Progress towards advanced modeling tools to explore HTS CORC® wire performance and guide its further optimization

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SuperPower Inc.
A Furukawa Company

BERKELEY LAB

CORC® Cables and Wires Pioneered by Advanced Conductor Technologies

CORC® cable principle based on strain management
Winding many high-temperature superconducting REBCO coated conductors from SuperPower in a helical fashion with the REBCO under compression around a small former to obtain high cable currents

CORC® wires (2.5 – 4.5 mm diameter)

- Current in the order of 5,000 A (4.2 K, 20 T)
- Flexible with bending down to < 50 mm diameter

CORC® cable (5 – 8 mm diameter)

- Current in the order of 10,000 A (4.2 K, 20 T)
- Flexible with bending down to > 100 mm diameter

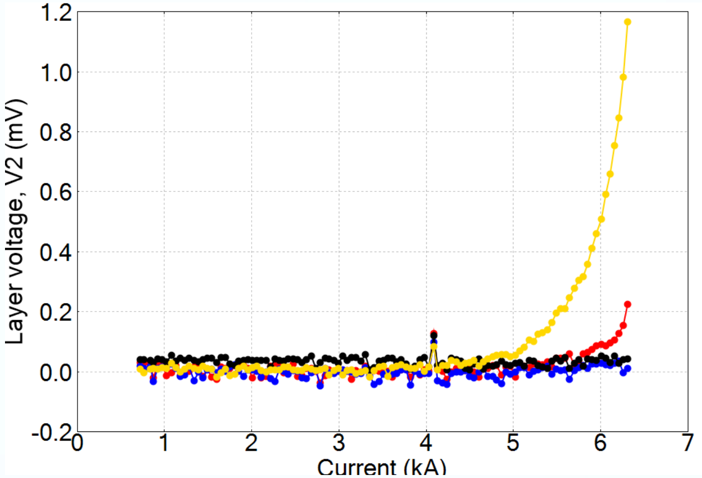
CORC®-Cable In Conduit Conductor (CICC)

- Performance as high as 100,000 A (4.2 K, 20 T)
- Bending diameter about 1 meter

CORC® Cable Development for High-Field Magnets

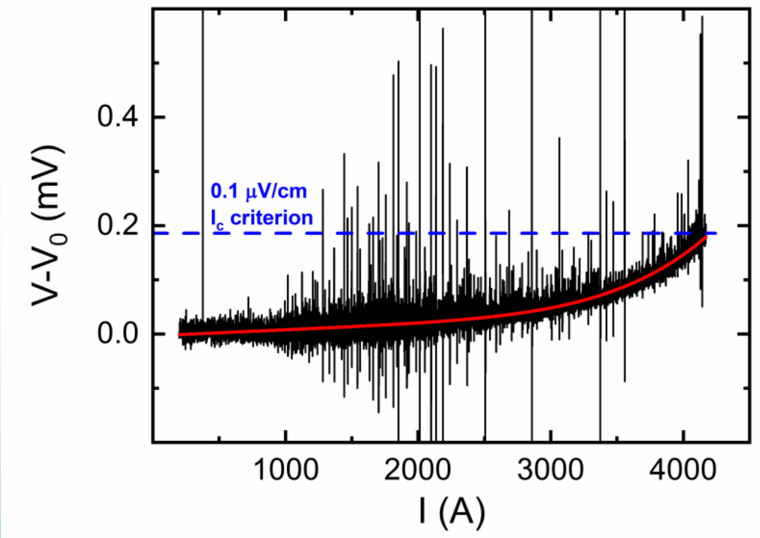
Canted-cosine-theta (CCT) accelerator magnets (with LBNL)

- Ultimately reach 20 T dipole field in LTS/HTS hybrid
- Recently achieved 2.9 T in a stand-alone CORC®-CCT



