High field magnet efforts at NHMFL, BNL & industry

Kathleen Amm, Mark Palmer, Brett Parker, Thomas Painter, Lance Cooley

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

UF
UNIVERSITY of FLORIDA

Los Alamos
NATIONAL LABORATORY
EST. 1943

NATIONAL HIGH MAGNETIC FIELD LABORATORY

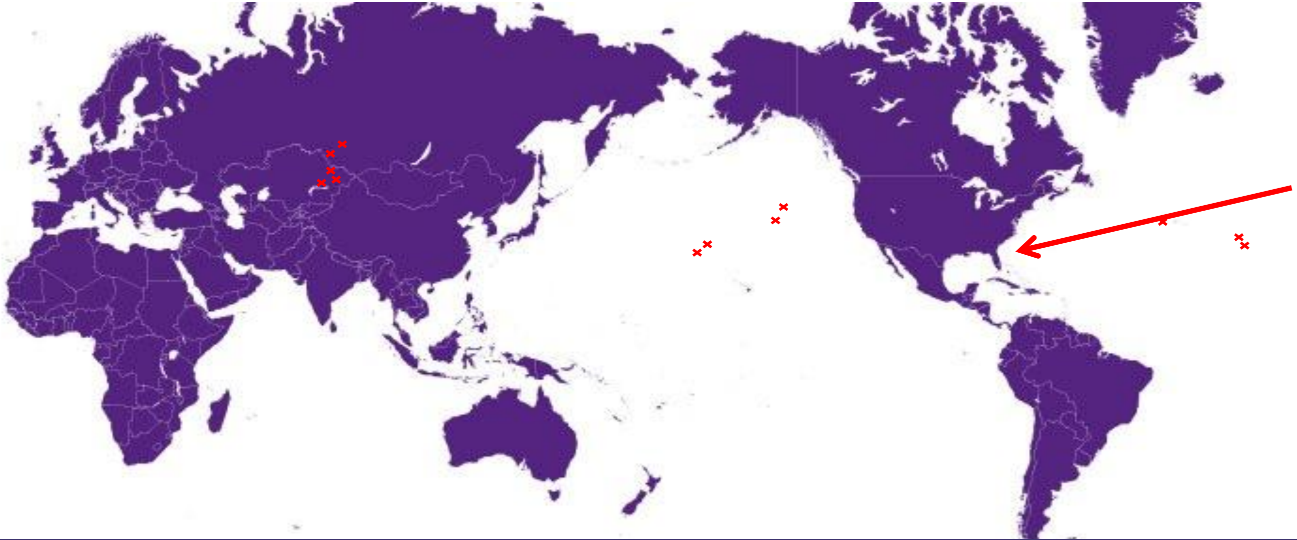
Our Mission:

- 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

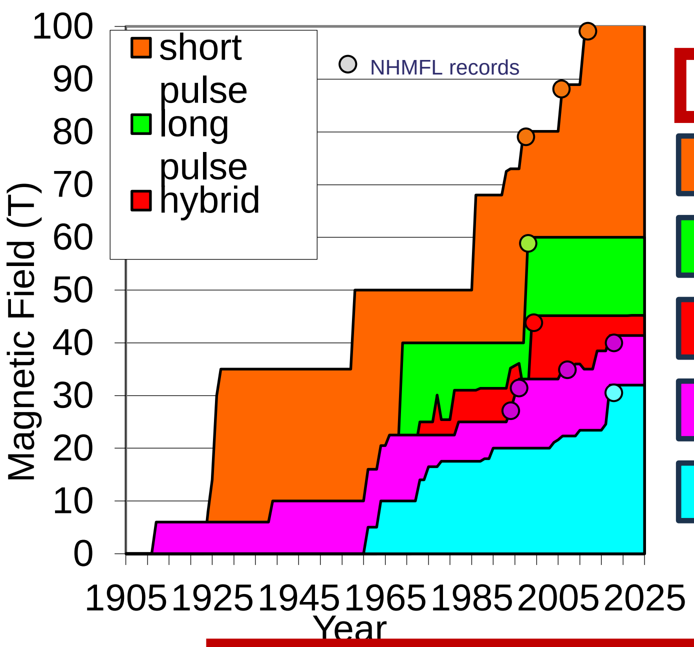
High magnetic field laboratories are located in China, France, Germany, Japan, The Netherlands and the United States.

