January 14, 2006

To: Distribution

From: Wayne Reiersen

Subject: Magnetic alignment implementation

Last Wednesday, January 11, Mike Zarnstorff presented a compelling argument for using magnetic alignment methods for positioning coils during field period and final assembly. The outcome of that meeting was a commitment to develop a plan for implementing magnetic alignment. There are several questions that need to be addressed:

- What are the opportunities for magnetic alignment?
- What equipment is required to perform magnetic alignment?
- What are the cost and schedule impacts?
- What is the benefit? Do realizable (low cost, low schedule impact) magnetic alignment methods really offer a quantum reduction in the risk of field errors over mechanical alignment methods?

The purpose of this memo is to outline a plan to address these questions and determine a path forward.

<u>Opportunities for magnetic alignment</u>

Any time two or more coils are put together, there is the potential to introduce field errors due to misalignment of the coils. Our baseline plan uses mechanical measurements made in the process of coil winding to estimate the current center path of each modular coil. After those measurements are made, there are still numerous steps to complete modular coil fabrication so there is uncertainty in where the current center actually is. The remaining coils – the TF, PF, and trim coils – will be fabricated in industry. Our baseline plan relies on mechanical measurements of the finished coils to infer where the current center path of each coil and to align them to the modular coils during field period assembly (FPA) and final assembly.

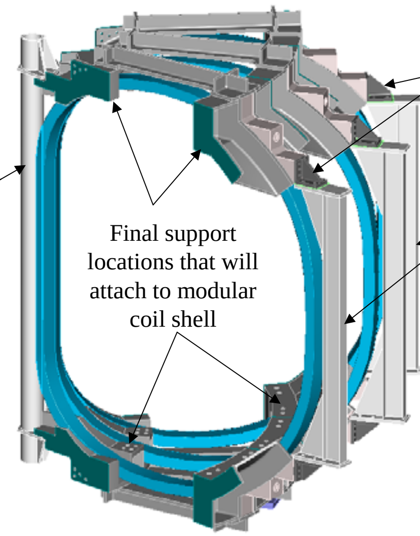
Zarnstorff advocated using null symmetric difference measurements of mutual inductances to increase sensitivity and reduce systematic effects. The argument goes that if you have at least 12 coils, then the mutual inductances contain enough information to solve for the relative positions and orientations of coils. With more coils, the additional information can be used to infer shape deviations from coil to coil.

> **Single modular coils**. In principle, measurements could be taken using a single modular coil with sense coils precisely mounted on a jig. Pairs of sense coils could be positioned and electrically connected such that the induced voltage would be identically zero when pulsing the modular coil if the modular coil was perfectly constructed and positioned in the jig. With a large enough number of

sense coils, deviations from zero voltage could in principle be analyzed to determine a “best fit” to where the coil was positioned, how it was oriented, and what shape deviations appear to have been built into the coil. This could be used to best register the current center relative to the monuments, filter out coils with unacceptable shape deviations, and match coils with offsetting shape deviations. However, we should be able to get all this information and more when assembling a 6-coil module. If so, *there does not seem to be a compelling reason to pursue making null symmetric difference measurements of mutual inductances on single modular coils*.

Modular coil 6-coil modules. Modular coils will be assembled in 3-coil modules (3-packs) that slide over each end of a VV period assembly and get bolted together to form a 6-coil modules (6-pack). We would like to align like coils in adjoining 3-packs to be symmetric with respect to the symmetry plan in the center of the 6-pack. Even in a full 6-pack, there are an insufficient (<12) number of coils to determine coil position and orientation so we will have to supplement the modular coils with an array of sense coils as described by Zarnstorff in his presentation. The array of sense coils would be mounted on a jig which would be positioned on the symmetry plan between the two Type A coils. The process could be as follows. Mount the jig to a Type A coil on the right-hand side (RHS) of the period assembly (an arbitrary choice). The Type B and C coils in the RHS 3-pack could be added anytime and would be aligned mechanically to the RHS Type A coil. When the left-hand side (LHS) Type A coil becomes available, it would be mechanically aligned to the RHS Type A coil. Magnetic measurements would be taken to determine what adjustments would be required for optimal alignment. The position of the LHS Type A coil would be adjusted appropriately. The LHS Type B and C coils would be magnetically aligned to their RHS counterparts in the same manner. Once the 6-pack was complete, it would be disassembled in a manner that it could be reassembled without any additional adjustments being required. Proper alignment of the 6-pack after reassembly could be confirmed by mutual inductance measurements without the use of a jig or additional sense coils. Note that throughout the magnetic alignment process, it is imperative that [1] coax leads (or maybe kickless cable) be used throughout (to eliminate cross terms); [2] the coax leads need to be routed to a patch panel so the circuits can be automatically reconfigured; [3] measurements will need to be made at multiple frequencies in order to extrapolate to the zero frequency response; [4] the testing needs to be automated because of the large number of measurements to be made; and [5] test results need to be processed on the spot in order to provide prompt guidance to the technicians performing the assembly tasks. Nobody said magnetic alignment was simple.

