Design and Manufacture of Tunable Permanent Magnet Based Quadrupole for Next Generation Electron-Ion Colliders

Fast-Track Award Number: DE-SC0015230
Program Managers: Manouchehr Farkhondeh & Michelle Shinn

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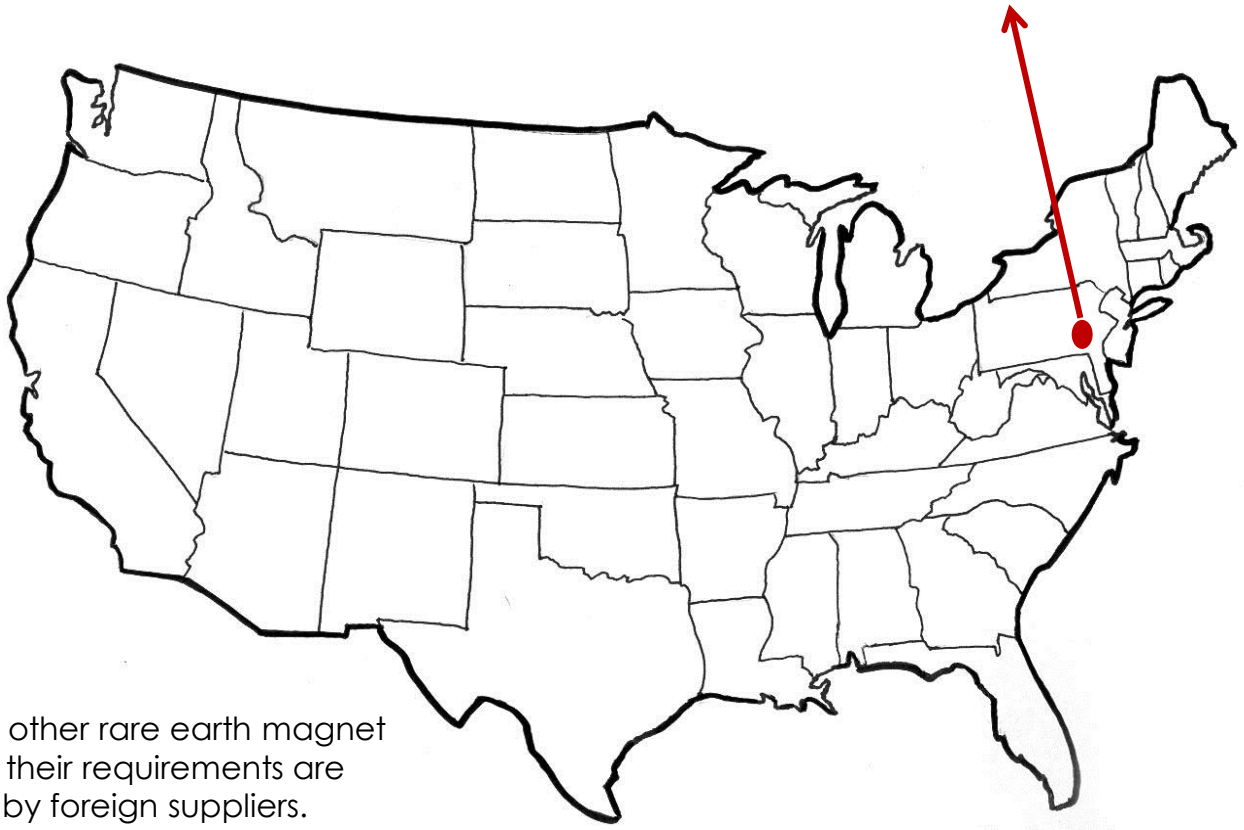
Outline

1. EEC Introduction
2. Project Description
3. Achievements
4. Schedule & Deliverables

1. EEC Introduction

First and the Only Rare Earth Magnet Producer in USA

EEC is the only remaining vertically integrated U.S. SmCo producer remaining in the country.

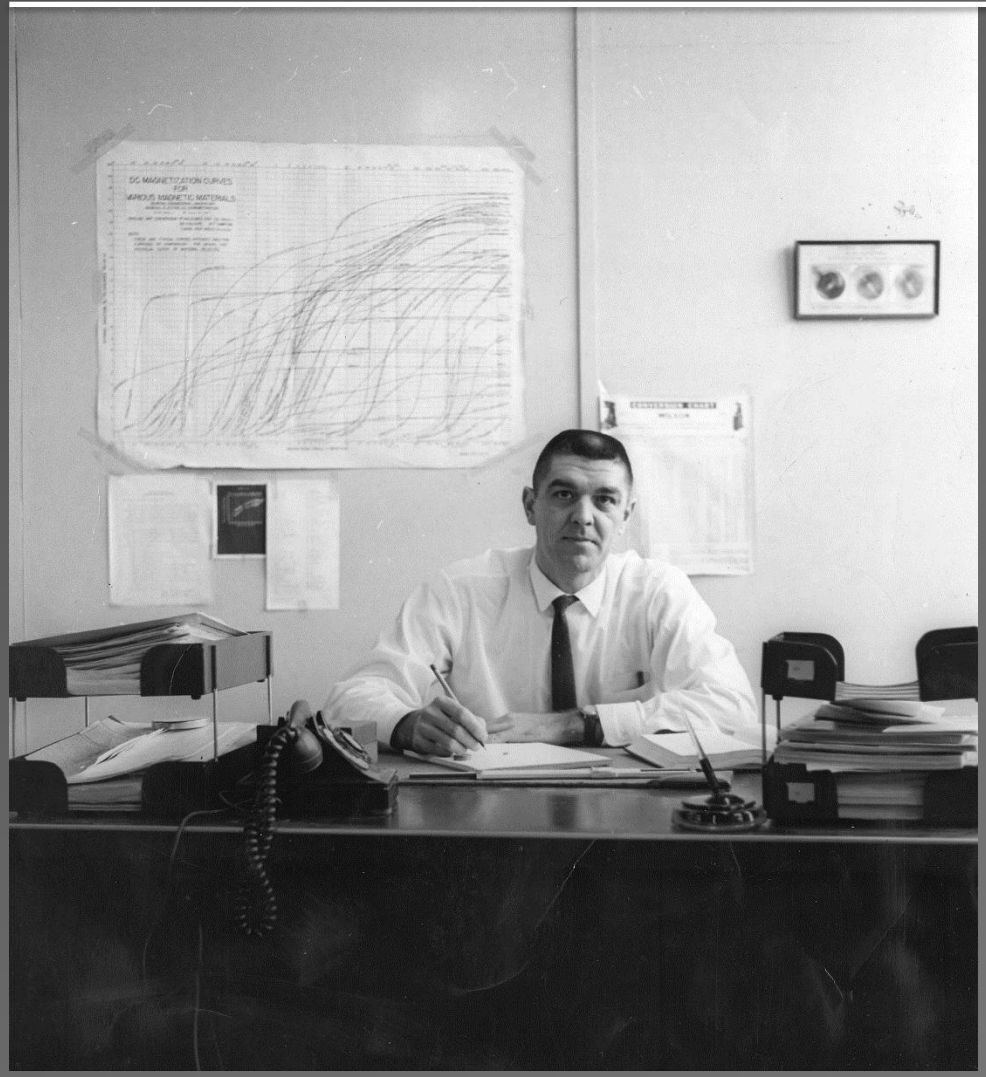


There are many other rare earth magnet suppliers, but their requirements are supported by foreign suppliers.

