PERLE Magnets Design

PERLE Collaboration Meeting

Presented by

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Supervisors

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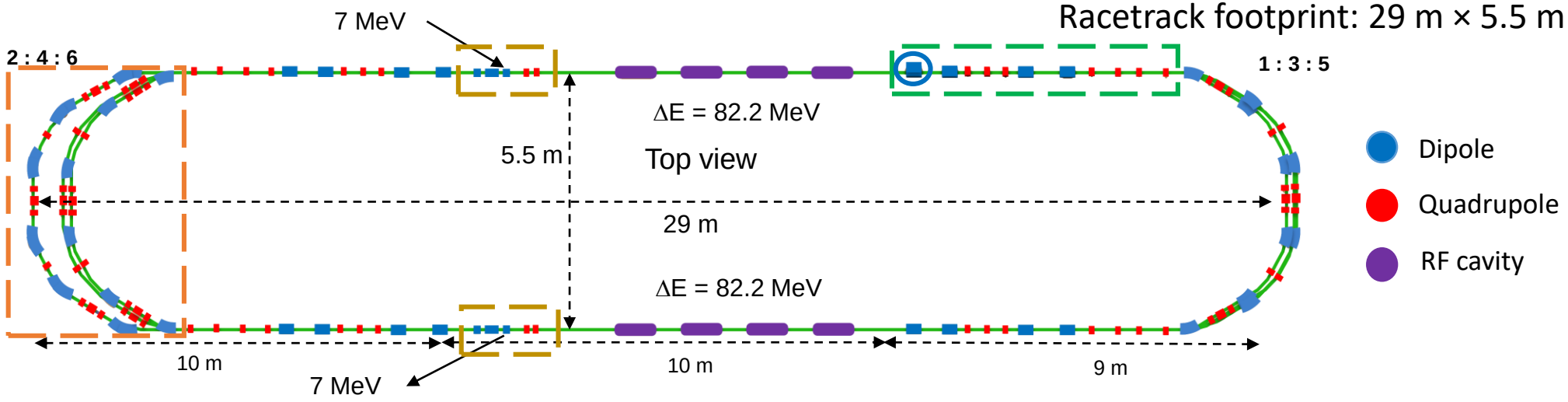
Outline

- Introduction to PERLE optics
  - General specification of PERLE dipoles
- B-com magnet
  - Specification and design
  - Field calculation and Harmonic content
  - Cooling system calculation
- Spreader/Recombiner sections concerns

PERLE Optics

Racetrack footprint: 29 m × 5.5 m × 0.9 m



Sections:

I. LINAC

Two cryomodules with four 5-cell SRF cavities.

II. Arcs

6 arcs for three-turn configuration.

III. Spreader/Recombiner

- Connect LINAC to arcs section.
- One common dipole magnet for the three arcs at each side called the **B-com** magnet.

IV. Chicane magnets for injection and dump

PERLE Dipole Magnets

- Total number of dipole (ERL only):
  - 60 dipoles for 250 MeV version
  - 78 dipoles for 500 MeV version

- R-Bend 33 cm is used in the spreaders for Arcs 3, 4, 5, and 6.

- S-Bend 33 cm is used in the spreader of Arcs 1, and 2 (vertical) and in Arcs 1, 2, and 3 (horizontal).

Type	Name	Number		Geometry	L, cm	|B|, T		I, mA	
1	Chicane 15cm	4		R-Bend	15	0.040		100	120
2	Chicane 30cm	2		R-Bend	30	0.040		100	120
3	B-Com 3-lines	2	4	R-Bend	33	0.451	0.866	100	120
4	B-Com 2-lines	2	4	R-Bend	33	0.451	0.866	60	80
5	R-Bend 33cm	8	16	R-Bend	33	0.451	0.873	20	40
6	S-Bend 33cm	6	12	S-Bend	33	0.472	0.907	40	
		18				0.472	1.342	20	40
7	S-Bend 66cm	18		S-Bend	66	0.453	1.323	20	40

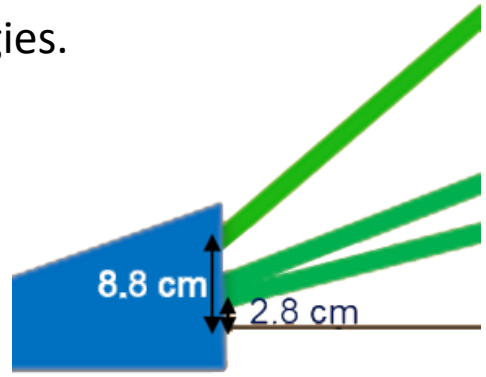
250 MeV 500 MeV

Courtesy to Alex Fomin

Spreader/Recombiner sections

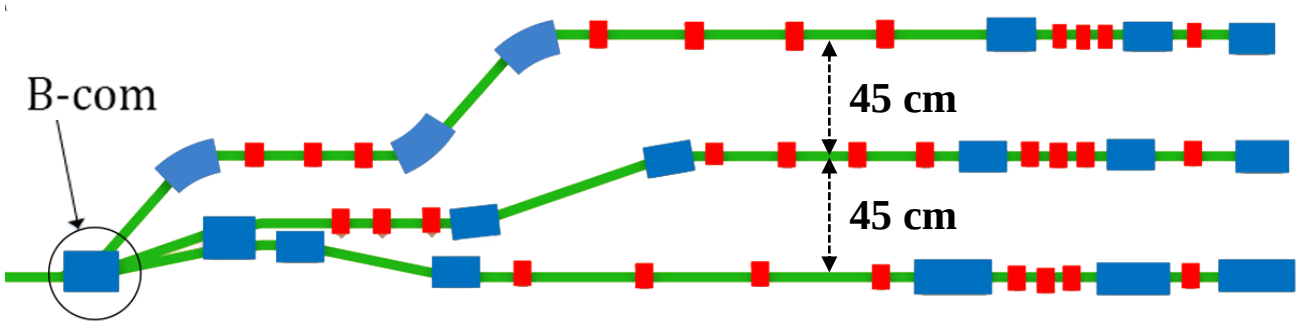
B-com magnet

- Common between three arcs.
- Vertical beam split at three different energies.



- 30° bending angle (8.8 cm exit point).

	Spreader/combiner										
	bS1 B[T]	bS2 B[T]	qS1 $l = 10\ cm$ G[T/m]	qS2 $l = 15\ cm$ G[T/m]	qS3 $l = 10\ cm$ G[T/m]	bS3 B[T]	bS4 B[T]	qS4 $l = 10\ cm$ G[T/m]	qS5 $l = 10\ cm$ G[T/m]	qS6 $l = 10\ cm$ G[T/m]	qS7 $l = 10\ cm$ G[T/m]
Arc1	-0.45	0.47	-4.3	4.9	-5.0	-0.47	0.47	4.0	-3.4	-0.53	-0.42
Arc2	-0.87	0.9	-8.2	9.5	-9.5	-0.9	0.9	7.3	-6.1	-1.8	0.61
Arc3	-0.45	0.45	-29.7	28.0	-23.4	-0.45	0.45	-16.0	19.0	-27.2	9.6
Arc4	-0.87	0.87	-32.0	35.7	-37.9	-0.87	0.87	-7.6	10.6	-10.8	10.2
Arc5	-4.5	4.5	b5S3 B[T] 4.5	b5S4 B[T] -4.5				-9.5	20.0	-14.8	31.9
Arc6	-0.87	0.87	b6S3 B[T] 0.87	b6S4 B[T] -0.87	qSA G[T/m] $l = 10\ cm$ -28.1	qSB G[T/m] $l = 15\ cm$ 27.7	qSC G[T/m] $l = 10\ cm$ -16.4	**-54.9**	44.4	30.9	-46.2