TF coils, trim coils, and final assembly. TF coils are assembled in 3-packs which are slid over the ends of a modular coil 6-pack. The TF coils are held in a 3-pack by the upper and lower 60-degree sections of the coil structures. Temporary supports (see figure below which is dated but makes the point) to tie the upper and lower sections together prior to attaching these sections to the modular coils during FPA are envisioned.



The baseline plan for final assembly is to set (all?) the TF coils back ~1/4" so that they do not wedge prior to the modular coils in one field period contacting the mating coils in the adjacent field period. (A gap between mating coil structures would seem to be needed as well.)

During field period assembly, upper and lower coil structures would be mechanically aligned and mounted to the modular coil structure. The temporary supports would then be removed. The TF coils could then be magnetically aligned to the modular coils. They can be properly indexed toroidally, oriented in a vertical plane, set to the proper elevation, and wedged together in the nose region. The trim coils which are mounted on the coil structures, could also be installed and magnetically aligned to the modular coils at this time. In a field period assembly, there are 6 modular coils, 6 TF coils, and more than 1 trim coil which put us above the magic number 12. In principle, additional sense coils would not be required for magnetic alignment of coils within a field period.

There is the problem of how to avoid the TF coils wedging before the modular coils during final assembly. One option would be to undersize the wedge pieces on the parting plane. (Alternatively, a single coil or all coils could be set back.) During final assembly, the field periods could be brought together and the *modular coil 6-packs could be magnetically aligned*. (Note that with 18 modular coils, additional sense coils should not be required.) Measurements could be taken to determine the exact thickness of shims to install between mating modular coils, TF coils, and coil structures. The field periods could then be retracted, shims installed, and the field periods brought back together with everything contacting simultaneously. *Finalizing the final assembly approach is critical for finalizing the design of the TF coils, coil structures, modular coil-to-coil interface, as well as tooling.*

Thoughts on test cell layout and the number of stations

A simplified representation of the baseline FPA schedule is shown in the attachment. Completion of modular coils drives the schedule for field period assembly. It appears that the anticipated slower pace for producing the modular coils presents an opportunity to complete installation of the flux loops and cooling tubes on all three field periods before we start assembling the modular coils over the vacuum vessel or assembling TF half periods. Since all three VV period assemblies will be on-site before the first is scheduled to be completed, there is a potential benefit to having multiple (2 or 3) VV prep stations.

Assembling the modular coils into 6-packs is paced by the arrival of each coil. It does not appear that would be a benefit for multiple stations for assembling the modular coils into 6-packs unless the delivery schedule accelerates or the time to assemble the modular coils into 6-packs takes longer than anticipated. Presently, the schedule shows over a month between times when this station is used.

Assembling the modular coils over the vacuum vessel seems to be an even briefer activity than assembling the modular coils into 6-packs. For the third field period, the vacuum vessel period assembly is sitting there fro three months before the modular coil 3-packs arrive. Therefore, there does not appear to be a real benefit in multiple stations here either.

Assembling TF coils into half-periods begins about the time work on the VV prep stations is completed. This station could occupy the space vacated by the VV prep station. According to the present schedule, all of the TF coil 3-packs are completed almost a month before we begin assembly of the second field period. Again, there does not appear to be a real benefit in multiple stations for assembling TF coil into half-periods unless their arrival is delayed.

Completion of the last field period is schedule critical. It is essential that we begin work completing the third FP as soon as the modular coil 3-packs are assembled over the vacuum vessel. In the present schedule, there is less than a week between the time that the second FP is completed and work on the third FP begins. In this case, we should plan to provide a second station for final FP assembly.

VPI'ing the last modular coils is scheduled to begin in October 2007. After that time, only one winding station will be required for final clamp installation and warm testing. If we used Station 4 for post-VPI activities, then all of the other MC manufacturing stations could be dismantled to make room for this second station. An even better idea might be to dismantle the station for assembling TF half-periods and to use that space. TF half-period assembly is scheduled to be completed in August 2007.

