Design of a Superconducting Self-Supplied Electromagnetic Launcher proof of concept using HTS REBCO conductor

A. Badel, J. Cicéron, R. Pasquet, E. Voisin, F. Forest, M. Schneider and P. Tixador

***Abstract*—A SMES (Superconducting Magnetic Energy Storage) is an attractive power supply for EMRL (ElectroMagnetic Rail Launchers), which require pulse currents to launch projectiles at very high speeds. Moreover, the accelerating force in an EMRL may be enhanced by adding a background field, a principle known as launcher augmentation. The S3EL concept (Superconducting Self-Supplied Electromagnetic Launcher) consists in using the SMES both as a power supply and for background field generation. The challenge is to reach the operating current and peak magnetic field of such launchers, which can be up to hundreds of kA and up to 10 T. The use of High Temperature Superconductor is mandatory to maintain superconducting operation during a launch, though operation at 4.2 K is foreseen to benefit from the REBCO high critical current densities.**

The aim of this work is to derive a practical design for a 1m-long small-scale S3EL proof of concept using REBCO Coated Conductor, with a reduced output velocity (100 m/s). After preliminary sizing studies, the spatial constraints for the SMES – Launcher integration is presented. A parametric joint analytical and FEM study is conducted to refine the design and maximize the operation margins while maintaining the launch performances. Finally cable design and discharge method suitable to reach the required operating current are presented.

***Index Terms*—REBCO, HTS, SMES, Pulse Power, ElectroMagnetic Rail Launcher.**

I. Introduction

THE principle of ElectroMagnetic Rail Launchers (EMRL) is to accelerate a projectile by means of Lorentz force. The interest of such launchers is that very high output speed may be obtained, over 2000 m/s, speeds that cannot be reached with conventional powder-based launchers. The main military applications are high speed guns and aircraft catapults. The envisioned civilian applications span from accelerating small projectiles at ultra-high speeds for high-pressure solid matter physics studies, to simulate micro-meteorite impacts, to injecting solid deuterium in a tokamak for continuous fusion operation, to launching nano-satellites on low earth orbit with large scale devices [1].

The launcher consists of two conducting rails, between which the projectile realize a sliding electrical contact. When the circuit formed by the rails connected through the projectile is powered with a current *I*, the projectile is accelerated by a force given by (1).

$$\vec{F} = I\vec{d} \times (\overrightarrow{B_{Launcher}} + \overrightarrow{B_{External}}) \quad (1)$$

Where *I* is the current in the projectile, *d* is the distance between the rails and *B* the averaged magnetic flux density surrounding the projectile, which is generated by the launcher itself and possibly by an external source. The interest of using such external field source to enhance the launching capability of a given EMRL was studied since a long time, leading to the concept of augmented launchers and notably the SARG (Superconducting-Augmented Rail Gun) [2].

EMRL are usually powered by capacitors, but the interest of using SMES to power such launchers was already established [3]. It comes from the fact that capacitors are voltage sources while SMES are current sources. As an EMRL is current-driven, a pulse forming unit is required with the former to control the current, while the latter can be connected directly. Moreover, energy density and life expectancy of power capacitors are very limited. SMES powering could be made more compact and enduring. However, SMES powering is a viable option only if high current output can be obtained, up to the hundreds of kA or even MA range for big launchers [4]. Such output current can hardly be obtained directly from a superconducting coil, but could be reached through the use of many modular coil elements using the XRAM principle which was tested with up to 60 kA using 20 resistive coils [5] and at reduced current using HTS coils [6]. It consists in charging the coil elements in series and discharge them in parallel to sum up their currents. Other means, such as flux compression techniques, have also been considered to increase the current output [7].

The concept of S3EL (Superconducting Self Supplied Electromagnetic Launcher) consists in using an HTS coil acting both as a pulse power SMES and an augmenting magnet [8],[9]. The interests of this concept compared to non-coupled SMES powering are mainly to decrease the required current due to the field augmentation and thus to increase the energy efficiency of the launch, as Joule losses become lower. In order for the

Automatically generated dates of receipt and acceptance will be placed here; authors do not produce these dates.

This work was supported by the DGA and the DGE under project RAPID BOSSE.

