Magnetic Field Calculation Tool for Alternative Mu2e-II PS Conductor

CalTech Workshop

Cole Kampa, Michael Schmitt

Northwestern University

March 28, 2023

Overview

- Statement of goals
- Mu2e PS/TS1 field requirements
- Tools: SolCalc GUI
- Some exploratory results
  - Cable-in-conduit conductor
  - Internally-cooled Al stabilized cable
  - HTS
  - Water-cooled resistive coil
  - LN_2-cooled resistive coil
- Next steps

Goals

- Explore plausibility of different PS conductor proposals, from a magnetic perspective.
- Using the conductors proposed during the MuCol/Mu2e-II: https://indico.cern.ch/event/1234843/contributions/5219538/attachments/2583849/4457046/HockerMu2e-II_PS_2020_update.pptx
- Work towards full field calculations of reasonable conductor configurations for more detailed studies.

Mu2e PS/TS Field Requirements

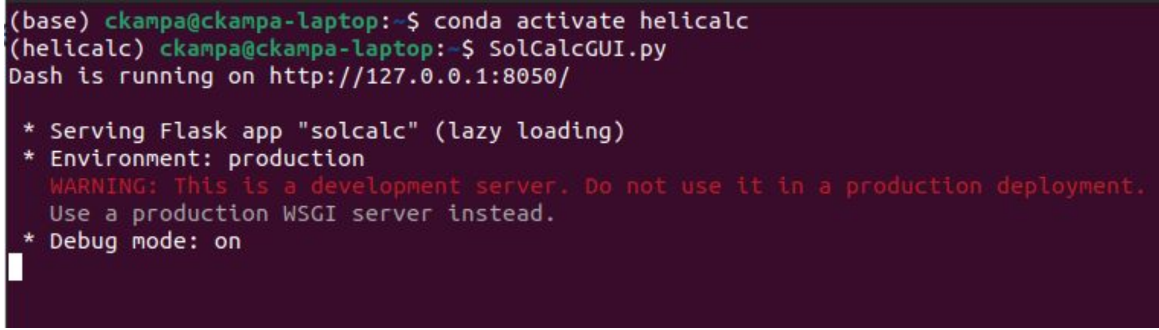
- PS:
  - PS1 region:
    - Bz > 4.5 T at s=-9.4 m (on axis)
    - Bz_max must be in PS1 region (on axis)
    - No local minimum (R<0.5 m)
  - PS2 region:
    - Bz = 2.5 T ±5% at PS2/TS1 boundary (on axis)
    - Uniform gradient, within 5% (on axis)
    - No local minima off axis (R < 0.25 m)
- TS1 region:
  - Bz = 2.4 T ±5% at TS1/TS2 boundary (on axis)
  - dBz / dz ≤ -0.02 T/m (R < 0.125 m)

Repo: https://github.com/Mu2e/FMS_helicalc
GUI: https://github.com/Mu2e/FMS_helicalc/tree/main/scripts/SolCalc_GUI
Commit: 6232a8a894405d7da44e8e75469e74fb6a9b24a7

