PF coil preconceptual design and electromagnetic analysis for the 2024 DEMO baseline

MAG-S.01.01-T031-D002/D004

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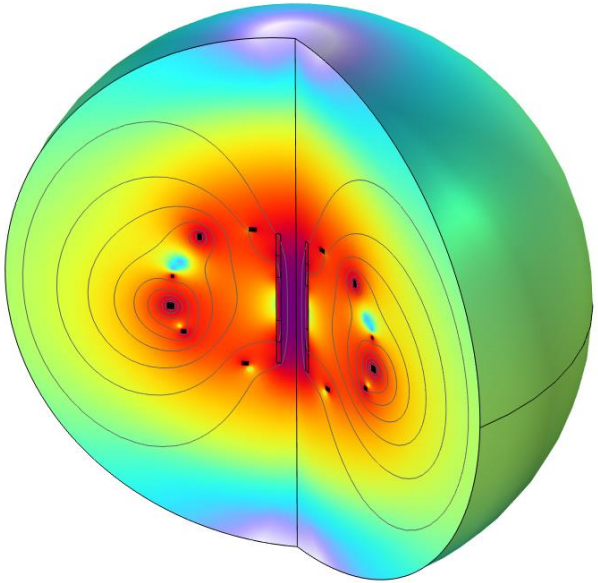
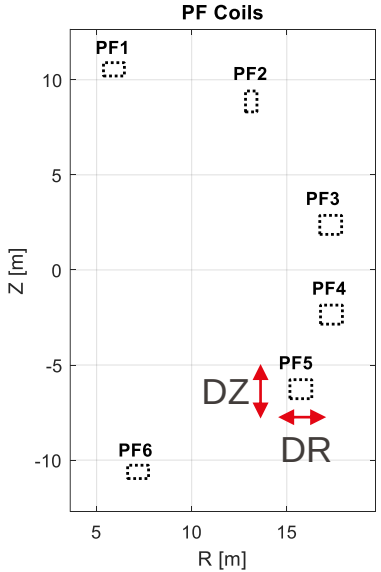


Geometric constraints

- The PF-coil locations are taken from Ambrosino [1] and are expressed in the machine (R,Z) coordinate system.
- Table lists the coil-box envelopes, with radial span DR and axial span DZ, together with the reference centre coordinates (R,Z) for PF1-PF6.
- Winding packs, including cable, layer, pancake, and ground insulation, are sized to fit within these envelopes.



	PF1	PF2	PF3	PF4	PF5	PF6
DR [m]	1.10	0.60	1.15	1.15	1.15	1.10
DZ [m]	0.70	1.10	1.00	1.00	1.00	0.70
R [m]	5.91	13.13	17.31	17.35	15.74	7.18
Z [m]	10.55	8.86	2.37	-2.35	-6.27	-10.62

Cable parameters and insulation thicknesses

- The cable-level parameters used for all PF coils. Partly taken from [3].

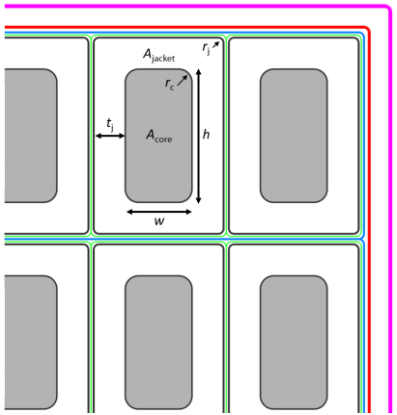
Object	Value
Theta	14 degrees
Void fraction	0.4
Strand diameter	0.82 mm
Cu:nonCu	1.4
Core aspect ratio w:h	1:2
Core fillet	5 mm
Steel fillet	2 mm

- The nominal insulation thicknesses adopted for the PF winding packs
  - These values are applied uniformly to PF1–PF6

Object	Value
Cable wrap	1 mm
Pancake wrap	1 mm
Double pancake wrap	2 mm
Ground wrap	8 mm

