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ORNL PUP-II STS Pulsed Dipole

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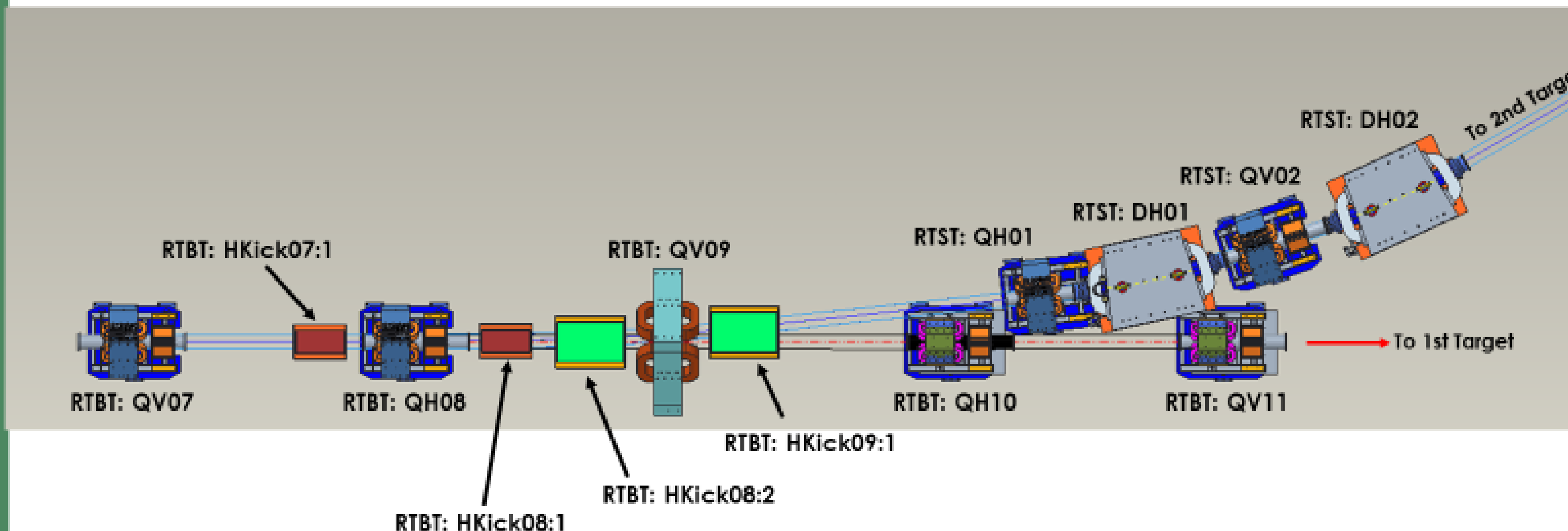
FDR Review

April 16, 2024

Magnets Layout

RTST Extraction Region Design Concept



- RTBT transports proton beam to first target
- RTBT optics to remain unchanged
- RTST proton beam to intersect truck entrance wall at prescribed position and angle

