U.S. MAGNET DEVELOPMENT PROGRAM

BCMT
BERKELEY CENTER FOR MAGNET TECHNOLOGY

User Defined Elements in ANSYS for Multiphysics Modeling of Superconducting Devices

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CHATS-AS, Szczecin, Poland

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Outline

A multiphysics approach in ANSYS for multi-filamentary conductor magnets

- adding equivalent magnetization, quench, and material property fits at the point of element matrix generation (user compiled ANSYS)
- coupling across electromagnetic, thermal, and circuit domains
- Ex. 1: simulating IFCC induced quench back in Nb_3Sn undulators
- Ex. 2: simulating CLIQ for a Nb_3Sn dipole (validation with STEAM/COMSOL)

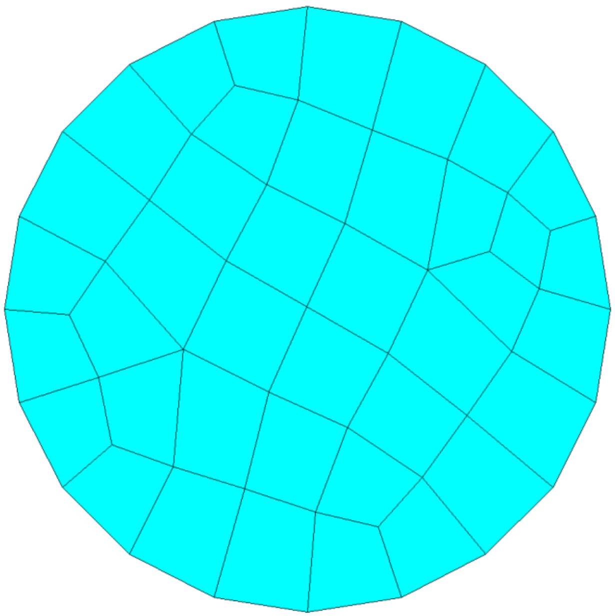
Implementing the E-J power law in ANSYS (initial verification studies)

- field trapping in bulk cylinder (axisymmetric)
- round filament magnetization (plane)

Our initial effort to share these elements with the community

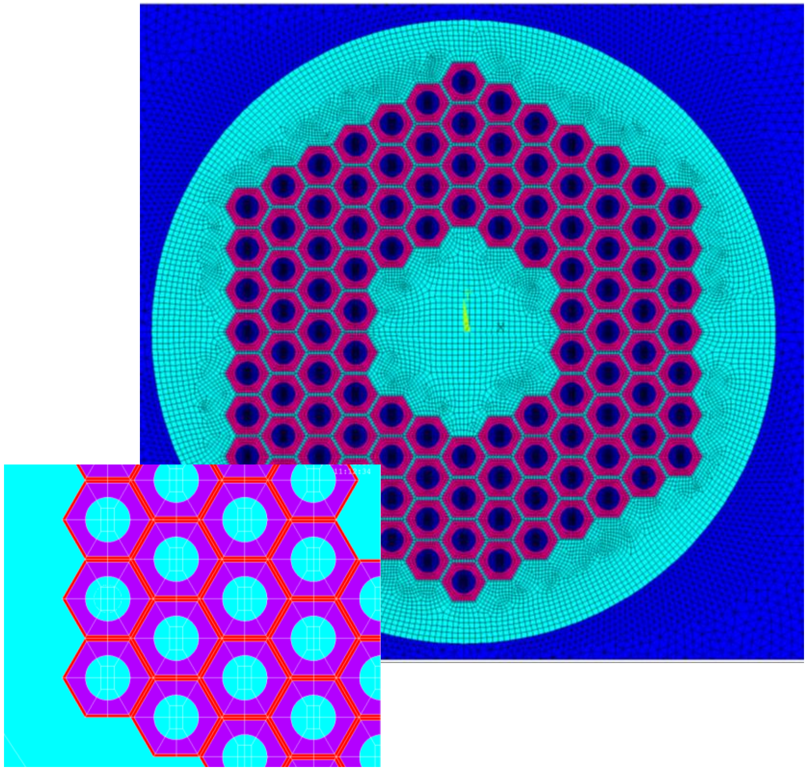
We have two approaches in ANSYS based on uniform (stranded) or computed current density (power law)

A-curr-emf (stranded)



- quench and current sharing is implemented with loss term based on Jc(T,B)
- equivalent magnetization used for coupling currents (a priori current path)
- optional resistive/inductive coupling to external circuit
- use for conductor regions of NbTi, Nb_3Sn magnet models

A-V formulation with E-J power law



- conductive paths resolved by mesh
- current distribution follows from DOF solution
- use for bulk devices, filament magnetization, etc.

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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

New 2D elements created by

- writing code which generates FEM matrices
- compiling a custom version of ANSYS

… and add what is missing with user elements

- equivalent magnetization for interfilament coupling currents
- current sharing + quench loss
- coupling to thermal model with full (T,B) mat. prop.

