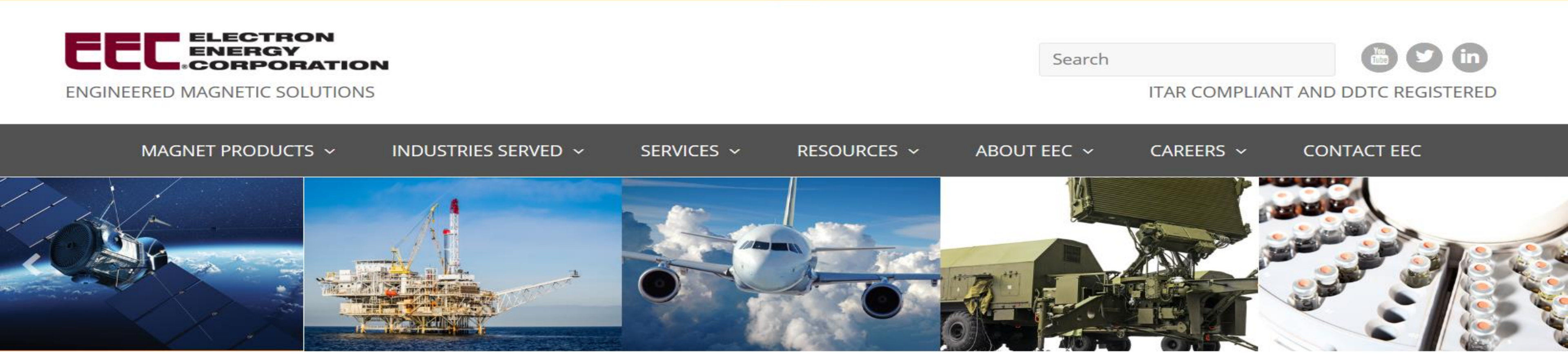
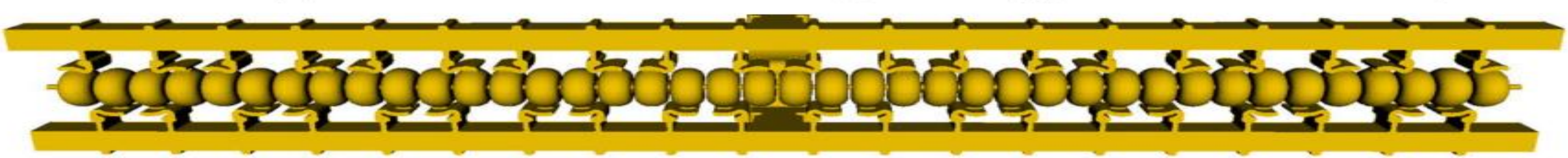


PERMANENT MAGNET TECHNOLOGY FOR KLYSTRONS AND BEAMLINE MAGNETS

August 31, 2023

Heeju Choi, Ph.D.
Electron Energy Corporation
924 Links Avenue, Landisville, PA 17538, USA
www.electronenergy.com

Cold Copper Accelerator Technology and Applications Workshop



Cornell University, August 31 – September 1, 2023

Outline

1. **EEC Introduction**
2. **Rare Earth Magnets**
3. **Beam Focusing Magnets**
    1) Traveling Wave Tube
    2) Klystron
    3) Accelerator
    4) Tunable Quadrupole
    5) Phase Shifter
4. **PM Replacing EM Examples**


Headquarter
ELECTRON ENERGY CORPORATION


Post-sintering Operations

EEC Introduction

EEC electron energy corporation 50 since 1970

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

EEC received 25th SBIRs & STTRs awards since 1996 from NASA, DOE, NSF, EPA, and DOD

(Rapid growth of business)

1960's — 1970 — 1972 — Mid 70's — 1985 — 2000 — 2002 — 2011 — 2012 — 2014 — 2015 — 2020

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

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

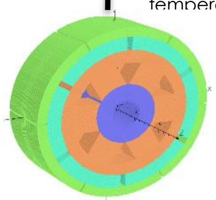
Developed Temperature Compensated SmCo that have near-zero change in magnetic field over temperature changes

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

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

EEC invests in additional equipment to meet increasing demand

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



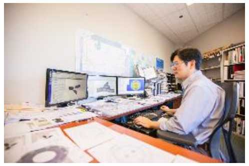
Magnetic design service

New plant layout to optimize floorplan and Equipment

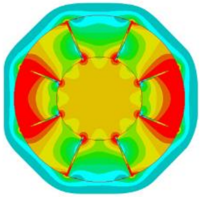
Products & Services

Full Service Provider of Engineered Products

Engineering Services

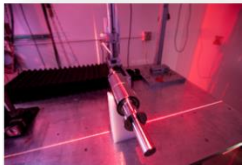


Research & Development



FEA modeling

Applications engineering



Prototyping

Developing solutions with customers

Permanent Magnet Materials

Samarium Cobalt

Neodymium Iron Boron

Alnico

Dielectric materials

Rapid in-house material customization

Assemblies

Rotors

Magnetic couplers

Sensors

Separators

Scalable operations

EEC's Core Business

Customer's trust EEC's magnetic experts with their "Mission Critical Solutions"

AEROSPACE & DEFENSE

- ***Missiles***
- ***Satellites***

IMPLANTIBLE MEDICAL DEVICES

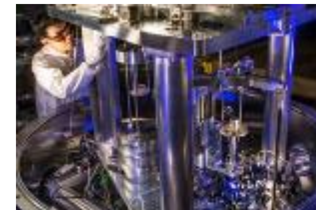
- ***Heart pumps***
- ***Surgical tools***

NUCLEAR

- ***Control Rods***
- ***Motion control***

MEDICAL EQUIPMENT

- ***Motors***
- ***Sensors***



SPECIALTY

- ***Watt Balance***
- ***Beam focusing***

Markets & Customers

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Communication	Raytheon	L3 communications	TELEDYNE TECHNOLOGIES Everywhereyoulook™	CPI Communications & Power Industries	
Motion & Sensor	MOOG	SL-MTI	WINDINGS Employee Owned	KOLLMORGEN	EATON
Defense	BWXT BWX Technologies, Inc.	LOCKHEED MARTIN	THALES	NORTHROP GRUMMAN	
Medical	stryker®	ABIOMED®	Abbott	BD	
Aerospace	BOEING	SPACEX	NASA	इसरो isro Indian Space Research Organization	esa European Space Agency
Instrumentation	Schlumberger	AMETEK®	HALLIBURTON	BLUE ORIGIN	

EEC MOTORSOLVER

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ROTOR CAPABILITIES

Combined 50+30 years of experienced producing precision rotors for a variety of markets and applications

- Balanced rotors for high speed motors
- Large rotor assemblies
- Carbon retention sleeved rotors
- Metallic sleeved rotors

IPM Rotors
(Interior Permanent Magnet)

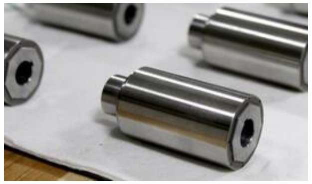
SPM Rotors
(Surface Permanent Magnet)

Magnet Production

Shaft Machining

Sleeve Machining

Carbon retention sleeves

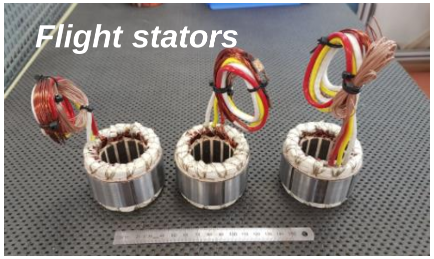


Balancing & Final Assembly

STATOR CAPABILITIES

Supplier of various stators prototypes, designs, and alpha-beta prototyping and testing.

- Distributed windings
- Concentrated windings
- Slotless windings
- Segmented stator windings
- Custom windings



Flight stators

Marine stator

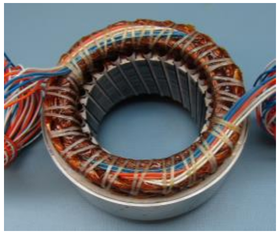
Lamination stacks

Bonded core assembly

Coil winding

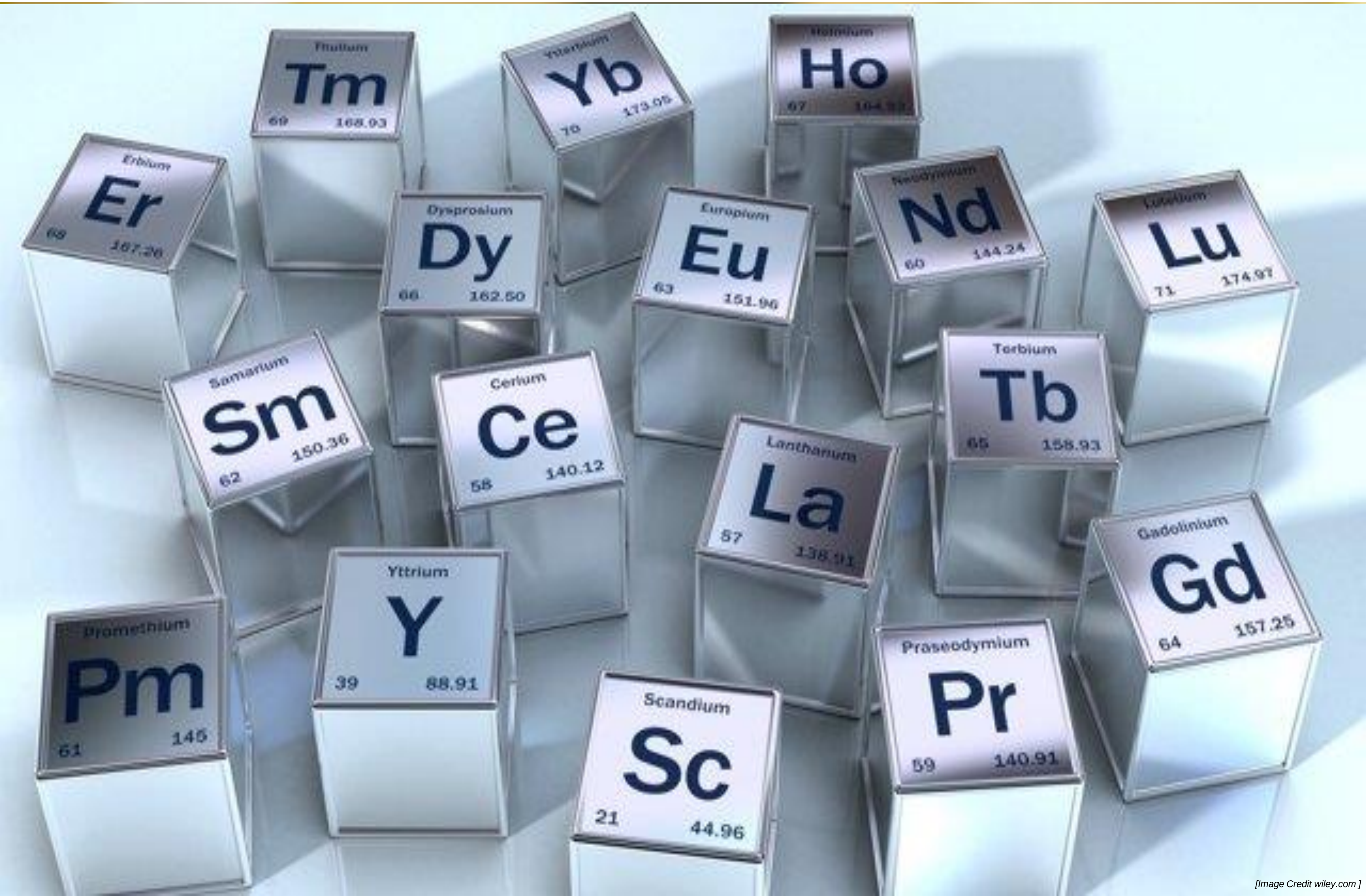
Slot liners

Installing coils



Final assembly
(lacing, impregnation, & testing)

Rare Earth Magnets

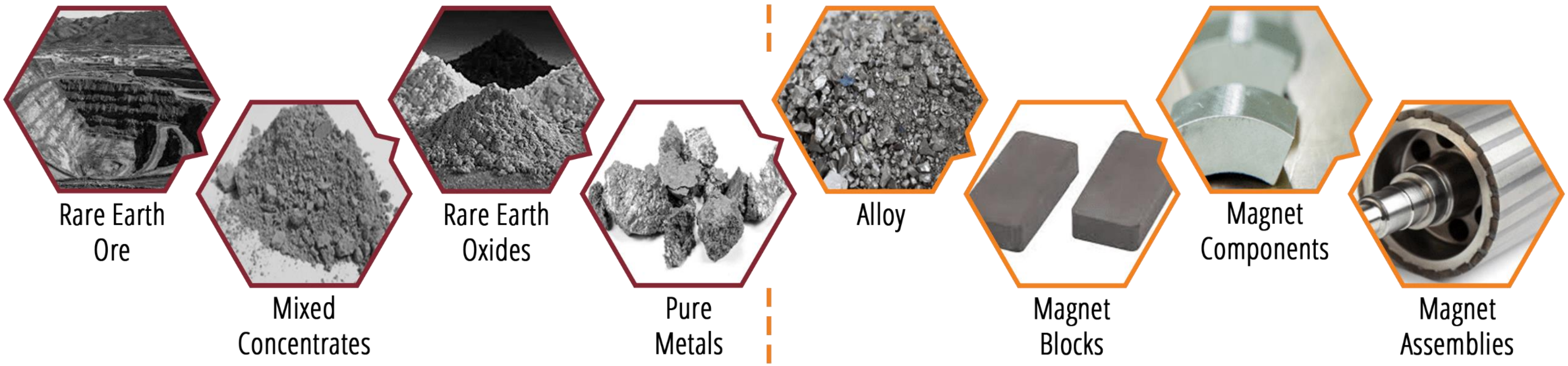


[Image Credit wiley.com]

