User Defined Elements in ANSYS for 2D Multiphysics Modeling of Bi2212 Magnets

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Overview

Development: user defined elements in ANSYS keep all meshing, solving, and post-processing capabilities, while adding

1. **interfilament coupling current losses**
2. **quench behavior**
3. **internal material property fits (T, B, quench state)**

Validation: comparison to existing COMSOL and LEDET codes (CERN)

First Application to HTS magnets:

1. **Bi2212 racetrack coils to be tested at LBNL**
2. **Bi2212 solenoid tested with background field at FSU/MAGLAB**

User Defined Elements can Extend the Capability of ANSYS to Include Superconducting Specific Behavior

Keep all features of standard ANSYS…

- modeler, mesher, post-processor
- transient electromagnetic and thermal solvers
- eddy currents in structure
- external circuit coupling
- yoke saturation

… and add what is missing with user elements

- eddy currents in conductor (IFCC, +)
- current sharing + quench propagation
- coupling to thermal model with full (T,B) mat. prop.

User Elements are Implemented by Replacing the Code Which Generates the Finite Element Matrices

Geometry Generation
Meshing
Boundary conditions
Loads

Solution

Post processing
Load transfer between models

Replace code which builds element matrices and compile custom ANSYS.exe

From Default ANSYS

node location
loads
node temp.
material prop.
ANSYS functions

User Programmed Matrix Generation Adds Features

- Equiv. magnetization for IFCC
- Mat. property fits (T, B, Jc, etc.)
- Current sharing + quench

Back to Default ANSYS

matrices: stiffness, damping, load, etc.

Material Property Fits are Internally Programmed for Simulations with NbTi, Nb_3Sn, and Bi2212

User chooses materials and fits using element key options and real const.

```
! thermal for conductor region only
et,12,user101
keyopt,12,1,0      ! 0=internal fits, 1=ANSYS tabl
keyopt,12,2,1      ! 0=no transfer to mag, 1=trans
keyopt,12,3,1      ! 0=NbTi, 1=Nb3Sn, 2 = Bi2212
keyopt,12,4,0      ! 0=Cu, 1=Ag
keyopt,12,5,0      ! 0=G10
keyopt,12,6,1      ! 0=NIST Cucv, 1=CUDI, 2=MATPRO
keyopt,12,7,0      ! 0=NIST Cukxx, 1=CUDI, 2=MATPR
keyopt,12,8,0      ! TBD (NbTi Cv)
keyopt,12,9,0      ! 0=NIST, 1=CUDI,  (Nb3Sn Cv)
keyopt,12,10,0     ! TBD  (Bi2212 Cv)
keyopt,12,11,0     ! 0=NIST  (G10 Cv)
keyopt,12,12,0     ! Agcv
keyopt,12,13,0     ! Agkxx


fcond = nturns*nstrand*ds*ds*pi/(4*across)  !cond
fsc=0.24     ! S.C. fraction
fst=0.25     ! Ag/Mg mech. stab fraction
Lp = 20.0e-3 ! filament twist pitch
feff = 1.0   ! rho_eff scaling
RRR = 187.5  ! Ag matrix RRR (from 273)

R,21,across,nturns,fcond,fsc,curdir,Lc   !set rea
Rmore,Li,RRR,Lp,feff,0,TauMult
Rmore,0,0,0,0,0,scIFCU
Rmore,fst,Mmult,
```