A. Badel is with the CNRS G2Elab / Neel Institute, Grenoble, France (e-mail: Arnaud.badel@neel.cnrs.fr)

J. Cicéron and P. Tixador are with Grenoble INP G2Elab/Neel Institute

R. Pasquet, E. Voisin and F. Forest are with Sigmaphi, Vannes, France

M. Schneider is with the French-German Institut Saint Louis, Saint Louis, France

Template version 7.2a, 04 August 2016

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TASC.2016.2626271, IEEE Transactions on Applied Superconductivity

concept to be effective, the SMES coil must be optimized not with regards to its energy density to maximize the launcher–coil coupling, the coil taking the shape of a dipole as shown Fig. 2.

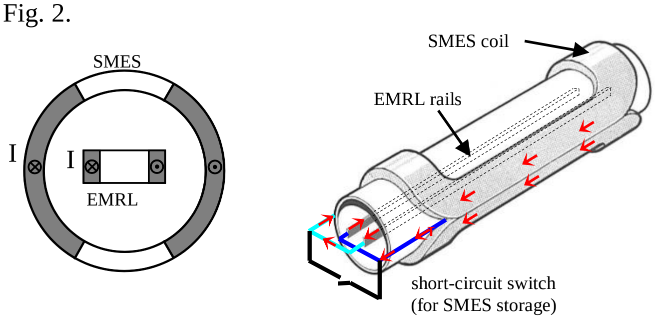

Fig 2. Possible SMES-launcher integration for S3EL concept with dipole-type coil. Cross section (left) and perspective view (right) (taken from [8])

In the framework of the BOSSE project, our aim is to demonstrate the practical feasibility of the S3EL concept with the realization of a 1-m long reduced-energy proof of concept whose characteristics are summarized in Table I.

II. BOSSE S3EL Preliminary Sizing

A coupled analytical model was already developed to obtain

TABLE I
BOSSE Launcher Characteristics

Length	1 m
Bore (and projectile) width	40 mm
Bore (and projectile) height	20 mm
Projectile mass	100 g
Inductance per unit length	0.7 µH
Contact friction	0-10 kg
Output speed	100 m/s
Projectile energy	500 J

the projectile acceleration and the evolution of the electrical quantities in a S3EL system, where the same current is flowing in the external coil and in the launcher. Equation (1) becomes (2):

$$F = {}^{1}\!/_{2}\, L'.I^2 + M'.I^2 \qquad (2)$$

Where L' and M' are the launchers self-inductance par unit length and the launcher – SMES mutual inductance per unit length respectively. It can be observed that for a given launcher (whose length is x_{max}) and a given current, the S3EL launch performance depend only on *M'*, which can be obtained from (3)

$$M' = {}^{k}\!/_{x_{max}} \sqrt{L_{SMES} \cdot L'} \qquad (3)$$

Where L_{SMES} is the SMES inductance, linked to the SMES stored energy, and *k* the coupling between the coil and the total length of the launchers rails. The S3EL performance in terms of operating current reduction derive therefore directly from SMES stored energy and SMES–Launcher coupling. Sensitivity studies on these two parameters, applied to the BOSSE project objectives, are presented Fig. 3a and b.

Increasing the initial stored energy, which is linked to the SMES inductance effectively lowers the required initial current for a successful launch, which makes sense as a bigger coil would create more external field. However, that comes with an increase of superconductor volume and thus of price. The curve Fig. 3a upper shows a change of slope, with less effect above 30 kJ. This value can be considered a good tradeoff between cost and effectiveness, and will thus be the target for the magnetic design.

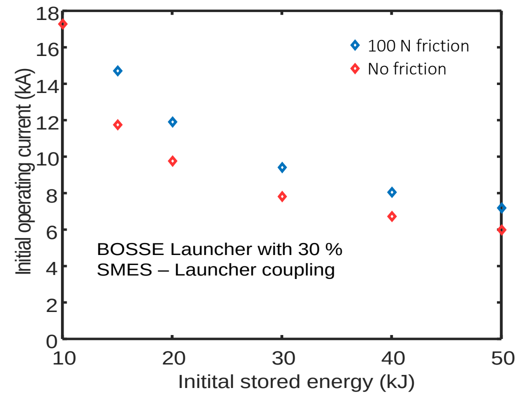

Fig 3a. Influence of the initial stored energy on the required current to launch a 100 g projectile at 100 m/s, for a given coupling (30 %)