EEC Founder

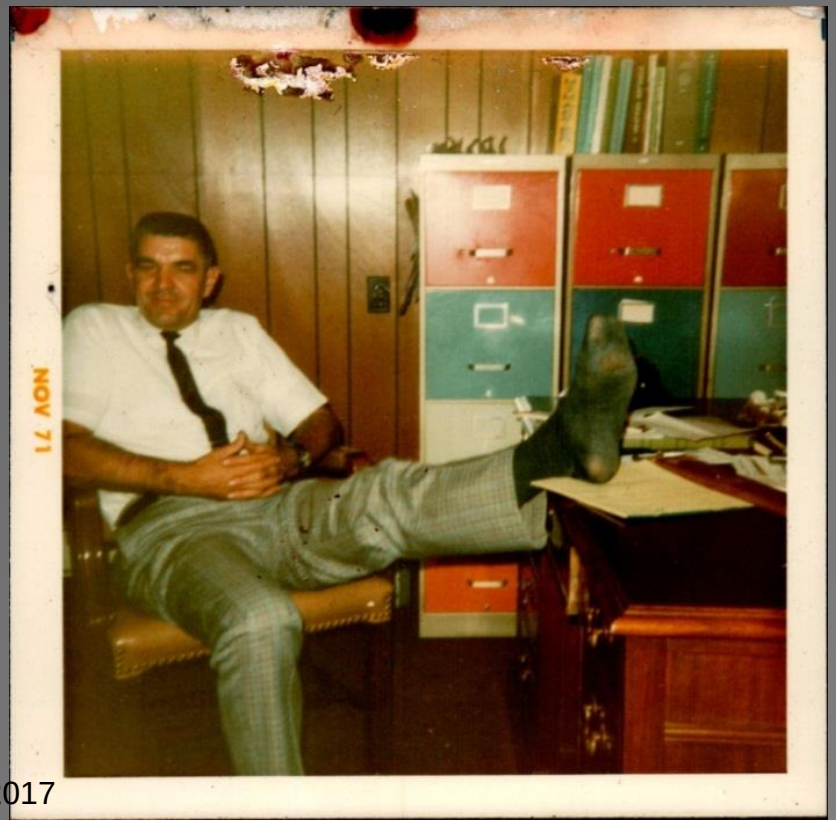
47 YEARS OF INNOVATION

ELECTRON ENERGY CORPORATION



Marlin Walmer

- Founder of Electron Energy Corporation
- Pioneered the processing and subsequent commercialization of an entirely new class of permanent magnets (SmCo) in 1970.



EEC History

EEC is founded in 1970 *(in a Milk House with 2 employees)* as Marlin Walmer pioneered the processing and subsequent commercialization of an entirely new class of permanent magnets (SmCo)

40,000 square foot facility was built to support the steady growth of business from 1970-1985

Add a new 45,000 square foot facility now housing the magnet finishing operation

(Rapid growth of business)

1960's — **Founder Marlin Walmer is working at Hamilton Watch pioneering platinum-cobalt magnets** for the world's first electric watches

1970

1972 — **Moved to 10,000 square foot facility** on Main St. Landisville

Mid 70's — **Developed Temperature Compensated SmCo** that have near-zero change in magnetic field over temperature changes

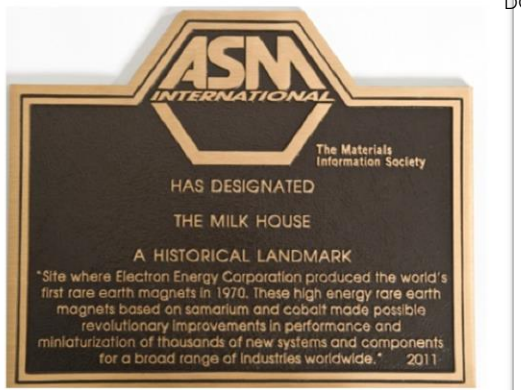
1985

2002 — **Patented Ultra-High Temp SmCo 2:17 magnets** in 2002 which operate at temperatures up to 550°C

2012 — EEC "Milk House" is recognized as an **ASM Historical Landmark**

2014 — **EEC has received 25 SBIRs & STTRs awards** since 1996 from NASA, DOE, NSF, EPA, and DOD

Hamilton Watch's 1st electric watch named the "Ventura"…made famous by Elvis Presley.



