PIP-II Booster ORBUMP Magnetic Design

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Outline

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

<table>
<thead>
<tr>
<th>Basic Parameters</th>
<th>value</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton Beam Energy (Nominal/ Max)</td>
<td>800</td>
<td>MeV</td>
</tr>
<tr>
<td>Magnetic field pulses ramp up/down</td>
<td>0.2 ÷ 0.4</td>
<td>ms</td>
</tr>
<tr>
<td>Magnetic field pulse Plato</td>
<td>0.6</td>
<td>ms</td>
</tr>
<tr>
<td>Pulses repetition rate</td>
<td>20</td>
<td>Hz</td>
</tr>
<tr>
<td>Beam bend direction</td>
<td>Vertical</td>
<td></td>
</tr>
<tr>
<td>Magnetic Properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field integral at nominal energy [800 MeV]</td>
<td>0.355</td>
<td>T-m</td>
</tr>
<tr>
<td>Good field (±0.05 % field homogeneity) width</td>
<td>250</td>
<td>mm</td>
</tr>
<tr>
<td>Peak current</td>
<td>≤ 20</td>
<td>kA</td>
</tr>
<tr>
<td>Physical dimensions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap</td>
<td>56</td>
<td>mm</td>
</tr>
<tr>
<td>Laminated core length</td>
<td>850</td>
<td>mm</td>
</tr>
<tr>
<td>Total magnet length including flanges</td>
<td>≤ 1.09</td>
<td>m</td>
</tr>
</tbody>
</table>
Magnet Geometry

- Laminated ARNON5 core
- Cooling tube Cu bar
- Current in
- Current out
- Cu Flags
- Front Cu plate
- Straight Cu bars
Magnet Design Evolution

✓ Old ORBUMP had ferrite CMD10 core. The new magnets have the gap field 0.41 T instead of 0.28 T and up to 1.5T in the core, the ferrite having saturation flux density 0.4 T can not be used.
✓ During conceptual design the magnet core length was 650 mm. After the integrated magnet strength increase the magnet length was increased to 850 mm.
✓ In 400 MeV ORBD magnets current leads generated a large quadrupole field component. Leads now relocated to the side and placed symmetrically.
✓ To reduce the laminated end packs heating added pole chamfers.
✓ Because of high RMS current added a water cooling to the current leads.
✓ To avoid lamination vibration at core ends added stainless steel end plates.
✓ To improve the integrated field quality added copper shims to straight bars.
✓ To provide the fast current ramp chosen low carbon steel of 0.127 mm thickness.
✓ Laminated core clamped by insulated rods. Core outer surface electrically insulated from the ground.
Laminated Steel Properties

For the magnet core chosen steel ARNON, 5 mil thick with type C5 coating.
Toroidal ARNON 5 steel lamination packs were measured at different frequencies. Rather low dependance from the frequency in the range of 500Hz÷1250Hz for 0.127 mm thick steel.
Laminated Core Losses

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

Analytic fitting formula used to calculate integrated core losses.

### Arnon 5 (W/kg)

<table>
<thead>
<tr>
<th>B(T)</th>
<th>1000</th>
<th>1500</th>
<th>2000</th>
<th>2500</th>
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</thead>
<tbody>
<tr>
<td>0.25</td>
<td>3.12</td>
<td>5.38</td>
<td>8.28</td>
<td>11.54</td>
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<tr>
<td>0.5</td>
<td>10.11</td>
<td>17.92</td>
<td>27.18</td>
<td>37.66</td>
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<tr>
<td>0.75</td>
<td>20.20</td>
<td>35.99</td>
<td>54.80</td>
<td>75.99</td>
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<tr>
<td>1</td>
<td>33.29</td>
<td>59.69</td>
<td>90.14</td>
<td>125.68</td>
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<tr>
<td>1.25</td>
<td>50.22</td>
<td>88.52</td>
<td>137.11</td>
<td>190.17</td>
</tr>
<tr>
<td>1.5</td>
<td>78.69</td>
<td>134.96</td>
<td>204.36</td>
<td>284.77</td>
</tr>
</tbody>
</table>

