

CHARGED FUSION PRODUCT TRAJECTORY SIMULATIONS

Omar Leon¹

Florida International University Department of Physics

Spherical tokamaks use magnetic fields to produce and confine plasmas, which are hot ionized gases. Due to the magnetic properties of plasmas and the magnetic fields of tokamaks, current diagnostics focus on detecting neutral particles. When the temperature of plasmas, composed of hydrogen isotopes, reach approximately 100 million degrees Celsius, the isotopes react with one another emitting protons and other charged particles. These reactions are called fusion reactions. A new diagnostic, the charged fusion product diagnostic, is geared towards detecting protons, tackling the issue of particles interacting with magnetic fields, in order to expand the methods of studying plasmas. However, the complex nature of plasmas and the magnetic fields makes calculating many plasma properties analytically impossible. A program called the Orbit Code was developed and tailored to the requirements of the diagnostic in order to numerically calculate charged particle trajectories in the tokamak's plasmas. This Orbit Code was used to determine the trajectories of protons emitted from fusion reactions inside in the Mega Amp Spherical Tokamak (MAST) located at the Culham Centre for Fusion Energy (CCFE). Using these predictions, the diagnostic can be placed in the locations that most effectively samples the plasmas.

Keywords: Fusion; Plasma; Fusion Emissivity Profile; Orbit Code

CONTENTS

I. Introduction	3
A. Background	3
B. The Orbit Code	5
II. Input Section	8
III. Fortran Section	9
A. Acquiring the Data	9
B. Coordinating and Executing Fortran subroutines	10
IV. Python Section	11
V. Results	14
VI. Conclusion	15
VII. Acknowledgements	16
References	17

I. INTRODUCTION

A. Background

Plasmas are produced by heating a gas until a large portion of the atoms have been ionized.¹ (pg.2-3) The fact that plasmas conduct electricity allows them to be altered by magnetic fields; machines, called tokamaks (figure 1), use this fact to produce and confine plasmas.

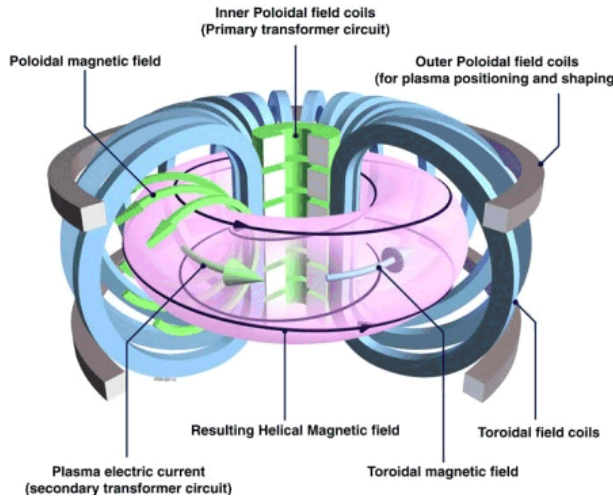


FIG. 1. General Setup of Tokamak²

The process by which tokamaks create and maintain plasmas includes several steps. First, gas is introduced into the tokamak and a current is run through the primary transformer circuit, located in the center of the tokamak, to induce a current (carried by a few pre-existing ions) through the gas, which acts as the secondary coil of the transformer. As the gas gains temperature, electrons are removed from the atoms, the gas becomes more and more ionized, and the gas transitions into a plasma state. This method of heating, by driving current through the plasma, is called ohmic heating.³

To achieve fusion within the plasma, the gas is composed of hydrogen isotopes, either deuterium, tritium, or a mixture of both, and plasma temperatures need to exceed 100 million degrees Celsius. To achieve these temperatures, two methods are employed, either simultaneously or individually: radio frequency heating and neutral beam injection. In radio frequency heating, currents of high frequency oscillations are induced in sections of the plasma that resonate with the current frequency. In doing so, the particles in the induced current gain kinetic energy, thus increasing the temperature in the region. In neutral beam injection, neutral deuterium atoms bombard the plasma

and the kinetic energy of the collisions increases the temperature.³

Due to the strong magnetic fields, diagnostic systems, instruments used to measure physical parameters, traditionally rely on detecting neutral particles as their trajectories are not altered by the magnetic fields of the tokamak. A charged fusion product diagnostic (CFPD), shown below, was developed to detect charged reaction products in order to determine the emissivity profile of plasmas, a distribution function representing the density of fusion reactions. The full diagnostic is shown in the figures below.

