Devising new models and methods for stabilising temperatures of permanent magnets in CBETA

Adam Steinberg, University of Oxford

Abstract:

Perhaps the most important consideration when designing a particle accelerator is beam control: the results of imprecise particle beam control can range from bad data to equipment damage. We exert this control using powerful magnets. As CBETA uses permanent magnets, the field strength varies with temperature, and a change in field would make us lose beam control. There are two possible ways to prevent this, either heating our magnets above room temperature, or cooling them below it. In this investigation, we focus on the latter. A simulation of the system performance leads us to believe that a combination of temperature control and small groups of magnets will give us the best results.

Introduction:

The Cornell-BNL ERL Test Accelerator (CBETA) is a proof-of-concept accelerator, demonstrating the use of a Fixed Field Alternating Gradient (FFAG) lattice as part of an Energy Recovery Linac. Although FFAG optics (using this type of magnet) have previously been tested, for example in EMMA [1], CBETA will be the first use of such a lattice for energy recovery. It will also be the first time that permanent magnets have been used in an FFAG lattice. The primary purpose of CBETA is to show that permanent magnets can be used for this purpose, but there are other positive outcomes. For example, the x-ray radiation it can produce could be used for a wide range of scientific experiments, such as improving polycrystalline materials [2].

There are several benefits to using FFAG optics in an accelerator, including extreme focusing and relatively small magnet size [3]. But the advantage most relevant to this project is the ability to use permanent magnets. In conventional accelerators, we use electromagnets, as they we can vary current to produce a constant magnetic. However, the power consumption of electromagnets is large, making their use expensive. In CBETA, the permanent magnets will produce a magnetic field without a power supply. Unfortunately, there is a new issue: we can’t alter the field of permanent magnets in a reliable way, and the strength of the field they produce will vary with their temperature.

Therefore, it is imperative that we keep the temperature of our FFAG magnets constant to within 0.5°C despite changing conditions in the experimental hall where they are housed. We investigate both heating and cooling methods, although we focus on the latter (as magnets at a higher temperature produce a weaker field). In CBETA, there will be 216 permanent FFAG magnets, around the entire length of the ERL. Therefore, we model a cooling ‘circuit’, where water flows from one magnet to the next, and temperature varies along the way. We begin to simulate different cooling algorithms, as well as different circuit lengths, in the search for an optimal cooling method.

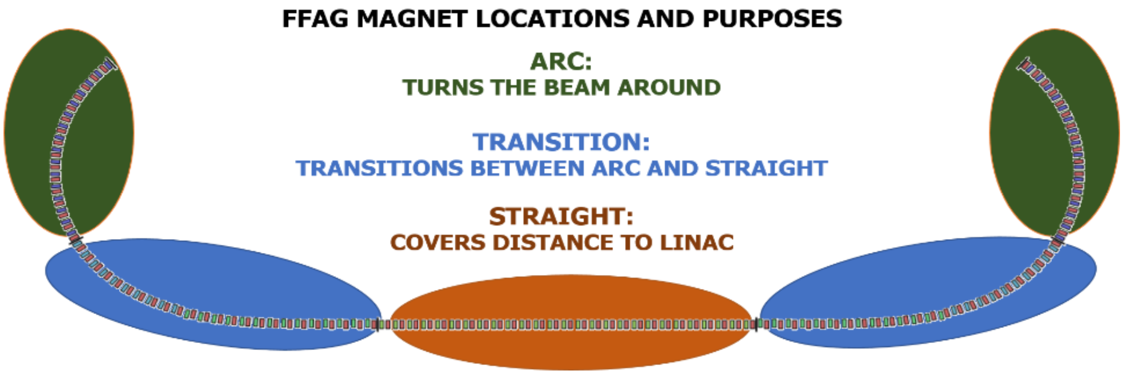

Figure 1: The sets of FFAG magnets, forming the return loop of the accelerator. Note that the total circumference of CBETA is 79.1 metres.

