CERN Internship Presentation

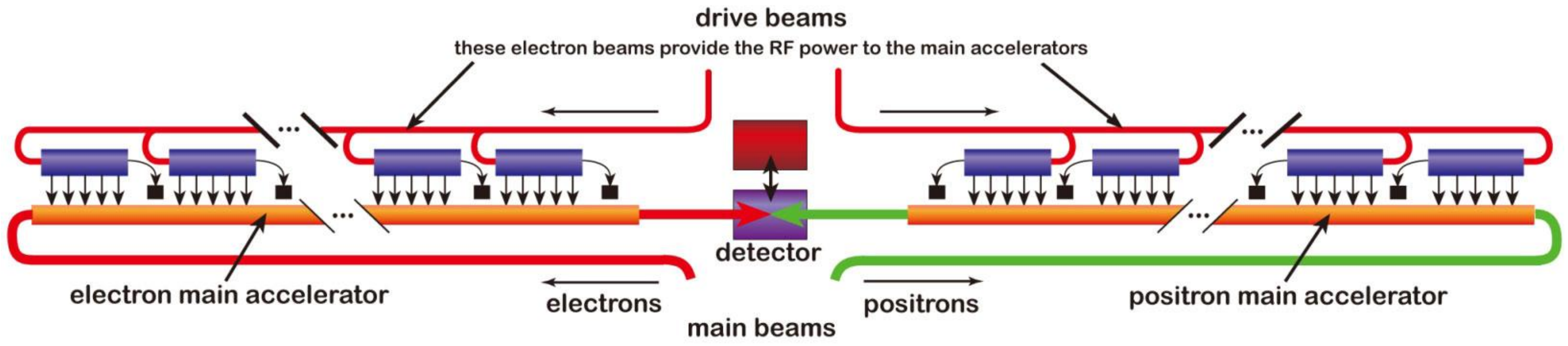
THE EFFECT OF MAGNETIC FIELDS FROM POWER LINES ON AN ELECTRON DRIVE BEAM

Introduction

- Jonathan Christie, 3rd year Physics
- Took part in an 8 week internship at CERN from 26th June to 18th August
- Worked under supervision of Chetan Gohil and Professor Philip Burrows
- Also had a 5-week lecture course on CERN and particle physics with students from all over the world

Background

- CLIC is a future linear collider, hoping to achieve particle energies of 3 TeV
- Need an accelerating gradient of around 100 MV/m
  - Can be achieved by decelerating a drive beam in special Power Extraction and Transfer Structures (PETS)



Problems

- Even with 100 MV/m accelerating gradient, accelerator needs to be around 30 km long
  - Makes drive beam and main beam very susceptible to external magnetic fields
- CERN is covered in power lines, each produces their own magnetic field
  - Extremely complicated field, hard to calculate analytically
  - Need to determine if external field needs to be accounted for with shielding, adjusting the beam mid-flight etc.

Aims of the Project

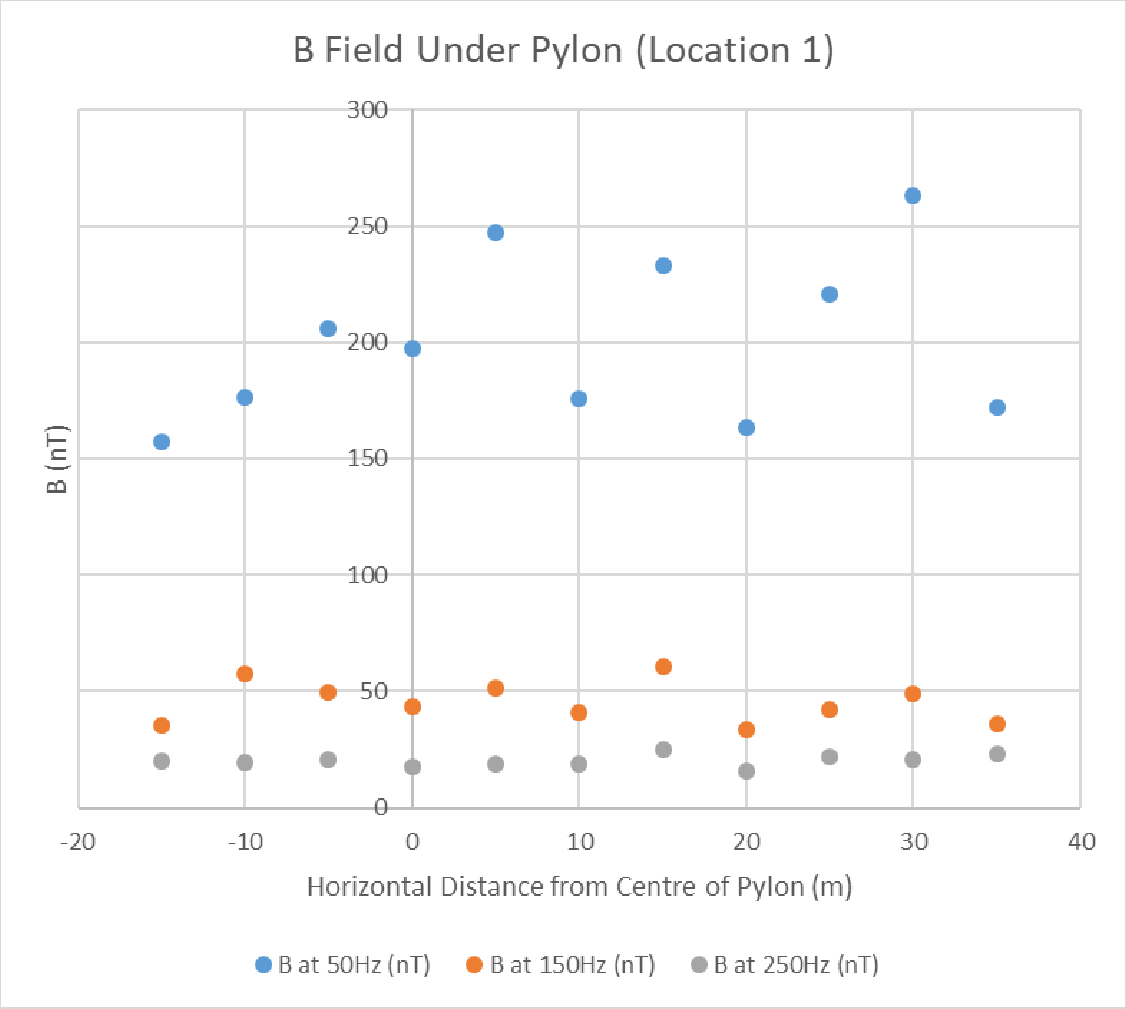
- Measure magnetic field from the power lines at CERN
- Create model of magnetic field from power lines
- Compare model with actual measured magnetic field
- Adjust model to fit the data
- Simulate a drive beam under the effect of the model magnetic field
- See how orientation of drive beam, number of FODO cells, and strength of quadrupole affects final offset and angle

