Goal of This Presentation

- Phd concepts of 20 T dipole magnets
  - Survey of all possible layouts
  - Eucard 2 magnet is one of the possible layouts and hence an interesting test bed (hoping to yield information to feedback into the survey)

- Show what we have been working on
- Share our ideas / Share information
- **Nothing is fixed!**
- Ideas / Discussions / Thoughts / Questions / Constructive Feedback all more than welcome

- Present our design considerations for
  - EUCARD-II YBCO magnet design (detailed)
  - EUCARD-II BSCCO magnet design (basic)

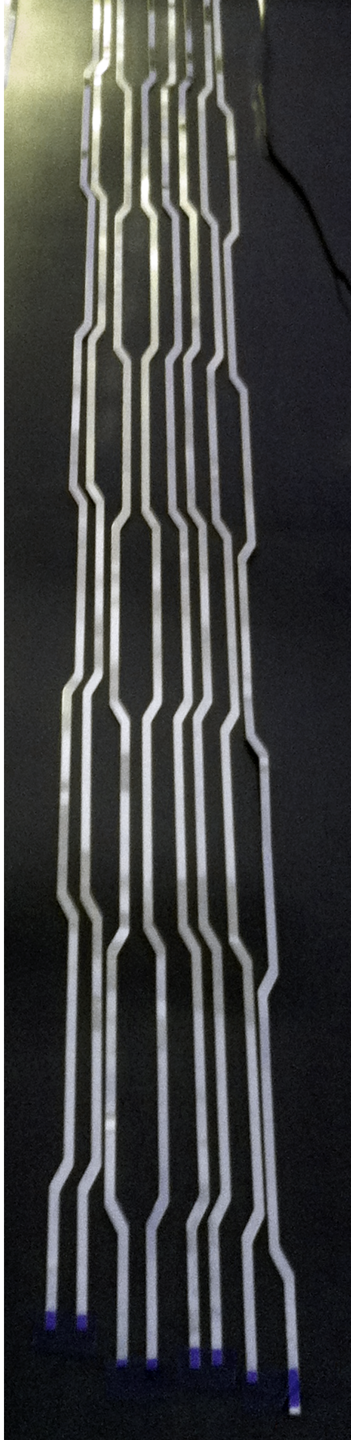
EUCARD-II Requirements

- Magnet requirements as presumed up to now
  - High Temperature Superconducting (HTS) cable
  - 10 kA Class Conductor (i.e. a cable)
  - 40 mm aperture
  - 5 T at center of aperture standalone
  - 100 mm outer diameter without yoke (FRESCA-II Aperture)
  - Build for Lorentz forces when operated in 13 T background field
  - Field quality (few units)

- Conductor Requirements (set at EUCARD-II Kickoff meeting)
  - For YBCO: 600 A/mm^2 for single tape, in perpendicular applied field of 20 T, at 4.2 K
  - For BSCCO: 600 A/mm^2 for single strand in applied field of 20 T, at 4.2 K
  - (for this work scaled critical surfaces to these values)

YBCO Insert

Design and Considerations



YBCO Coated Conductor

Angle-Dependent U(I) Measurements of HTS Coated Conductors

P. M. Leys, M. Klaeser, F. Schleissinger, and T. Schneider

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 23, NO. 3, JUNE 2013

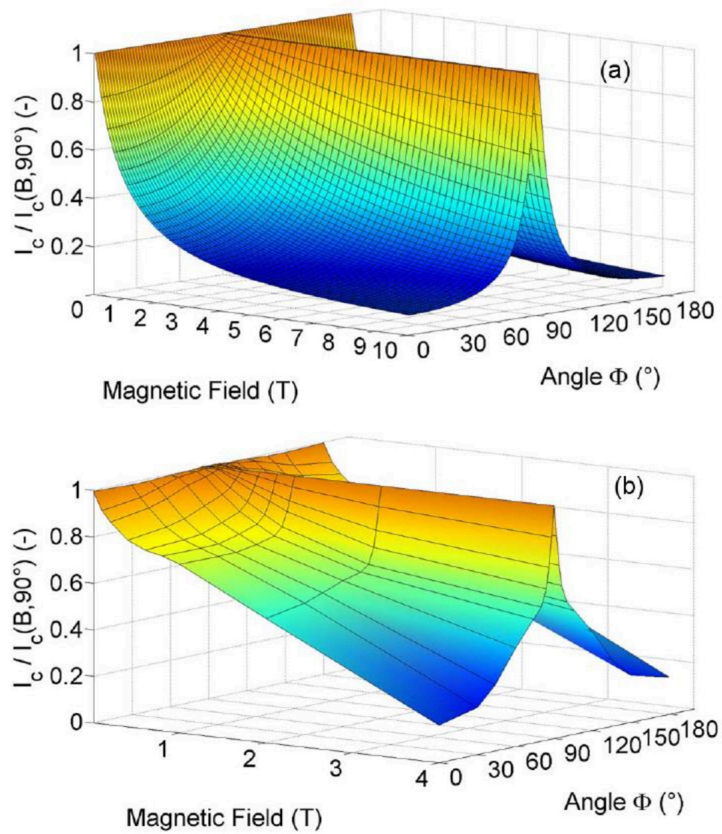
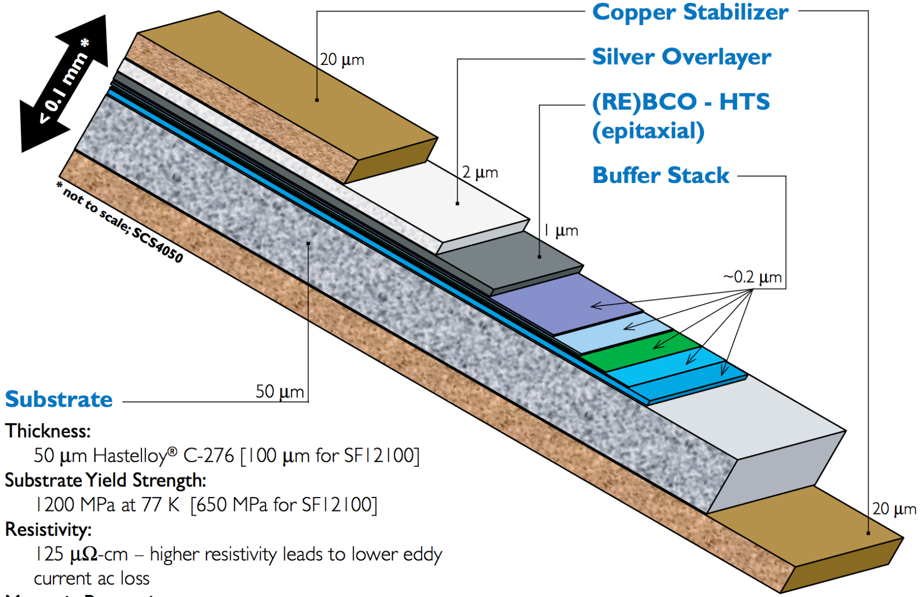


Fig. 9. Normalized $I_c(B,\Phi)/I_{c0}(90°,B)$ surface at (a) 4.2 K and (b) 77 K with steel laminate.



Substrate

Thickness:
50 μm Hastelloy® C-276 [100 μm for SF12100]
Substrate Yield Strength:
1200 MPa at 77 K [650 MPa for SF12100]
Resistivity:
125 μΩ-cm – higher resistivity leads to lower eddy current ac loss
Magnetic Properties:
non-magnetic, leads to lower ferromagnetic ac loss

- Comes in tape form
- Large dependence on incident magnetic field angle
- Factor of 5 difference between parallel and perpendicular
- Potential for very large critical current densities
- How to exploit?

Roebel Cable

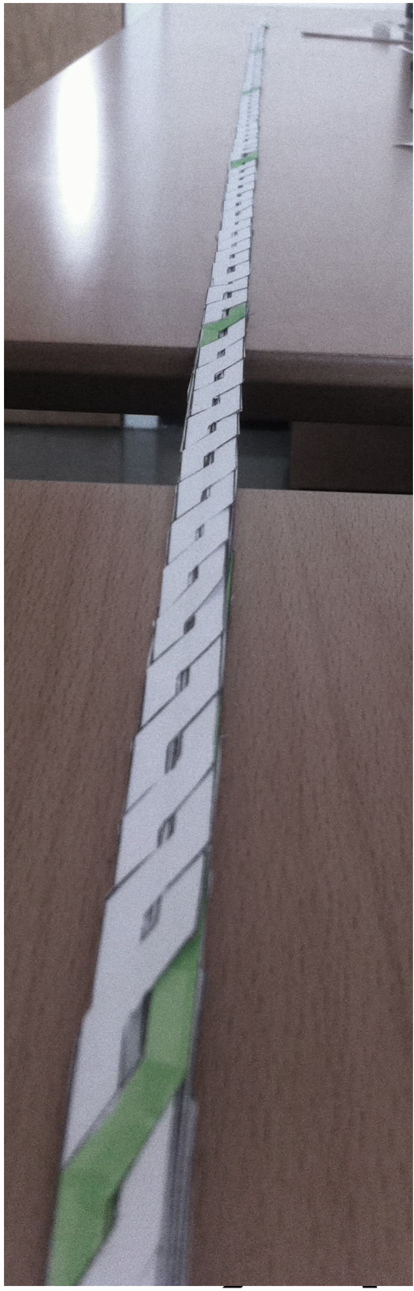
KIT

General Cable

- Fully Transposed Cable - High Compaction factor - High Je (see talk A. Ballarino and J. Fleiter)
- Also only cable type that has exploitable angle dependence.
- Different designs by Karlsruhe Institute of Technology (KIT) and General Cable (GC)
- 12 mm wide (current maximum tape width)
- Thickness and twist pitch depend on number of tapes
- Tapes can be doubled to get to higher current without increasing the twist pitch (KIT)
- Assumed minimal bending radii: ~11 mm (source goldacker) in softway and ~2 m (!?) in hardway (dummy cable)

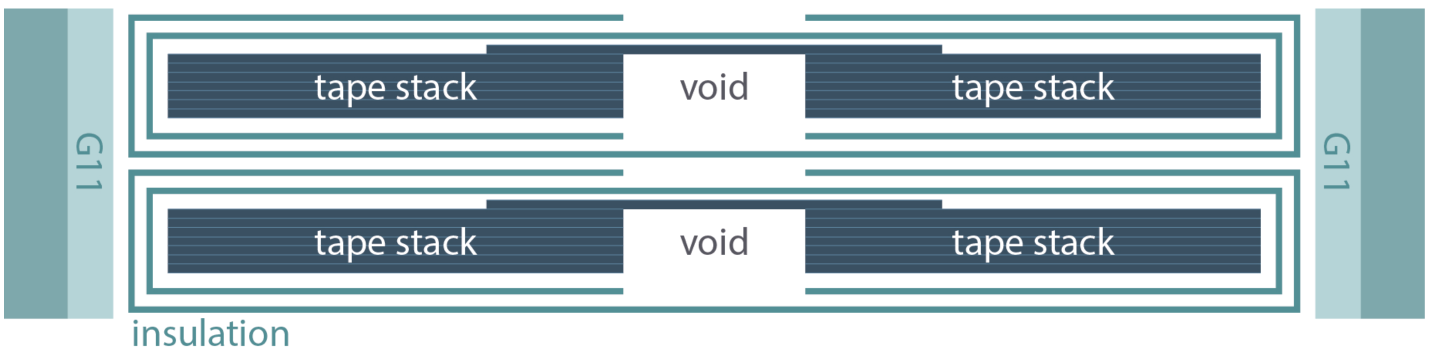
Dummy Cable

- First made paper cable which unfortunately has not survived kick-off meeting (=
- Several, 3 m long, GC layout, stainless steel dummy cables were produced
  - Water-Jet Cutting gives sharp ridges on sides and buckled strands (too violent)
  - Chemical Etching nice and clean and thus better method
- Near Future:
  - Chemical etched KIT layout dummy cable
  - 150 MPa pressure test with fuji paper (and copper pressure spreaders)
  - Multistack measurement of Modulus and breakdown voltage for various insulation schemes
  - (Creation of bend test setup)



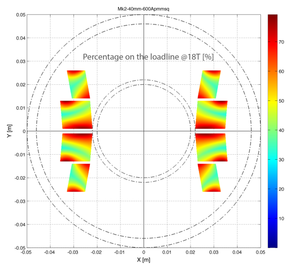
Insulation Tests

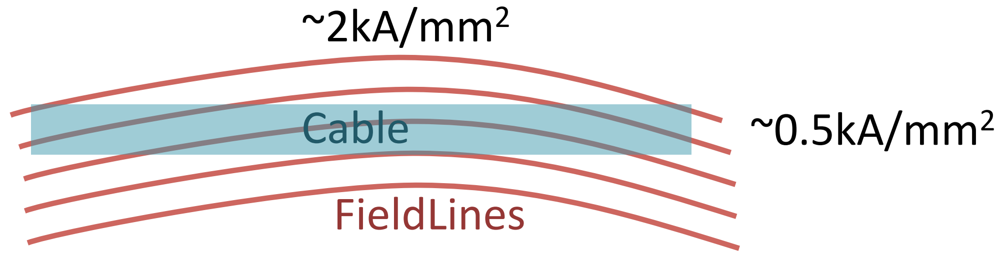
- Insulation provides means to stabilize cable during winding
- Insulation schemes
  - C-wrap (single/double)
  - 50% overlap standard insulation
  - Other?
- Tried to put some kapton insulation on GC dummy cable by hand (so far failed, the cable moves too much)
- Will try to pre-fold kapton sheet in C-shape before putting it on next time
  - Any other ideas?
- Spreading out stress with copper strip? (to be tested at 150 MPa in press)
- Specialized tooling required



Current Density Calculation

- Suppose we have a straight YBCO cable inside a curved magnetic field



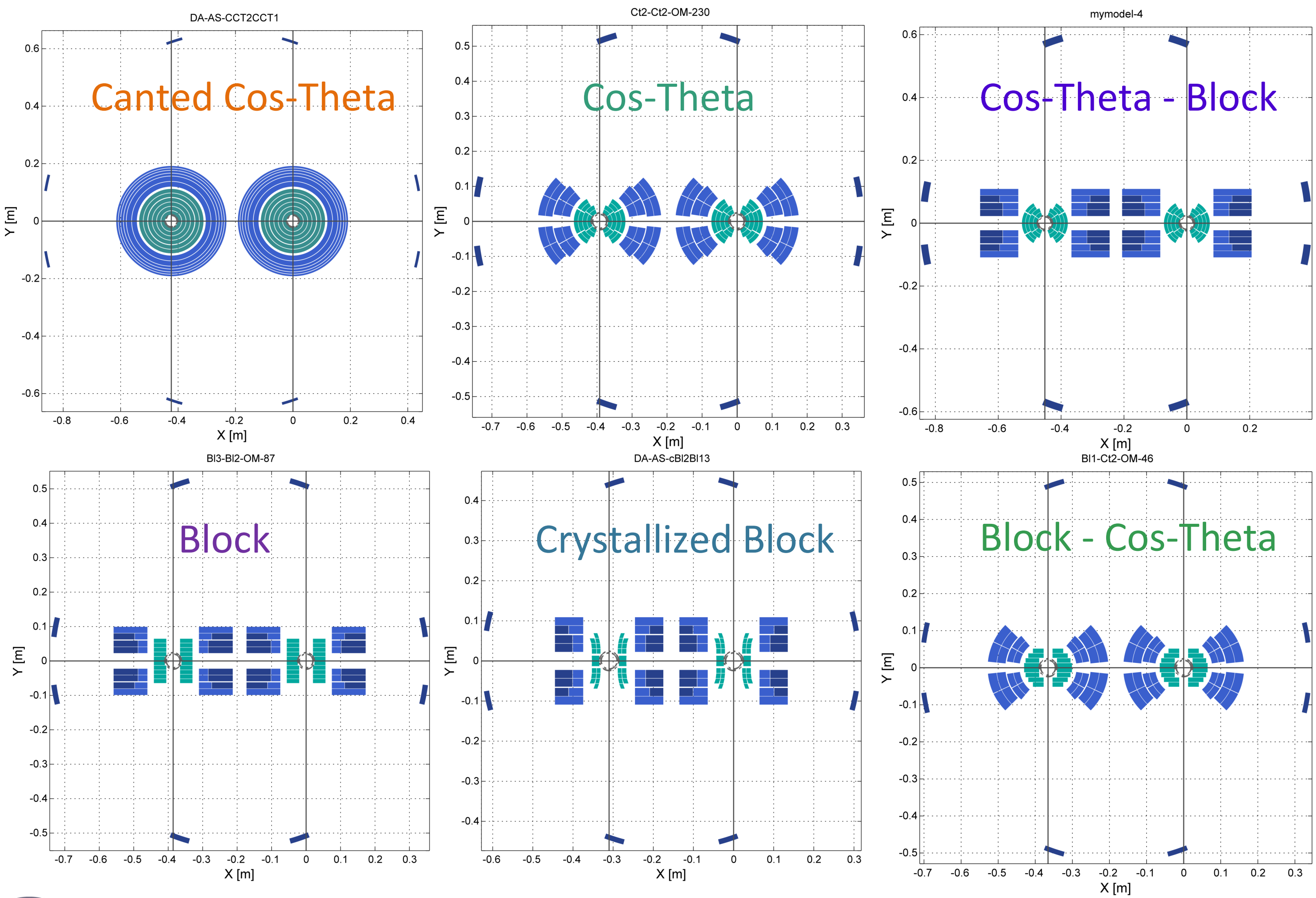


- At the center of the cable the field angle is low thus Jc is high
- At the edges of the cable the field angle is high thus Jc is low

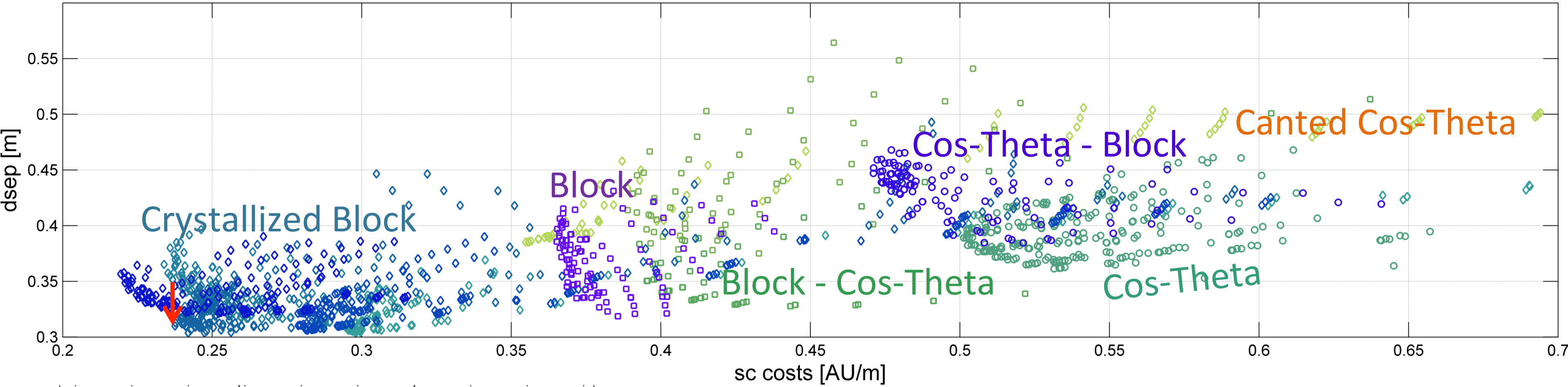
- How to determine the critical current density of the cable?
  - Method 1: Take lowest value at edges Jc1. (safe option)
  - Method 3: Take average current density over tape (i.e. one side of cable) Jc3. Assuming the occurrence of current sharing in tapes.
  - Method 2: Integrate over cable and divide by surface area Jc2. Assuming there will be current sharing throughout the cable. (pushing tech. limits)
  - In reality will be somewhere in between 1 and 2
  - To be determined experimentally (non evident)

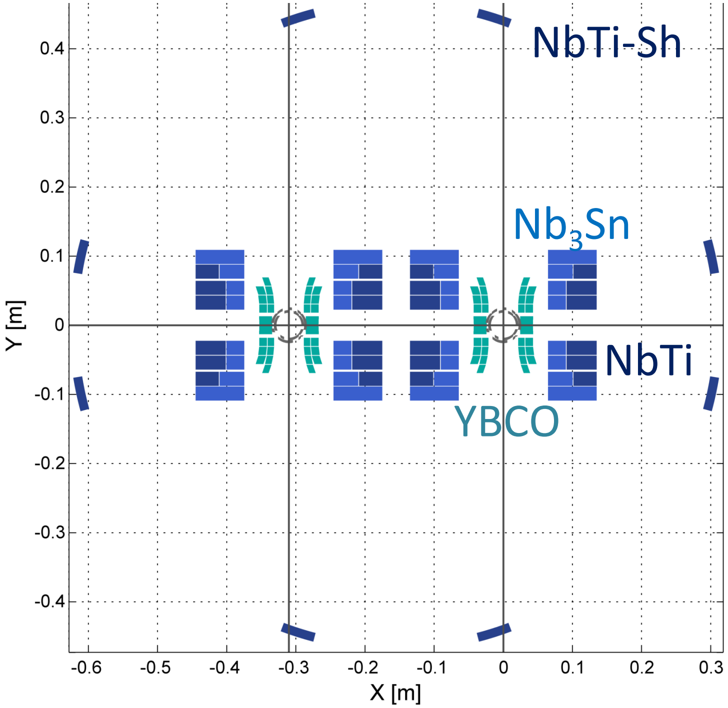
PSCO – YBCO 2D Layout Comparison

- PHD. JvN
- Created many 2D coil layouts here shown is just a selection (1000)
- YBCO – Nb3Sn – NbTi



