Radiation Heat-Loads on Superconducting Magnets

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Outline

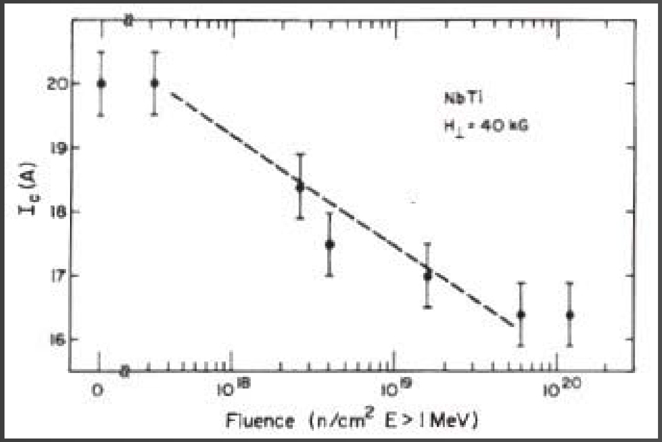
- **The talk is divided onto two parts**
  - Part –1: *Materials*
    - Superconductor
    - Cable Insulation
    - Coil End-parts
    - Potting Compound
  - Part – 2: *Heat-Deposition Studies*
    - Current NbTi LHC IR Quad
    - LARP IR Quad
    - LARP Separation Dipole
- **Summary**

Radiation Loads

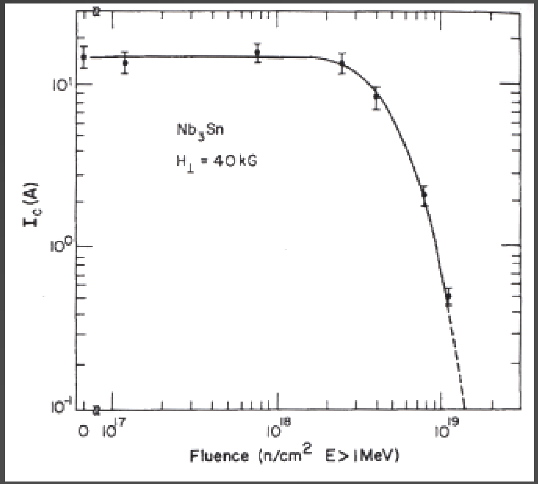
- **Expected radiation loads in various machines**
  - ITER: Neutron fluence of 1×10^{18} n/cm^2 (E > 0.1 MeV) [1]
  - LHC IR Region: Neutron fluence of 1×10^{16} n/cm^2 (E > 0.1 MeV) over the first 10 years [2]
  - LARP IR Quad: Neutron fluence of 2.5×10^{16} n/cm^2 (E > 0.1 MeV) [3]

Superconductor

- **NbTi**
  - "Reduction in Ic (40 kG) was observed for fluences greater than 3 x 10^{17} n/cm^2 and saturation at 18% was observed for fluences above 3 - 4 x 10^{19} n/cm^2 [4]"



- **Nb_3Sn**
  - "Little or no reduction in Ic (40 kG) was observed for neutron fluence below 10^{18} n/cm^2. Between 2 and 3 x 10^{18} n/cm^2, however, there is an apparent threshold where a rapid reduction in Ic was seen[4] "



Cable Insulation

- **NbTi cable is typically insulated with Kapton® – a polyimide tape which has high radiation resistance**
- **Various insulation materials have been used for Nb_3Sn all of which have high radiation resistance**
  - S2 fiberglass sleeve or tape [widely used]
  - Ceramic tape [FNAL]
  - Quartz tape [SLAC]

Coil End-Parts

- **Current LHC IR quads have G-11 end-parts. This is part of the reason that limits the magnet lifetime to about 7 years for a nominal luminosity level of 10^{34} cm^{-2}s^{-1}**
- **Magnet lifetime would be further reduced if highest possible LHC machine luminosity was considered**
- **For Nb_3Sn magnets, metallic end-parts are typically used in order to sustain high reaction temperatures**
  - This puts greater demand on cable insulation, but from radiation prospective, end-parts should not be an issue

Potting Compound

- **Currently Nb_3Sn magnets are being impregnated with epoxy that have low radiation resistance**
  - Ultimate tensile strength of fiber reinforced epoxy laminates degrade by up to 36% after irradiation to 1 x 10^{22} n/m^2 (E > 0.1 MeV) [1]
- **Alternate materials for vacuum impregnation needs to be investigated in order to improve radiation resistance of the coil, thus increasing the magnet lifetime**

ITER Studies

- **ITER Coil Insulation R&D Program**
  - G-11 essentially became unusable at the radiation dose level of 5.0 $x10^{22}$ m^{-2} * [5]
  - The shear strength of some modified epoxy resins such as CTD 101 dropped by about 20% at 1.0 $x10^{22}$ m^{-2} and 50% at 5.0 $x10^{22}$ m^{-2} [5,6]
  - The shear strength of bismaleimide system dropped by 38% at 5.0 $x10^{22}$ m^{-2} [5]
  - Polyimide system sustained least damage due to irradiation – the strength remained almost constant even at the highest radiation dose level [5]

*** Neutron fluence levels of 1.0 $x10^{21}$, 1.0 $x10^{22}$, 5.0 $x10^{22}$ m^{-2} (E > 0.1 MeV) translate to total absorbed dose levels (neutron+gamma) of 4.7 $x10^{6}$, 4.7 $x10^{7}$, 2.3 $x10^{8}$ Gy**

Alternate Materials for Impregnation

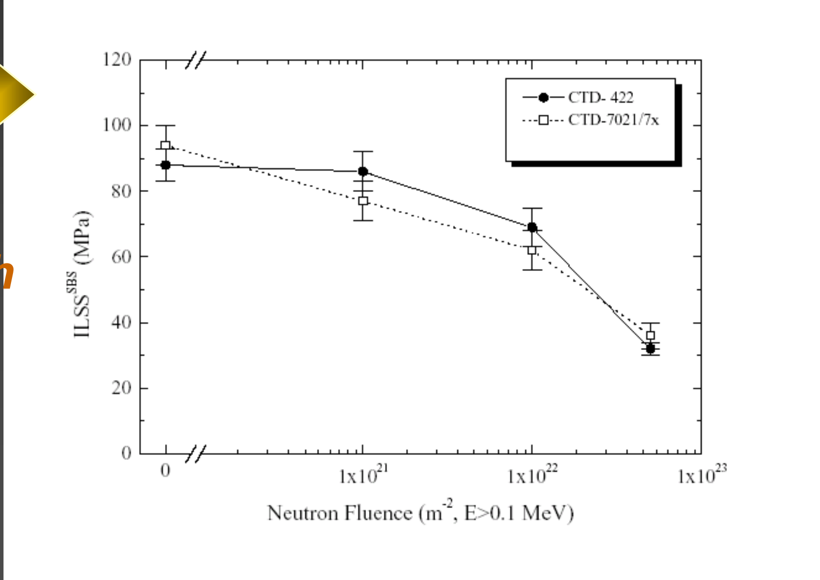
- **JPL/NASA's work on the Precision Segmented Reflector/Telescope Technology program studied different resins that offer good radiation resistance** [7]
  - The study identified EX-1515, a commercially available cyanate ester resin with 121 ^{o}C cure temperature
  - Irradiation tests showed that the strength of the material dropped from 130 MPa to 104 MPa after irradiation to 10^7 Rads

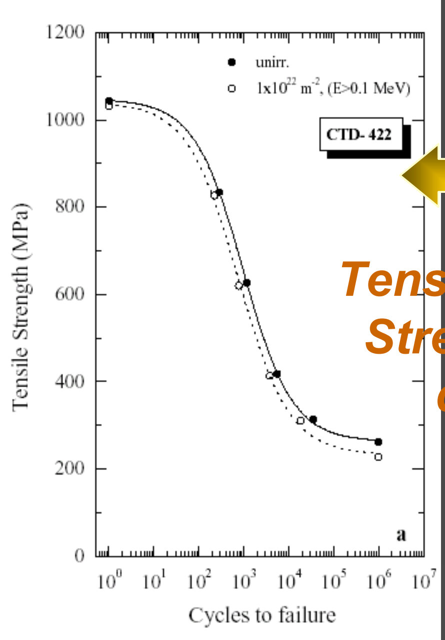
Cyanate Ester

❖ More recently CTD Inc. in USA and Atomic Institute in Vienna are collaborating in developing and testing various cyanate ester based hybrid resins [1,8]

