Finite Element Calculation of the Critical current and Magnetic "Levitation" Force between a Permanent Magnet and a ZFC YBaCuO Sample in Mixed State

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Introduction

This work presents a new method for estimation of Jc as a bulk characteristic of Bulk melt textured high temperature superconducting (MT-HTS) pieces can be used as main elements in current leads, fault current limiters or "levitators", i.e., self stable magnetic suspension units. In all cases, interactions between the high temperature superconductor unit and magnetic field sources occur and may have high intensity. In this work we present a new methodology to perform computational simulation of magnetic interaction ("levitation") force between a HTS disc and a cylindrical permanent magnet, as well a value of an effective current density Jc. In that method, to avoid microscopic description and to use available finite element method (FEM) software packages it is proposed to substitute the "frozen" Abrikosov lattice for an effective current density that generates the macroscopic magnetic response of the sample. In a first approach, it is used a critical state model. Within the framework of a critical state model, the effective current density that flows throughout the sample is exactly the critical one (Jc). In the present work we use the calculates induced magnetic dipole in the MT-HTS and the corresponding magnetization M= M(H). Then, we calculated the B(H) curve of a superconducting MT-HTS, but wtih an artificial saturation imposed in the B(H), in order to attend the convergence requirements of the calculation program. The value of the imposed saturation field must be very higher than the greatest applied magnetic field in the problem, in order to assure accuracy and reliability of results. As a demonstration of the reliability of our technique, we have reproduced numerically a real experiment. With the inverse problem, we calculated Jc from the measured "levitation" force: changing Jc value until the simulation of the levitation curves are fitted.

Methodology

The finite element calculation of the interaction force between a superconducting sample and a permanent magnet must take into account that the sample is in the mixed state, and so there will be magnetization due to vortex penetration. As vortex diameter is neglectable (approximately 1 nm) in front of sample dimensions, the magnetization can be treated as a continuous process. Such continuity is described by the Bean Model, and within this formalism we will build the magnetization curves of the superconducting sample, making possible the characterization of the sample in the materials data list of a FEM program.

Bean model sates that a screenig current density J_C flows through the cylindrical sample surface, when it is exposed to an applied H, till the depth . From this statement, we can calculate the induced magnetic dipole (Γ_{ind}) in the sample and its magnetization M= M(H)

$$\Gamma_{ind} = \pi J_c h \int_{R-x_o}^{R} x^2 dx \rightarrow \Gamma_{ind} = \frac{\pi J_c h}{3}\left[(R-x_o)^3 - R^3\right]$$

Where $x_0 = H / Jc$ is the distance within the cylinder that H penetrates. So, we have the results:

$$M(H) = \frac{\Gamma}{V} = \frac{\Gamma}{\pi R^2 h} = -H + \frac{H^2}{J_c R} - \frac{H^3}{3(J_c R)^2}$$

$$B = \mu_o\left[H + M(H)\right] \Rightarrow B(H) = \mu_o\left[\frac{H^2}{J_c R} - \frac{H^3}{3(J_c R)^2}\right]$$

Recognizing $H_P = J_C R$ (Full penetration)

$$B(H) = \mu_o\left[\frac{H^2}{H_P} - \frac{H^3}{3H_P^2}\right]$$

Results

Figure 1 shows the B×H curve, that is the graphic for the B(H) function above for a cylindrical sample with radius R = 23 mm, height h= 20mm and iteractivelly changing values of J_C up to the value $J_C = 6,5 \times 10^7$ A/m².

A saturation was artificially imposed in B = 0,99 T, beginning in H=1,5×10⁶ A/m, in order to attend the convergence requirements of the calculation program. If we have not imposed this artificial saturation, the program would start a never ending loop of iterations and would never complete the calculations. The value of the imposed saturation field must be very higher than the gratest applied magnetic field in the problem, in order to assure preciseness and reliability of results. As a demonstration of the power of our technique, we have reproduced numerically a real experiment described.