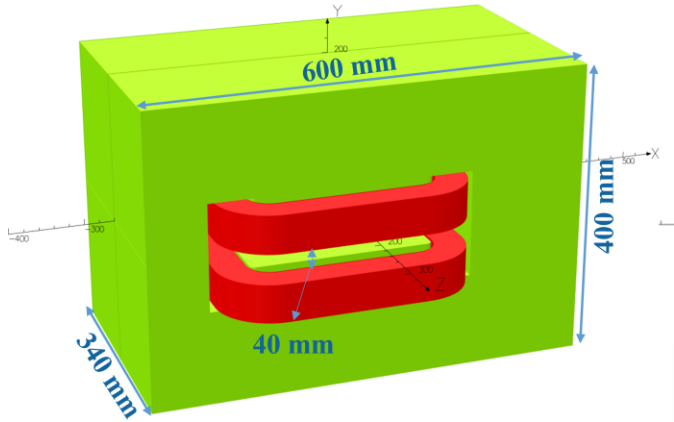


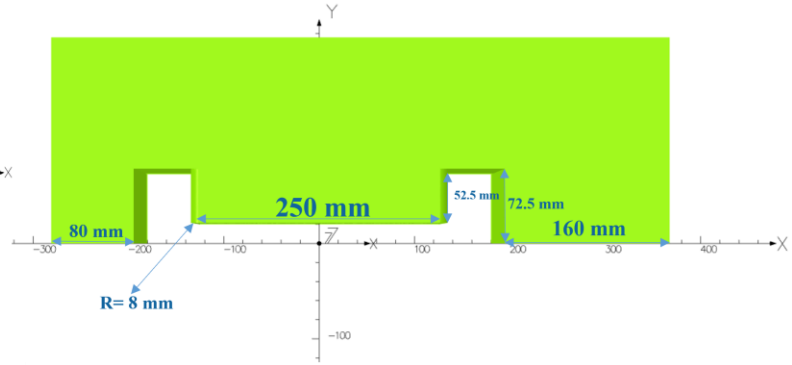
B-com Magnet

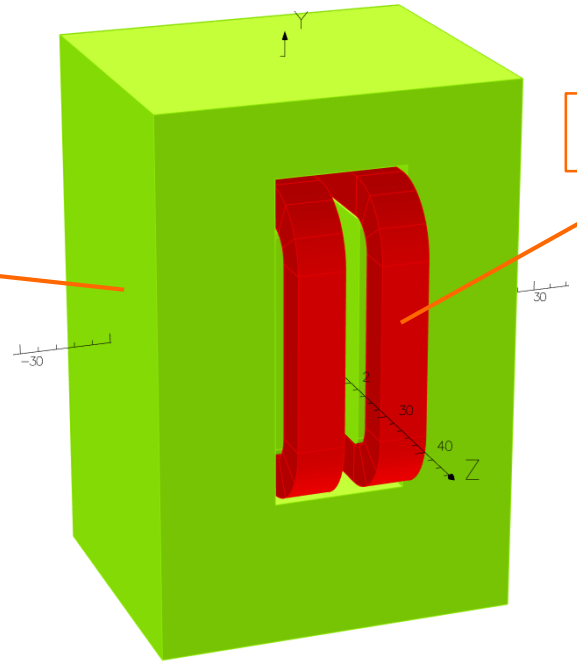
Design parameters

- Optimized aperture of 40 mm.
- Pole blend radius modified for lower harmonic content.

Magnet geometry	*Old design	New design
Width	400 mm	400 mm
Height	570 mm	600 mm
Length	340 mm	340 mm
Aperture	36 mm	40 mm
Pole width	220 mm	250 mm
Pole height	52.5 mm	52.5 mm
Pole blend radius	24 mm	8 mm







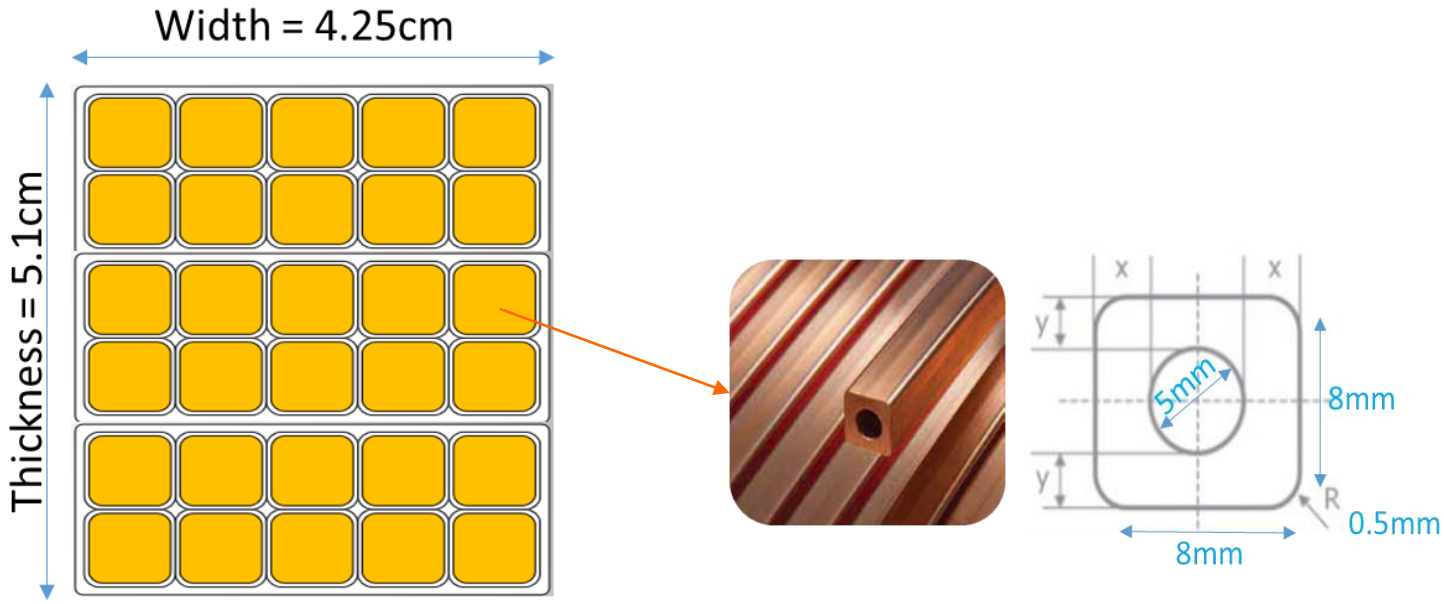
Yoke material: standard steel (C content < 0.1%)

90° clock-wise rotation around z-axis.

Tool: Opera 3D

* Courtesy to Jay Benesch.
This work is in collaboration with Jay Benesch from JLab.