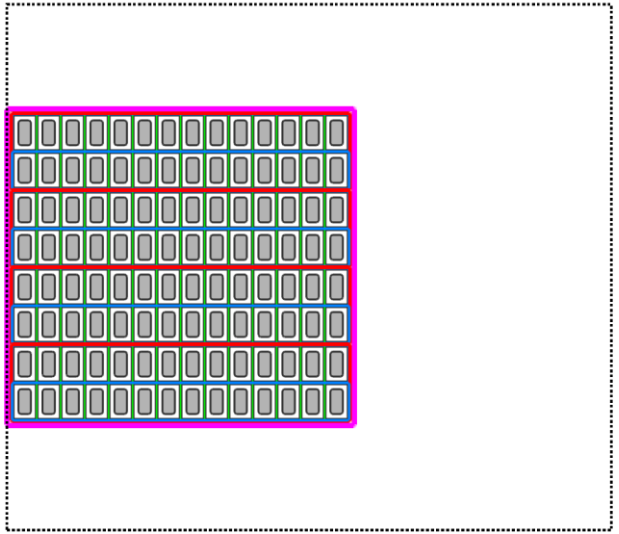
MATLAB model

- Generates cross section of winding pack geometry



PF5 cross-section

- Calculates number of SC and Cu strands
  - $N_{SC} = \lceil I_{cable}/(J_c(B_{max}, T_{op} + T_{mar}) \cdot A_{strand,nonCu} \rceil$
  - $N_{Cu} = \max(0, \lceil A_{Cu,need} - A_{Cu,SC}/A_{per-Cu} \rceil)$

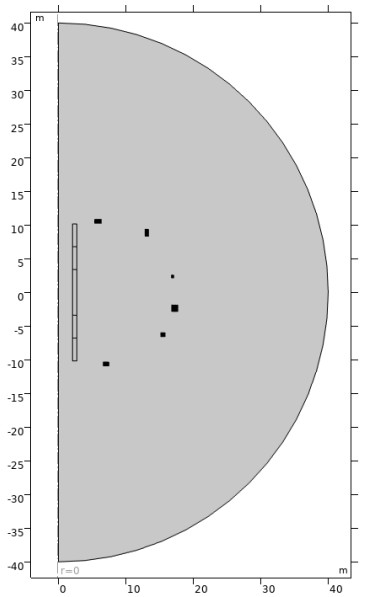


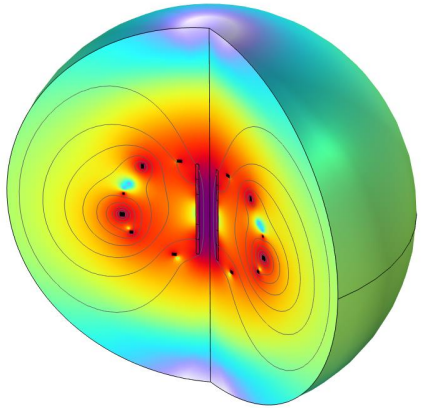
- Jacket stress:
  - $p_m = B_{max}^2/(2\mu_0)$
  - $\sigma_\theta = p_m \cdot (a^2+b^2)/(b^2 - a^2)$
  - $\sigma_j = A_{tot}/(A_{tot} - A_{core}) \cdot \sigma_\theta$

COMSOL model

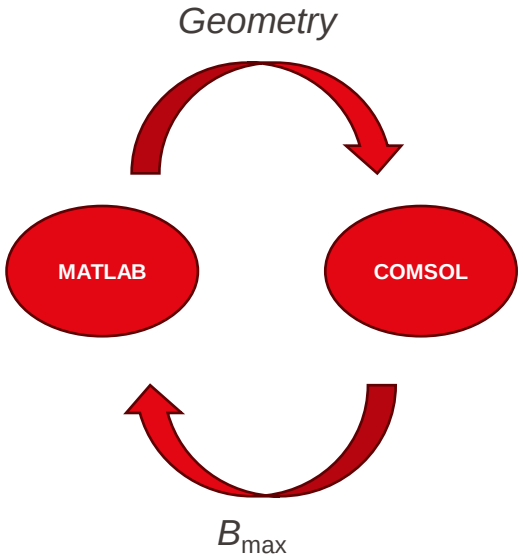
- The electromagnetic model is two-dimensional **axisymmetric** (*r*,*z*) using COMSOL's *Magnetic Fields (mf)* interface
- The central solenoid (CS) is represented as a single rectangular block.
- 4 coil powering scenarios investigated with different coil currents

