CBETA

Magnet Buildability Review report : C-Beta Magnets

Date: December 16th, 2016
Reviewers: T. Tanabe (chair), M. Anerella, M. Harrison, A. Temnykh and J. Tuozzolo
Participants: S. Peggs, K. Smolenski, G. Mahler, S. Berg, D. Trbojevic, S. Brooks, F. Willeke, H. Witte

The CBETA "Magnet Buildability Review" (MBR) was conducted from 9pm to 4pm on December 16th, 2016. Here are charge questions:

1. Do the modeling and analysis results validate the hybrid and Halbach magnet designs?

2. Do the prototype magnets accurately represent the final product? Do they use sufficiently detailed material properties?

3. Are the temperature compensation schemes sufficiently proven and robust? Do tests or alternate approaches need to be considered?

4. Do the two engineering designs faithfully reproduce the required magnet physics design? Have issues of mechanical stability and rigidity been considered?

5. Are there techniques or solutions to reduce the cost or complexity of the two magnet styles, in order to reduce manufacturing costs?

6. Do the designs lend themselves to tightly controlled magnet-to-magnet variations, through either the design or the manufacturing process?

7. Are there design aspects that demand extremely challenging tolerances or assembly requirements (precision sorting, critical material specifications, et cetera)?

8. Do the magnet designs adequately accommodate mounting the correctors, and mounting and positioning the magnets and correctors on the girders?

Here are the general comments on this project by the committee:

1) Clear specifications for magnet properties must be better defined to allow clear determination of acceptable magnetic performance. Specification on variation of gradient must be defined.
2) Either magnet is viable and buildable.
3) Any decisions should not be based on buildability.

General comments on the hybrid design magnets are as follows:

1) This is a complicated design which can lead to tolerance build-up.
2) There are many individual pieces which can result in errors.
3) A proto-type has only 50% of field strength and 25% of required force. “Full strength” proto type must be demonstrated.
4) No engineering concept/prototyping on correctors.
5) Temperature compensation scheme in real design has not been demonstrated. (only by C shape magnet)
6) Cross talk was presented as a 10% effect on magnetic field which is significant. Cross talk is estimated only with simulation, not measurement. It was stated that crosstalk could be corrected by magnet placement (offset). How and when this is done during the production process was not defined.
7) Shimming may not be necessary after measuring and sorting permanent magnet material blocks. There is a provision to correct field quality of the assembled magnet on the measurement system bench. This has not been tested yet.

General comments on the Halbach type magnets are as follows:

1) Only proof-of-principle magnets have been fabricated and successfully tested.
2) The proof of principle magnets did not include the separation feature that is required to insert the beam vacuum chamber. The design must include this feature and it most demonstrate that it will not affect field quality.
3) No stress analysis or deflection analysis for the separation noted in comment 2 above was presented.
4) Because the present design and prototyping samples demonstrated very large (200%) margin in magnetic field strength, higher coercivity with lower magnetization material than current selection can be used to improve demagnetization characteristics.

1. **Do the modeling and analysis results validate the hybrid and Halbach magnet designs?**

   Yes for both in terms of magnetic field quality.
   No for both in terms of mechanical analysis for production magnet.

Comments:

- There has been extensive magnetic analysis done on both designs. Field maps have been used in lattice development.
- From S. Berg's summary the hybrid magnet field cross talk "requires iteration between lattice design and field map construction (by magnet design codes) in the design/simulation stage". While it is stated that this is doable, it has not been done yet.
- For the Halback extensive work has been done for the 250 MeV CBeta requirements. Magnetic analysis was presented for the 150 MeV CBeta.
- No detailed mechanical analysis of the effect of magnetic forces on deflecting the pole tips was presented. Tolerance build up analysis of the designs was not presented. There is concern because the last hybrid prototype need jacking screws for pole tip alignment and did not meet field quality expectations.
- Mechanical modeling and analyses were not presented for either design.

2. **Will the prototype magnets accurately represent the final product, and use sufficiently detailed material properties**? **No for both**

Comments:

- Iron-dominated Hybrid design prototype geometry was correct but does not represent the final product in that the field was ½ strength (forces ¼ strength); incorrect steel was used and only half of the required quantity of PMs. In addition, top to bottom alignment features (pins) were not included.

- The latest hybrid prototype (#3?) was a "fast track" fabrication with lower quality lamination material for the pole tips that would saturate if all the permanent magnet material blocks were used to meet the full field specification. Therefore it had fewer permanent magnet material blocks. It also lacked alignment pins or features for splitting. In addition, jacking screws were added to aid in pole tip alignment which is not the plan for production magnets.

- Halbach team did not build magnets that could be considered prototypes. The aperture and gradient are incorrect for CBeta 150 MeV operation. "Proof of principle" magnets of similar style which had higher gradient were built, but that had significantly more stable structures, specifically, full circular metal support rings as opposed to the split design required for CBeta. It lacked the ability to be split and no analysis was presented to show that they could be split without causing a deflection or tolerance misalignment that would be unacceptable.

3. **Are the temperature compensation schemes sufficiently proven and robust? Do tests or alternate approaches need to be considered?**

➔ **Not quite for both. Hybrid's situation is more advanced, though.**

Comments:

- Hybrid temperature compensation scheme with Ni Fe shunt appears sufficiently robust and was proven on "C" magnet testing. Testing should be repeated on CBeta prototype magnets.