Design parameters

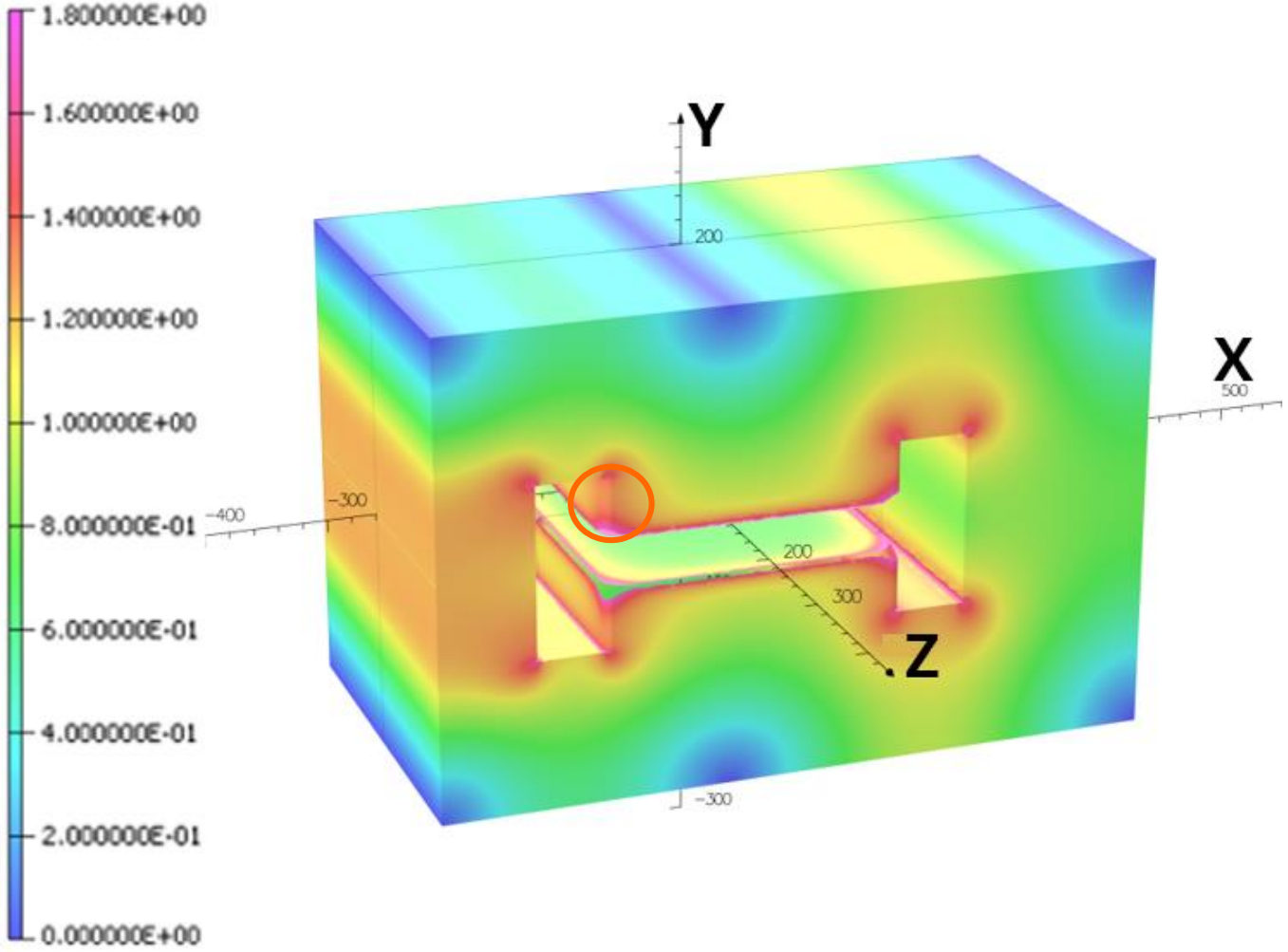


Coil Parameters	Value
Excitation current NI	11520.2625 A.turn
Number of turns/coil	5×6 = 30
Current	384 A
Coil cross section	$72.25\ mm^2$
Current density J	$5.315\ A/mm^2$
Material	Copper

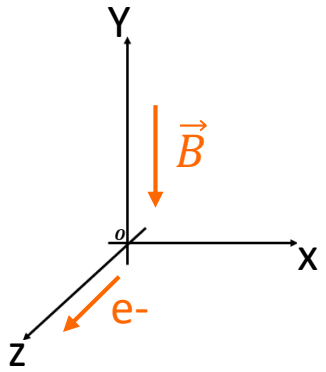
Excitation current calculated for **B = 0.87 T**

Hollow copper conductor from Luvata company https://www.luvata.com/products/hollow-conductors .

