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Towards a 5 T Solenoid for SiD

R.P. Smith, Bob Wands

Fermilab

Solenoid & Steel of SiD

- What's Novel, Defined, Undefined
- HEP Solenoid Evolution
- Choosing an "Existence Proof"
- Extrapolationg CMS to SiD: Coil, Iron
- Winding Design
- Steel Yoke Concepts
- Coil Stress Analysis
- Cold Mass Support Ideas
- Towards a Conceptual Design

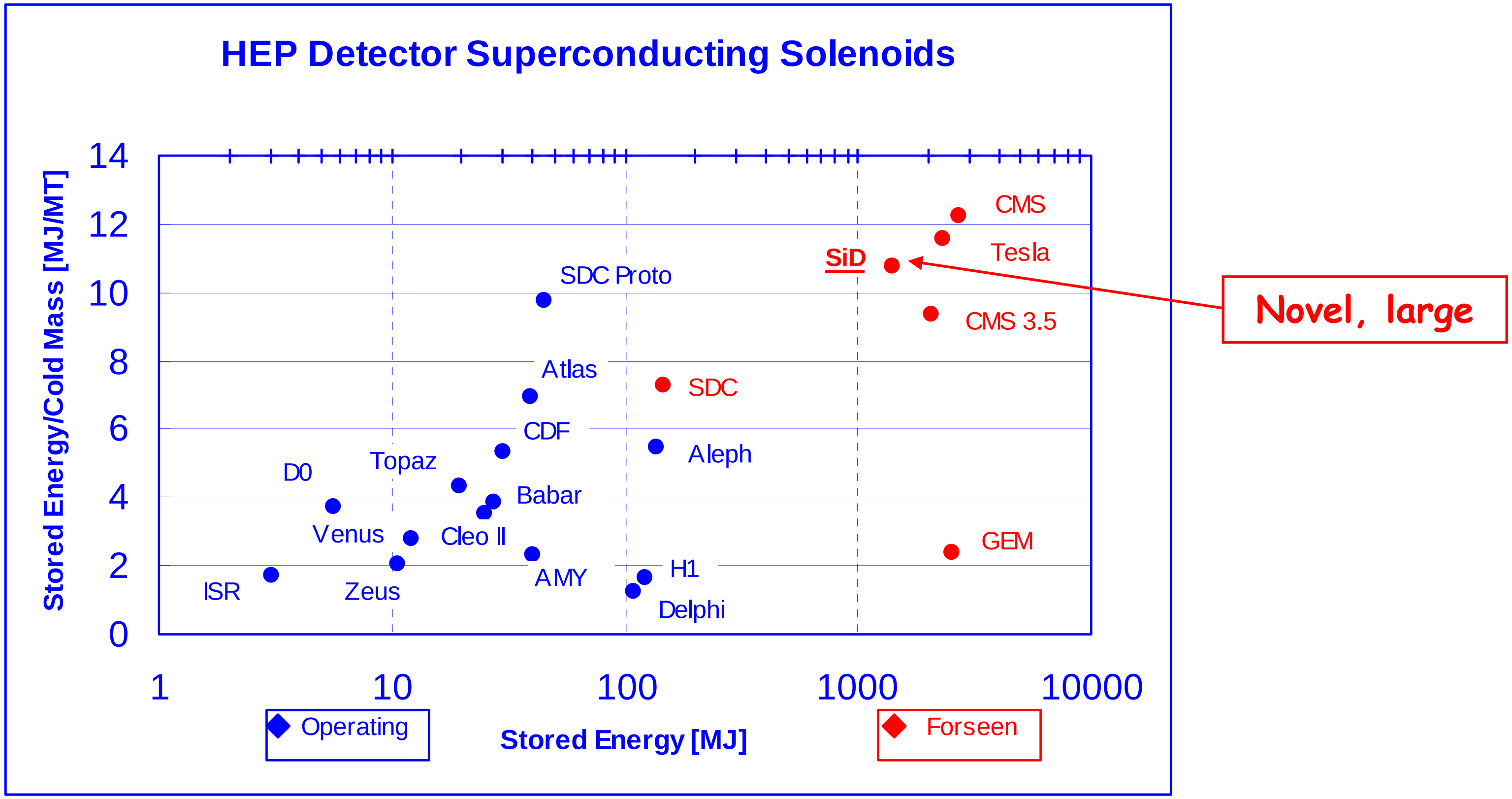
Getting Started…

- B(0,0) = 5T
- Clear Bore Ø~ 5m; L = 6 m
- ➔Stored Energy ~ 1.4 GJ
- Laminated Iron Yoke, End Laminations not re-entrant
- Field Homogeneity not specified
- Radiation Transparency not specified
- “Fallback” field (below which physics is compromised) not specified

Novel

Large

History of HEP Solenoids



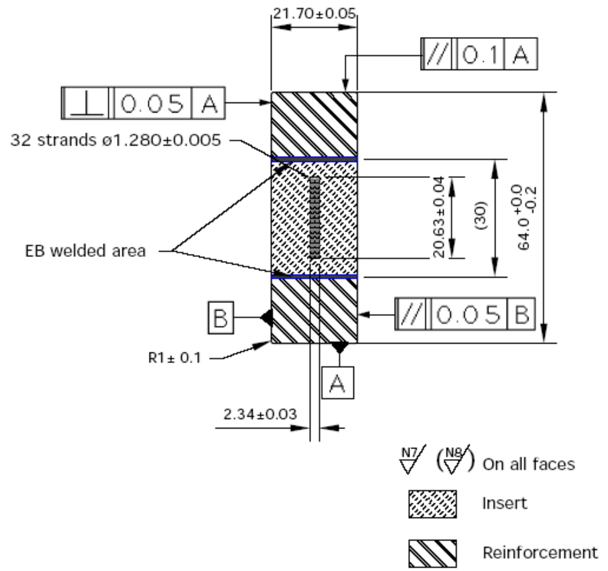
- Quench Safety…

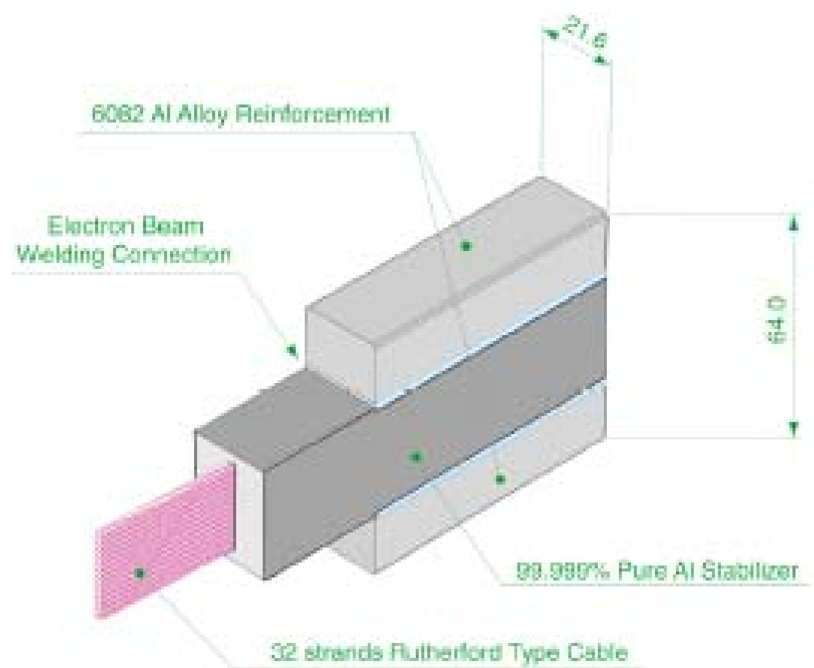
Recent High-Field HEP Solenoids

- High Field, Large Size create many challenges
  - Look for Proof of Principle!
    - Only “High Field” Operating Solenoids at 2T: DØ, Atlas; at 3T: AMY
  - Closest is (may be?) CMS: 4 T, 2.7 GJ, Ø = 6m, L = 13 m
- Develop Preconceptual Design “Along Lines of” CMS
  - Expedites Approach to Credible Conductor/Winding Designs
  - Credible Engineering Approach for Industrial Fabrication
  - Credible Cost Estimates
- Not Inappropriate to examine AMY approach (cryostable; mixed Al/CU conductor)

CMS Conductor Design

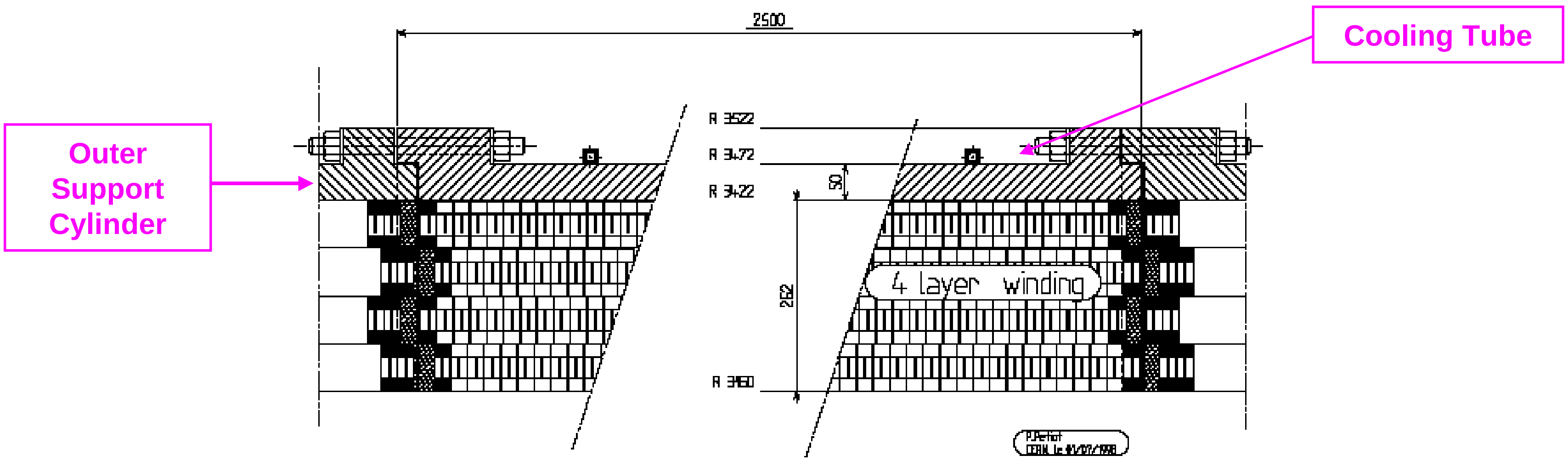
- Aluminum Stablized (low magnetoresistivity)
- Aluminum Reinforced (high strength)