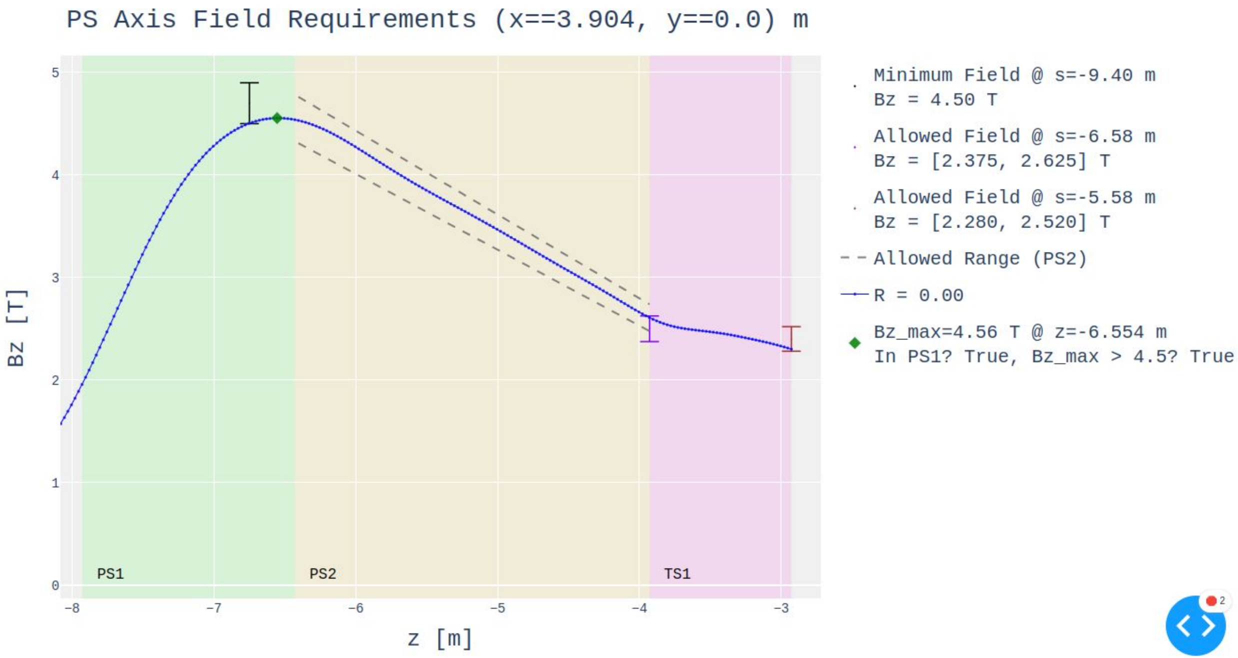
Tools: SolCalc + GUI

- *SolCalc* is built-in to the *helicalc* Python package that Mu2e uses for magnetic field calculations.
  - Ideal solenoid approximation
  - Exact field from a filamentary loop integrated radially and axially (cylindrical shell of current)
  - Ported from original Matlab *SolCalc* routine [M. Lopes https://lss.fnal.gov/archive/2014/conf/fermilab-conf-14-138-td.pdf]
- Package includes a Plotly Dash application for quickly exploring field given different conductor configurations: *SolCalcGUI.py* script.

Demo

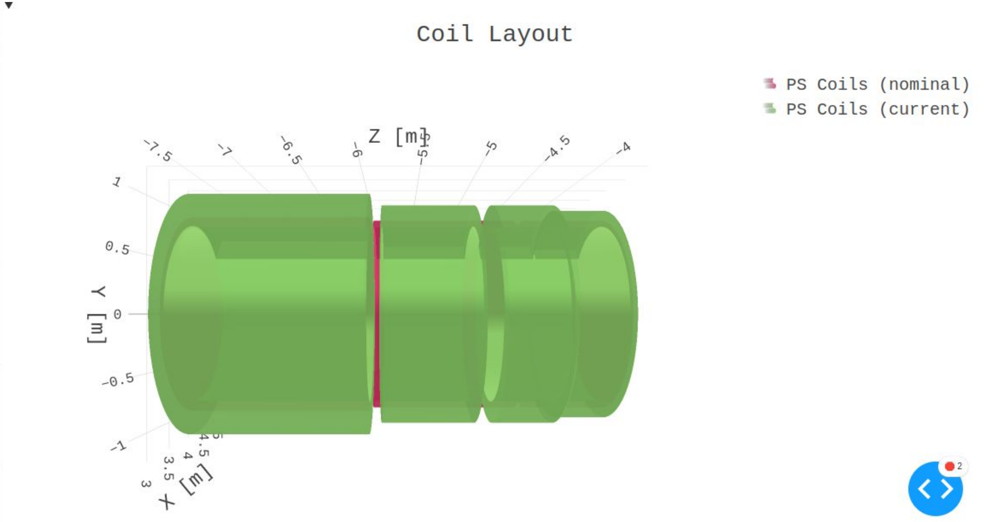


- Main output is plots to determine if field is to Mu2e PS/TS spec.
- Axial field
- Profiles of field gradient
- Calculation of cable length needed and resistive power (for non-S.C. conductor)



Demo (2)

- Coil and conductor parameters are tunable
- Can add or remove coils
- Config file to create and load different conductor initializations
- 3D plot showing coil configuration