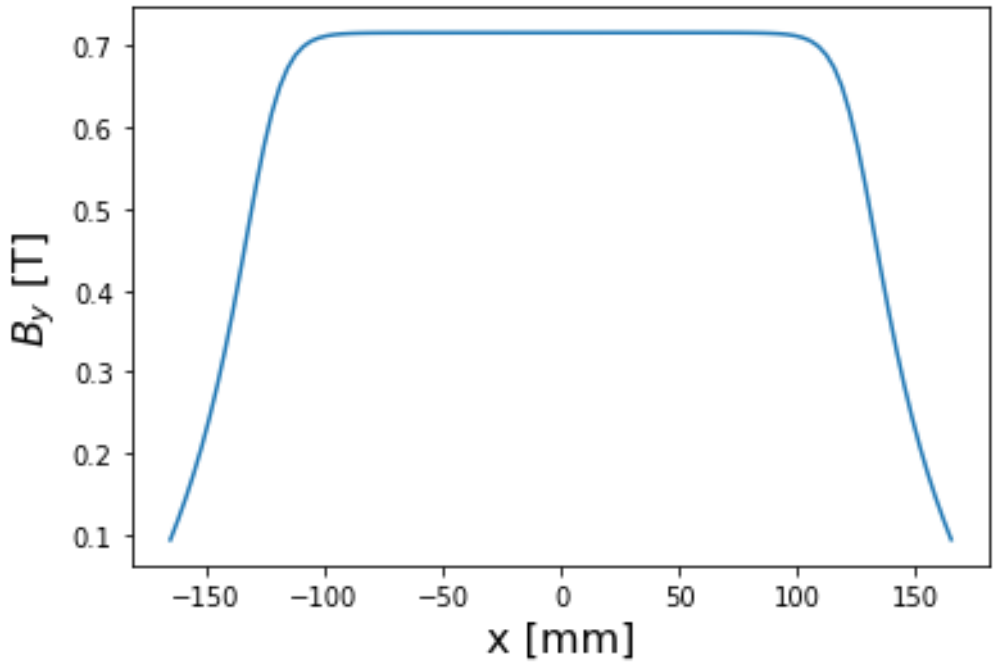
Field calculations



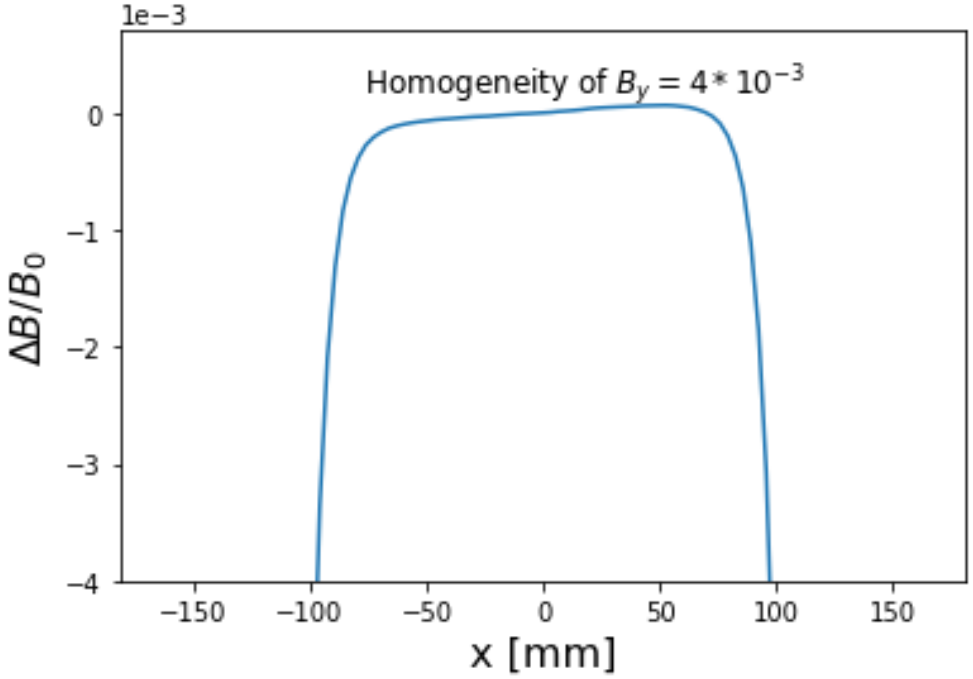
- Edges with field larger than 1.8 T are not displayed.
- No chamfer or shims is added to the pole.
- Only a blend radius of 8 mm is used.



Field calculations



$By\ (0,0,0)\ =\ 0.716382\ T$



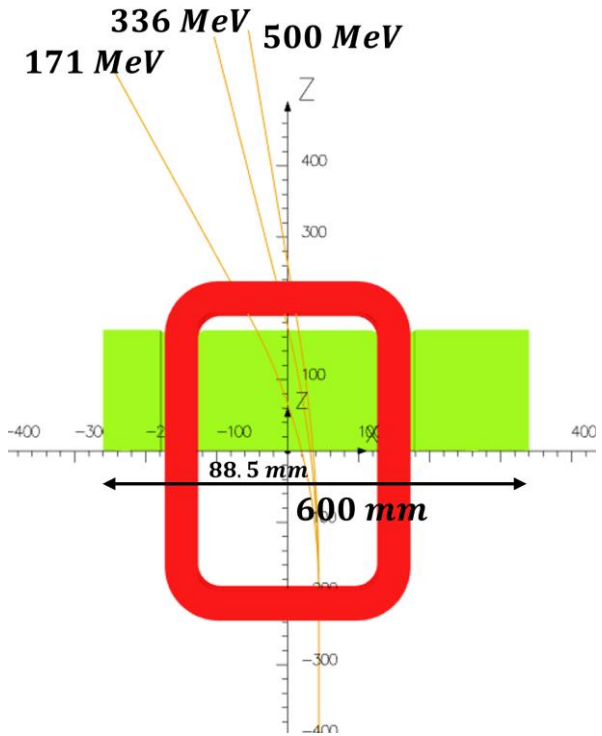
$$\frac{\Delta B}{B_0} = \frac{B(x) - B_0}{B_0}$$

$\int B.dl = 0.3$ T. m along the magnet length

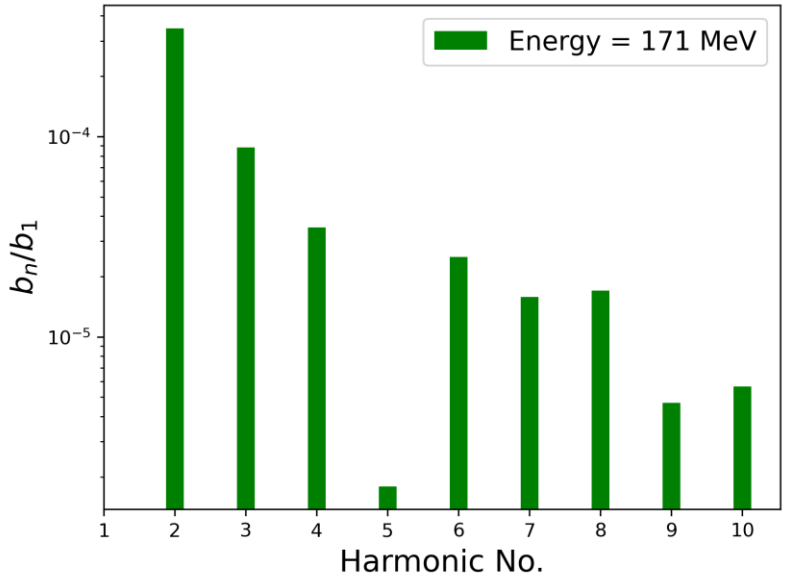
for 0.34 m yoke length → B = 0.88 T

B-com Magnet

Harmonic content



Energy	b1	b2	b3	b4	b5	$\sqrt{\sum_{n=1}^{5} b_n^2}/b_1$
171MeV	-2.90E+01	-1.11E-02	3.06E-03	2.19E-04	-4.99E-04	3.594E-04
336MeV	-2.81E+01	1.84E-03	1.14E-04	1.05E-04	-4.69E-04	6.79E-05
500MeV	-2.79E+01	2.77E-03	3.85E-04	-1.77E-06	-2.49E-04	1.01E-04



- 0.036% field homogeneity along the beam path.
- Quadrupole and sextupole components can be dealt with in the lattice.
- Initial design: 0.1% field quality

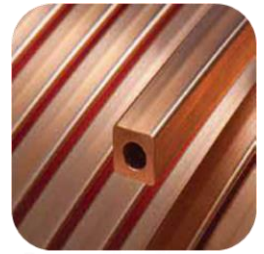
Improvement by one order of magnitude!

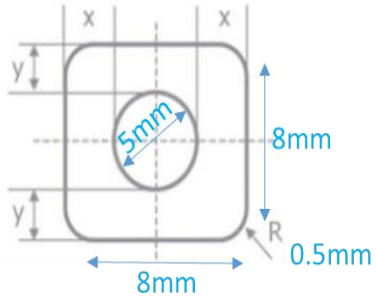
Energy	Exit point [mm]			Angle[°]	Vertical Shift [mm]
	x	y	z		
171MeV	-44.64	0.00	170.95	27.41	88.64
336MeV	1.13	0.00	169.17	14.22	42.87
500MeV	15.11	0.00	170.99	9.59	28.89

