Vortex penetration and dynamics of Nb, N-doped Nb and NbTi plates

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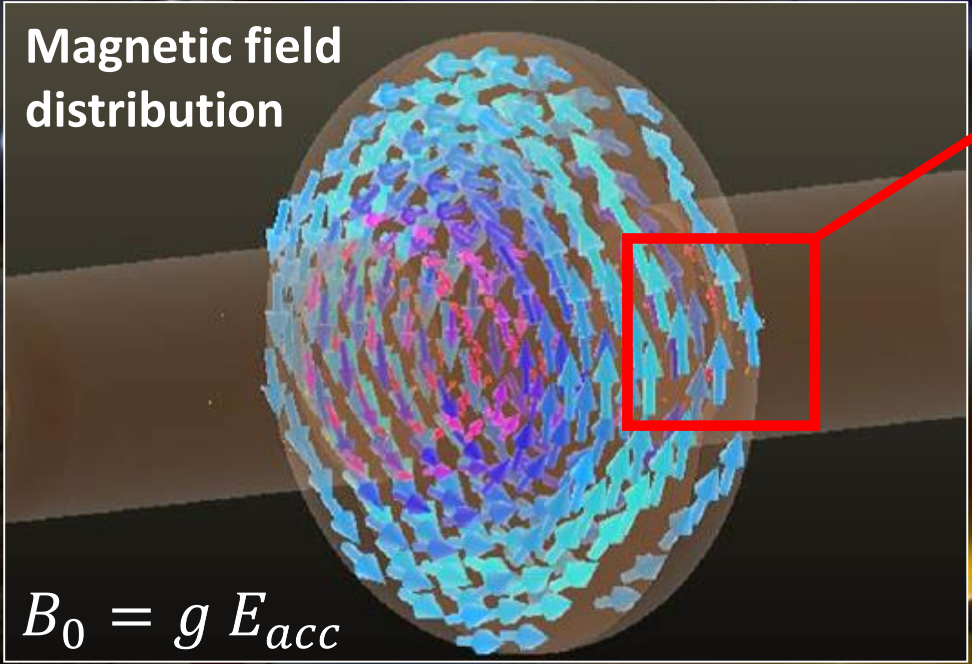
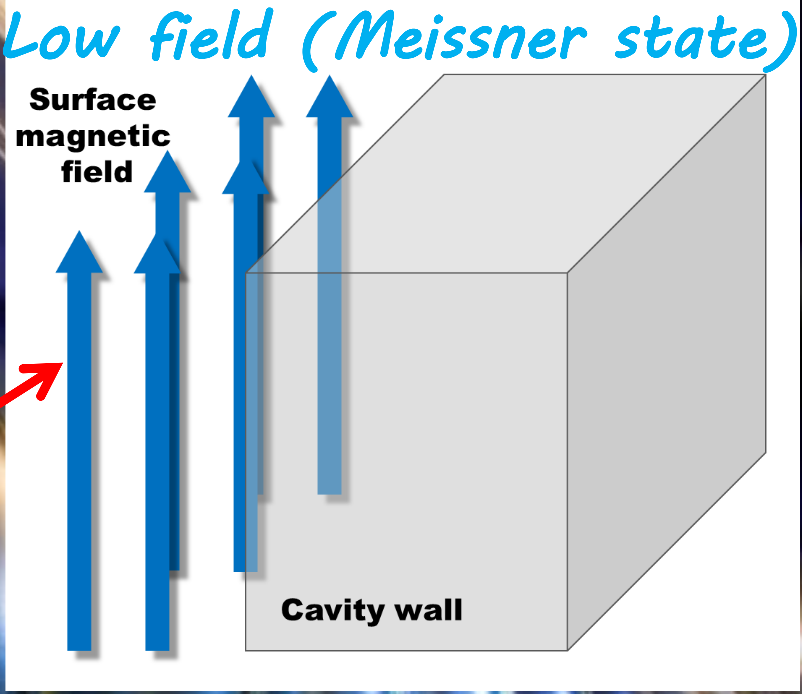


$$B_0 = g\,E_{acc}$$



g is a constant defined by cavity shape
(e.g., $g = 4.26\text{mT/(MV/m)}$ for Tesla shape cavity)

