ORTA DOĞU TEKNİK ÜNİVERSİTESİ
MIDDLE EAST TECHNICAL UNIVERSITY

A Comparison of Velocity Skin Effect Modeling with 2-D Transient and 3-D Quasi-transient Finite Element Methods (FEMs)

IEEE NPSS
NUCLEAR & PLASMA SCIENCES SOCIETY

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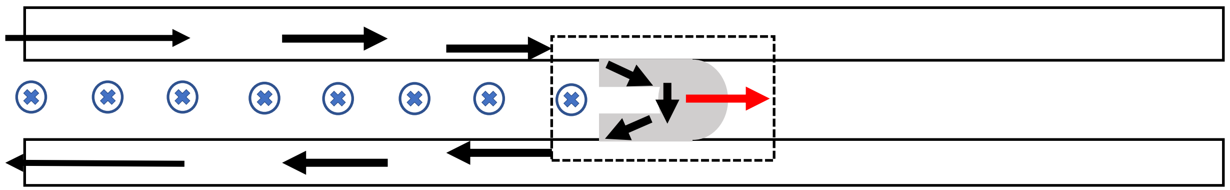
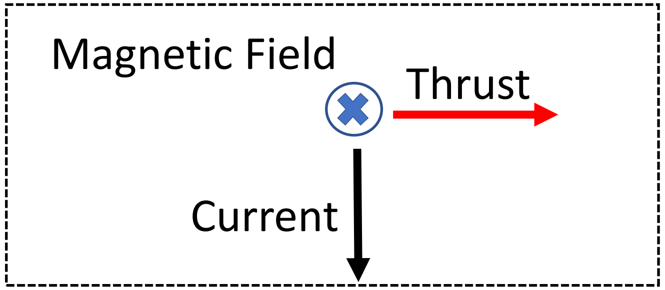
Outline

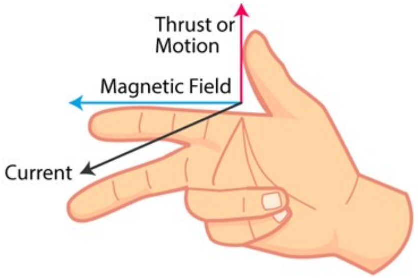
- Fundamentals of Electromagnetic Launchers (EMLs)
- Velocity Skin Effect (VSE)
- Hybrid FEM model – a figure of merit
- Quasi-Transient strategy
- Comparison and results
- Drawbacks

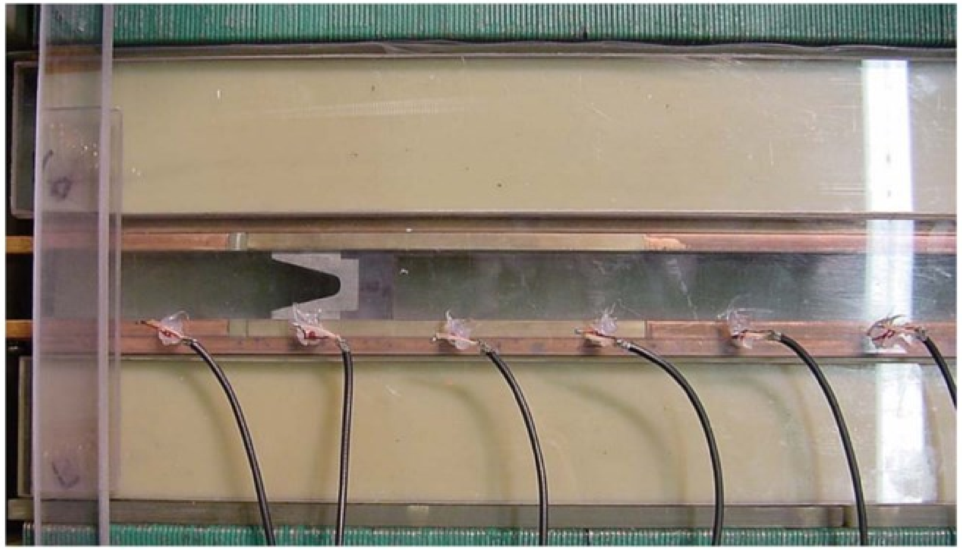
Electromagnetic Launchers - Fundamentals

- Electromagnetic launchers (EMLs) are linear electromechanical energy conversion devices.





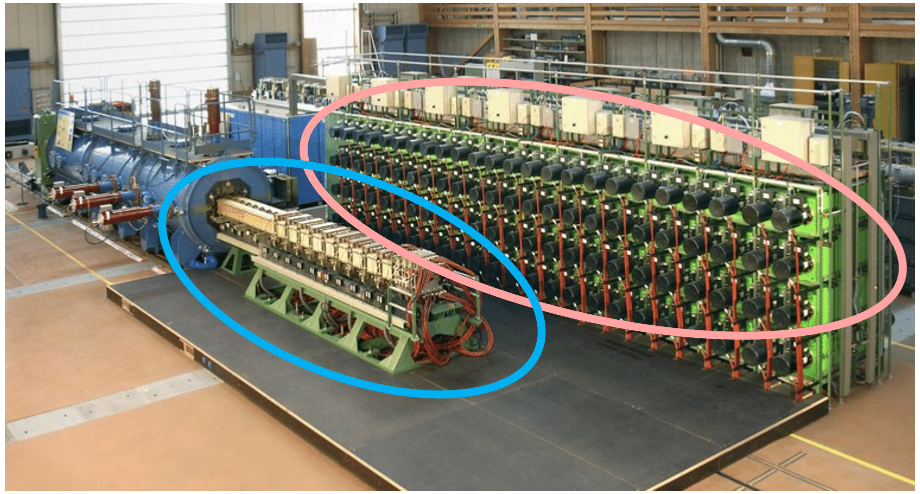




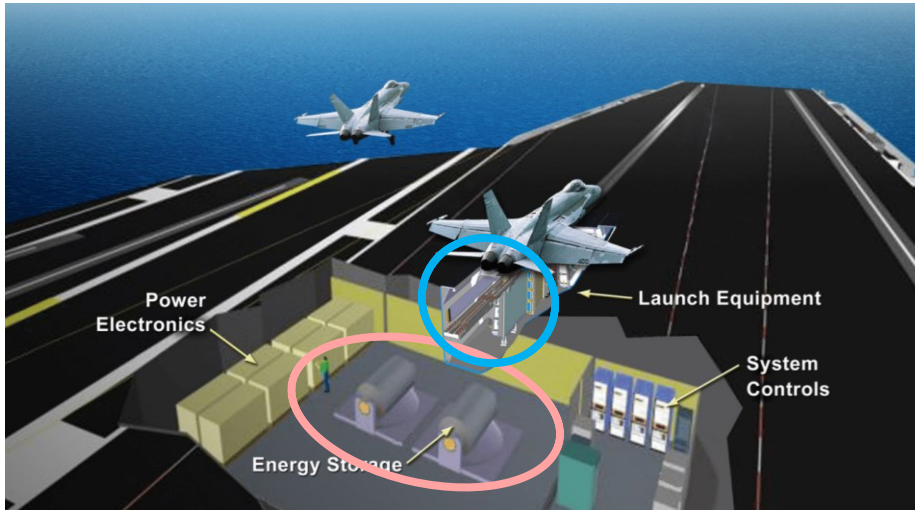
- Lorentz force creates the motion.
- Rail currents are in order of **a few MA (1-3 MA)**
- Rail pressures are in order of **several hundred MPa (200-400 MPa)**
- Temperature gradients melts the armature easily.

They have extreme physical conditions.
Simulations are <u>crucial.</u>

Electromagnetic Launchers - Applications



(a)



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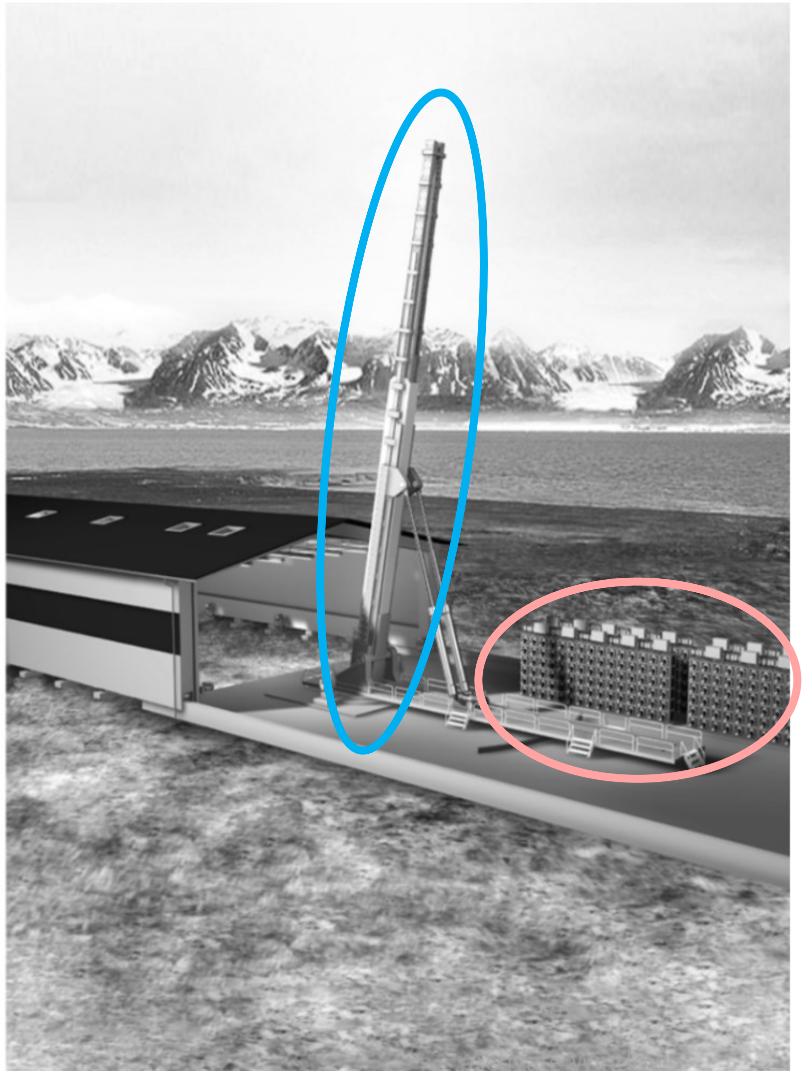