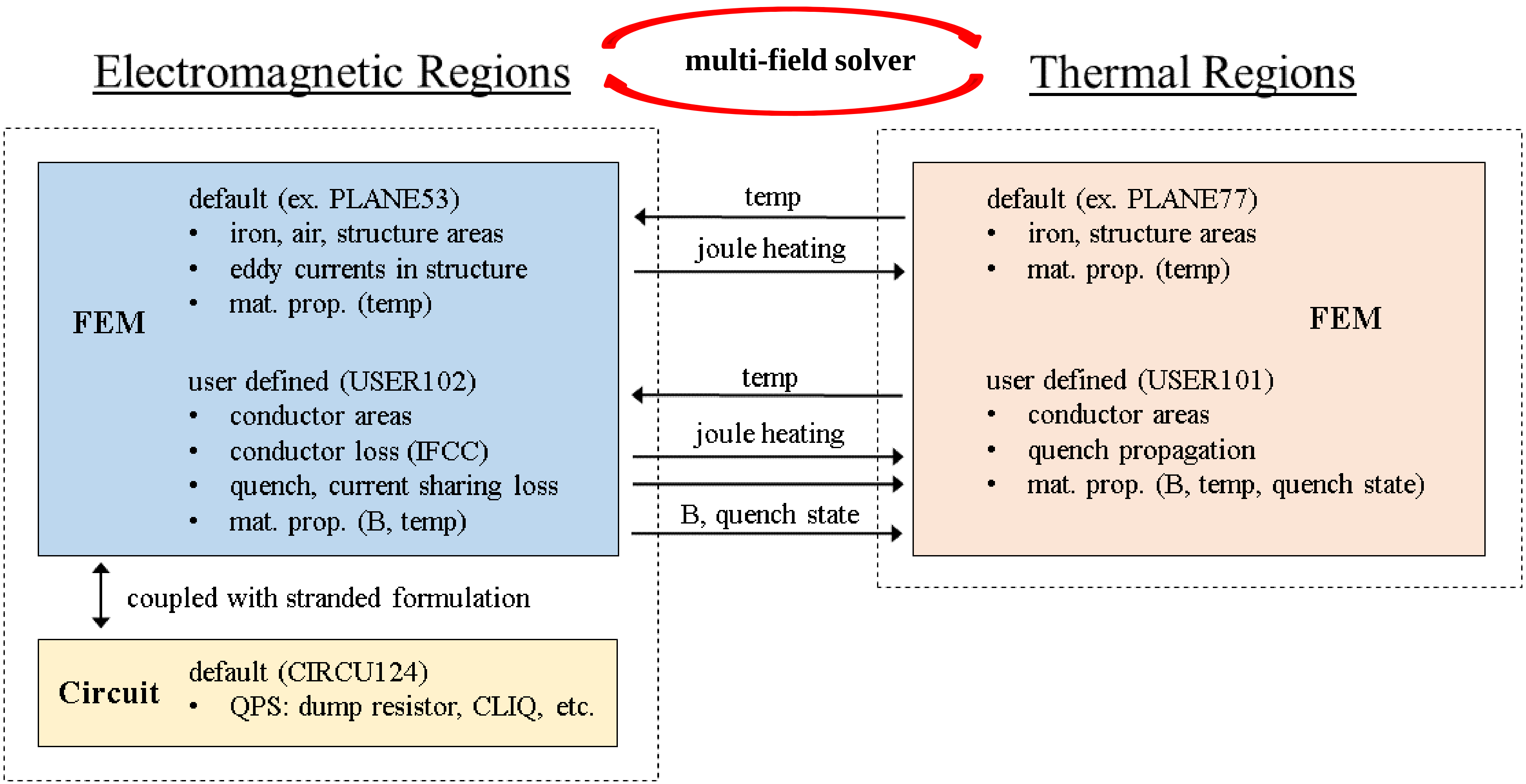
Example format: NIST rhocu(T, RRR, B)*

```
!*********************************************************************
      function rhocunist(tt,rrr,bb)
!*********************************************************************

! rhocu returns the resistivity of copper in the SI
! for a given temperature, RRR and magnetic field.
! Units are ohm*m

      DOUBLE PRECISION tt, rrr, bb, b, rhocunist
      DOUBLE PRECISION rho0, rhoi, rhoiref, rhcu, lgs, poly, corr

      b=abs(bb)
      rho0=1.553D-8/rrr
      rhoi=1.171D-17*(tt**4.49)/(1+4.48D-7*(tt**3.35)*exp(-(50/tt)**6.428))
      rhoiref=0.4531*rho0*rhoi/(rho0+rhoi)
      rhcu=rho0+rhoi+rhoiref
      if (b.lt.1D-1) then
         rhocunist=rhcu
      else
         lgs=0.43429*log(1.553D-8*b/rhcu)
         poly=-2.662+lgs*(0.3168+lgs*(0.6229+lgs*(-0.1839+lgs*0.01827)))
         corr=(10**poly)
         rhocunist=(1.+corr)*rhcu
      endif
      end function rhocunist
```

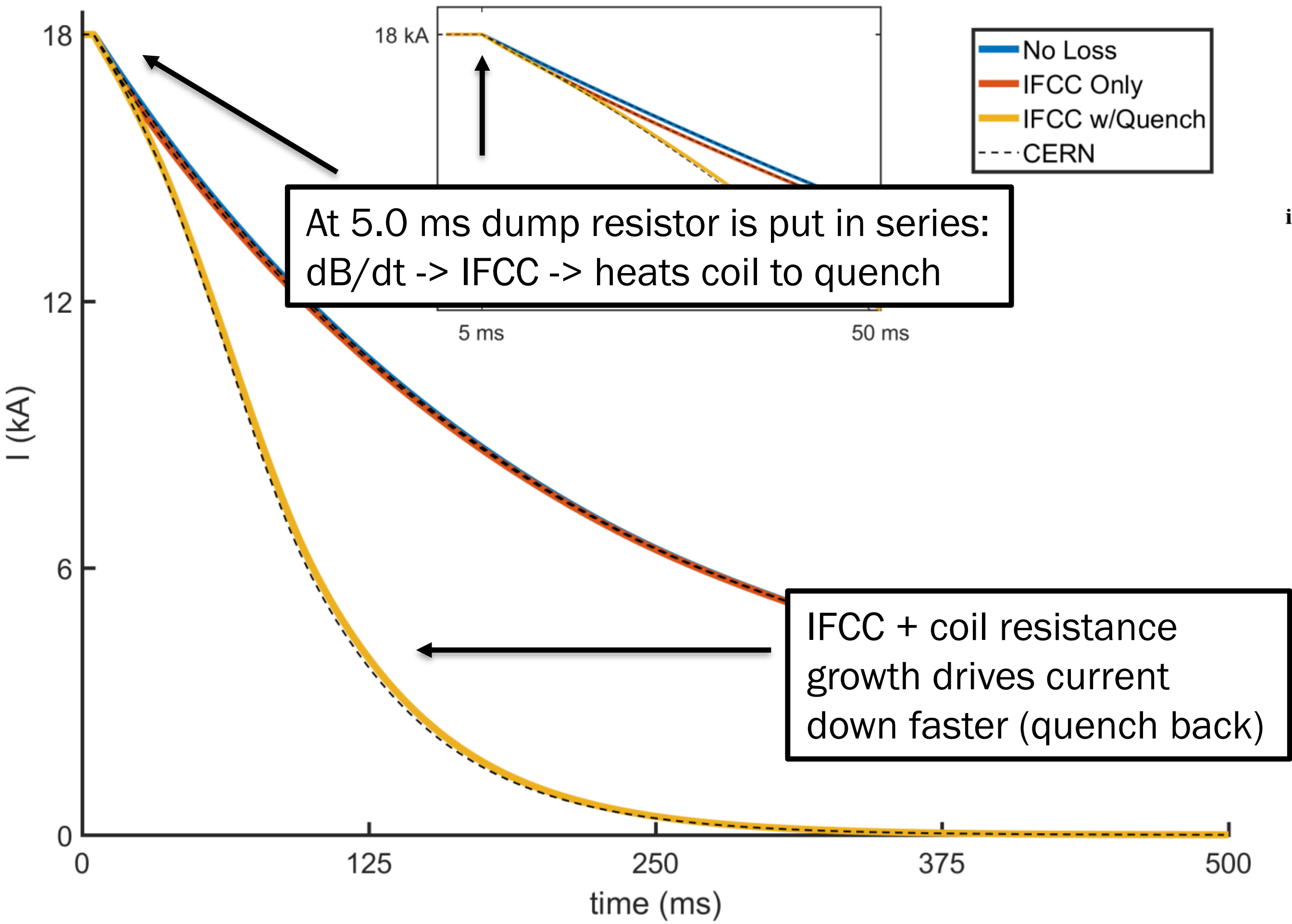
Heat capacity, resistivity, thermal conductivity, critical current, etc.