Method:

Creating the simulation:

Before we can simulate our cooling system, we must define an exhaustive set of constants relating to properties of the magnets and the cooling pipes. Many of these can be found trivially – either from reference tables, by research, or by simple measurement – whereas others require more thorough experiment. These were all standard, and so we do not include details here. The values we used can be found in the *appendix*, and can easily be changed for future projects.

The real-world situation we wish to model has water flowing in tubes past our magnets at a constant rate. To simulate this, we divide the water into 'cylinders', which move through the pipes at a constant speed. Further, even though time is continuous, we must perform our simulation in discrete steps. We choose to move our 'cylinders' along every 0.01 seconds, as his produces realistic results without excessive computing time. We also update our cooler system and take measurements once every 10 seconds, which is likely to be the measurement frequency in our real system.

Performing each step:

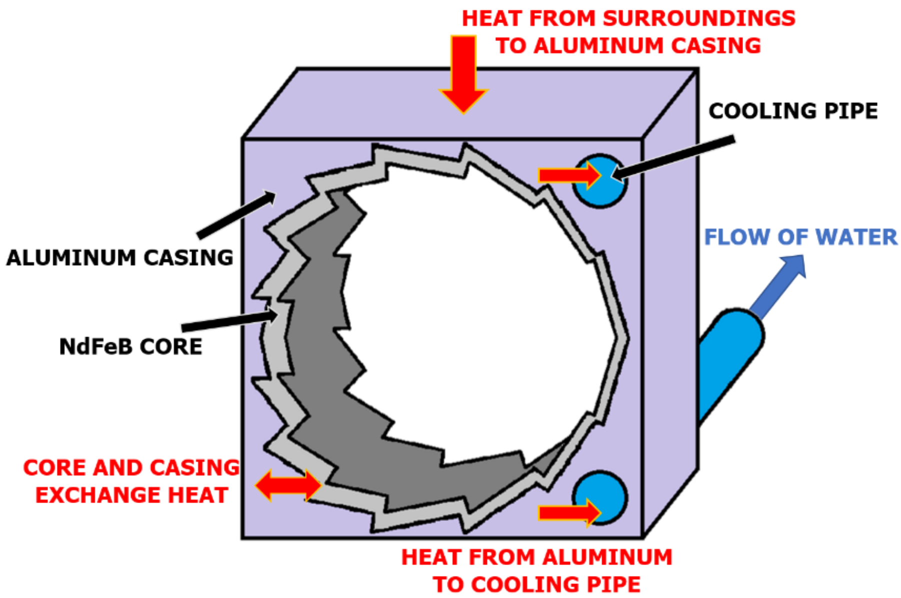

Figure 2: A summary of the continuous thermal transport processes in each FFAG magnet (NdFeB is the Neodymium-Iron-Boron magnet core). Note that this is not to scale: for magnet dimensions, see appendix.

We simulate the system shown in Figure 2 using several steps, each representing a different part of the system:

1. We move the 'cylinders' of water along in the pipes, by propagating the temperature down the line. We also set the first set of cylinders to the exact temperature of the cooler.
2. As the cylinders are colder than the aluminum, power goes from the blocks to the cylinders they touch. This power depends on the difference in temperature between the cylinder and the metal, as well as coefficients of conduction.
3. Once we know the power going to each cylinder, we apply this for one time-interval (0.01s) and calculate the temperature change, which depends on the heat capacity of the water cylinders, as well as their previous temperatures
4. The temperature of the NdFeB core evolves, based only on the aluminum block surrounding it. We can calculate the power flow due to the temperature difference, and using this, find first the change in energy, then in temperature.
5. Finally, the aluminum block changes temperature based on heat gain due to free convection from surroundings, cooling by the pipe (which we model as conduction, rather than forced convection), and changes in the core temperature.

Results and analysis:

We have so far used our simulation to find three main sets of results, and hope that our model can be used and refined in the future to produce further data. The model allows us to change both dynamical variables (i.e. time) and control variables (i.e. number of magnets) as well as our cooler algorithm, allowing for detailed study.