PSCO – YBCO 2D Layout Comparison



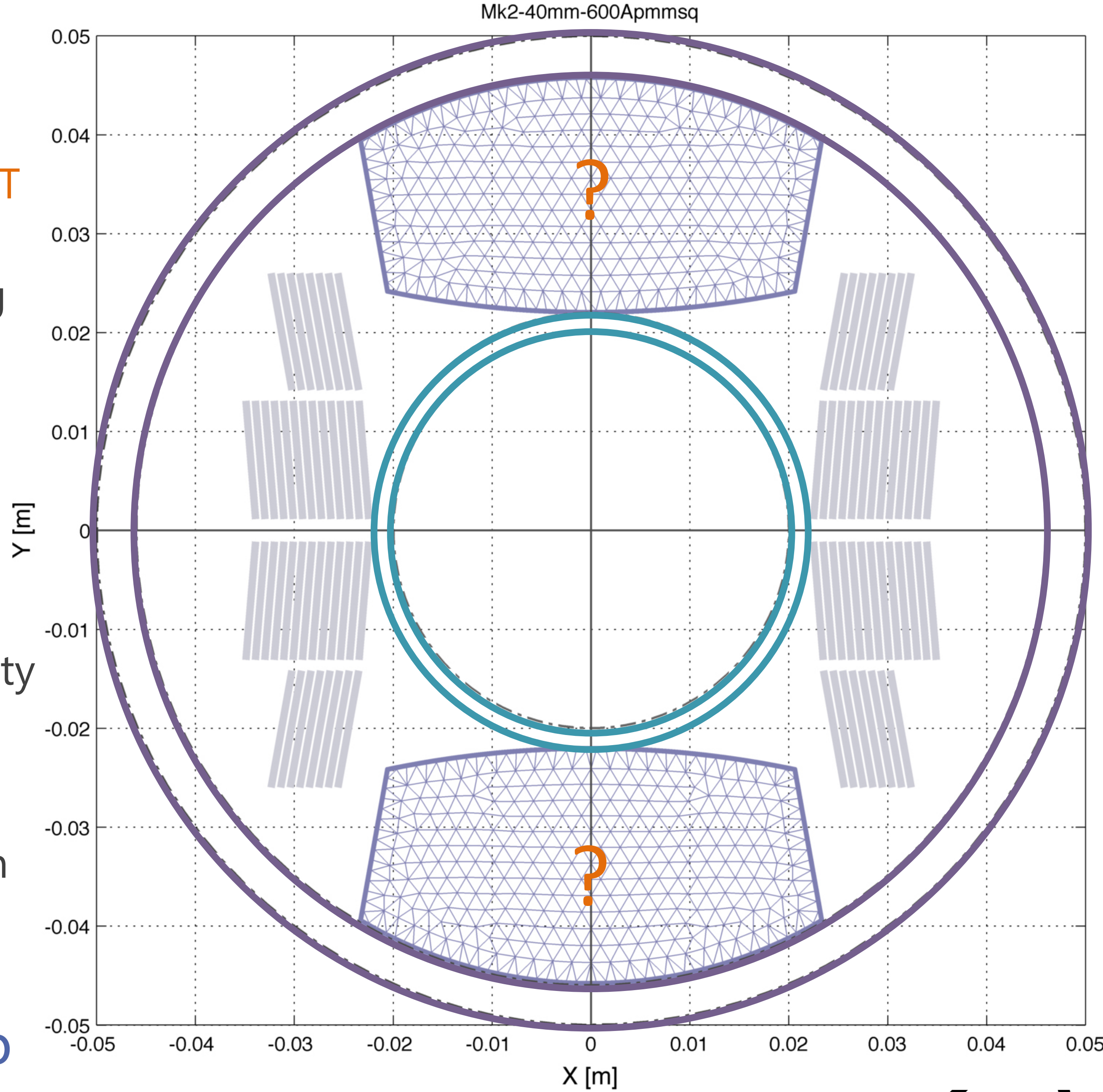


Crystalized Block

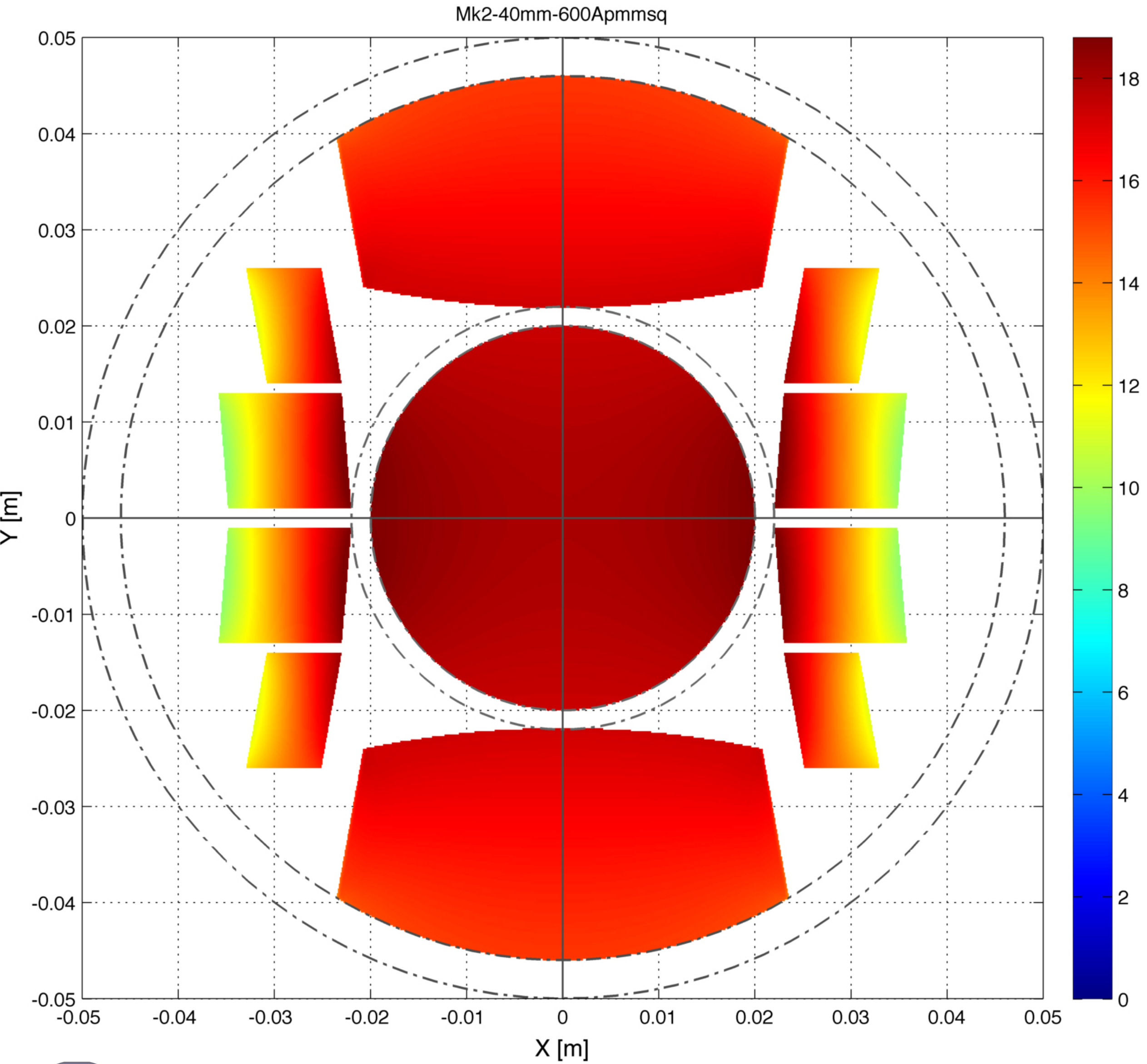
- Blocks are sheared to optimize field angle
- Efficient grading feasible
- Good field angle on YBCO (~8 deg @ 18 T)
- High current density in insert ~600 A/mm^2
- Compact layout with relatively low stored energy
- Used method 1 for current density calculation

Conceptual 2D Coil Layout

- Use PSCO 2D code
- Generate 5T (including iron poles) inside background field of 13T
- 2 decks 12 mm cable
- 2 mm aperture spacing
- 4 mm support cylinder
- Optimize block angles
- Smooth layer-to-layer transition
- 80% on angular dependent loadline
- Calculate current density using safe method 1 (need more margin for coil ends anyways)
- 4 mm spacing between pole and blocks
- Low field quality req.

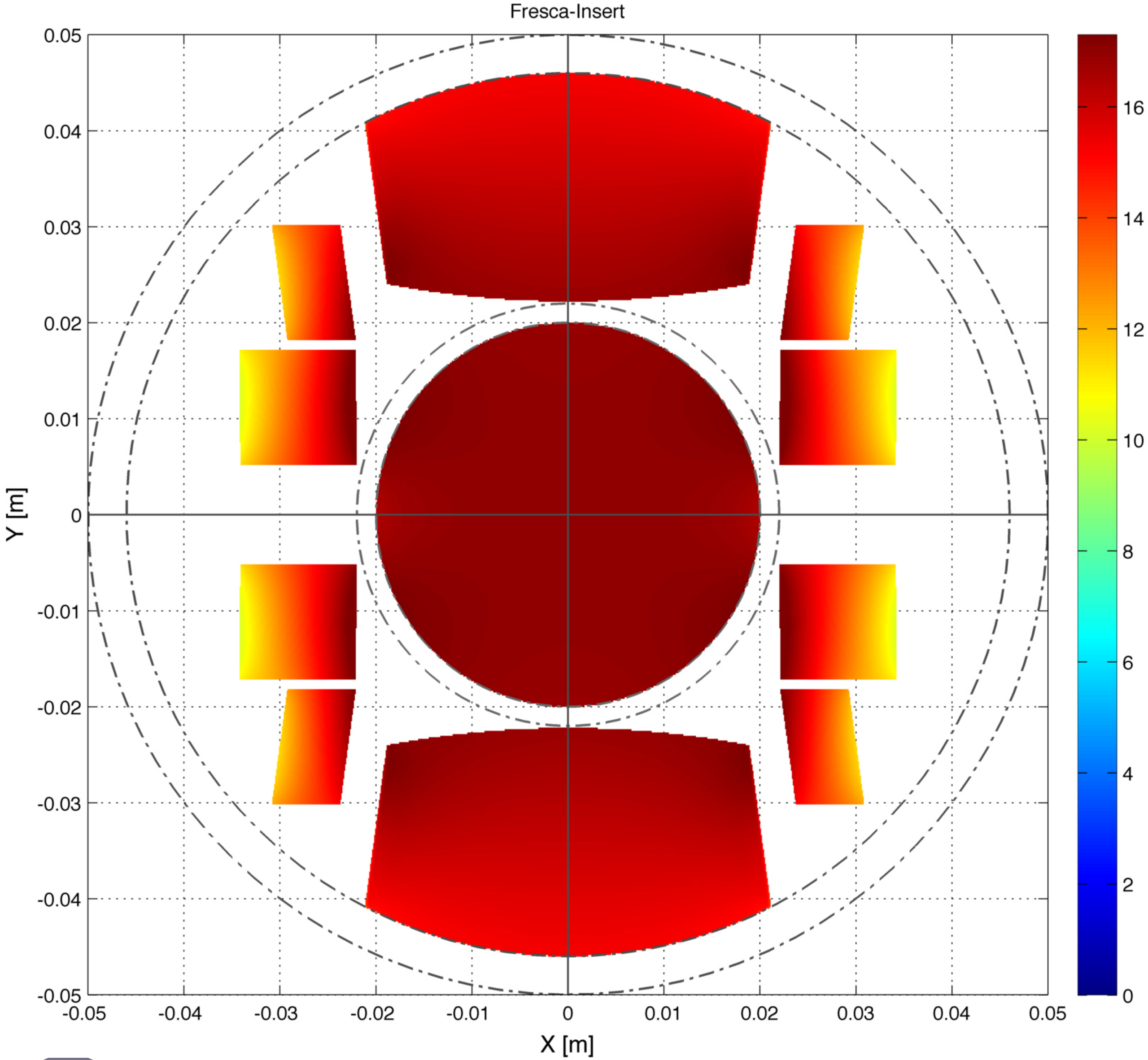


Magnetic Field Calculation



- Current density 780 A/mm²
- 13 T background field
- 18 T central field
- Field quality is pretty bad B_3 = ~250 units standalone

Field Quality Trade-Off

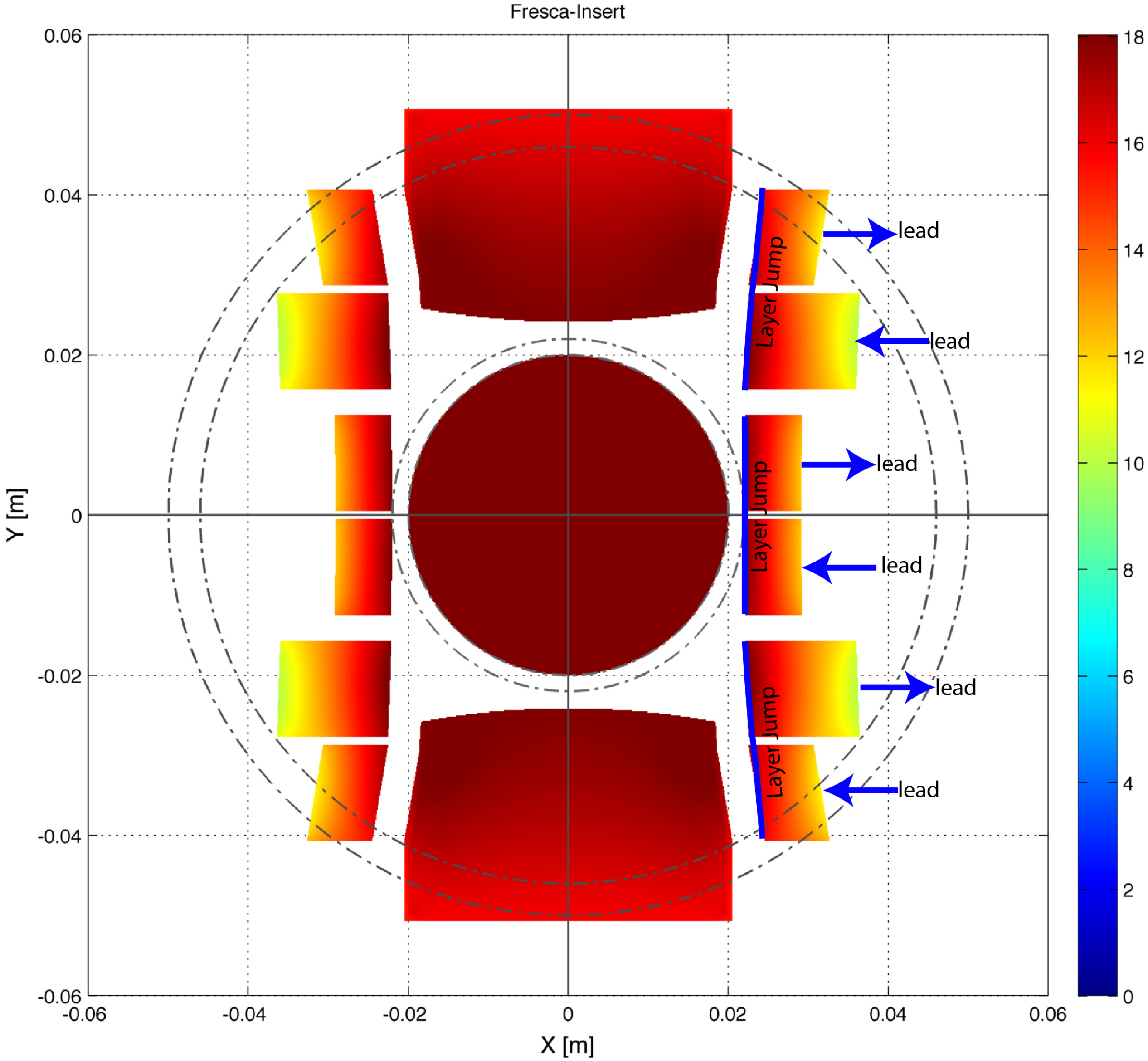


- If field quality is important
- Basic first order B_{cen3} Field quality can be attained by splitting coils
- This lowers attainable field in background
- And lowers margin for 5T standalone
- Stay within Fresca Aperture
- Shorter coil ends
- Higher order field quality requires more degrees of freedom
- I.e. More decks/blocks

