

A New Software for Modeling and Optimizing Superconducting Direct Wind Magnets

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Abstract

Superconducting Magnet Division (SMD) at Brookhaven National Laboratory (BNL) has the unique capability of developing direct wind magnets, like those that will be used in the Electron-Ion Collider (EIC). Such magnets rely on highly flexible and precise design algorithms translating electromagnetic concepts directly to winding instructions, enabling intricate coil geometries and rapid prototyping without costly tooling. I am developing and upgrading the software used in the SMD to design these kinds of magnets with a more modern front and back end. This will allow magnet designers at the SMD to design magnets in a faster and more user-friendly way with better visualizations of the actual magnet designs through an improved user-friendly interface and faster optimization process.

Intro: What are Direct-Wind Magnets?

Direct-wind magnets are coils of superconducting material that wrap around the body of some support structure, such as an accelerator beam tube. These superconductors allow for an extremely high current to pass, thus inducing a large magnetic field in the beam tube. The geometry of these coils can then be manipulated to form different kinds of magnetic fields, depending on what your beamline requires.



(Fig. 1: A direct-wind magnet being wound at BNL (1))

Intro: Why Do Magnetic Fields Matter?

When creating magnets for use in particle accelerators, the applied magnetic field is extremely important, as the strength of the applied field (as well as the type of applied field) has different effects on the particles and their energy. For example, in the case of a dipole field, the energy that the accelerator can reach is directly proportional to the magnetic field strength. Thus, the purer the dipole field, and the larger the field strength is, the higher energy the accelerator can reach, allowing us to reach the physics requirement with minimum complexity and energy investment. However, dipole magnets are not the only type of magnets that accelerators use. Quadrupole magnets are used to focus particle beams in an accelerator by pushing particles closer to the center of the beam line. Sextupole magnets are also used, these magnets ensure that particles with different energies focus properly.

$$F_{\text{Mag}} = ma_c \implies qvB = m \frac{v^2}{r} \implies qvB = (mv) \frac{v}{r} \implies p = qBr$$

$$E \approx pc \implies E \approx (qBr)c$$

(Fig. 2: The equation that relates the energy of a particle in a loop to the dipole field applied to it)

Intro: What are Field Harmonics?

Magnetic fields are composed of an infinite sum of terms called *harmonics* and *skew harmonics*. Each type of magnet, or *pole*, has an associated harmonic term. To ensure the desired accelerator field, or *main field*, is maximized, we want to minimize undesired field harmonics, so that the main field has the best quality it can have. The region through which we want to minimize these undesired harmonic terms is called the *reference radius*. This is the main radius through which most of the beam passes.

$$b_n = \frac{\mu_0 I}{2\pi} \left(\frac{R_0}{a} \right)^n \cos[(n+1)\phi]$$

$$b_{\text{norm}} = \frac{b_n}{b_{\text{main}}} \cdot 10^4$$

$$a_n = -\frac{\mu_0 I}{2\pi} \left(\frac{R_0}{a} \right)^n \sin[(n+1)\phi]$$

$$a_{\text{norm}} = \frac{a_n}{b_{\text{main}}} \cdot 10^4$$

(Fig. 3: The equations for the harmonics as well as the skew harmonics and their normalized form (2))