*"Review of ROXIE's material property database for quench simulation", G. Manfreda, CERN EDMS Nr: 1178007, 2011.

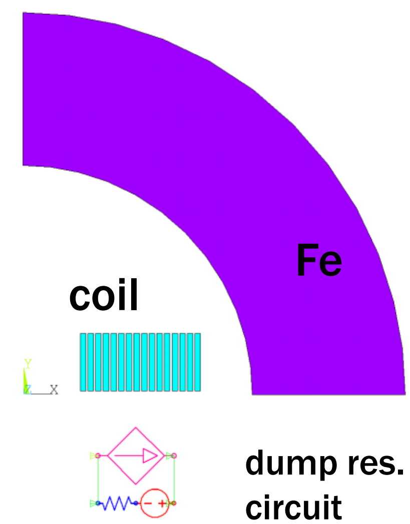
Coupled EM, Circuit, and Thermal Simulations can be Performed using the Multi-Field Solver



ANSYS user elements have been verified by CERN/STEAM using IFCC induced quench back simulations for a Nb_3Sn dipole



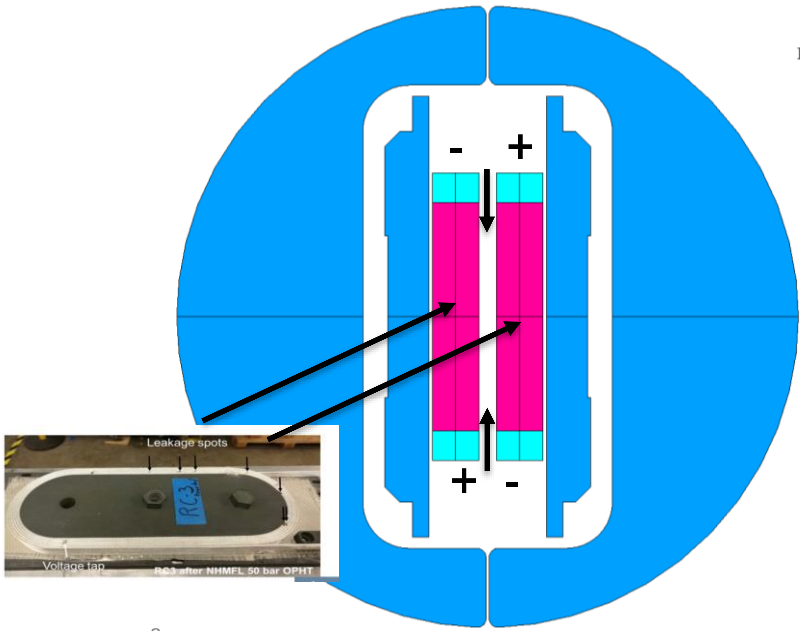
Crosscheck of the ANSYS-COMSOL 2D FEM implementations for magnetothermal transients in accelerator magnets



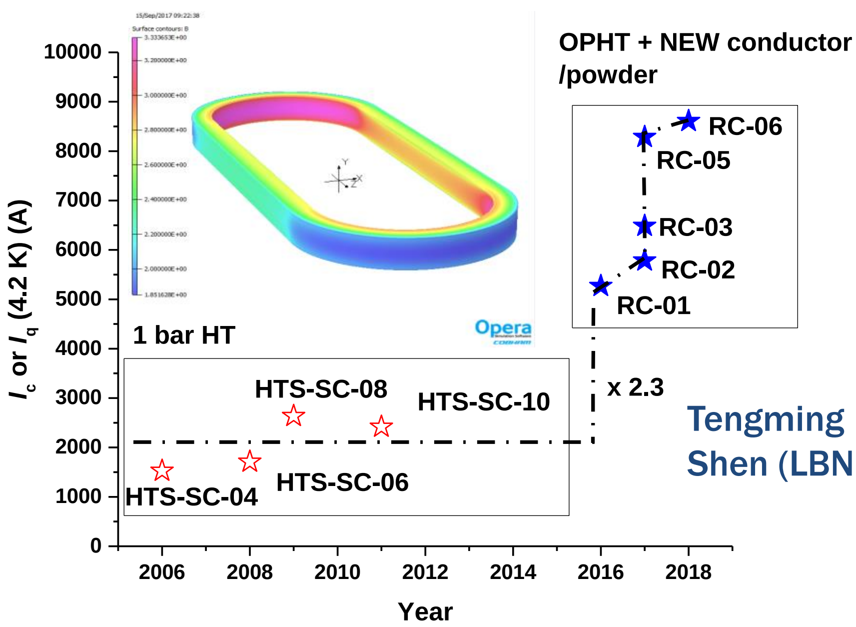
Agreement requires accuracy across EM, circuit, and thermal coupling

HTS Subscale Magnet Program at LBNL Motives Study of the Quench Behavior of Bi2212 Racetrack Coils

Upcoming test of two racetracks in a common coil configuration (~5 T dipole)



RC series wound at LBNL and OP reacted at MAGLAB have demonstrated a dramatic increase in Jc for single coils

