Radiation Hardened Opto-Atomic Magnetometer (RHOM)

Progress Update

DOE Funding Opportunity: DE-FOA-0001770
Grant Number: DE-SC0018586
Period of Performance: 05/28/19 to 11/30/21

DOE Program Manager: Dr. Michelle D. Shinn
Office of Science – DOE
Phone: (301) 903-8363

Principal Investigator: Jae Choi, Ph.D.
Hedgefog Research Inc.
San Pedro, CA 90731
August 2021

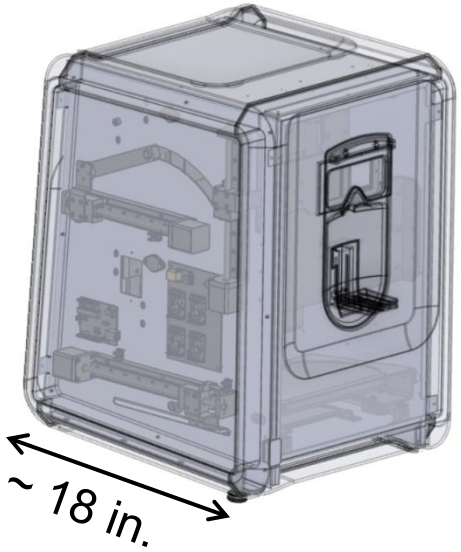
Subcontractor: Argonne National Laboratory (w/ Dr. Jerry Nolen, Jeongseog Song, Amy Renné, and Ravi Gampa)

Thanks to Drs. Georg Bollen and Steven Lidia @FRIB

Company Overview

Hedgefog Research (HFR) is a young, fast growing company; its team has expertise in the fields of optical metrology/sensing, atomic/molecular spectroscopy, atom-based sensors, mass spectrometry, and electrical/mechanical engineering.

- **Optical system design** and **metrology/sensor development**
- ISO 13485:2016 certified
- Full-cycle product development



Automated Vision Tester *being developed for USAF*

- All-in-one vision tester for Air Force pilots
- SBIR Phase I started in 2016
- Currently in Phase IIB / Phase III

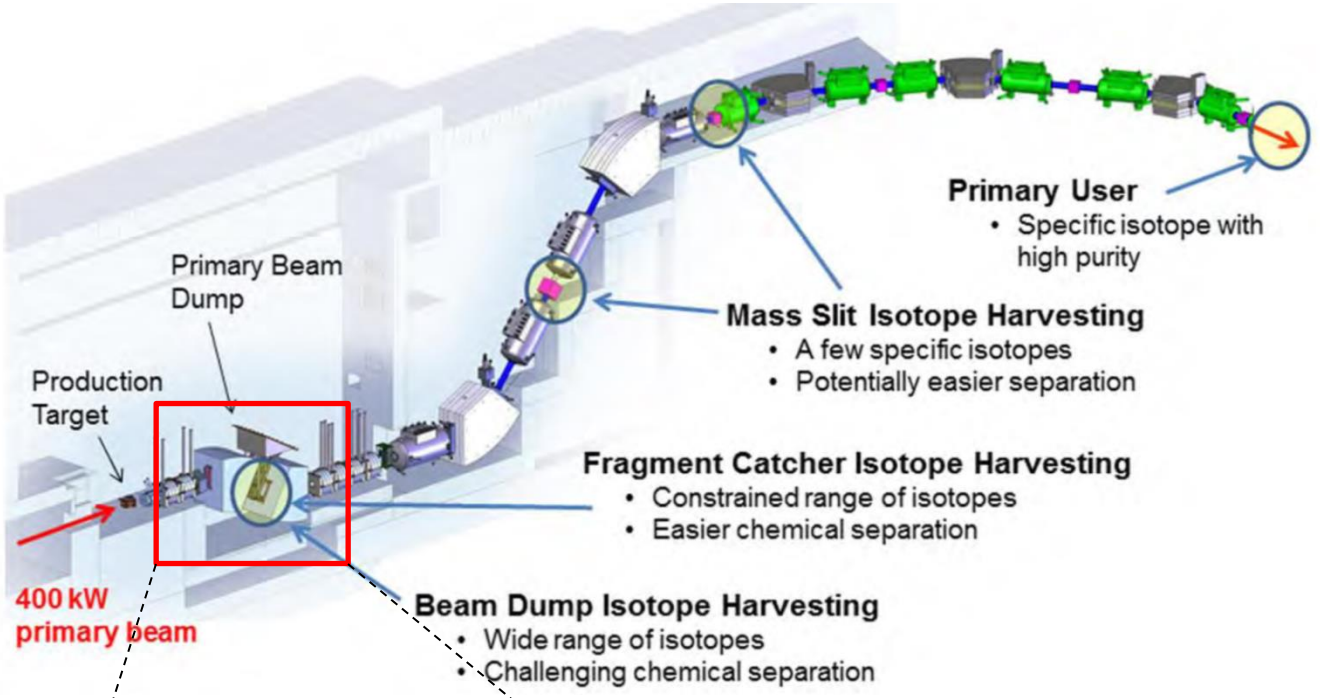
High-Power Target Facilities/Accelerators

