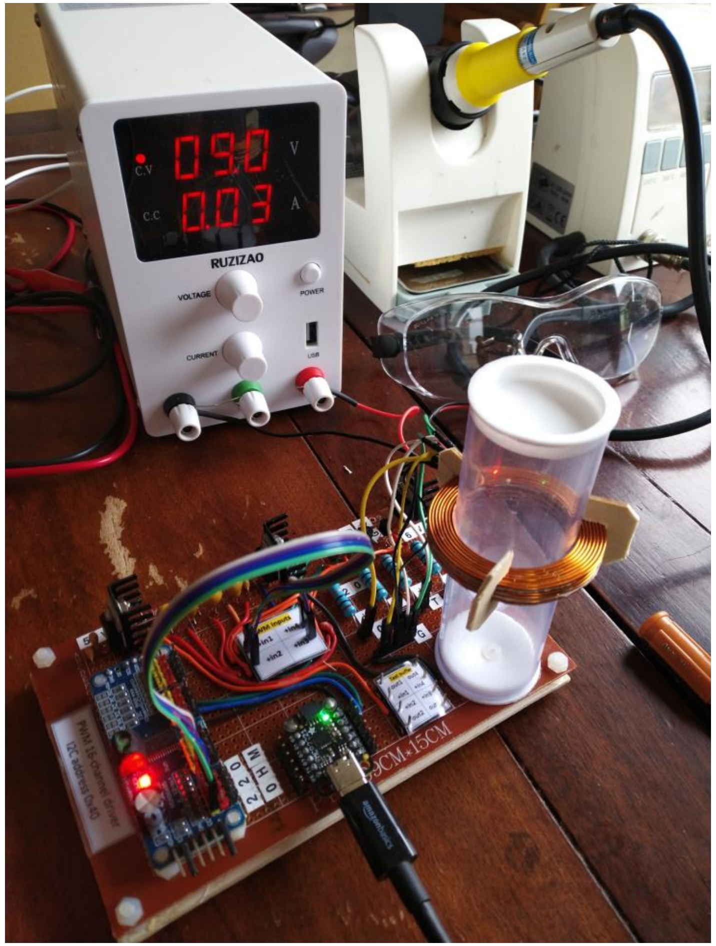
1D shimming coil design and optimisation