Rare Earth Magnet Supply Chain Steps

electron energy corporation

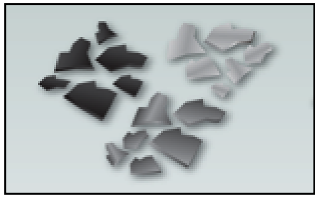
EEC's magnet alloys, blocks, and components **produced** in the United States



DFARS Regulations Apply

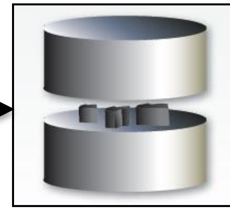
DDTC REGISTERED · DFARS COMPLIANT · ITAR COMPLIANT · NIST 800-171 COMPLIANT

Typical Sintered Sm-Co Magnet Production

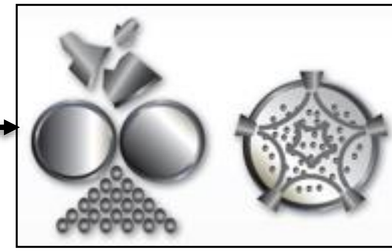


Raw Material
EEC purchases pure raw materials-Sm,Co,Fe,Cu,&Zr for the in-house production of SmCo 1:5 & 2:17 alloys

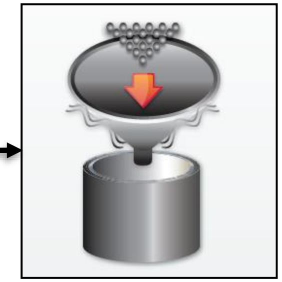
Induction Melting
Pure metals are alloyed in an inert gas using an induction melting furnace. Precise control of alloy chemistry allows EEC to produce a wide range of materials to meet your demanding requirements.



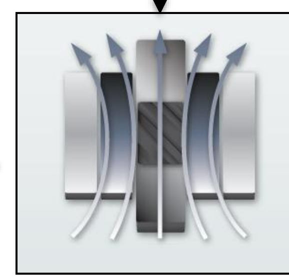
Crushing
Using a crushing process, rare earth alloys (inter-metallic compounds) are reduced in particle size to ≈ 250 microns



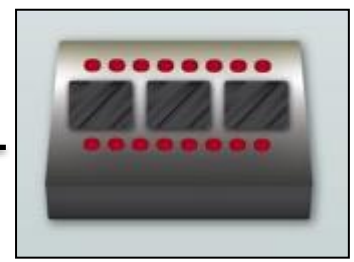
Ball or Jet Milling
We process crushed alloy by milling and reducing to a particle size of ≈ 3 microns. Because the resulting fine powder is chemically reactive and pyrophoric in nature, it requires protection from air (oxygen) using inert gas.



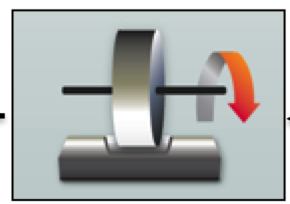
Blending
Our ability to precisely control material compositions during the blending operation helps us achieve specific magnetic properties.



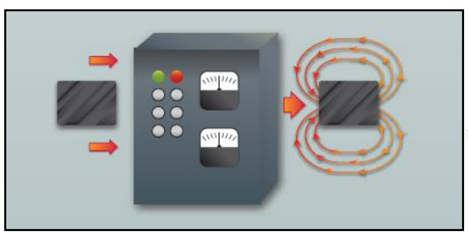
Axial, Transverse & Isostatic Pressing
Axial pressing force is parallel to alignment created by magnetic field. Transverse pressing force is perpendicular to magnetic alignment field. Isostatic pressing provides equal pressure from all directions for pre-aligned powder.



Sinter
Densification and the development of magnetic properties are accomplished through sinter, solution and aging processes in the presence of a vacuum or an inert gas.

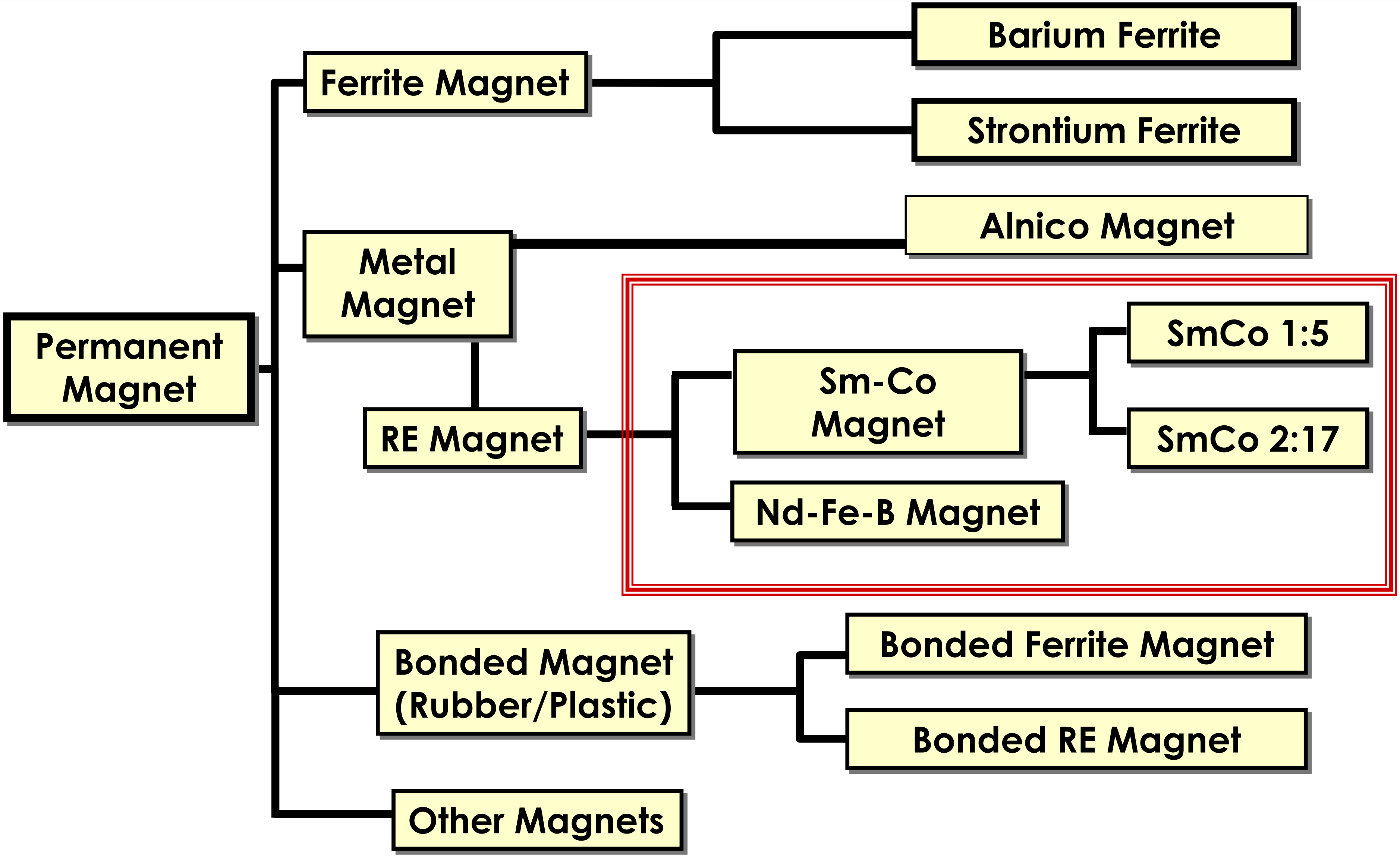


Machining
Sintered rare earth magnets, because of their brittle nature, are machined to final dimensions using grinding, slicing, or wire EDM technology.

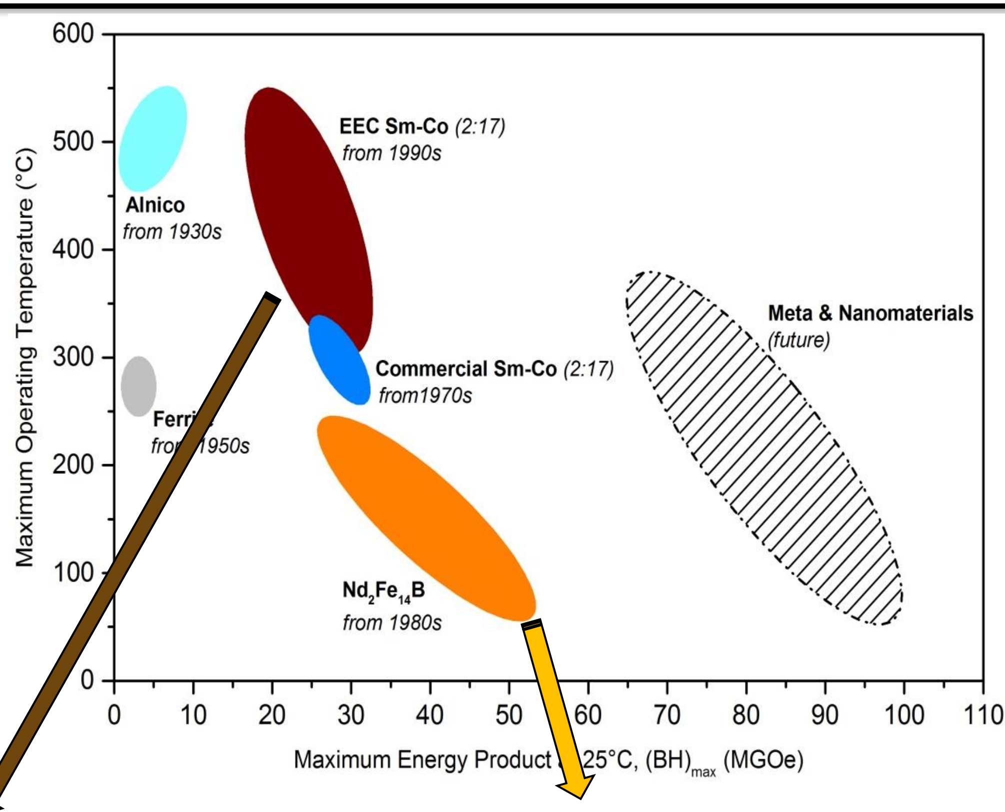


Magnetizing, Testing, & Quality Assurance
Magnetization, stabilization and testing of rare earth magnets are done to satisfy your specific requirements.

Magnet Types



Magnets vs. Temperature



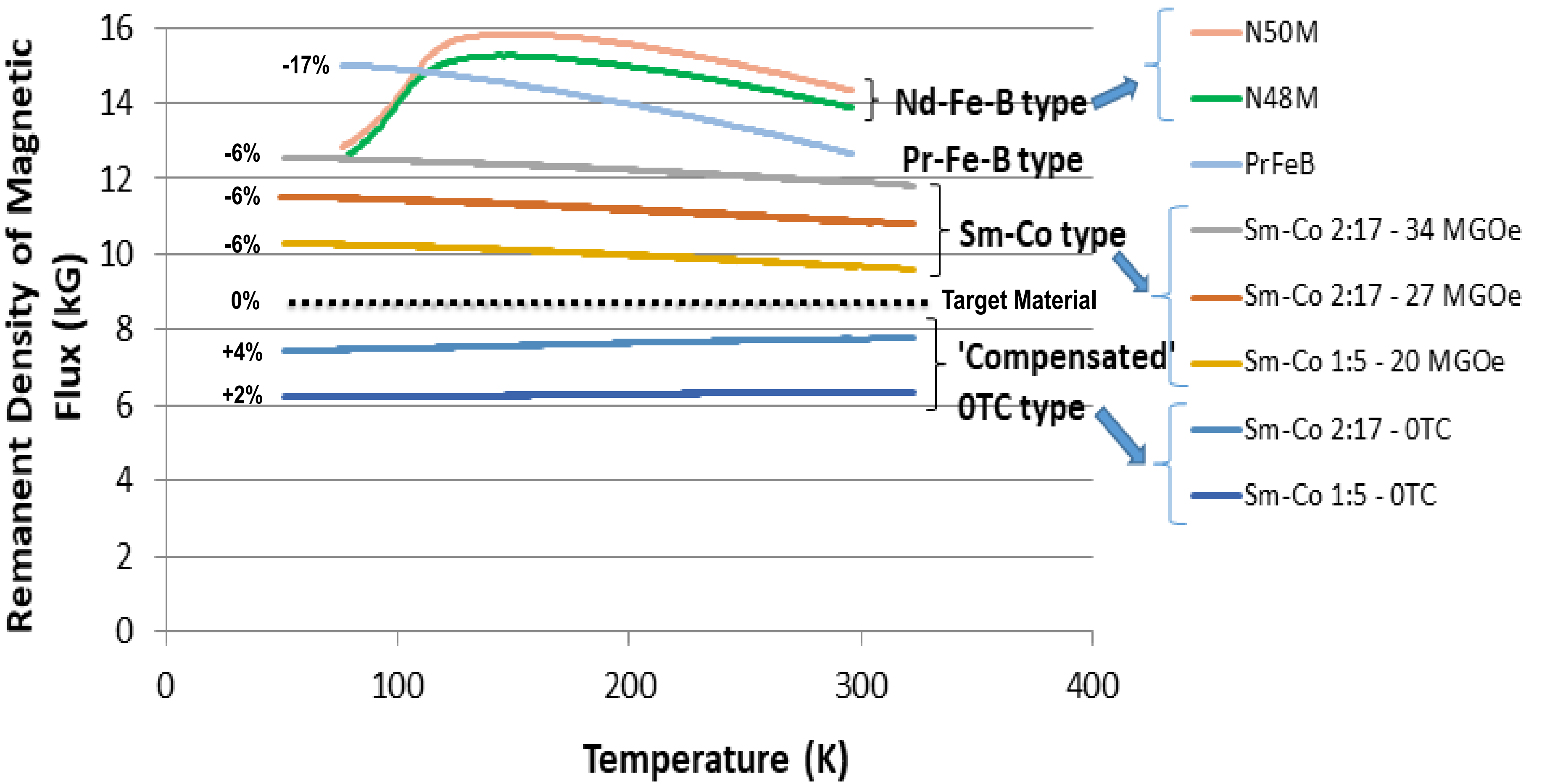
SmCo magnets

- Highest $(BH)_{max}$ available up to 33 MGOe
- Corrosion resistance is excellent; no surface coating required
- Maximum operating temperature: 550℃
- Superior thermal stability