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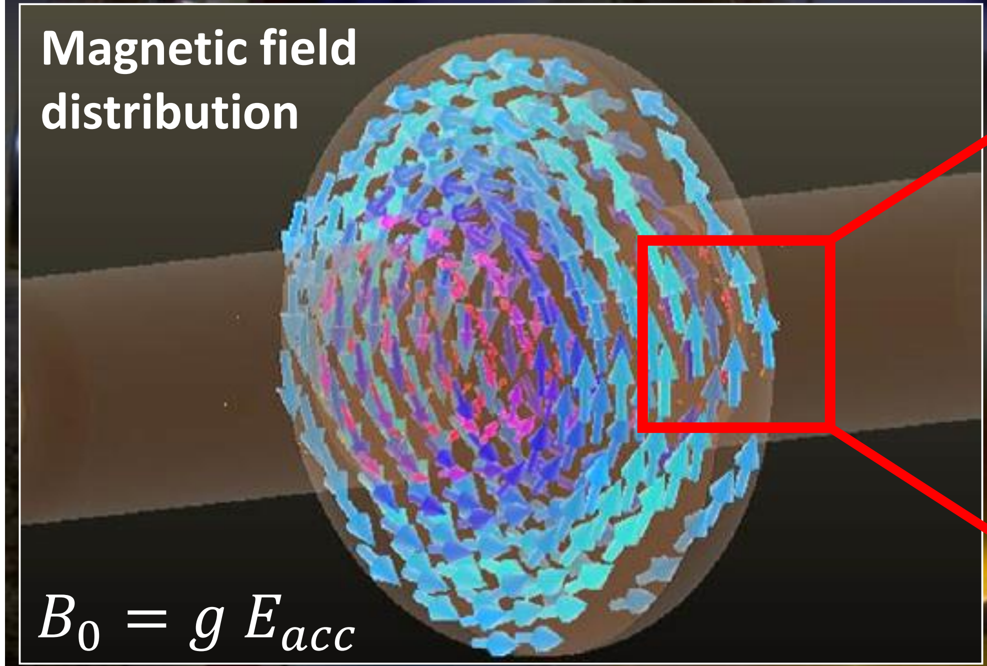
Courtesy of Peng Sha