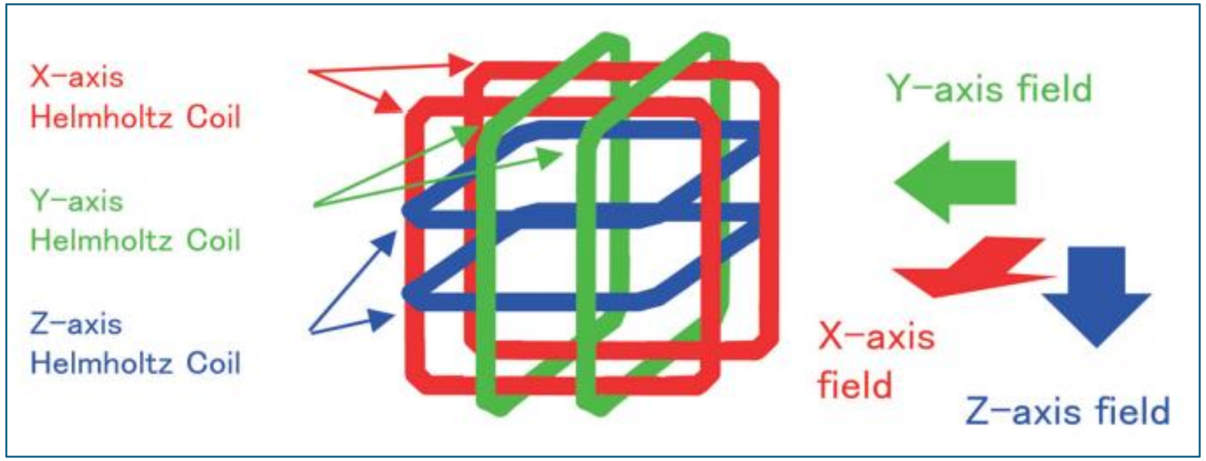
Yujie Zhao, MIT Chemistry



GitHub: https://github.com/Yujie-Zhao/Shimming_Coil

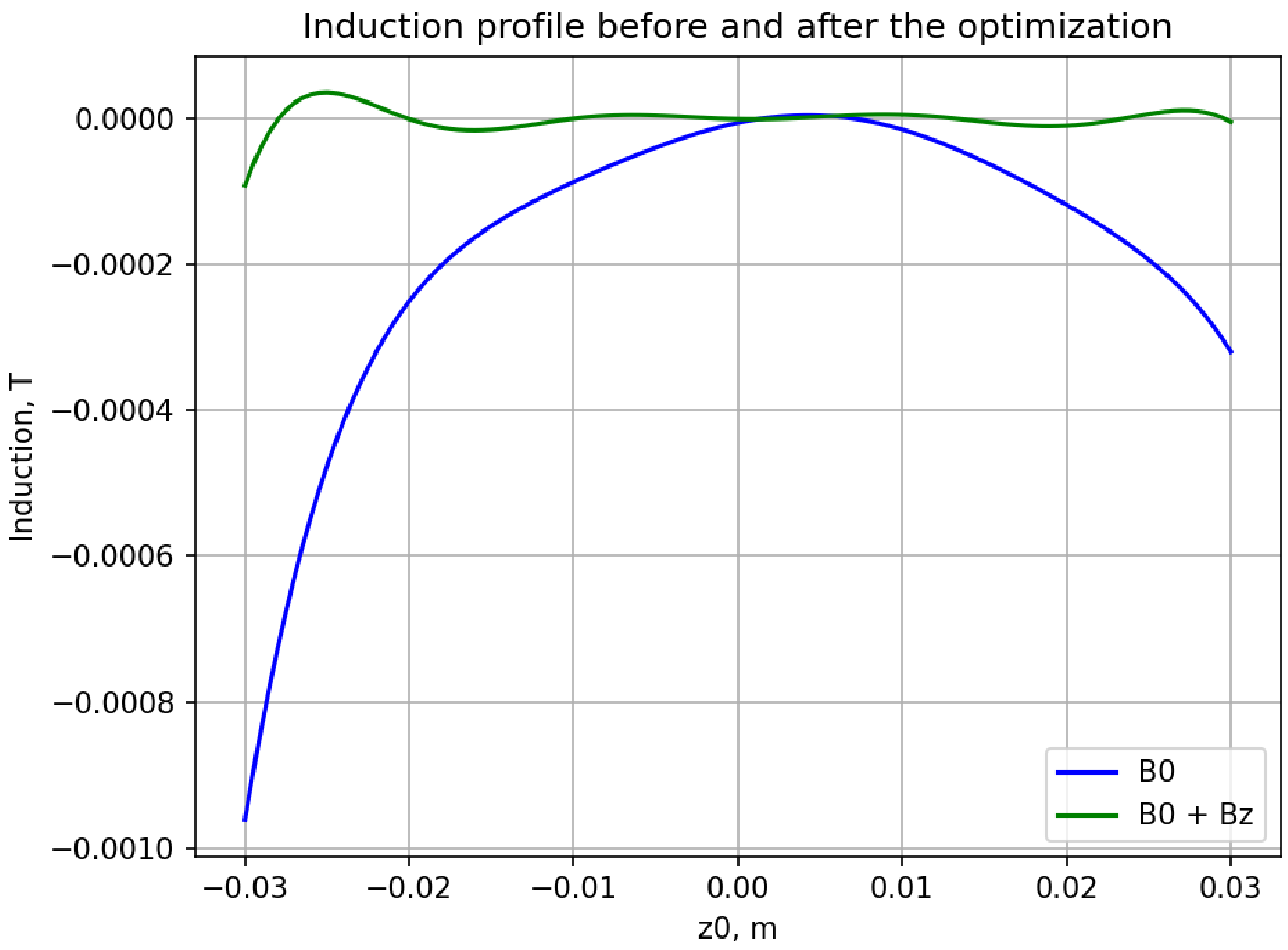
Compensation of unwanted magnetic fields: an old technical challenge

1D Shimming: A magnetic compass adjustment achieved using a dipole created from two iron spheres to counteract magnetic interference caused by metal components of the ship.



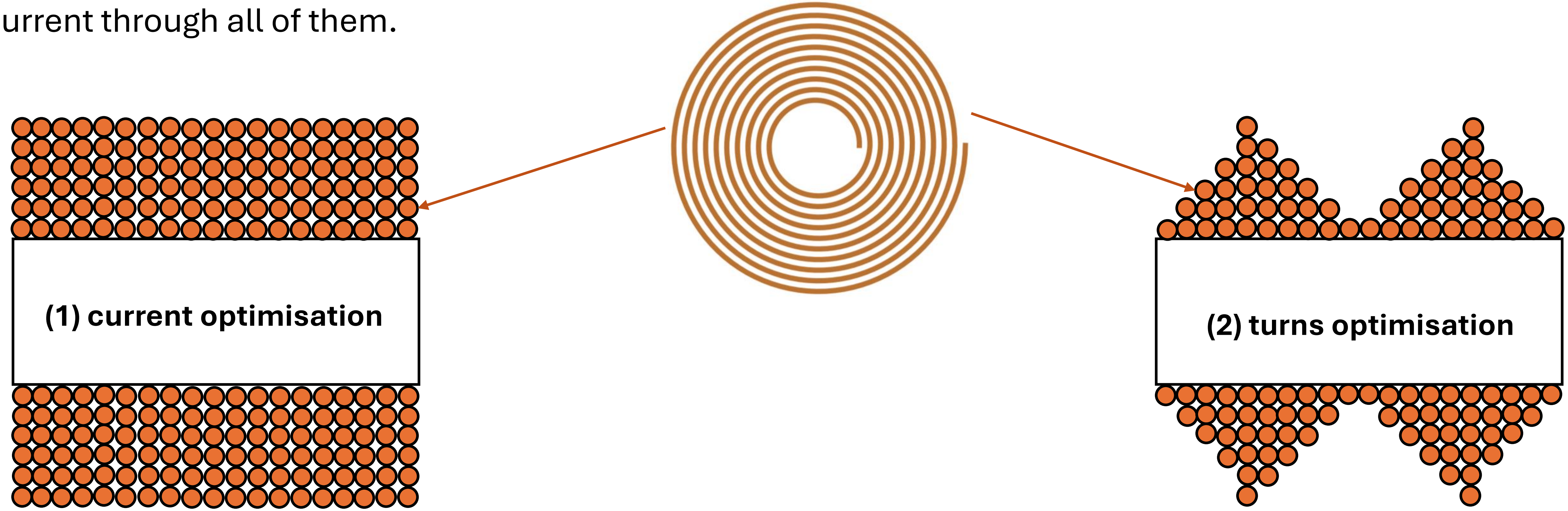
3D shimming: Three Helmholtz coils generating magnetic fields in three mutually perpendicular directions to compensate for the Earth's magnetic field in a small central volume. Application: calibration of magnetic sensors.

Result achieved: our method effectively compensates for complex magnetic field inhomogeneities along a single axis