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

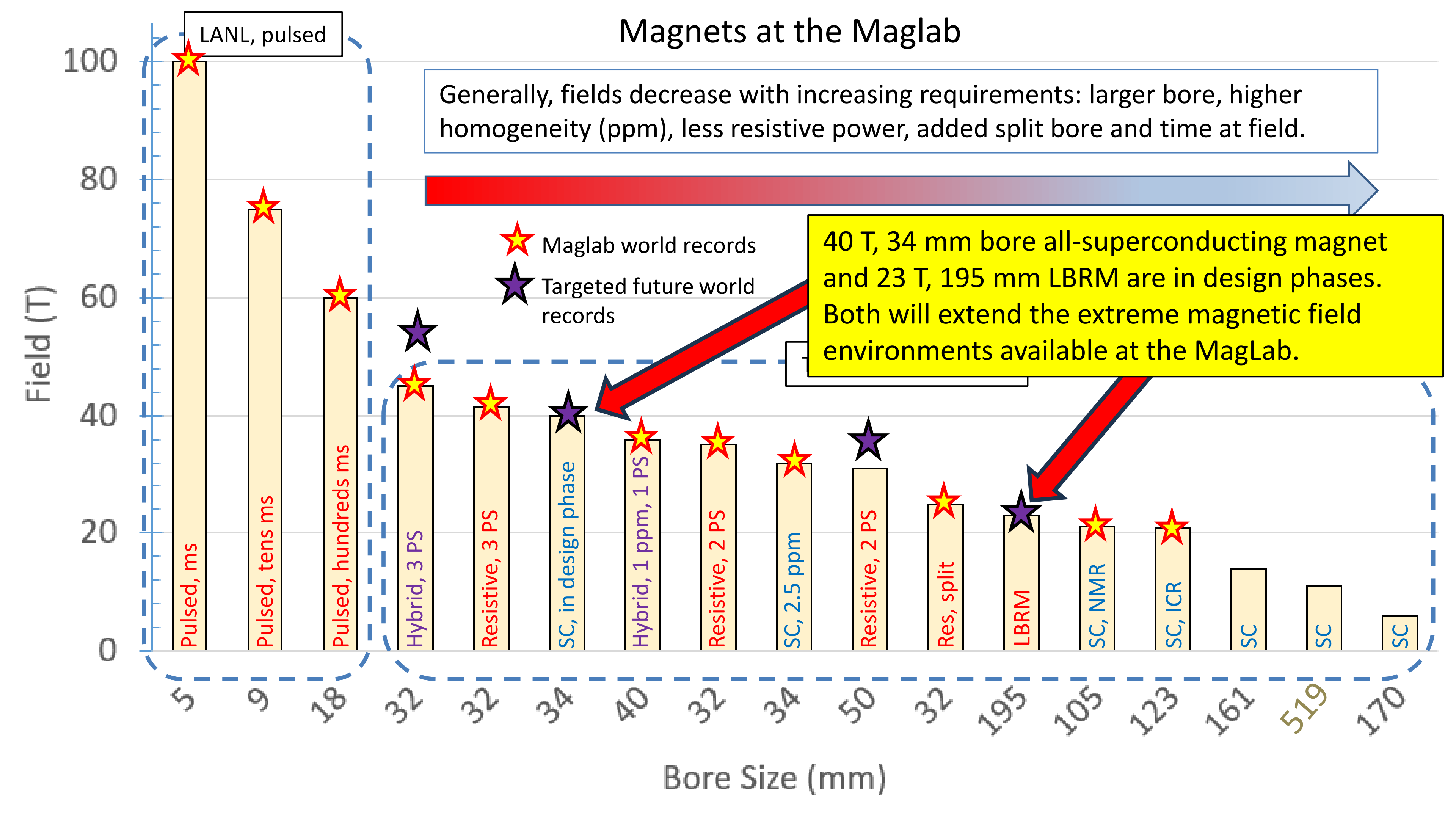
36T/1ppm Series Connected Hybrid, 2017
26T Neutron Scattering Magnet (Berlin), 2015
25T Split Resistive Magnet, 2011
21T/105mm Small Animal MRI, 2004

- 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.

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

- 40 T, 34 mm all-superconducting magnet

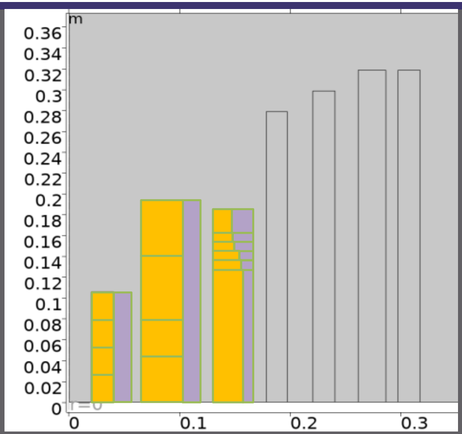
- 23 T, 195 mm resistive magnet convertible to 11.5 T, 350 mm bore



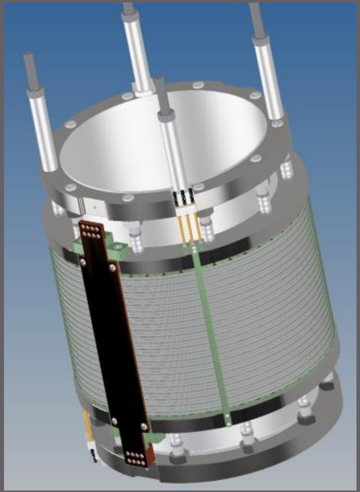
Magnets at the Maglab
LANL, pulsed
Generally, fields decrease with increasing requirements: larger bore, higher homogeneity (ppm), less resistive power, added split bore and time at field.
Maglab world records
Targeted future world records
40 T, 34 mm bore all-superconducting magnet and 23 T, 195 mm LBRM are in design phases. Both will extend the extreme magnetic field environments available at the MagLab.
Field (T)
100
80
60
40
20
0
Pulsed, ms
Pulsed, tens ms
Pulsed, hundreds ms
Hybrid, 3 PS
Resistive, 3 PS
SC, in design phase
Hybrid, 1 ppm, 1 PS
Resistive, 2 PS
SC, 2.5 ppm
Resistive, 2 PS
Res, split
LBRM
SC, NMR
SC, ICR
SC
SC
SC
5
9
18
32
32
34
40
32
34
50
32
195
105
123
161
519
170
Bore Size (mm)

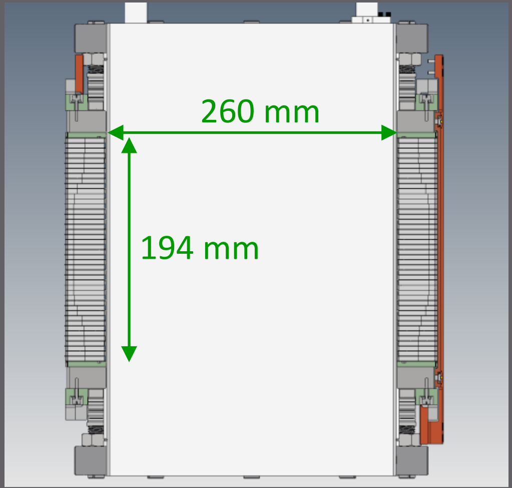
MS&T Strategic Priority: 40 T, 34 mm bore all-SC magnet