Nd-Fe-B magnets

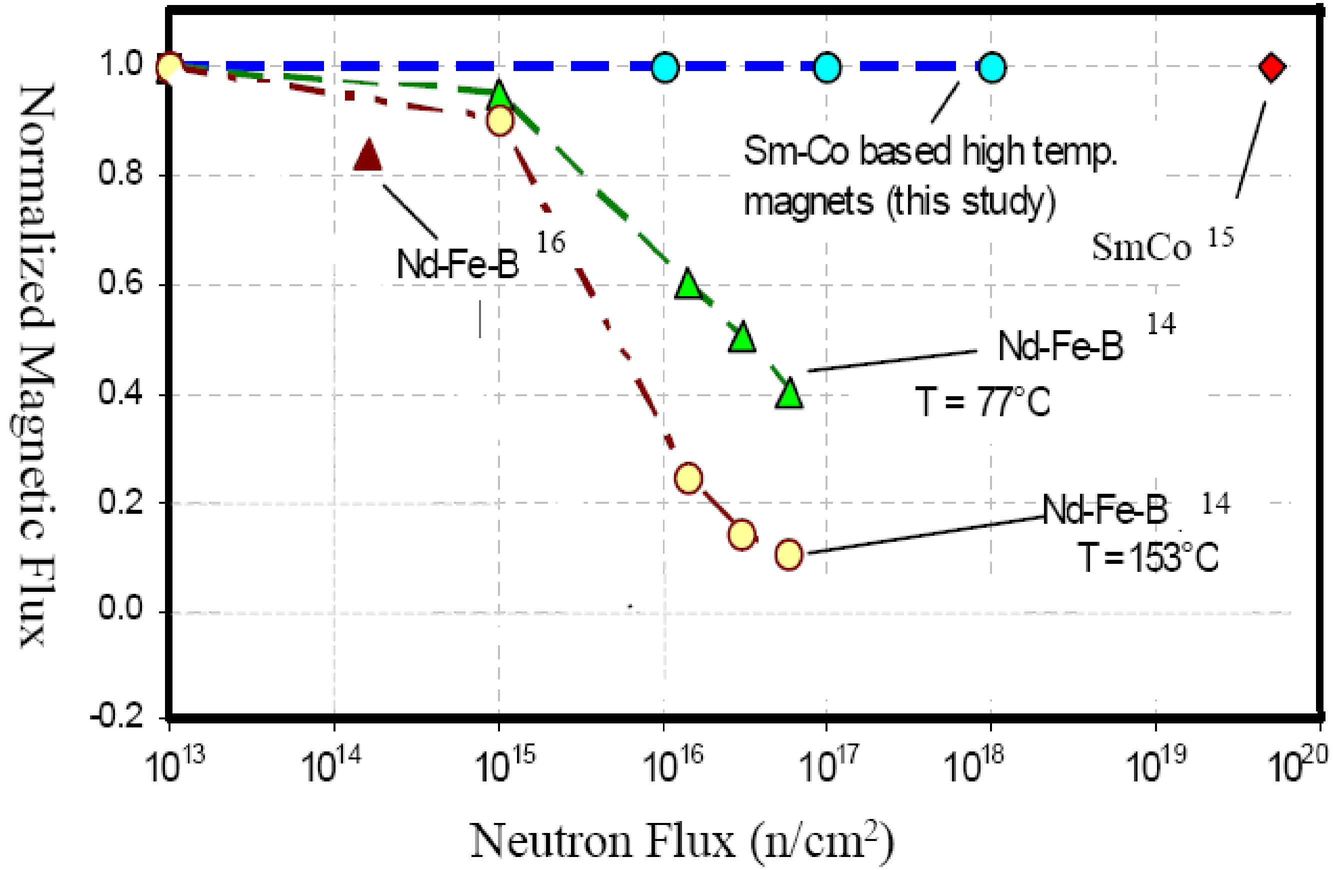
- Highest $(BH)_{max}$ available up to 52 MGOe
- Corrosion resistance is low; surface coating is needed.
- Maximum operating temperature, ~180°C for most grades, is relatively low compared to SmCo magnets (>300°C).

Magnets vs. Cryogenic Temperature



- **EEC Sm-Co reversible temperature coefficient (RTC) -0.035 vs. -0.11%/°C of Nd-Fe-B.**
- **EEC Sm-Co magnets are safe in liquid nitrogen** and don't require plating.
- Nd-Fe-B and Pr-Fe-B magnets provide the higher flux strength than Sm-Co magnets, however, they would require electromagnets for precision control due to the flux variation vs. temperature.

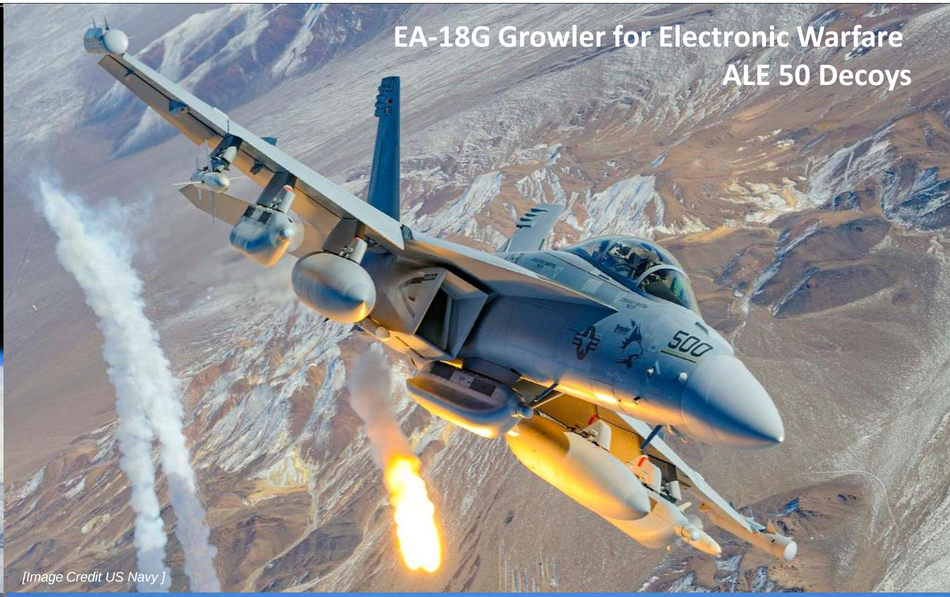
Magnets vs. Radiation



- The major radiation damage in magnet is caused by radiation-induced thermal spike accompanied by a localized temperature, especially when exceeding the curie temperature Tc of magnets.
- **Sm-Co's Tc is 750~825°C** depending on the grades. **Nd-Fe-B's Tc is 320°C**.
- **Sm-Co** exhibits significant demagnetization when irradiated with a **proton beam of 10^9 to 10^{10} rads**.
- **Nd-Fe-B** loses all of the magnetization at **10^6 to 10^7 rads.**
- Coating and pre-exposure to expected radiation levels to aid thermal stability is recommended.

[J. Liu, *et al.* 'Thermal Stability and Radiation Resistance of Sm-Co Based PMs', Proceedings of Space Nuclear Conference 2007. Bost, MA June 24~28, 2007]

Traveling Wave Tube Applications



What is Traveling Wave Tube?

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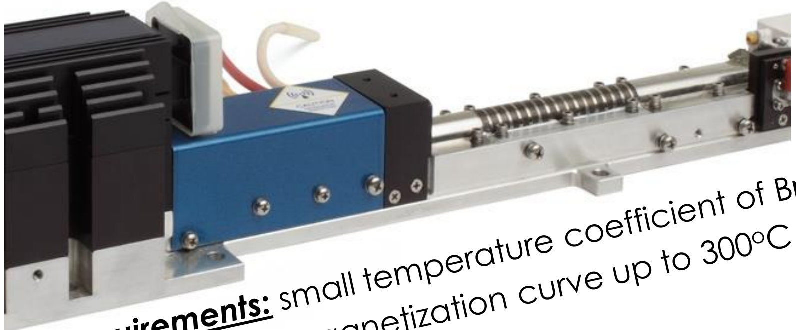
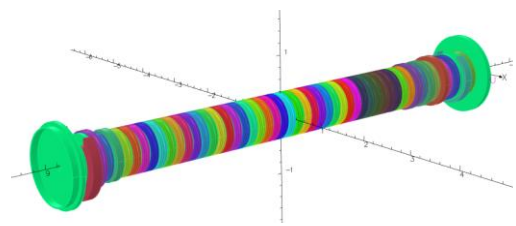
- Traveling wave tubes (TWTs) **amplify radio frequency waves** by converting electron beam energy into microwave energy.
- EEC magnets and assemblies are used in sophisticated, performance-critical components of advanced technology systems, such as traveling wave tubes (TWTs), klystrons, and magnetrons. These are all used to **amplify signals at microwave frequencies for high-performing radar, communications and electronic countermeasure systems**.

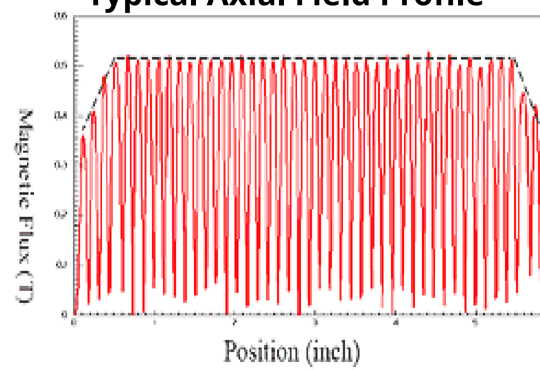


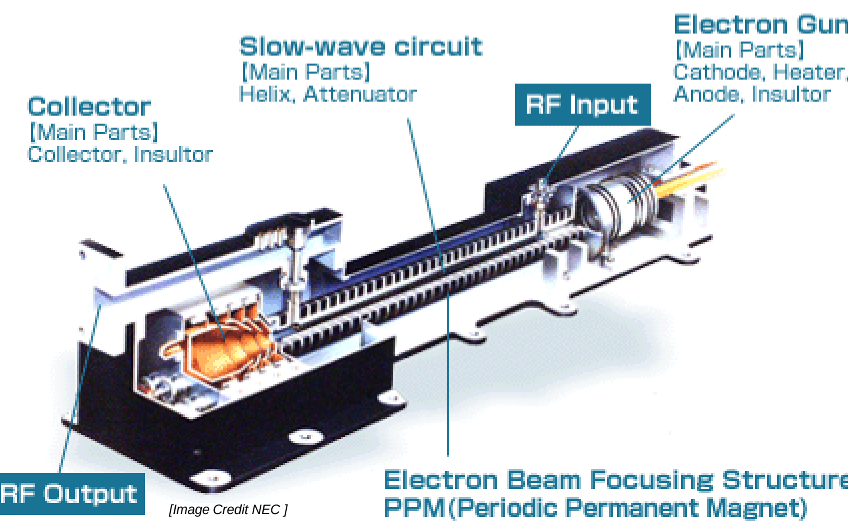
Requirements: small temperature coefficient of Br; straight-line demagnetization curve up to 300°C