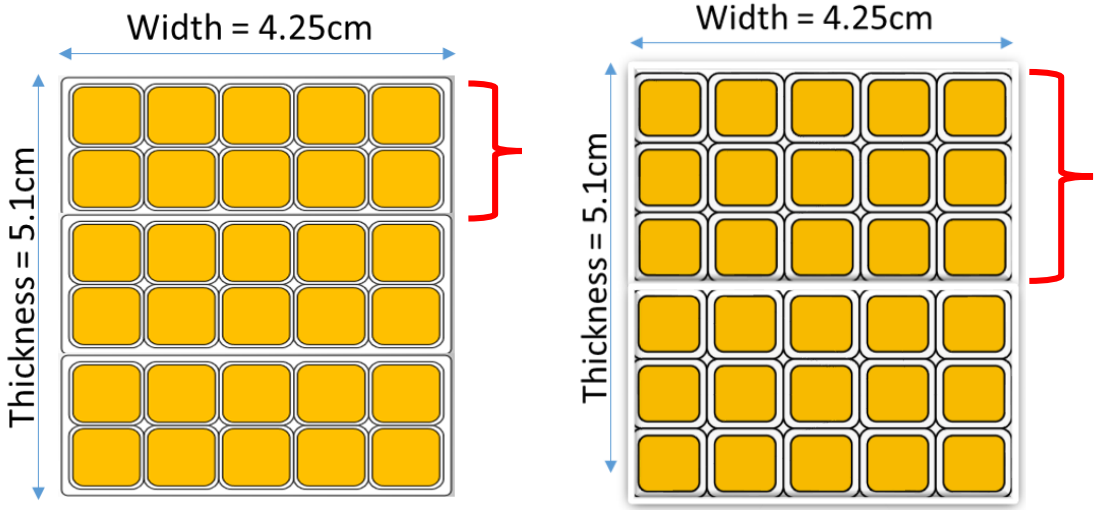
Cooling and Electrical Calculations: 8X8 conductor 2 vs. 3 Pancakes

Magnetic Field (T)	0.866			
NI Coil (AT)	11 520			
Diameter	5		5	
Conductor	8x8		8x8	
I (A)	384		384	
Number of turns	30		30	
Section Cu	44.15		44.15	
Number of pancake	3		2	
One turn length	1211		1211	
Coil turns (m×n)	5	6	5	6
Layer length (mm)	6055		6055	
Pancake length (mm)	12110		18165	
Coil length (mm)	36330		36330	
Copper mass (kg)	14.275		14.275	
J (A/mm2)	8.698		8.698	
Coil resistance (Ω)	0.014		0.014	
Disputed coil power (KW)	2.222		2.196	
R cable (Ω) 20m with r/km = 0.554	0.022		0.022	
Voltage drop U2 (V)	8.509		8.509	
U1+U2	14.295		14.228	
CHARACTERISTICS	384A - 15V		384A - 15V	
Resistance per pancake	0.005		0.007	
Flow rate per pancake q (L/min)	0.663		0.982	
Pressure for one pancake (bars)	1.988		1.965	
Water velocity in a pancake (m/s)	0.169		0.505	
Reynolds number (water 30 ° C)	0.562		0.834	
Fluid dynamics	3511.909		5206.609	
Resistance per pancake	CB laminar or Turbulent		Turbulent	
	CB Accepted		Accepted	

- Initial design with 3 pancakes of 10 turns each.
- Investigation of 2 pancakes of 15 turns each showed the feasibility of such fabrication.
- For reducing the needed current, smaller conductors are needed.

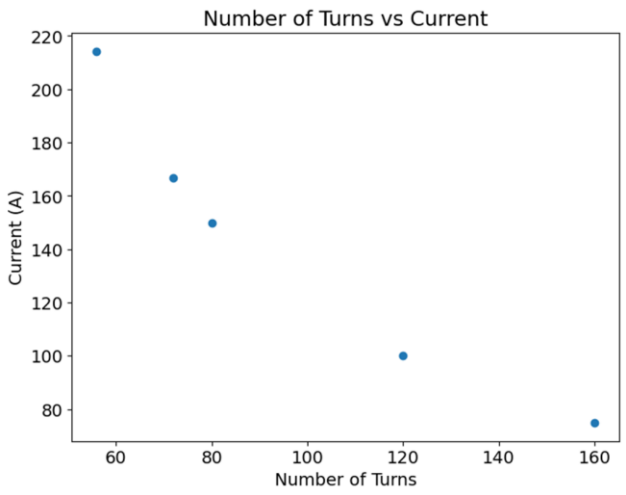


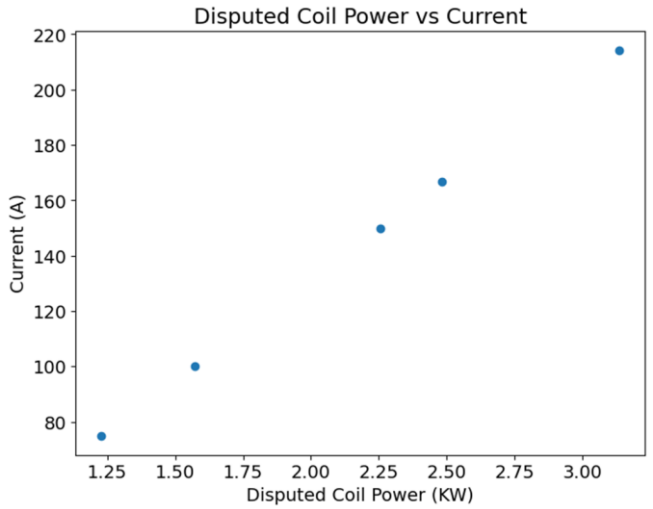


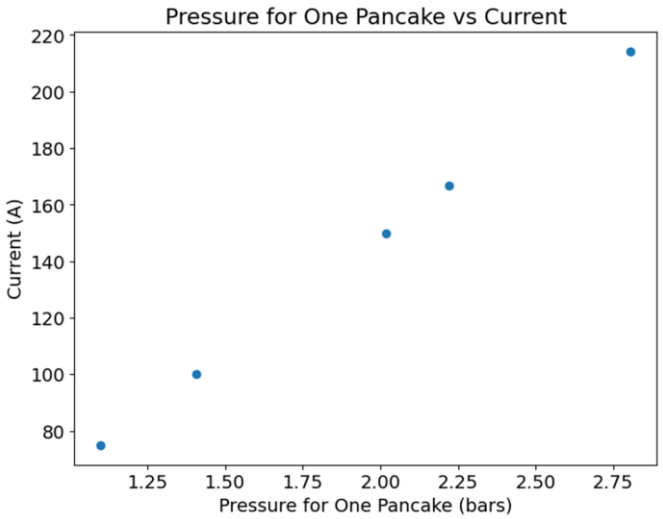


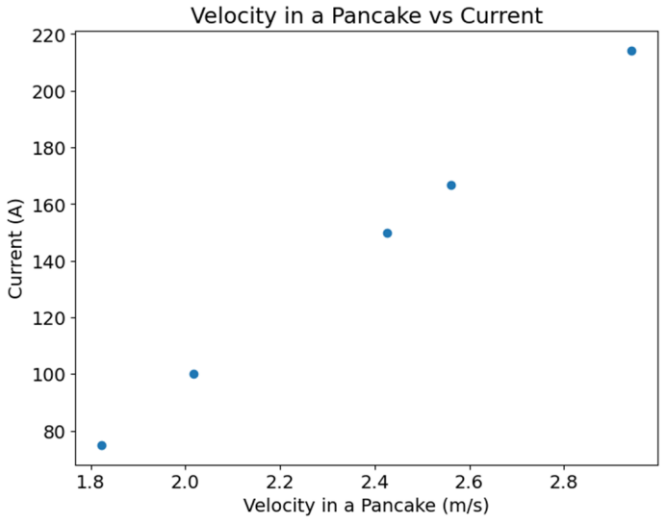
Courtesy to Abd-alrahman Marshoud,An-Najah, Palestine.