- In rare isotope beam (RIB) facilities, **production and manipulation of the reaction products**, including ionization, purification, acceleration, and transport, need to be optimized individually to achieve maximum production rate of target nuclei.
- **Precise electromagnetic manipulation of reaction products** is needed to deliver intense rare-isotope beams with good ion optical quality and desired timing/energy characteristics.
- **Magnetic-field probing** is one of the diagnostic tools routinely used in the operation of RIB facilities.
- Nuclear magnetic resonance (NMR) probes commonly used in these applications have **limited lifetime** (~ weeks) due to radiation-induced damage. This results in facility downtime and increased operation cost.

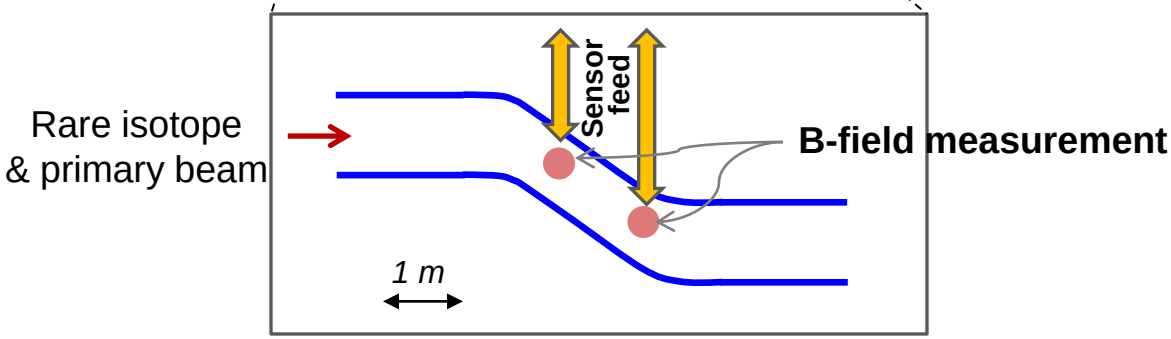
DOE Needs

- Magnetic-field sensing in high-radiation environments (gamma ray and **neutron**, **0.1 ~ 10 MGy/yr**), replacing NMR probes
- Target operation lifetime **> 1 year**
- Field range: **0.2 ~ 5 T**
- Precision ($\Delta B/B$) better than 10^{-4}, **10^{-5} desired**
- Field gradient (in one direction): 10^{-4} cm^{-1}
- Rep. rate: higher than 1 min^{-1}, **1 Hz desired**