Material Property Fits are Internally Programmed for Simulations with Nb-Ti, 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
```

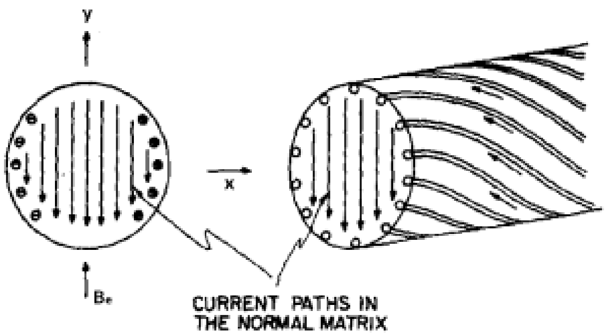
Heat capacity, resistivity, thermal conductivity, critical current, etc.

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

Interfilament coupling currents (IFCC) can be modeled using an equivalent magnetization formulation

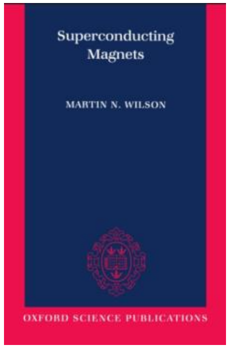
Instead of modeling currents themselves (A-V), assume the induced current path is known and use an equivalent magnetization

For a transverse field (2D magnet) this leads to (from Wilson, etc.)



$$M_e = -\frac{2\tau}{\mu_0}\dot{B}_i.$$

$$\tau = \frac{\mu_0}{2\rho_{et}}\left(\frac{L}{2\pi}\right)^2$$



Heat deposition (which can drive coil to quench)

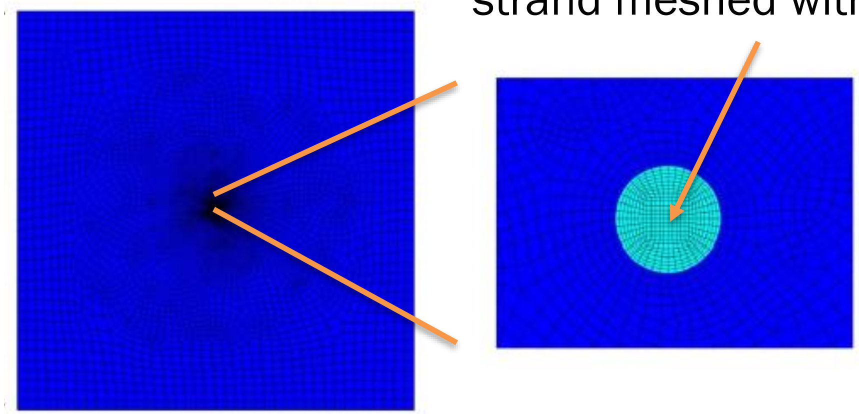
$$P_e = \vec{M}_e \cdot \frac{\partial \vec{B}}{\partial t}$$ ← mechanism for CLIQ*

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

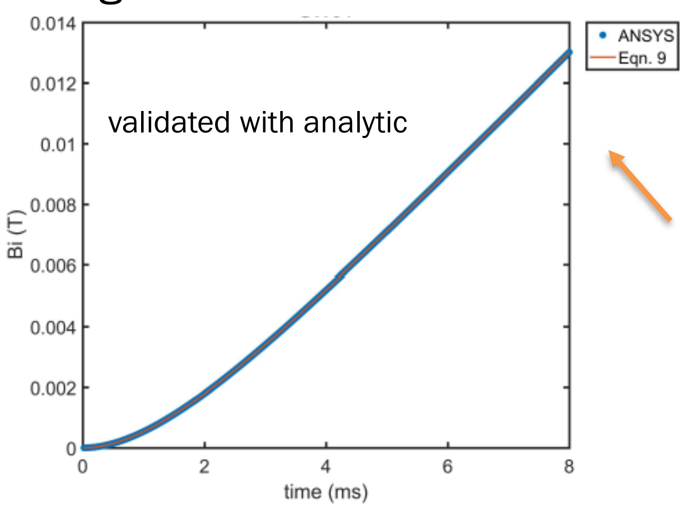