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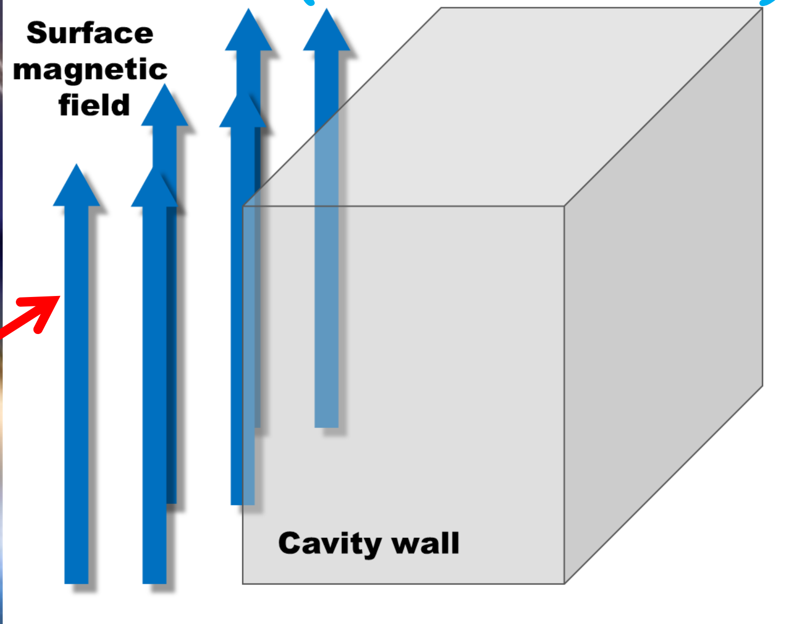