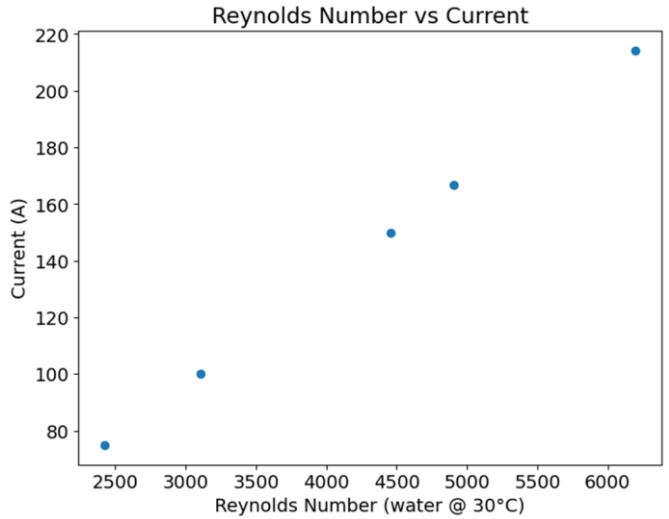
Cooling and Electrical Calculations: 5X5 conductor in 4 Pancakes



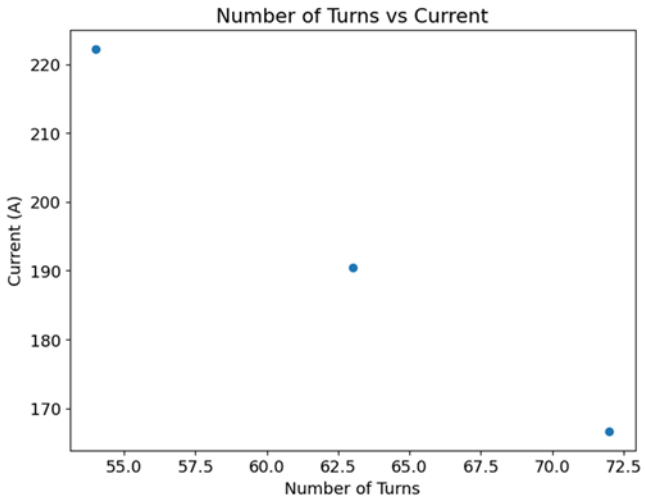


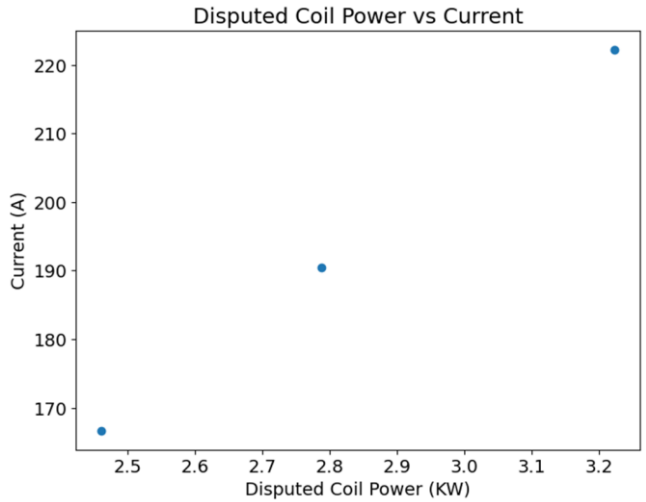


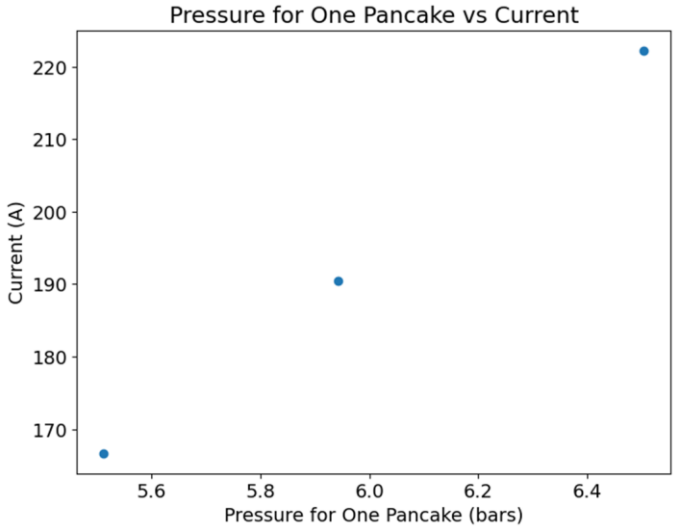


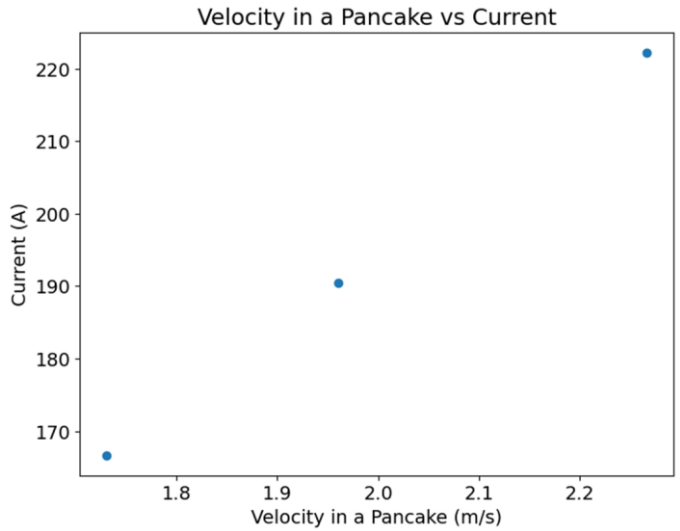


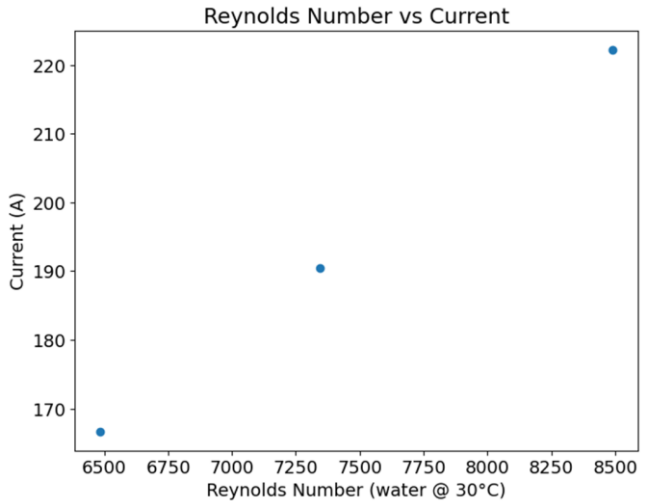
Cooling and Electrical Calculations: 5X5 conductor in 3 Pancakes