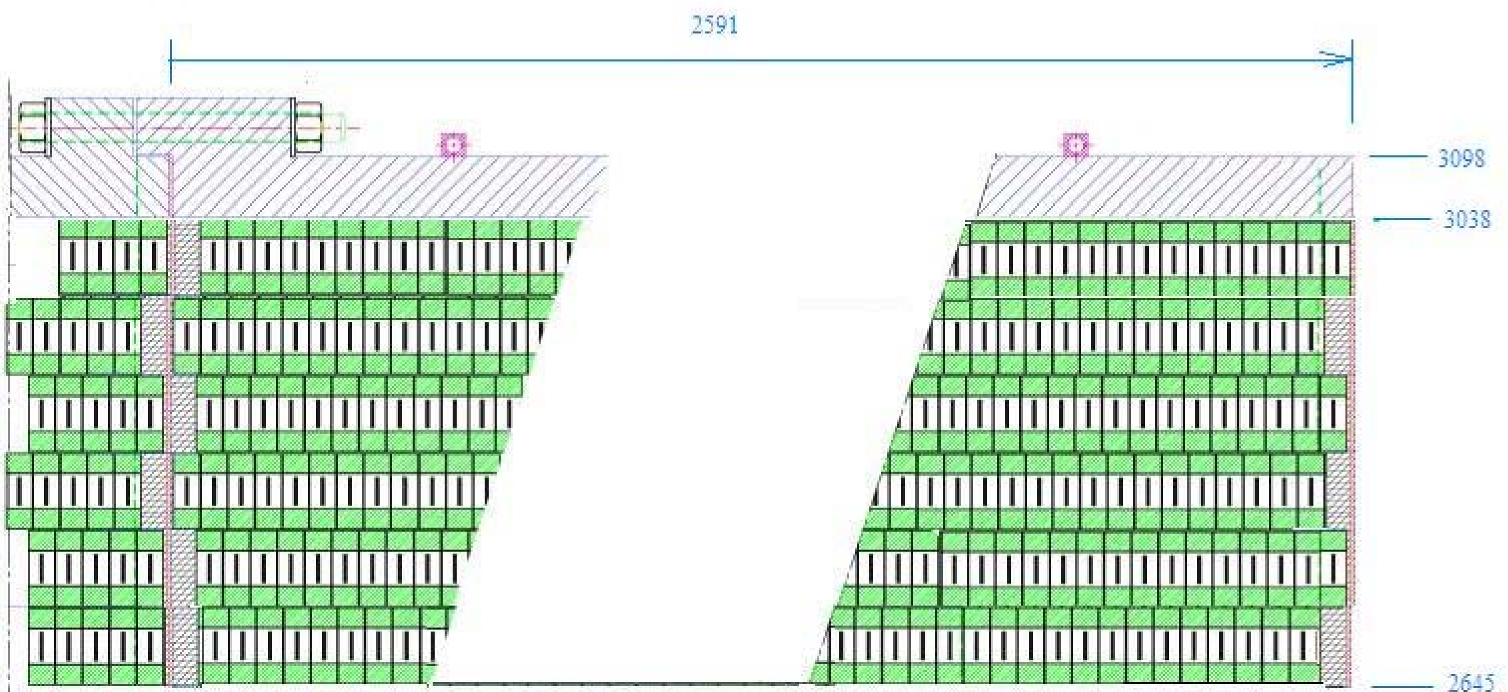
FNAL/ETHZ/Saclay/CERN/INFN

CMS Winding Design



- CMS Coil wound in 5 separate Modules, each 2.5 m long
- 4 Winding Layers (108 turns/layer)
  - 2.7 km long conductor length (one per layer) => no joints in layer; all on coil OD
  - Interturn insulation 0.64 mm, Interlayer 1.04 mm
- Outer "Support" Cylinder for "quenchback" quench safety, supports external forced-flow (two-phase) cooling via thermosiphon; provides anchor points for cold mass support links

SiD Winding Design

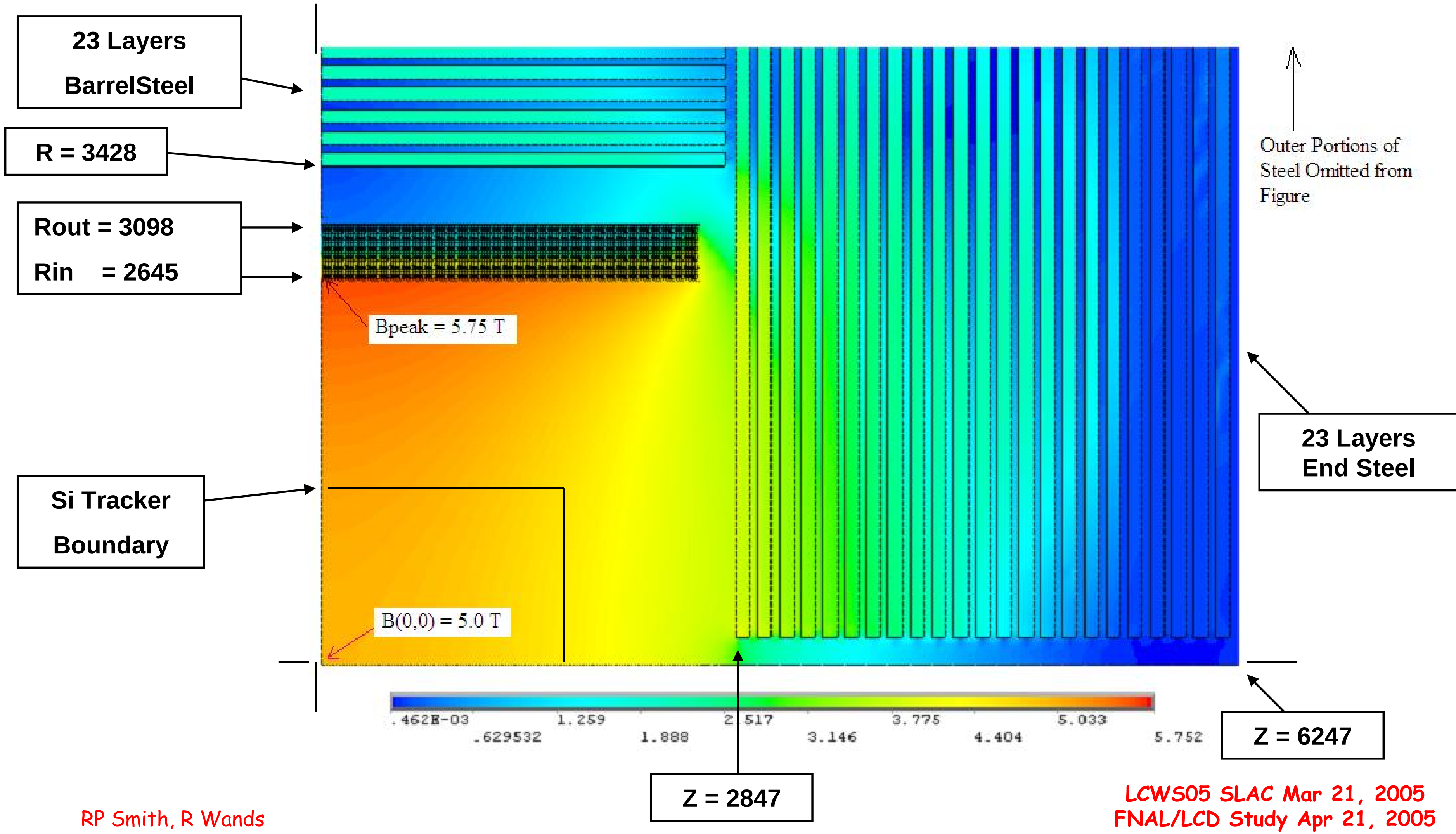


SiD Half-coil 6 layers x116 t/l

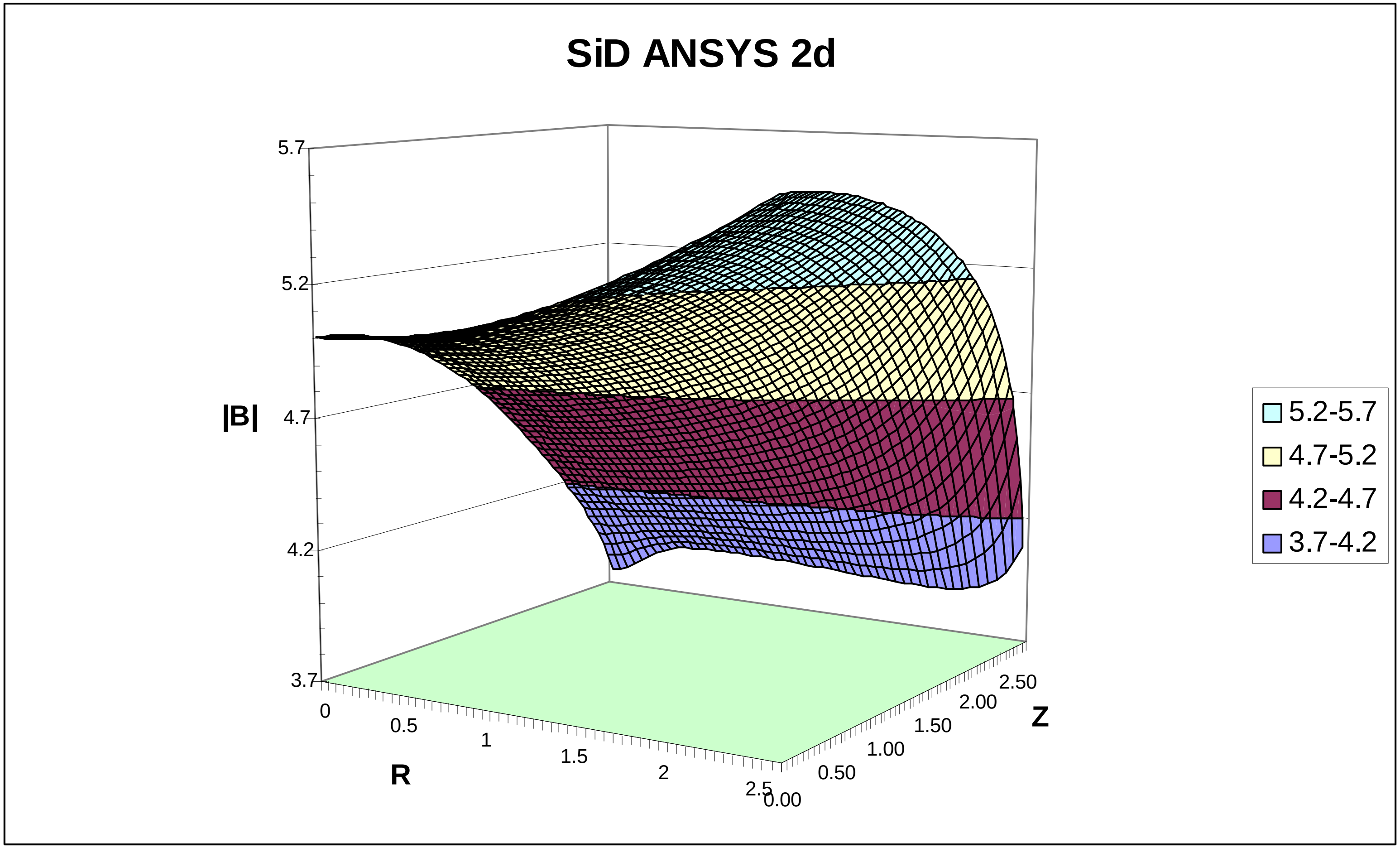
Specifics for SiD

- Choose 6 layers (tradeoffs), "derate" CMS conductor to 5.8 T peak field (vs. 4.6 for CMS). I (CMS) = 19500; I (SiD) = 18000.
  - Critical current Ic(4.2K,Bpeak) derates 46900/59000 ~ 0.79
  - Iop derates ~ 0.92
  - Stability expectations require modeling; 32 CMS strands => 34 for SiD?
- Have one module per coil half
  - Bolted joint at Z = 0 for easy assembly, transportablilty
  - Conductor length OK; Winding prestrain > CMS though
  - Winding, vacuum impregnation per CMS
- Outer support cylinder per CMS, except 60 mm thick
- FEA studies for Energization stress, conductor strain; Cooldown stresses
- Stored Energy per Kg cold mass (<CMS) ➔ quench safety ~OK?
- Cooldown, Energization Stresses and Strains OK ?