Modeling & Optimization Methodology

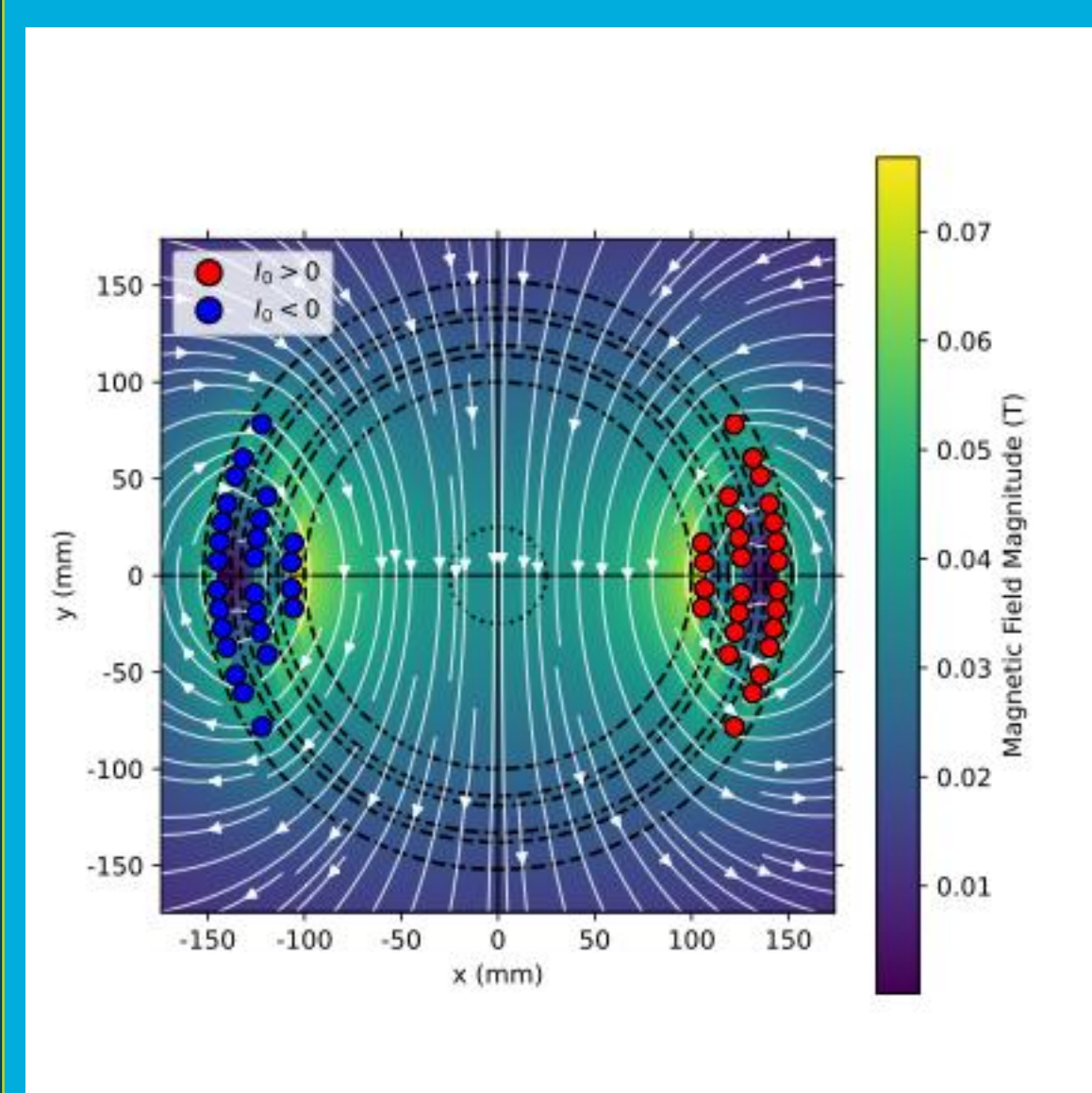
- Modeling:
 - Direct-wind magnets are modeled by plotting conductors in an arrangement provided by the user.
 - Calculations are then done, of both the individual harmonics and the total magnetic field throughout the region.
- Optimization:
 - This program uses the *Nevergrad* Python library, which uses an *Evolutionary Strategy* Optimizer to vary the spacing between conductor blocks
 - The program then iterates a given number of times, until it converges and finds a spacing configuration that minimizes the desired field harmonics, which is controlled by a user assigned weight value

