Magnetic Field Enhancement of the Quad Confinement Thruster

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***Abstract* — The following report details the contribution of EMS to the completion of a thesis submitted in part fulfilment of the requirements for the degree of Master of Science in Advanced Aeronautical Engineering of Imperial College London. EMS was central to this project and was first used to model the 3D magnetic field of the thruster studied, the Quad Confinement Thruster (QCT). The QCT model built allowed a deeper understanding of the QCT's behavior and successfully provided an explanation for its poor observed thrust efficiency. The insight gained further allowed for the design of a new iteration of the QCT, entitled QCT Phoenix.**

I. Introduction

THE Quad Confinement Thruster or QCT, was conceived in 2009 within the Surrey Space Centre for low power Electric Propulsion (EP) for small satellites. Similarly to a Hall Effect Thruster (HET), a perpendicular magnetic field is imposed between the external cathode neutralizer and a metallic anode at the base of the QCT channel. The major difference being that the QCT's quadrupole arrangement of eight electromagnets, seen in Fig.1, produces an open rather than a closed ExB drift. The device's main advantages are that it functions at low anode voltages and that it can vector thrust without the use of mechanical gimbals. Its thrust efficiency however is quite poor. While for similar HET devices thrust efficiency is usually around 40%, in the case of the QCT it is less than 6% [1].

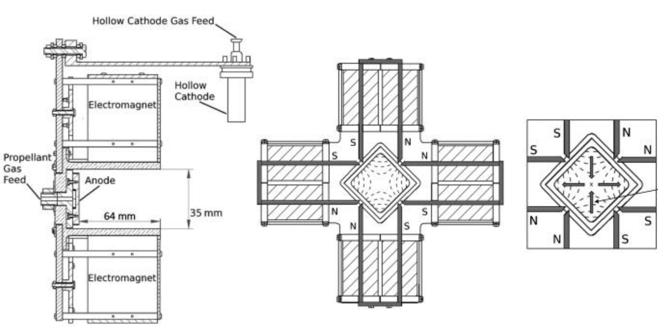

Figure 1. On the left: cross section view of the QCT. In the center: top view of the QCT featuring iron blades (grey), coils (hatched), and magnetic field lines inside the channel (dashed). On the right: close-up of the magnetic field lines inside the channel with ExB drift vectors. [1]

Ion velocity measurements were taken in the thruster's plume using laser-induced fluorescence (LIF) in an effort to investigate the cause of this poor observed thrust efficiency, and also to characterize the steerability of the ion beam. These measurements, presented in Fig. 2, revealed that ion acceleration was happening with strong beam divergence 8 cm downstream of the thruster exit plane. Results further pointed to a possible link between the location of the acceleration front and the electromagnetic topology of the thruster [2].

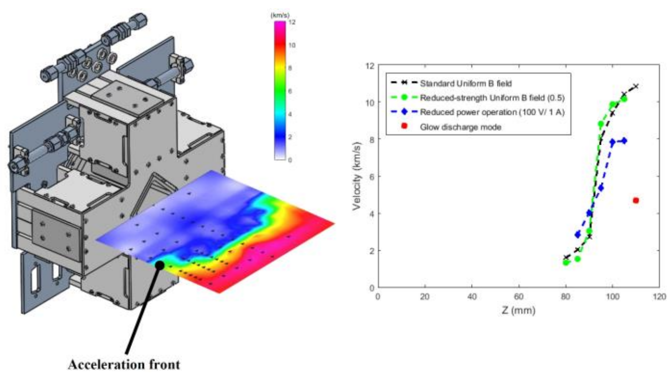

Figure 2. "On the left: ion (axial) velocity flow downstream of the thruster exit plane. On the right: ion acceleration profile under different testing conditions" [2]

The objective for the project was therefore to model the QCT's 3D magnetic field using EMS to explore the nature of the link between the observed acceleration front and the electromagnetic topology. It was expected that the understanding gained from this model would allow the conceptual design of a new QCT with a modified electromagnetic topology. The main goal of this new design iteration being the relocation of the ion acceleration region closer to the thruster exit plane and the reduction of beam divergence [3].

II. QCT and QCT Phoenix Model Design

A stripped-down version of the QCT featuring only the thruster's acceleration channel, as well as the iron railing and coiling of the electromagnets was built in SolidWorks. This was deemed satisfactory as the CAD was primarily used to model the QCT's 3D magnetic field. Dimensions for the electromagnets and acceleration channel, which can be seen in Fig. 3, match those of the most commonly used laboratory QCT model, internally referred to as the QCT-II. Special care was taken for this step as the goal was to ensure that the magnetic field modelled was as close to possible to the QCT-II's actual magnetic field.