First ANSYS 2D, 3D Modeling



Field Variation in Central Region



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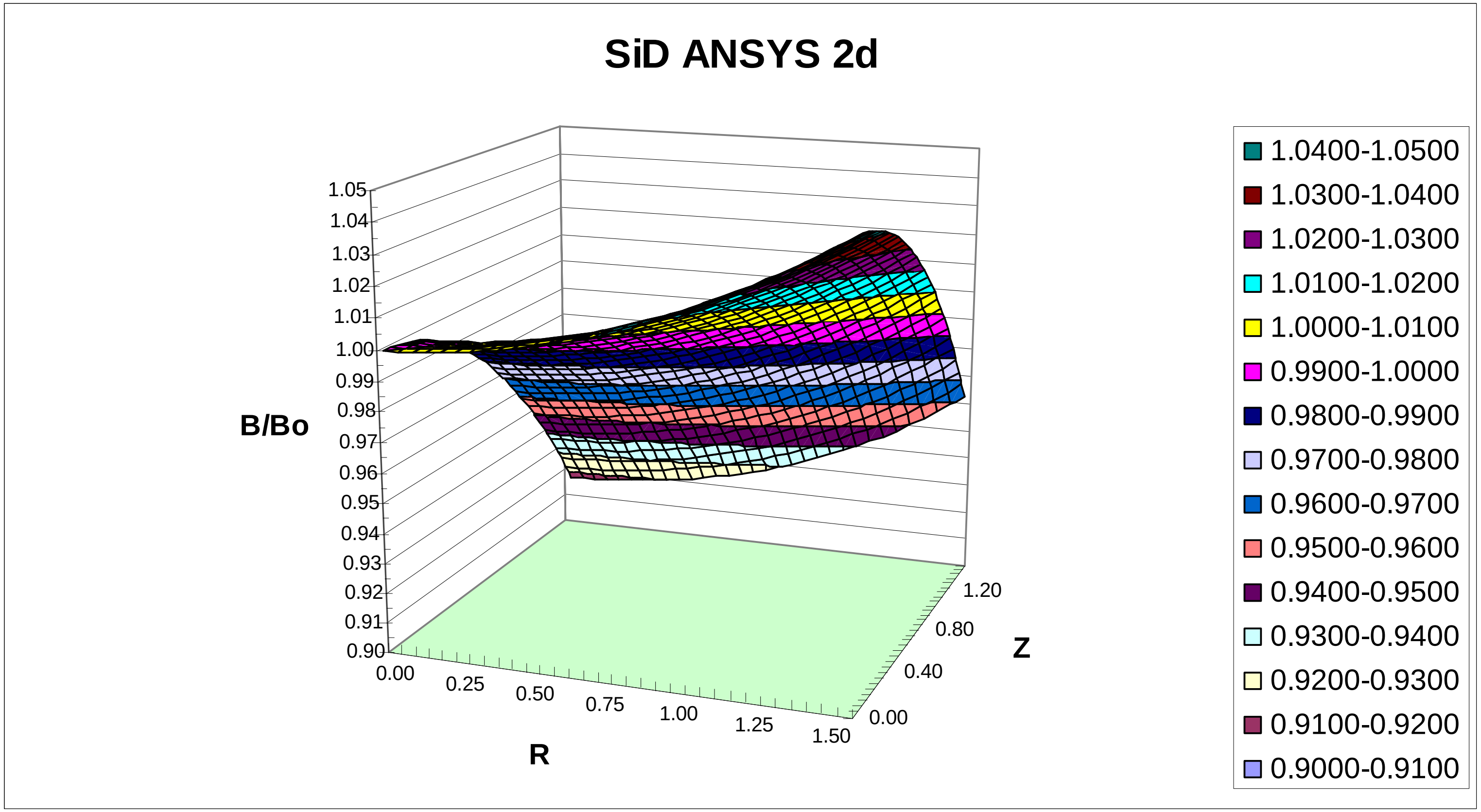
LCWS05 SLAC Mar 21, 2005
FNAL/LCD Study Apr 21, 2005

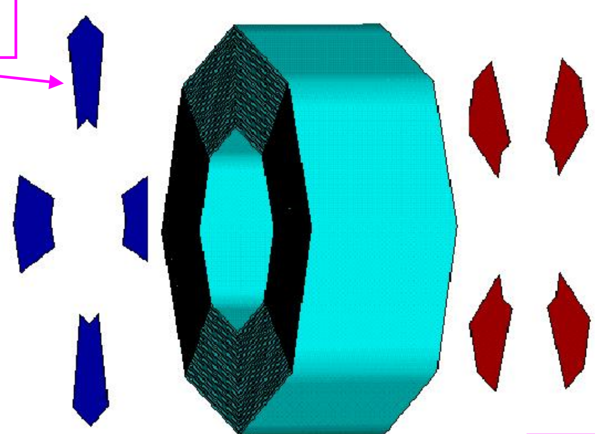
Field Variation in Tracker Region

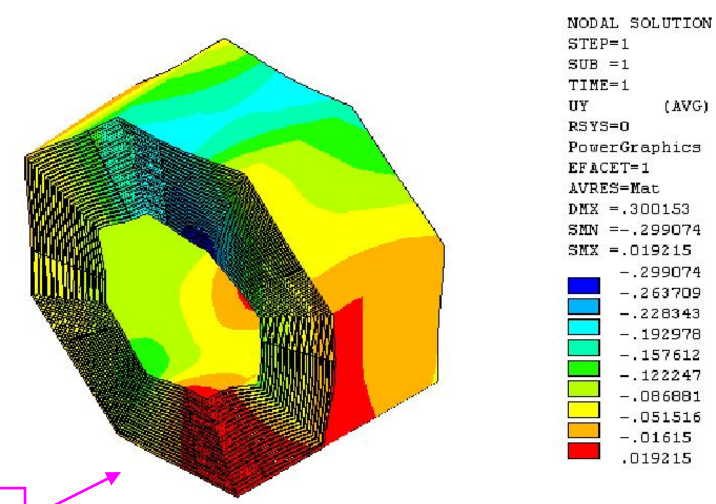


Supporting the Steel, Off Which Everything Hangs

- Muon system/Flux Return: 10 cm thick Iron, 5 cm chamber gaps
  - Overall Octagonal Shape of Barrel Yoke; can "tile" chambers at vertices for hermiticity
  - Barrel Octagon Layers Spaced/Supported by Staggered Corner Gussets
  - Allows Insertion of Muon Chambers from Alternate Ends, "tile" at centerline

Corner Plates tie barrel shells together

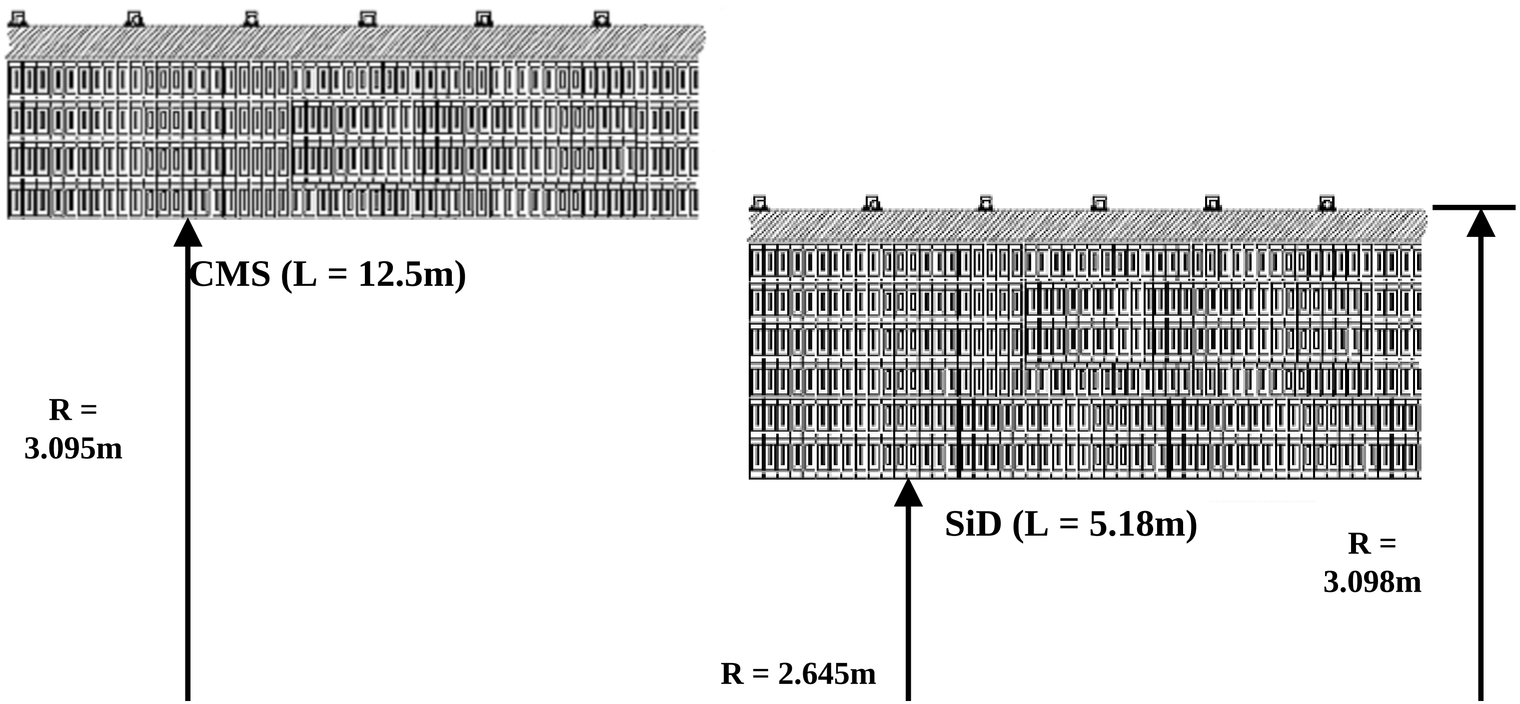




Vertical Deflections for Staggered Barrel Iron Connections
(units = inches)

Resulting Structure shows acceptable deflections (~0.3 in)

