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To: Distribution

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Subject: Reflections on the recent project meeting

The recent project meeting turned out to be an excellent forum for finding out where we are across the board. Some of the highlights (and lowlights) were…

- Progress reported on StellOpt-CoilOpt merger (PPPL StellOpt versions merged, ORNL StellOpt merged with Coil Opt, awaiting update of ORNL StellOpt to PPPL StellOpt in merged StellOpt-CoilOpt) [Zarnstorff]
- CoilOpt modifications implemented and new cases have been generated, excellent summary table presented [Strickler]
- The M12 (a 21-coil) modular coil design appears better than any of the 18-coil modular coil designs, primarily in the core quasi-symmetry (and energetic particle confinement) [Ku]
- Changing the current and pressure profiles while maintaining stability substantially degrades quasi-symmetry [Ku]
- A modified boundary shape (li383T3) was found that has good performance with both the reference and transport-consistent profile [Ku]
- M12 (0227) modular coil design achieves improved performance (relative to the reference coil design, 1017) with increased coil (12 v. 10 modes) and winding surface complexity (45 v. 30 modes), resulting in decreased (unacceptable) minimum bend radius [Williamson]
- The NBI access target distance of 26cm (?) might need to be increased slightly to ensure adequate access [Williamson]
- The minimum bend radius calculated by Strickler (analytic calculation?) is significantly different than the minimum bend radius in the Pro/Engineer representation, calculated by a spline fit through many points [Williamson]
- The M12 coil design was modified by removing points in the regions of highest curvature. This increased the minimum bend radius from about 5cm to 9cm. The impact on the fit was previously calculated by Brooks. The average error increased from 0.46% to 0.49%. The maximum error increased from 2.07% to 2.51%. The modified M12 coil design has been made available for Physics to assess the plasma properties. [Williamson]
- Access is a generic problem with 21 modular coils and 21 TF coils, whether the TF coils are centered on the modular coils or not. [Williamson]

- Recent 18-coil options feature modular coil lying on smoother winding surfaces (25 modes v. 45 modes) than the M12 design which has coils that were offset from the winding surface. This should benefit the design of the structural shell. Access in the 18-coil options also appears significantly improved. Bend radii are improved substantially from 5cm to 8-9cm. Costs should be less due to the reduced number of coils (18 v. 21) and coil types (3 v. 4). [Williamson]
- Nelson identified some creative ideas for dealing with the unacceptable bend radius: go to 18 coils, spline smooth the coils locally in the regions of unacceptable curvature, or miter the corners. Brooks will see if the mitered corner option compromises performance. Nelson is planning to conduct R&D to develop a firmer limit on the radius of curvature. [Nelson]
- The 5-coil PF option appears to have a minimal impact on access [Cole] while allowing basically the same performance as the low order multipoles [Pomphrey]. Pomphrey plans to wrap up his flexibility assessment of the 5-coil PF soon.
- Two non-1/R options were identified which have fewer coils and a better fit of toroidal field lines to the magnetic axis. ORNL will identify which of these options is configurationally advantageous. The preferred option will be sent to Pomphrey to assess flexibility. [Reiersen]
- Progress reported fixing bugs in PIES [Reiman] and developing the code for dynamical healing [Hudson]
- Plans are in place for validating trim coil design [Brooks]
- Defining (and refining) requirements is an ongoing process. Requirements issues should be tracked at each project meeting until the December (final) requirements review. Deficiencies in the current General requirements were discussed at this meeting. At the next meeting, we will focus on tracking progress in remedying those deficiencies and examining deficiencies in the WBS 1-2 requirements. It became clear that a process to effect changes was needed real soon. [Reiersen]
- A wealth of data was provided from which a stay-out zone could be determined. Laying out envelopes for the divertor and cryopump would follow this step, although Mioduszewski suggested that active pumping of the divertor might not be appropriate for short (1s) pulse lengths. These envelopes are critical for developing a modular coil design that does not encroach on this space and permits assembly as planned. [Mioduszewski et al]
- Accomodating inboard RF and providing access for Thomson scattering at v=0.5 looks promising except for sliding coils over the vacuum vessel. Segmenting the vessel in six pieces instead of three might solve this problem. [Cole]
- Progress is being made in modifying the vessel geometry to improve fabricability and performance (flexibility). Subsequent to the meeting, Brown discovered that the M12 coil design (and probably others) does not provide enough space inboard to accommodate present radial build elements. [Brown]

- Preparations for the August Information Meeting appear to be on track. Preparation of draft manufacturing specs appears to be the pacing item. [PH]

Reflecting on these findings, how do they affect what we had planned to do? Let's consider this area by area, starting at the plasma and moving out.

<u>Plasma and PFCs</u>

This is one of the pacing areas of activity. We know we need to create more space inside the vacuum vessel for the stay-out zone and divertor. Originally, we laid out a stay-out zone that started 2cm off the plasma inboard and increased monotonically to 10cm outboard. In examining the Poincare plots generated by Grossman, it is clear that the width of this stay-out zone should increase as we approach the tips from both the inboard and outboard sides. (I am referring to the v=0 cross-section in this description, but the logic holds over the length of the divertor.) For shape flexibility, we might want to keep a generous separation on the outboard side. I do not think we can afford anything significant on the inboard side.