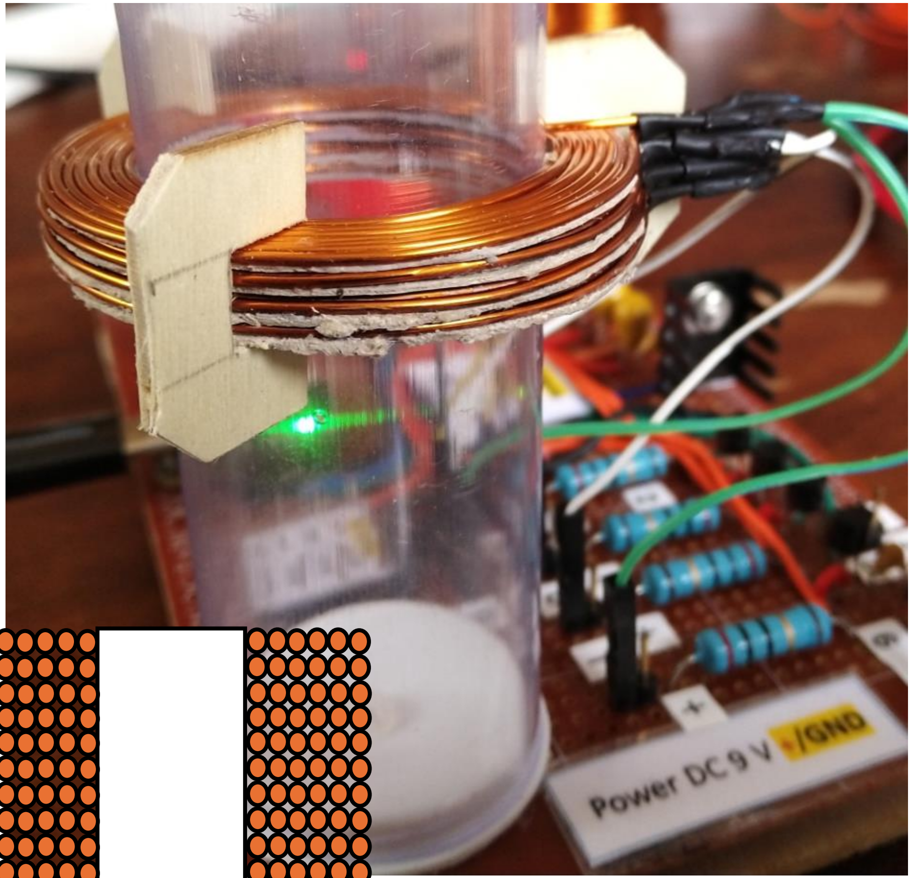


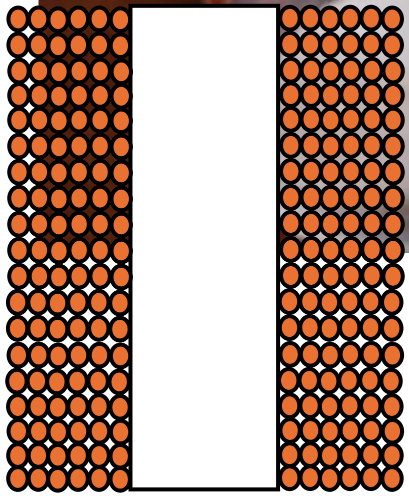
Two configurations of the 1D shimming coil

- Both configurations were based on **a planar spiral coil** as the fundamental structural unit.
- The overall design of the shimming coil was conceived as an optimization of a stack of spirals.
- Optimization can be achieved either by **(1) adjusting the individual currents** in the spirals having the same number of turns or by **(2) adjusting the number of turns** in the spirals while maintaining a fixed current through all of them.