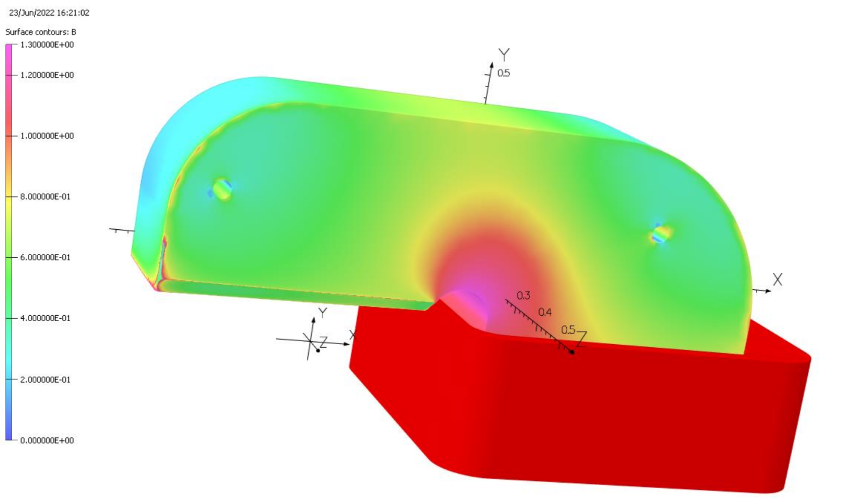
2 OAK RIDGE National Laboratory

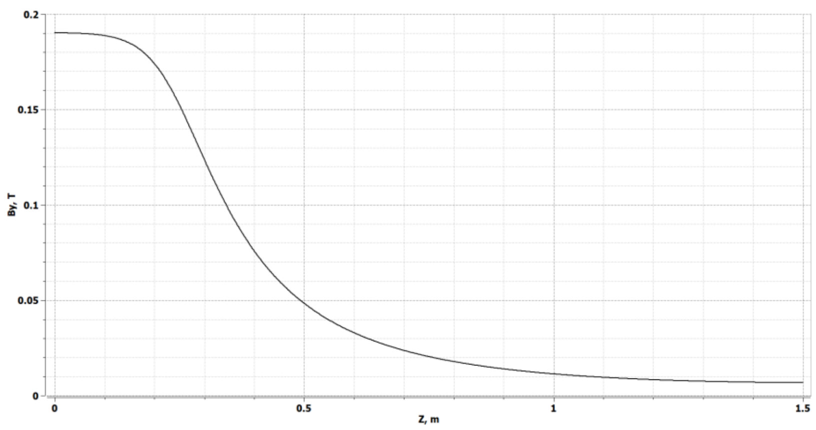
Pulsed magnets : K07:1, K08:1, K08:2, K09:1.

Pulsed Magnet Specification

Parameter	Unit	Spec
Vertical aperture no less than	m	0.2473
Horizontal aperture no less than	m	0.35
Center field	T	0.189
Effective length	m	0.88
Integrated field	T-m	0.1662
Remnant field in the gap less than	Gauss	5.0
Peak current less than	A	1750
Pulses repetition rate 15 Hz with the period	ms	66.66
Inductance less than	mH	3.5
Resistance less than	mΩ	7.0
Good field area width/height	mm	± 45 / ± 57