I am a little uncomfortable with the notion of a canonical 120 m connection length. Particles will diffuse across the field lines. Requiring longer connection lengths on the field lines starting closest to the last closed magnetic surface (LCMS) and shorter lengths on those further away might be a more effective strategy. In the case of a divertor on a tokamak, this is certainly the case - the connection length just outside the separatrix (the LCMS) approaches infinity and drops off as you go away from it.

ORNL needs to define two boundaries. The first boundary is the stay-out zone for all internal hardware – nothing can encroach upon it. Between the first and second boundaries, the field lines can intercept only the divertor and baffles. The vacuum vessel and other internal hardware must lie in the region outside the second boundary. ORNL should lay out the geometry of the divertors/baffles over the helical extent of the divertor. Consideration should be given to designing a divertor with vertical and horizontal surfaces to simplify fabrication. In addition, ORNL should assess the design impacts of requiring active pumping versus not requiring active pumping. Once these are defined, we can lay out the vessel and quantify a stay-out zone for the coils.

Coil designs are being developed in two ways – using the coupled StellOpt-CoilOpt codes (in which the plasma is developed concurrently with the coils) and using CoilOpt (in which the target plasma [li383_1.4m] is fixed). It appears that in order to use the coupled StellOpt-CoilOpt codes, it is necessary define a minimum acceptable offset either from the plasma surface or from a "bloated" surface that corresponds closely to the second boundary. The winding surface for the modular coils would be constrained by this minimum (definitely nonuniform) offset. For coil designs being developed with CoilOpt alone, we could do things a bit more accurately since we are working with a fixed target plasma. We could lay out the surface of the vacuum vessel on the inboard side and develop an imaginary surface it would blend into on the outboard side.

Vacuum Vessel

There are a number of factors requiring changes to the vacuum vessel design. Prior to the project meeting, Brown proposed an alternate vacuum vessel shape featuring flat sides (on radial cross-sections). Kharkov reviewed the alternate shape and described those features that seemed favorable and those that seemed unfavorable for a vessel formed by explosive forming. We reviewed the input from Kharkov and determined that another iteration on the vessel shape was warranted. In addition, we owe a response to Kharkov on what (if anything) we would like them to do next. Perhaps the most interesting idea was developing a design concept for attaching the port extensions to the vessel shell.

Following the project meeting, Brown reviewed the M12 coil design and found significant interferences (inadequate envelopes) between the coils and the vacuum vessel surface. In principle, this should not happen. ORNL should verify Brown's findings and determine the root cause of the problem (if it exists). Perhaps changes in the current metric in the CoilOpt code (minimum plasma-coil separation) are needed.

Cole described the design impacts of adding a requirement for inboard RF. Perhaps the most significant impact was that the vacuum vessel needed to be expanded in the vicinity of the v=0.5 cross-section. This expansion exacerbates the problem of sliding the coils over the vacuum vessel from the bolted joint at v=0.5. It was suggested that perhaps the best remedy for this problem would be to move the bolted joint from v=0.5 to around v=0.35. This would increase the number of joint locations and assembly segments from 3 to 6. Three of the segments would have two modular coils per segment. The RF launchers and inboard limiters would be located entirely in these segments. The other three segments would have five (four) modular coils per segment for the 21-coil (18-coil) option. The helical divertor would be located entirely in these segments. ORNL should determine if this is the best way to remedy the assembly problem introduced by expanding the vessel for inboard RF access (and accommodating a helical divertor).

The other factor requiring changes to the vacuum vessel design is the addition of a helical divertor. ORNL should assess the design impacts to the vessel as well as the PFC design.

Modular Coils

Modular coils continue to be our biggest problem. The favorite design among the physicists is the M12 design, a 21-coil design developed using a background (aiding) TF field and the largest number of total modes (12 for the coils and 45 for the winding surface) of any of the candidate designs. The large number of modes adds to the complexity of the coils and the integral structure.

Inadequate bend radii are still a problem – 5cm v. the required 9cm. Williamson has increased the minimum bend radii substantially through spline smoothing. Ku has all the information required to assess the impact on plasma performance. Nelson has proposed a mitered bend concept that might alleviate the problem. ORNL needs to provide coil geometries with and without mitered bends so Brooks can assess the impact on performance. ORNL is also planning on doing winding R&D to firm up our design criteria.

The space allowed for NB access on the M12 design is supposedly adequate but the minimum clearance is TBD. The M12 coil design is the one the Brown found a significant interference with the vacuum vessel, so it needs to be regenerated to avoid interfering with the vessel anyway.

The 18-coil options are favored among the engineers. The winding surfaces (and hence, integral structure) and coils are smoother. They have better access and they should be less expensive (3 coil types instead of 4, 18 coils instead of 21). The awkward modular coils at v=0 (the ones in which the outer leg had to be pulled out beyond the crossing of the neutral beams) can be avoided. The minimum coil-plasma separation is increased from 17.5cm to around 20cm.

