Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

PIP-II Booster ORBUMP Magnetic Design

Vladimir Kashikhin

PDR review

30 May 2019

OUTLINE

- Magnet main parameters
- Choice of yoke material
- Magnet model
- Field simulations
- Magnet geometry for the mechanical design
- Possible improvements and modifications
- Summary

Magnet Main Parameters

Basic Parameters	value	units
Proton Beam Energy (Nominal/ Max)	800	MeV
Magnetic field pulses ramp up/plato/down	0.2/0.6/0.2	ms
Pulses repetition rate	20	Hz
Bend direction	Vertical	
Magnetic Properties		
Field at nominal energy [800 MeV]	0.34	T
Field integral at nominal energy [800 MeV] (0.2328 spec)	0.23316	T-m
Good field (5 units field homogeneity) width	250	mm
Peak current	15	kA
Physical dimensions		
Gap	56	mm
Maximum aperture width (inside steel)	350	mm
Coil width	20	mm
Effective magnet length	0.6855	m
Core length	0.65	m

Laminated Steel Properties

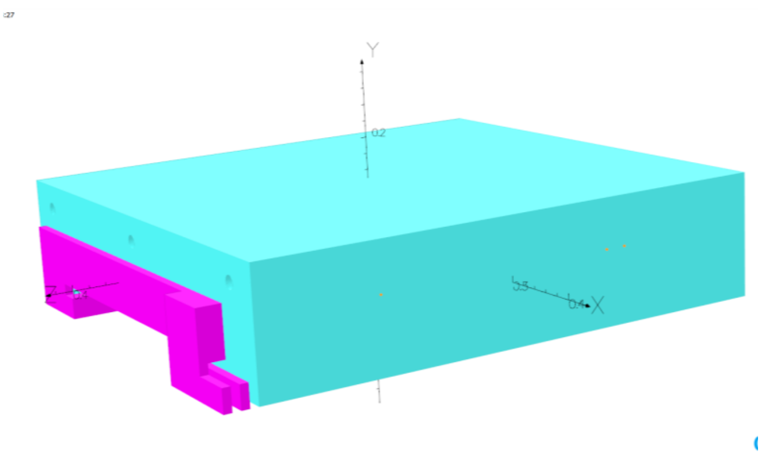
ARNOLD MAGNETIC TECHNOLOGIES

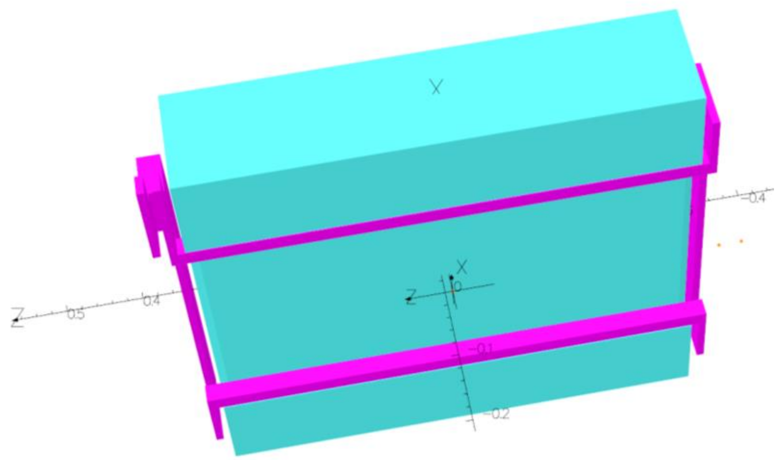
Rolled Products Division
300 North West St.
Marengo, IL 60152
815-568-2000

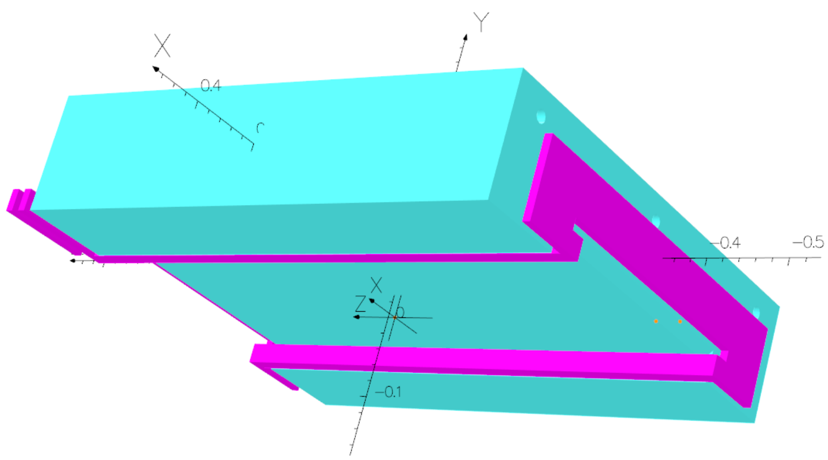
Arnold Capabilities for Coated and Slit Silicon Steel