High-field CORC® solenoids

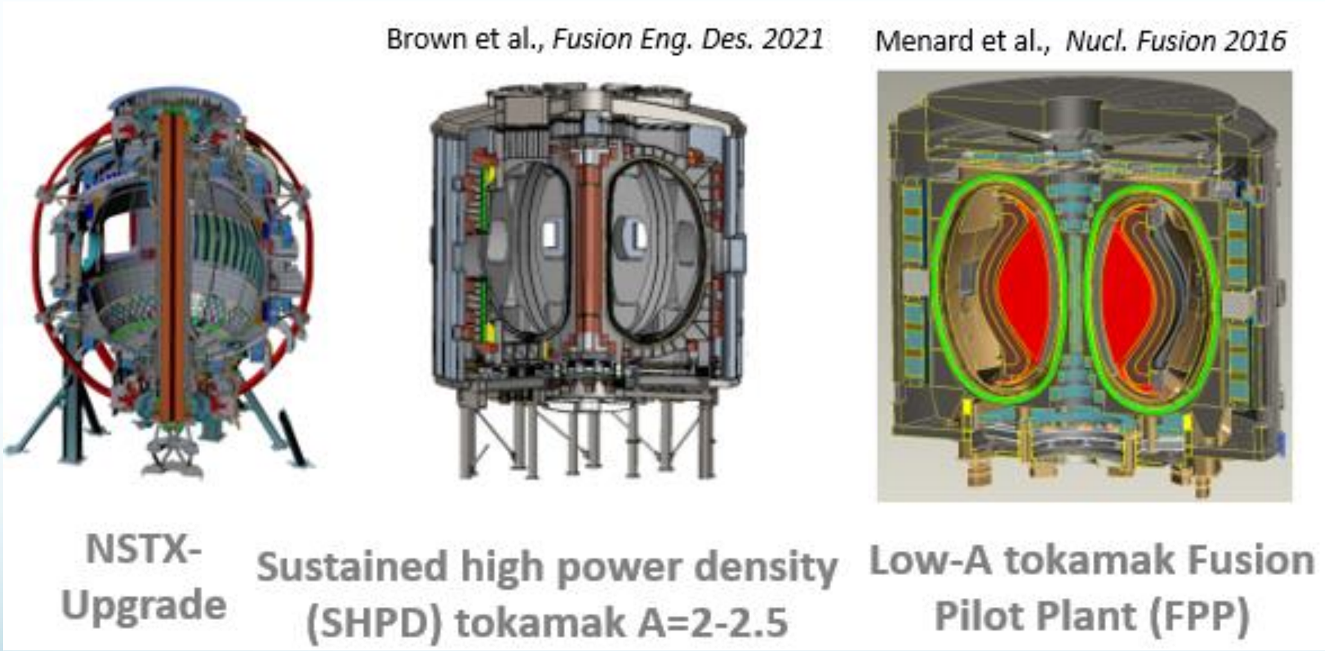
- CORC® insert solenoid operated within a 14 T LTS solenoid
- Reached a peak field of 16.77 T at a current of 4,400 A
- Peak unsupported hoop stress of 275 MPa