	Premag	SOF	SOB	EOF
I_{CS3U} [MAt]	31.05	13.04	24.08	-8.63
I_{CS2U} [MAt]	35.08	3.01	0.58	-29.15
I_{CS1} [MAt]	70.16	-1.77	-7.31	-69.90
I_{CS2L} [MAt]	35.08	-8.32	-8.26	-35.08
I_{CS3L} [MAt]	33.76	26.82	24.25	-21.16
I_{PF1} [MAt]	9.62	11.65	6.58	-1.95
I_{PF2} [MAt]	2.30	-8.32	-8.32	-8.92
I_{PF3} [MAt]	-1.59	0.15	2.86	1.55
I_{PF4} [MAt]	3.09	-5.89	-12.90	-11.38
I_{PF5} [MAt]	-1.37	-6.55	-2.00	-4.11
I_{PF6} [MAt]	9.62	8.66	7.24	2.91





Design objectives and Iteration process



- MATLAB model with geometry is made, with the strand count, copper stabilizer, and jacket section.
- COMSOL calculates B_{max} on coil, which is fed back into the MATLAB sizing model, which get updated to keep the non-Cu current density, the copper current density, and the jacket stress within their targets.
- The process repeats until successive B_{max} estimates differ by less than 2%.

Object	Value
J_c max	<1000 A/mm^2
Max Copper current	<100 A/mm^2
Max steel stress	<300 MPa
Max cable current	<60 kA
Min jacket thickness	>4 mm
Temperature margin	2 K

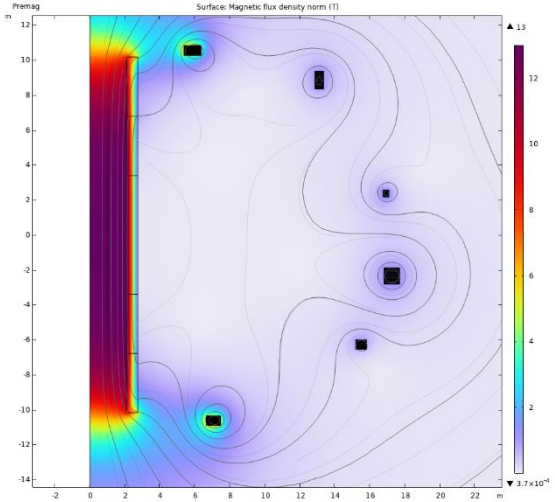
Critical current

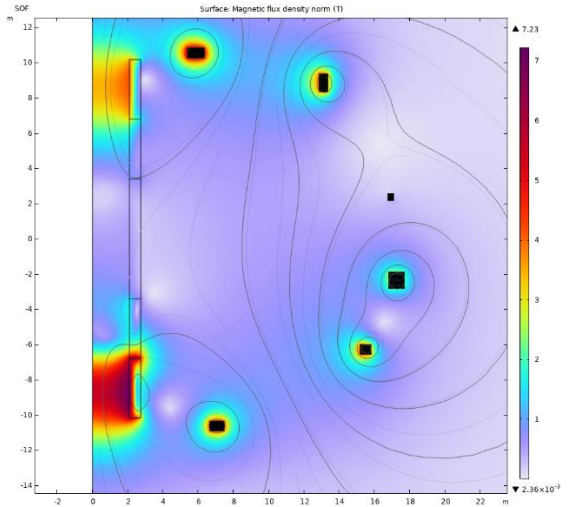
- The conductor performance is referenced to a Summers-type scaling law for Nb-Ti. The upper critical field is
  - $B_{c2}(T) = B_{c2}(0)[1 - (T/T_c)^{1.7}]$,
- and the critical current density is
  - $J_c(B,T) = \frac{C_0}{B}\left[1 - \left(\frac{T}{T_c}\right)^{1.7}\right]^{\gamma}\left(\frac{B}{B_{c2}(T)}\right)^{\alpha}\left(1 - \frac{B}{B_{c2}(T)}\right)^{\beta}$,
- By construction $J_c = 0$ for $B \geq B_{c2}(T)$ or $T > T_c$.