- Halbach temperature compensation scheme depends on water cooling to prevent temperature variations. No thorough review of this system - thermal gradient within magnet, effects of varying corrector heating from magnet to magnet, etc. – were presented.

4. **Do the two engineering designs faithfully reproduce the required magnet physics design? Probably**

   Have issues of mechanical stability and rigidity been considered?
   Yes, for hybrid.
   Not sufficiently for Halbach due to lack of split design.

Comments:

- Engineering analysis (structural, thermal) was not presented for either design.

- Engineering solid models and detailed drawings were previously made available for the Hybrid design. Preliminary solid models and select preliminary drawing check prints were previously made available for the Halbach design.

- Hybrid magnet “probably” (due to the uncertainty of the physics design) reproduced the magnetic physics design by virtue of the significantly rigid steel bolted structure and the existence of the assembled prototype.

- Halbach preliminary design may not reproduce the magnetic physics design due to large deflections.

5. **Are there techniques or solutions to reduce the cost or complexity of the two magnet styles, in order to reduce manufacturing costs?**
   Could be, but not major cost reduction.
   For Halbach type, magnetic measurement and shimming procedure should be streamlined.

Comments:

- Hybrid magnet costs could be reduced by re-optimizing / minimizing the size of the magnets, and also by simplifying the shapes of the many clamps (eliminate tapered surfaces, quantities of bolts, etc.). These savings are not considered to be worthwhile in terms of the adverse schedule delays that would result.

- The hybrid magnet presented a simple formula for shimming that could be done quickly while the magnet was still on the measurement stand.

- The Halback magnet shimming as presented was more complex and might be more time/labor intensive. It needs to be better defined.

- Halbach magnet costs should be reduced by developing algorithms to correct field by shimming in a single iteration.

- There was extensive discussion on the quality of the permanent magnet material and its allowable variation. The allowable variation needs to be better defined for both and magnet types for the procurement specifications and for cost estimating. Also acceptance testing specifications and methods need to be defined in order to understand the manufacturing costs.

6. **Do the designs lend themselves to tightly controlled magnet-to-magnet variations, through either the design or the manufacturing process?**
Yes, for both.

Comments:

- Magnet-to-magnet variations do not appear to be a major issue.
- As noted above, both magnets use of shimming to reduce magnet to magnet variation.
- The hybrid magnet can be shimmed during the measurement step to achieve a constant value.
- The Halbach magnet needs to have shims placed in the aperture depending on the permanent magnet material field strength after measurement after acceptance testing of the permanent magnet material blocks. As noted above, a streamlined method for testing permanent magnet material needs to be developed and tested.

7. **Are there design aspects that demand ~~extremely~~ challenging tolerances or assembly requirements (precision sorting, critical material specifications, et cetera)?**

→ **No for both (for extremely challenging)**

Comments:

- Splitting magnets for vacuum chamber insertion is a challenge to both designs.
- There are challenging mechanical tolerance requirements for both magnets.
- Halbach magnet design is based on maximum variation in PM strength of ± 2% while vendor specification is larger (± 5%?). This apparently significant design weakness was defended by the performance of 12 magnets built and tested to have 0.2% variation, which may not be repeated with larger sampling.
- The hybrid magnet field is driven by the accurate stamping or machining of the quadrupole pole tips which are laminated assemblies. These stacked laminations fit into accurately machined aluminum alignment pieces that fit into the accurately machined outer steel plates. The steel outer plates are designed to be split for vacuum chamber installation. As noted a prototype magnet that has been properly aligned has not been built that meets field quality specifications.
- The Halbach magnet depends on accurate positioning of the permanent magnet material blocks and alignment of their fields. This has been successfully demonstrated on the proof of principle magnets that were fabricated with plastic parts from a 3D printer. These magnets met specification and were repeatable after shimming. As noted, a split design required for vacuum chamber installation has not been designed or tested.
- The material specifications for the permanent magnet material need to be better defined. Methods were presented for both magnet types to shim the magnets to achieve magnet to magnet field strength consistency. The hybrid magnets can be shimmed after measurement by shunting the permanent magnet material blocks, not sure this has been demonstrated. The Halbach magnets can be shimmed during assembly with spacer shims between blocks after the permanent magnet material has been tested. How this testing of material blocks will be done and the time and equipment needed to do this has not been defined.

8. Do the magnet designs adequately accommodate mounting the correctors? → Yes for both in terms of modeling.
Do the magnet designs adequately accommodate mounting and positioning the magnets and correctors on the girders? → No for both

- Halbach has a design for mounting correctors.
- Hybrid has no design for mounting.
- Neither magnet design incorporates mounting and positioning magnets on girders.
- Magnetic analysis was presented for correctors for the hybrid magnets. Because of the quadrupole shape of the hybrid, quadrupole correction coils are easy. Dipole correction is more difficult because the beam chamber is very flat and wide resulting in complicated coil windings. Detailed engineering design has not been done of these coils and prototypes have not been built or tested.
- The Halbach type uses simple window frame wire wound correctors that are commonly used in accelerators. A test was successfully done with an available oversized corrector with a Halbach magnet.
- The hybrid correctors will be more challenging and expensive then the Halbach correctors.
- Halbach correctors have very large opening and its interaction with adjacent magnet has not been examined.