CTD-422: Cyanate ester/epoxy blend

Shear Strength





Tension-Tension Stress-lifetime diagram

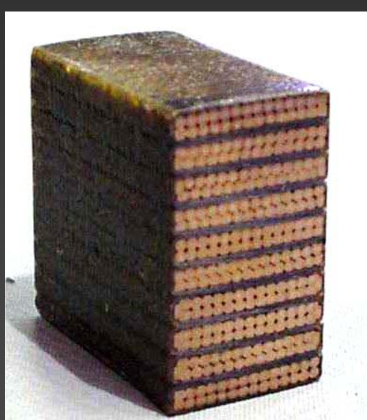
Bismaleimides

- **Fermilab has recently looked into commercially available polyimide and/or bismaleimide resins for VPI [9]**
  - Matrimid® 5292, a two-component bismaleimide system from Vantico was identified as a possible candidate

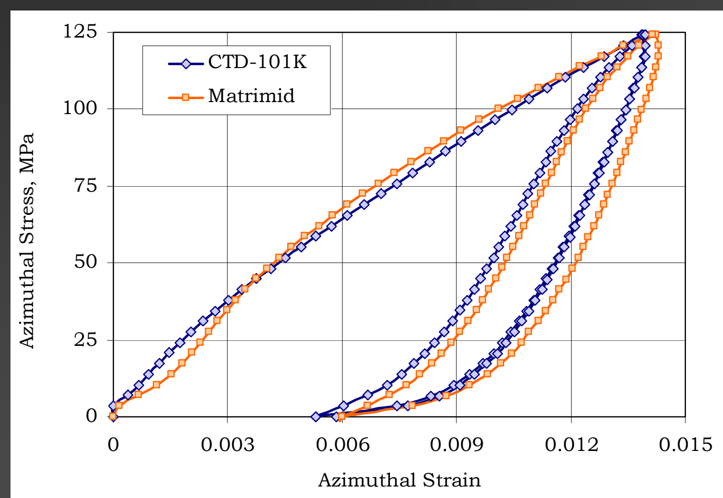
Temperature, ^{o}C	Viscosity, cps	Potlife, min
75	5000	>1000
100	*800*	*1000*
125	10	100
>200	<10	1

Matrimid® 5292

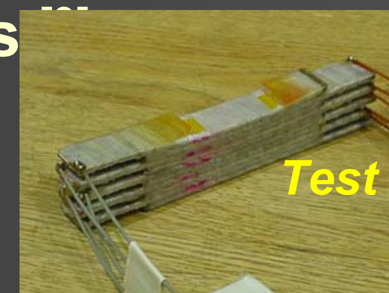
- Ten-stack samples were impregnated with Matrimid to understand and optimize impregnation process. Impregnation was performed at 100 °C as the viscosity is about 800 cps with a potlife of 17 hrs



Impregnated Ten-stack sample

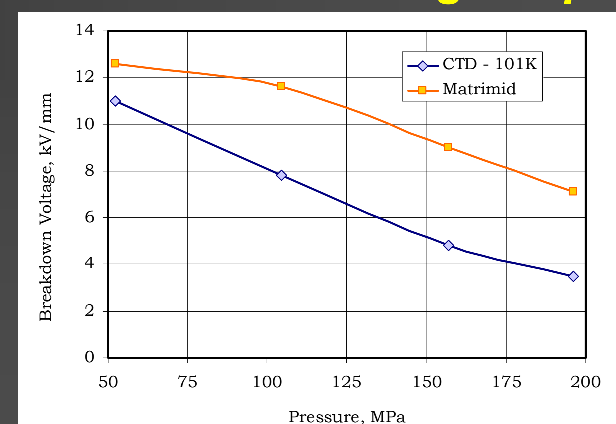


Mechanical Behavior in the Vertical direction at 300 K



Test Sample

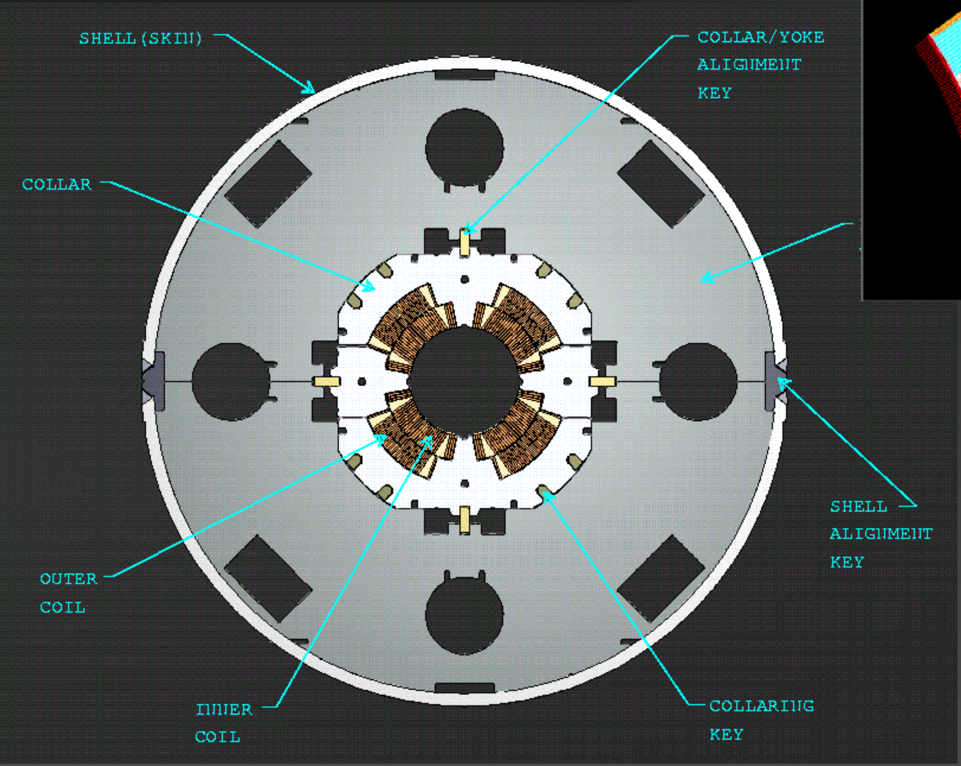
Break-Down Voltage Expt



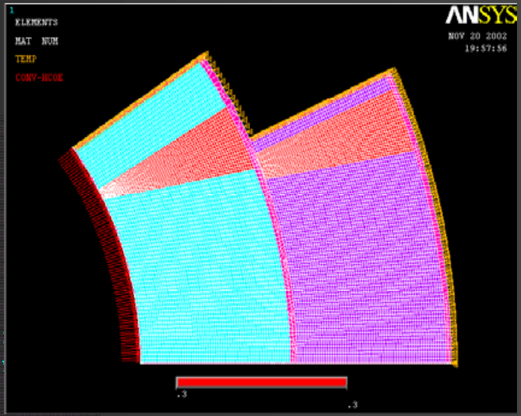
Radiation Heat-Loads

- **Different configurations were analyzed by varying boundary conditions to estimate the peak temperature in the coil due to radiation heat load**
  - Current NbTi LHC IR Quad
  - Proposed LARP Nb_3Sn IR Quad
  - Proposed LARP Nb_3Sn Separation Dipole
- **Analysis was done by Zlobin et al.,[10,13]. Brief summary of results are presented in the next few slides**