Magnetic Material	Three Percent Silicon Electrical Steel							
Coating Material	AISI Type C-5 - Inorganic magnesium phosphate coating with inorganic fillers and organic resin							
Characteristic	**Width Range (Inch)**	**Tolerance (Inch unless otherwise specified)**						
		Grain Oriented				ARNON™ (Non-Oriented)		
		1-mil	2-mil	4-mil	6-mil	5-mil	7-mil	
							Regular	Special
Loss per ASTM A348 (Max.)	All Available	11.0 Watts per Pound @ 12 kG, 400 Hz	8.5 Watts per Pound @ 15 kG, 400 Hz	6.5 Watts per Pound @ 15 kG, 400 Hz	9.0 Watts per Pound @ 15 kG, 400 Hz	5.5 Watts per Pound @ 10 kG, 400 Hz	7.5 Watts per Pound @ 10 kG, 400 Hz	6.5 Watts per Pound @ 10 kG, 400 Hz
Thickness	All Available	±0.00010	±0.00015	±0.00020	±0.00030	±0.00025	±0.00035	±0.00035
Width	Up to 1.00	±0.003						
	> 1.00 and up to 9.00	±0.005						
	> 9.00 and up to 16.00	±0.010						
Burr (Maximum)	All Available	0.0001	0.0002	0.0004	0.0006	0.0005	0.0007	0.0007
Flatness (Maximum Deviation from Flat)	All Available	0.030 per Inch of Width			0.070			
Flatness Height to Length Ratio (Max.)	All Available	5%	4%	3%				
Crossbow (Maximum Deviation from Flat)	All Available	0.250			Greater of 0.100 or 0.020 per Inch of Width			
Crossbow Height to Length Ratio (Max.)	All Available	5%	4%	3%				
Coil Set (Max. in 3 ft. Vertical)	Up to 0.500	6						
	> 0.500 and up to 16.00	3						
Camber (Max. in 8 ft.)	Up to 0.250	1.50						
	> 0.250 and up to 1.500	0.50						
	> 1.500 and up to 16.00	0.25						
Coil Size (I.D. x Max. O.D.)	Less than 0.75	6 x 20						
	0.75 to 16.00	16 x 32						
Center Type	Up To 7.00	Cardboard center						
	> 7.00 and up to 16.00	Steel Center						
Coating Thickness	All Available	0.000020 to 0.000080 per side						
Average Surface Insulation Resistivity per ASTM A 717-81 (Min.)	All Available	10 Ω cm^2 per lamination (two surfaces)						
Surface	All Available	Uniformly coated. Minimum surface irregularities such as creases, wrinkles, pinpricks, dents, scratches using the best practices of Arnold Rolled Products Division. Surface irregularities occur randomly; no repeating irregularities within a ten-foot section are permitted.						
Miscellaneous	All Available	Non-Oriented coils may be formed by interleaving continuous lengths. Grain Oriented coils may be formed by tape splicing. All breaks will be flagged.						
As Rolled Width available upon request.								