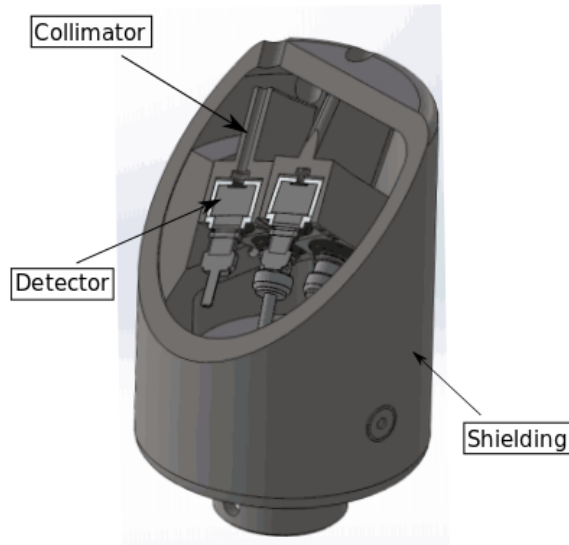


FIG. 2. Sliced view of Fully Constructed CFPD⁴ (pg.1)

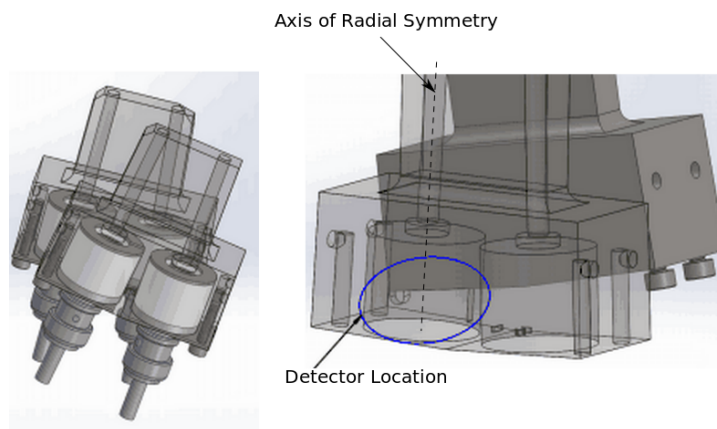


FIG. 3. The left side of the image is the collimator & detector Setup. The right side of the image is a transparent view of same setup⁴ (pg.1)

Figure 2 shows the CFPD diagnostic, where it is shown that each detector varies in distance relative

to the top of the shielding. Figure 3, shows a more detailed view of the detectors in conjunction with their respective collimators, mechanical structures that filter incoming particles . To test this diagnostic, deuterium plasmas were studied heated with neutral beam injections. This fusion reaction results in one of the two following reactions:

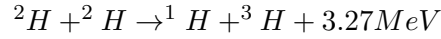


FIG. 4. Deuterium (2H) and Deuterium react to create a proton (1H) and a triton (3H) with a release of energy , given in MeV.¹ (pg. 18)

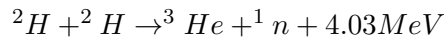


FIG. 5. Deuterium (2H) and Deuterium react to create a neutron (n) and helium-3 ions (3He) with a release of energy, given in MeV.¹ (pg. 18)

The proton of the above reactions will be detected by the CFPD while the neutron will be detected by a neutron camera. The data collected by the CFPD will be compared to the data obtained by the neutron camera. As the emitted charged particles move through the tokamak they experience a force due to the magnetic field. A new convention of angles was defined to describe where the detectors are oriented with respect to the center of the tokamak (shown in figure 6).

The center of the tokamak is the origin in figure 6, the ϕ angle is defined as the angle between the detector and the x-z plane, and the θ angle is the angle between a projection of the detector on the x-z plane and the z-axis.

To alter the CFPD's distance from the center of the tokamak and to rotate it, the CFPD is mounted on a reciprocating probe arm (see figure 7) that is controlled remotely and is taken to be along the x axis of figure 6 for the purposes of determining the orientation of the detectors.