The simplest example: magnetization of a single strand in a changing background field

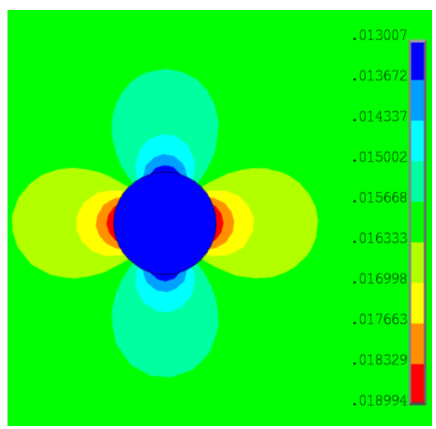
B.C. on edges of air used to apply constant ramp of background field, set IFCC time constant as constant 1.5 ms

strand meshed with user elements

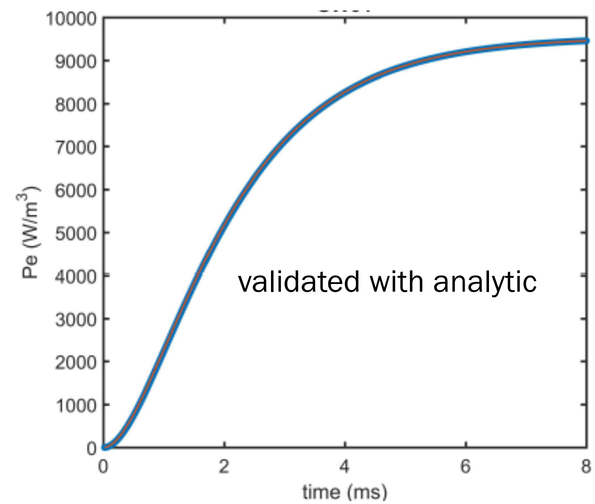


Magnetic field inside the strand

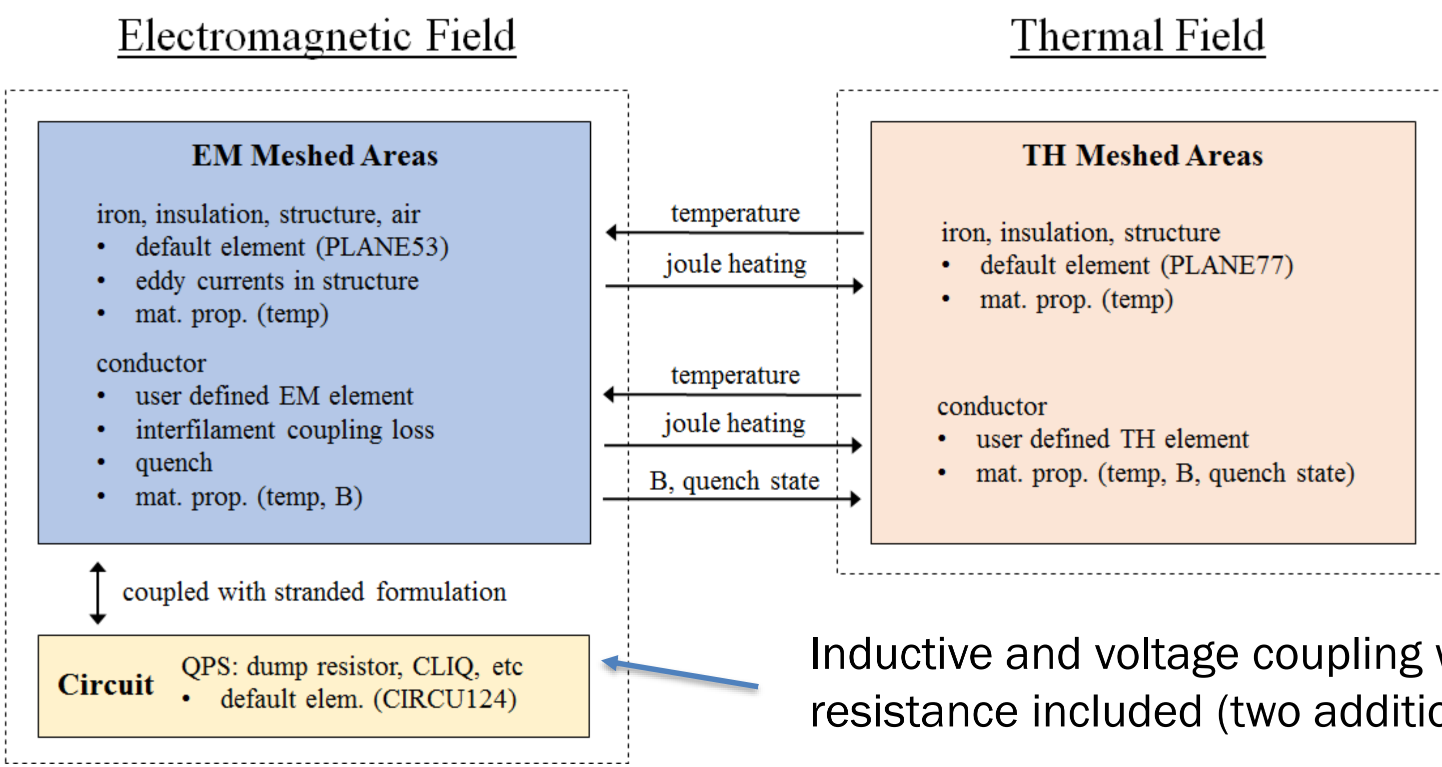




Heating inside the strand



A fully coupled magnet simulation uses independently meshed electromagnetic and thermal domains, each with their own user element

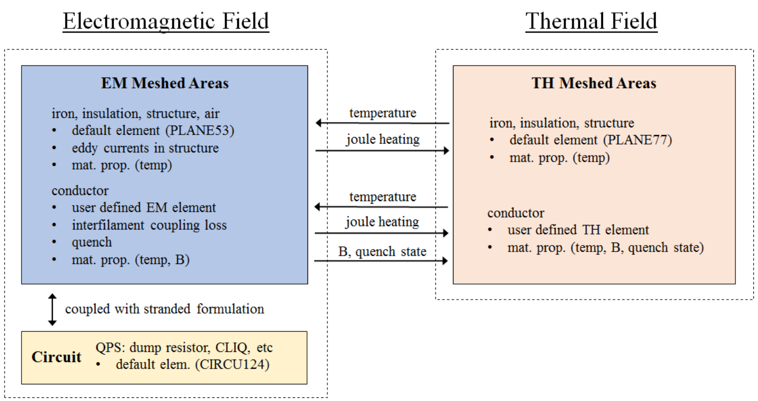


Inductive and voltage coupling with quench resistance included (two additional DOF)

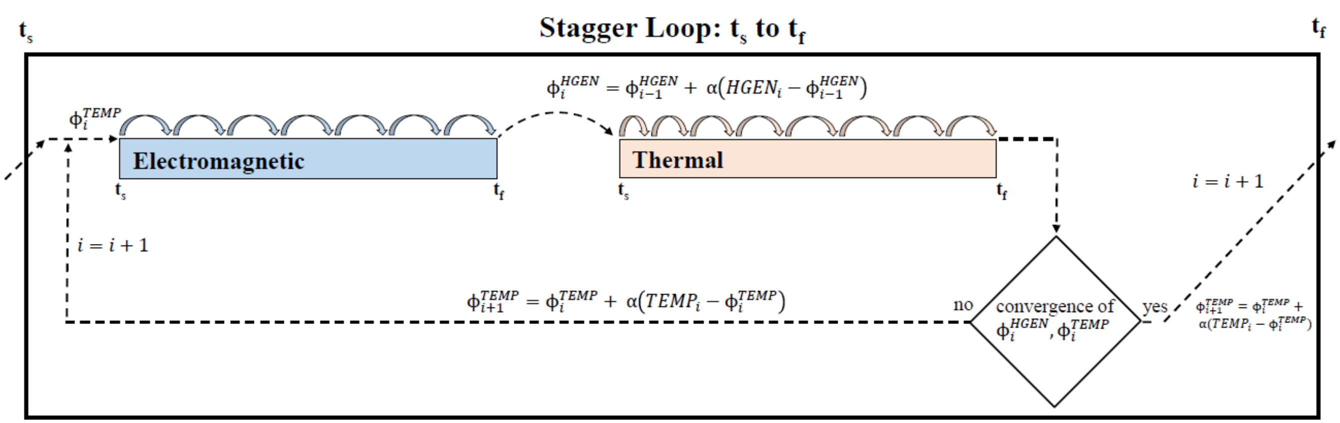
$$[C^{AA}]\,\frac{\partial}{\partial t}\{A\} + [K^{AA}]\,\{A\} + [K^{Ai}]\,\{i(t)\} = \{0\}$$

$$[C^{eA}]\,\frac{\partial}{\partial t}\{A\} + [K^{ee}]\,\{e(t)\} + [K^{ei}]\,\{i(t)\} = \{0\}$$

Iterative coupling across domains is achieved using the multi-field solver