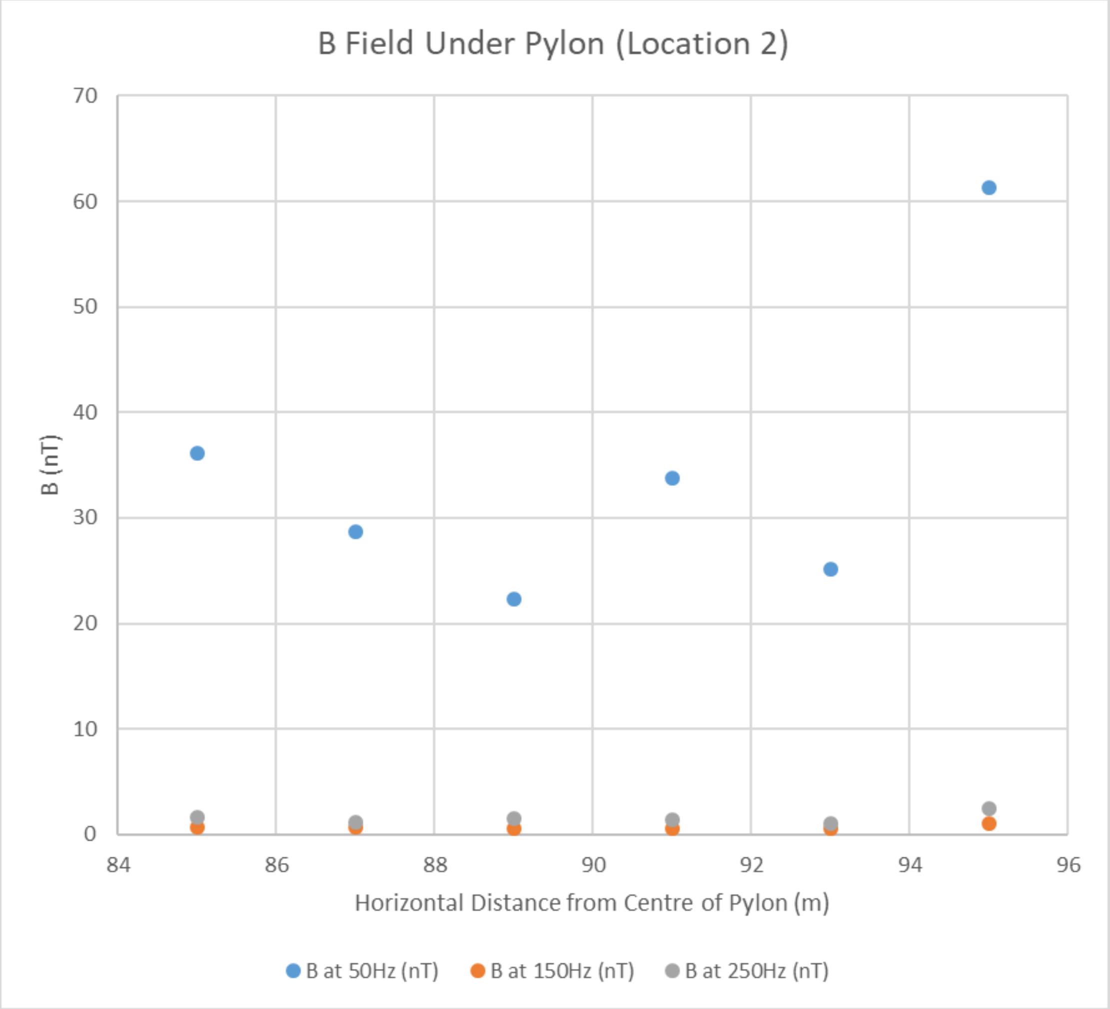
Collecting Data

Measuring the Magnetic Field

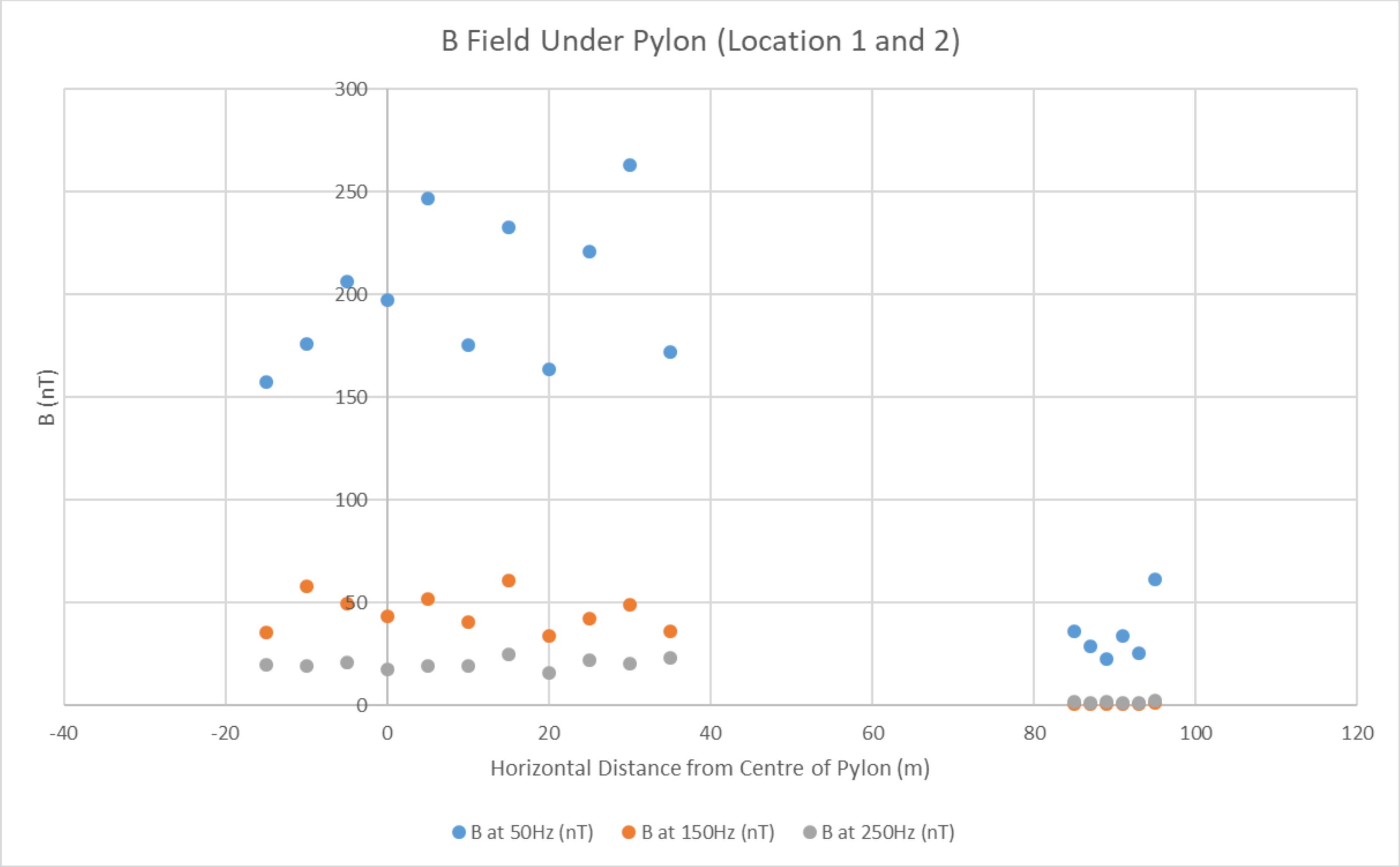
- Used a LEMI-144 Magnetometer to measure the magnetic field underneath a power line
- Took measurements at two different locations on CERN site
  - In the parking lot outside Building 40
  - In the grassy area outside Restaurant 1

Magnetic Field Data





Magnetic Field Data



Magnetic Field Data

- Magnetic field has 50 Hz, 150 Hz, and 250 Hz components
  - 50 Hz is main signal, 150 Hz and 250 Hz are harmonics
- Field strongest directly under wires, rapidly drops off as you get further away
- May notice large gap in measurements…

Problems With Measurements

- Detector could only measure a maximum field of 250 nT
  - All of the data in Location 1 is likely saturated and thus inaccurate
- Detector stopped working properly after the first 6 measurements at Location 2
  - Could not get a replacement in time to take more readings
  - Was planning on taking measurements up to 50m away
- Very difficult to accurately model magnetic field using obtained data

Creating the Model

Theory

- Can use Biot-Savart law to calculate magnetic field from each wire
- Assume wires are perfectly straight, run along z-axis

$$\bar{B}_x = \mu_0 \sum_{i=1}^{n} \frac{(y_i - y) \cdot l \cdot \bar{I}_i}{4\pi \cdot d_i^2 \cdot \sqrt{d_i^2 + \frac{l^2}{4}}},$$

$$\bar{B}_y = \mu_0 \sum_{i=1}^{n} \frac{(x - x_i) \cdot l \cdot \bar{I}_i}{4\pi \cdot d_i^2 \cdot \sqrt{d_i^2 + \frac{l^2}{4}}},$$

$$\bar{B}_z = 0,$$

$$d_i = \sqrt{(x - x_i)^2 + (y - y_i)^2},$$

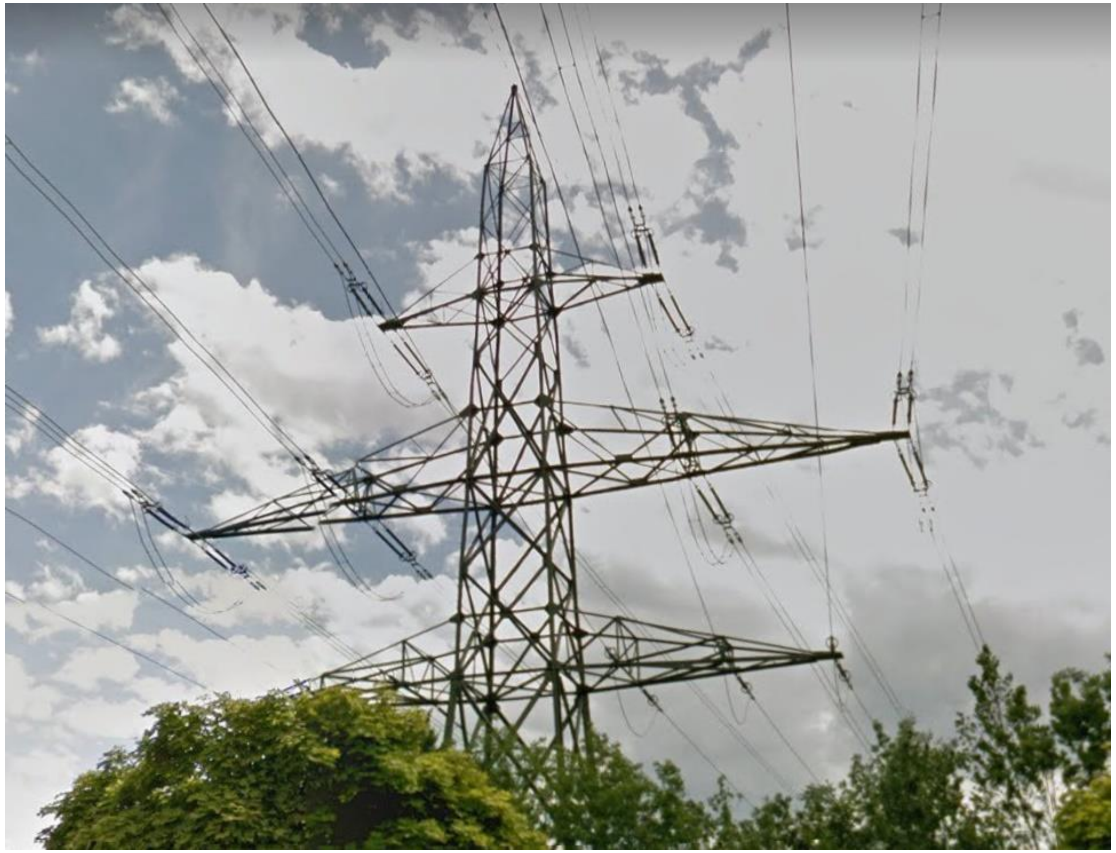
Theory

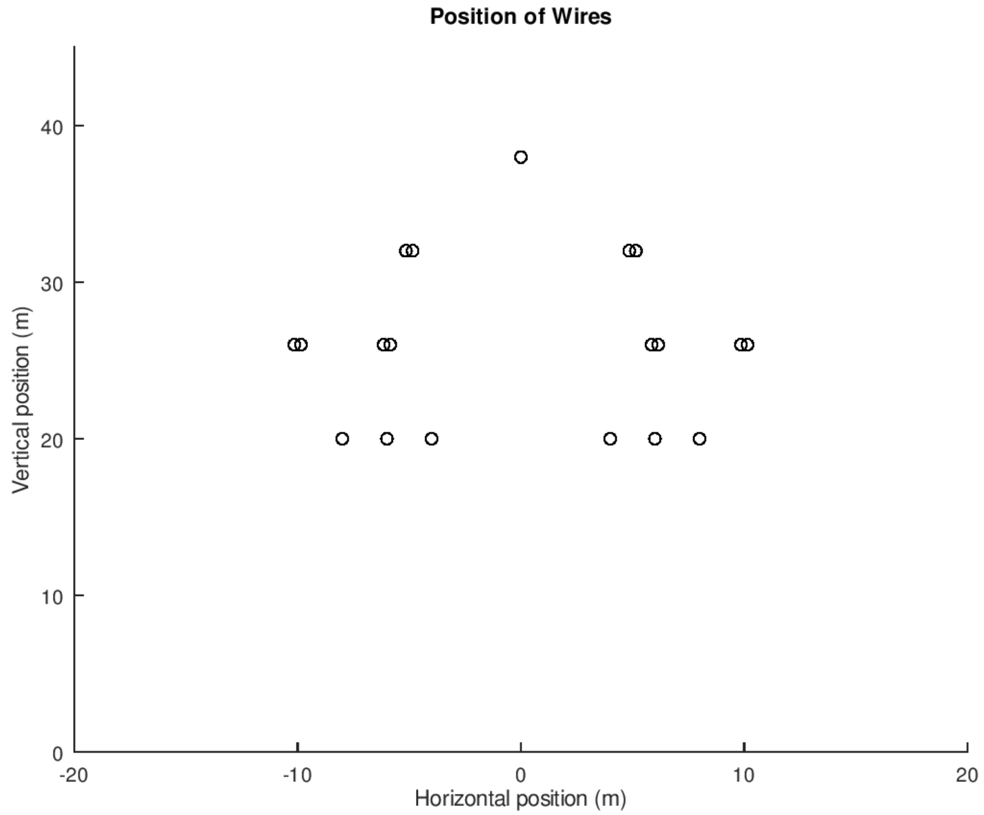
- System is linear
  - Can add together magnetic field from every wire to get total magnetic field
- Wrote Octave script to calculate magnetic field component from each wire
- Then sums up all of the components to get total magnetic field
- Need to know positions of wires, current in wires, and the relative phases between the wires