FEA: Stress, Strain



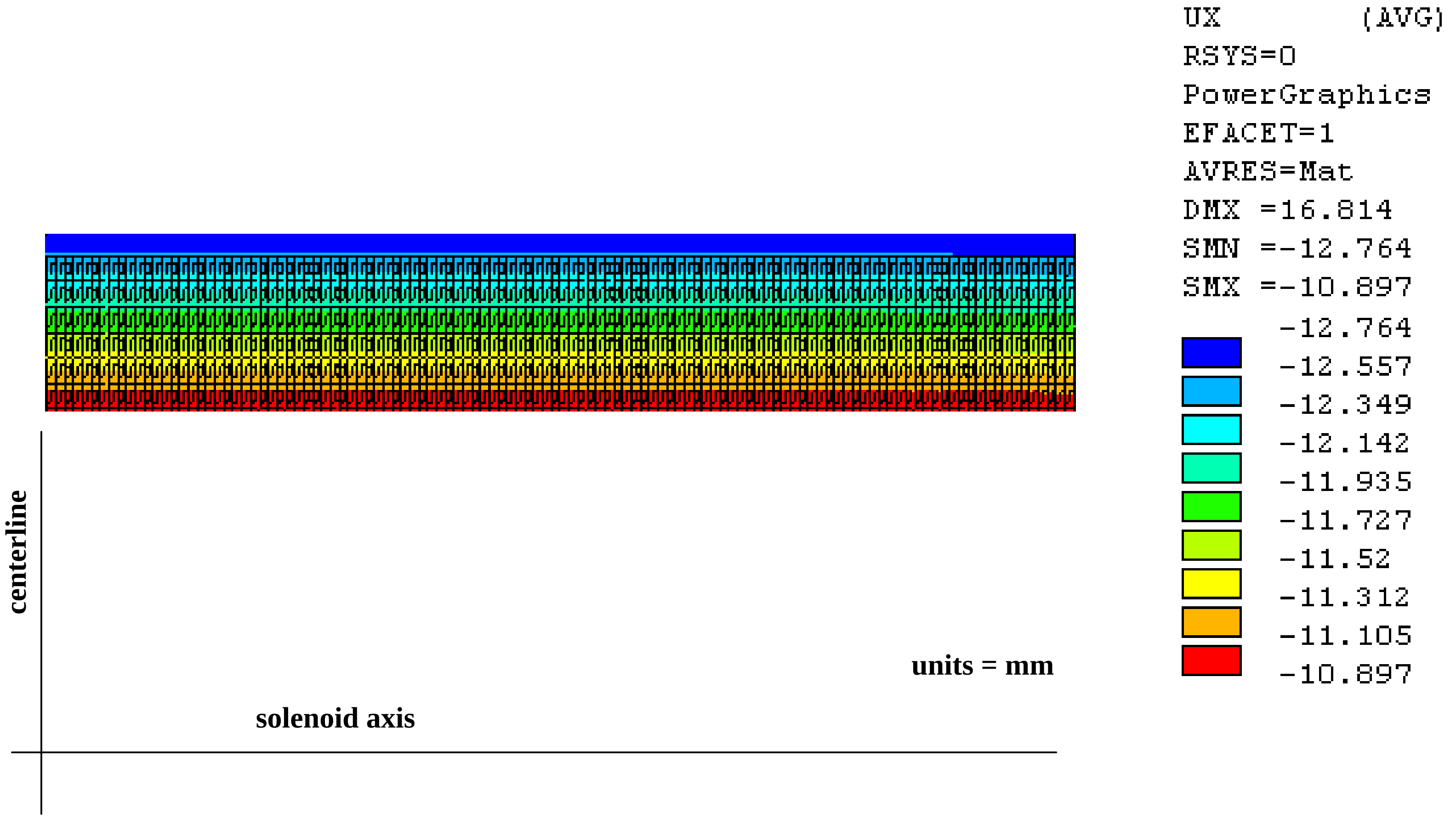
Comparison of Hoop Stress Behavior

- Assume solenoid behaves as thin-walled cylinder under internal pressure, with $P = B^2/2\mu_o$
- Define figure of merit as $B^2 r_m/t_{al}$, where B = central field, r_m = mean coil radius, and t_{al} = thickness of aluminum
- For CMS: B = 4T, r_m = 3.26m, t_{al} = 0.325m; FOM = 160
- For SiD: B = 5T, r_m = 2.87m, t_{al} = 0.453m; FOM = 158
- Hoop stresses should be very similar for both solenoids

Comparison of Axial Stress Behavior

- The smaller aspect ratio of SiD (L/r_m= 1.8 for SiD, vs. 3.8 for CMS) makes it more likely to experience larger axial compressive forces due to field wrap-around at the ends
- As measure of axial stiffness, calculate $r_m t_{al}/L$
- SiD solenoid $r_m t_{al}/L$ = 0.25 ; CMS solenoid $r_m t_{al}/L$ = 0.085
- The SiD solenoid is about 3 times stiffer axially relative to magnetic forces applied at ends
- SiD is likely to experience higher axial forces, but lower axial displacements, compared to CMS

Cooldown Radial Displacements



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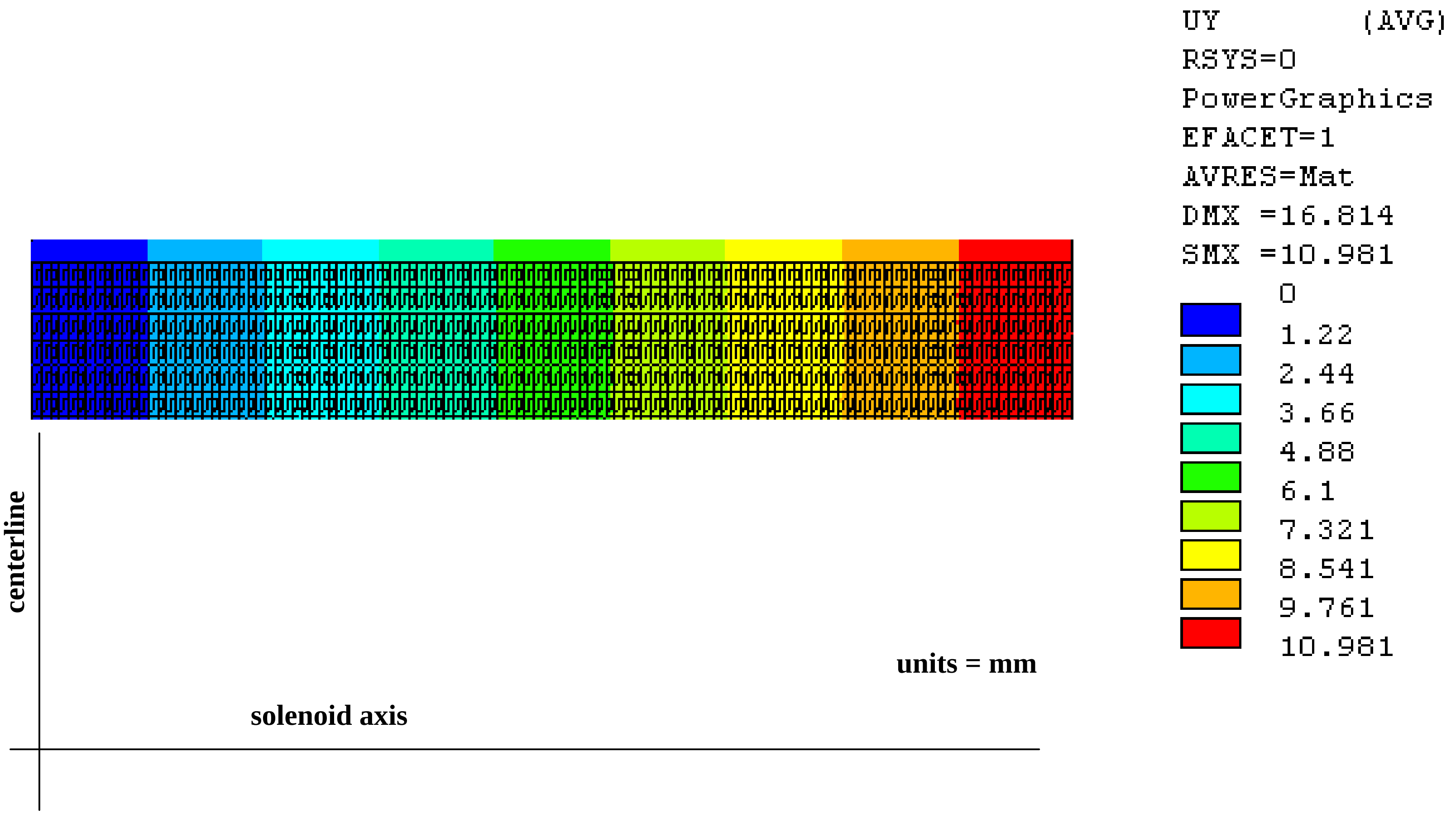
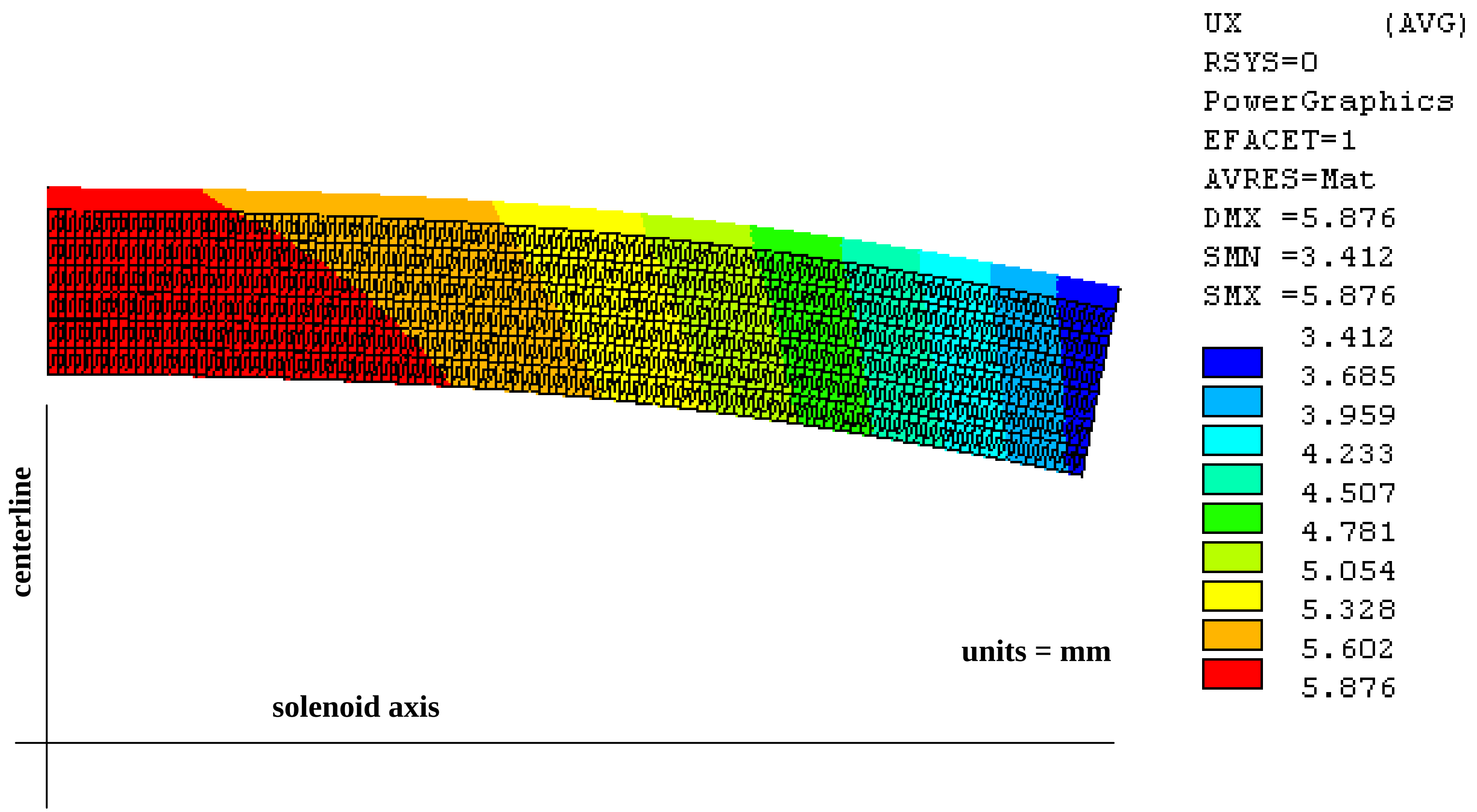
Cooldown Axial Displacements