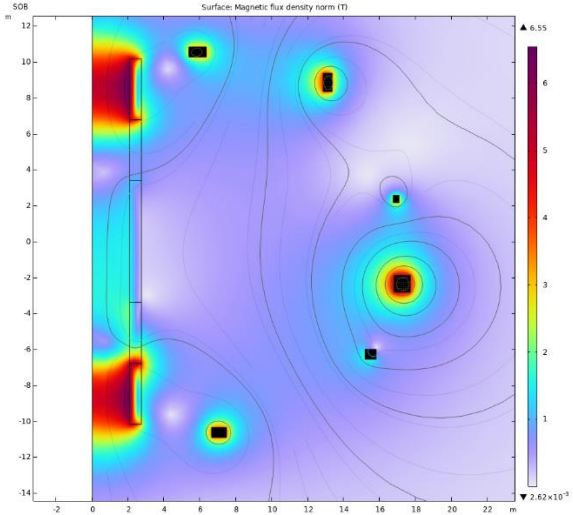
Parameter	Value
C_0	168,512 A/T/mm^2
B_{c2}	14.61 T
T_c	9.03 K
α	1
β	1.54
γ	2.1

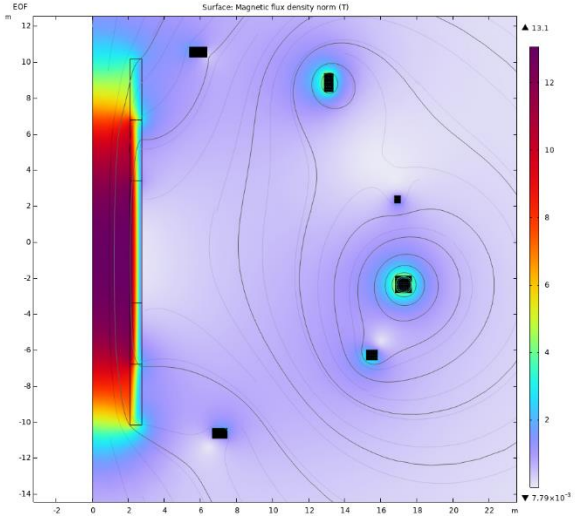
Magnetic field profiles

B_{max} [T]	Pre mag	SOF	SOB	EOF
PF1	5.53	5.72	3.27	1.93
PF2	1.21	4.33	4.29	4.62
PF3	1.71	0.40	3.30	1.96
PF4	1.22	2.48	5.31	4.64
PF5	0.97	4.49	1.90	3.13
PF6	5.69	4.51	3.72	1.96









