U.S. MAGNET DEVELOPMENT PROGRAM

US Magnet Development Program
Updated roadmaps - 2019

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US Magnet Development Program
Lawrence Berkeley National Laboratory

Outline

- Short review of overall program to-date
- Strategic considerations/areas driving the updated roadmaps
- Key directions and their motivations
- New roadmaps for key areas and their interconnections
- Summary

The program has been structured to align with the primary goals

Magnets	Lead
Cosine-theta 4-layer	Sasha Zlobin
Canted Cosine theta	Diego Arbelaez
Bi2212 dipoles	Tengming Shen
REBCO dipoles	Xiaorong Wang

Area I →

Area II →

Technology area	LBNL lead	FNAL lead
Modeling & Simulation	Diego Arbelaez	Vadim Kashikhin
Training and diagnostics	Maxim Martchevsky	Stoyan Stoynev
Instrumentation and quench protection	Maxim Martchevsky	Thomas Strauss
Material studies – superconductor and structural materials properties	Ian Pong	Steve Krave

Area III →

Cond Proc and R&D	Lance Cooley

Area IV →

US Magnet Development Program (MDP) Goals:

GOAL 1:

Explore the performance limits of Nb_3Sn accelerator magnets with a focus on minimizing the required operating margin and significantly reducing or eliminating training.

GOAL 2:

Develop and demonstrate an HTS accelerator magnet with a self-field of 5 T or greater compatible with operation in a hybrid LTS/HTS magnet for fields beyond 16 T.

GOAL 3:

Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.

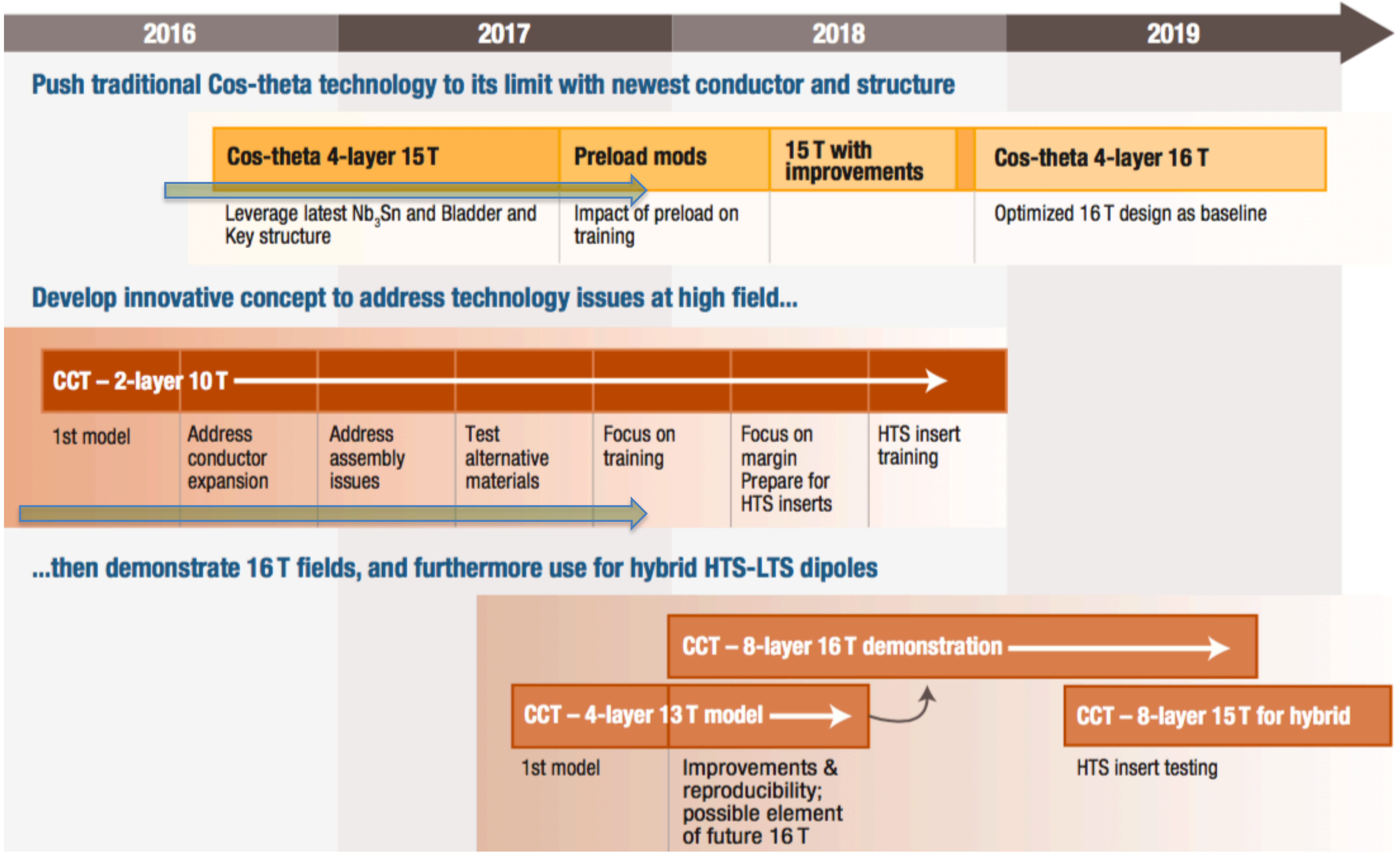
GOAL 4:

Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.

The MDP Nb3Sn magnet efforts had a two-pronged approach, based on ongoing efforts at the time and limited funding of the program

Area I: Nb_3Sn magnets

- Our focus has been on:
  - The Cos-t demonstrator
  - Investigation of the CCT concept



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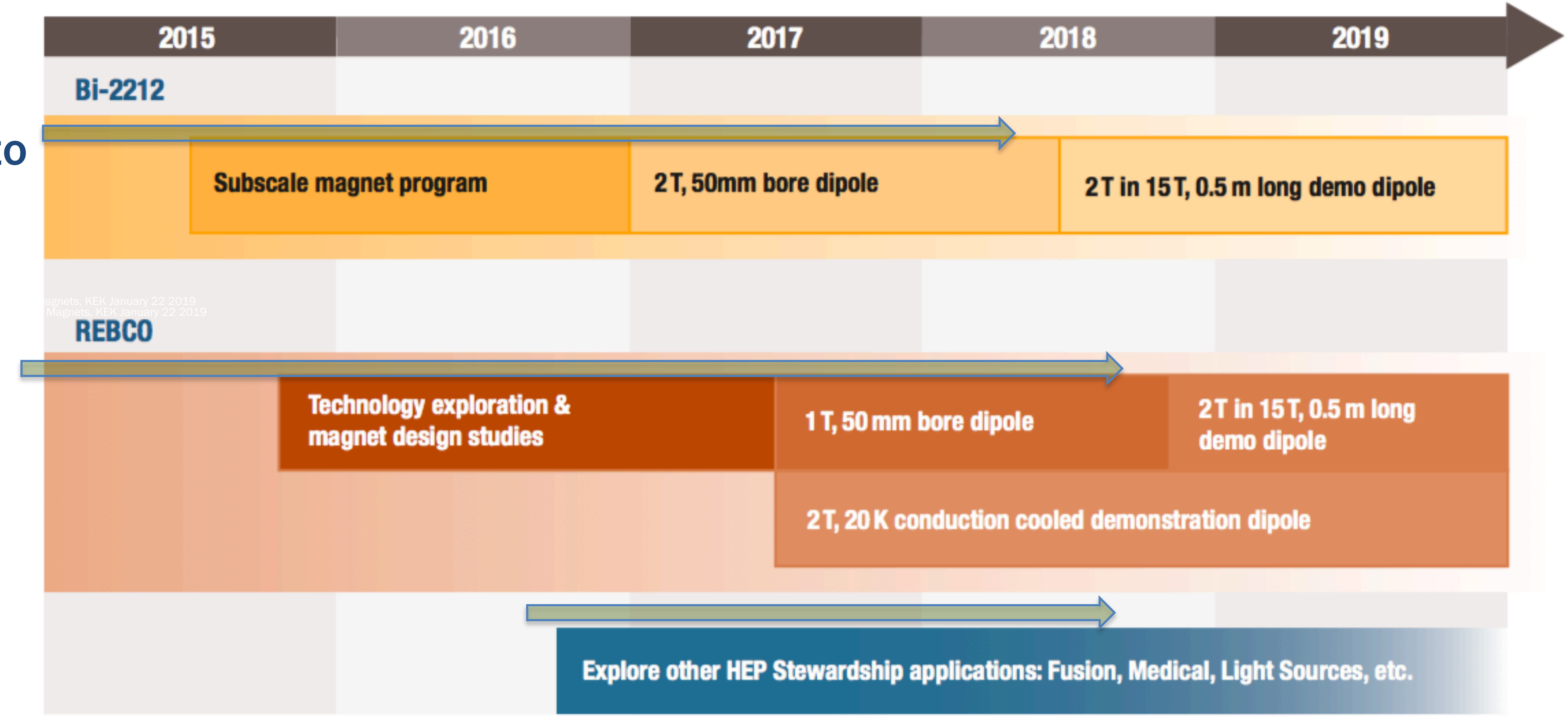
The MDP HTS magnet development was initiated with efforts in both REBCO and Bi2212

Area II: HTS magnet technology

- Focus has been on:
  - Racetrack Bi2212 to develop technology
    - Now starting CCT Bi2212 in preparation for hybrid testing
  - CCT REBCO coil development