(c)

(a) Military applications (Guns)
(b) Aircraft-UAV launches
(c) Low-orbital satellite launches

Pulse power supplies are used as source.

Pulse power supplies

Launchers

Test Setup

Test setup consists of;

- EMFY-2 Launcher (Elektromanyetik Fırlatma Yolu 2)
- 4 MJ Pulse Power Supply (PPS)

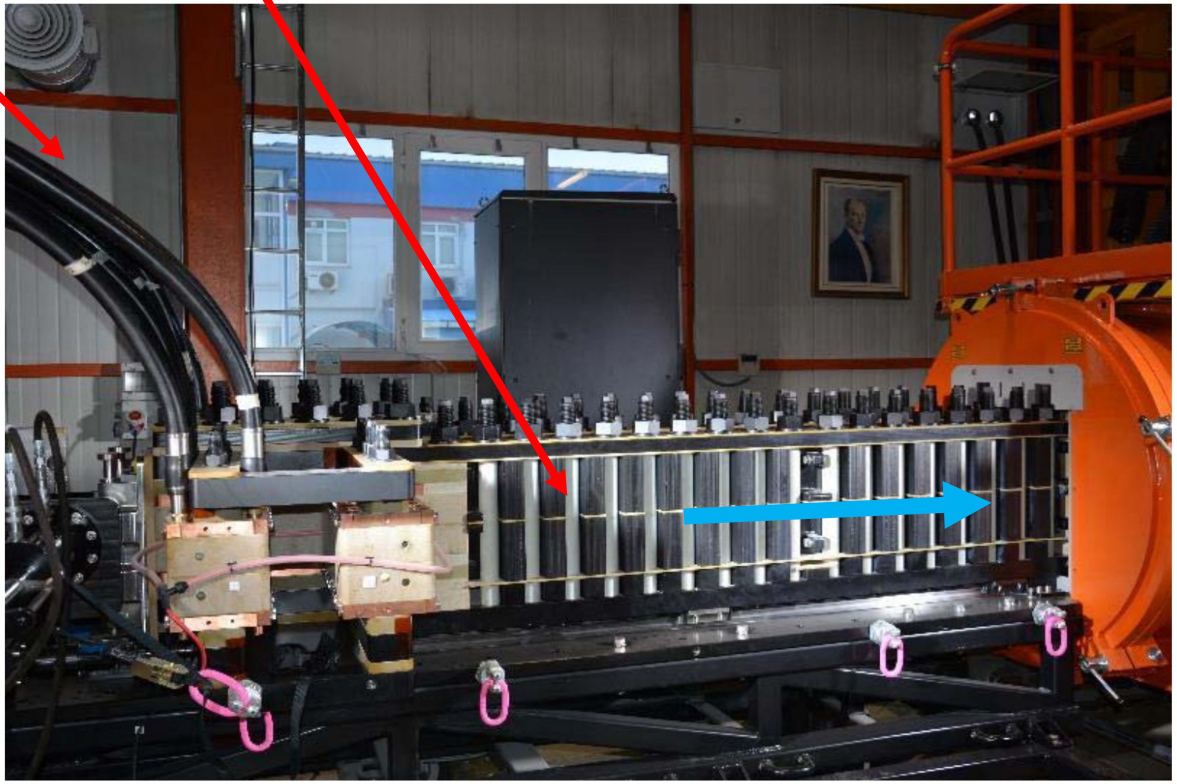
Mechanical Supports

The direction of the thrust

Cables

Source

4 MJ pulse power supply

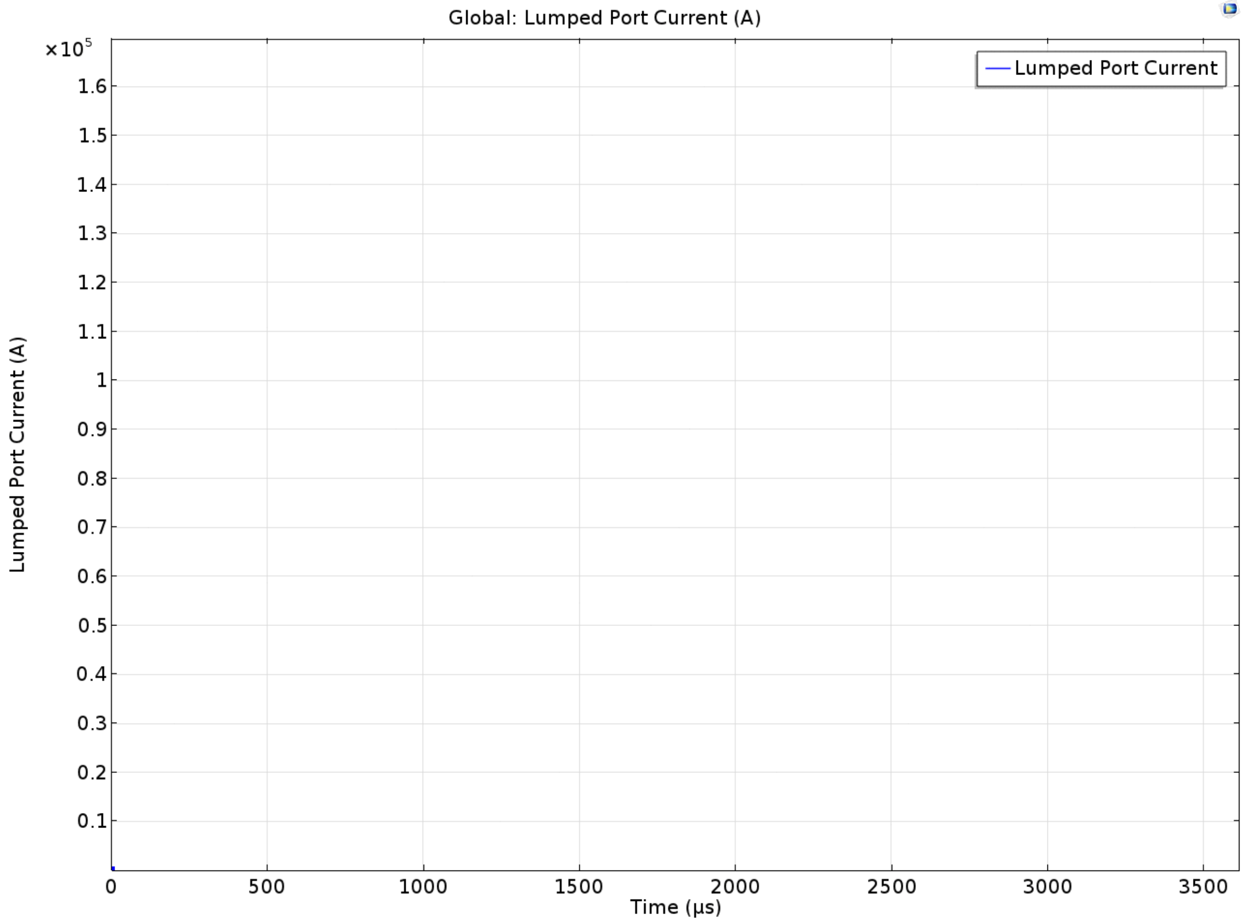


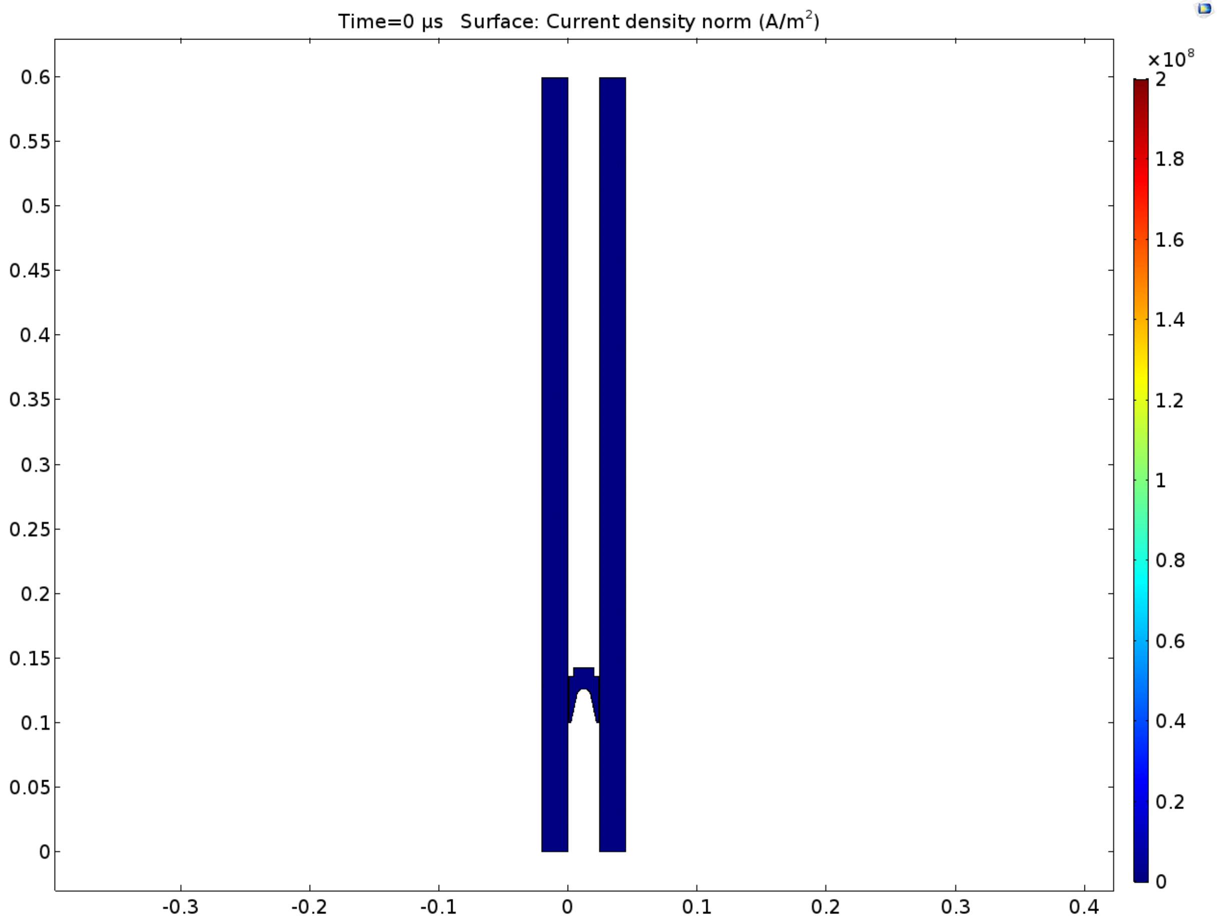
Actuator

EMFY-2 Launcher

Electromechanical Conversion

Electrical Energy → Linear Mechanical Energy





Velocity Skin Effect (VSE)

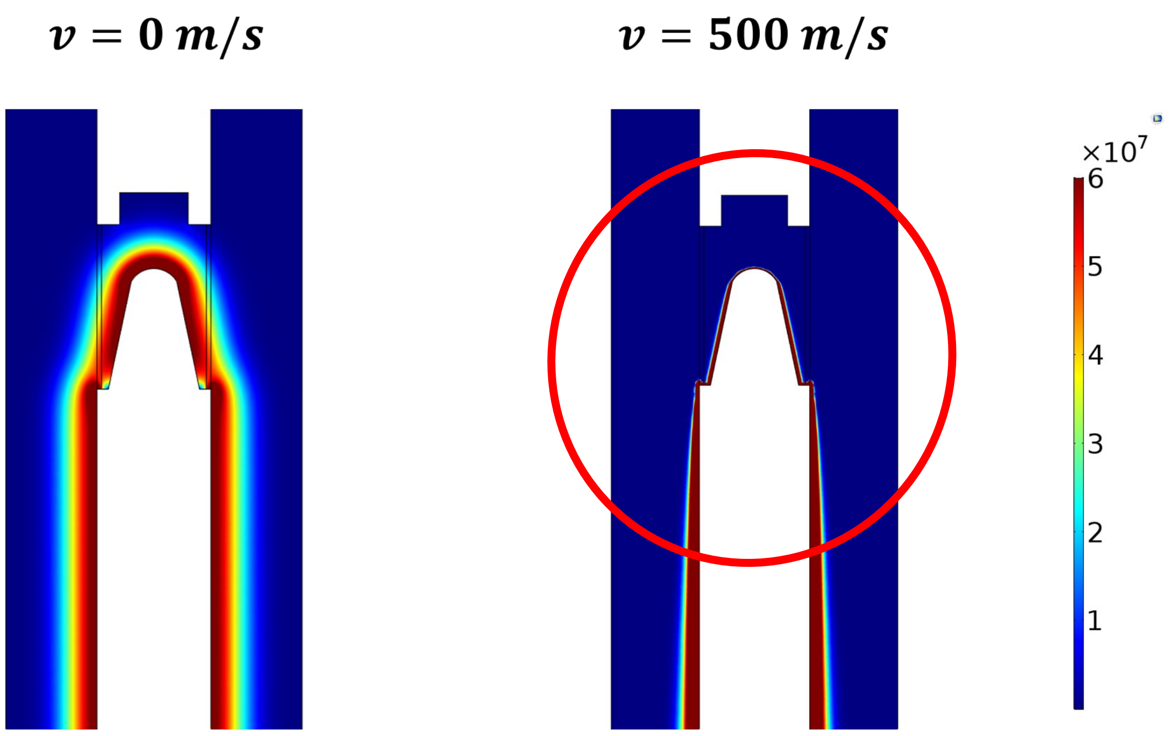
The velocity skin effect (VSE) is an EML specific phenomenon that occurs in the rails at the vicinity of the armature.

The reason is the large velocity (>500 m/s) of the armature.

Due to large armature velocity, transient 3-D FEM has a convergence problem due to interpolation errors between stationary and moving nodes.