Integrated field homogeneity	%	± 0.1
Magnet maximum dimensions (width x height x length)	m	1.2 x 1.0 x 0.7

Field Simulation





Parameter	Unit	Value
Gap field (at 38543 A)	T	0.188
Yoke peak field	T	1.3
Gap	m	0.25
Gap width	m	0.52
Yoke length	m	0.5
Integrated field (Spec 0.166)	T-m	0.166
Total magnet length	m	0.65
Integrated field homogeneity in the good field area	%	+/-0.07*
Magnet efficiency IwGap/IwTotal	%	97

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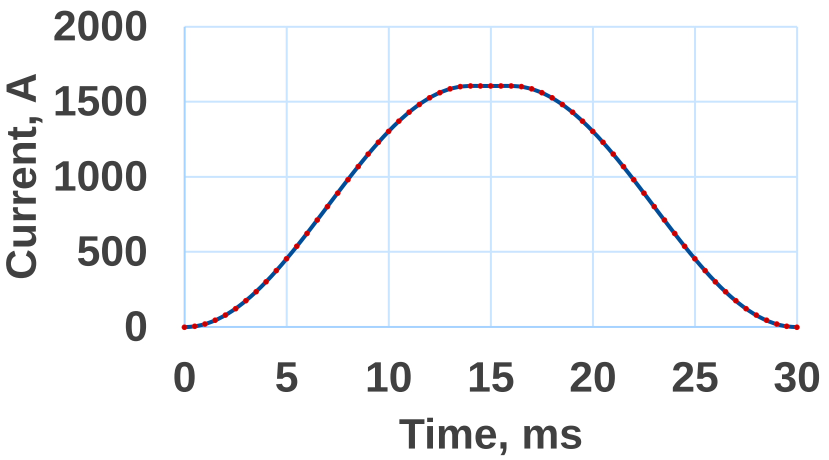
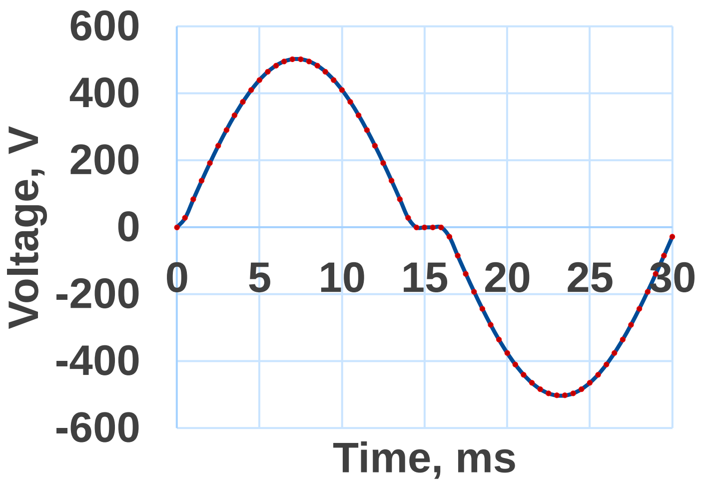
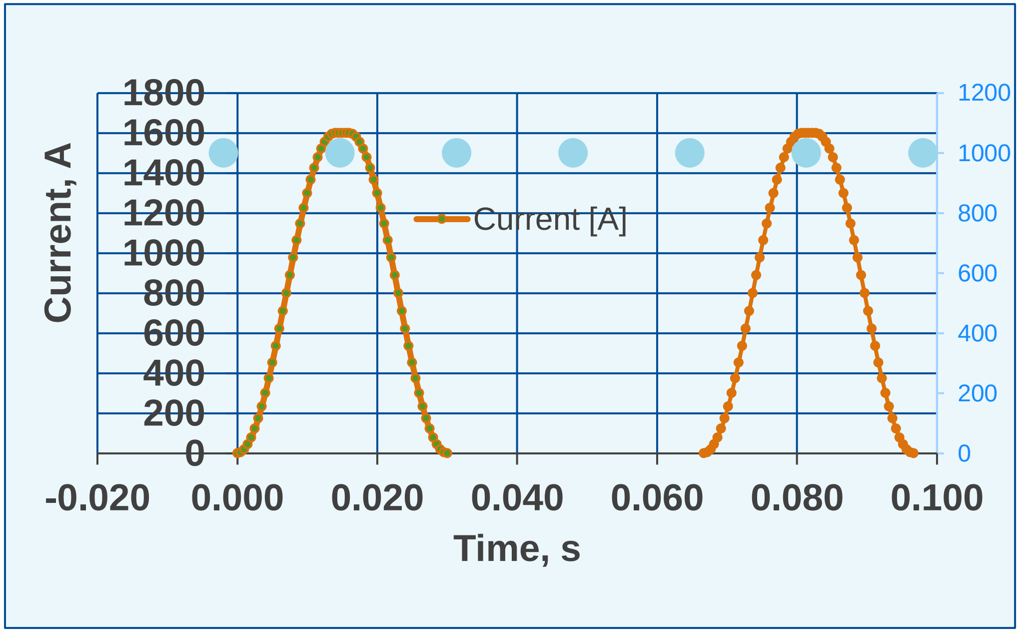
Power Losses in Coil