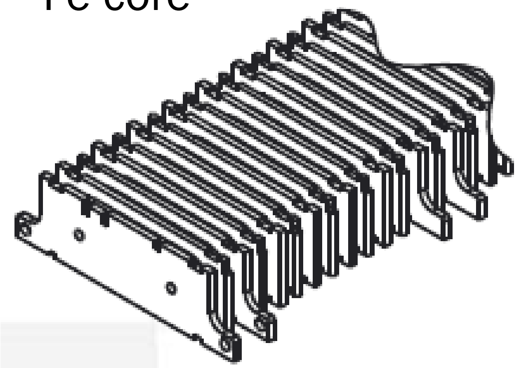
Total time is broken up into "stagger" loops which iterate until loads converge

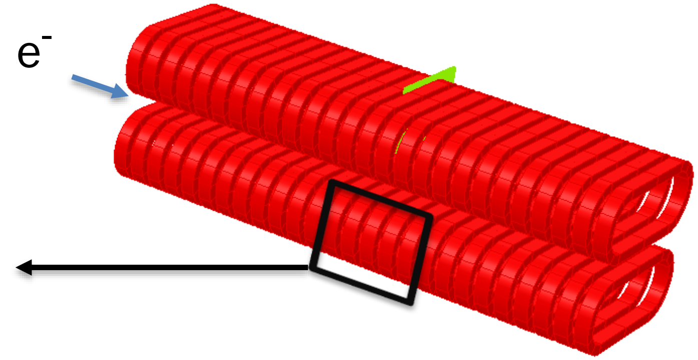


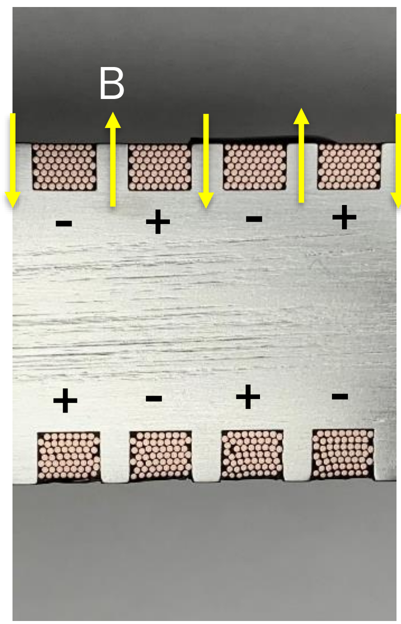
Example 1: Superconducting Nb_3Sn Undulators for Free Electron Lasers

Interaction of electron beam with alternating fields produces light in a FEL

Fe core







4-5 T field on the conductor field

Example of a fully coupled quench back simulation of a Nb_3Sn undulator in a dump resistor circuit

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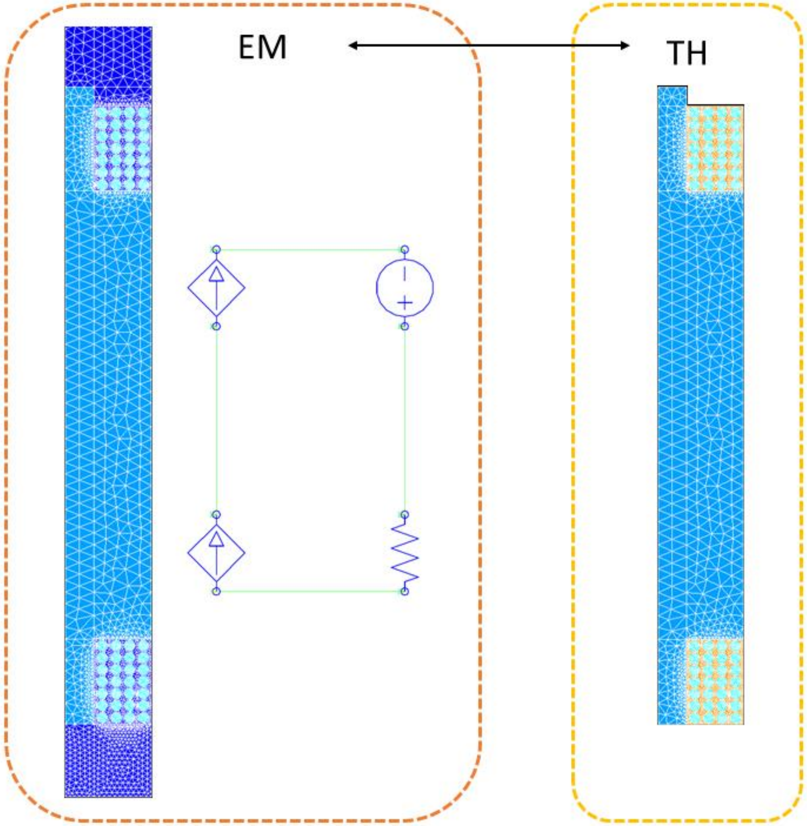
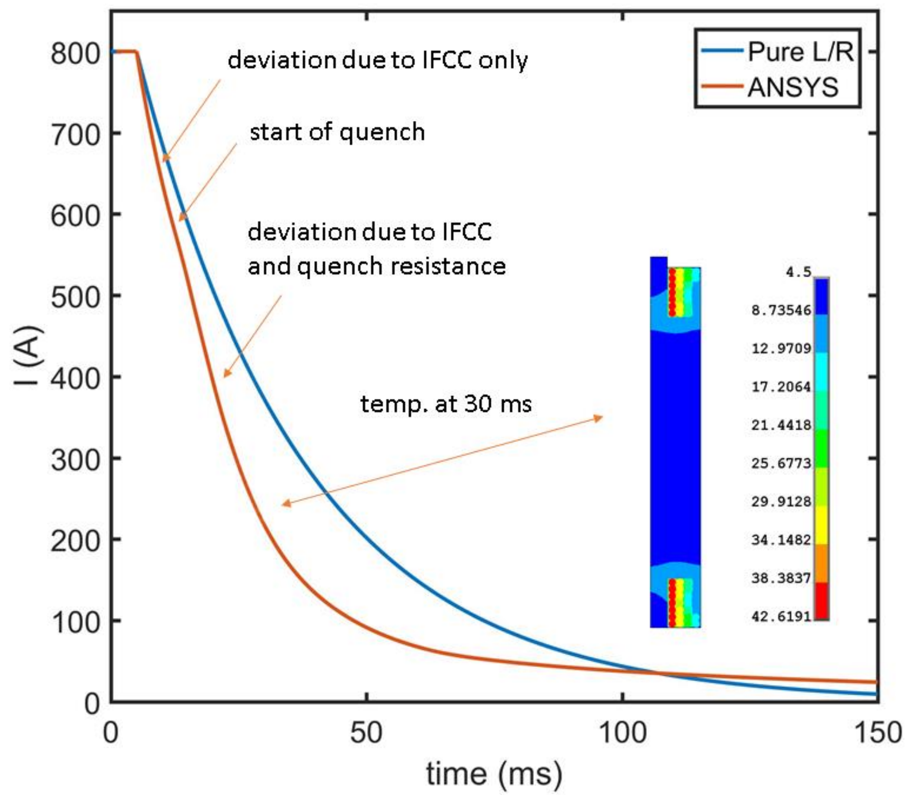
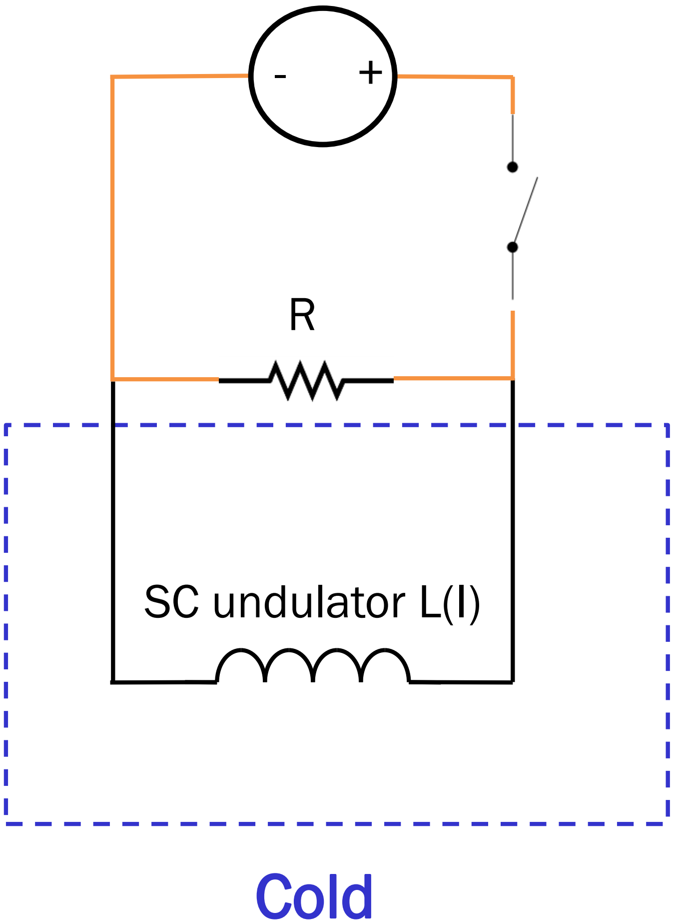




Extreme current densities require advanced quench protection + modeling (Nb_3Sn at low field)

- 5100 A/mm^2 in Cu post quench -> energy has to be extracted quickly to avoid burning
- accurate prediction of peak temperatures and current decay are critical

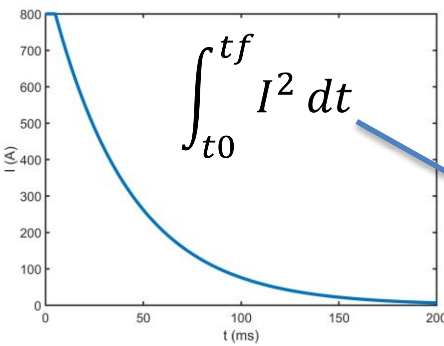