www.asminternational.org/membership/awards/historical-landmarks

Headquarter

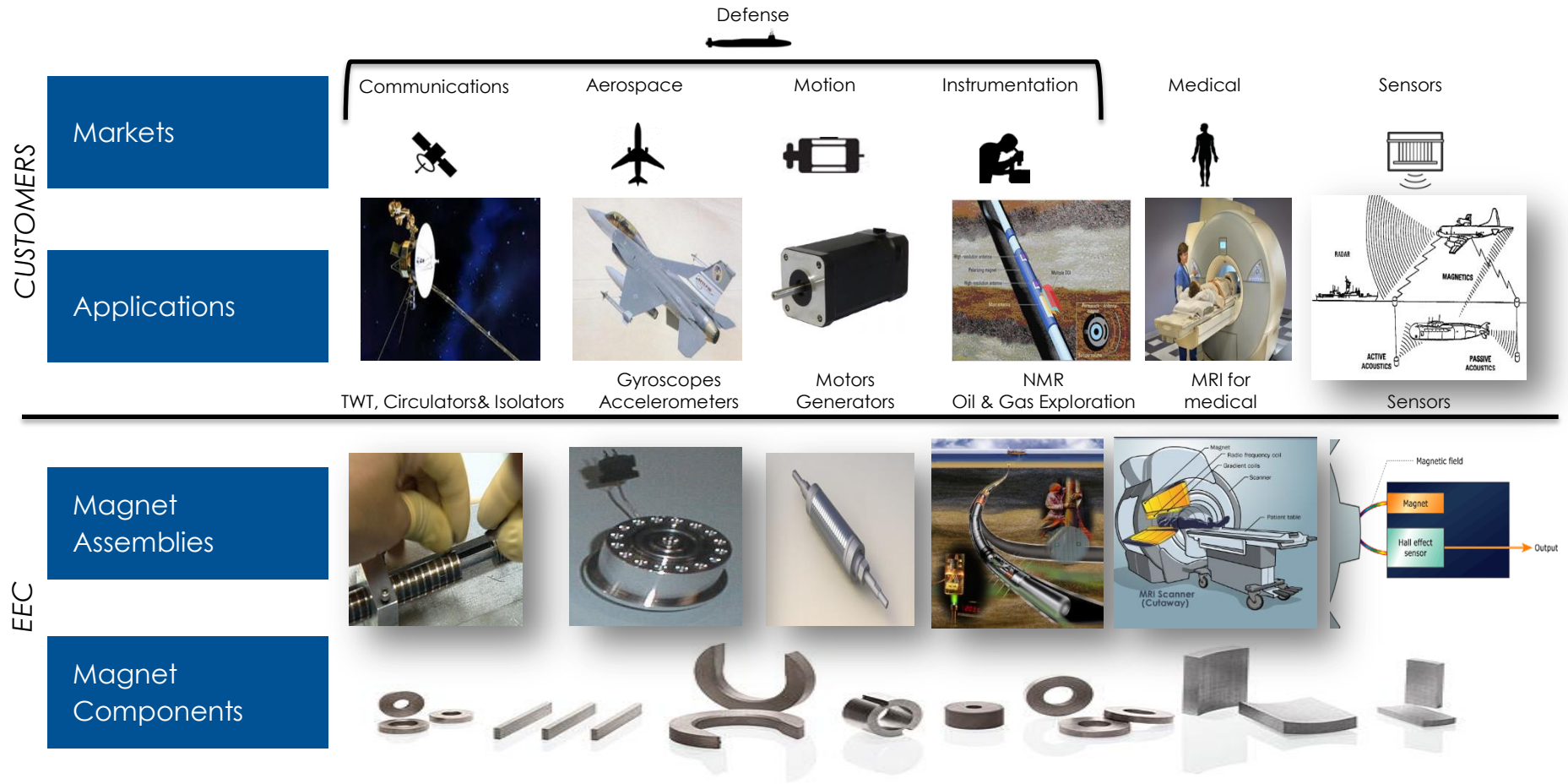
Post-sintering Operations

EEC Technology Center

Strong and highly skilled engineering support body for efficient realization of customer solutions

- +14 Engineers with a passion for customer magnetic solutions
- Material adaptations for specific needs
  - Production requirements
  - Laboratory scale materials
- FEA Analysis (2D & 3D)
- Application Engineering development and advisory services
- Testing capabilities
- Analysis of magnetic properties
- Over 200 publications
- Diverse engineering team with scientist from China, Romania, India, South Korea, & United States

EEC Applications

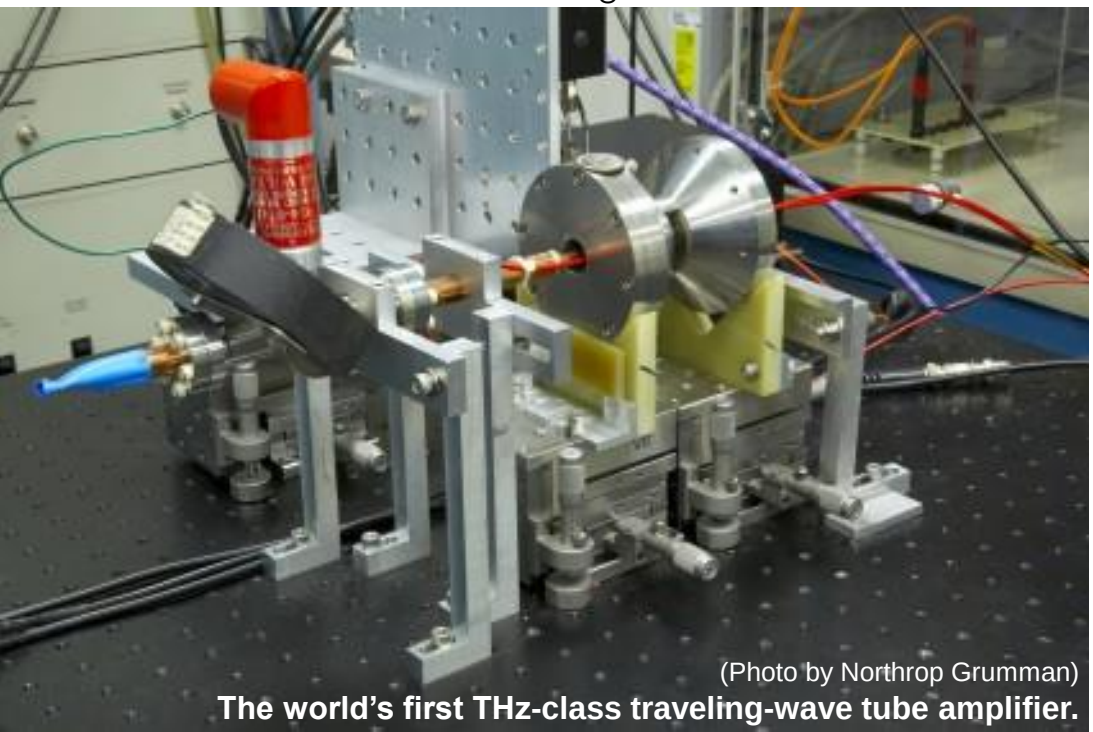


EEC Magnets for Defense Applications

EEC High Temperature Magnets are used for the Nuclear Aircraft Carrier and Submarine.

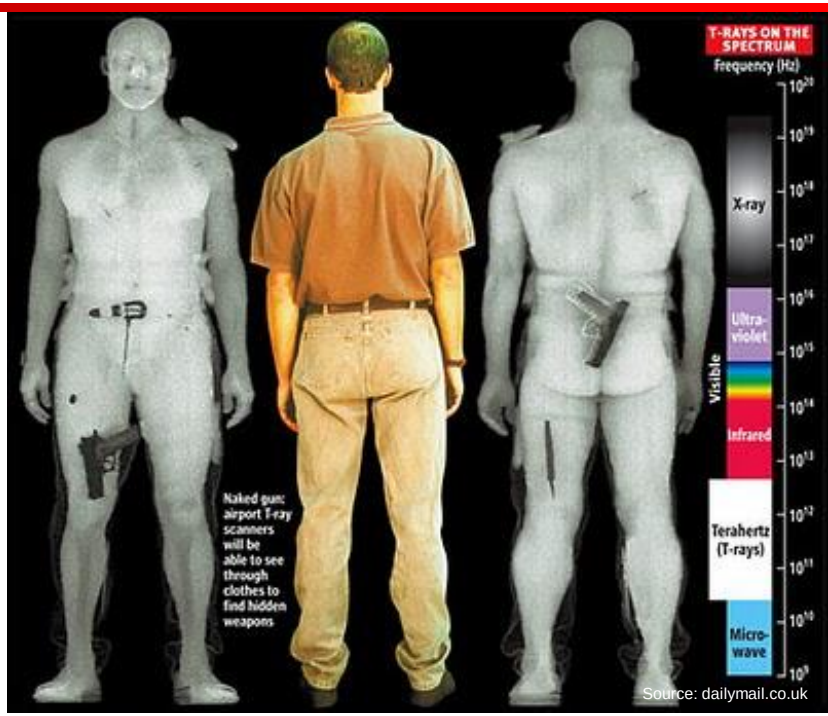
THz Wave Technology

- THz waves are found between microwaves and infrared on the electromagnetic spectrum. This type of radiation was chosen for security devices because it can penetrate matter such as clothing, wood, paper and other porous material that's non-conducting..
- **Security** – Image resolution similar to that viewed with the human eye under visible light. Scanning detect explosives, plastic weapons and drugs from tens of meters away.
- **Health** - T-ray is a lot safer than an X-ray because its radiation is non-ionizing.
- **Communication** – Having a much higher frequency than microwaves, there is huge potential for them to be used to create wireless networks exceeding 100 GBs/s.