Magnet Model Geometry

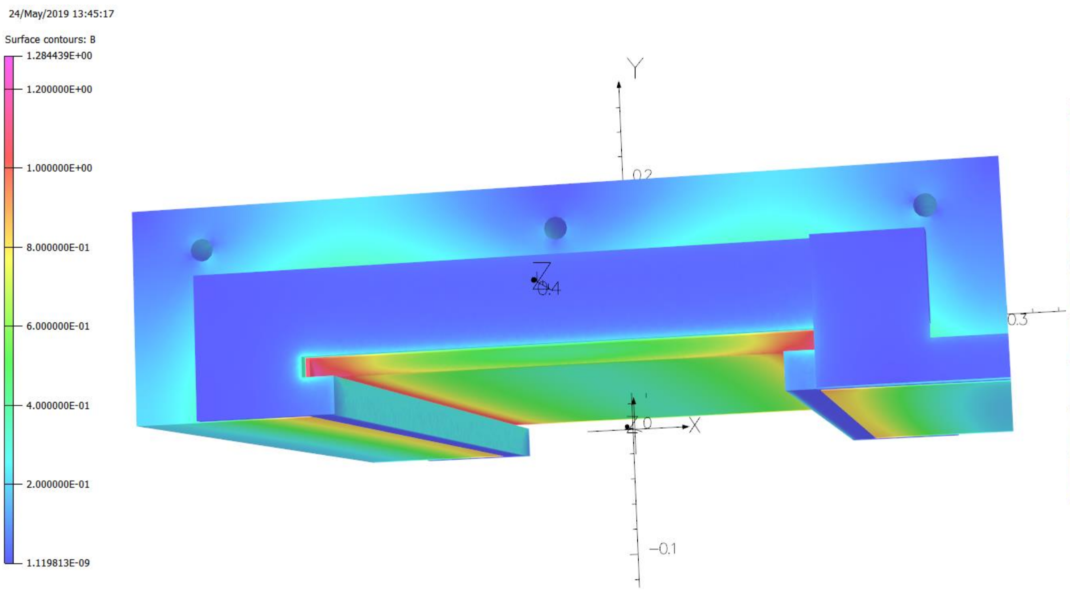


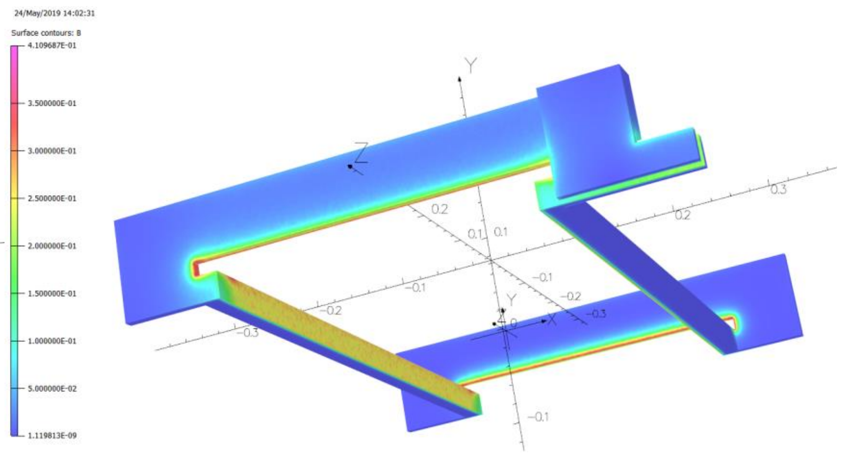




Laminated yoke – blue
Copper single turn coil – pink
Lamination thickness – 5 mils (0.127 mm)
Copper thickness in the gap – 20 mm, at ends – 10 mm.