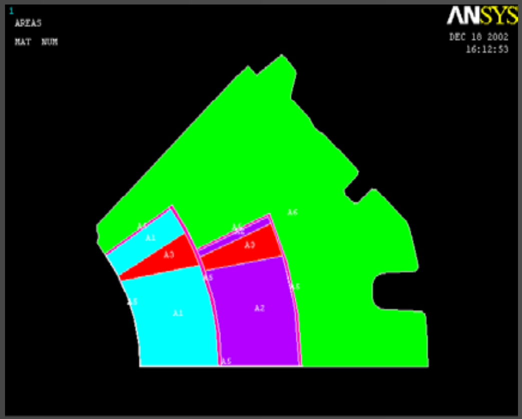
Current NbTi LHC IR Quad

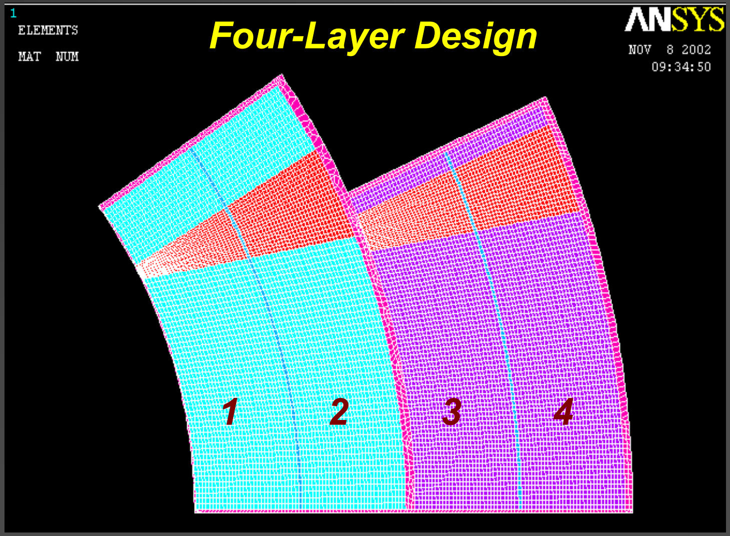


Two-Layer Design



Two-Layer Design with Collar

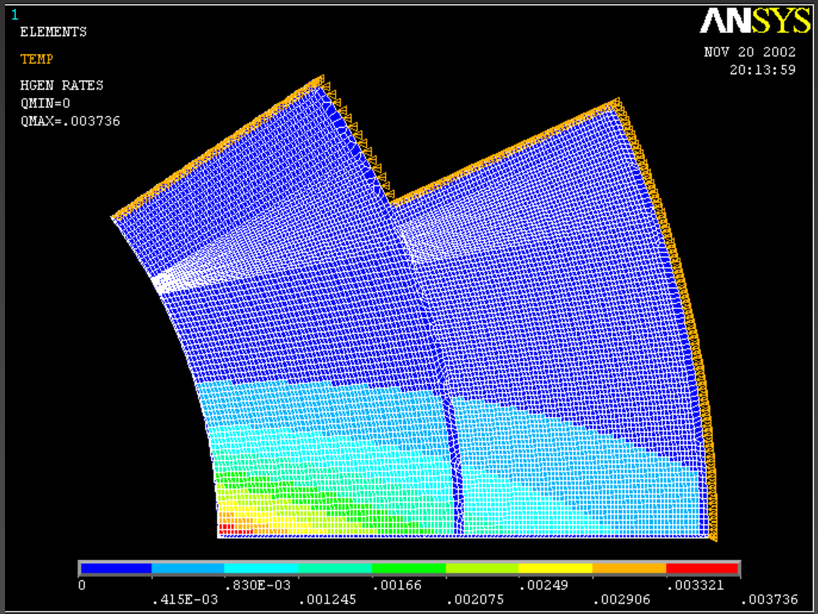




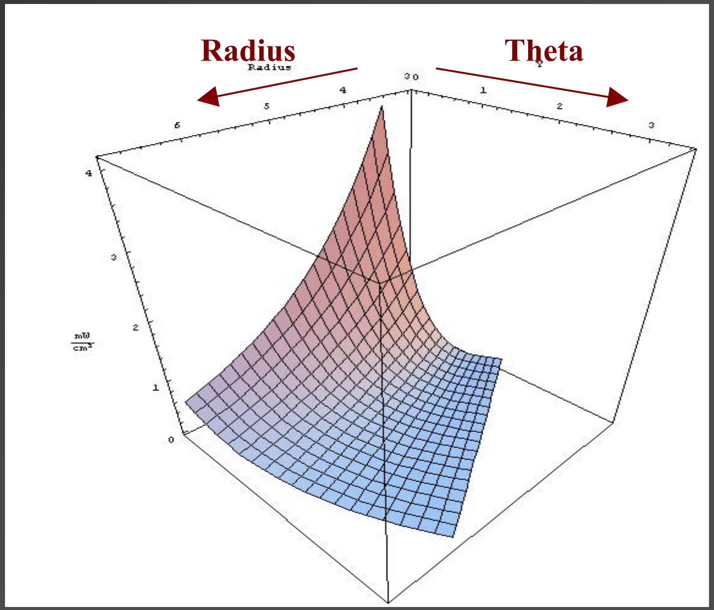
1. *Coil perimeter was held at 1.9 K*
2. *For two layer with collar design, collar surface was held at 1.9 K*

LHC IR Quad Thermal Model

- **Heat Deposition in Magnet Coils**
  - The heat loads were applied as a element body loads, which are a function of the element's radial and azimuthal location (*from N. Mokhov*)