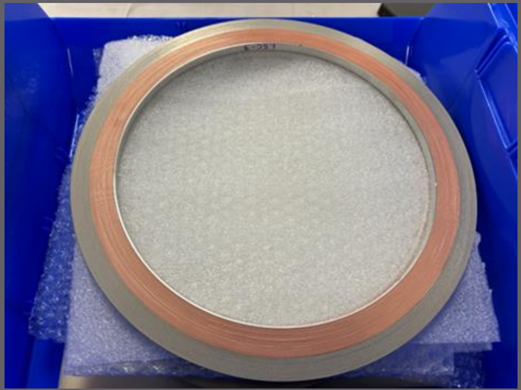
Large Scale test Coil (LSC) is imminent



- 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.

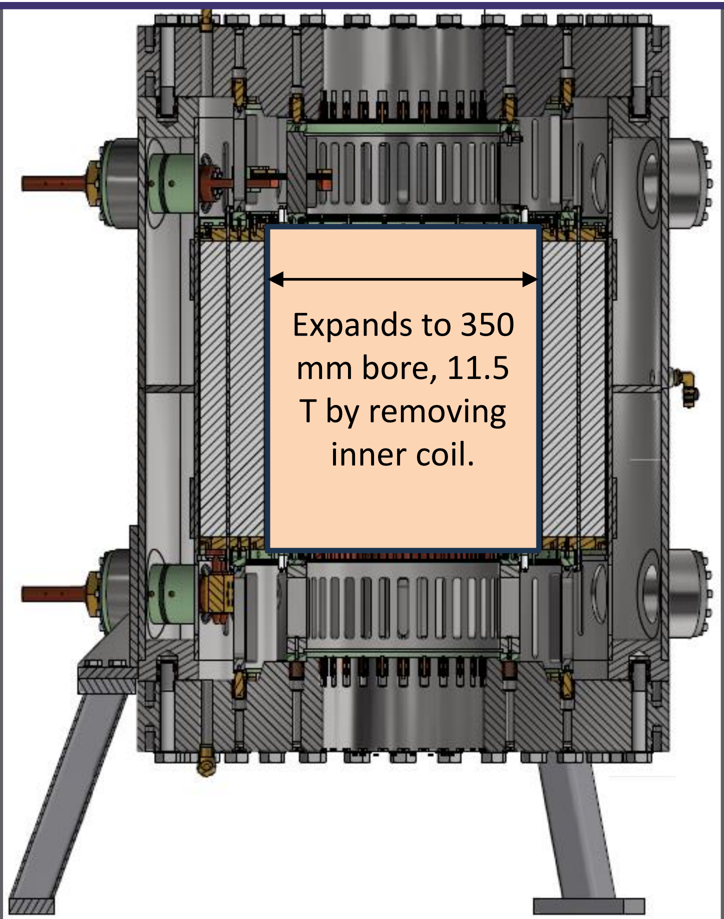




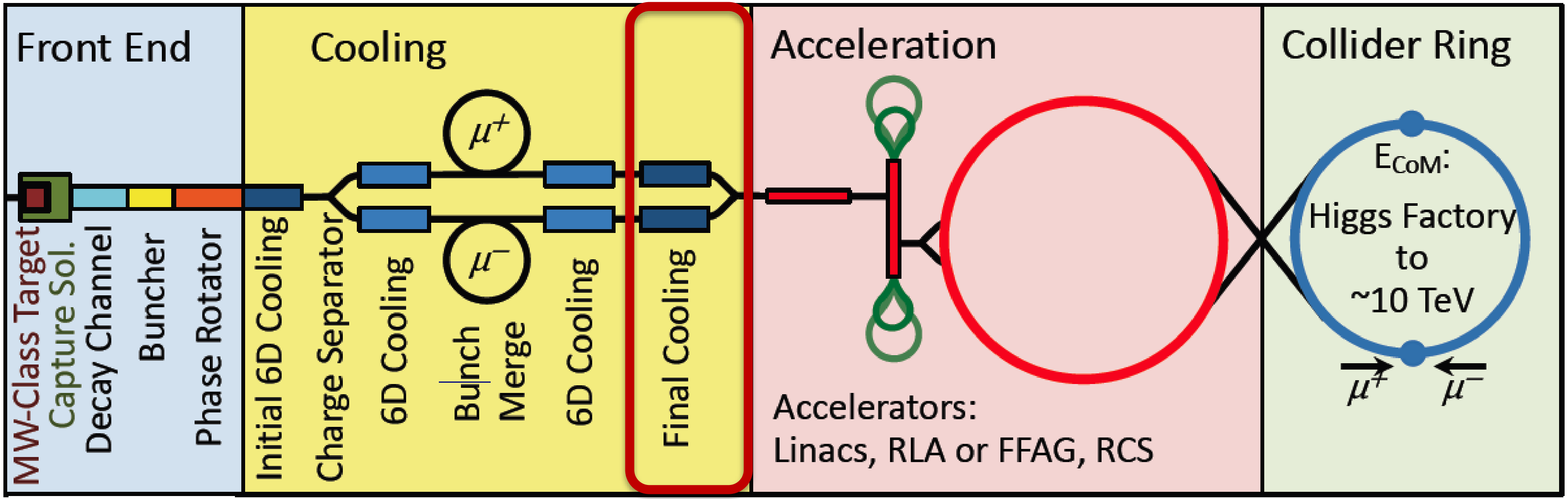


MS&T Strategic Priority: 23 T, 195 mm bore resmag

- Large bore allows testing of insert coils under combined:
  - High field,
  - High stress,
  - High fraction Ic,
  - 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

