

# Effect of HTS stack sectioning on pulse magnetization efficiency in a motor

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**Abstract.** Stacks of HTS superconductors can be magnetized and used as a surface mounted magnet for electrical machines. Pulse field magnetization is considered as a practical method; however, the amplitude of the pulse can be limited in an electrical motor which results in an under-saturated stack with the superconducting currents penetrating only a part of it making the magnetization less efficient. A solution to this problem could be sectioning the stack along its width enabling effective penetration of the superconducting currents. In this paper we investigate the effect of sectioning of HTS surface mounted stacks on the efficiency of pulse magnetization method in trapping the flux using low pulsing field. It is shown that the sectioning of wide stacks into several narrower parts results in a higher trapped flux at low pulses. Experimental measurements are performed on a lab-scale motor to validate the theoretical analysis.

## 1. Introduction

Stacks of superconductors can be used as trapped field magnets with several advantages, such as good thermal conductivity, robust mechanical properties and can be shaped and sized according to the applications. Stacks of superconductors can be made into a self-sustaining stack and be inserted in a motor as a trapped field magnet [1], [2]

Trapped field magnets can be magnetized with several methods, to mention, field cooling, zero field cooling, pulse field magnetization and flux pumping. High trapped magnetic fields have been reported in literature. [3], [4, p. 6]

For electrical motor applications, pulse field magnetization can be practical as an in-situ magnetization method. However, its amplitude can be limited in an electrical motor with the presence of ferromagnetic material and armature windings. In an electrical motor, we aim to have efficient pulse magnetization methods by trapping higher flux using a relatively low pulse amplitude.

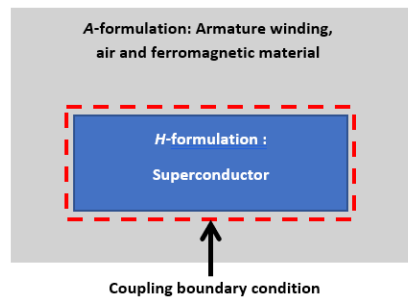
In this work, we study the effect of the HTS sectioning on the efficiency of the pulse magnetization method.

## 2. Model

For the models presented herein; the stack is approximated as a bulk. The approximation results in a relatively low computation time. The model is intended for Qualitative study.

The finite element method with the commercial software COMSOL is used [5]. The model uses 2 electromagnetic formulations, Figure. 1.





**Figure 1.** Coupled model. The superconductor is modelled using  $H$ -formulation; the cooper armature winding, air and ferromagnetic material is modelled using  $A$ -formulation.

The  $H$ -formulation is used for the superconducting part, equations (1) and (2): [6]–[8].

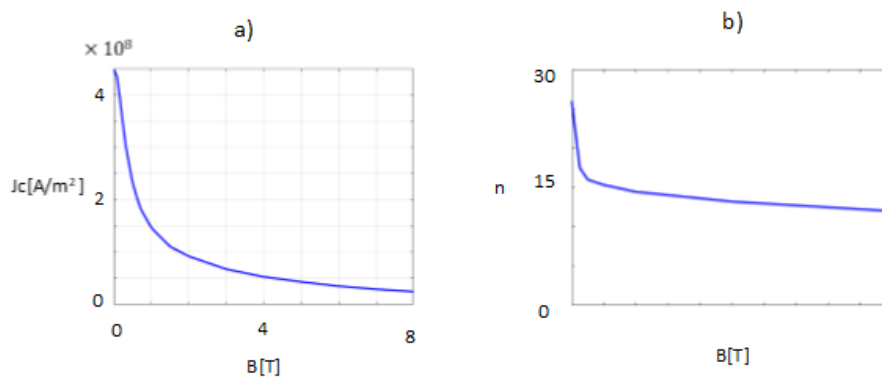
$$\mu_0 \frac{\partial \mathbf{H}}{\partial t} + \nabla \times \mathbf{E} = 0 \quad (1)$$

$$\mathbf{E} = \rho \nabla \times \mathbf{H} \quad (2)$$

The resistivity of the superconductor is computed by equation (3) where  $E_c = 10^{-4} \text{ V m}^{-1}$ . The current density  $J$  is computed by equation (4). We consider the dependence of the critical current density and the  $E$ - $J$  power law exponent  $n$  on the magnetic field at a temperature of 77K., Figure. 2.

$$\rho = \frac{E_c}{J_c(B)} \left| \frac{J}{J_c(B)} \right|^{n(B)-1} \quad (3)$$

$$J = \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \quad (4)$$



**Figure 2.** Field dependency of the superconductor properties. a) Field dependency of the current density on the magnetic flux density at 77K. b) Field dependency of the  $E$ - $J$  power law exponent  $n$  on the magnetic flux density.

