

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

$$h = 2 \cdot h_{\text{GFR}} + 2 \cdot d_{\text{vacuum}} + d_{\text{tolerance}} \quad (1)$$

$$= 2 \cdot 23 \text{ mm} + 2 \cdot 2 \text{ mm} + 2 \text{ mm} = 52 \text{ mm} \quad (2)$$

1.3 Flux Density

Total bending angle:

$$\theta_{\text{tot}} = 3 \cdot 36^\circ = 108^\circ \quad (3)$$

Total length

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

$$\theta_{\text{mag}} = \frac{l_{\text{mag}}}{\rho} \Rightarrow \rho = \frac{l_{\text{mag}}}{\theta_{\text{mag}}} = \frac{397.2 \text{ mm}}{0.6283 \text{ rad}} = 0.642 \text{ m} \quad (5)$$

$$B_{\text{min}} = \frac{(B\rho)_{\text{min}}}{\rho} = \frac{0.383 \text{ T m}}{0.642 \text{ m}} = 0.596 \text{ T} \quad (6)$$

$$B_{\text{max}} = \frac{(B\rho)_{\text{max}}}{\rho} = \frac{0.766 \text{ T m}}{0.642 \text{ m}} = 1.19 \text{ T} \quad (7)$$

1.4 Pole width and yoke thickness

$$\frac{\Delta B}{B_0} = 1e - 3 \quad (8)$$

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

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

$$a_{\text{optimized}} = \frac{h \cdot x_{\text{optimized}}}{2} = \frac{52 \text{ mm} \cdot 0.7171}{2} = 18.645 \text{ mm} \quad (11)$$

Pole width:

$$\text{GFRx}' = \text{GFRx} + \underbrace{\rho(1 - \cos \theta/2)}_s = 20 \text{ mm} + 31.42 \text{ mm} = 51.42 \text{ mm} \quad (12)$$

