Restoring force and stability in superconductor-magnetic levitation

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***Abstract*—This contribution describes a mean field model dedicated to the reproduction of the restoring force and the determination of the condition of stability of superconducting systems in magnetic levitation.**

Keywords—magnetic levitation, restoring force, mean field model

I. INTRODUCTION

The restoring force is the most important characteristic of a levitating system based on the interaction between a magnetic field source and a field cooled superconductor since it determines the system stability. The restoring force depends on the distance between the field source and the superconductor during field cooling in a way opposite to the levitation force: the larger the cooling distance, the lower the restoring force. Considering Maglev applications, this means that one must choose a cooling distance resulting in a restoring (or guidance) force satisfying the safety requirements of the railways industry. The choice of the cooling distance determines the system levitation force.

In this contribution, we report measurements of the restoring force carried out on systems consisting either of a 70 mm diameter MgB_2 disc and a 80 mm diameter NdFeB magnet (PM80) or of a 56 mm diameter YBCO disc and a 45 mm diameter magnet (PM45). While levitation is stable for this last system, it is unstable below some threshold for the system consisting of the PM80 magnet and the MgB_2 disc. We describe an analytical mean field model permitting to reproduce the measurements with no fitting parameters and we determine the condition required to ensure the stability of superconducting magnetic levitating systems.

II. EXPERIMENTAL

The superconductors were cooled down in an axisymmetric configuration ($Y=0$) at distance Z_{cp} from the magnet, respectively at T=20K for the MgB_2 disc and T=77K for the YBCO disc. This process is called Field Cooling (FC). Then, the magnet-superconductor distance was set to Z and the magnet was moved by 1 mm steps parallel to the superconductor surface to Y_{max} where the direction of motion was reversed and distance Y decreased to Y_{min} before increasing to $Y=0$. The lateral force F_y acting on the magnet was measured during the whole process. Basically, if $\frac{\partial F_y}{\partial y}$ is negative near $y = 0$ levitation is stable. If it is positive, as it is the case for two magnets with opposite magnetizations, the levitating system is unstable.

III. MODELLING

In a way similar to the mean field model proposed for reproducing the levitation force [1], the lateral force is written as :

$$F_Y = m(\Delta B)\frac{\partial \bar{B}_Z}{\partial Y} \qquad (1)$$

In Eq.(1) $m(\Delta B)$ is the magnetic moment of the superconducting currents flowing in the superconductor and ΔB takes the form:

$$\Delta B = \bar{B}_{PM}(Y = 0, Z_{cp}) - \bar{B}_{\phi}(Y, Z) \qquad (2).$$

$\bar{B}_{PM}(Y = 0, Z_{cp})$ is the vertical component of the magnetic field applied to the centre of the superconductor at the cooling point and $\bar{B}_{\phi}(Y, Z)$ the mean value of the vertical magnetic field applied to the superconductor at location *(Y,Z)*. Magnetic moment m is calculated according to the expression proposed by E.H.Brandt [2]. We emphasize that depending on the relative values of $\bar{B}_{PM}(0, Z_{cp})$ and $\bar{B}_{\phi}(Y, Z)$, $m(\Delta B)$ and $\frac{\partial F_y}{\partial Y}$ are either positive or negative and the levitating system is either stable or unstable.

IV. RESULTS

Considering the system including the PM80 magnet, after field cooling at Z_{cp}=30mm, levitation is stable if $Z \geq 24\,mm$ and unstable if $Z < 24\,mm$ (see Fig.1 as an example). In the case of the system including the PM45 magnet, the lateral force stabilizes the magnet above the superconductor at any magnet-superconductor separation after FC at Z_{cp}=20.5 mm, Z_{cp}=10.5 mm and Z_{cp}=7.5 mm (see Fig.2 for an example).

The calculated F_y are shown as blue lines in Figures 1 and 2. The lateral forces are well reproduced in the vicinity of Y=0 that is the area of interest. The model accounts for the transition from the stable to the unstable regime with a good accuracy. Stability exists only if:

$$\bar{B}_{\phi}(0,Z) \leq \bar{B}_{PM}(0,Z_{cp}) \quad (3).$$

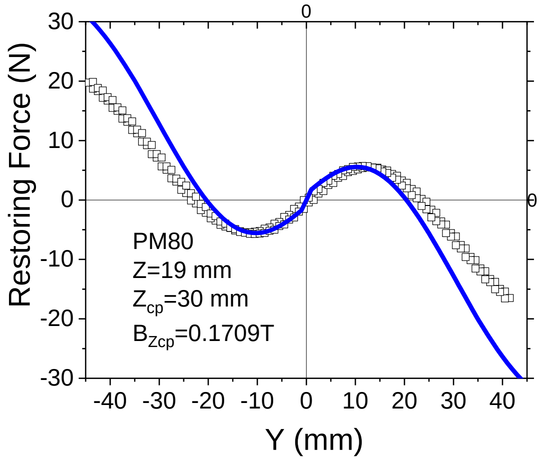

Figure 1 : Symbols: Measurements of the lateral force applied to the PM80 magnet at *Z=19 mm* after FC the MgB_2 disc at Z_{cp}=30 mm; blue line: reproduction of the measurements with the model.