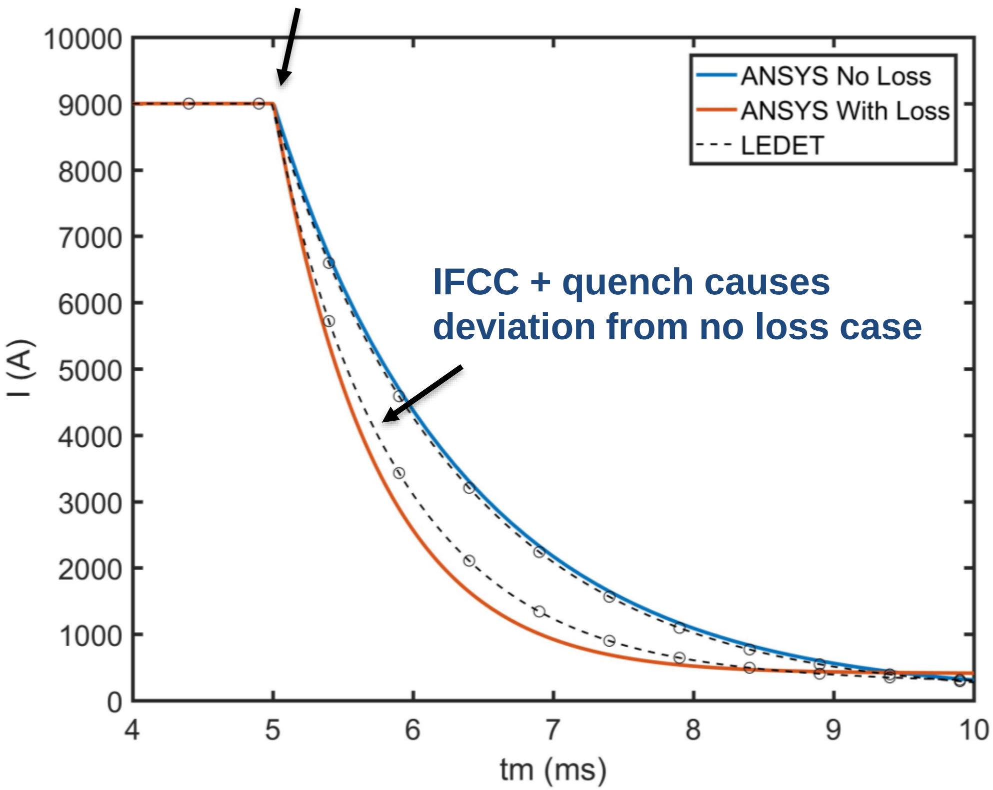


Tengming Shen (LBNL)

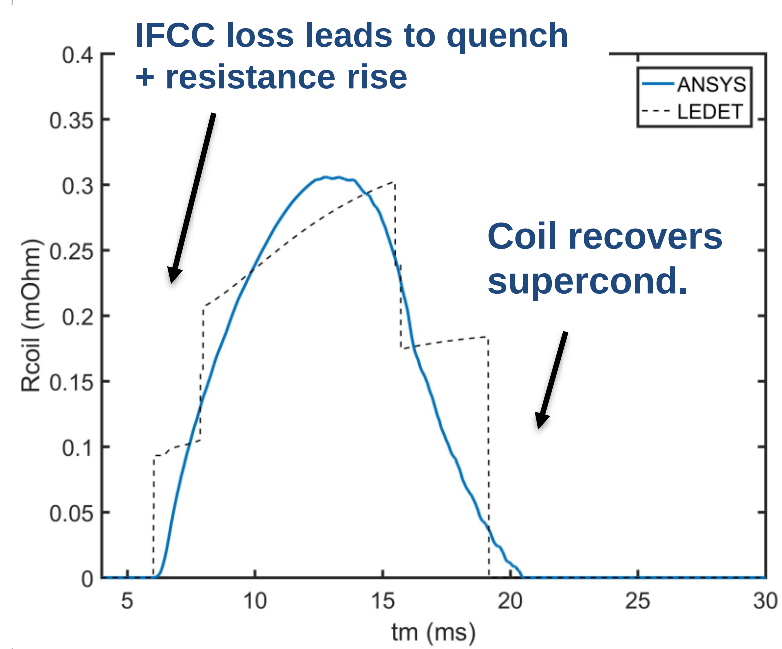
Test bed for quench behavior studies (Dan Davis – FSU PhD Thesis)

ANSYS Predicts Current, Resistance, and Temperature Rise for Bi2212 Racetrack Coils During Extraction

At 5.0 ms a 20 mOhm dump resistor is placed in series with the magnet (extraction at 90% of SS)