B. The Orbit Code

The complicated magnetic fields inside a tokamak plasma require a numerical solution of the equation of motion for the charged particles. The code (Orbit Code) was modified to calculate a proton trajectories and the proton emissivity of the plasma along these trajectories using MAST's equilibrium magnetic field configuration and physical limitations. For the CFPD, the Orbit Code

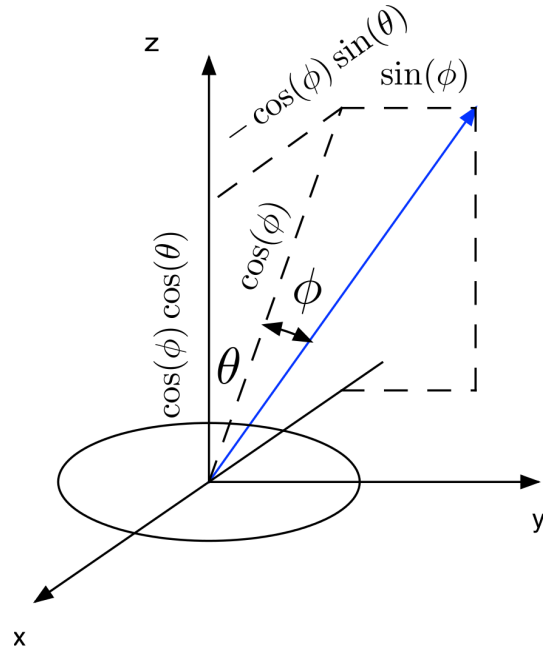


FIG. 6. Angles Defined for Detector Orientation

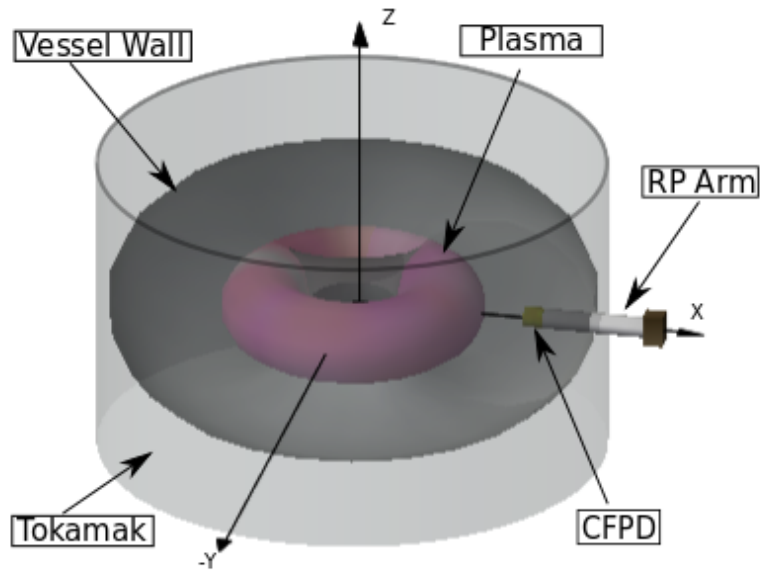


FIG. 7. Rendering of Detector Setup Within Tokamak (not to scale)

needed to be adapted to more accurately approximate the experimental setup. The new version can determine which portions of the plasma was sampled by each detector. This made the Orbit Code an invaluable part of the experiment when deciding how to orient the diagnostic between

each experimental run for the most effective data collection.

The code is structured into three different portions: the input section, the Fortran portion, and the Python portion. Each section had its own alterations to meet the experiment's demands. The original graphical output of the Orbit Code is shown in figure 8.