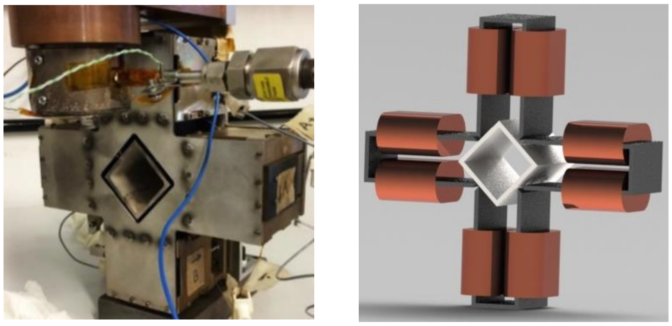

Figure 3. Laboratory model QCT-II [5] (left) and corresponding SolidWorks model [3] (right)

Following the interpretation of the standard QCT-II magnetic field configuration, an optimized magnetic field topology was investigated for the QCT Phoenix. This new thruster was modelled using SolidWorks once again. The SolidWorks model features only key iron railing pieces, coiling of the electromagnets, and the thruster's acceleration channel (see Fig. 4). The new thruster's geometry was built around an acceleration channel whose dimensions were based on the original QCT-II.

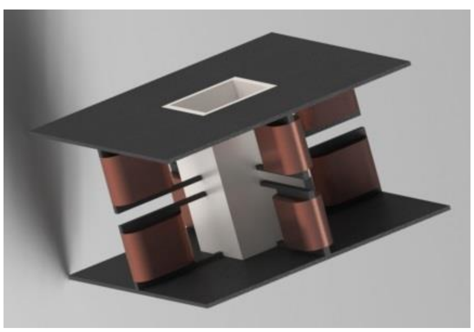

Figure 4. Isometric view of the QCT Phoenix SolidWorks model [3]

III. Simulation Setup

For the study of the QCT's 3D magnetic field, a magnetostatic study was set up using the multi-core iterative solver with a residual error of 10^{-6}. The model fit into a volume of 191x191x74 mm and was therefore placed in an outside air region of 400x400x260 mm. As recommended the air inside the thruster's channel was modelled separately and a mesh control parameter of 2.5 mm was applied to it. The same process was applied to the QCT Phoenix SolidWorks model.

	Conductivity [Mho/m]	Relative permeability
Air	0	1
Copper	57 000 000	0.999991
Purified Iron	11 235 000	200 000
Boron Nitride	0	1

Table 1. EMS material properties

The materials used in both cases were purified iron for the electromagnet railings and cap pieces, copper for the coils, and boron nitride for the ceramic acceleration channel. As was mentioned hereabove, both models were placed in air. These materials were taken directly from the EMS materials libraries. Their properties are presented in Table 1.

IV. QCT Simulation Validation

Before they were used for analysis of the QCT's 3D magnetic field, EMS simulation results were checked against other simulation and experimental results available. To start with, results from a 2D FEMM simulation used in several past papers [1] [4] were compared to results obtained at the QCT's mid plane with EMS. Fig. 5 presents the magnetic flux density values obtained with the FEMM simulation side by side with the values obtained in EMS. The field lines layered over the EMS flux density values were generated by postprocessing in Matlab.

As can be seen in Fig. 5 the results from the EMS and FEMM simulations match nicely. One small difference is the shape of the magnetic field lines between the coils of each electromagnet pole. In the EMS case these field lines can be seen to extend towards the electromagnet caps while for the FEMM simulation they are straight lines. The likely explanation to account for this discrepancy are 3D effects captured by the EMS model that FEMM was unable to account for.

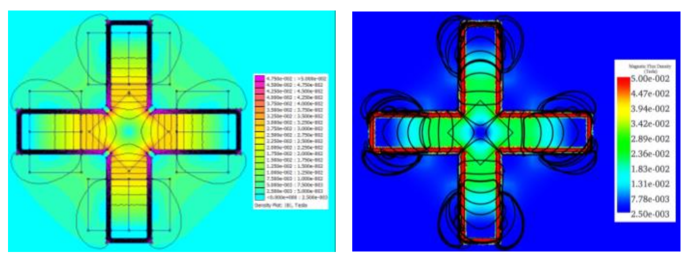

Figure 5. Magnetic flux density plots for the QCT obtained with FEMM [1] [4] (left) and EMS [3] (right)

The first set of experimental measurements used to validate the EMS QCT model were taken from data gathered by researcher Lars Havekost at the Surrey Centre [5]. The 2-dimensional topology of the magnetic field was surveyed using a magnetic probe (Gauss meter) downstream of the QCT channel exit. It can be seen that the EMS simulation results closely match the experimental observations (see Fig. 6a and Fig. 6b).