2-D transient FEM models are capable to model VSE, unlike 3-D transient FEM.

<u>However, the error measure of the 2-D assumption is unknown.</u>



2-D transient FEM simulations results with different armature velocities; Current density distributions are shown.

Hybrid FEM model – *a figure of merit*

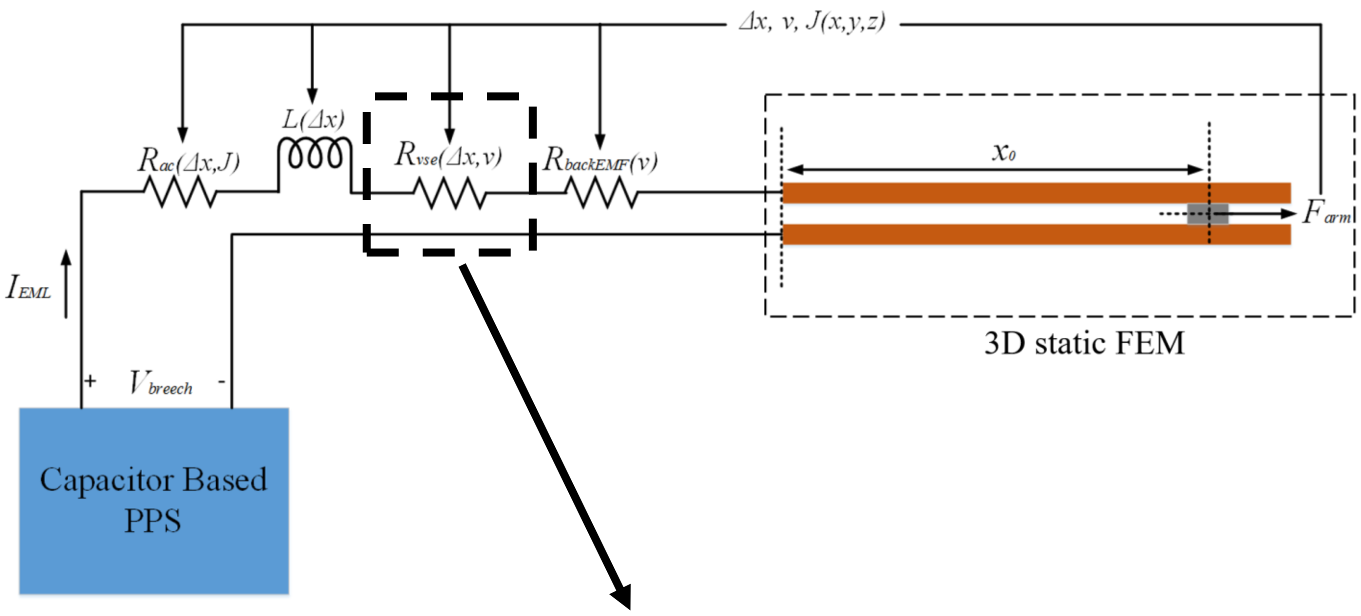
Most of the time 3-D FEM models are required for EML design and analysis. However, there are challanges;

1. EML has large aspect ratio (long thin rails).
   - Total number of mesh elements are massive.
   - λ is extremely large. (Relatively large conductor with respect to the minimum excitation wavelength)

2. The armature motion can not be modelled.
   - Sliding electrical contact problem in FEM formulations.

Thus, partial modeling is a great option. The physical effects due to the armature motion can be emulated with pre-calculated lumped parameters.