(Photo by Northrop Grumman)

The world's first THz-class traveling-wave tube amplifier.



Mars Rover Curiosity

The $2.5 billion robotic explorer, landed on the Red Planet Aug. 6, 2012.

EEC Magnets are used in gyro systems for Curiosity Rover on Mars.

Length: 10 feet (3 meters)
Width: 9 feet (2.7 meters)
Height: 7 feet (2.2 meters)
Mass: 1,982 pounds (899 kilograms)

[Photo courtesy of NASA]

NASA Mars mission

The Curiosity rover is designed to travel Mars studying climate and geology. The rover is looking for signs of carbon, the building blocks of life. Some of the rover's features:

Robotic arm
Used to examine and manipulate soil and rocks; it also has two scientific instruments, one uses X-rays to determine materials' composition and the other is a magnifying camera

Laser
Burns small holes in rocks and soil up to 23 feet away and identifies chemical elements

Color cameras
Stereo mastcams on either side of the rover's mast take color pictures and movies in 3-D

UHF antenna
Primary transmission antenna

Plutonium power source
A nuclear battery that converts heat into electricity

Neutron detector
Detects water in rocks and soil

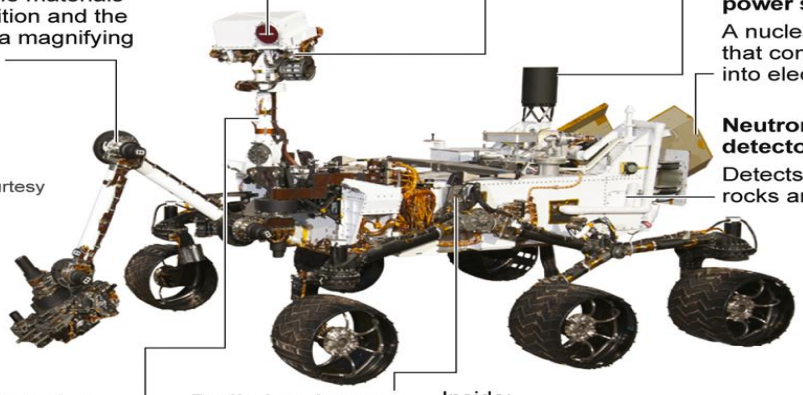


Photo courtesy of NASA

Weather station
Records wind speed/ direction, air pressure, humidity, temperature and UV radiation

Radiation detector
Measures radiation from the sun, supernovae and other sources

Inside:

Chemistry lab
Analyzes rock and soil samples for organics

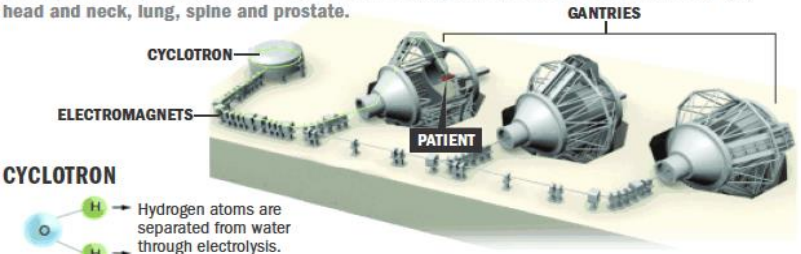
Mineral detector
Shines an X-ray beam at a rock or soil sample to identify types of minerals

SOURCE: NASA AP

Proton Therapy Technology

Treating cancer with protons

Proton therapy is a kind of radiation used to kill cancer cells and stop them from growing. Doctors can better aim proton beams onto a tumor, so there is less damage to the surrounding healthy tissue. This allows doctors to use a higher dose of radiation with proton therapy than they can use with X-rays. Proton therapy can treat cancers of the brain, eye, head and neck, lung, spine and prostate.



CYCLOTRON

Hydrogen atoms are separated from water through electrolysis.

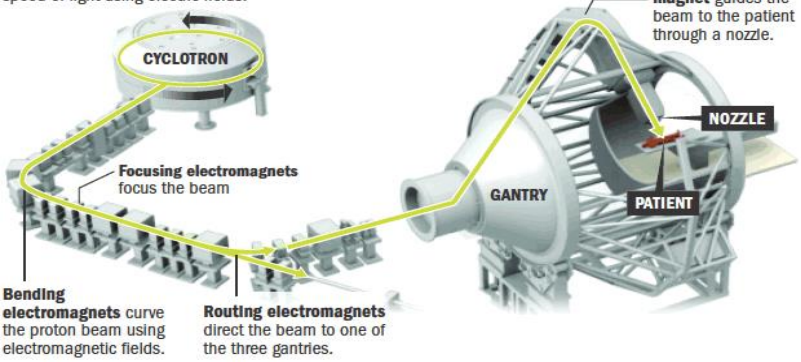
The positively charged **protons** are extracted from the hydrogen atoms and injected into the **cyclotron**.

Within fractions of a second, the **cyclotron** accelerates the **protons** to two-thirds the speed of light using electric fields.

GANTRY

Each of the three gantries is three stories tall and weighs 200,000 pounds. It can rotate 360 degrees around the patient and position the nozzle in the correct angle to the tumor.

A 21,000-pound **magnet** guides the beam to the patient through a nozzle.

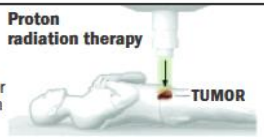


NOZZLE

Brass aperture
The aperture is cut to the outline of the tumor to prevent the radiation from damaging the surrounding tissue.

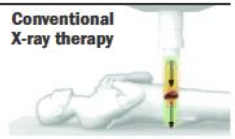
Lucite compensator
Various depths are cut out of Lucite to squeeze the beam to the shape of the tumor.

Proton radiation therapy



By adjusting the speed of the protons, a physician can control how deeply they will penetrate into the body. The protons then release their energy at the tumor and cause less damage to the surrounding tissue.

Conventional X-ray therapy



Because conventional radiation doesn't release its energy at a specified depth, it can damage the tissue surrounding the tumor as it travels through the body.