Next steps

From the limited consideration given to this issue thus far, a few immediate actions come to mind:

1. **Resolve technical issues with field period assembly and final assembly before attacking magnetic alignment issues (Cole, Brown)**. Open

issues include [1] what does the modular coil-to-coil interface hardware (including that used for alignment) look like? [2] how will final assembly be accomplished, ensuring that the modular coils can be properly positioned without interference from the TF coils, structures, or vacuum vessel? [3] are any changes in the TF design needed to accomplish final assembly? [4] how will mechanical alignment of the coil systems (which will still be done prior to magnetic alignment) be performed? I believe we need to think this through at a deeper level than we have done before (or at least documented before). The only documents I can find are the Field Period Assembly Plan and Final Assembly Plan that were generated in 2003. These documents look really dated.

2. **Resolve inconsistencies between the FPA MIT/QA plan and the PMB (Viola, Brown, Strykowsky)**. The PMB shows a Station 5 for TF half-period assembly. It also shows the ports being welded on in Station 4 during Final FPA. The MIT/QA Plan does not show a Station 5 and it shows the VV ports being welded on in Station 3. The number stations and the work done on each station needs to be resolved.

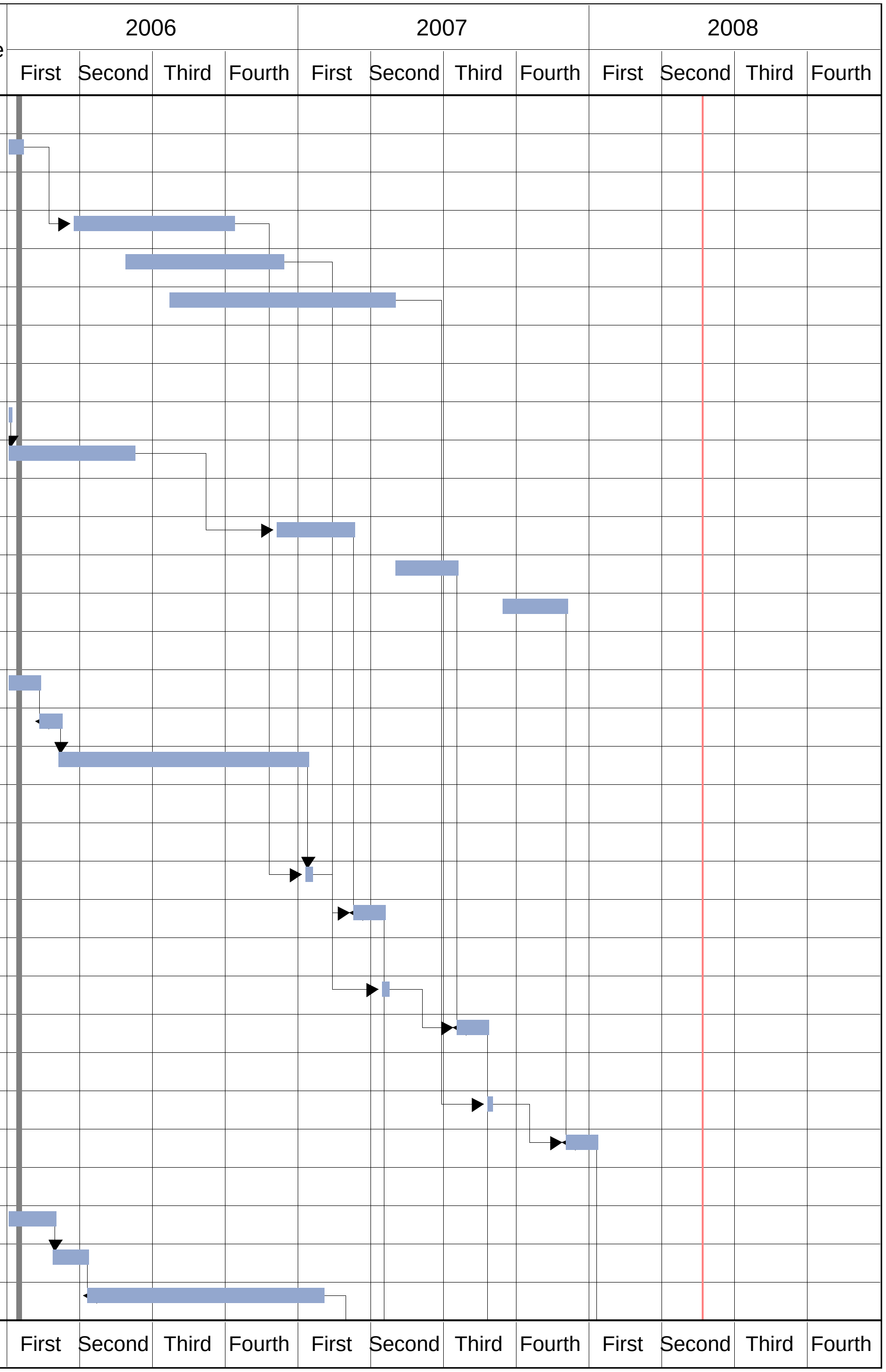
3. **Prove that practical magnetic alignment methods offer a quantum reduction in the risk of field errors over mechanical alignment methods (Zarnstorff, Stratton, Brooks, Sichta)**. This step is crucial before taking magnetic alignment any further. Zarnstorff's presentation provided a compelling reason to entertain the magnetic alignment option but it did not prove it could be made to work. Based on a manageable number of sense coils built and installed to a reasonable accuracy, can we really improve our understanding of coil position, orientation, and shape deviations in the presence of field errors from eddy currents, magnetic material, and the earth's background magnetic field?