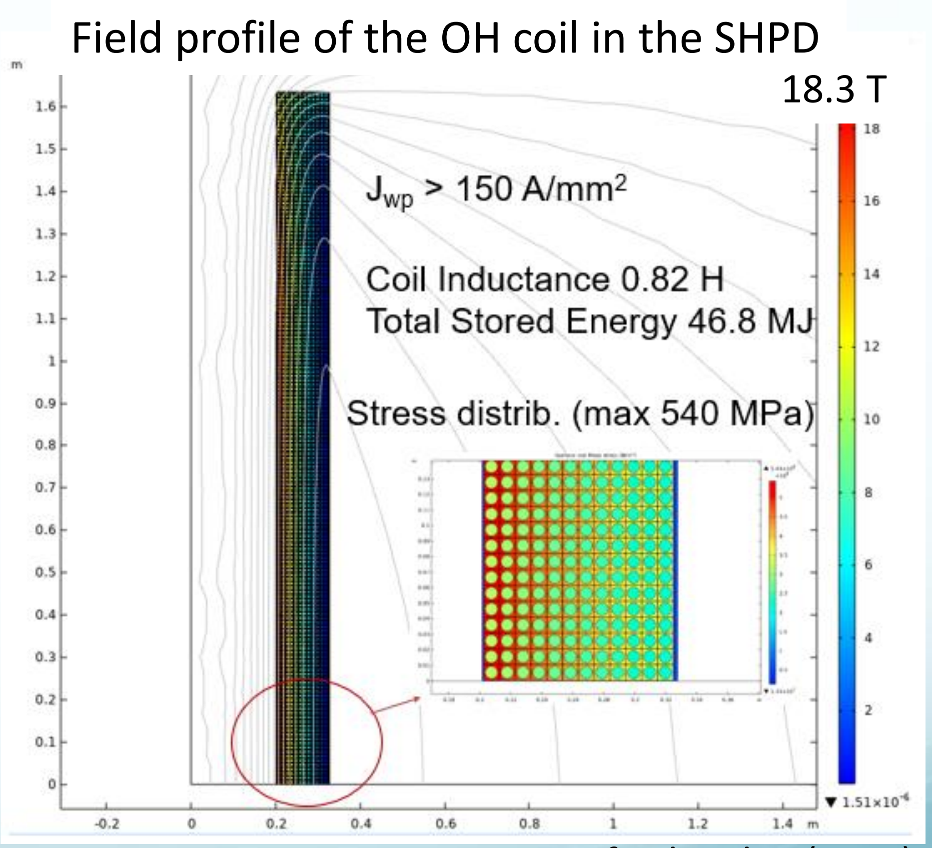


CORC® Cable Development for Compact Fusion Magnets

Ohmic Heating (OH) coils

- CORC® cables allow high winding current density OH coils (J_w > 150 A/mm^2)
- Allowing the OH coil to be placed outside the TF coils, between the inner legs
- High current (I_{opp} > 10 kA) windings allow for high field sweep rates to provide the required flux swing





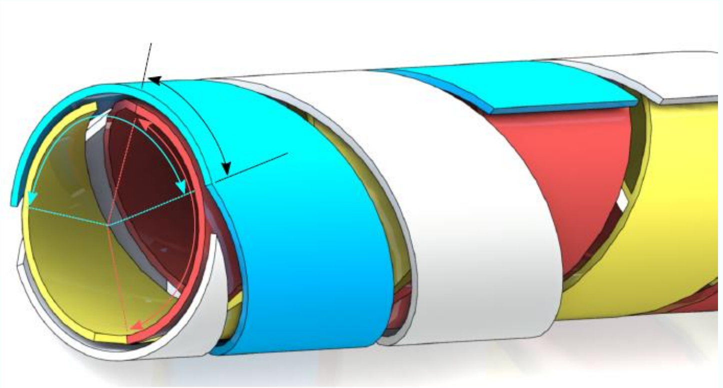
Courtesy of Yuhu Zhai (PPPL)

Problems to be Addressed in INFUSE Program with LBNL

CORC® cable performance in OH coils that ramp at 2 – 5 kA/s is unknown

- Inductance of the 30 – 50 tapes depends on the CORC® cable design
- Current distribution between tapes at 2 – 5 kA/s:
    - Driven by **the terminations** in short (1 – 5 meter long) CORC® cables
    - Driven by **the individual tape inductance** in long (200 – 500 meter) CORC® cables
- **Inhomogeneous current distribution will limit** the CORC® cable performance
- Current sharing between tapes may even out the current distribution (to some extend)

These important design factors need to be understood to optimize CORC® cables for operation in fast ramping Ohmic Heating coils



Development of CORC® Cable Toolbox at LBNL: Requirements

Requirements for the CORC® cable toolbox

- Solve magnetostatic Maxwell equations with the finite element method (→ need curl conform elements)
- Handle highly non-linear material models
- Handle thin structures
- Model quenching, current sharing and stresses

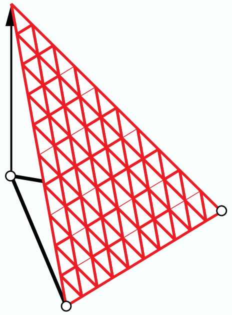
Not feasible to build upon existing commercial codebase
➡ A custom finite-element framework is designed in C++

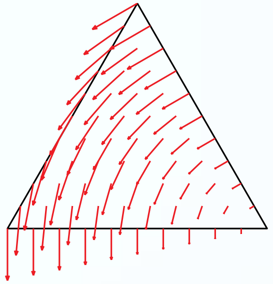
Requirements for underlying finite-element framework

- Support state-of-the art formulations such as:
  h-a ("scalar potential") and h-ϕ ("vector potential")
- Need an open and very flexible data structure

Minimization of development effort

➢ Use state-of-the art open-source libraries such as
  - MUMPS
  - PETSc
  - STRUMPACK (LBNL)


Lagrange Element
(standard FEM)


Nédélec Element
(Maxwell FEM)

$$= c \left(\frac{\| \boldsymbol{j} \|}{j_c} \right)^{n \quad 1}$$

"power law" for electric resistance

STRUMPACK
STRUctured Matrix PACKage
https://portal.nersc.gov/project/sparse/strumpack/

Development of CORC® Cable Toolbox at LBNL : Basic Concept

Geometry definition

- text editor (simple)
- Python script (complex)

→ *.geo → **GMSH**

- open source mesh generator

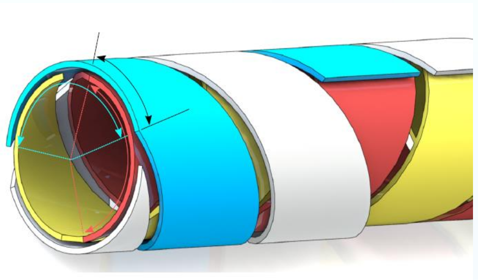
↓ *.msh

User input file

- material characteristics
- boundary conditions
- solver settings
- mesh topology
- …