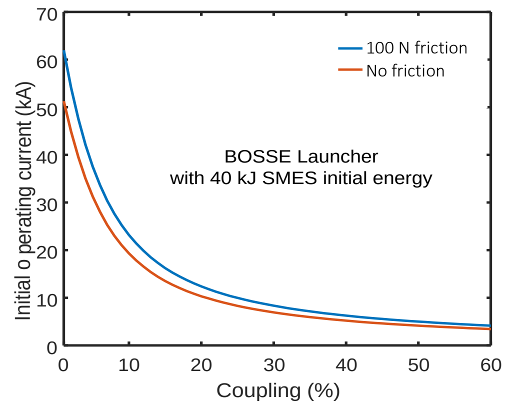

Fig 3b. Influence of the coupling on the required current to launch a 100 g projectile at 100 m/s, for a given initial stored energy

Increasing the coupling is very promising but ultimately limited by to the spatial constraints of SMES – launcher integration. Fig 3b shows a steep decrease up to 30 % coupling, with a required current more than 6 times lower than without, and then a kind saturation above. 30 % is therefore a good target for the magnetic design.

III. Electro-Magnetic Design of the S3EL Coils

The launcher is placed in the SMES cryostat room-temperature bore. This bore consist in inner and outer cryostat wall with isolation between them. It must accommodate the launcher and its complete mechanical structure as no force (and as small vibrations as possible) should be transferred from the launcher to the cryostat. For the SMES coil a simple twin racetrack configuration is preferable to saddle coils design for a practical implementation, due to the very challenging implementation of REBCO tapes. To obtain a practical magnetic design of the coils the size of this bore must be known. However, designing the rails mechanical support requires in turn the magnetic field distribution on the rails and the current flowing in them. That is why the mechanical studies presented in § III.A and the electro-magnetic studies presented in § III.B and IV were performed iteratively until reaching a coherent design.

A. BOSSE S3EL spatial constraints and final configuration

Dynamic 3D mechanical studies of the launcher during a launch are required to reduce the launcher cross-section as much as possible while ensuring that the rails displacement is small enough to guarantee a good sliding contact between the projectile and the rails (less than 1 mm). These studies, carried out at Institut Saint Louis are not the main focus of this work and will thus be presented briefly, more details will be presented in [10]. The cross section presented Fig. 4 corresponds to the final iteration with the definitive electro-magnetic design

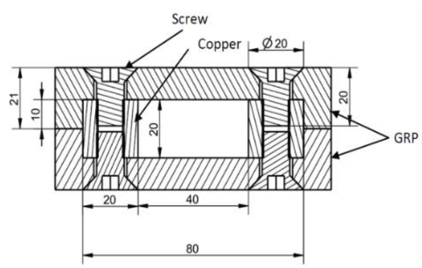

Fig 4. Cross-section of the optimized rail / structure assembly

The optimized structure is comprised of 20 x 20 mm copper rails assembled to grooved 20 mm-thick x 100 mm wide GRP plates by stainless steel bolts. Its external dimensions are 42 x 100 mm. It is surrounded by the cryostat room temperature bore 48 mm x 106 mm (the 3 mm margin around ensures that there is no contact even in case of small misalignment). The cryostat walls are 2 mm thick, more than usual due to their flat surface. There is 12 mm of vacuum between, in which Multi Layered Insulation is placed. There is no active thermal shield (helium gas or liquid nitrogen cooled) in this design in order to limit the insulation thickness as much as possible. The cryostat cold bore, which limits the coils placement, is therefore 80 x 138 mm.