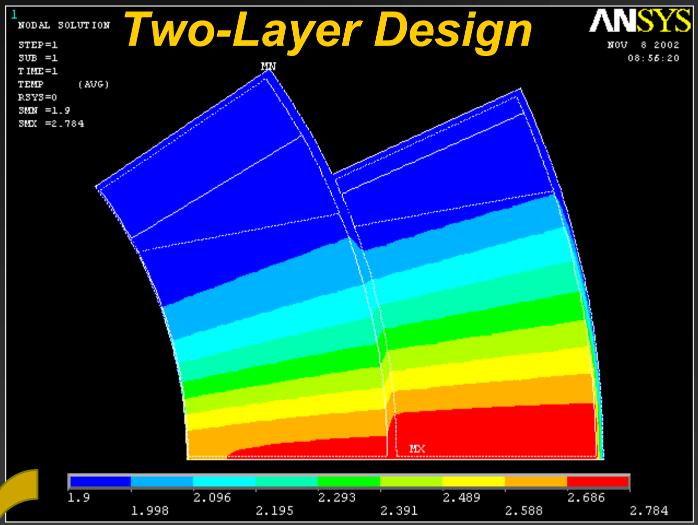


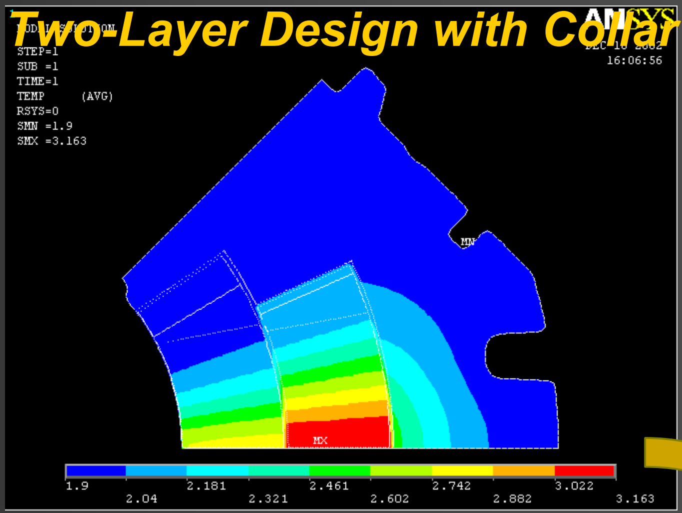
Applied Heat Loads in mW/mm³



3-D Plot of the applied coil heat-loads

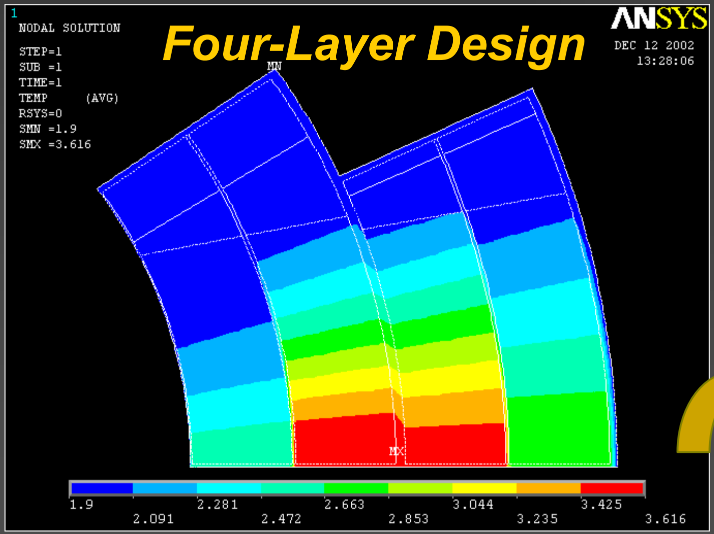
LHC IR Quad Thermal Model





T_{peak} = 2.784 K

T_{peak} = 3.163 K

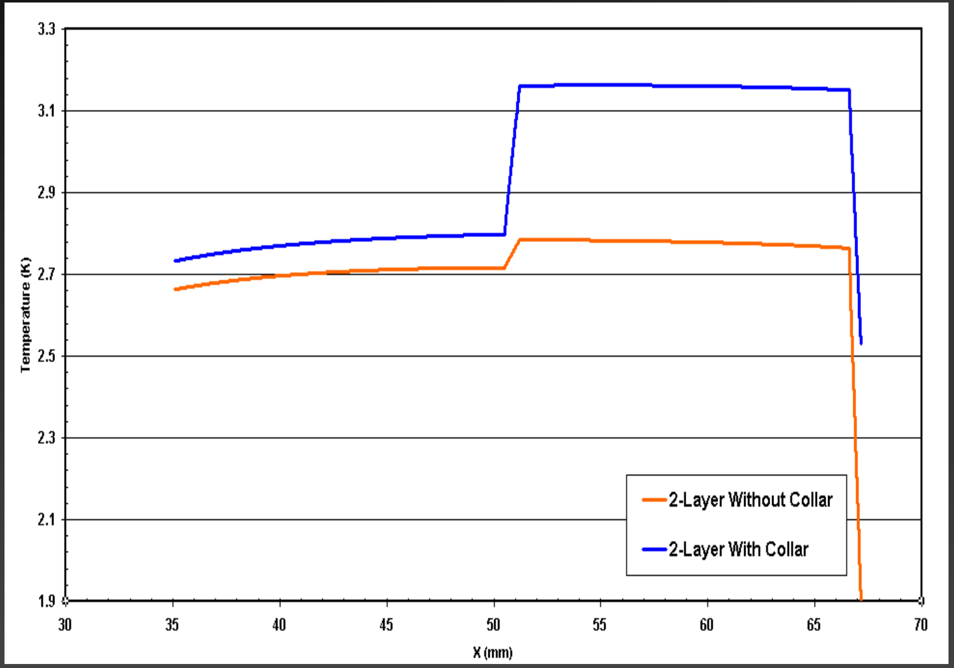


Temperature contour plots for various designs

T_{peak} = 3.616 K

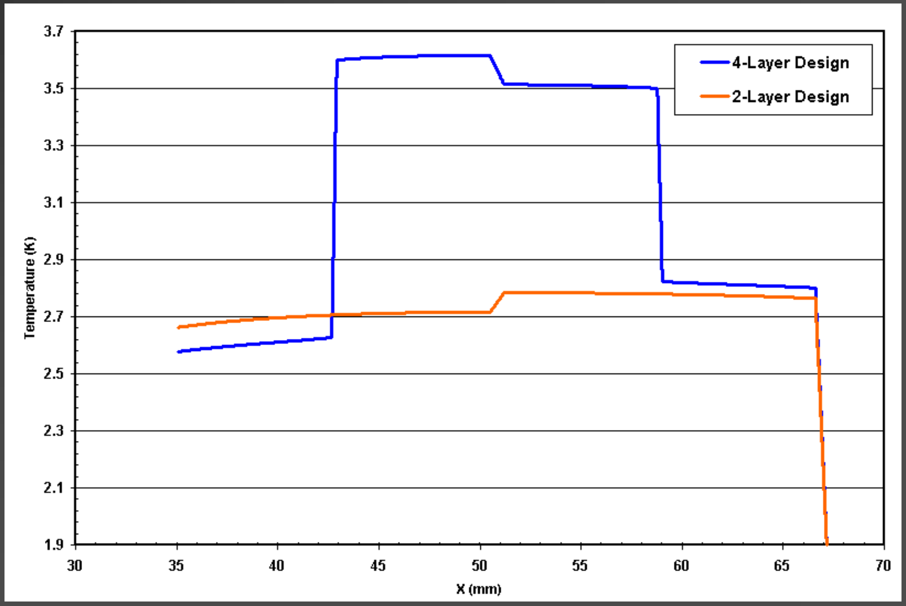
Analysis by Yadav & Zlobin [10]

LHC IR Quad Thermal Model



Temperature profile along the mid-plane nodes for 2-layer design with and without collars

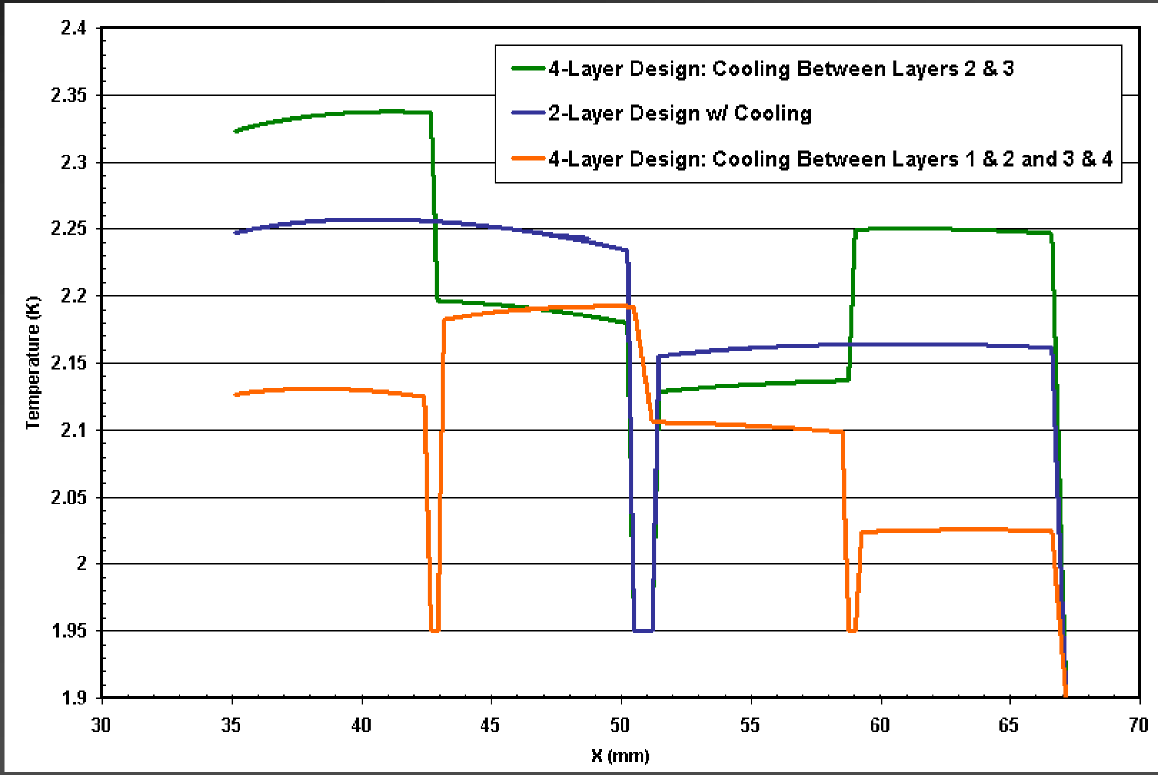
Temperature profile along the mid-plane nodes for 2-layer and 4-layer designs



Analysis by Yadav & Zlobin [10]