Energization Radial Displacements



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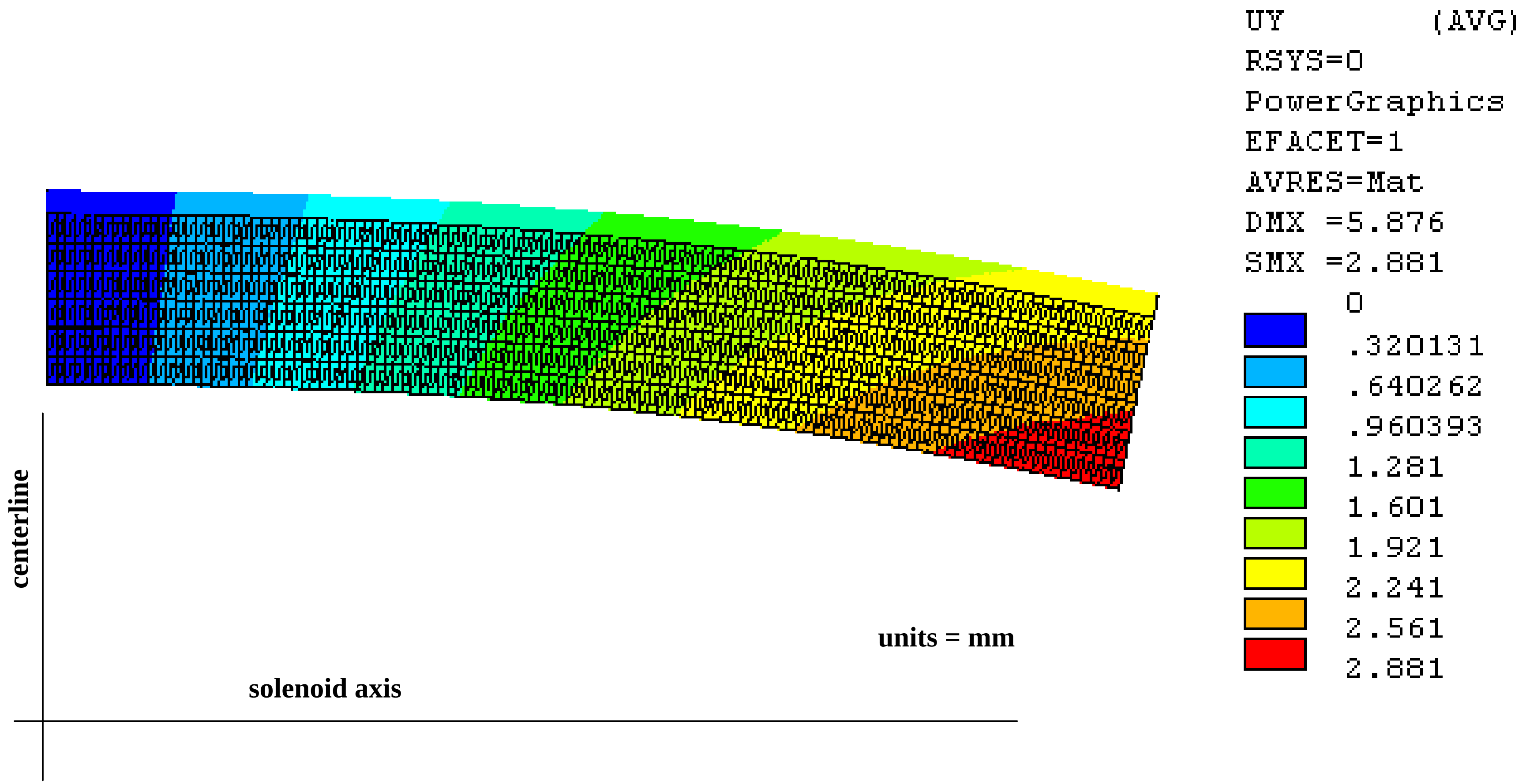
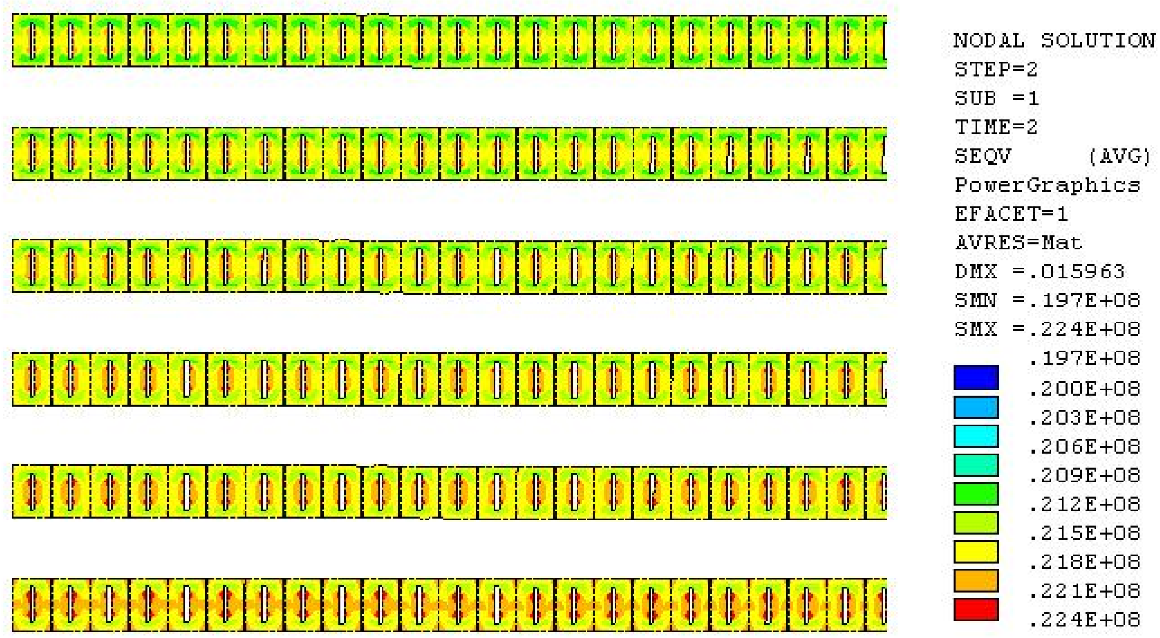
Energization Axial Displacements



Von Mises Stress in HP Al, Cold & Energized



22 Mpa = 3190 psi

Compare CMS, SiD Cooldown+ Energization Stresses, Displacements

Quantity	SiD	CMS (from Desirelii CERN; Pes SACLAY)
Von Mises Stress in High-Purity Al	22.4 MPa	22 MPa
Von Mises Stress in Structural Al	165 Mpa	145 MPa
Von Mises Stress in Rutherford Cable	132 MPa	128 MPa
Maximum Radial Displacement	5.9mm	~5mm
Maximum Axial Displacement	2.9mm	~3.5mm
Maximum Shear Stress in Insulation	22.6 MPa	21 MPa

Compare CMS, SiD Decentering Forces, Stored Energy

Quantity	SiD	CMS
Radial Decentering	38 kN/mm	38 kN/mm
Axial Decentering	230 kN/mm	85 kN/mm
Stored Energy	1.4 GJ	2.8 GJ

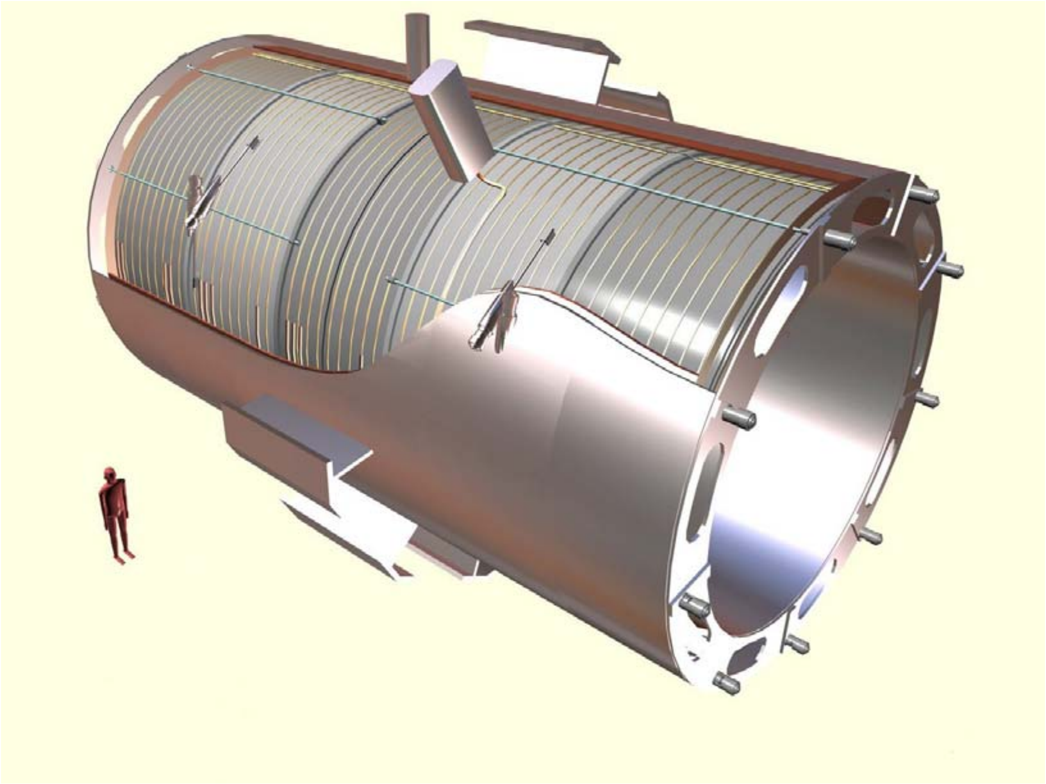
Cryostat, Cold Mass Support Design Concepts

Requirements

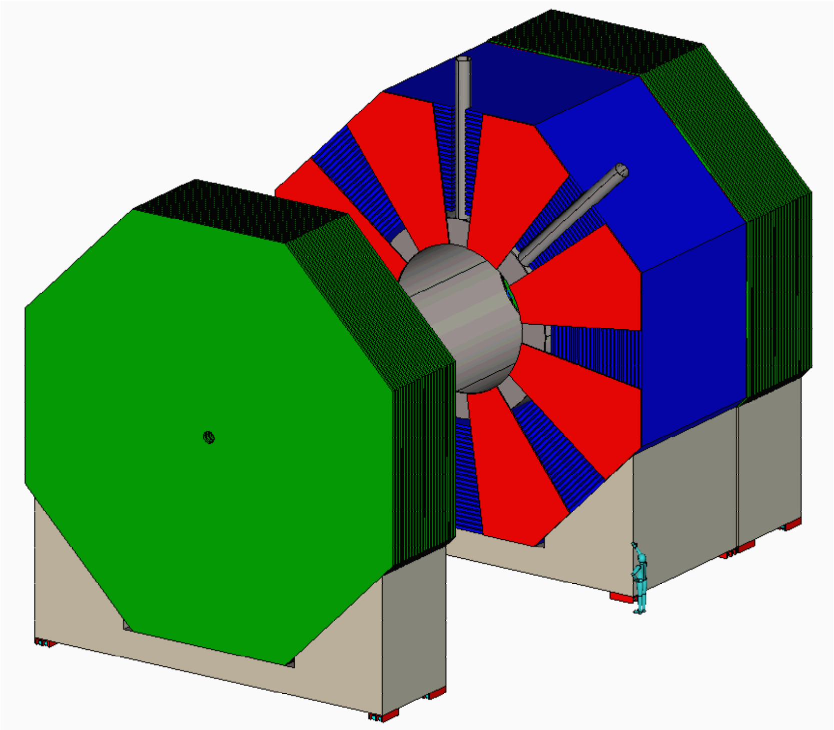
- Cold mass support – 130 Mt
- React decentering forces, seismic, cooldown, steady-state operation