FEA 3D Model



Typical Axial Field Profile

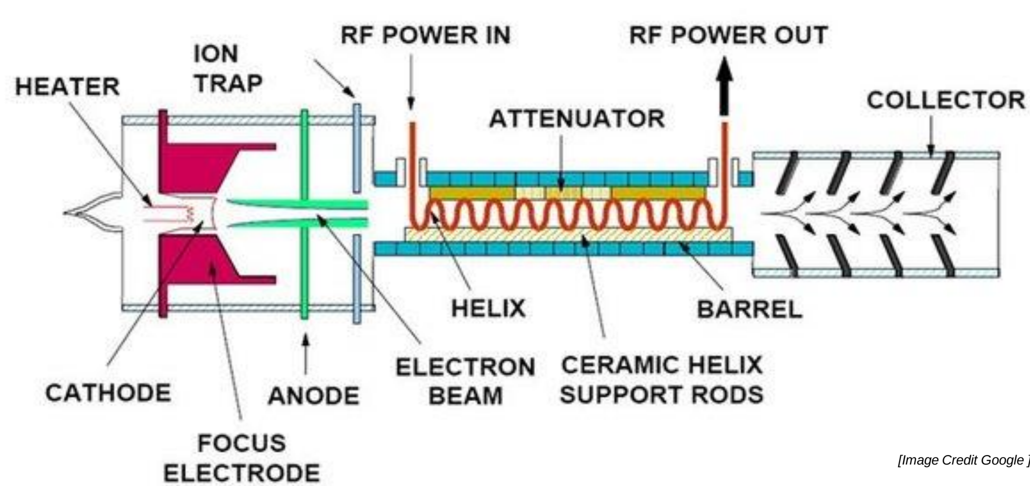




[Image Credit NEC]

PRINCIPAL COMPONENTS OF A HELIX TWT

Figure 3



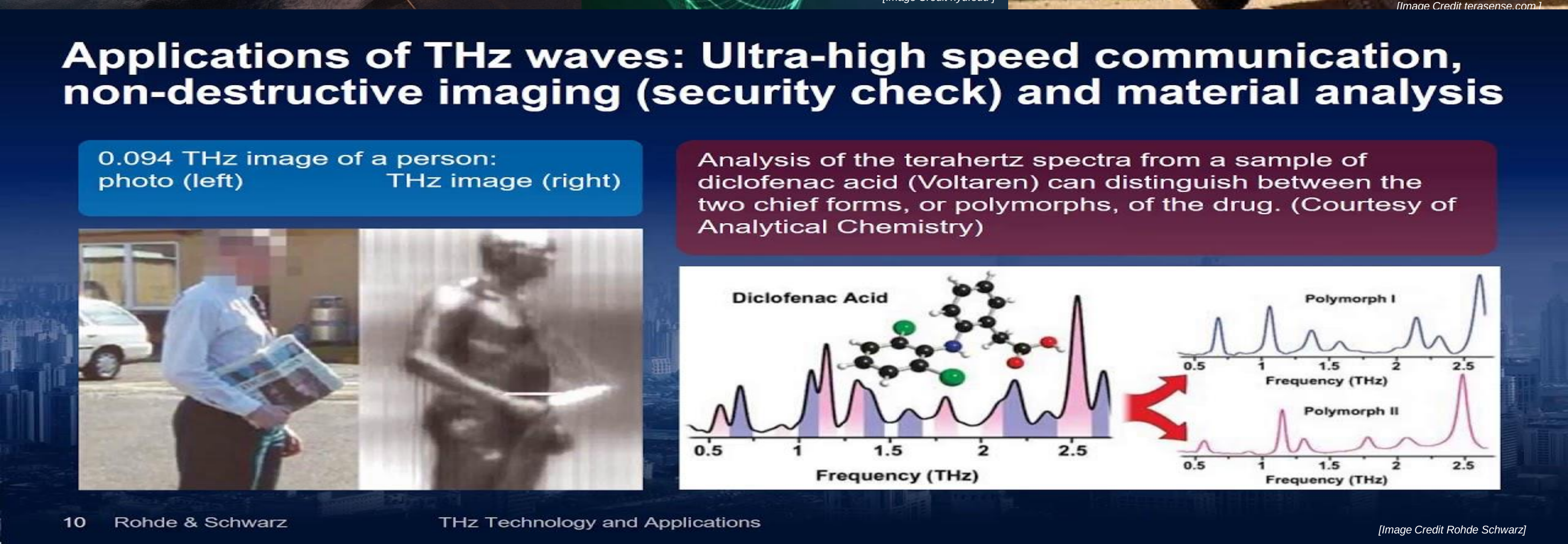
[Image Credit Google]

Klystron Applications

[Image Credit sofrep.com]

[Image Credit nyu.edu]

[Image Credit terasense.com]



[Image Credit Rohde Schwarz]

THz Wave Technology

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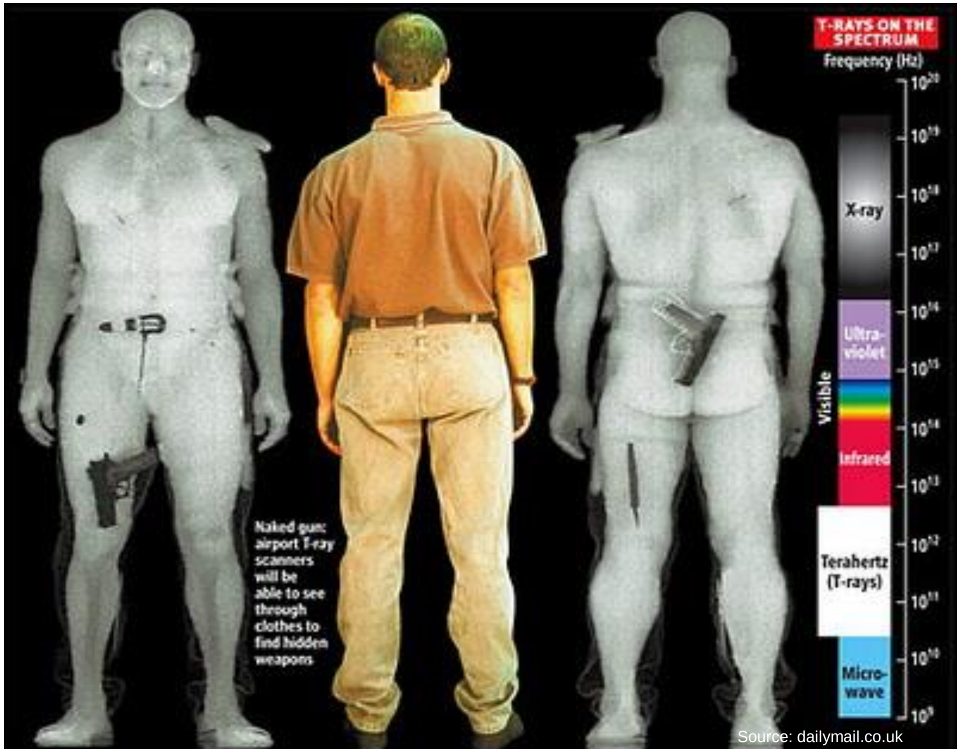
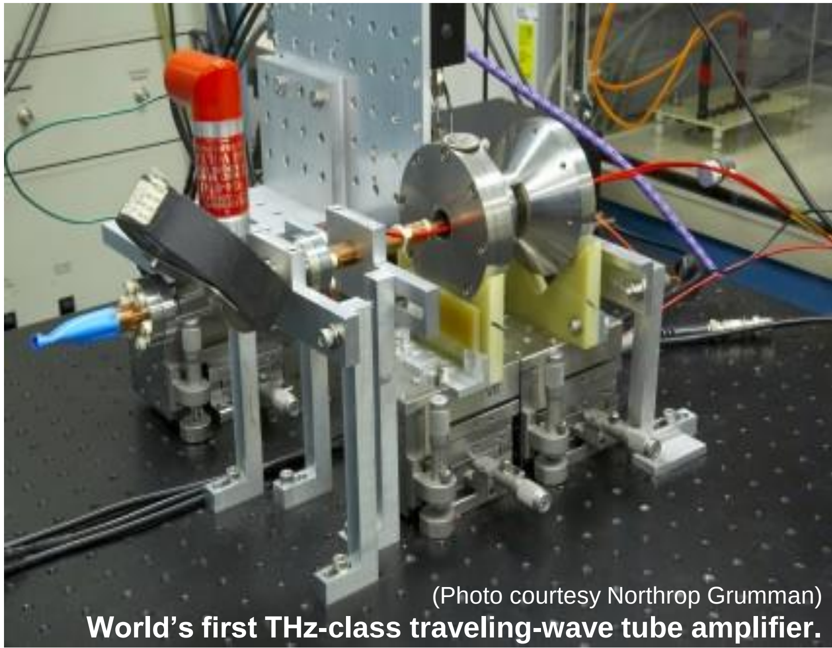
- **THz waves** are found between microwaves and infrared on the electromagnetic spectrum. This type of radiation can penetrate matter such as clothing, wood, paper, ceramic, and other porous material that's non-conducting..
- **Security** – Image resolution similar to that viewed with the human eye 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** – ultra-high speed 5G data delivery exceeding 100 GBs/s, i.e., 95GHz SBK technology is 150 times faster than the current 4G network we have today.



Source: dailymail.co.uk


DARPA VISAR program for AC-130 Gunship

DARPA Photo illustration


(Photo courtesy Northrop Grumman)

World's first THz-class traveling-wave tube amplifier.

Active Denial System

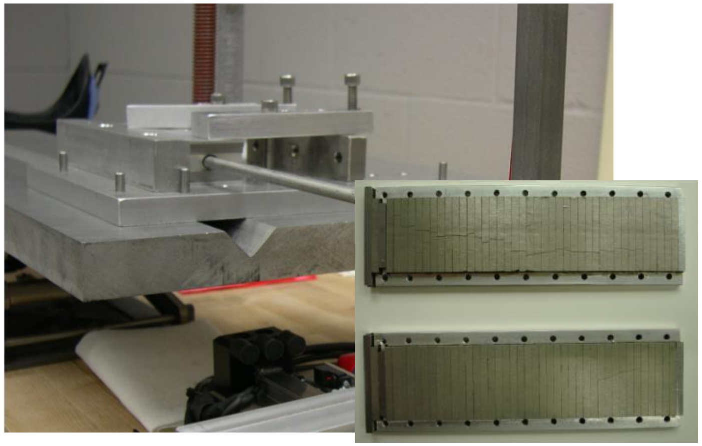
Non-lethal Weapon

ADS projects a focused millimeter wave energy beam which induces intolerable heating sensation on an adversary's skin (0.4mm deep) and cause that individual to be repelled without injury. The invisible '**pain ray**' can travel up to 500m (1,640ft).

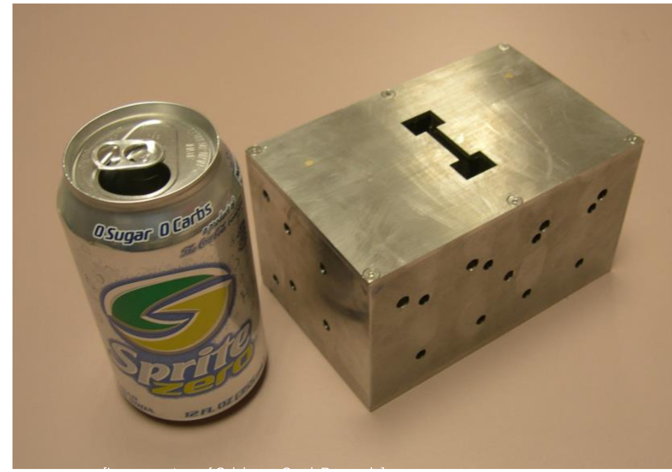
[https://www.youtube.com/watch?v=kzG4oButPbA&start=59]

Klystron Magnet Examples

95 GHz Klystron for Active Denial Systems



Calabazas Creek Research for THz TWT



94 GHz Klystron for 5G Communication

[Image courtesy of Teraphysics]

