

NATIONAL HIGH  
**M**MAGNETIC  
FIELD LABORATORY

# High field magnet efforts at NHMFL, BNL & industry

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FLORIDA STATE  
UNIVERSITY



**UF** UNIVERSITY of  
FLORIDA

# Outline

- NHMFL high field magnets
- BNL capabilities for FCC
- Synergies with industry



# NHMFL High Field Magnets

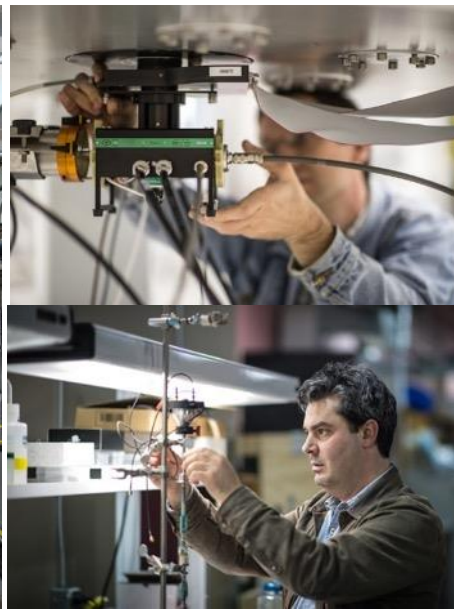


# NATIONAL HIGH MAGNETIC FIELD LABORATORY

The only facility of its kind in the United States and the largest and highest-powered magnet laboratory in the world.



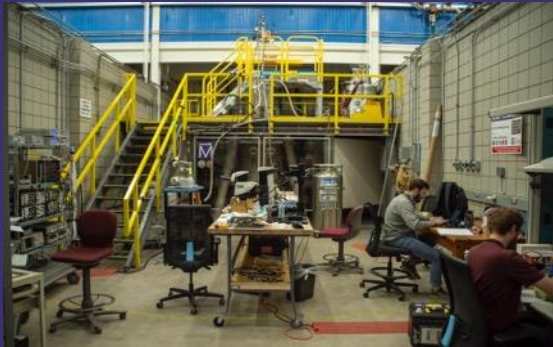
FLORIDA STATE UNIVERSITY



# NATIONAL HIGH MAGNETIC FIELD LABORATORY

## Our Mission:

- Operate a world-leading high-magnetic-field user program
- Carry out in-house research in support of the user program
- Maintain facility and develop new magnets/instrumentation
- Conduct education and outreach activities

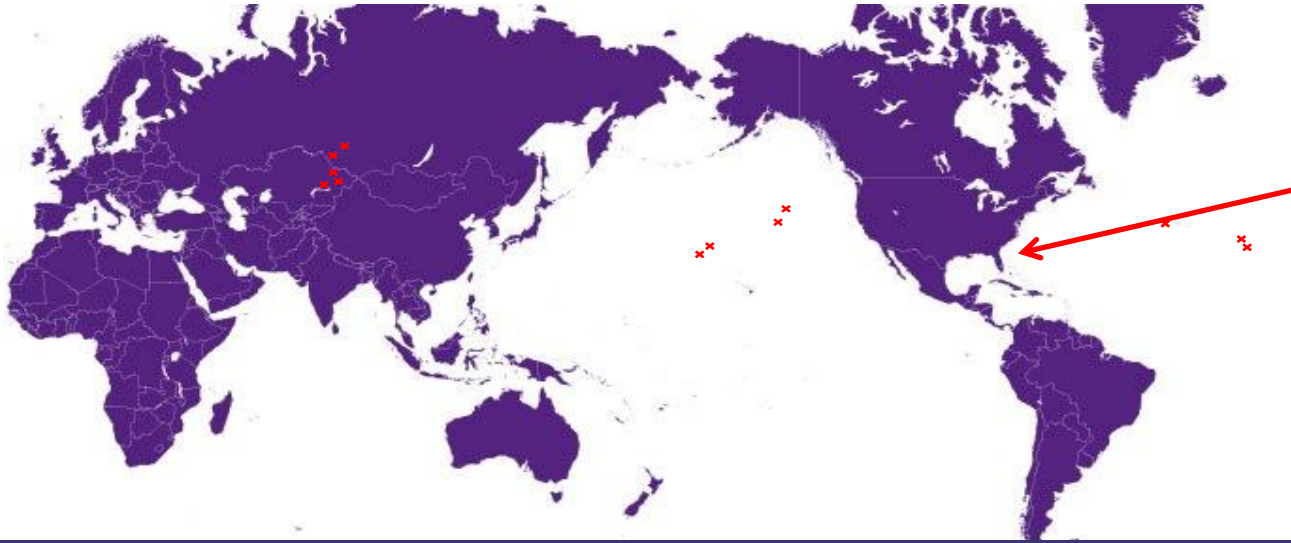




# World-Record Magnets

High magnetic field laboratories are located in China, France, Germany, Japan, The Netherlands and the United States.

The National MagLab is home to 16 world record magnet systems, including:

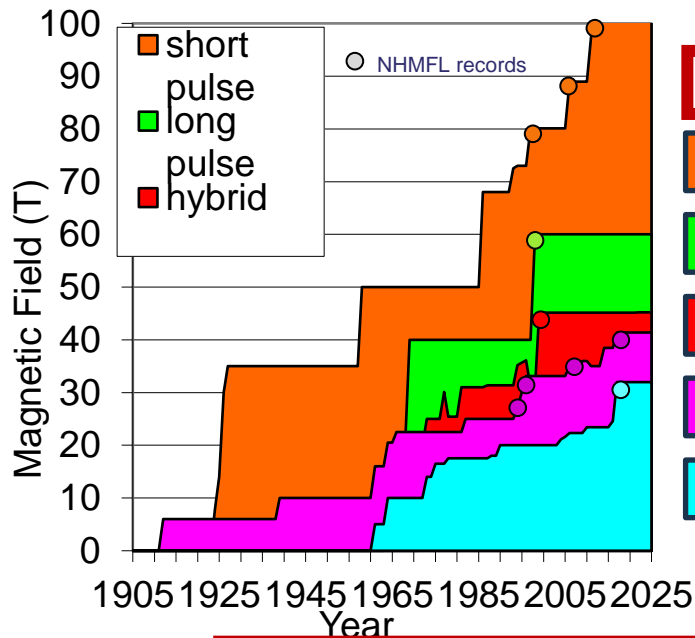


- Hybrid: 45T
- Short Pulse: 100 T
- Long Pulse: 60 T
- Superconducting FT-ICR: 21 T
- Resistive Magnet: 41 T
- All-Superconducting: 32 T
- Split: 25 T
- Superconducting coil in background magnet: 45.5 T
- NMR: 36 T
- MRI study of living animal" 21.1 T