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

1.5 Excitation Current

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

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

1.6 Nominal Current and Turns

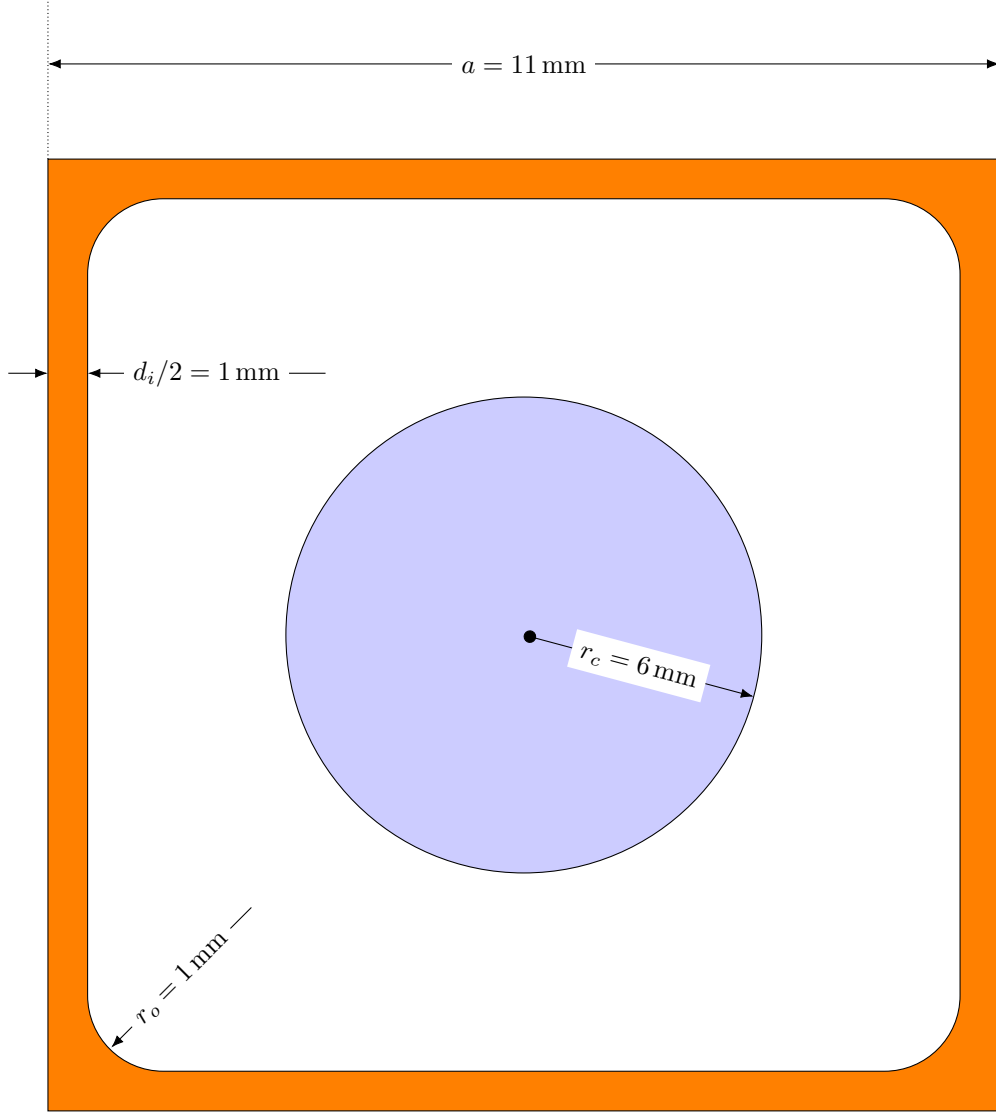


Figure 1: Cross section

Copper winding area

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

$$A = 91.867 \text{ mm}^2 \quad (17)$$

with $a = 11 \text{ mm}$, $R = 1 \text{ mm}$, $c = 6 \text{ mm}$.

Total allowed current: $I_{\text{max,PS}} = 600 \text{ A}$

Maximum possible current limited by the winding cross section:

$$I_{\text{max}} = 6 \text{ A mm}^{-2} \cdot 91.867 \text{ mm}^2 = 551.202 \text{ A} \quad (18)$$

Minimum number of turns:

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

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

1.7 Coil Parameters

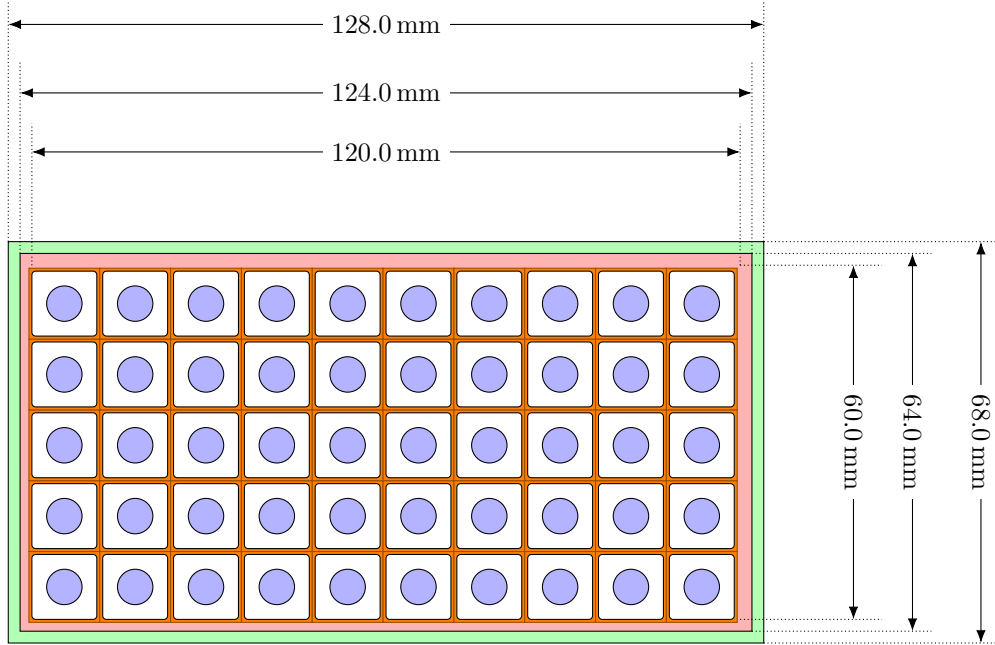


Figure 2: Coil cross section

1.8 Cooling

Length of cooling circuit:

$$l = \frac{K_c N l_{\text{avg}}}{K_w} = \quad (21)$$

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

$$\Delta p = 60 l \frac{Q^{1.75}}{d^{4.75}}, \quad (22)$$

the maximum water flow Q is

$$Q = \left(\frac{\Delta p \cdot d^{4.75}}{60 \cdot l} \right)^{\frac{1}{1.75}} = 999 \text{ L min}^{-1}. \quad (23)$$

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

$$Q = 14.3 \frac{P}{\Delta T} \cdot 1 \times 10^{-3}, \quad (24)$$

the maximum allowed dissipated power is

$$P = \frac{Q \cdot \Delta T}{14.3 \cdot 1 \times 10^{-3}} = 999 \text{ W}. \quad (25)$$

Average water velocity:

$$u_{\text{avg}} = 16.67 \cdot \frac{Q}{A} = 16.67 \cdot \frac{4 \cdot Q}{\pi d^2} \quad (26)$$

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

$$R_e = d \cdot \frac{u_{\text{avg}}}{v} \cdot 1 \times 10^{-3} = 999 \quad (27)$$

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