Air, armature windings and ferromagnetic material surrounding the superconductor are modeled with  $A$ -formulation; the coupling of the formulations is ensured through boundary conditions, Figure. 1. The coupling is outlined in details in [9].

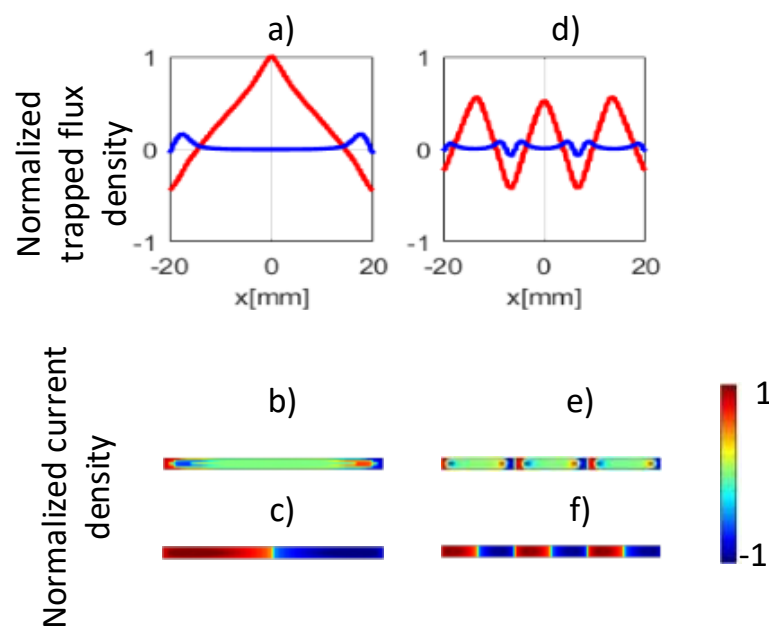
### 3. Magnetization in the air vs in the motor

In this part, we have two configurations; the first one deals with magnetization of straight superconductors in the air and the second one deals with the magnetization of a curved superconductor placed in an electrical motor with the presence of ferromagnetic material. The Iron used for the model is soft iron without loss in COMSOL.

#### 3.1. Magnetization in the air

We consider the magnetization of a wide straight stack and a sectioned stack. We use the same values of critical current density at the same temperature. The wide tape length is 40 mm and the width is 0.77 mm. The sectioned stack is made by cutting the wide tape into 3 equal parts.

The external magnetizing field varies according to a triangular shape. The normalized values of the trapped field and trapped current after magnetization are represented in Figure 3.



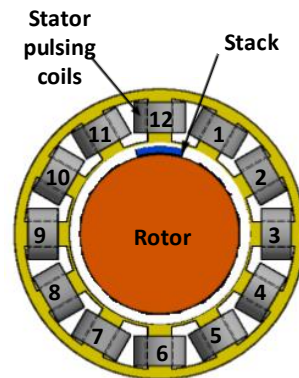
**Figure 3.** Magnetization of straight wide and sectioned superconductor in the air with a normal field varying with a triangular shape in time. The 2 types of stacks are magnetized with the same amplitudes in each case: in one case, the amplitude results in undersaturated stacks and the other results in saturated stacks. The flux densities are normalized to the maximum value of the trapped flux for comparison. a) normalized flux density trapped at 1 mm of the wide stack, b) current density distribution in undersaturated case for the wide stack, c) current density of the saturated wide stack. d) normalized trapped flux density in the case of sectioned stack, e) current density distribution in the case of undersaturated sectioned stack, f) current density distribution in the case of saturated sectioned stack.

Wide tapes trap a low flux when undersaturated with M shape waveform generated by two current loops. When saturated, the wide stack traps a high magnetic flux density with a pyramidal waveform generated from one current loop fully penetrating the superconductor.