# MS&T History and Context



NHMFL Records
Short Pulsed – 101 T, 2012
Long Pulsed – 60 T, 1998
Hybrid – 45 T, 2000
Resistive – 41.5 T, 2017
Superconducting – 32 T, 2017

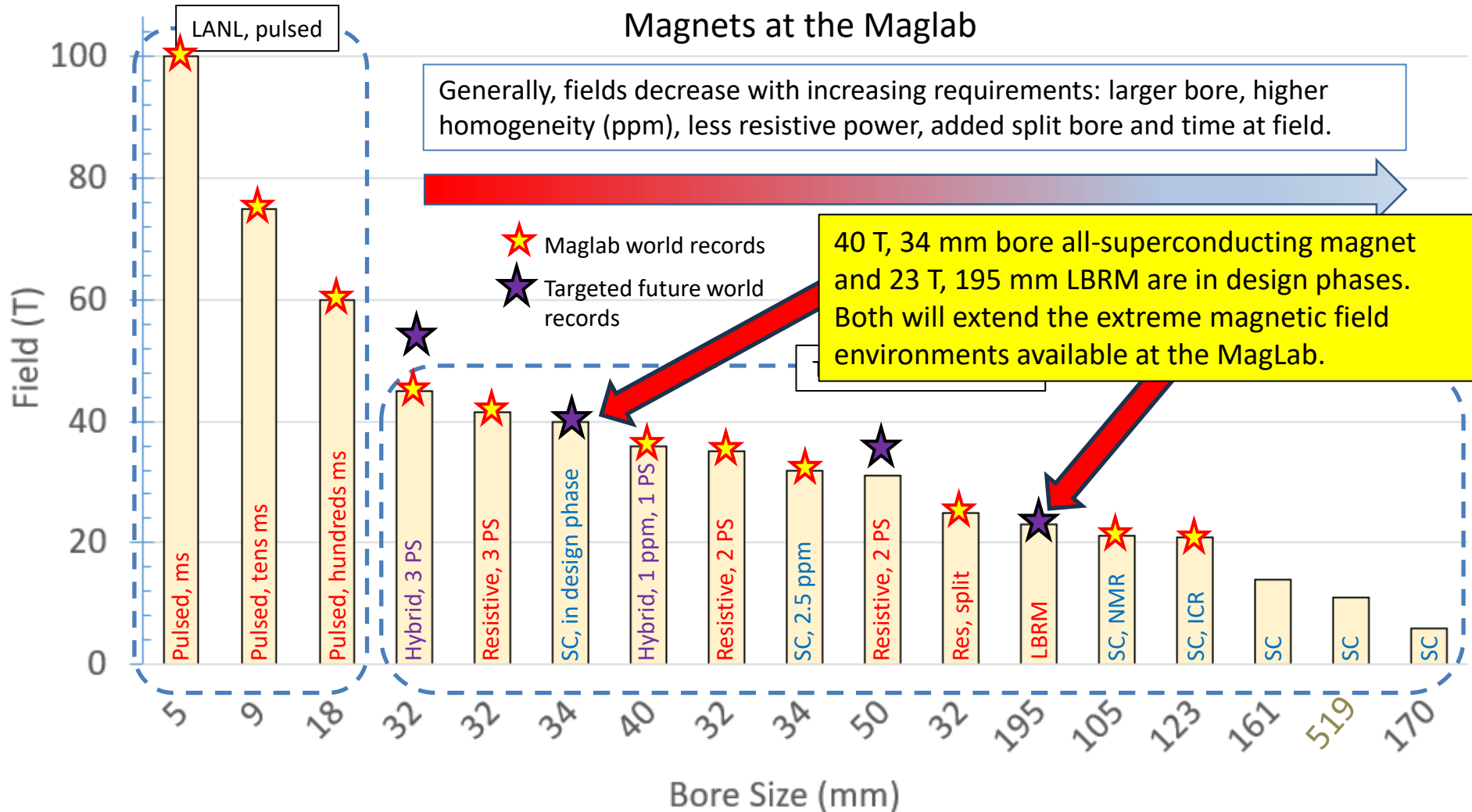
36T/1ppm Series Connected Hybrid, 2017
26T Neutron Scattering Magnet (Berlin), 2015
25T Split Resistive Magnet, 2011
21T/105mm Small Animal MRI, 2004

Two new high-field magnets are presently in the design phase:

- 40 T, 34 mm all-superconducting magnet
- 23 T, 195 mm resistive magnet convertible to 11.5 T, 350 mm bore

- The US and the NHMFL have set many world records due to the **continued support of the National Science Foundation** over the last 30 years.
- The high temperature superconductor (HTS) **REBCO** is having a **revolutionary** impact on high-field magnet systems, reducing their size and cost and making higher fields more achievable.
- Worldwide REBCO magnet competition is intense.

# Magnets at the Maglab

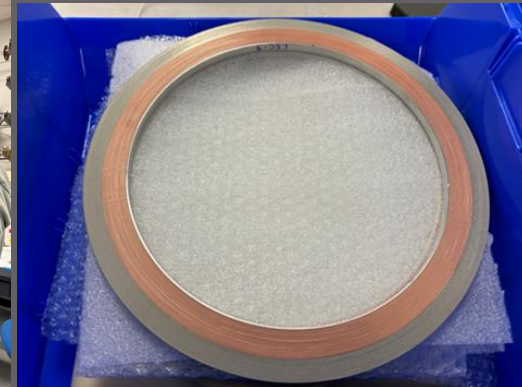
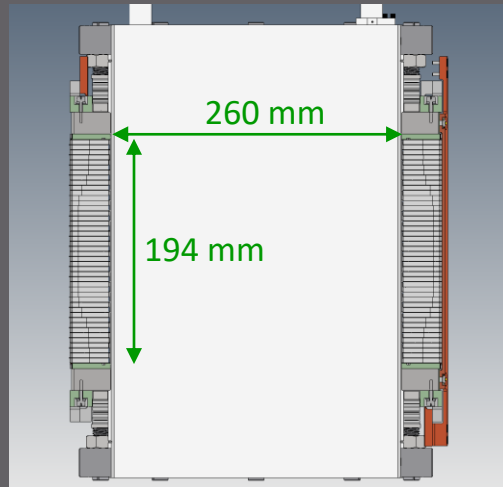
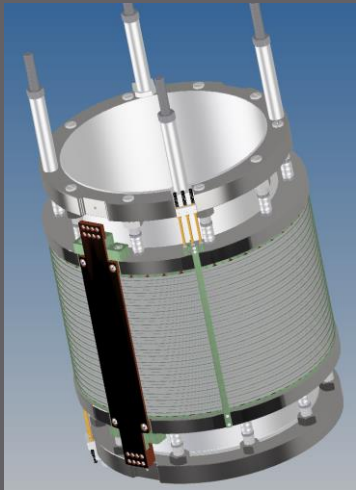
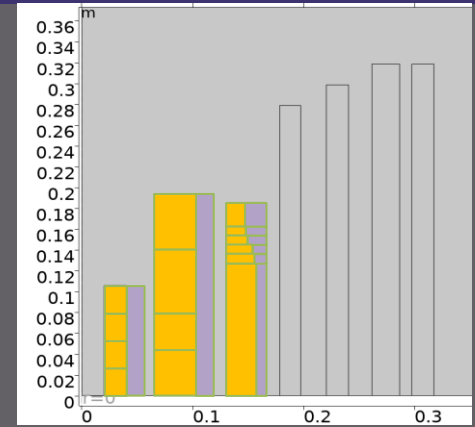