Interested readers/listeners can check references.

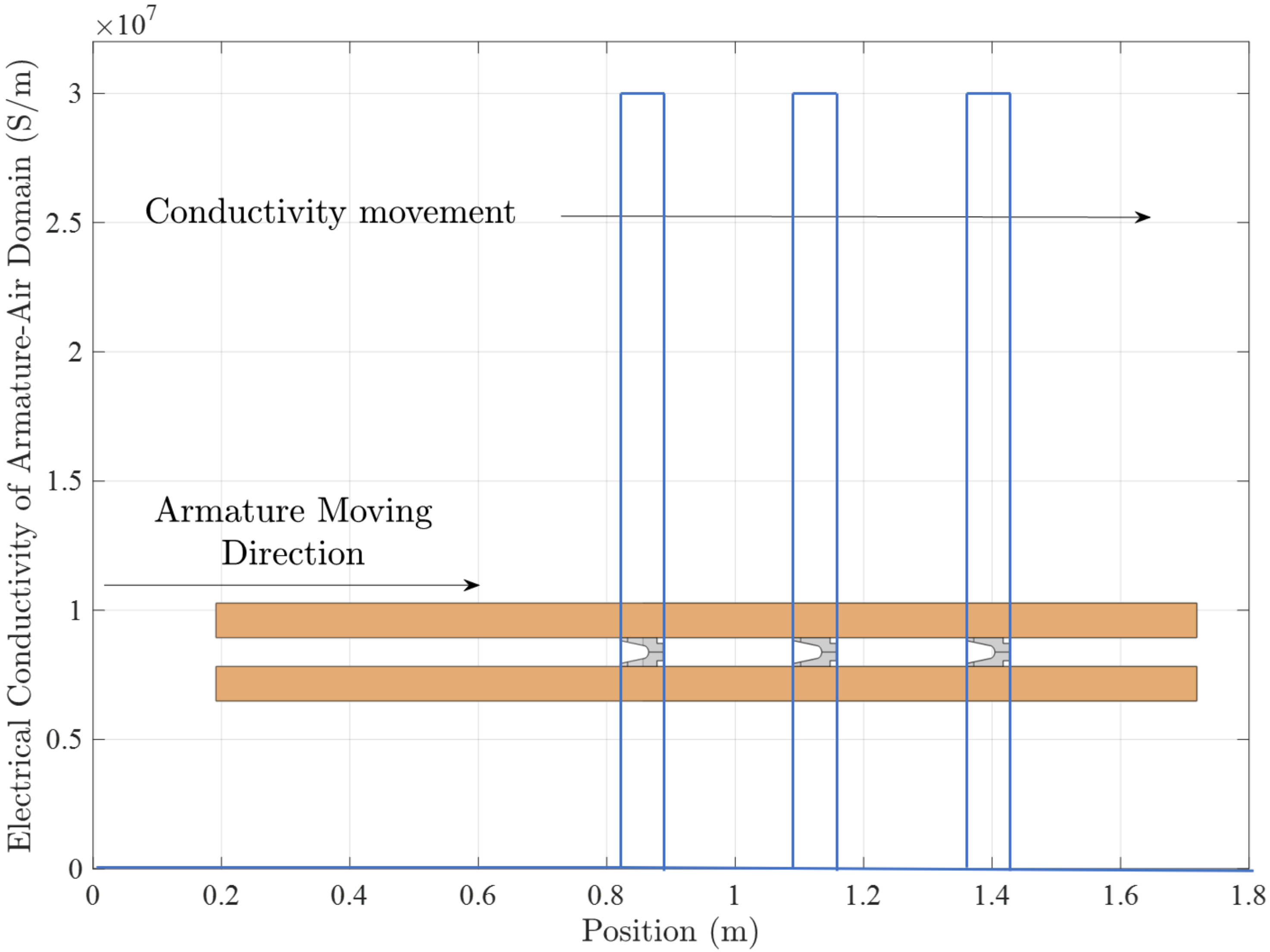


<u>VSE resistance should be modeled.</u>

D. Ceylan *et al.* , "Simulations and Experiments of EMFY-1 Electromagnetic Launcher," in *IEEE Trans.on Plasma Science*, vol. 47, no. 7, pp. 3336-3343, July 2019, doi: 10.1109/TPS.2019.2916220.

N. Tosun *et al.*, "A Hybrid Simulation Model for Electromagnetic Launchers Including the Transient Inductance and Electromotive Force," in *IEEE Trans. on Plasma Science*, vol. 48, no. 9, pp. 3220-3228, Sept. 2020, doi: 10.1109/TPS.2020.3016930.

Quasi-Transient (Eulerian) Strategy



The movement of the armature can not be modelled directly in 3-D.

The question is;

Can we emulate the movement of the armature with time-position dependent electrical conductivity?

How much error?

Verification

3-D FEM use Ampere's law as formulation.

Ampere's law

$$\sigma \frac{\partial \vec{A}}{\partial t} + \nabla \times (\mu_0^{-1} \nabla \times \vec{A}) + \sigma \nabla V = \vec{J}_e$$

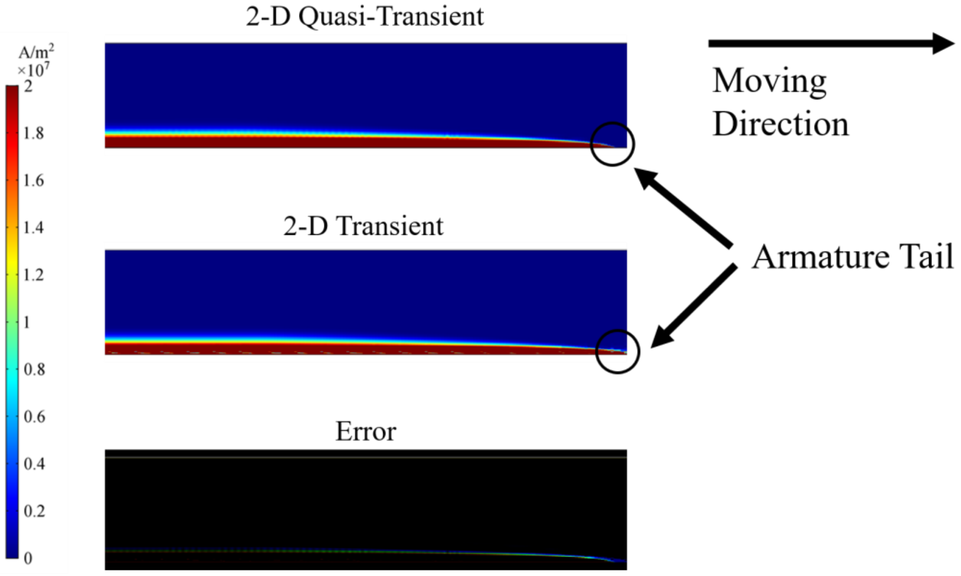
∇V term diminishes when all materials are homogeneous in terms of electrical conductivity.

Ampere's law (V-reduced, A formulation)

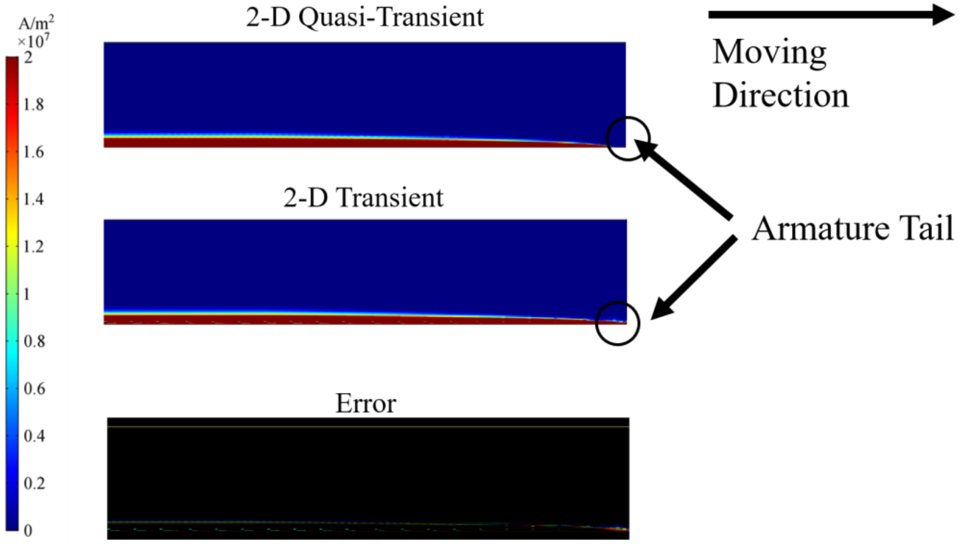
$$\boxed{\sigma \frac{\partial \vec{A}}{\partial t} + \mu_0^{-1} \nabla \times (\nabla \times \vec{A}) = \vec{J}_e}$$

Since, quasi-transient models use heterogeneous conductivity, thus ∇V creates error theoratically.