Sectioned stack traps a low flux when undersaturated with 3 waveforms, each one has an M shape generated from two current loops. The same sectioned stack traps a higher flux when saturated with 3 peaks of pyramidal shape generated by one current loop per section. For the same magnetizing field, wide stacks trap more than the sectioned ones.

### 3.2. Magnetization in the motor

In this part, the stack is magnetized inside a motor where the pulse is generated by an iron core coil and the superconductor is surrounded by iron. Figure. 4. Coil 12 is used to generate the magnetizing field, dimensions can be found in [10]. We study 2 cases where we have a sectioned stack and a wide stack. The magnetizing field has a triangular shape with maximum amplitude of 300 A.



**Figure 4.** Sketch of the stack magnetized in an electrical motor. The stack is curved along the rotor. The dimensions and details are published in [10]

#### *Current density distribution:*

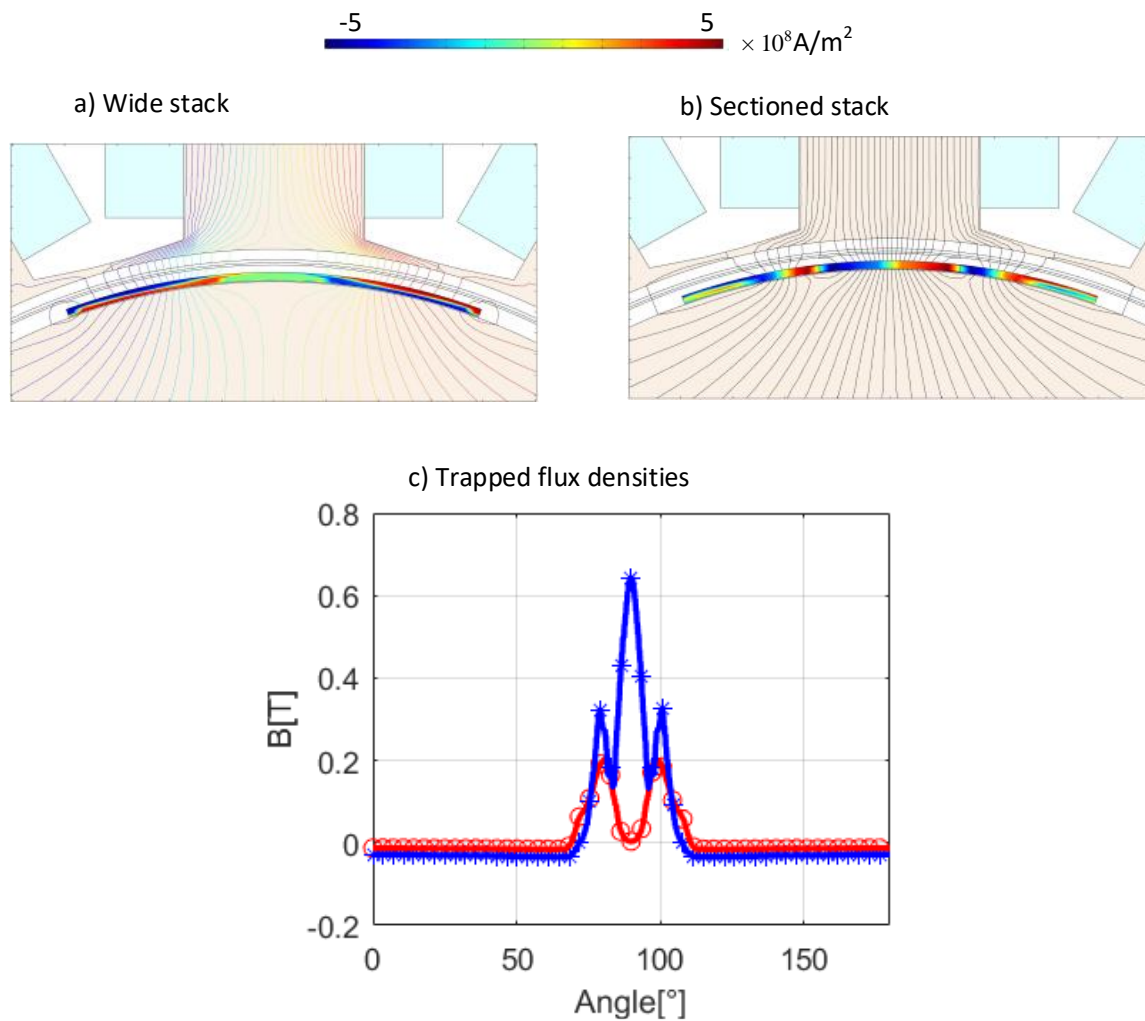
Figure. 5 a), the current density distribution in the wide stack has 2 current loops. The presence of the ferromagnetic material, the curvature and the magnetizing field being only applied from the stator make the current densities penetrates from the top surface first. This behavior is similar to one in the magnetization of bulks with a vortex coils. [11]–[13]

