MISSFIT Collaboration Research Overview

Trace Johnson
Mentor: Athanasios Petridis
Drake University
Physics Department

Outline

- The MISSFIT Collaboration
- Proposed Conceptual Design
- Radiation and Energy Loss
- Magnetic Field Calculation
- Particle Tracking Code
- Experimental Studies

The **M**agneto **I**onization **S**pacecraft **S**hield **F**or **I**nterplanetary **T**ravel Collaboration

- Student run research group composed of various task forces
- Each task force works on different parts of the project and communicates findings to other task forces
- Each task force meets weekly in addition to a meeting where everyone attends
- Currently six task forces:
  - Coding group
  - Biological Group
  - Mechanical Group
  - Experimental Group
  - Magnetic Group
  - Radiation Group

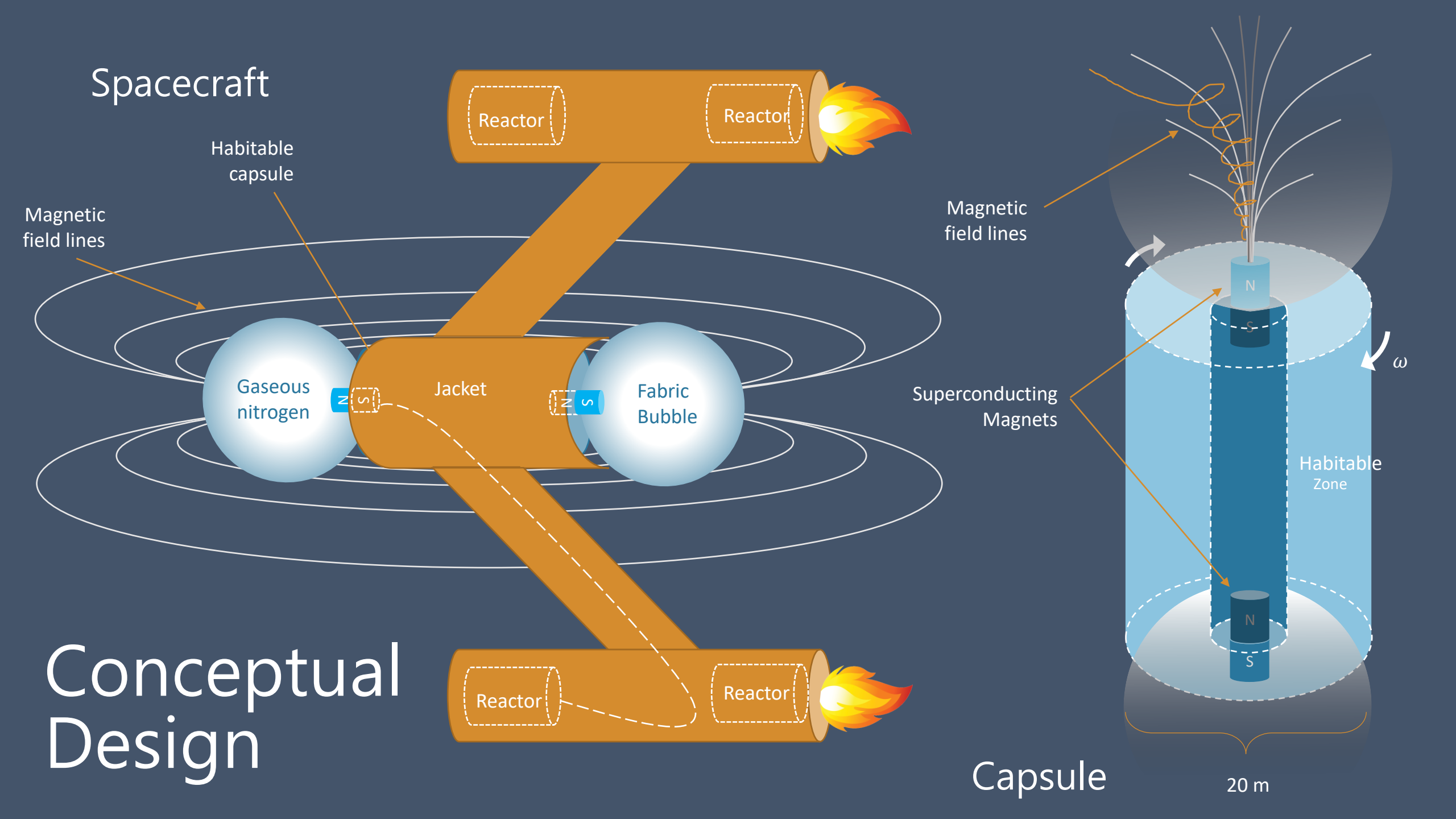
The MISSFIT Collaboration

Mission:

Develop a conceptual spacecraft design that uses passive and active shielding in conjunction with artificial gravity to protect astronauts from ionizing radiation and detrimental effects of microgravity

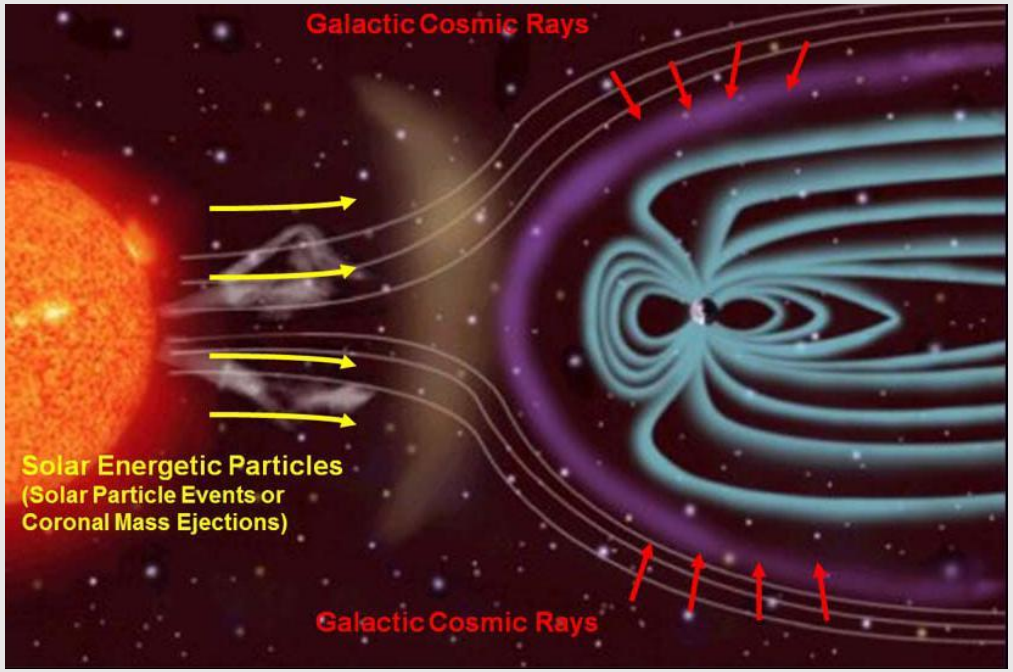
Proposed Conceptual Design

- In order to accomplish this goal, MISSFIT has created a conceptual design that mimics Earth's "solution" to the radiation problem
- Design consists of active shielding (superconducting magnets) and passive shielding (ionized gas and radiation absorbing material)
- Astronaut's chambers will be able to rotate to produce artificial gravity
- Magnetic field will deflect high energy particles and funnel low energy particles into the ionized gas where they lose their energy