Creating the Model

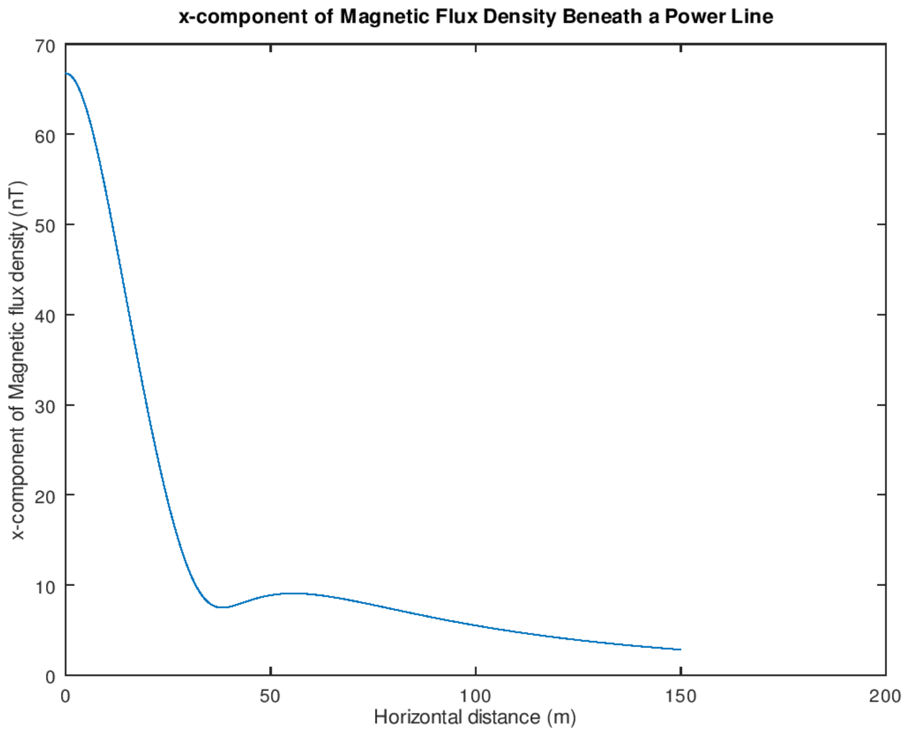
- Determined height of pylon by comparing its shadow length with that of the CERN Globe
  - Then could determine approximate positions of the wires
- Wires on left-hand side of pylon were at 400kV, right-hand side at 130kV
  - Current in wires on right-hand side greater by a factor of 400/130
- Relative phases between wires were unknown
  - Likely to be a 3-phase system

