The NASA Space Radiation Laboratory at Brookhaven National Laboratory

K.A. Brown

Collider Accelerator Department, BNL
Outline

The NASA/BNL Space Radiation Program
Sampling of experiments
The NSRL Facility
Operations
Beam Characteristics
Uniform Beams
Dosimetry
Large Dynamic Range Camera Imaging System
Solar Particle Simulator
Summary
“Because astronauts are spending more time in space, the National Aeronautics and Space Administration (NASA) is working with Brookhaven National Laboratory and others here on Earth to learn about the possible risks to human beings exposed to space radiation. To study the radiobiological effects using beams that simulate the cosmic rays found in space, a new, $34-million NASA Space Radiation Laboratory (NSRL) has been established at Brookhaven Lab.”

Human Environments in Space

Present

1 year mission, 2005

30 day mission, 2015-2020

Future

30 month mission, 2025-2030
### Radiation Doses on Earth and in Space

<table>
<thead>
<tr>
<th>Area / Mission</th>
<th>Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>1y in Houston</td>
<td>100 mrem</td>
</tr>
<tr>
<td>1y in Denver</td>
<td>200 mrem</td>
</tr>
<tr>
<td>1y in Kerala, India</td>
<td>1,300 mrem</td>
</tr>
<tr>
<td>Apollo 14</td>
<td>1,100 mrem (9-day to the Moon)</td>
</tr>
<tr>
<td>Skylab 4</td>
<td>18,000 mrem (87-day in orbit)</td>
</tr>
<tr>
<td>Shuttle mission 41-C</td>
<td>5,600 mrem (18-day in orbit)</td>
</tr>
<tr>
<td>Mission to Mars</td>
<td>130,000 mrem (30 month)</td>
</tr>
<tr>
<td>at solar minimum</td>
<td>30,000 mrem in 1.5 y on Mars</td>
</tr>
<tr>
<td></td>
<td>80,000 mrem in 1 y in space,</td>
</tr>
<tr>
<td></td>
<td>+20,000 mrem from a solar flare</td>
</tr>
<tr>
<td>Chest X-ray</td>
<td>50 mrem</td>
</tr>
<tr>
<td>PET scan</td>
<td>1,000 mrem</td>
</tr>
<tr>
<td>Treatment of brain cancer</td>
<td>500,000,000 mrem (to normal brain)</td>
</tr>
</tbody>
</table>
The NASA/BNL Space Radiation Program

NSRL became operational during summer 2003

> 100 experimenters from 24 institutions (U.S. and abroad)

Brookhaven researchers and other NASA-sponsored scientists irradiate a variety of biological specimens, tissues, and cells, as well as DNA in solution. Other experimenters use industrial materials as samples, studying their suitability for space suits and spacecraft shielding.
Sampling of experiments

- Effect of Deep Space radiation on Human Hematopoietic Stem Cells
- Risk Assessment and chemoprevintion of HZE-induced CNS damage
- Heavy Ion Induced Chromosome Damage and Biomedical Countermeasures
- DNA damage clusters in low level radiation responses of human cells.
- Complex Space Radiation-induced DNA damage Clusters in Human Cell Transformation: Mechanisms, relationships and Mitigation.
- Induction of Bystander Effects by High LET Radiation in Cells
- Gene Expression in the Nematode C. elegans following Irradiation with Charged Particles
- Heavy Ion Particle Impact on Simulated Martian Regolith
- MSL/RAD Technology Demonstration Model Characterization
- Spacecraft shielding and components experiments
- Ion fragmentation experiments
1 GeV Fe tracks in cells.
Local Polyethylene Shielding Study

Dose Pt. 1

Polyethylene radiation shield

Dose Pt. 2

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Heavy Ions

Charged Ionizing Radiation
Outer-Space is full of them

Fig. 3.5. Typical energy spectra for protons, helium ions, carbon ions, and iron ions from “top to bottom,” respectively, at solar minimum. The solid line is the local interstellar spectrum (Simpson, 1983a).
Booster Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>201.78 (1/4 AGS) m</td>
</tr>
<tr>
<td>Ave. Radius</td>
<td>32.114 m</td>
</tr>
<tr>
<td>Magnetic Bend R</td>
<td>13.8656 m</td>
</tr>
<tr>
<td>Lattice Type</td>
<td>Separated Function, FODO</td>
</tr>
<tr>
<td>No. Superperiods</td>
<td>6</td>
</tr>
<tr>
<td>No. of Cells</td>
<td>24</td>
</tr>
<tr>
<td>Betatron Tunes,X,Y</td>
<td>4.82, 4.83</td>
</tr>
<tr>
<td>Vacuum Chamber</td>
<td>70 x 152 mm Dipoles 152 mm (circular) Quads</td>
</tr>
<tr>
<td>Max. Rigidity</td>
<td>17 Tm</td>
</tr>
<tr>
<td>Injection Rigidity</td>
<td>2.2 Tm (200 MeV protons)</td>
</tr>
<tr>
<td>Acceleration Rate</td>
<td>8.9 T/s (7.5 Hz)</td>
</tr>
</tbody>
</table>
R-Line: From Booster to NSRL