Quench Protection with a Dump Resistor Requires Balancing Hotspot Temperature and Peak Voltage

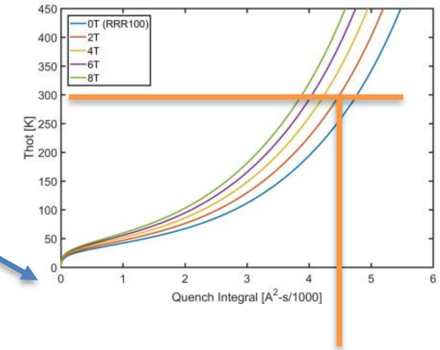


Choose the smallest dump resistor possible to keep hotspot temp reasonable (this limits voltage) => to do this it is critical to accurately simulate the current decay profile including quench back

Adiabatic hotspot temp is proportional to quench integral

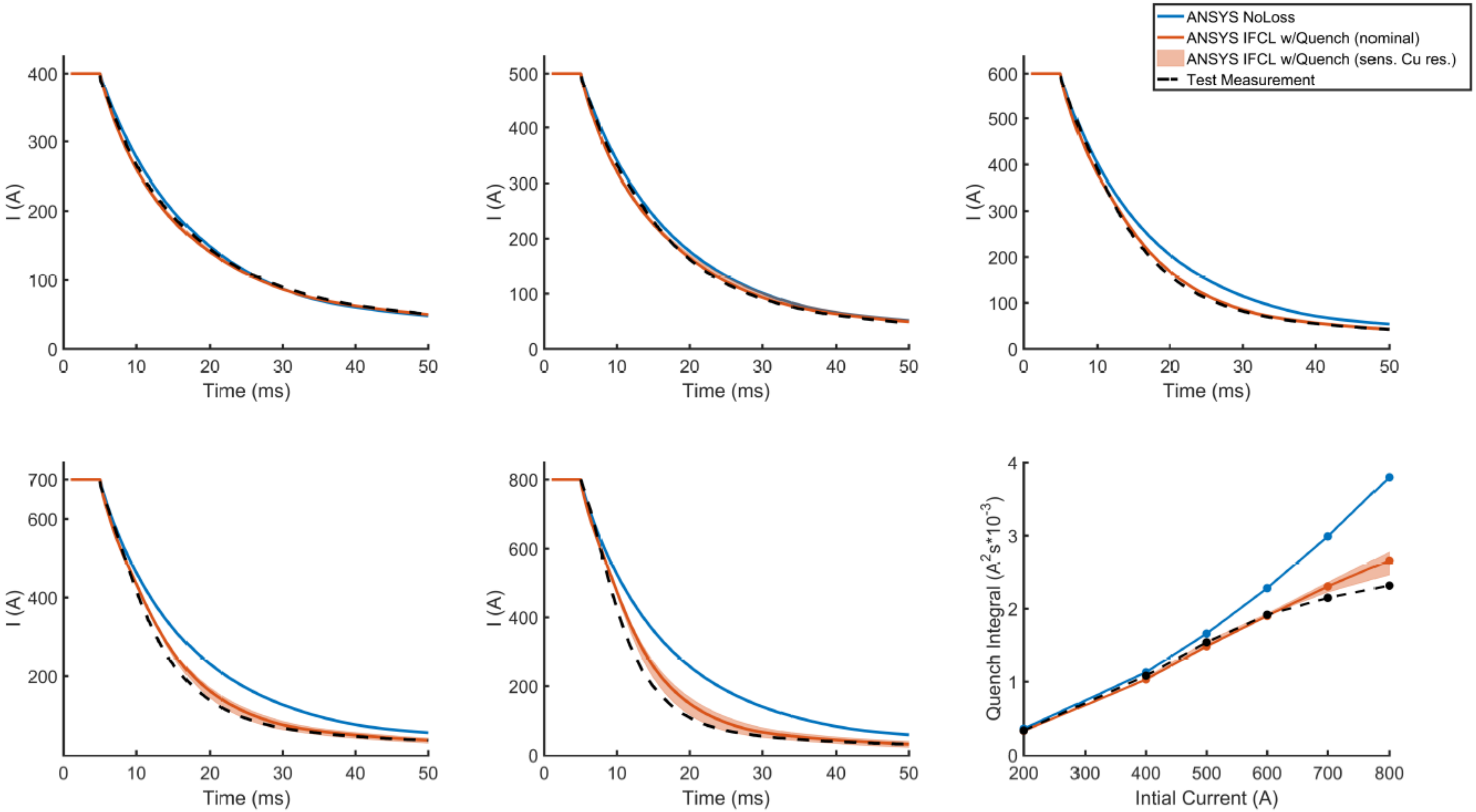
Vpeak = I_0R





Example 300 K limit on integral at 4.5 T

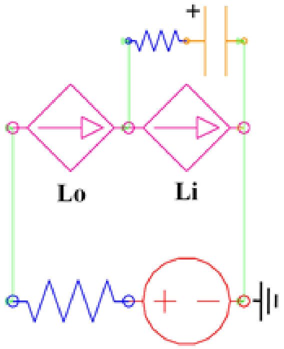
The user elements replicate quench back for a short undulator prototype tested at Berkeley

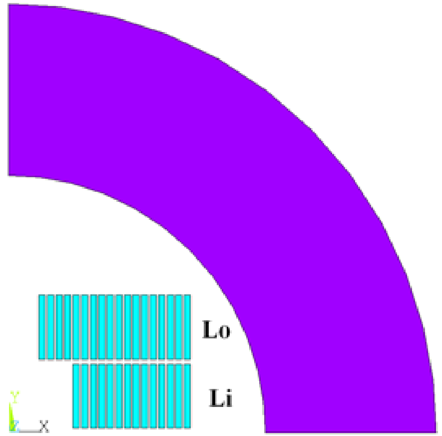


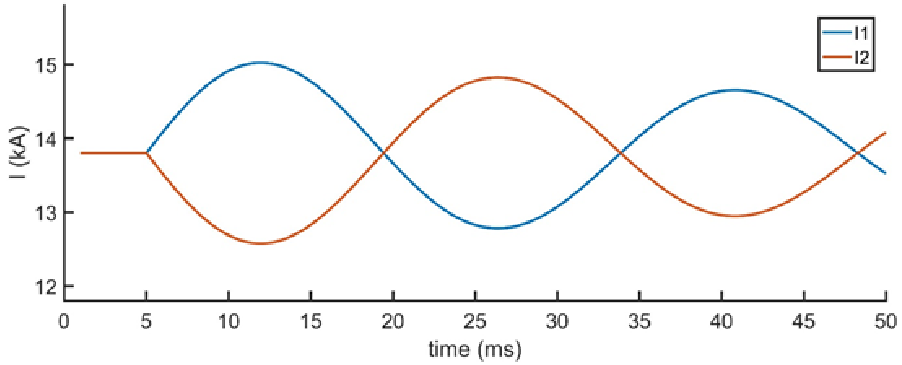
~ 34% less quench integral at high current allows us to reduce dump resistor (terminal voltage)

Long benchmarking and verification study complete with CERN/STEAM: B. Auchmann, L. Bortot, E. Stubberud

Includes CLIQ comparison for a Nb_3Sn block dipole



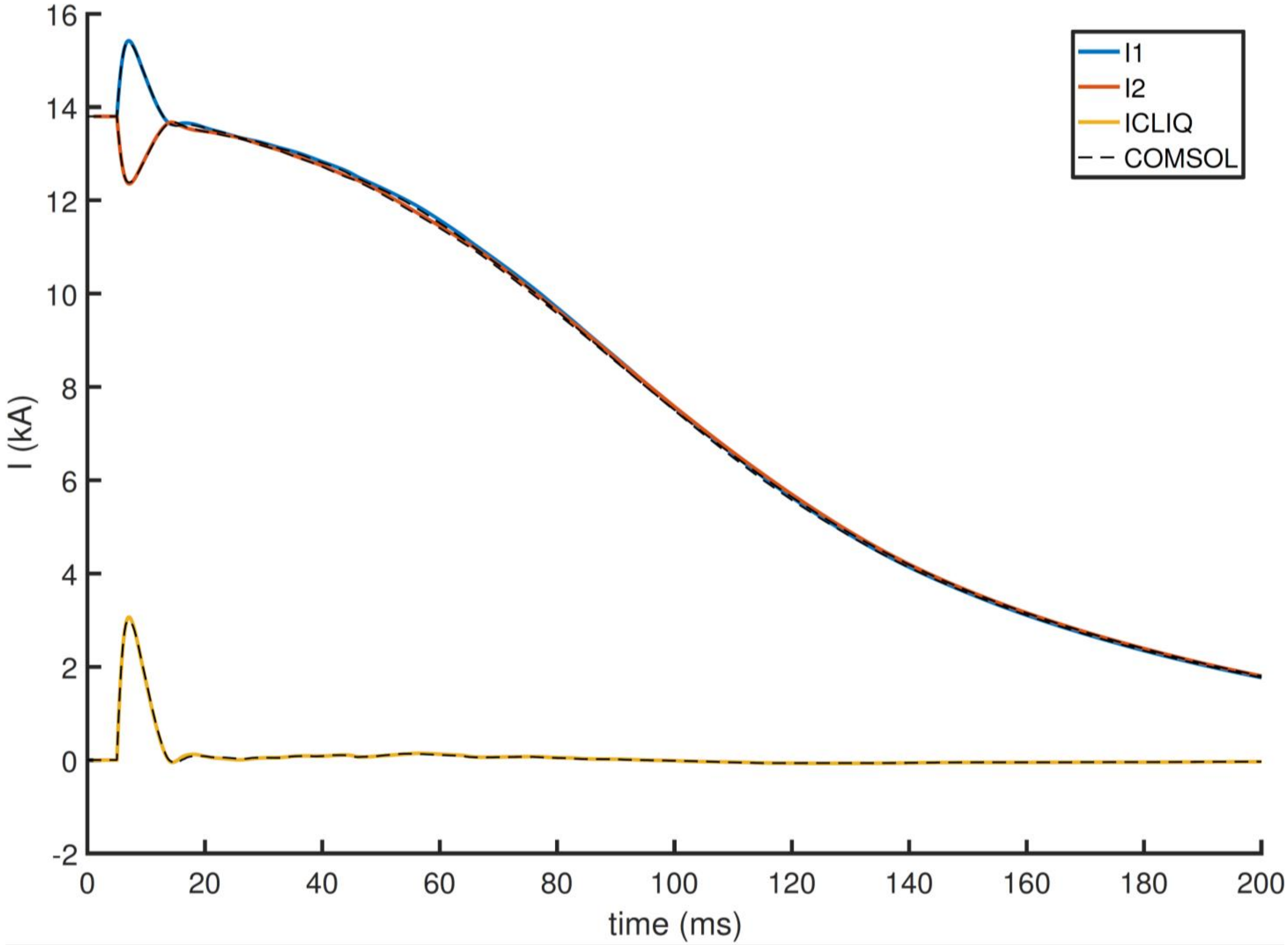