Figure. 5 b), the middle part of the sectioned stack is saturated with two current loops; the two other parts at the extremities are undersaturated.

#### *Trapped flux density in the air gap:*

Figure. 5, c) the wide stack traps a flux with an M shaped field generated from 2 current loops. The sectioned stack traps a pyramidal waveform with 3 peaks of different amplitudes. The middle one is the highest and corresponds to the saturated middle part of the stack, the other ones are with peaks of lower amplitudes corresponding to the 2 undersaturated parts at the extremities.

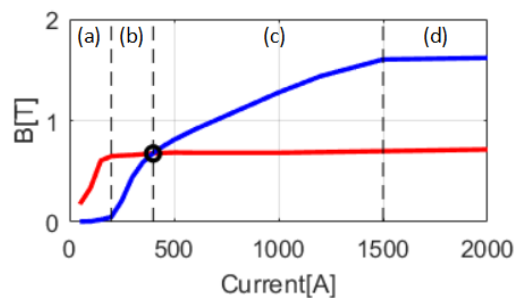
To summarize this part, the sectioned stack traps more field than the wide one for this value of pulse making it more efficient. In the next part we will compare the efficiency between the wide and sectioned stack for different values of pulse.



**Figure 5.** Magnetization of stacks of superconductors in an electrical machine. a) and b) the current density is represented in the stacks. The iron and the air are represented with uniform colours to make sense of the direction of the flux line; c), represents the radial trapped flux density in the airgap.

#### 4. Effect of the sectioning of the stack on the efficiency of the pulse field

In this part, we increase the current of the magnetizing coil and we compute the peak of the trapped field at the airgap for the wide and sectioned stack. Figure. 6. The values of currents are not necessarily feasible in our experimental set up but are computed for this study purposes.



**Figure 6.** Peak of the trapped flux at the air gap by sectioned and wide stack magnetized in an electrical motor.

*Region (a),  $I \in [50, 200]$  A:*

The trapped flux of the wide tape is very low and near zero; the flux trapped by the sectioned stack is higher and increases rapidly with pulse till it stabilizes at 0.65T at  $I=200$ A.

*Region (b),  $I \in [200, 400]$  A:*

In this region, the trapped flux of sectioned stack is at its maximum; the flux trapped by the wide stack starts increasing with the pulse.

*Cross over point,  $I=400$ A:*

At this value, 400 A, both stacks trap a flux density with the same peak amplitude, we call this point the crossover point.

*Region (c),  $I \in [400, 1500]$  A:*

The trapped flux by the sectioned stack is still stable at 0.65T; the trapped flux by the wide stack increases with increasing the current in the magnetizing coil with a different slope than the previous region.

*Region (d),  $I > 1500$ A:*

At 1500A, the trapped flux by the wide stack also reaches its peak and stabilizes at 1.61T; an increase in the current in the magnetizing coil does not increase the trapped flux density.

Both Wide and sectioned stacks have the same trend, the peak of the trapped flux increases with increasing the current in the magnetizing coil till it reaches a maximum. At low amplitudes of current in the magnetizing coil, the sectioned stack is more efficient in trapping flux than the wide stack. At higher amplitudes of current in the magnetizing coil, the wide stack continues trapping more flux and exceeds the one of the sectioned stacks.

## 5. Current density distribution and trapped flux profile.

Figure. 7 represents the flux density waveforms and current density distributions for both stacks at 4 different amplitudes of current of the magnetizing coil.