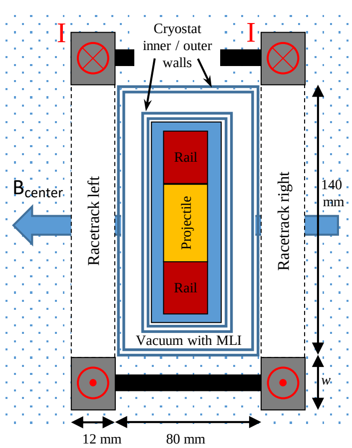

Fig 4. Cross section schematic of the BOSSE S3EL configuration with the final dimensions of the room temperature bore

The launcher and the two racetracks are placed so that the central field is in the horizontal plan, for practical reasons related to the fitting of the coil current leads.The cross-section schematic Fig. 4 presents the selected configuration. The two racetracks attract each other. It was decided to design the racetracks so that their inner diameter is equal or bigger than the cold bore width (140 mm), in order to be able to maintain those using straight spacers. Moreover the use of flat racetrack prevents to place the coils any closer than 80 mm due to the cold bore thickness. With these two dimensions fixed, and assuming the use of 12 mm wide tapes, obvious if one aims at high current operation, there is only one dimension left to be determined, the coil block thickness *w*.

B. Determination of the electric and magnetic operation conditions for various coil block thicknesses

For the comparison between different coil block thicknesses to be meaningful, especially in terms of cost, it is made for a constant length of superconducting tape, so both the number of turns in the coil windings, and the amount of superconductor in each turn, must remain the same. The number of turns is obtained by dividing the total ampere.turns required to reach the desired stored energy, by the required initial current. It is fixed at 15 per racetrack. The minimum coil block thickness for the parametric study is 6 mm, a value for which the overall current density is close but lower to the typical critical current density obtained in REBCO tapes from the selected supplier (SuperOx). For each studied thickness an iterative process is conducted, starting with 2D FEM magneto-static studies (using Flux®) of the coils, the rails and the combination of the two. These permit the determination of the SMES and rails inductances (as the turn number is constant), as well as their coupling. These values are used as inputs for the launch simulation code presented in § II in order to assert the required operating current. For the first step an initial stored energy of 30 kJ is assumed, in accordance with the preliminary sizing.

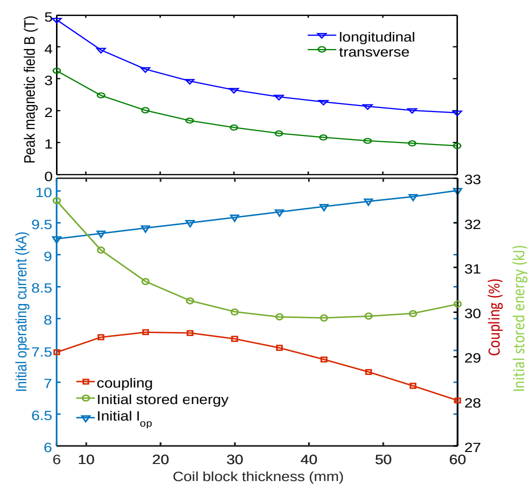

Fig 5. Operating current, stored energy and magnetic coupling evolution for various coil block thickness (below) as well as the evolution of peak longitudinal and transverse field values on the conductors (above)

The calculated required current is applied at the next step in the FEM model in order to obtain the actual stored energy, then the launch simulation is again performed with the updated stored energy, until a convergence is reached (usually after no more than a couple of steps). The results are presented Fig. 5 for coil

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TASC.2016.2626271, IEEE Transactions on Applied Superconductivity

block thicknesses ranging from 6 mm (the absolute minimum where the block is filled with bare 0.1 mm thick REBCO tapes) and 60 mm. There is a continuous increase of the required current with the coil block thickness, but the variations of the properties in the studied range are limited. All the coil configuration studied here match the preliminary sizing, with large but not unreachable operation current, provided that we operate at 4.2 K. The peak field values are decreasing a lot with the coil thickness, which is positive for the safety of operation.

C. Determination of the critical current margin

Based on the in-field angular-dependent critical current densities of the selected REBCO tapes obtained previously [11] one can obtain the current margin for the various possible coil thicknesses (Fig. 6), starting from the evaluated operating current and peak field values presented in Fig. 5.