Isotope Harvesting at FRIB

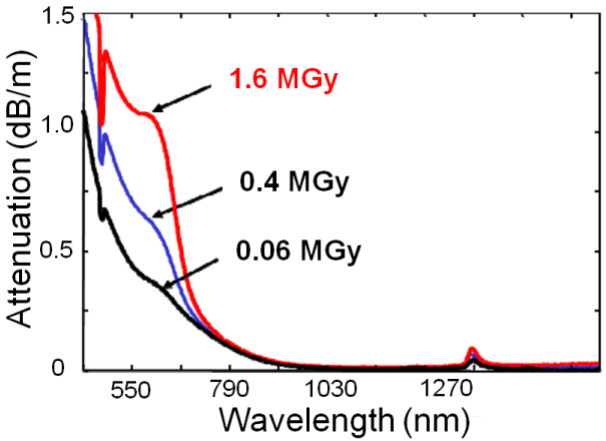


**** FRIB: Opening New Frontiers in Nuclear Science***
August 2012



Radiation Hardening

- "***If in doubt, leave it out***"
  The fewer components exposed to radiation, the better. Nice to have system components that can be easily replaced at low cost
- **Electronic, electrical, mechanical, and optical** components could be susceptible to radiation damage
  (example: capacitors have a damage threshold level of 10^2 ~ 10^5 Gy)
- Radiation may reduce light transmission by **darkening optical materials**. Transmission in visible tends to be worse than in **NIR**.
- Optical fiber (the most susceptible probe component to radiation) can be **replaced quickly (~1 min) at low cost (<$50)**

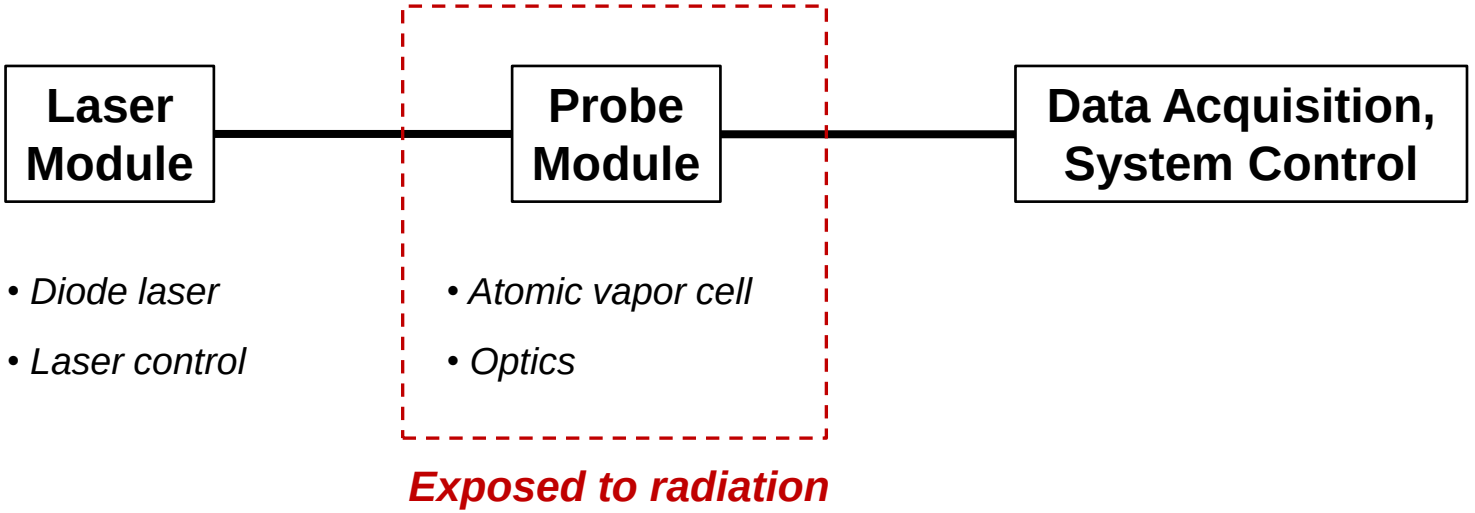


** Optical fiber in radiation from fusion reactor tested up to 1.6 MGy (mostly gamma-ray radiation)*

Brichard, et.al. Journal of Non-Crystalline Solids, 353, pp.466-472, 2007

Radiation Hardened Opto-Atomic Magnetometer

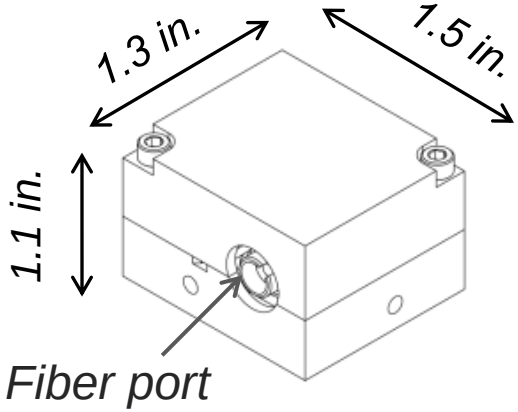
- Contains **minimal number of radiation-hard components** exposed to radiation (glass cell, metallic mirror, optical fiber, mechanical housing)
- RHOM accuracy guaranteed by quantum mechanics; **no need for device calibration**
- Sensitivity better than **10^{-5} T**
- Relative precision **($\Delta B/B$) better than 10^{-5} at 1 T**
- **>1 Hz** sampling rate