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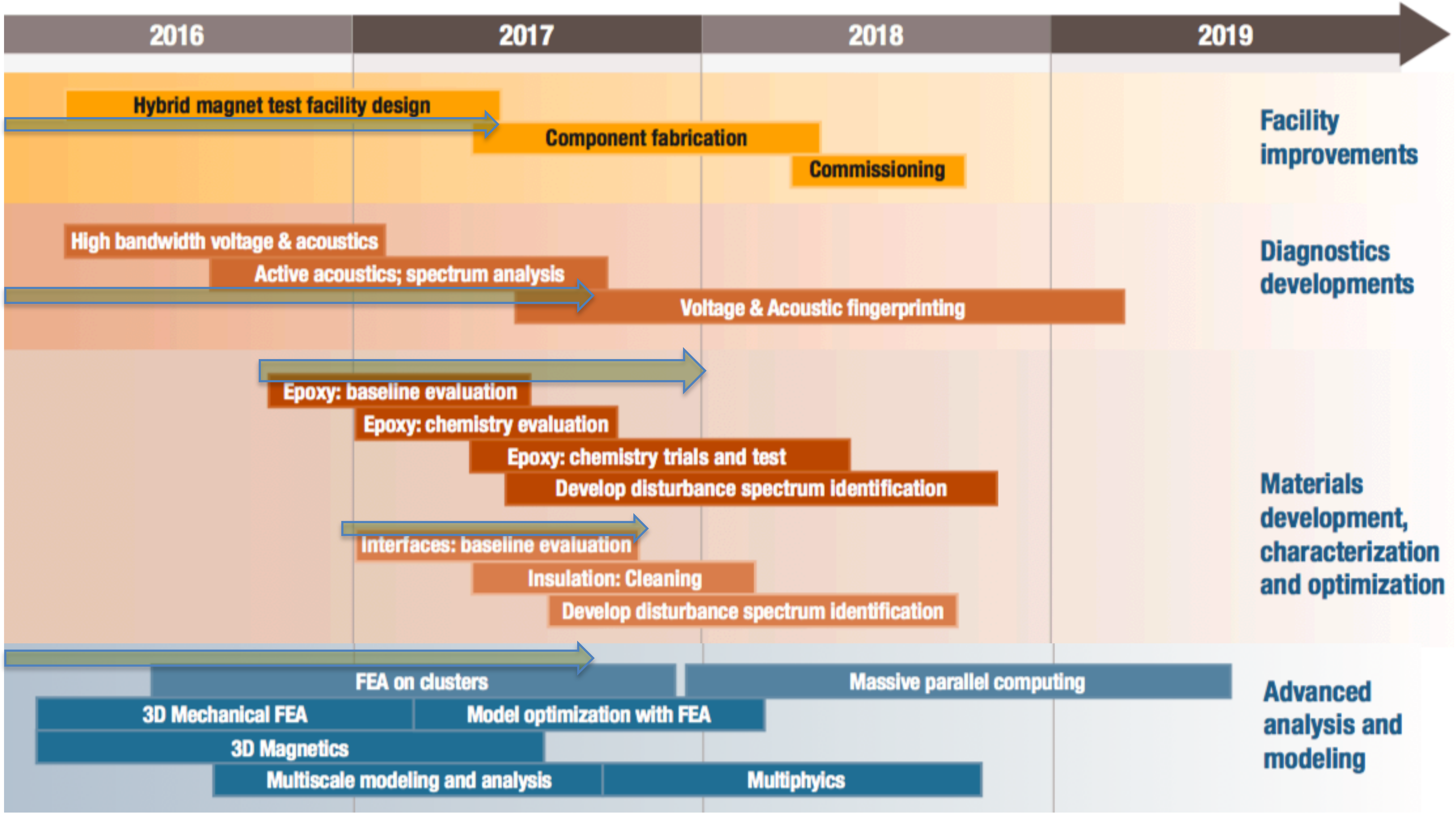
A key science components of the MDP Plan is Technology Development, focused on enhancing our understanding of what drives magnet performance

Area III:

The science of magnets: identifying and addressing the sources of training and magnet performance limitations via advanced diagnostics, materials development, and modeling

Focus has been on

- advanced modeling with user-defined Ansys finite elements
- Passive and active acoustic diagnostics
- Investigation and testing of alternative epoxies



Conductor development has been pursued through leveraged investments and coordination of industrial efforts

Area IV: Conductor Development

- Nb_3Sn advances continue to be pushed
  - ✓ Very significant potential of APC and Hf-doped material is materializing – can it become commercially viable?

- Advances in Bi2212 powder processing + overpressure processing
  - ✓ Dramatic improvement in wire Jc – now surpasses Nb_3Sn above 11T

- REBCO development focused on leveraging SBIR and complementary programs;
  - ✓ MDP provides measurements and conductor performance feedback to developers and vendors
  - ✓ Focus is on CORC cables – route to competitive wire Jc has been identified and steady progress made

- *Determining the performance limits of Nb_3Sn and HTS conductors.*
- *Understanding uniformity and reliability, especially of HTS*
- *conductors.*
- *Understanding of future conductor scalability and cost.*
- *Evaluating factors critical for eventual worldwide capacity ramp-up for future projects so as to minimize start-up costs and allow more competition.*

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Roadmap for Conductor Procurement, Research and Development
October 6, 2017

Covering DOE FY 2018

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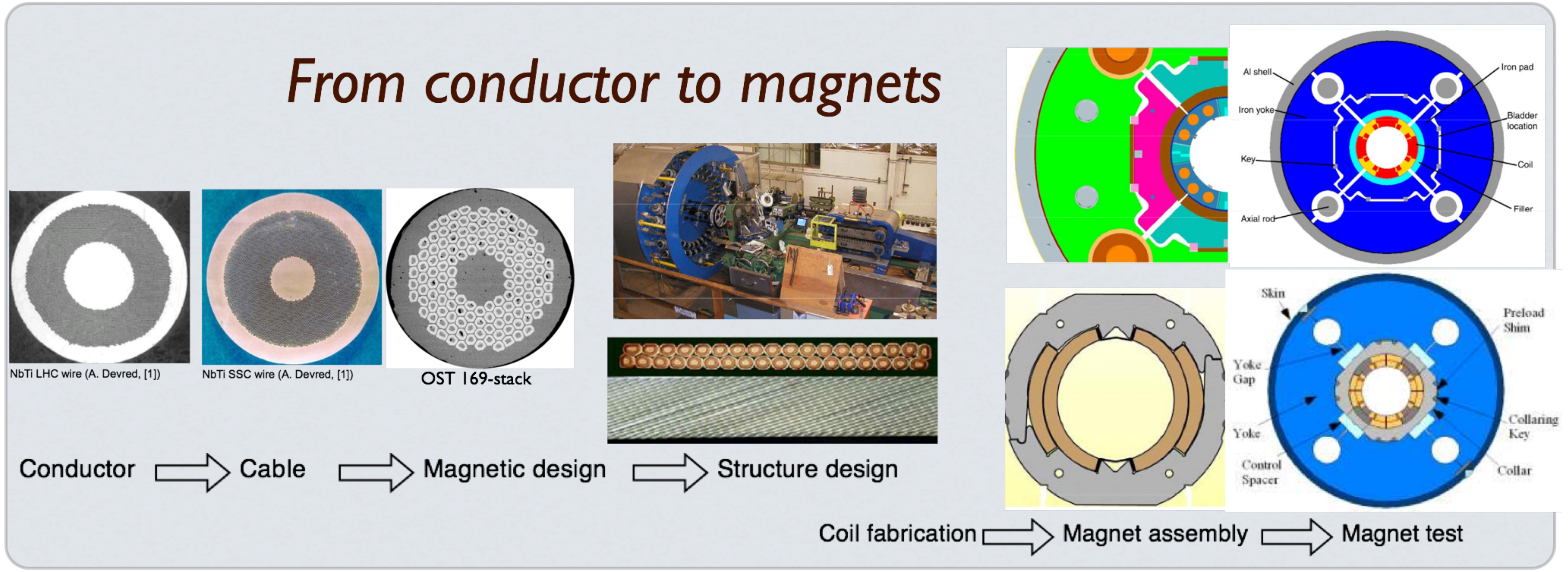
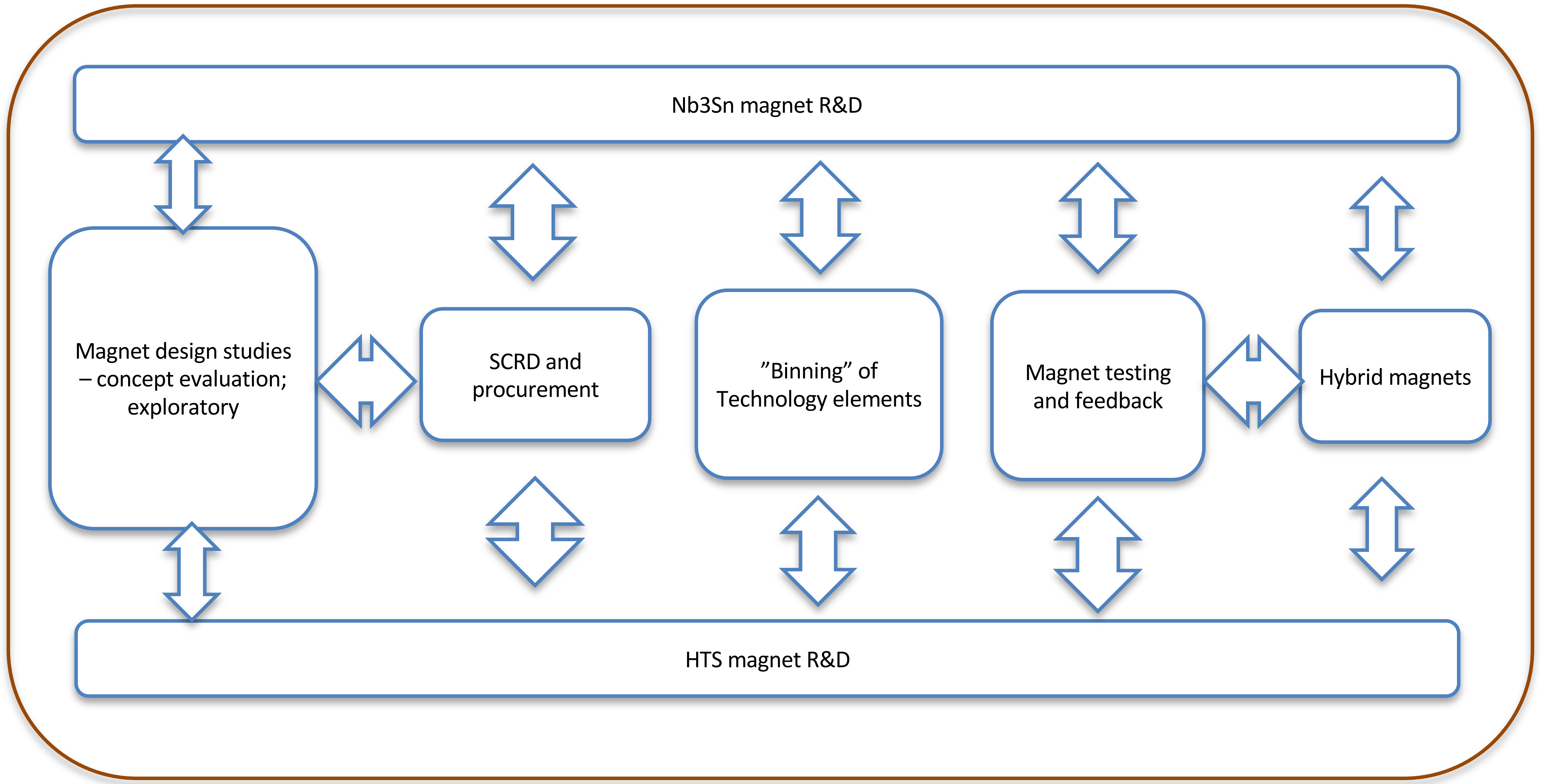
Strategic considerations/areas driving the updated roadmaps

