Rectilinear 6D Cooling Magnet Design

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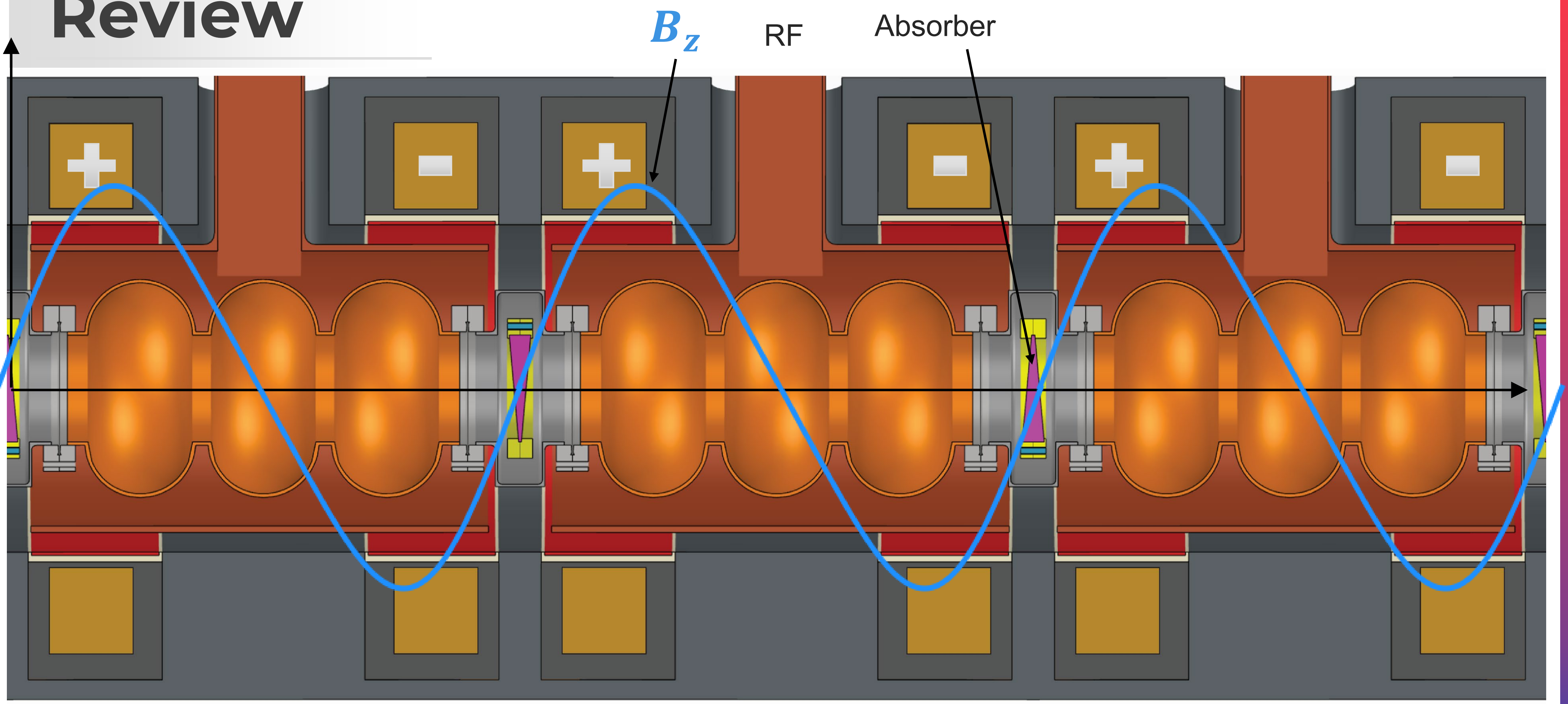
Review



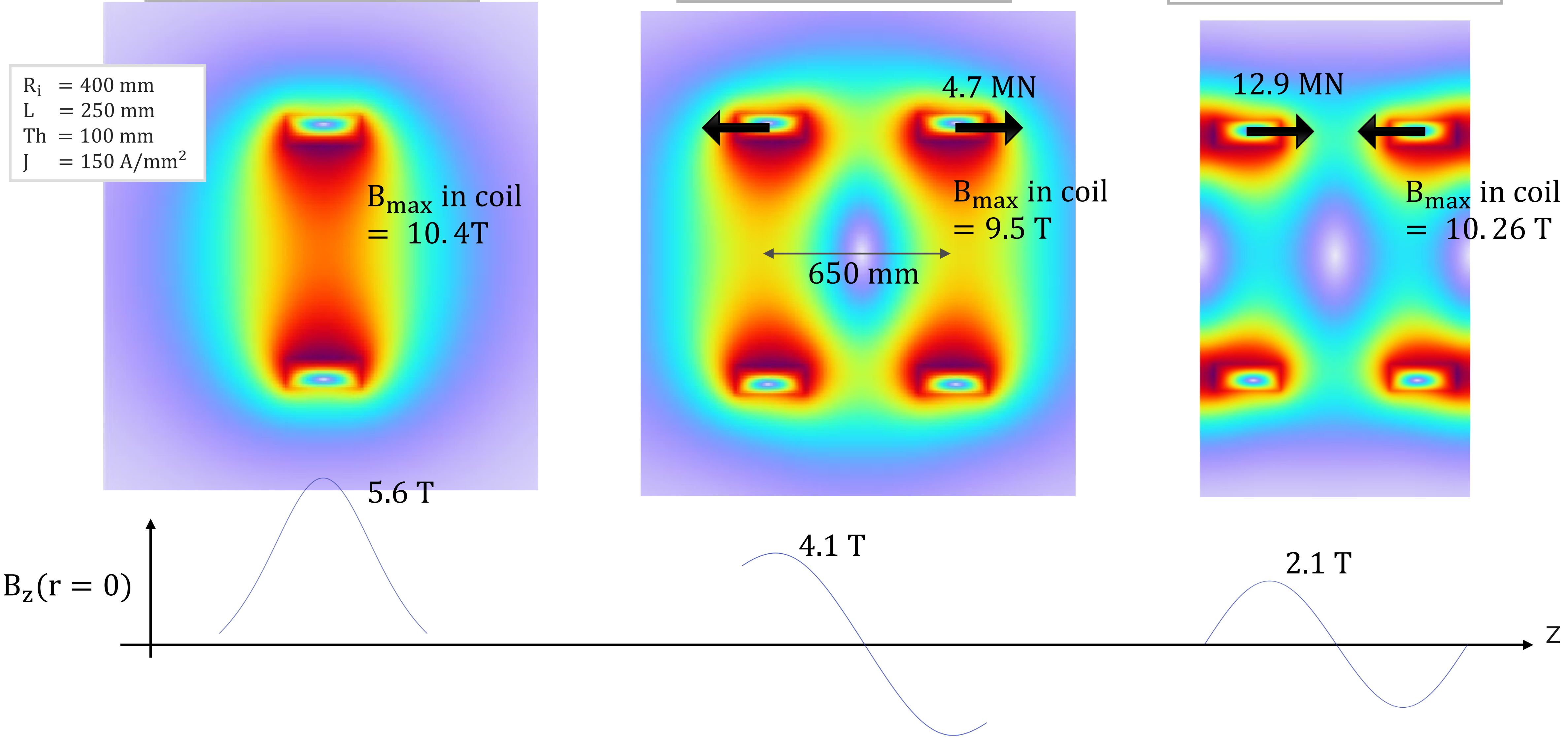
Alternating polarity solenoids create an oscillating field B_z in z.

This field can be described by harmonic components, $B_z = B_1 \sin\left(\frac{2\pi z}{L_{cell}}\right) + B_2\, sin\left(\frac{4\pi z}{L_{cell}}\right) + B_3\, sin\left(\frac{6\pi z}{L_{cell}}\right) + \ \ldots$

Review

Solenoid Operating Environments

Single Solenoid | Single Cell, 1 m | Cell in a Lattice



Review

9 T on-axis should be easy, right?

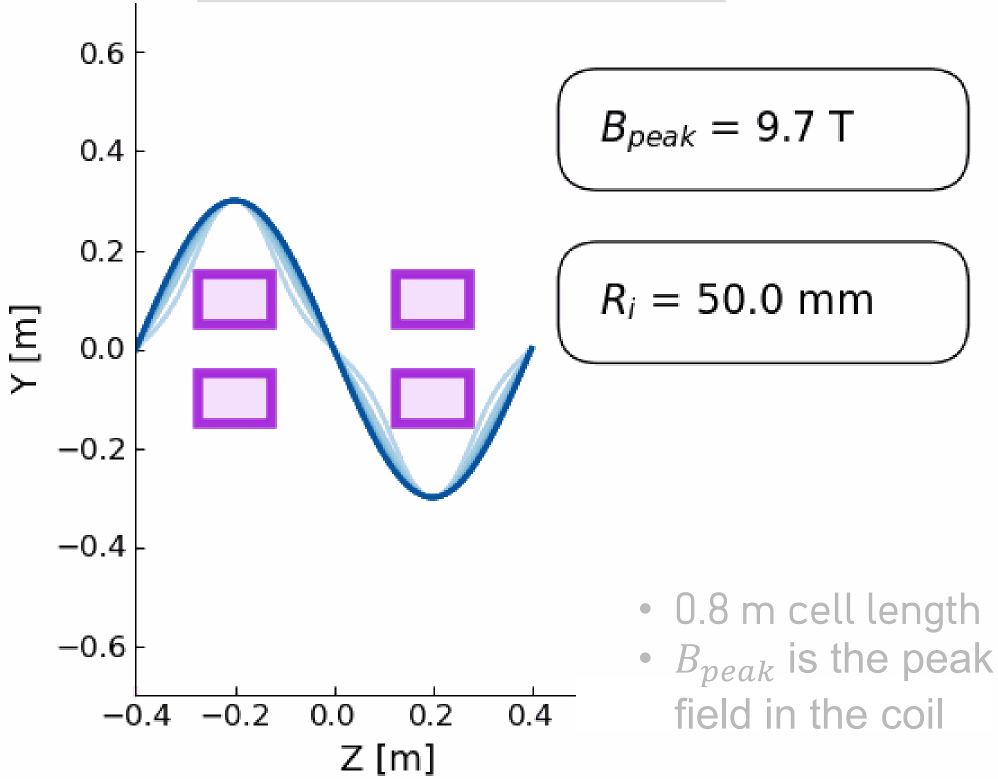
… **how close together** are the **opposite** polarity solenoids?

…what is the **bore radius**?

…what is the **cell length**?

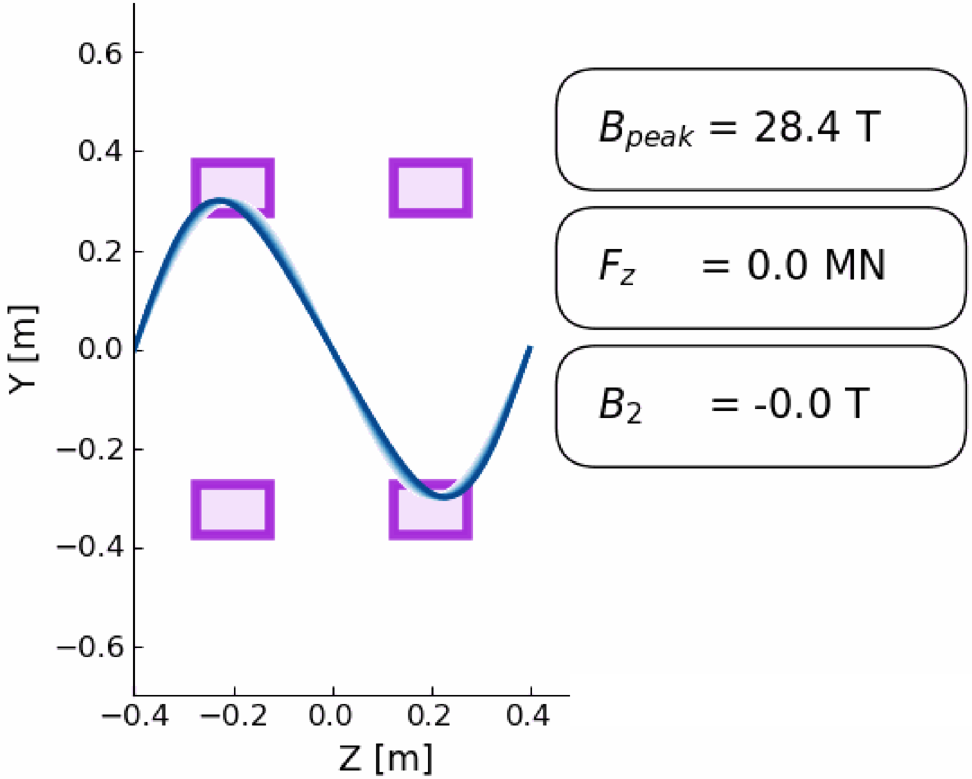
Example, maintain 9 T peak on-axis while:

Increasing R_i



- 0.8 m cell length
- B_{peak} is the peak field in the coil

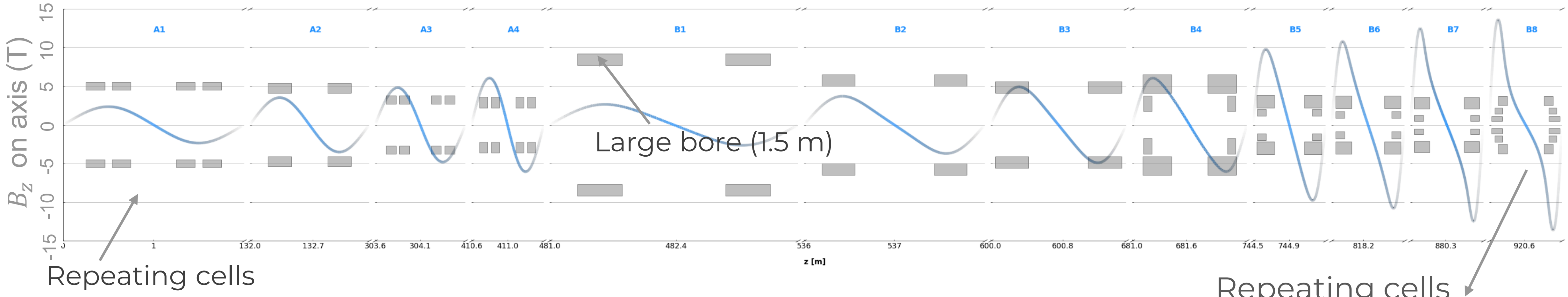
Increasing the gradient (B_2)



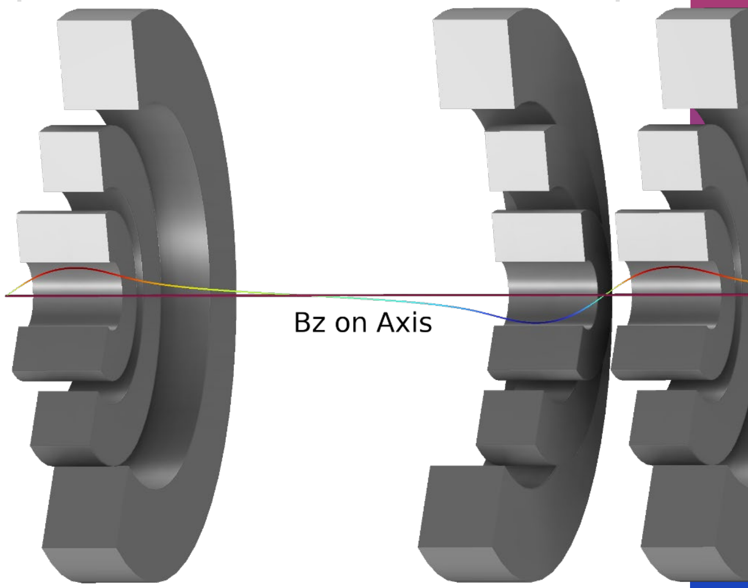
Review

Baseline Reference (MAP) Evaluation

~3000 solenoids per ~1 km long cooling chain | **18 unique** solenoid types
On axis field 2.4 T to 13.6 T | **Bore size** from 90 mm to 1.5 m



Repeating cells



Un-optimized from engineering perspective

- Large average **hoop stresses** (peak 340 MPa)
- Tensile **radial stresses** (peak 20 MPa)
- Large stored **magnetic energies** (up to 45 MJ in one coil)
- Largest contributor to **cost** of magnets & powering in 3 TeV machine

Design Considerations

1. The solenoids should be designed to within reasonable engineering limits.

   ➡ What are the limits on stresses, forces, magnetic energy density, spacing of HTS solenoids in our size range?

2. Solenoid features (stress, energy, ..) vary depending if they are operated stand-alone, in a single cell, or in a lattice.

   ➡ Should solenoids be designed based on the worst-case scenario or more optimistically with advanced protection mechanisms?

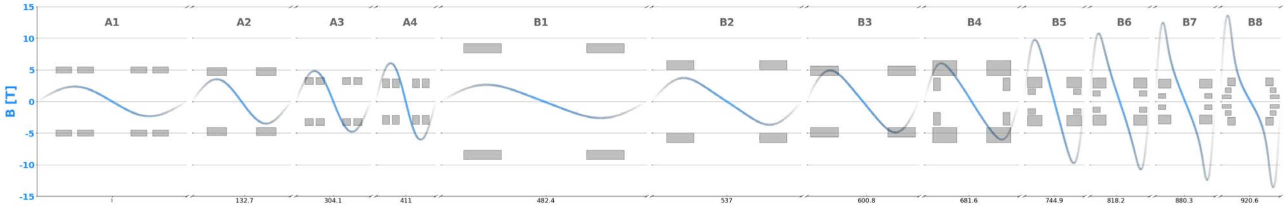
3. The most efficient/cost-effective (also operating costs) SC material should be used.

   ➡ Can lower field cells be designed with LTS, or focus more on uniformity using HTS throughout (cryogenic considerations)?

Timeline

2023 — US-MAP Magnet Analysis

Magnets were designed to fit desired on-axis field.
Only constraint: the peak field of the solenoid does not exceed the limits of Nb_3Sn.



Low J_E

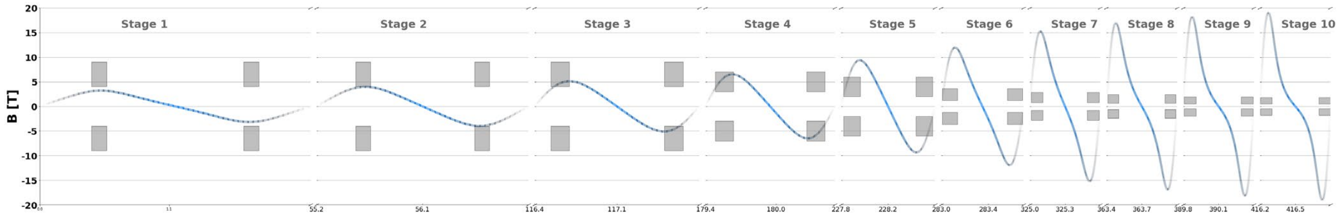
Cell	J_E (A/mm^2)	B_{peak} (T)	E_{Mag} (MJ)	e_{Mag} (MJ/m^3)	σ_{Hoop} (MPa)	σ_{Radial} (MPa)
A1	63.25	4.1	5.4	20.5	34	−4.6/0.0
A2	126.6	9.5	15.4	76.3	137	−28.3/0.0
A3	165	9.4	7.2	72.8	138	−28.5/0.0
A4	195	11.6	8.4	91.5	196	−49.4/0.0
B1	69.8	6.9	44.5	55.9	95	−13.5/0.0
B2	90	8.4	24.1	61.8	114	−20.1/0.0
B3	123	11.2	29.8	88.1	174	−36.6/0.0
B4	94	9.2	24.4	42.4	231	−23.5/19.7
B5	168	13.9	12	86.3	336	−55.7/21.1
B6	185	14.2	8.2	68.3	314	−43.1/22.3
B7	198	14.3	5.7	59.6	244	−37.4/20.7
B8	220	15.1	1.4	20.3	119	−22.9/22.1

→ Un-optimized

Develop optimization tool

Jan. 2024 — New Optics Configuration & Analysis

Magnet initial design to fit desired on-axis field by optics.
Magnets not constrained, highly unrealistic.



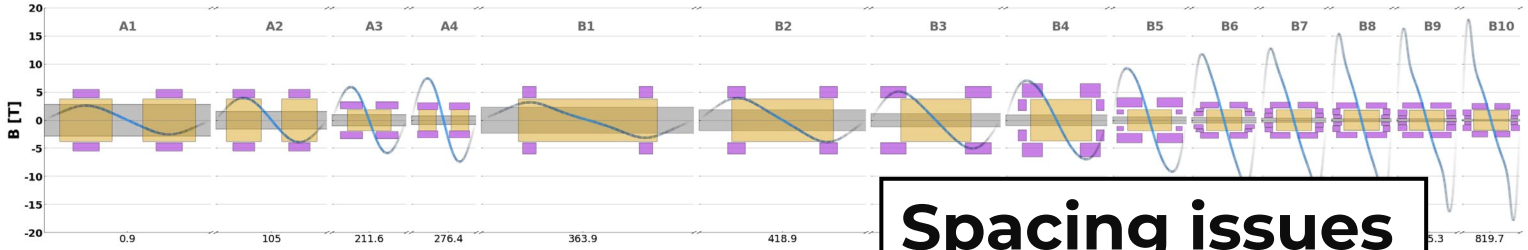
Analysis shows excessive:

- Hoop stresses (> 800 MPa)
- Radial stresses (>80 MPa)
- Stored energies (>300 MJ/m3)
- Peak fields in conductor (>30 T)
- Large forces, ….

Jun./ Aug. 2024

New Optics Configuration & Analysis

Magnets constrained using our guide (next slide).



Spacing issues

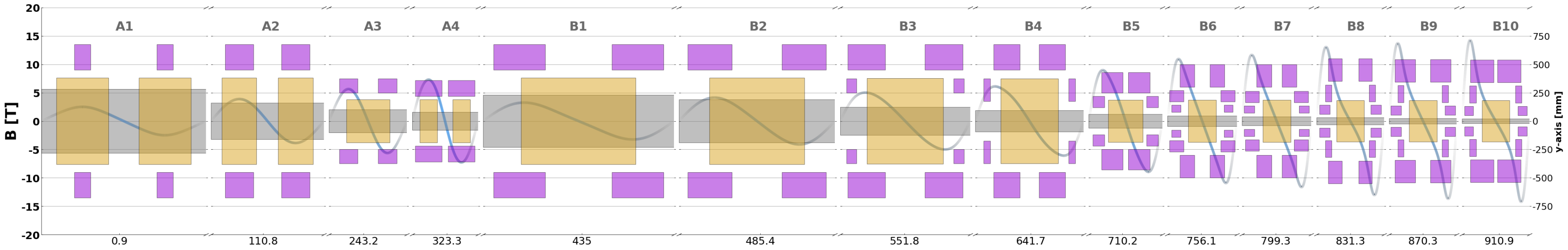
Cell	E_{Mag} (MJ)	e_{Mag} (MJ/m^3)	Coil	J_E (A/mm^2)	B_{peak} (T)	σ_{Hoop} (MPa)	σ_{Radial} (MPa)
A1	5.4	20.5	A1-1	63.25	4.1	34	-5/0
A2	15.3	75.8	A2-1	126.6	9.5	137	-28/0
A3	7.2	72.8	A3-1	165	9.4	138	-29/0
A4	8.4	91.5	A4-1	195	11.6	196	-49/0
B1	44.5	55.9	B1-1	69.8	6.9	95	-14/0
B2	24.1	61.8	B2-1	90	8.4	114	-20/0
B3	29.8	88.1	B3-1	123	11.2	173	-37/0
B4	24.1	42.4	B4-1	94	9.2	231	0/20
			B4-2	70.3	7.8	66	-24/0
B5	12	86.3	B5-1	157	13.9	336	0/21
			B5-2	168	12.3	159	-55/0
B6	8.2	68.3	B6-1	185	14.2	314	-1/22
			B6-2	155.1	10.3	118	-43/0
B7	5.6	58.6	B7-1	198	14.2	244	-1/21
			B7-2	155	10.1	118	-37/0
B8	1.4	20.3	B8-1	220	15.1	255	-3/22
			B8-2	135	6.2	110	-2/5
			B8-3	153	6.2	41	-23/0

Demonstrator magnet design (providing valuable input/feedback)