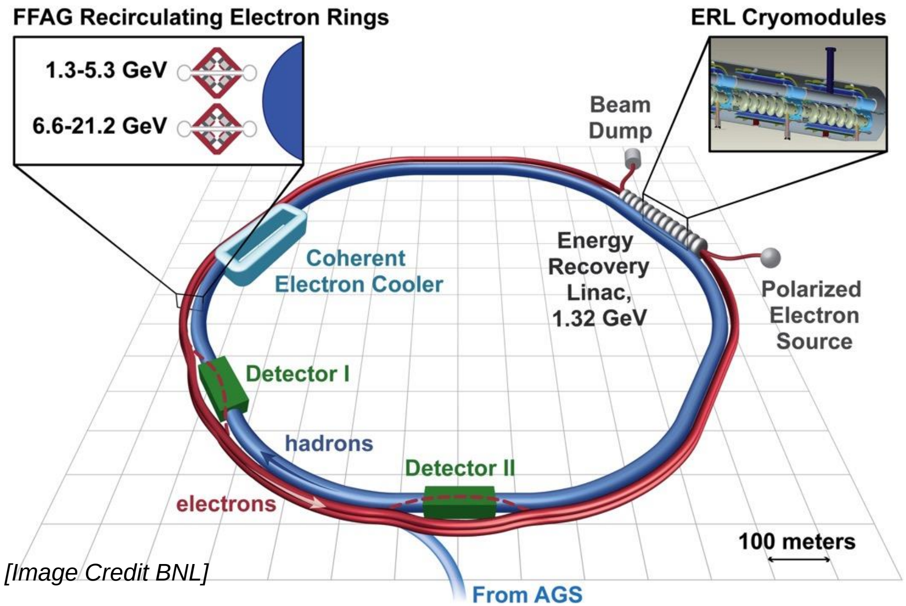
SLAC Klystron for Homeland Security

BNL Accelerator

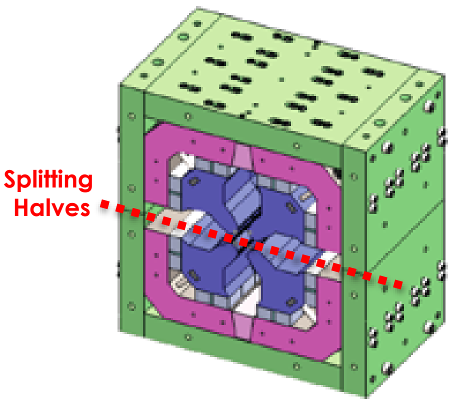
Kick-off meeting in April 2016 at BNL

Quadrupole Magnet for Collider

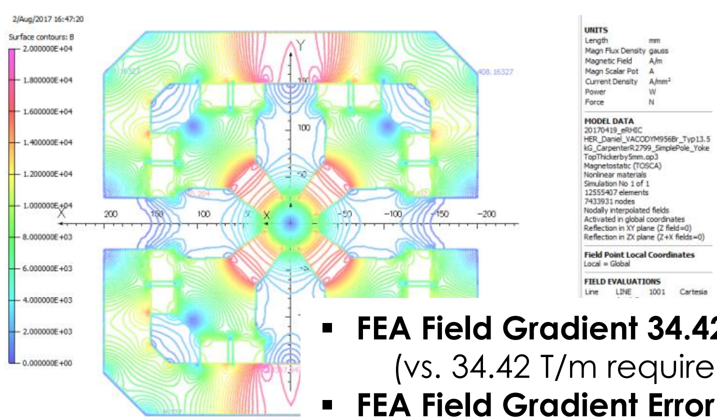
DOE Fast-Track Program (DE-SC0015230, 2/22/2016~3/21/2019)



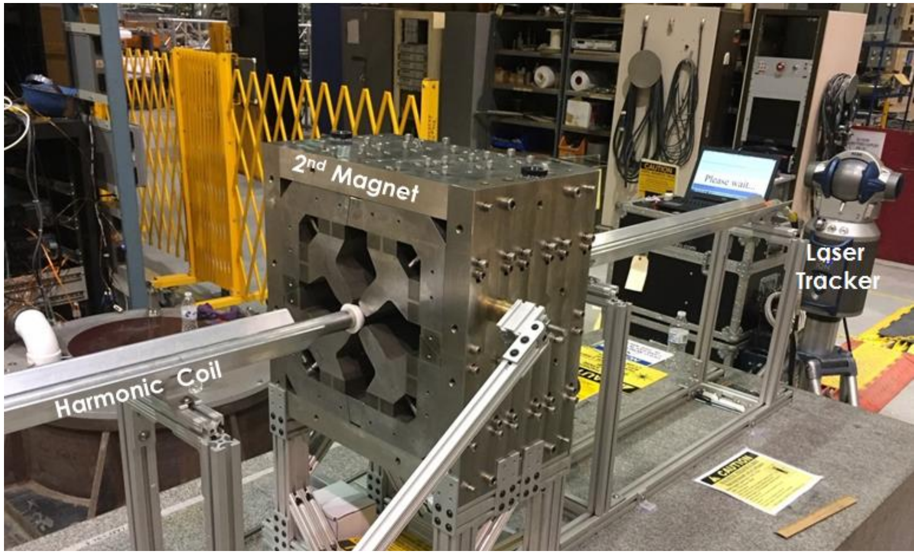
[Image Credit BNL]



- **Iron-dominant quadrupole** for future electron ion collider (BNL eRHIC)
- **Size: 500 x 514 x 300 mm** (19.7" x 20.2" x 11.8")
- **Weight: 470 kg** (1,040 lbs)
- Technical assistance from **Dr. Dejan Trbojevic** and **Dr. Peter Wanderer** at BNL



- **FEA Field Gradient 34.42 T/m** (vs. 34.42 T/m required)
- **FEA Field Gradient Error 0.02%** (vs. <0.1% required)



- **Field Harmonics are measured** using harmonics coil.
- EEC quadrupole magnets proved a unique adjusting mechanism to **improve the field harmonics**.

Test Results

Normal Harmonics		As-is Magnet	1st Magnet	2nd Magnet
Dipole	b1	-	-	-
Quadrupole	**b2**	**10,000**	**10,000**	**10,000**
Sextupole	**b3**	**-3.14**	**-0.74**	**-0.71**
Octupole	**b4**	**-5.61**	**-5.67**	**-3.45**
Decapole	b5	-0.48	-0.23	-0.27
Dodecapole	b6	7.46	7.77	-3.52
14-pole	b7	-0.10	-0.05	-0.04
16-pole	b8	-0.09	-0.09	-0.05
18-pole	b9	0.02	0.02	0

- ✓ Octupole component should be less than 1. Dodecapole & Dodecapole (b6) harmonics more than 1 are allowed.
- ✓ **Sextupole component comes from imbalanced poles (different amount of flux)** and should be less than 1 unit out of 10,000. Adjusting pole technique helped to reduce the Sextupole to 0.74 from 3.14.
- ✓ **Octupole component comes from very likely the geometrical non-symmetry of pole** and should be less than 1. Both adjusting and shunting methods didn't help to minimize the Octupole component.
- ✓ The tunable modular magnets proved the adjusting capability to improve the harmonics up to a certain point.
- ✓ Another finding is in reality it is hard to adjust mechanically due to the limit of laser tracker resolution .001" and tweak magnetically the field due to the limited harmonics data. The harmonics test doesn't tell where the strong/weak field position, which requires another field map test at each measurement.

Octupole Solution

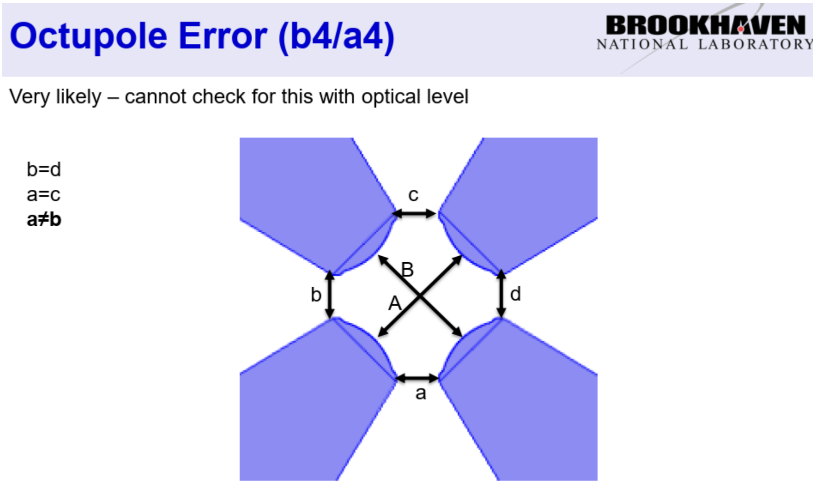
Challenge

Field Harmonics while Tuning

Solution

Shunt Rods + Ni-Fe Alloy Sleeve

0.5 mm in Diameter **Shunt Rod Effect** → **0.001998 unit** in Octupole Harmonics
1.2 mm Thickness Ni-Fe Sleeve Effect → 0.000014 unit in Octupole Harmonics



- ✓ In reality **the Perfect Symmetry is challenging** in terms of the magnetic and mechanical tolerance.
- ✓ **Sextupole error** from imbalanced poles (different amount of flux) & bad dipole → **Solution: Shunt.**
- ✓ **Octupole error** from imperfect geometrical symmetry → **Solution: Shunt**.
- ✓ The shunt is designed to tweak slightly the field, if needed, to reduce the undesired harmonics component.
- ✓ The shunt size and locations will be determined based on the field harmonics measurement.

Tuning Solutions

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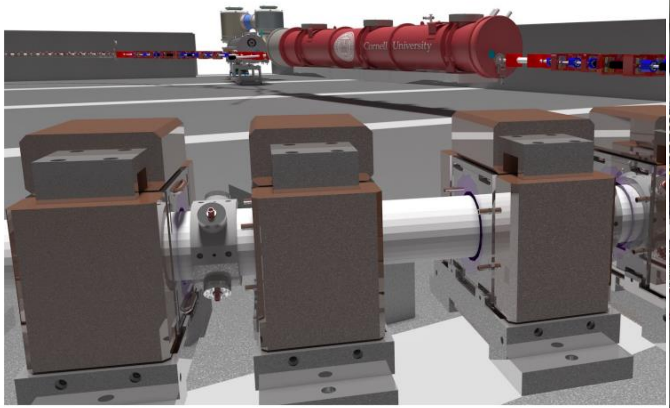
Challenge 1. Magnetic Adjusting Limitation

Solution 1. Corrector/shunting coils would help to improve the harmonics by adjusting the non-symmetric field. Like the permanent magnet based Halbach quadrupole magnets for CBETA, it would be possible to adjust magnetically the field harmonics using the corrector coils. Based on the FEA of our quadrupole magnet, the field tuning capability is 0.09% ($\Delta B/B \leq 9\text{x}10^{-4}$) with four outermost conductors and current density 2.06 A/mm^2 (25 AWG, 0.457A, 18 Turns, 4mm^2).

CBETA
CORNELL-BNL ERL TEST ACCELERATOR

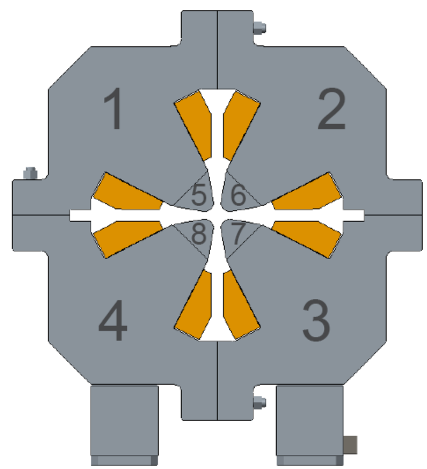


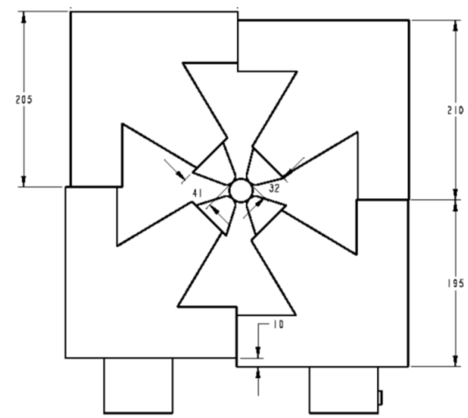
Christopher Mayes – September 9, 2017

Georg.Hoffstaetter@cornell.edu - September 8, 20

Challenge 2. Mechanical Adjusting Limitation

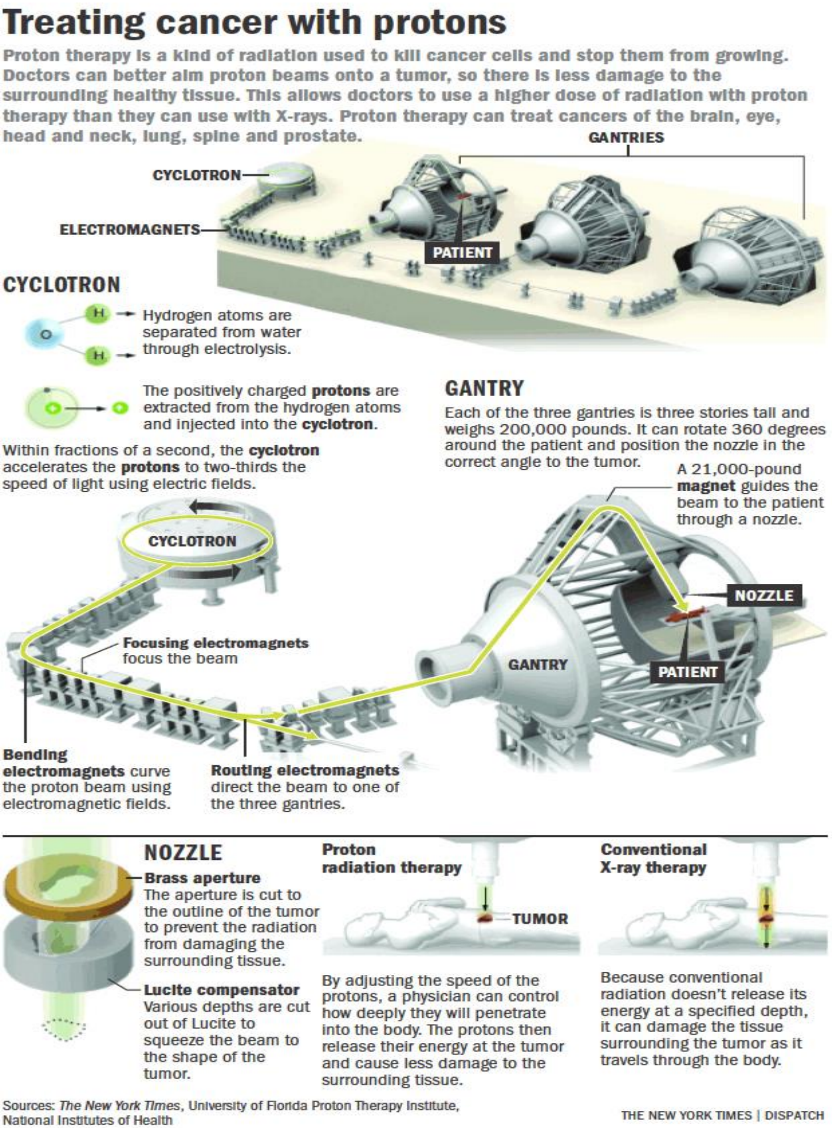
Solution 2. Mark Jaski's idea of 8-pieces quadrupole concept would enable not only to adjust easily the tips of each pole using crisscross dowel pins, but also provide a simple method for producing a quadrupole using standard machining techniques, which could result in a final tolerance accuracy of the resulting construct better than ours and improve the geometrical symmetry.