- **Based on progress to-date and the perspective of MDP scientists and engineers, the program roadmaps will focus on the following strategic directions:**
  - **Probing stress management structures**
  - **Hybrid LTS/HTS designs**
  - **Understanding and impacting the disturbance spectrum**
  - **Advancing both LTS and HTS conductors, optimized for HEP application**

These elements are pursued in parallel

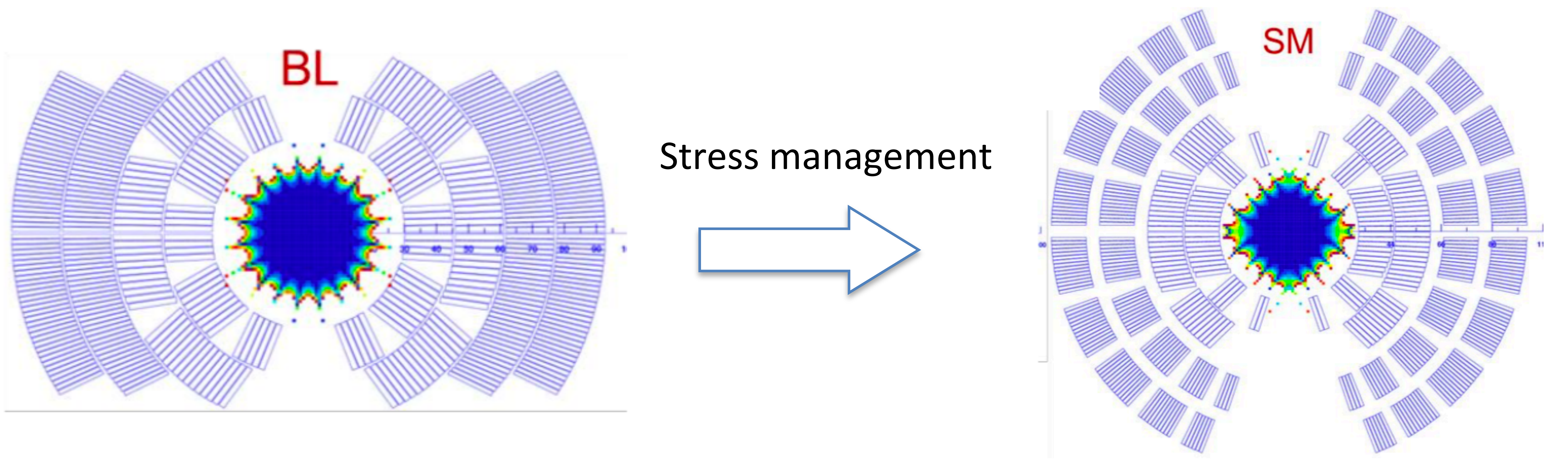


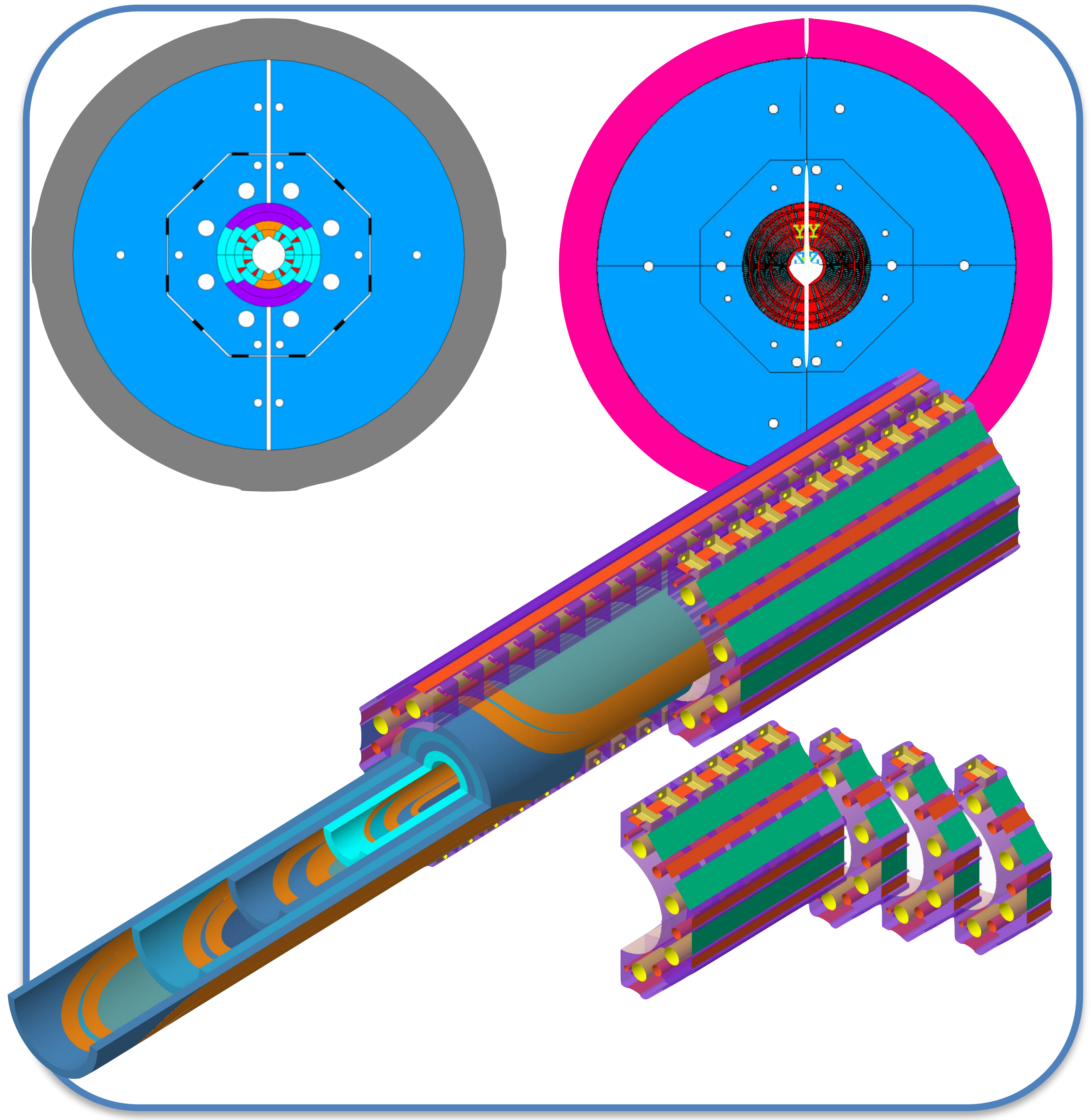


Strategic direction 1: Addressing strain-sensitivity of high-performance superconductors through stress managed structure concepts

- Stress-management structures
  - Combination of high-field and strain-sensitive materials motivates structures that "control" strain
    - Nb_3Sn, REBCO, and Bi2212 are all strain-sensitive and susceptible to degradation
  - Q: can we avoid shifting the problem to interfaces, or engineer the interfaces to mitigate disturbances?