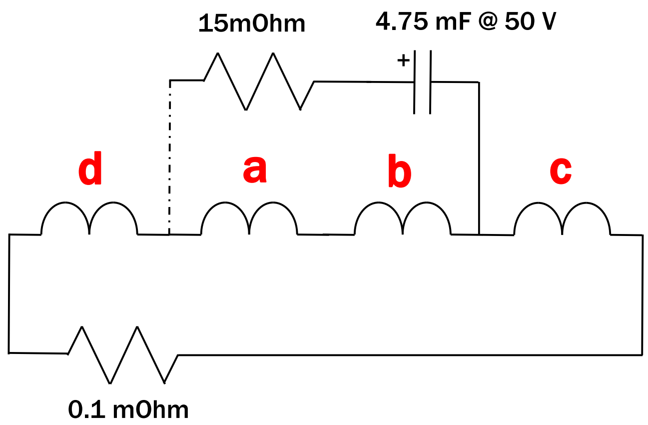


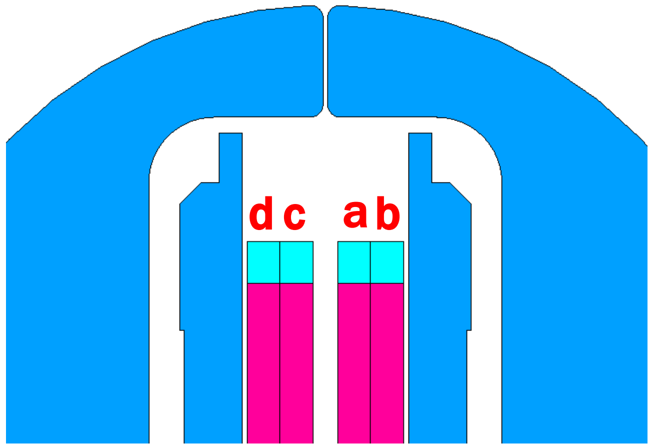
ANSYS Hotspot: 43 K
LEDET Hotspot: 45 K



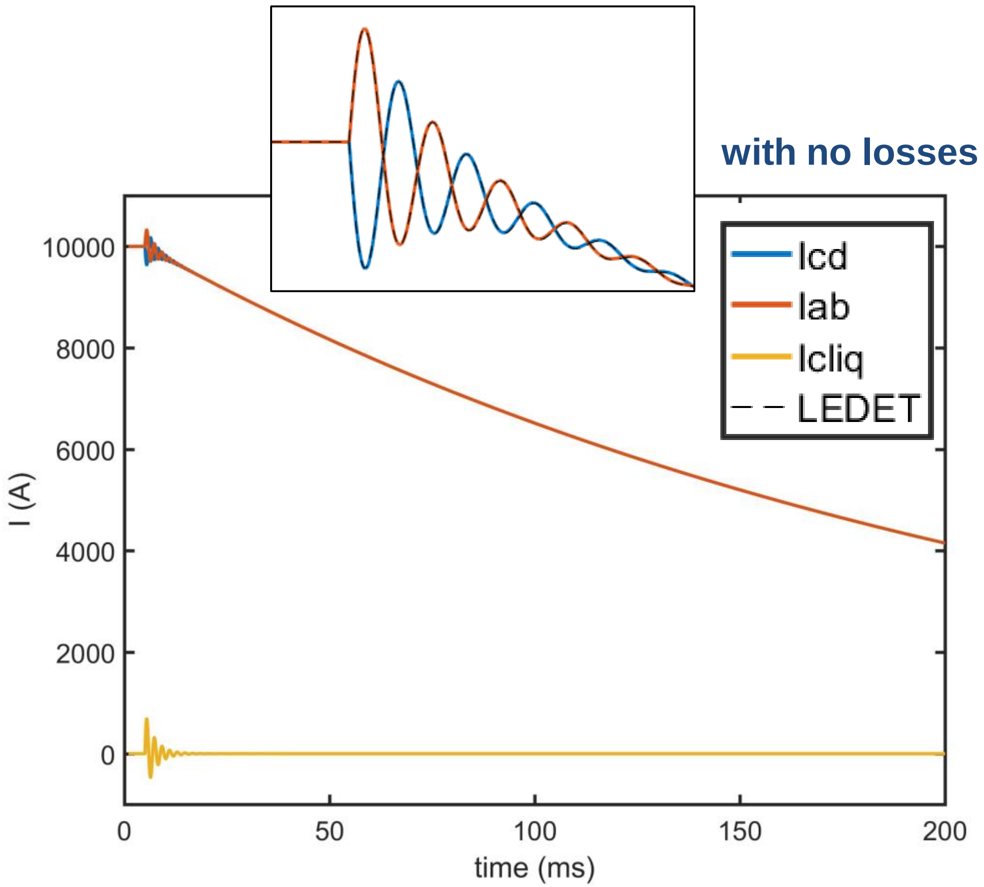
Two very different codes (ANSYS-FE, LEDET-Lumped Elem.) predict similar behavior

ANSYS is also being used to prepare for upcoming testing of the RC coils with a CLIQ unit