# MS&T Strategic Priority: 40 T, 34 mm bore all-SC magnet

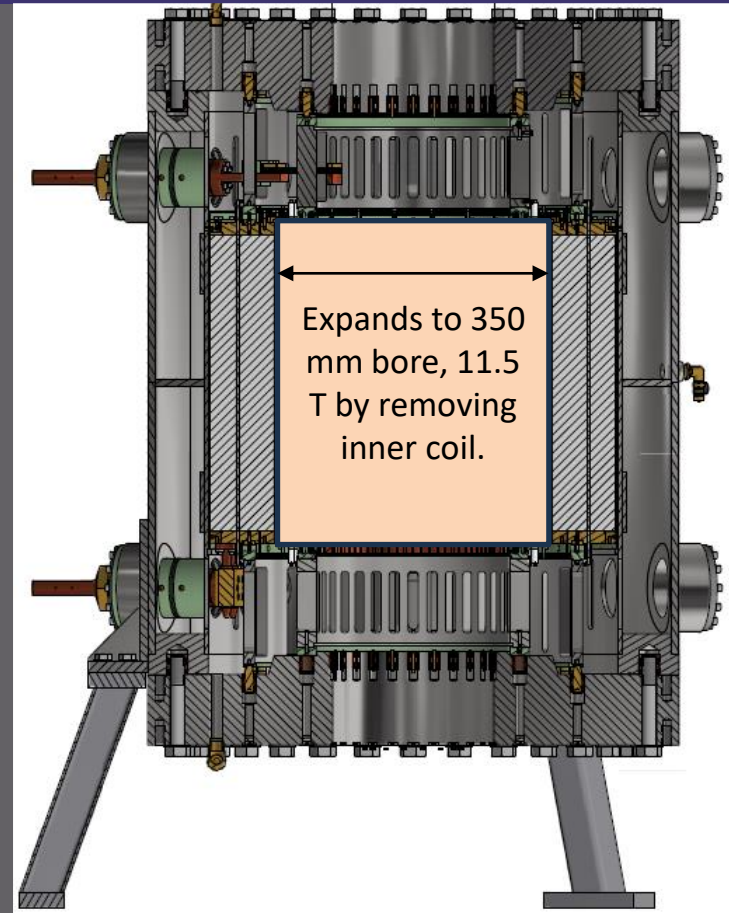
## Large Scale test Coil (LSC) is imminent

- The updated 40 T design defined the requirements for the Large-Scale test Coil.
- Coil is half-height of 40 T insert design Coil 3.
- Will be tested in 45 T outsert.
- Scheduled for testing by end of 2024.

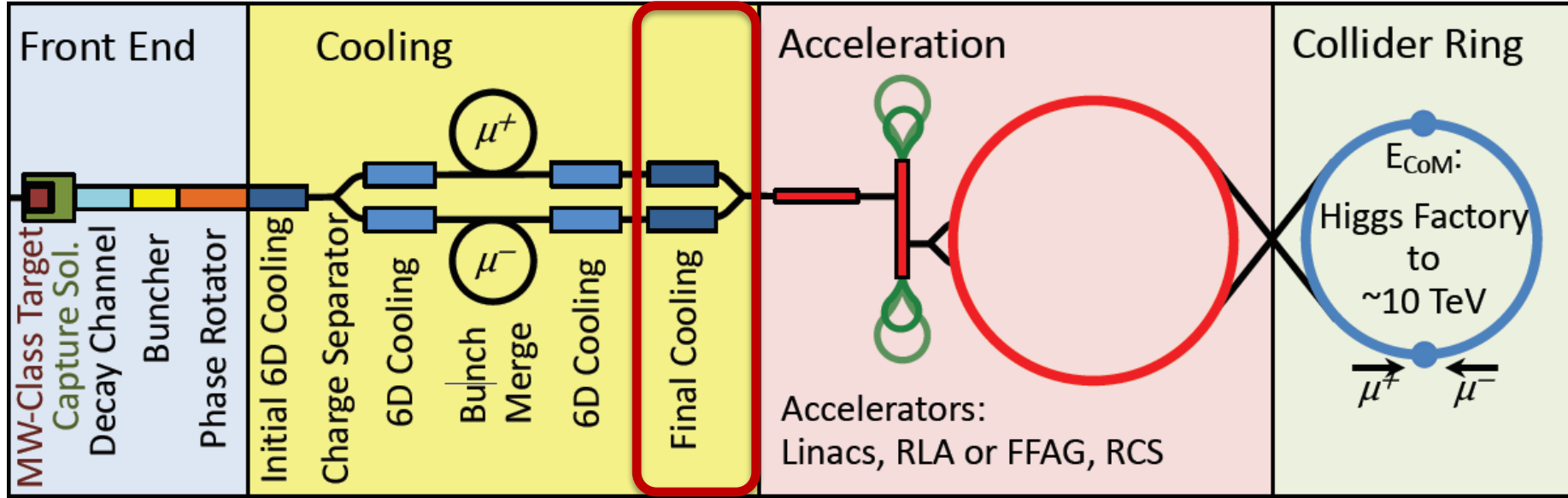


# MS&T Strategic Priority: 23 T, 195 mm bore resmag

- Large bore allows testing of insert coils under combined:
  - High field,
  - High stress,
  - High fraction  $I_c$ ,
  - Quench transients.
- Qualifies:
  - Joints,
  - Terminations,
  - Reinforcement,
  - Fabrication procedures,
  - Analyses.
- The larger the bore and higher the background field, the less extrapolation is required from the HTS test coils to the HTS real coils. Reduces Risk!
- Advantage over superconducting magnets:
  - Fast outsert field ramping capabilities.
  - No risk of quench.
  - No outsert LHe costs.
- Disadvantage:
  - Cyclic fatigue testing is limited.