Magnet Field at 0.3 ms



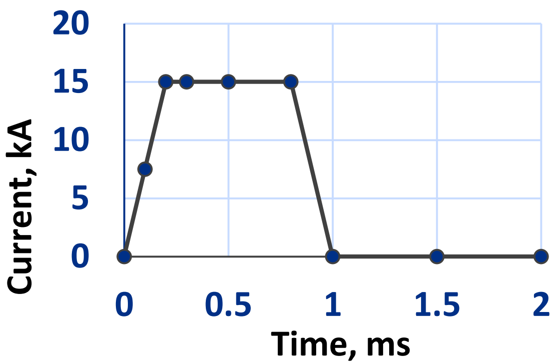


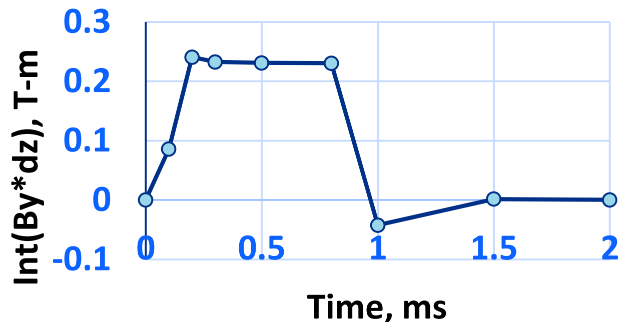
Yoke Bmax=1.28 T

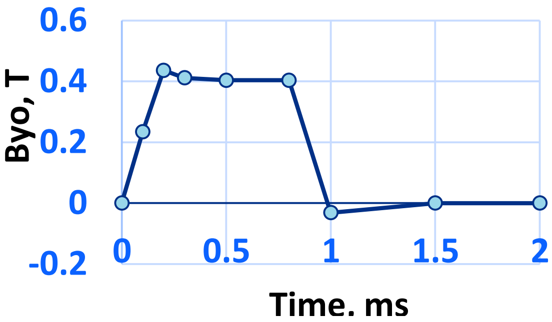
Coil Bmax= 0.41 T

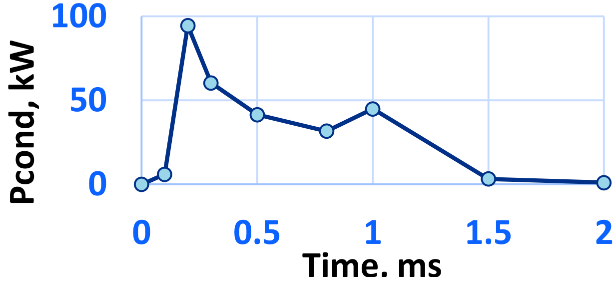
Single turn magnet powered by 15 kA pulses with 20 Hz repetition rate. Pulses have 0.2 ms ramp up/down, 0.6 ms plato.