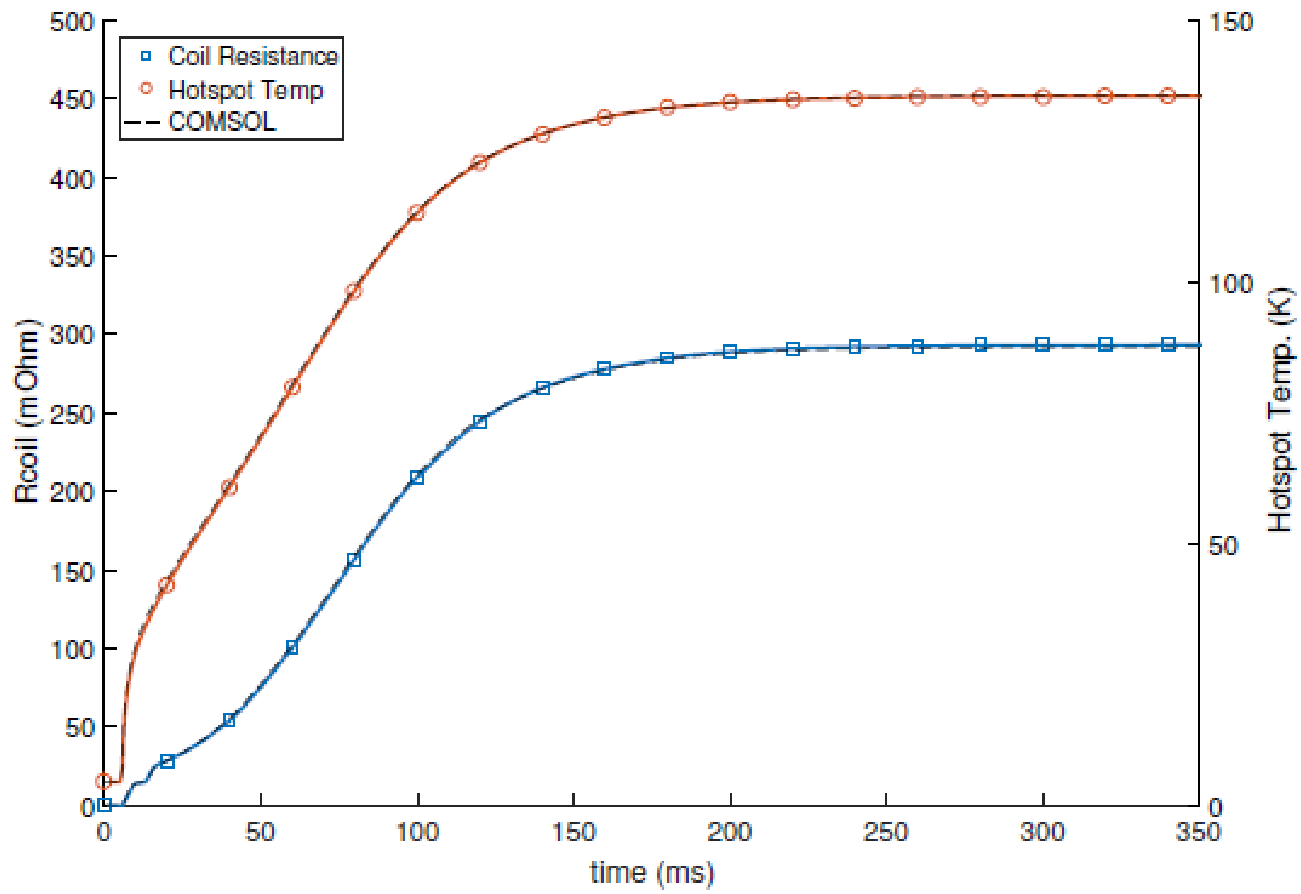
Crosscheck of the ANSYS-COMSOL 2D FEM Implementations for Superconducting Accelerator Magnets

Contents

Comparison of coil and CLIQ currents to COMSOL (w/CERN) shows agreement

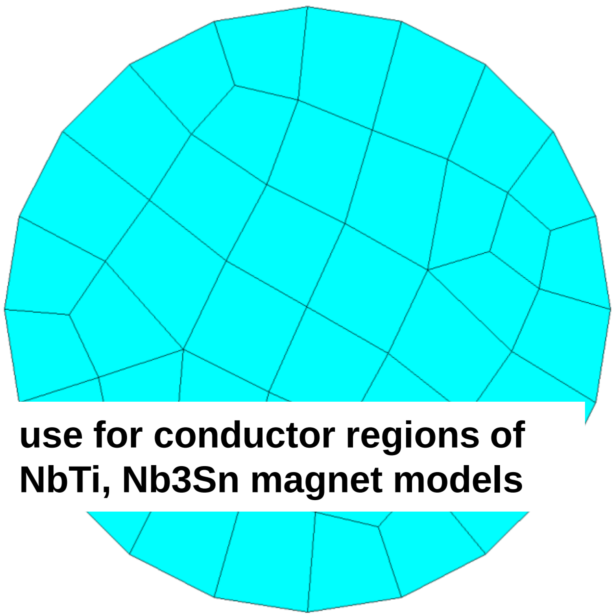


Comparison of coil resistance and hotspot temperature for CLIQ simulation to COMSOL (w/CERN) shows agreement



We have two approaches in ANSYS based on uniform (stranded) or computed current density (power law)

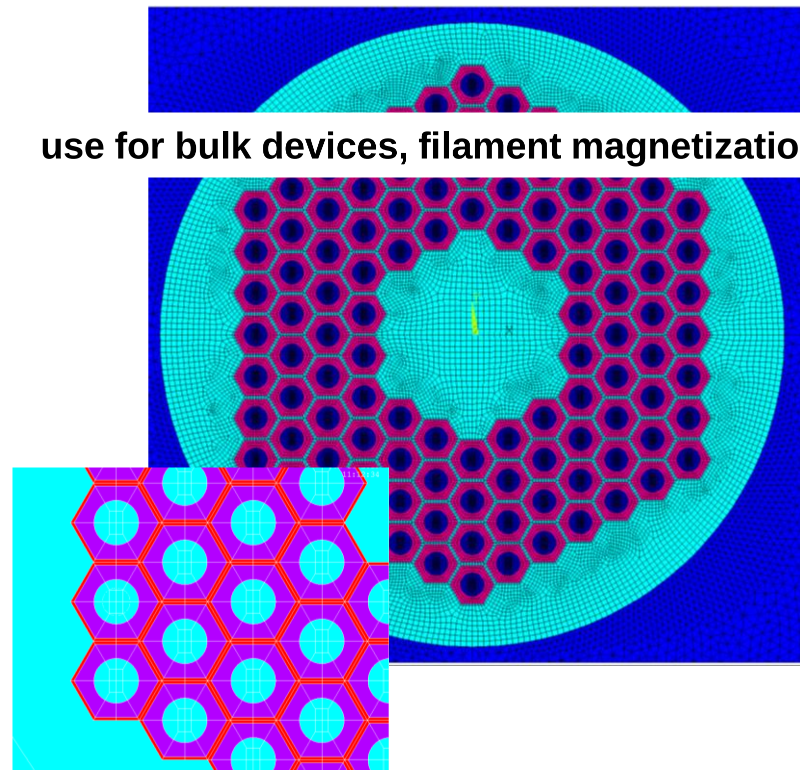
A-curr-emf (stranded)



use for conductor regions of NbTi, Nb3Sn magnet models

- quench and current sharing is implemented with loss term based on Jc(T,B)
- equivalent magnetization used for coupling currents (a priori current path)
- optional resistive/inductive coupling to external circuit

A-V formulation with E-J power law



use for bulk devices, filament magnetization, etc.

- conductive paths resolved by mesh
- current distribution follows from DOF solution

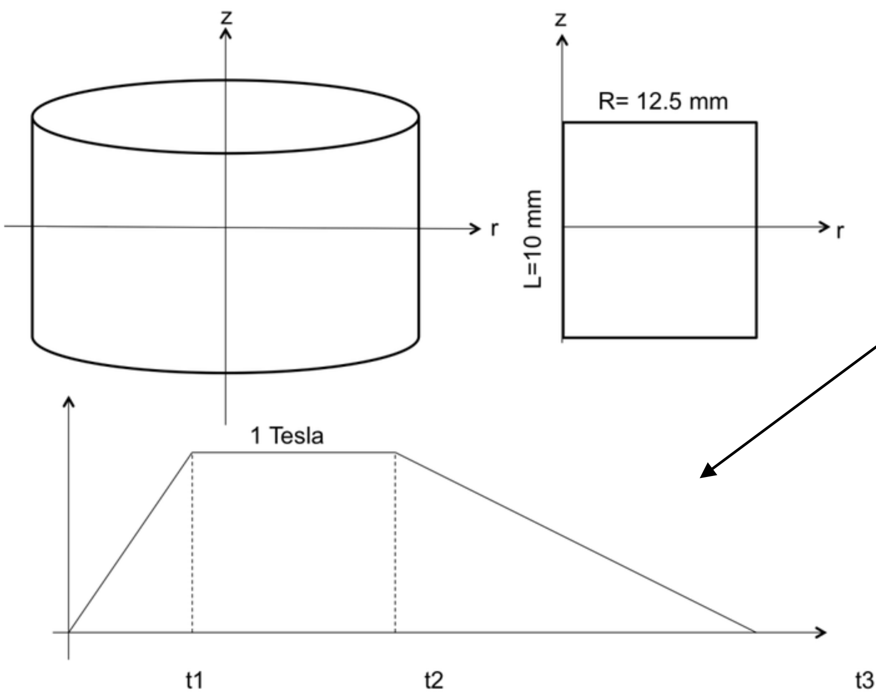