Sources: *The New York Times*, University of Florida Proton Therapy Institute, National Institutes of Health

THE NEW YORK TIMES | DISPATCH

Quadrupole Magnet for Proton Therapy

Proton radiosurgery is a specialized form of proton therapy characterized by the precise delivery a high dose of radiation in a single treatment session to a small target such as a brain tumor metastasis. Recent research has suggested that **magnetic focusing** of the proton beam immediately upstream of the patient could be used to reduce this particle scattering leading to **improved dose distributions, dose rate and more efficient dose delivery.**

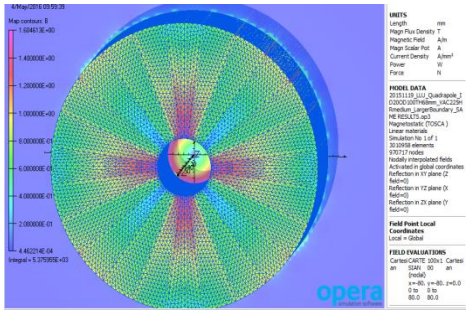


Fig 4. FEA Magnetic field distribution (**field gradient 150 T/m**, 1.5T at pole)

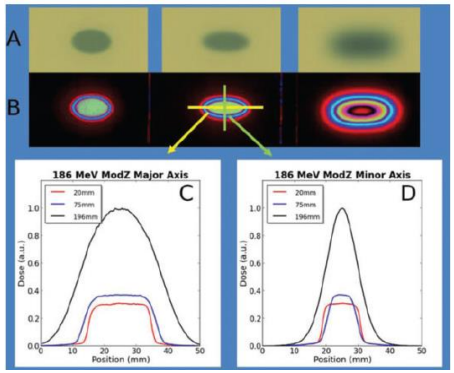


Fig 6. Beam spot **symmetry of 186 MeV focused proton beam** revealed in EBT2 film (A & B) and diode detector (C & D) data is indicative of quality quadrupole fields.

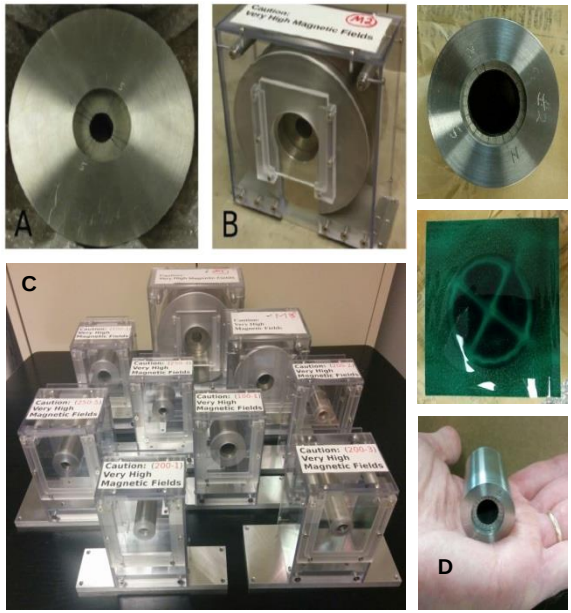


Fig 5. Focusing magnets consist of 24 segments of Sm_2Co_{17} material adhered into Halbach cylinders and encased in nonmagnetic stainless steel and placed in Lexan safety/mounting cases.

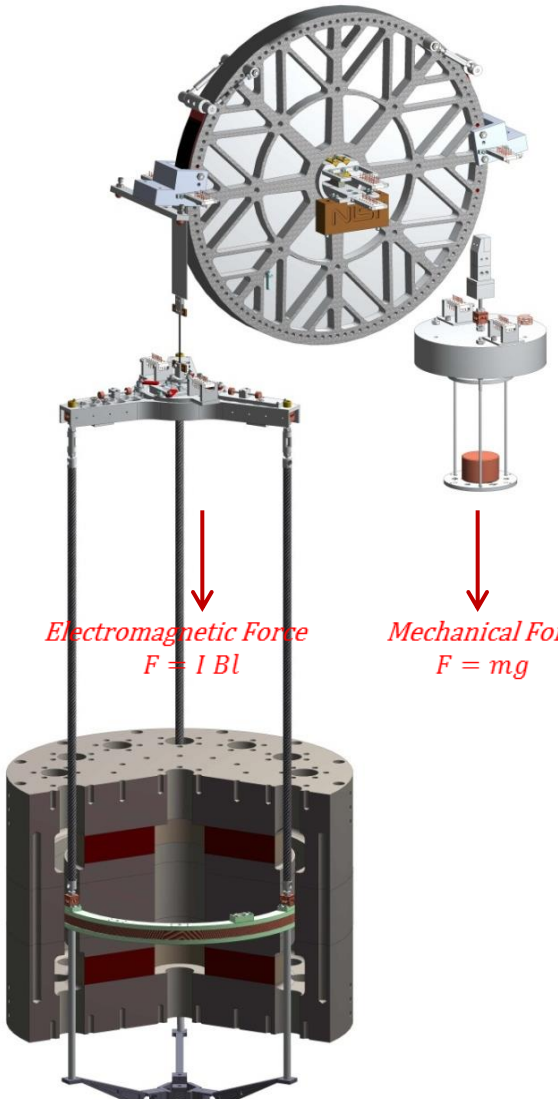
[H. Choi, L. Haley, J. Liu, G. McAuley, and A. Wroe, '**Design and Development of Permanent Magnet Based Quadrupole for Proton Radiosurgery Applications**', *Proceedings of the 24th International Workshop on Rare Earth and Future Permanent Magnets and Their Applications (REPM 2016)*, August 28–September 1, 2016, Darmstadt, German.]