# Relevance to Muon colliders Final Cooling Channel



Final Cooling solenoids

Field:  $\geq 30$ T (MAP),  $\geq 40$ T (IMCC), ideally  $\geq 50$  T

Bore: 50 mm

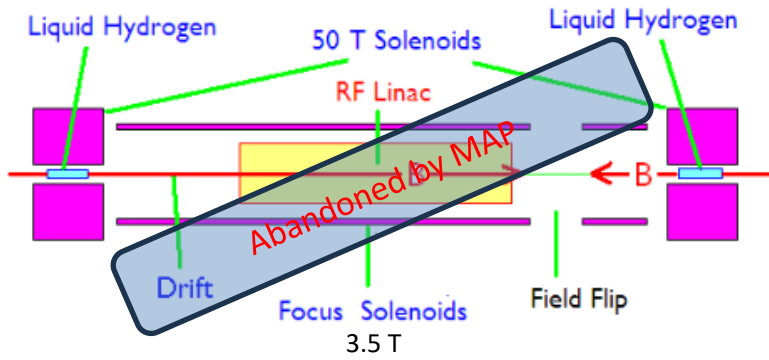
Length:  $\approx 500$  mm (x 17)

Radiation heat: TBD

Radiation dose: TBD

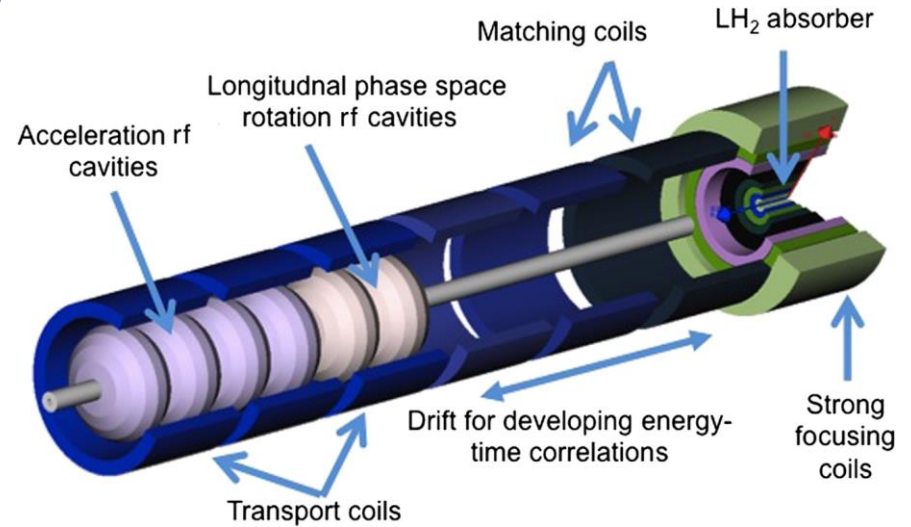
## Ionizing Cooling Cell

- 16 Cells (MAP)
  - Set of eight superconducting coaxial coils
  - Peak field of **30T**, 50 mm diameter
  - Sayed et al. *Phys. Rev. ST Accel. Beams* **18**, 091001
- 14 Cells (CERN-IMCC)
  - $B > 40T$ , 50 mm diameter



R. Palmer, BNL

## Final cooling Cell

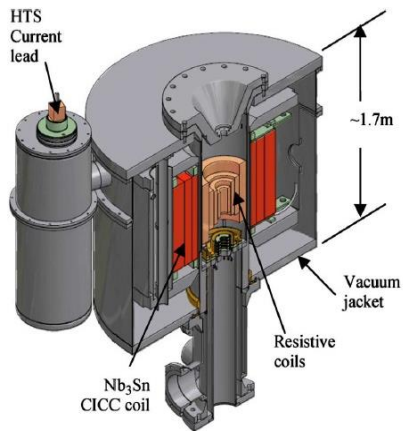


MAP 30T Design

# MagLab has developed high field solenoids

<https://nationalmaglab.org/user-facilities/dc-field/magnets-instruments/>

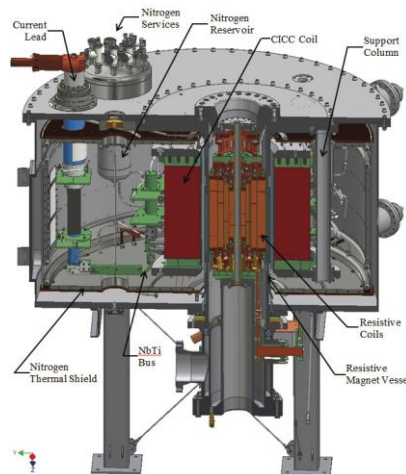
[http://english.hmfl.cas.cn/uf/ms/202202/t20220224\\_301451.html](http://english.hmfl.cas.cn/uf/ms/202202/t20220224_301451.html)



Tallahassee magnet system.

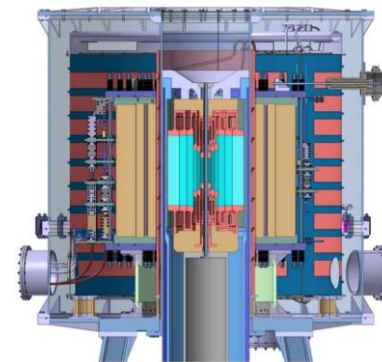
Cross section of **45 T, 32 mm** NHFML user facility solenoid

Hybrid Magnet 33.5 T from resistive insert, 11.5 T by superconducting outsert  
**30 MW** power consumption



Cross section of **36 T, 48 mm** NHFML user facility (NMR) solenoid

Hybrid Magnet 23 T from resistive insert, 13 T by superconducting Nb<sub>3</sub>Sn CICC outsert  
**14 MW** power consumption