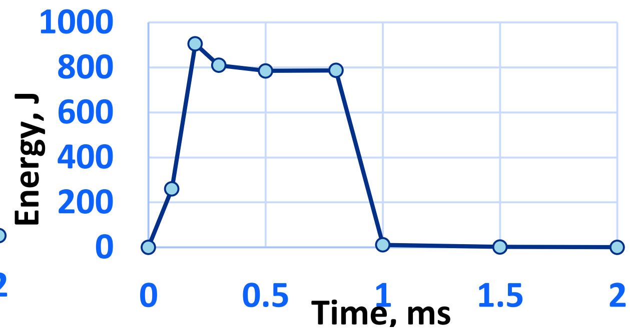
Magnet Parameters vs. Time

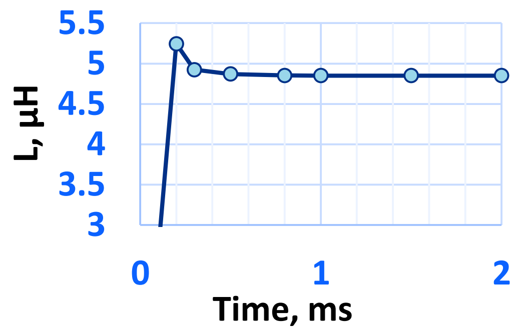


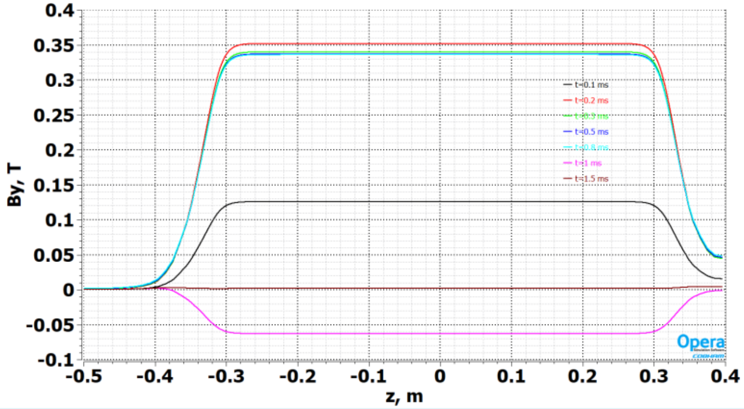






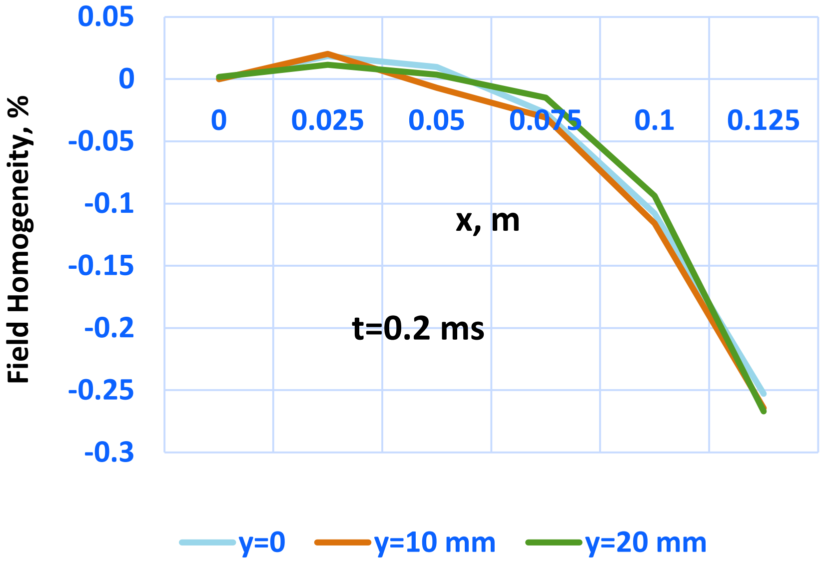


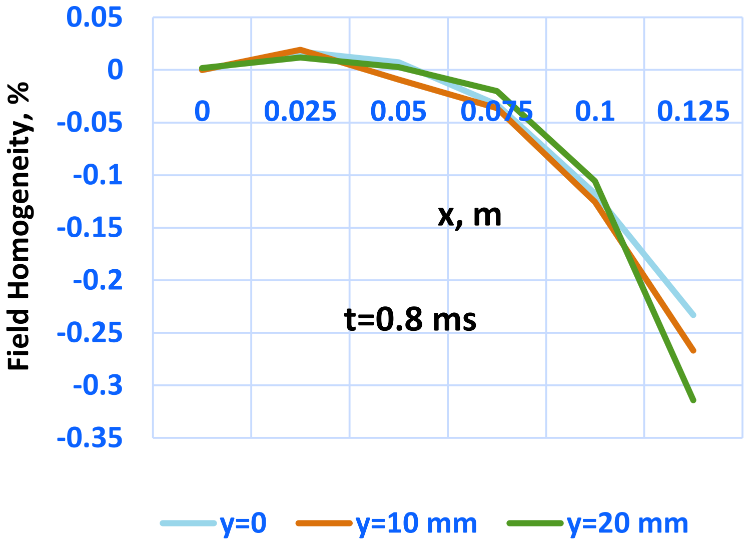




Average power losses in the conductor are 790 W (at 20 Hz), integrated field 0.23 T-m, inductance 5 µH.

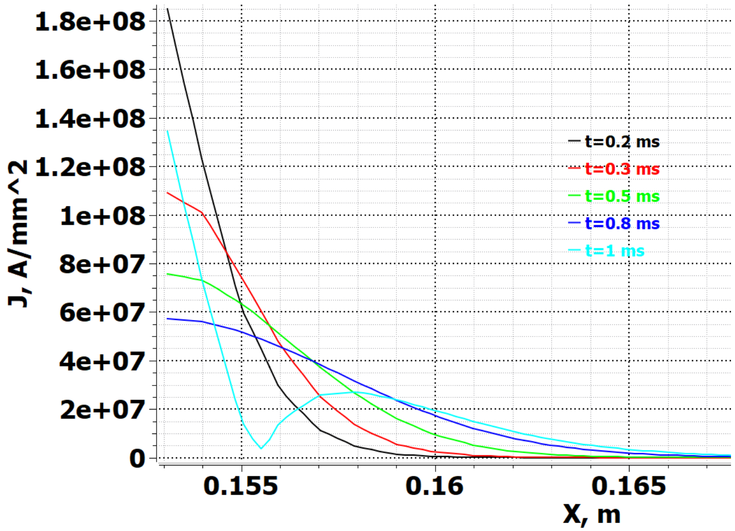
Integrated Field Homogeneity in the Aperture

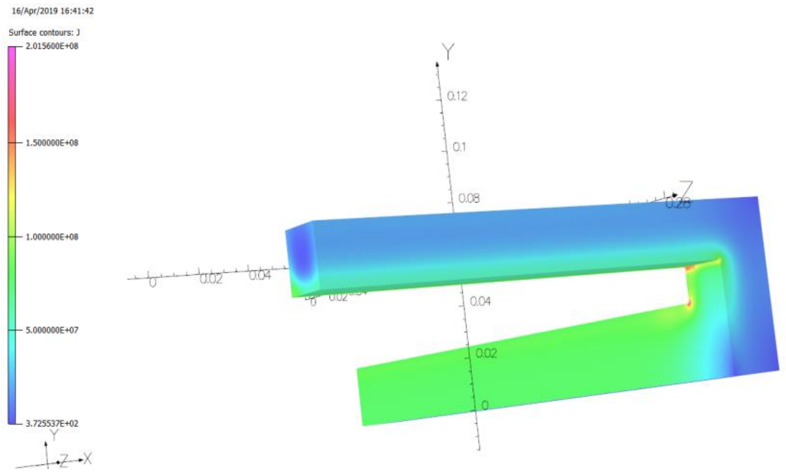




There is a -30 units of sextupole field component because of iron saturation. It will be compensated by pole profile shimming after measurements of AC yoke steel properties.