TE Technology Department

CERN

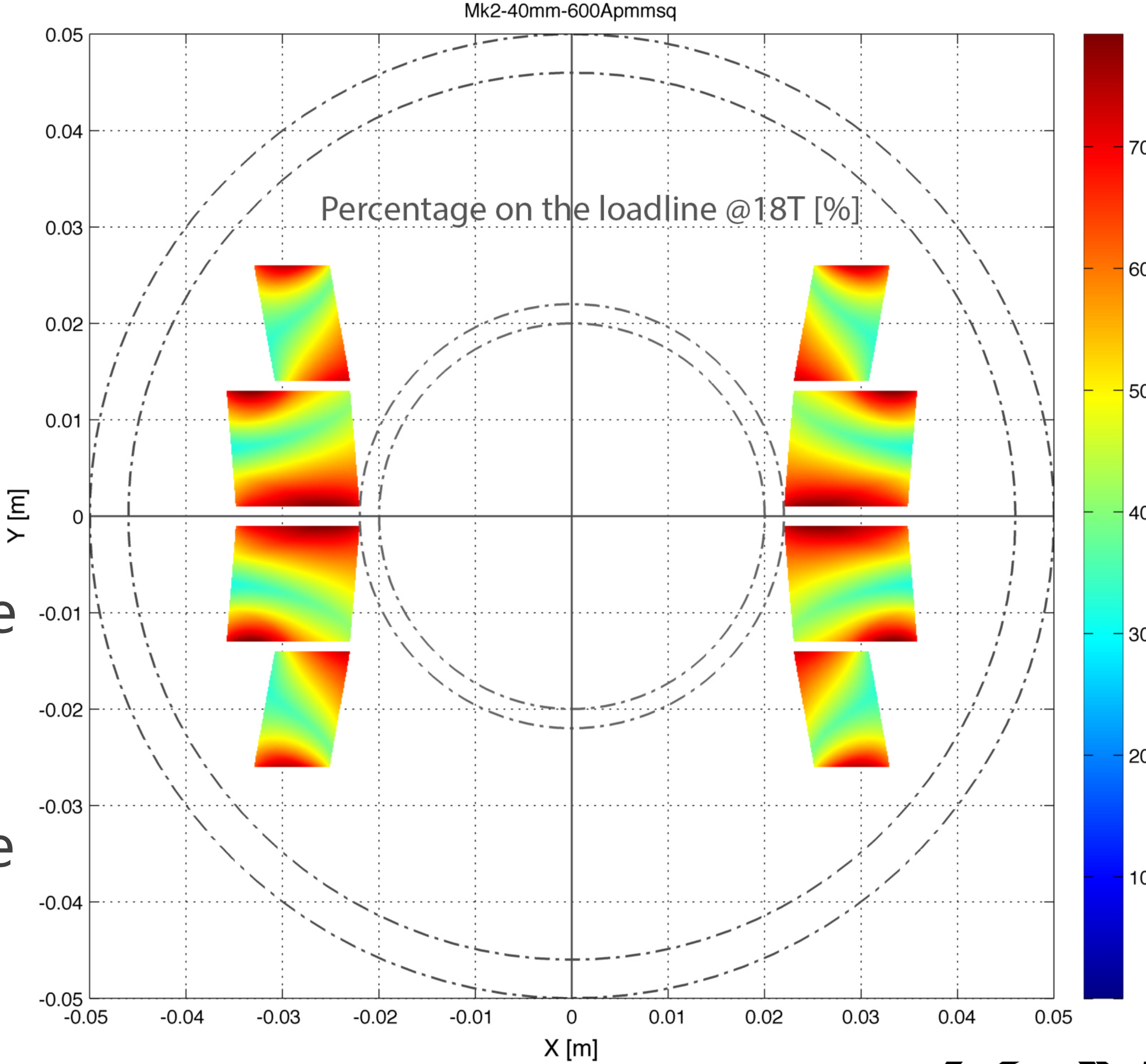
Field Quality Trade-Off



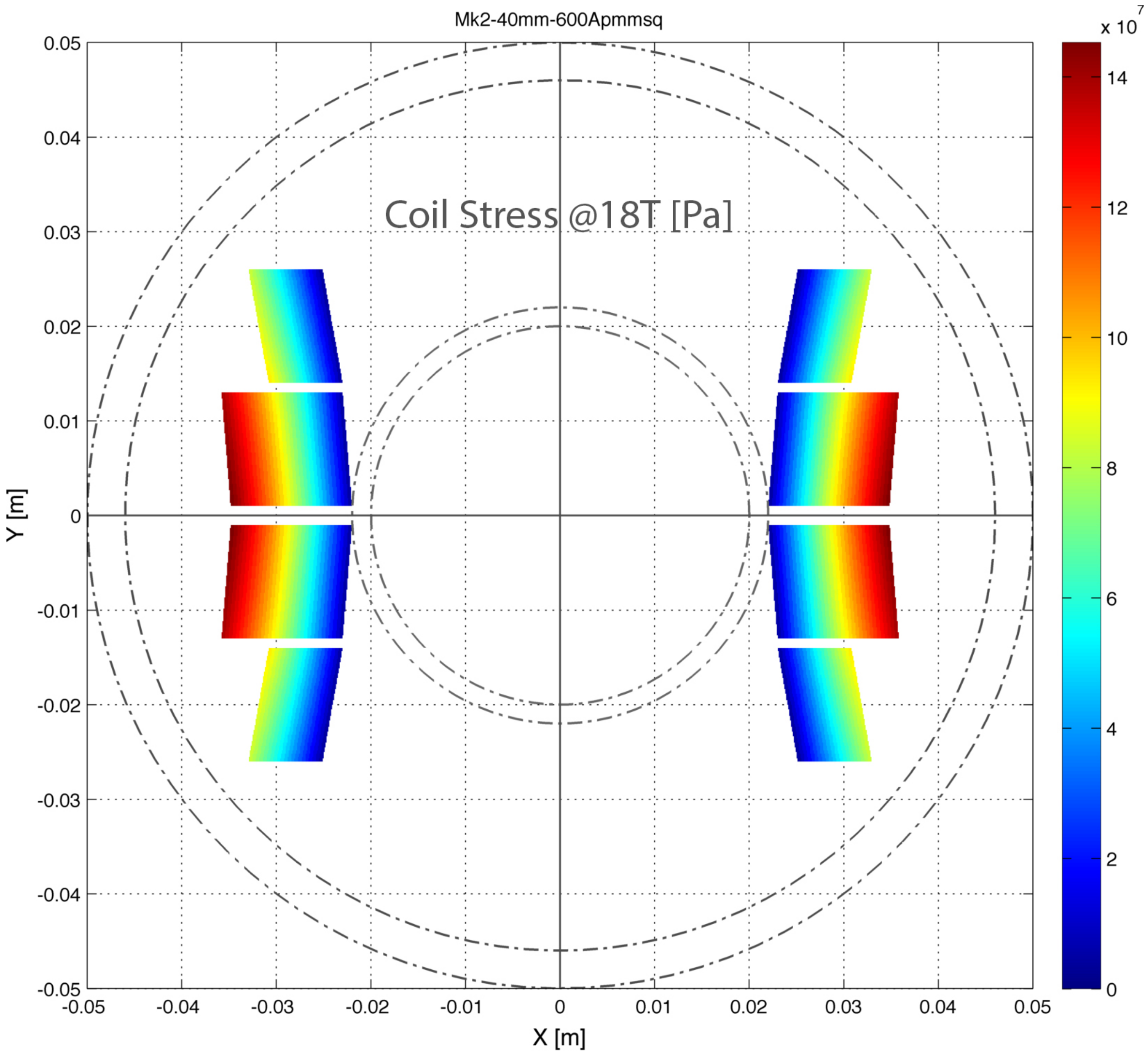
- Higher order field quality can be attained with an extra deck
- Loose Fresca-2 insert capability
- Field contribution at center is 5 T
- Harmonics $B_{cen3} = B_{cen5} = B_{cen7} = 0$
- More complex design.
- Nonlinearity iron poles?
- For now continuing with 2 deck design

Operating Point on Loadline

- In 13 T background field
- The operating point on the loadline should be calculated at each pixel
- Influence from field magnitude and angle
- Operating point varies between 30-80% in each cable
- Very different from classical magnets!



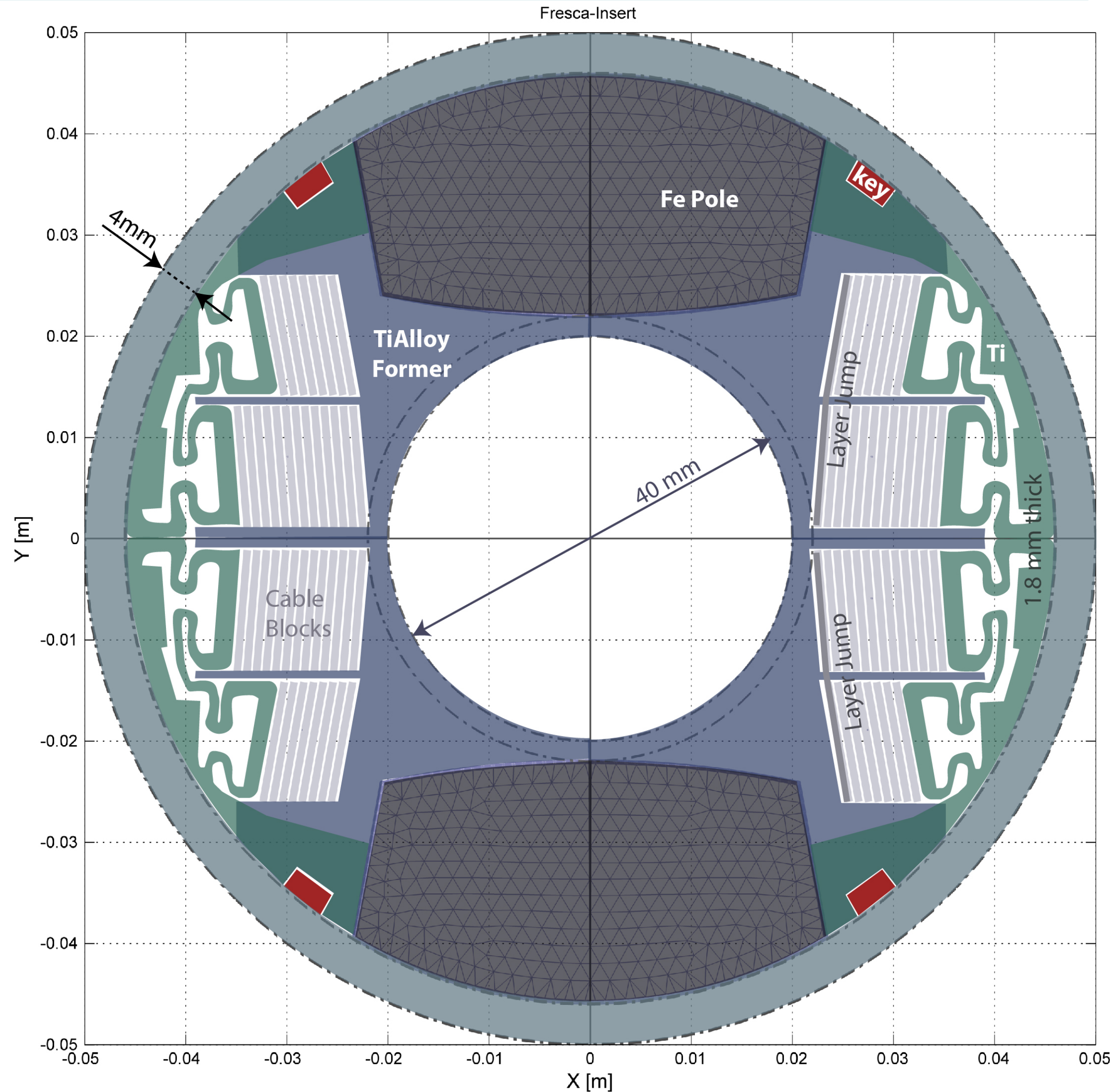
Stresses in the Coil



- In 13 T background field
- Coil stress when just starting to unload on inside
- 145 MPa on central blocks
- 90 MPa on wing blocks
- Need pre-stress to prevent blocks from unloading

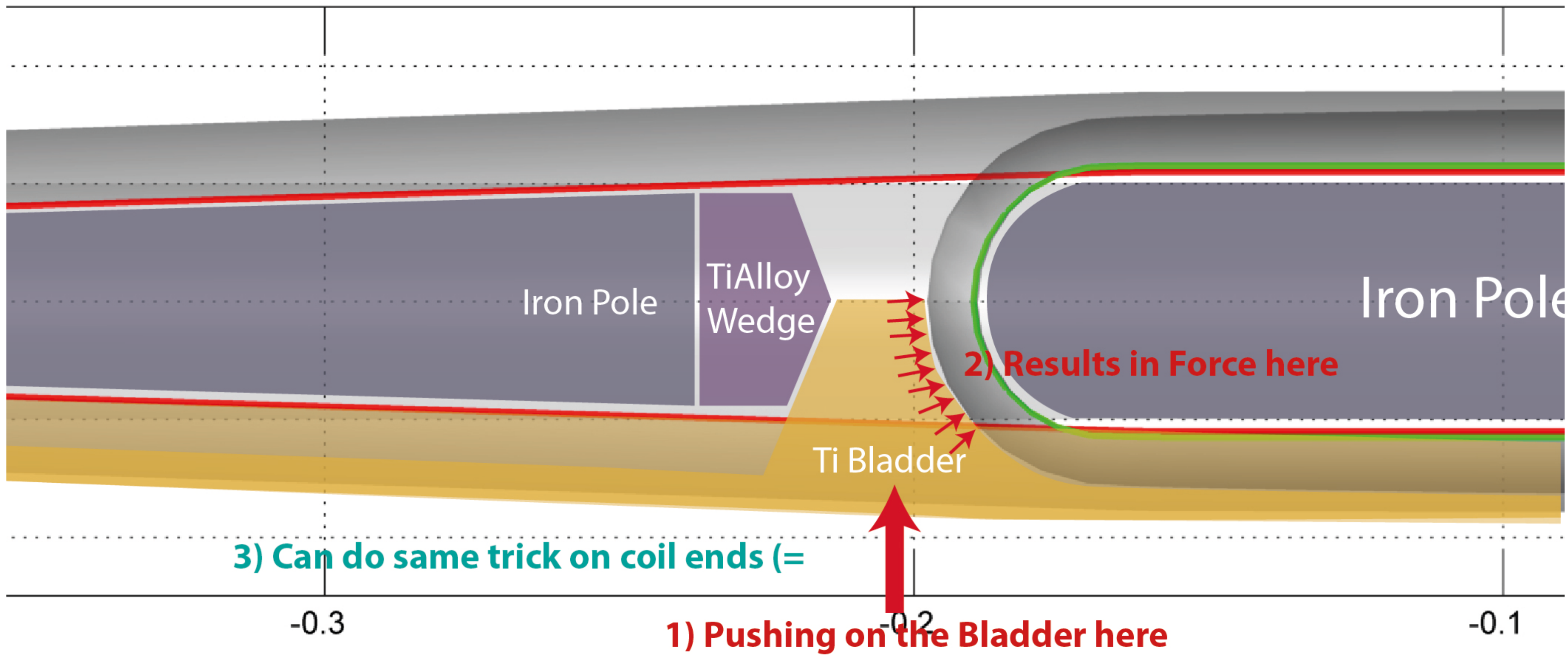
Bladder Concept

- Use bladders all around coils to apply and maintain pre-stress
- Pump bladders with glass filled epoxy or liquid metal (ask Vladimir)
- Including the coil ends
- Need 150 MPa including cooldown
- Bladders and former can be 3D-printed in titanium alloy using laser sintering
- Initial sponginess is taken out by pressing bladder onto coils after which it can be locked with key
- Still need to optimize bladder 2D layout

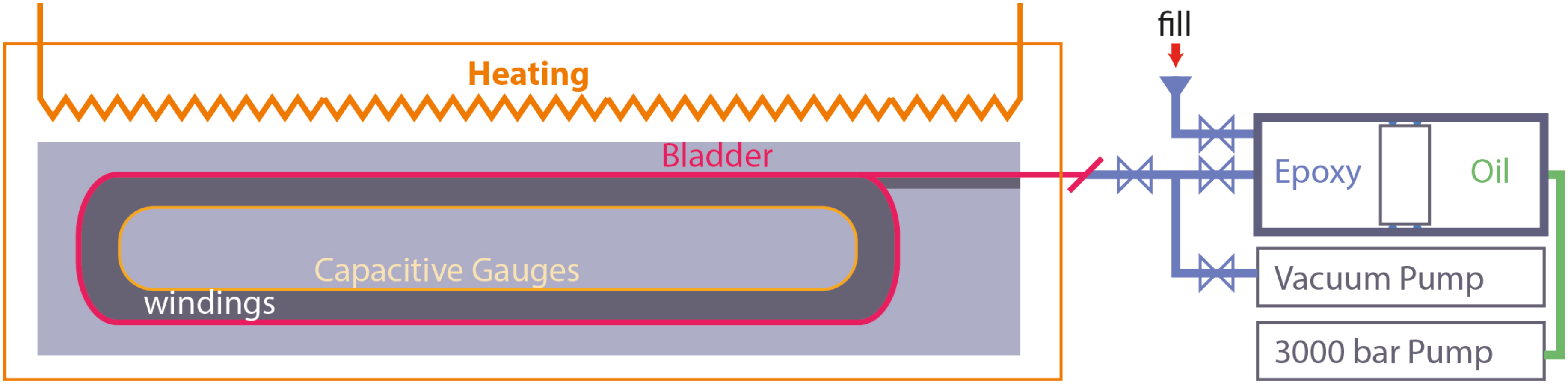


Bladder Wedge Concept

- At coil ends wedge shape could provide means to lock bladder in place



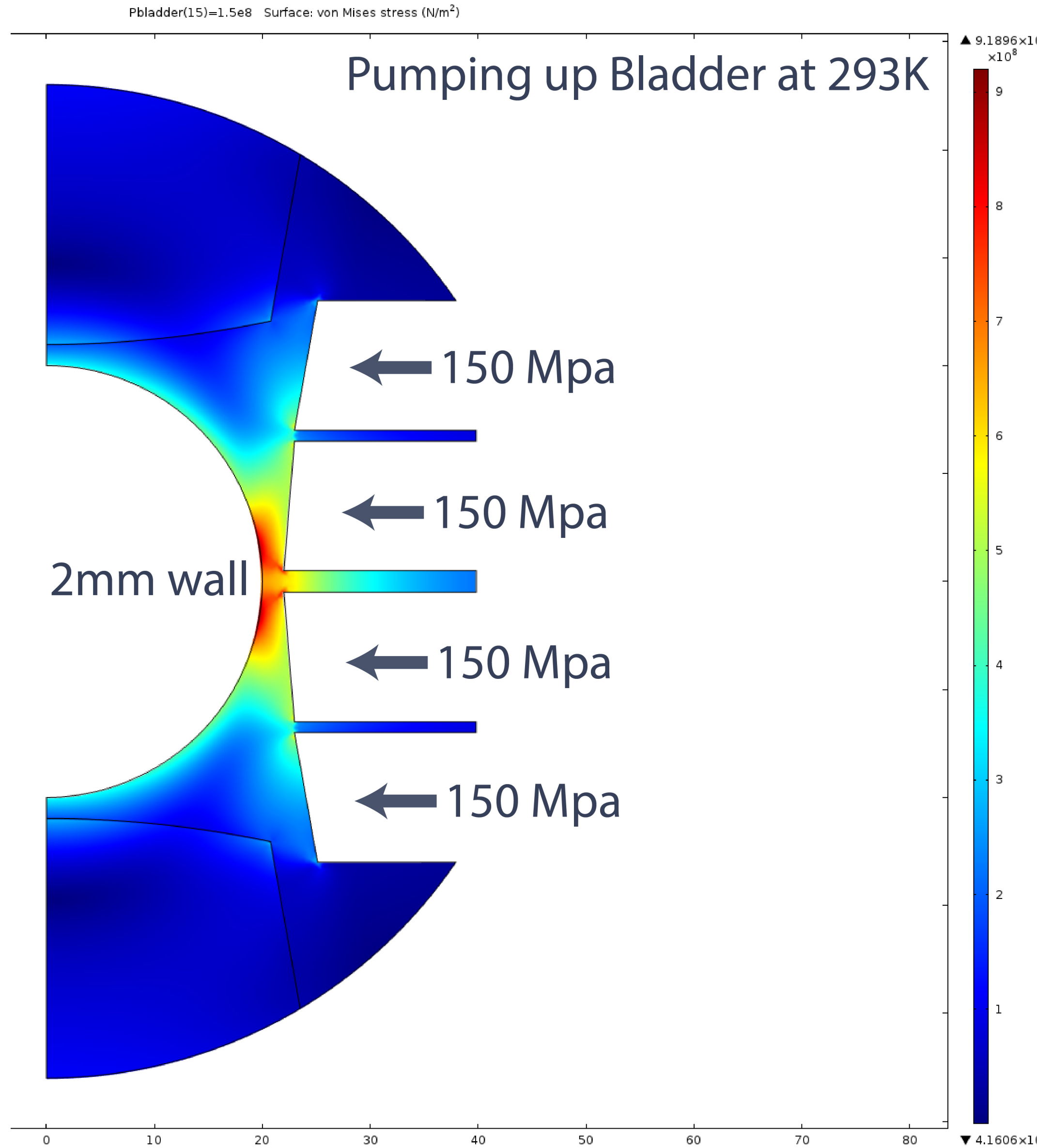
Bladder Concept



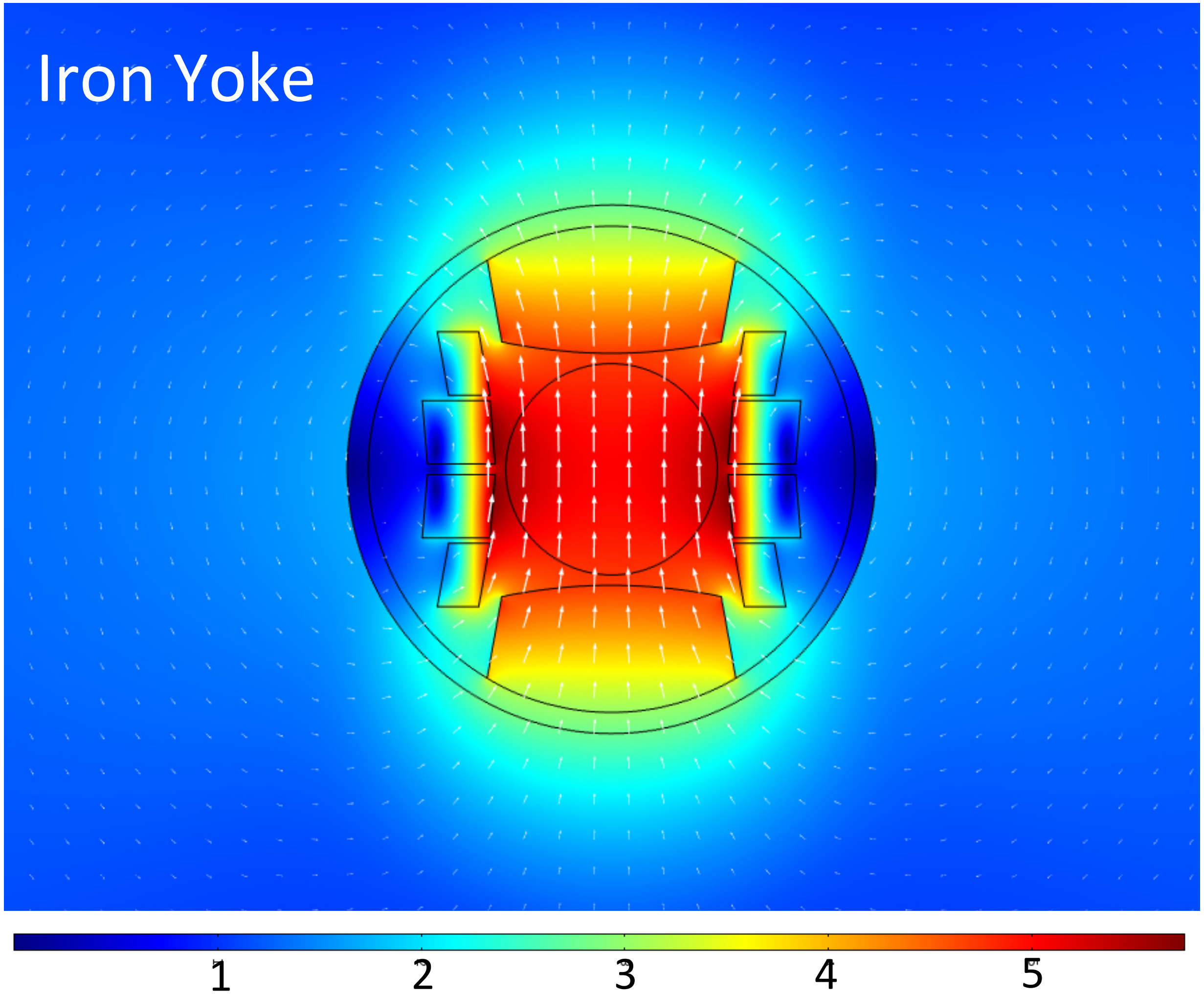
- Used before with woods metal
- Can use CERN 3000 bar = 300 MPa handpump to get pressure
- Use piston to transfer pressure to working fluid
- Will need to vacuum the bladder initially to ensure no air gets trapped inside
- Use capacitive pressure sensor / strain gauges / optical fiber to monitor process

Stresses in Former

- Pumping up bladder at room temperature
- 150 MPa on all coil blocks
- Maximum former stress: 900 MPa
- Which is a bit on the high side
- Options: (?)
  1. Decrease bladder pressure and leave rest to thermal contraction
  2. Increase wall thickness