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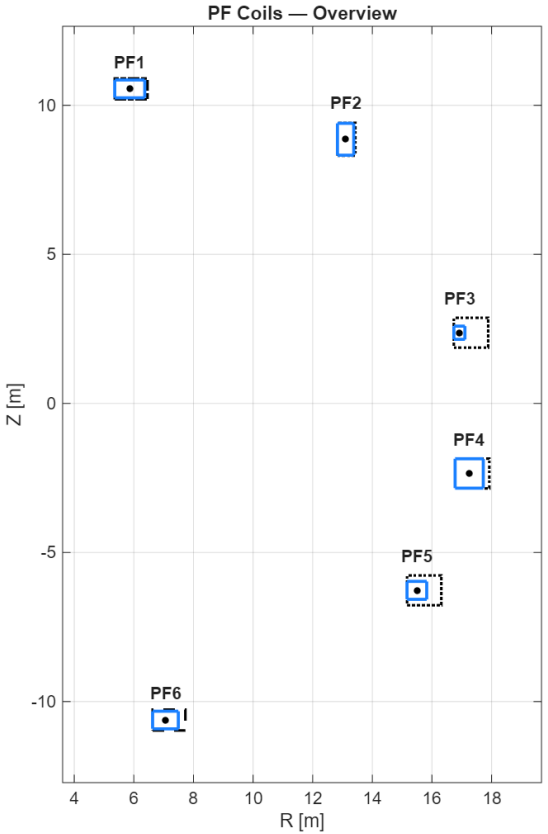
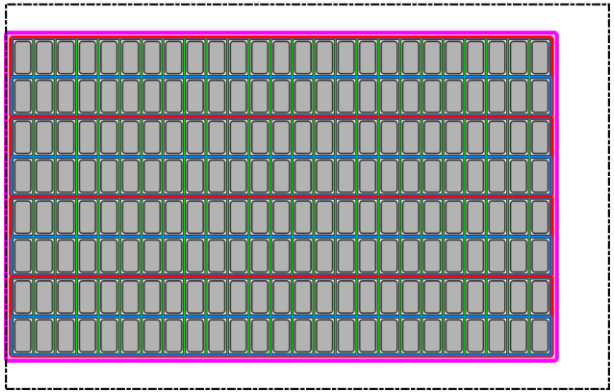
Resulting coil design

	PF1	PF2	PF3	PF4	PF5	PF6
DR [mm]	1005	545.79	370.86	946.64	661.16	862.31
DZ [mm]	597.12	1069.3	443.29	984.85	602.47	592.24
R [m]	5.8625	13.103	16.92	17.248	15.496	7.0612
Z [m]	10.55	8.86	2.37	-2.35	-6.27	-10.62
$N_{pancakes}$	8	14	6	12	8	8
N_{turns}	25	11	8	18	14	21
I_{cable} [A]	58250	57922	59583	59722	58482	57262
A_{SC} [mm²]	424.46	77.01	59.63	162.17	73.49	356.25
A_{Cu} [mm²]	594.25	579.42	596.27	597.24	585.05	572.68
J_{SC} [A/mm²]	137.23	752.09	999.19	368.27	795.74	160.74
J_{Cu} [A/mm²]	98.02	99.97	99.93	100.00	99.96	99.99
$J_{c,max}$ [A/mm²]	137.24	753.80	1000.00	368.45	797.32	160.83
$J_c(B_{max}, T=4.5$ K) [A/mm²]	2231	3294	4480	2685	3358	2284
N_{SC}	1929	350	271	737	334	1619
N_{Cu}	0	893	971	701	913	140
Θ [deg]	14	14	14	14	14	14
A_{metal} [mm²]	1018.71	656.43	655.90	759.41	658.54	928.93
w [mm]	29.32	23.62	23.61	25.37	23.65	28.01
h [mm]	58.64	47.23	47.22	50.74	47.31	56.03
t_j [mm]	4	11	9	12	10	5
σ_j [MPa]	232.59	271.14	276.81	279.55	266.98	262.50
L_{hyd} [m]	920.88	905.61	850.51	1950.74	1363.06	931.70