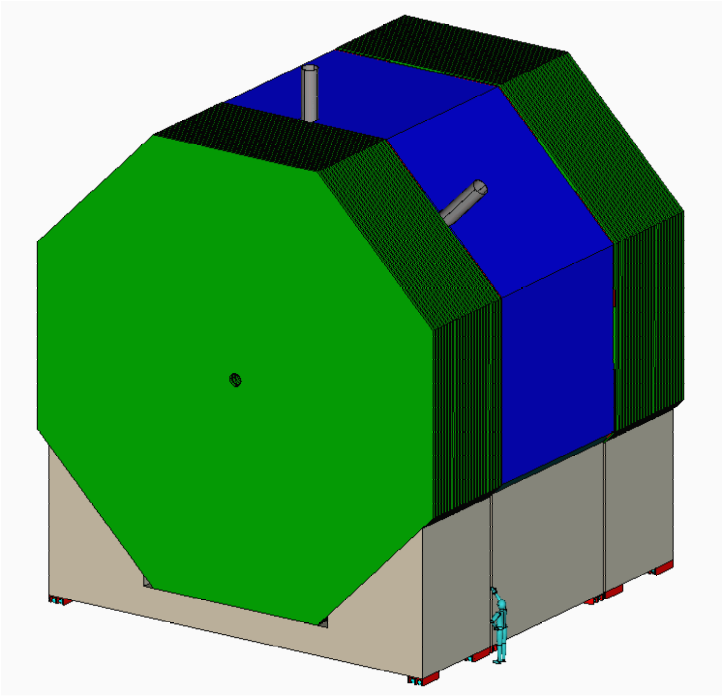
CMS Concept

- Thin metallic rods preloaded in tension
- Axial rods for axial loads
- Vertical rods for dead weight
- Additional tangential rods (in preloaded pairs) for radial loads



Overall Detector





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Conclusions

- Need iterations with Detector/Physics Groups to select "most probable" performance parameters
  - How to "Open" detector ?
  - Must Detector Roll "off beamline" ?
  - Compensators (dipoles/solenoids) ?
  - Final Focus Quads?
  - EndCap Steel Details
- Need Overall Management Plan which leads to Preconceptual Design, Cost Estimate
- Continue to Look for "Show Stoppers", Cost Savings
- Collaborative Effort among Engineering Teams/Institutions/Physicists

Machine Issues (Seryi SLAC, Parker BNL)

SLAC-PUB-11038

Novel Method of Compensation of the Effects of Detector Solenoid on the Vertical Beam Orbit in a Linear Collider

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(Dated: January 19, 2005)

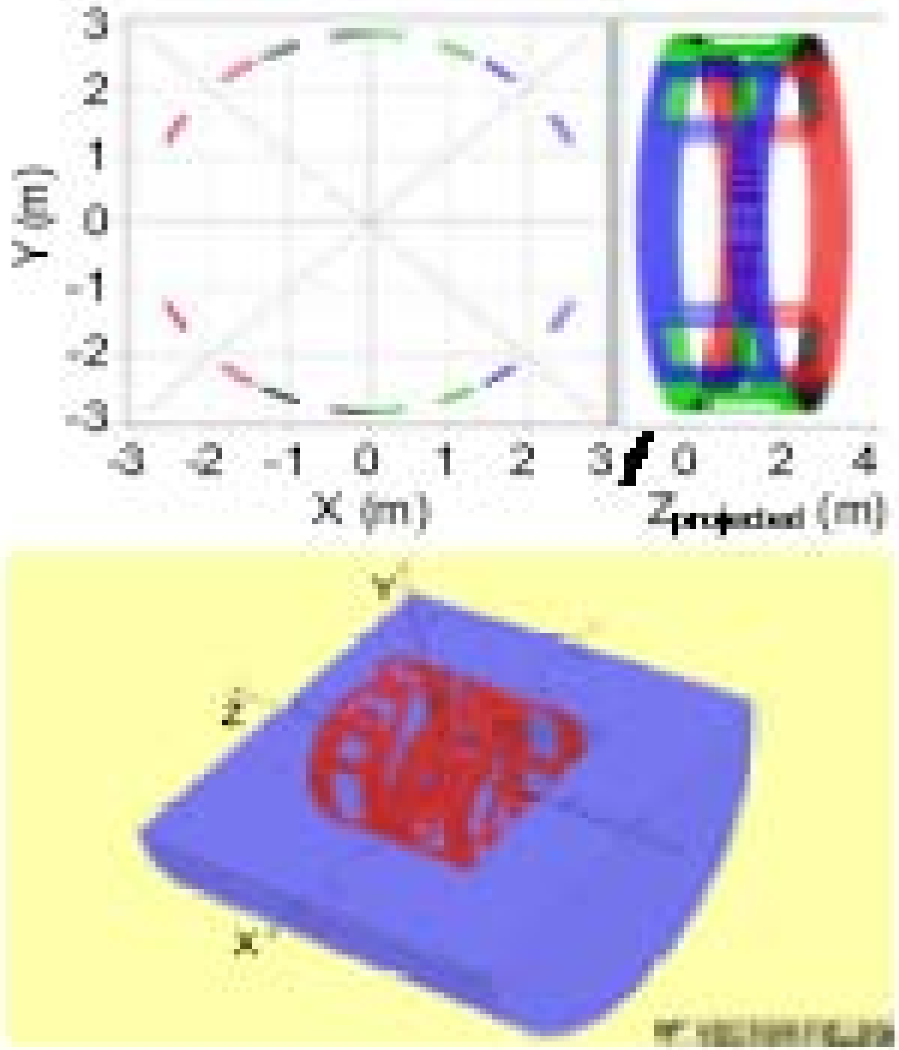
This paper presents a method for compensating the vertical orbit change through the Interaction Region (IR) that arises when the beam enters the Linear Collider detector solenoid at a crossing angle. Such compensation is required because any deviation of the vertical orbit causes degradation of the beam size due to synchrotron radiation, and also because the nonzero total vertical angle causes rotation of the polarization vector of the bunch. Compensation may be necessary to preserve the luminosity or to guarantee knowledge of the polarization at the Interaction Point (IP). The most effective compensation is done locally with a special dipole coil arrangement incorporated into the detector (Detector Integrated Dipole). The compensation is effective for both e^+e^- and e^-e^- beams, and the technique is compatible with beam size compensation either by the standard method, using skew quadrupoles, or by a more effective method using weak antisolenoids.

Machine Issues (Seryi SLAC, Parker BNL)

VI. CONCLUSION

A special dipole can be added in the Linear Collider IR to correct the effect of the vertical deflection caused by the beam passing through the detector solenoid field with a horizontal crossing angle. To be most effective, the correction (Detector Integrated Dipole) needs to be local, and thus is incorporated into the detector solenoid winding. The DID corrector can be used to compensate for rotation of the beam polarization or to minimize the beam size growth due to synchrotron radiation. The solution presented uses the DID Corrector to provide local compensation of the orbit and works both for $e^+e^-$and e^-e^-cases. This method is compatible with beamsize compensation using weak antisolenoids. The DID corrector can also be used for upgrades of other colliders, such as B-factories.

Machine Issues (Seryi SLAC, Parker BNL)



Compensation of Detector Solenoid Effects on the Beam Size in Linear Collider

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Abstract: In this paper, we discuss the optics effects of the realistic detector solenoid field on beam size at the Interaction Point (IP) of a future Linear Collider and their compensation. It is shown that most of the adverse effects on the IP beam size arise only from the part of the solenoid field which overlaps and extends beyond the final focusing quadrupoles. It is demonstrated that the most efficient and local compensation can be achieved using *weak antisolenoids* near the IP, while a correction scheme which employs only skew quadrupoles is less efficient, and compensation with strong antisolenoids is not appropriate. One of the advantages of the proposed antisolenoid scheme is that this compensation works well over a large range of the beam energy.

Machine Issues (Seryi, Nosochkov SLAC)

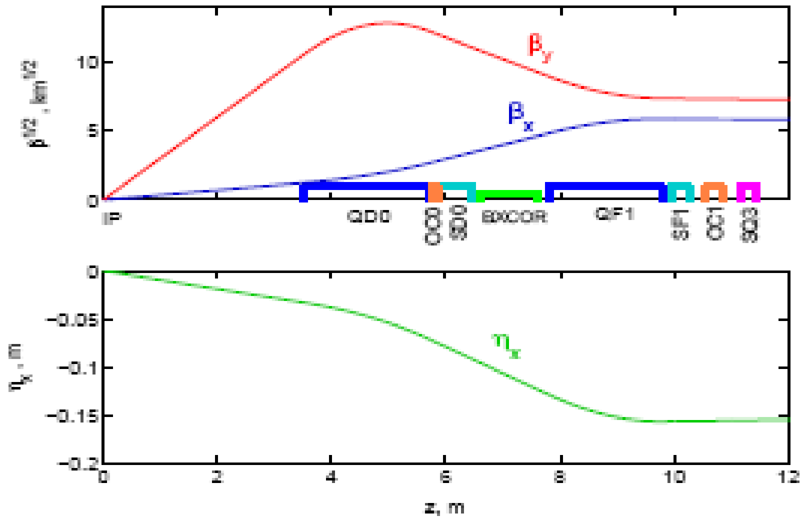

FIG. 2: Optics of the Next Linear Collider Beam Delivery System near the Interaction Point showing betatron functions (top plot) and horizontal dispersion (bottom plot). Locations of the Final Doublet magnets are shown, including quadrupoles QD0 and QF1, sextupoles SD0 and SF1, octupoles OC0 and OC1, skew quadrupole SQ3 and optional vertical corrector BXCOR.