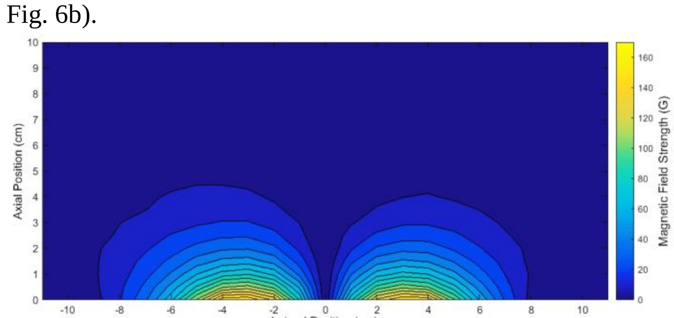

Figure 6a. "2D scan of the magnetic field strength downstream of the QCT's exit plane" [3] [5]

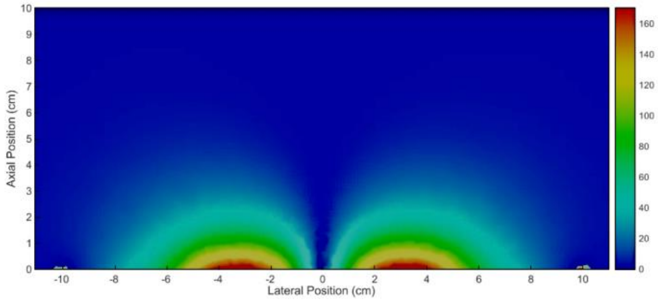

Figure 6b. "Magnetic field strength downstream of the QCT's exit plane obtained with the EMS model" [3]

The second set of experimental measurements used to validate the EMS QCT model were provided by Dr Knoll [4]. These axial magnetic field strength values, shown in Fig. 7, were taken along the acceleration channel's top corner. In the experimental case they were collected using a commercial Gauss meter. By convention, the distance scale in this plot is referenced to the channel exit, with negative values falling within the channel of the QCT device.

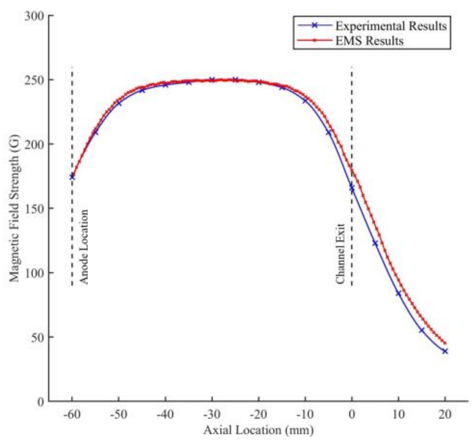

Figure 7. "Comparison of the axial magnetic field strength obtained experimentally [4]and with EMS" [3]

The experimental values, plotted in blue in Fig. 7, follow closely the simulated results, and show that the field strength within the channel is relatively constant within the channel volume and only falls near the anode and at the channel exit. This topology is uncustomary for other cusped field thrusters like, for example, cylindrical Hall thrusters [6]. The simulation and experimental results depart slightly downstream of the channel exit. Despite this small mismatch, it is fair to say that the experimental results match the global trend exhibited by EMS' 3D QCT model.

V. QCT SIMULATION RESULTS

The objective of the EMS QCT model was to explore the nature of the link between the position and shape of the ion acceleration front, and the thruster's electromagnetic topology. LIF measurements taken at Stanford (see Fig. 2) had indeed not only confirmed that the nature of acceleration was electrostatic but had also pointed to the existence of such a link [2].

The EMS model has confirmed some basic findings of prior 2-dimensional simulations (Fig. 1, Fig. 5). The structure of the four-point quad confinement topology was confirmed within the channel (see Fig. 8a). The EMS results further illustrate that the field lines launched within the channel remain largely planar; perpendicular to the axis of the channel (see Fig. 8b).