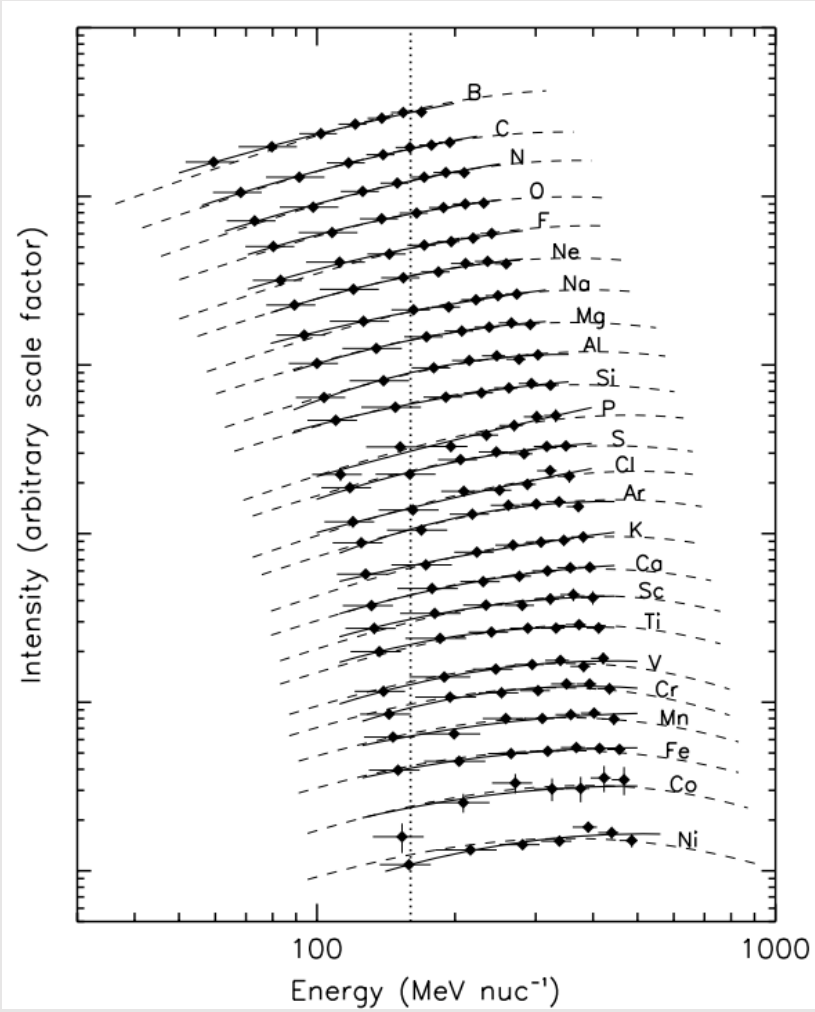

Spacecraft
Habitable capsule
Magnetic field lines
Reactor
Reactor
Gaseous nitrogen
N
S
Jacket
N
S
Fabric Bubble
Reactor
Reactor
Conceptual Design
Magnetic field lines
Superconducting Magnets
N
S
ω
Habitable Zone
N
S
Capsule
20 m

Radiation and Energy Loss

- Main concern is interplanetary radiation consisting of galactic cosmic rays, solar winds, and high energy gamma rays
- Once outside of the Earth's magnetosphere and ionosphere, radiation will present a much larger problem
- Better understanding of the spectra of interplanetary radiation is needed for realistic inputs to our particle tracking code



Radiation Composition



Intensity of particles at various energies during a solar maxima event.

GCRs

- Composed primarily of high energy protons (85%) and helium (14%)
- Significant amount originate from explosions of supernova

Gamma Rays

- Electromagnetic radiation with energies above 100 KeV
- Not affected by magnetic fields and must be attenuated by material shielding

Solar Wind

- Composed of protons electrons and alpha particles
- Includes some trace amounts of atomic nuclei and heavy ions
- Typical energy is between 0.5 and 2 keV/nucleon, but particles can reach energies of 0.5 GeV [1]

Energy Loss

- The Stopping and Range of Ions in Matter (SRIM) software is used to determine energy loss of a particle moving through a gas [2,3]
- The program uses the relativistic Bethe-Bloch equation with various corrections to give the stopping powers for a range of energies
- We are investigating nuclear (collisions leading to thermal excitation) and electronic (collisions leading to atomic excitation and possible ionization) energy loss effects currently

$$S = \frac{\kappa Z_2}{\beta^2} Z_1^2 [L_0(\beta) + Z_1 L_1(\beta) + Z_1^2 L_2(\beta)]$$

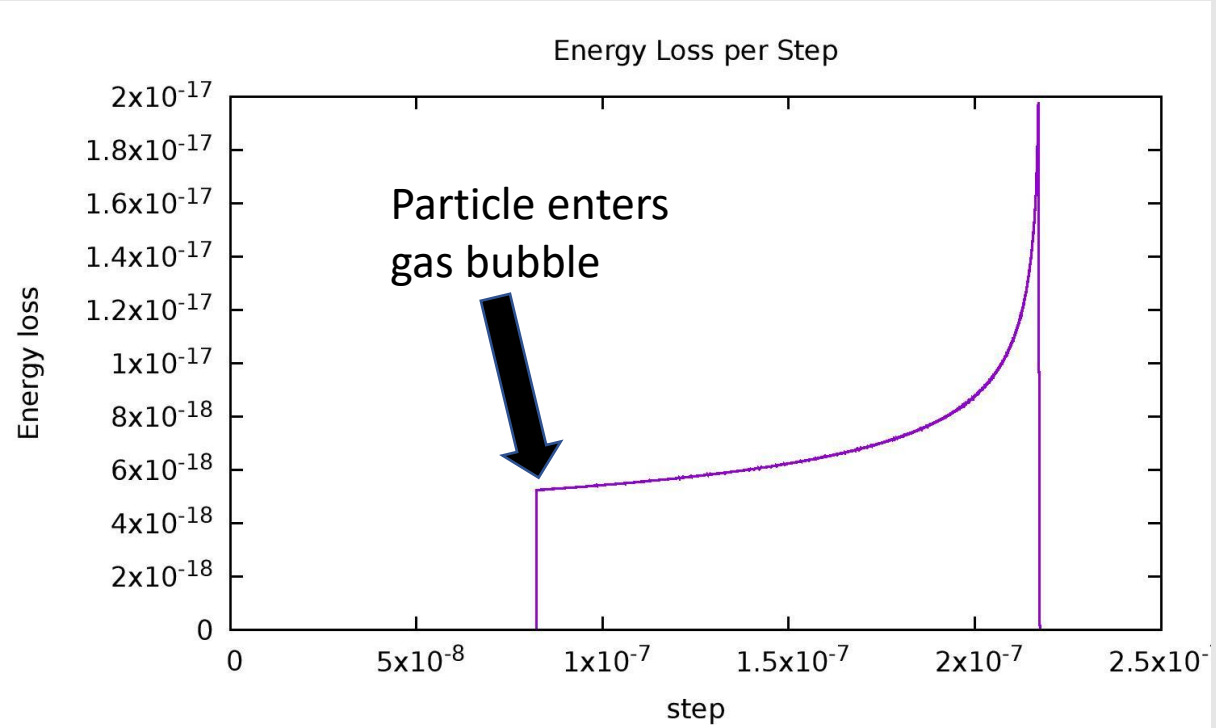
Shell/Density/Mean Ionization Corrections