Machine Issues (Seryi SLAC, Parker BNL)

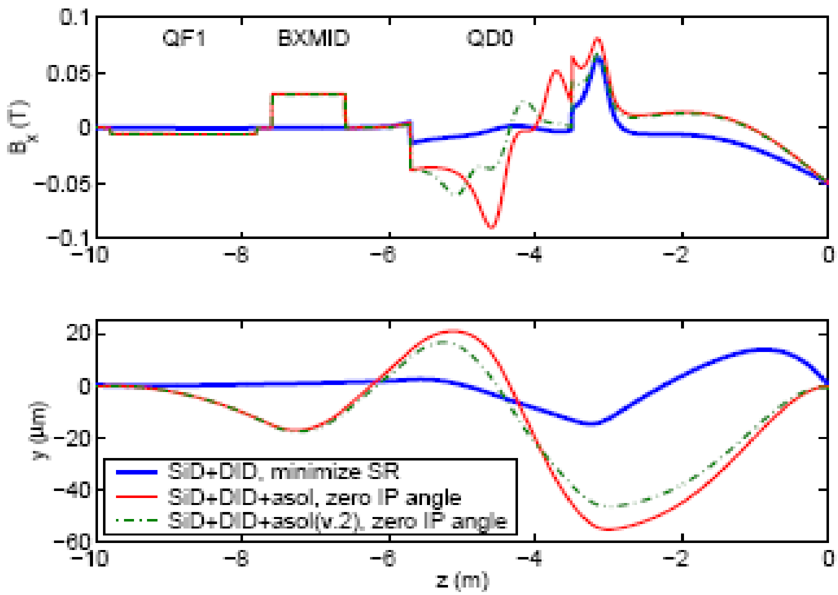

FIG. 8: Horizontal field on the beam axis (top plot) and the beam orbit determined by tracking (bottom plot) in three cases: a) bare SiD (no antisolenoid) and DID strength is optimized to minimize SR beam size growth – blue thick line, $\Delta\sigma_y^{sr} = 0.034$ nm; b) SiD with antisolenoid (parameters from [1]) – red line, $\Delta\sigma_y^{sr} = 0.83$ nm; c) SiD with antisolenoid optimized to minimize SR effects – green dash-dotted line, $\Delta\sigma_y^{sr} = 0.33$ nm. In the last two cases the IP angle is compensated by the DID, FD offsets and BXMID without introducing any linear or second order dispersion.

Machine Issues (Seryi SLAC, Parker BNL)

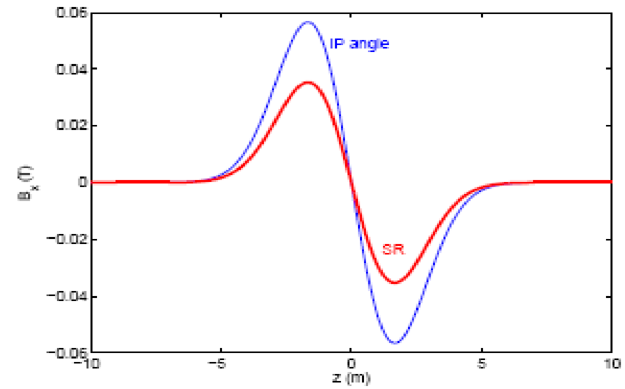

FIG. 6: Horizontal field of the Detector Integrated Dipole (DID) for the SiD detector. The DID strength is optimized to zero the IP vertical angle (blue line) or to minimize the SR vertical beam size growth (red line) in the case of bare SiD without antisolenoids.

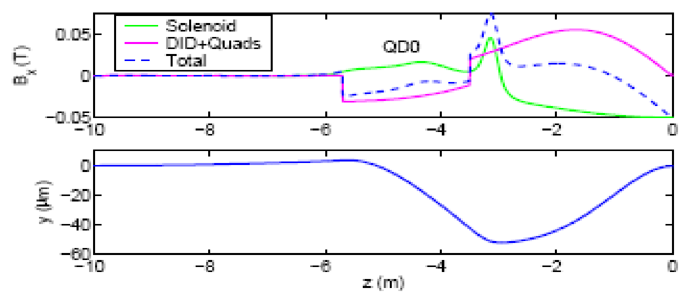

FIG. 7: Horizontal field on the beam axis (top plot) and the beam orbit (bottom plot), the IP angle has been compensated using DID and offsets of QD0 and QF1 quadrupoles. The orbit is determined by tracking. The beam size growth from synchrotron radiation is $\Delta\sigma_y^{sr} = 0.26$ nm.

Machine Issues (Seryi SLAC, Parker BNL)

Outline: Final Doublet, Anti-solenoid & Extraction Line Magnets for the ILC.

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Final Doublet:

- For 20 mr X-ing Scheme we propose that QD0 and first extraction compensator magnet use He-II (1.9°K) cooling for extra compact coils (they start at same L*).
- CAD layout in progress; capture details needed for energy deposition calculations.
- First estimation of cooling capacity; give feedback for E-Dep' and cryostat design.

Anti-Solenoid:

- More details of Anti-Solenoid design have been elaborated and field calculations for practical coils surrounded by laminated yoke (SiD geometry) were completed.
- Preliminary space allocation made; now examine MDI issues (anchor 15 Ton force).

Machine Issues (Seryi SLAC, Parker BNL)

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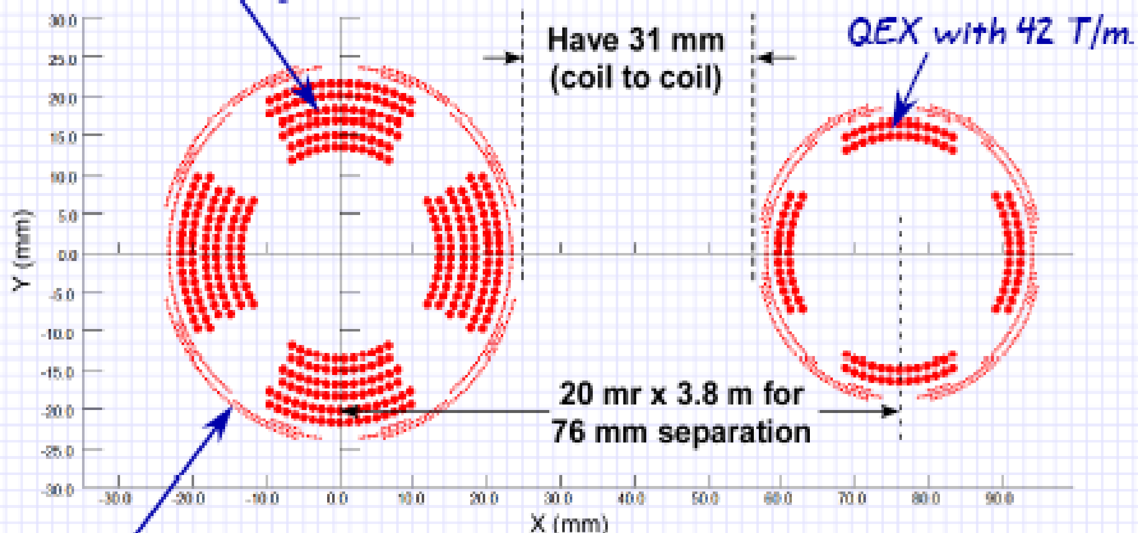
Very compact QD0 and QEX coils side-by-side & both having fringe field compensation.

Need only 6 cable layers to achieve 144 T/m QD0 gradient.

Operate at 1.9°K (pressurized HE-II)



Both magnets have dipole, skew-dipole and skew-quad windings to compensate fringe and detector fields (outbound beam & DID).

Coil Separation @ 3.8 m with 20 mr X-ing angle

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But can we direct wind coils with 6-around-1 cable at such a small bend radius?

Yes!

Quadrupole pattern with 1 mm cable wound on 25.4 mm diameter tube.

The tightest bend radius in this pattern is about four times the cable diameter.

By the third corner John Escallier had found process parameters that worked for automatic winding of the rest of the coil (two layers were wound).

Idea was to try "semi-automatic" winding with a mechanical assist for the first turn.

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Overview of QD0 Design for 20 mr X-ing.

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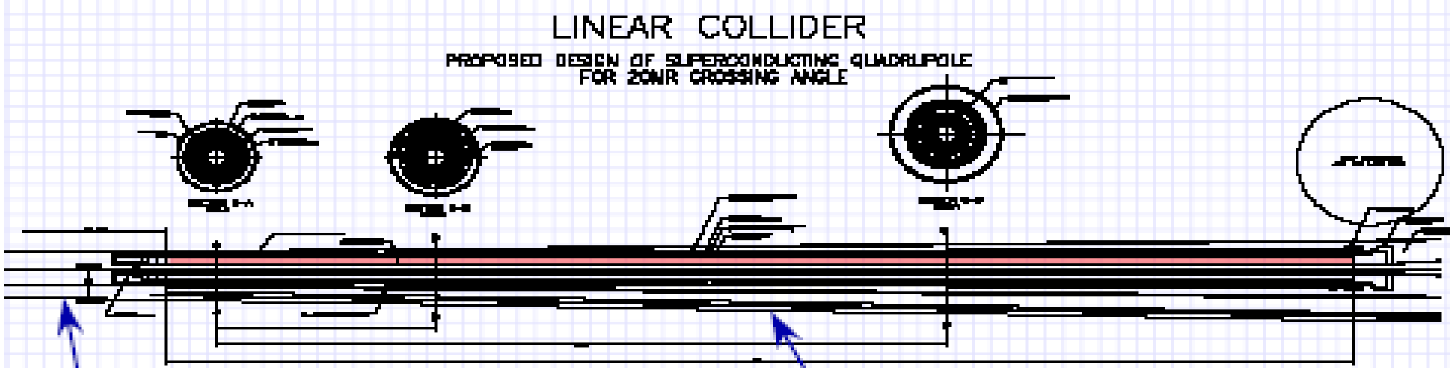

Lines of sight to IP with 20 mm crossing angle as indicated.

Edge of extraction line magnet.

Here the QD0 cryostat is circular in cross section but it is tapered along its length.

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Energy Deposition & Superconducting Coils.

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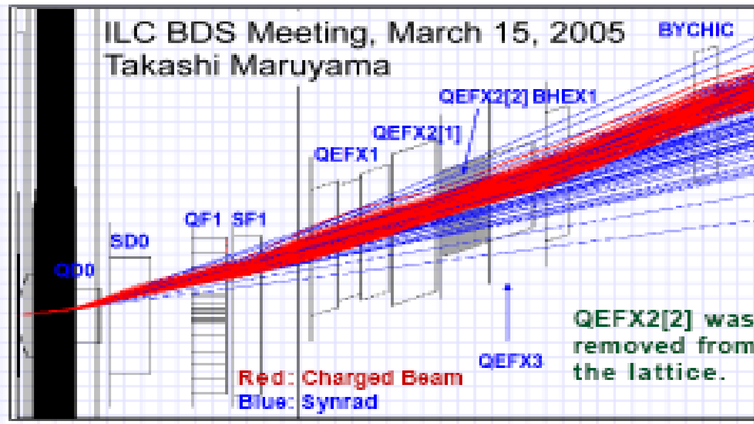
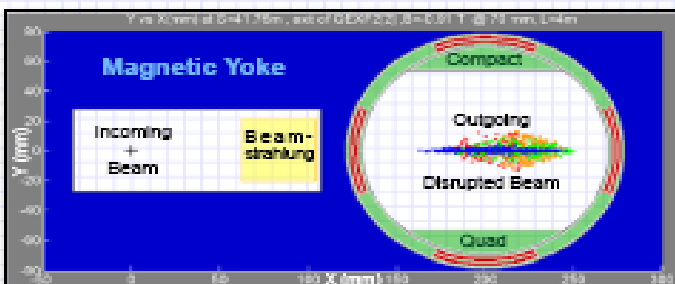
Super Septum Design Challenge

Must be careful with energy deposition in a superconducting magnet. For some cases even a few watts heating can be significant.

For the super septum magnet we need to protect the septum region.





Even if the main part of the disrupted beam and beamstrahlung pass cleanly, there can be synrad hits from upstream magnets.

Advice: Only go with a superconducting magnet when sure that a normal conducting or permanent magnet solution is not practical or not desirable for some reason.

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Anti-Solenoid Design Developments.