Example: SMCT concept and a "utility structure" design

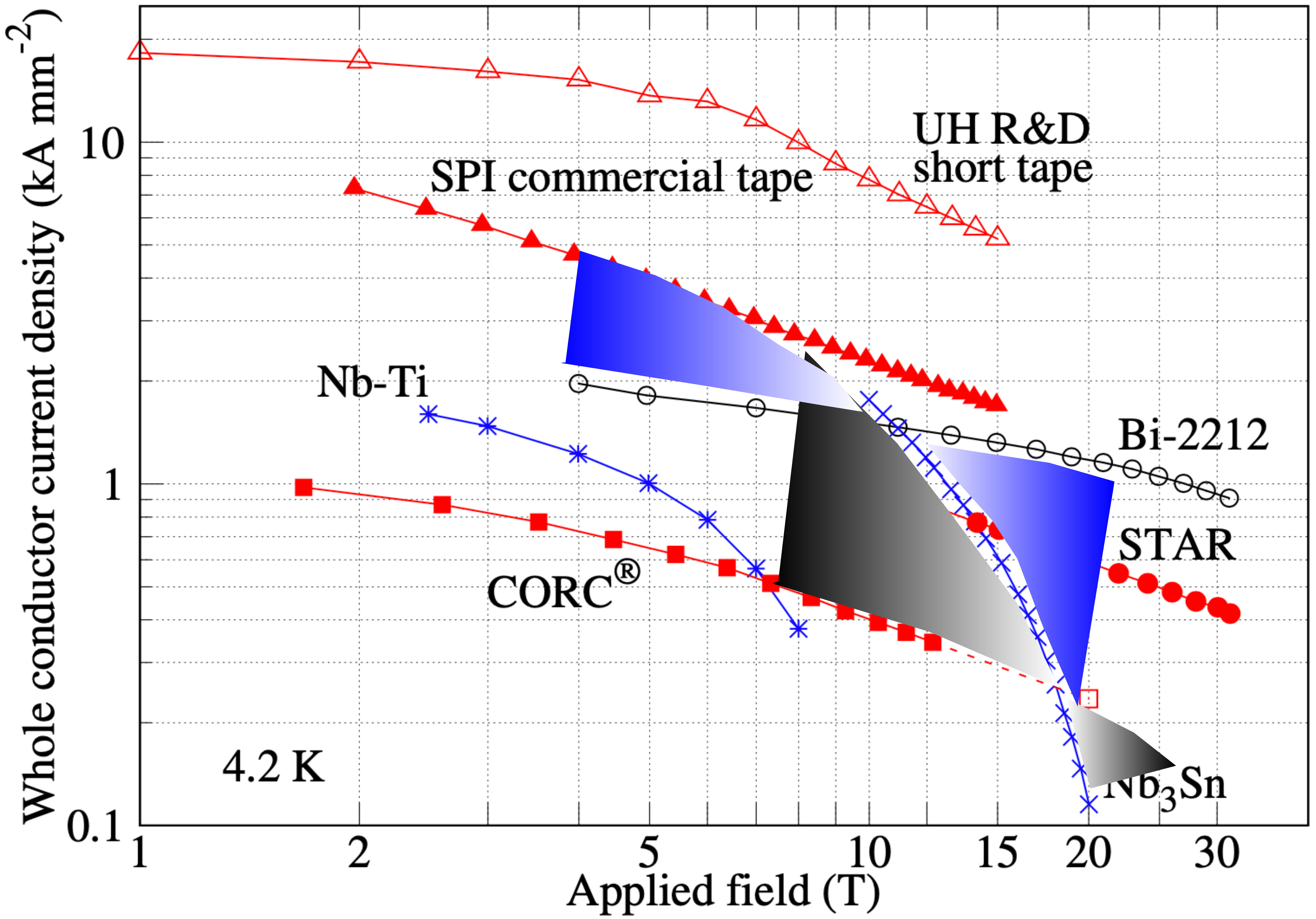




Strategic direction 2: Investigate the potential for hybrid LTS/HTS accelerator magnets

- **Hybrid LTS/HTS designs**
  - Current conductor costs make hybrid designs necessary
  - Requires integrated designs, fabrication techniques, testing infrastructure
  - Q: do hybrid designs inherit the “best” or “worst” c LTS and HTS materials?

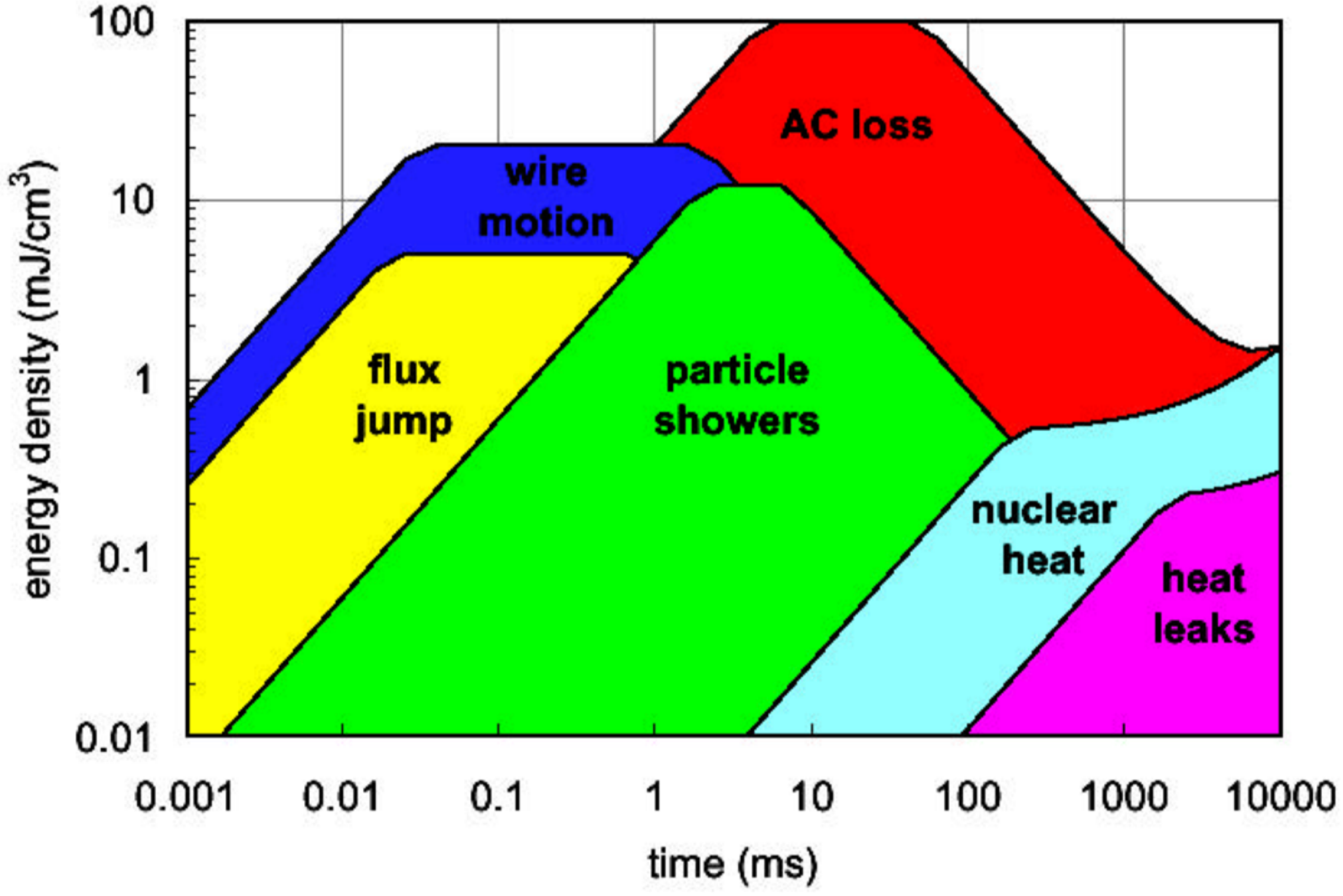
We are also evaluating all-HTS magnet designs, should HTS conductor cost reduce substantially and the potential for training-free behavior of HTS magnets hold up at high field



Strategic direction 3: Quantify, and identify mechanisms to influence, the disturbance spectrum

- Understanding and impacting the disturbance spectrum
  - Improvements in diagnostics (many first pursued decades ago) are providing dramatic insight into the disturbance spectrum
  - Advances in magnet materials (e.g. epoxies) and conductors (e.g. high Cp-doping) promise some ability to impact the spectrum and conductor response
  - Q: can we engineer control of the disturbance spectrum and magnet response to reduce operating margin and enhance reliable performance?