12” beam pipe

8” beam pipe
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# Operations

Beams delivered, NSRL-5 to NSRL-7

<table>
<thead>
<tr>
<th>Ion</th>
<th>Energy (MeV/n)</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>1000</td>
<td>$3.4 \times 10^{10}$</td>
</tr>
<tr>
<td>C</td>
<td>290</td>
<td>$1.2 \times 10^{10}$</td>
</tr>
<tr>
<td>O</td>
<td>1000, 600</td>
<td>$4.0 \times 10^{9}$</td>
</tr>
<tr>
<td>Si</td>
<td>600, 300</td>
<td>$3.0 \times 10^{9}$</td>
</tr>
<tr>
<td>Cl</td>
<td>500</td>
<td>$2.0 \times 10^{9}$</td>
</tr>
<tr>
<td>Ti</td>
<td>1100</td>
<td>$8.0 \times 10^{8}$</td>
</tr>
<tr>
<td>Fe</td>
<td>1000, 600, 300</td>
<td>$2.0 \times 10^{9}$</td>
</tr>
</tbody>
</table>
Extraction Point

Equilibrium Orbit bump for NSRL slow extraction

- Nominal (c7=-150, d1=440, d4=-50, d7=400, e1=0)
- shift d6 position -5 mm (d4=-80, e1=-50)
- shift d6 position -2.5 mm (d4=-50, e1=-100)

Beam Excited by Resonance and Extracting.
Horiz. Phase Space

- (green) D6: 0.01 cm full aperture foil, 5k particles
- (violet) D6: wire foil, 100k->1k particles
- (black) D6: collimator 0.5 mm, 10k->1k particles

Vert. Phase Space

Real Space
2 GeV Protons

Active Filter Off 300 msec Spill.

300 MeV/n Carbon

Active Filter On 300 msec Spill.

Spill Servo And Active Filter On.

Dosimetry Beam Cutoff

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Beam Spills Delivered
Uniform Beams

Octupole:

\[ x' = x' + O(x^3 + 3xy^2) \]
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256-Element Ion-Chamber (Beam Imaging)
Beam Image on the 256-element IC
During E. Blakely’s experiment (NSRL-2).
32-Element Ion-Chamber (Dosimetry)
0.025 + 0.1 + 0.4 + 3.2 + 6.4 = 10.125 cm

Binary Filter
Range: 0 – 25.575 cm
C. KE=294.1 MeV/n, LET\textsubscript{water}=13.6 KeV/\mu m

Si. KE=580.6 MeV/n, LET\textsubscript{water}=53.8 KeV/\mu m

Fe. KE=577 MeV/n, LET\textsubscript{water}=176.1 KeV/\mu m

Fe. KE=968.4 MeV/n, LET\textsubscript{water}=151.4 KeV/\mu m

Ti. KE=1019 MeV/n, LET\textsubscript{water}=107.3 KeV/\mu m
Beam Profile Camera System
Side Elevation View

Adam Rusek
Photographic consultant

Kevin Brown

I-Hung Chiang
Nothing happens Without this man’s Approval.

Charlie Pearson
Engineering design

Nothing happens Without this man’s Approval.
Lens control (zoom, iris, focus)

~200 ft of FireWire

camera controller (PS, FW junction)

NSRL beam event

PC (Windows XP) with Microscopy software (Compix C-Imaging)
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Solar Particle Simulator

The main motivation is to be able to reproduce energy spectra of the environment in space, particularly solar events.

NSRL Ground rules

- Need to be able to irradiate a single sample over entire energy spectrum within as little as a 1 hour period.
- Need a clean beam, as clean as any current NSRL experiment now receives.
- Need to know the energy of the beam as well as any current NSRL experiment.
- Need to know the dose as well as any current NSRL experiment.
Solar Proton Events

Large solar proton event integral fluence spectra at 1 AU.
Actively Changing Energy at NSRL

A high level interface has been designed and constructed. Is now being commissioned.

Theses parts are working well and are commissioned.

Connection to Dosimetry has been done. Now being commissioned.

- Booster Optics Control
- Booster Orbit & Extraction Septa
- NSRL Beam Line
- Dosimetry System
- Sequence (Tape)
- Permit Link
- Booster Main Magnet
- High Level User Interface

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Average Delivered Beam intensity during Energy stepping studies.