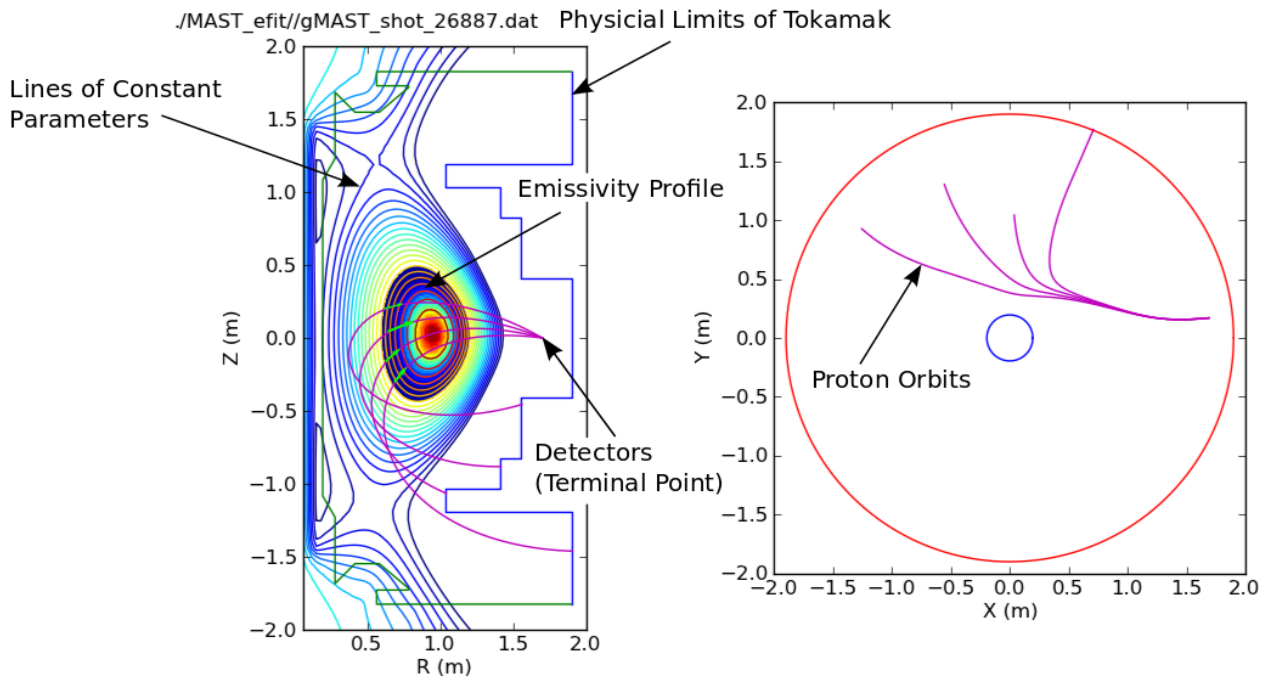


FIG. 8. Original Output Graph of the Orbit Code

In figure 8, the leftmost graph is a vertically sliced view of the tokamak and plasma presenting the lines of constant parameter, such as pressure and magnetic flux; the colored region describes the emissivity profile where the most dense region is deep red; and the purple lines demarcate the proton trajectories, or orbits. Protons that are emitted from the emissivity profile, tangential to the orbits, towards the outside of the tokamak will be detected as they terminate on the same point. The rightmost graph is a top of the horizontal mid-plane of the tokamak and proton trajectories. There were several factors in the code that limited how well it could approximate the physical experimental setup. Chief among these factors was the inability to individualize each detector orientation, calculate the effects of rotation on the CFPD.

II. INPUT SECTION

There were initially three main input files:

: Efit file:

Is the data file that gives the magnetic field configuration of the plasma at an instant in time, which is then used to model the plasma's overall shape and the trajectories of the particles emitted from fusion reactions.

: Limiter file:

Is the data file which provides the physical structure inside the tokamak, setting limits to many of the calculations performed by the Orbit Code.

: Name list (.nml) file:

Is the data file that contains a variety of parameters that are necessary for calculation, including the detector orientations and where the collimator entrances are located in the tokamak, and what efit and limiter files are used and their respective directories.

This .nml file needed to be altered to allow for a greater degree of flexibility for each detector. Prior to alterations, many parameters were determined by using a step function with an initial value. For example, the θ angles of the detectors were written in the following way:

```
theta_port = 60.  
vary_theta_port = F  
theta_port_stop = 83.  
theta_port_step = 7.5
```

In this manner, the Fortran portion of the code would use the initial position given and then, if vary_theta_port equaled True, it would alter the initial value by the step amount until the stop limit was reached.

In order to grant the user the ability to choose which detector and how many to use in the analysis and the individual orientation, the .nml file was divided into two files. The first file is called Static_MAST.nml where the parameters that rarely change are stored. Examples of these parameters are the efit file and the model used to model the plasma's emission profile. The second file is called dynamic_input.data and it contains the information that changes more frequently such as the radial positions of the detector with respect to the center of the tokamak. This second file is

used exclusively in the Python portion of the Orbit Code and includes all of the physical parameters of the detector system and the radial position of the collimator entrance closest to the plasma. The input format of the Static_MAST.nml file is identical to its unaltered counterpart; it is in the dynamic_input.data file where the format changes. When the two files are used in conjunction, the .nml file created and used by the Fortran portion has the following, altered format:

```
detectors = 4
detector_number(1)= 1
detector_number(2)= 2
detector_number(3)= 3
detector_number(4)= 4
theta_port(1)= 40.0
theta_port(2)= 40.0
theta_port(3)= 40.0
theta_port(4)= 40.0
```

In this new format, the detectors and detector_number allow the user to choose how many detectors and which detectors to use in the analysis. Additionally, every parameter that used to be calculated using the step method described above is given its own value independent of the other parameters.

