Progress Report
on
Magnetic and Mechanical Design
of
Coil Ends

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With contributions from Dr. Gerry Morgan (consultant)
Goals of End Design

**Magnetic Design**
- Optimize for low integrated harmonics
- Guide design towards lower peak field without large increase in length
- Compute cross talk and fringe fields

**Mechanical Layout**
- Minimize strain and tilt of the cable in the end. Minimize large changes
- Cable and entire ends should be well supported (constrained)

In low field magnets, magnetic design drives the end design, whereas, in high field (high force) magnets, the mechanical design must! These guiding principle are common to our all high force magnet designs (including 12 T common coil dipole design).
Ends of Cosine Theta Cable Magnets
Superconducting Magnet Division

Ends of Cosine Theta Cable Magnets

R. Gupta, BNL, LANL Review, April 29, 2002
Design A

• The design is well optimized magnetically
  
  Produces low integral field harmonics.

• Mechanical turn layout is developed based on prior experience

• Large radius means lower tilt and lower strain on cable in ends
  
  Large bend radius, however, also means dealing with large forces.

The magnetic design optimization process will be discussed in detail for this design.
Design B

Design philosophy: Let mechanical design drive the ends

- Start with a good mechanical lay out of each turn and relationship between the subsequent two
- Adjust end spacers to minimize integrated harmonics and peak fields.

This is a magnet where end forces are large!

The ends would play a major role on quench performance of the magnet.
Ends without spacer  
(large harmonics and peak field)

Ends with spacer  
(integrated harmonics & peak field reduced)

- End spacers increase the straight section length of some turns (turns at midplane go further out)
- Now consider the integral field generated by each turn. The harmonic component generated by a turn will depend on the angular location of it. The integral strength will depend on the length.
- A proper choice of end spacer can make integral end-harmonics small. However, note that the local values are large.
- Spacer also reduce the maximum value of field on the conductor (peak field) in the end.
Layout of Turns in Return End

Design A (Gerry Morgan)  

P. Walstrom concept (LANL)

Design B will use best of all features in keeping with a good mechanical layout

Fig. 4. End-turn layout on the developed winding cylinder with the shape function of Fig. 1, the 2-D design of Table II, and the block group definition of Table II, showing individual turns.
Modified constant perimeter end: Find a good combination of tilt and strain.

**The following codes are used for end optimization:**

- **CNSTND15**: Used for first turn. Starting ellipses. Designs end post.
- **CNSTND22MB**: Designs relative mechanical layout of all turns. Optimize tilt and deviation from constant perimeter (parameter AKF).
- **SMINSQ22MB**: Minimize harmonics by adding straight sections to turns.
- **ENDHRM22MB**: Generates 3-d coordinates of Return end for all turns. Also generates end spacers and wedge tips.
- **LENDHRM22MB**: Same as ENDHRM22MB but for lead end.

Past practical experience is incorporated in how these programs optimize ends.
Block Structure

Straight section (6 blocks, 70 turns):
30 20 10 4 3 3
  (counting from midplane)
3 3 4 10 20 30
  (counting from pole)
End section (8 blocks, 70 turns):
10 5 8 4 13 4 6 20
  (counting from pole)
Straight section => pole
  3,3,4 => 10
  4,10, 20 => 5, 8, 4, 13
  30 => 4, 6, 20
Must avoid large Ultum spacers
  (subdivide, if necessary)
Tilt of Turns in Various End Blocks (at far out position)

Small Tilt with monotonic change

Block with Midplane Turns

Block with Pole Turns
AKF indicates the deviation from constant perimeter (hence strain on the cable)
Large Deviation from 1.0 is bad

Small deviation with monotonic change

Block with Pole turns

Block with Midplane turns
Coil Ends: Design A

And this is how one end would appear!

Programs have been written that take PARENOPT output and generate input for OPERA3d
Coil Ends: Design A
Coil End: Design A
Coil Ends: Design A
Parameters optimized:

End spacers in block #2 (with 5 turns) and end spacer in block #7 (with 4 turns).
All spacers within a block have the same size.

Changing the size of two groups of end spacers was adequate to get all harmonics small.

Computed values:

- $B_5 < 1$ unit-meter;
- $B_9$ and $B_{13} < 0.1$ unit-m

Effective Magnetic Length $\sim 15.6$ cm
Mechanical Length $\sim 28$ cm
Harmonic Calculations with Opera-3d (Z-scan)

A set of programs are written to automatically generate/manipulate OPERA-3d input.