- **Si Intensity (ions/pulse)**
- **Booster Extraction Energy (GeV/n)**

- *302 Ion Chamber*
- *Dump Ion Chamber*
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Current Capabilities

1. Beam energies from 0.05 to 1 GeV/n with any ion that can be produced by a Tandem Van de Graff
2. Lowest intensities operated \( \sim 10^2 \) ions/cm\(^2\)/cycle
3. Smallest beams around 1 cm, smaller possible (not uniform, Gaussian). Largest beams around 20x20 cm\(^2\) uniform
4. Mixed field of protons and ions on a single target
5. 1 – 3 msec pulsed beams
6. Fast Extracted Beams (1 to 3 200 nsec pulses in 5 usec, or one 4 usec pulse)
7. Solar particle simulator
   1. Large range of ion energies over single irradiation
   2. Fast energy change
Future Capabilities

EBIS (electron beam ion source) will provide
- All ions up to U, including noble gases
- Higher intensities for current ion set
- Multiple mixed field ions (more than 2 ions species/irradiation)

Pulsed synchronized beams (with experimenter signals)
1. Synchronize beam with breathing, heart rate, EKG, ….
2. For low energy beams, allow for time of flight analysis
Supplemental
Slow Extraction Dynamics

Transverse fields in a normal sextupole are:

\[ B_x(x, y) = -6B_s xy \]
\[ B_y(x, y) = -3B_s (x^2 - y^2) \]

where,

\[ B_s = -\frac{1}{6} \left( \frac{d^2 B_y}{dx^2} \right)_0 \]

A particle with a magnetic rigidity \( B\rho \) receives (thin lens) kicks by a sextupole of length \( L \),

\[ \Delta x' = \frac{1}{2} \frac{L}{B\rho} \left( \frac{d^2 B_y}{dx^2} \right)_0 (x^2 - y^2) \]

and,

\[ \Delta y' = -\frac{L}{B\rho} \left( \frac{d^2 B_y}{dx^2} \right)_0 (xy) \]

define the normalized sextupole strength as

\[ S = \frac{1}{2} \beta^{3/2} \frac{L}{B\rho} \left( \frac{d^2 B_y}{dx^2} \right)_0 \]

The Kobayashi Hamiltonian

\[ H = \frac{\varepsilon}{2} (X^2 + X'^2) + \frac{S}{4} (3XX'^2 - X^3) \]

where

\[ X = \frac{x}{\sqrt{\beta_x}} \quad \text{and} \quad X' = \frac{\alpha_x}{\sqrt{\beta_x}} x + \sqrt{\beta_x} x' \]

are the normalized phase space coordinates, and,

\[ \varepsilon = 6\pi\kappa Q = 6\pi (Q_{\text{particle}} - Q_{\text{resonance}}) \]

The first term in \( H \) describes particle motion in the linear unperturbed lattice (\( S = 0 \)). The trajectories are circles with radius \( \sqrt{2H / \varepsilon} \) in normalized phase space.

The second term (perturbative term) distorts the circle.
Slow Extraction Dynamics

when H has the value \( \left( \frac{2 \varepsilon}{3} \right)^3 / S^2 \) it factors into 3 terms,

\[
\left( \frac{S}{4} X + \frac{\varepsilon}{6} \right) \left( \sqrt{3} X' + X - \frac{4 \varepsilon}{3S} \right) \left( \sqrt{3} X' - X + \frac{4 \varepsilon}{3S} \right) = 0
\]

The 3 lines define the boundaries between stable and unstable regions of phase space. The size of the stable region is determined by the ratio \( \varepsilon / S \).

\[
h = \frac{2 \varepsilon}{3} S = \frac{4\pi}{S} \delta Q
\]

The area of the stable region is

\[
A = 3\sqrt{3} h^2 = \frac{48\sqrt{3}\pi}{S^2} (\delta Q^2) \pi
\]

The area within a particular particle's linear unperturbed motion is called the single particle emittance.

\[
E = a^2 \pi, \quad \text{where} \quad a^2 = X_0^2 + X'_0^2
\]

Particle motion remains stable as long as the particle motion lies within the stable triangle.

\[
E_{\text{stable}} \leq \frac{48\sqrt{3}\pi}{S^2} (\delta Q^2) \pi
\]

This criteria for stability can be rewritten in terms of absolute betatron tune, with

\[
\delta Q = Q_{\text{particle}} - Q_{\text{resonance}}
\]

\[
Q_{\text{resonance}} - \frac{1}{48\sqrt{3}\pi S} \sqrt{\frac{E}{\pi}} < Q_{\text{particle}} < Q_{\text{resonance}} + \frac{1}{48\sqrt{3}\pi S} \sqrt{\frac{E}{\pi}}
\]

This can be shown graphically by plotting the action variable, \( \sqrt{E} \), as a function of betatron tune.
Slow Extraction Dynamics

Extraction Methods:
1. Widen stopband by increasing S
2. Move particles into resonance by changing betatron tune (AGS).
3. Increase particle amplitudes until it encounters the unstable region (rf knockout method).