Skin Effect



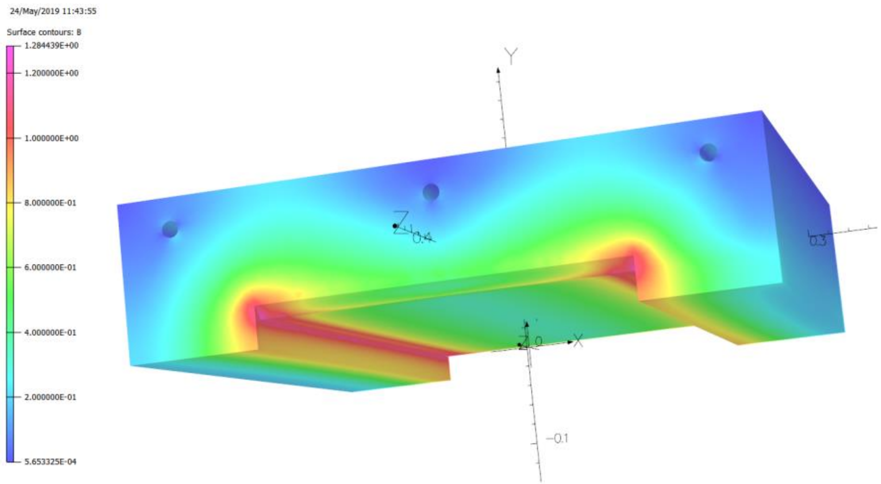


Because of skin effect the conductor current concentrated in 5 mm of the external copper surface.

The skin depths for 1250 Hz frequency (0.2 ms ramp) are:

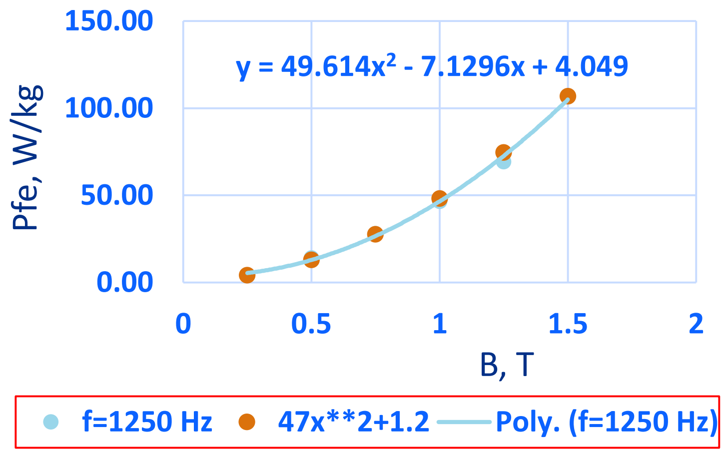
- Electrical steel – 0.137 mm
- Copper 1.94 mm
- Stainless steel – 12.3 mm.