Editable Parameters

Initialize Conductor:

ITER_CICC_Nb3Sn

- HTS_VIPER_REBCO
- ICASC_NbTi
- **ITER_CICC_Nb3Sn**
- Mu2e_PS_NbTi
- RC_Cu_20C
- RC_Cu_77K

×	3.0000	0.8500	-4.5000	4.0
×	4.0000	0.8500	-3.9500	3.0

ADD COIL

	Coil_Num	Ri	z	N_layers	N_turns	I_turn
×	1.0000	0.8500	-6.8170	3.0000	285.0000	9200.0000
×	2.0000	0.8500	-5.2543	2.0000	222.0000	9200.0000
×	3.0000	0.8500	-4.0920	2.0000	125.0000	9200.0000

ADD COIL

Conductor Parameters:

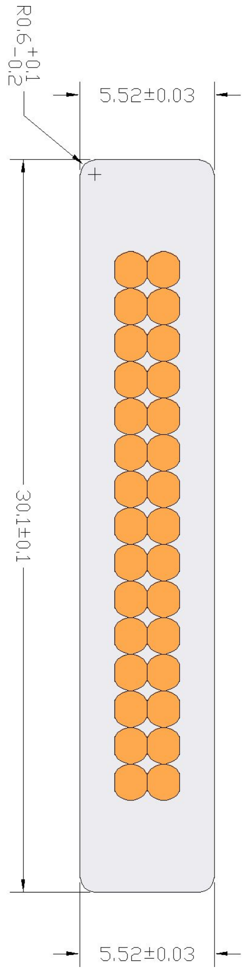
TOGGLE COLUMNS

Coil_Num	h_cable	w_cable	h_sc	w_sc	t_gi	t_ci	t_il
1.0000	0.0301	0.0055	0.0208	0.0026	0.0005	0.0003	0.0010
2.0000	0.0301	0.0055	0.0208	0.0026	0.0005	0.0003	0.0010
3.0000	0.0301	0.0055	0.0208	0.0026	0.0005	0.0003	0.0010

1. Mu2e PS (NbTi SC, Al stabilized)

- A system of 3 coils wound “the hard way”
- 9,200 A
- Of course, magnetic requirements are satisfied.

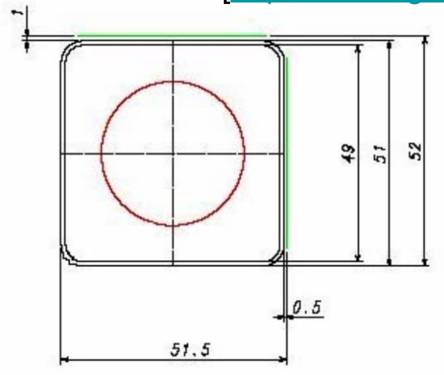
- It is not clear what we will need to do for Mu2e-II
  - Use the Mu2e PS and HRS until it breaks
  - Replace PS, HRS, cryostat
- Even after replacing PS and HRS, using the Mu2e PS conductor may be difficult
  - e.g. Run with superfluid helium to maintain adequate temperature margin.
- Lots of thought on this in previous workshops, e.g. here: https://indico.cern.ch/event/1234843/contributions/5219538/attachments/2583849/4457046/HockerMu2e-II_PS_2020_update.pptx

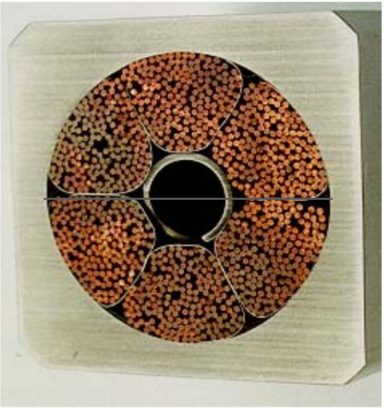


2. Cable-in-conduit conductor (CICC, SC)

- ITER winds "pancake" coils, rather than "helical" coils (Mu2e). I think either should work.
- Area of S.C. / Total Cable Area:
  - ITER: 6.5%
  - Mu2e: 17.1%
- Current density in S.C.:
  - ITER: 289 A/mm^2
  - Mu2e: 379 A/mm^2
- Total current in cable:
  - ITER: 45,000 A
  - Mu2e: 9,200 A