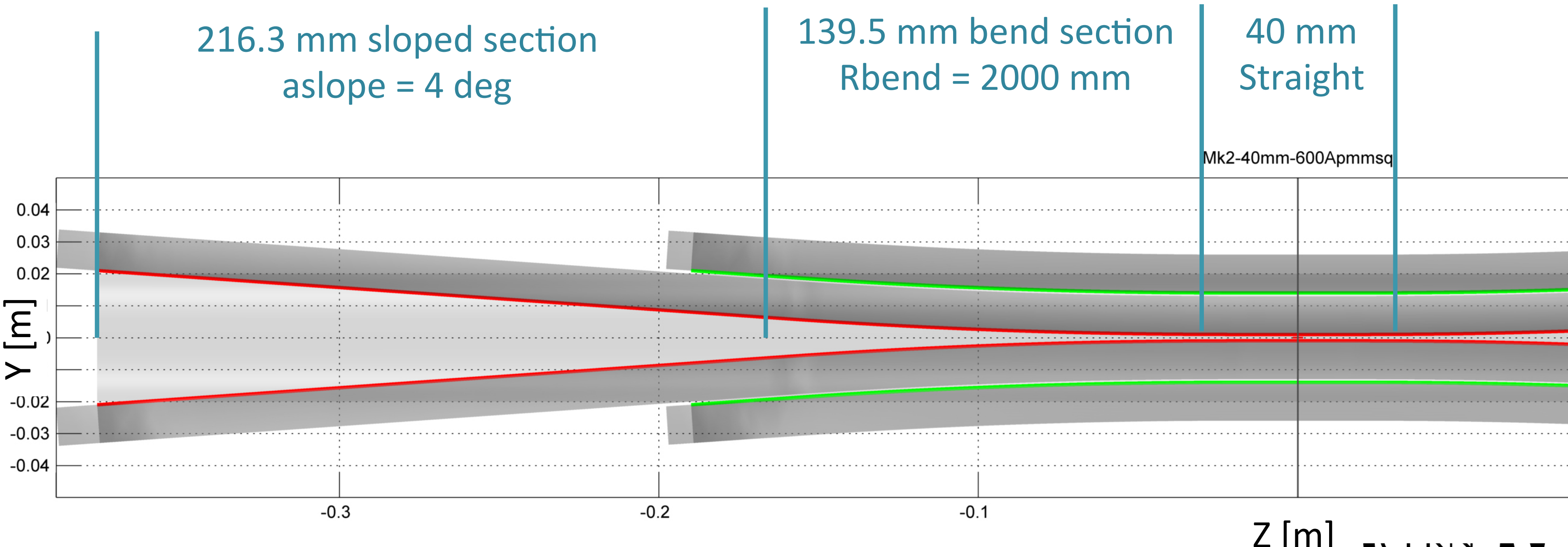
Standalone Operation



- Standalone add 100 mm iron Yoke
- Current density 550 A/mm^2
- Very good field angle in higher field region! (to our surprise)
- According to critical surface we get Jc1 >1200 A/mm^2 (=
- With this margin might be able to do first order field quality

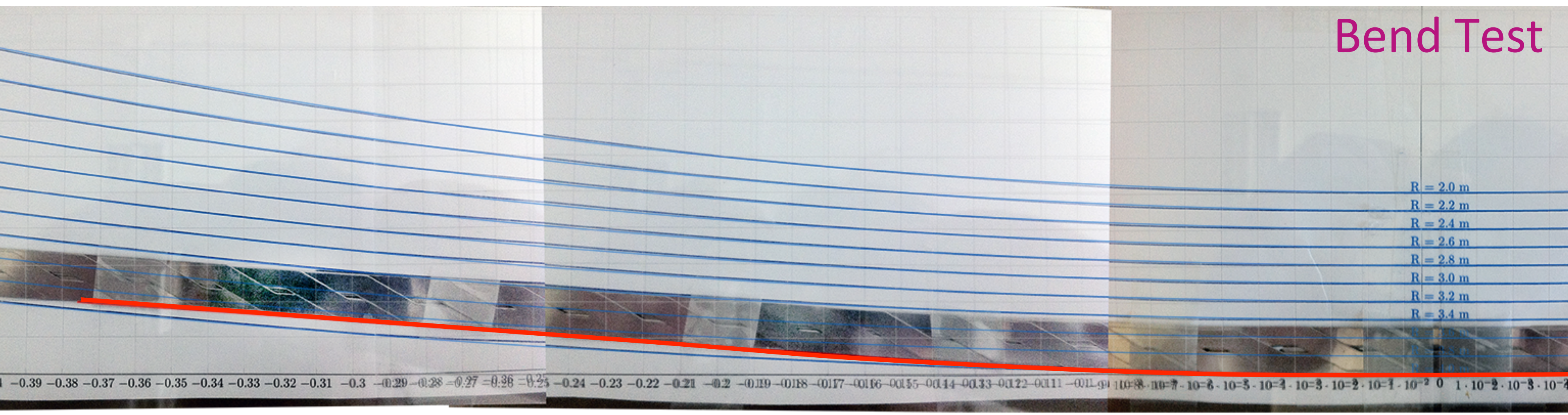
ZY-profile

- Started with designing side profile of coil
- 4 deg maximum allowed angle on ends
- 2000 mm bend radius (only over short length)
- 20 mm height gained (1 mm over beampipe)
- Second curve just follows first until 6 mm height gained



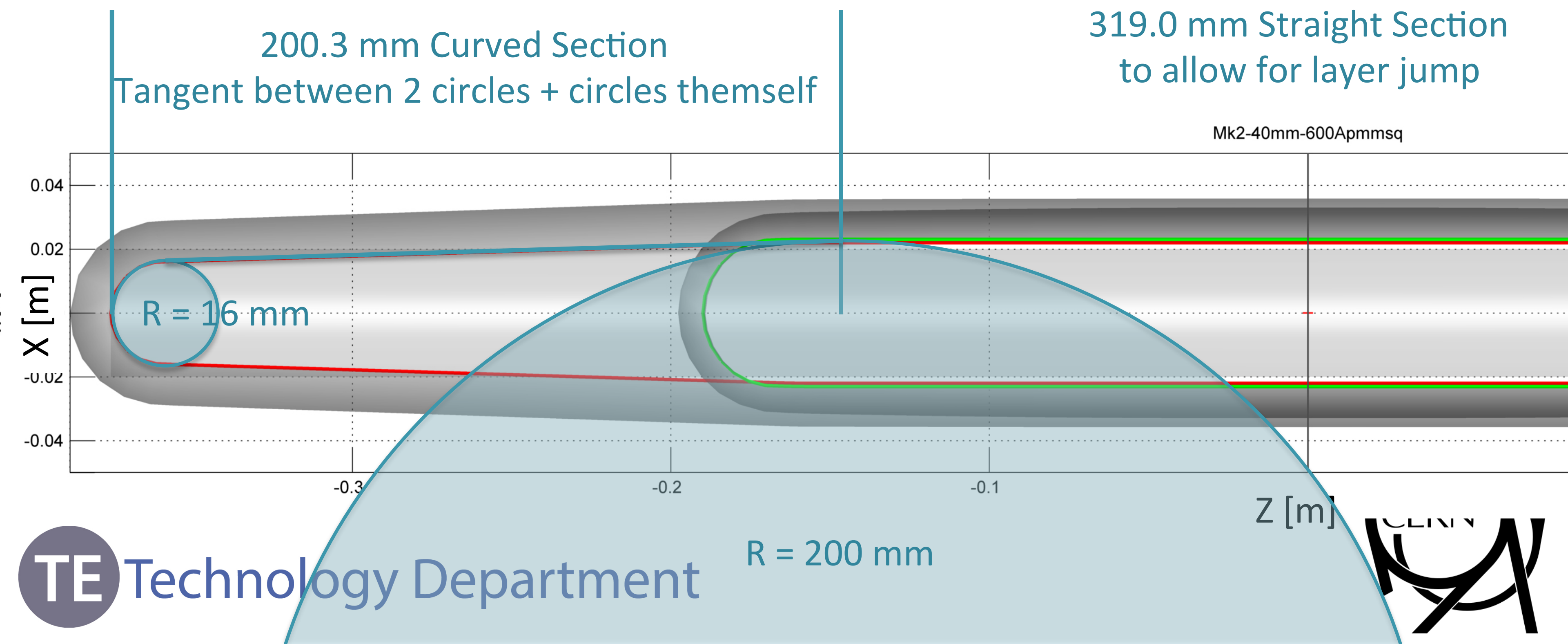
Basic Hardway bend test

- Test to see wether ZY-profile is realistic with cable
- Dummy cable pressed and locked between glass plate and table
- Assumed that superconducting properties start to degrade when tape starts to buckle
- At profile of coil design cable is okay (=
- Both radius and length of bending play role



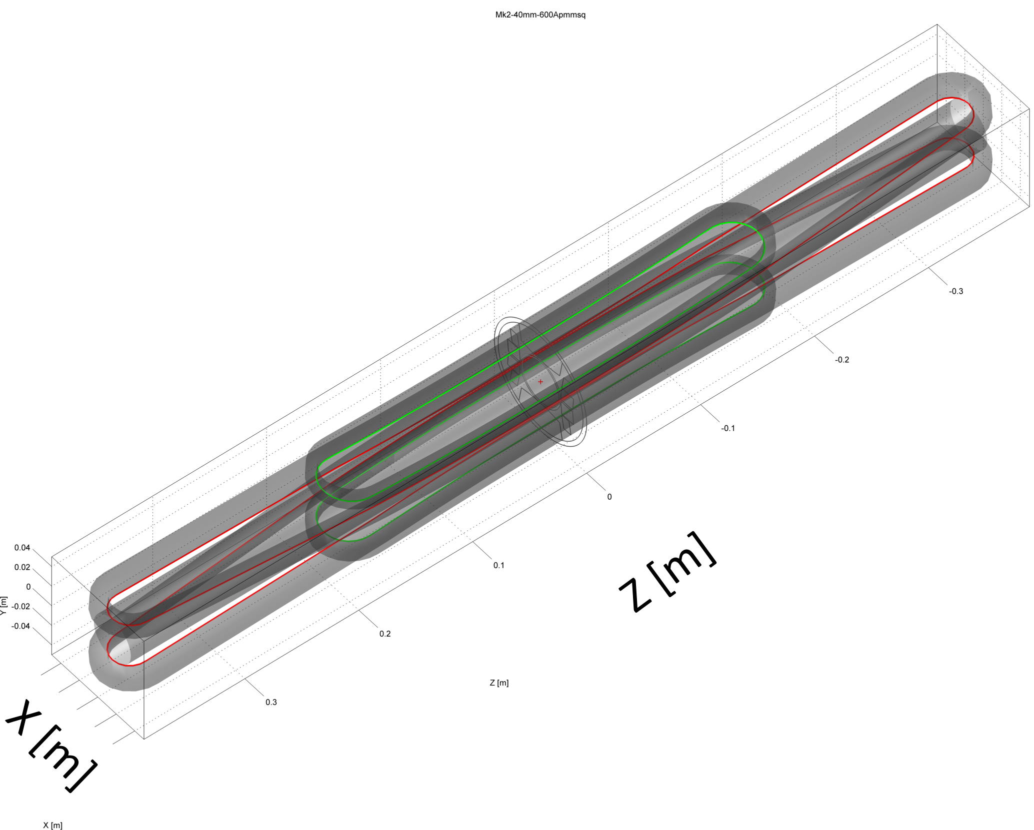
Conceptual 3D layout – ZX-profile

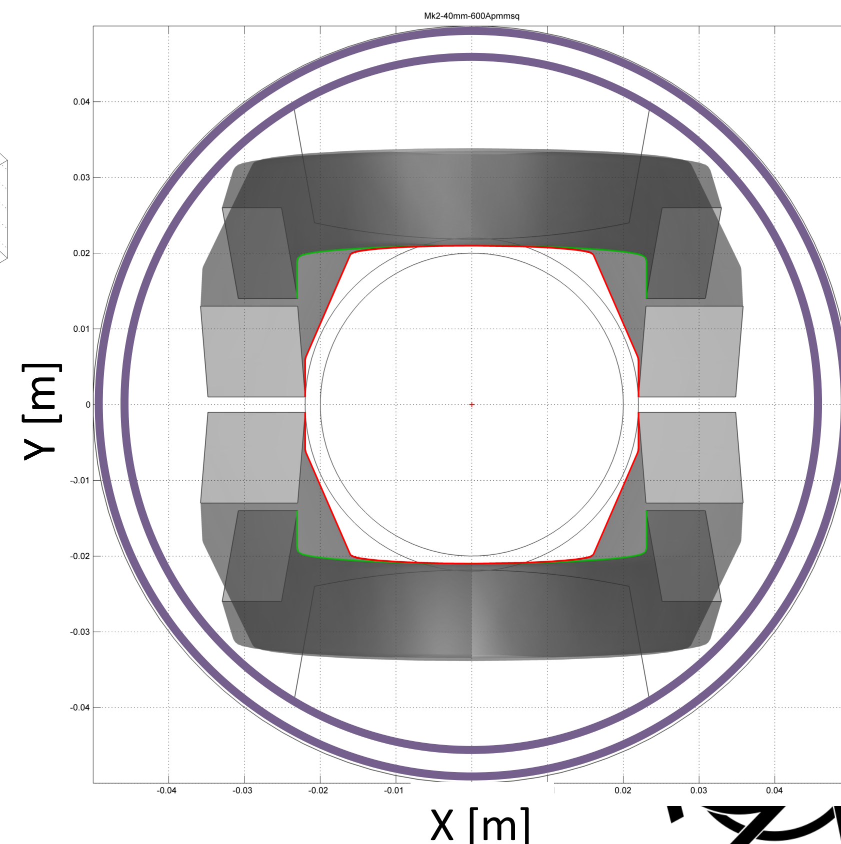
- When coils are moving in Y-direction they also need to move inward to fit inside support cylinder
- 16 mm cable bending radius at end (more than required)
- Used tangent between two circles to construct profile
- Deck 2 follows deck 1 as long as possible for smooth layer transition



Conceptual 3D layout – XY-profile

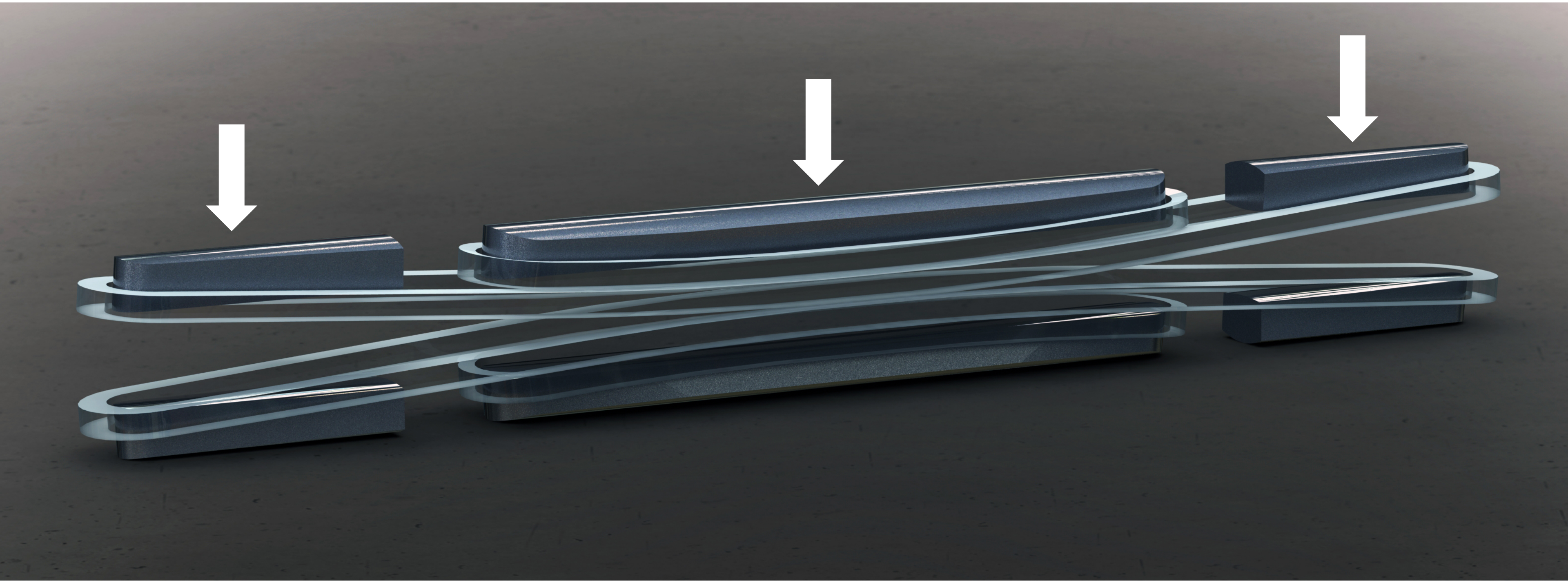
- XY-profile follows automatically from ZX and ZY profiles
- All curves are generated using script making it easier to add changes
- Block shear angle can be tuned everywhere (but is zero at coil ends)
- Bend radius not violated
- Support cylinder safely cleared (=
- Need to print plastic test former to see full 3D-compatability with cable





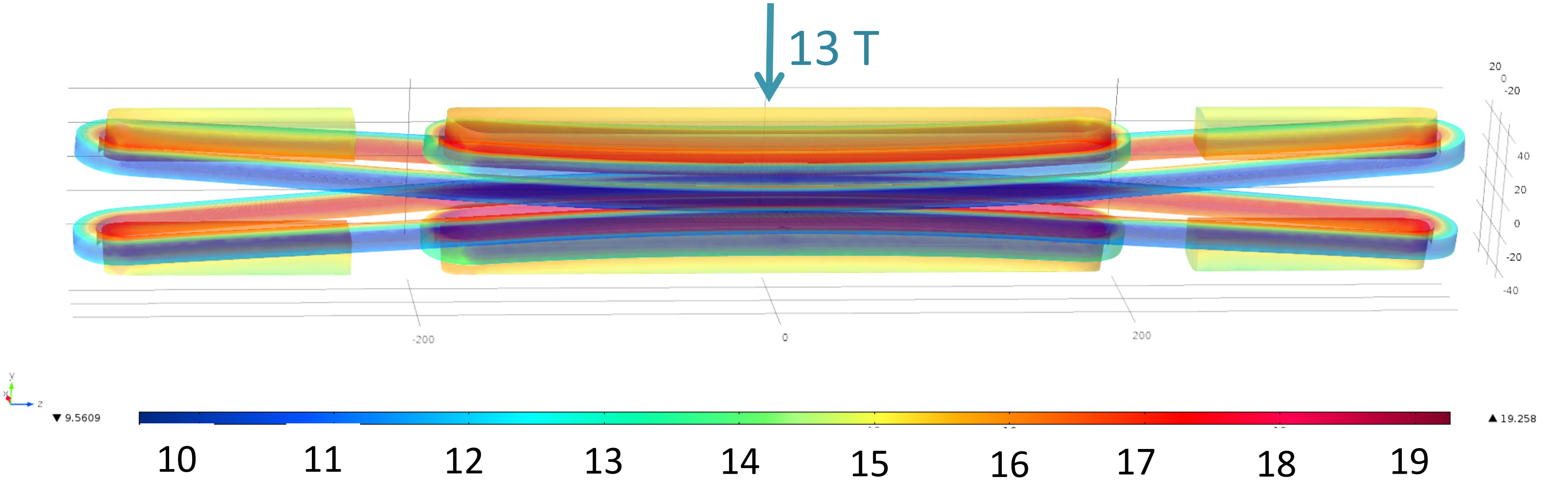
3D Model

- Added iron end-poles and central-poles to help guide the field.