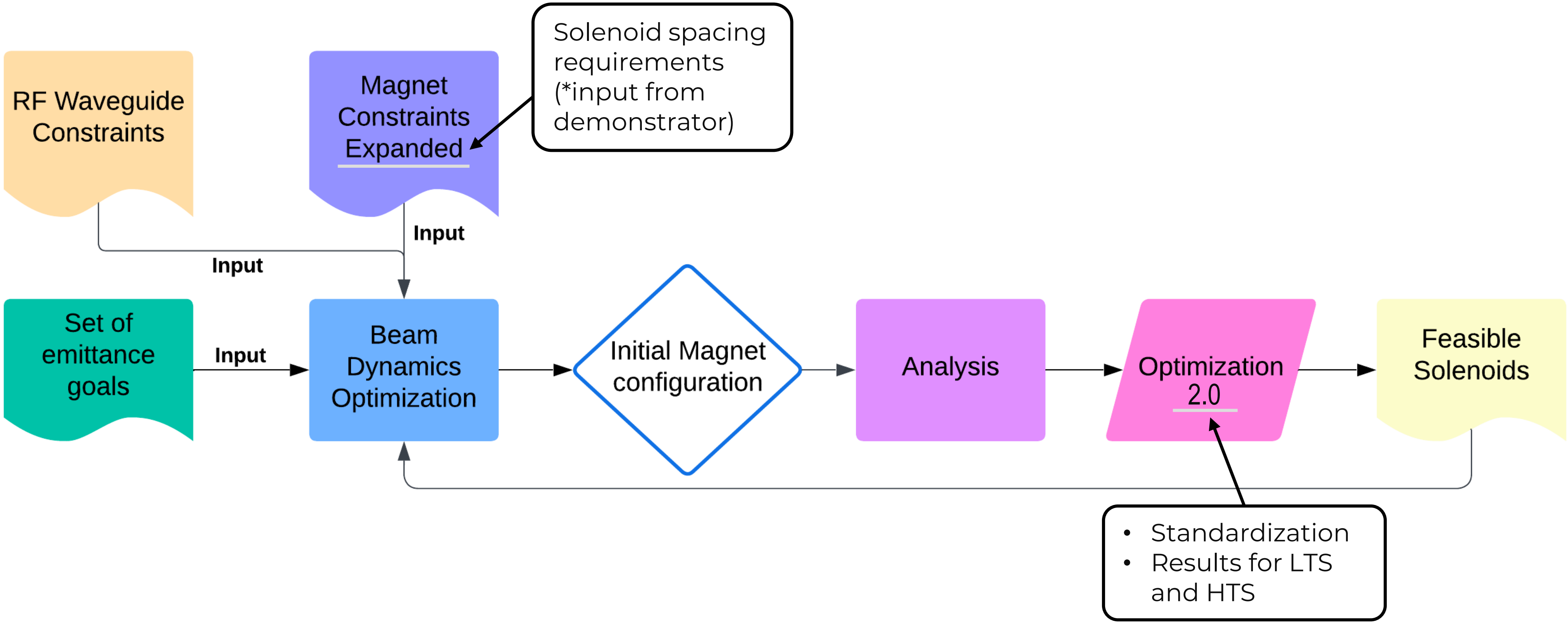
US-MAP optics optimization

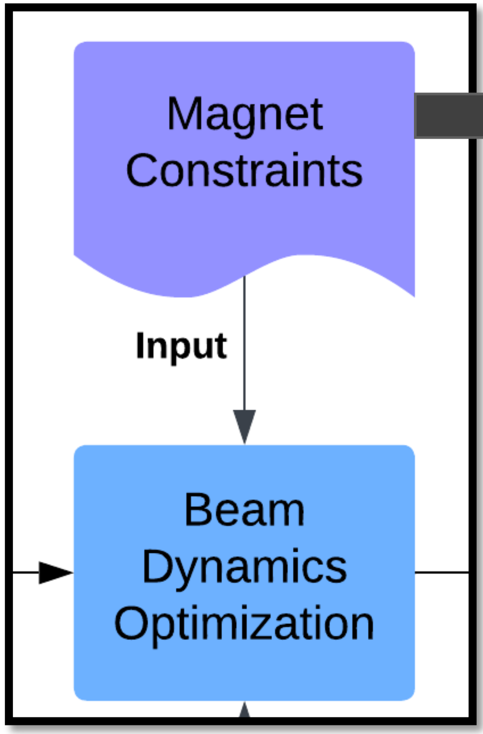
2025

New Optics Configuration & Analysis



Workflow 2025





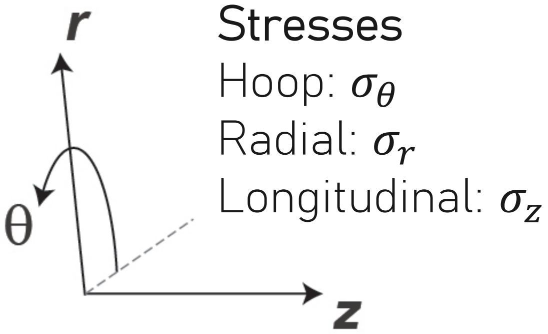
Set of semi-analytic equations describing a single solenoid,

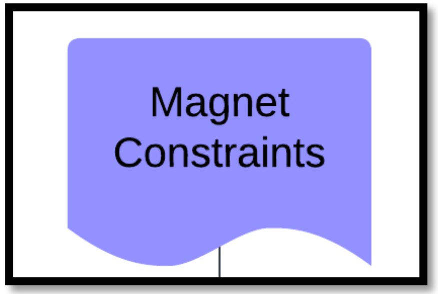
- $\boldsymbol{\sigma_\theta}$: hoop stress
- $\boldsymbol{\sigma_r}$: radial stress
- $\boldsymbol{e_m}$: magnetic energy density
- $\boldsymbol{J_c}$: critical current density

Limits

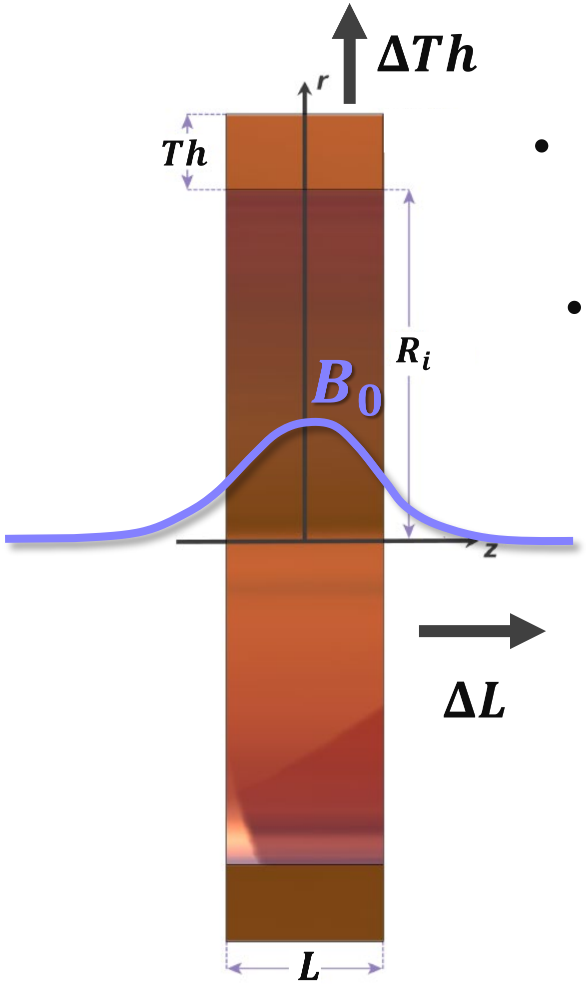
Example limits

- $\boldsymbol{\sigma_\theta \leq 300}$ MPa
- $\boldsymbol{\sigma_r \leq 20}$ MPa (Tensile)
- $\boldsymbol{e_m \leq 150}$ MJ/m3
- $\boldsymbol{J_c}$: HTS at $\boldsymbol{T_{op} = 20}$ K and 2.5 K margin (Fujikura FESC-SCH tape)

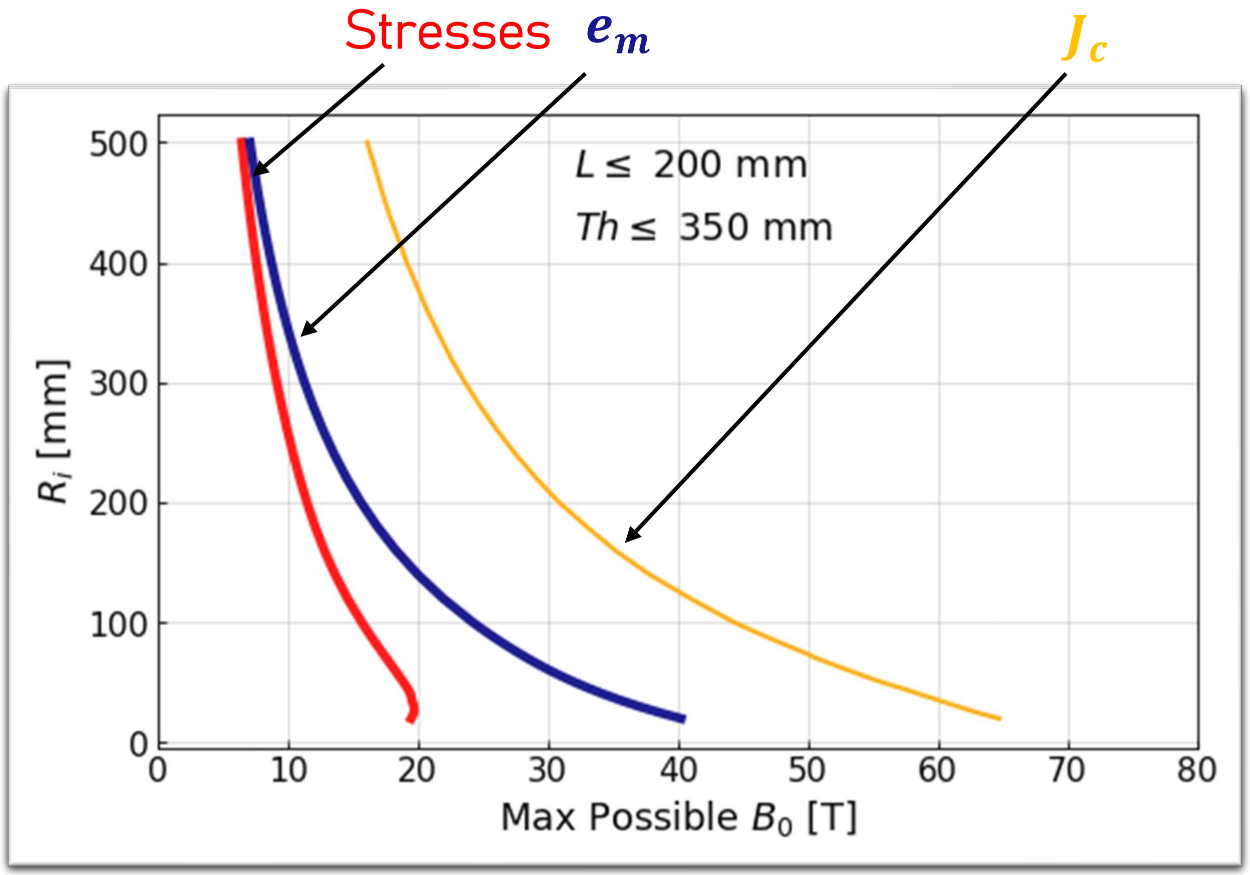


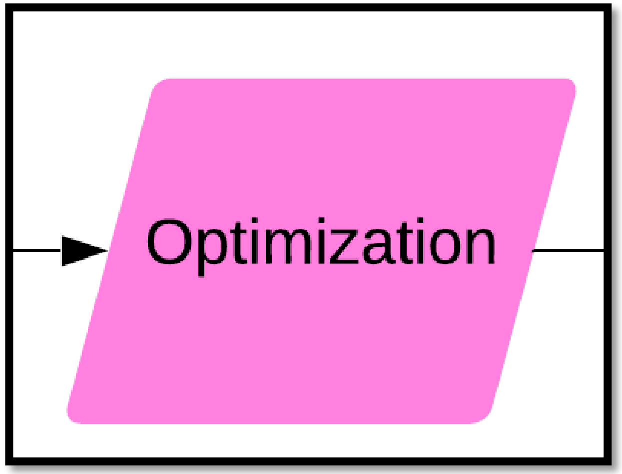


Visualization tool → AB Plots



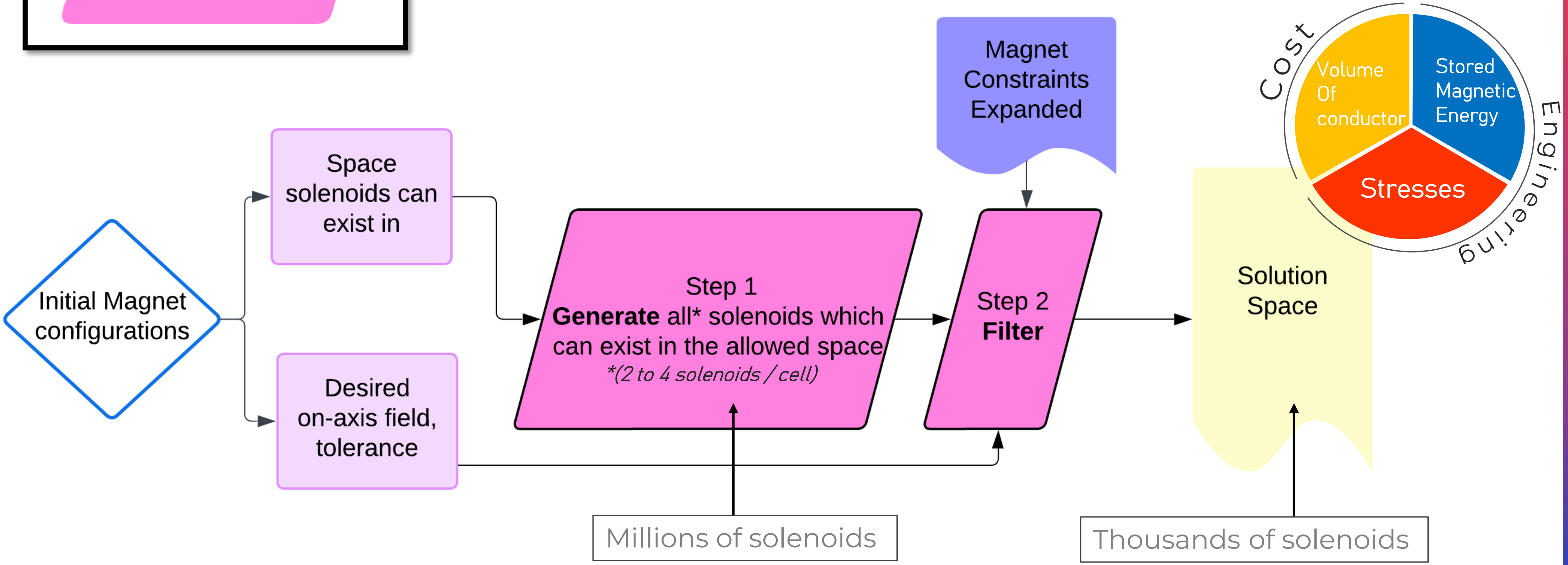
- At each radius, finely scan in $\boldsymbol{L}$ and $\boldsymbol{Th}$
  - Compute $\boldsymbol{B_0}$ & scale by limits
    - ❑ $\sigma \propto B_0^2$
    - ❑ $e_m \propto B_0^2$
    - ❑ $J_c(\mathrm{B})$ …