However, transient and quasi-transient models are compared in terms of field distribution, and the error is not significant.

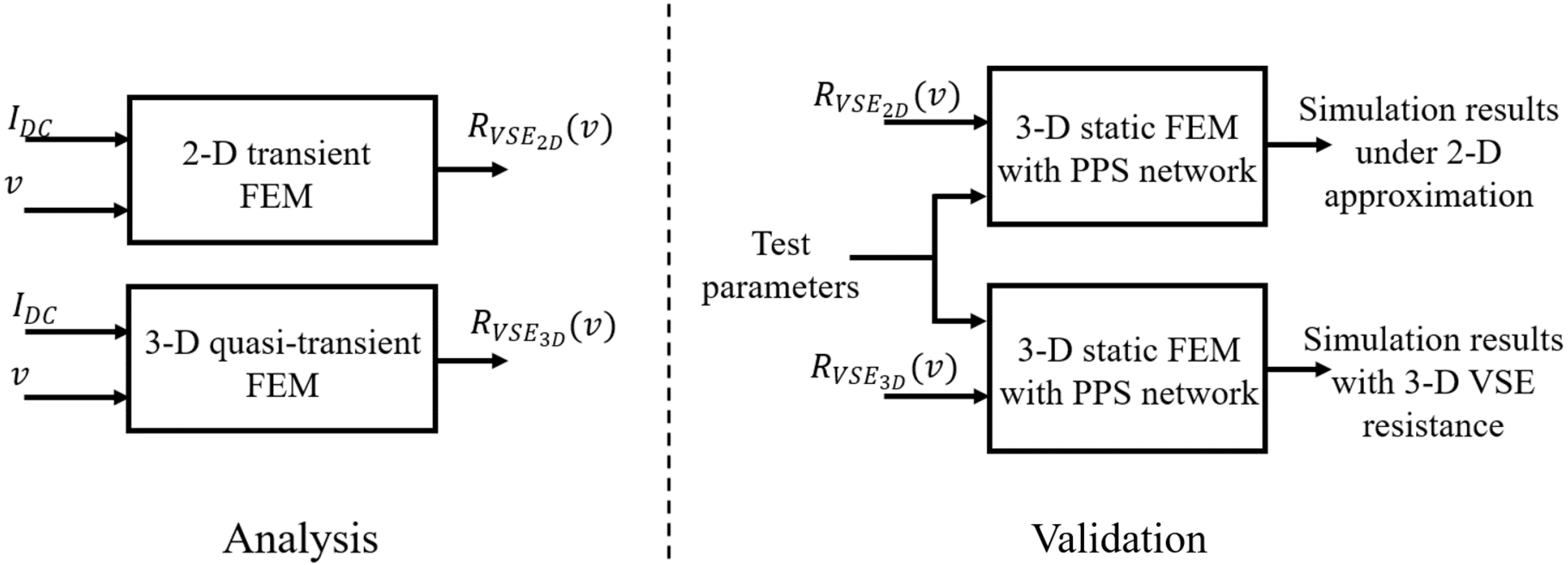


(a) 1000 m/s

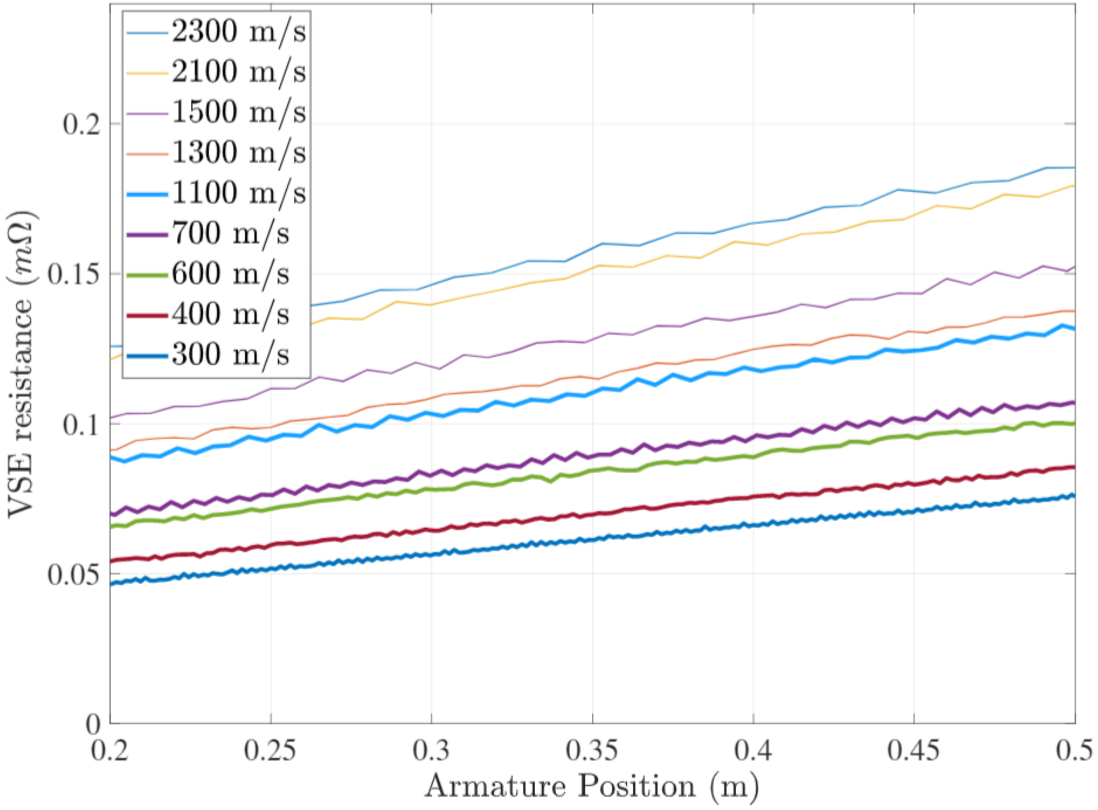


(b) 2000 m/s

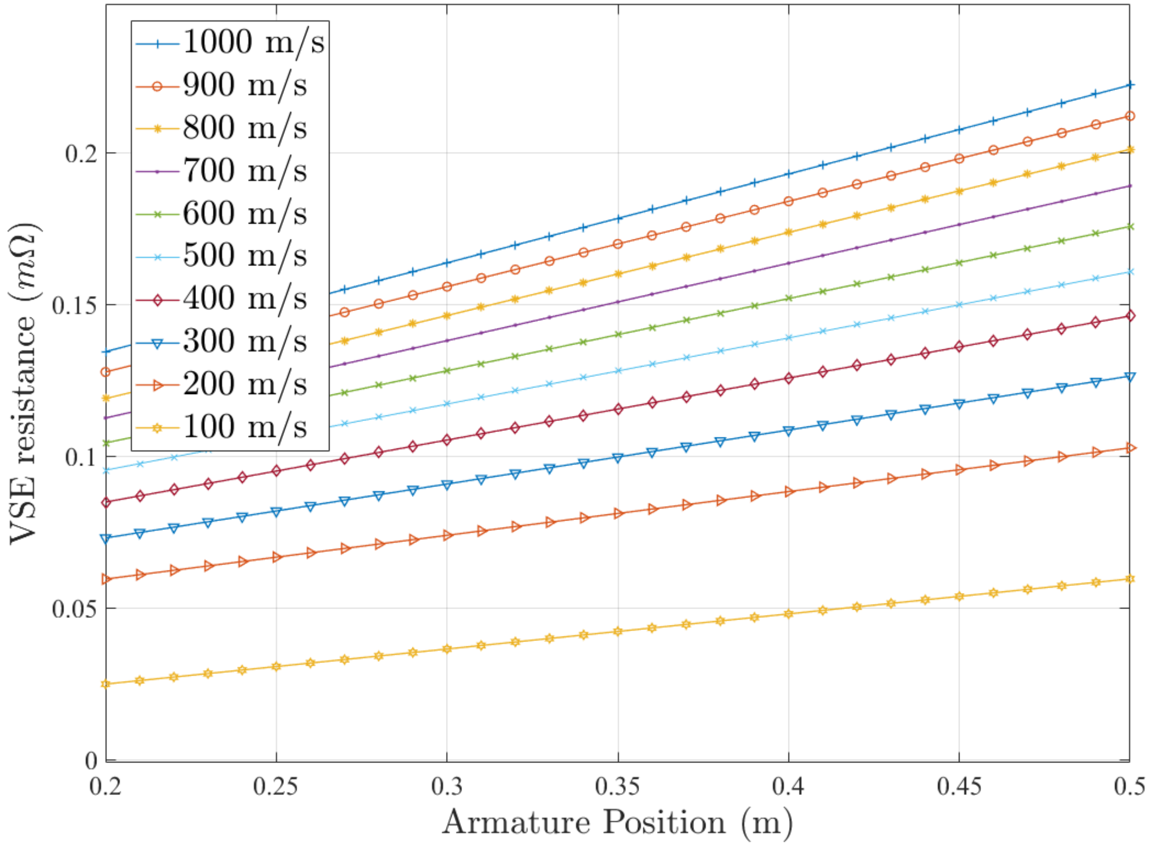
Methodology



Analysis - Results

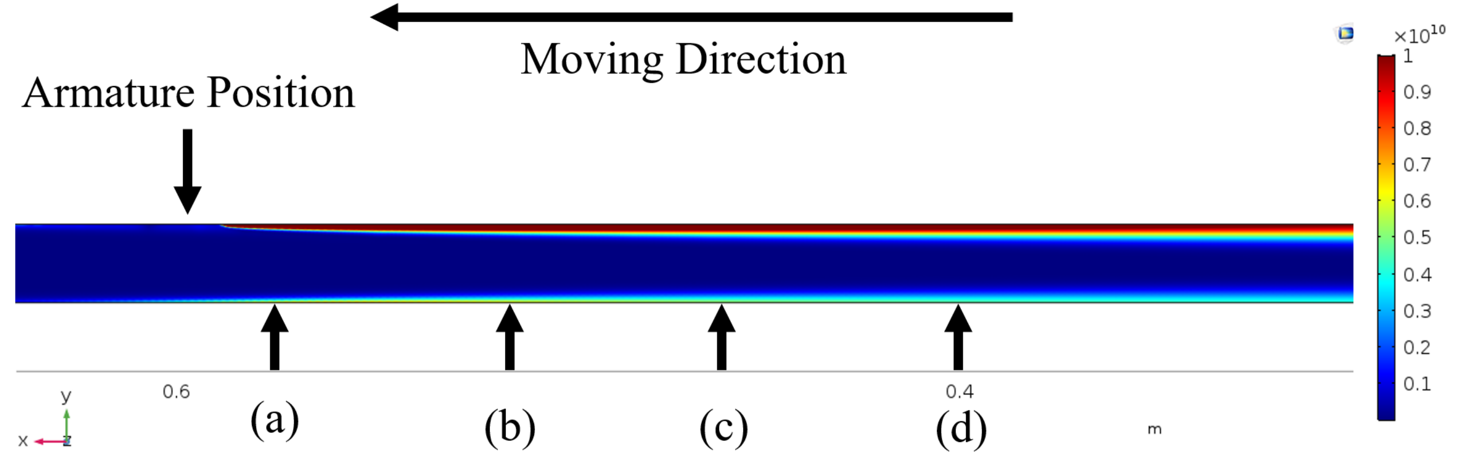


3-D Quasi-Transient



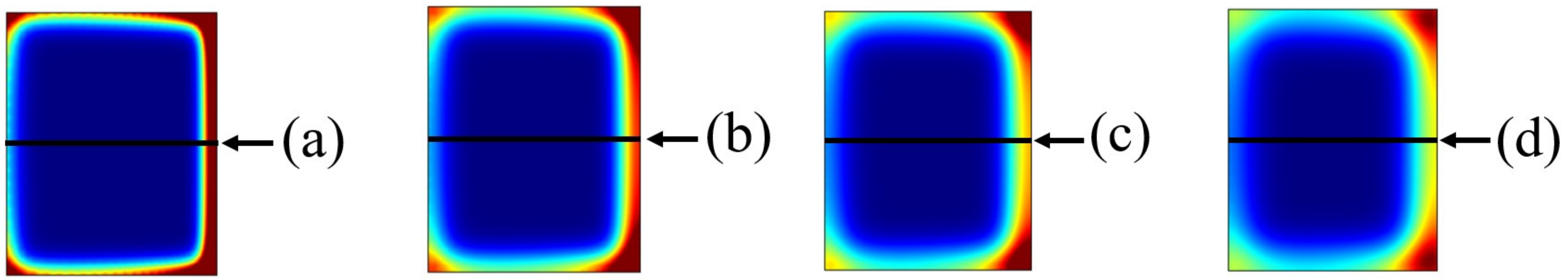
2-D Transient

3-D Quasi-Transient Results



Current narrowing phenomena occurs only the middle surface!

<u>2-D assumption overestimate the VSE!</u>