[Image Courtesy Mark Jaski, ANL]

Halbach Quadrupole Magnets for Proton Therapy



- EEC made **Halbach quadrupole magnets** are in use for magnetic focusing of the proton radiology at **Loma Linda University Medical Center**.
- **Since 2015**, more than a dozen quadrupole magnets demonstrates a required **field gradient ranging from 100 to 260 T/m** within a 10~20 mm bore.
- **24-segments Halbach** magnets produce high quality quadrupole fields suitable for proton radiosurgery.

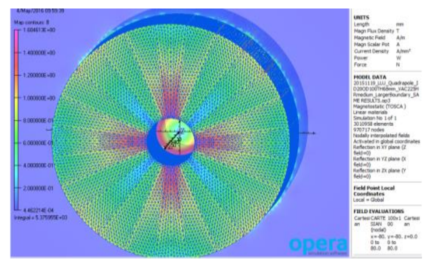


Fig 4. FEA Magnetic field distribution (**field gradient 150 T/m**, 1.5T at pole)

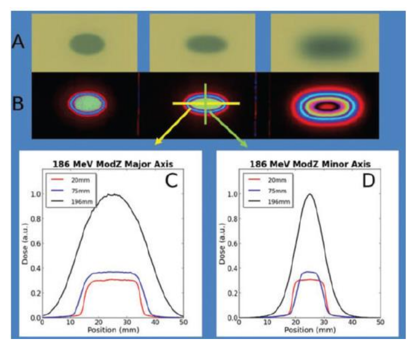


Fig 6. Beam spot symmetry of 186 MeV focused proton beam revealed in EBT2 film (A & B) and diode detector (C & D) data is indicative of quality quadrupole fields.

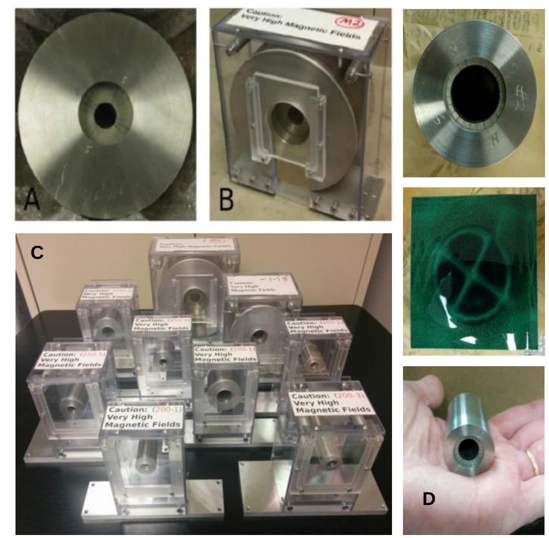


Fig 5. Focusing magnets consist of 24 segments of Sm_2Co_{17} material adhered into Halbach cylinders and encased in nonmagnetic stainless steel and placed in Lexan safety/mounting cases.

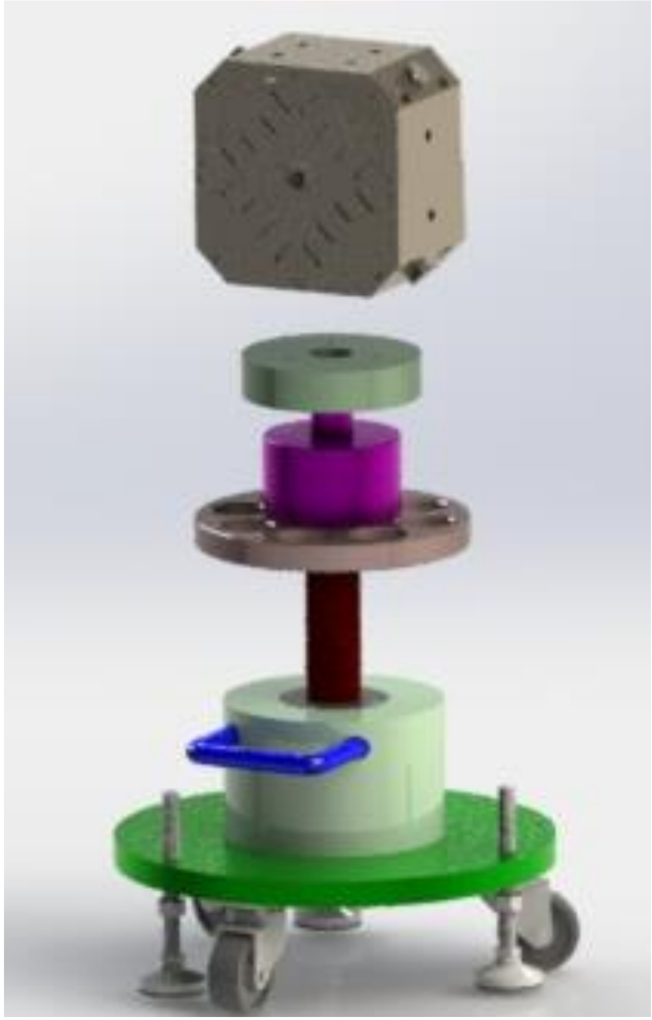
[H. Choi, L. Haley, J. Liu, G. McAuley, and A. Wroe, '**Design and Development of Permanent Magnet Based Quadrupole for Proton Radiosurgery Applications**', *Proceedings of the 24th International Workshop on Rare Earth and Future Permanent Magnets and Their Applications (REPM 2016)*, August 28~Setember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

Tunable Halbach Quadrupole

[Image Courtesy Emilio Nanni/SLAC]

Mechanical Design

Tunable Quadrupole Magnet with Splitter Stand



16-Segments Halbach Quadrupole
- EEC Sm_2-Co_{17} 31 material
- Magnet size ID 17 x OD 140 mm
- Magnet length 120 mm
- Shield OD ~240 mm

Innovation 1
- **Thermally compensated EEC Sm-Co magnets** minimize the field variation against the thermal drift (77~82 K).

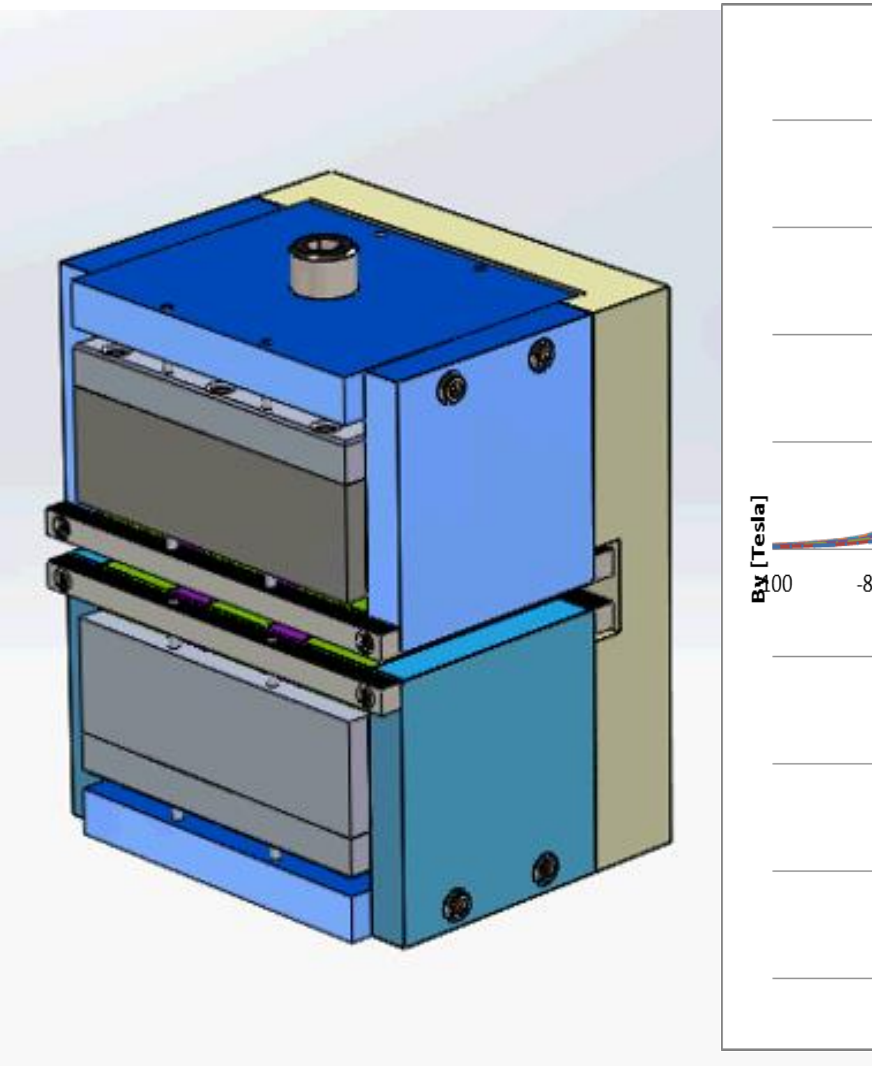
Innovation 2
- **Unique tuning approach** enables the magnets to provide the minimum field gradient while maintaining the required field harmonics.
- Field adjustability up to 44% from 202~114 T/m.

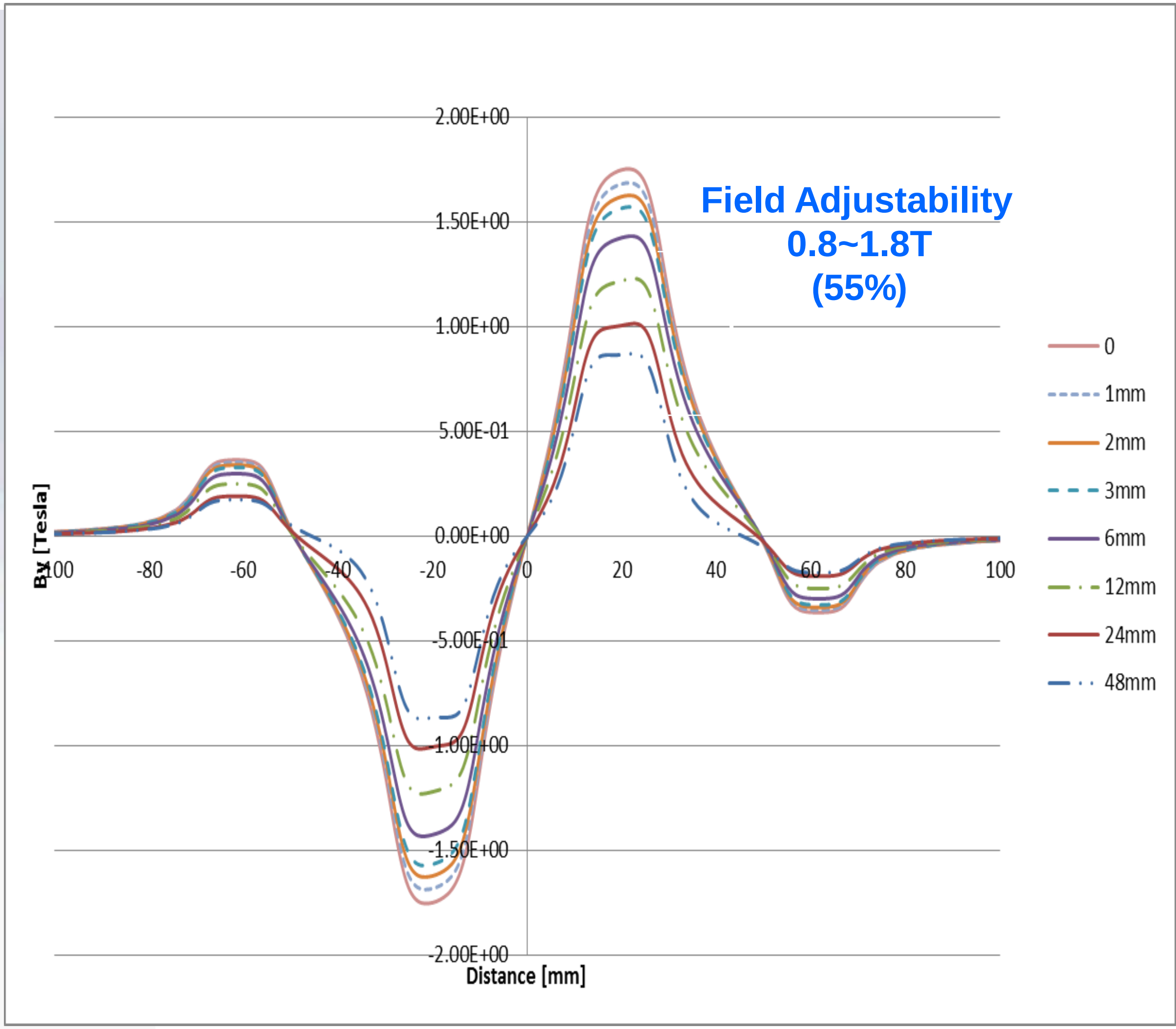
Innovation 3
- **4-arc modular magnets** attract together magnetically while 4 subassemblies in each quarter repel each other, which is helpful in controlling magnets and **splitting halves**.