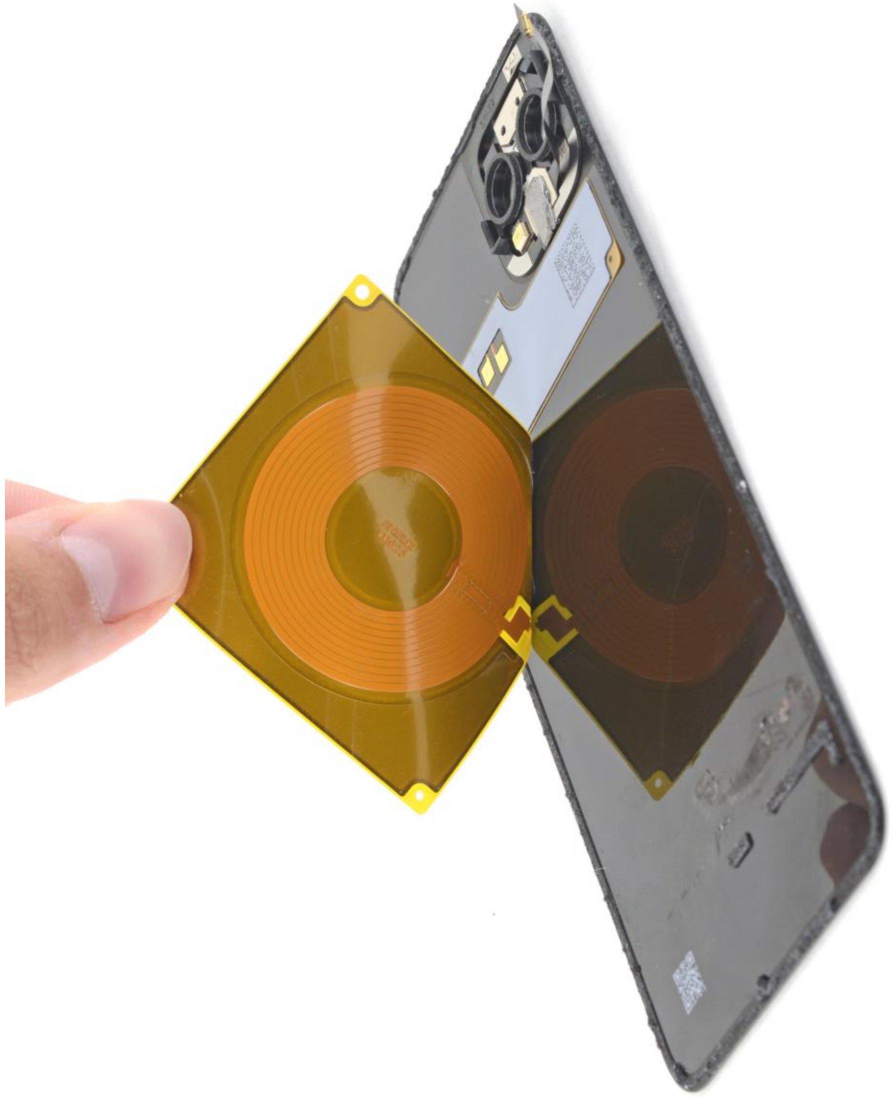


Spiral coils made of enamelled wire, wound turn-to-turn





Spiral coils made of microstrips on a rigid or flexible PCB

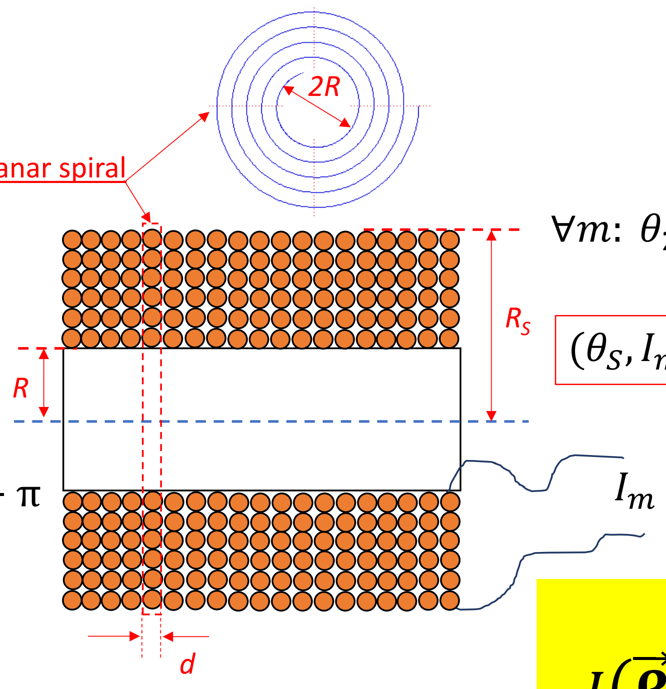


Optimisation algorithm: current optimisation

$$B_z(z_0,\vec{\boldsymbol{\theta}}_1,\vec{\boldsymbol{\theta}}_2,\vec{\mathbf{I}}) = \frac{\mu_0}{4\pi\gamma}\sum_{m=1}^{M} I_m \left(\ln\left(\frac{2\gamma\theta_{2m} + d + \sqrt{(2\gamma\theta_{2m} + d)^2 + 4(z_0 - z_m)^2}}{2\gamma\theta_{1m} + d + \sqrt{(2\gamma\theta_{1m} + d)^2 + 4(z_0 - z_m)^2}}\right) + \right.$$
$$\left. + \frac{2\gamma\theta_{1m} + d}{\sqrt{(2\gamma\theta_{1m} + d)^2 + 4(z_0 - z_m)^2}} - \frac{2\gamma\theta_{2m} + d}{\sqrt{(2\gamma\theta_{2m} + d)^2 + 4(z_0 - z_m)^2}} \right)$$

Induction from a stack of the spiral coils

Elementary planar spiral



$$\forall m:\ \theta_{2m} = \frac{2\pi R_S}{d} - \pi = \theta_S = const$$

$(\theta_S, I_m) -$ optimisation vector

$$\forall m:\ \theta_{1m} = \frac{2\pi R}{d} - \pi$$

Optimisation parameter – **current vector**

$$J(\vec{\boldsymbol{\beta}}) = \sum_{q=1}^{Q}\left(B_z\left(z_q,\vec{\boldsymbol{\theta}}_1,\vec{\boldsymbol{\theta}}_2,\vec{\boldsymbol{\beta}}\right) + B_0\left(z_q\right)\right)^2$$ **– objective function**

Coordinates along the axis

Interpolated residual induction

Inverse Hessian's matrix

Gradient

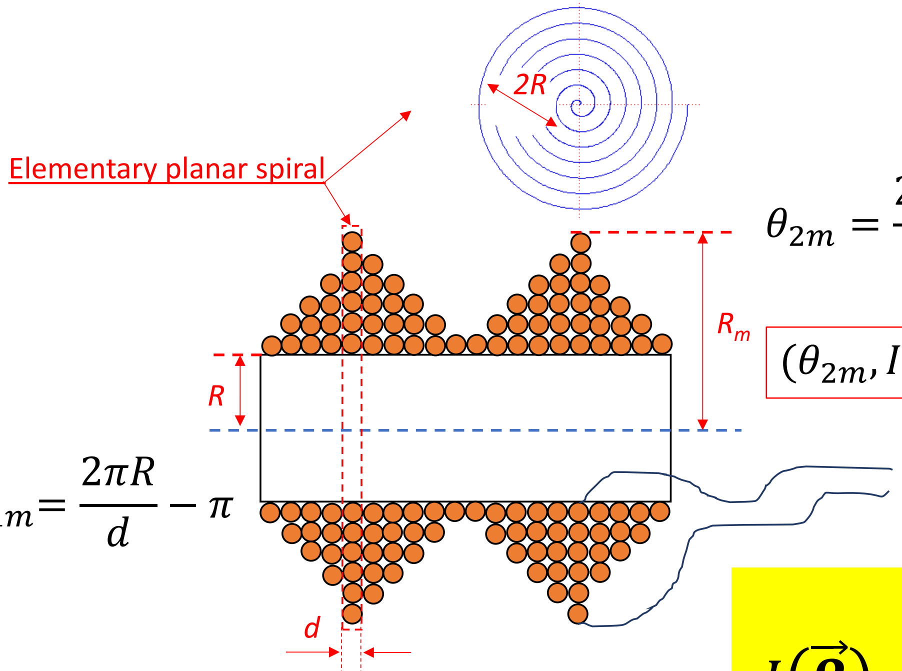
Python's optimisation library

$$\vec{\boldsymbol{\beta}}^{k+1} = \vec{\boldsymbol{\beta}}^{k} - [\vec{\boldsymbol{\nabla}}^2 J(\vec{\boldsymbol{\beta}}^{k})]^{-1} \times \vec{\boldsymbol{\nabla}} J(\vec{\boldsymbol{\beta}}^{k}),\quad k \geq 0$$ **– Newton's iteration method**

