Overview of the NASA Space Radiation Laboratory

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Abstract

The NASA Space Radiation Laboratory (NSRL) is a multidisciplinary center for space radiation research funded by NASA and located at the Brookhaven National Laboratory (BNL), Upton NY. Operational since 2003, the scope of NSRL is to provide ion beams in support of the NASA Humans in Space program in radiobiology, physics and engineering to measure the risk and ameliorate the effect of radiation in space. Recently, it has also been recognized as the only facility in the U.S. currently capable of contributing to heavy ion radiotherapy research. This work contains a general overview of NSRL structure, capabilities and operation.

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1. Introduction

The increasing permanence of humans in Low Earth Orbit (LEO) and, in the future, in extended deep space missions beyond Earth, requires studies for assessing the risk from space radiation exposure and finding effective countermeasures. This has been the motivation for developing ground-based programs where the space radiation environment could be simulated.

The NASA Space Radiation Laboratory (NSRL) (Lowenstein and Rusek, 2007; Schimmerling, 2016) is a multidisciplinary accelerator-based center that provides charged particles for space radiation research. Commissioned in 2003, the facility is funded by NASA and managed in collaboration with Brookhaven National Laboratory (BNL), Upton NY, where it is located.

During its 13 years of operation, NSRL has served a large variety of experiments supported by the NASA Humans in Space program (Miller and Zeitlin, 2016). The roadmap encompasses radiobiology studies for understanding the link between radiation exposure and carcinogenesis, Central Nervous System (CNS) damage, degenerative tissue, sterility and so on. These areas have been studied in acute and chronic exposure conditions to comprehend the short and long term effects of radiation on the astronauts' health. In addition, the optimization of shielding materials for dose mitigation, the issue of radiation sensitivity of electronics and nuclear physics measurements for model benchmarking have also been addressed in the program. Investigators unsupported by NASA have also been taking advantage of this facility, mostly researching topics common to NASA activities. Recently NSRL has been recognized as the only facility in the U.S. currently capable of contributing to heavy ion radiotherapy research (Held et al., 2016; Pompos et al., 2016). This has led to new interest in the facility and its capability from the medical community, creating opportunities to broaden the scope of activities outside the NASA interests.

Since the beginning of operations, NSRL has undergone many upgrades. As a result, three modes of operation are available: single species and monoenergetic beams, Solar Particle Event (SPE) simulator and Galactic Cosmic Ray (GCR) simulator.

The general features of NSRL are presented here. The overview will include a description of the beam line, details of the beam characteristics and delivery modes as well as the calibration procedures for various setups.

2. The facility

2.1. Beam line

A schematic representation of the transport line from the ion source to NSRL exposure room is shown in Figure 1 together with a map of the facility.

Figure 1: Layout of the accelerators and user facility for NSRL: sources (EBIS, Tandem and LINAC), synchrotron (Booster), transport segment between the Booster and the exposure room (R-Line) (Tsoupas et al., 2007) and NSRL building.

Three sources can provide ions to the Booster and ultimately to NSRL. These are the LINAC (protons only), the Tandem Van de Graaff (certain ions and protons), and the Electron Beam Ion Source (EBIS) (any ion except protons). Of these, the most used is the EBIS, now capable of selecting from a menu of solid source materials by use of Laser Ion Source (LIS) controlled by software which enables movement from target to target without expert assistance. The overall solid material ion switching can be done in one minute. EBIS is also equipped with two additional gas sources, which requires expert attention to change. Once all sources are in place, switching among them can be achieved within a minute. Current upgrade plans include the capability to accelerate protons from EBIS and preliminary tests have already been performed.

The particle beams produced by any of the sources mentioned above are injected into the Booster synchrotron where they are further accelerated to

54 reach the final energy and delivered to NSRL via a single line branching off
 55 from the Booster (R-Line). A detailed description of all R-line elements is
 56 reported in (Tsoupas et al., 2007). The beam time structure can be varied
 57 over a large range from 300 ms to over 2 s, with particles bunches (referred to
 58 as spills) delivered every 4–6 s, depending on the other Booster activities.