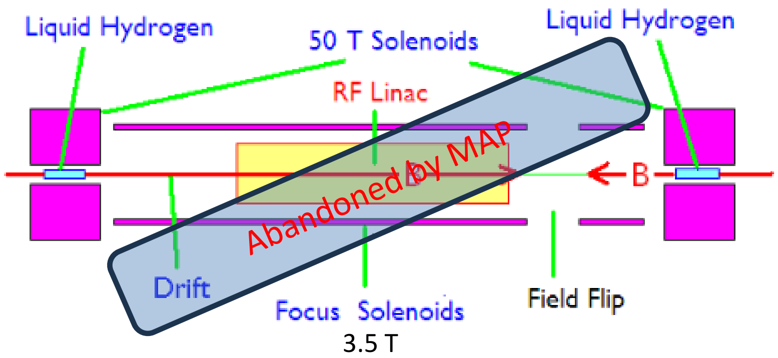


Final Cooling solenoids
Field: ≥30T (MAP), ≥40T (IMCC), ideally ≥50 T
Bore: 50 mm
Length: ≈ 500 mm (x 17)
Radiation heat: TBD
Radiation dose: TBD

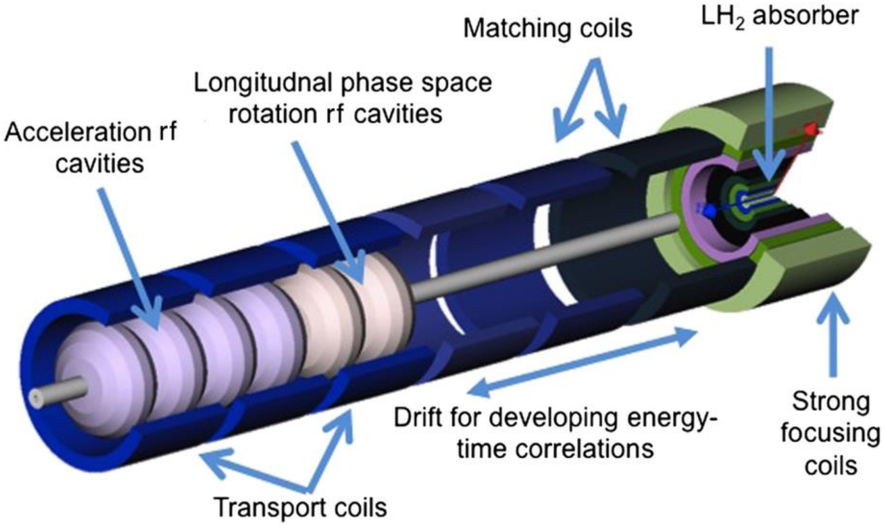
Ionizing Cooling Cell

Final 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

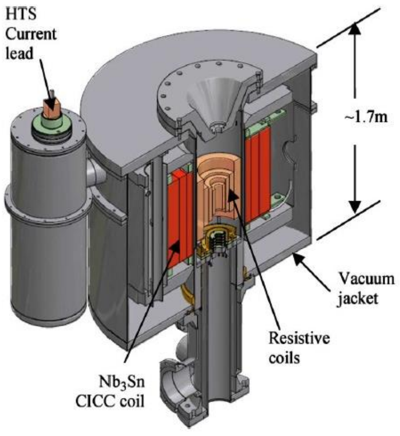


MAP 30T Design

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

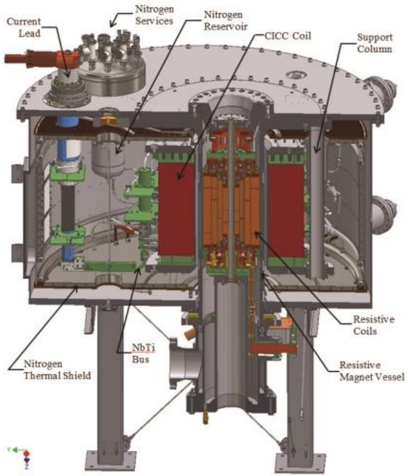


Tallahassee magnet system.

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

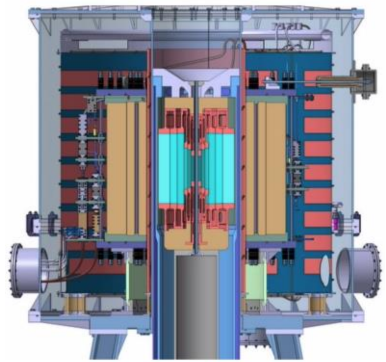
30 MW power comsumption



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

Hybrid Magnet 23 T from resistive insert, 13 T by superconducting Nb_3Sn CICC outsert

14 MW power comsumption



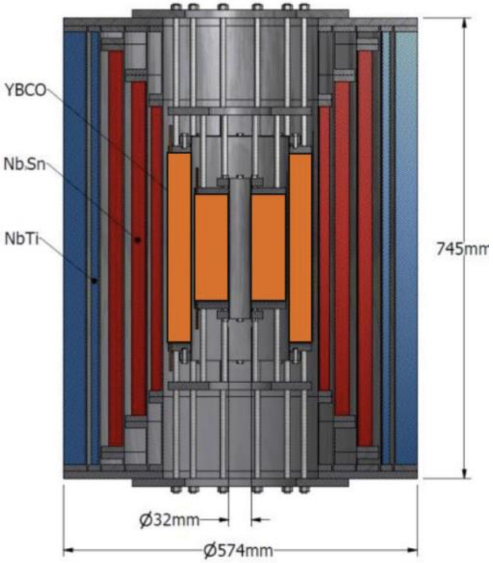
Cross section of **40*/37 T**, **32/50 mm** **CHMFL** user facility solenoid