Results

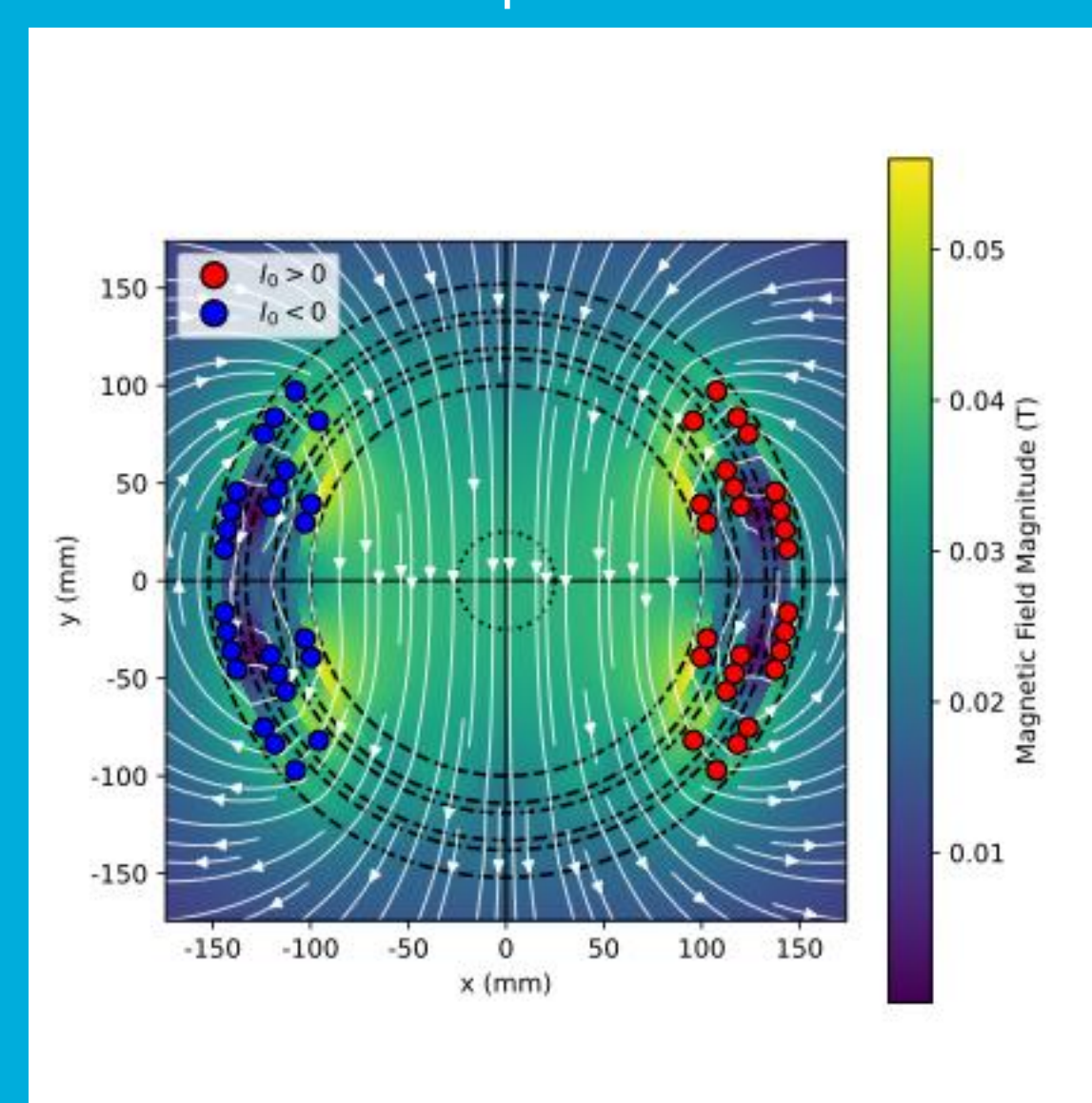
During this example run, a dipole magnetic field was first modeled, with user defined spacing around the blocks. The sextupole component was notably large, so we targeted that in the optimization process as a harmonic to minimize. Running the optimization program for only 10 iterations reduced the sextupole component from 278.56 to 128.00.

This increase in the dipole field quality can be seen by the larger uniformity in field magnitude after the optimization process. This increase in uniformity will allow for a larger energy to be achieved from this magnet.