Figure 2 shows a comparison of our numerical results obtained with FEM (using FEMM4.0 with a mesh of nearly 5,000 nodes and 9000 elements) and the experimental results. An excellent agreement can be seen.

Figure 3 provides a comparison between experimental values of force with results obtained numerically for zero field cooled sample in mixed state and in Meissner state. The purpose of such a comparison is getting a measure of the efficiency of the sample as a repulsion force generator, once that in Meissner state, we obtain the maximum force that one sample can generate. The nearer the two curves are, the better the flux screening capacity of the sample, and the closer it will be to the maximum force sample can create.

Figure 4 shows the computer generated distribution of magnetic flux lines for the interaction between the sample in zero field cooled sample in mixed state and the magnet. We can note the partial penetration of flux lines in the superconductor.

Figure 5 shows the computer generated distribution of magnetic flux lines for the interaction between the sample in Meissner state and the magnet. We can note the total screening of flux lines in the superconductor.

Meissner state is simulated in a FEM program in a very easy way: by considering the perfect diamagnetism and its null magnetic permeability μ by means of a very small value of μ, in such a way that for all desired effects can be understood as a numerical zero by the calculation program. We have used the value μ = 10⁻⁶ Tm/A. The FEM program will treat the sample in Meissner state as a bulk material with extremely low magnetic permeability, and the sample in mixed state as a nonlinear magnetic material, which is good enough for the superconductors applications intended for maglev based technology, such as maglev vehicles and magnetic bearings.
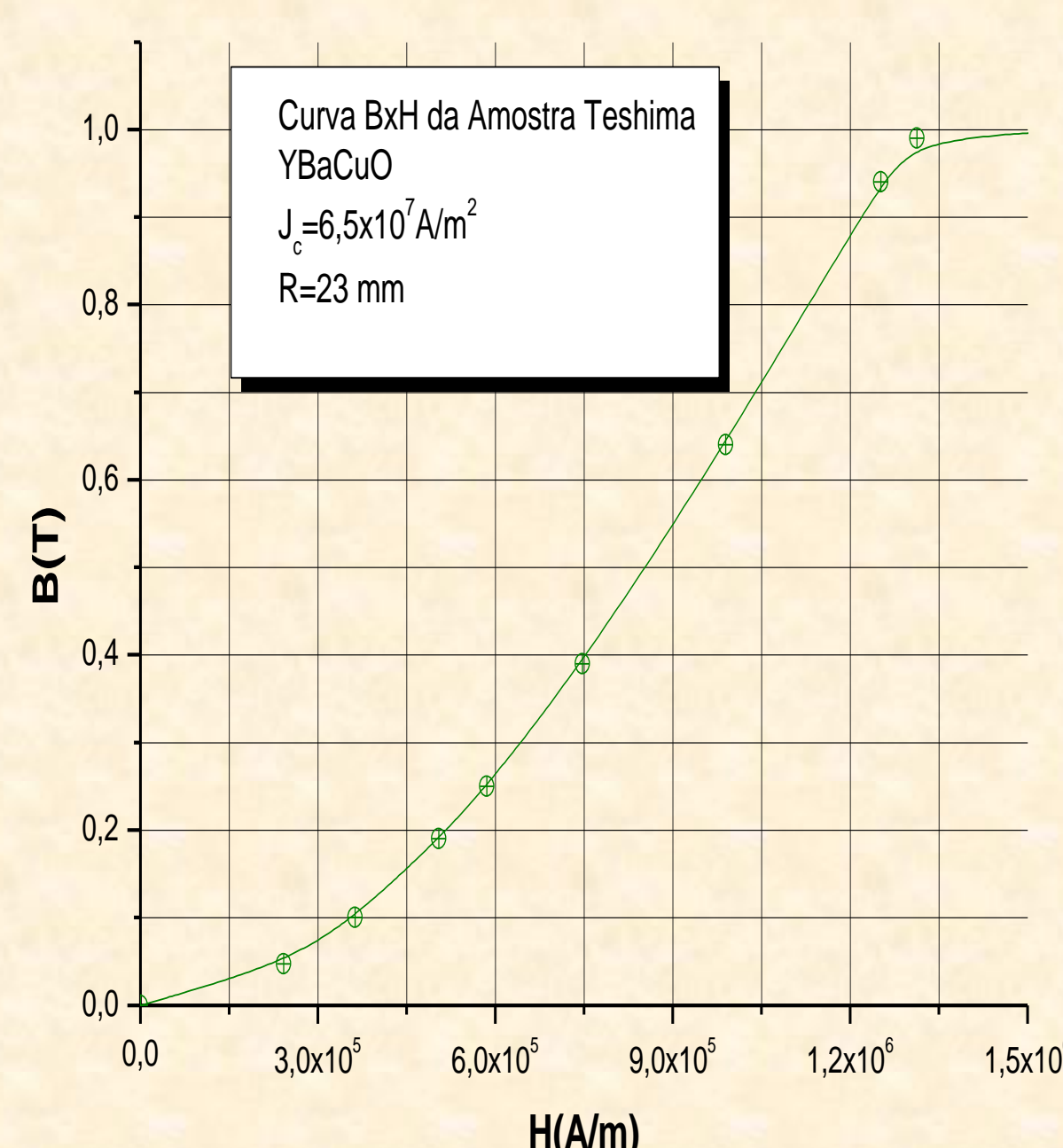