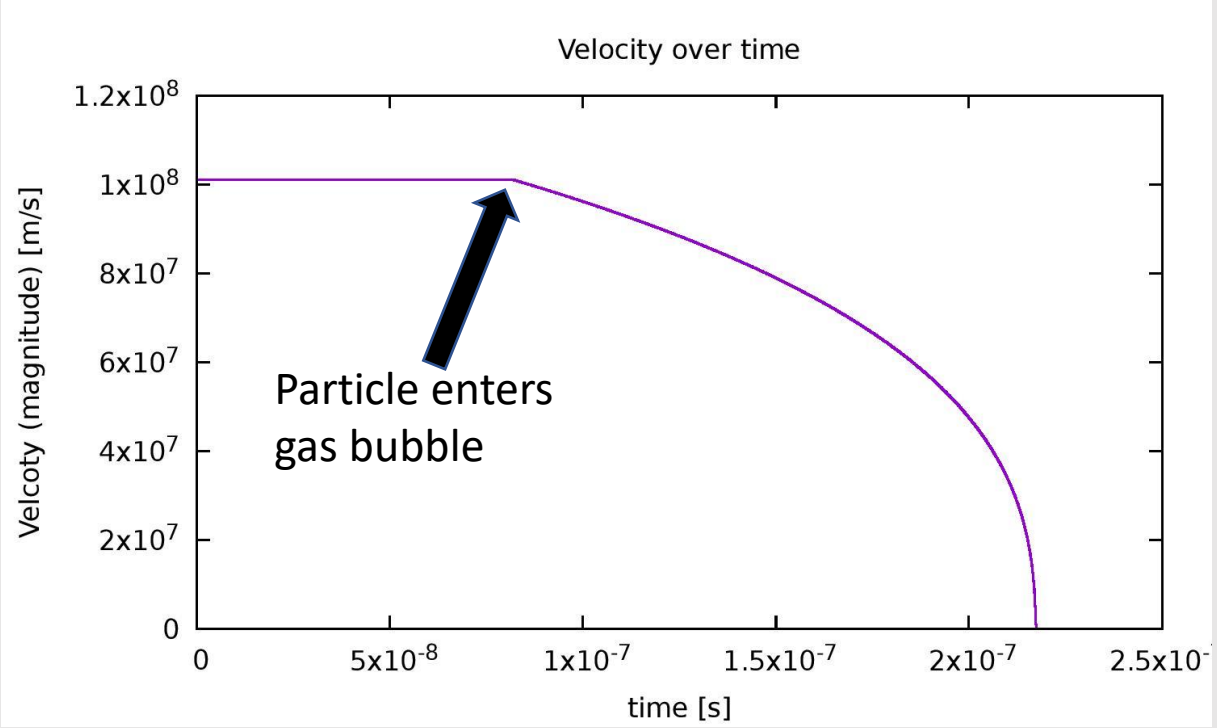
Barkas-Anderson Correction

Bloch Correction

Energy Loss Code

Proton traveling at 33% of the speed of light





Energy loss per time step of a proton out from our code with no magnetic field present. The proton loses energy over time as expected producing a Bragg peak.

Magnitude of the velocity of the proton over time. The particle begins to lose velocity as soon as it enters the gas bubble and starts to lose energy.

Magnetic Field Calculation

- Magnetic field configuration must be studied to determine which configuration provides the most protection
- Magnetic field calculation program output is used by the particle tracking code to allow for simulation of realistic magnetic fields
- Program solves the Laplace equation to find the vector potential at all points on a grid and then calculates the magnetic field at those points

$$\nabla^2 \vec{A} = 0$$

Build n^3 grid →

Set Boundary conditions:

- $\vec{A} \rightarrow \vec{0}$ as $\mathrm{r} \rightarrow \infty$
- Variable at spacecraft

→

Solve for $\vec{A}$ at each grid point using relaxation method [4]

Magnetic Field Program

- Program uses successive overrelaxation to calculate $\vec{A}$ at each grid point
- Grid point is approximated with a residual and scaled by an optimization parameter
- Parity ordering is used to speed up convergence
- Magnetic field is then determined at each grid point

Overrelaxation:

$$f_{opt} = 2 - \frac{2\pi}{n}$$

$$res = \frac{(a_n + a_e + a_s + a_w)}{4} - a_c$$

$$next = a_c + f_{opt} * \mathrm{res}$$

Magnetic field:

$$\vec{B} = \vec{\nabla} \times \vec{A}$$

$$B_x(i,j,k) = \frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z}$$

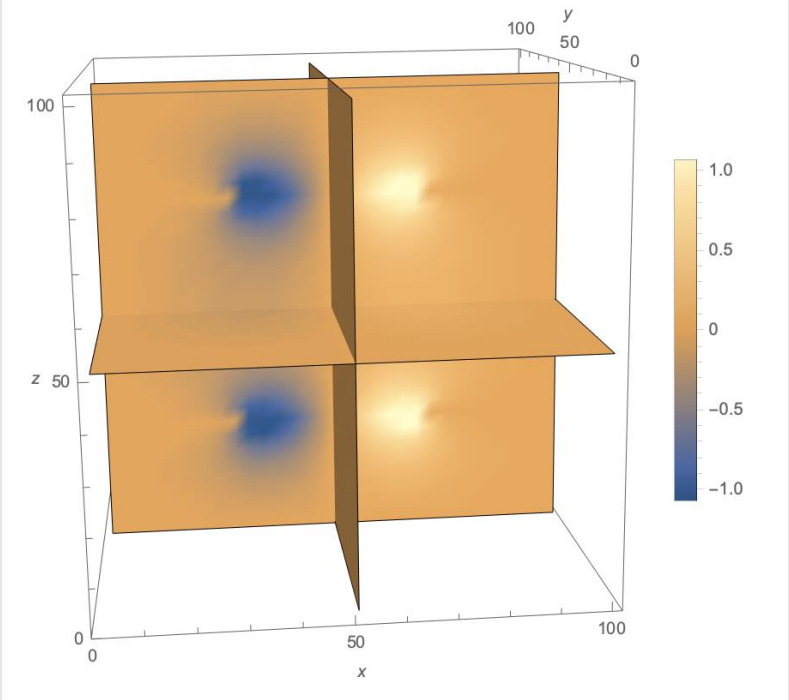
Finite Difference Forward Differentiation:

$$\frac{\partial A_z}{\partial y} \approx \frac{A_z(i,j+1,k) - A_z(i,j,k)}{dy}$$

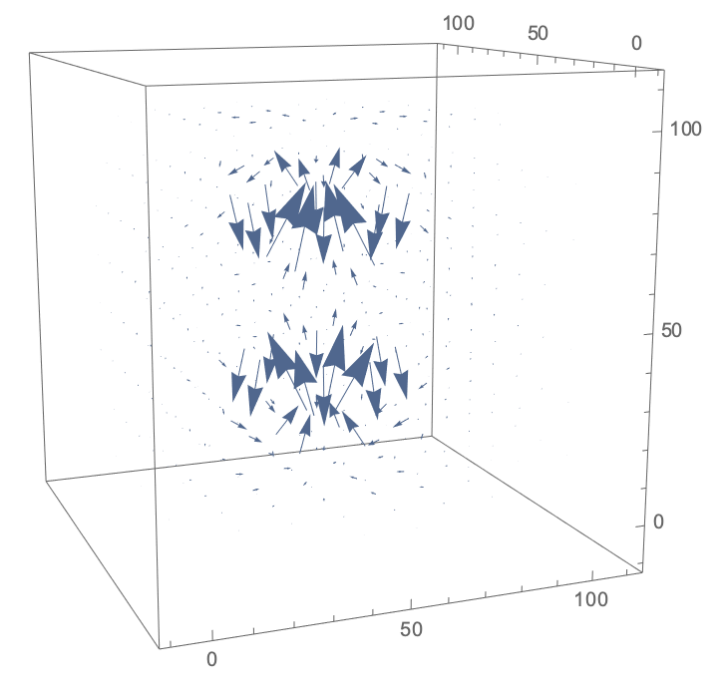
Magnetic Field Plots

Top right: Bx field over the y-axis with x and z held constant at grid point 122 near the edge of the midpoint of the spacecraft

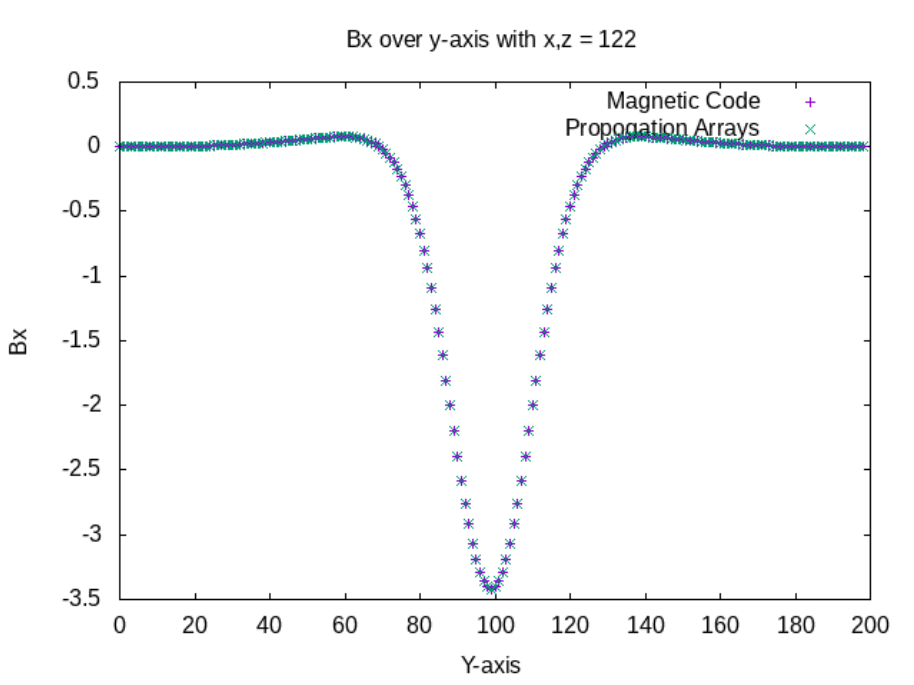
Bottom right: Bz field over the z-axis with x and y held constant at grid point 102 corresponding to the center of the spacecraft

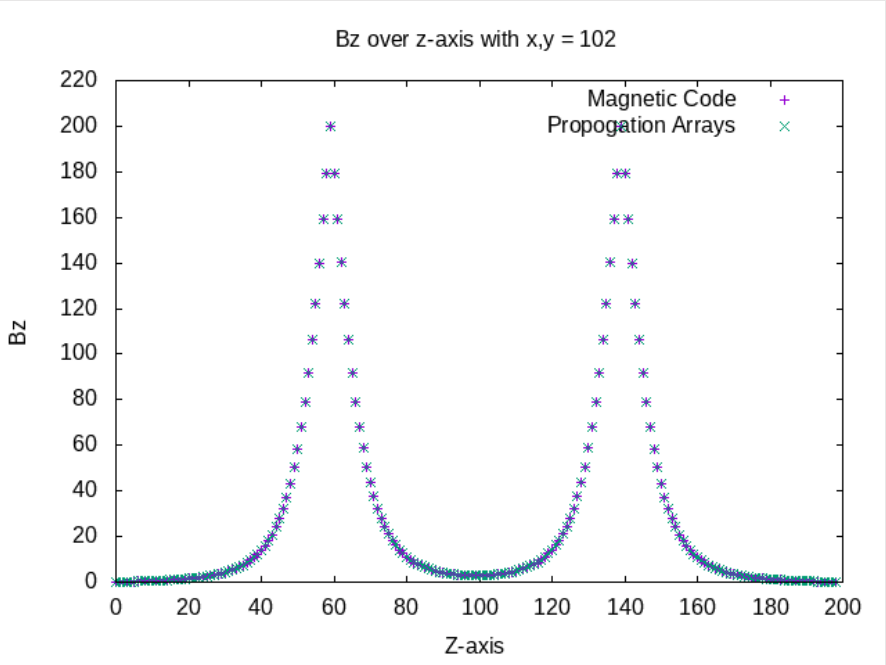


A_y field produced by two circular currents on either side of a cylinder.