LHC IR Quad Thermal Model

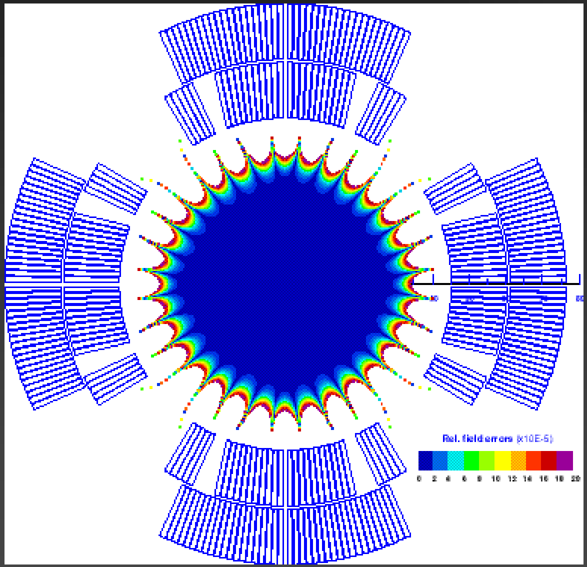
- **Effect of Interlayer Cooling**

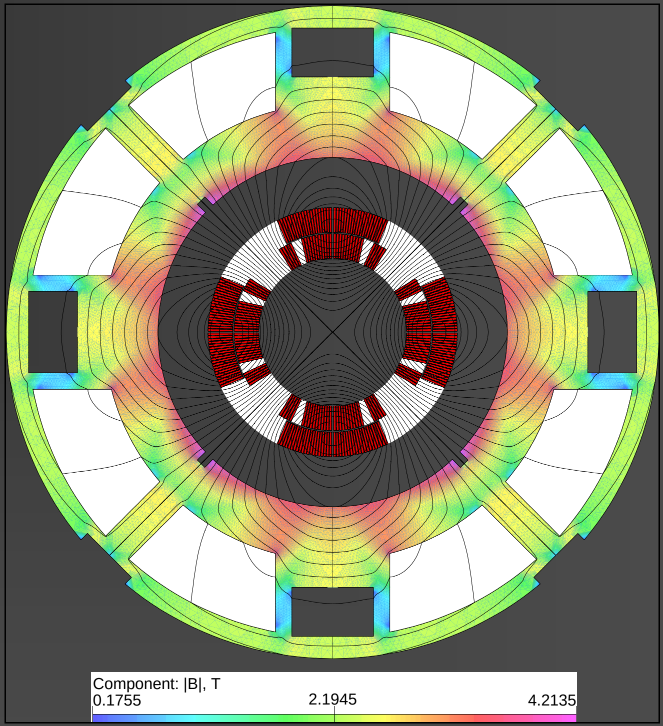


Analysis by Yadav & Zlobin [10]

LARP Nb_3Sn IR QUAD

- **Proposed coil geometry** *(Kashikhin & Zlobin[11])*





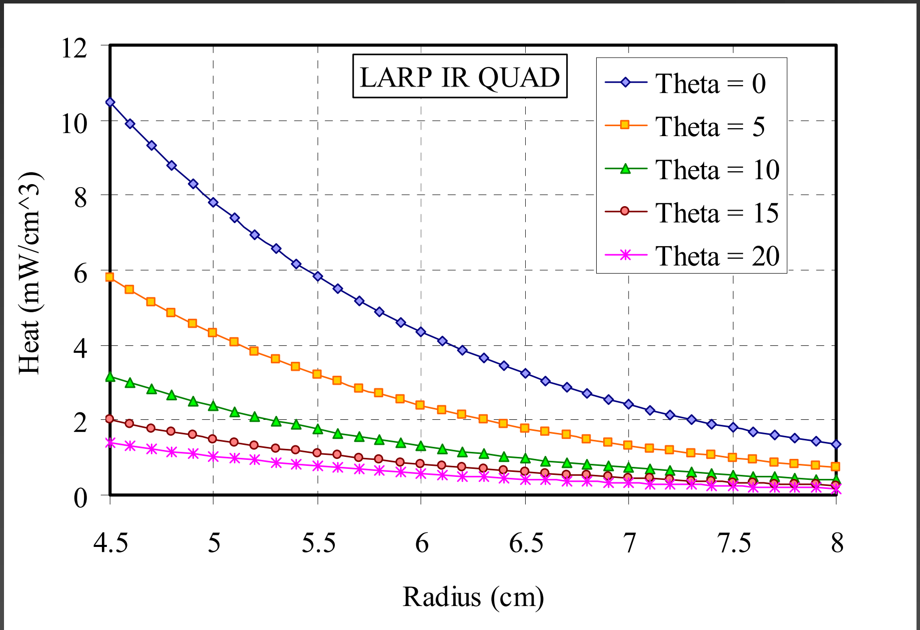
Bore Diameter = 90 mm
Number of Turns = 144
Total superconductor area = 48.1 cm²

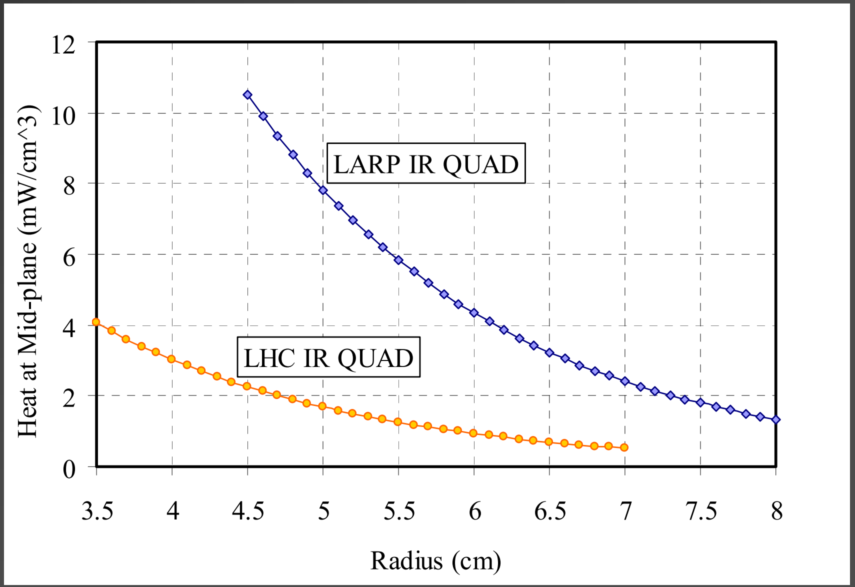
LARP IR QUAD Heat loads

- **Heat-loads as a function of radius and angle were evaluated as follows (*Zlobin+Mokhov*[12])**

$$Q(r,\alpha)=1.5\times\exp\left(-\left(\frac{r-4.5}{1.7}\right)\right)\ \frac{mW}{g}\times 7\ \frac{g}{cm^3}\times F(\alpha),$$

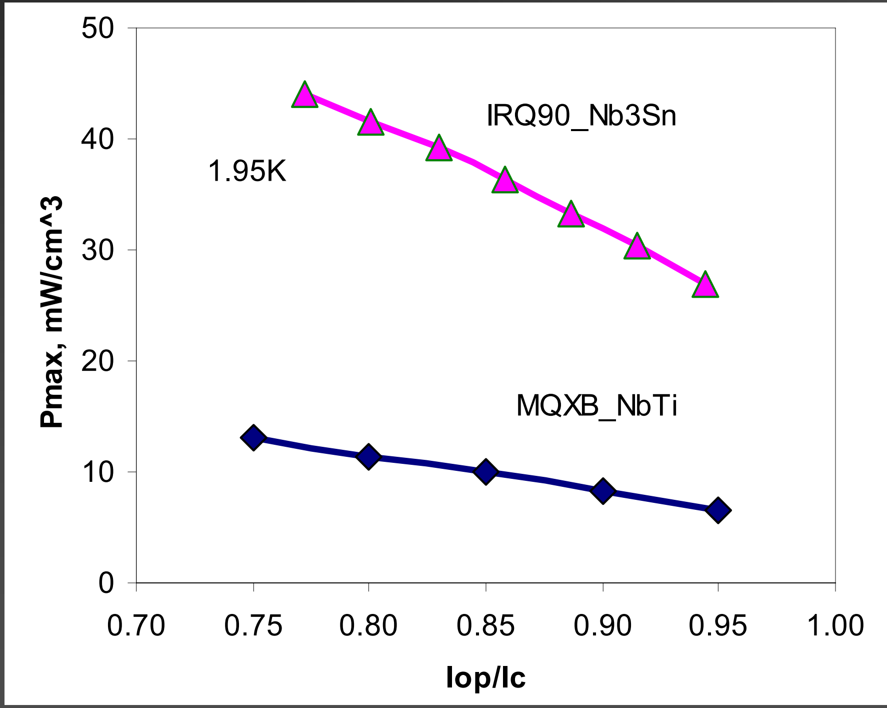
$$where\quad F(\alpha)=\frac{1}{\left(1+(10*\alpha)^{1.5}\right)}$$