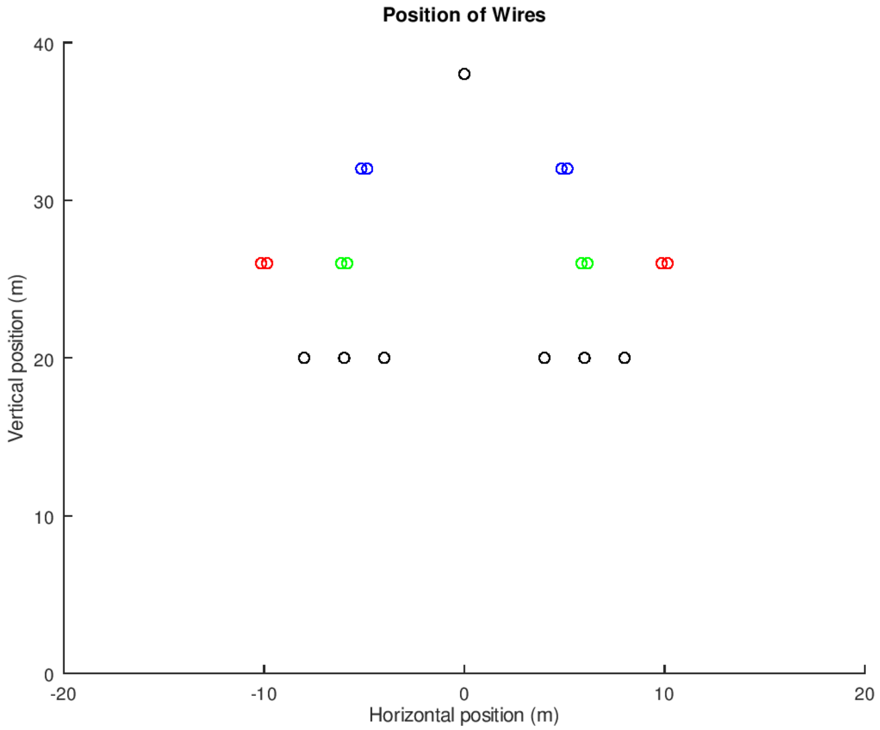
Pylon Layout





Example Graphs



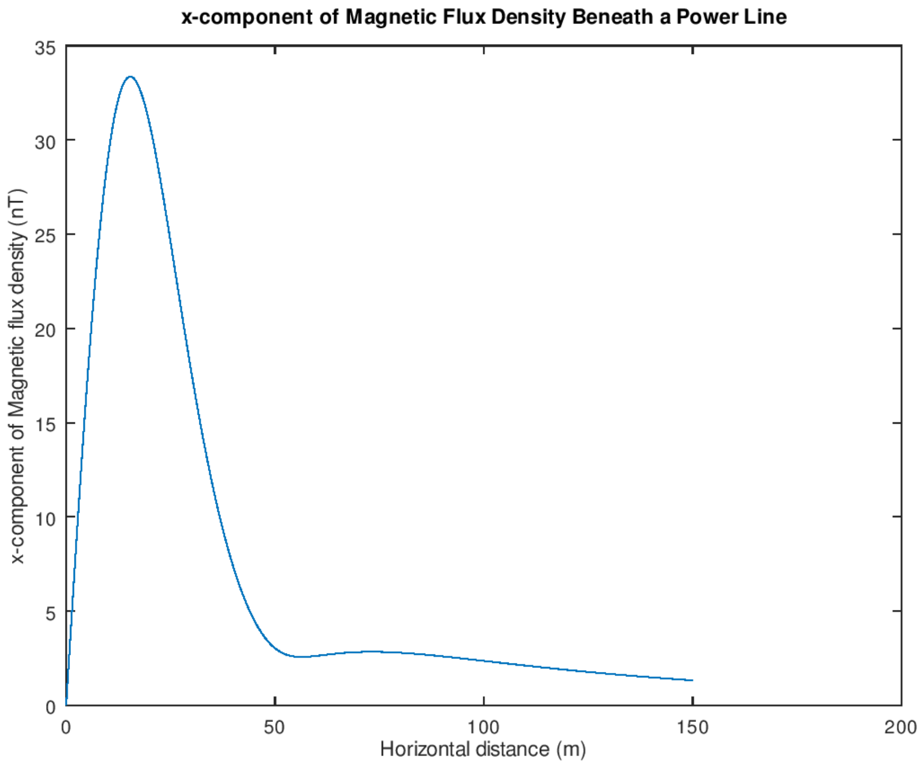


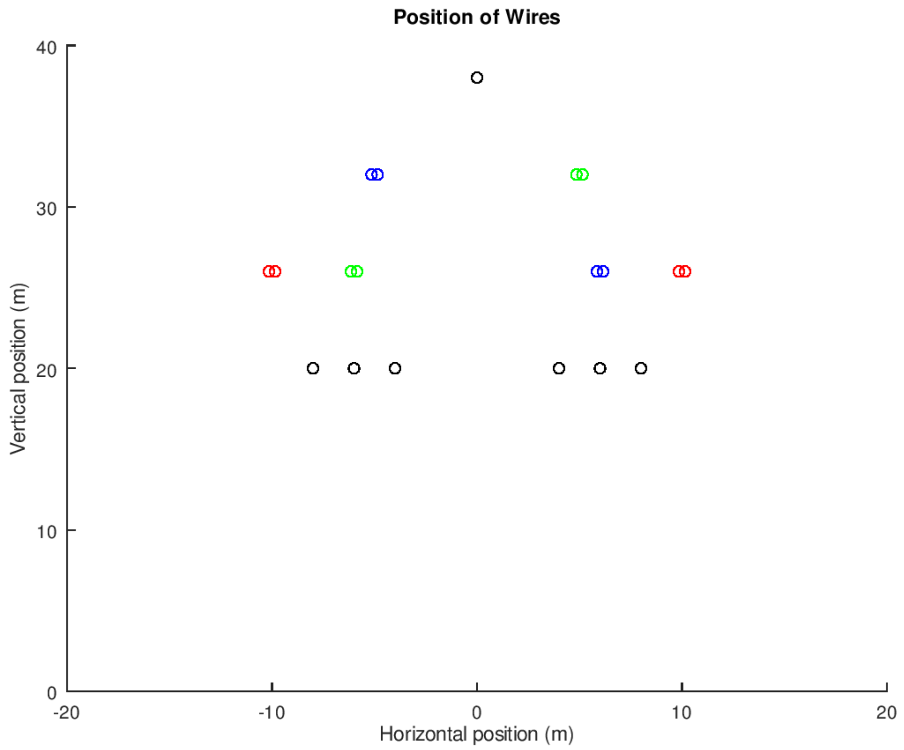
Blue points have phase of 0 degrees

Green points have phase of 120 degrees

Red points have phase of 240 degrees

Example Graphs





Blue points have phase of 0 degrees

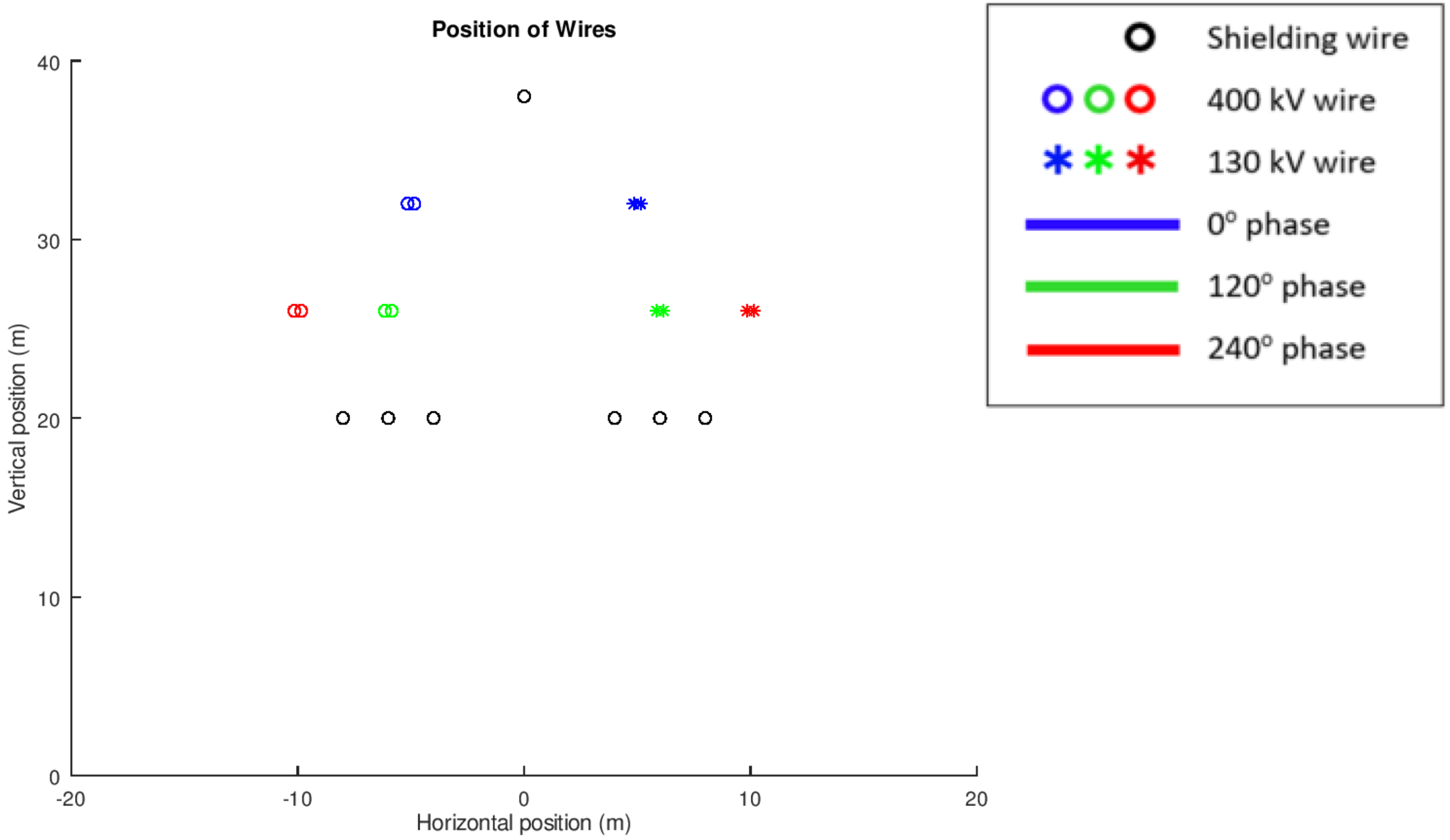
Green points have phase of 120 degrees

Red points have phase of 240 degrees

Fitting the Model to the Data

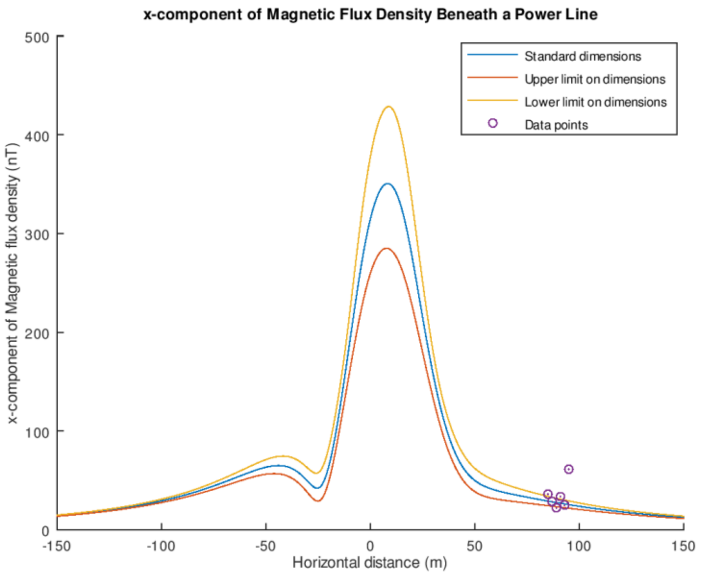
- For each phase configuration, I found current values such that the model fit the data within error (due to positions of wires)
  - Since magnetic field was split into 50Hz, 150Hz, and 250Hz components, had to fit to each data set individually
  - Gave us 3 currents, combine to find total RMS current
- Chose phase configuration which best matched our data within errors due to geometry