Replacing EM with PM

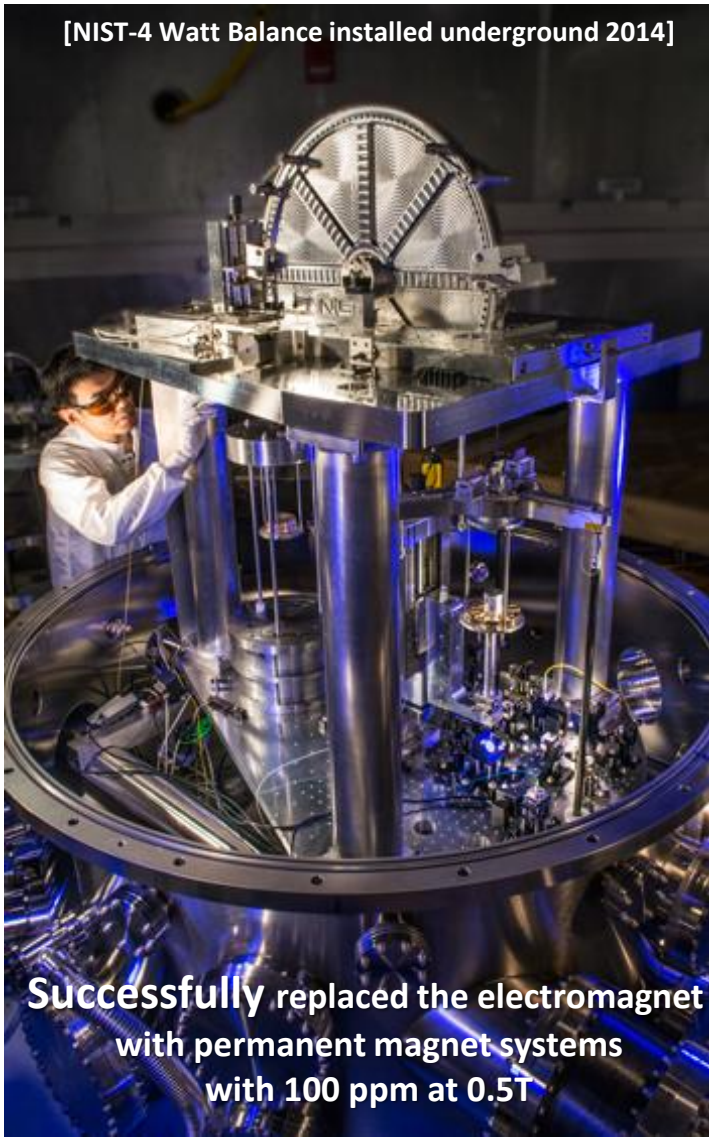
Watt Balance is an electromechanical weight measuring instrument to define a kilogram mass by comparing electrical power to mechanical power.


[NIST-3 Superconducting Magnet]

[NIST-4 Permanent Magnet]



[Graphic courtesy of NIST]


[NIST-4 Watt Balance installed underground 2014]

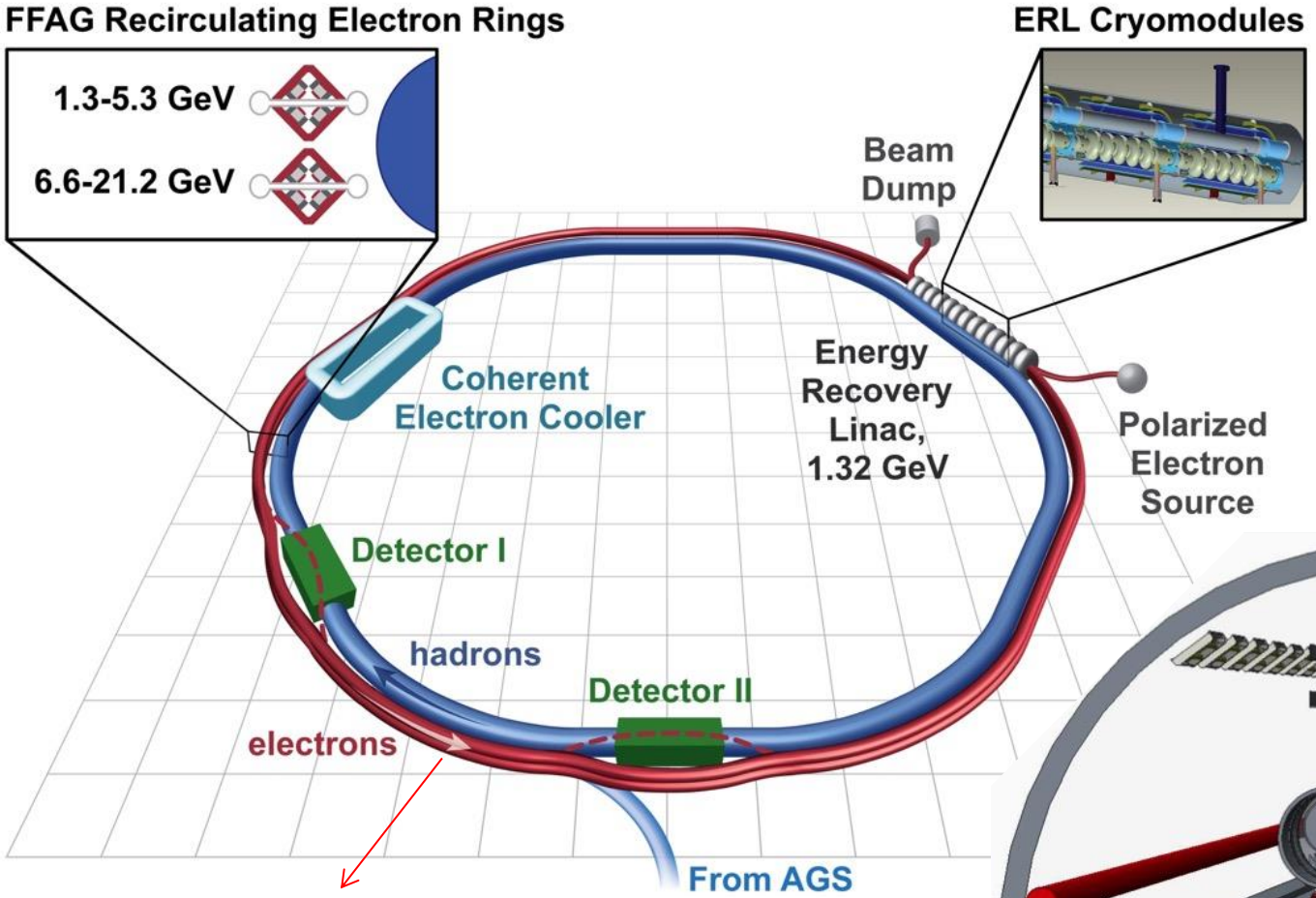
Successfully replaced the electromagnet with permanent magnet systems with 100 ppm at 0.5T