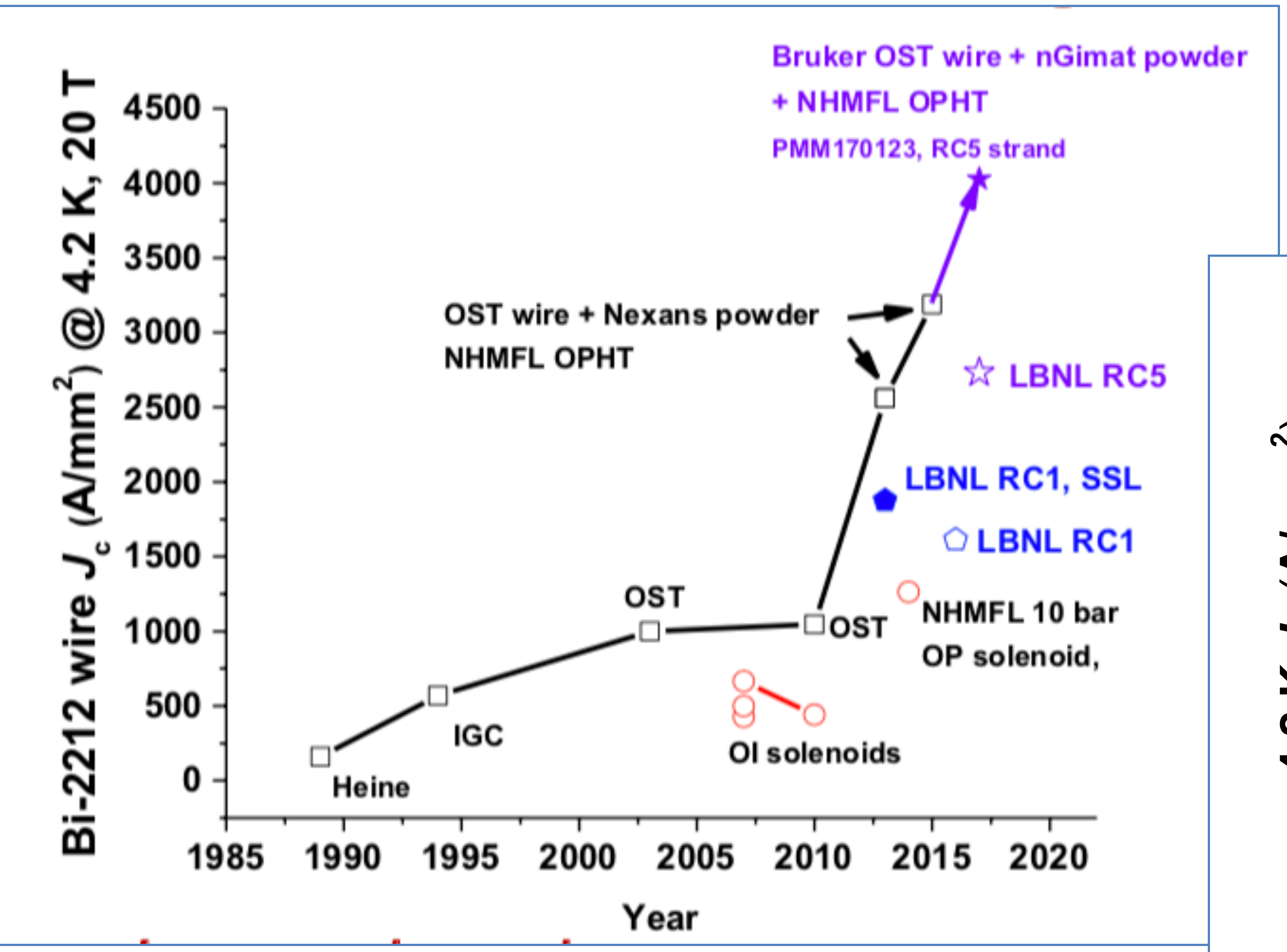
Luca Bottura



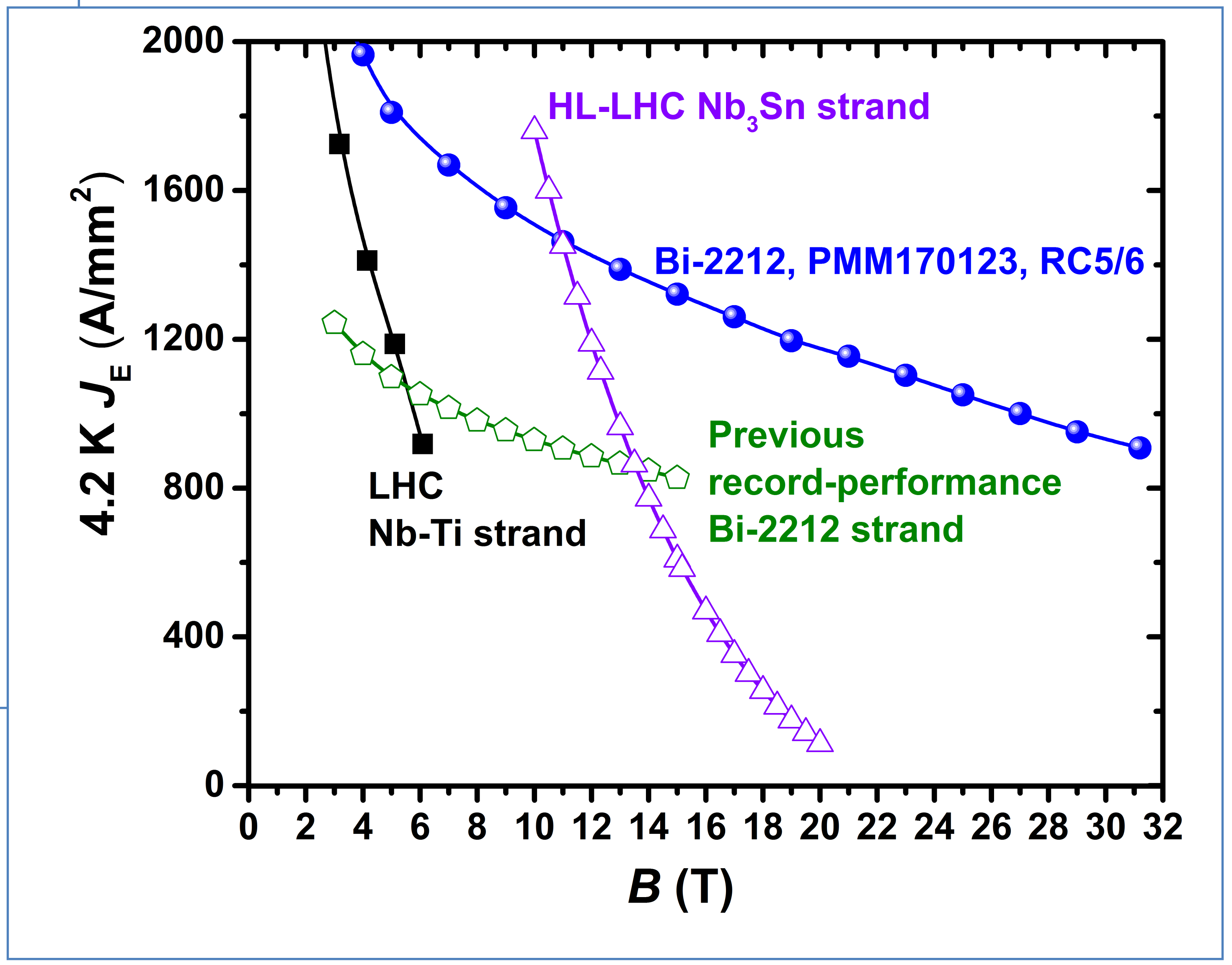
Diagnostics requirements:
- Large bandwidth to address temporal regimes
- Sufficient sensitivity to discern energy deposition regimes
- Redundancy with independent physics to tighten σ

Strategic direction 4: Pursue advances in both LTS and HTS conductors, where opportunities for significant breakthroughs are most likely

- Push for advances in Nb_3Sn conductors (APC/Hf and high-Cp doping)
- Support the maturation of HEP-relevant, industry-produced, HTS materials



Bi2212 R&D with industry/University/lab collaboration very effective

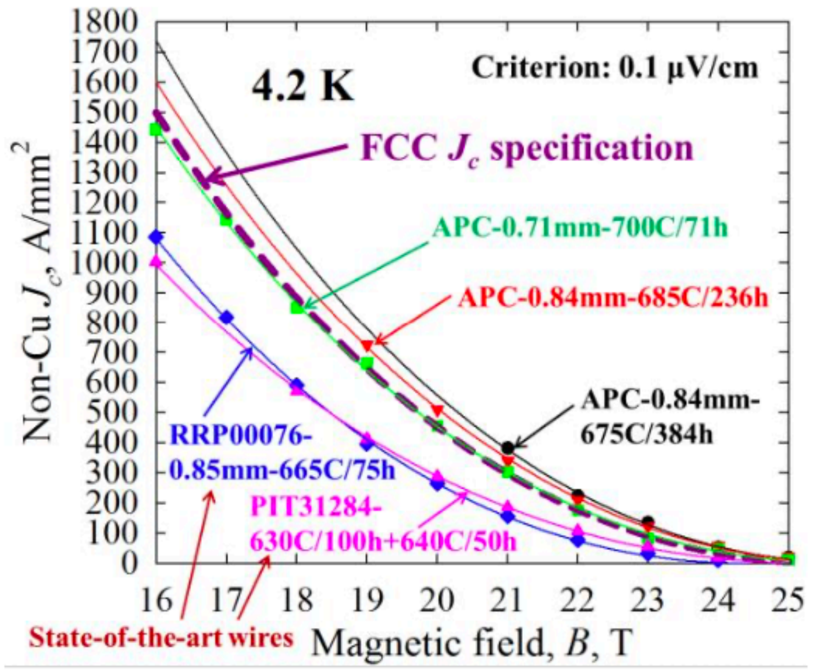


Felice, MT26 Plenary

Artificial Pinning Center

Courtesy of X. Xu

Internal oxidation of Nb-1%Zr
- Pinning point: ZrO_2 particles
- enhance J_c
- High J_c but stability < 16 T compromised
- Small Magnetization but J_c compromised