For our initial testing, we use a proportional temperature controller for our cooler, which gets colder when the magnets get warmer, and vice-versa. We test only the temperature of the 'middle' magnet, whereas more effective algorithms might check more. Further, there is a simplification in our cooler code: it is 'perfect', in that we do not account for a reservoir, instead just using an output temperature. We hope to produce a more realistic algorithm in the future, but this is sufficient for an initial study.

Using 10 magnets, we compared the temperature variation over a full 'day' (simulated using a sine curve), first using no controller, then a proportional one.

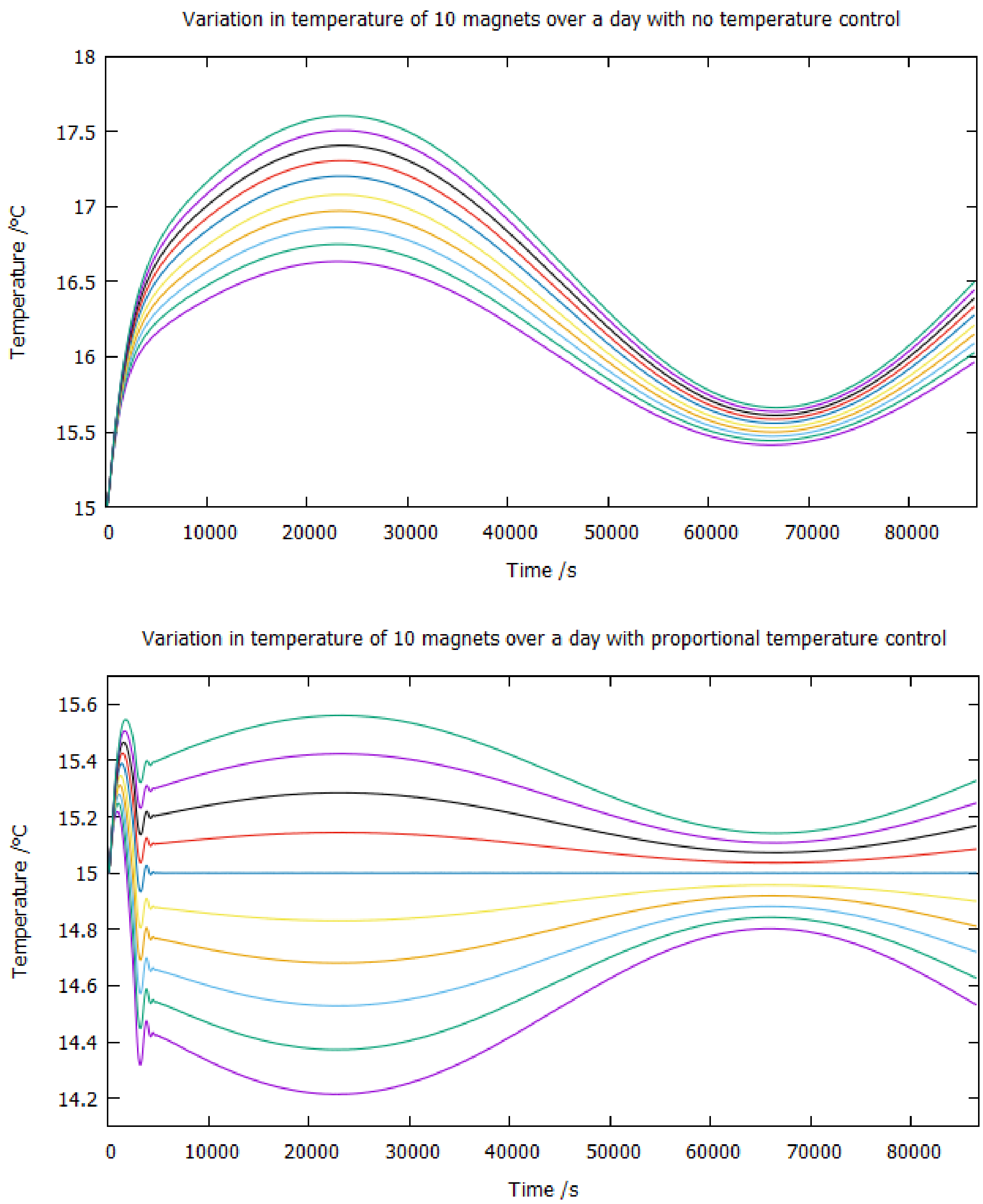

Figure 3: a) Temperature variation in 10 magnets over 1 day, with no cooler control

b) The same, with proportional control

In Figure 3a, we see that the temperature of our magnets follow the sinusoidal ambient temperatue curve: the cooler at a constant temperature leaves the magnets at equilibrium temperature, with early magnets staying colder. Conversely, Figure 3b has significantly less temperature variation. Indeed, the middle magnet, which we control for, is almost constant over the day! This suggests that a proportional controller might be a viable option for small 'circuits'. In both figures, there is an initial 'jump' in temperature at the start of the day. This is due to the magnet quickly reaching thermal equilibrium between the temperature of the surroundings, and that of the cooler.