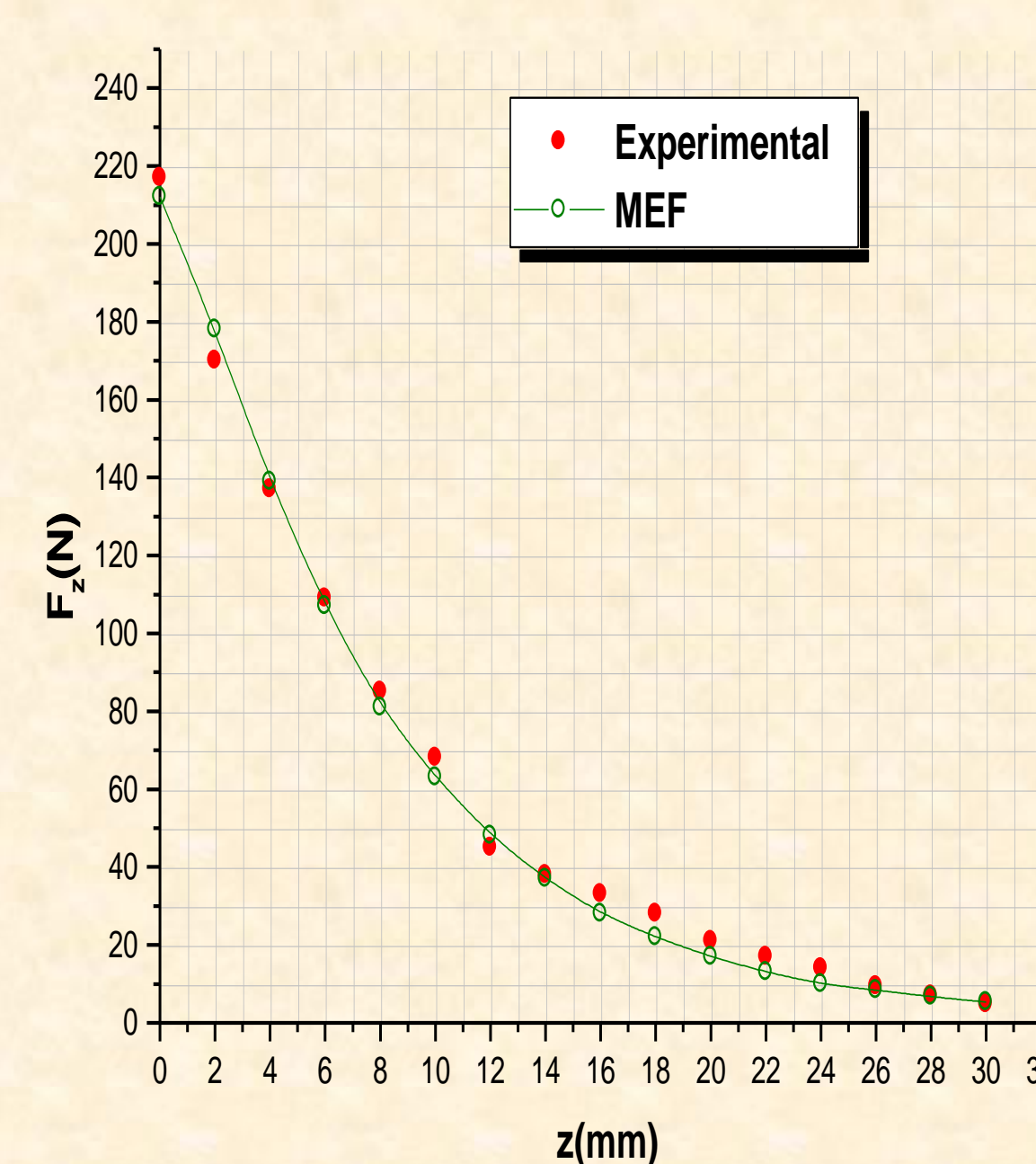**Figure 1 - B x H curve built by applying Bean model to the YBaCuO**