III. FORTRAN SECTION

All of the computations for the plasma parameters including the particle trajectories, the magnetic flux, and the emissivity profile occur in this section of the Orbit Code.

A. Acquiring the Data

The .nml file is read by a file called rdpar_nml.f, short for read parameters name list, and the parameters in the .nml file are stored as several variables. In the original file, rdpar_nml.f used the step and stop inputs to create each detector orientation. This file was altered to execute the following code instead:

```
do i = 1, detec
    ports(i) = theta_port(detector_number(i))*dtr
```

```

portsph(i) = phi_port(detector_number(i))*dtr
Al0s(i) = gyro_angle(detector_number(i))*dtr
be0s(i) = pitch_angle(detector_number(i))*dtr
rds(i) = rdist(detector_number(i))
zds(i) = zdist(detector_number(i))
phda(i) = phdangle(detector_number(i))
end do

```

where *dtr* is the conversion value from degrees to radians. In this manner, each detector is assigned a unique set of variables.

B. Coordinating and Executing Fortran subroutines

A separate file, named *orbit.f*, organizes the data and calls a separate subroutine, named *chrien*, to execute all of the calculations to model the plasma, emissivity density, and particle trajectories. This process occurred through a series of conditional statements based on the original *.nml* file. Since these conditionals became obsolete after the *.nml* file was changed, the *orbit.f* file was altered to do the same function with a single *loop* as follows:

```

do j= 1, detec
    port = ports(j)
    portph = portsph(j)
    RD = rds(j)
    be0 = be0s(j)
    al0 = al0s(j)
    zd = zds(j)
    phd = phda(j)
    call chrien
end do

```

Now each time *chrien* is called, each detector has its own unique parameters.

IV. PYTHON SECTION

The Python section runs the Fortran executable, organizes the output files created by Fortran and generates a plot that visually represents the results. The original code ran using two Python scripts, `run_orbit_nml.py` and `plot_orbits_combined.py`. The former executed the Fortran executables and organized the output files created by these executables whereas the latter plotted the Fortran output files. A separate Python file, `run_all.py`, was created to accomplish several tasks. The file reads the `dynamic_input.data` and `Static_MAST.nml`, extracts all of the necessary information, and stores them as variables. These variables are then used to calculate the following (figure 9 will be used as a reference) :