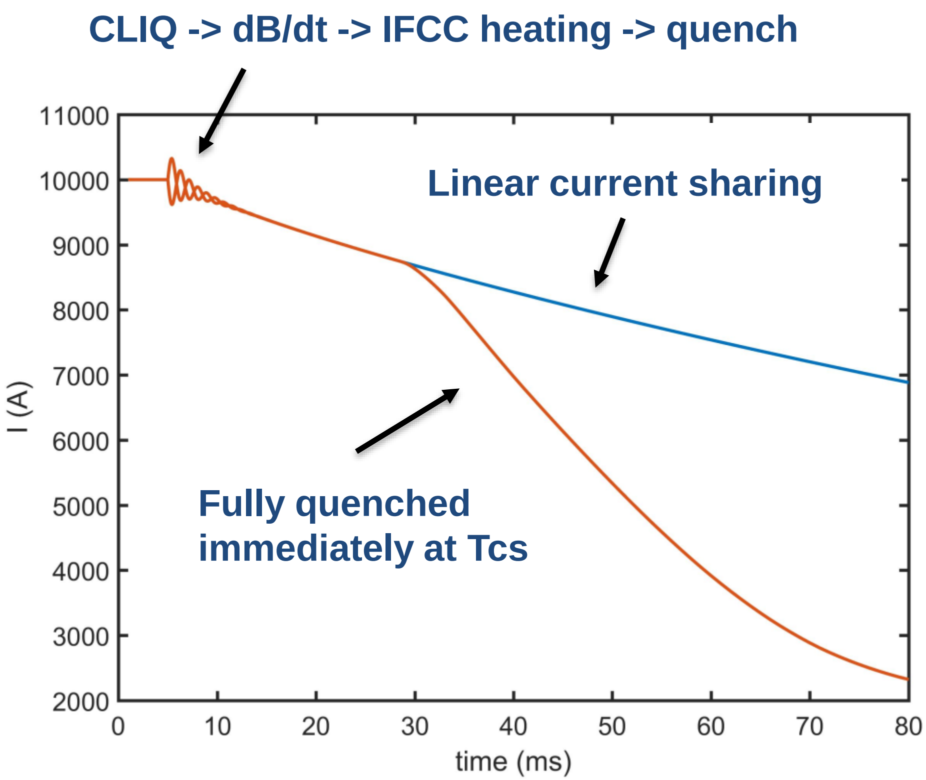


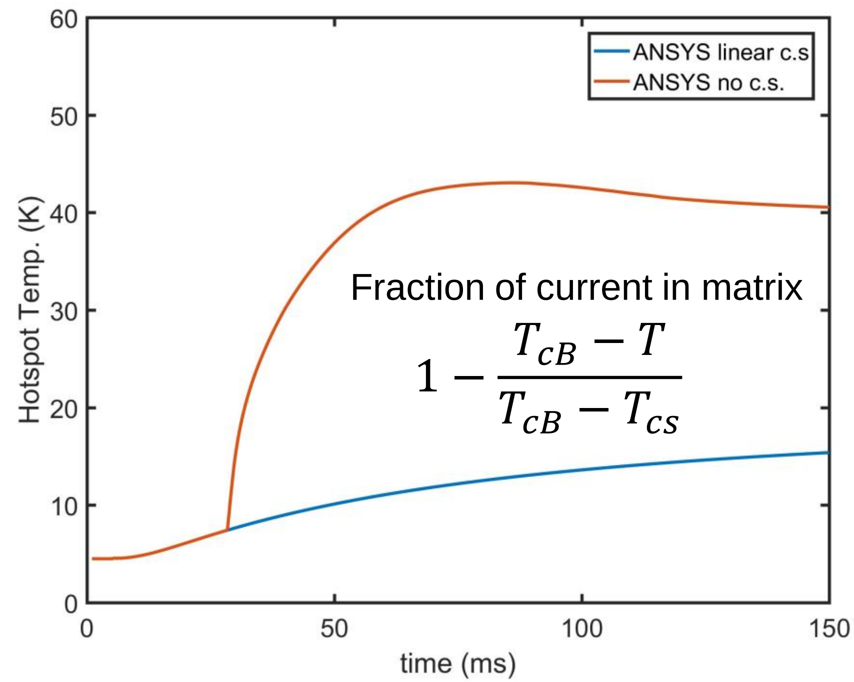
Capacitor bank (CLIQ) is discharged across coils to induce field oscillation (increases IFCC losses)



E. Ravaioli. CLIQ: A New Protection Technology for Superconducting Magnets, PhD Thesis, Univ. Twente

A Simple Current Sharing Model Dramatically Changes the CLIQ Results for the Common Coil with Losses Included



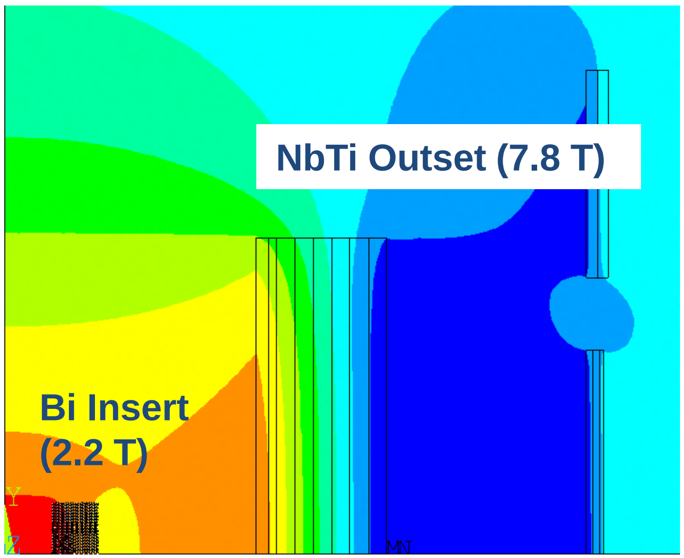


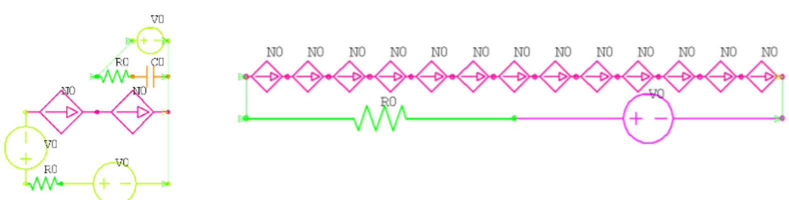
Upcoming tests at LBNL will probe CLIQ induced quench behavior

Test of "PUP4" Bi2212 Solenoid in Background Field at MAGLAB Allows for First Comparison of Modeling with CLIQ Data

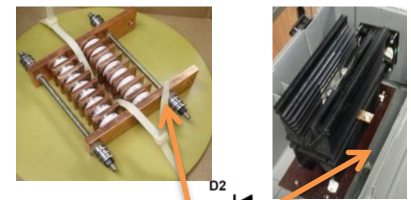
ANSYS model with insert, outsert, and their equivalent circuits