59 Ion species from protons to gold are presently available, at energies rang-
 60 ing from 50 MeV/u to 2500 MeV for protons and 1500 MeV/u for ^{56}Fe .
 61 Lower energies can be achieved with passive absorbers. The range versus
 62 LET in water for a number of particle species and kinetic energies featured
 63 at NSRL is plotted in Figure 2.

Figure 2: Range versus LET in water for several ion species and kinetic energies featured at NSRL.

2.2. Beam characteristics

Beam shaping is done in the 100 m long transport segment between the Booster and NSRL irradiation room (R-Line). Since the facility was intended to accommodate radiobiology work as well as physics and engineering experiments, the R-line was designed to produce a large square beam spot with a uniform radiation field. The most common size used is 20x20 cm², although it can be made as large as 60x60 cm². This beam spot is achieved by use of a combination of dipole, quadrupole and octupole magnets, without any active beam scanning (Tsoupas et al., 2007). Examples of a pencil beam and the standard field are shown in Figures 3a and 3b, respectively.

Custom-shaped beams are achievable with the aid of collimators and shielding blocks of different sizes and materials (Figure 4).

Intensities available at NSRL are ion and energy dependent. Typical dose rates for the NASA work do not exceed 1 Gy/min independent of the beam type. However, higher intensities can easily be achieved either by increasing the ion flux directly at the source or by reducing the field size. Lower values, down to approximately 100 particles cm⁻², can be achieved for all ion species combining collimation and beam optics. This is done upstream of the R-Line to ensure beam purity and to preserve spatial uniformity at all intensities.

2.3. SPE and GCR simulators

Both SPE and GCR simulators aim at providing a radiation environment closer to what will be encountered on interplanetary missions.

The SPE simulator uses a proton beam with energies ranging from 50 to 150 MeV. The initial energy is set to the highest value and degraded with the binary filter. The fluence for each beam is modeled after two SPE events (1972 and 1989) to reproduce the dose profile in a human or, if appropriately scaled, in a small animal such a mouse or rat.

The GCR simulator (GCRSim) is designed to deliver a mixed radiation field consisting of different ions, from protons to Fe, at energies ranging from about 100 MeV/u to 1500 MeV/u for all ions, with protons going up to 2500 MeV. This project required many upgrades and additions in both hardware and control-software to bring to fruition. The ability to rapidly and reliably switch ion species is achieved by use of the LIS (Section 2.1) . Controls were also upgraded to enable switching of the charge state produced by the EBIS and the energy to which the booster accelerates the beam, again without expert assistance. Ion and energy changes can now be achieved by a single command within less than two minutes. Furthermore, the original beam line

Figure 3: Typical profiles for a round beam (a) with 1 cm diameter and a $20 \times 20 \text{ cm}^2$ field (b). In panel (b), the right figure shows a typical $20 \times 20 \text{ cm}^2$ beam overlaid on the image of one of the dosimetry ion chambers (Section 3) while the left figure presents a beam image acquired with the Digital Beam Imager (Section 3.2) and processed with ImageJ to obtain the horizontal and vertical profiles.

Figure 4: Collimators and shielding blocks available at NSRL for producing custom-shaped beams. (1) Composite three-layer collimators made of polyethylene, aluminum and lucite optimized for reducing the out-of-field dose to less than 2% when irradiated with a 600 MeV/u ^{56}Fe beam. They have been used for other ions up to energies that would result in a background dose not above 3%. Different sizes and hole configurations are available. (2) Brass collimators with round apertures between 14 and 18 mm. They are used for reducing the beam size and halo as well as to produce parallel pencil beams. (3) Tungsten blocks of various dimensions with which various collimator shapes can be achieved. A combination of custom blocks resulted in an out-of-field dose of 2% when exposed to 1000 MeV/u ^4He . (4) A copper collimator with adjustable size up to $10 \times 10 \text{ cm}^2$, originally intended for shaping low-energy beams.