*Flux density wave form Figure.7, a), b):*

At 100 A, the trapped flux density of the wide tape is almost zero; the sectioned stack; however, has a waveform with three main parts, the one in the middle has an M-shape form and the two others at the extremities have one peak each.

At 300 A, and for the sectioned stack, we have an increase in the trapped flux amplitude with the middle part reaching its maximum having one peak rather than an M-shape form; the wide stack has an M shape trapped field.

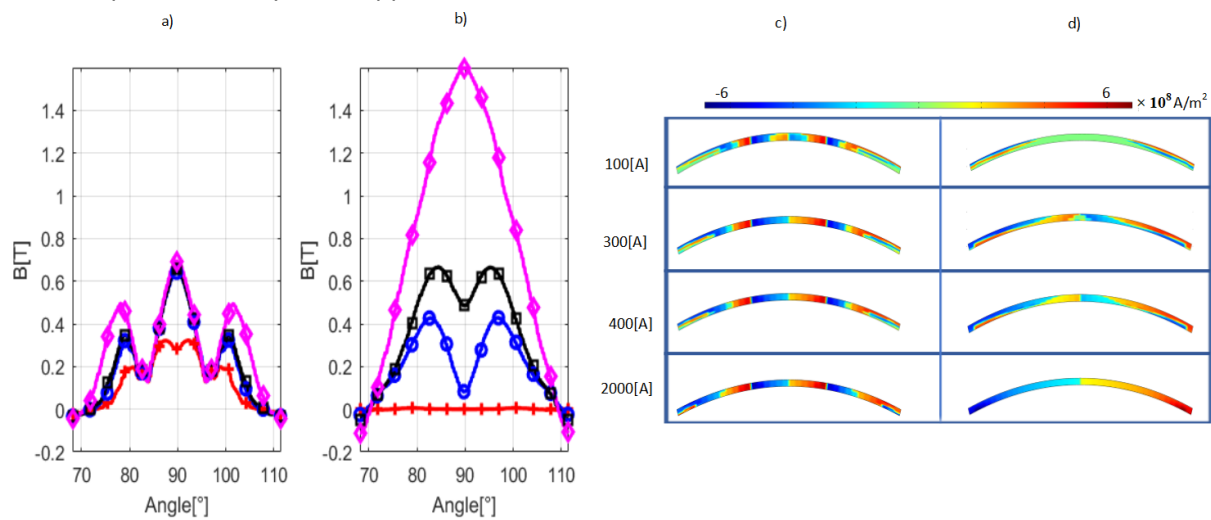
At 400 A, we have the cross over point, the sectioned stack waveform is only increasing at the 2 peaks at the extremities; the middle part is still at its maximum. The wide stack increases in amplitude with an M shape where minimum in the middle is getting higher towards a pyramidal shape.

At 1000 A and 2000 A, and for the sectioned stack, the middle peak is stable at its maximum and increasing the pulse only increases the amplitude at the peaks of the extremities. The trapped flux of the wide tape increases with the pulse from an M shape to a pyramidal shape; the wide stack now has reached its maximum trapped flux.

*Current density distribution Figure.7, c), d)*

At 100 A, the middle part of the sectioned stack is fully penetrated with currents with 2 current loops; this explains the M shape wave form, the two other extremities are undersaturated with one major current loop which explains the one peak at the extremity. The current density penetrated the middle part more than the adjacent parts because of the effect of the curvature and the presence of ferromagnetic material. Moreover, the middle part sees more field as a result of superposition of the applied field and the field created by the two parts at the extremities.

For the wide tape, the stack is undersaturated with 2 current loops penetrating from the top surface, which explains the very low trapped flux.



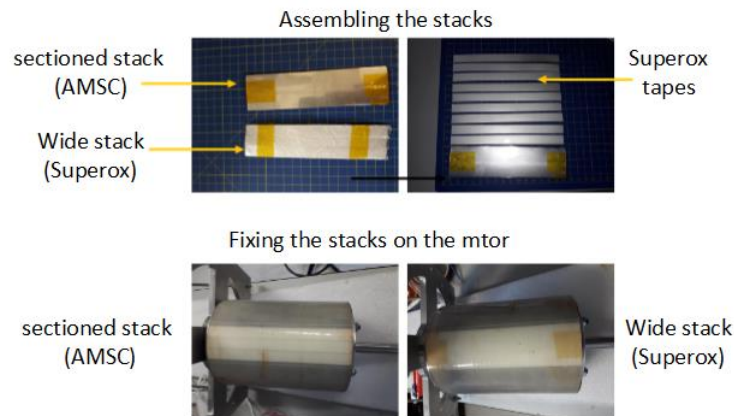
**Figure 7.** The flux density and current density distribution at different amplitudes of pulses for wide and sectioned stack. A) flux density distribution for sectioned stack, b) flux density distribution for wide stack, c) current density distribution for sectioned stack, d) current density distribution for a wide stack.