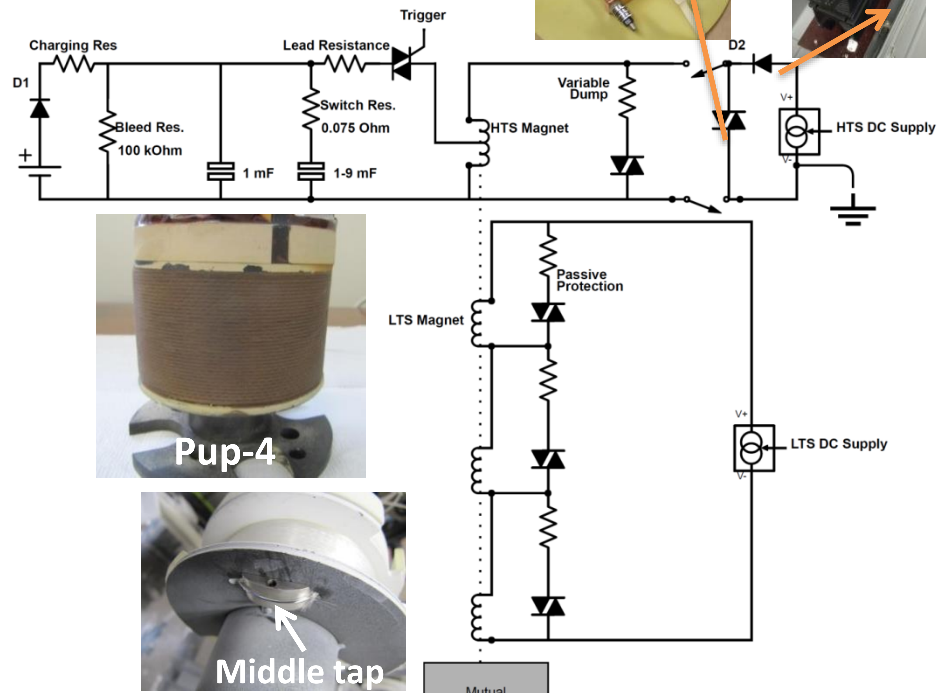
10.0 T Bore





Experiment led by Dan Davis (FSU/MAGLAB)





Capacitor bank (CLIQ) is discharged across two sections of the solenoid to induce current oscillation (increases IFCC losses)

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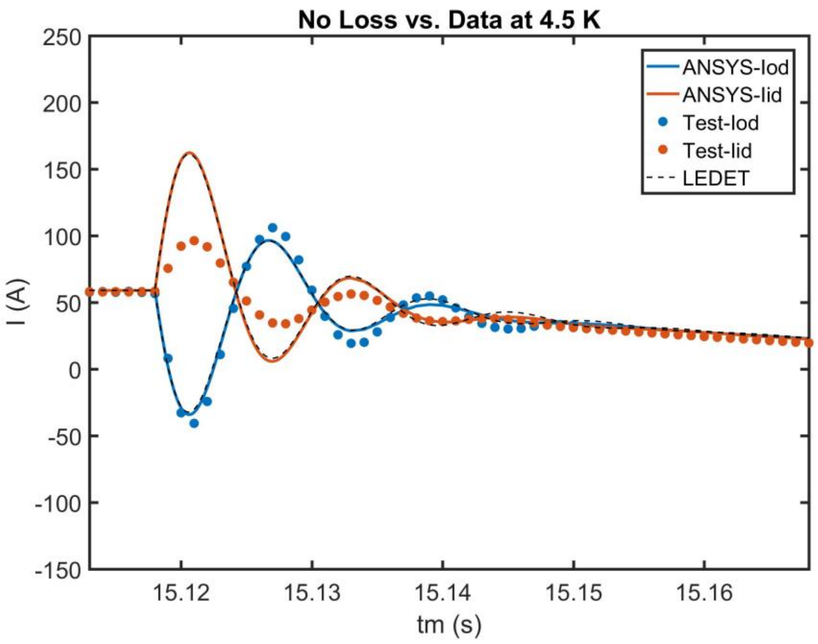
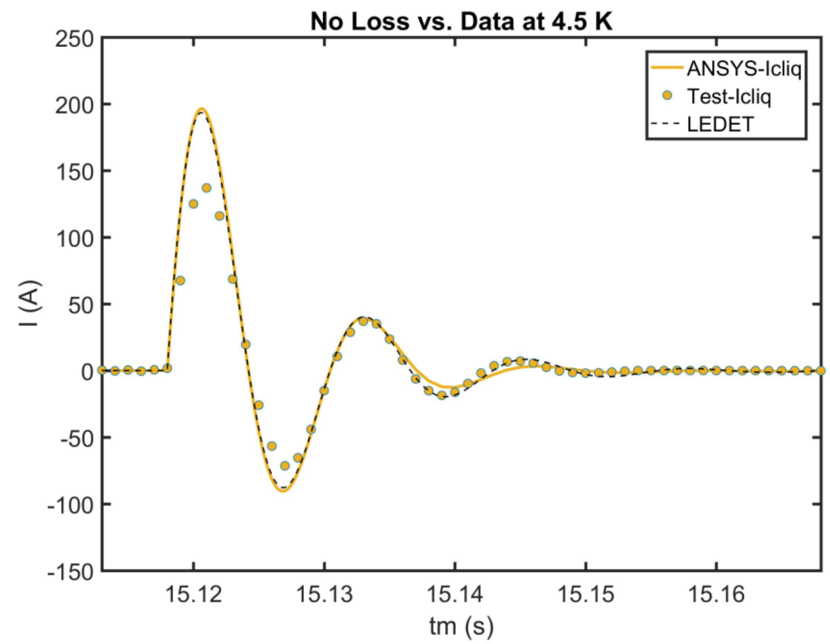
Comparison of ANSYS to Data From the PUP4 Tests at 4.5 K

