Magnet design for MedAustron

February 17, 2022

1 Analytical

1.1 Magnet type decision

Use H-type

- Mechanical rigid
- Symmetrical
- (-) hard to get the beam pipe in/out

1.2 Aperture Height

$$\begin{aligned} h &= 2 \cdot h_{\mathrm{GFR}} + 2 \cdot d_{\mathrm{vacuum}} + d_{\mathrm{tolerance}} && (1) \\ &= 2 \cdot 23\,\mathrm{mm} + 2 \cdot 2\,\mathrm{mm} + 2\,\mathrm{mm} = 52\,\mathrm{mm} && (2) \end{aligned}$$

1.3 Flux Density

Total bending angle:

$$\theta_{\mathrm{tot}} = 3 \cdot 36° = 108° \tag{3}$$

Total length

$$l_{\mathrm{mag}} = (l_{\mathrm{iron}})_{max} + 2hk = 0.340\,\mathrm{m} + 2 \cdot 0.55 \cdot 52\,\mathrm{mm} = 397.2\,\mathrm{mm} \tag{4}$$

$$\theta_{\mathrm{mag}} = \frac{l_{\mathrm{mag}}}{\rho} \Rightarrow \rho = \frac{l_{\mathrm{mag}}}{\theta_{\mathrm{mag}}} = \frac{397.2\,\mathrm{mm}}{0.6283\,\mathrm{rad}} = 0.642\,\mathrm{m} \tag{5}$$

$$B_{\mathrm{min}} = \frac{(B\rho)_{\mathrm{min}}}{\rho} = \frac{0.383\,\mathrm{T\,m}}{0.642\,\mathrm{m}} = 0.596\,\mathrm{T} \tag{6}$$

$$B_{\mathrm{max}} = \frac{(B\rho)_{\mathrm{max}}}{\rho} = \frac{0.766\,\mathrm{T\,m}}{0.642\,\mathrm{m}} = 1.19\,\mathrm{T} \tag{7}$$

1.4 Pole width and yoke thickness

$$\frac{\Delta B}{B_0} = 1e - 3 \tag{8}$$

$$x_{\text{unoptimized}} = 2\frac{a_{\text{unoptimized}}}{h} = -0.36 \ln\left[\frac{\Delta B}{B_0}\right] - 0.90 = 1.5898 \tag{9}$$

$$x_{\text{optimized}} = 2\frac{a_{\text{optimized}}}{h} = -0.14 \ln\left[\frac{\Delta B}{B_0}\right] - 0.25 = 0.7171 \tag{10}$$

$$a_{\text{optimized}} = \frac{h \cdot x_{\text{optimized}}}{2} = \frac{52\,\text{mm} \cdot 0.7171}{2} = 18.645\,\text{mm} \tag{11}$$

Pole width:

$$\text{GFRx'} = \text{GFRx} + \underbrace{\rho(1 - \cos{}^{\theta}\!/_{2}}_{s} = 20\,\text{mm} + 31.42\,\text{mm} = 51.42\,\text{mm} \tag{12}$$

$$w = 2 \cdot (\text{GFRx'} + a_{\text{optimized}}) = 140.13\,\text{mm} \tag{13}$$

1.5 Excitation Current

$$(NI)_{\text{dipole, min}} = \frac{B_{\min}\, h}{2\,\mu_0} = \frac{0.596\,\text{T} \cdot 52\,\text{mm}}{2 \cdot \mu_0} = 12.331\,\text{kA} \tag{14}$$

$$(NI)_{\text{dipole, max}} = \frac{B_{\max}\, h}{2\,\mu_0} = \frac{1.19\,\text{T} \cdot 52\,\text{mm}}{2 \cdot \mu_0} = 24.621\,\text{kA} \tag{15}$$

