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Extracted verbatim from "Halbach Magnets for CBETA"

4. SUMMARY

We presented a technical design, detail cost estimate, and time schedule of the Halbach type of magnets. We are very confident that they can be immediately used for the existing CBETA project where the base line design of the maximum energy is E_{max}=150 MeV. We are basing this confidence on the already built twelve prototype Halbach magnets for the previous CBETA design where the maximum energy was E_{max}=250 MeV. We have been able to develop detailed procedures and necessary fixtures for building them. The magnetic field correction procedures we developed obtain superb quality of the magnetic field in the Halbach magnets.

Our firm opinion that the previous decision to select the Hybrid-iron-dominated magnet (March 2016), driven by the report from the some of the magnet review committee members was not correct. The current information on the Halbach magnets was not available at the time of that review. Some of the committee members were familiar with existing experience in building the iron-dominated magnets. In all prior applications the beam was in the center of the magnets (synchrotrons). The Non-Scaling Fixed Field Alternating Gradient (NS-FFAG) has a significant range of beam positions in the magnets, not a single point. Several committee members posed questions, objections and concerns about Halbach magnets; all have been addressed in this document in the section 1.10 (pages 37-45).

Halbach magnets are a better choice than the Hybrid-iron dominated magnets for the following reasons:

1. The accelerator physics of NS-FFAG is based on using the **combined function magnets** to achieve transfer of particles with a large energy range (4 times in energy for CBETA) in a small aperture. This is possible due to the strong focusing and small dispersion function $\Delta x = D_x * \delta p/p$. The most efficient way is **to use the defocusing combined function magnet but** not radially displaced quadrupole. This argument is clearly shown in Figures 2 and 3 (page 5). The misplaced quadrupole (in this case the displacement is 17.3 mm) makes a requirement for **the good field region equal to 36 mm**. The result of this is enormous inefficient magnet with large outside dimensions equal to **66 cm**, compared to the 6.8 cm of the Halbach defocusing magnet.

2. The twelve prototype Halbach magnets obtained **superb field quality** [Results presented in Tables on pages 31, 32, and 33]. The largest measured magnetic multipoles are equal or less than one unit (10^{-4} at 1 cm). **This is an extraordinary result.**

3. Concerns with respect to the effects between the neighboring Halbach magnets, as well as, between Halbach magnets and the corrector iron frames were studied with the OPERA 3D magnetic field simulations. In addition we have performed a detailed harmonic coils measurements of all possible combinations:

   3.1. The magnetic field was measured from the two Halbach magnets separated by 6 cm spacer with and without the other magnet present and with the other magnet twisted 90^o. All results confirmed that there is no cross talk between the magnets. There was no measurable difference of the magnetic field in any combination.

3.2. The corrector iron frame was placed around the Halbach magnet and measured with harmonic coil in every possible case: magnetic field without the iron frame, with the frame but without powering the correctors, with powering horizontal corrector, powering the vertical corrector and so on. The effect measured was 0.2 % change of the quadrupole field!!! The Hybrid magnet has significant cross talk.

4. The Halbach magnets allow use of the round vacuum pipe instead of the flat required for the Hybrid iron magnets. This simplifies the construction and the vacuum system removing necessary transitions from the flat to the round pipe required for the horizontal alignment. It also allows use of the four button BPMs instead of 6 button BPMs. The total cost saving of the BPM electronic boards is reduced from $660,000.0 to $330,000, a saving of 50%.
5. The size and the weight of the magnets are dramatically reduced. This simplifies the installation and is an efficient way of building future ERL's with small magnets.
6. The difference in cost between Halbach and Hybrid iron magnets is 1.2 Million dollars, based on the existing bids.

The first Section shows details of the Halbach magnet design and results from the built CBETA Halbach prototypes. The present base line design with the maximum energy of 150 MeV is used for the Halbach magnet lattice design. Dimensions of the drifts and lengths of the magnets from baseline design were copied (all of it is presented in the section **1.3**). The maximum orbit offsets in the focusing Halbach quadrupole are $\Delta x \approx \pm 22$ mm with respect to the center of the magnet. Orbit offset is defined with respect to the central circular orbit (where $x=0$ from the linear magnetic field: $B(x) = Bo + G\,x$). The inner distance from the center of the focusing quadrupole to the permanent magnet material is 4.5 cm. It is very important **to emphasize a difference in orbit offsets** for the **same gradients** and **same magnet sizes** of the two options. The maximum orbit offset from the center of the focusing Hybrid-iron magnet is $\Delta x \approx 31.5$ mm. The same size of the maximum orbit offset of $\Delta x \approx 31.5$ mm, from the center of the misplaced defocusing Hybrid quadrupole.

The lattice parameters are presented in the section 1.3.2. They are obtained from tracking electrons through the 3D OPERA magnetic fields. This approach was previously confirmed by excellent agreement between the OPERA 3D predictions and the harmonic coil measurements in the 12 twelve Halbach prototype magnets. The Halbach magnet gradients are adjusted during this procedure, until an agreement of the Twiss parameters between the hard-edge model and the 3D OPERA fields tracking are obtained.

The mechanical design including details of the assembly procedures with the fixtures used for all magnets, details and frames for disassembling the magnets if necessary are presented in the section 1.4. **Special attention was given to this assembly and disassembly procedure**. For example **Fig. 12** shows the fixture-frame required for not only assembling the magnet, but also for assuring the best possible alignment between the upper part of the Halbach magnet and the lower part. It is important to emphasize that the alignment pins required for accurate assembling are defined after the upper and lower parts are pressed together making the perfect circular structure. An additional frame for disassembling the magnet at the top of the corrector frame is shown in Figure 14.

The shimming procedure is a repeat of the same procedure as in the previous prototype magnets (section 1.7).

The vacuum design for the Halbach magnets is presented in the Section 1.8 with detail picture of the girder pipe design shown in Fig. 17. This is very important advantage of the Halbach magnet design with respect to the Hybrid-iron magnet resign as the vacuum round pipe will simplify the assembly and allow use of 4 button BPMs. This is well defined and proven in the Cornell CESR, as stated previously, this presents a significant savings

The prototype magnet development, design and measurement results are shown in Section 1.9. This is the most important and critical part of this report as it shows the main arguments for the magnet choice. As mentioned above the superb quality of the Halbach magnetic field is shown at pages 31-33.

The most important reason for using the Halbach magnets rather than Hybrid-iron magnets is the lower cost with a difference of at least $1.2 million dollars. Details are shown in Section 2.

A copy of the magnet production plan of one of the competitors is shown in Section 3.