LARP IR Quad Thermal Analysis

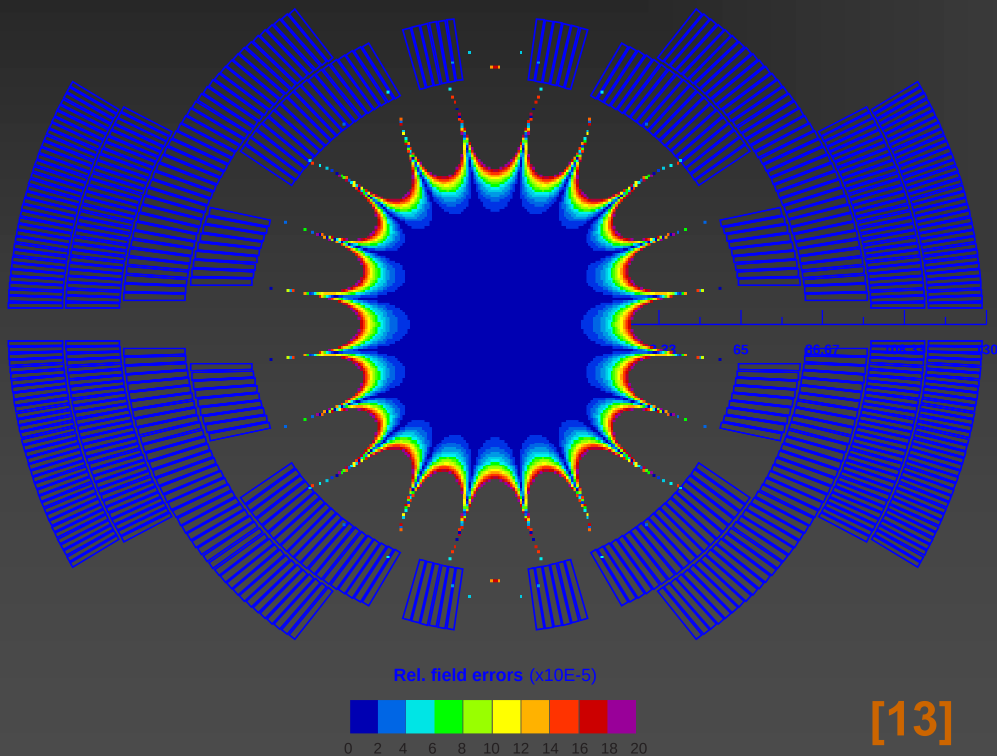
- Nb_3Sn magnet designed with 20% quench margin can tolerate up to 40 mW/cm^3 of peak power dissipation in the mid-plane turns [12]



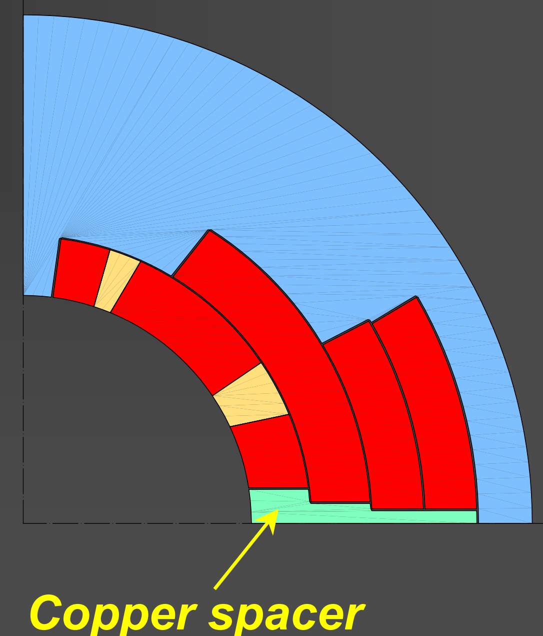
LARP Separation Dipole

D_{bore} = 130 mm, J_c(12T,4.2 K) = 3000 A/mm^2

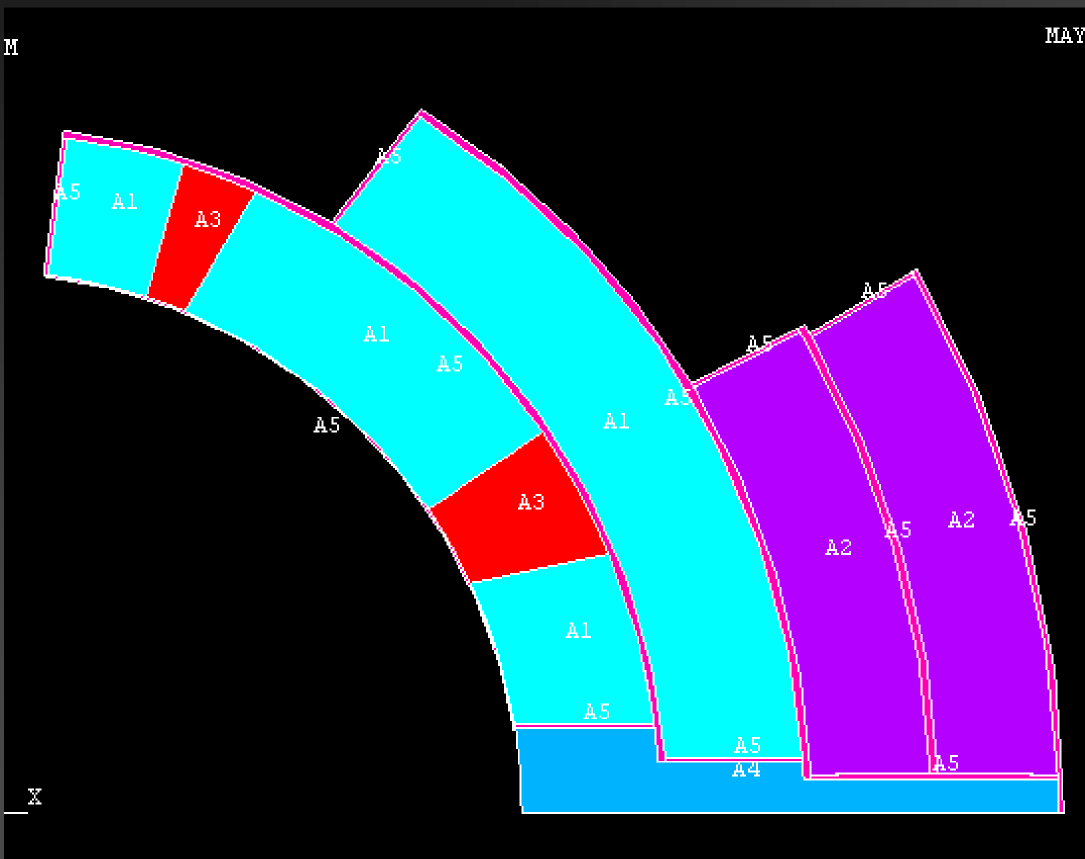
B_{q_bore} = 15.8 T
N_{turns} = 282
S_{coil} = 119.1cm^2



[13]



LARP Dipole Thermal Model



Thermal conductivity in mW/mm/K at 1.9 K

```
MATERIAL NUMBER =        1
 KXX    =    5.0000
 KYY    =   0.18000E-01
 KZZ    =    0.0000

MATERIAL NUMBER =        2
 KXX    =    5.0000
 KYY    =   0.18000E-01
 KZZ    =    0.0000

MATERIAL NUMBER =        3
 KXX    =    140.00

MATERIAL NUMBER =        4
 KXX    =    140.00

MATERIAL NUMBER =        5
 KXX    =   0.20000E-01
```