1.6 Nominal Current and Turns

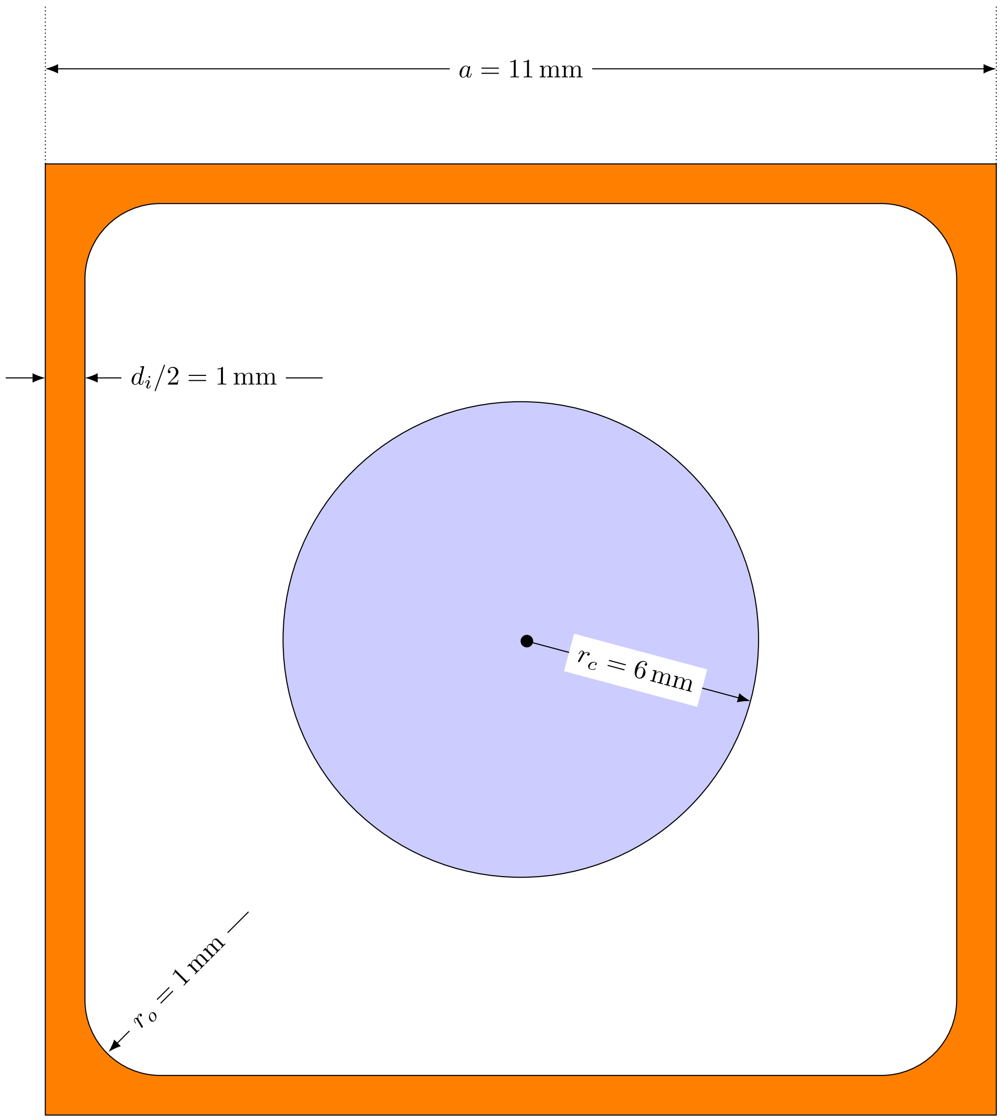

Figure 1: Cross section

Copper winding area

$$A = a^2 - R^2(4 - \pi) - \pi \left(\frac{c}{2}\right)^2 \tag{16}$$

$$A = 91.867\,\mathrm{mm}^2 \tag{17}$$

with $a = 11\,\mathrm{mm}$, $R = 1\,\mathrm{mm}$, $c = 6\,\mathrm{mm}$.
Total allowed current: $I_{\mathrm{max,PS}} = 600\,\mathrm{A}$
Maximum possible current limited by the winding cross section:

$$I_{\mathrm{max}} = 6\,\mathrm{A\,mm^{-2}} \cdot 91.867\,\mathrm{mm^2} = 551.202\,\mathrm{A} \tag{18}$$

Minimum number of turns:

$$N_{B,\mathrm{min}} = \left\lceil \frac{(NI)_{\mathrm{min}}}{I_{\mathrm{max}}} \right\rceil = 23 \tag{19}$$

$$N_{B,\mathrm{max}} = \left\lceil \frac{(NI)_{\mathrm{max}}}{I_{\mathrm{max}}} \right\rceil = 45 \tag{20}$$

1.7 Coil Parameters

Coil width:

$$w_{\mathrm{coil}} = N_{\mathrm{horizontal}} \cdot (a + d_{\mathrm{insulation}}) + 2 \cdot (d_{\mathrm{epoxy}} + d_{\mathrm{air}}) = 128\,\mathrm{mm} \tag{21}$$