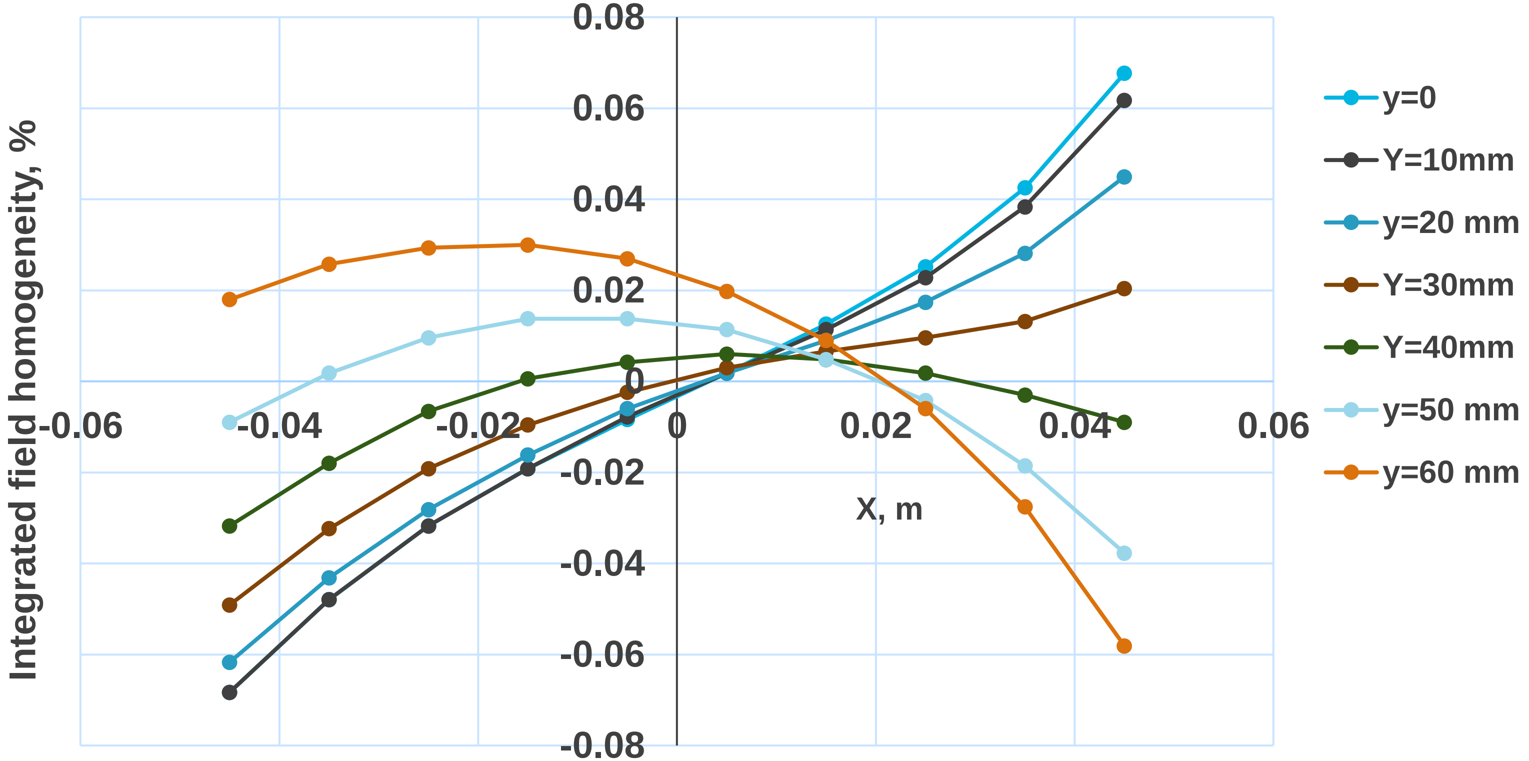






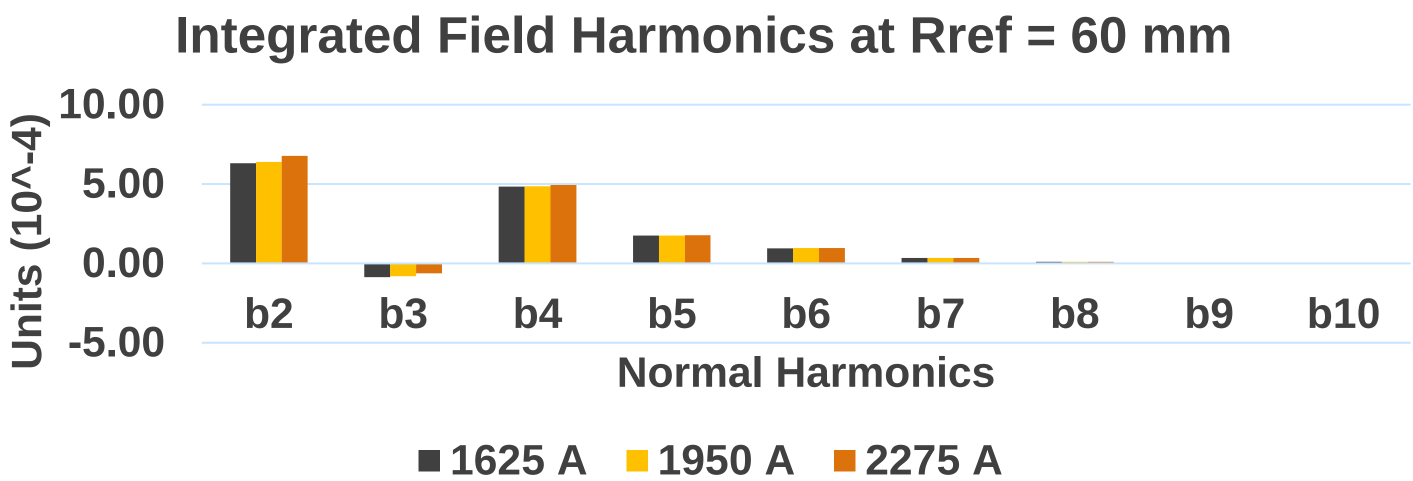
- ✓ Updated current pulses from L. Boyd and D. Harding.
- ✓ Peak current 1606 A.
- ✓ Peak AC voltage 502 V.
- ✓ Average power losses 3371 W for the period of 66.66 ms.

Integrated Field Homogeneity



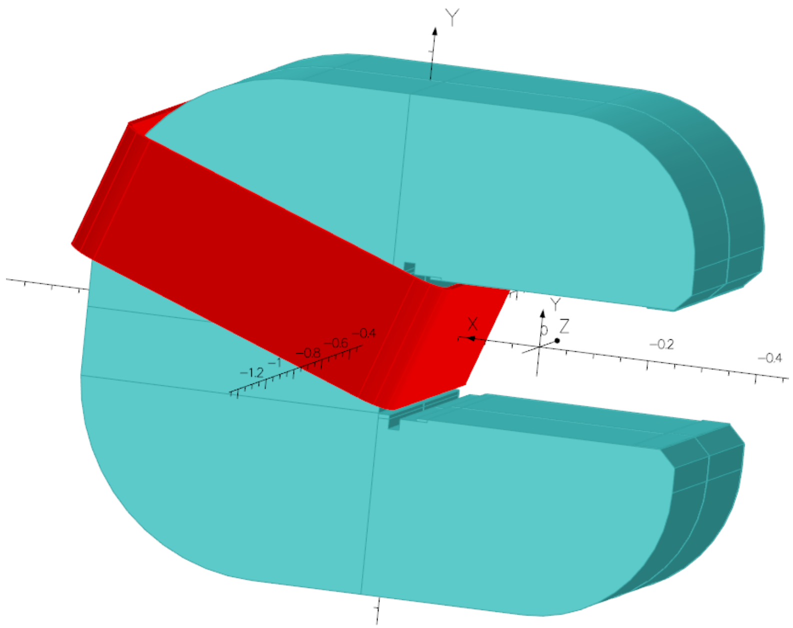
Integrated field V29: 0.16692 T-m
Integrated field homogeneity +/- 0.07 % (spec. +/- 0.1 %) in the good field area x=+/- 45 mm, y=+/- 60 mm.