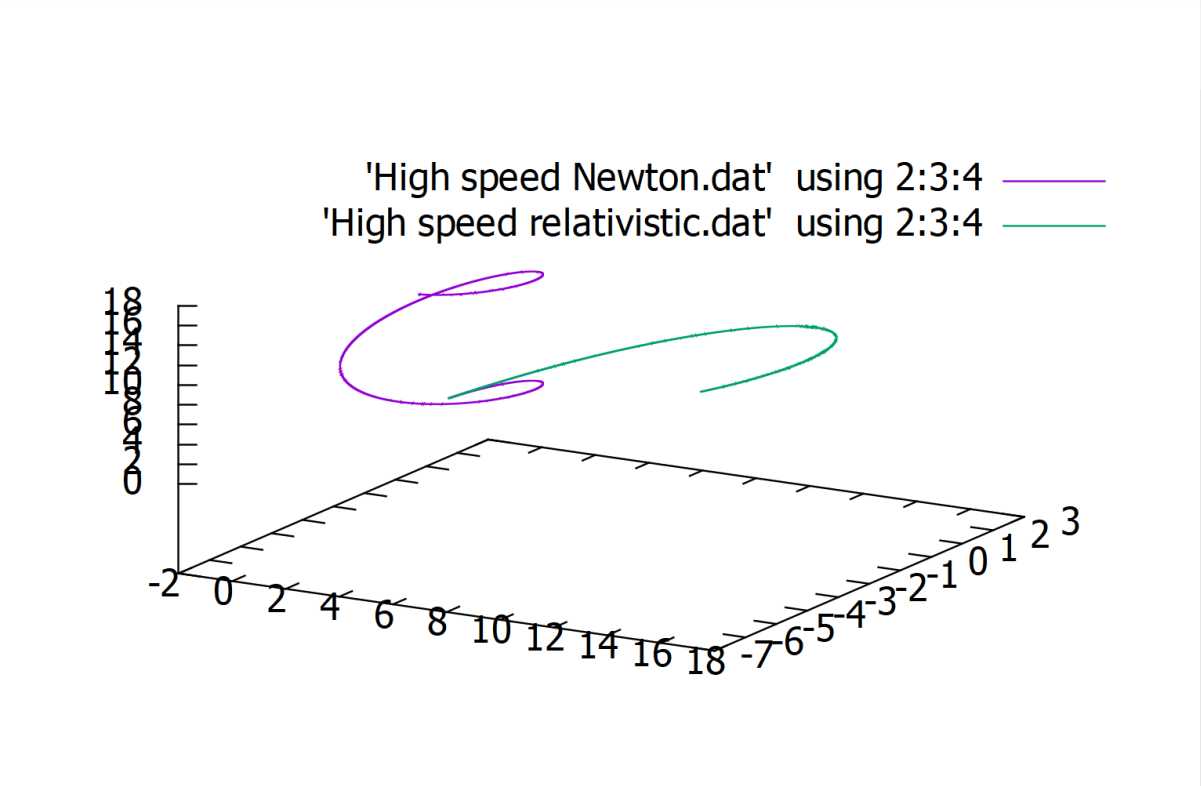
Vector plot showing the magnetic field produced by the potential associated with plot on the left.





Particle Trajectory Code

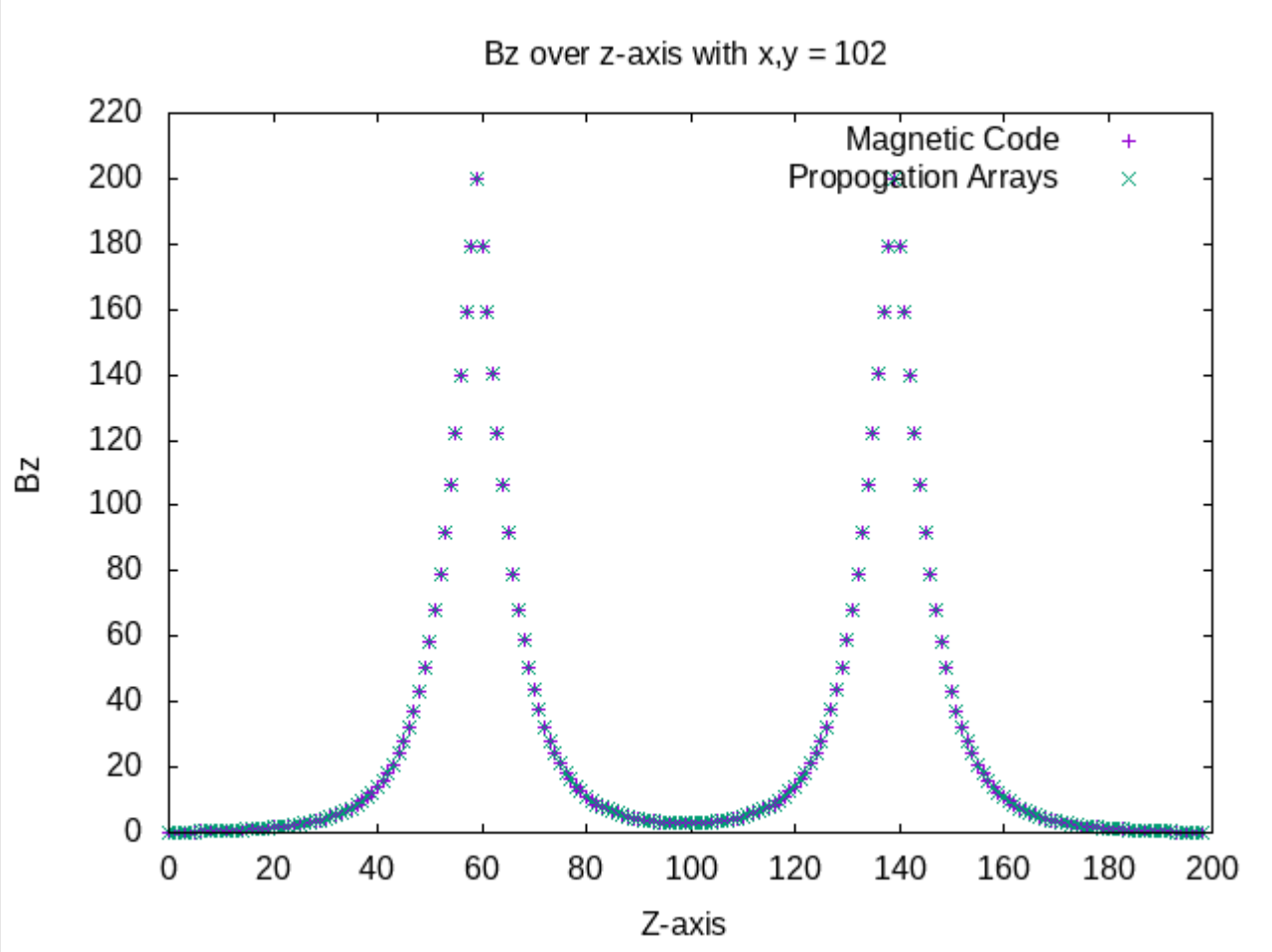
- The particle trajectory code uses a second order algorithm with respect to the time step *dt*
- Uses relativistic dynamics equations
- Simulates a realistic magnetic field input from the magnetic field program using 3-D interpolation between grid points
- Energy loss is calculated by interpolating between stopping powers input to the code from the SRIM program



This plot compares the trajectories of an electron with a velocity of 97.5% the speed of light using non-relativistic (purple) and relativistic (green) code.