Optimisation algorithm: turns optimisation

$$B_z(z_0,\vec{\boldsymbol{\theta}}_1,\vec{\boldsymbol{\theta}}_2,\vec{\mathbf{I}}) = \frac{\mu_0}{4\pi\gamma}\sum_{m=1}^{M} I_m \left(\ln\left(\frac{2\gamma\theta_{2m}+d+\sqrt{(2\gamma\theta_{2m}+d)^2+4(z_0-z_m)^2}}{2\gamma\theta_{1m}+d+\sqrt{(2\gamma\theta_{1m}+d)^2+4(z_0-z_m)^2}}\right) + \frac{2\gamma\theta_{1m}+d}{\sqrt{(2\gamma\theta_{1m}+d)^2+4(z_0-z_m)^2}} - \frac{2\gamma\theta_{2m}+d}{\sqrt{(2\gamma\theta_{2m}+d)^2+4(z_0-z_m)^2}} \right)$$

Induction from a stack of the spiral coils



$\theta_{2m} = \dfrac{2\pi R_m}{d} - \pi -$ optimised profile

$(\theta_{2m}, I) -$ optimisation vector

$\forall m:\ \theta_{1m} = \dfrac{2\pi R}{d} - \pi$

$\forall m:\ I_m = I = const$

Optimisation parameter – **spiral angle vector**

$$J(\vec{\boldsymbol{\beta}}) = \sum_{q=1}^{Q}\left(B_z\left(z_q,\vec{\boldsymbol{\theta}}_1,\vec{\boldsymbol{\beta}},\vec{\mathbf{I}}\right) + B_0\left(z_q\right)\right)^2$$ **– objective function**

Coordinates along the axis

Interpolated residual induction

Inverse Hessian's matrix

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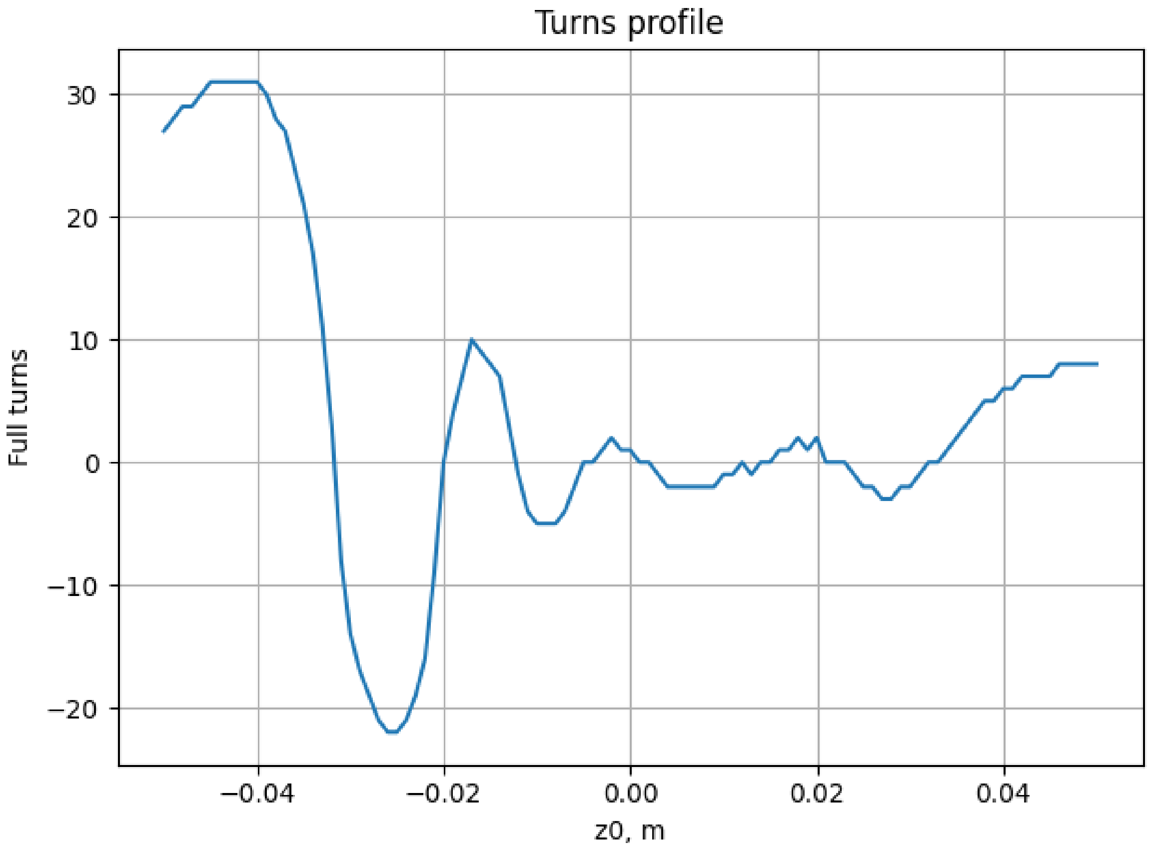
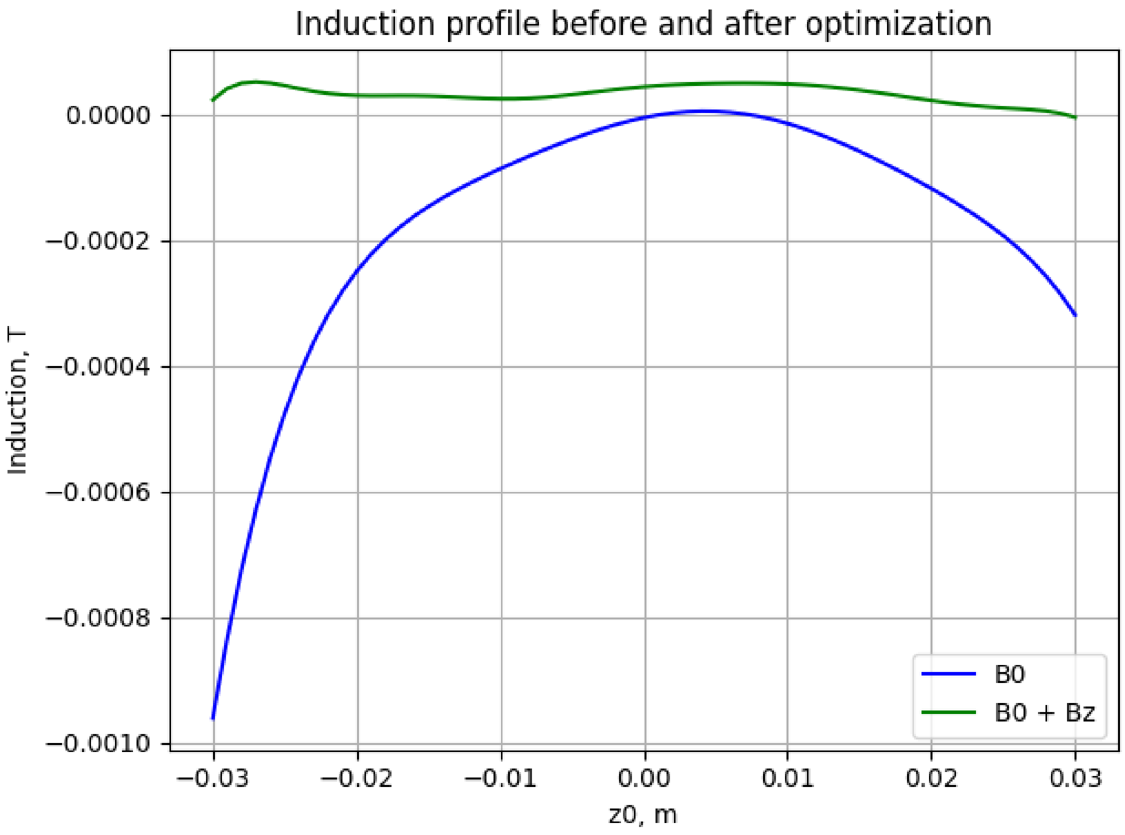
Python's optimisation library