Can we extend this to 216 magnets, the full loop? In Figure 4, we see a huge variation in magnet temperature. Clearly, no control is a totally nonviable option, as the temperature varies too much both other the day, and between different magnets. Interstingly, our proportional controller can't cope with so many magnets: the cooling power of water is too poor in our model, and our cooler goes to extremely low temperatures. This is clearly not realistic, so we do not include this in our results. In our current model, it is apparent that we can't use the full 216 magnets in a single water 'circuit'.

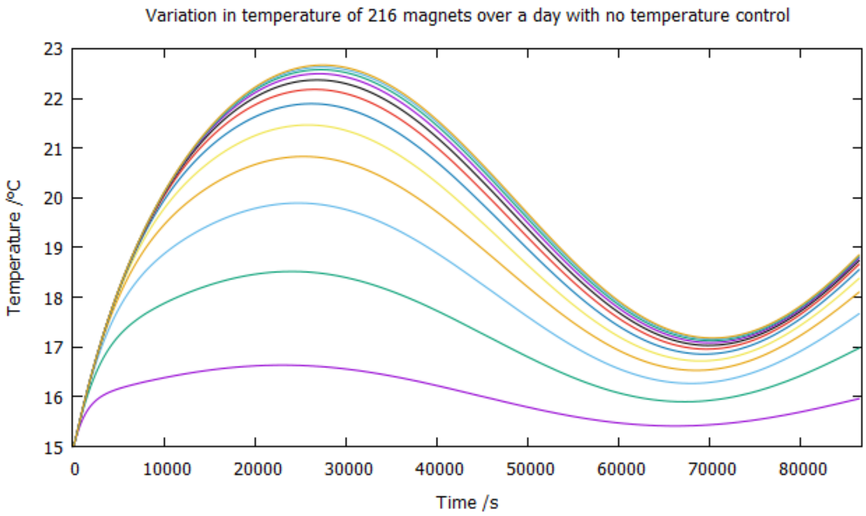

Figure 4: Temperature variation in 216 magnets over 1 day, with no cooler control

We then want to investigate what our stable temperature is for different numbers of magnets at different ambient temperatures. This will be useful in determining a maximum number of magnets, if we have a maximum allowed temperature (equivalent to a minimum field strength).

As is clear in Figure 5, the first magnet temperature only varies with ambient temperature, whereas the middle and final magnets also vary with the number of magnets. The variation with number of magnets seems to follow a negative exponential curve, which makes good sense: as water passes magnets, it heats up, and therefore has less of a cooling effect on later magnets.