Tunable Phase Shifter

Kick-off meeting in November 2016 at SLAC

Tunable Phase Shifter Magnet Design





Other Phase Shifter Examples

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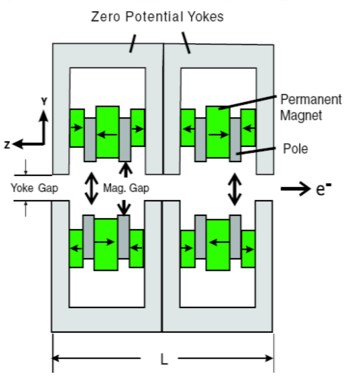
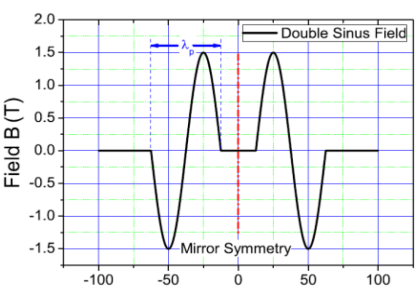
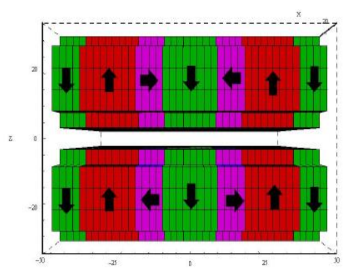
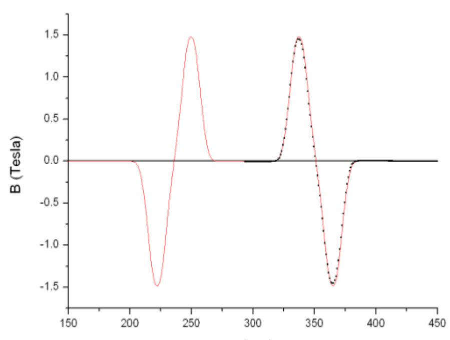
European-FEL



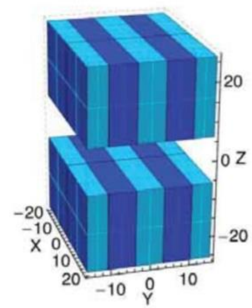


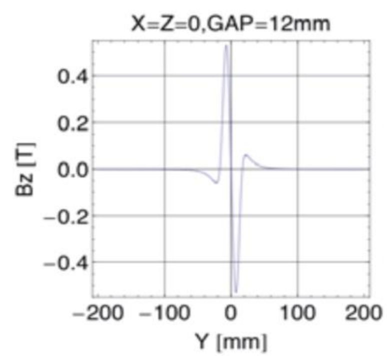
Korea-PAL



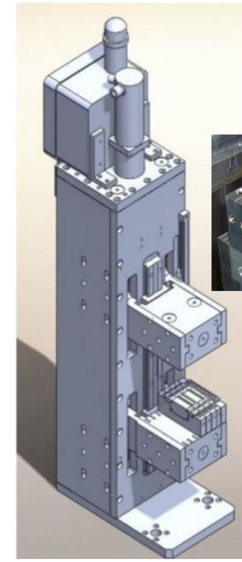


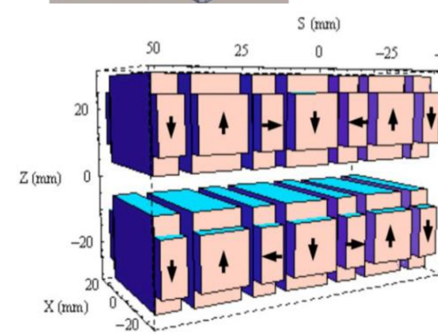
Swiss - FEL

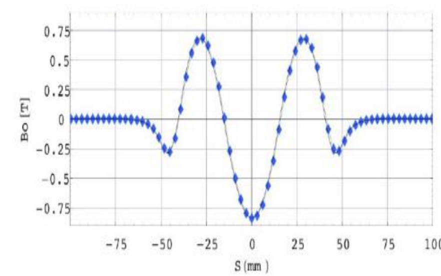




Italy-FERMI



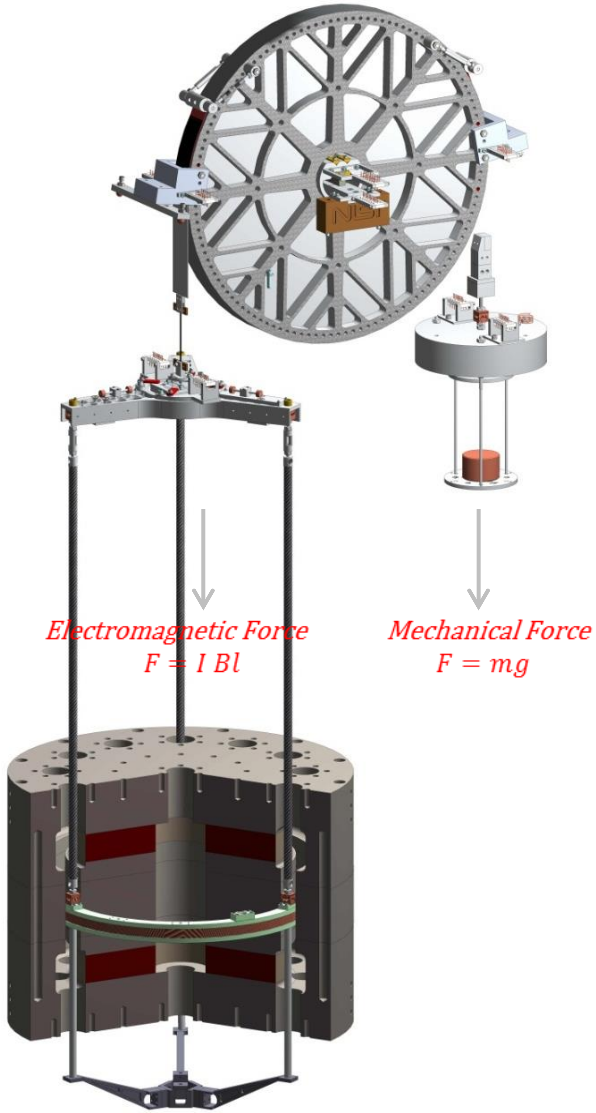




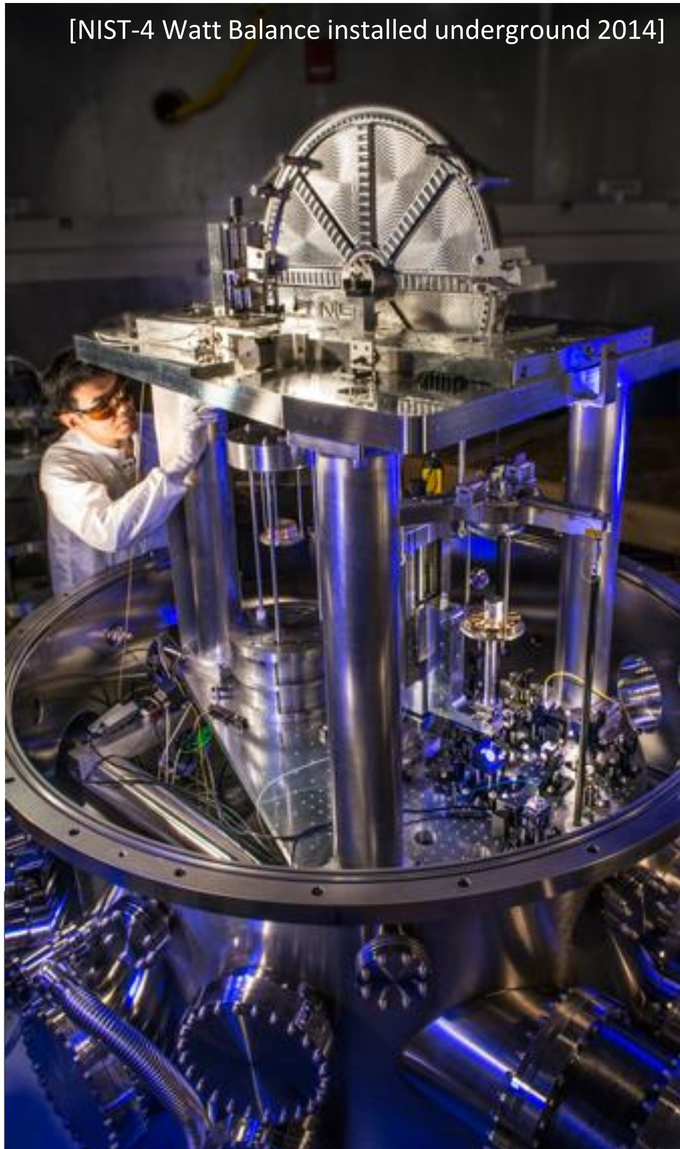
Electromagnet to Permanent Magnet

Change the Way to Define the Kilogram 11/16/18

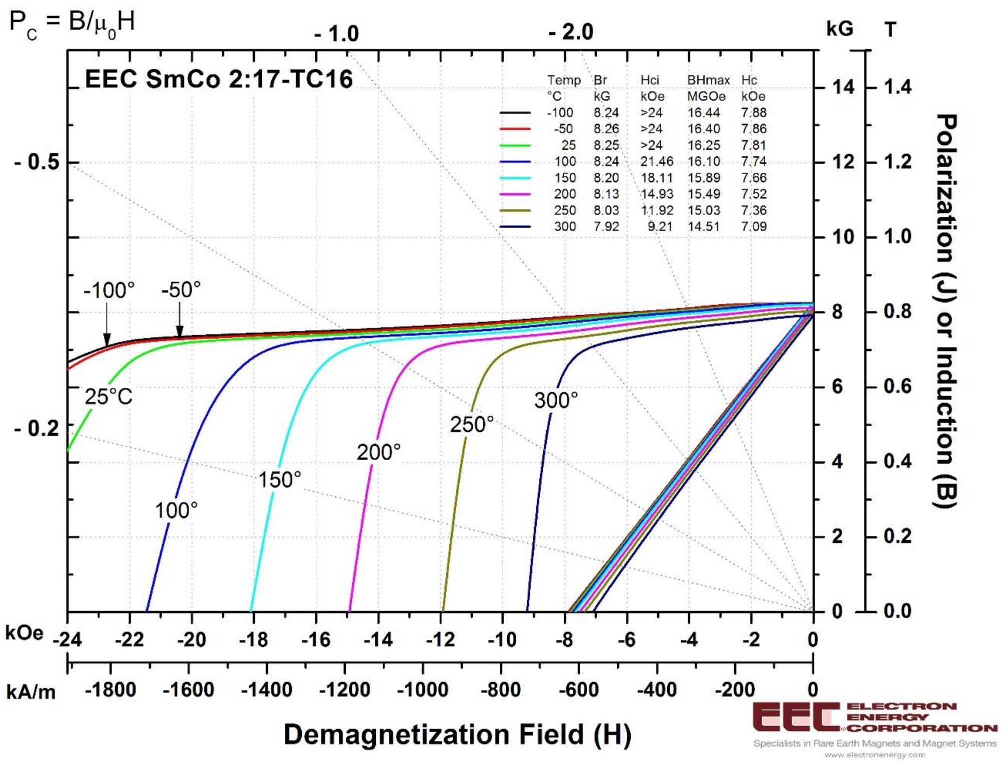
Kibble Balance is the electromechanical weight measuring instrument to define a kilogram mass by comparing electrical power to mechanical power.



[Image Courtesy NIST]



EEC Temperature Compensated Magnet



What is 'TC' Magnet Material?

EEC TC magnet material, developed in 2009, shows no change in the magnetic field over a wide operating temperature (**Sole Manufacturer**).

Why Important?

1) Reversible temperature coefficient of Br <**-0.001%/C** vs. -0.11%/C of Nd-Fe-B),
2) Straight normal BH curves,
3) **Strong thermal stability** to temperature and radiation,
4) High corrosion resistance.

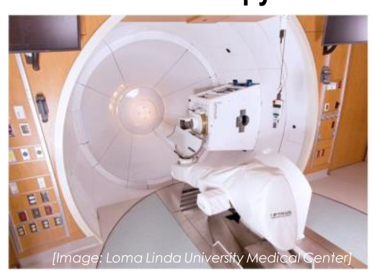
When/Where Needed?

1) High precision electronics such as TWT, gyro, klystron, accelerator, torquer, imaging, ADS
2) State-of-the-art technologies like Kibble balance, beam focusing, quantum diamond magnetometer.