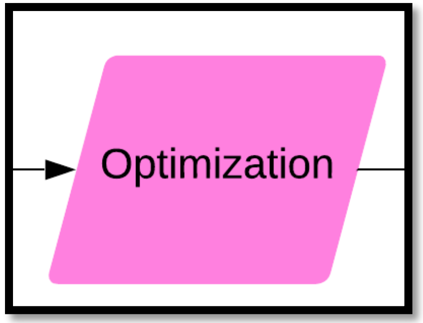




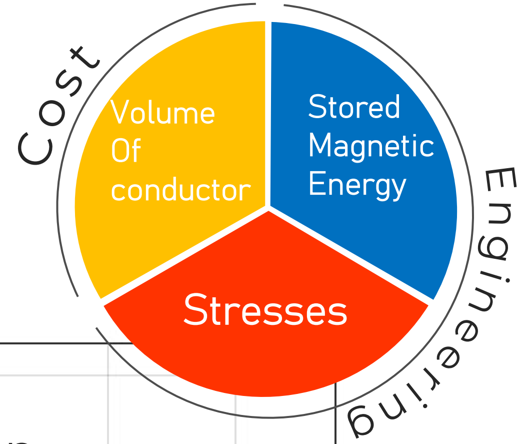
Solenoid in-Cell Optimization (SiCO)

a **numerical optimization tool** which can search for the **best** solenoid solution depending on weighted design criteria and technology options.



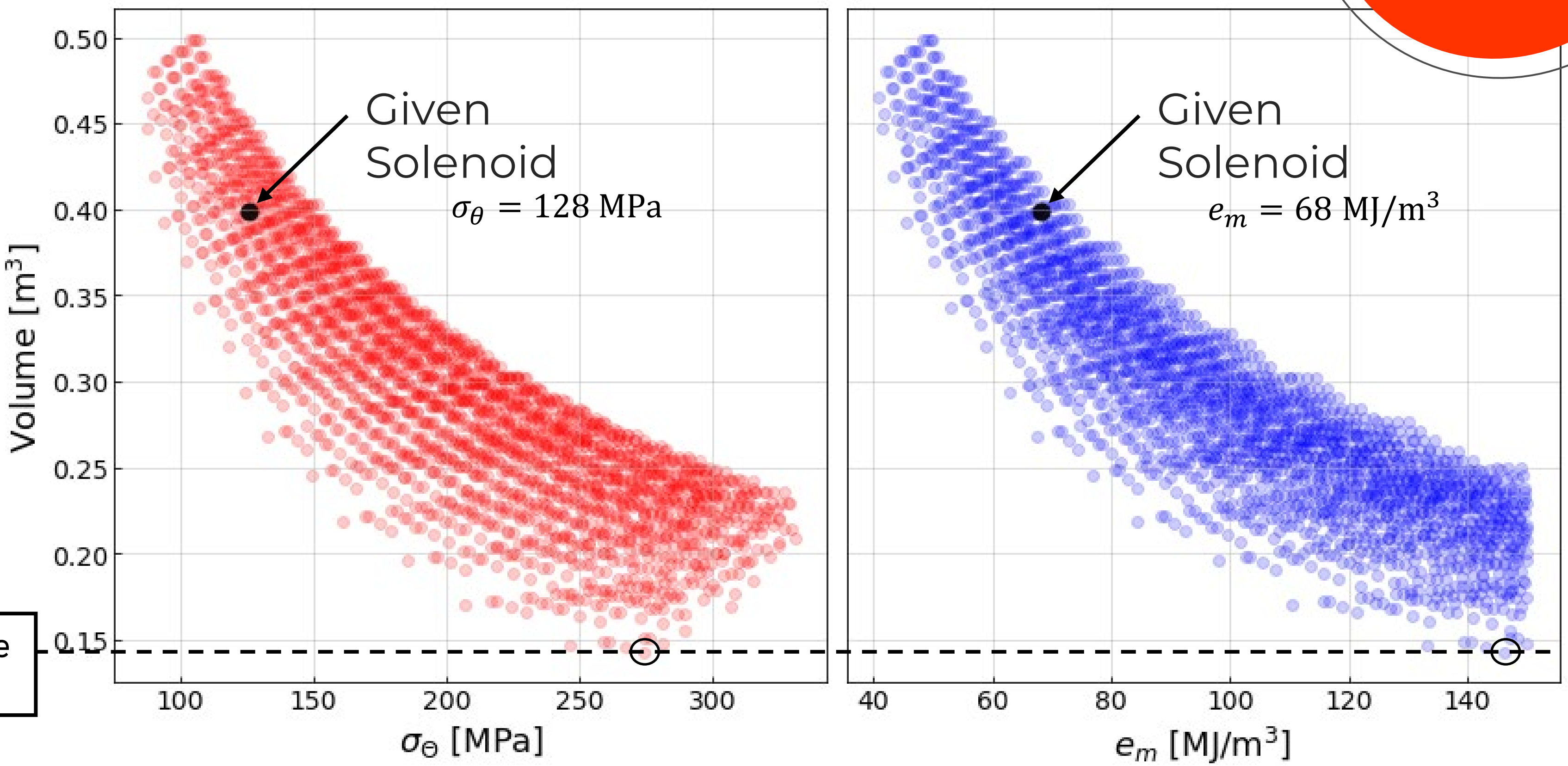


Ex. US-MAP, Cell B1



Solution Space

(2.4 k solutions)

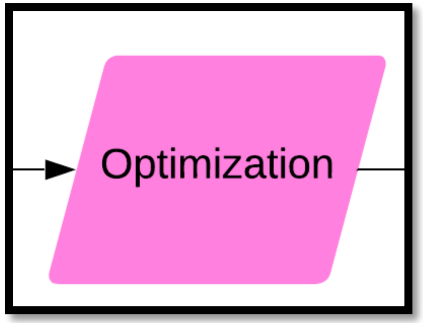


Min. Volume solution

Volume reduction by 63%

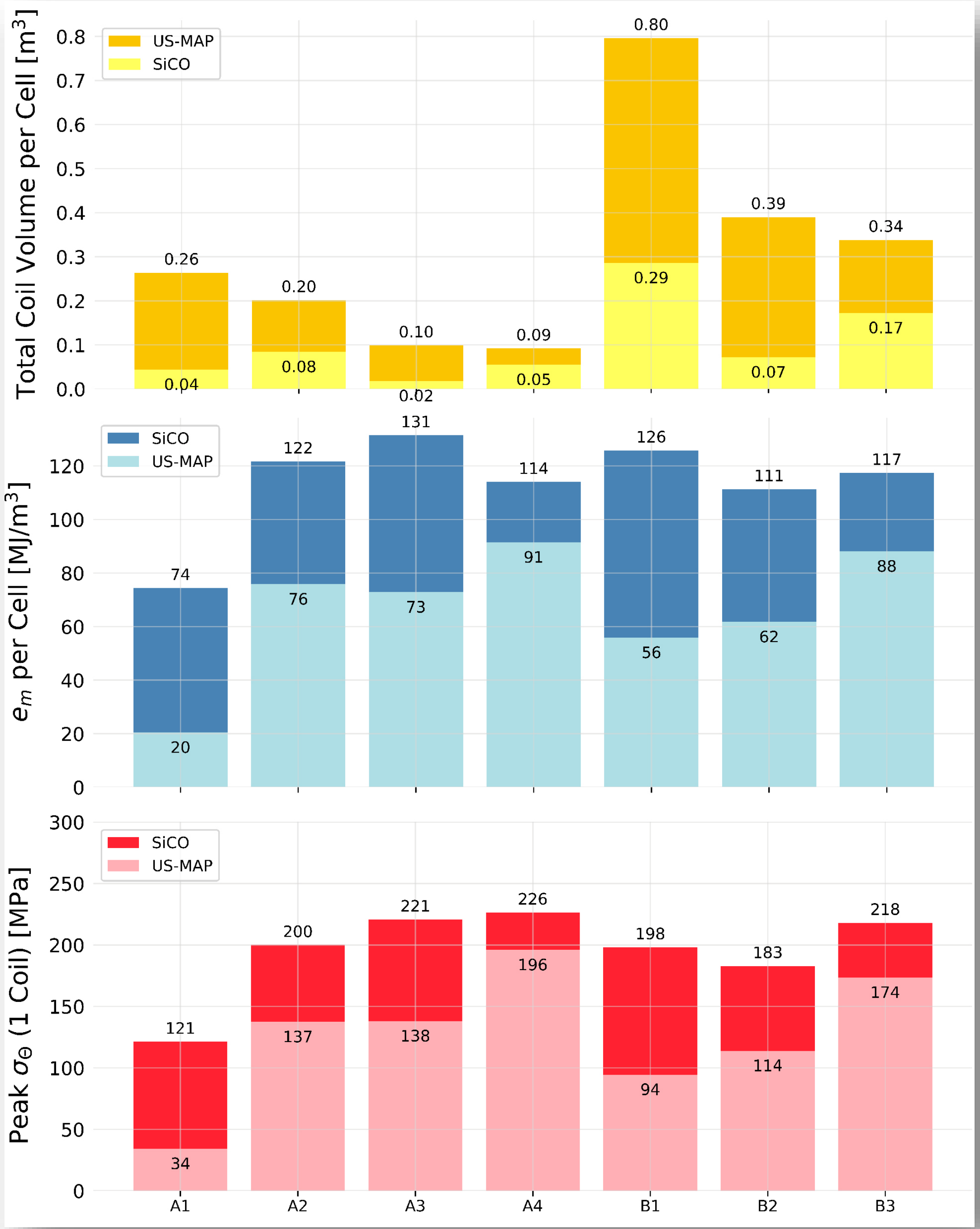
Operating Stand-alone
- $\sigma_\theta = 276$ MPa
- $e_m = 147\ \mathrm{MJ/m^3}$

Operating in a Lattice
- $\sigma_\theta = 200$ MPa
- $e_m = 126\ \mathrm{MJ/m^3}$



Results, US-MAP A1-A4, B1-B3

Minimum volume solutions (SiCO)



new optics analysis

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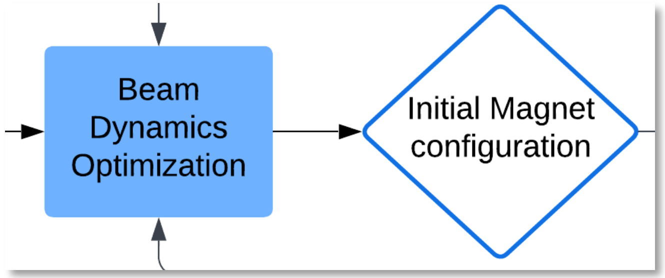
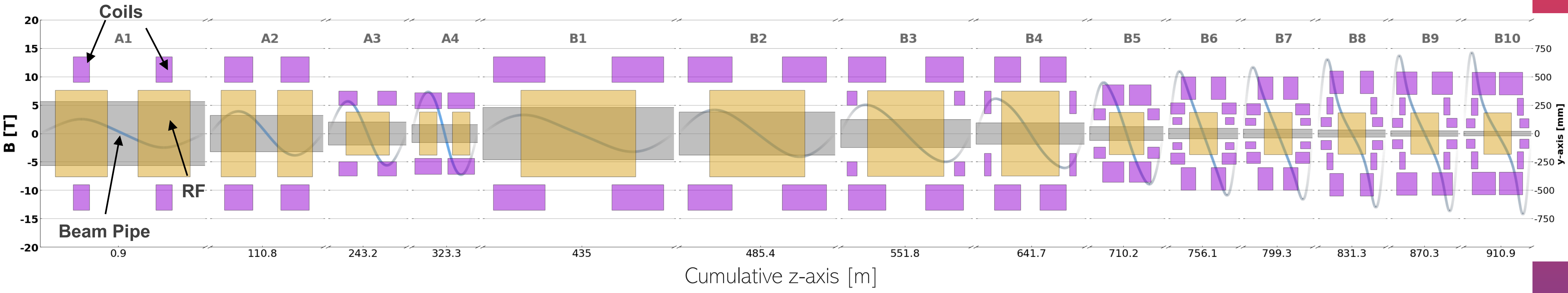
(March 2025)