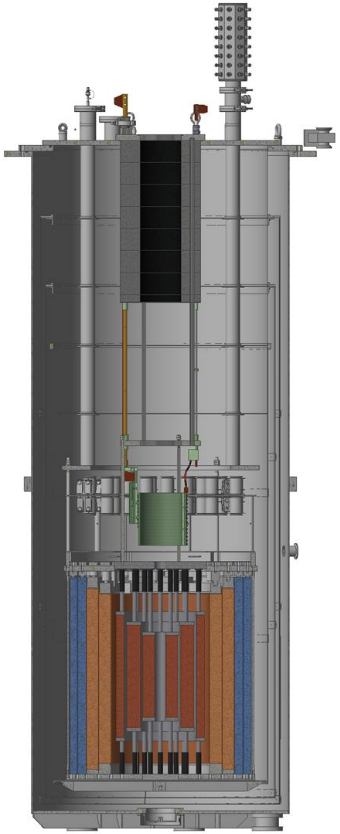
Hybrid Magnet 29/26 T from resistive insert, 11 T by superconducting Nb_3Sn CICC outsert

20 MW power comsumption

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/



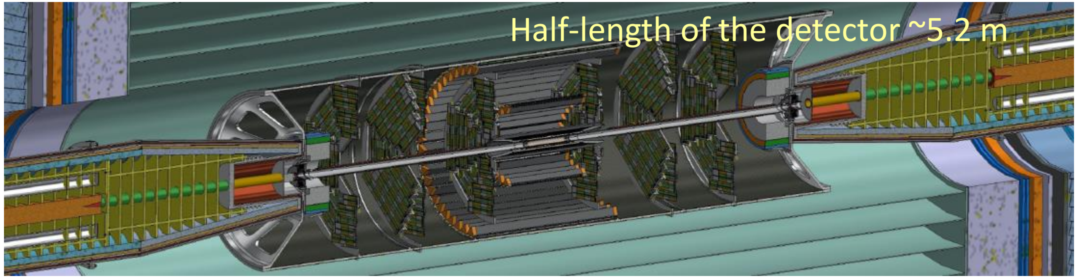


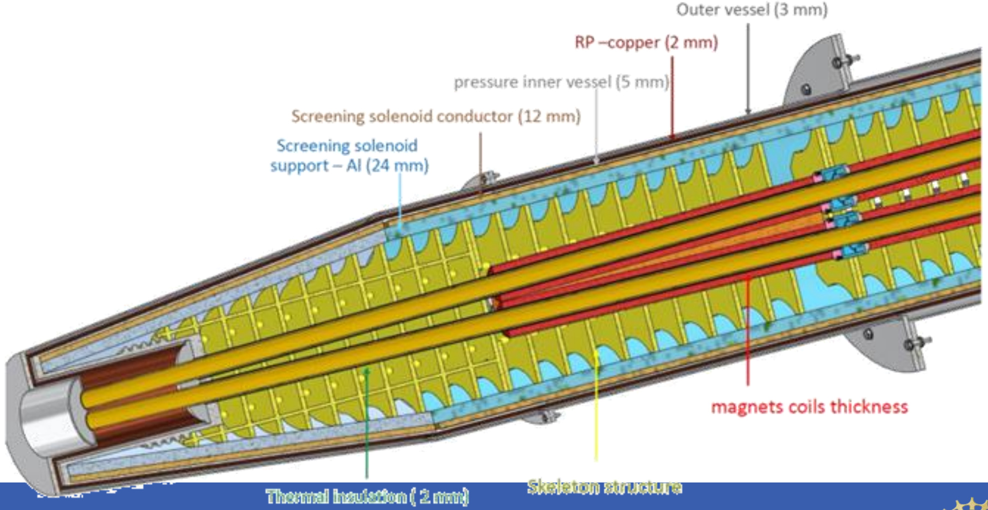
40 T magnet cross section

Potential BNL contributions to FCC-ee

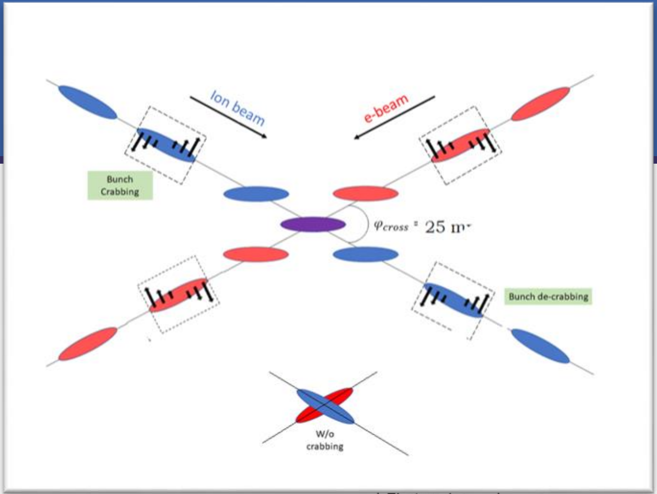
FCC-ee IR challenges

- 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.