Analysis - Results

EMFY-1 Launcher – outdoor

EMFY-2 Launcher – at ASELSAN Laboratory

GEOMETRIC PARAMETERS OF LAUNCHERS

	EMFY-1	EMFY-2
rail thickness	20 mm	60 mm
rail height	25 mm	60 mm
rail seperation	25 mm	50 mm
rail height	3 m	3 m

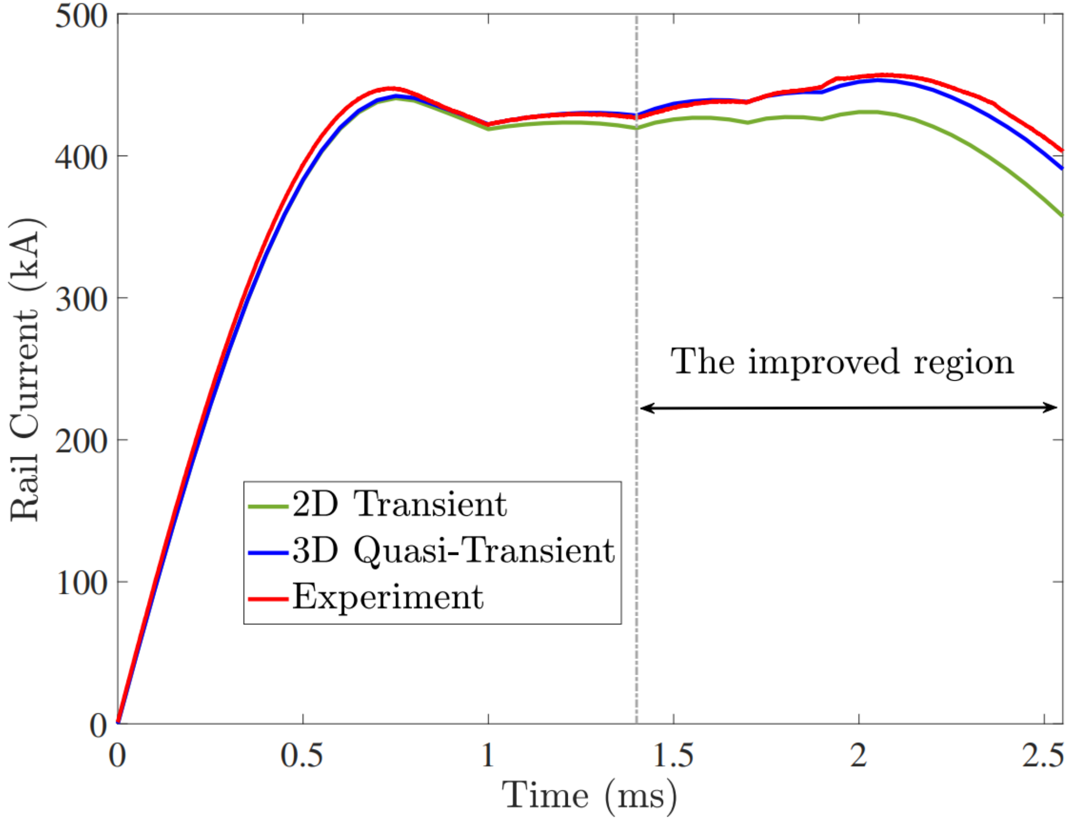
PARAMETERS OF EMFY-1 AND EMFY-2 EXPERIMENTS

	EMFY-1		EMFY-2	
	Exp. A	**Exp. B**	**Exp. C**	**Exp D.**
Initial Electrical Energy	750 kJ	625 kJ	1227 kJ	3241 kJ
Launch Package Mass	41.4 g	41.6 g	932 g	1033.2 g
Capacitor Voltage	3560 V	3250 V	4000 V	6500 V