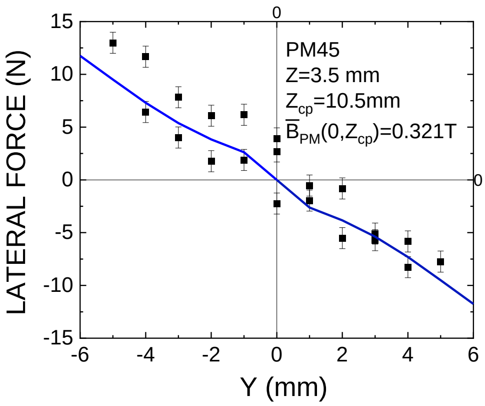

Figure 2 : Symbols: Measurements of the lateral force applied to the PM45 magnet at *Z=3.5 mm* after FC the YBCO disc at Z_{cp}=10.5 mm; blue line: reproduction of the measurements with the model.

This is evidenced in Figs.(3 and 4) which show $\bar{B}_{\phi}(0,Z)$ for the investigated systems and where $\bar{B}_{PM}(0,Z_{cp})$ is represented as the red straight line. For the system including the PM80 magnet, as Z decreases, $\bar{B}_{\phi}(Y,Z)$ increases and instability occurs for Z<24 mm. This does not occur with the system comprising the YBCO disc because the superconductor diameter is larger than that of the magnet. As a result, the difference between $\bar{B}_{PM}(0,Z_{cp})$ and $\bar{B}_{\phi}(0,Z)$ is much larger than in the system consisting of the MgB_2 disc and the PM80 magnet.

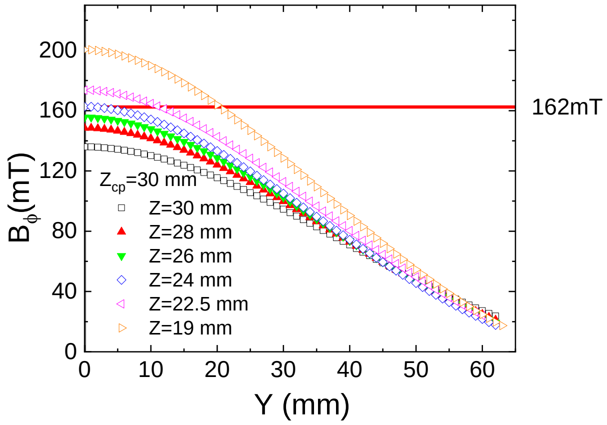

Figure 3 : Mean value $\bar{B}_{\phi}(Y)$ for various Z of the field applied by the PM80 magnet to the MgB_2 disc. The horizontal lines show the corresponding $\bar{B}_{PM}(0,Z_{cp})$.

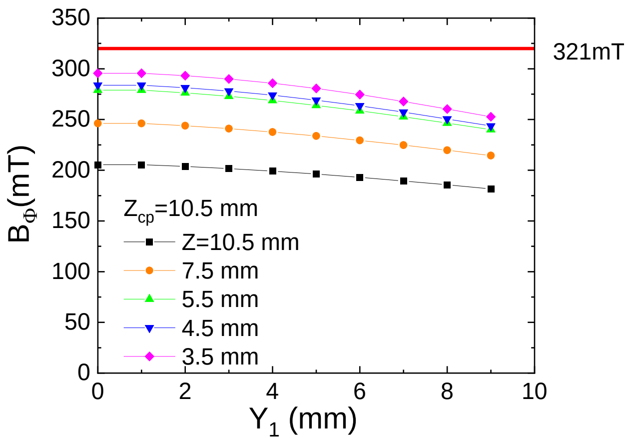

Figure 4 : Mean value $\bar{B}_{\phi}(Y)$ for various Z of the field applied by the PM45 magnet to the YBCO disc. The horizontal lines show the corresponding $\bar{B}_{PM}(0,Z_{cp})$.

V. CONCLUSION

In this contribution we report measurements of the lateral force carried out on two different levitating set-ups and we propose a mean field model reproducing the measurements. A very important result of this work is that, in order to be stable, levitating systems must work in conditions in which Eq.(3) is valid.

References

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