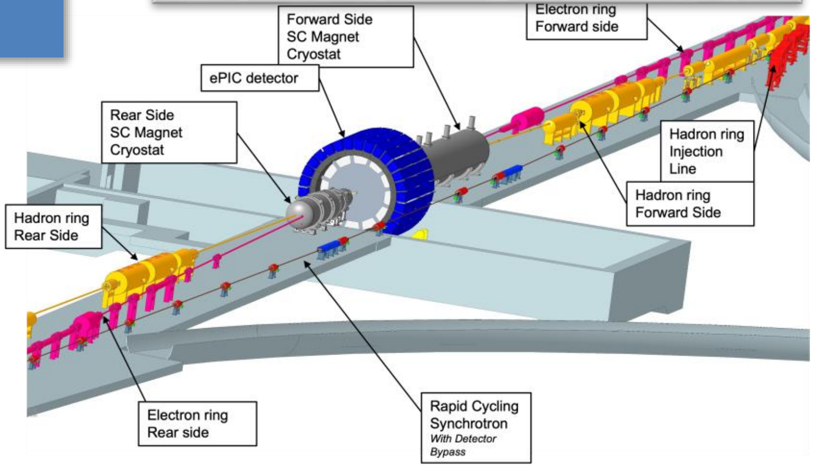


EIC Interaction Region



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

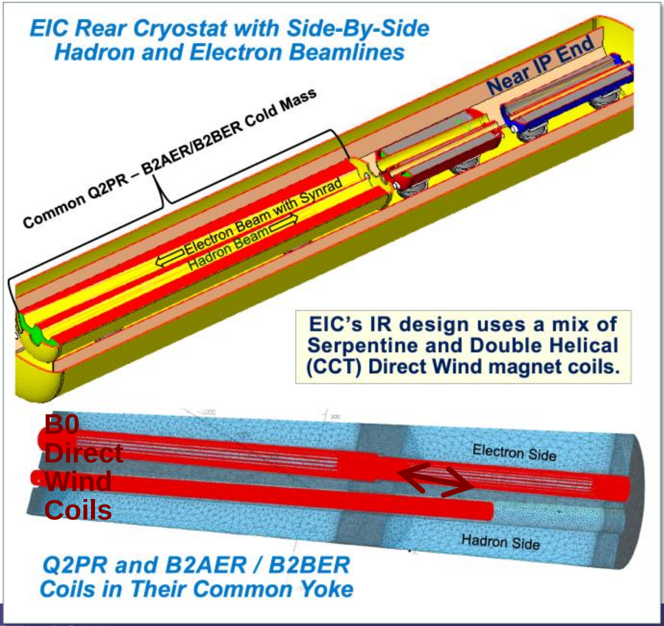
Machine Detector Interface
- Large detector acceptance
- Forward spectrometer
- No magnets within - 4.5 / +5 m from IP
- Space for luminosity detector, neutron detector, “Roman Pots”

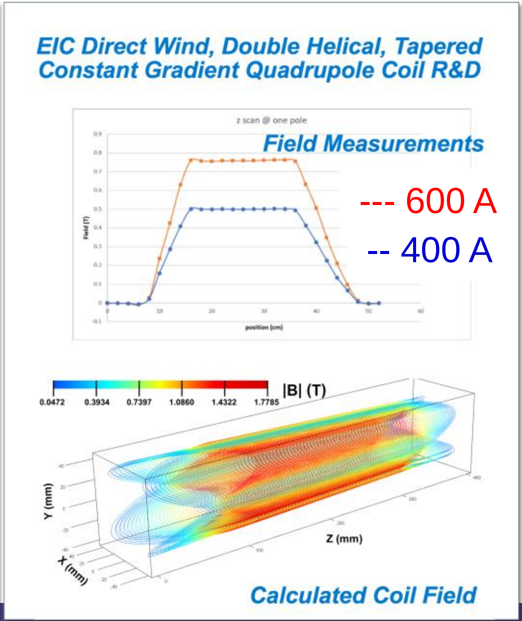


EIC IR Superconducting magnets

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



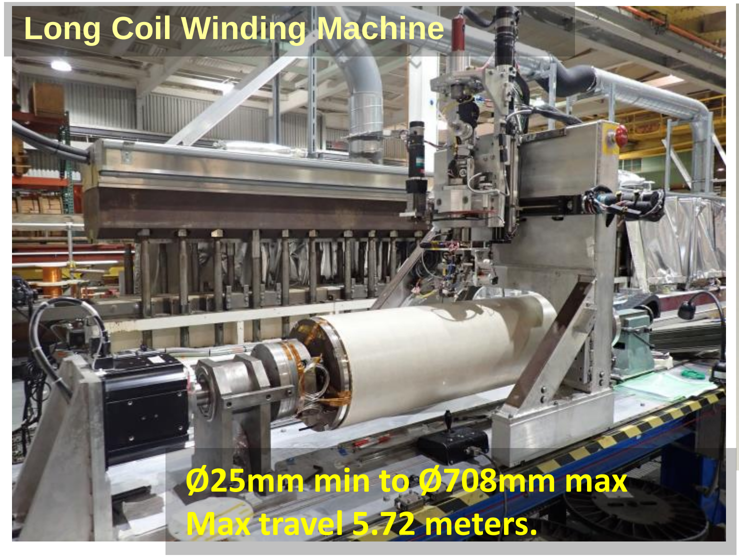


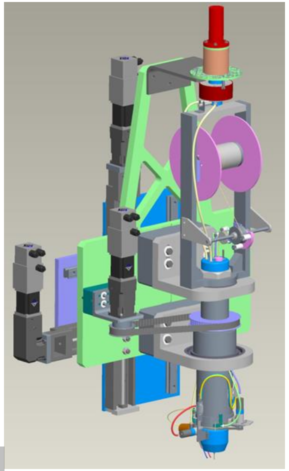
The FCC-ee IR magnets intrinsically require very carefully tailored field profiles to enable variable CM energy strong focusing while handling magnetic crosstalk and local optics correction (dipole, skew-dipole and skew-quadrupole coils).