Magnet at High Power



Current		100%	120%	140%
Current, A		1625	1950	2275
Peak voltage, V		682	818	955
Power, kW		3.37	4.85	9.51
Center field, T		0.19	0.228	0.266
Water flow, l/s		0.138	0.138	0.138
Water temp. rise C		5.8	8.4	16.5

C-Magnet Mechanical Concept

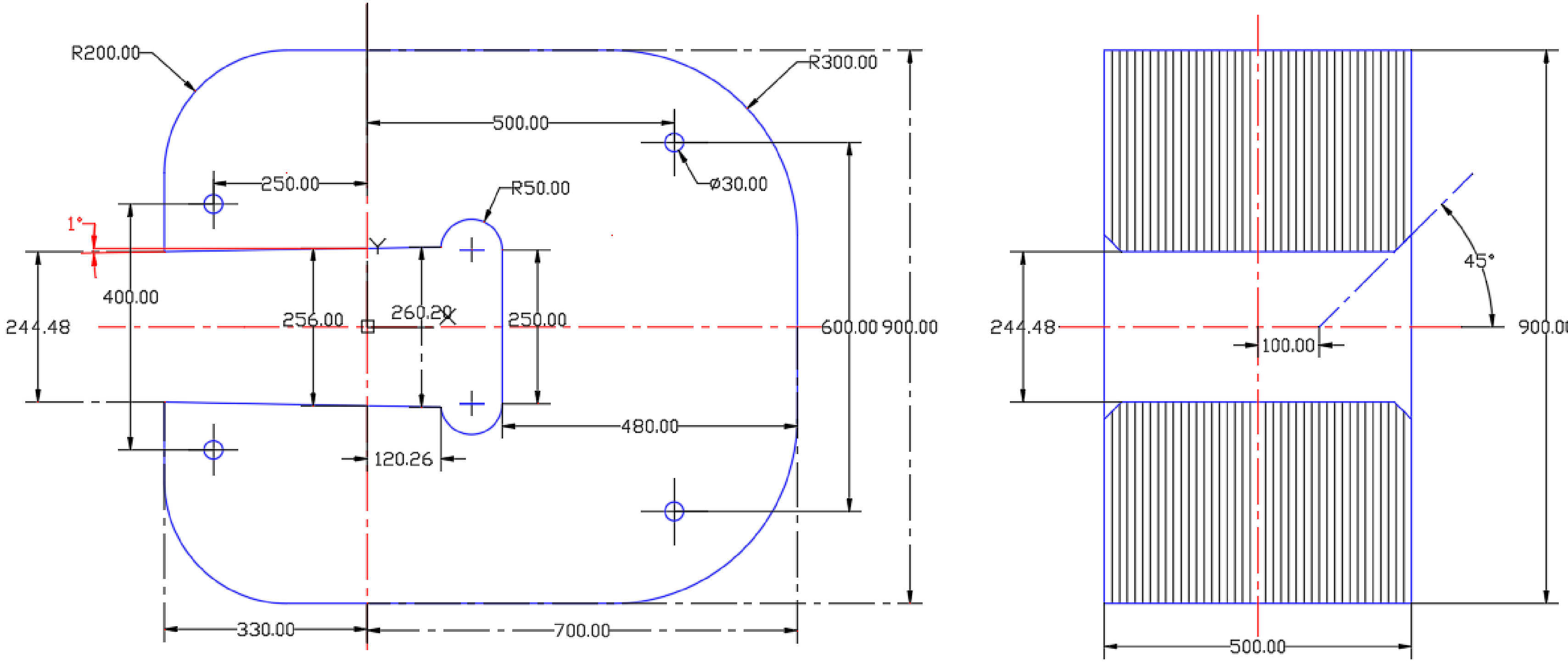


- ✓ C-magnet yoke assembled from the low carbon electrical steel laminations. 3D core .igs file transferred in NX for the mechanical design.
- ✓ The possible core material is steel AK M15, with C-5 electrical insulation.
- ✓ The core could be stamped, laser cut or EDM machined.
- ✓ The racetrack winding has two sections mounted through the magnet gap as shown.