Phase Configuration 1

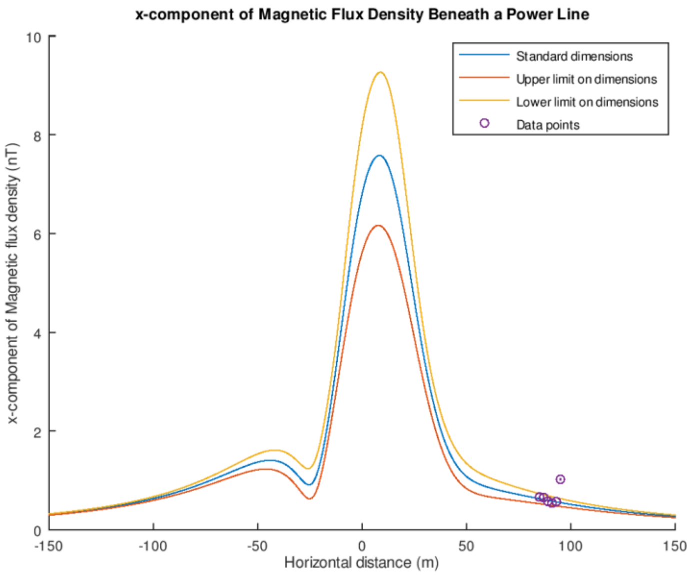


Phase Configuration 1

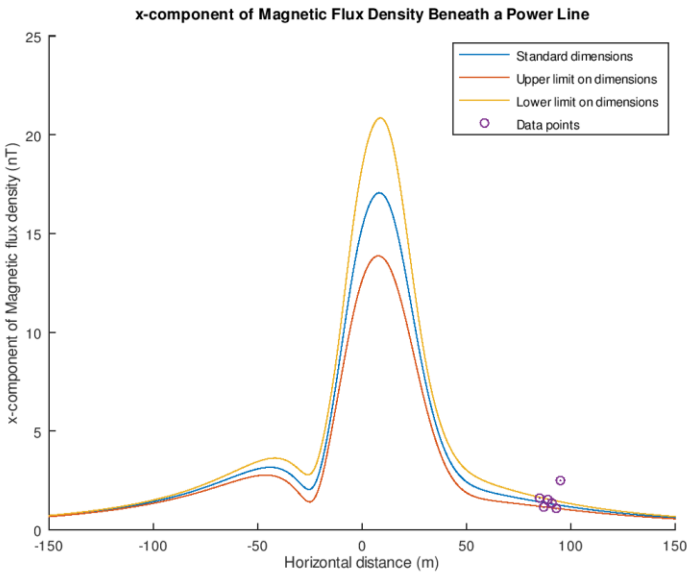
50 Hz, I = 37A



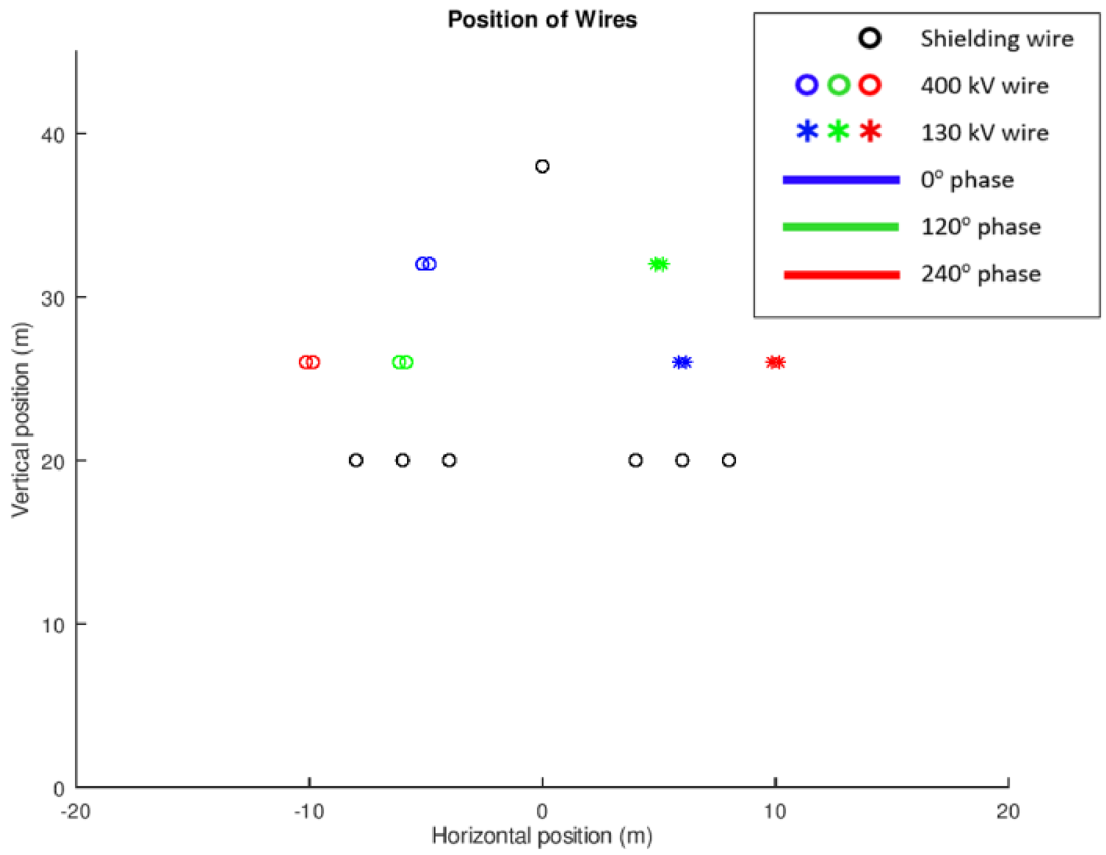
150 Hz, I = 0.8A



250 Hz, I = 1.8A

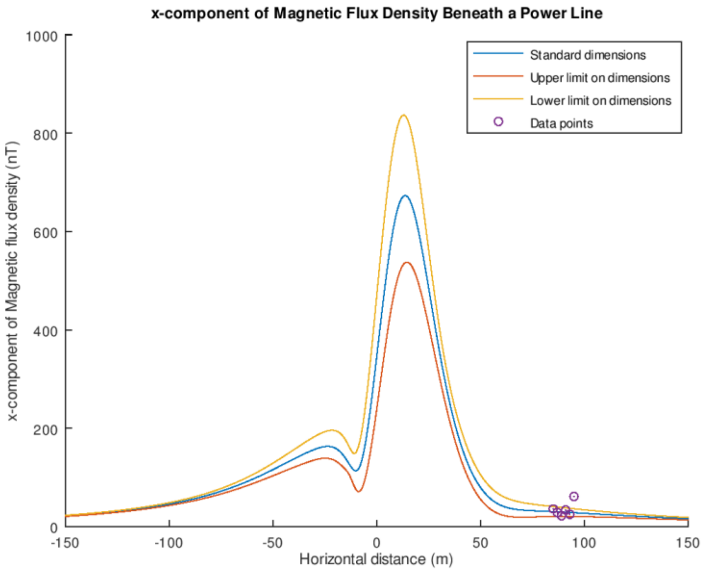


Phase Configuration 2

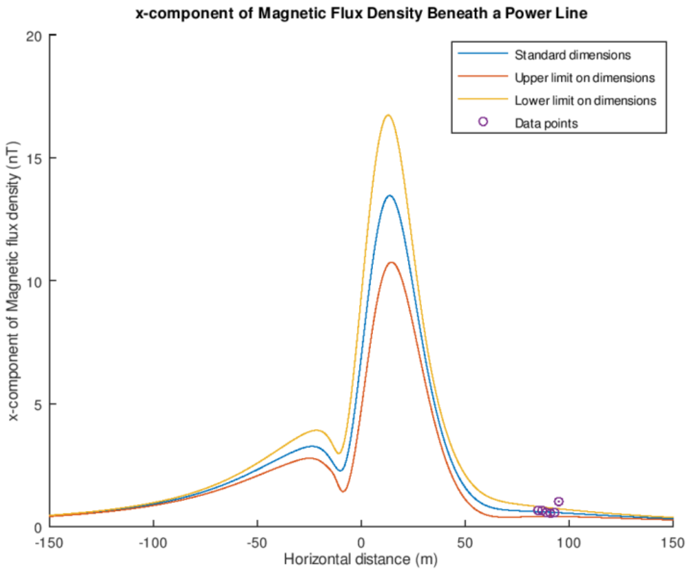


Phase Configuration 2

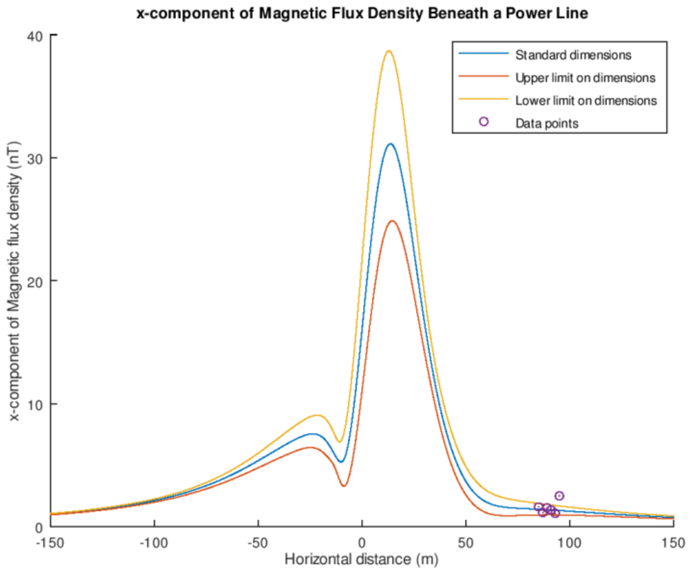
50 Hz, I = 80A



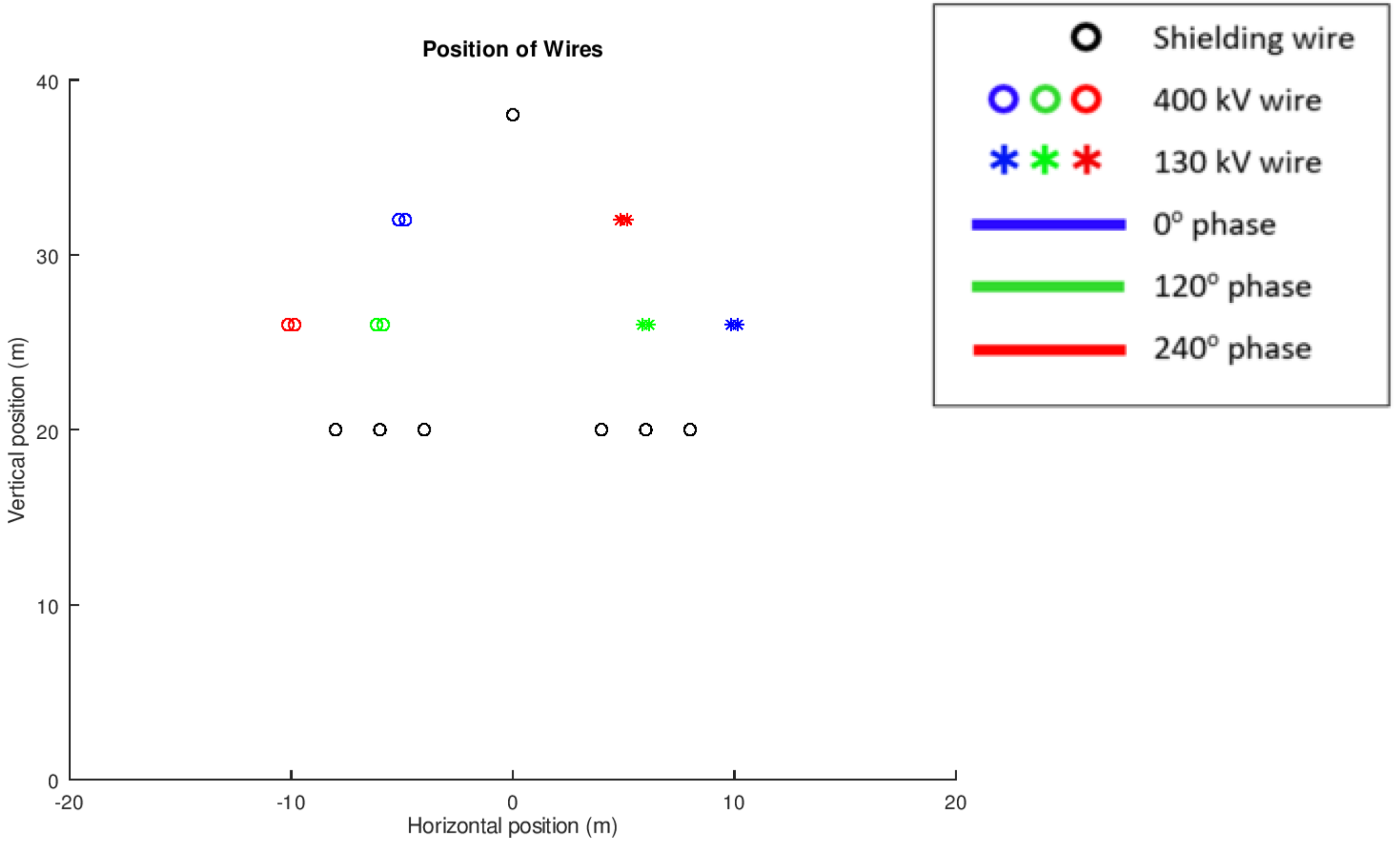
150 Hz, I = 1.6A



250 Hz, I = 3.7A

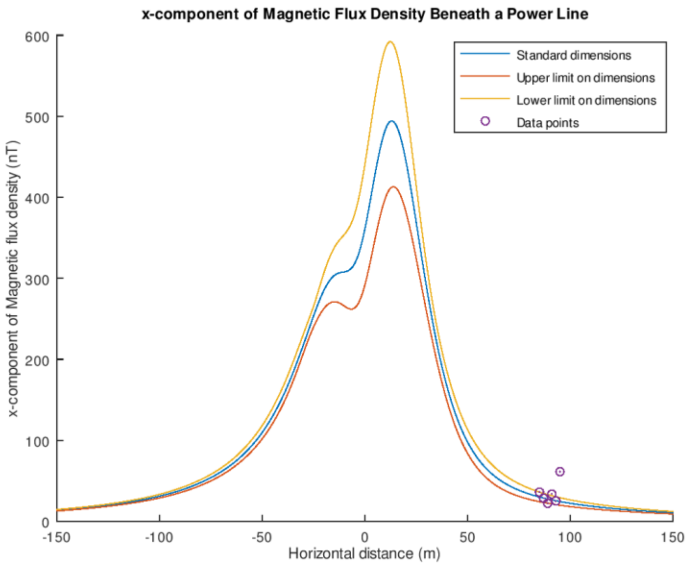


Phase Configuration 3

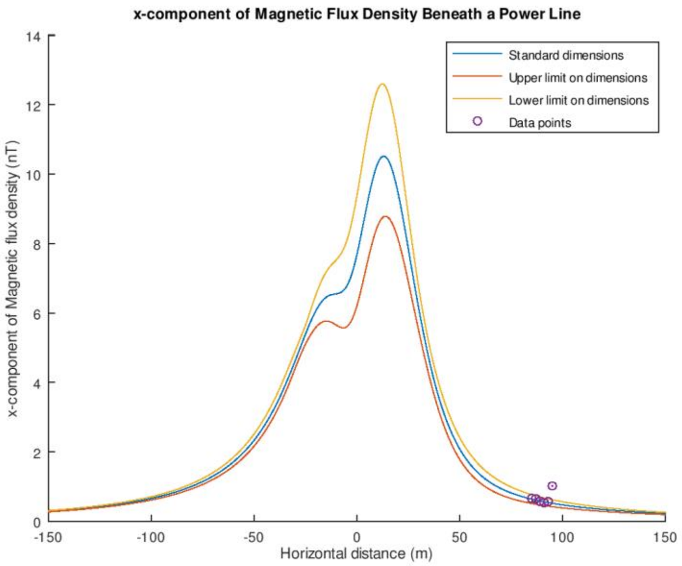


Phase Configuration 3

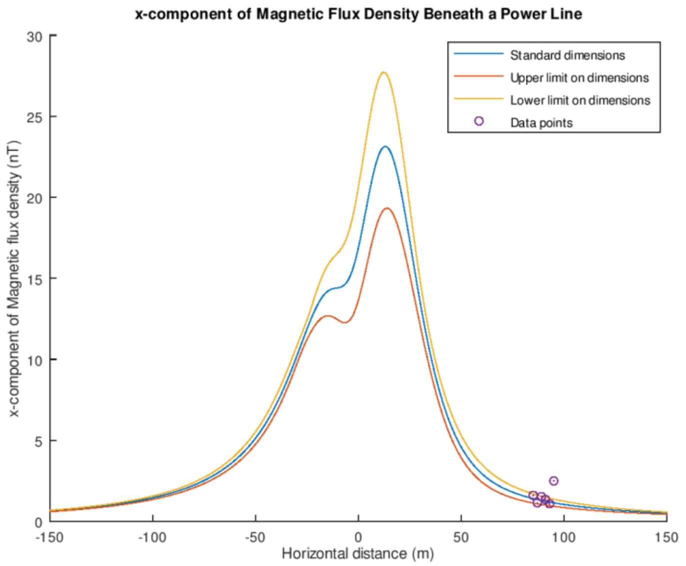
50 Hz, I = 47A



150 Hz, I = 1.0A



250 Hz, I = 2.2A



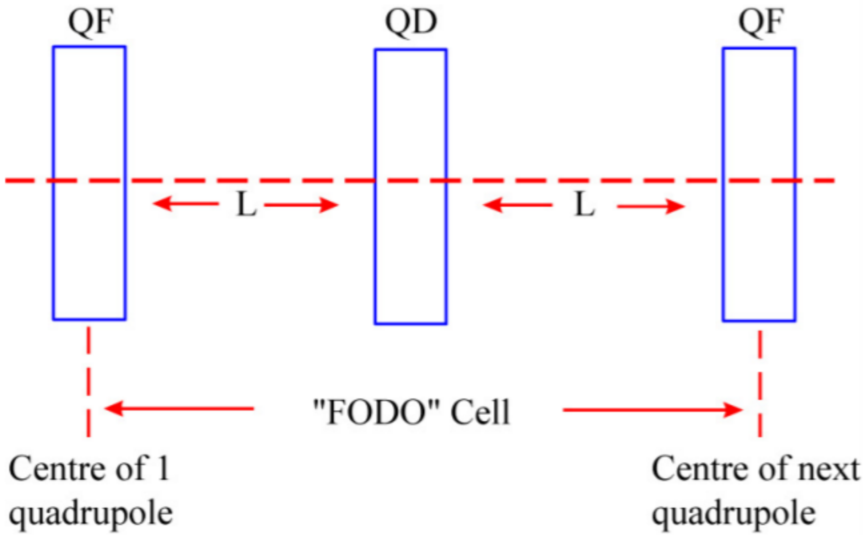
Which Phase Configuration?

- Decided to use phase configuration 2, fit data best out of the 3 different configurations
- Now need to simulate a drive beam and determine the effect of the magnetic field on the final offset and angle

Simulating the Drive Beam

Properties of Drive Beam

- Made up of series of focusing and defocusing quadrupole magnets (FODO cells)
  - Can vary strength of magnets and number of FODO cells to see what would produce the smallest final offset and angle
- Beam energy of 9 GeV



Location of Drive Beam

- Drive beam located 100m underground
  - Need to take attenuation due to the ground into account
  - Skin depth is inversely proportional to square root of angular frequency
  - Different frequency components of magnetic field will be attenuated by different amounts
- Two different orientations; parallel to wires, and perpendicular to wires
  - Simulate both drive beams, see which one produces the smallest final offset and angle

Calculating Twiss Parameters

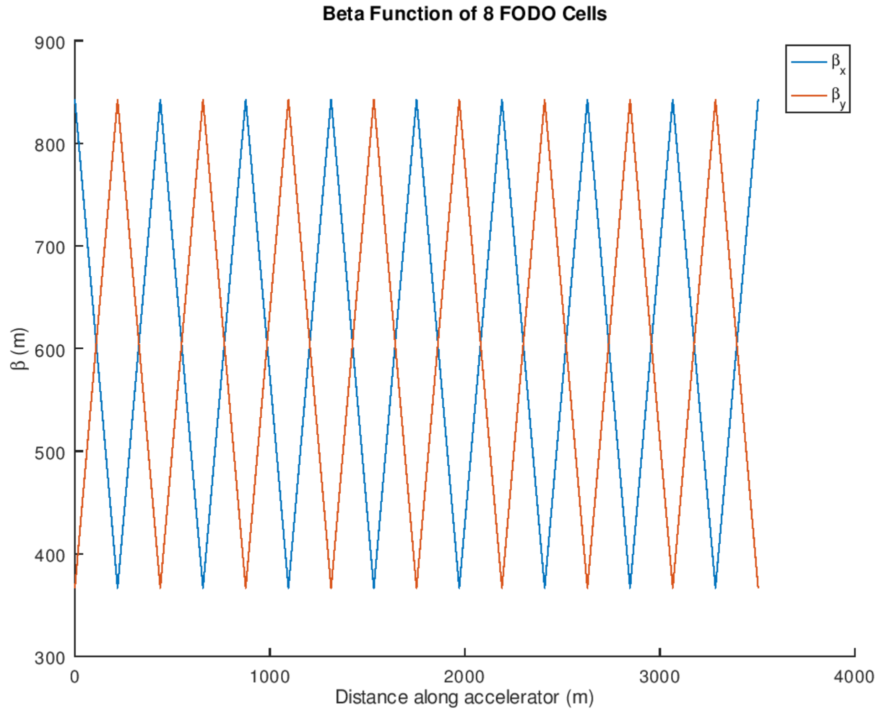