CLIQ at 4.5 K with 7.8 T background field: C = 4.75, V = 100 V

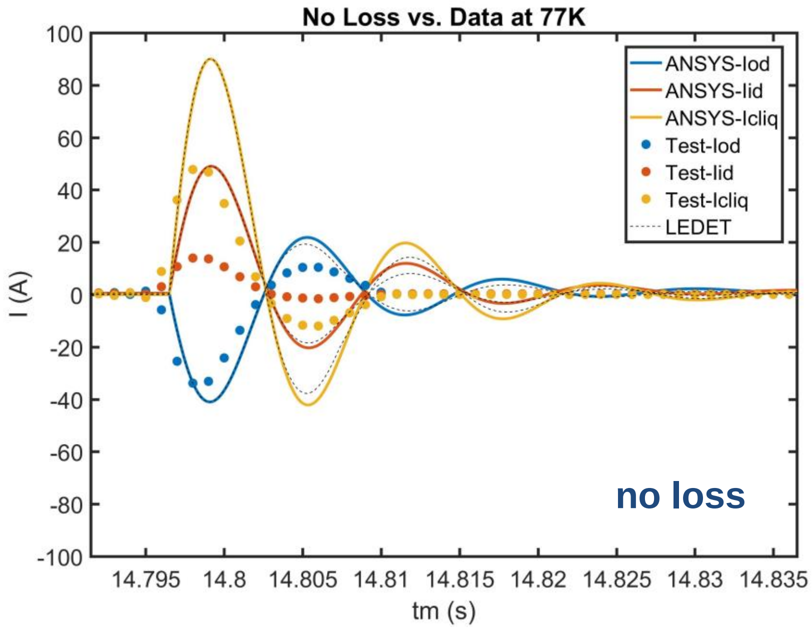


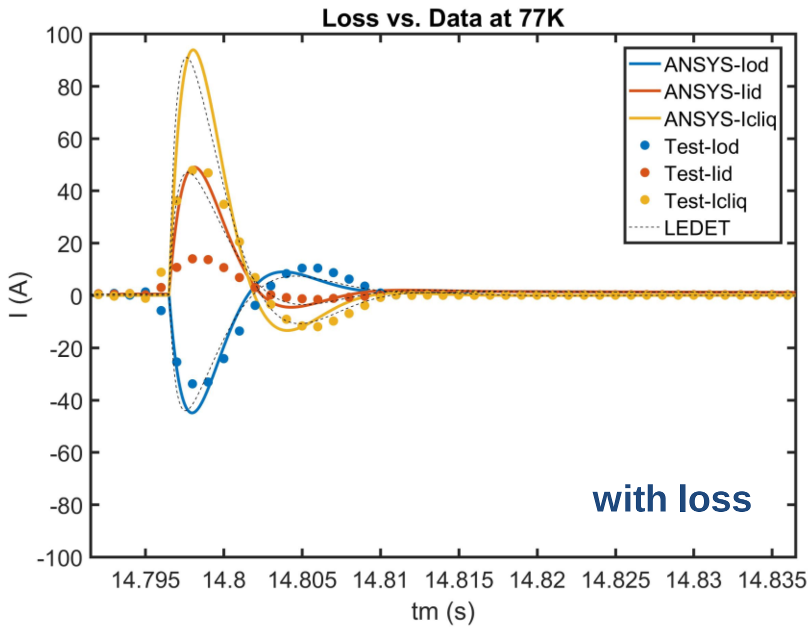


ANSYS/LEDET show agreement, match to data is promising

First Comparisons of ANSYS to 77 K Tests Show Loss Case Better Representing Data

CLIQ at 77 K with no background field: C=4.75 mF, V=50V





ANSYS/LEDET show agreement, loss case better matches data
- there is still much to understand and more data coming from the racetrack tests

Summary

User Elements in ANSYS can

- **simulate IFCC and quench**
- **include NbTi, Nb_3Sn, and Bi2212 in the same simulation**
- **include full material property fits (T, B, quench state, etc.)**

Initial validation studies comparing to existing COMSOL and LEDET codes are complete (with CERN)

First studies are being performed to support Bi2212 and Hybrid tests within the US-Magnet Development Program

- **modeling predictions guide upcoming Bi2212 racetrack tests (LBNL)**
- **comparisons to first Bi2212 CLIQ test data is promising (FSU)**

Thanks To

Paul Scherrer Institute

- Bernhard Auchmann, Jiani Gao

Cern

- Edvard Stubberud, Lorenzo Bortot, Bernhard Auchmann

LBNL

- Diego Arbelaez, Daniel Davis (also FSU-Maglab), Emmanuele Ravaioli (also CERN), Tengming Shen, and others

Our goal is develop a tool for the broader community. If you are interested in helping or using the elements please let us know. lnbrouwer@lbl.gov

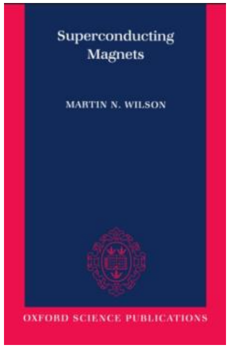
Extra Slides

Equiv. Magnetization Term is Included in the FEM Formulation to Include IFCC Losses in ANSYS

Equivalent Magnetization for Inter-filament Coupling Current Losses has already been successfully implemented in many codes (ROXIE, LEDET, COMSOL, etc.)

$$\mu_0 \mu_r \vec{M}_{eddy} = \tau_{eq} \frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \left(\mu_0^{-1} \mu_r^{-1} \nabla \times \vec{A} \right) = \vec{J}_{ext} + \nabla \times \vec{M}_{eddy}$$



Tau is dependent on conductor properties: twist pitch, rho_eff(T,B,RRR)

Implementation is User Friendly

ANSYS scripted input

```
!**********EM Elements*******************************
et,1,plane53         !2d EM: Az
keyopt,1,1,0
!et,2,user102    !2d EM: Az,cur,emf (stranded circu)
!***************************************************

et,2,user102
keyopt,2,1,0            ! AZ
keyopt,2,2,0            ! no field transfer to therm
keyopt,2,3,1            ! LBNL Jc fit
keyopt,2,5,0            ! table/fixed for rsvx
keyopt,2,7,0            ! allow c.s. + quench
keyopt,2,8,0            ! yes IFCC

fsc=1
fcond=1
RRR=200
Lp = 1.0
feff = 1.0

R,2,0,0,fcond,fsc,0,   !set real constants
Rmore,0,RRR,Lp,feff

cmsel,s,cond1
cmsel,a,cond2
```

These lines are the only deviation from a default ANSYS simulation using plane53

- choose USER102 for conductor
- set keyopts (IFCC_flag, mat. prop fit. Etc)
- set real constants (RRR, Lp, ect.)

No modification to re-run existing models, very little new knowledge required beyond default ANSYS