Collaboration between FNAL [LDRD], Hypertech and OSU

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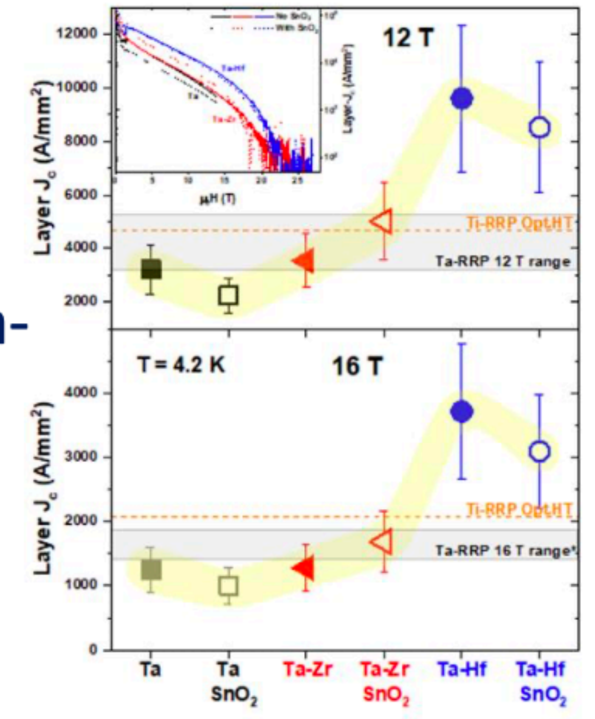
Hf alloying of Nb-Ta

Courtesy of S. Balachandran

- Improved pinning through Hf dopping
- Nb or NbTa rods can be replaced by Nb-Ta-Hf alloy without change of architecture
- Prototype wire *(Extrapolated values)*

Alloy	SnO_2	J_{clayer} (A/mm²) 12 T	16 T	Eq. RRP non-Cu J_c 16 T (A/mm²)
Nb-Ta-Hf	No	9609 ±2744	3714 ±1061	2229 ± 636
Nb-Ta-Hf	Yes	8523 ±2434	3093 ± 883	1856 ± 530



Jan Evetts SUST Award 2019

Shows untapped potential of Nb_3Sn
Optimization in progress

ASC/NHMFL, FSU

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Top-down program – a management perspective

Detailed roadmaps have been developed in a bottoms-up manner, with lead researchers coordinating input

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Updated Roadmaps:

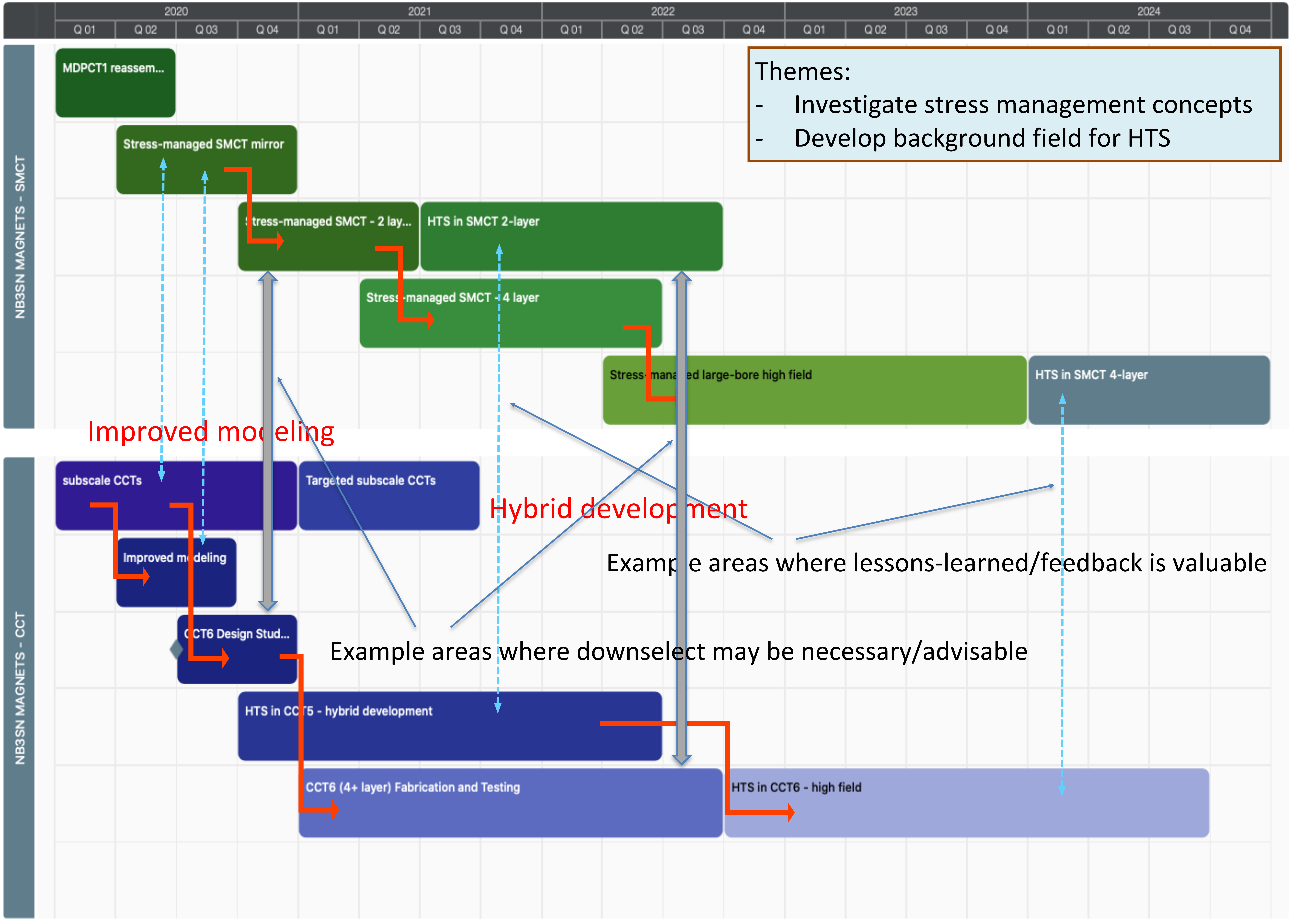
Nb_3Sn Magnets

1. "Stress-managed" cos-theta (SMCT)
2. Continued CCT development

Leverage opportunities for sharing lessons-learned

Multiple scenarios for HTS insert testing – provides robustness

Potential for "downselect" of technology for more costly large magnets



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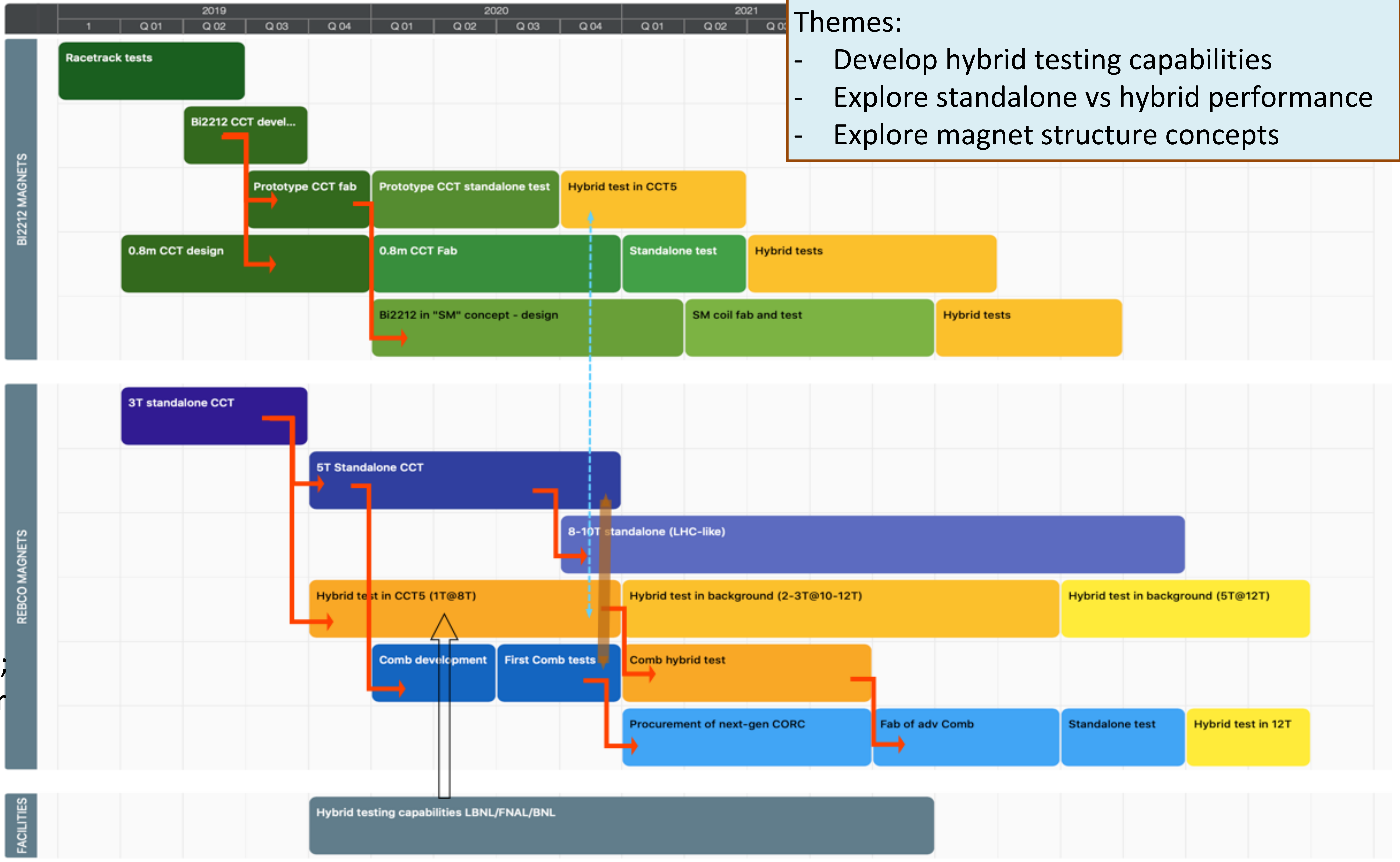
Themes:
- Develop hybrid testing capabilities
- Explore standalone vs hybrid performance
- Explore magnet structure concepts