Figure 2: Comparison between experimental and FEM numerical values of interaction force between a zero field cooled YBaCuO sample (ϕ = 46 mm, h = 20 mm e $J_C \cong 6,5 \times 10^7$ A/m²) in mixed state, and a NdFeB magnet(ϕ = 50 mm e B_o = 0.5T)
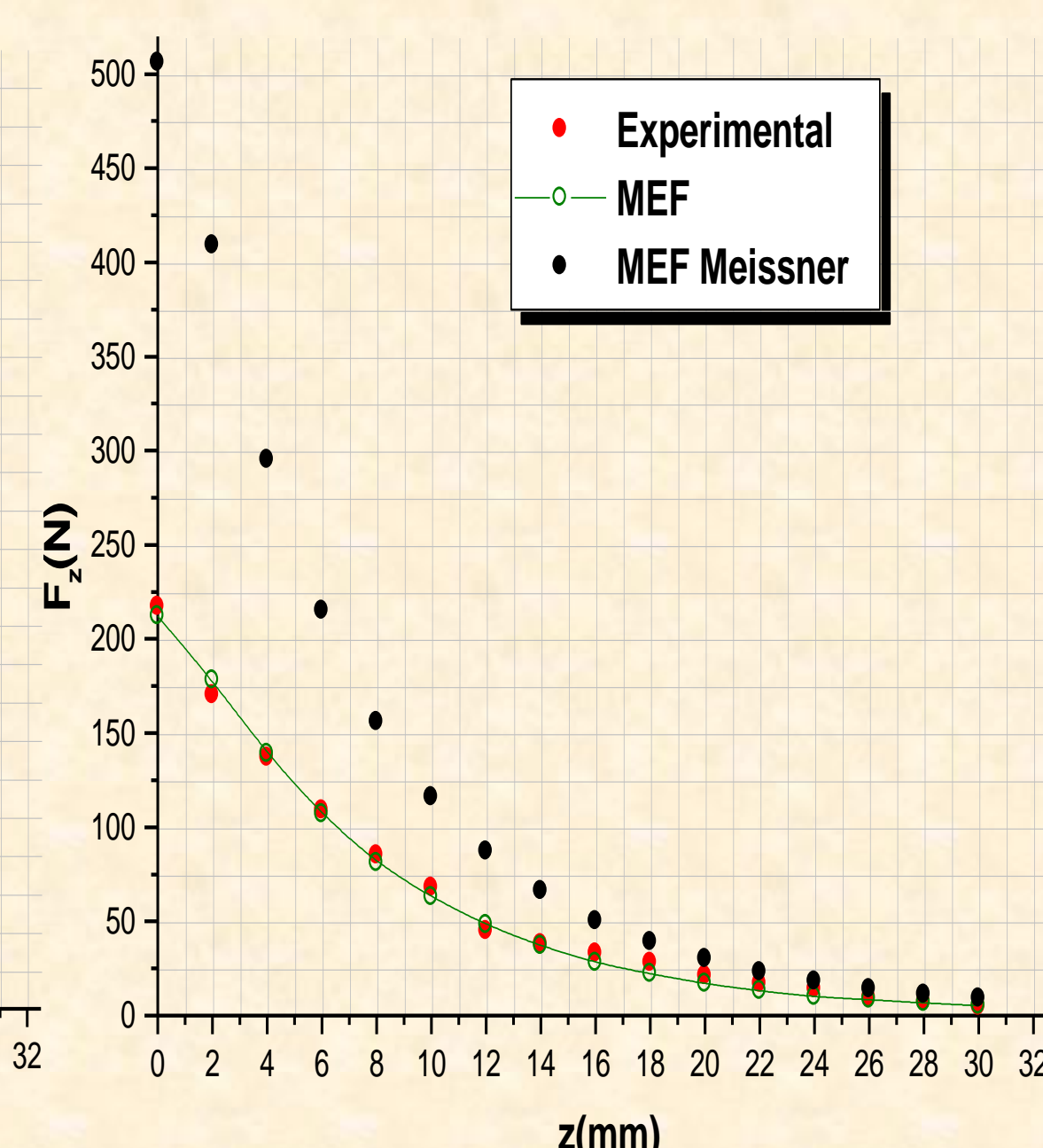