[https://doi.org/10.1109/FUSION.2005.252874]



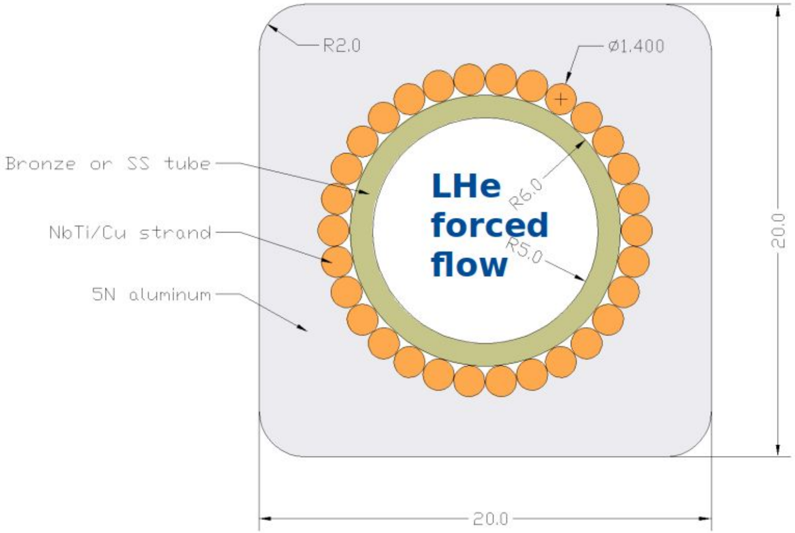


→Expect CICC cables would occupy more physical space to achieve similar field strengths

- Since LHe runs through cable directly, maybe less of the cryostat volume is required for heat transfer elements.
- Critical temp. of Nb_3Sn is 18.3 K (vs. ~10 K for NbTi), so my naive guess is we should be able to use a higher J than in Mu2e PS, if we run at the same temperature.
- ITER to run @ 12 T, limits J that they use. (J_C = 1,000 A/mm^2 vs. J_C = 2,725 A/mm^2 Mu2e @ 5 T – 4.2 K)

3. Internally-cooled Al stabilized cable (ICASC, SC)

- I will assume the cross-section in the diagram to the right is reasonably close to what can be built.
- I will assume that the Cu/non-Cu ratio of the S.C. strands matches that of the Mu2e PS (=0.9).
- I will assume that the current density can match that of the Mu2e PS.
- Area of S.C. / Total Cable Area:
  - ICASC: 7.1%
  - Mu2e: 17.1%
- Current density in S.C.:
  - ICASC: 379 A/mm^2
  - Mu2e: 379 A/mm^2
- Total current in cable:
  - ICASC: 9,200 A
  - Mu2e: 9,200 A



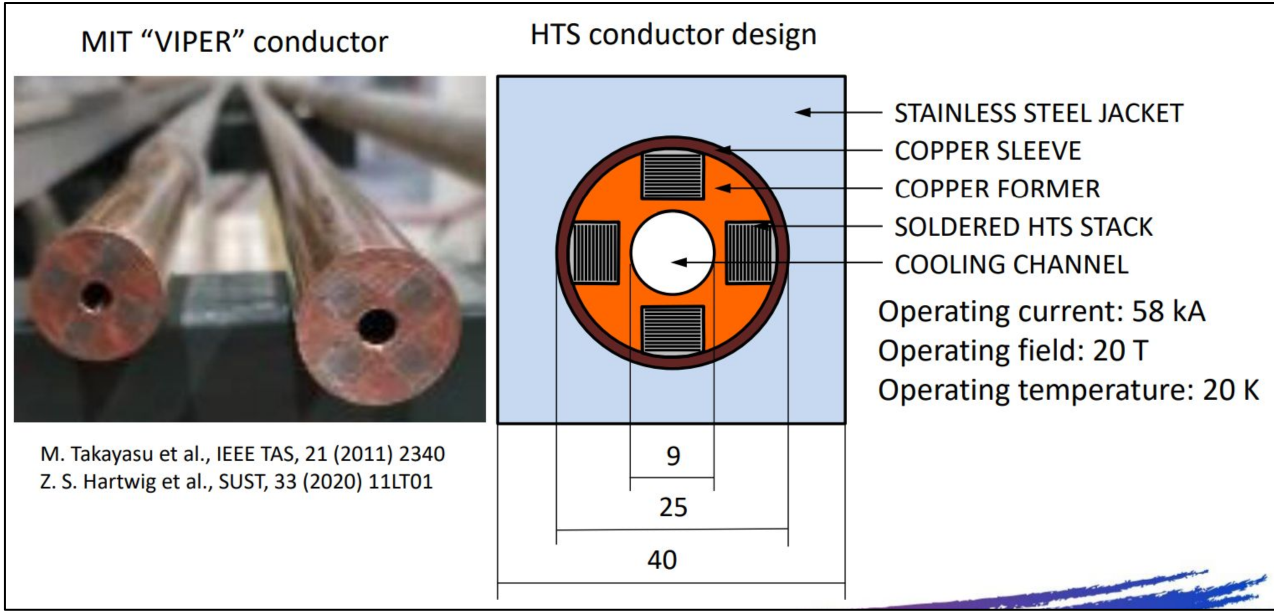
→Similar expectations to CICC, but unlikely to be able to increase J.