Before Optimization:

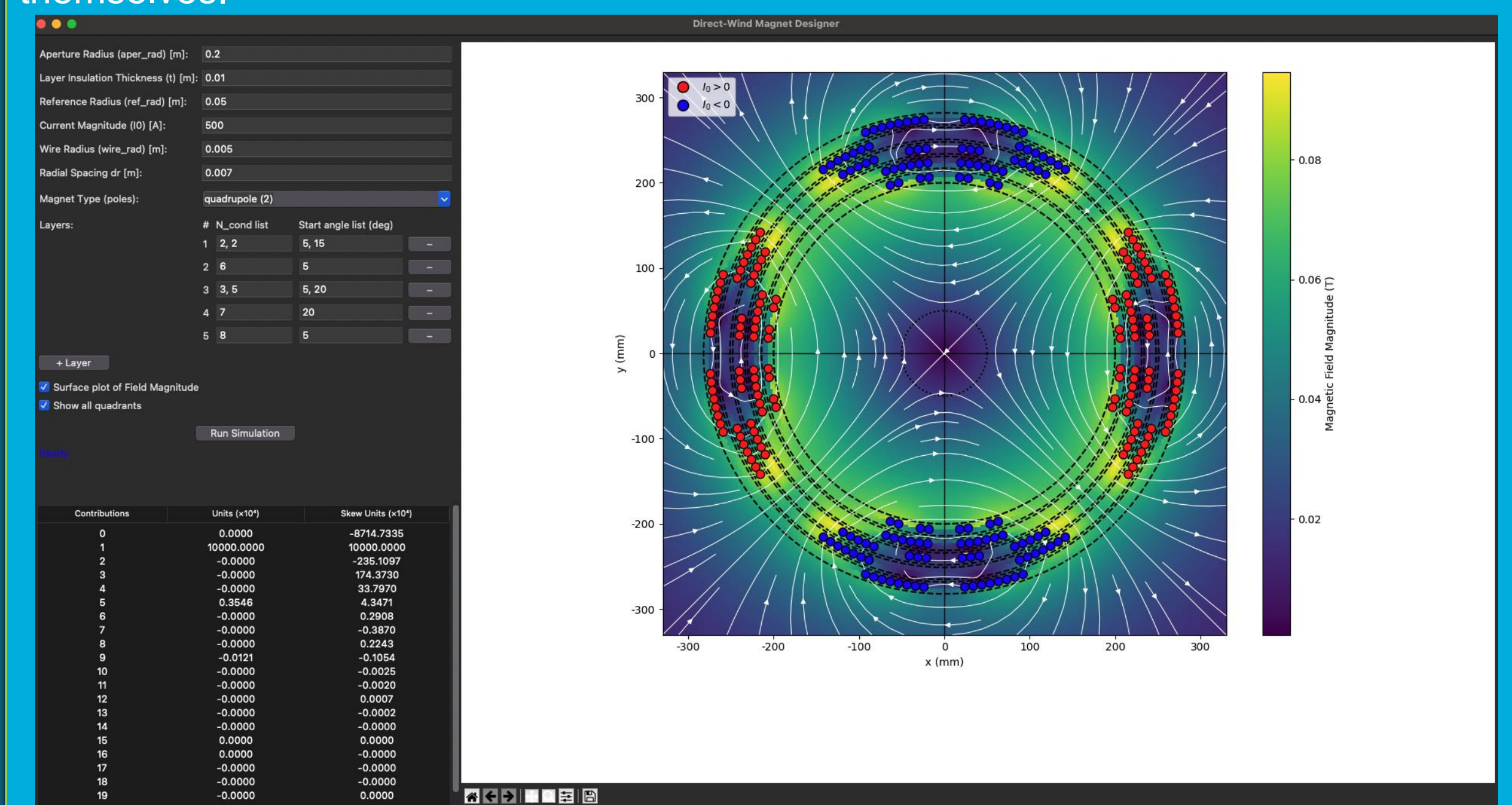


After Optimization:



Discussion & Conclusion

Through this project, we were able to successfully develop a more modern, Python-based program for modeling and optimizing direct wind magnets. In addition to developing an algorithm to model and optimize the conductor configurations and the fields they produce, we also began work on a graphical user interface (GUI) for this program. This will allow magnet designers to be able to simulate magnets much quicker and not have to worry about editing any sort of files or changing any code themselves.



(Fig. 4: An experimental GUI that we created for modeling direct-wind magnets, the geometry shown here is that of a quadrupole)

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