At 300 A the middle part of the sectioned stack is fully penetrated with 2 current loops, this corresponds to the maximum trapped flux for the middle section. After this point, increasing the current of the pulse will only affect the 2 parts at the extremities because they are undersaturated compared to the middle one. The wide tape is almost fully penetrated with currents with 2 current loops. At 2000A, the wide stacks end up having 2 current loops and trap their maximum with a pyramidal waveform.

## 6. Experimental results

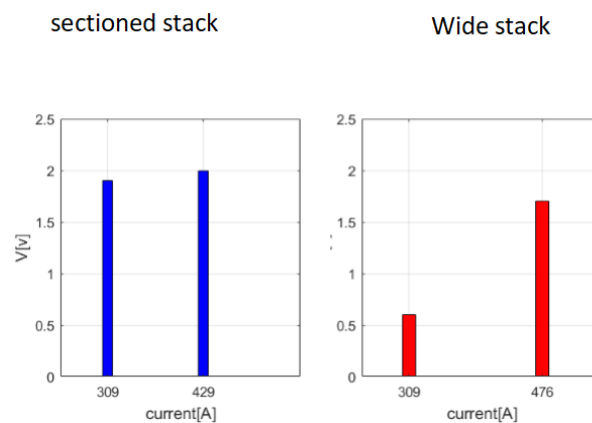
To validate the above results, we performed an experiment on the motor at liquid nitrogen temperature. The wide superconductor is composed of nine 40 mm AMSC tapes; the sectioned one is made by assembling 3 narrow stacks of Superox of 12 mm, each narrow stack contains nine tapes. Figure. 8.

The stacks are held together by Kapton tape and then sandwiched between the rotor and G10 jacket; this method of fixing the stacks is reliable for the purpose of this experiment and offers us the flexibility to reuse the tapes for other configurations.



**Figure 8.** Experimental set up showing the stacks and the rotor

The stacks are magnetized using magnetization coils in the stator. After magnetization, the motor is rotated, and voltage is measured. A similar experiment is performed in [10] and more details are available. The peak of the pulse is measured using a current clamp. The results are represented in Figure.9.



**Figure 9.** Experimental measurement of peak voltage generated by a magnetized sectioned and wide stack

At 309 A pulse, the sectioned stack traps 1.8 V, and the wide stack traps 0.6 V. The sectioned stack is more efficient at this level of pulse.

Increasing the pulse to 429 for the section stack does not cause a significant increase in the voltage; the sectioned stack is at its maximum.

For the wide stack, increasing the pulse from 309 to 472 causes the trapped flux to increase from 0,6 to 1,8V.

This behavior is the same as the one presented in Figure, 6; the sectioned stack traps higher flux density than the wide one; at higher pulses the sectioned stack is stable at its peak and the wide stack continues trapping more.

## 7. Conclusion

In this paper, we carried out a study on the efficiency of sectioning of wide tapes in the pulse magnetization method in a motor. An experiment was performed to validate the latter.

The curvature of the stack, the presence of ferromagnetic material and the fact that the pulse coil is only placed on one side, that is the stator in our case, causes current density to penetrate first from the top surface for the wide stack, similar to the case of split coil magnetization in the air.

At low pulses, sectioned stack traps more flux than wide stacks then stabilize at its peak. The wide stack traps lower flux.



At higher pulses the wide stack continues to trap more flux until it stabilizes at its peak. At high pulses, the peak of the wide stack is higher than the one of the sectioned stacks.

At a certain pulse value, the sectioned stack and the wide stack traps the same value of flux, we named this value, the crossover point.

## ACKNOWLEDGEMENTS

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