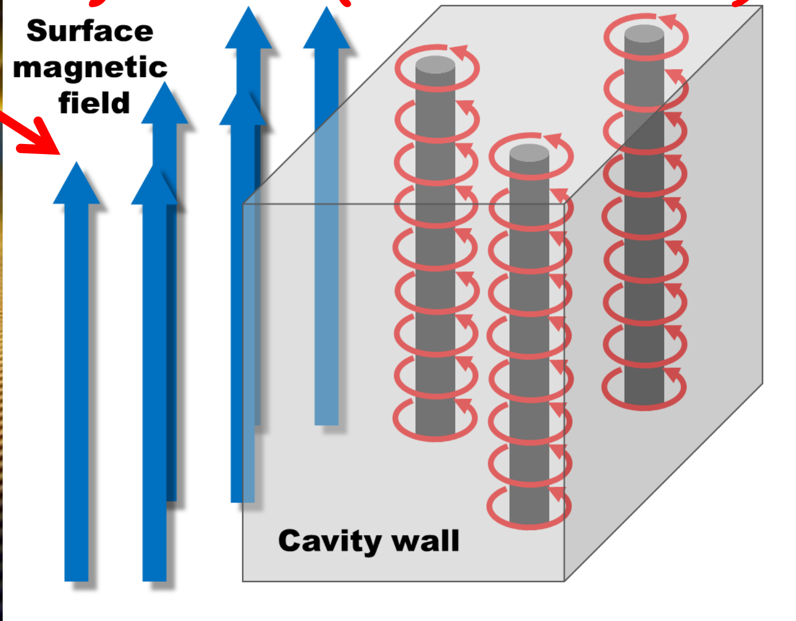
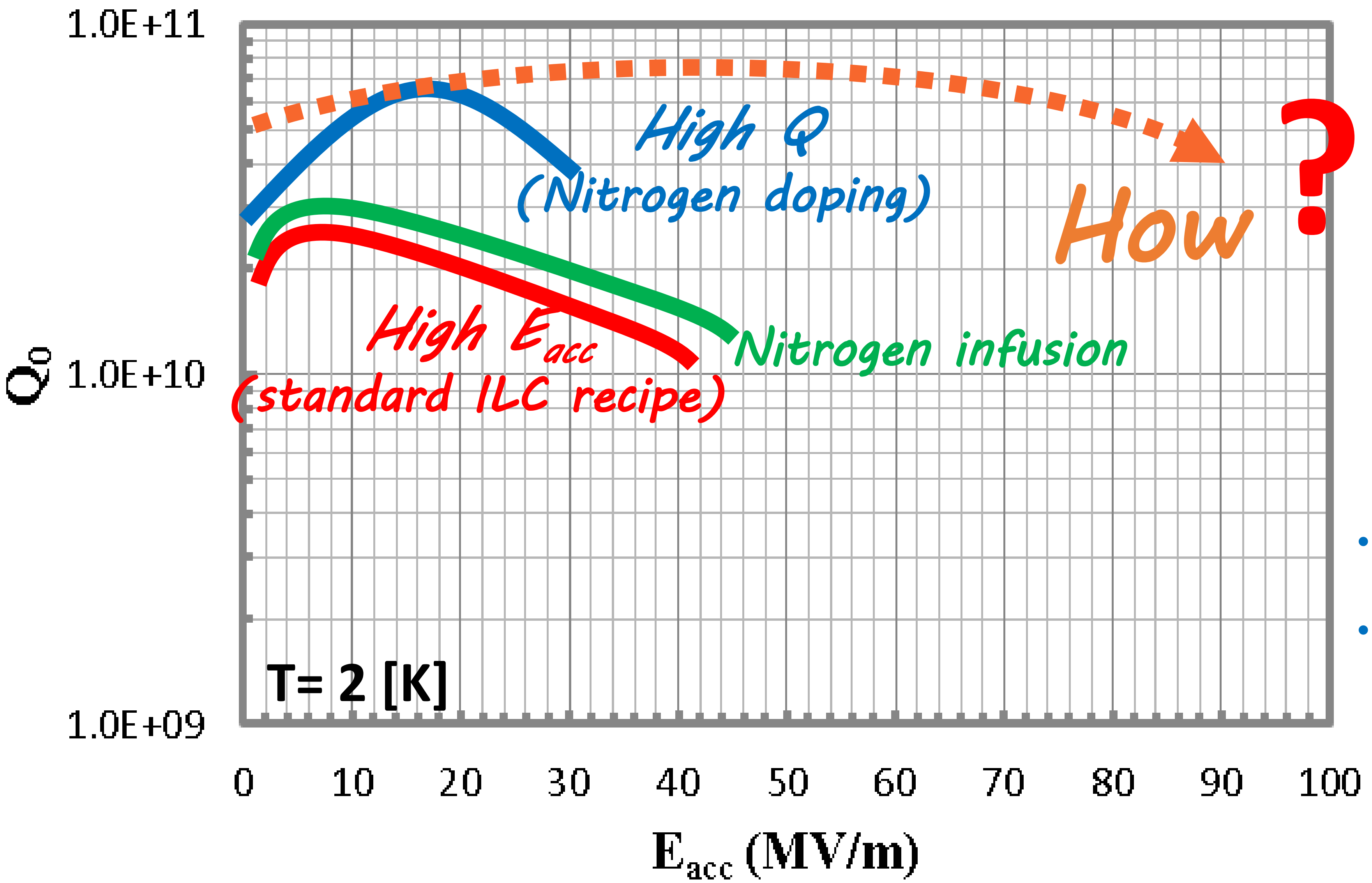
Low field (Meissner state)