- Is it crazy to suggest a second ring of S.C. filaments to ~x2 Area of S.C./Total Cable Area?
  - Maybe it is important for the S.C. to directly contact the conduit in the center.

4. High-temperature superconductor (HTS, SC)

[L. Bottura, https://indico.cern.ch/event/1234843/]

- MIT VIPER (REBCO) seems like a nice option.
- Will use MuC Target Solenoid conductor as a starting point.
- Area of S.C. / Total Cable Area (ESTIMATE):
  - VIPER: 2.2%
  - Mu2e: 17.1%
- Current density in S.C. (ESTIMATE):
  - VIPER: 1,657 A/mm^2
  - Mu2e: 379 A/mm^2
- Total current in cable:
  - ICASC: 58,000 A
  - Mu2e: 9,200 A



→Expect VIPER cables would occupy more physical space to achieve similar field strengths

- As with the comparisons to ITER, we will run at lower field than MuC (5 T vs. 20 T)
  - Increase in J_C?
- Run at a lower temp. to increase J_C?

5. Water-cooled resistive coil (RC)

- Cu or Al, but I will choose Cu as a starting point since it has a higher conductivity.
- For easier comparison of total current, I'll pick cable cross section = Mu2e PS cable (5.52 mm x 30.10 mm).
- Area of R.C. / Total Cable Area:
  - Cu, H_2O: ?? (I am guessing it's high… >80% ?)
  - Mu2e: 17.1%
- Current density in S.C.:
  - Cu, H_2O: ~5 A/mm^2 (can we go higher?)
  - Mu2e: 379 A/mm^2
- Total current in cable:
  - Cu, H_2O: 665 A (w/ 80% conductor in the cable)
  - Mu2e: 9,200 A

6. LN_2-cooled resistive coil (RC)

- Cu or Al, but I will choose Cu as a starting point since it has a higher conductivity.
- For easier comparison of total current, I'll pick cable cross section = Mu2e PS cable (5 mm x 30 mm).
- Area of R.C. / Total Cable Area:
  - Cu, H_2O: ?? (I am guessing it's high… >80% ?)
  - Mu2e: 17.1%
- Current density in S.C.:
  - Cu, H_2O: ~50 A/mm^2 (statement from A. Hocker's talk at MuCol / Mu2e-II workshop is resistivity decreases by ~x6-10) [https://indico.cern.ch/event/1234843/]
  - Mu2e: 379 A/mm^2
- Total current in cable:
  - Cu, H_2O: 6,650 A (w/ 80% conductor in the cable)
  - Mu2e: 9,200 A

Lengths of Cable & Power Consumption

1. Mu2e PS (NbTi): 8.65 km
2. CICC (Nb_3Sn): 2.18 km (4 coils, used 42,000 A instead of nominal 45,000 A)
    a. ITER central solenoid: 5.94 km. Not sure the cost.
3. ICASC (NbTi): 9.81 km (used 8,900 A instead of nominal 9,200 A)
4. HTS (VIPER REBCO): 1.44 km (4 coils)
5. Water-cooled Cu: 112 km, 6.28 MW (far from spec)
6. LN_2-cooled Cu: 13.5 km, 7.11 MW (5 coils; in spec; did not extend into HRS)