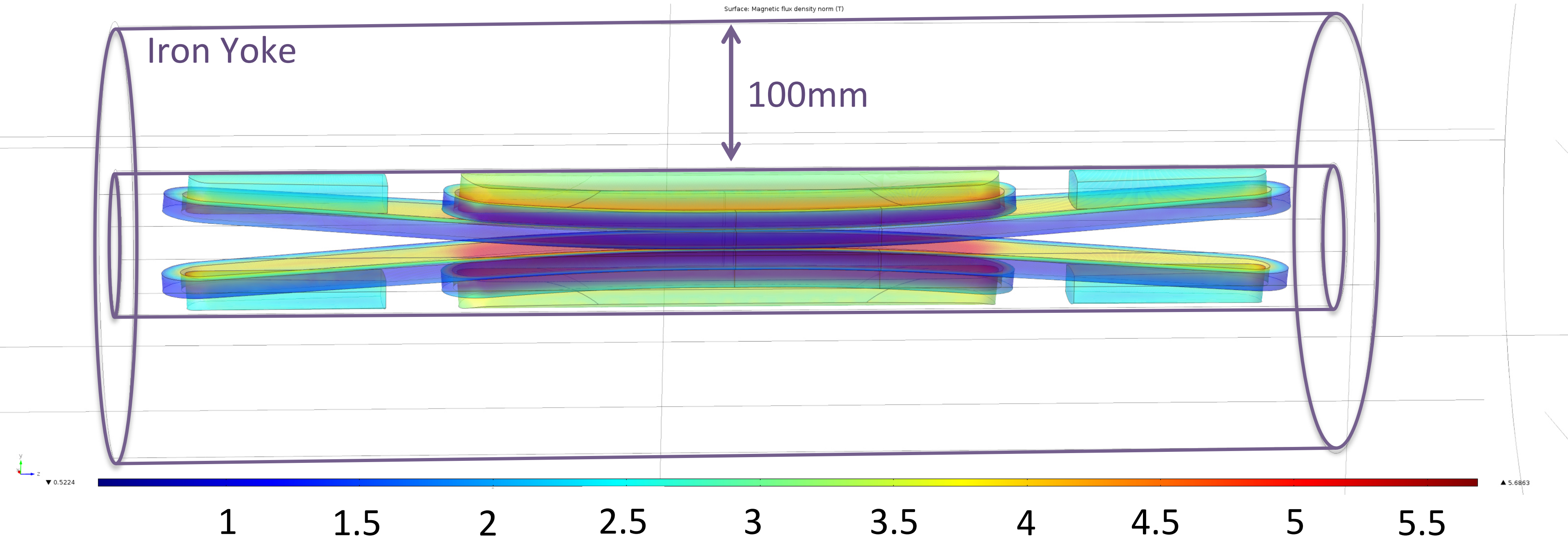
FEM 3D Field Calculation – bgfield

- Performed 3D field calculation using FEM In 13 T background field
- Current density 780 A/mm^2 (prediction from 2D model)
- Generated 3D FieldMap used to calculate angle dependent Jop

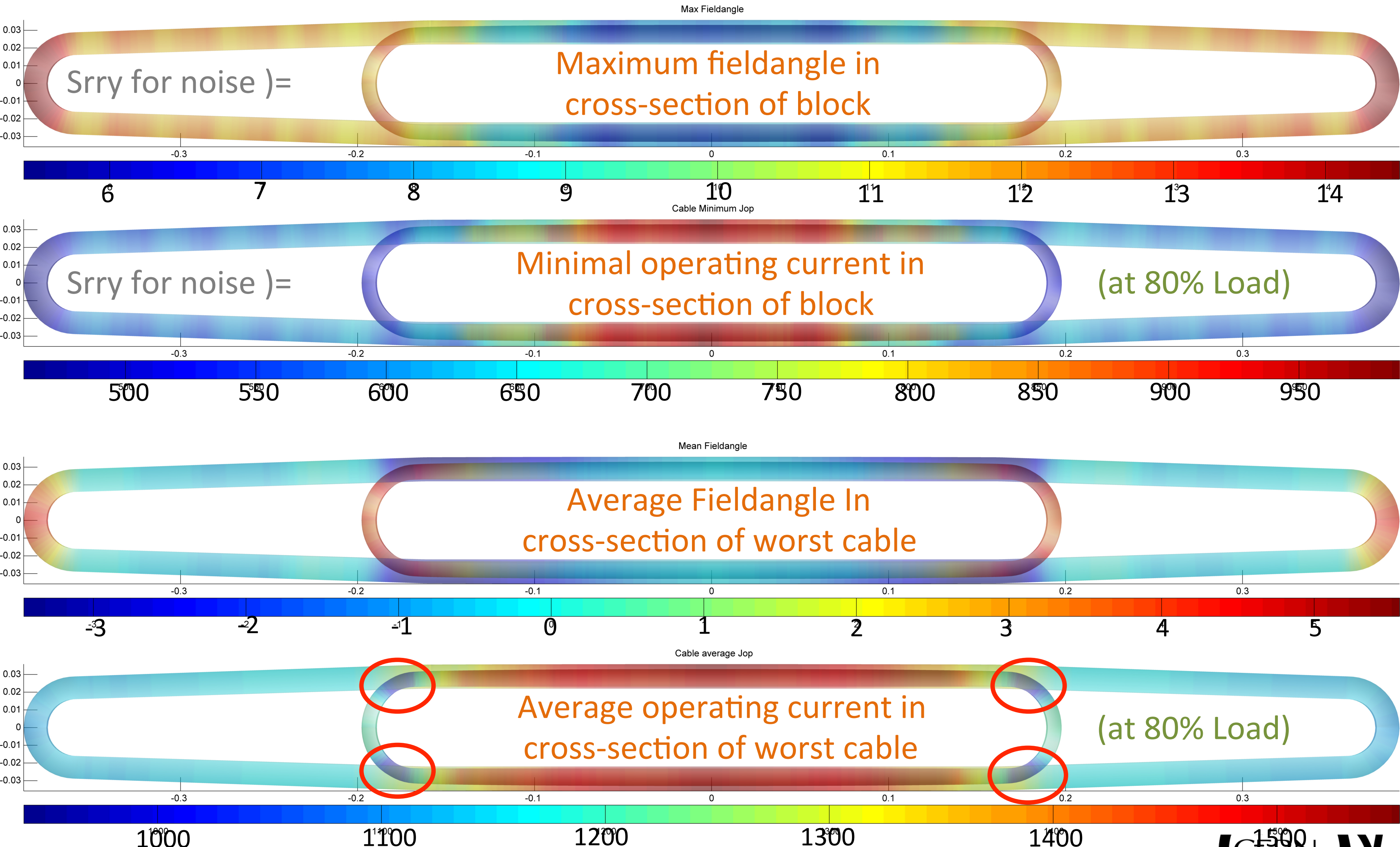


FEM 3D Field Calculation – Iron Yoke

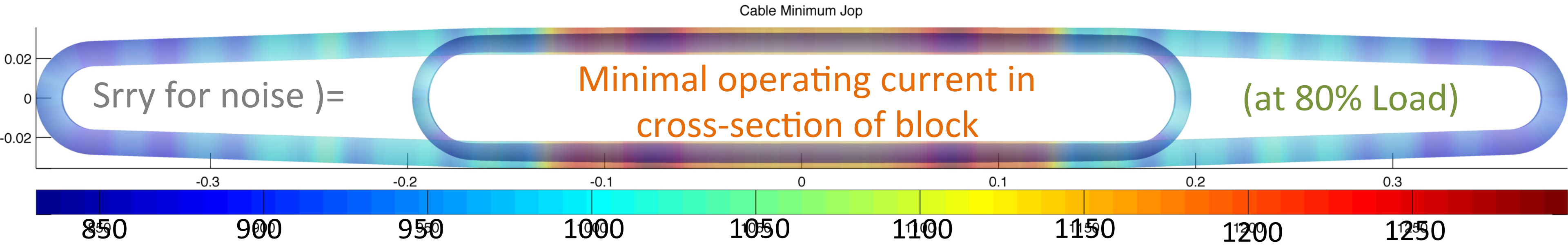
- Performed 3D field calculation using FEM In Standalone with iron yoke (100 mm thick)
- Current density 550 A/mm^2 (predicted from 2D model)
- Generated 3D FieldMap used to calculate angle dependent Jop

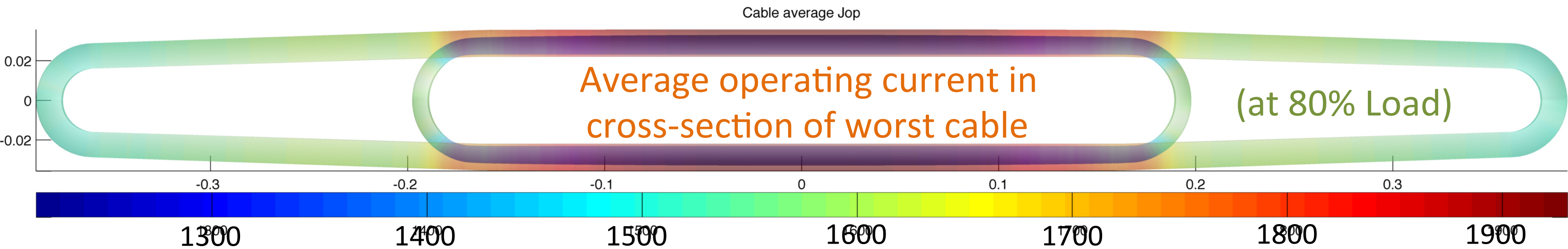


Analysis – In Background Field



Analysis – Standalone

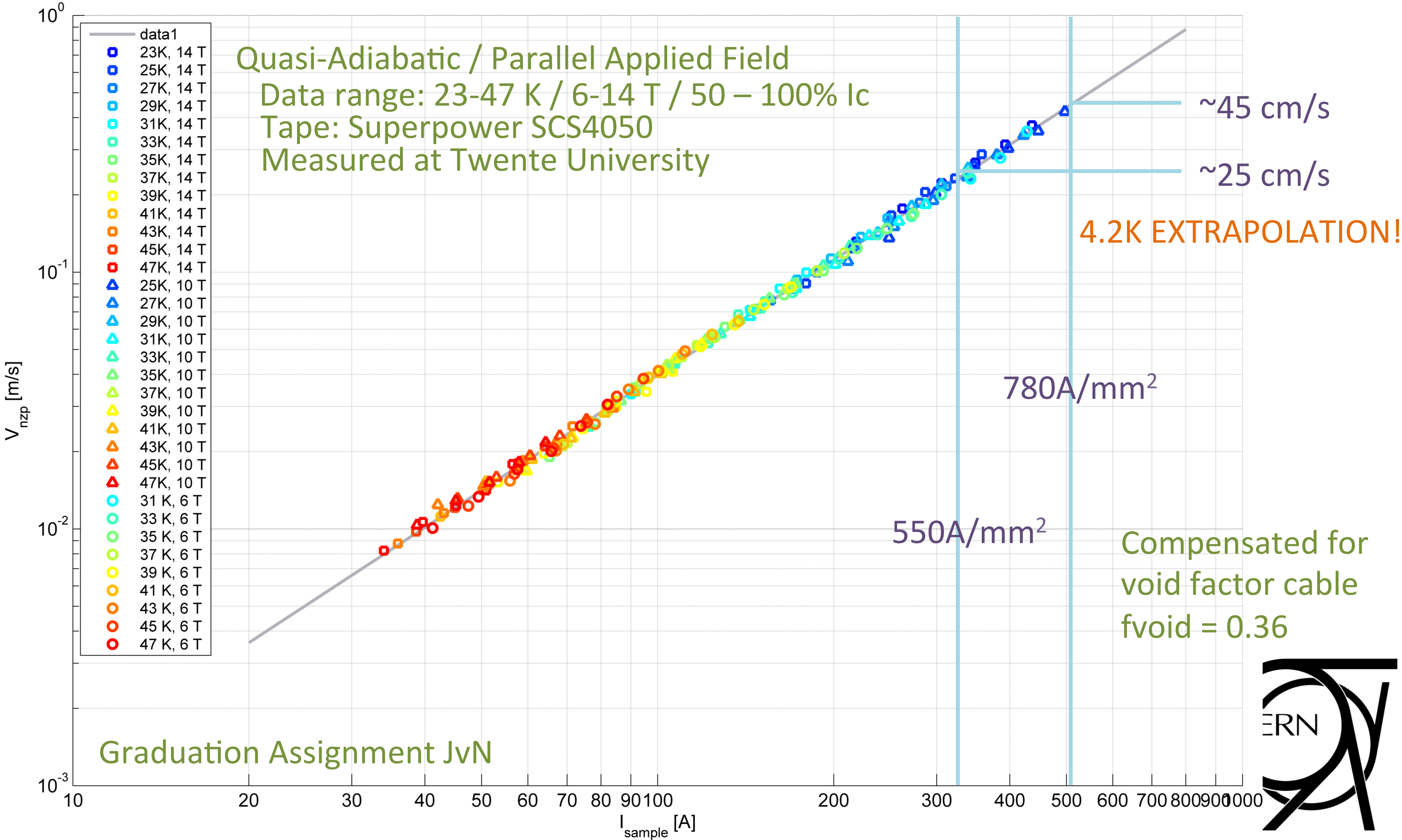




- Standalone with 100 mm iron yoke
- Fieldangle is 90 deg but only in (very) low field regions
- J_{op} is in the range of 850 – 1300 A/mm^2 only need 550 A/mm^2 to meet requirement of 5 T standalone
- More details in Appendix

Quench Protection – NZP Data

- HTS has high Minimal Quench Energy (MQE) and low Normal Zone Propagation Velocity (Vnzp)
- When adding cooling to surrounding becomes significantly lower (can be zero)



Quench Protection

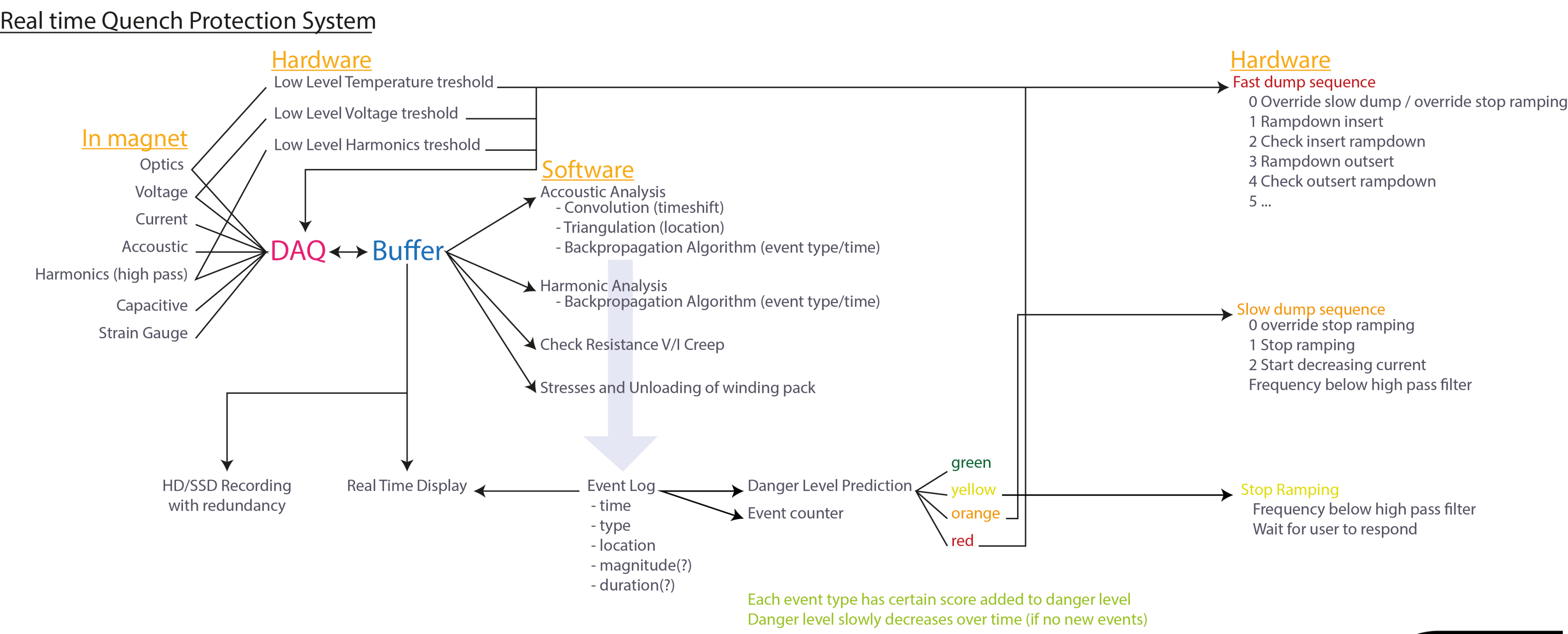
- Classical voltage detection
  - Because of low Vnzp, quench protection triggers when the hotspot temperature is already very high, resulting in little or no reaction time
  - When some cooling to environment is present a (by voltage) undetectable non-propagating normal zone may occur (resulting in local burnout without warning)

- Need different detection methods
  - Pickup-Coils (quench antennas) (with high-pass filter?)
  - Optical temperature/strain detection (?)
  - Acoustic (cryogenic microphones LBNL)
  - Co-wound insulated MgB_2 / NbTi wire at core
  - Anyone have other ideas?

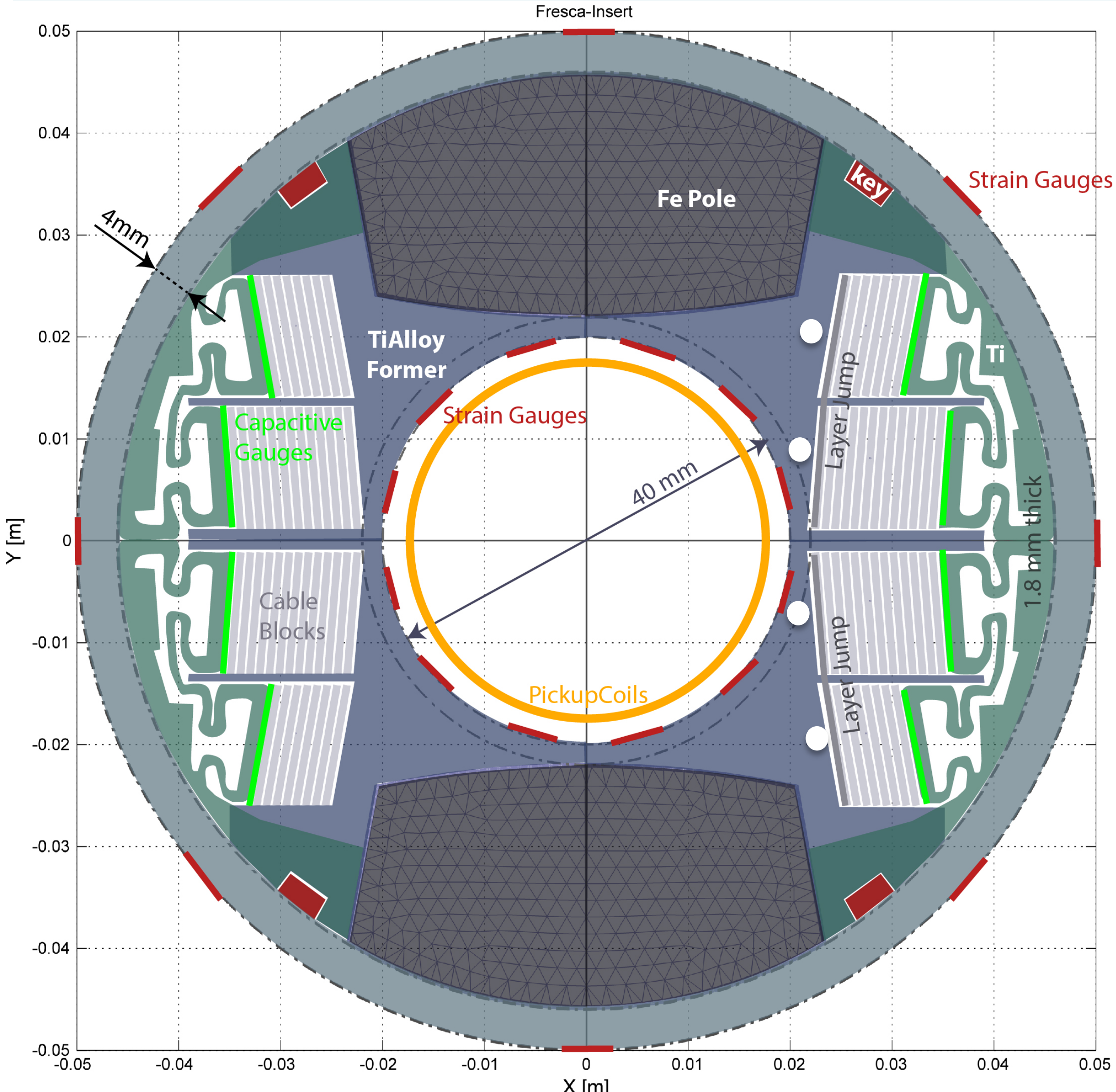
- Best would be not to quench an HTS magnet at all (to my opinion)
  - High MQE thanks to large margin (thus far more stable than LTS) helps with this
    - Direct helium contact?
    - Improves when larger margin is possible.
  - Correlate data from different sensors (precursor detection) to predict when the magnet is reaching its limits
    - Log anomaly events, magnitude, duration, position
    - Bit like predicting an earthquake
  - Detect transition to current sharing regime
    - Increase in bubbles (noise) / change in field harmonics (?)
  - Can start with cable that contains many copper strips and add more superconductor when feeling confident

Quench Protection

- Need time to develop such a system
- Will Require training to recognize specific events
- Need fine-tuning of all settings
- Test system on magnet that is safe to experiment on for debugging



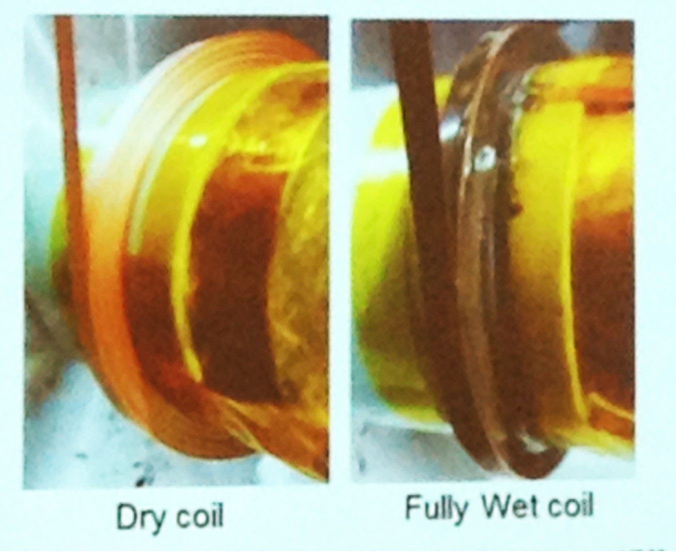
Sensor Placement



- Sensors are very cheap compared to conductor cost
- So lets have various different sensors
- Need good multichannel data acquisition and real-time processing system

To Pot or Not to Pot, That is the Question

- Direct Helium Contact
  - Improves cable stability (higher MQE)
  - Lowers Vnzp (which was too low anyways)
  - Kapton wrap/c-shape insulation
  - Need to close strand sides with silver/copper plating (start with non-cu-stabilized conductor)
  - Need to avoid high stresses in cable (co-wind kapton/copper/indium stress spreader)
  - No mess



- Fully wet coil winding (wind with and into wet epoxy)
  - Presented by SuperPower at MT23
  - Alumina loaded epoxy (still decent thermal conduction)
  - No additional insulation required?
  - No need for bladders?
  - Electrical contact between strands in cable???
  - Sticky Messy one-shot-process?
    - Surely need to practice this

- Bees Wax?