Figure 3: Comparison between experimental and FEM numerical values of interaction force between zero field cooled YBaCuO sample in mixed state and FEM numerical results for YBaCuO sample in Meissner state.
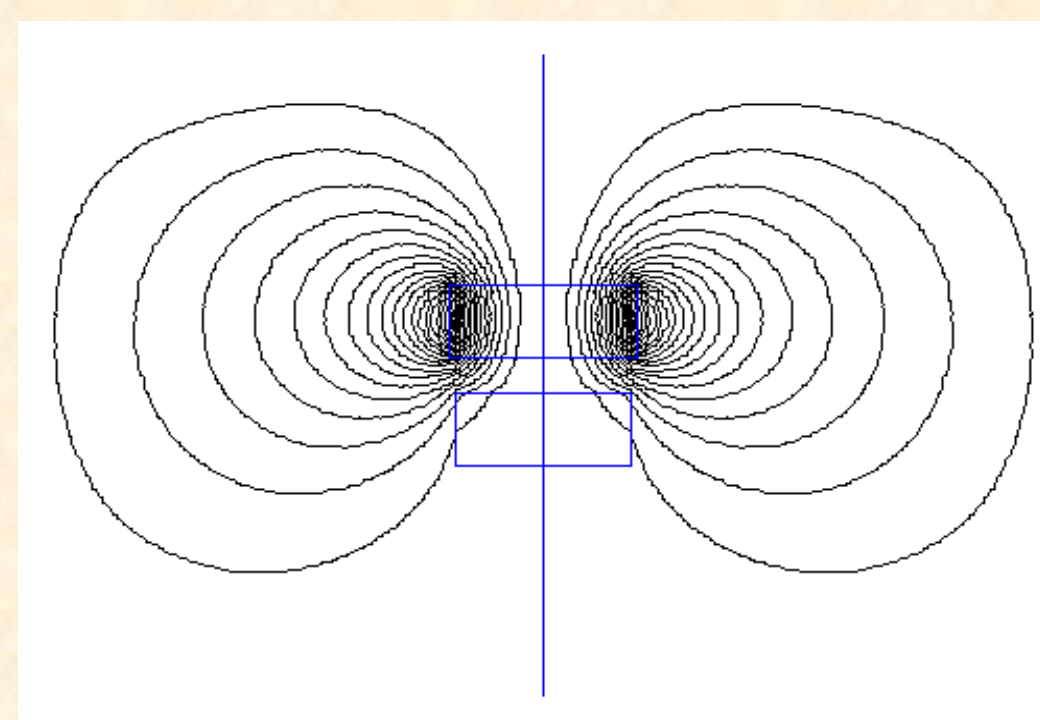