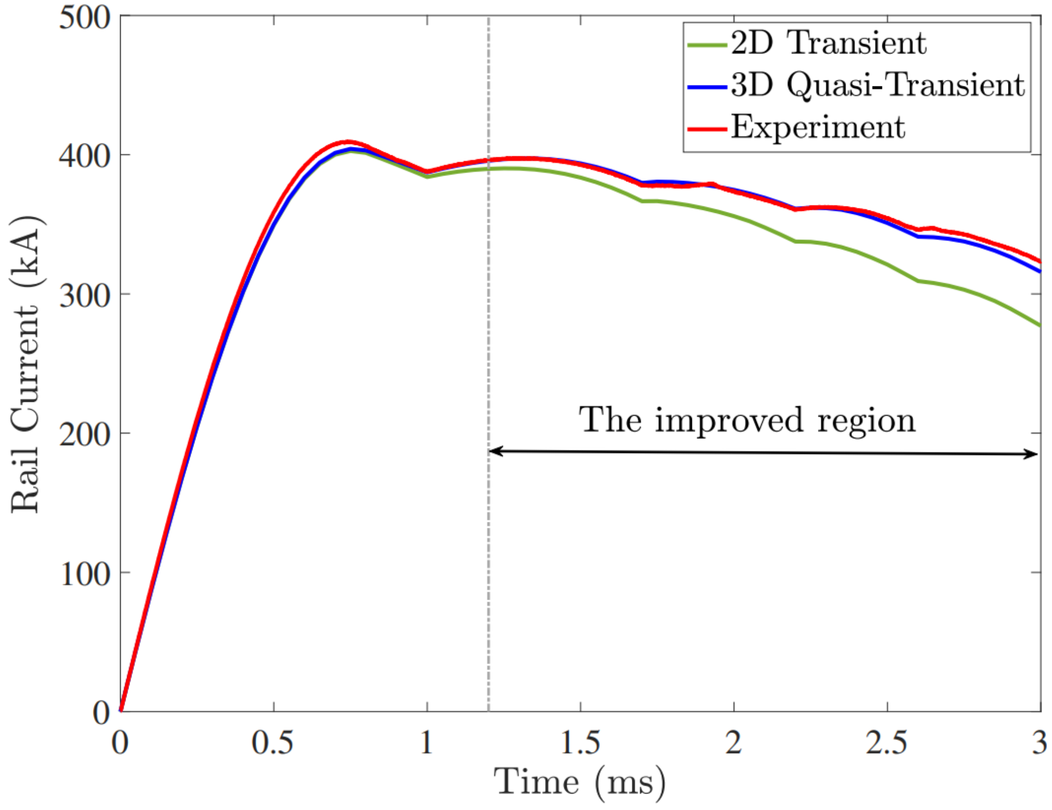
Experimental Results – EMFY-1 Launcher

2D Transient – VSE resistanse is calculated with 2D Transient FEM, then exported to the hybrid model.

3D Quasi-Transient – VSE resistanse is calculated with 3D Quasi-Transient FEM, then exported to the hybrid model.



Experiment – A

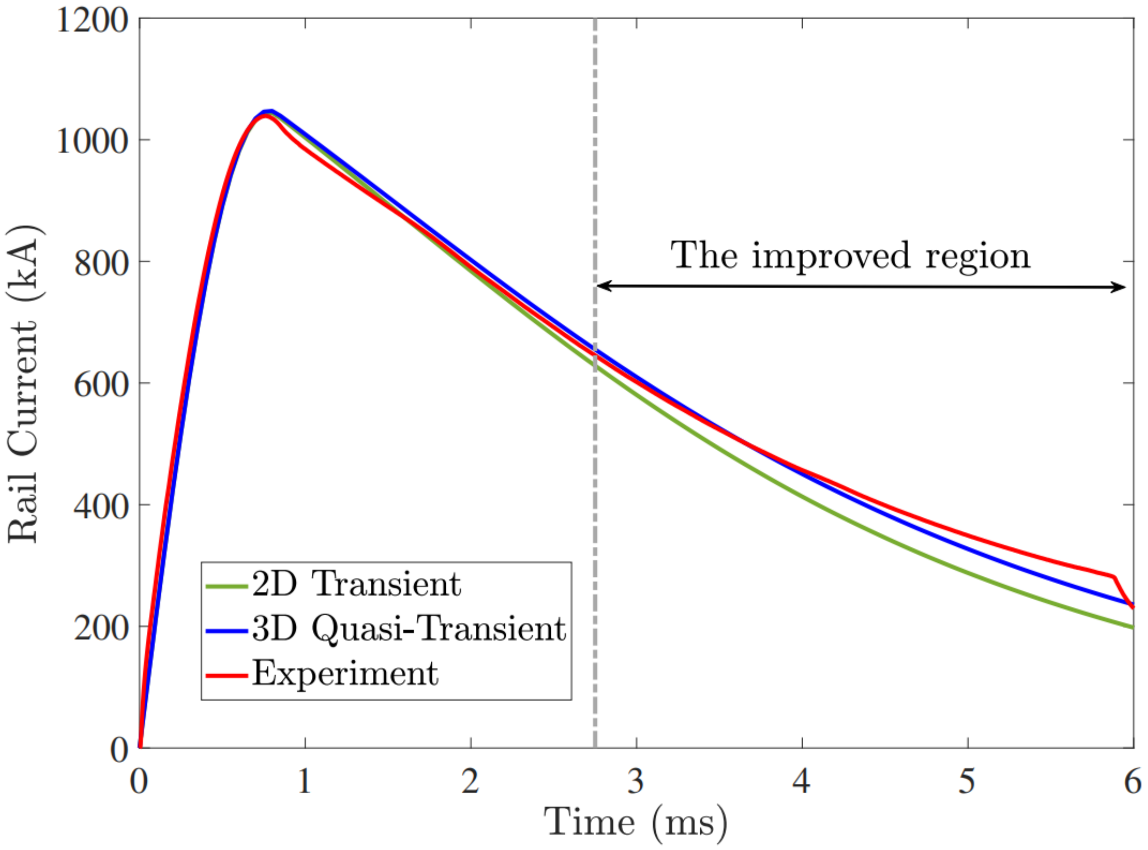


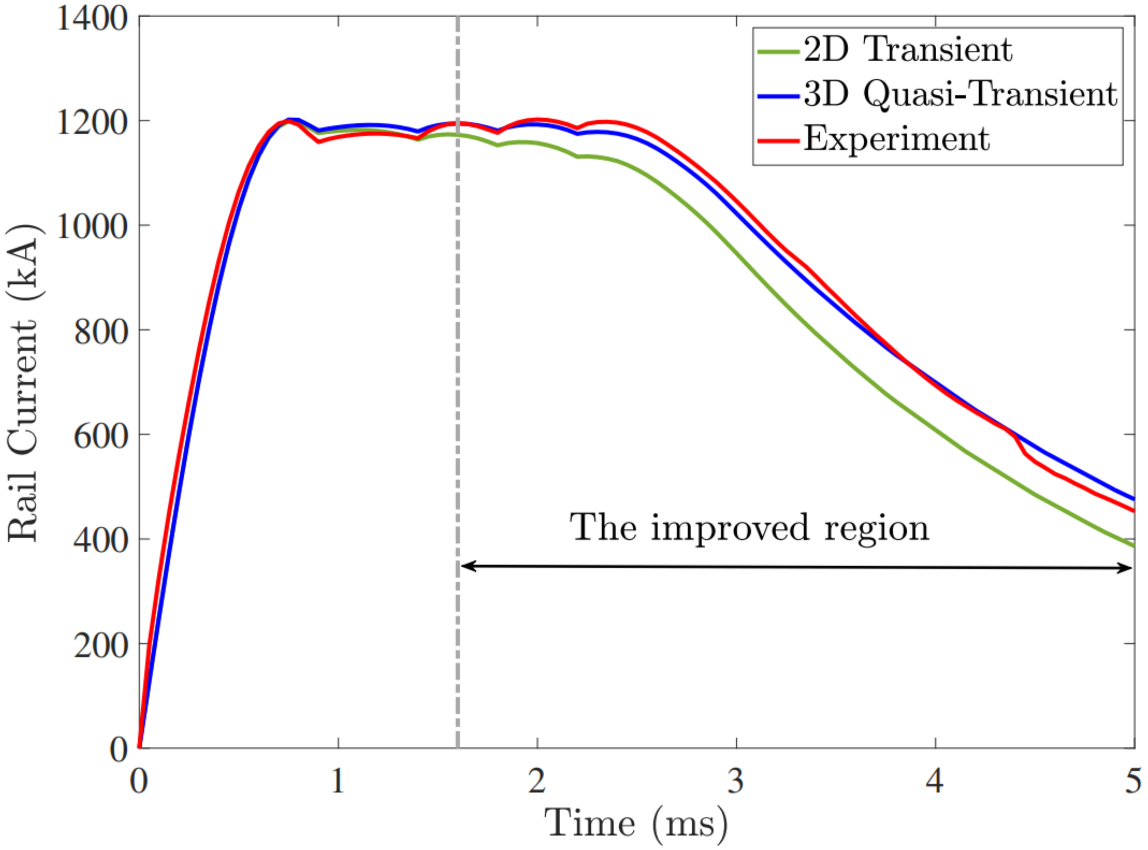
Experiment – B

Experimental Results – EMFY-2 Launcher

2D Transient – VSE resistanse is calculated with 2D Transient FEM, then exported to the hybrid model.