→ *.txt → **Topology analyzer**

- identify tape contacts
- create contact resistors



↓ *.msh ↓ *.hdf5

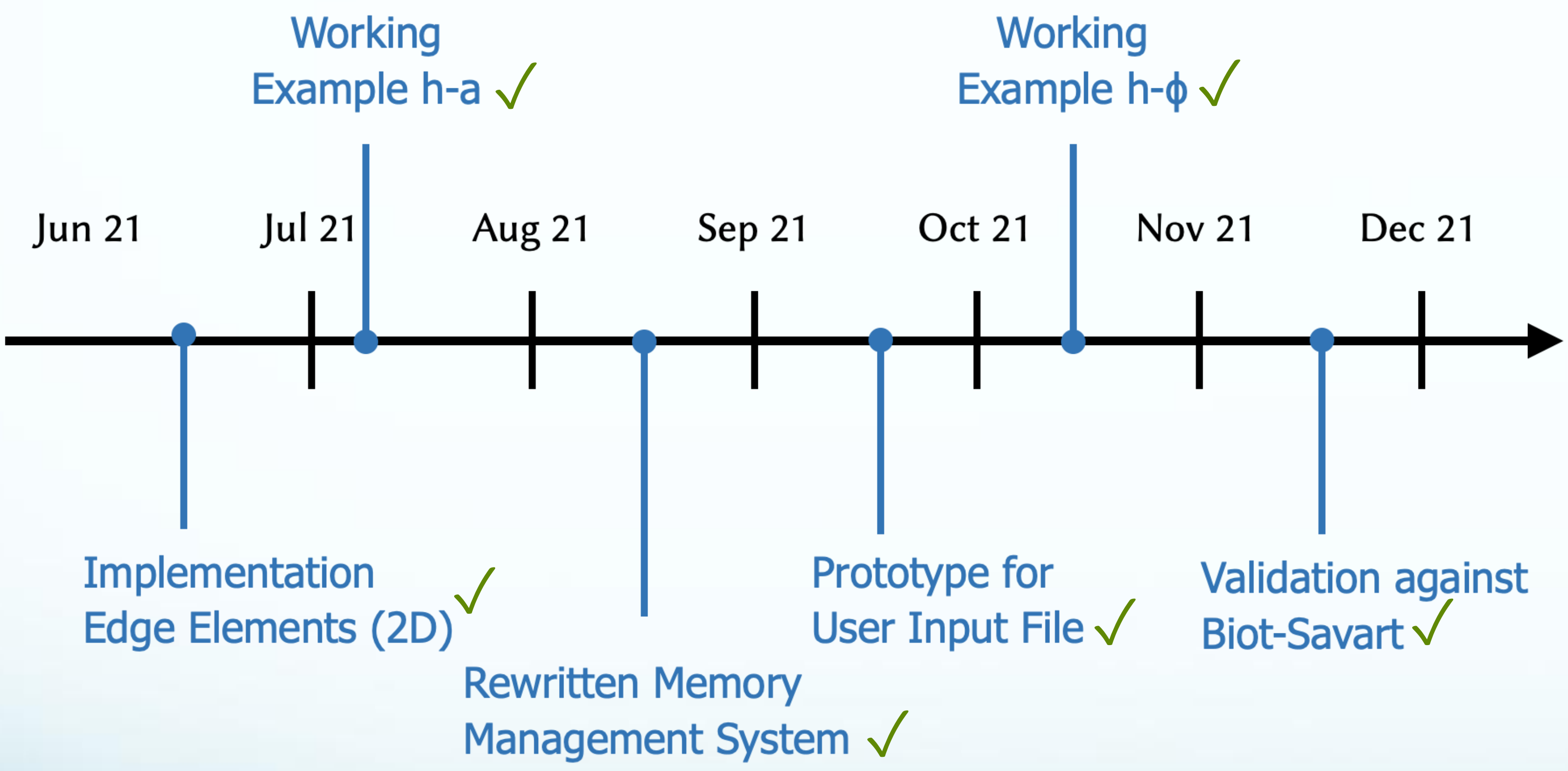
User input file → *.txt → **Finite element code**