Coil height:

$$h_{\mathrm{coil}} = N_{\mathrm{vertical}} \cdot (a + d_{\mathrm{insulation}}) + 2 \cdot (d_{\mathrm{epoxy}} + d_{\mathrm{air}}) = 68\,\mathrm{mm} \tag{22}$$

with $N_{\mathrm{horizontal}} = 10$, $N_{\mathrm{vertical}} = 5$, $a = 11\,\mathrm{mm}$, $d_{\mathrm{insulation}} = 1\,\mathrm{mm}$, $d_{\mathrm{epoxy}} = 2\,\mathrm{mm}$ and $d_{\mathrm{air}} = 2\,\mathrm{mm}$.
Average turn length:

$$l_{\mathrm{avg}} = \text{pole perimeter} + 4 \cdot w_{\mathrm{coil}} + l_{\mathrm{mag}} = 32\,514.2\,\mathrm{mm} \tag{23}$$

$$poleperimeter = 2 \cdot (ironlength + 2 \cdot polewidth + coilwidth) = 9999. \tag{24}$$

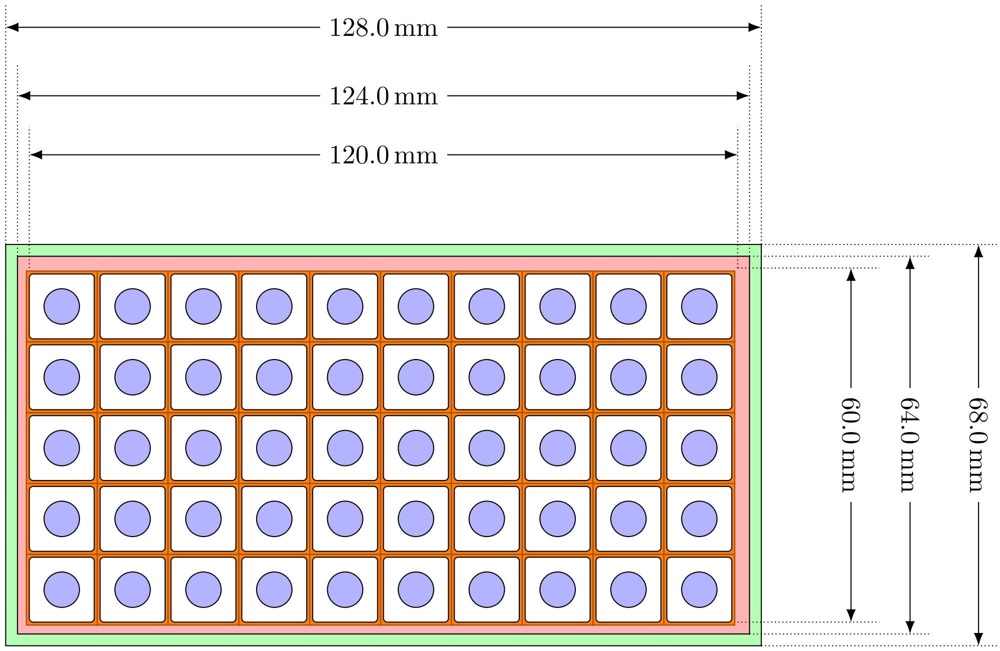

Figure 2: Coil cross section

1.8 Cooling

Length of cooling circuit:

$$l = \frac{K_c \, N \, l_{\text{avg}}}{K_w} = \tag{25}$$

With the maximum allowed pressure drop of $\Delta p = 0.7\,\text{MPa} = 7\,\text{bar}$, the hydraulic diameter $d = 6\,\text{mm}$ and using

$$\Delta p = 60\, l \frac{Q^{1.75}}{d^{4.75}}, \tag{26}$$

the maximum water flow Q is

$$Q = \left(\frac{\Delta p \cdot d^{4.75}}{60 \cdot l} \right)^{\frac{1}{1.75}} = 999\,\text{L}\,\text{min}^{-1}. \tag{27}$$

Using this result and the maximum allowed temperature increase of $\Delta T = 15\,\text{K}$ together with

$$Q = 14.3 \frac{P}{\Delta T} \cdot 1 \times 10^{-3}, \tag{28}$$

the maximum allowed dissipated power is

$$P = \frac{Q \cdot \Delta T}{14.3 \cdot 1 \times 10^{-3}} = 999\,\text{W}. \tag{29}$$

Average water velocity:

$$u_{\text{avg}} = 16.67 \cdot \frac{Q}{A} = 16.67 \cdot \frac{4 \cdot Q}{\pi d^2} \tag{30}$$

Reynolds number (with $v = 6.58 \times 10^{-7}\,\text{m}^2\,\text{s}^{-1}$):

$$R_e = d \cdot \frac{u_{\text{avg}}}{v} \cdot 1 \times 10^{-3} = 999 \tag{31}$$

From $R_e >< 4000$ turbulent flow can/cannot be assumed.