\[ \sqrt{E} \]

\[ Q_{\text{resonance}} \]

Distrib. Of particles

Unstable region

Stable region
Booster Resonant/Slow Extraction

1 GeV/n Fe using 15 π mm-mR round beam

- particles at D3 (3 mrad D3 kick)
- particles at D6 (3 mrad D3 kick)
- Separatrix at D6
- Separatrix at D3
Injection, Acceleration, and Tune Space Manipulations
Energy Measurement in an Accelerator

Energy

\[ \beta = \frac{2 \pi R_{\text{booster}} f_{\text{rf}}}{hc} \]
\[ \gamma = \frac{1}{\sqrt{1 - \beta^2}} \]
\[ \text{K.E.} = (\gamma - 1)mc^2 \]

Symbols:

- \( h \) = harmonic #
- \( c = 2.99792458 \times 10^8 \text{ m/s} \)
- \( R_{\text{booster}} = R = 32.113 \text{ m} \)
- \( f_{\text{rf}} = \text{accelerating frequency} \)

Uncertainty

\[ d\beta^2 = \left( \frac{2\pi f_{\text{rf}}}{hc} \right)^2 dR^2 + \left( \frac{2\pi R}{hc} \right)^2 df_{\text{rf}}^2 \]
\[ d(\text{K.E.}) = mc^2 \beta (1 - \beta^2)^{-3/2} d\beta \]

Values used in figure:

- \( dR = 5 \text{ mm} \)
- \( df_{\text{rf}} = 10 \text{ Hz} \)
- \( h = 3 \)

Fractional Uncertainty in K.E. vs \( \gamma \)

![Graph showing the fractional uncertainty in K.E. vs \( \gamma \)]
Spill and Ripple

Time Structure Formalism

Definitions:
- \( Q \) = horizontal betatron tune
- \( \xi \) = horizontal chromaticity = \( \frac{dQ/Q}{dp/p} \)
- \( I_m \) = current in the Main Dipoles and Quadrupoles
- \( N \) = number of particles \( \left( \frac{dN}{dQ} \right) \) represents the particle distribution in tune space
- \( T \) = period over which particles are extracted

Low frequency duty factor:

\[
D_f = \frac{\left[f_r S(t)dt\right]^2}{T \int f_r [S(t)]^2 dt} \Rightarrow \left(\frac{f_{aw}}{f_{rms}}\right)^2 \text{in general}
\]

where

\[
S(t) = \frac{dN}{dt} = \frac{dN}{dQ} \frac{dQ}{dt}
\]

if there is no ripple,

\[
S(t) = \frac{dN}{dQ} \dot{Q}_0
\]

where \( \dot{Q}_0 \) is the rate at which particles move into resonance.

\[
\dot{Q}_0 = \frac{Q \xi dI_m}{I_m \frac{dI}{dt}}
\]
If there is ripple on the magnet power supplies:

\[ S(t) = \frac{dN}{dQ} (\dot{Q}_0 + \dot{Q}_v) \]

where \( \dot{Q}_v \) is the variations in the rate at which particles move into resonance.

\[ \dot{Q}_v = \frac{Q \xi}{L_m L_{vn}} \sum V_h \]

\( L_m \) is the total inductance of the main dipoles and quads and \( V_h \) is the sum of the 60 Hz harmonics amplitudes (in volts).

Reducing Time structure using RF Phase Displacement

\[ S(t) = \frac{dN}{dQ} \dot{Q}_0 (1 + \frac{\dot{Q}_v}{Q_0}) \]

For 1 particular frequency we can write the duty factor as

\[ D_f = \frac{1}{1 + \frac{1}{2} (\frac{Q_0}{Q_0})^2} = \frac{1}{1 + \frac{1}{2} (\frac{\omega Q_0}{v_0})^2} \]

where

\( \omega = \text{frequency} \)

\( \delta Q = \text{relative ampl. of that freq. in tune space} \)

\( v_0 = \text{speed that beam crosses resonance} \)

\[ v_0 = \frac{\Delta p}{p} \frac{1}{T} \]
\( D_f \) is increased by

1. decreasing \( \delta Q \)

2. increasing \( v_0 \)

One way to increase \( v_0 \) is to increase \( \Delta p \). To further increase it we use RF phase displacement, using a high frequency RF cavity. In this case RF buckets are centered on the resonance.

The buckets are empty and beam is forced between them.

Now,

\[
D_f = \frac{1}{1 + \frac{R_P \rho T}{V \Delta p} (\omega \delta Q)^2}
\]

Without RF phase displacement, a 100\% modulated spill has \( D_f = 0.67 \). In this case,

\[
\omega \delta Q \geq \frac{\Delta p \, 1}{p \, T}
\]
Spill and Ripple

Graphs showing data before bunches and after bunches.