- Model drive beam consists of a series of FODO cells with the below specifications

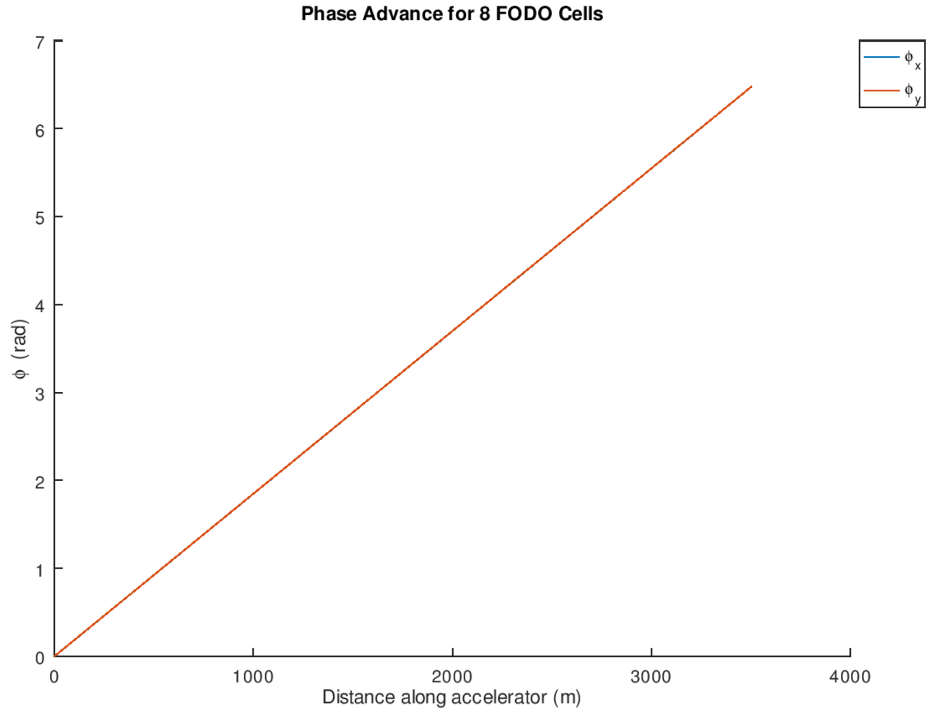
Section	Length (m)	Magnet Strength (T/m)
Focusing quadrupole	0.36	0.01
Drift	218.64	0
Defocusing quadrupole	0.36	-0.01
Drift	218.64	0

- Used MAD-X to determine Twiss parameters α and β, as well as the phase advance ϕ in both the x and y directions

Beta Function and Phase Advance

- For quadrupole strength of 0.01 T/m, 8 FODO cells





Calculating Total Offset and Angle

- Drive beam system is linear
- Can calculate the total offset and angle by:
  - Dividing up the drive beam into smaller pieces
  - Applying the magnetic field to one particular piece
  - Working out the final offset and angle due to the magnetic field 'kick' at the single piece
  - Repeating for every single other piece until the length of the drive beam is covered
- The total offset and angle at the end of the drive beam is the sum of all of the final offsets and angles

Offset and Angle

- Offset x and angle x' at a location s due to a kick at s_0 is given by

$$x(s) = \sqrt{\beta_x(s)\beta_x(s_0)} \cdot \Delta\chi_y(s_0) \cdot \sin\left(\phi_x(s) - \phi_x(s_0)\right)$$

$$x'(s) = \frac{\Delta\chi_y(s_0)\sqrt{\beta_x(s_0)}}{\sqrt{\beta_x(s)}} \cdot \Big(\cos\left(\phi_x(s) - \phi_x(s_0)\right) + \alpha_x(s) \cdot \sin\left(\phi_x(s) - \phi_x(s_0)\right)\Big)$$

$$y(s) = \sqrt{\beta_y(s)\beta_y(s_0)} \cdot \Delta\chi_x(s_0) \cdot \sin\left(\phi_y(s) - \phi_y(s_0)\right)$$

$$y'(s) = \frac{\Delta\chi_x(s_0)\sqrt{\beta_y(s_0)}}{\sqrt{\beta_y(s)}} \cdot \Big(\cos\left(\phi_y(s) - \phi_y(s_0)\right) + \alpha_y(s) \cdot \sin\left(\phi_y(s) - \phi_y(s_0)\right)\Big)$$

where $\beta_{x,y}$ and $\alpha_{x,y}$ are the Twiss parameters of the beam, $\phi_{x,y}$ is the phase advance, and $\Delta\chi(s_0)$ is the kick at location s_0.