Total Number of Solenoids in 1 chain: **3026**

Total Length: **945 m**

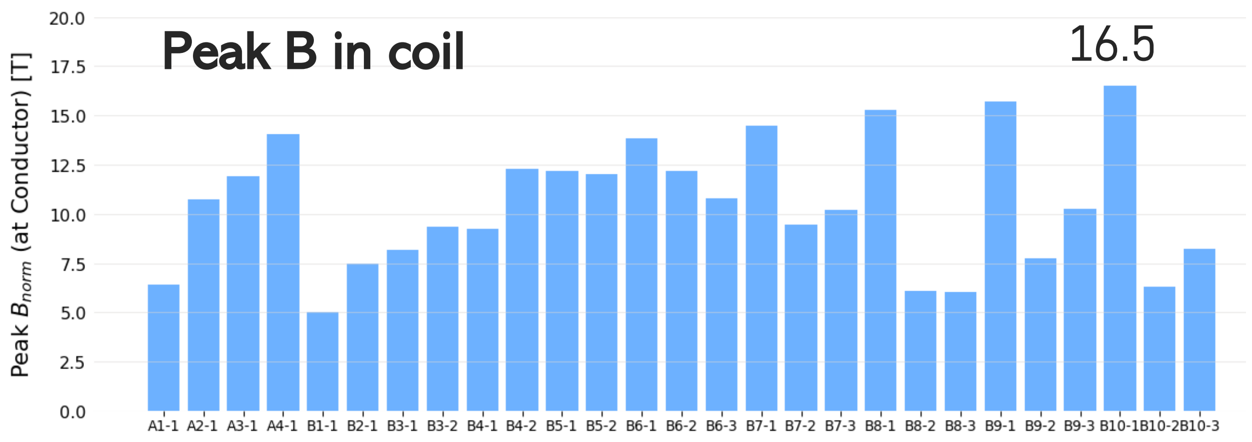
On axis field from **2.5 T** to **14.3 T** (in Lattice)

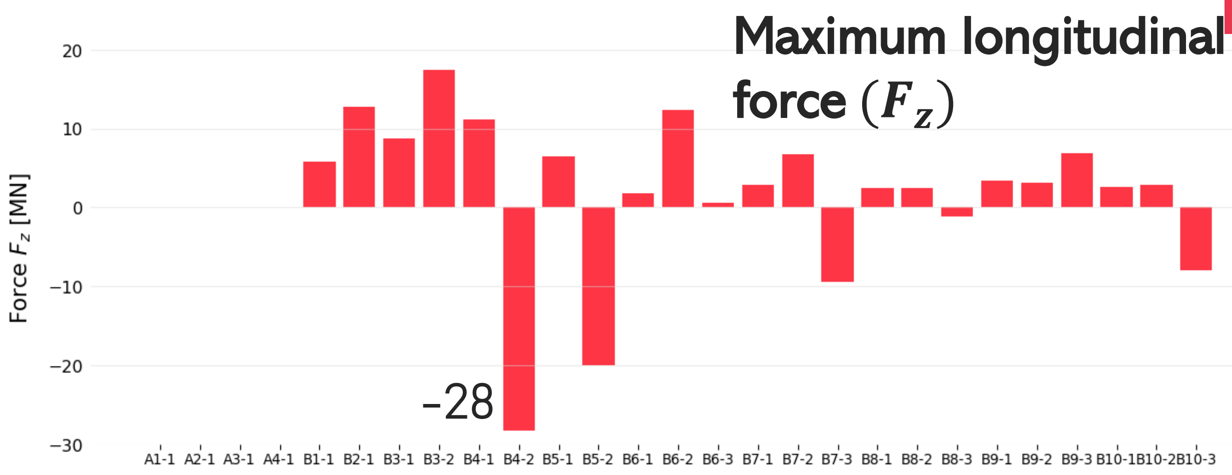


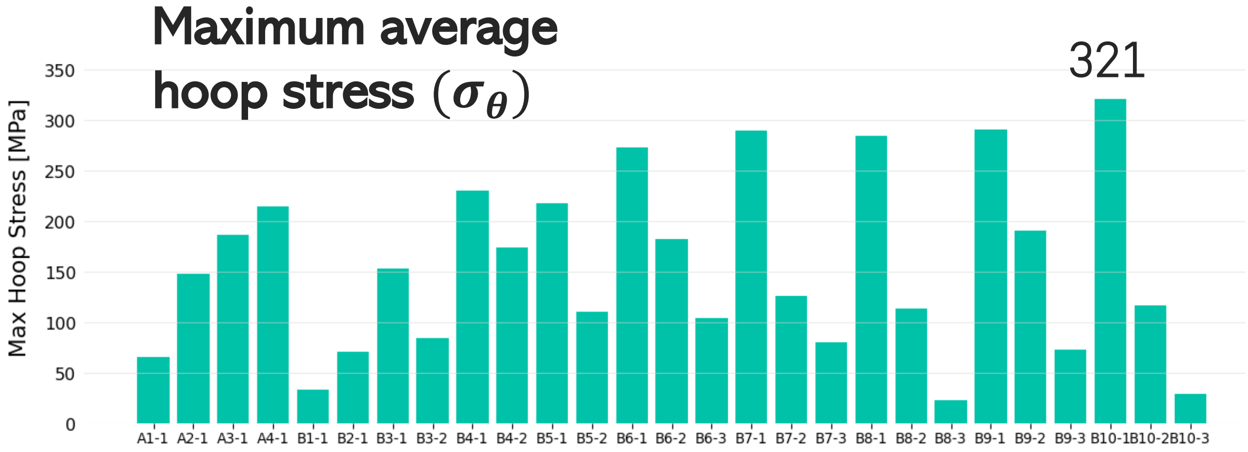
27 unique solenoid types

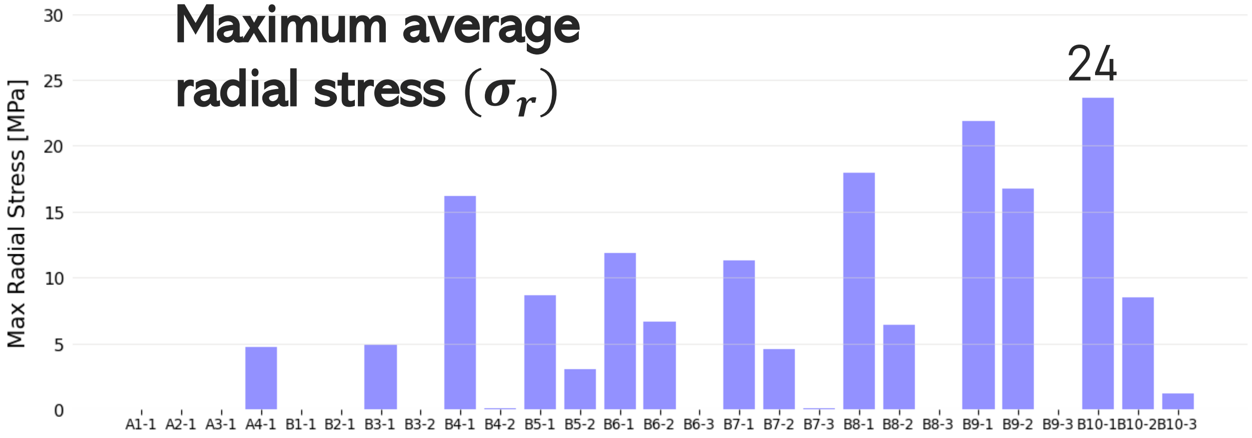
- **Bore radius** from **50 mm** to **450 mm**
- **Length** from **70 mm** to **600 mm**
- J_E from **32 A/mm2** to **255 A/mm2**
- **Cell Length** from **0.76 m** to **2.2 m**
- **Number of cells** from **23** to **146**

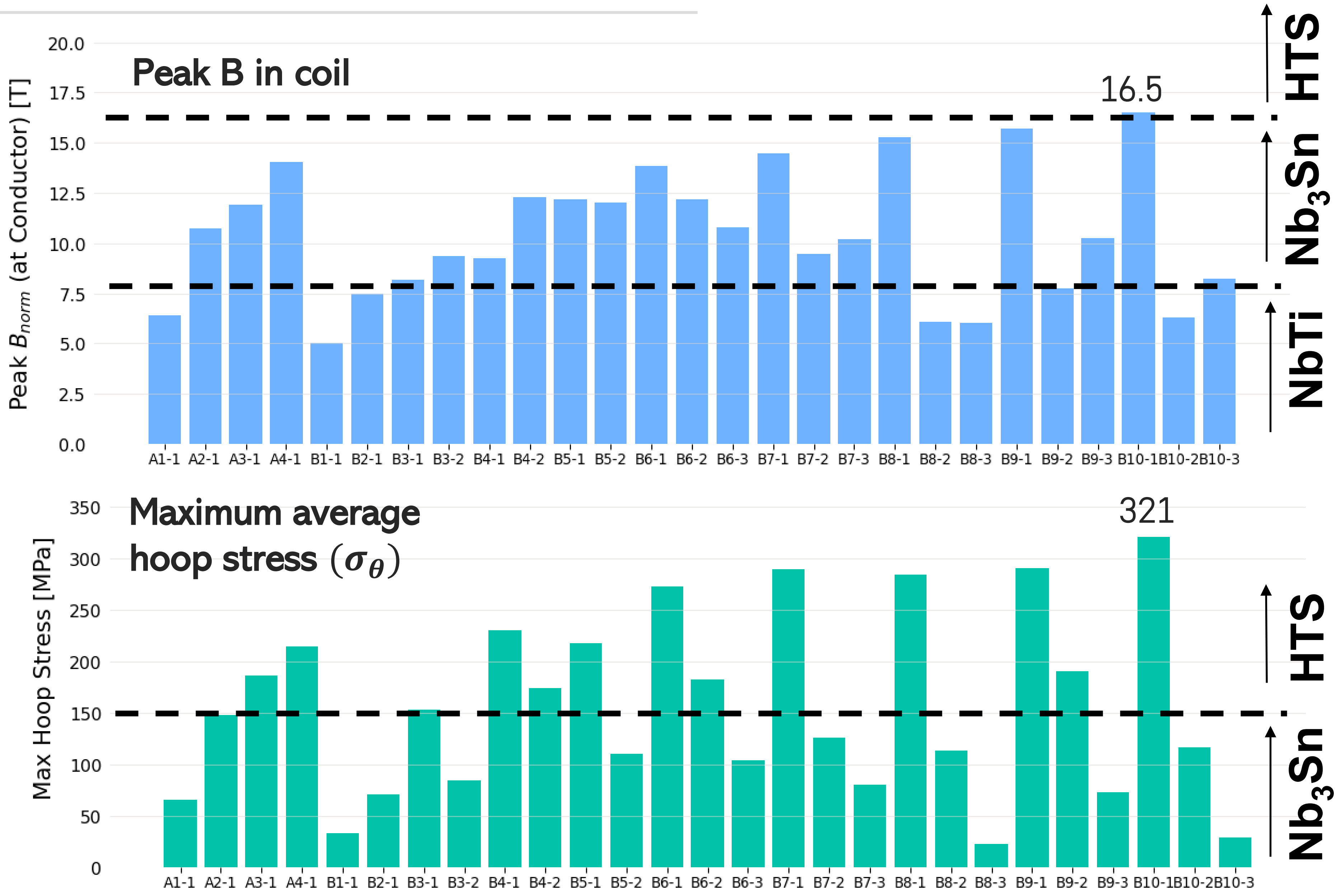
Analysis, Op. in Lattice










Peak B in coil
Peak B_{norm} (at Conductor) [T]
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
16.5
HTS
Nb_3Sn
NbTi
A1-1 A2-1 A3-1 A4-1 B1-1 B2-1 B3-1 B3-2 B4-1 B4-2 B5-1 B5-2 B6-1 B6-2 B6-3 B7-1 B7-2 B7-3 B8-1 B8-2 B8-3 B9-1 B9-2 B9-3 B10-1 B10-2 B10-3
Maximum average hoop stress (σ_θ)
Max Hoop Stress [MPa]
350
300
250
200
150
100
50
0
321
HTS
Nb_3Sn
A1-1 A2-1 A3-1 A4-1 B1-1 B2-1 B3-1 B3-2 B4-1 B4-2 B5-1 B5-2 B6-1 B6-2 B6-3 B7-1 B7-2 B7-3 B8-1 B8-2 B8-3 B9-1 B9-2 B9-3 B10-1 B10-2 B10-3