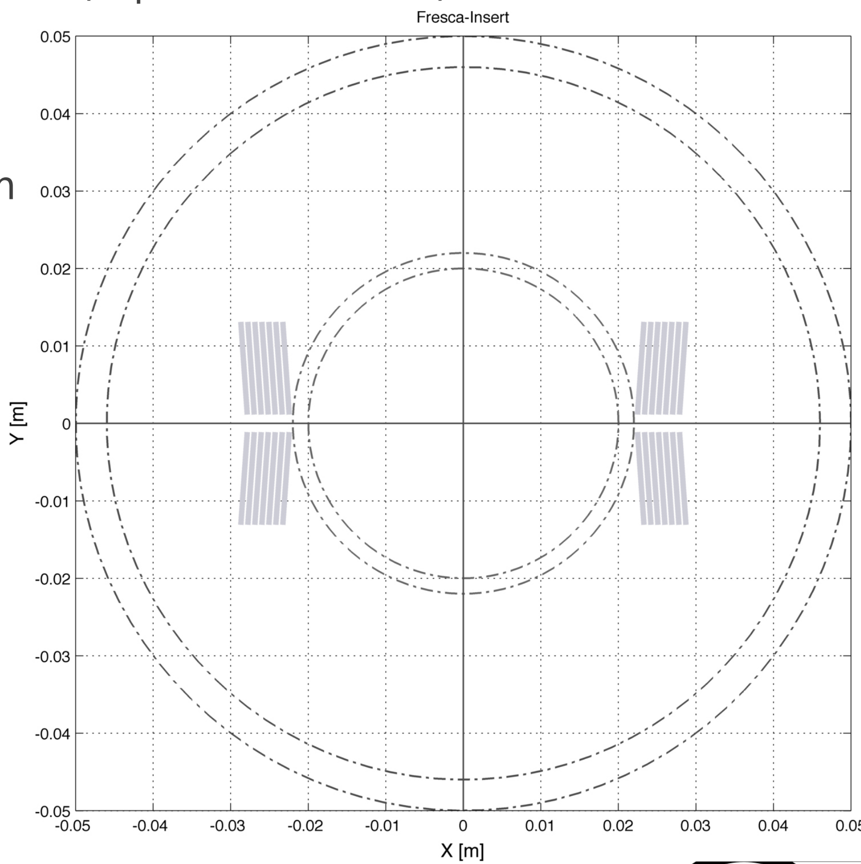
YBCO Magnet Possible Development Plan

Possible steps to take

1. Cable level development
   - Optimization of cable layout - number of strands / stacks - Twist pitch?
   - Epoxy impregnation or direct Helium contact? (superfluid helium?)
   - Influence on cable stress limit
   - Influence on quench behavior
   - Possible insulation schemes
   - Start working on quench protection system

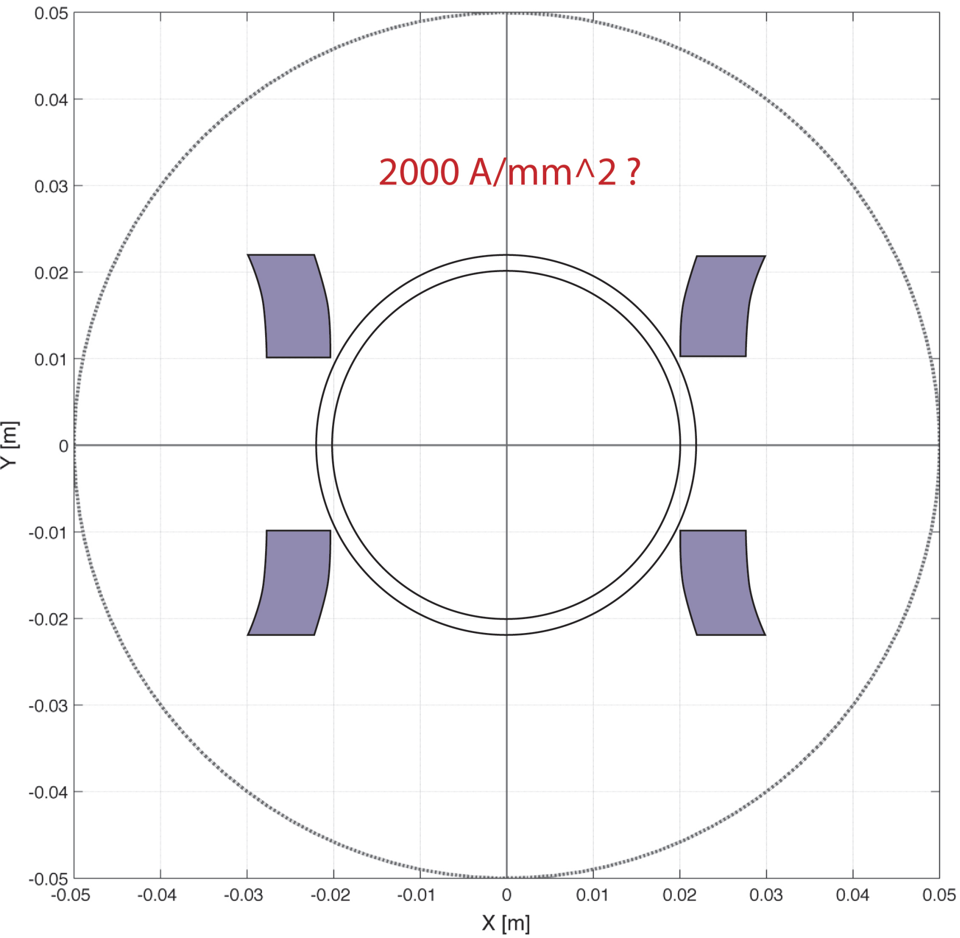
2. Single Deck 2-3 Turn Test Coil that has an aperture
   - Gain experience with quench protection
   - With iron poles at end?
   - Roebel cable winding (hardway bend)
   - Bladder test

3. Dual deck full design with aperture
   - Iron yoke test
   - 5 T standalone achievement!



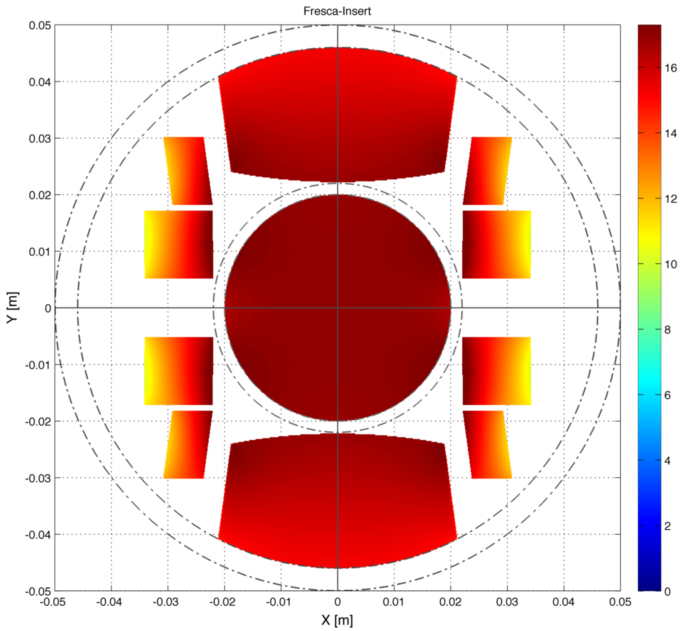
*Wind all coils with dummy cable first

Crazy Ideas

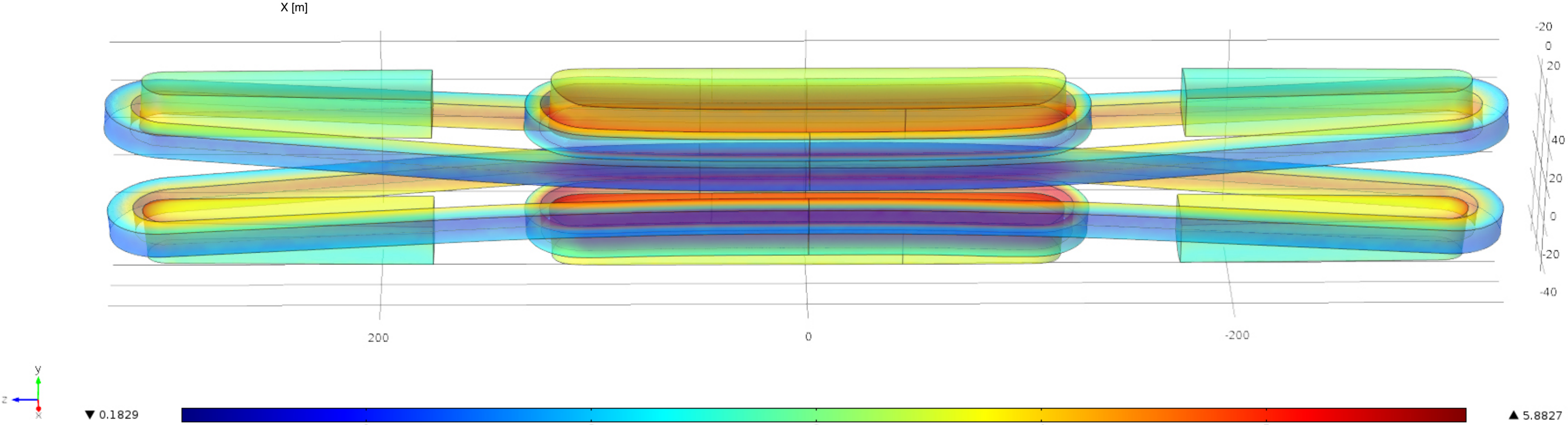


- Use Polyimide-Teflon coating on the former as ground insulation and low friction surface
  - Glyn found company in Germany that can do this
- Bend cables to follow field lines completely?
  - Harder to bend cable at coil ends
  - Very hard to follow field lines at coil ends
  - Quench protection?
  - Pretty insane idea (=
  - For future consideration

Last nights work

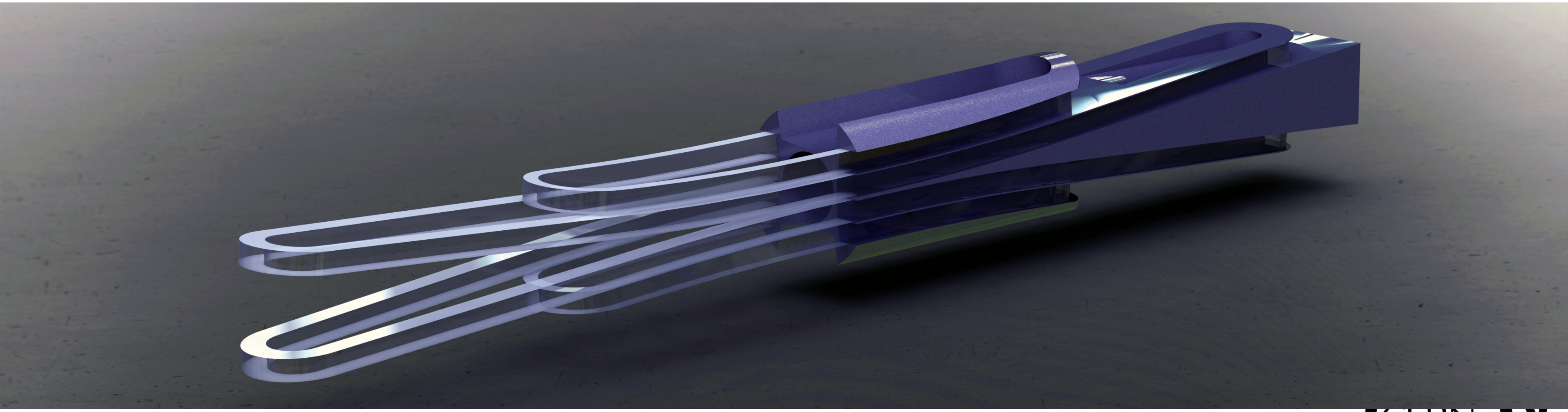


- 5 T standalone
- Run at 650 A/mm²
- Jop = 800-1200 A/mm²
- B3 = 0
- B5 = 20 units
- GC cable 7.4 kA



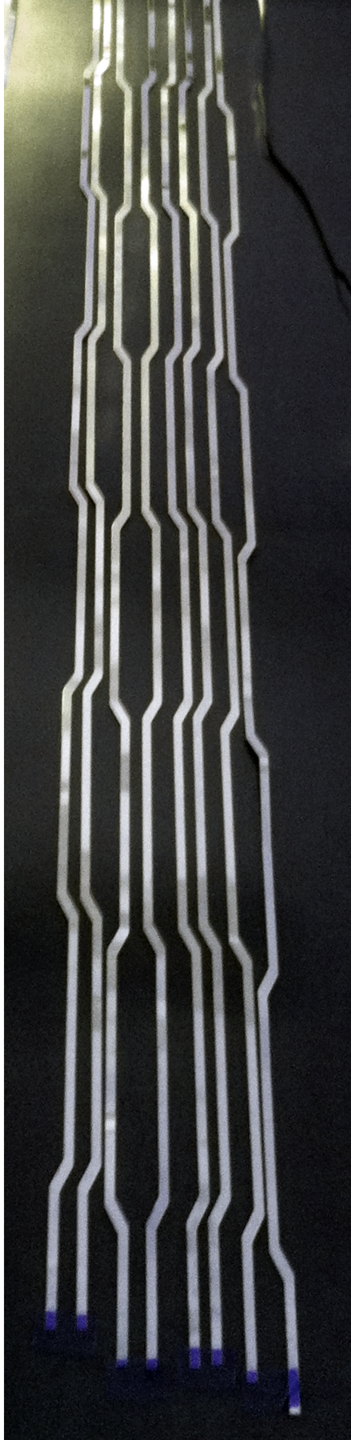
YBCO Insert Conclusion

- Introduced conceptual design for YBCO cable based coil that can be tested as insert inside FRESCA-II
  - Exploited conductor anisotropy by adjusting block angles
  - Because of this, uncertainty in achievable current density. But 5 T standalone target should easily be achieved.
  - Because of outer space restriction chosen not to get field quality.
  - Bladder provides means to apply pre-stress
  - Quench protection (my) present main concern



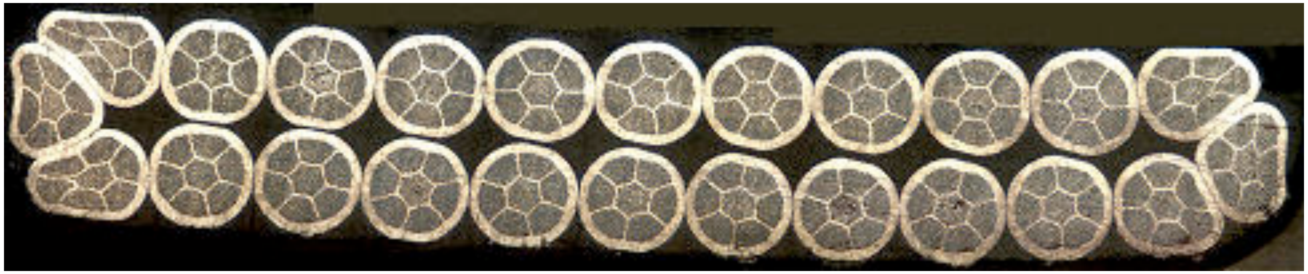
BSCCO Insert

Basic Design



BSCCO Cables

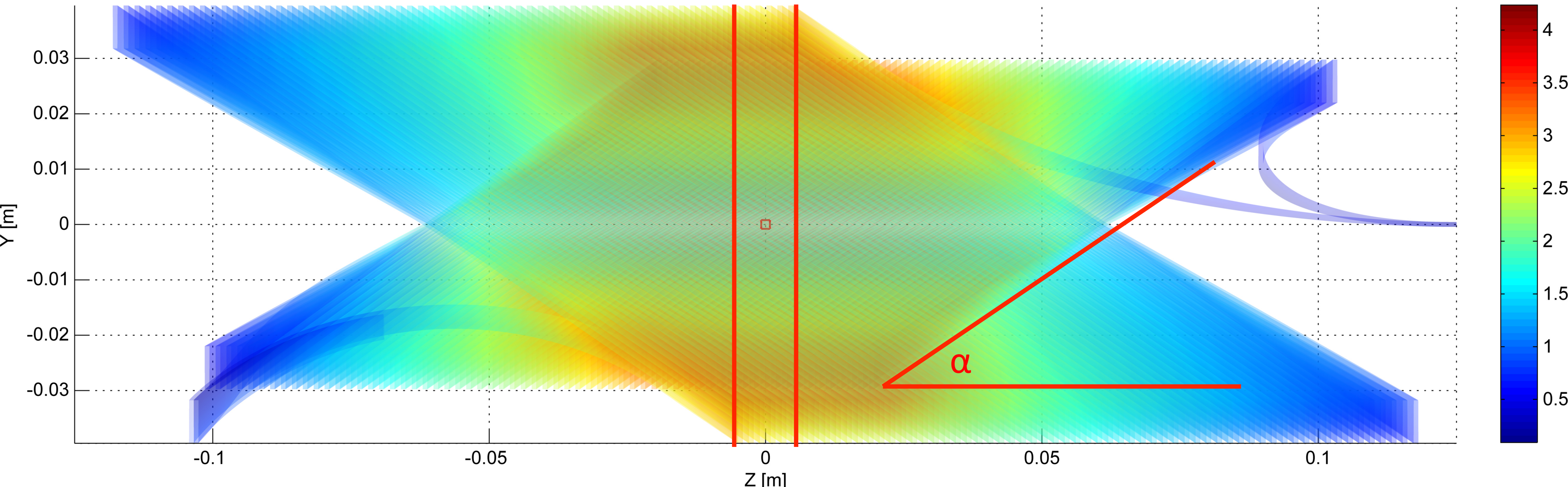
- No angle dependence (at least not in strands)
- Round strands -> Rutherford cable
- Powder In Tube (PIT) process
- Heat treatment ~890 °C at high pressure 100 bar
- Temperature during heat treatment has to be controlled very precisely +-1°C
- Low stress limit ~80 Mpa (like a bag of BiSCuits)



(Source FermiLab)

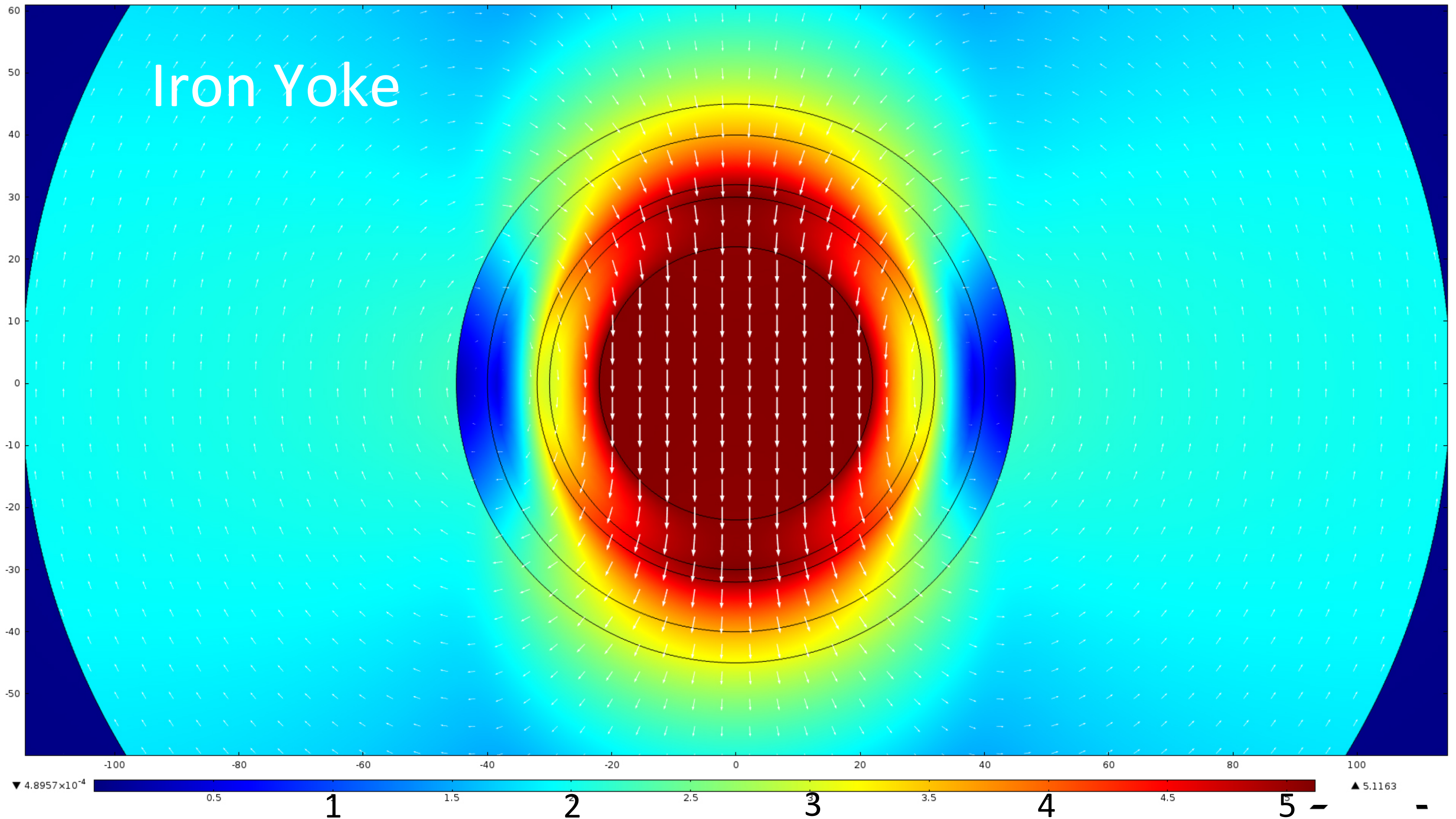
BSCCO Insert

- The Canted Cosine Theta (CCT)
  - Low stresses on cables because of ribs
  - Inherently has coil ends and thus an accessible aperture
- Preferred 2 layers for simplicity (each 8-9 mm thick required)
- Skew angle (α) determines length of central part and the attainable field
  - 250 mm total coil length to fit inside printing chamber for former (print in one go)
  - Skew angle should be at least 32 deg (central field optimum)
- Could again use (same) iron yoke to help meet 5T standalone requirement