Updated Roadmaps: ***HTS Magnets***

Continue to pursue REBCO and Bi2212 technology

Growing multi-lab interest; addition of BNL adds experience

Hybrid testing dominates landscape; multiple scenarios for HTS insert testing provides robustness



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Updated Roadmaps: *Technology*

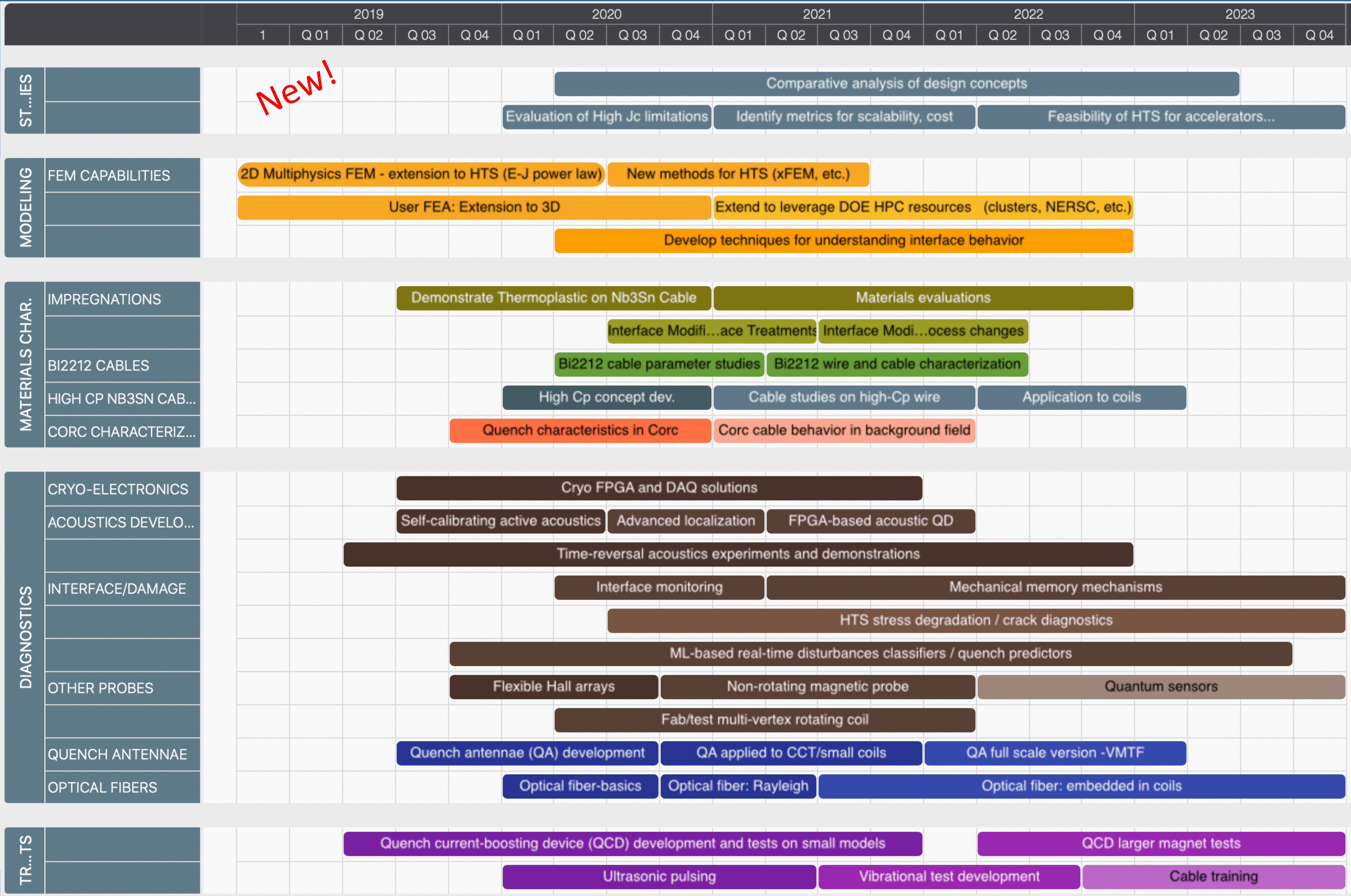
Leverage advanced computing: FEM, systems modeling, and machine learning

Invest in magnet materials, e.g. impregs.

Rapidly advance independent diagnostic capabilities

Investigate potential for training rate enhancement

Study future directions: alternative cost-effective concepts



U.S. DEPARTMENT OF ENERGY | Office of Science

Some thoughts on our roadmaps so far – Nb3Sn magnets

- ***Magnets*** are drivers for the program
  - … but can at best be only as good as the conductors that go into them, motivating continued conductor R&D

- Our focus / driving consideration is ***stress-management***
  - The program must deliver on the question: “Can stress-managed structures really work?”
    - Q: How do we define ”success” for a given structure?
    - Q: What technical insights are most effective at addressing limitations?
    - Q: What specific experiments are most useful to feed magnet design/fab/test?
  - Design studies can predict, and model magnet R&D has to confirm,
    - To what degree SM structures deviate from “traditional” Cos-t, block, common coil,…
    - How structures (in particular SM) are impacted by / leverage advanced Nb_3Sn
    - What additional limitations are encountered by advanced Nb_3Sn (protection, stability,…)
  - Try to quantify scalability & cost drivers for various structures

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Some thoughts on our roadmaps so far – HTS magnets

- We are still just developing basic HTS magnet technology…
  - But the path to high field is fairly clear

- We should identify key questions along the way and how we intend to answer them
  - Q: Do we need to worry about HTS magnet training and degradation?
  - Q: Do HTS magnets need traditional protection, e.g. extraction, heaters, etc.?
  - Q: Is hybrid operation effective, or do we inherit problems from both HTS and LTS?

- We plan significant hybrid tests
  - Pursuing a multi-pronged approach:
    - BNL has some hybrid testing capability; near term focus for MDP is on Corc cable tests
    - LBNL is developing hybrid testing capability; near term plan is to use CCT5
    - FNAL is developing hybrid testing capability as part of HTS cable test facility
    - What questions will these tests answer? Is there a priority (in time? Cost?)

Some thoughts on our roadmaps so far – Technology

- Lots of ideas and concepts to explore
  - Need to keep focus on questions that drive magnet performance
  - Need to strongly leverage "outside" sources – if they can benefit from a technology development, lets strive for "skin in the game"
  - Lets not reinvent the wheel
    - Always reach out to "current" experts, give them credit, and get us up to speed as quickly as possible
    - Then collaborate with the "current" experts to move things along faster
      - Our reputation should be one of an ***"excellent collaborator"***

- We need to identify the platforms being used for various studies
  - Ex: what is the right test bed for the "QCD" experiments?
  - Are the machine learning databases "generic", or magnet-specific? How will we be able to tell?