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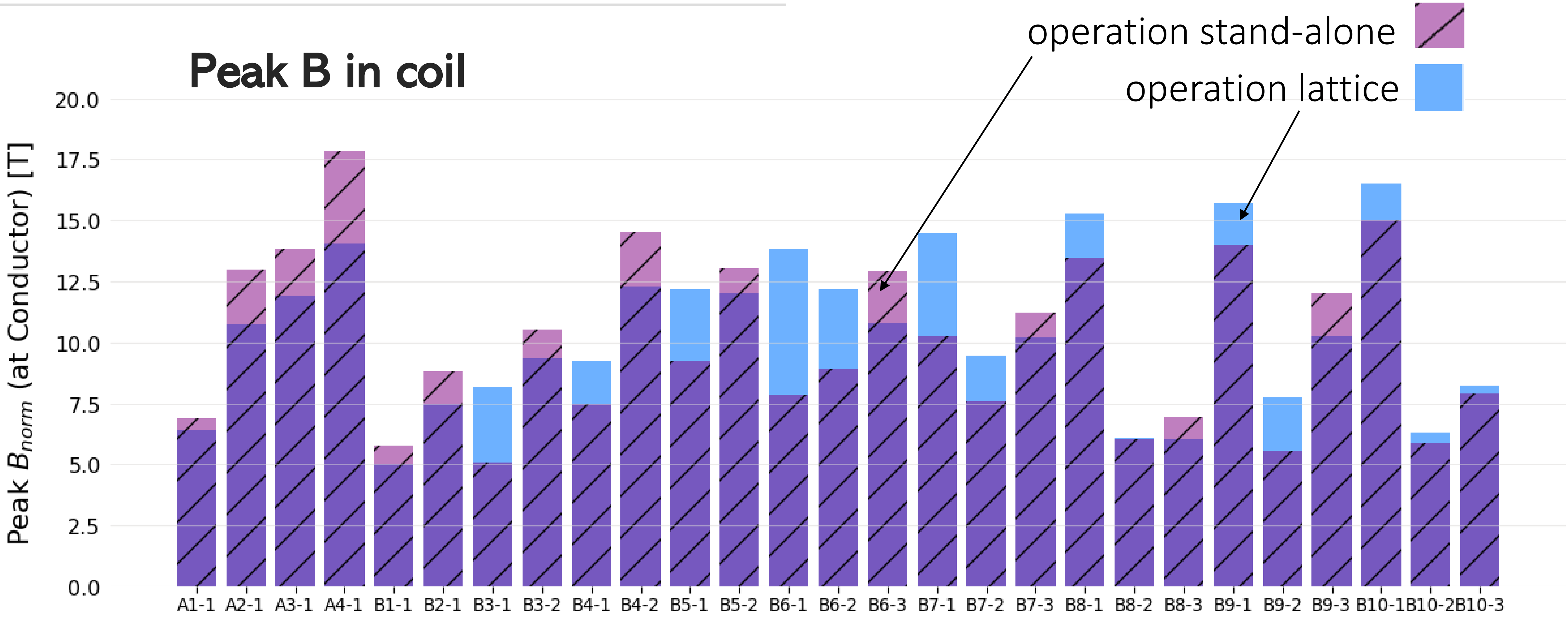
Peak B in coil



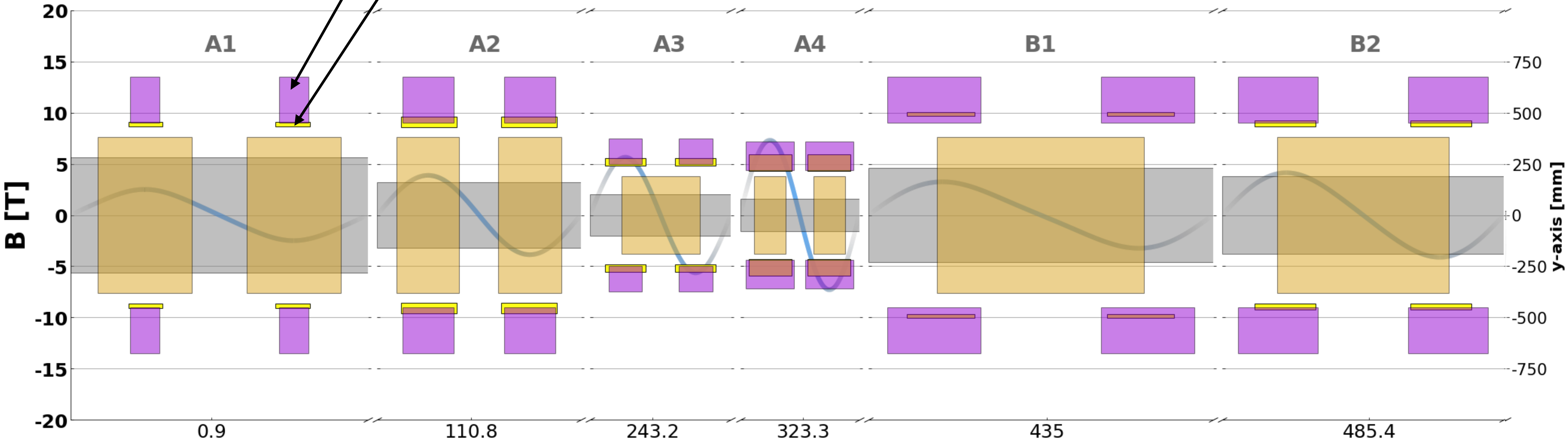
Minimum volume solutions Cells A1 to B2

(SiCO = Solenoid in-Cell Optimization)

Optimization

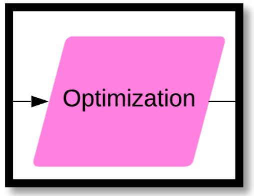
Given coil geometries

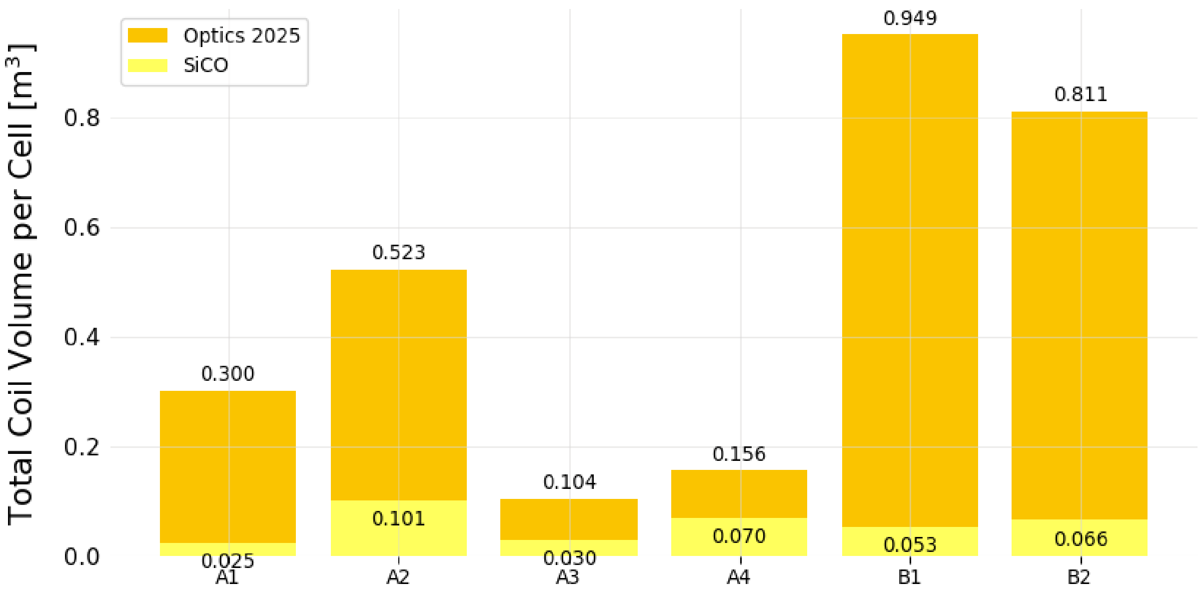
Optimize coil geometries

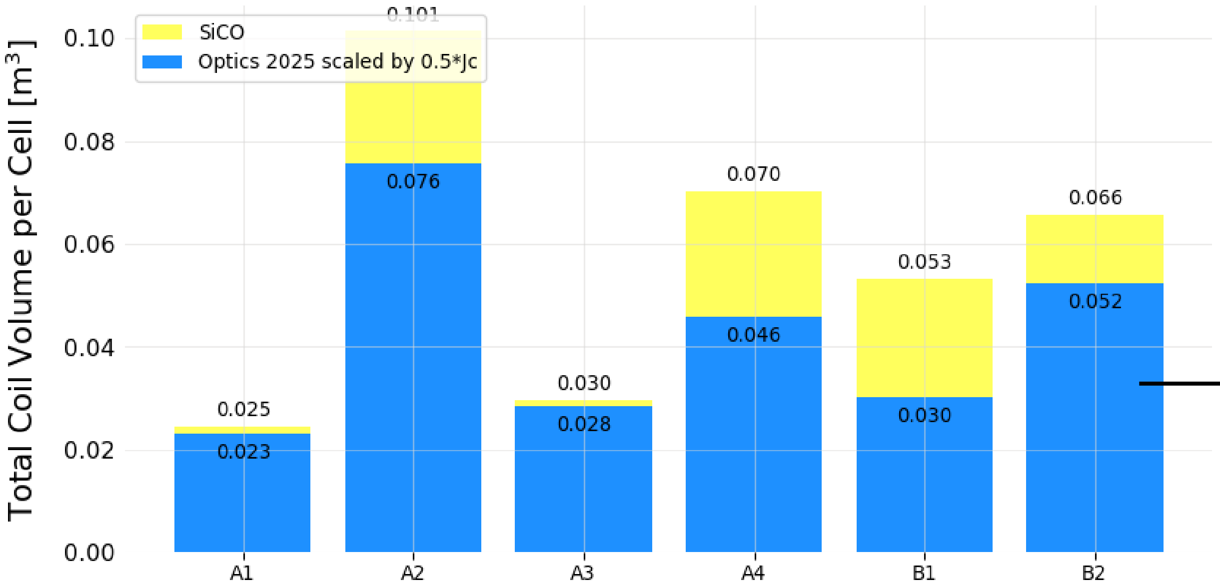


Minimum volume solutions Cells A1 to B2

(SiCO = Solenoid in-Cell Optimization)





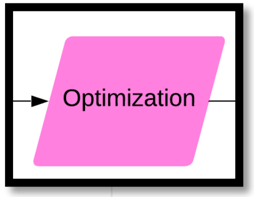


$$V = V_{given}\frac{J_E}{0.5J_C}$$

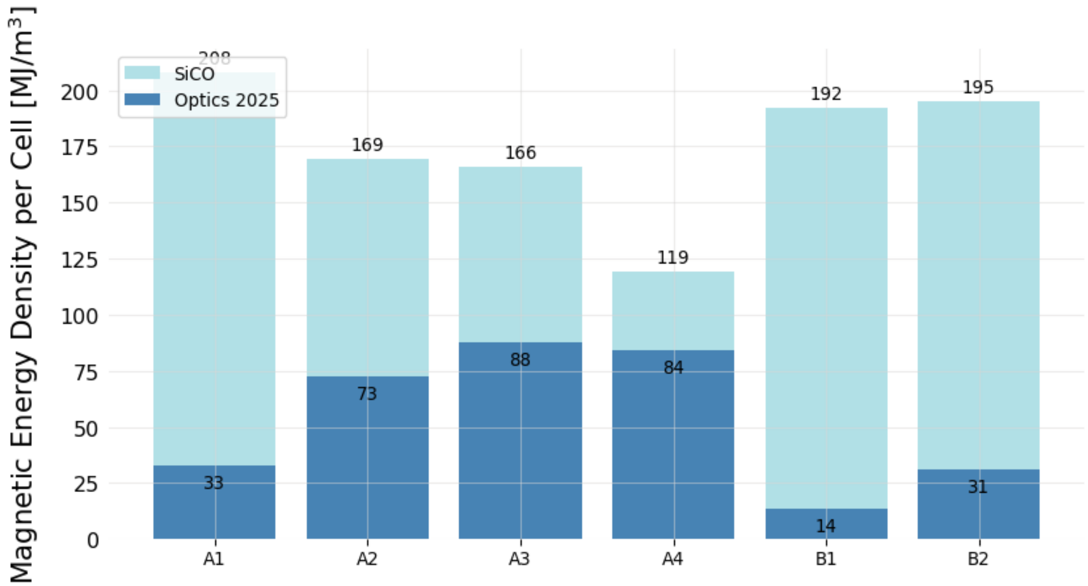
Jc from Faraday: YBCO 2G HTS 0.066x12 mm2 (https://htsdb.wimbush.eu/)