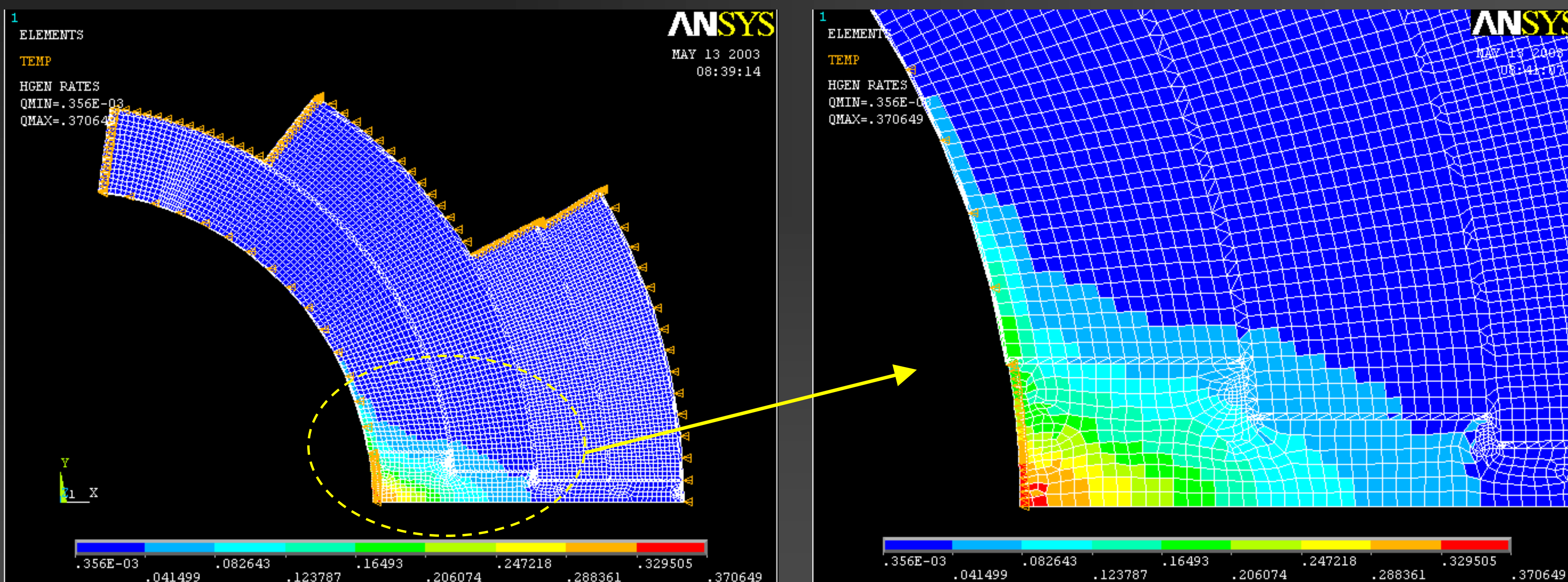
Analysis by Yadav & Zlobin [12]

Coil perimeter was kept at 1.9 K

LARP Dipole Thermal Model

Heat deposition in the coil (from N. Mokhov [14])

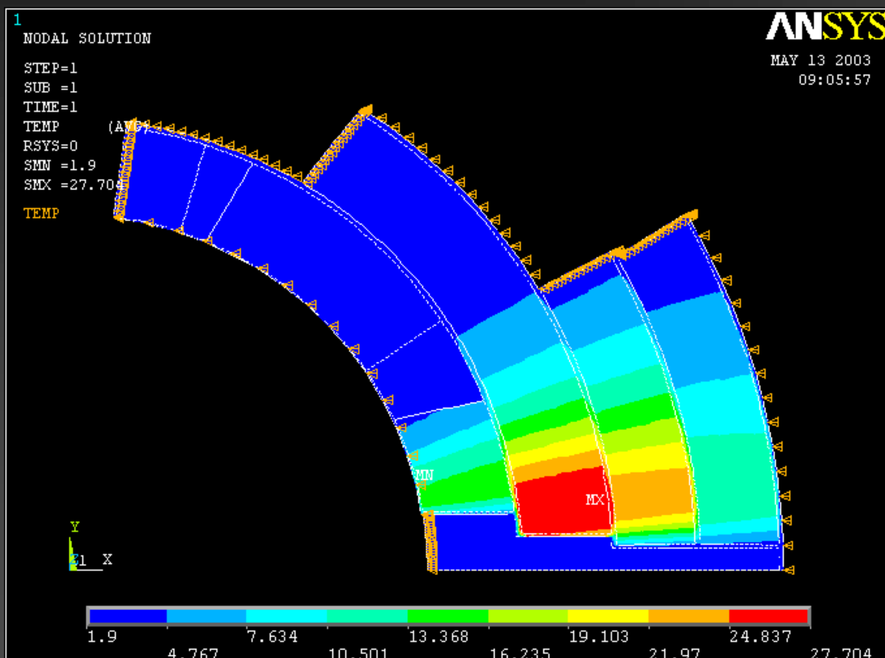
Applied heat loads on coil elements in mW/mm^3



$$Q_{peak\_spacer} = 49\ mW/g;\ \ Q_{peak\_coil} = 13\ mW/g = 20 \times Q_{peak\_MQXB\_coil}$$