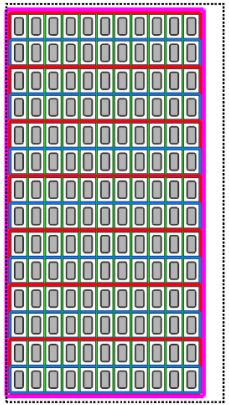


Coil cross-sections

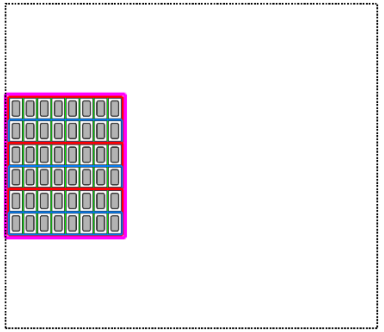
PF1 cross-section



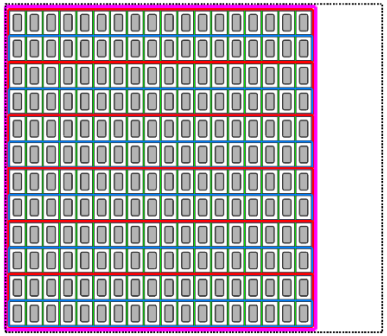
PF2 cross-section



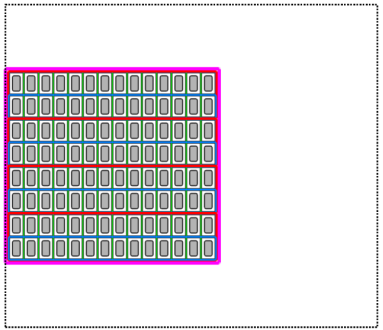
PF3 cross-section



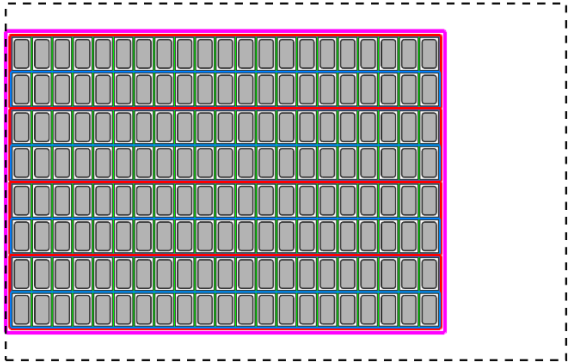
PF4 cross-section



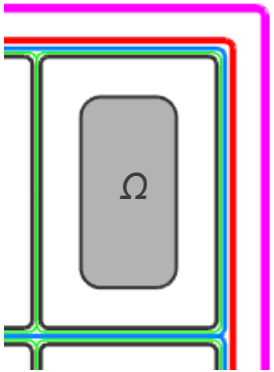
PF5 cross-section



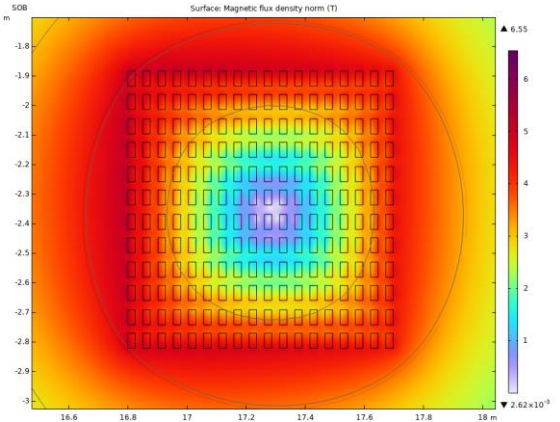
PF6 cross-section



Effective magnetic field calculation

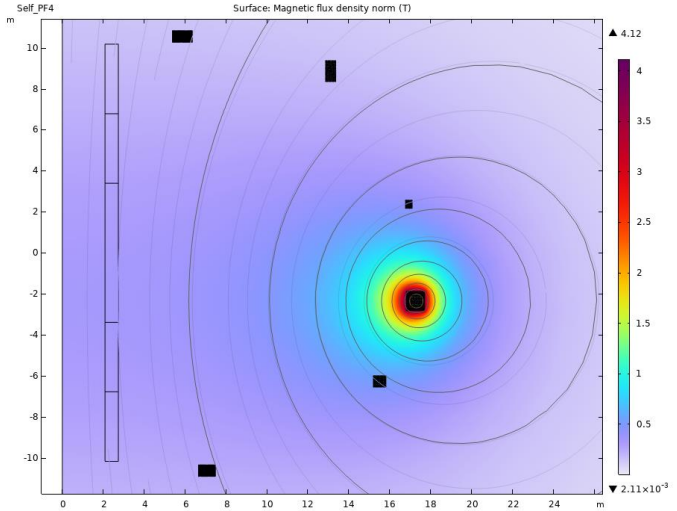


- For a given turn domain Ω, the centerline field is taken at the geometric centroid (r_c, z_c),
  - $A = \int_\Omega \, dA \,,\; r_c = \frac{1}{A}\int_\Omega \, r \, dA \,,\; z_c = \frac{1}{A}\int_\Omega \, z \, dA \,.$
- The centerline magnitude and components are then
  - $B_c^{\mathrm{nom}} = |\mathbf{B}(r_c, z_c)|,\; B_{r,c} = B_r(r_c, z_c),\; B_{z,c} = B_z(r_c, z_c).$
- To obtain the effective critical current, we use a power mean of order $-n$, where $n = 20$, applied to J_c at temperature $T = 6.5$ K:
  - $J_{c,\mathrm{eff}} = \frac{1}{A}\left(\int_\Omega \, [J_c(B,T)]^{\,-n} dA\right)^{-1/n}.$
- The effective magnetic field magnitude B_{eff} is defined implicitly by requiring that the uniform-field model at temperature T reproduces the same effective J_c
  - $J_c(B_{\mathrm{eff}}, T) = J_{c,\mathrm{eff}}.$
- B_{eff} is then found by solving the nonlinear equation
  - $J_c(B,T) - J_{c,\mathrm{eff}} = 0$



Inductance calculation