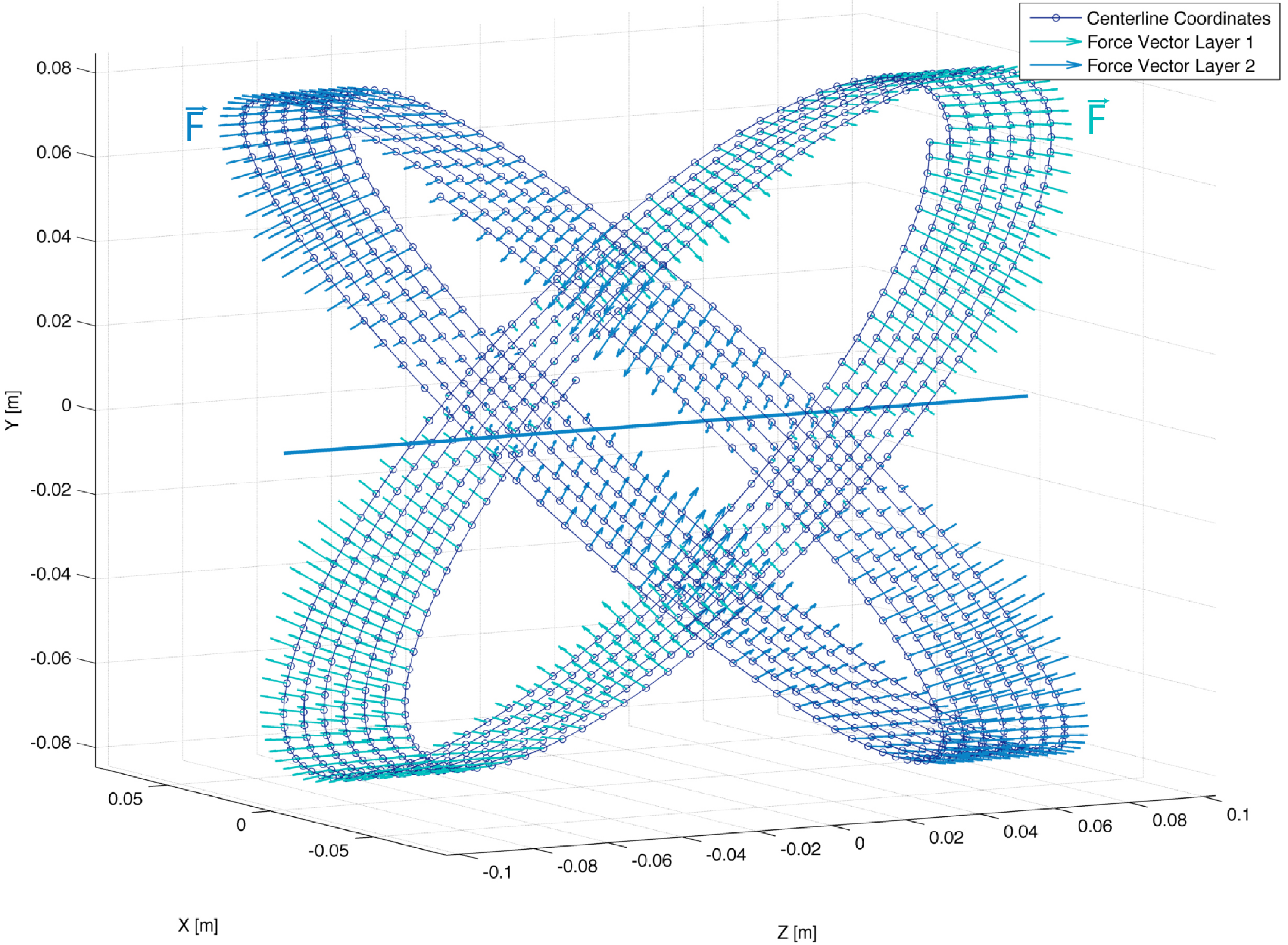
Iron Quasi-2D Approximation

- For this magnet 3D-model does not include iron yet
- Quasi-2D FEM model using superposition of perfect Cosine-Theta dipole current and Solenoidal current
  - 0.8 Packing factor // 550 A/mm^2 current density



Forces CCT

- Calculated Lorentz forces on section of BlueWhale
- Lorentz forces opposite in layers
- Coil only short length -> wind both layers on same former?



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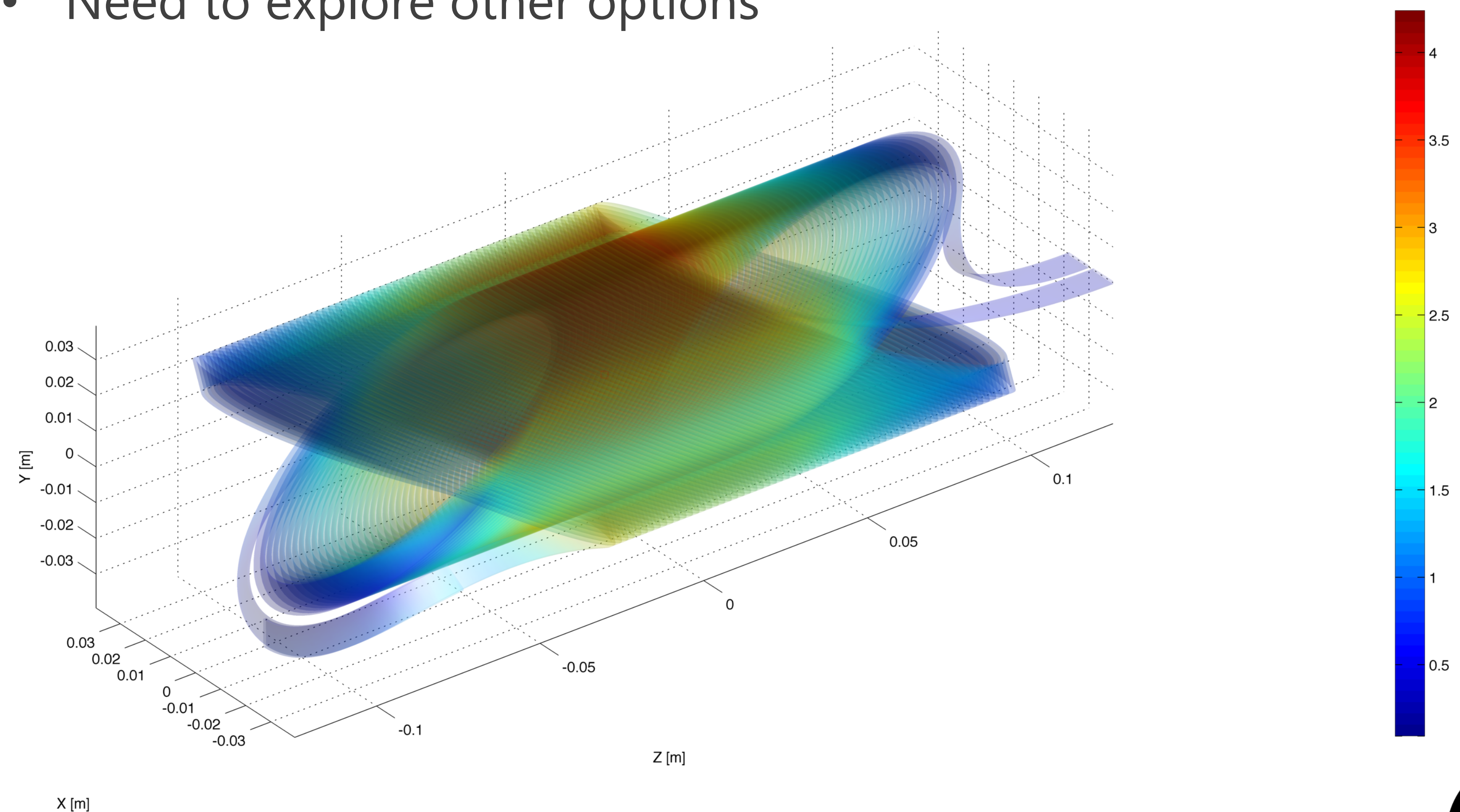
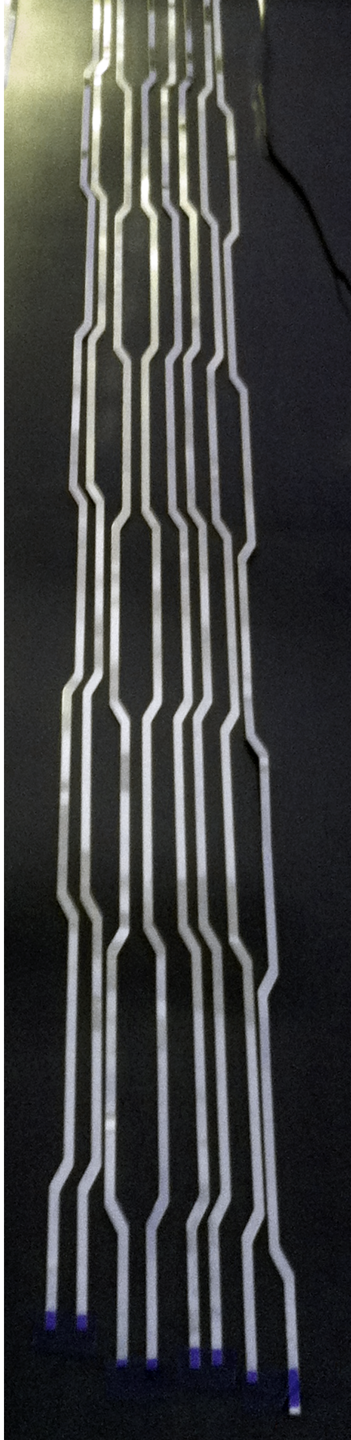
BSCCO Insert Conclusion

- BSCCO needs design that provides solution for stresses
- Basic concept for a BSCCO Canted Cosine Theta design introduced
- Need to explore other options



Thank you for your attention

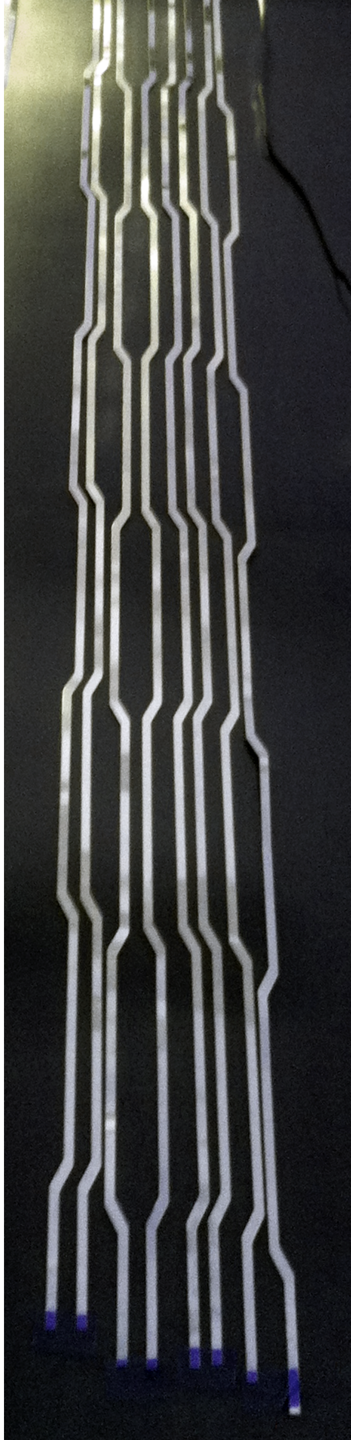


Feel free to send additional comments / ideas / questions to my mail address:

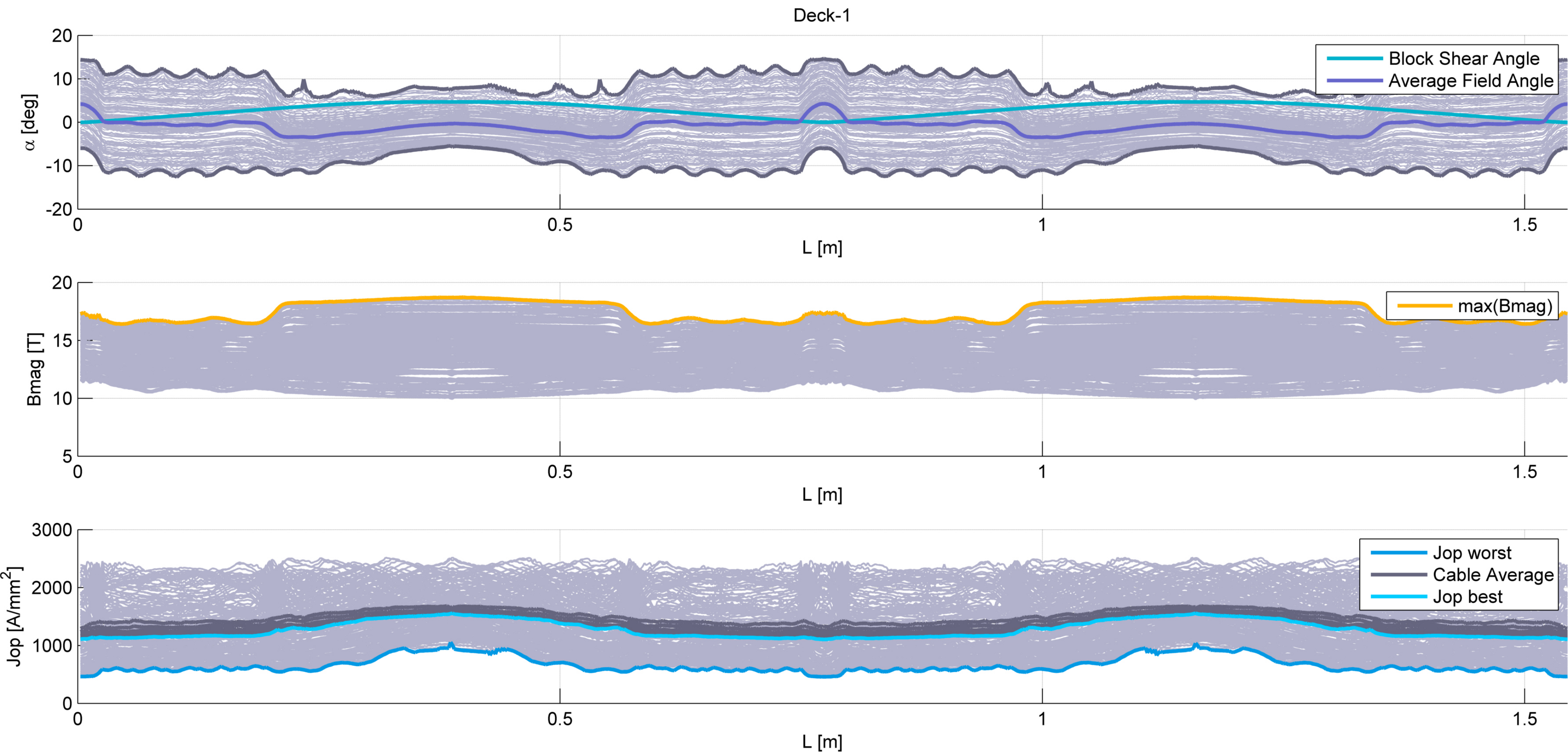
Jeroen.van.nugteren@CERN.CH

AppendiX

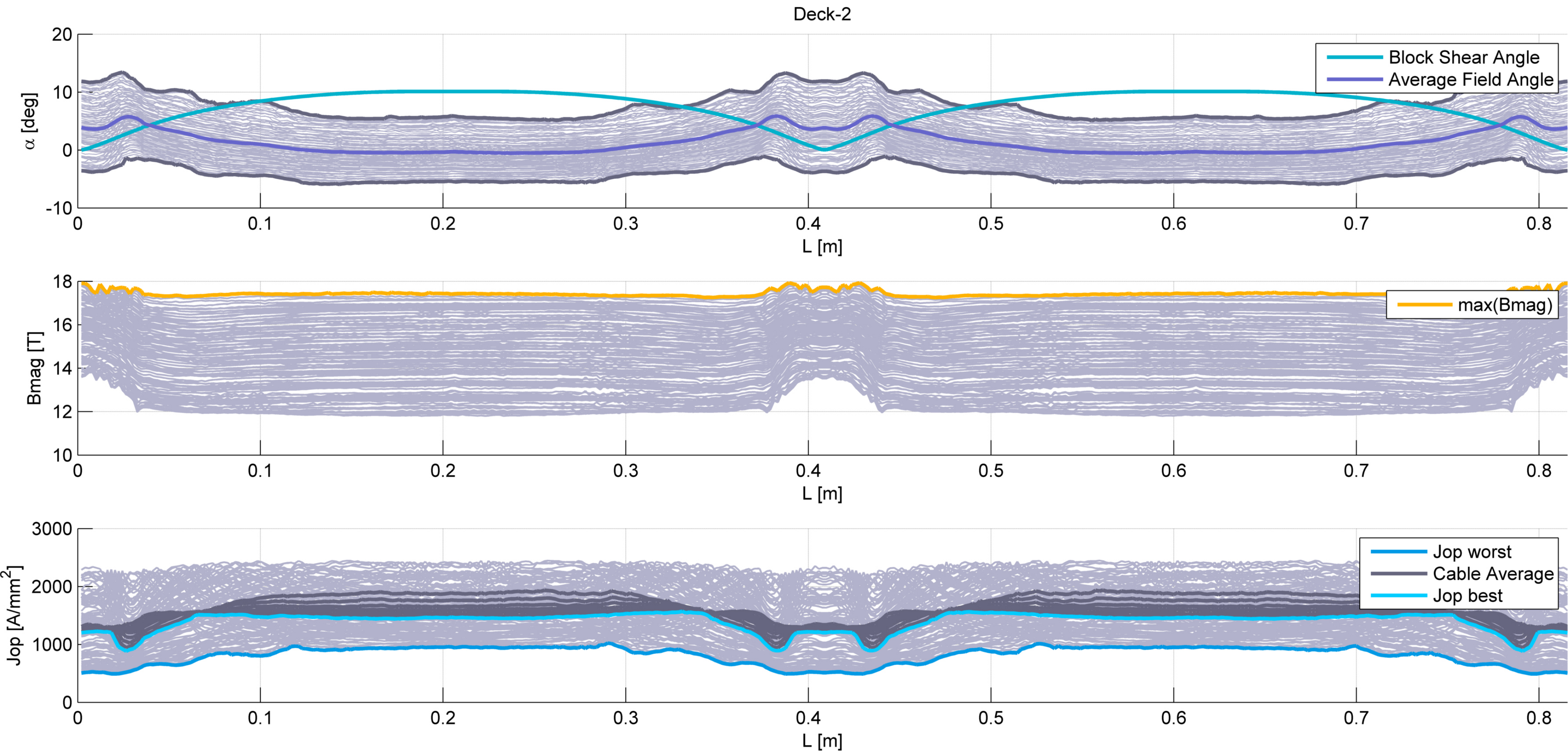
Extra stuff I couldn't fit in



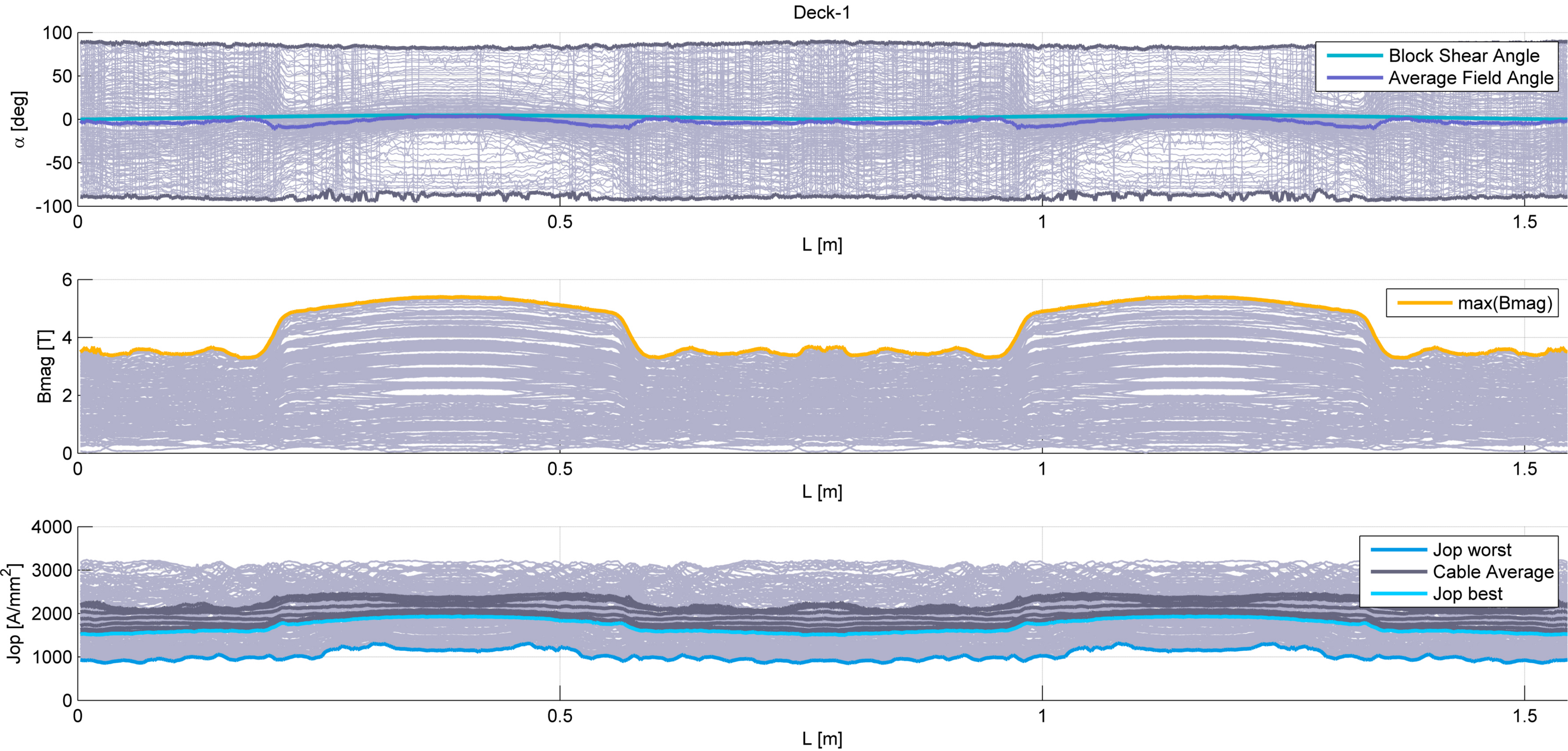
In Background Field – Deck 1



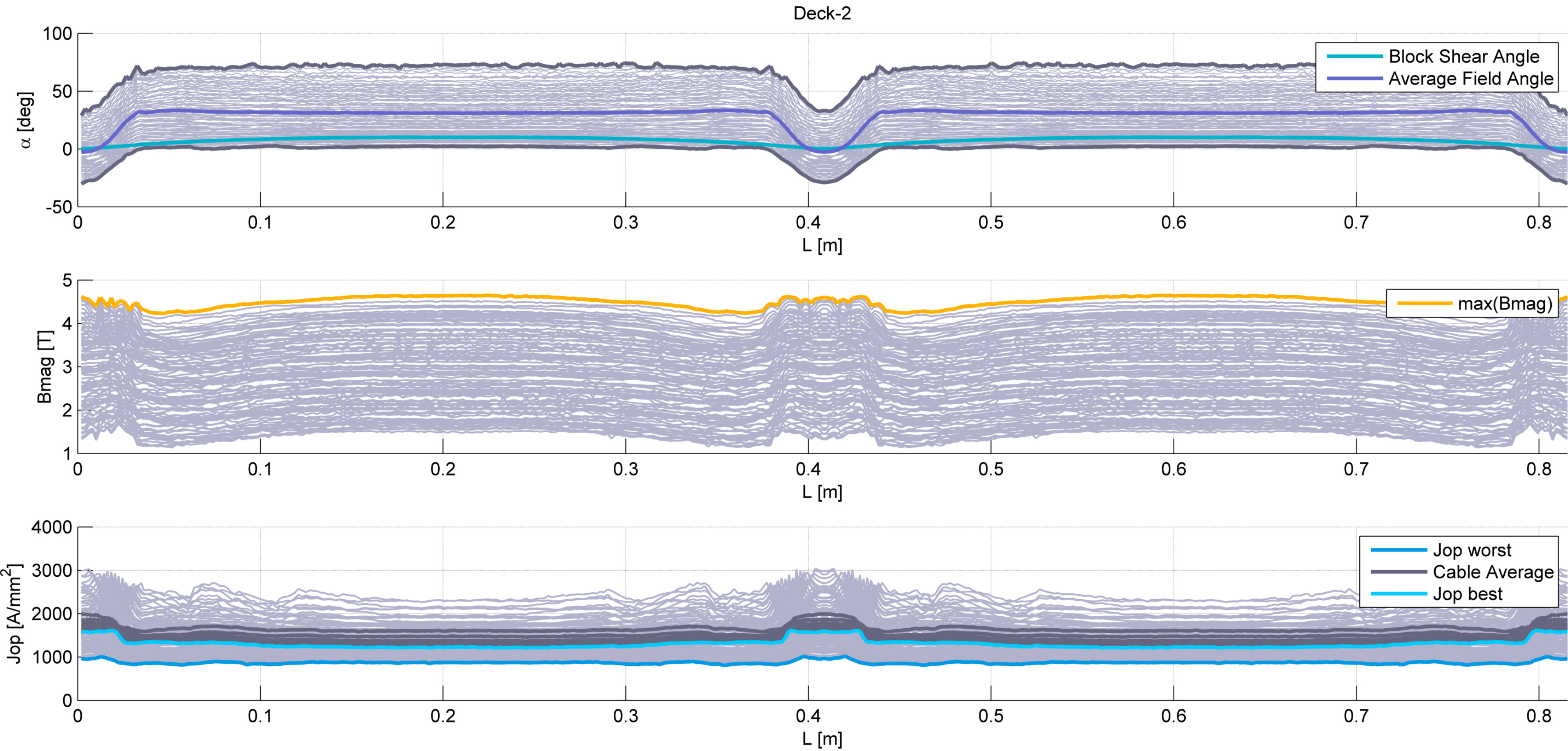
In Background Field – Deck 2



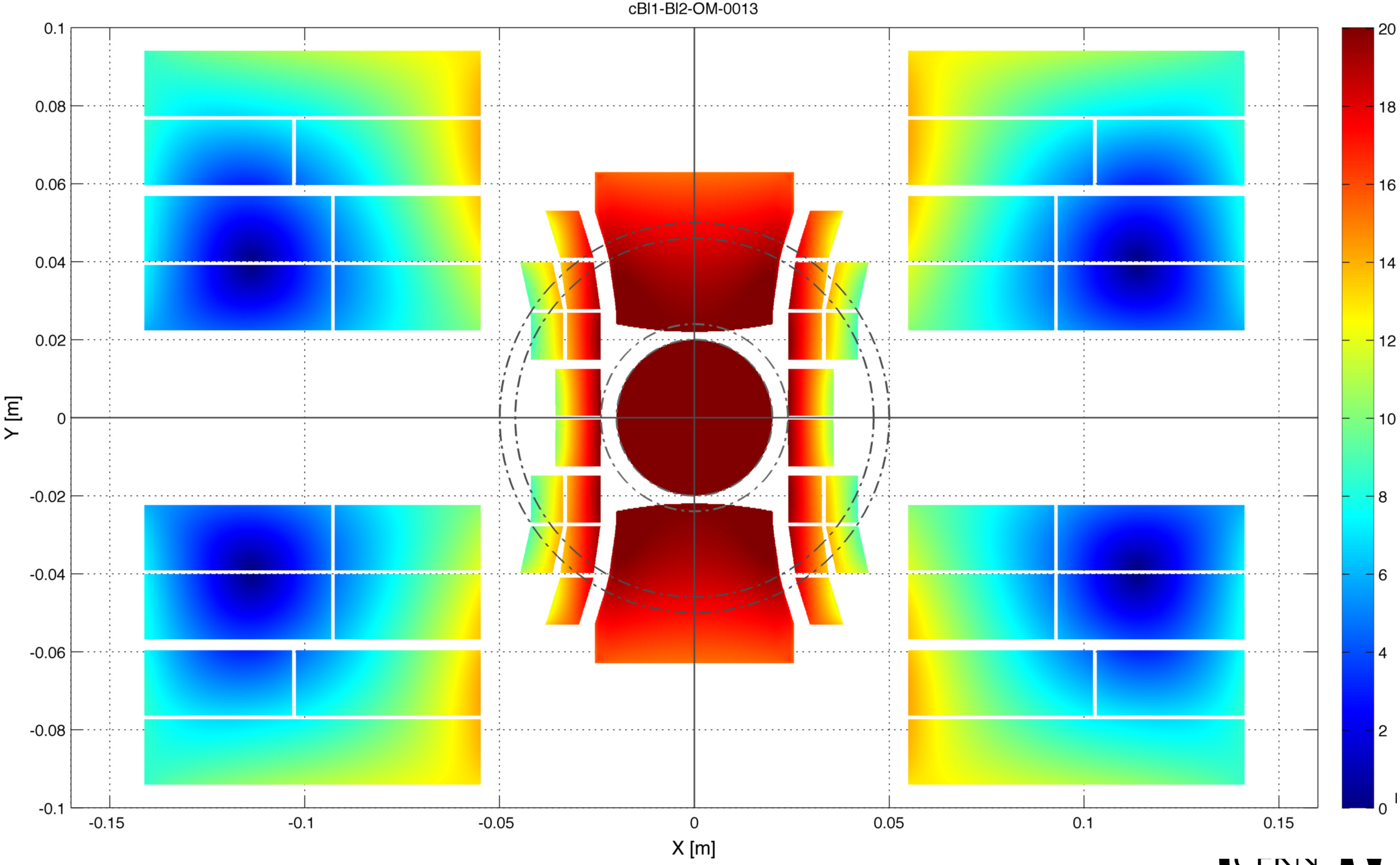
Standalone In Yoke – Deck 1



Standalone In Yoke – Deck 2



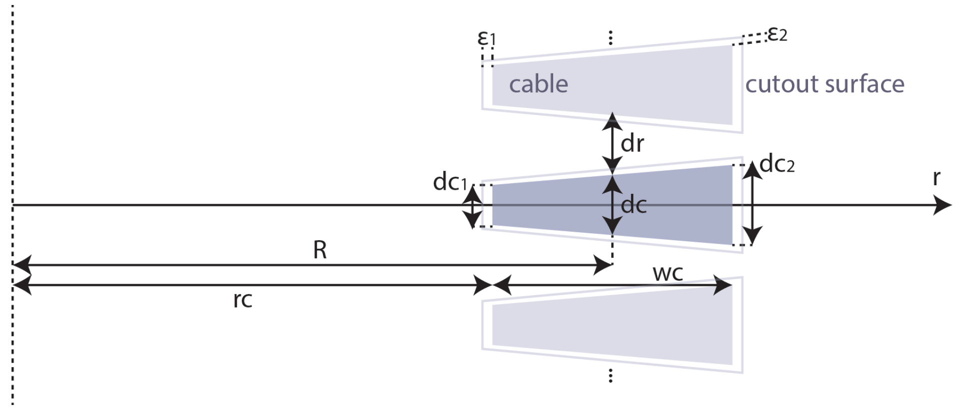
Combination of Insert and Outsert

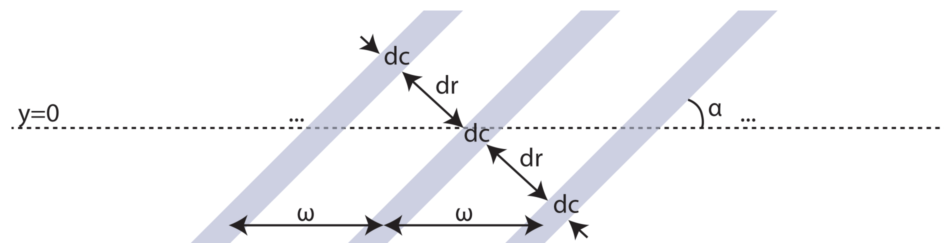


CCT Parameters

- General
  - $dc = (dc_1+dc_2)/2$
  - $f_{pack} = dc / (dc + dr)$
  - $\omega = (dc + dr)/\sin(\alpha)$
- Currents
  - $J_{av} = J_{cable}$ fpack
  - $J_{dipole} = J_{av} \cos(\alpha)$
  - $J_{solenoid} = J_{av} \sin(\alpha)$ (alternating sign from layer to layer)
- Quasi-2D Approximation
  - $J_x = J_{solenoid} \sin(\text{atan2}(y,x))$
  - $J_y = -J_{solenoid} \cos(\text{atan2}(y,x))$
  - $J_z = J_{dipole} \cos(\text{atan2}(y,x))$

  (Jx and Jy alternating sign between layers)





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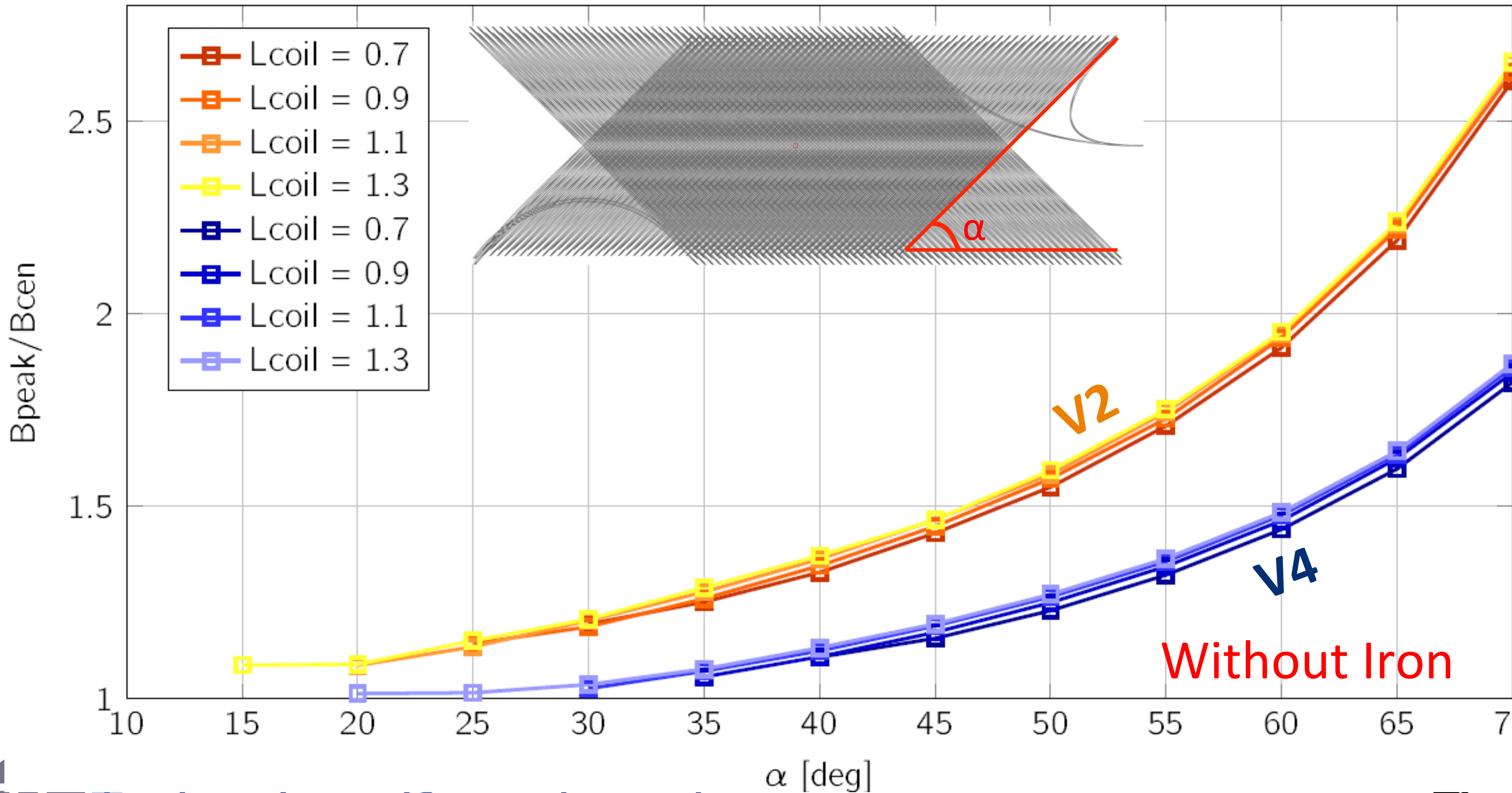
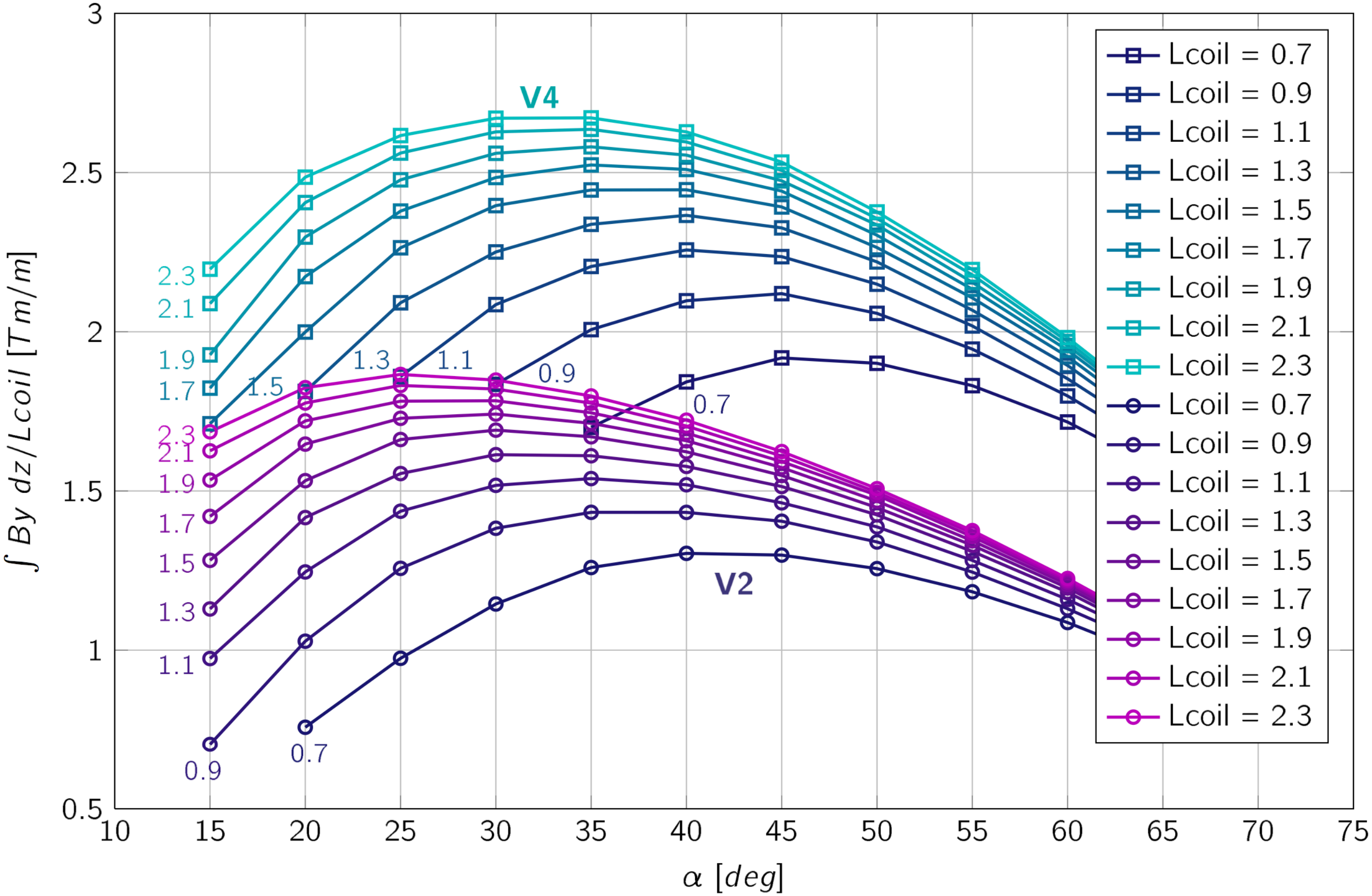
Skew Angle Optimization

- Peak field enhancement is determined by the skew angle and the number of layers (no influence from coil length)
- This result was found for MCBX, but should generally be valid



Skew Angle Optimization

- Larger skew angle -> less dipole field (and larger peak field)
- Lower skew angle -> longer coil ends
- Result for MCBX



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