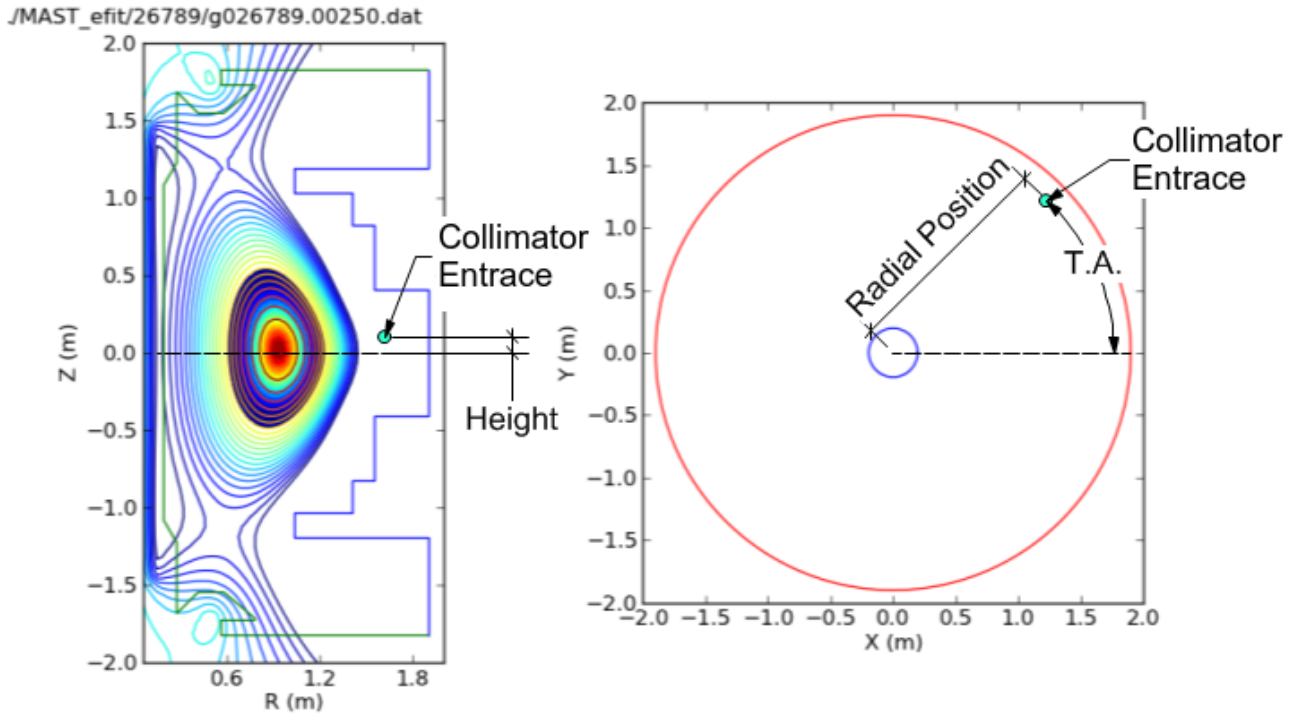


FIG. 9. Output Detailing the Detector Height, Toroidal Angle (T.A.), and Radial Distance

- The distance of each collimator entrance from the center of the tokamak, as shown in the right most portion of figure 9.

The radial position is measured from the center of the tokamak to the position of collimator entrance that is closest to the plasma; this entrance is used as a reference for the other entrances.

$$RDist = RDist_{coll} + \Delta_{coll_pos} * 1. * 10^{-3}$$

where $RDist_{coll}$ is the position of the reference collimator and $coll_pos$ is the distance from the reference collimator to each collimator in the system.

- The height of each collimator entrance relative to a central horizontal plane, as shown in the left most portion of figure 9.

This is calculated through the following equation:

$$Det_height = RP_height + coll_height_offset * 1. * 10^{-3}$$

where RP_height is the height of the reciprocating probe arm and $coll_height_offset$ is the height of each collimator entrance relative to the radial axis of the system.

- The toroidal angle (T.A.) of the collimator entrances , as shown in the right most portion of figure 9.

This angle dictates where the collimator entrances are positioned within the tokamak.

$$PHDangle = Probe_angle + \arctan\left(\frac{coll_horizontal_offset * 1. * 10^{-3}}{RDist}\right)$$

where $Probe_angle$ is the toroidal angle of the reciprocating probe and $coll_horizontal_offset$ is the horizontal distance of each collimator entrance from the radial axis of the system.

- Update the θ and ϕ angles of the detectors if the reciprocating probe arm is rotated.

The following steps show how this was calculated:

1. Before the probe arm is rotated, the x,y, and z positions of each detector, denoted by a vector \hat{r} , is given by

$$x = -1 * \cos(\phi) * \sin(\theta)$$

$$y = \sin(\phi)$$

$$z = \cos(\phi) \cos(\theta)$$

After a rotation by an angle, α , the new vector, \hat{r}' is calculated using the rotation matrix $\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & -1 * \sin(\alpha) \\ 0 & \sin(\alpha) & \cos(\alpha) \end{pmatrix}$ obtaining

$$\begin{aligned}
x' &= x \\
y' &= y * \cos(\alpha) - z * \sin(\alpha) \\
z' &= y * \sin(\alpha) + z * \cos(\alpha)
\end{aligned}$$

2. The angle between the vector normal to the x-z plane, \hat{n} , and \hat{r}' is calculated using the definition of the dot product which produces

$$\cos(\beta) = \hat{r}' \cdot \hat{n}$$

Since the complimentary angle to β is the new phi angle, ϕ' , β can be written as $90 - \phi'$. Therefore, $\cos(\beta)$ is equivalent to $\sin(\phi')$. The new ϕ' is given by

$$\phi' = \arcsin(y')$$

3. To find θ' , \hat{r}' was projected onto the x-z plane by using the matrix $\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$ and the definition of the dot product. Therefore,

$$\theta' = \arccos\left(\frac{\vec{r}_{xz} \cdot \hat{z}}{|\vec{r}_{xz}|}\right) = \arccos\left(\frac{z'}{\sqrt{x'^2 + z'^2}}\right)$$

- The input value for the reciprocating probe arm controller.