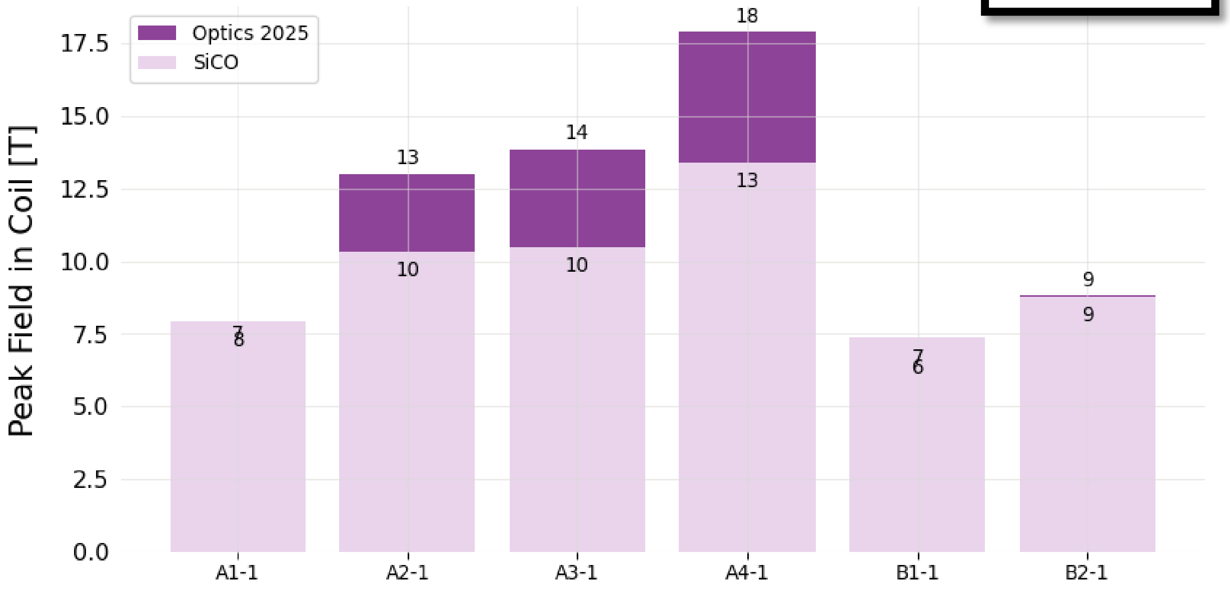
Minimum volume solutions Cells A1 to B2

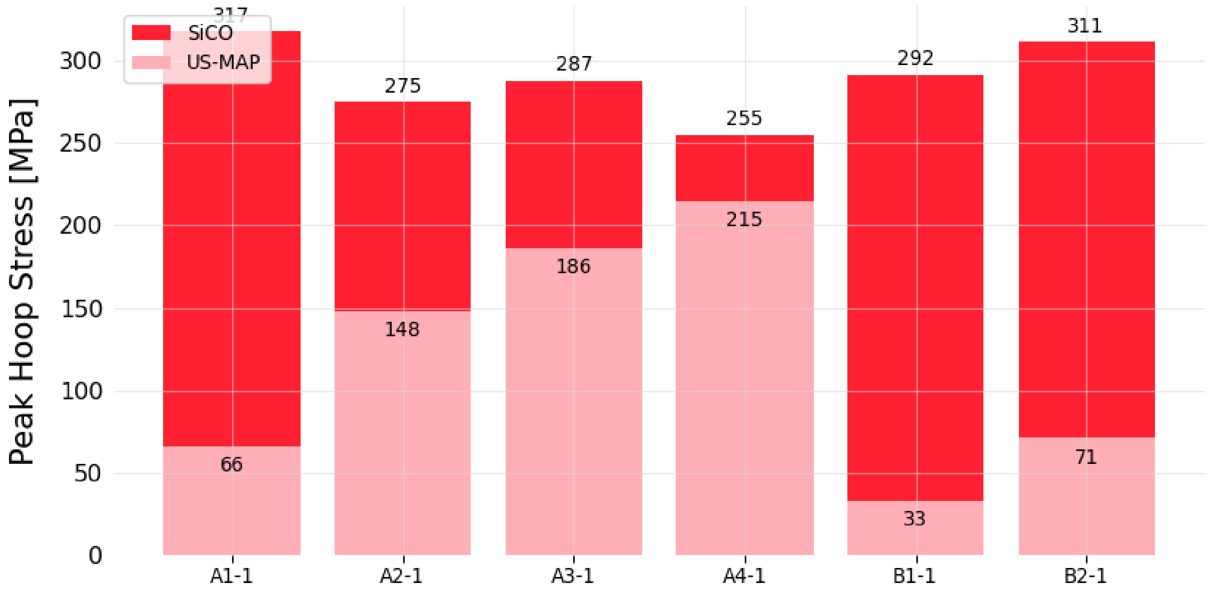
(SiCO = Solenoid in-Cell Optimization)



Operation in Lattice







Conclusions

- A **new optics (2025)** has been produced following input spacing constraints.
- Initial **analysis** shows some reasonable parameters, but to be studied further (forces, spacing, radial tensile stress etc.)
- Initial **optimization** has been performed on cells A1-B2.

Next steps

- Factor in correct **waveguide spacing**.
- Incorporate **standardization** into optimization routine (for cost consideration).
- Continue implementing evolving understandings from the **demonstrator design**, such as **quench analysis**.

Thank you

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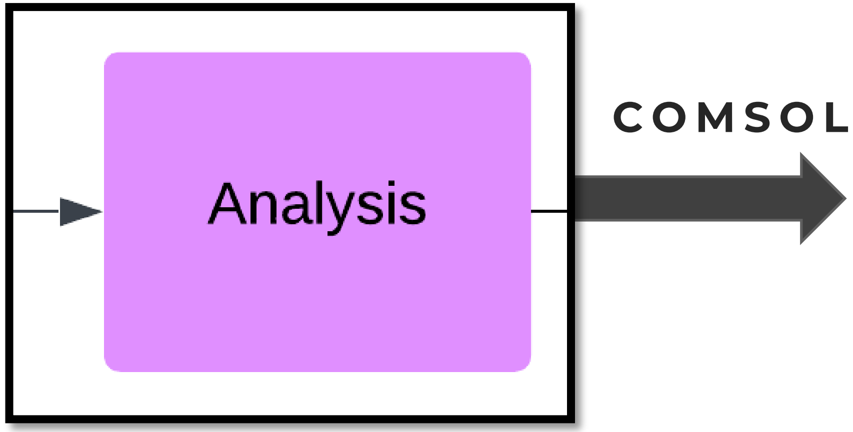
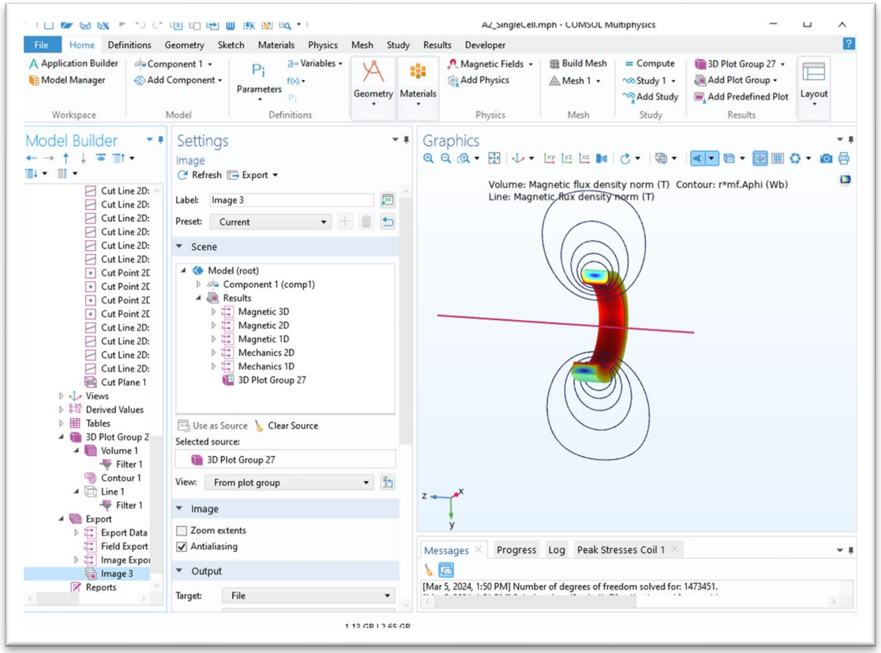
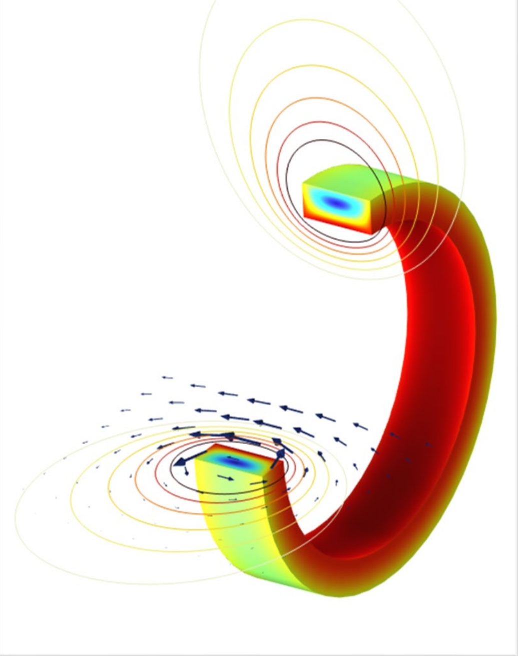
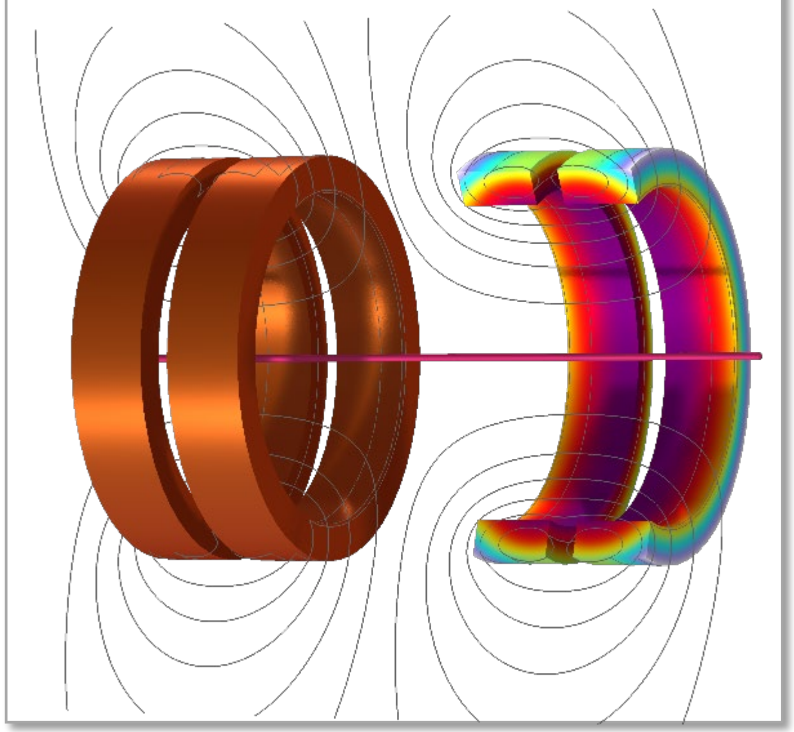




Single Solenoid



Single Cell / Lattice



Set-up

- Homogenous material
- Fine mesh
- Rollers placed to oppose net axial force

Analysis

- Peak field in coils
- Stored magnetic energy
- Stresses
- Forces
- … inductance, stray fields, …

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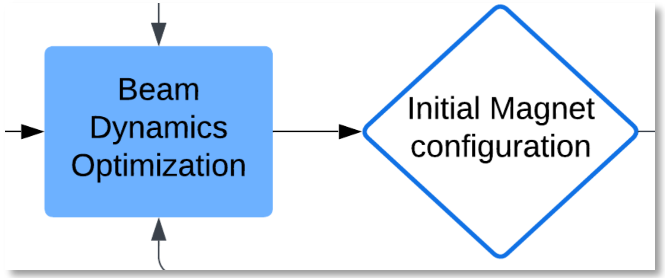
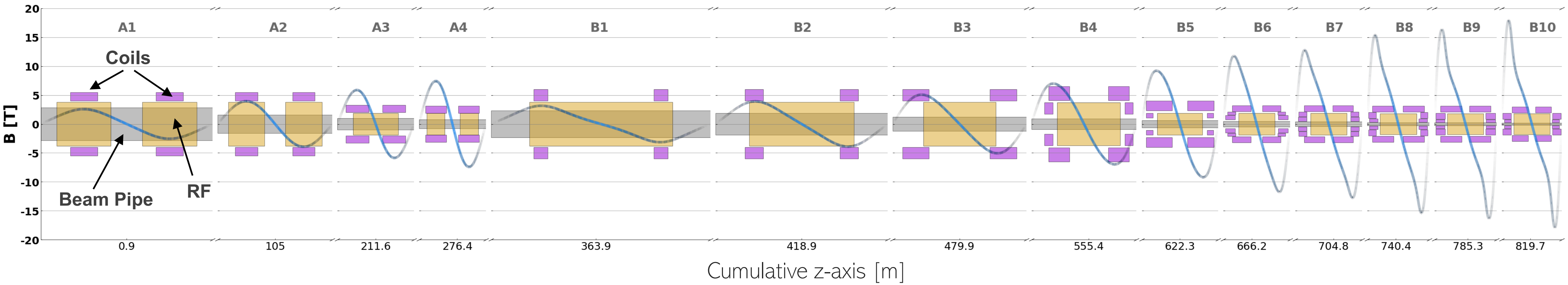
(August 2024)