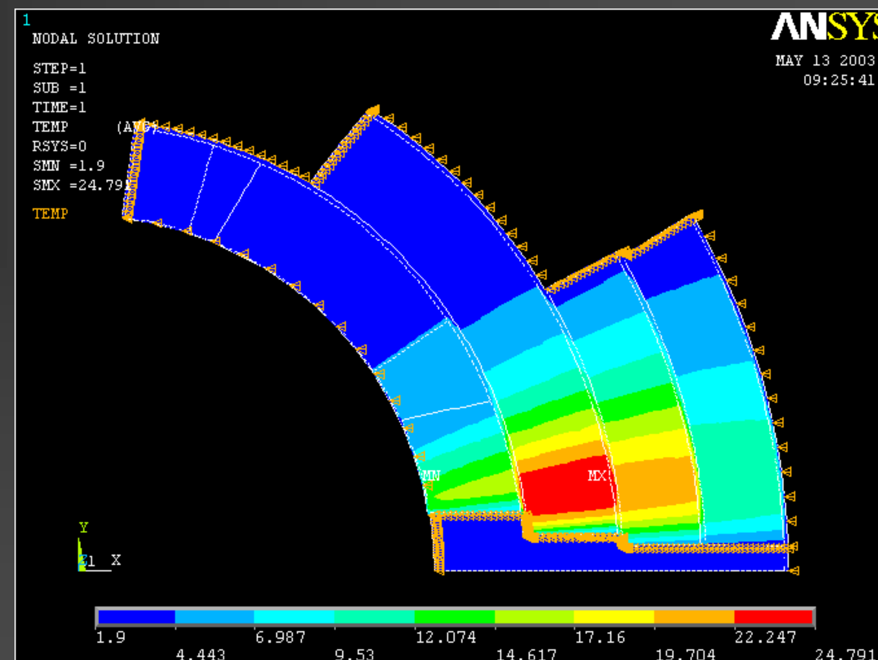
LARP Dipole Thermal Model

External Cooling



T_{peak} = 27.7 K

+ Midplane Cooling

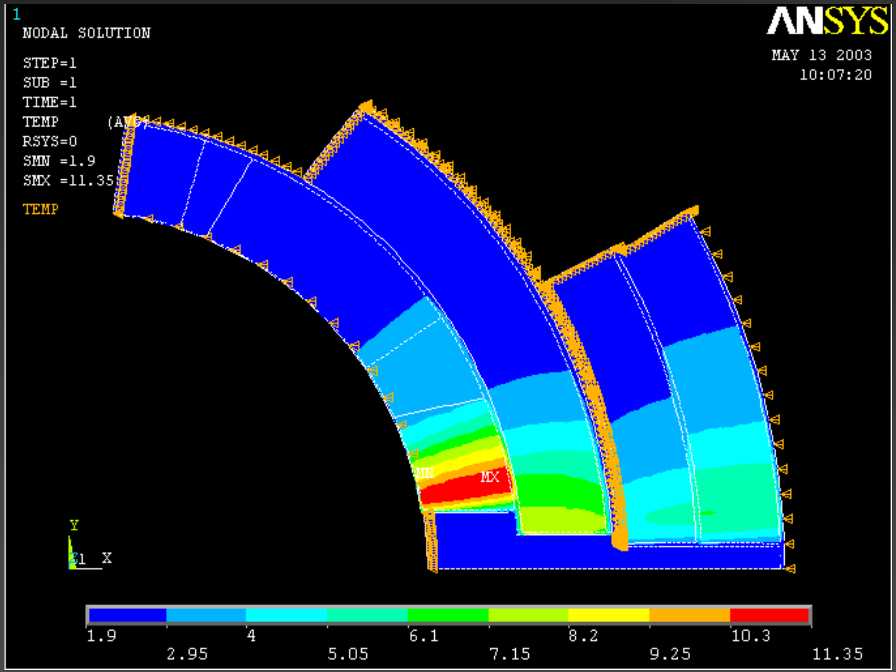


T_{peak} = 24.8 K

Analysis by Yadav, Kashikhin,& Zlobin [13]

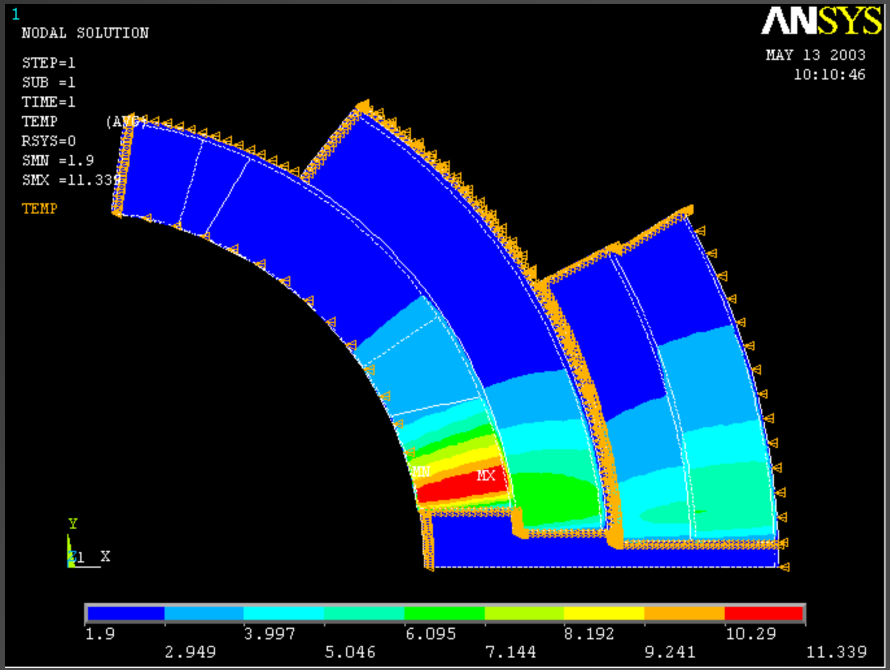
LARP Dipole Thermal Model

External + Interlayer Cooling



T_{peak} = 11.35 K

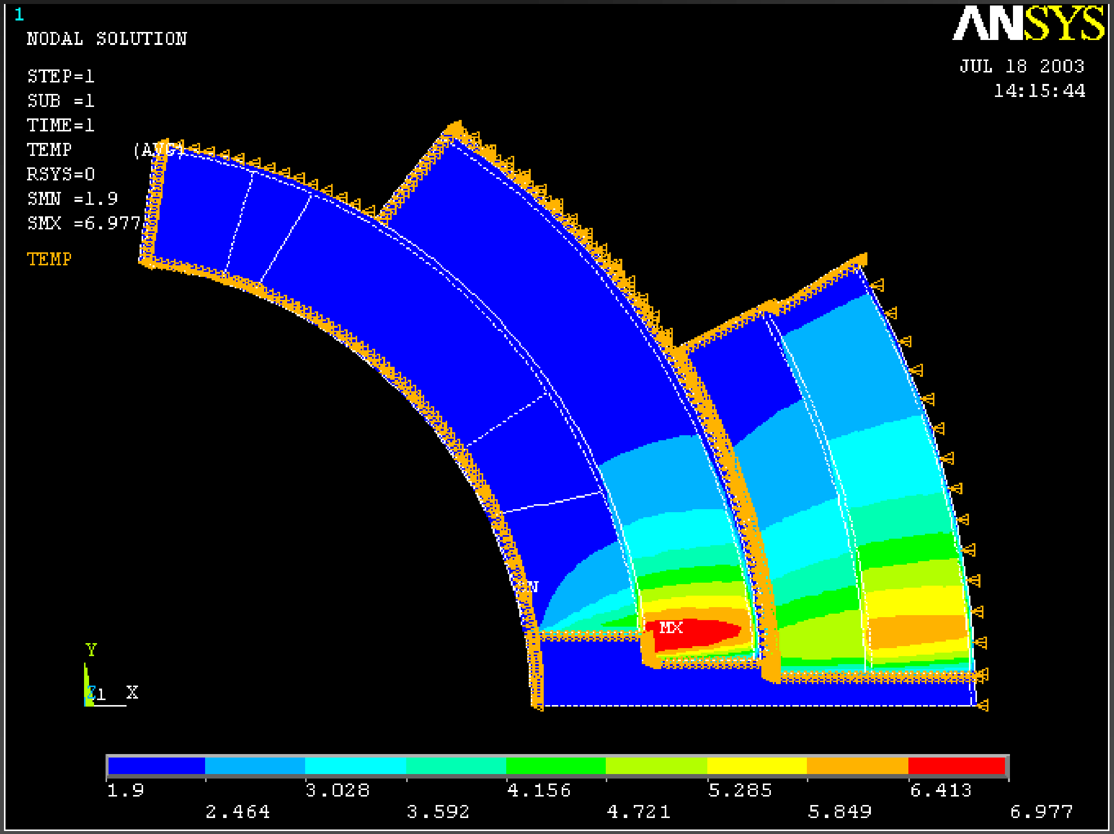
+ Midplane Cooling



T_{peak} = 11.34 K

Analysis by Yadav, Kashikhin,& Zlobin [13]

LARP Dipole Thermal Model



Perforated insulation at the inner coil surface significantly reduces the peak temperature

$T_{peak} = 7\ K$

Analysis by Yadav, Kashikhin,& Zlobin [13]

Summary: Materials

- **Nb_3Sn superconductor seems to have enough margin even after irradiation up to 10^{18} n/cm^2**
- **The cable insulation materials and the coil end parts being considered for Nb_3Sn magnets are not an issue with respect to radiation**
- **The potting compound will eventually determine the magnet lifetime**
  - Possible candidates are High Tg epoxies, Cyanate esters such as EX-1515 & CTD 422, bismaleimides such as Matrimid 5292 and polyimides
  - More research needs to conducted in this area to identify and evaluate various potting compounds

Summary: Thermal Studies

- Analysis on current NbTi LHC IR quads for both two and four-layer design showed that these magnets have sufficient margin for the nominal LHC luminosity. However, additional inter-layer cooling channels will provide increased temperature margin
- Thermal analysis of LARP Nb_3Sn IR Quad showed that for a critical current margin of 20%, the magnet could tolerate up to 40 mW/cm^3 of peak power dissipation in the coil mid-plane turns which is an order of magnitude higher than the heat depositions in the coil at the nominal LHC luminosity

Summary: Thermal Studies

- **Thermal analysis on LARP separation dipole that are placed in front of IR triplet region showed that,**
  - Peak temperatures in the coil reach as high as 25 K with only external + mid-plane cooling
  - Cooling inner coil surface with perforated insulation in addition to external and inter-layer cooling seems to be the way to manage the temperature rise due to heat loads

References

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