- Sum all (x, y) and (x’, y’) to get total final offset and angle

Magnetic Field Kick

- Kick at a given location is given by

$$\Delta\chi_y(s_0) = \frac{lqB_y(s_0)}{p}$$

$$\Delta\chi_x(s_0) = \frac{lqB_x(s_0)}{p}$$

- l = Total distance kick is applied for
- q = Electronic charge
- p = Momentum of electron
- $B_{x,y}(s_0)$ = Magnetic field strength in x and y directions at s_0

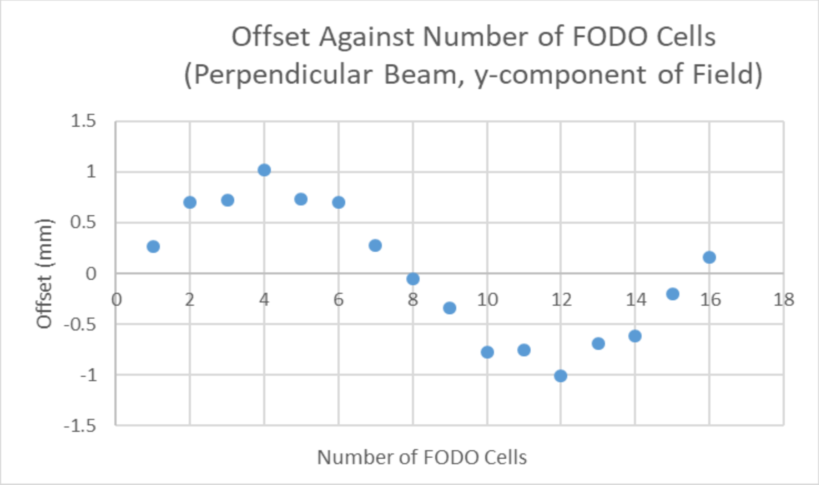
- Total kick experienced depends on orientation of beam relative to pylon wires
  - Parallel orientation $\Longrightarrow$ Constant magnetic field
  - Perpendicular orientation $\Longrightarrow$ Non-constant magnetic field

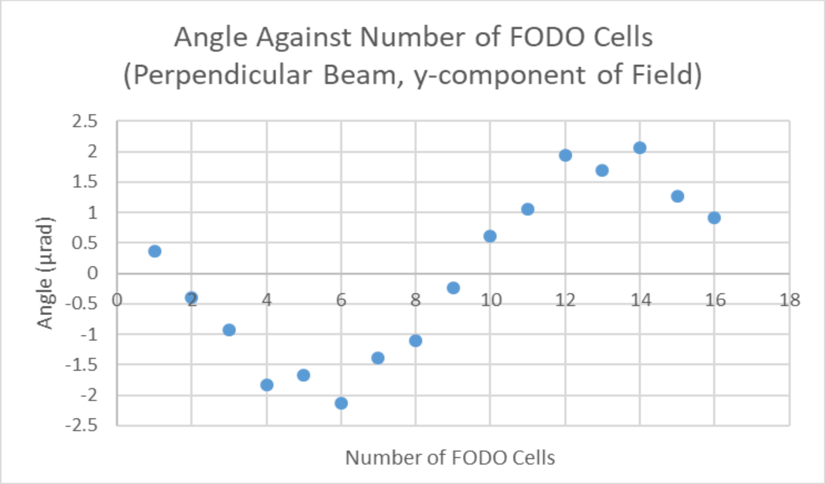
Using the Model

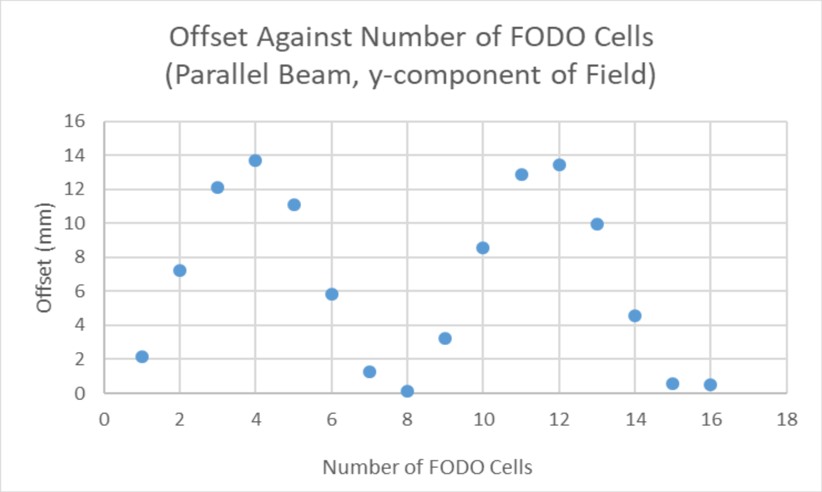
- Created MATLAB script using magnetic field from the model and the calculated Twiss parameters to work out the final offset and angle for any drive beam setup
- Now can investigate:
  - The number of FODO cells that produces the smallest total offset and angle
  - The strength of the quadrupole magnets that produces the smallest total offset and angle

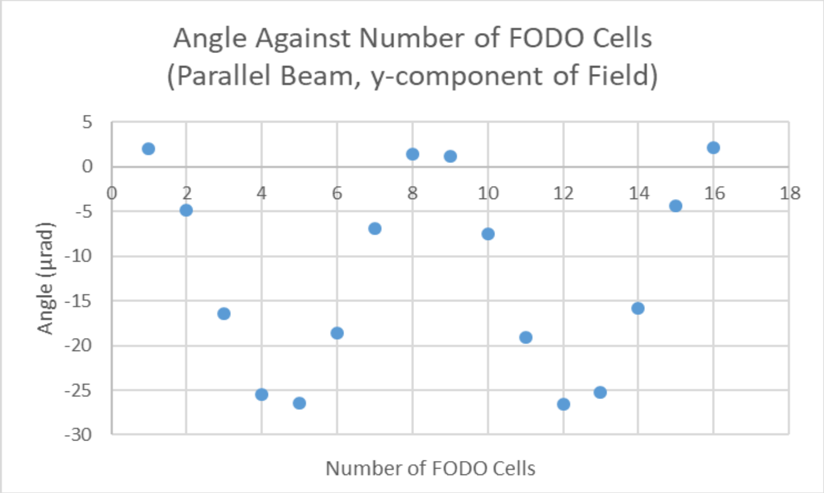
Effect of Number of FODO Cells

Offset and Angle vs Number of FODO Cells (y-component of Field)