101 design was limited to 1000 MeV/u, so an upgrade to 1500 MeV/u was carried
 102 out, as required by the GCRSim specifications. This was accomplished by
 103 upgrading the extraction magnet to handle the higher currents needed for
 104 the higher fields, and the addition of a third magnet in the 20 degree bend.
 105 No new or additional power supplies were needed, though some repairs and
 106 upgrades to the extraction magnet power supply were performed. A variable-
 107 thickness stripping-foil changer has also been installed at the upstream end
 108 of the extraction magnet, to improve control over the source-beam shape
 109 going into the R-Line. This is a very important factor, controlling the beam
 110 shape at the sample stand and, consequently, the validity of the calibration
 111 in going from one ion/energy combination to another.

112 Several strategies have been proposed to use the GCR simulator for re-
 113 producing space radiation fields in different scenarios. Details can be found
 114 in (Slaba et al., 2016; Kim et al., 2015) while a general review of the project
 115 including its impact on the NSRL scientific program is presented in (Kim
 116 et al., 2015).

117 While the GCRSim offers the possibility to deliver a custom mix of ions
 118 and energies within the available choices, two reference fields have been de-
 119 fined (Slaba et al., 2016). One approach (referred to as external field) ap-
 120 proximates the external, free space GCR spectrum with discrete ions and
 121 energy beams and deliver them onto a shielding material placed in front of
 122 the sample. The absorber is used to modulate the incoming beams in a
 123 manner similar to vehicle or habitat shielding for a deep space mission. An
 124 alternative to the external field, called local tissue field approach, is to deliver
 125 a mix of beams that directly reproduce the dose profile in a representative
 126 tissue of an astronaut behind a shielding. Details on how to reproduce the
 127 external and local tissue fields are described in (Slaba et al., 2016). An
 128 example of the dose profile in a mouse-like phantom exposed to isotropic
 129 radiation and corresponding LET spectrum necessary to deliver it are shown
 130 in Figure 5.

131 **3. Beam delivery and dosimetry**

132 *3.1. Ion species and energy*

133 Given a Booster magnetic rigidity and the ion species and charge state,
 134 it is possible to predict what energy the beam will have at the sample posi-
 135 tion. However, the beam type and energy are verified for each experiment.

Figure 5: Dose profile in a mouse-like phantom (right) exposed to isotropic radiation and corresponding LET spectrum (left) necessary to deliver it. The latter is calculated using a continuous reference field (line) and discrete beams (dots). Figure taken from (Slaba et al., 2016).

136 Using the program LET² (Zajic, 2004), the range of the selected ions in High
 137 Density Polyethylene (HDPE) is predicted. Upon performing a Bragg curve
 138 measurement using a binary filter made of HDPE, and checking the parti-
 139 cles' range, we can be sure that the ion we are requesting is indeed the one
 140 delivered and the energy can be measured to greater precision at the sample
 141 position. Examples of Bragg curves for 205 MeV protons, 293 MeV/u ¹²C
 142 ions and 963 MeV/u ⁵⁶Fe ions are shown in Figure 6.

143 Producing a Bragg curve uniquely identifies the beam characteristics and
 144 thus represents the best method to assure that the desired ion at the desired
 145 energy is being delivered.

146 3.2. Field size and uniformity

147 Beam images are acquired every spill with the Digital Beam Imager (DBI)
 148 shown in Figure 7. This detector, placed behind the sample stand, is trig-
 149 gered at the beginning of each spill and features a 40x40 cm² fluorescence
 150 screen and a pair of mirrors that acts as a periscope allowing the CCD cam-
 151 era (Hamamatsu ORCA-AG) to remain out of the direct beam. The light

²A comparison between LET and SRIM (Ziegler et al., 2010) programs resulted in negligible differences over the energy range used at NSRL.

Figure 6: Bragg curves of 205 MeV protons, 293 MeV/u ^{12}C ions and 963 MeV/u ^{56}Fe ions measured in High Density Polyethylene (HDPE).