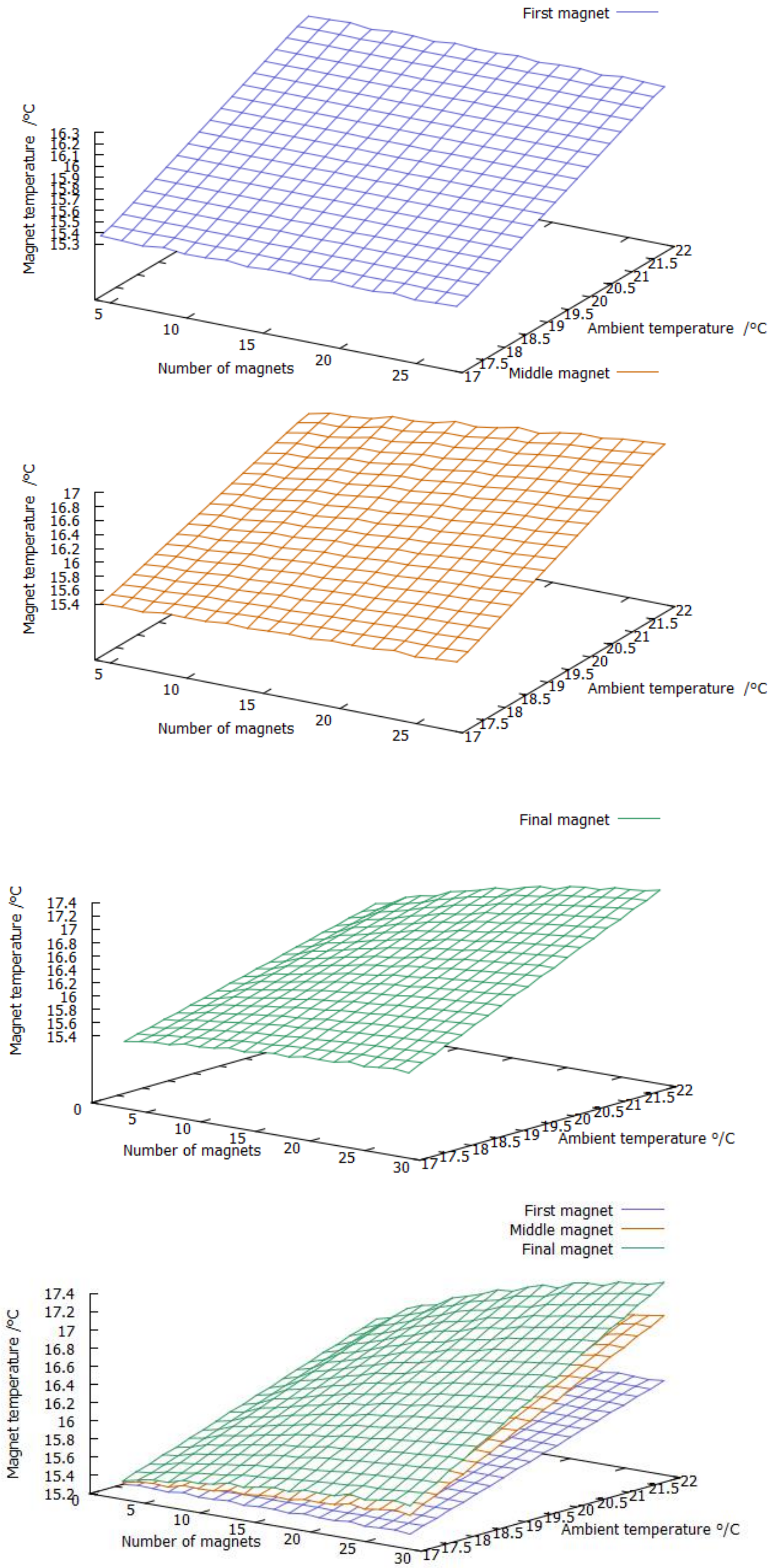

Figure 5: variation in stable temperature with number of magnets, measured for three different magnets in the 'circuit'. The measured magnet is labelled by color in the top right of each diagram.