- build the model
- solve the physics

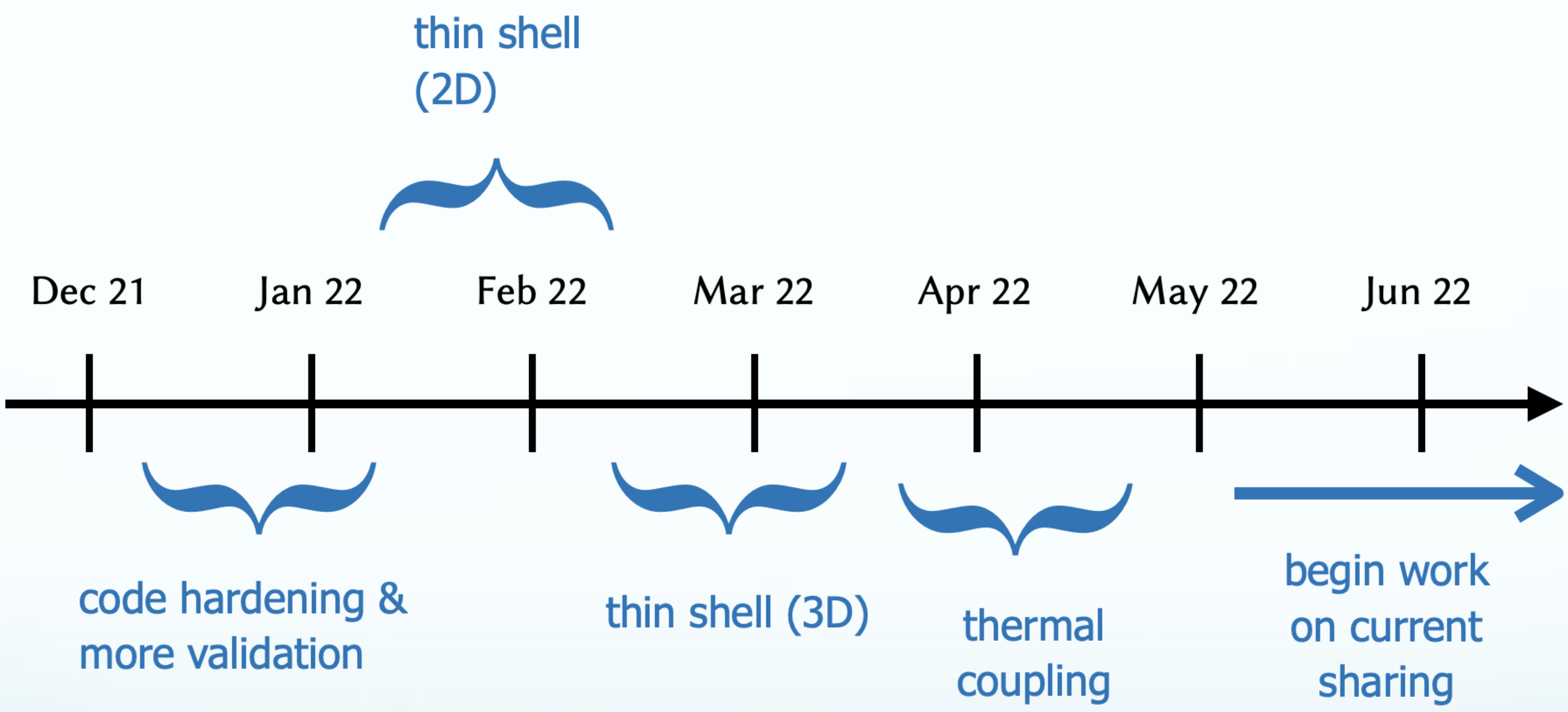
→ *.exo → **ParaView**

- postprocessing
- visualization

Development of CORC® Cable Toolbox at LBNL: Progress



Development of CORC® Cable Toolbox at LBNL: Next Steps



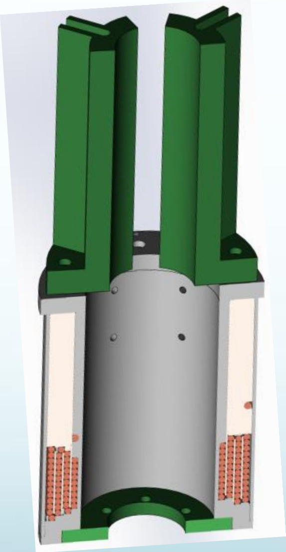
Impact of INFUSE Program

The modeling toolbox will

- Help us understand how the CORC® cable behavior will change when moving from short-sample length scales of 1 – 20 meters to actual Ohmic Heating coils in which single CORC® cable piece lengths will exceed 200 – 500 meters
- Help mitigate many of the risks to develop major magnet systems, such as the OH coils in compact fusion magnets, by optimizing the CORC® cable layout

Short-sample CORC®

Sub-scale CORC® coils



Actual fusion device