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.**



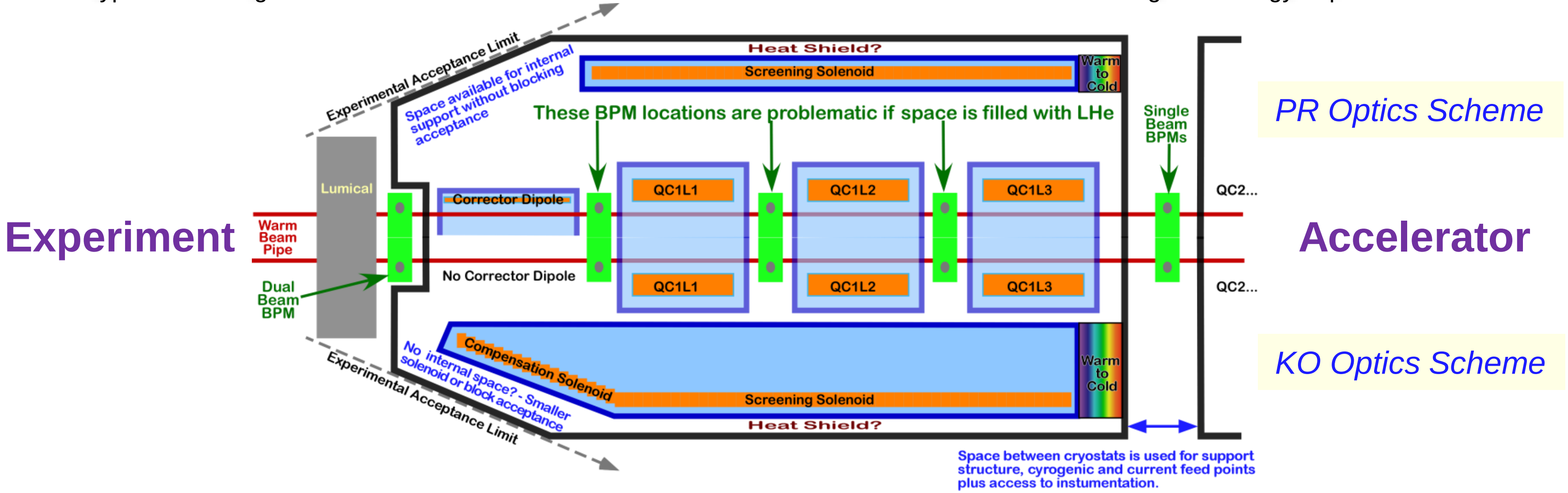


New winding heads providing greater speed, extended wire lengths for longer / larger diameter patterns.

Magnet Systems

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

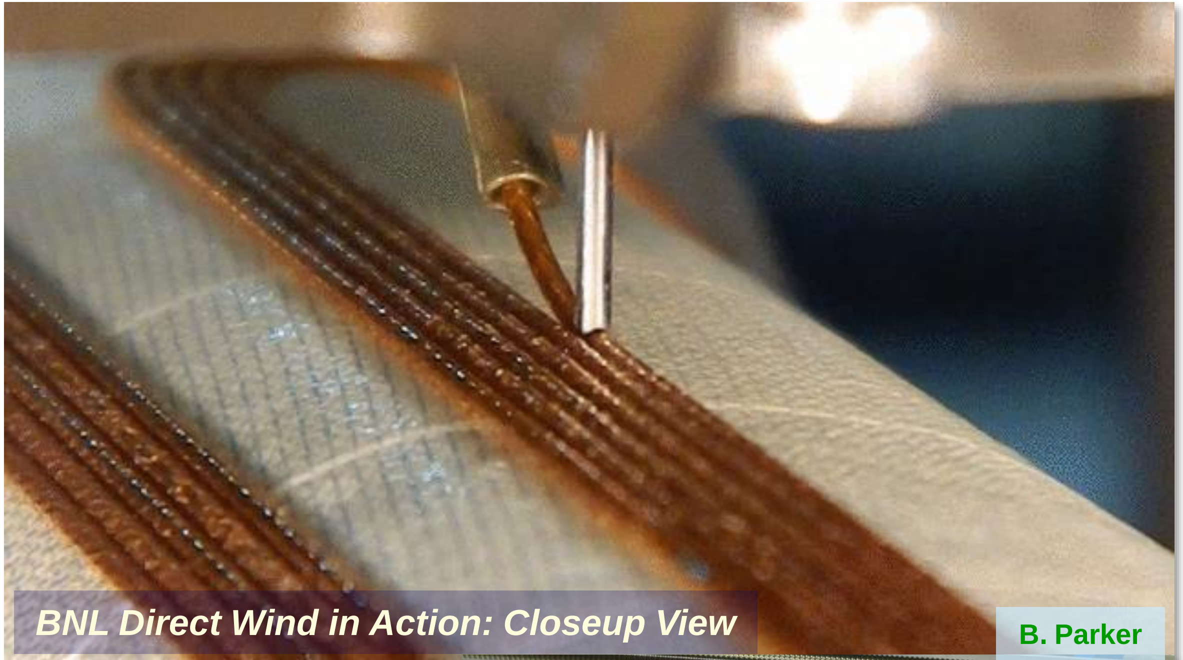
IR Magnet Design
Quadrupole strengths for different CM energies
Detector solenoid compensation implementation
Optics tunning and necessary correctors
Dealing with energy deposition in cold mass

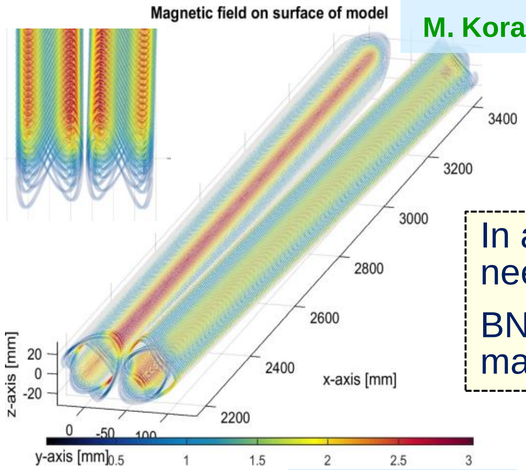


IR Cryostat Design
Cold mass optimization
Internal support structure
Thermal management
Internal BPM interface