$$\vec{\boldsymbol{\beta}}^{k+1} = \vec{\boldsymbol{\beta}}^{k} - [\vec{\boldsymbol{\nabla}}^2 J(\vec{\boldsymbol{\beta}}^{k})]^{-1} \times \vec{\boldsymbol{\nabla}} J(\vec{\boldsymbol{\beta}}^{k}),\quad k \geq 0$$ **– Newton's iteration method**

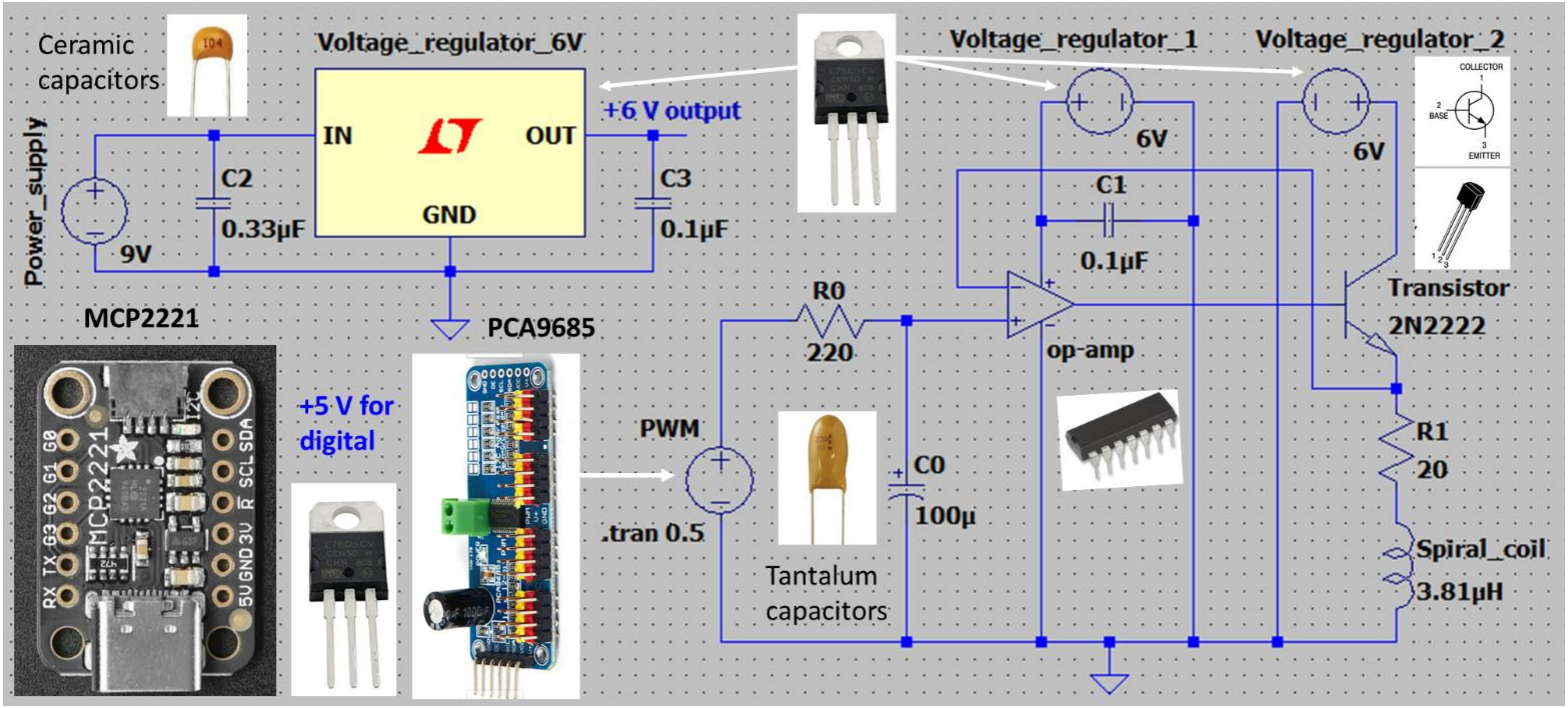
An example of the turns optimisation for a current of 0.2 A: 100 spirals

```
total conductor diameter = 0.521 mm
total substrate width, including the wire diameter = 1 mm
residual induction length = 60 mm
total optimisation length = 100 mm
internal radius = 15.86 mm
total length of the spirals = 117 m
total wire resistance = 10 Ω
power dissipated in the whole wire stack = 0.4 W
```