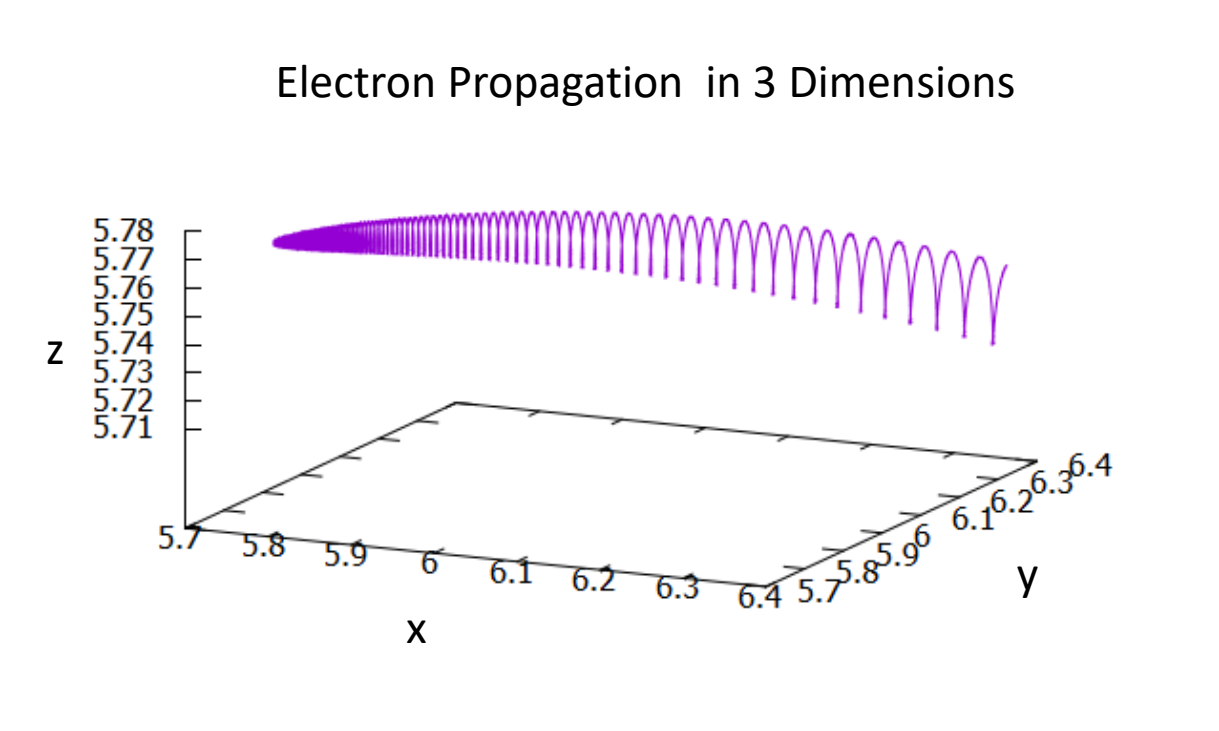
Integration of Magnetic Field Code

- Magnetic code produces a file containing the components of the magnetic field at each point in a 3D grid
- The file is read by the propagation code and dynamically allocated into memory
- Tests were run to ensure the magnetic field output from the magnetic field code was properly allocated into memory and 3-D interpolation between grid points was performed correctly

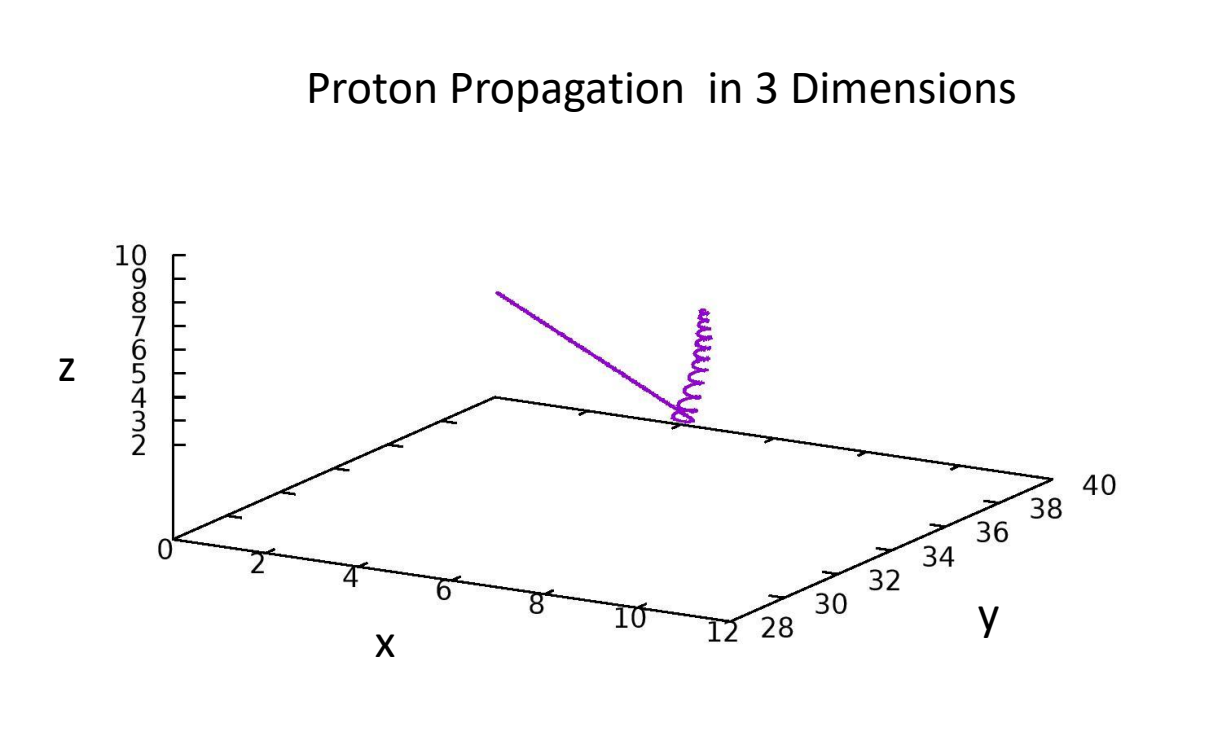


Comparison of magnetic field in the z direction along the z-axis with x and y held constant at the grid point 102 from magnetic code and propagation code.

Particle Propagation Plots



An electron in a magnetic field with energy loss constant over the entire region. As the particle loses energy, its spiral becomes tighter.