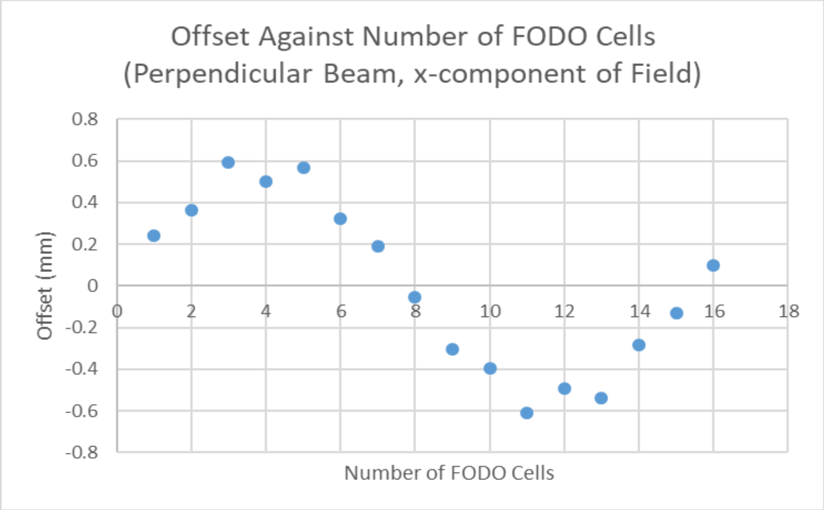


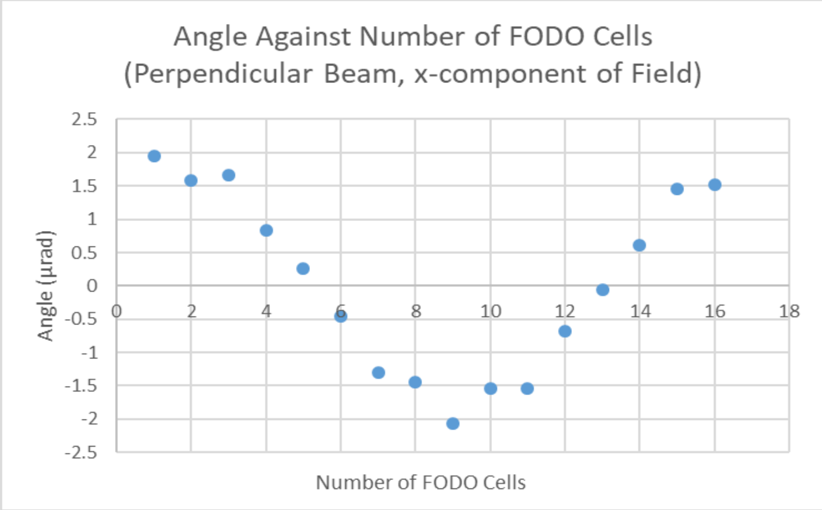


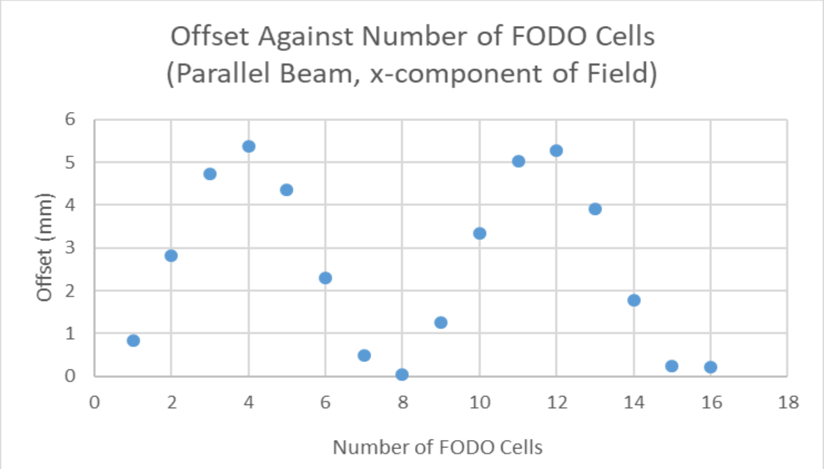


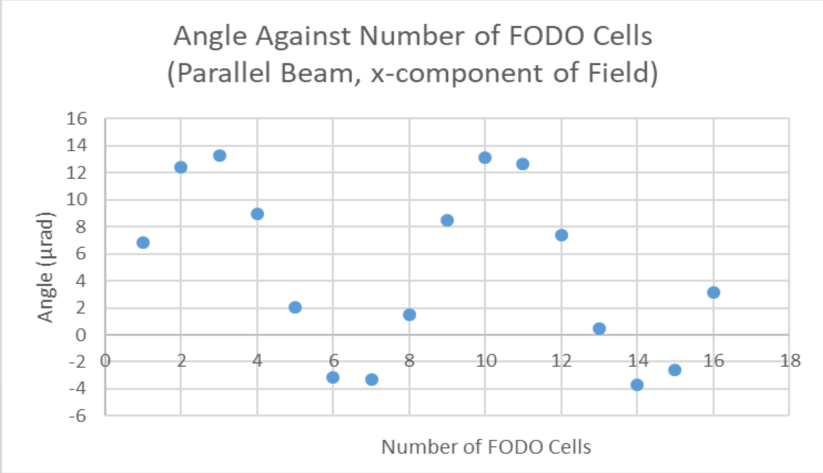


Offset and Angle vs Number of FODO Cells (x-component of Field)









Effect of Beam Line Orientation

- Parallel beam line has a much greater angle and offset than the perpendicular beam line, regardless of number of FODO cells
  - Field becomes much weaker as you go further away for the perpendicular beam
  - Field has less effect outside the central part of the beam
  - Parallel beam has fairly strong constant magnetic field throughout
  - Field has large effect at every point of the beam
- Perpendicular orientation much better for minimising total offset and angle

Total Offset and Angle

- Total offset for the perpendicular beam varies sinusoidally with number of FODO cells for both the x- and y-components
  - 8 FODO cells produces smallest offset in both cases
- Total angle varies as a negative sine wave for the y-component of the field and as a cosine wave for the x-component
  - 9 FODO cells produces smallest angle for y-component
  - 13 FODO cells produces smallest angle for x-component
- Trade-off between having smallest angle possible and smallest offset possible

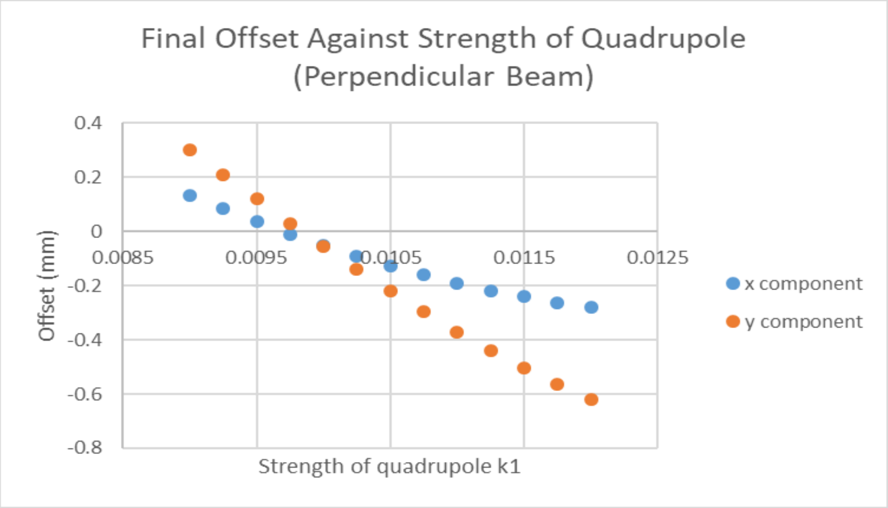
Effect of Strength of Quadrupoles

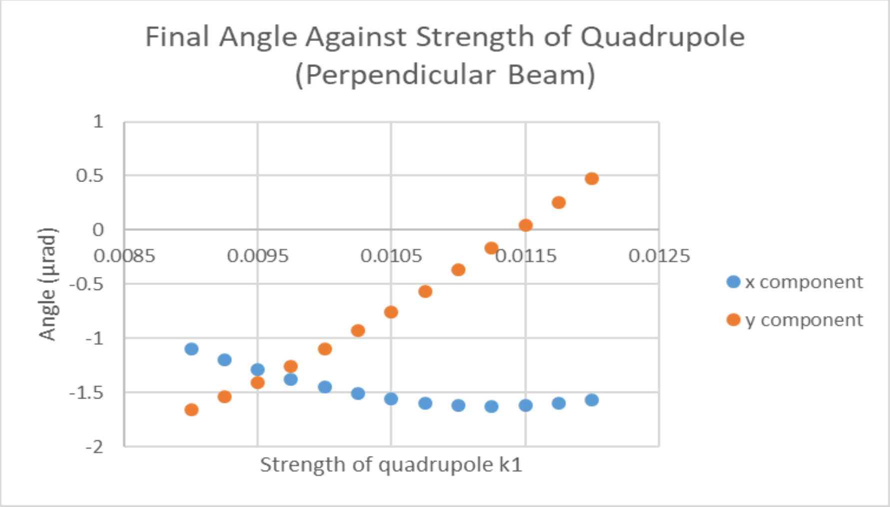
Effect on Beta Function

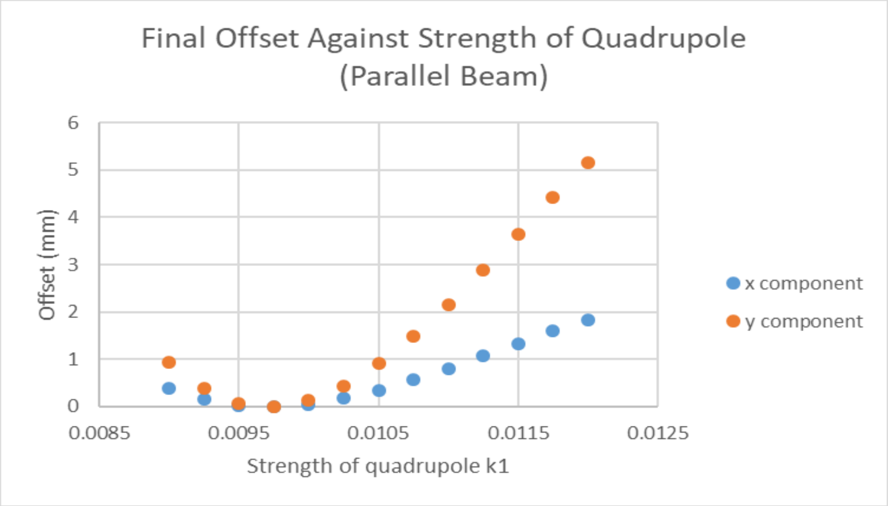
- Increasing the strength of the quadrupoles decreases the value of β

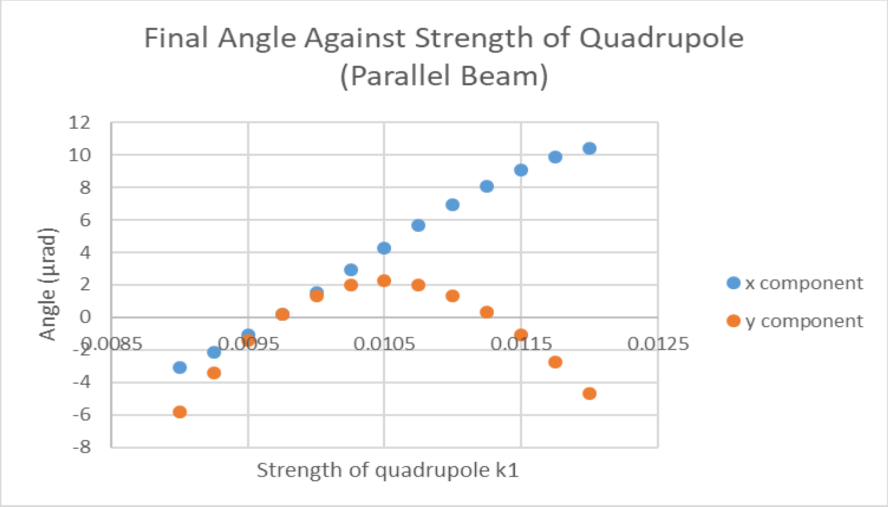
Strength of Magnet (T/m)	β max	β min
0.00900	894.41	426.49
0.00925	880.13	410.30
0.00950	866.79	394.98
0.00975	854.33	380.45
0.01000	842.68	366.66
0.01025	831.81	353.56
0.01050	821.65	341.09
0.01075	812.18	329.20
0.01100	803.35	317.87
0.01125	795.12	307.04
0.01150	787.47	296.69
0.01175	780.38	286.78
0.01200	773.81	277.29

Offset and Angle vs Strength of Quadrupoles









Total Offset and Angle

- Parallel beam line has a much greater angle and offset than the perpendicular beam line once again
- Total offset for the perpendicular beam varies almost linearly with the strength of the quadrupoles for both the x- and y-components
  - 0.00975 T/m produces smallest offset in both case
- Total angle for the perpendicular beam also varies almost linearly
  - 0.01150 T/m produces smallest angle for y-component
  - 0.00900 T/m produces smallest angle for x-component

Conclusion

- Perpendicular orientation is best for minimising total offset and angle
- Drive beam consisting of 8 FODO cells with quadrupole strengths of 0.00975 T/m produces the smallest total offset whilst also having a total angle that is not too large
- Due to lack of data obtained, difficult to determine how accurate our model for the magnetic field is, especially underneath the wires
- Once a more accurate magnetic field measurement is made, can easily be applied to this model to determine the necessary quadrupole strength and number of FODO cells to give the smallest total offset and angle

Thanks for Listening!