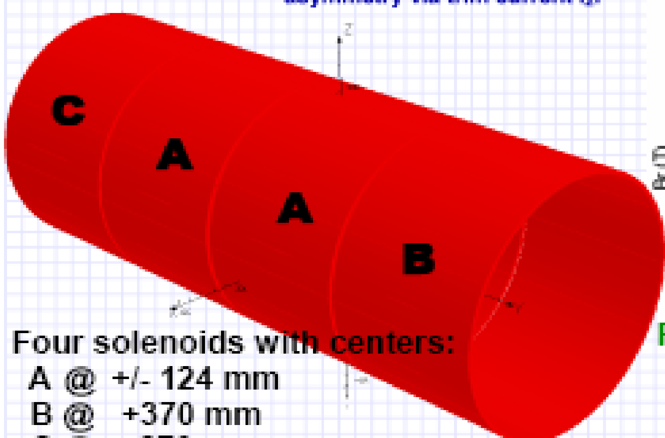
Anti-Solenoid Split Into Four Subcoils

$I_a = I_o + I_1$

$I_b = I_o - I_1 + I_2$

$I_c = I_o - I_1 - I_2$

If each subcoil has the same number of turns, then overall strength is determined by I_o. Modify width via trim I_1 and asymmetry via trim current I_2.

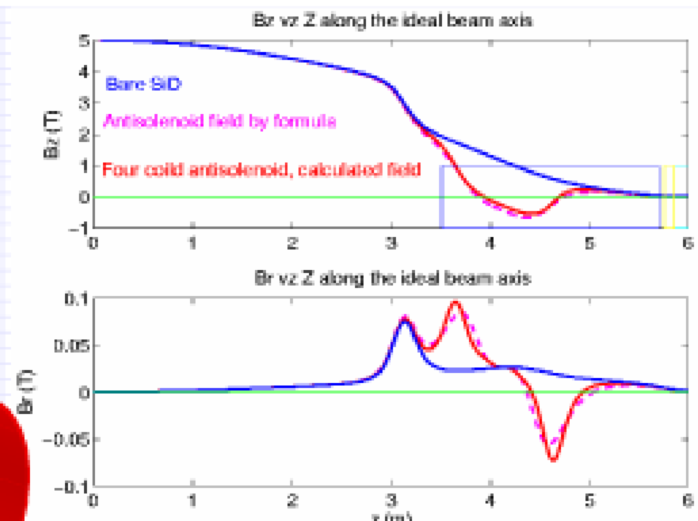


Four solenoids with centers:

A @ +/- 124 mm
B @ +370 mm
C @ -370 mm

L_s = 240 mm, R_{inner} = 190 mm

Thickness = 6 mm, $\bar{J} \approx -200$ A/mm^2



Field approximation by formula: σ_y/σ_{y_o} = 1.38

Calculated (in air) coils: σ_y/σ_{y_o} = 1.45

(not using the current knobs)

For comparison: without anti-solenoid σ_y/σ_{y_o} = 27.6 for ILC parameters

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Anti-Solenoids+DID: Compensate Beam Size, Minimize IP Angle and SR Beam Size Growth.

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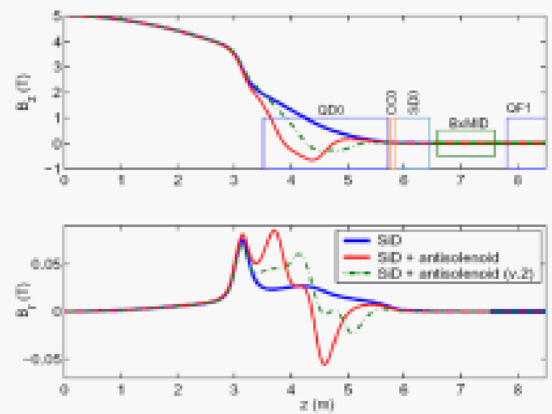

FIG. 3: Longitudinal and radial magnetic field in SiD calculated by ANSYS, without and with the weak antisolenoid which cancels the beam distortions produced by the detector solenoid. The red line shows the field with the antisolenoid parameters suggested in [1], and the green dot-dashed line shows the field with another configuration of the antisolenoids, optimized to reduce SR effects (see text). The radial field is at the nominal beam trajectory with half crossing angle $\theta_c = 10$ mrad. Locations of the Final Doublet elements (quadrupoles QD0 and QF1, sextupole SD0, octupole OC0 and an optional dipole corrector BXMID) are also shown. The IP is at $z = 0$ m.

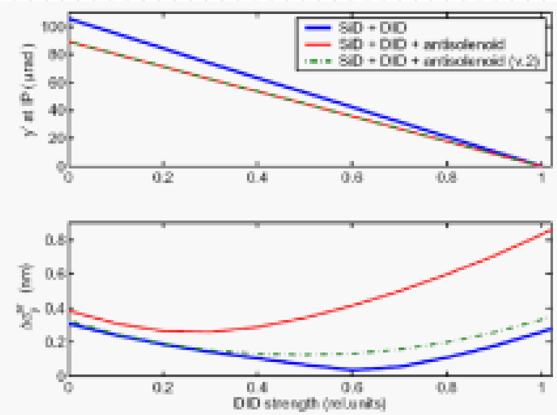

FIG. 9: Vertical angle at the IP (top) and the beam size growth due to synchrotron radiation (bottom), versus strength of the DID corrector, without antisolenoid (thick blue line), with the antisolenoid with parameters suggested in [1] (red line), and with the antisolenoid optimized to reduce the SR effects (green dash-dotted line).

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(Position of antisolenoids was not exactly the same as in latest layout, but very similar)

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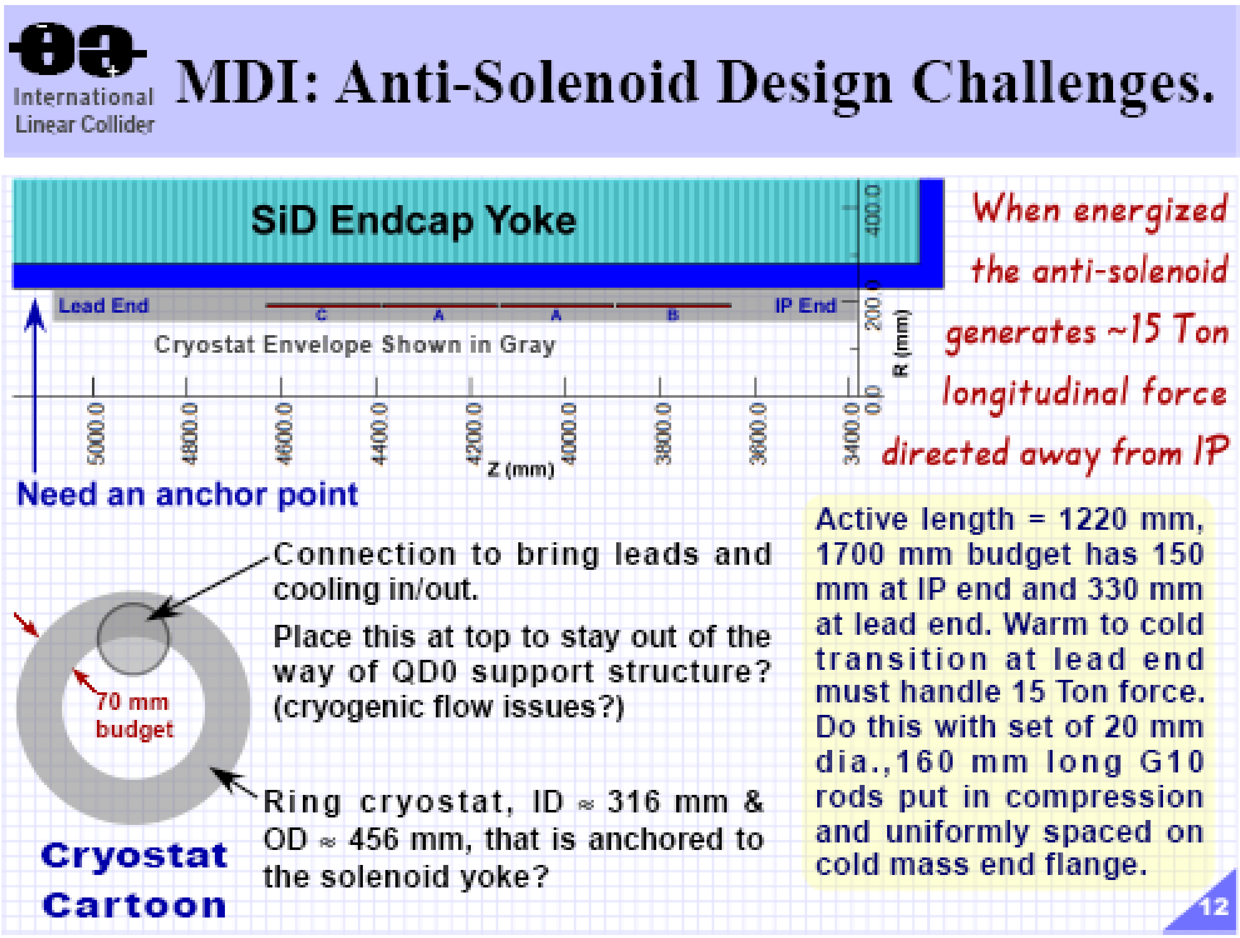

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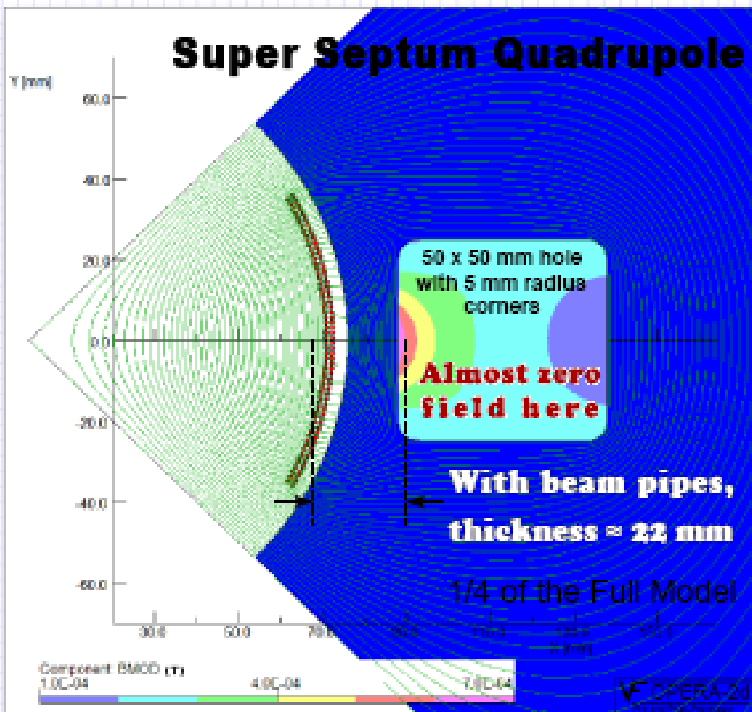
Special Magnets for 2 mr Extraction Line.



There are places where beams are not well separated but we need to focus one and not deflect the other. This happens frequently along the 2 mr X-ing angle extraction beamline.

If the field at the conductor is low enough, then we can consider making a thin superconducting coil via the direct wind technique. Then we surround this coil with a magnetic yoke that has a hole for the "reduced field" region.

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