neutron ambient dose equivalents, $H(10)$, were measured at several positions inside the treatment room at four angles: 0°, 45°, 90°, and 135° with respect to the beam line direction, and at different distances.

A generally good agreement among $H(10)$ values within 30% was observed for the different types of used detectors. The highest neutron $H(10)$ value of about 60 $\mu\text{Sv}/\text{Gy}$ was measured along the beam axis at distance of 1.15 m from isocenter. However, the lowest neutron $H(10)$ value measured in the treatment room was about 1.1 $\mu\text{Sv}/\text{Gy}$ at distance of 4.25 m, and at 90° with respect to beam line.

Measurements with BSS provided valuable information on the spectral energy distribution of secondary neutrons and $H^*(10)$ at 4 different angles around the water phantom. Secondary neutron spectra generated by a proton beam impinging a water phantom were also calculated using Monte Carlo simulation with the GEANT4 code.

Dosimetry measurements in the phantom included different passive detectors (RPL, several types of TLDs and CR-39). Their future analysis will give insight in dose contributions from different radiation types depending on the position in the phantom and distance from the target volume.

The results of this large set of intercomparison measurements and Monte Carlo simulations may be valuable for medical physicists and radiation protection officers.

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Radiation safety study for conventional facility and siting pre project phase of International Linear Collider

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The International Linear Collider is a proposed high energy collider which consist of two liner accelerators, two dumping rings, electron and positron source, and single colliding hall with two detectors. The total length and CMS energy of ILC reach 31 km and 500 GeV, respectively (50 km with 1 TeV for future upgrade). In 2013, Technical research document (TDR) of ILC was published and Japanese candidate of ILC site was determined at Kitakami. After this, the design phase move to pre-project which includes accelerator detailed design, R&Ds for cost-effective production, site study, conventional facility and siting(CFS) designs. The CFS design in pre-project intends to determine not only actual design of accelerator tunnel and related infrastructure but also to design tunnel structure, beam dump housing, local shield for positron production target, ventilation, cooling water circulation and drainage, therefore it requires radiation safety studies. KEK radiation science center will take place this study according to request from ILC project management. In this talk, outline of ILC accelerators and several ongoing topics of related radiation safety study is presented including separation shielding wall thickness with design criteria.