Precision Guidance

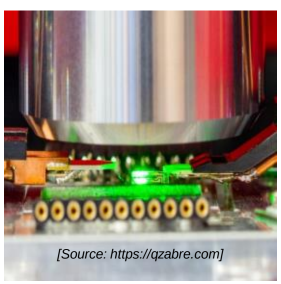
Miniature Mass Spectrometer

Proton Therapy



THz Communication

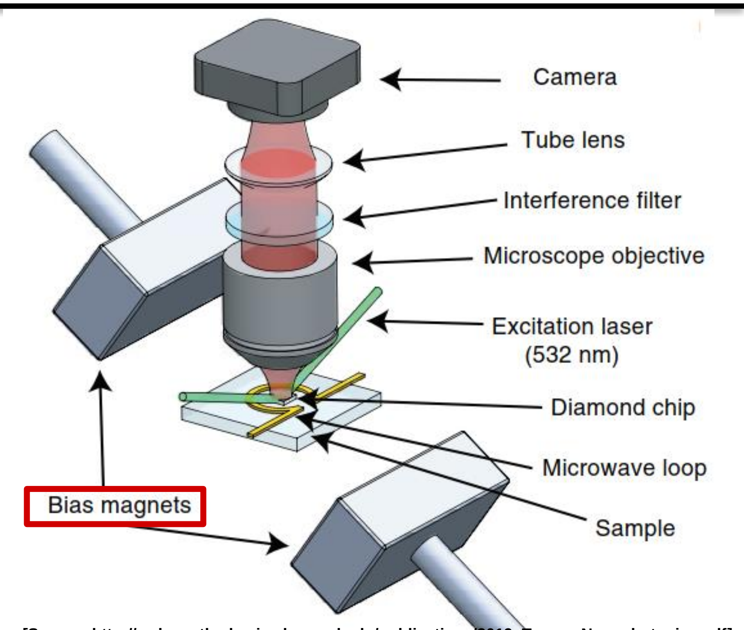
Quantum Diamond Microscope



Quantum Diamond Magnetometer

What is it?

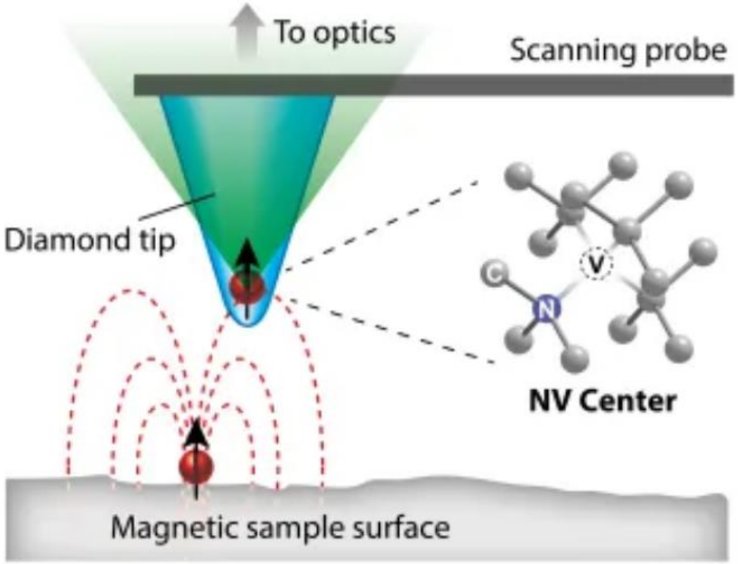
- ✓ Next-generation scanning probe microscope that utilizes a so-called nitrogen-vacancy (NV) center as an atomic size magnetic field sensor.
- ✓ Because NV centers show quantum behavior even at room temperature, the scanning NV magnetometer can exploit quantum metrology techniques to achieve very high magnetic field sensitivity.



[Source: http://walsworth.physics.harvard.edu/publications/2019_Turner_Nanophotonics.pdf]

How it works?

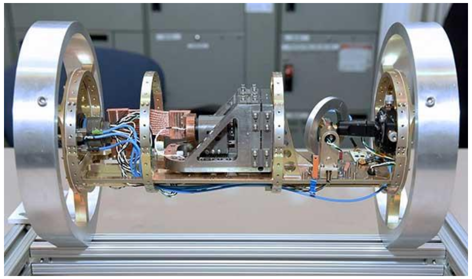
- ✓ The scanning NV magnetometer records the interaction of the NV center with the local magnetic field.
- ✓ As the magnetic field at the location of the NV center increases, the magnetic interaction becomes stronger – more energy is required to flip the magnetic orientation of the NV center. This energy can be probed by the technique of electron paramagnetic resonance (EPR) spectroscopy.



What Applications?

- ✓ Quantitative analysis of current distributions in semiconductors, graphene devices, photoactive films, integrated circuits.
- ✓ Vector field analysis of magnetic domains, defects, and nanostructures.
- ✓ Nanoscale thermometry.
- ✓ Imaging of biomagnetic structures and nanoparticle markers.
- ✓ GPS.

[Image Source Lockheed Martin]



Precision Gyroscope

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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.

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

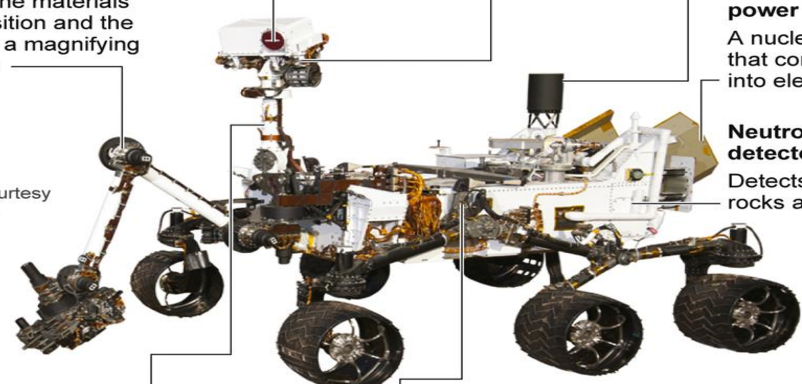


Photo courtesy of NASA

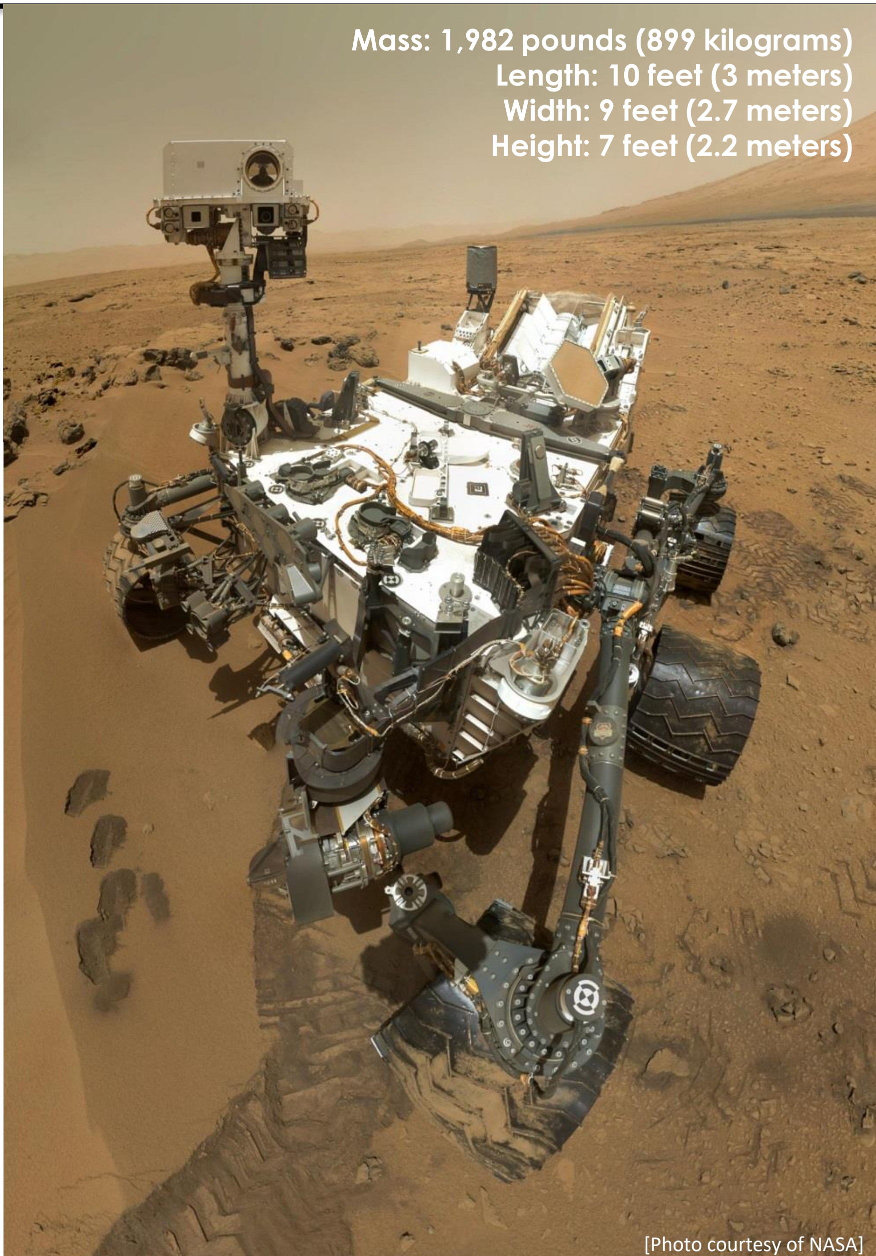
Weather station
Records wind speed/ direction, air pressure, humidity, temperature and UV radiation

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



[Photo courtesy of NASA]

Precision Guidance

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The **precision guidance** enables the rescue team to accurately target the starting point of the drill hole, then carefully control the orientation and direction of the drill hole to hit the target with the help of EEC magnets.

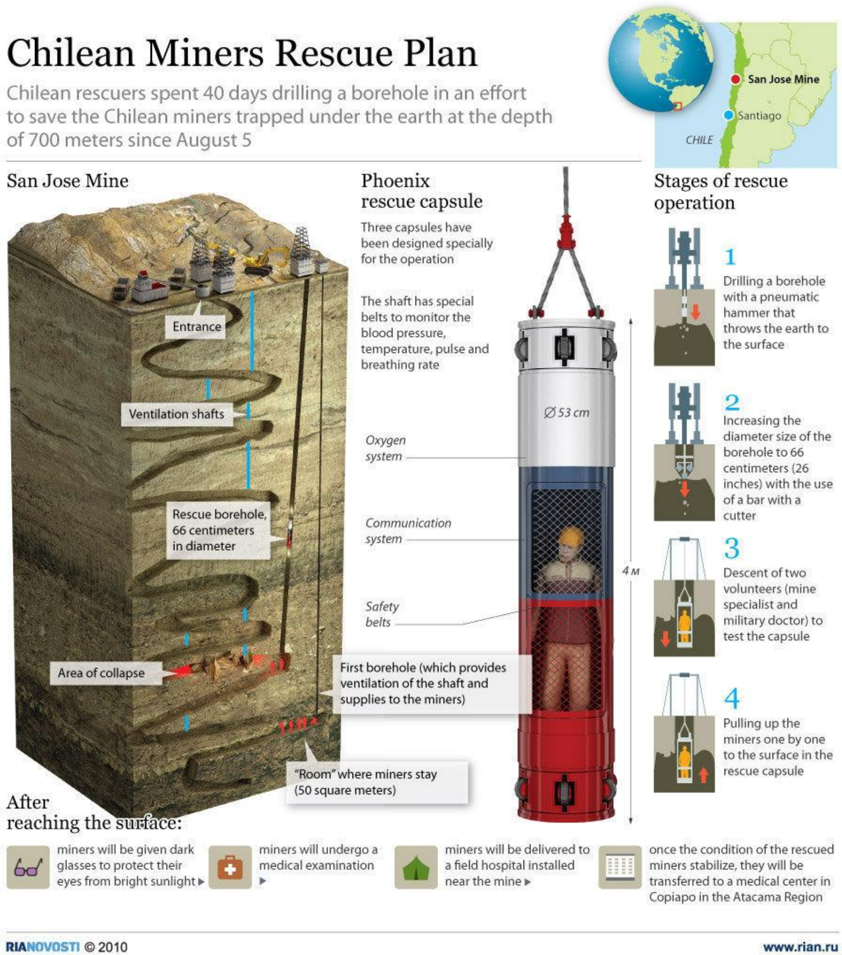

Photo by H. Choi at Smithsonian Museum

Drill bit

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THANK YOU

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Acknowledgements

Part of this material is based upon work supported by the U.S. Department of Energy, Office of Nuclear Energy, under Award Numbers DE-SC0015230, DE-SC0019537, DE-SC0021719. This financial assistance from DOE is gratefully acknowledged.

FAQ

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Does a rare earth magnet lose it's strength?

Permanent magnet could lose strength if:

- ✓ the working temperature exceeds the specified maximum operating temperature; (thermal demagnetization)
- ✓ the magnets are demagnetized by external magnetic field; (electrical / magnetic demagnetization)
- ✓ the magnets are heavily corroded or oxidized.

FAQ

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What are the coating options?

Sm-Co Magnets

No coating is required.

Nd-Fe-B Magnets

Ni plating: very popular for sintered neo. In order to have better protection, Ni-Cu-Ni plating is commonly applied.

Aluminum IVD: for applications with tight tolerance

Epoxy coating: Very common for bonded neo magnets. Best choice for outdoor applications or very humid environment.