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

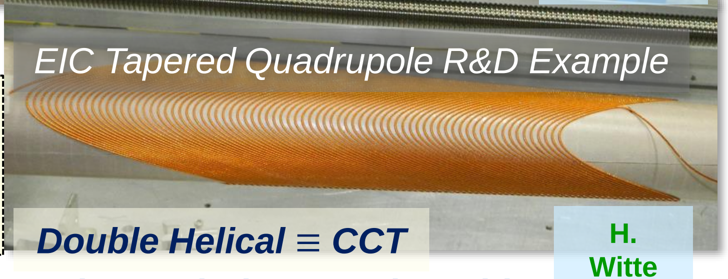




M. Koratzinos

In addition to main quad coils, FCC-ee needs a slew of correctors (b_1, a_1, a_2...).

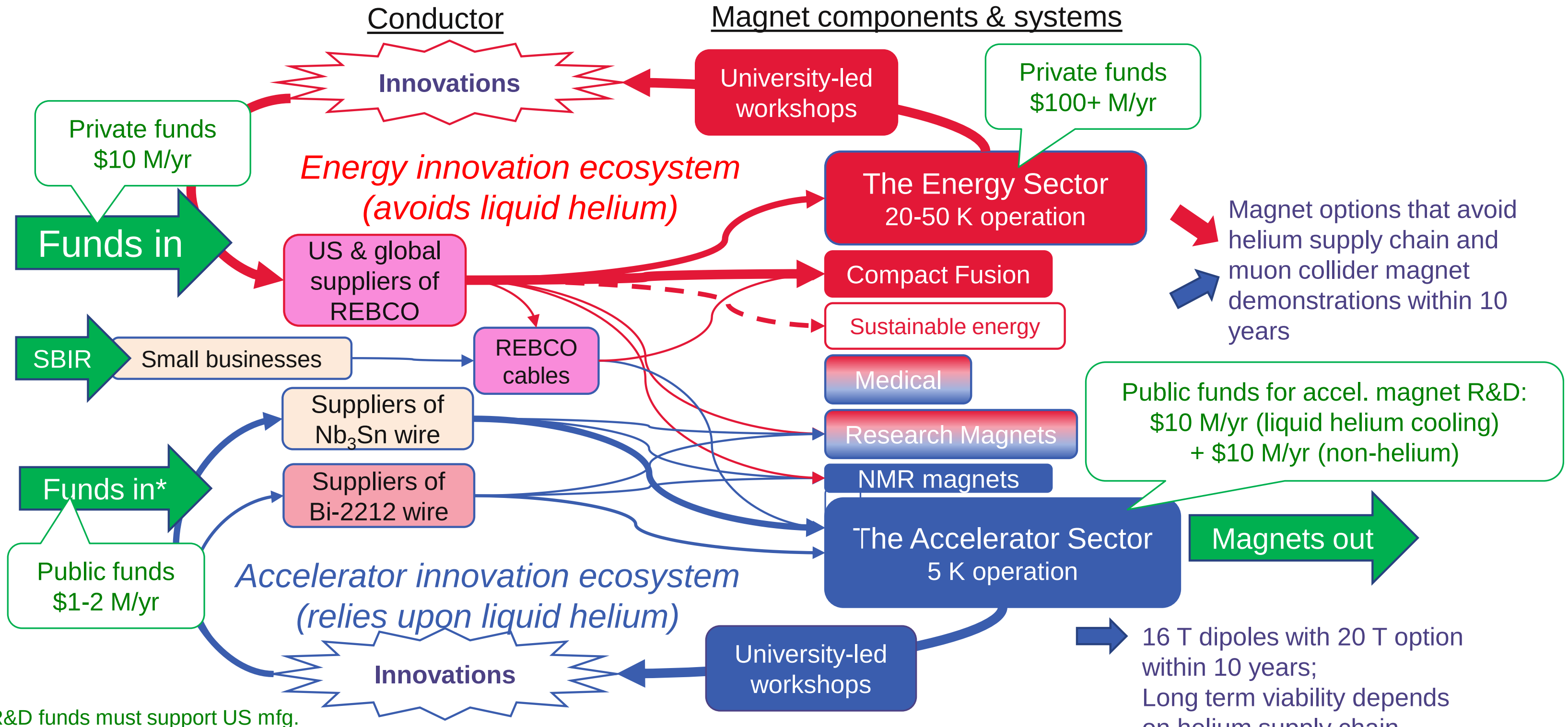
BNL Direct Wind process is natural for making the necessary correctors.



Direct Wind Tapered Double Helical Coil

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

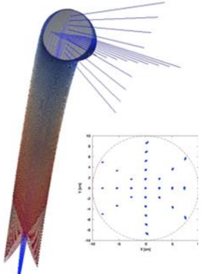
Physics → Facilities → Magnet and Materials Technology

Benefits more than particle and condensed matter physics

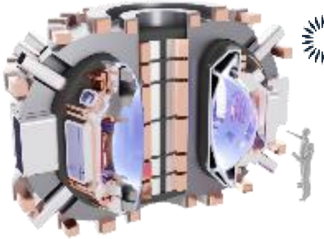
Broader Applications/Societal Benefits

Clean Energy

MRI and High Field Science



Particle Therapy



Commonwealth Fusion Systems

Compact Fusion Reactors

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 !

Kathleen Amm

ammk@magnet.fsu.edu

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