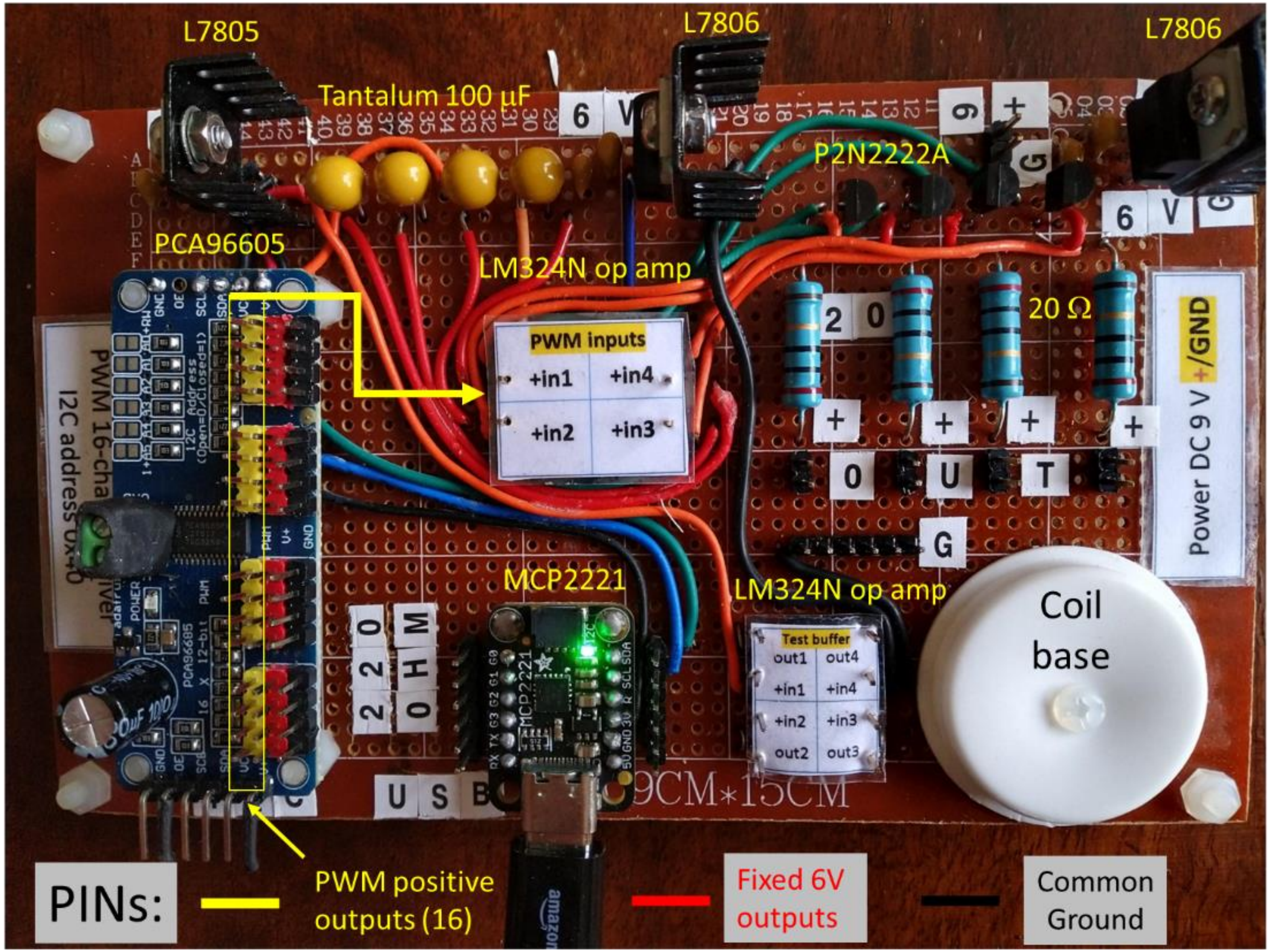


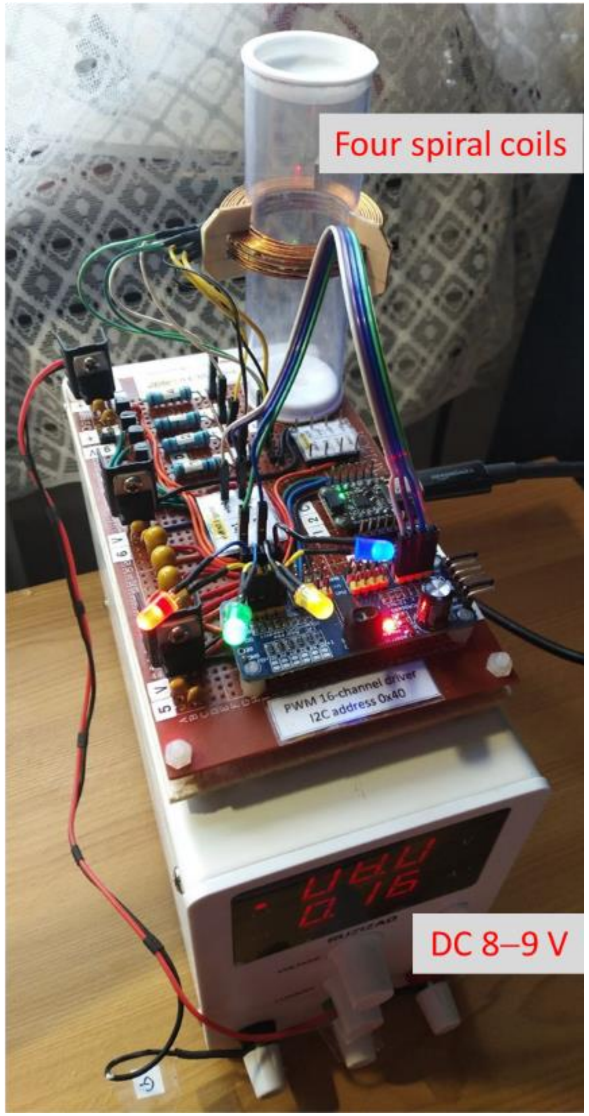


Implementation of the current driver: schematic diagram

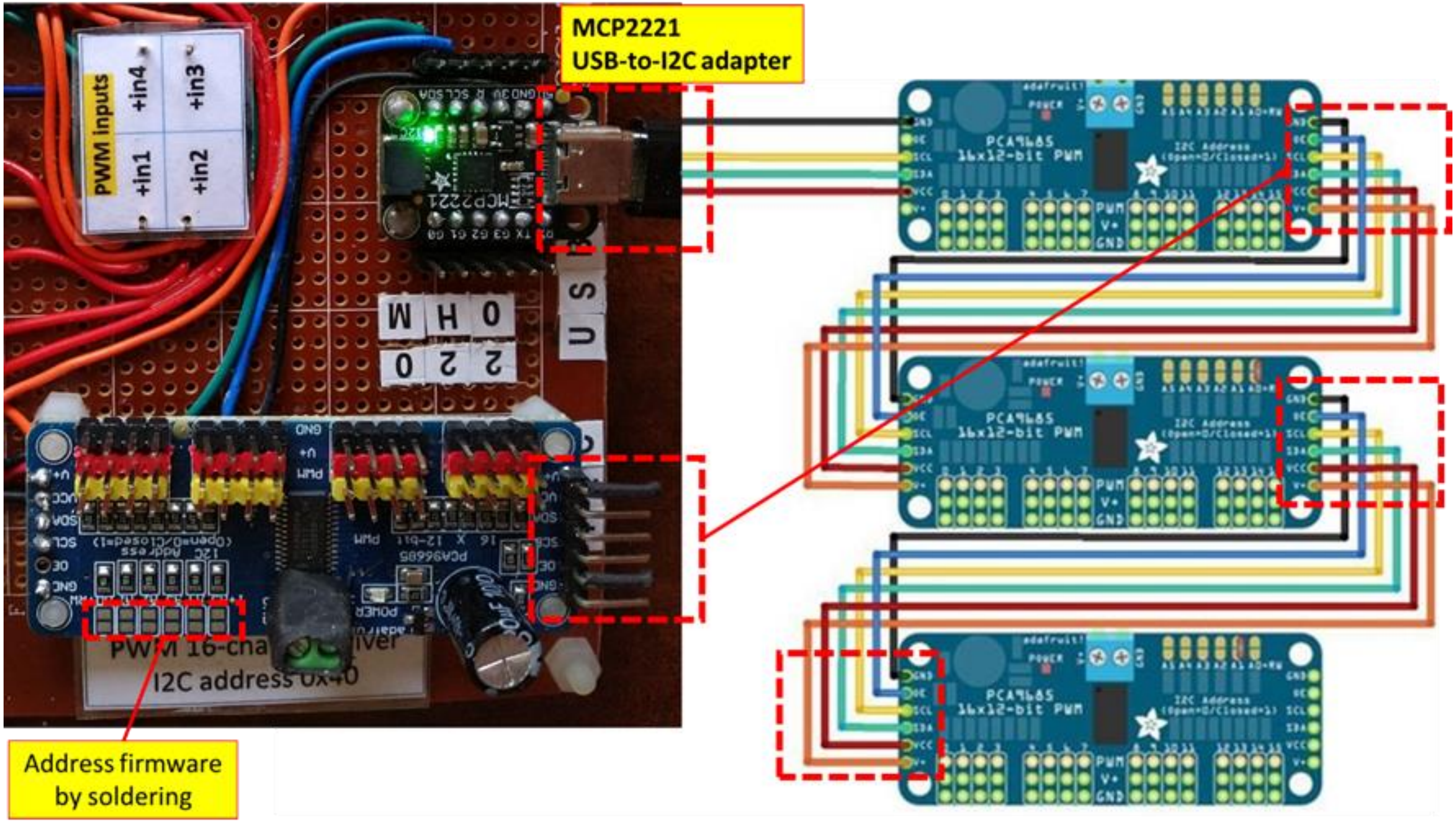


Implementation of the current driver: prototyping