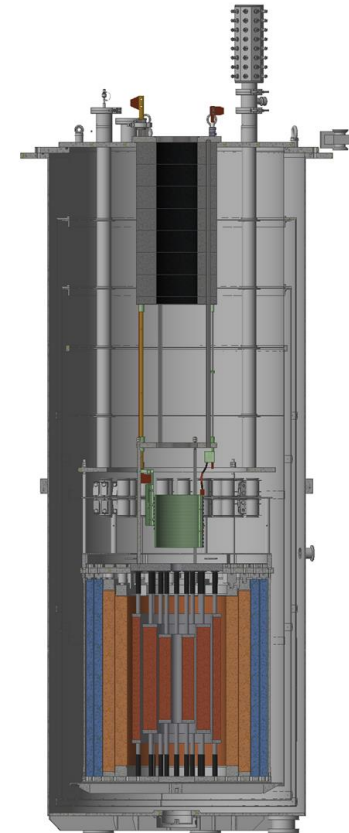
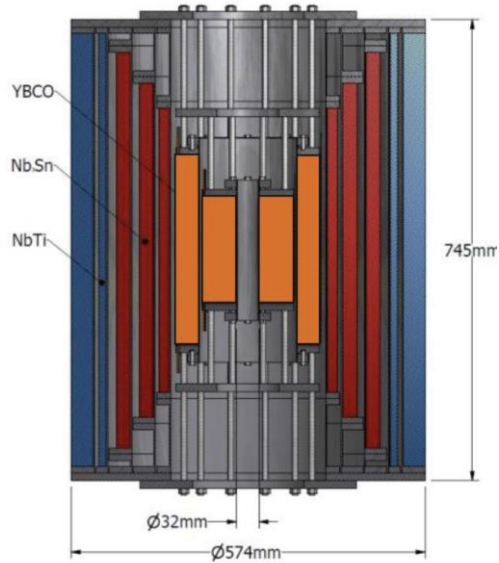
Cross section of **40\*/37 T, 32/50 mm** CHMFL user facility solenoid

Hybrid Magnet 29/26 T from resistive insert, 11 T by superconducting Nb<sub>3</sub>Sn CICC outsert  
**20 MW** power consumption

# Getting closer to muon collider needs – 32 T and 40 T

Cross section of **32 T** (15 T LTS, 17 T two ReBCO double pancake coils), **32 mm** user facility solenoid

<https://nationalmaglab.org/user-facilities/dc-field/magnets-instruments/>



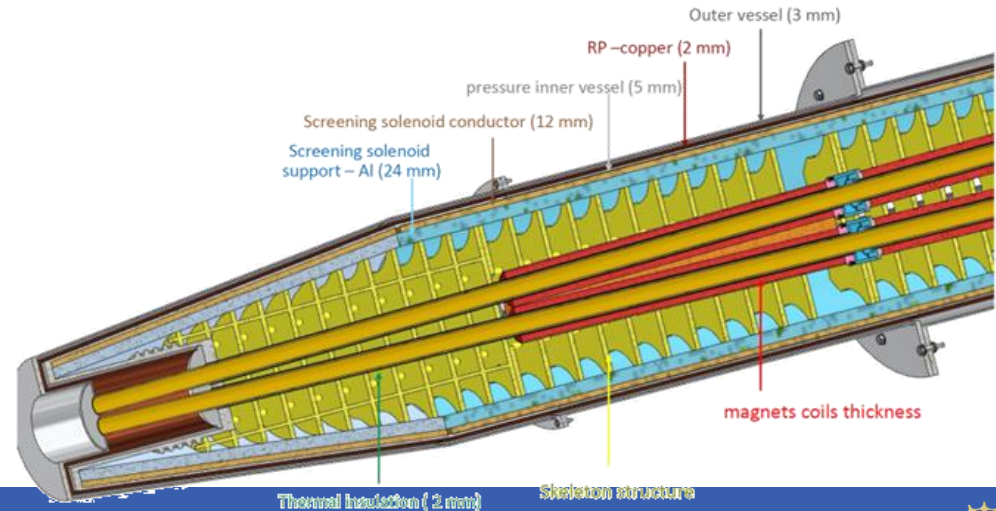
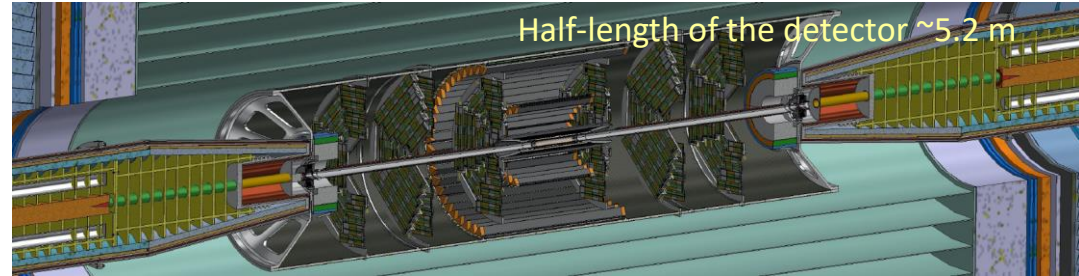
40 T magnet cross section



# Potential BNL contributions to FCC-ee

# FCC-ee IR challenges

- Very tight MDI requirements
- Strong anti-solenoid field 300kN (30Ton)  
→ large forces, no space for support
- Warm beam pipe inside cold magnet (1.9K)
- Cross-talk field compensation between beam lines
- Warm BPMs embedded in LHe
- Cryostat support (from detector or external)
- Utility interface (cryogenics, leads etc.),
- Detector installation
- Stray field, radiation shielding requirements.

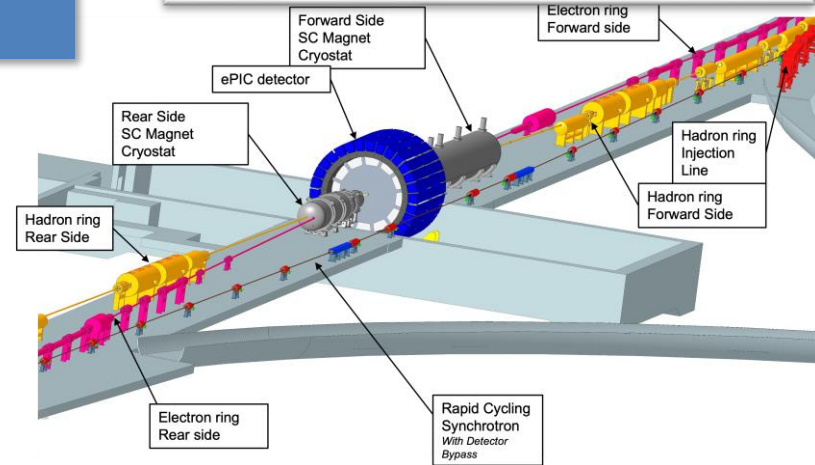
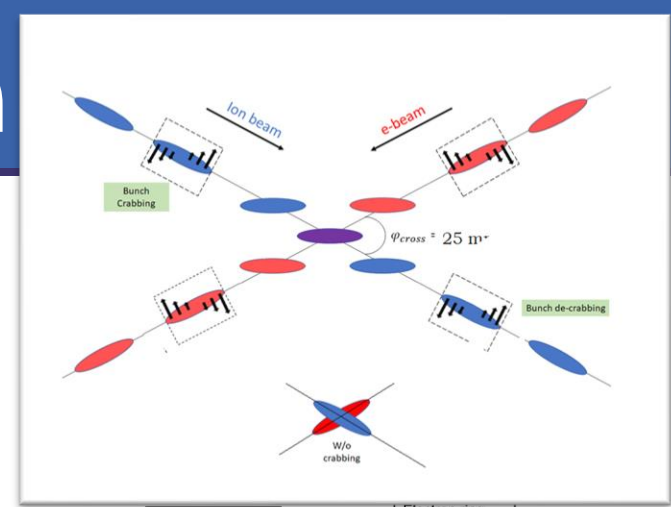