Figure 4: Flux lines distribution in the interaction between zero field cooled YBaCuO sample in mixed state and permanent magnet. Figure shows magnet (source of flux lines), YBaCuO sample (bellow magnet) and vertical axis of cylindrical symetry. Note the partial penetration of flux lines
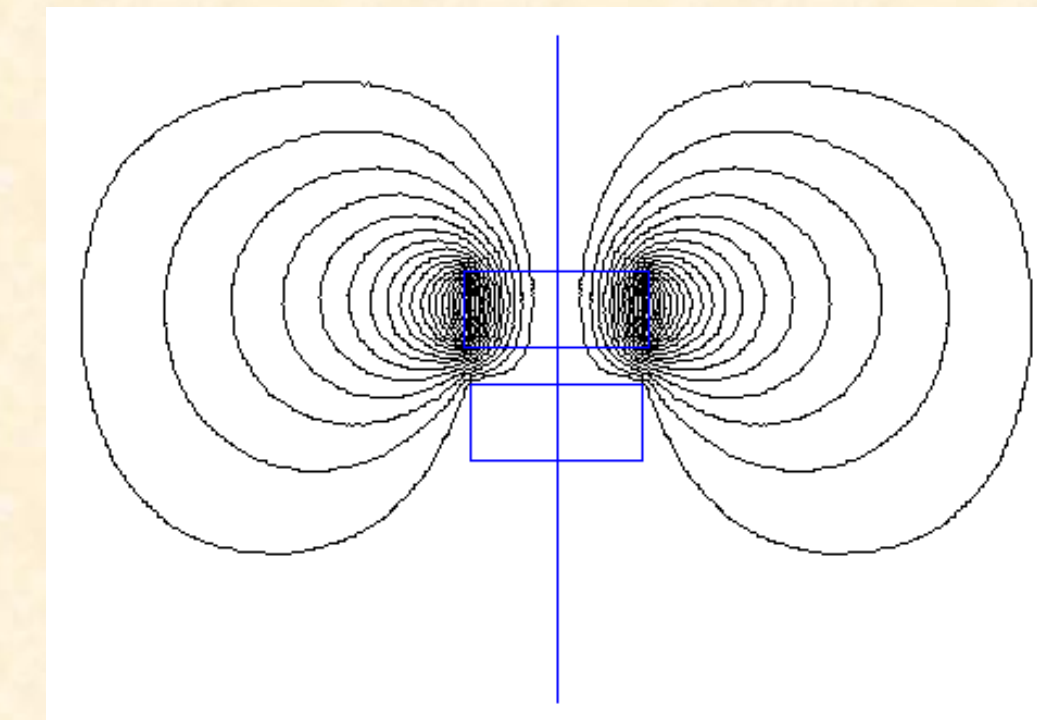

Figure 5: Flux lines distribution in the interaction between YBaCuO sample in Meissner state and permanent magnet. Figure shows magnet (source of flux lines), YbaCuO sample (bellow magnet) and vertical axis of cylindrical symmetry. Note the total screening of flux lines.

CONCLUSIONS

We developed and improved a methodology that allows a non-destructive evaluation of Jc in bulk HTS superconductors.

We propose improvements using other critical state models.

References

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