A set point value that determines the distance the collimator entrances will have to the center of the tokamak must be dialed into the probe arm controller. The value depends on whether the gas is on or off, a parameter controlled by MAST. The calculations are

$$pdo = coll_dist - .165$$

$$SpGO_n = 1200 - (2526 - RDist * 1000. - pdo * 1000.)$$

$$SpGO_ff = 1200 - (2526 - RDist * 1000. - 105.4 - pdo * 1000)$$

where coll_dist is the distance from the end of the reciprocating probe arm and the collimator entrance farthest from it.

After the above calculations are implemented, all of the parameters are written into the new .nml file. Finally, the script runs run_orbit_nml.py, prompts the user to run plot_orbits_combined.py, and gives the value to be physically entered to the controller of the probe arm.

A separate script, setpoint.py, is created to quickly determine where the detectors need to be repositioned inbetween runs. This script also calculates where the protons intersect the $z = 0$ plane within

the area of emissivity; it reads the Orbit Code output file on particle trajectories and searches for radial positions whose corresponding z -position are relatively close to 0. By calculating the radial positions of protons that intersect the $z = 0$ plane, the data taken by the CFPD can be more accurately compared to the data taken by the neutron camera.

V. RESULTS

After all of the changes, the new output graphs appear as shown in figure 10.

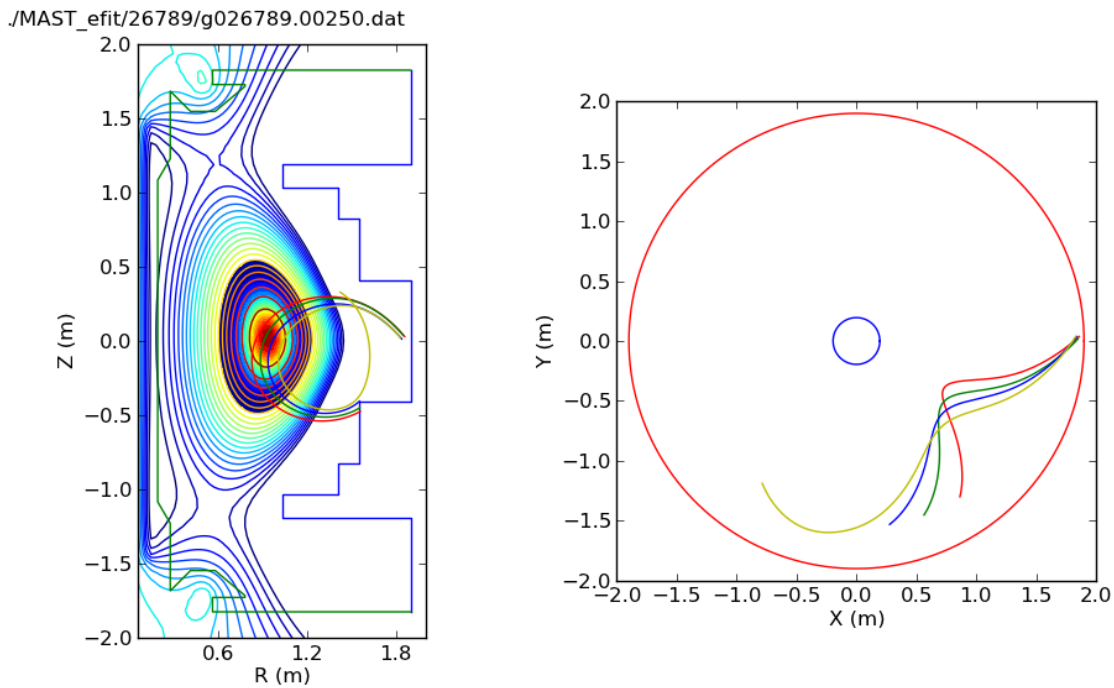


FIG. 10. Current Output Graph of the Orbit Code

The new graph correctly represents the physical position of the detectors relative to each other. The lines also have different colors to better differentiate the proton trajectories.

To view the region a detector will probe, figure 11 shows the necessary output.

The colored region of lines that terminate at the same point describes the area probed by one, specific detector.