board for a stack of four spiral coils

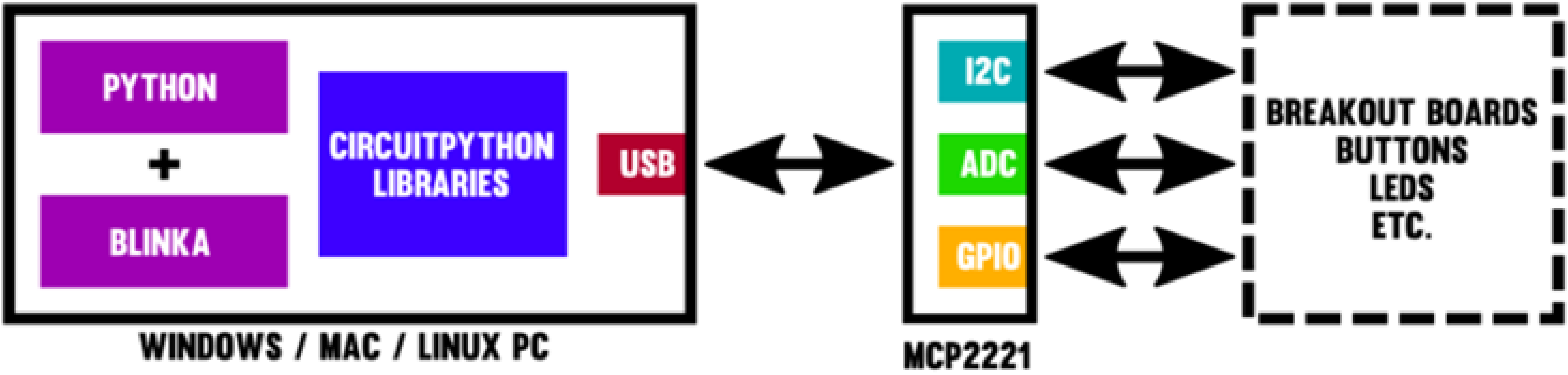




Board extension for controlling up to 992 spiral coils



Driver control with GUI in Python



Welcome to the world of scientific instruments!