It is perhaps more useful to investigate the range in temperature over a day, as the main purpose of this investigation is to determine temperature stability. We check over 30 magnets, our previous data that shows that more would cause too much variation.

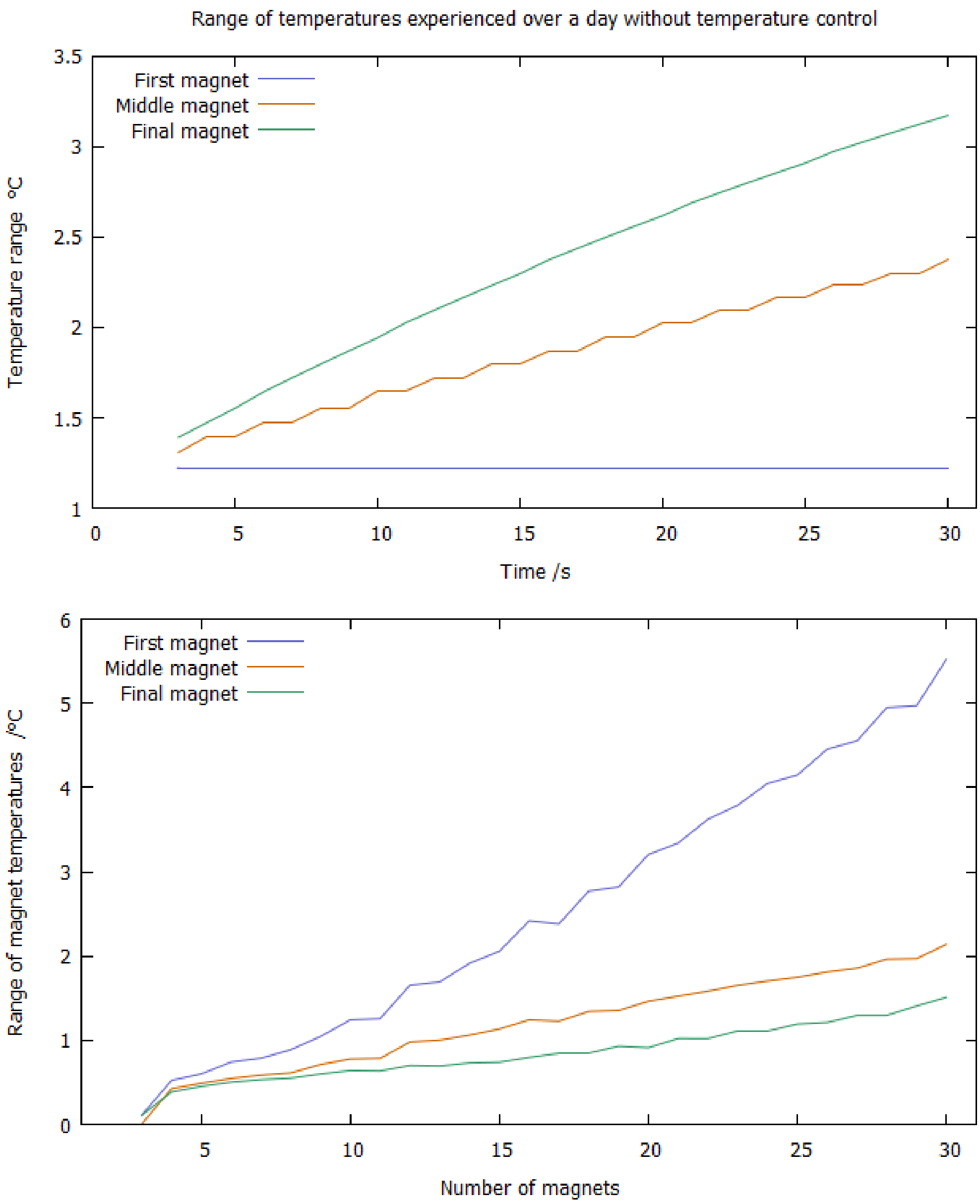

Figure 6: a) The temperature variation of magnets over 1 day, with no cooler control

b) The same, but with proportional cooler control

In Figure 6a, our results are much as expected: the first magnet, directly following the cooler, doesn't vary depending on the number of magnets. Further, the difference between the first and middle magnets is greater than between the middle and final, again showing the diminishing impact of the cooling system. Note that the baseline is above 1.1°C variation, showing that no temperature control is always unsuccessful.