Harmonics (including gradient) are computed at an interval of 1 cm.

These calculations don’t include iron.

Iron will not change behavior qualitatively. Calculations with iron to be done next.

Gradient from Straight section to End
Harmonic Calculations with Opera-3d (Z-scan)
A high peak field reduces the magnet quench performance.  

➢ A large effort was undertaken in 2-d optimization.

About thousand cases were examined to:

• Minimize harmonics
• Find a solution with lower peak field
• Good mechanical turn configuration (wedges, tilt angle, etc).

• New 70 turn configuration has several percent higher margin than the previous 69 turn configuration; primarily because of lower peak field.

A series of computer programs have been written to carry out the above optimization in an exhaustive and systematic manner.
Peak Field in the Body of the Magnet

Peak Field Location (pole turn)
Peak Field Location (pole turn)

Note: Min/Max range changed
Peak Field in the End
Peak Field in the End
Peak Field in the End
Peak Field in the End

Selected Range
Peak Field in the End

Selected Range
Based on the preliminary calculations, the peak value in Design A is larger in the end. The peak field in the end will be minimized more in Design B.

In typical end design, we remove iron (or increase yoke i.d.) to reduce field in the end. That option is not that effective here.
Peak Field in the End
Initial modeling work: Compute cross talk, etc. as the separation changes. The cross talk may be significant if the flux cannot be contained in the yoke.

Need only ½ of this model for calculations. Apply boundary conditions on right and left side to simulate various cases. Need only ¼ of the model if boundary condition is the same on the left and right side.
3-d Calculations with Iron (work in progress)

More views of the model

If cross talk is present, it would be maximum when the separation between the two quads is minimum. It should drop rapidly as the separation increases.
Cross Talk Along the Axis
2-d Simulation (Worst case scenario)

Change the location of boundary to simulate the change in separation.
2-d simulation presents a worst case scenario as the flux lines can go to in third dimension (towards the end where field is lower) to reduce the impact.

The problem is not cross talk; it is lack of symmetry!

Leakage field \( \sim 700 \) G for boundary at \( X=34 \) cm.

The separation becomes quiet large by the time we reach S.S.

At 3 meter point it is over 78 cm \([2\sin(\theta/2)]\). For yoke width use \([2\tan(\theta/2)]\) but leave small gap.

However, at the end saddle, the separation becomes over 94 cm and at S.S. over 104 cm.
More POISSON Calculations for 3-d Simulation

For Animesh Jain’s new design (yoke to x = 36 cm)

Boundary condition is put at X=50 cm, near the beginning of mechanical straight section.

The computation is again done at the design field.

Leakage field ~100 G for X=36 cm (as per Animesh Jain’s new design).
Flux Leakage for 40 cm Yoke Outer Radius

Simple model for quick estimates

See Animesh Jain’s talk for detailed and complete calculations

Max Flux outside yoke: 0.08 T (800 G)
Max Flux outside yoke: $\sim 0.001 \, T (10 \, G)$
At this level, we don't have a problem.
More Cases: Vary Yoke O.D.

O.R. = 37.5 cm
Max Leakage field 2.3 kG

O.R. = 42.5 cm
Max Leakage field 150 Guass
Recall: the problem in harmonics is primarily due asymmetric iron, whose width is not enough on the horizontal axis.

If space, where the magnet end start is not restricted by other reasons, consider higher yoke o.d.

If space is not available then consider cutting iron only at the entry point where the field (and amount of flux) is lower anyway.

Also the penalty will be small if asymmetry is not large.

Other benefits:
• It would remove non-allowed harmonics due to iron in all cases.
• It would reduce fringe fields.
• Higher field (gradient) option would not be a field quality issue.
End Design Optimization: Design B

**Design B**

Design philosophy: Let mechanical design drive the ends

- Start with a good mechanical lay out of each turn and relationship between the subsequent two
- Adjust end spacers to minimize integrated harmonics and peak fields.

This is a magnet where end forces are large!
The ends would play a major role on quench performance of the magnet.

Use CAD software to visualize how the cable turns are being developed.
Observe tilt and strain on the cable.
Develop next turn in relation to the previous turn.
Coil Ends: Design B
(Start with a good mechanical layout)
Coil Ends: Design B
(Start with a good mechanical layout)
SUMMARY

• This is work in Progress!

• Issues are large forces and mechanical layout of turns.

• Our initial model and techniques are in place
  ➢ Need to carry out this optimization process further.

• The goal of optimization process is to produce a design that is good both mechanically and magnetically.