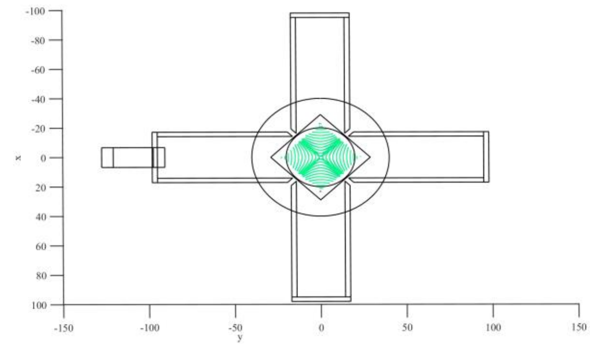

Figure 8a. "Magnetic field lines inside the QCT's acceleration channel launched at different heights along the channel – top view" [3]

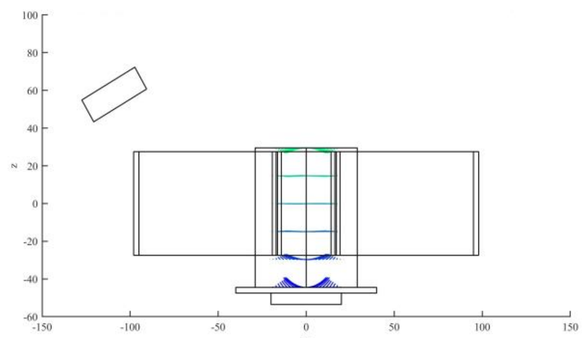

Figure 8b. "Magnetic field lines inside the QCT's acceleration channel launched at different heights along the channel – side view" [3]

The EMS model has significantly increased our understanding of the magnetic topology downstream of the channel exit, which is largely 3-dimensional in nature. It was found that the magnetic field bulges into four semi spherical quadrants (see Fig. 9a and Fig. 9b). We conclude that the shape of the magnetic field is crucial in establishing the direction and location of the ion acceleration front. The characteristics of the 3-dimensional topology reflect the LIF measurements of the ion acceleration region of the device observed experimentally.

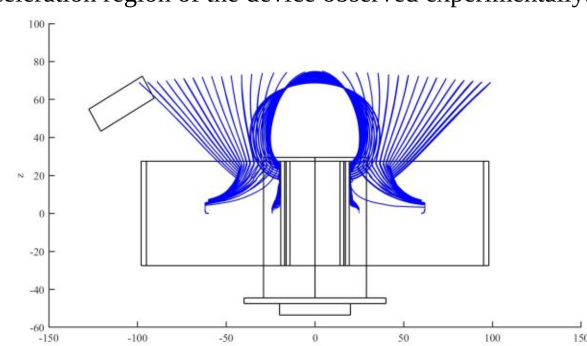

Figure 9a. "Magnetic field lines launched at the cathode plane, approximately 3cm downstream of the QCT's exit plane – side view" [3]

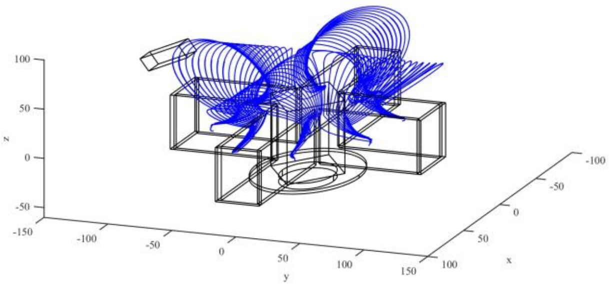

Figure 9b. "Magnetic field lines launched at the cathode plane, approximately 3cm downstream of the QCT's exit plane – isometric view" [3]

It is anticipated that the ions accelerate perpendicular to the magnetic field lines, and therefore accelerate along a spherical region matching the spherical shape of the field lines within the four thruster quadrants. The potential drop that triggers this circular acceleration front is attributed to electrostatic effects and linked to both electron movement along the magnetic field lines and the location of the externally mounted cathode. The concentration of electrons along a relatively thin circular region causes a breakdown of quasi-neutrality, and as a consequence causes the potential jump responsible for ion acceleration in that region [2].

One remaining question is why the acceleration region occurs 8cm downstream of the channel exit, which isn't clearly explained by examining the structure of the magnetic field. It was speculated that the position of the acceleration front was due either to the height of the electromagnet blades or the position of the cathode downstream of the exit plane. The electromagnet blades do indeed have a marked effect on the magnetic field topology. Moreover, the distance between the cathode position in the plume and the acceleration front is roughly equal to the height of these electromagnet blades. Further experiments can establish the sensitivity of the acceleration region to blade height and cathode position.

VI. QCT Phoenix Simulation Results

The QCT's thrust efficiency is very strongly impacted by the circular shape of its acceleration front. Indeed, it is this shape that causes large ion beam divergence which in turn causes substantial thrust efficiency loss. As it was determined that the shape of the acceleration front is directly linked to the shape of the magnetic field lines, the major goal for the QCT's redesign was to 'flatten' the magnetic field lines downstream of the exit plane. EMS was used to ensure that the redesign had not only accomplished this goal but had also managed to conserve the QCT's key characteristics.