Magnet Parameters

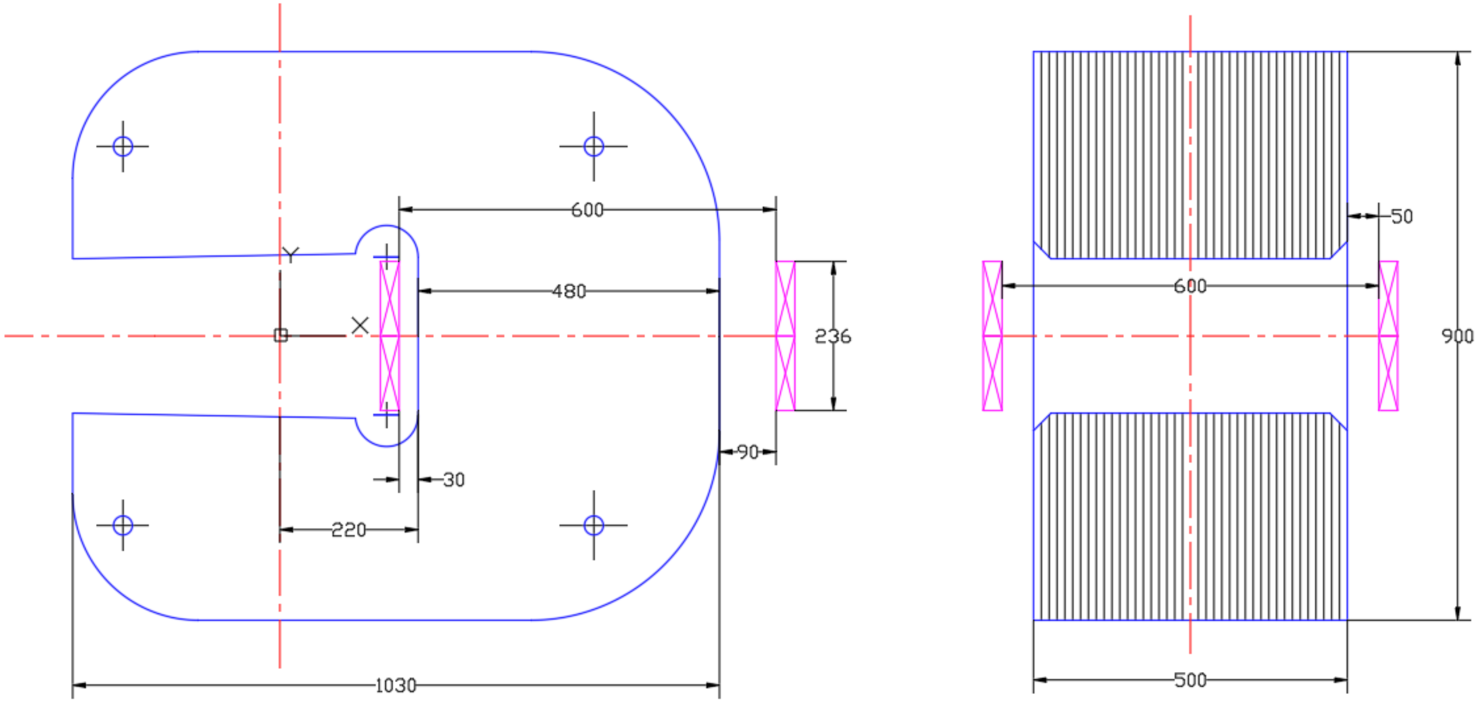
Parameter	Unit	Value
Gap	m	0.25
Total ampere-turns	A	38543
Peak current	A	1606
Gap center field	T	0.188
Yoke length	m	0.5
Integrated field	T-m	0.166
Effective length	m	0.883
Number of turns for 2 coils		24
Magnet inductance	mH	2.79
Peak voltage	V	682
Average power losses	kW	3.371
Conductor dimensions (hole diameter)	mm	12 x 18 (8)
Water pressure drop (20 psi)	MPa	0.138
Total water flow	l/s	0.138
Water velocity	m/s	1.375
Water temperature rise at 2 water circuits	°C	6

Magnet Main Dimensions



Dimensions in mm to start the mechanical design.

Coil Position



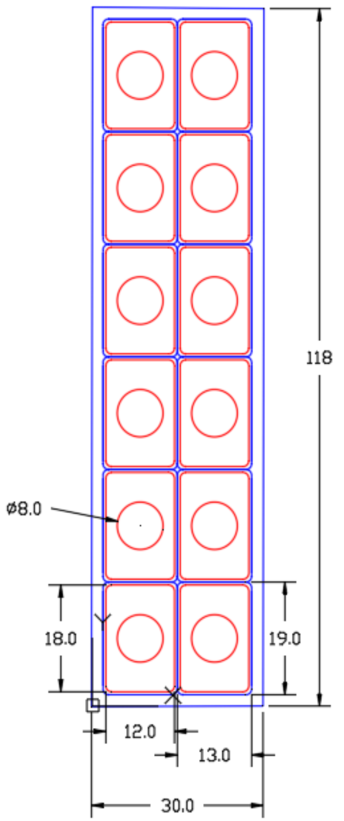
Laminations from M15 low carbon steel have 0.5 mm thickness.

At magnet core ends placed stainless steel plates of 10 mm thick (not shown).

Longitudinal rods should be electrically insulated from laminations.