Progress Summary (Aug 2021)

- Developed a compact, production-ready radiation-hard probe prototype (ϕ1″×L1″)
- Evaluated RHOM performance at ~ 0.3 T (within the field range of interest for FRIB applications)
- Developed numerical calculation codes allowing direct conversion of RHOM measurements to B-field values
- Demonstrated absolute determination of B-field without need for calibration
- Verified B-field sensitivity suitable for the DOE application
- Developed full system design for future development

Phase II Probe Prototype and Test Setup

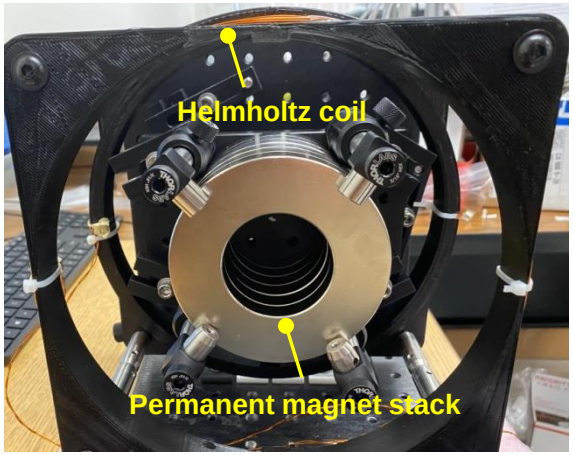


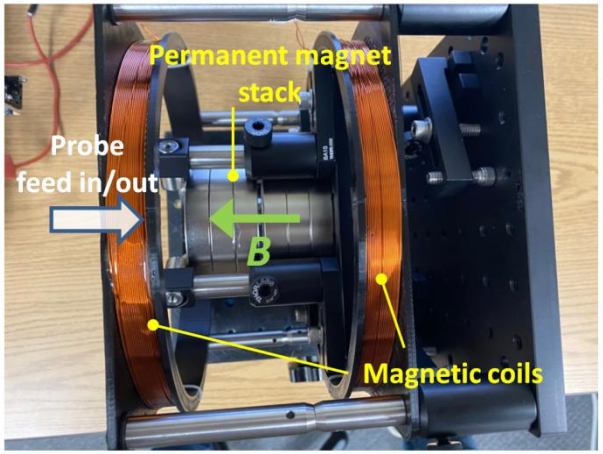
RHOM Probe

** non-magnetic construction*

Test Setup

Axial view





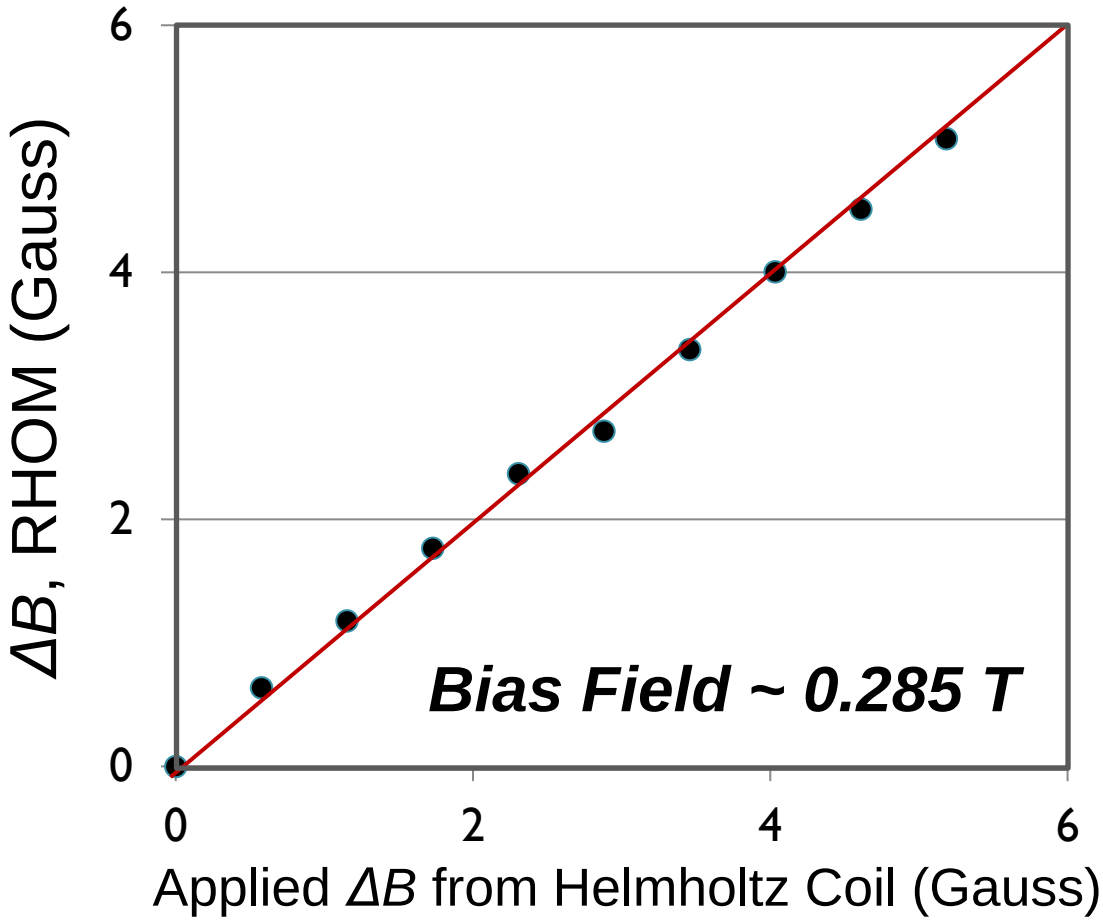
Side view

Magnet / Coil assembly (generating ~ $0.2845 \pm 20\times10^{-4}$ T)

Ring magnets *Helmholtz coil*

- Test field is significantly more inhomogeneous spatially than the field at FRIB

Magnetic Field Measurement



Calibration-free determination of magnetic field

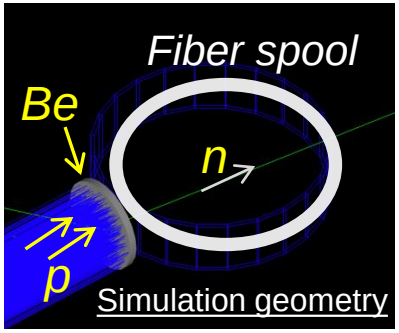
Phase II Development

- Full technical feasibility successfully demonstrated
- Probe is (nearly) production-ready
- Radiation hardness test to be performed in September 2021
- Preliminary layout of support system (laser controller, DAQ module, etc.) developed

Neutron Radiation of Optical Fibers

- Laser light to and from the rad-hard magnetometer via ~50 m of optical fiber may determine the lifetime of the instrument
- The irradiation is planned using the 16-MeV proton beam at the UWisconsin/Madison Medical Cyclotron in collaboration with Prof. Jon Engle (Planned irradiation: 12 hours at 40 μA)
- Neutron flux prediction based on Monte Carlo simulations normalized to experimental data*
- The **6-m segment of fiber** closest to the beryllium target will receive the highest integrated neutron flux (equivalent to **6 full-power, 400 kW, FRIB days** with a neutron flux of 12x the FRIB rate of 10^{15} n/cm^2/day)
- The average dose to the full 50-m sample equivalent to 2 FRIB-days
- Rad-hard quartz-based fiber to be compared with a conventional fiber

** Experimental data from Lone, et al. NIM 143 (1977) p331-344*



Technology Transition (Post-Phase II)

- Full system design (probe & support system) to be finalized
- User interface and system automation to be developed and tested
- Manufacturing plan to be established

  HFR will take advantage of existing manufacturing base and quality control (ISO 13485:2016).

Thank you!