Verification #1: HTS modeling benchmark for bulk magnetization

Benchmark #4

[Go to available solutions]

A superconducting bulk cylinder subjected to magnetization. With the use of an axis-symmetric model the geometry can be reduced to 2-D Cylinder's radius: R=12.5 mm Cylinder's height: L=10 mm Jc=3·10^8 A/m^2, [t1,t2,t3]=[5,10,15] s, magnetic field ramp: as displayed at the bottom of the figure below (Bmax=1 T)

Compare J distributions and magnetization at t1, t2, t3; Bz profiles 2 mm above surface, dissipation.



HTS MODELLING WORKGROUP

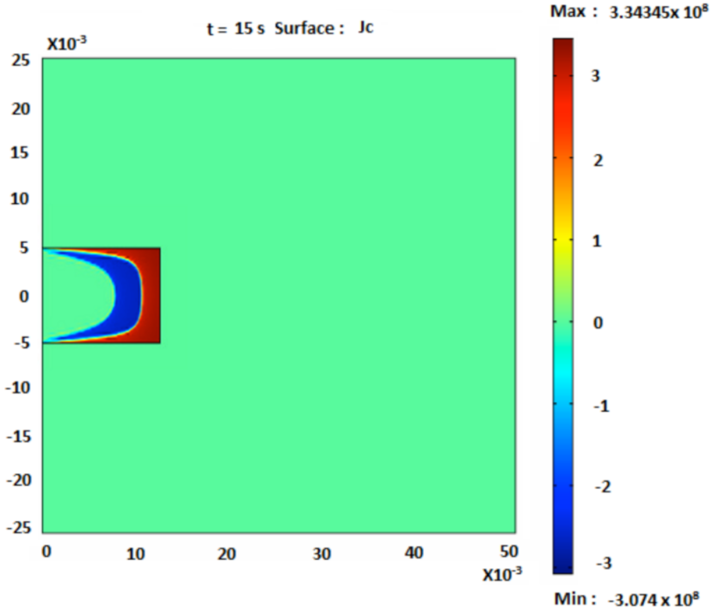
Bulk cylinder of constant Jc is magnetized using vertical field profile as a function of time

$$E = -\partial t A_z - \nabla V$$

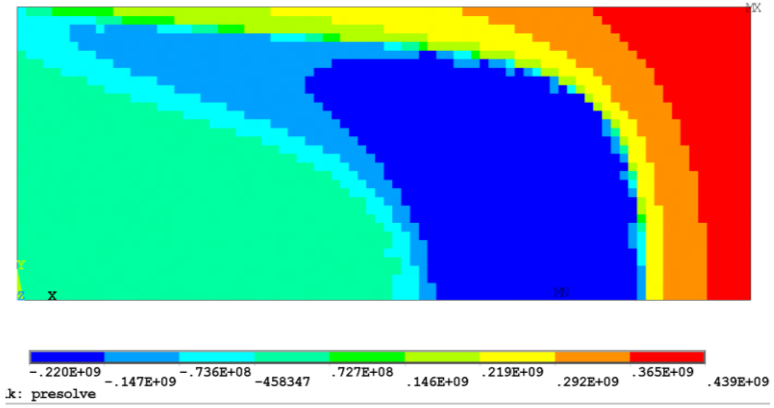
$$\rho(E) = \rho_0 + \frac{E_c^{1/n}}{J_c} E^{(n-1)/n}$$

Current Density at Profile End

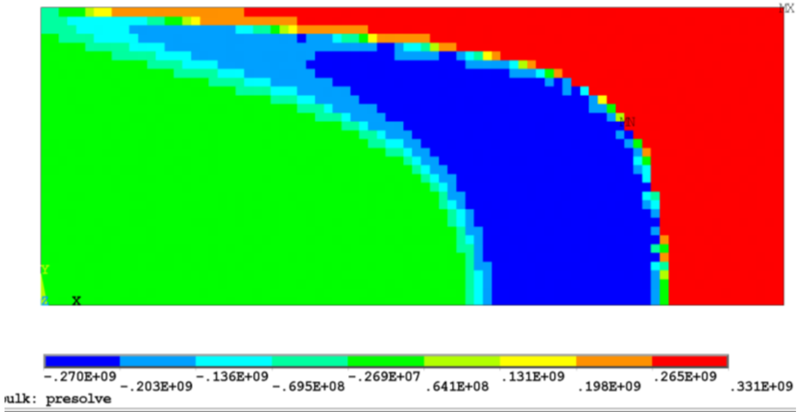
Comsol Benchmark



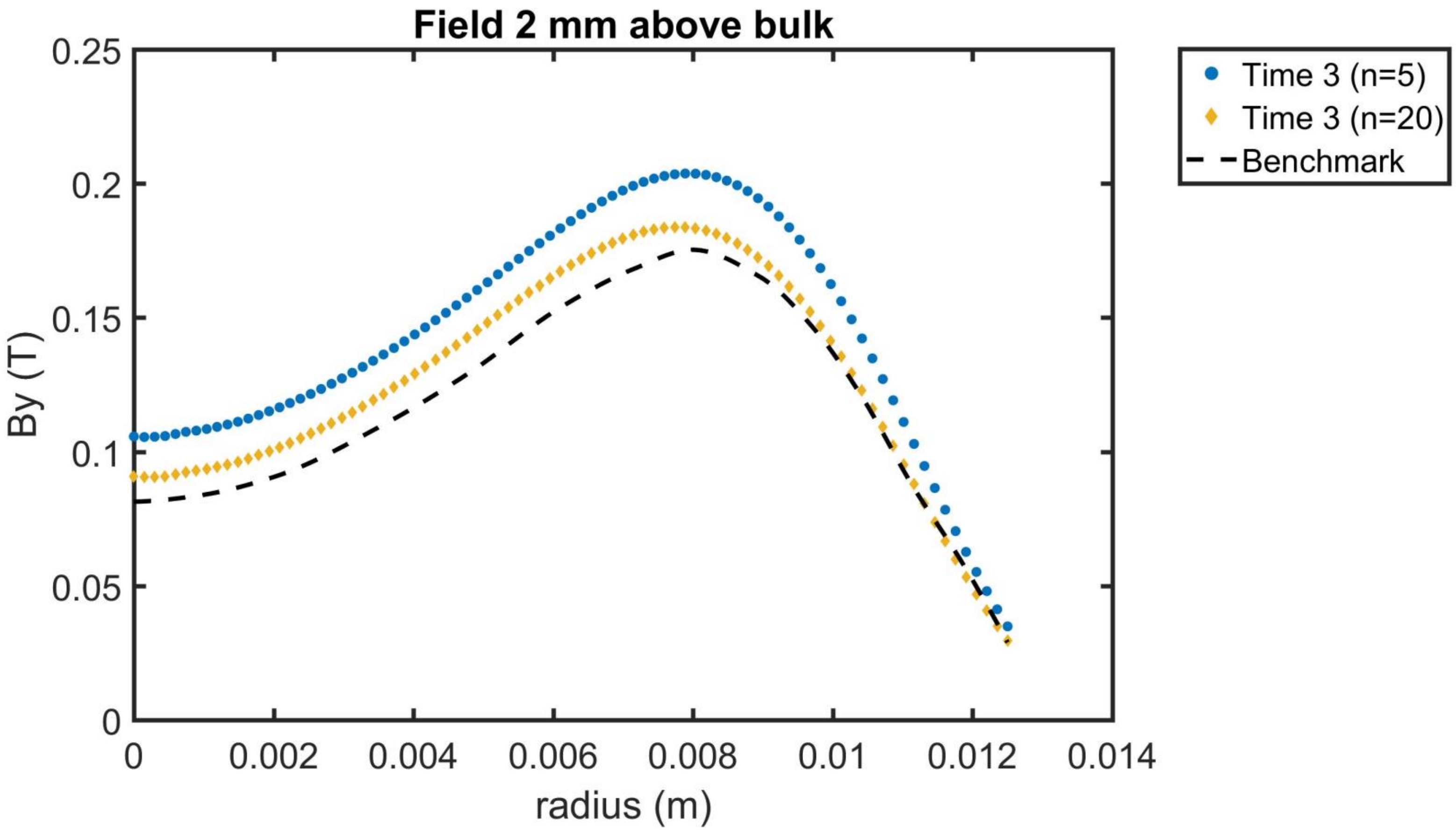
ANSYS (n=5)



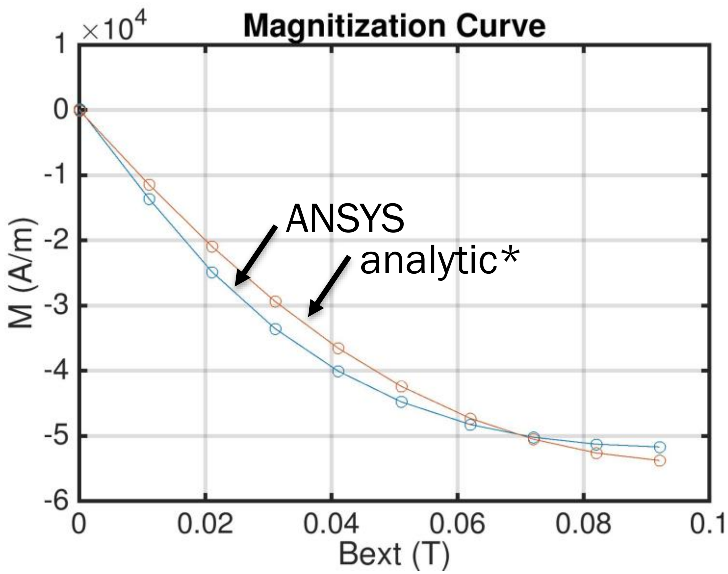