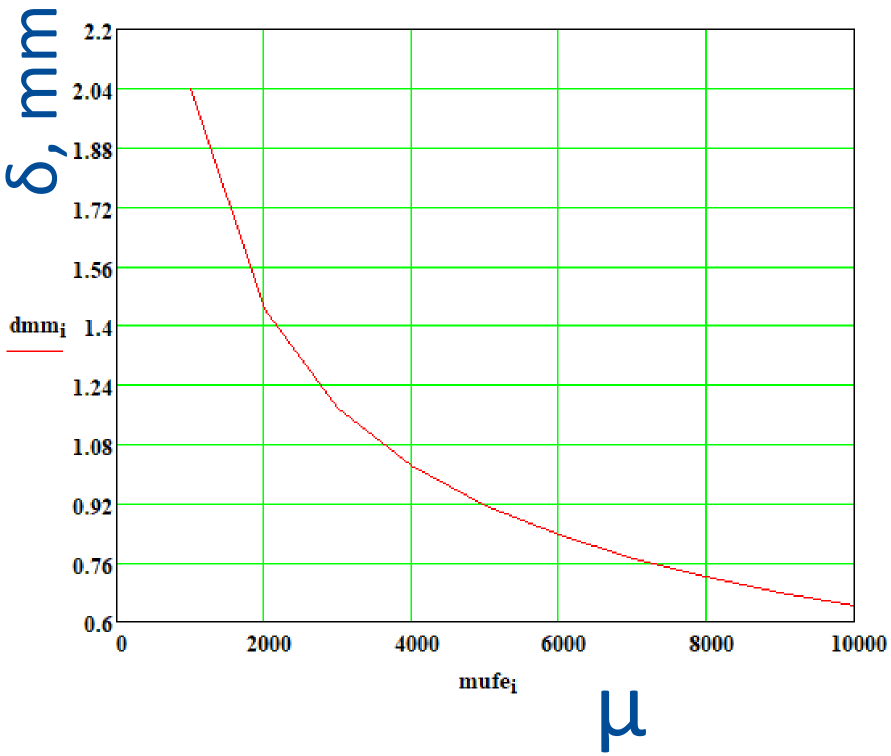
Dimensions in mm to start the mechanical design.

Coil Requirements



- ✓ Copper conductor 12 x 18 dia. 8 mm.
- ✓ Coil number of turns 12
- ✓ Turn electrical insulation 0.5 mm.
- ✓ Coil ground insulation 2 mm.
- ✓ Two coils mounted vertically through the magnet gap.
- ✓ Coil dimensions could be increased to avoid interference with laminations clamping structure.
- ✓ High pot test at 3 kV.

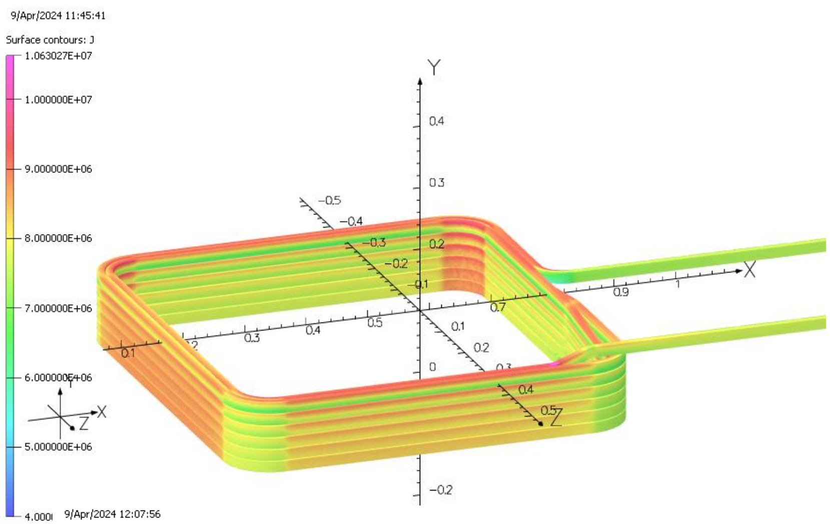
Iron Lamination Skin Depth

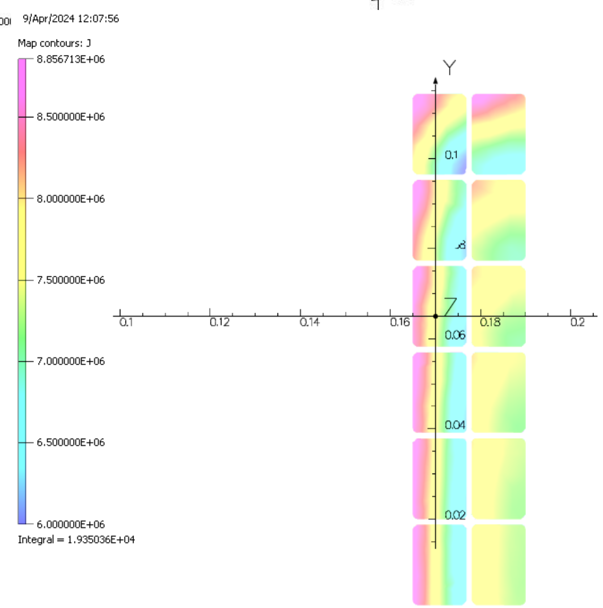


The steel skin depth is in the range of 2 mm – 0.8 mm for the magnetic permeability range of 1000 – 6000 at 28Hz. The steel thickness of 0.5 mm provides full magnetic field penetration in laminations. The steel AC losses and laminated core average magnetic permeability will be included in the design after steel properties magnetic measurements.