We see a very different result when we apply the proportional control in Figure 6b. Recall that we control for the middle magnet, which explains the extremely poor control over the temperature of the first magnet for large ‘circuits’. We expect the temperature tolerance to be less than 0.5°C variation over the day, so this graph suggests an optimal circuit of around 5 magnets for the proportional controller.

Conclusions:

Now that we have an initial magnet simulation, it is now feasible to refine it to produce more accurate results. We believe that the next useful step will be to produce a more realistic algorithm that accounts for a finite-power cooler, and accurately simulates the variation in the reservoir temperature depending on the number of magnets.

There are many ways we could improve the accuracy of our magnet simulation. For one, we have ignored the copper corrector coils next to each magnet, which will likely produce some amount of waste heat. We have not taken temperature gradients within our magnets into account, which might have an impact depending on our geometry. Finally, we believe our results to be a ‘worst case’ scenario, as we expect the cooling to be more effective in a real system. This is thanks to a combination of factors such as rate of water flow, thermal mass, and cooler control.

For now, our preliminary results have indicated that we will need to use a low number of magnets per circuit with a sophisticated cooler control algorithm. We hope that we can keep our magnets within the acceptable 0.5°C variation, and by following these lines of inquiry we produce an effective cooling system.

References:

[1] "The EMMA non-scaling FFAG", IPAC10, Kyoto, May 2010, THPEC090, R. Edgecock *et al,* (2010)

[2] Cornell Energy Recover Linac Project Definition Design Report, Section 1.2, version as of April 8 2011, Georg Hoffstaetter *et al*

[3] The Cornell-BNL FFAG-ERL Test Accelerator White Paper arXiv:1504.00588v1 [physics.acc-ph] (2015)

(Note that all data is produced using **C++**, and plotted in **gnuplot**. Source file 'Magnet Heat Simulation version 1.0', later editions may produce different results)

Acknowledgements:

- **Karl Smolenski** and **Steve Peggs, t**he mentors for this project, whose guidance, experience, and patience were the most valuable resources for this project.
- **Carl Franck, Scott Berg, Rachel Bass** and **Nate MacFadden,** whose suggestions changed the course of the project, leading to far greater clarity.
- **Corpus Christi College, University of Oxford,** which awarded Adam an 'Expanding Horizons' scholarship, enabling him to come to Cornell.

CBETA is generously supported by the New York State Energy Research and Development Agency (NYSERDA)

Special thanks to the Cornell High Energy Synchrotron Source for supporting the Summer Undergraduate Research in Science and Engineering (SUNRiSE) program

Appendix:

Table of constants used in all simulations so far

Variable:	**Value:**	**Unit:**
Water specific heat capacity	4184	J/(kg·K)
NdFeB specific heat capacity	460	J/(kg·K)
Aluminum specific heat capacity	900	J/(kg·K)
Air convection coefficient	20	W/(m·K)
Water thermal conductivity	4	W/(m·K)
NdFeB thermal conductivity	6	W/(m·K)
Aluminum thermal conductivity	205	W/(m·K)
Coolant pipe radius	0.02	m
NdFeB outer radius	0.06	m
Aluminum block length	0.128	m
NdFeB mass	6.0	kg
Aluminum mass	5.4	kg
Water speed through pipes	10	m/s
Aim temperature for FFAGs	15	°C

Other relevant values, such as the ambient temperature of the surroundings, temperature of the cooler, and number of magnets vary between simulations, and are recorded where relevant in our original output data.