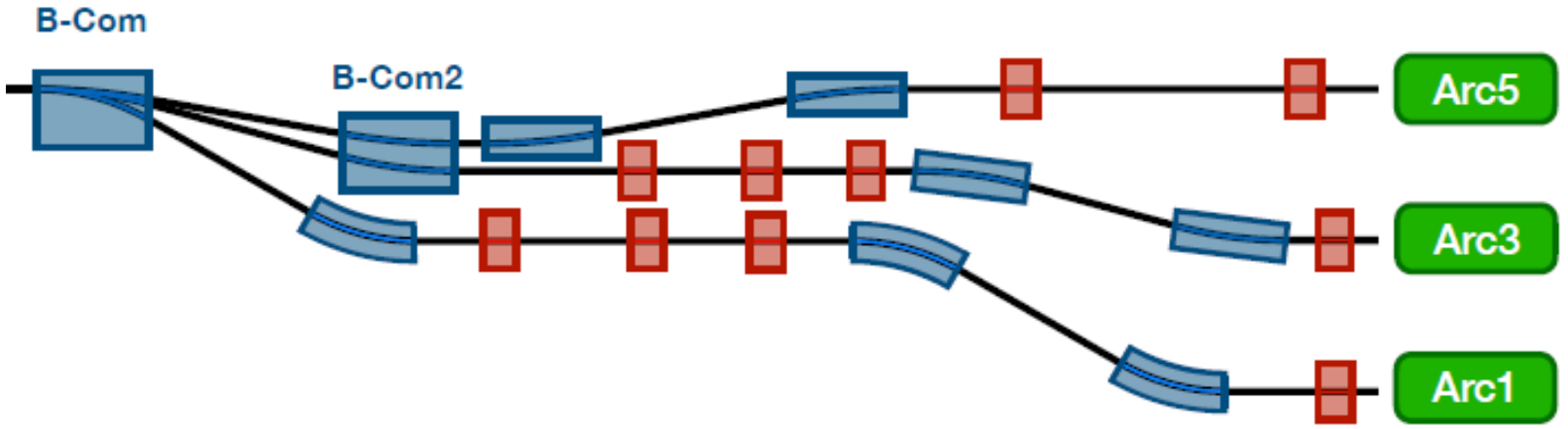








Space Constraints in Spreader/Recombiner Sections



- Space between the Arcs = 45 cm.
- In spreaders, the separation is around 20 cm.
- Current design of quadrupoles: height of 25 cm. → Impossible to fit two quads on top of each other.
- Design of dipoles (S-Bends) is ongoing "*Internship 2 months – Thiab Dubeik from An-Najah in Palestine".*

See Alex Fomin presentation

Conclusion and Outlook

- ✓ The B-com magnet is designed to generate vertical field of 0.7 T and field integral of 0.88 T along the magnet length with harmonic content in the order of 10^{-4} meeting the accepted tolerances of the beam dynamics.
- ✓ Cooling circuit parameters are calculated for the B-com coil used in the design.
- ✓ Different configurations (conductor area, number of turns, different arrangements) have been investigated to decrease the current from the power supply.

Outlook

- Investigation of different yoke materials for the magnets is ongoing.
- Preliminary cost estimation of the coil and the magnet is under study.

Thank You!

Cooling and Electrical Calculations

- Smaller conductor (5×5)
- Motivation: less current from the power supply is needed.
- For $I < 150\ A$, the coil geometry does not match the available space.

Magnetic Field (T)	0.866						
NI Bobine (AT)	12 000						
Dia:	3	3	3	3	3	3	3
Conducteur	5x5	5x5	5x5	5x5	5x5	5x5	5x5
I (A)	75	100	150	166.6666667	166.6666667	190.4761905	214.2857143
Number of turns	160	120	80	72	72	63	56
Section Cu	17.85	17.85	17.85	17.85	17.85	17.85	17.85
number of pancake	4	4	4	4	3	3	4
one turn length	1346	1291	1236	1225	1214	1203	1203
Coil section (xxy conductors)	20 8	15 8	10 8	9 8	8 9	7 9	7 8
pancake length (mm)	53840	38730	24720	22050	29136	25263	16842
Copper length (mm)	215360	154920	98880	88200	87408	75789	67368
Copper mass (kg)	34.2131664	24.6113658	15.7085712	14.011893	13.88607192	12.04021949	10.70241732
I/S (a/mm2)	4.201680672	5.602240896	8.403361345	9.337068161	9.337068161	10.67093504	12.00480192
Coil resistance (Ω)	0.205104762	0.147542857	0.094171429	0.084	0.083245714	0.07218	0.06416
Disputed coil power (KW)	1.228128857	1.570593714	2.255523429	2.483833333	2.461529524	2.787686531	3.136147347
CHARACTERISTICS	75A - 20V	100A - 20V	125A - 20V	125A - 20V	167A - 20V	191A - 20V	215A - 20V
Resistance per pancake	0.05127619	0.036885714	0.023542857	0.021	0.027748571	0.02406	0.01604
Flow rate per pancake q (L/min)	0.274693878	0.351292517	0.504489796	0.555555556	0.734089191	0.831357305	0.701457726
Pressure for one pancake(bars)	1.823543201	2.017406243	2.425858322	2.561574553	5.512082012	5.942083051	2.942534637
speed in a pancake (m/s)	0.647719621	0.82833683	1.18957125	1.309982723	1.730959484	1.960314671	1.654015503
Reynolds number (water 30 ° C)	2426.754846	3103.457658	4456.863283	4907.998491	6485.235557	7344.540715	6196.956229
Fluid dynamics	CB laminar or Turbulent	CB laminar or Turbulent	Turbulent	Turbulent	Turbulent	Turbulent	Turbulent
	Not Accepted	Not Accepted	Not Accepted	Accepted	Accepted	Accepted	Accepted

Preliminary Cost Estimation: Coil

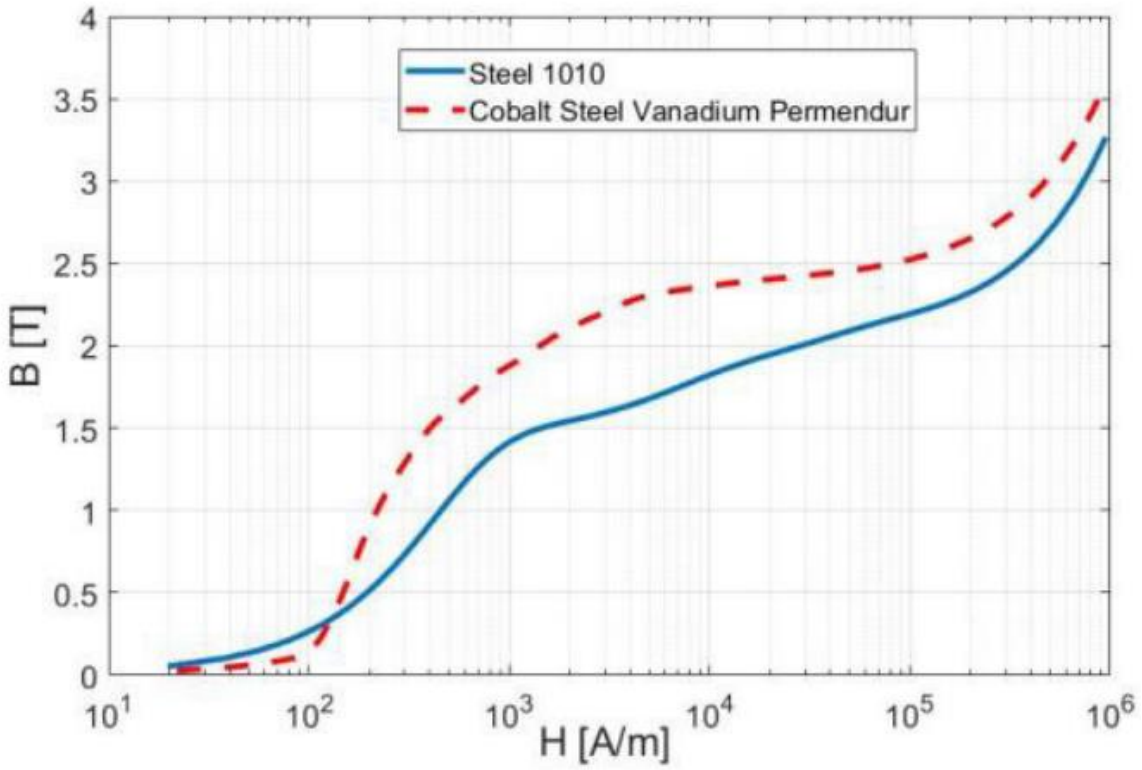
Magnetic Field (T)	0.866			
Diameter	5.00			
Conductor	8x8			
I (A)	384.00			
Number of turns	30.00			
Number of pancake	3.00		2.00	
Copper mass (kg)	14.28		14.28	
Estimation range cost (€)	428.26	713.77	428.26	713.77
Average Estimation cost (€)	571.01		571.01	