Laminated Core Steel Losses



Losses W/kg

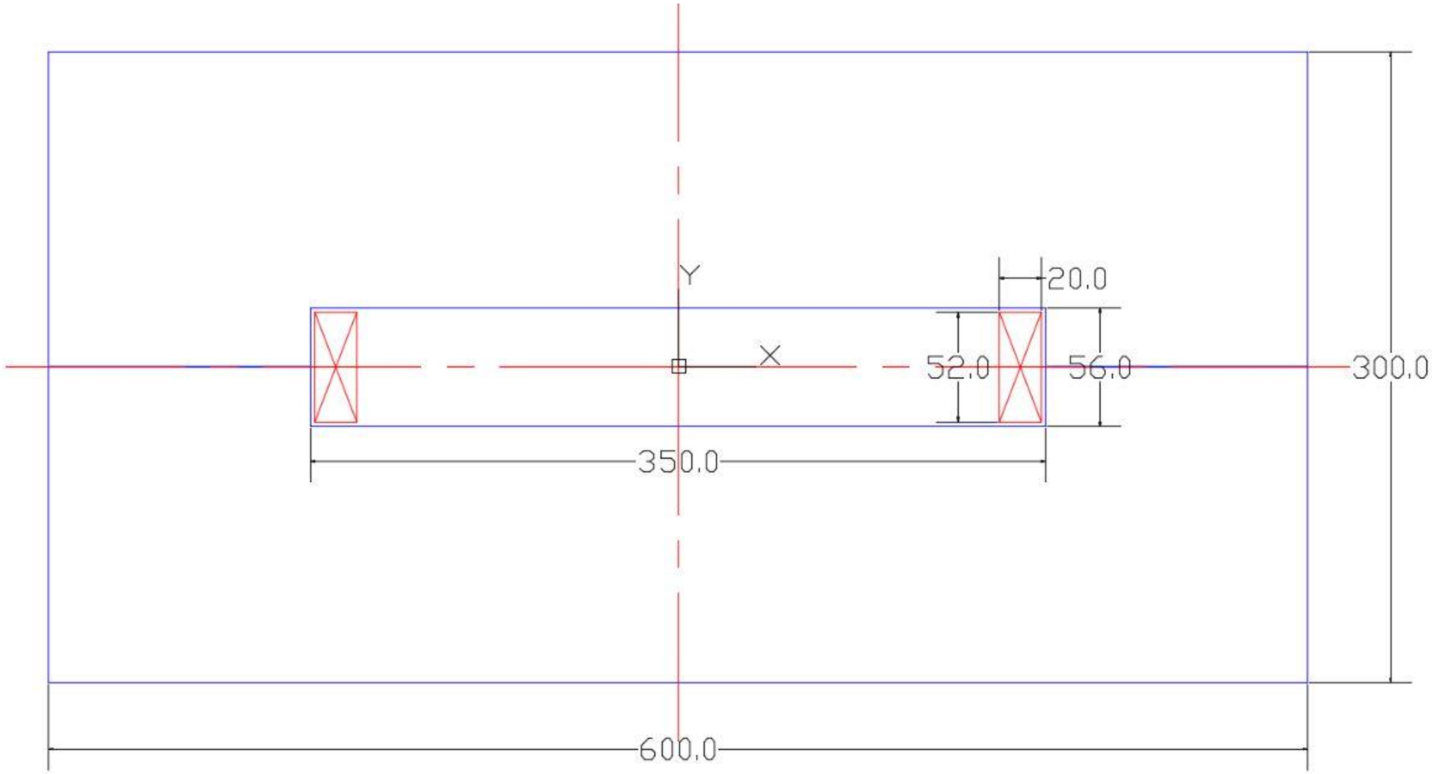
Arnon 5 (W/kg)		Frequency, Hz			
	B(T)	1000	1500	2000	2500
	0.25	3.12	5.38	8.28	11.54
	0.5	10.11	17.92	27.18	37.66
	0.75	20.20	35.99	54.80	75.99
	1	33.29	59.69	90.14	125.68
	1.25	50.22	88.52	137.11	190.17
	1.5	78.69	134.96	204.36	284.77



At 0.2 ms current ramp rate the equivalent frequency will be 1250 Hz.