The main problem with the 18-coil option appears to be performance, specifically quasi-symmetry. The 18-coil options appear to have worse quasi-symmetry in the core than the M12 (a 21-coil) option. Quasi-symmetry can be targeted directly when using the coupled StellOpt-CoilOpt code to generate new coils and plasma configurations. When using CoilOpt alone, there might an advantage to fitting to two surfaces (perhaps s=0.3 and s=1) rather than just one (s=1) to improve the core quasi-symmetry.

In all fairness, we do not have the data necessary to support a decision between the 18- and 21-coil options. The M12 and the candidate 18-coil options are different in many aspects, not just the number of modular coils. Other substantial differences exist in:

- The number of modes defining the modular coils and the winding surface
- The minimum plasma-coil separation
- The minimum bend radius
- The background TF (1/R) field

It would be useful to generate apples-to-apples solutions for the 18- and 21-coil options so would could focus on one for the configuration development work that needs to be going on.

Zarnstorff has requested that we document engineering constraints for all coil systems to assure that they are properly addressed in CoilOpt. What are these constraints?

- Minimum coil-plasma separation – Right now, all we are looking at is the minimum plasma-coil separation. This is an inadequate metric. The minimum required plasma-coil separation is non-uniform. This is something we need to fix (per our discussion of stay-out zones under PFCs). Furthermore, the absolute minimum (something that cannot be violated – a necessary but not sufficient constraint) should be documented along with the build elements from which it was derived. What is it? All candidate coil designs must respect this limit. One way of treating this constraint (and one that would put more daylight between candidate coil designs) would be to set an inviolable boundary corresponding to the closest that a winding pack can approach the plasma and determining the radial build of the winding pack from the minimum distance from the winding surface to that boundary. For instance, let's say that the winding pack had to stay at least 15cm away from the plasma. If the minimum distance from the winding surface to the plasma was 18cm, then the maximum radial build of the winding would be 6cm. If the minimum distance from the winding surface to the plasma was 20cm, then the maximum radial build of the winding would be 10cm.

- Coil current density – Once the minimum coil-to-coil separation is determined, the radial build of the winding is determined, and the modular coil currents are determined, it should be possible to estimate the lateral build of the winding pack and the current density. The current density is an extremely important metric that we are not looking at directly in comparing candidate options. In fact, we probably should have a limit on the current density in the copper. What should it be? The closest thing in Strickler's table is I-mod,max/C-C,min which strongly favors options with an aiding TF background field. However, it does not reflect the impact of reduced radial builds due to smaller coil-plasma separations.
- Minimum radius of curvature – The fundamental constraint here appears to be that the minimum radius of curvature cannot be less than 3x the conductor thickness measured at the surface (?) of the conductor. This means that the lateral and radial builds of the conductor pack and the number of turns all matter in setting the radius of curvature constraint and that the direction of curvature is important. In practice, that might not be so easily determined. However, we could take the maximum of two radii of curvature limits and use that as our constraint when looking at a filamentary winding (?). What we have been doing is comparing the calculated minimum radius of curvature to a fixed constraint. What we need to do is to compare it to a limit that is derived from the geometry of the winding pack.

These are but three prominent constraints that we see in the design of modular coils. What others should we be imposing? For the TF and PF coils?

We are still struggling just to find a solution that simultaneously satisfies performance requirements and engineering constraints and we have not yet come to grips with the problems related to pushing the coils further away (due to the divertor upgrade, inboard RF, and existing interferences) and Hudsonizing for good surfaces. Let's hope the promise of the coupled StellOpt-CoilOpt code is realized in full and soon.

Ku also shed light on another problem – the core quasi-symmetry appears much worse for pressure and current profiles developed from a 1-D power balance than for the reference profiles. This difference appears large compared to the difference in core quasi-symmetry between the 18- and 21-coil options. What are the implications? Are we going to adopt the more robust LI383T3 as the new reference plasma configuration?

<u>PF and TF Coils</u>

Pomphrey reported on progress testing out the proposed 5-coil PF design. So far, it looks adequate (on an absolute scale) and better than the existing 4-coil reference PF design. We probably should process this change at our earliest convenience because it does affect our configuration development effort.

Reiersen reported on 12-coil and 18-coil non-1/R TF options. In subsequent discussions with Nelson, it was concluded that it would be best to explore the flexibility of the 18-

coil (1 circuit and 3 circuit) options versus the reference 21-coil (1 circuit and 4 circuit) options. The motivation for picking the 18-coil TF option is that it is consistent with our current machine segmentation. Pomphrey has the files required for this flexibility study.

The flexibility study needs to be based on a coil design that has no background TF field as its neutral point (ala 1017). This raises an interesting question - how would the presence of a non-1/R background field affect the design of the modular coils? Is this something else Strickler could look at or should we arrange to do some of the production runs at PPPL, freeing up Strickler to stay focused on the merging of StellOpt-CoilOpt and making upgrades to the CoilOpt code?

Well, I have run out of time. Perhaps we can discuss these issues at our next Wednesday telecon…