152 produced by the particles passing through the screen is redirected by the
 153 mirrors to the CCD, which collects it for the entire spill length and then
 154 produces an image.

Figure 7: Scheme of the Digital Beam Imager (DBI).

155 With the help of the DBI, the beam size can be set at the beginning of each
 156 experiment, and checked continuously and adjusted during the exposures.
 157 Examples of images recorded by the Beam Imager are displayed in Figure 3b.

158 The DBI is also the main tool for assessing the beam uniformity. Saving
 159 a gray-scale image and analyzing it in ImageJ or equivalent software allows
 160 one to quantify the uniformity, as shown in the left picture of Figure 3b. The
 161 bright yellow frame at the edges of the beam field (right picture of Figure 3b)
 162 is translated into "ears" in both the horizontal and vertical profiles (left
 163 picture of Figure 3b). This feature is the result of the method used to create
 164 a large uniform beam, employing octupole magnets. As the outer frame has
 165 a higher dose than the uniform central field, it is never used for irradiations.
 166 We have learned from experience that independent of the particle type and
 167 energy a 3% uniformity can be achieved by eye.

168 3.3. Dose calibration

169 Calibration of dose is done against a NIST-traceable thimble ion chamber
 170 (referred to as the EGG counter), normally placed at the center of the beam.

171 Almost all work at NSRL is carried out with a large, spatially uniform beam.
172 In Figure 3b an image of the dosimetry ion chamber is shown, overlaid with
173 a beam image. The only material intercepted by the beam is the thin films in
174 the ion chamber, never coming close to the ion chamber frame. The area used
175 for dose measurement is completely contained within the uniform area of the
176 beam. This makes the calibration both easy to perform, and much more
177 reliable and meaningful over the entire uniform area of the beam (excluding
178 the bright edges).

179 The availability of heavy ions at NSRL presents a unique opportunity to
180 cross check the NIST-traceable ion chamber against scintillation counters.
181 This chamber is calibrated with gamma radiation, the calibration given in
182 coulombs per Roentgen. This number is converted to recycling integrator
183 counts per Rad in water, using a method well-documented in the litera-
184 ture (ICRU, 1998), but is intended for work with protons only. With heavy
185 ions one can use beams at low enough rate to read out both an ion chamber
186 response and count individual ions in a 1 cm² scintillation counter, thus ty-
187 ing together the dose measurement to the flux. With good enough control
188 over beam shape and purity, which NSRL has, one can cross calibrate the
189 thimble chamber. Such an effort was carried out at NSRL, using several ions
190 including C and Fe, establishing a 2% agreement between the NIST-traceable
191 calibration chamber and the scintillation counter.

192 3.4. *Cutoff*

193 One of the three ion chambers located just upstream of the exposure
194 stand can be chosen to be calibrated against the NIST-traceable thimble ion
195 chamber, located at the point where the beam is to be delivered, and then
196 used to measure the dose at that location during irradiation. The readout
197 system and the associated irradiation control module can cut the accelerator
198 beam off as soon as the desired dose is reached. The cutoff time is on the
199 order of 1 ms, representing a small fraction of a percent uncertainty on the
200 integrated dose measurement. At low intensities, where the ion chamber is
201 substituted by the scintillation counter, the cutoff is achieved with a count-
202 based method.

203 3.5. *NSRL exposure room layout*

204 A sketch of the beam line downstream of the exit window in the NSRL
205 exposure room is displayed in Figure 8. All elements are mounted on a

206 rail system and thus can be moved to accomodate different setups. Dis-
 207 tances indicated in Figure 8 are typical of most experiments. Thicknesses
 208 of all elements are given in Table 1 and further details can be found in
 209 <https://www.bnl.gov/nsrl/userguide/material-in-the-beam.php>. Values for
 210 the range shifter and the EGG counter are not reported because they are re-
 211 moved from the beam path once the dose calibration and energy verification
 212 procedures are completed.