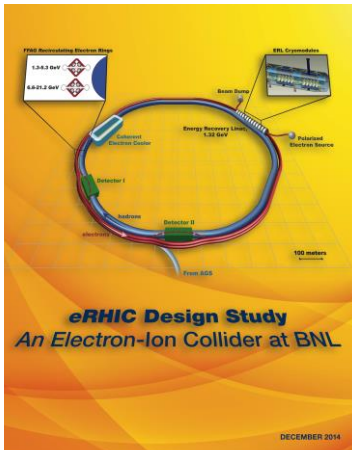
2. Project Description

Kick-off meeting at BNL in April 2016

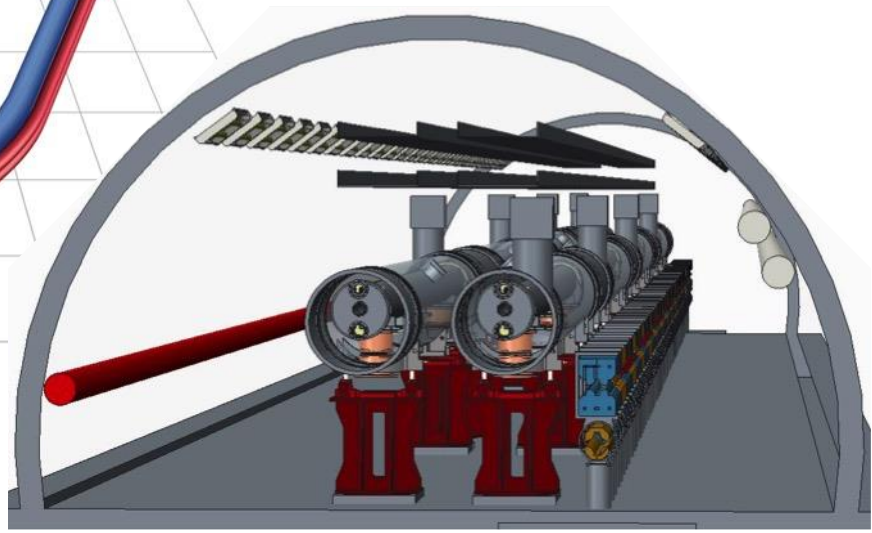
BNL eRHIC Configuration

Layout of highly advanced and energy efficient eRHIC collider





[Source: BNL]



- ✓ The magnetic structure of two vertically stacked recirculating beamlines is based on permanent magnets.
- ✓ Main idea of FFAG lattice approach and PM technology is to lower machine construction and operation cost.

Magnet Development for Future EIC

What Goals?

1. Manufacture prototype magnet using a permanent magnetic material.
2. Projects of interest:
   - eRHIC Electron Ion Collider in the present RHIC tunnel (~4500 magnets).
   - Proton cancer therapy for medical treatment.

Why Permanent Magnets?

1. No Power consumption results in significant construction, operation and maintenance cost reduction.
2. Occupy small volume as compared to the electromagnets or the same area of useful magnetic field.

What Objectives?

1. Conduct design, construction, and testing of a tunable focusing quadrupole magnet prototype with high performance at low cost.
2. Achieve specifications (Field gradients 34.42 T/m, Field gradient error ≤ 0.1%, Good field region R13.4+2mm, Length 1.010 m for BD & 1.187 m for QF)

3. Achievements

Progress Update as of Aug 7, 2017

Task 1: Magnet Design Finalization – Phase II Year 1 Q1~ Q2

1.1. Finalize design modification with open mid-plane and pole-alignment adjusting mechanism (***Complete***).
1.2. Verify the magnetic field performance (***Complete***).
1.3. Optimize the mechanical structure and make mechanical drawings (***Complete***).
1.4. Set the details of pole measurement and field testing procedure (***Complete***).

Task 2: 1st Magnet Prototyping – Phase II Year 1 Q3 ~ Year 2 Q1

2.1. Order the parts of magnet, laminates, Ni-Fe alloy, and retention fixtures (***Complete***).
2.2. Fabricate assembly base and fixtures (***Target Date 8/21/2017)***.
2.3. Make subassemblies and assemble 0.3-m long magnet. (***Target Date 12/18/2017)***

Task 3: 1st Magnet Measurement and Testing – Phase II Year 2 Q1 Future Work

3.1. Check mechanical alignment using FARO laser tracker (***Target Date 12/22/2017)***.
3.2. Measure magnetic field gradient using a customized 2D probe on XYZ station (***Target Date 1/15/2018)***.
3.3. Conduct magnetic field correction and magnetic alignment (***Target Date 1/29/2018)***.
3.4. Check the repeatability test (***Target Date 2/19/2018)***.

Task 4: 2nd Magnet Fine Tuning and Production – Phase II Year 2 Q1~Q3 Future Work

4.1. Fine tuning the first prototype design if necessary.
4.2. Produce a 1-m long, full length 2nd magnet assembly.

Task 5: 2nd Magnet Field Testing and Delivery – Phase II Year 2 Q4 Future Work

5.1. Verify magnetic field performance and make final adjustment.
5.2. Deliver to BNL for beam performance evaluation.

Final Design Configuration

Company Proprietary

Magnetic Circuit Design

3D Nonlinear FEA Field Contour Map for 1-m Long Magnet Assembly

Company Proprietary

Field Harmonics

3D FEA Field Harmonics Results for 1-m Long Magnet Assembly

Company Proprietary

Mechanical Stress Analysis

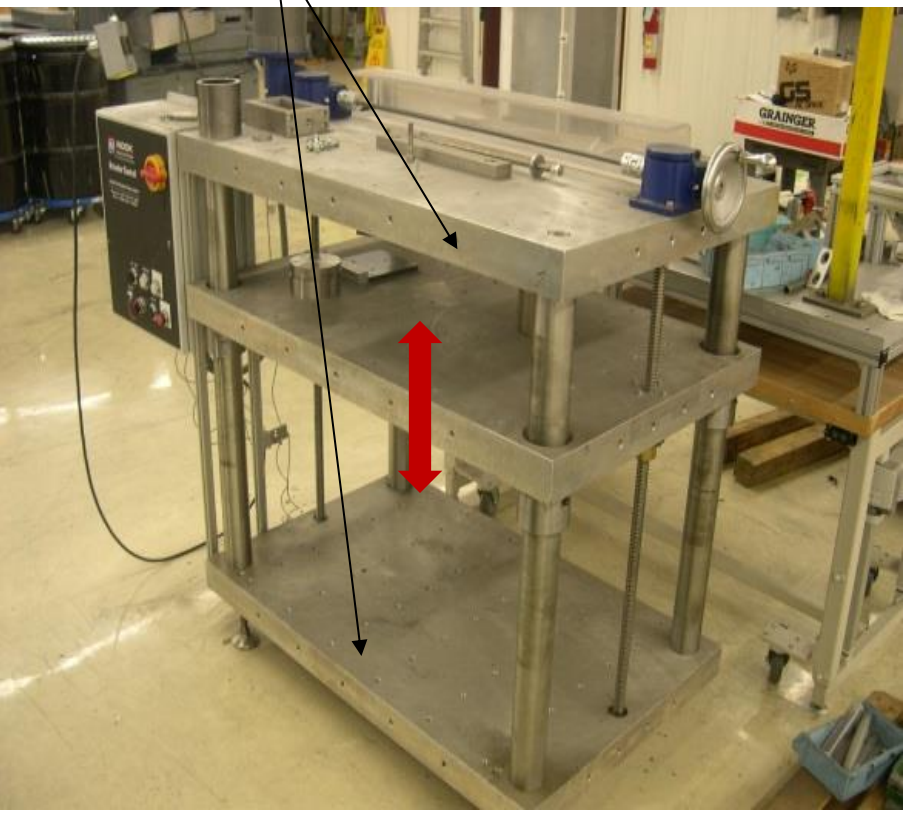
Mechanical Stress Analysis for 1-m Long Magnet Assembly