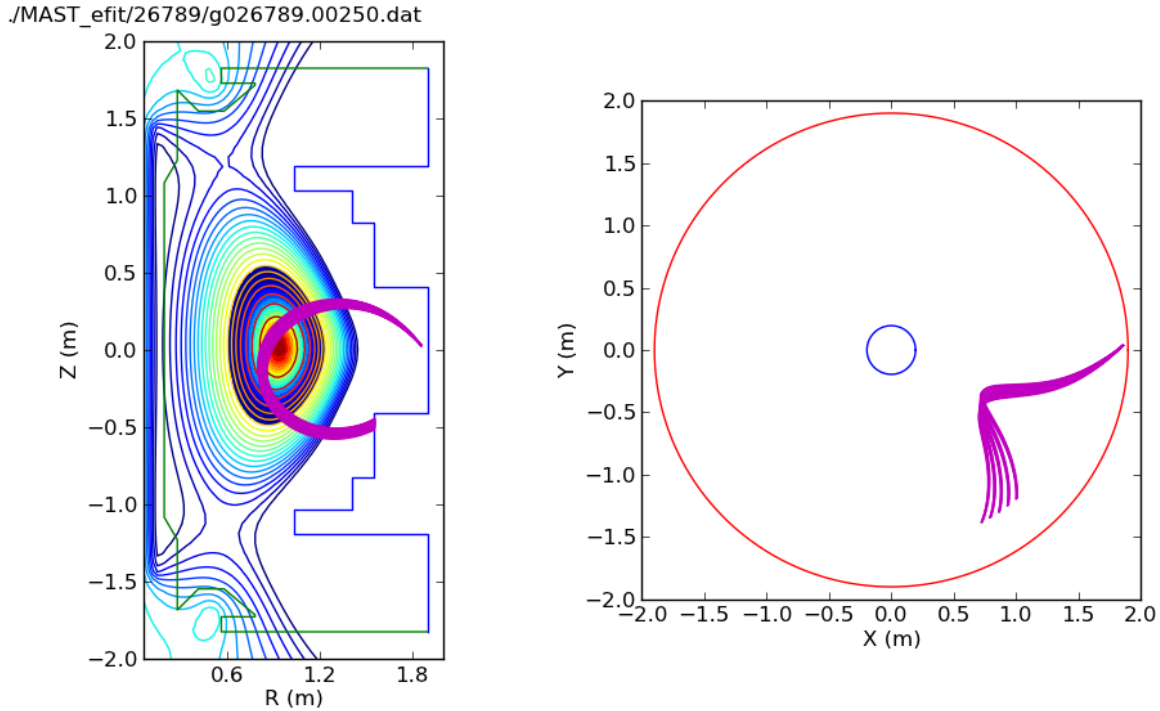


FIG. 11. Single Detector Probing Fusion Region

VI. CONCLUSION

The modified Orbit Code is an integral part of planning each experimental run for the charged fusion product diagnostic. Inputting efit files of different times of the same plasma into the Orbit Code provides an insight into how the plasma behaves over time. This insight allows for a better educated decision of where the detectors need to be positioned in order to probe as many different sections of the plasmas as possible. These theoretical models also determine the safest proximities the detectors can have to the plasma. This important safety feature ensures that the system will remain out of harms way as any damage to the detector system may also damage the tokamak causing unpredictable consequences. The code also calculates the set point value for the control box ensuring an accurate position of the reciprocating probe arm.

VII. ACKNOWLEDGEMENTS

I would like to acknowledge Dr. Werner U. Boeglin, Dr. Douglass Darrow, and Mrs. Ramona Valenzuel Perez for giving me the opportunity and guidance to assist in this project. Scott Allan and Nigel Thomas-Davies for their tireless effort in aiding the FIU Plasma Physics Research Group along with the rest of the MAST workforce. Finally, the McNair program for their support in this endeavor, the undergraduate volunteers could not have made it to Culham, England without them. Lastly, I'd like to thank Adrianna Angulo, Pierre Avila, and Carlos Lopez for their help in making the Orbit Code as user friendly and error free as possible. This material is based upon work supported by the Department of Energy under Award Number DE-SC0001157.

REFERENCES

¹J. A. Bittencourt, *Fundamentals of Plasma Physics*, 3rd ed. (Springer, New York, New York, 2004) print.

²CCFE, “How fusion works,” (2012), http://www.ccfе.ac.uk/How_fusion_works.aspx.

³CCFE, “The tokamak,” (2012), <http://www.ccfе.ac.uk/Tokamak.aspx>.

⁴R. Valenzuela Perez, “Pd_22_design_062013,” (2013).