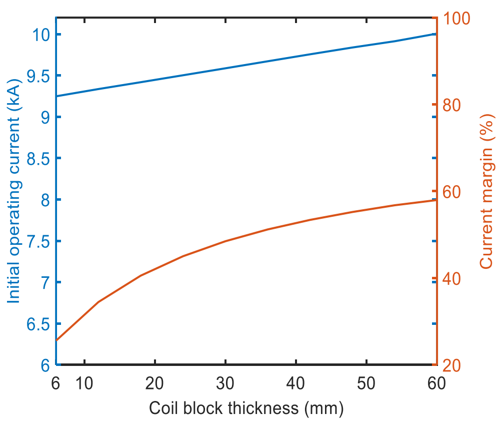

Fig 6. Operating current and evaluated current margin for various coil block thicknesses, based on field and angular dependent critical current density measured on SuperOx tapes.

Though the operating current increase for thick coil configuration, the margin is actually getting much higher, passing from 28 % to 58 %. A thicker configuration leads also to a significant decrease of current density (208 instead of 1900 A/mm²), which makes protection in case of quench easier. Even thicker configuration were considered (not shown here) but we can observe that the gain in terms of current margin starts to saturate above 40 mm, and the total length of conductor start to increase when considering very thick coil blocks due to the coil heads. Finally a 60 mm coil block thickness is a good compromise.

IV. Conductor Structure and Discharge Method

To reach an initial current in the range of 9-10 kA, multiple REBCO tapes must be placed in parallel, even at 4.2 K under low field. In order to ensure the feasibility and reduce the cost, a simple conductor configuration is preferred for the BOSSE project instead of a cable, with the use of XRAM current multiplication to achieve the rated current [5]. Indeed, some cables were successfully tested in the 10-kA range [12], [13] but the cost of assembling such cable is high, and in any case current multiplication will be mandatory for future full-scale launcher, with operating current in the 100 kA range and higher.

The conductor is made of two 12 mm-wide tapes soldered face-to-face, following the concept successfully tested for the Eucard I European project test insert dipole [14], [15]. The soldering of two tapes enables current redistribution from one tape to the other in case of defect, effectively averaging the critical current density inhomogeneities. The use of a face-to-face configuration limits the magnetization issues existing with stack cables.

A 4-stages XRAM can be used if each racetrack is a co-winding of two isolated conductors, as this create four coil elements with equal coupling: two on the left racetrack, two on the right. The four elements are charged in series and discharged in parallel to sum up their currents, the co-winding and symmetry of the coils guaranteeing equal coupling. Fig. 6 present the twin co-wound conductor structure. With this architecture, the transport current for one face-to-face conductor is reduced to between 2.5 kA, while the number of turn is multiplied by a factor 4, to reach 60 per racetrack (30 turns of twin co-wound conductor.

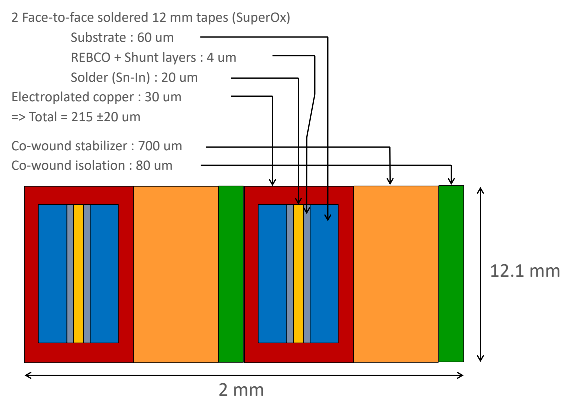

Fig 6. Architecture of the conductor for the Racetrack winding (Cross section). The overall width is 12.1 mm, the overall thickness varies from 0.4 to 2 mm by varying the shunt and stabilizer thickness depending on the selected coil block width

In this configuration, the complete 1-m length magnet can be wound using only four 70 m-long unit lengths of face-to-face soldered conductor.

V. Conclusion

We demonstrate that a 1-m long launcher with an associated 30 kJ twin racetrack coil wound with commercial available REBCO tape can launch a 100 g projectile at 100 m/s, the total length of required conductor being very modest (280 m of 12 mm wide face-to-face soldered tapes). The selected electro-magnetic design ensure a very high current margin (up to 60 %) that should be enough to obtain safe operation during the launch, when a lot of energy will be deposited in the winding due to the pulse operation of the launcher. Studies are underway to quantify these AC losses and design the mechanical structure supporting the coils.