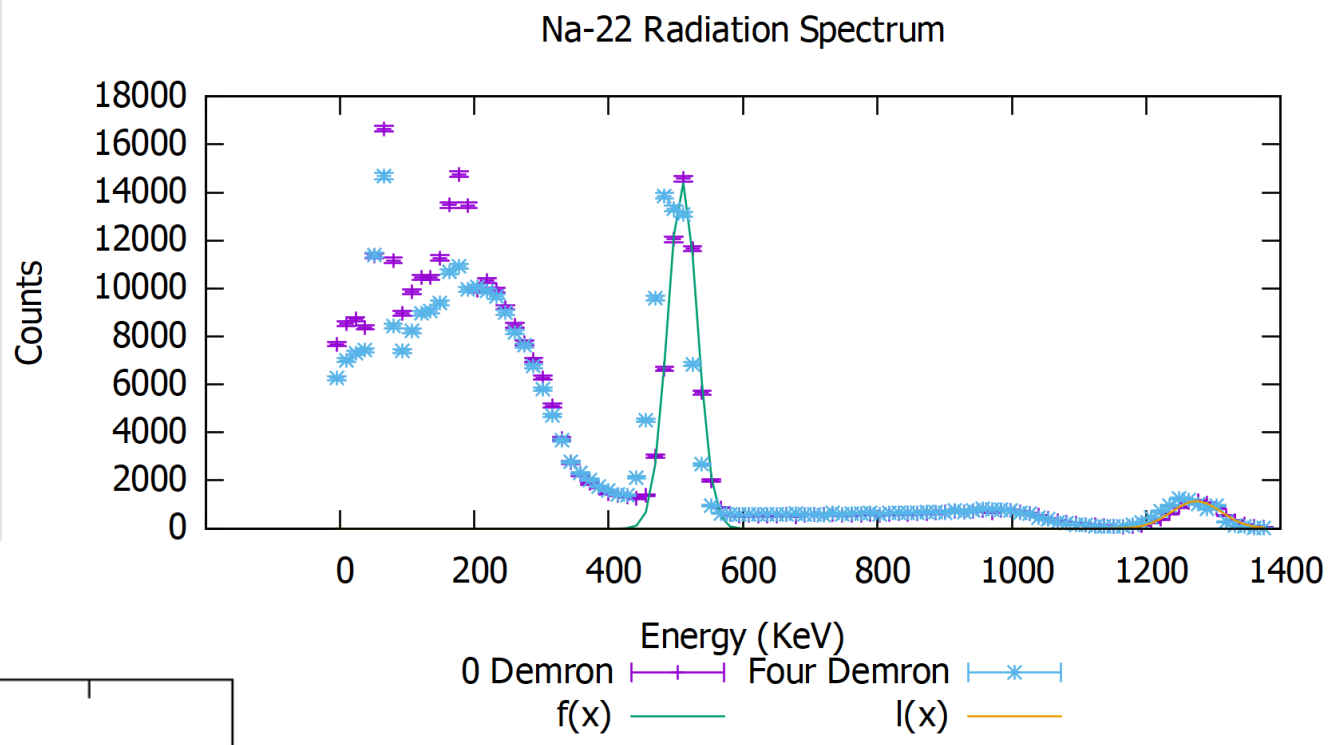
A proton in a magnetic field with energy loss confined to a sphere.

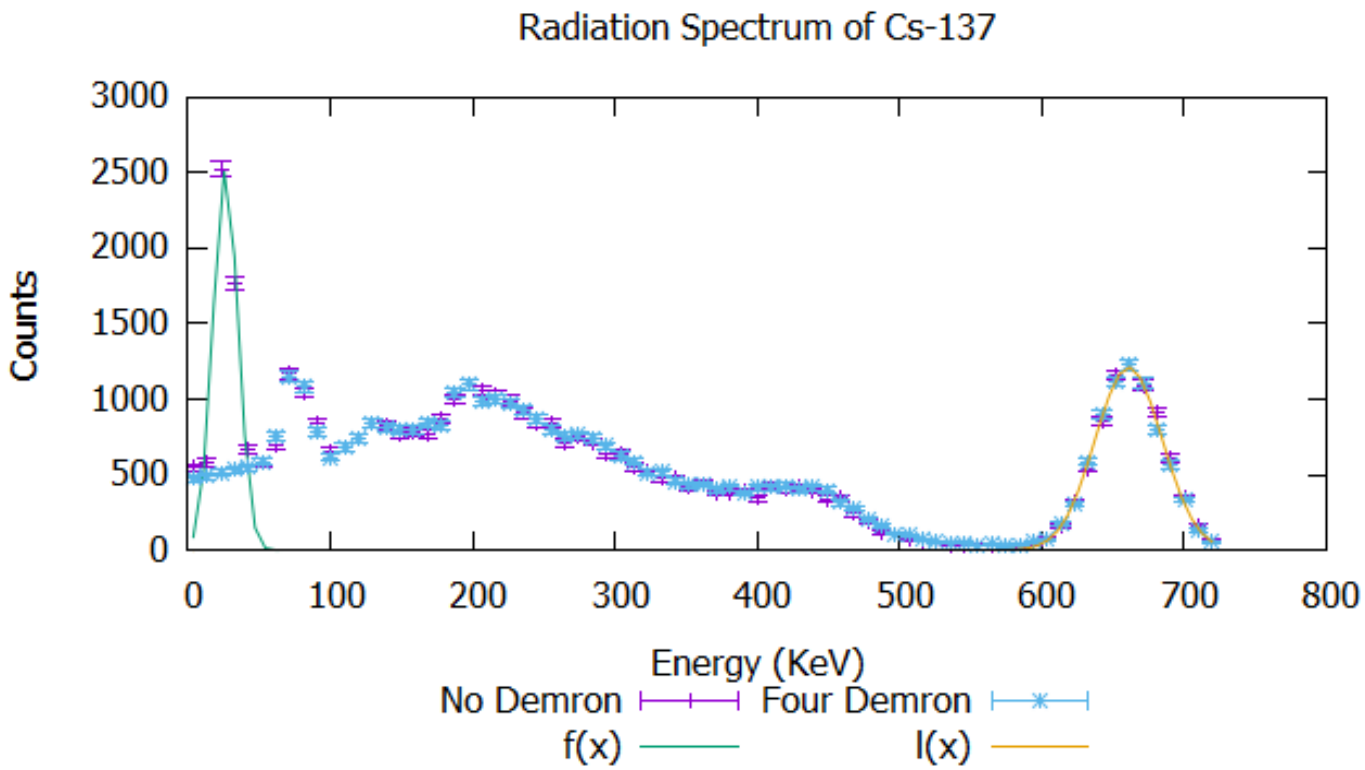
Material Experiments

- Investigation of fabrics and materials claimed to have radiation shielding properties for passive shielding
- Want to understand how effective materials are at attenuating gamma-rays and X-rays
- Demron composite fabric was exposed to X-rays and gamma-rays of various energies from several radioactive sources including Na-22, Co-60, Ba-133, and Cs-137
- NaI scintillator in combination with a photomultiplier was used to determine the photon counts across a range of energies
- Understand pair production and its possible role in gamma-ray protection