Summary & Next Steps

- I have adapted the SolCalc ideal solenoid integrator to include a GUI for studying different conductor configurations for the Mu2e-II PS.
- I have started exploring different proposed conductors to see if a field within spec seems plausible to construct
  - Cable-in-conduit conductor: Yes, but coldmass outer radius is larger than Mu2e.
  - Internally-cooled Al stabilized cable: Yes, but coldmass outer radius is larger than Mu2e.
  - HTS: Yes
  - Water-cooled resistive coil: Maybe, but needs serious tuning. Very large footprint.
  - LN2-cooled resistive coil: Yes, but needs tuning to decrease power consumption.

- Fine tune parameters to get a field in-spec for each conductor type, if possible.
  - Differential programming may suit this optimization problem, and is gaining a lot of traction in the field (see e.g. upcoming MODE Workshop: https://indico.cern.ch/event/1242538/)
- Generate a complete PSMap, as well as recalculations of TSuMap, TSdMap, DSMap (probably very small impact here). These maps can be used in simulation to determine in more detail whether the proposed configuration will work for Mu2e-II.

Backups

NbTi vs. Nb_3Sn

- For temp of interest, critical field is approx. x2.5 larger for Nb_3Sn

~ Mu2e operating temp.

[https://www.osti.gov/servlets/purl/937570]

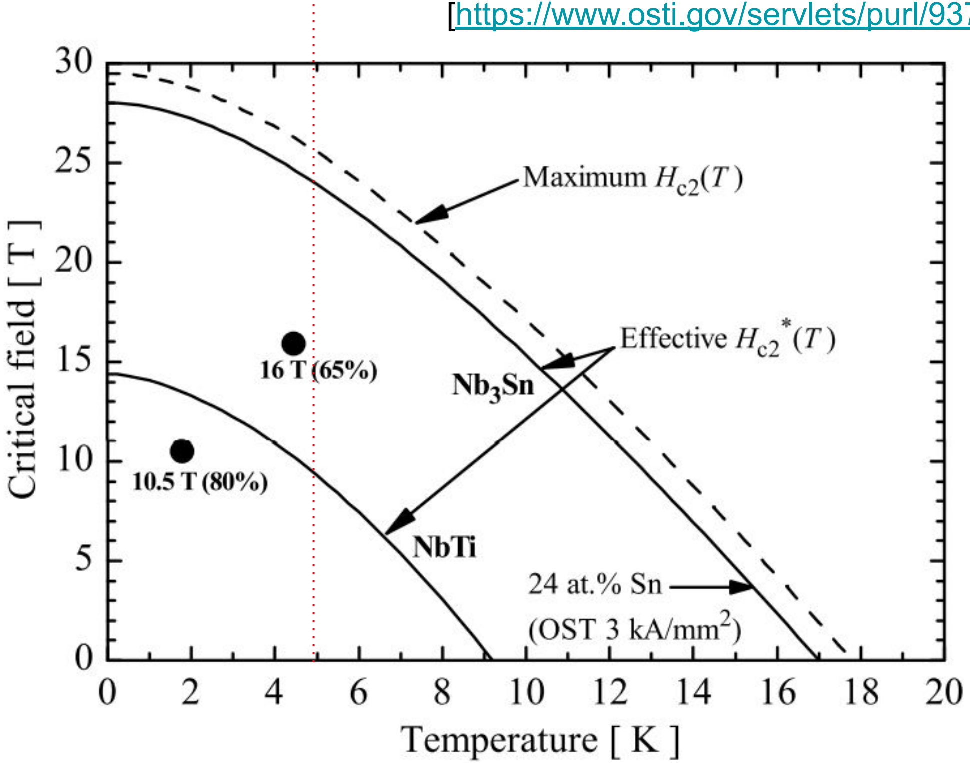


Fig. 1. Field-temperature phase boundaries and record magnetic fields in dipole magnets for NbTi and Nb_3Sn.