Acknowledgment

The authors would like to thank M. Amiet for his sustained support of this work

REFERENCES

[1] Lehmann P, Reck B, Vo MD, Behrens J. Acceleration of a suborbital payload using an electromagnetic railgun. IEEE Transactions On Magnetics. 2007 Jan; 43(1):480–485.

[2] Homan CG, Cummings CE, Fowler CM. Superconducting Augmented Rail Gun (SARG). IEEE Transactions On Magnetics. 1986; 22(6):1527–1531.

[3] A. Badel, P. Tixador, M. Amiet, V. Brommer. “SMES to supply an Electromagnetic Launcher”. IEEE Trans. On Appl. Supercond. 23(3) : 5700204, 2012

[4] Lehmann P, Peter H, Wey J. First experimental results with the ISL 10 MJ DES railgun PEGASUS. IEEE Transactions On Magnetics. 2001 Jan; 37(1):435–439.

[5] P. Dedie, V. Brommer and S. Scharnholz, "Twenty-Stage Toroidal XRAM Generator Switched by Countercurrent Thyristors," in *IEEE Transactions on Plasma Science*, vol. 39, no. 1, pp. 263-267, Jan. 2011.

[6] Badel A, Tixador P, Dedie P. Test of a Twin Coil HTS SMES for High Power Pulse Operation. IEEE Transactions On Applied Superconductivity. 2011; 21(3):1375–1378.

[7] A. Sitzman, D. Surls and J. Mallick, "Stretch Meat Grinder: A Novel Circuit Topology for Reducing Opening Switch Voltage Stress," *2005 IEEE Pulsed Power Conference*, Monterey, CA, 2005, pp. 493-496.

[8] A. Badel, P. Tixador, M. Amiet. “Optimized use of Superconducting Magnetic Energy Storage for Electromagnetic Rail Launcher powering”. Supercond. Sci. Technol., 25(1): 014006, 2012.

[9] M. Amiet, P. Tixador, A. Badel. *Electromagnetic rail launchers and associated projectile-launching method*. U.S. Patent No 9,032,857, 19 mai 2015

[10] M. Schneider, M. Roch, F. Forest, R. Pasquet, E. Voisin, et al, “Design Criteria for a Railgun with Augmenting Coils made from high Tc Supercoductors”, submitted to IEEE Trans Plasma Sci.

[11] T. Benkel, Y. Miyoshi, G. Escamez, D. Gonzales, X. Chaud, A. Badel, P. Tixador, “REBCO performance at high field with low incident angle and preliminary tests for a 10 T insert”,*IEEE Trans. Appl. Supercond.*,26 (2016) 4302705

[12] A. Badel, A. Ballarino, C. Barth, L. Bottura, M. Dhalle *et al*., "Advances in the Development of a 10-kA Class REBCO Cable for the EuCARD2 Demonstrator Magnet," in *IEEE Transactions on Applied Superconductivity*, vol. 26, no. 3, pp. 1-8, April 2016.

[13] D. C. van der Laan, L. F. Goodrich, P. Noyes, U. P. Trociewitz, .A. Godeke, D. Abraimov, D. C. Larbalestier, “Engineering current density in excess of 200 A mm− 2 at 20 T in CORC® magnet cables containing RE-Ba2Cu3O7− δ tapes with 38 μm thick substrates”. *Superconductor Science and Technology*, *28*(12), 124001, (2015).

[14] J. M. Rey, M. Devaux, F. Bertinelli, X. Chaud, F. Debray, M. Durante, G. Favre, P. Fazilleau, T. Lécrevisse, C. Mayri, C. Pes, F. Pottier, M. Sorbi, A. Stenvall, P. Tixador, J. M. Tudela, T. Tardy and G. Volpini, “HTS Dipole Insert Developments”, *IEEE Trans. Appl. Supercond.* vol. 23, no. 3, Jun. 2013, Art. No. 4601004.

[15] Miyoshi, Y.; Badel, A.; Chaud, X.; Benkel, T.; Vincent, et al., "Performance Tests of Prototype High-Field HTS Coils in Grenoble," *Applied Superconductivity, IEEE Transactions on* , vol.25, no.3, pp.1,5, June 2015