# EIC Interaction Region

- 25 mrad crossing angle,
- 10 ns bunch spacing
- Variable CM energy 20-140  $\sqrt{(Z/A)}$  GeV
- Hadron beam species from protons up to Uranium
- Small  $\beta^*$  to reach luminosity  $10^{34}\text{cm}^{-2}\text{s}^{-1}$  requires crab cavities and large final focus quadrupole aperture

## Machine Detector Interface

- Large detector acceptance
- Forward spectrometer
- No magnets within - 4.5 / +5 m from IP
- Space for luminosity detector, neutron detector, “Roman Pots”



# EIC IR Superconducting magnets

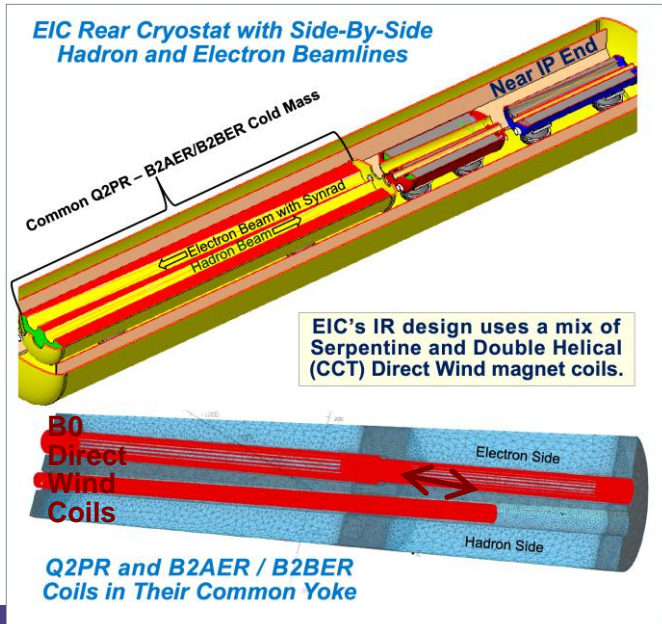
## EIC IR Magnet Challenges:

Highly integrated superconducting electron and hadron magnets (NbTi).

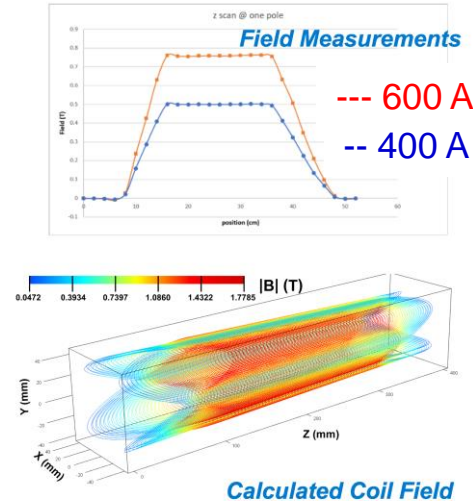
Need to prototype, manufacture and test multiple one of a kind magnets.

Most magnets done using Direct Wind technique (use collared coil technology only for highest fields / gradients).

The customized tooling for collared coils is expensive



*EIC Direct Wind, Double Helical, Tapered Constant Gradient Quadrupole Coil R&D*

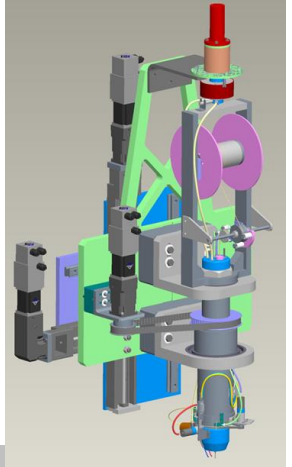


The FCC-ee IR magnets intrinsically require very carefully tailored field profiles to enable variable CM energy strong focusing while handling magnetic crosstalk and local optics correction (dipole, skew-dipole and skew-quadrupole coils).

Direct Wind coil fabrication enables flexible implementation of radially thin, compact correctors to adapt to demanding IR space and magnetic field configuration requirements.

# Direct Wind Coil Fabrication (NbTi)

- Unique BNL Direct Wind capability for high precision, specialty and IR magnets
- FCC-ee can benefit from EIC upgrades to two existing capabilities:
  - Modernized computer control hardware / software for increased precision
  - Enhanced reliability capable of winding longer / larger-diameter coils.
- **This is the only practical technology foreseen for making the FCC-ee IR magnet correction coils on very tight spaces.**



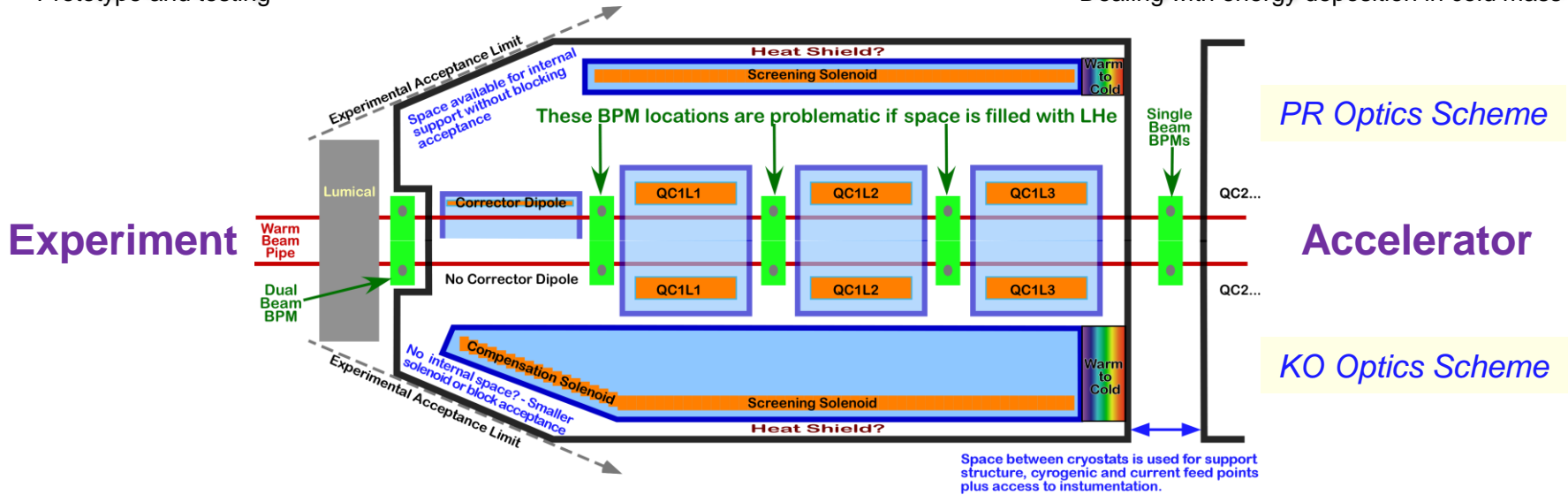
New winding heads providing greater speed, extended wire lengths for longer / larger diameter patterns.