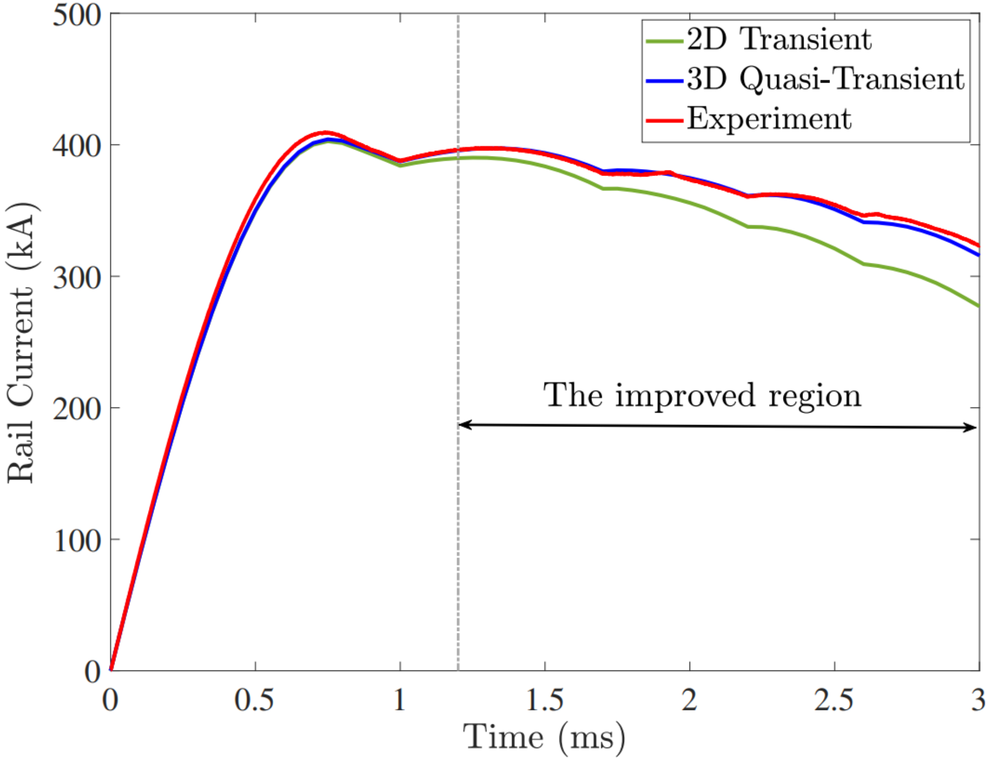
3D Quasi-Transient – VSE resistanse is calculated with 3D Quasi-Transient FEM, then exported to the hybrid model.

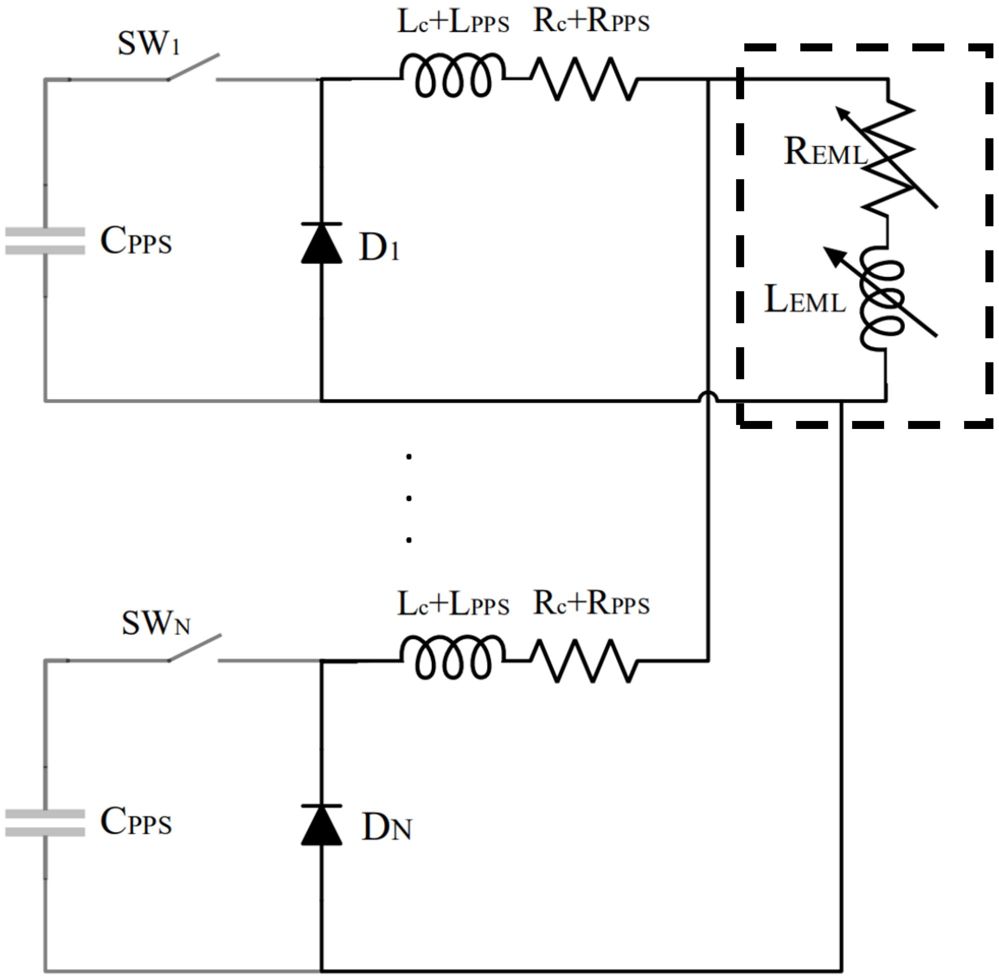




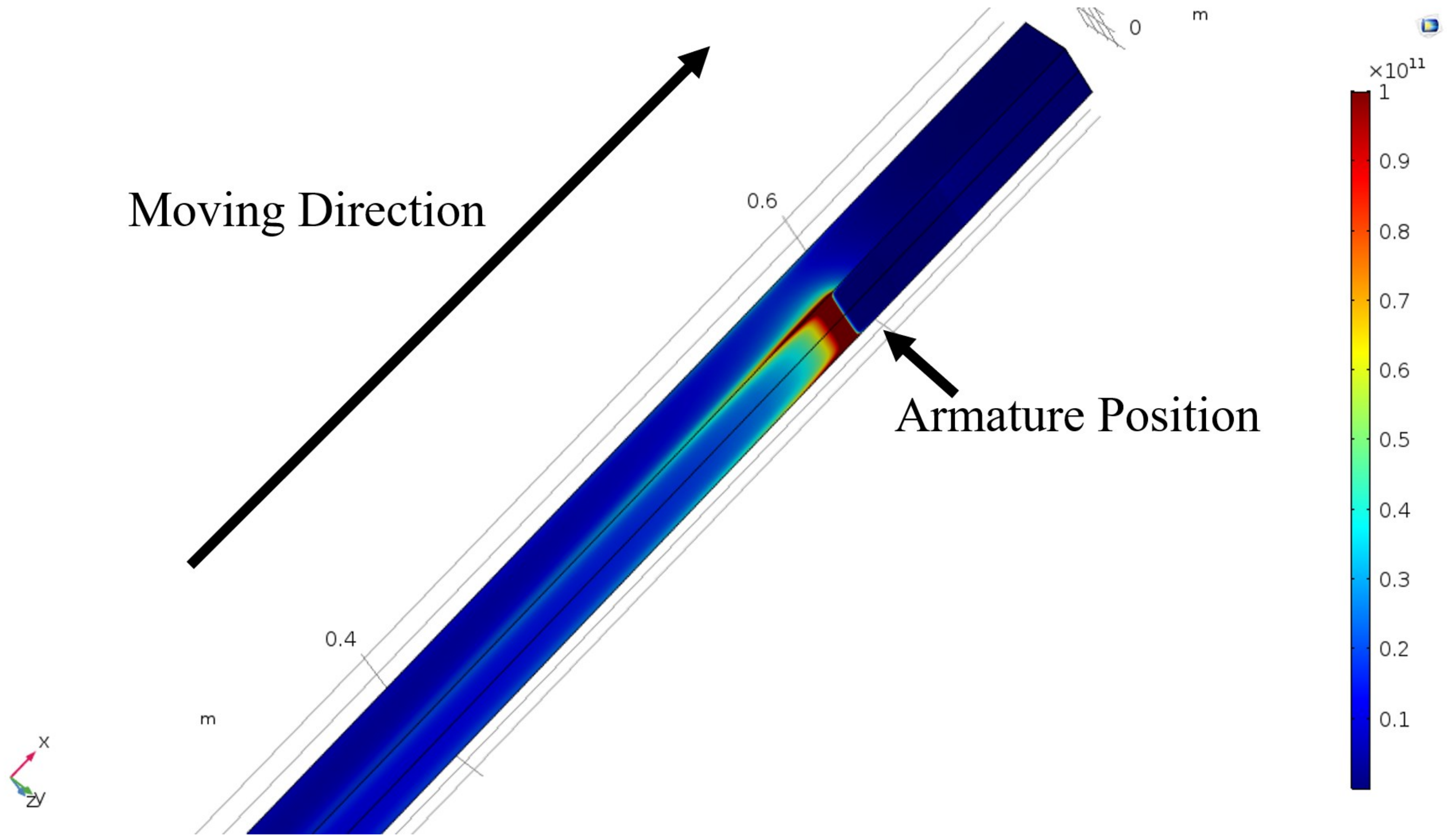
Deviations – Why?

The 2-D transient simulations have faster decay than experimental results due to the overestimation of R_{EML}. It should be noted that discrepancy at the late stage of the experiments links up with R_{VSE} dominance at the late stage of the launch.





Drawbacks



Simple (rectangular prism) armature geometry is allowed.

Need series of long (20 h each) simulations to fit VSE resistance

Armature field distribution can not be obtained.

Thank you for listening

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