Company Proprietary

Magnet Assembly Plan

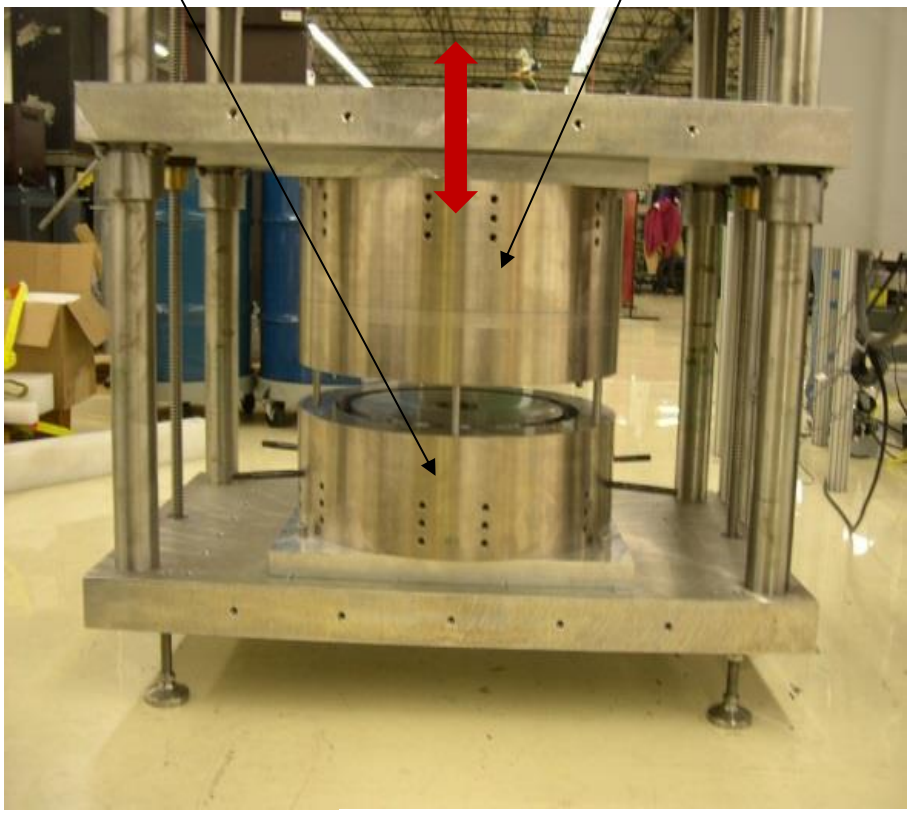
Quadrupole Magnet Assembly using Die-Set

Top and bottom plate are fixed



Stainless steel housing to be fixed to stationary end plate

Modules to be attached to center plate and positioned one at a time

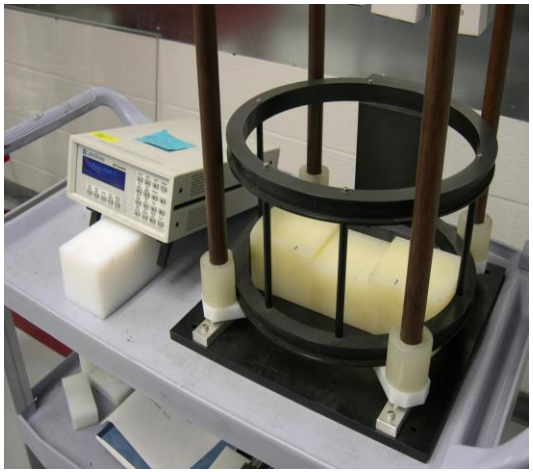


[Reference: NIST Watt Balance Assembly in 2013]

Magnet Test Plan

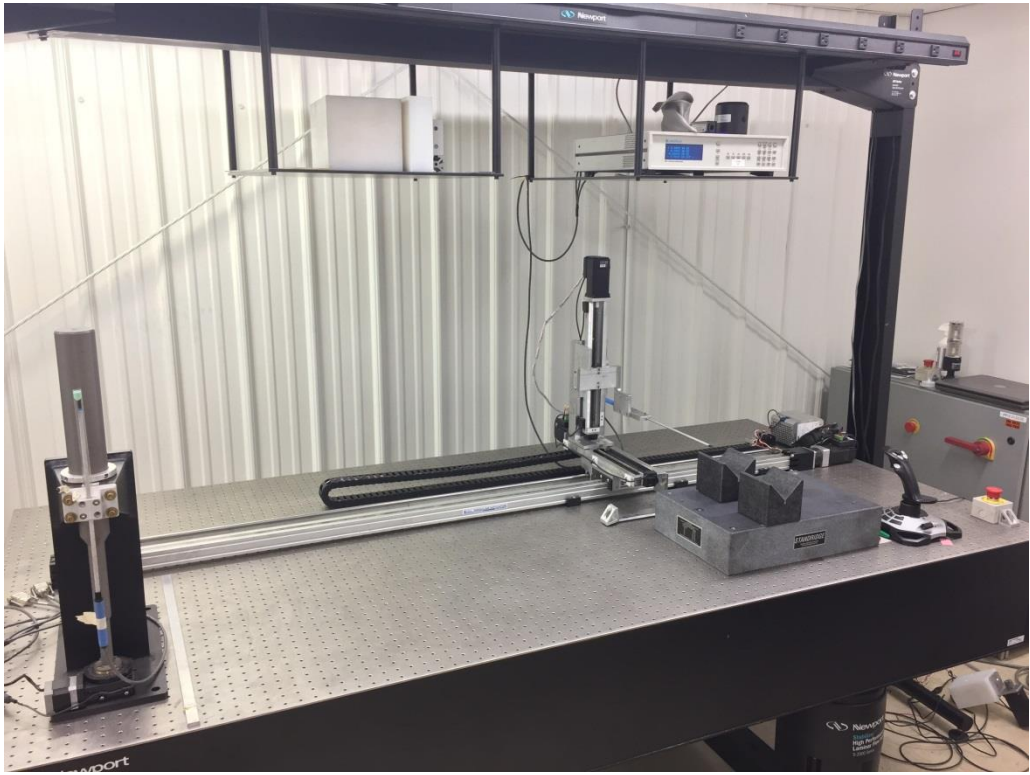
Magnetic Field Uniformity Test

Magnet Uniformity Test



- Can be measured using Helmholtz Coil
- Magnetic flux variation < 1%
- Magnetization angle < 3-5º
- Flux through surface perpendicular to pole piece

Modular Sub-assembly Uniformity Test



- 3D field mapping around pole tip
- Precision XYZ station with 3D hall probe mounted

4. Schedule & Deliverables

Task	Milestone Description	%of time	Year 1				Year 2			
1	HER magnet design finalization	10								
2	HER 1st magnet prototyping	30								
3	HER 1st magnet testing	15								
4	HER 2nd magnet fine tuning and production	30								
5	HER 2nd magnet testing and delivery	10								
6	Report	5								

Deliverables

1. **300-mm long, modular quadrupole magnet –** Qty 1, Target Date: 2/19/18.
2. **1-m long full length, modular quadrupole magnet –** Qty 1, Target Date: 11/20/18.