Figure 8: Layout of NSRL irradiation room. IC 302, QC1 and QC3 are Ionization Cham-
 bers. As all elements are movable, the distances can be changed from setup to setup. The
 values reported are typical of most experiments and expressed in cm.

Table 1: Thickness of all elements in the NSRL exposure room.

Element type	Thickness (g cm ⁻²)
Exit window (Al)	0.103
IC 302	0.123
IC QC1	0.068
IC QC3	0.068
Air (20 degrees, 760 mm Hg)	0.698
Total	0.991

213 3.6. Non standard setups

214 Two additional irradiation modes have been developed for certain exper-
 215 iments, especially those related to particle therapy: the stopping beam and

216 the Spread Out Bragg Peak (SOBP).

217 In the former, the monoenergetic beam has to stop inside the sample or
218 even at a specific depth, e.g. where the layer of cells is located. The challenge
219 of this setup is to get an accurate measurement of the Bragg peak position,
220 which can be achieved at a submillimeter precision with the DBI. Once the
221 absorber thickness required for stopping the particles has been theoretically
222 estimated, several images of the beam are acquired by adding or removing
223 slabs of the binary filter to the initial calculated value. As the particles slow
224 down in the degrader, the image brightness increases, reaches its maximum
225 at the Bragg peak and then drops steeply, following the Bragg curve trend.
226 Identifying the absorber thickness for which the image is brightest provides
227 an accurate measurement of the beam stopping point. The calibration pro-
228 cedure for this setup cannot be accomplished with the standard methodology
229 described in Section 3.3 but must be reckoned from dose measurements car-
230 ried out by an ion chamber which intercepts the beam before it reaches the
231 degrader, at a point where the energy is high enough to give a reliable and
232 stable measurement.

233 NSRL has the capability of producing a Spread Out Bragg Peak with both
234 an active change of the primary beam energy or by passive range modulation.
235 Even if the process of changing energy is relatively fast (below 5 min), it was
236 never optimized as it was beyond the scope of the facility. Thus, the passive
237 method with the use of a range shifter wheel is usually preferred. Typically,
238 the wheel has a 1 mm step size as a narrower Bragg peak cannot be produced
239 in the range of energies considered. This value takes into account the intrinsic
240 energy spread of the beam in the Booster as well as the energy straggling in
241 the absorber. For the dosimetry, the SOBP is considered as a combination of
242 monoenergetic stopping beams, each calibrated according to the procedure
243 explained above.

244 The high energy heavy ion beam provided at NSRL combined with the
245 stopping beam mode allow Single Event Effects (SEE) testing of electronics
246 without delidding the components. The ions can have a long enough range in
247 silicon to completely penetrate the parts under test. This makes testing much
248 simpler, avoiding the need for vacuum chambers and obviating a detailed map
249 of the internal structure of the parts.

250 By using degraders of varying thickness, the Bragg peak can be scanned
251 across the sensitive volume within the parts, studying the LET-dependence
252 of upsets. LET scans typically begin at the highest beam energy (lowest
253 LET) with the ions completely penetrating the device under test (DUT). By

254 adding degrader to reduce the beam energy, it is possible to observe how
255 upsets initially increase in number with increasing LET and then abruptly
256 stop as the ions no longer have the energy required to reach the sensitive
257 volume of the DUT. In this way, it is not necessary to have a detailed map
258 of the internal structure of the DUT. Instead, the upset rate as a function of
259 degrader thickness can be used to make a maps of the internal structure.

260 This Variable Depth Bragg Peak (VDBP) Method (Buchner et al., 2011)
261 has been proven to be a powerful tool in electronics testing. The variable
262 degrader allows for a simple and quick measurement of the effective thickness
263 of parts. Placing the DBI behind the parts to be tested allows for a mea-
264 surement of the range of the ion beam in polyethylene with and without the
265 part in the beam, immediately giving the polyethylene equivalent thickness
266 of the part.

267 The large beam spot allows for tests of entire systems of electronics. Some
268 sensitivities to radiation do not show up at the part level, giving evidence
269 only at the system level. The highly penetrating ions and large sample area
270 allows complete circuit boards to be tested at once.