MDP Update Roadmaps: summary

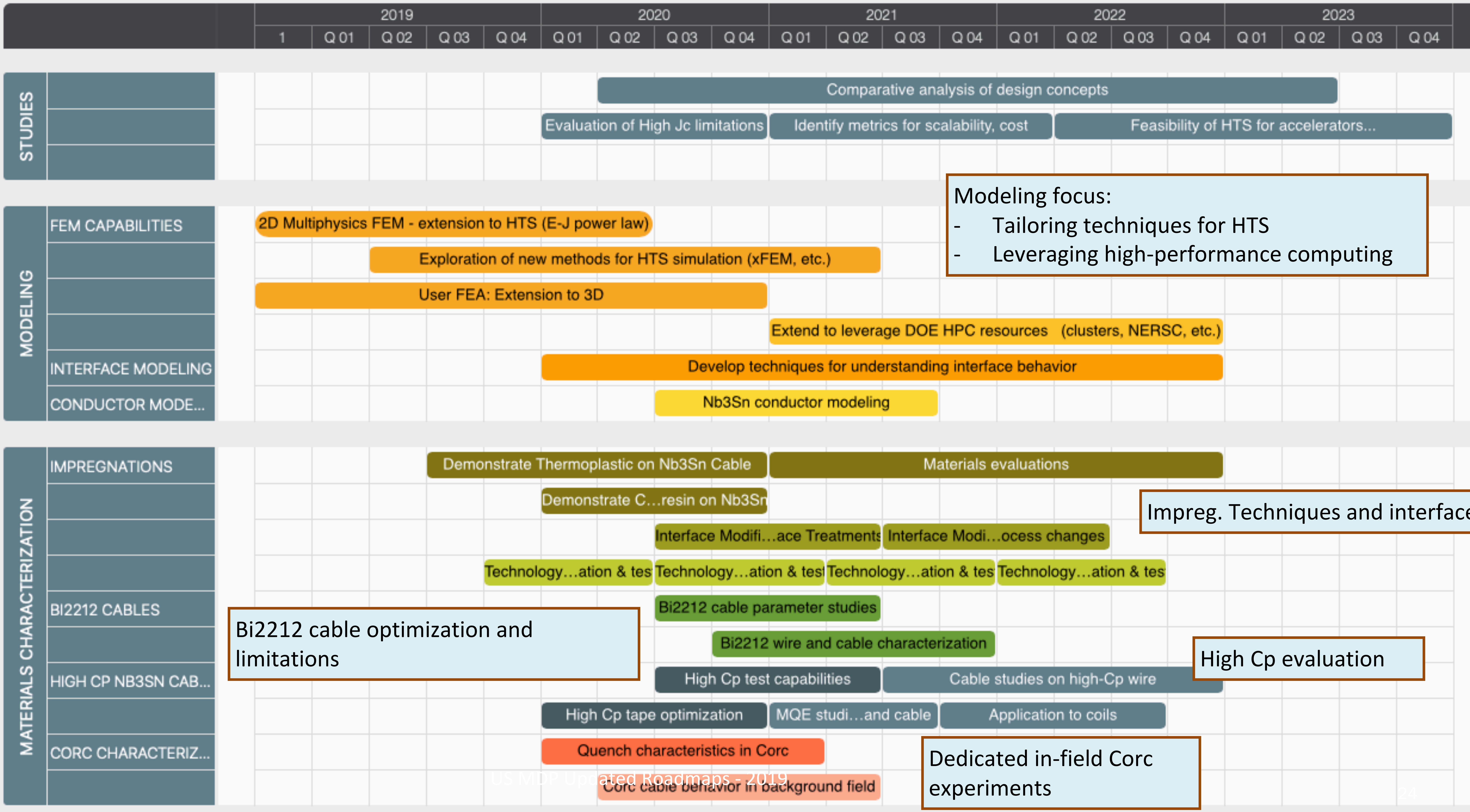
- Push for advances in Nb_3Sn conductors (APC/Hf and high-Cp doping), and magnet designs that can leverage the enhanced performance
- Support the maturation of HEP-relevant, industry-produced, HTS materials
- Continue to advance HTS magnet technology, with a focus on hybrid magnet designs that explore and test HTS accelerator magnet designs at high field
- Advance technology areas on multiple fronts:
  - Modeling of interfaces to guide design and materials optimization
  - Modeling of hybrid systems to support safe series and parallel hybrid magnet testing scenarios
  - Develop a suite of impregnation materials and techniques tailored to magnet needs, in particular to reduce intrinsic strain from diff. thermal contraction, and to reduce energy dep. during operation
  - Continue to advance a “toolbox” of diagnostics that provide insight into magnet performance, in particular the disturbance spectrum, with focus on providing feedback to magnet design
    - Using diagnostic data, leverage machine learning algorithms to identify hidden interconnections and prognosis capabilities
  - Initiate a design studies effort that focuses on identifying and prioritizing additional design concepts that should be explored if resources were made available

Backup slides

Roadmaps were updated with input and discussion from all team members

- A series of six group meetings were devoted to discussions on roadmaps
- Coordinators were identified for each of the key areas, and tasked with communicating with interested parties to generate draft roadmaps
- In the Technology arena, a plethora of ideas were submitted and discussed
- A major requirement of any roadmap element is that it have a well-articulated connection to one or more of the MDP goals;
  - A suggested approach was to identify questions associated with the goals that the roadmap element will answer

Technology areas support the magnet developments



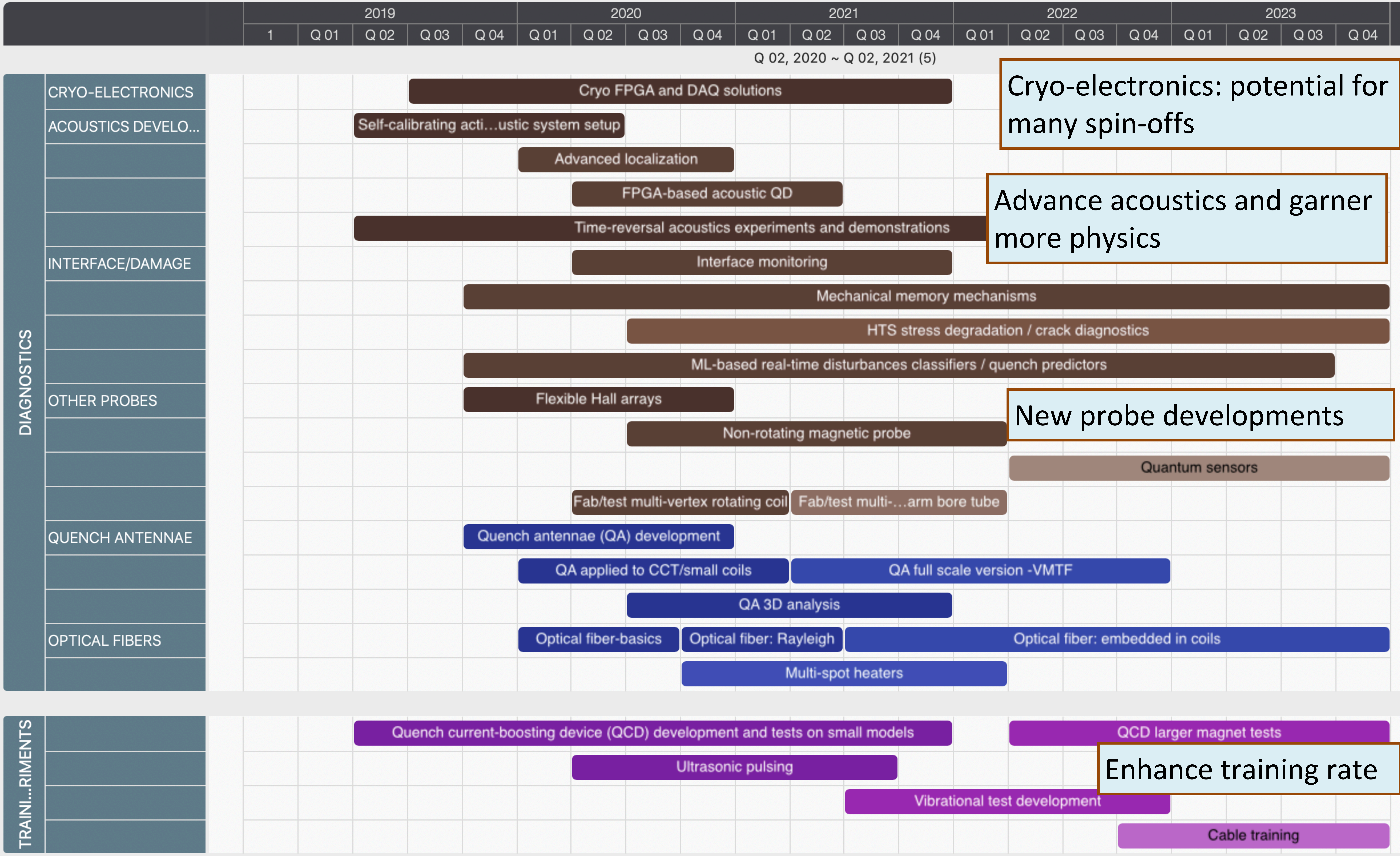
Modeling focus:
- Tailoring techniques for HTS
- Leveraging high-performance computing

Impreg. Techniques and interface

Bi2212 cable optimization and limitations

High Cp evaluation

Dedicated in-field Corc experiments


2019
2020
2021
2022
2023
1
Q 01
Q 02
Q 03
Q 04
Q 02, 2020 ~ Q 02, 2021 (5)
DIAGNOSTICS
CRYO-ELECTRONICS
Cryo FPGA and DAQ solutions
ACOUSTICS DEVELO...
Self-calibrating acti…ustic system setup
Advanced localization
FPGA-based acoustic QD
Time-reversal acoustics experiments and demonstrations
INTERFACE/DAMAGE
Interface monitoring
Mechanical memory mechanisms
HTS stress degradation / crack diagnostics
ML-based real-time disturbances classifiers / quench predictors
OTHER PROBES
Flexible Hall arrays
Non-rotating magnetic probe
Quantum sensors
Fab/test multi-vertex rotating coil
Fab/test multi-…arm bore tube
QUENCH ANTENNAE
Quench antennae (QA) development
QA applied to CCT/small coils
QA full scale version -VMTF
QA 3D analysis
OPTICAL FIBERS
Optical fiber-basics
Optical fiber: Rayleigh
Optical fiber: embedded in coils
Multi-spot heaters
TRAINI...RIMENTS
Quench current-boosting device (QCD) development and tests on small models
QCD larger magnet tests
Ultrasonic pulsing
Vibrational test development
Cable training
Cryo-electronics: potential for many spin-offs
Advance acoustics and garner more physics
New probe developments
Enhance training rate