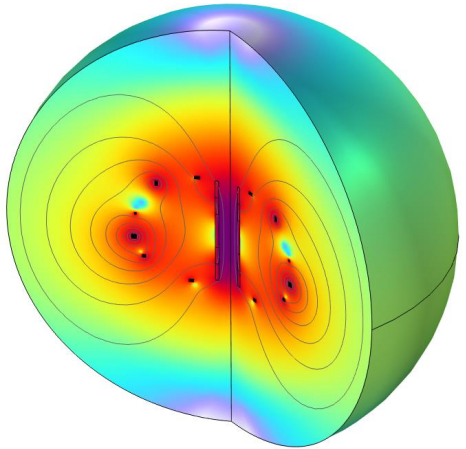
- The inductance matrix was obtained with the energy method
  - $L_{ii} = \frac{2E_{ii}}{I^2}$.
- Mutual inductance between coils *i* and *j:*
  - $M_{ij} = \frac{E_{ij}}{I^2} - \frac{1}{2}(L_{ii} + L_{jj})$.



	PF1	PF2	PF3	PF4	PF5	PF6
PF1	21.349	5.230	2.619	1.680	1.084	0.236
PF2	5.230	59.868	14.840	8.628	5.189	0.983
PF3	2.619	14.840	97.040	27.570	14.648	2.379
PF4	1.680	8.628	27.570	79.37	27.642	3.712
PF5	1.084	5.189	14.648	27.642	78.32	5.522
PF6	0.236	0.983	2.379	3.712	5.522	28.20

Conclusion

- All coils can be built within the prescribed coil envelope, and within the required specifications.
  - All PF coils can be made out of Nb-Ti
- Various aspects need to be studied more in detail to refine the design.
  - For this design, a fixed conductor aspect ratio height to width of 2:1 is chosen. However, it is not determined that this is the most optimal aspect ratio.



Thanks for your attention!

References

- [1] R. Ambrosino and E. Acampora, "2024 DEMO Single Null baseline with aspect ratio 2.8: reference electromagnetic plasma scenario " EUROfusion, 2024.
- [2] M. Kumar, " MAG-2.1-T025-D003 - Design of the PF coil based on the 2018 DEMO reference" EUROfusion, 2020. [Online]. Available: https://idm.euro-fusion.org/default.aspx?uid=2MVZQV
- [3] K. Sedlak, "MAG-S.01.01-T001-D004 - Revise Design Philosophy Manual," EUROfusion, 2023. [Online]. Available: https://idm.euro-fusion.org/default.aspx?uid=2P8ZVJ