Total Number of Solenoids in 1 chain: **3030**

Total Length: **849 m**

On axis field from **2.6 T** to **17.9 T** (in Lattice)



26 unique solenoid types

- **Bore radius** from **25 mm** to **400 mm**
- **Length** from **75 mm** to **287 mm**
- J_E from **58 A/mm2** to **327 A/mm2**
- **Cell Length** from **0.63 m** to **2.3 m**
- **Number of cells** from **49** to **124**

Spacing issues

https://arxiv.org/abs/2409.02613

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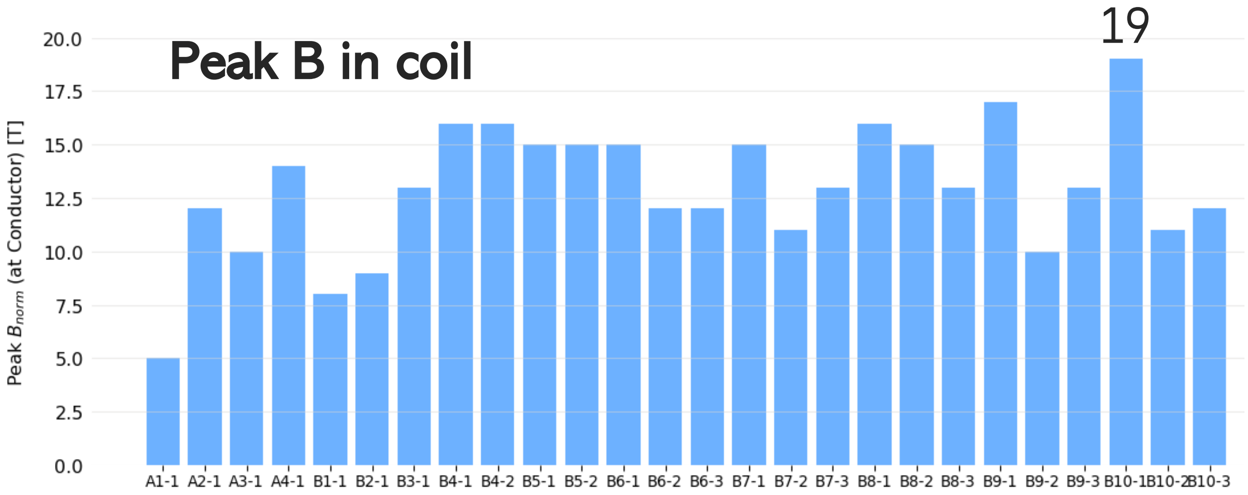
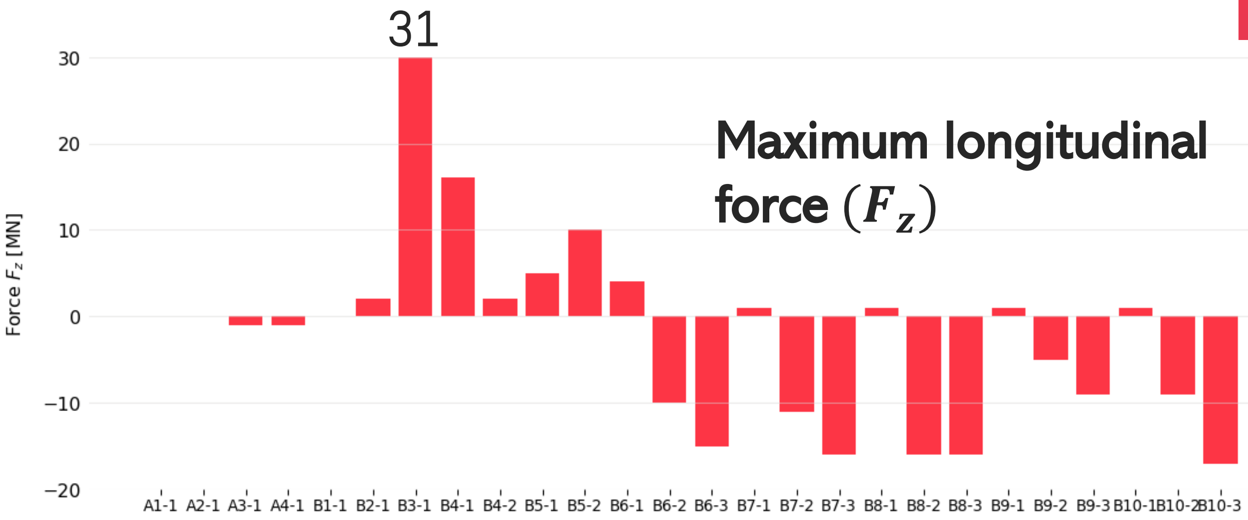
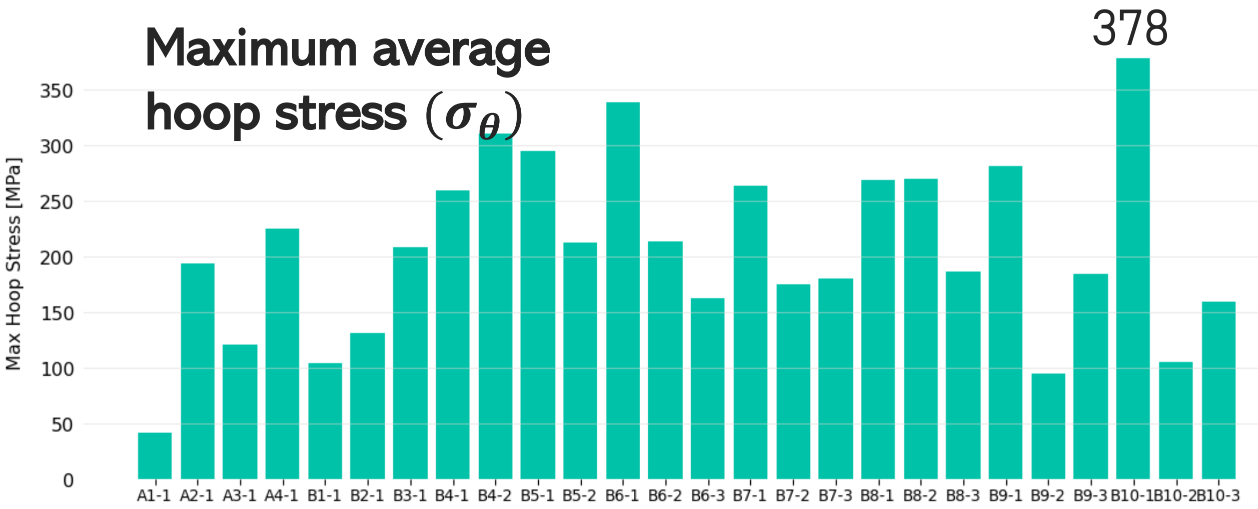
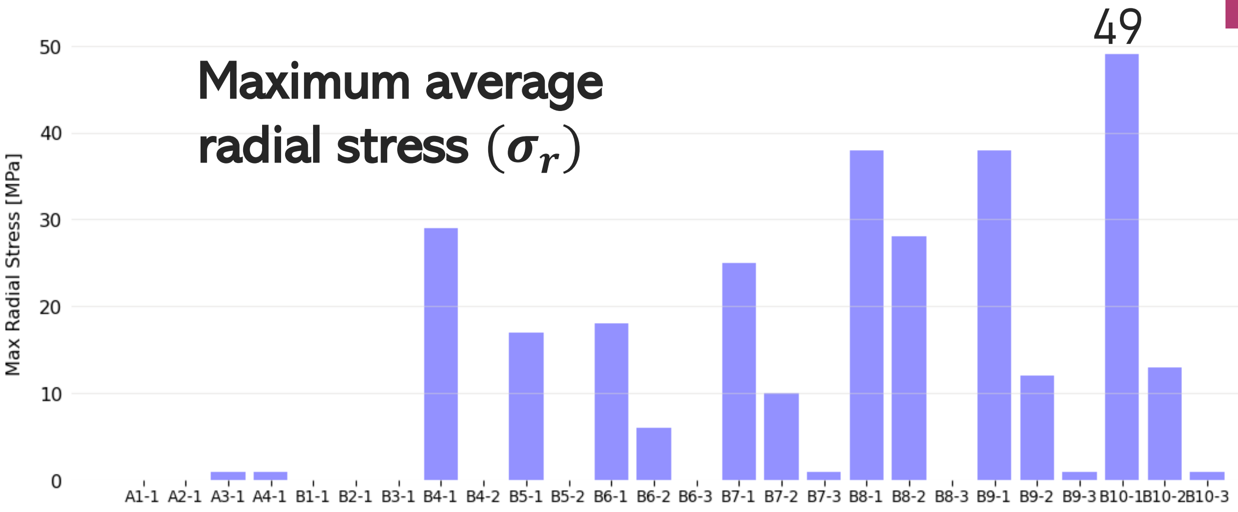
(August 2024)

Analysis, Op. in Lattice



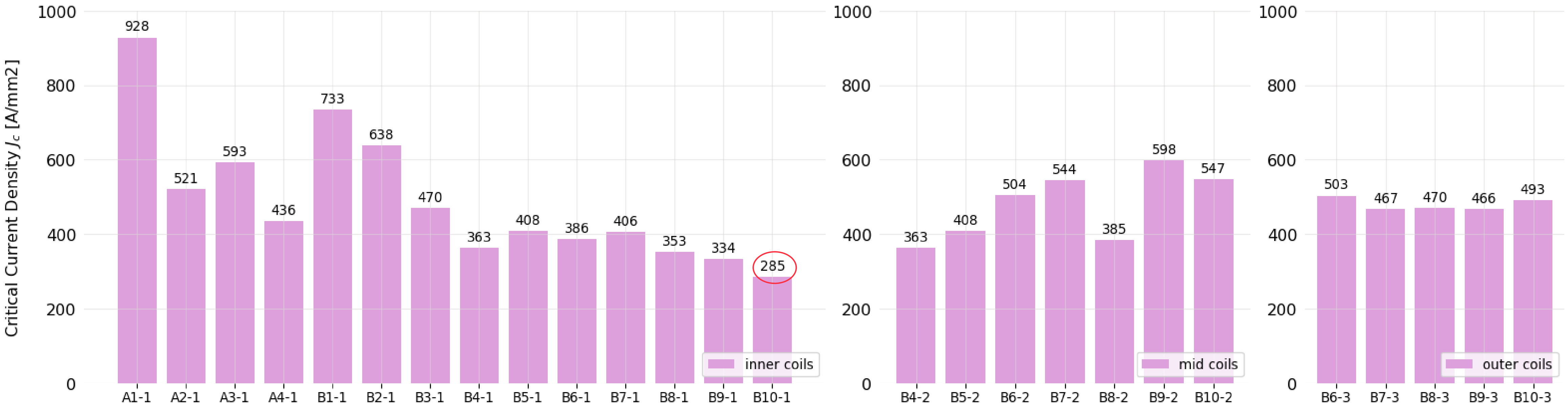






IMCC New Optics Version 3.0

(August 2024)



	A1-1	A2-1	A3-1	A4-1	B1-1	B2-1	B3-1	B4-1	B4-2	B5-1	B5-2	B6-1	B6-2	B6-3	B7-1	B7-2	B7-3	B8-1	B8-2	B8-3	B9-1	B9-2	B9-3	B10-1	B10-2	B10-3
Bore Radius	400	400	200	190	400	400	400	175	410	110	230	80	160	220	50	130	220	30	100	210	25	85	210	25	85	195
Thickness	150	150	125	125	200	200	200	200	240	80	170	70	50	100	70	80	100	60	100	105	50	100	105	50	100	105
Length	287	233	245	217	146	194	277	91	277	70	274	105	81	196	89	84	213	87	78	223	96	100	225	75	89	168
J [A/mm2]	57.6	149.5	131.5	193.2	96.9	102.1	127.9	88.5	153.6	179.6	154.0	214.4	211.5	212.7	183.3	153.9	210.3	193.7	202.1	212.8	256.4	88.5	204.9	326.8	146.1	207.8
Cell Length	1.8	1.2	0.8	0.7	2.3	1.8	1.4	1.100		0.800		0.700			0.700			0.650			0.650			0.630		
N Cells	58	89	81	124	24	34	54	61		55		55			51			69			53			49		