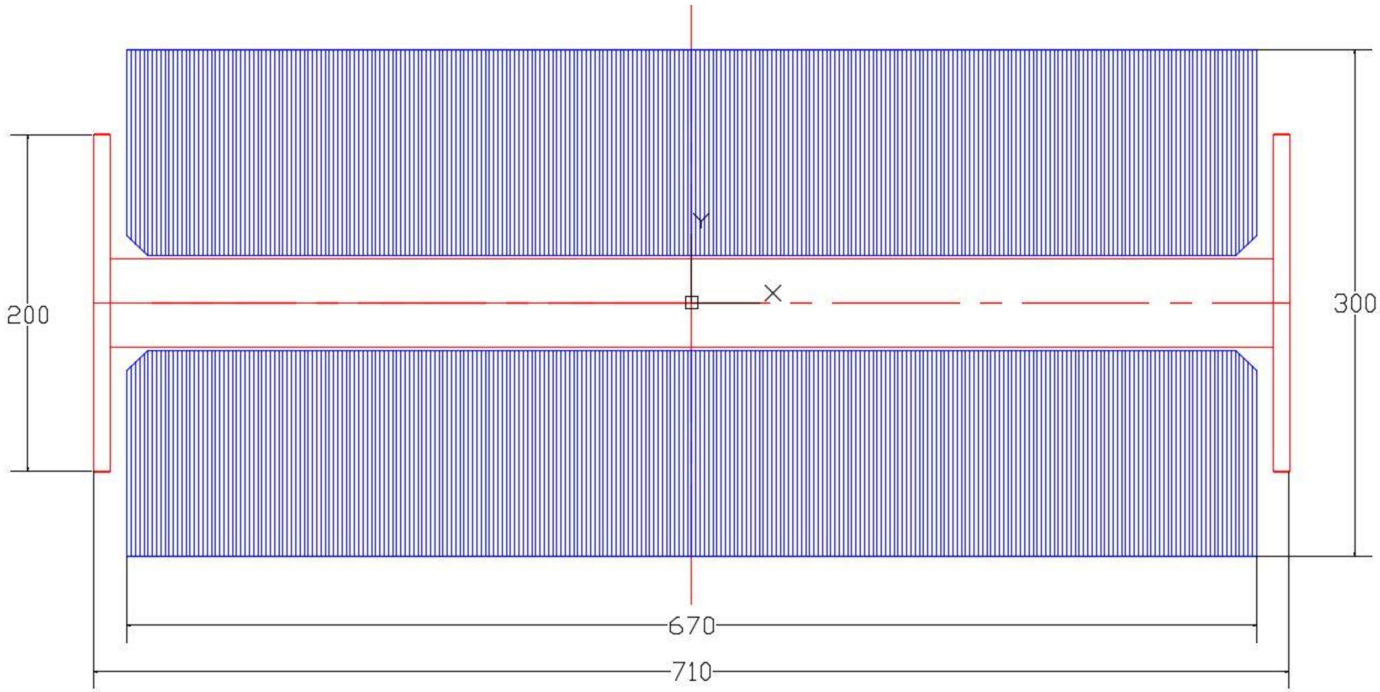
The integrated average power losses in the yoke steel are 110 W.

Magnet X-Y Cross Section



- Laminated iron core assembled from 5 mils (0.127 mm thick) electrical steel laminations.
- Coil water cooling tubes could be brazed only at coil ends like in the old magnet. Thermal analysis will be needed.

Magnet Y-Z Cross Section



- The laminated core with the length 650 mm is a subject of vibrations under magnetic forces at the ends. The stainless steel slotted end plates should be added to prevent laminations separation.
- Water cooling tubes must be properly externally electrically insulated.

Magnet Mechanical Design

- The iron core must be laminated and have electrical insulation between laminations. Two variants might be considered: mineral insulation and polyimide prepreg. The mineral insulated core will have holes for longitudinal tightening rods, the polyimide insulated core glued by heating (technology used for the Booster correctors).
- The core should not have shorts between laminations, an outer case, and the coil.
- The copper coil should be electrically insulated from the core.
- Coil terminals should be arranged in a way to cancel fringe field of each other in the magnet aperture vicinity and between magnets.
- The magnet should be mounted in the vacuum box.
- Two magnets in one vacuum vessel is an attractive option.
- The coil and core should be water cooled removing about 1 kW of losses.
- As a guidance for the design could be used the design of the old ferrite based ORBUMP magnet.

Next Steps

- What is needed:
  - Measure steel properties for the specified field pulses and repetition rate.
  - Finish preliminary mechanical design.
  - Update the field model with dimensions from the mechanical model and measured steel properties.
  - Build the magnet model and perform verification tests with the new power source.
  - Update the magnet design.

Possible Issues and Improvements

- In previous ferrite based ORBUMP magnets was observed rather large quadrupole field component. In this design current leads are symmetrical relatively the aperture center.
- The electrical basses between magnets could cause field distortions. To reduce this effect busses should have close to coaxial configuration (f.e. one in the center and two on sides).
- Yoke core ends have chamfers to reduce ends heating.
- Yoke end shims could be added to improve the measured field quality.
- If the peak field will be around 0.3 T the ferrite yoke is possible, which resolves some technical issues.
- Two magnets in one vacuum vessel saves some very needed longitudinal space.

Summary

- The fixed bending angle defines the integrated field.
- At 800 MeV the peak field is 0.34 T, integrated field 0.233T-m the effective length is 0.6855 m.
- For ~0.3 T gap field might be considered a ferrite yoke.
- For the 1GeV and the same effective length the peak current will be proportionally larger.
- The end field is 0.1 T at the distance 30 mm from the yoke end.

  This field is critical for the foil and should be less than 0.1 T.
- Total power losses in the iron and copper are 1 kW.