Comparison of the magnetic flux density values at the center plane of the acceleration channel for the QCT and QCT Phoenix (see Fig. 10) confirms that key characteristics were preserved. Indeed, in both cases the magnetic flux density reaches a maximum at the cusps along the walls and cancels out at the channel center. Additionally, Fig. 11 shows that the QCT Phoenix was successful in achieving a quad-cusp magnetic field line profile.

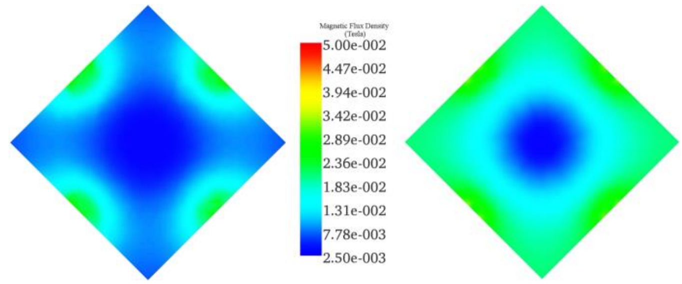

Figure 10. "Magnetic flux density in the acceleration channels of the QCT Phoenix (left) and QCT (right) – top view" [1]

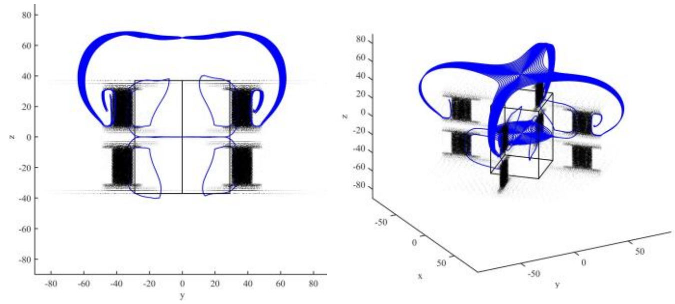

Figure 11. "Magnetic field lines of the QCT Phoenix launched at the center plane and approximately 20mm downstream of the exit plane" – side view (left) and isometric view (right) [1]

The major goal for the QCT Phoenix's design was the relocation of the ion acceleration front closer to the exit plane, in a region where the magnetic field lines were `flat'. It is expected that achieving this goal should greatly reduce ion beam divergence and as a result significantly improve the QCT's thrust efficiency. As can be seen from Fig. 11, the magnetic field lines indeed `flatten' approximately 25 mm downstream of the thruster exit plane. If speculation concerning the QCT is correct and the acceleration front appears at a distance downstream of the cathode that is equal to the height of the electromagnets, then placing the cathode at the QCT Phoenix's exit plane should cause the acceleration region to occur approximately 3cm downstream of the exit plane. This would be a significant improvement over the QCT.

VII. Conclusion

EMS was used to create a 3D model of the QCT's magnetic field. This model was then validated against FEMM simulation results, and results from two experimental campaigns. Analysis of the model's results provided an explanation for the puzzling shape of the QCT's ion acceleration layer, giving insight into the cause of the thruster's poor observed thrust efficiency. This new understanding was the basis for the design of an improved version of the QCT, dubbed QCT Phoenix. Future work will involve the build and testing of the QCT Phoenix design.

References

[1] A. K. Knoll, D. Lamprou, V. Lappas, M. Pollard and P. Bianco, "Thrust Balance Characterization of a 200W Quad Confinement Thruster for High

Thrust Regimes," *IEEE Transactions on Plasma Science*, pp. 185-189, 2015.

[2] A. Lucca Fabris, A. K. Knoll, C. Young and M. Cappelli, "Ion Acceleration in a Quad Confinement Thruster," in *The 35th International Electric Propulsion Conference*, 2017.

[3] E. Rosati Azevedo, "Magnetic Field Enhancement of the Quad Confinement Thruster," London, 2018.

[4] A. Knoll, T. Harle, V. Lappas and M. Pollard, "Experimental Performance Characterization of a two-hundred-watt Quad Confinement Thruster," *Journal of Propulsion and Power*, pp. 1445-1449, 2014.

[5] L. Havekost, "Magnetic Field Enhancement of the Quad Confinement Thruster," Surrey, 2017.

[6] Y. Raites and N. J. Fisch, "Parametric Investigations of a nonconventional hall thruster," *Physics of Plasmas*, pp. 2579-2586, 2011.