IR Magnet Design  
 Anti-solenoid optimization  
 IR quadrupole design  
 IR corrector design  
 Prototype and testing

# Magnet Systems

IR Magnet Design  
 Quadrupole strengths for different CM energies  
 Detector solenoid compensation implementation  
 Optics tuning and necessary correctors  
 Dealing with energy deposition in cold mass



Experiment

IR Cryostat Design  
 Cold mass optimization  
 Internal support structure  
 Thermal management  
 Internal BPM interface

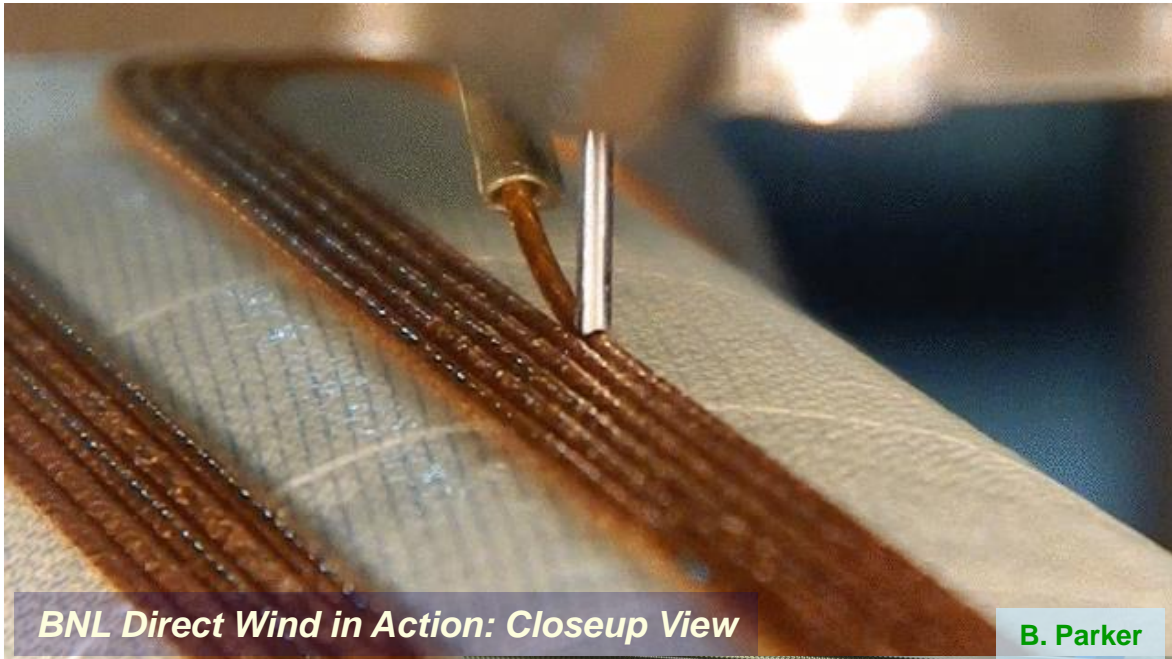
IR Cryostat Design  
 Installation, support and alignment  
 Vibration stability studies (for nanobeams!)  
 Utility access requirements (cryogenics, current leads, instrumentation etc.)  
 Experimental detector interface (with experimental access)

Topics for Possible Contributions for FCC-ee IR Magnets with MDI



First FCC IR Prototype

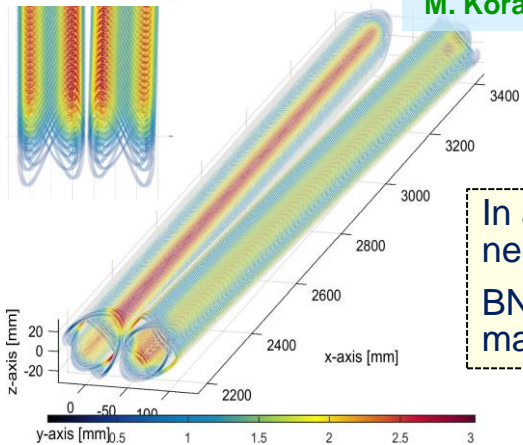
M. Koratzinos



BNL Direct Wind in Action: Closeup View

B. Parker

Magnetic field on surface of model



M. Koratzinos

In addition to main quad coils, FCC-ee needs a slew of correctors ( $b_1$ ,  $a_1$ ,  $a_2$ ...). BNL Direct Wind process is natural for making the necessary correctors.