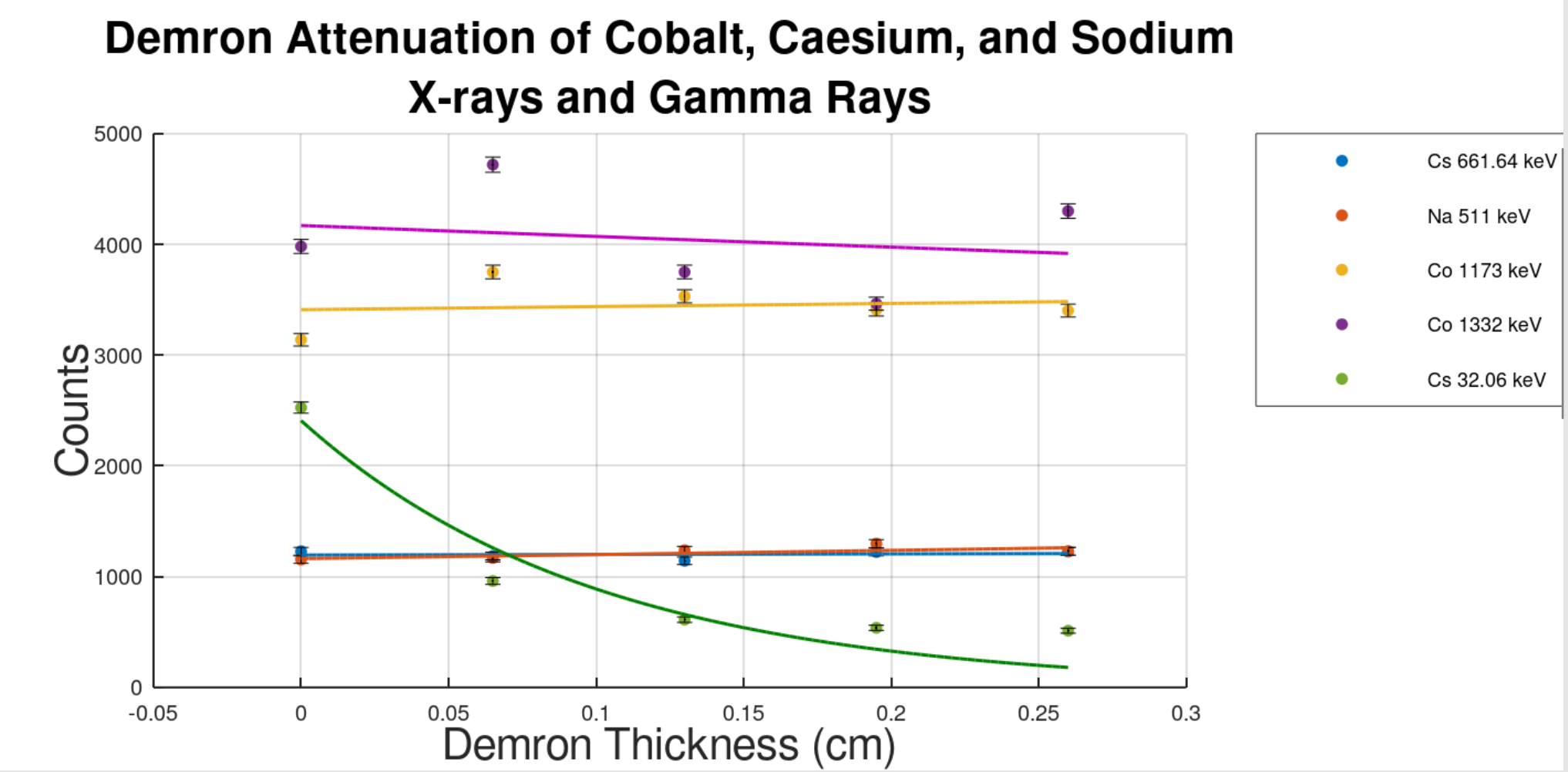
Experimental Data

Plot on the right shows photon counts per energy level for Na-22 with 0 and 4 layers of Demron. Gamma ray peaks were observed at 511 keV and 1274 keV.





Plot on the left shows photon counts per energy level for Cs-137 with 0 and 4 layers of Demron. An X-ray peak was observed at 32.06 keV and a gamma-ray peak was observed at 661.64 keV.



Attenuation curves for X-rays and gamma-rays of Na-22, Co-60, and Cs-137. The curves are produced by fitting data with an exponential function. They show no attenuation for gamma rays from Cs, Na, and Co, but significant attenuation for the X-ray peak from Cs.

Experimental Results

- Demron was found to be efficient at X-ray attenuation but exhibited no attenuation for gamma-rays

Energy level/Element used	Linear attenuation coefficient (cm^-1)
NA-22 511 keV	0.221017 +/- 0.3408
NA-22 1274 keV	-0.351167 +/- 0.1743
Cs-137 661.64 keV	-0.0430281 +/- 0.1721
Cs-137 32.06 keV	3.7717 +/- 0.2669
Co-60 1173 keV	-0.08166 +/- 0.3592
Co-60 1332 keV	0.239791 +/-0.6627
Ba-133 81 keV	3.77169 +/- 0.2669
Ba-133 30.85 keV	25.3302 +/- 1.847

Table shows linear attenuation coefficients of Demron for X-ray and gamma-ray peaks produced from each radiation source.

Artificial gravity

- Generate with rotation of the living quarters of the spaceship
- Understand the biological implications of artificial gravity and work to mitigate them
- Coriolis force is present when in a rotating reference frame
- Effects include dizziness and nausea
- The Coriolis Force where $\boldsymbol{\Omega}$ is the rotation vector and primed coordinates are relative to the rotating reference frame

$$\boldsymbol{F}' \underbrace{- m\frac{\mathrm{d}\,\boldsymbol{\Omega}}{\mathrm{d}\,t} \times \boldsymbol{r}'}_{\text{Euler force}} \underbrace{- 2m\boldsymbol{\Omega} \times \boldsymbol{v}'}_{\text{Coriolis force}} \underbrace{- m\boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \boldsymbol{r}')}_{\text{centrifugal force}} = m\boldsymbol{a}'$$

Mechanical Properties

- Investigation of mechanical properties of possible radiation shielding materials
- The materials will contain the gases used for energy loss
- Understand how these materials hold up against micrometeorite collisions
- Search for potential radiation absorbing materials

Future work

- Experimental:
  - More data collection using a new source, different materials, and different thicknesses
  - Experiments to understand mechanical properties of radiation absorbing materials
  - Experiments to understand the effects of artificial gravity on the human body
- Radiation/Energy Loss:
  - Understand how energy lost to gas is deposited into the spacecraft (UV/Visible light emission from previously ionized gas)
  - Other forms of energy loss like heat
  - Examine satellite data of solar winds and GCRs
- Particle Propagation:
  - Monte Carlo simulations using Amazon Web Server to examine various magnetic field configurations
  - Consideration of straggling due to the random scattering angle when particles collide

Acknowledgements

This project is based upon work supported by the Iowa Space Grant Consortium under **NASA Award No. NNX16AL88H**. A special thanks to Dr. Athanasios Petridis, founder and supervisor of the MISSFIT collaboration.

References

[1] Ogilvie, K. W. and Coplan, M. A. “Solar Wind Composition.” (1995) Rev. of GeoPhys. 615.

[2] Ziegler, James F, et al. “SRIM - The Stopping and Range of Ions in Matter.” SRIM, SRIM-2013, 2013, www.srim.org/.

[3] Zigler, James F. “The Stopping of Energetic Light Ions in Elemental Matter.”(1999) J. Appl. Phys/Rev. Appl. Phys. 85, 1249-1272.

[4] Hansen, Per Brinch, "Numerical Solution of Laplace's Equation“ (1992). Electrical Engineering and Computer Science Technical Reports. 168.