Magnetic Field (T)	0.866							
Diameter	3.00							
Conductor	5x5							
I (A)	150.00	166.67	214.29	166.67	190.48	166.67	190.47	222.22
Number of turns	80.00	72.00	56.00	72.00	63.00	72	63	54
Number of pancake	4.00	4.00	4.00	3.00	3.00	3.00	3.00	3.00
Copper mass (kg)	15.71	14.01	10.70	13.89	12.04	13.89	12.04	10.23
Estimation range cost (€)	342.13 / 513.20	246.11 / 369.17	157.09 / 235.63	140.12 / 210.18	107.02 / 160.54	416.58 / 694.30	361.21 / 602.01	306.77 / 511.29
Average Estimation cost (€)	427.66	307.64	196.36	175.15	133.78	555.44	481.61	409.03

Recommended materials for the magnets manufacture

I. Low Carbon Steel (AISI M1010 or AISI 1010):
There are slight differences in composition and mechanical properties between AISI M1010 and AISI 1010, which are both types of low carbon steel.

II. Cobalt Steel Vanadium Permendur:
(provides high field).



Martial	cost	Cost - 10%	Cost + 10%	The estimated value of the cost (€)	
				from	to
Low Carbon Steel (AISI 1010)	1.116	1.0044	1.2276	602.64	736.56
Vanadium Permendur	128.5	115.65	141.35	69390	84810

Low Carbon Steel (AISI M1010)

Mechanical Properties:

Properties		T (°C)	Treatment
Density (×1000 kg/m3)	7.7-8.03	25	
Poisson's Ratio	0.27-0.30	25	
Elastic Modulus (GPa)	190-210	25	
Tensile Strength (Mpa)	1158	25	oil quenched, fine grained, tempered at 425°C
Yield Strength (Mpa)	1034		
Elongation (%)	15		
Reduction in Area (%)	53		
Hardness (HB)	335	25	oil quenched, fine grained, tempered at 425°C

Cobalt Steel Vanadium Permendur

Mechanical Properties:

Physical Data	
Density (lb / cu. in.)	0.292
Mean Coeff Thermal Expansion	9.8
Mechanical Data	
Form	Strip
Condition	Annealed
Temper	70
Tensile Strength	175
Yield Strength	185
Elongation	1
Brinnell	35

Preliminary Cost Estimation: B-com magnet

Item	Cost indication (€)	Approximate amount (kg)	Cost Estimation for the B-com(€)	
Production-specific tooling	5000 – 15 000	-	5000	15 000
Steel sheets	1.0-1.5 / kg	600	600	900
Vanadium Permendur	110-150/kg	600	6000	9000
Copper conductor	10-15/kg	10-15	100	225
Yoke manufacture	6-10/kg	600	3600	6000
Coil manufacture	30-50/kg	10-15	300	750
Total		Steel sheets	15000	30975
Contingency	10-20%		1500	6195
Total + Contingency			16500	37170
Total		Vanadium Permendur	9600	22875
Contingency	10-20%		960	4575
Total + Contingency			10560	27450

PERLE Dipole Magnets: Summary

	Type	Geometry	E1, α	E2, α	Field Map #	Field Map name	|α|, °	|α|, rad	Field |B|, T					E, MeV				
1	Chicane 15cm	R-Bend	0	1	1	bChicA_0	15	0.2617994	0.0401811					7				
					2	bChicA_1	1.1611571	0.0202660						89.167				
					3	bChicA_2	0.6042613	0.0105463						171.333				
					4	bChicA_3	0.4083976	0.0071279						253.5				
					5	bChicA_4	0.3084260	0.0053830						335.667				
					6	bChicA_6	0.2070560	0.0036138						500				
2	Chicane 30cm	R-Bend	0.5	0.5	7	bChicB_1	2.3223141	0.0405320	0.0401811					89.167				
					8	bChicB_2	1.2085225	0.0210927						171.333				
					9	bChicB_3	0.8167953	0.0142558						253.5				
					10	bChicB_4	0.6168521	0.0107661						335.667				
					11	bChicB_6	0.4141120	0.0072276						500				
3	B-Com 3-lines 33cm	R-Bend	0	1	12	b1S01	30	0.5235988	0.4506411	0.8659151				89.167	171.333			
					13	b2S01_250	15.0825754	0.2632406	0.4506411					171.333				
					14	b4S01	14.7861843	0.2580676	0.8659151					335.667				
					15	b3S01	10.1292120	0.1767881	0.4506411					253.5				
					16	b6S01	9.8653134	0.1721822	0.8659151					500				
					17	b5S01	6.1250946	0.1069031	0.4506411					417.833				
4	B-Com 2-lines 33cm	R-Bend	0	1	18	b2S02_250	15.0825754	0.2632406	0.4506411					171.333				
					19	b4S02	14.7861843	0.2580676	0.8659151					335.667				
					20	b3S02	10.1292120	0.1767881	0.4506411					253.5				
					21	b6S02	9.8653134	0.1721822	0.8659151					500				
					22	b5S02	6.1250946	0.1069031	0.4506411					417.833				
5	R-Bend 33cm	R-Bend	0	1	23	b3S03_250	10.1292120	0.1767881	0.4506411					253.5				
					24	b6S03	9.8653134	0.1721822	0.8659151					500				
					25	b5S03	6.1250946	0.1069031	0.4506411					417.833				
			0.5	0.5	26	b2S03_250	15.0825754	0.2632406	0.4545729					171.333				
					27	b4S03	14.7861843	0.2580676	0.8731740					335.667				
					28	b3S03_500	10.1292120	0.1767881	0.4524074					253.5				
6	S-Bend 33cm	S-Bend	0	0	29	bAA1	30	0.5235988	0.4719102	0.9067841	1.3416556			89.167	171.333	253.5		
7	S-Bend 66cm	S-Bend	0	0	30	bAA4			0.4533921	0.6708278	0.8882633	1.1056986	1.3231338	171.333	253.5	335.667	417.833	500