4. **Assess the cost and schedule implications of implementing magnetic alignment (Strykowsky et al)**. This task would be undertaken upon successful completion of the previous step. Cost elements include special jigs, automated test equipment, current feeds for every coil being tested, algorithm development to process the measurements, and labor to perform the measurements and process the data. There are also schedule elements to be considered. The coils will be mechanically aligned first and then magnetically re-aligned if necessary so there will be a schedule hit.

Your comments on this subject would really be appreciated. Please send me an e-mail, give me a call, or just stop by. I will try to fold everyone's comments into our assessment of what needs to be done and then have a meeting to discuss the plan forward.

Cc: Zarnstorff, Stratton, Pomphrey, Raftopoulos, Brown, Nelson, Cole, Neilson, Viola, Strykowsky, Simmons, Edwards, Sichta, Brooks

	Activity Name	Duration (Work Days)	Start Date	Finish Date
1	**VV prep station**			
2	Complete fabrication and installation	37.00	12/1/05	1/20/06
3	Install flux loops and coolant tubes			
4	*FP1*	141.00	3/27/06	10/9/06
5	*FP2*	141.00	5/30/06	12/12/06
6	*FP3*	200.00	7/25/06	4/30/07
7	**MC half-period assembly station**			
8	Preliminary Design	5.00	12/1/05	12/7/05
9	Final Design	20.00	12/8/05	1/4/06
10	Procure/fab tooling and fixtures	109.00	1/5/06	6/6/06
11	Assemble MC half periods			
12	*FP1*	66.00	12/8/06	3/9/07
13	*FP2*	55.00	5/3/07	7/18/07
14	*FP3*	56.00	9/17/07	12/3/07
15	**MC installation station**			
16	Preliminary Design	52.00	12/1/05	2/10/06
17	Final Design	18.00	2/13/06	3/8/06
18	Procure/fab tooling and fixtures	221.00	3/9/06	1/11/07
19	Assemble MC over VV			
20	*FP1*			
21	Mount VV	4.00	1/12/07	1/17/07
22	Install modular coils	27.00	3/12/07	4/17/07
23	*FP2*			
24	Mount VV	4.00	4/18/07	4/23/07
25	Install modular coils	27.00	7/19/07	8/24/07
26	*FP3*			
27	Mount VV	4.00	8/27/07	8/30/07
28	Install modular coils	27.00	12/4/07	1/9/08
29	**TF half-period assembly station**			
30	Preliminary Design	64.00	12/1/05	2/28/06
31	Final Design	30.00	3/1/06	4/11/06
32	Procure/fab tooling and fixtures	211.00	4/12/06	1/31/07



	Activity Name	Duration (Work Days)	Start Date	Finish Date
33	Assemble TF half-periods			
34	*FP1L*	15.00	3/30/07	4/19/07
35	*FP1R*	15.00	4/20/07	5/10/07
36	*FP2L*	15.00	5/11/07	5/31/07
37	*FP2R*	15.00	6/1/07	6/21/07
38	*FP3L*	15.00	6/22/07	7/12/07
39	*FP3R*	15.00	7/13/07	8/2/07
40	FInal FP assembly station			
41	Preliminary Design	133.00	12/1/05	6/5/06
42	Final Design	26.00	6/6/06	7/11/06
43	Procure/fab tooling and fixtures	131.00	7/12/06	1/10/07
44	Final FP assembly			
45	*FP1*			
46	Attach ports	38.00	4/18/07	6/8/07
47	Attach TF coils	11.00	6/11/07	6/25/07
48	Install large hz ports, trim coils. Complete.	46.00	6/26/07	8/28/07
49	*FP2*			
50	Attach ports	38.00	8/27/07	10/17/07
51	Attach TF coils	11.00	10/18/07	11/1/07
52	Install large hz ports, trim coils. Complete.	46.00	11/2/07	1/4/08
53	*FP3*			
54	Attach ports	38.00	1/10/08	3/3/08
55	Attach TF coils	11.00	3/4/08	3/18/08
56	Install large hz ports, trim coils. Complete.	46.00	3/19/08	5/21/08