M. Koratzinos

EIC Tapered Quadrupole R&D Example

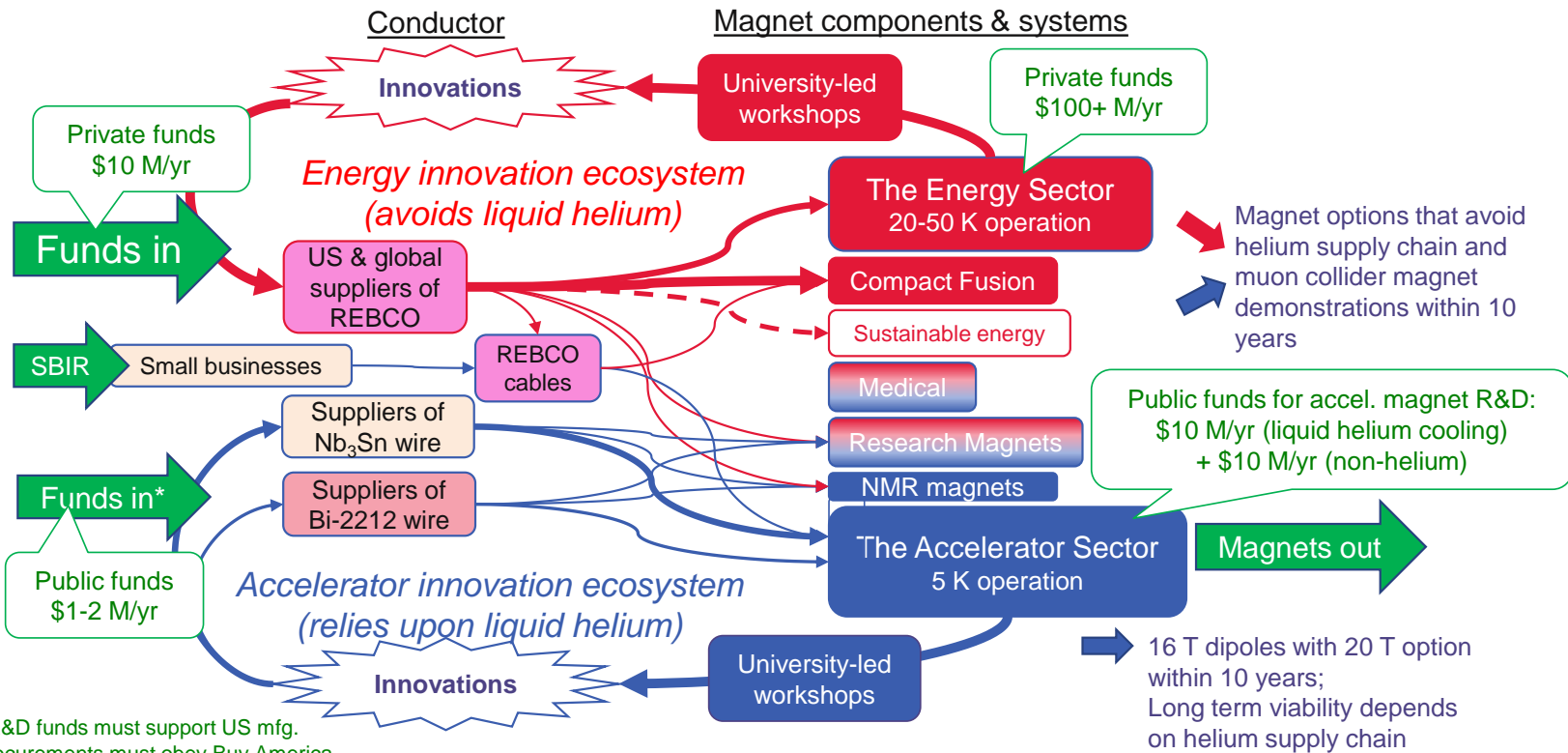
Double Helical  $\equiv$  CCT

Direct Wind Tapered Double Helical

H. Witte

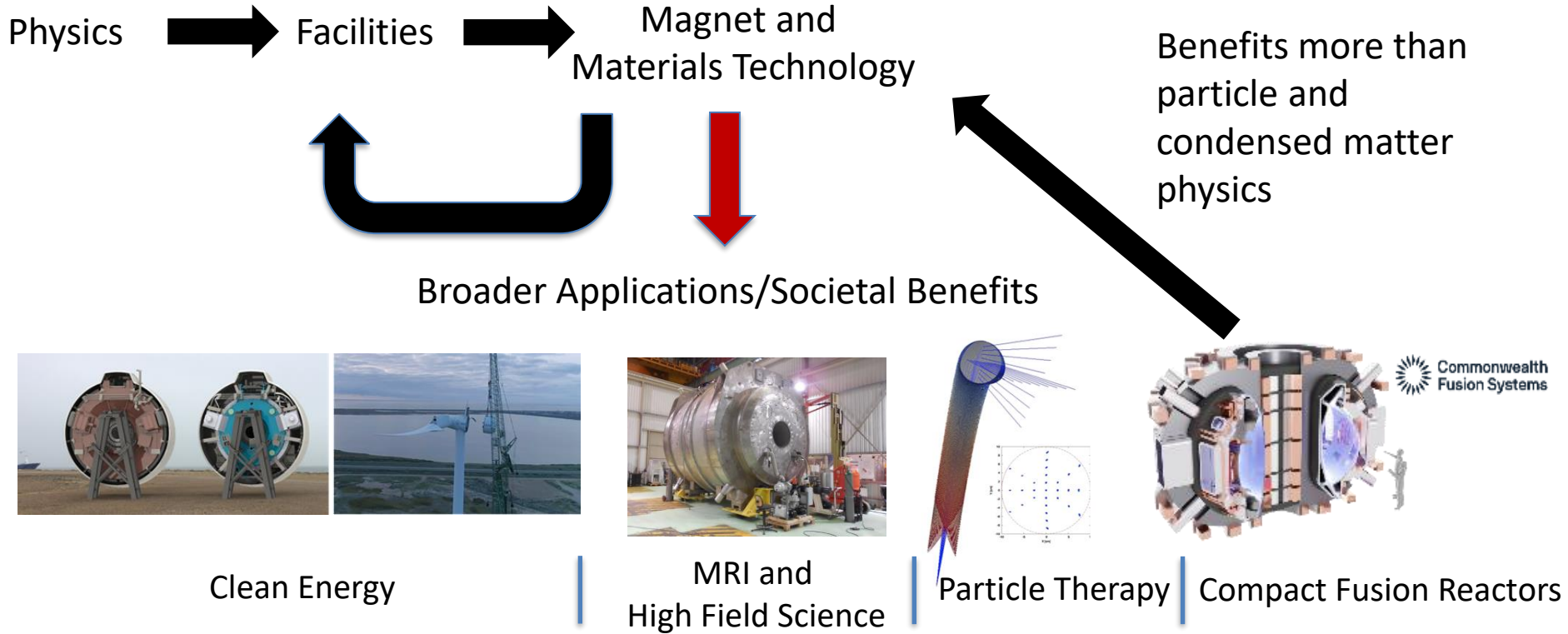
Some FCC-ee IR Magnet Coil Production Technology Possibilities

# The different communities should synchronize innovation ecosystems



\* R&D funds must support US mfg.  
Procurements must obey Buy America

# HEP/NSF-Driven Magnet Technology Chain



# Conclusions

The high field magnet community is having a transformational moment

- Large high field magnets are needed for future HEP and NSF science – FCC, muon colliders, materials R&D, NMR, MRI, ...
- Major industrial markets are emerging for HTS conductors – fusion, green energy
- The US magnet community can contribute in a significant way to these global initiatives



# Thank you !

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