271 3.7. Overall dose uncertainty

272 Contributors to the overall dose uncertainty are beam purity, beam uni-
273 formity, calibration, readout electronics, cutoff. Of these, the dominant ones
274 are beam uniformity (3%) and calibration (2%). Combining these in quadra-
275 ture yields an overall dose uncertainty of 3.6%.

276 4. Support

277 NSRL is staffed with several scientists and technicians at all times during
278 running hours. Technical support is available for planning and designing
279 experiments at NSRL, including engineering, design and fabrication of sample
280 holders, special degraders and collimators. User-driven ideas and designs
281 have led to many improvements and additions to NSRL's capabilities, and
282 are welcomed.

283 For biology work there is a fully staffed laboratory complex in the BNL
284 Biology Department, where lab space and support are available, as well as a
285 fully AAALAC³-accredited animal facility (BLAF, Brookhaven Laboratory

³Association for Assessment and Accreditation of Lab Animal Care.

286 Animal Facility). Personnel from both the biology support team and the
287 BLAF are present at NSRL to support irradiation time involving their areas
288 of responsibility.

289 For non-biology work, support is offered for both planning and carrying
290 out of measurements or experiments.

291 In general, at least one NSRL physicist is present for all irradiations to
292 ensure beam and dosimetry quality, interact with the main control room, and
293 provide the oversight for smooth and safe operation.

294 5. Summary

295 For over a decade, researchers have been making use of the NSRL to
296 conduct studies of the effects of space radiation on biological and electronic
297 samples in an effort to reduce the risk of space flight on humans. During that
298 time, NSRL has increased its capabilities and flexibility to better simulate
299 the radiation environment of space. With the addition of the EBIS, changes
300 in ion species and energy can be accomplished in a matter of minutes. The
301 recent upgrade in beam energy enables NSRL to cover a greater part of
302 the galactic cosmic ray spectrum. Tools like the SPE Simulator have been
303 developed to meet the needs of researchers.

304 The large beam spot makes it possible to expose large numbers of samples
305 at once, increasing the throughput and efficiency. Precise control of the
306 beam cutoff, under the control of the experimenters, makes for accurate dose
307 delivery.

308 Good uniformity of the radiation field intensity also contributes to re-
309 duce uncertainties in the delivered dose. The dose calibration is maintained
310 through regular verification of the performance of the ion chambers used in
311 the dose measurement. Cross checking the calibration using ion counting
312 techniques validates the entire calibration procedure.

313 NSRL is currently the only facility in the world which combines all the
314 following features:

- 315 - all ions relevant for space radioprotection and ion therapy available in
316 the energy range of interest (up to 2500 MeV for protons and 1500
317 MeV/u for ^{56}Fe particles and below);
- 318 - fast switching of ion species and energy;
- 319 - SPE and GCR simulators;

- 320 - large uniformly-distributed beam suitable for biology work as well as
- 321 physics and engineering testing;
- 322 - dose-based cutoff achieved with a dedicated dosimetry system;
- 323 - high-quality spill by spill beam monitoring;
- 324 - animal facility.

325 Unlike other facilities, which are limited in ion selection and energy range,
 326 have to schedule around the main customers (as medical centers) or cannot
 327 accomodate animal work, NSRL does not have any of these constrains. It has
 328 been designed to maximize flexibility in the exposure area, labs and schedul-
 329 ing with room for upgrades arising from experience gained over the years of
 330 operation. As an example, in response to the growing interest in heavy ion
 331 therapy in United States, NSRL has been recognized as the only place where
 332 basics studies can be performed. Its role can be viewed as complementary
 333 to future ion therapy facilities, supporting all the experiments where clinical
 334 conditions are not required.

335 The goal of the NSRL is to provide a tool that can accurately simulate the
 336 radiation environment of space, that experimenters can use without concerns
 337 about the accuracy or reproducibility of the delivered dose. We continue to
 338 work towards that goal.

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