High field (vortex state)



We want to go beyond the limits of the present Nb technologies!



For a better performance , we need

- **High Q**
- **High E_{acc}**

- A. Grassellino et al, Supercond. Sci. Technol. **26,** 102001 (2013)
- P. Dhakal et al., Phys. Rev. ST Accel. Beams **16**, 042001 (2013); in proceedings of IPAC2012, New Orleans, Louisiana, USA (2012), p. 2426, WEPPC091

Our understanding and motivation:

- The present choice of Nb is only a natural and preliminary selection from the natural materials. It gives no reason why we should NOT have other materials with better performance of high-Q and high-E_{acc}
- The cavity related vortex physics (vortex penetration, expulsion, pinning and dynamics) is still under intensive investigation. There must be other methods to improve Q and E_{acc}.
- We thus investigate the vortex penetration, dynamics of pure Nb, N-doped Nb and NbTi plates with magnetic field parallel and perpendicular to the plates.

Suppose the surface is polished to the ideal case, the vortex penetration is limited by the Bean-Livingston barrier

The conditions at the surface of a superconductor are:

- The magnetic induction should be continuos
- The SC current at the normal direction is zero

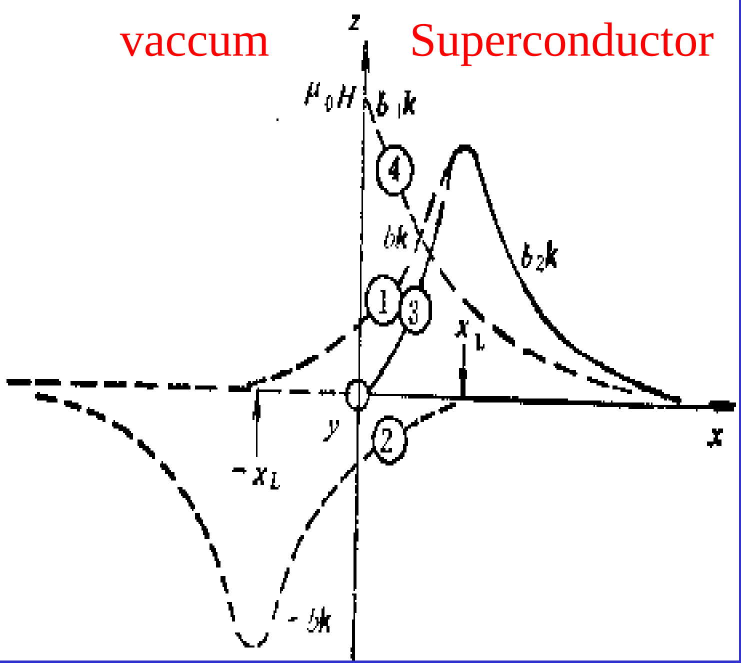
$$\vec{b}\,|_{x=0} = \mu_0 H \vec{k}$$

$$(\nabla \times \vec{b})_n\,|_{x=0} = (\mu_0 J)_n\,|_{x=0} = 0$$

By solving the GL equations, Bean-Livingston realize that the boundary conditions are identical to the case given by the vortex and its anti-vortex image at the negative side.

$$\overrightarrow{b_2} = \vec{b}_{x=x_L} + \vec{b}_{x=-x_L}$$

Bean-Livingston image force



Sketch for the magnetic induction of the external field, vortex and its image

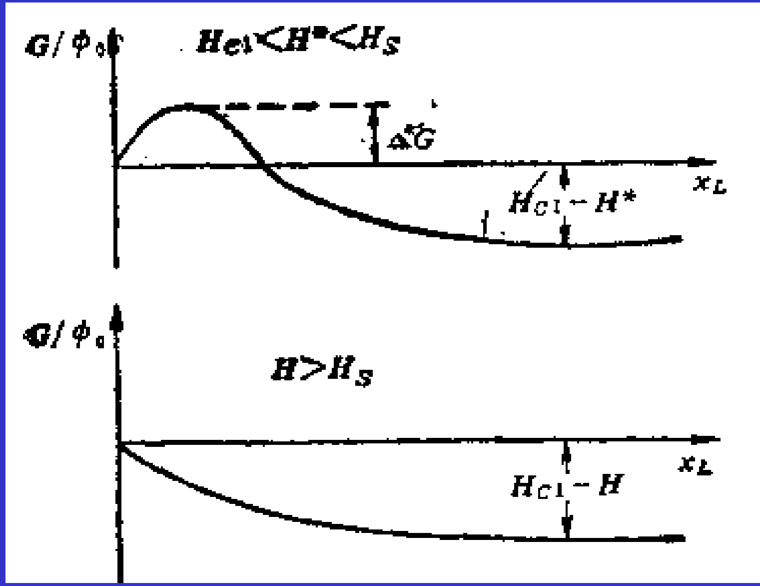
Surface barrier for the penetration of the flux go into the interior of the SC sample

Assuming we have a vortex at x_L, $\xi \ll x_L \ll \lambda$,

$$G = \Phi_0 H e^{-\frac{x_L}{\lambda}} + H_{c1}\Phi_0 - \frac{1}{4\pi\mu_0}\left(\frac{\Phi_0}{\lambda}\right)^2 \ln\left(\frac{\lambda}{2x_L}\right) - H\Phi_0$$