PDR recommendation: Evidence of skin depth in steel.

Coil AC Losses



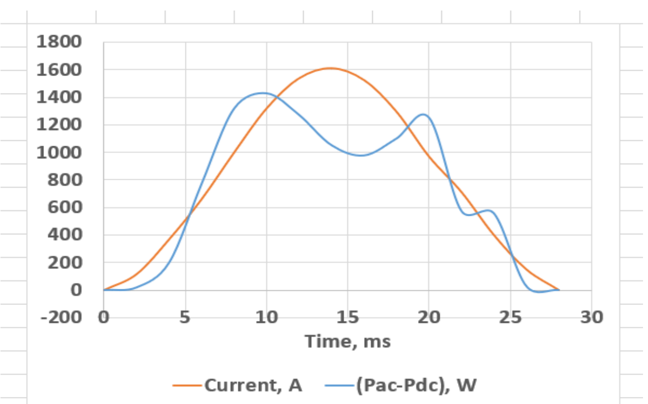


PDR Question:

Is Joule heating in the conductor included in the Opera analysis?

The magnet AC analysis showed an 8.2 % power loss increase relative to the DC case.

This effect and possible conductor area variations were included as an 11 % conductor resistivity increase.



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Laminated Core AC Losses

CLIFFS

TABLE 2 – STANDARD GAUGES

Electrical Steel Gauge Number	Thickness in. (mm)
24	0.0250 (0.635)
26	0.0185 (0.470)
29	0.0140 (0.356

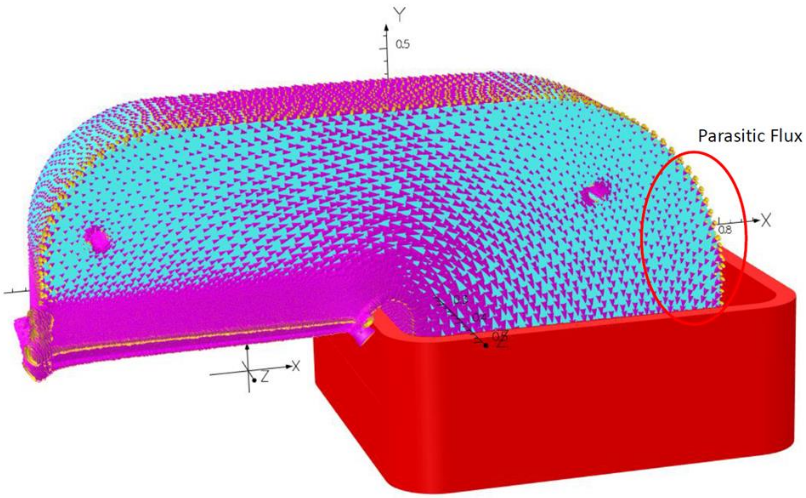
TABLE 5 – CORE LOSS LIMITS FOR FULLY PROCESSED MATERIAL AT 60 HZ* (ASTM A677) (W/LB.)

Grade	15 kG		
	0.014 in. (29 gauge)	0.0185 in. (26 gauge)	0.025 in. (24 gauge)
DI-MAX M-15	1.45	1.60	–
DI-MAX M-19	1.55	1.65	2.00
DI-MAX M-22	1.65	1.80	2.10
DI-MAX M-27	1.75	1.90	2.25
DI-MAX M-36	1.85	2.00	2.35
DI-MAX M-43	1.95	2.10	2.50
DI-MAX M-45	2.05	2.40	2.75
DI-MAX M-47	–	2.80	3.20

*As-Sheared, 50/50.

Preliminary estimation:
Core losses P'=1.6 W/lb=3.53 W/kg.
Thickness 0.47 mm, Bm=1.5 T, f=60 Hz.
Losses P=K*(Bm*f)^2 or for f=33Hz,
Bm=0.65 T, P'=0.84 W/kg.
Losses/magnet at 0.45 duty factor: 1041W.
The air-cooled core temperature rise is ~22C. It could be reduced to 18C for 29 gauge steel 0.35 mm thick.
More accurate data will be obtained after the chosen steel samples test.

Coil Configuration



PDR Recommendation:

The coil lead routing leads to 23.75 turns instead of the design 24 and creates a loop. Recommend moving the power leads as close together as possible.

The 100% magnetic field and the field quality in the C-magnet gap are formed by only part of the coil placed in the magnet gap.

The outer part of the coil generates parasitic flux in the core back leg and parasitic fringe field in an external space (red circle).

This might be an issue in window frame magnets as unbalanced left and right turns will generate huge short-circuited unwanted flux through the core.

In our case, if we even remove part or all turns on the magnet back side we improve the magnet parameters and reduce the fringe field.

But, of course, external power cables should be close to each other to reduce a local fringe field.

Thank You!