The analytic fitting formula used to calculate integrated core losses is:

\[
y = 49.614x^2 - 7.1296x + 4.049
\]

where \( x \) represents the magnetic flux density \( B \) in Tesla (T) and \( y \) represents the losses in W/kg at a frequency of 1250 Hz.
For the final magnetic design, the magnet geometry was transferred from the final NX mechanical model.
Laminated yoke – blue
Copper single turn coil – pink and green
Lamination thickness – 5 mils (0.127 mm)
Copper thickness in the gap – 20 mm, at ends – 10 mm.
Magnetic Field Transient Analysis

✓ Magnetic field simulated by OPERA3D code.
✓ Capacitors based power supply current pulse (top left);
✓ At the Plato of pulse (time 0.7 ms):
  - Current 19.004 kA;
  - Center field 0.415 T;
  - Integrated field 0.3705 T-m;
  - Effective length 893 mm
  - Stored energy 1107 J;
  - For spec. 0.355 T-m operating current 18.209 kA.
At time 0.7 ms:
- Inductance 6.2 uH;
- Resistance 0.16 mΩ;
- Coil losses 62 kW;
- Iron losses 10.5 kW;

Average parameters for 20Hz repetition pulses rate (time period 50 ms):
- Copper losses 1539 W;
- Iron core losses 260 W.
Integrated field homogeneity calculated for the middle Plato of current pulse time 0.7 ms. It is in the range of +/- 0.05% in the good field area of dx=+/-125 mm, dy=+/-20mm.
Maximum current density 150 A/mm$^2$ concentrated on inner surfaces of copper coil. At the time of 0.8 ms it drops two times because of magnetic field diffusion inside the copper. The skin depth for 1250 Hz frequency (0.2 ms current ramp) are:
- Electrical steel – 0.137 mm;
- Copper – 1.94 mm;
- Stainless steel – 12.3 mm.
There are two options of power supplies based on Switched Capacitors (SCap) or PFN.

- SCap has longer current pulse and ramp time.
- PFN PS has shorter pulse and fast ramp time.
- SCap has lower AC losses and larger DC losses than PFN PS.
- Total coil losses about the same for SCap PS are 1539 W, for the PFN PS 1578 W.
- Total iron losses SCap PS 260 W, PFN PS 228 W.
Guidance for the Mechanical Design

➢ The iron core must be laminated and have electrical insulation between laminations. The mineral insulated laminations will have holes for longitudinal tightening rods. Rods should be electrically insulated from the core.

➢ The core should not have shorts between laminations, to an outer case, and the coil.

➢ The copper coil should be electrically insulated from the core using a high voltage ground insulation up to 2-6 kV. The peak voltage defined by the type of used power supply.

➢ 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.

➢ The coil and core should be water cooled removing at least 2 kW of losses.

➢ As a guidance for the design could be used the design of the old ferrite based ORBD magnet.
Next Steps

➢ Using the final choice of power supply and updated current pulse, recalculate more accurately magnet transient analysis using measured steel properties.
➢ Transfer the coil, leads, clamps power losses to the thermal analysis.
➢ Update the integrated field homogeneity.
➢ Implement minor drawings corrections, if needed, to improve the magnetic performance.
➢ Analyze results of first magnet magnetic measurements.
➢ Compare results of measurements with simulations.
➢ Update if needed drawings and fabrication technology.
Summary

➢ The magnetic design made in an agreement with the physical specification.
➢ In the design resolved the main issue for this fast pulsed magnet by using very thin laminations to reduce eddy currents and losses in the core.
➢ Added copper coil water cooling to remove about 2 kW heat load.
➢ Added copper shims to improve the dynamic magnetic field homogeneity.