ANSYS (n=20)

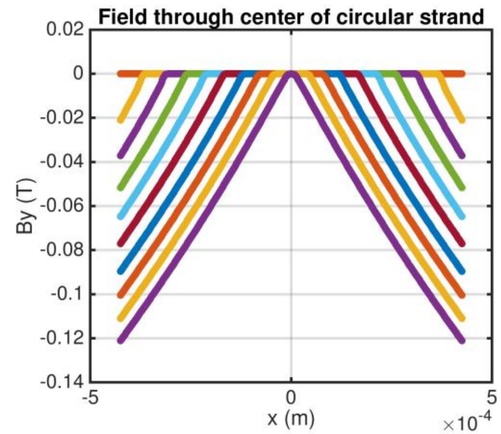


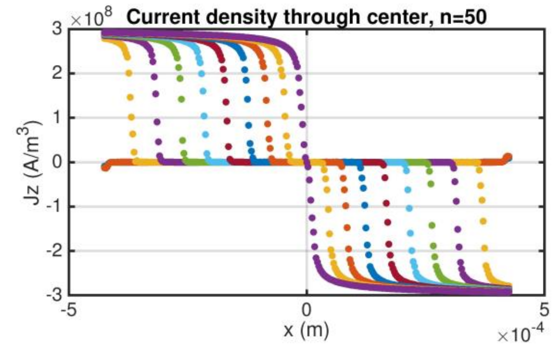
Trapped field at profile end is converging towards benchmark



Verification #2: magnetization of a round filament of fixed Jc = 3x10^8

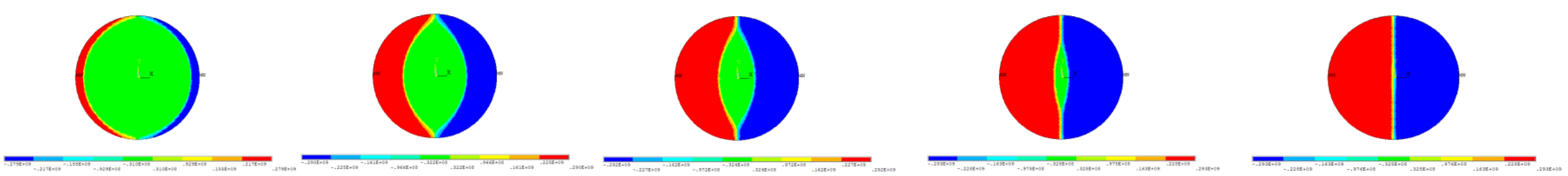






*model is slightly different than analytic based on how fields are applied

increasing Bext up to 0.09 T



It is our goal to make these element available to those interested within the community

FEM approach is geometry and material independent

- accelerator magnets, solenoids, persistent switches, quench heaters, etc…
- Nb-Ti, Nb_3Sn, Bi2212 (or mixed/hybrid)
- very little additional knowledge beyond ANSYS needed

We have a first package with examples and documentation to share with the community (see http://usmdp.lbl.gov/scpack-code/ or contact me at lnbrouwer@lbl.gov)

Initial publication: https://doi.org/10.1088/1361-6668/ab2e63

Summary

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