External field repulsive, push the vortex move inward

Surface attractive, hinder the vortex entry



Surface barrier

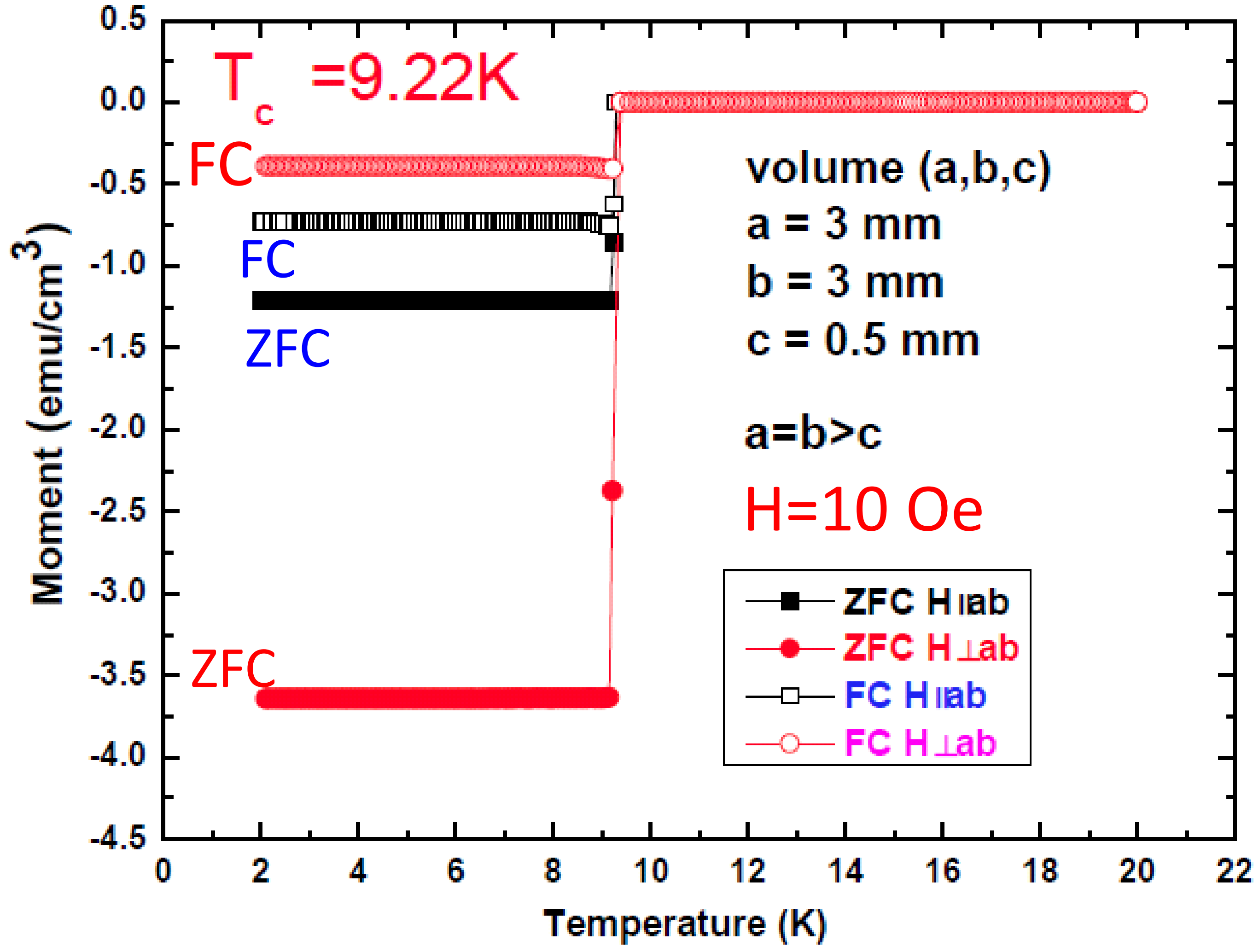
When $H_s > H > H_{c1}$, the vortices can enter the sample but are attracted to the surface. The interior is still in the Meissner state.

When $H > H_s$, the vortex can get rid of the surface attraction and enter the sample, the Meissner state will turn into the mixed state.

Minimize the Gibbs free energy to x_L one gets:

$$H_s = H_{c1}\frac{\kappa}{\ln \kappa}$$

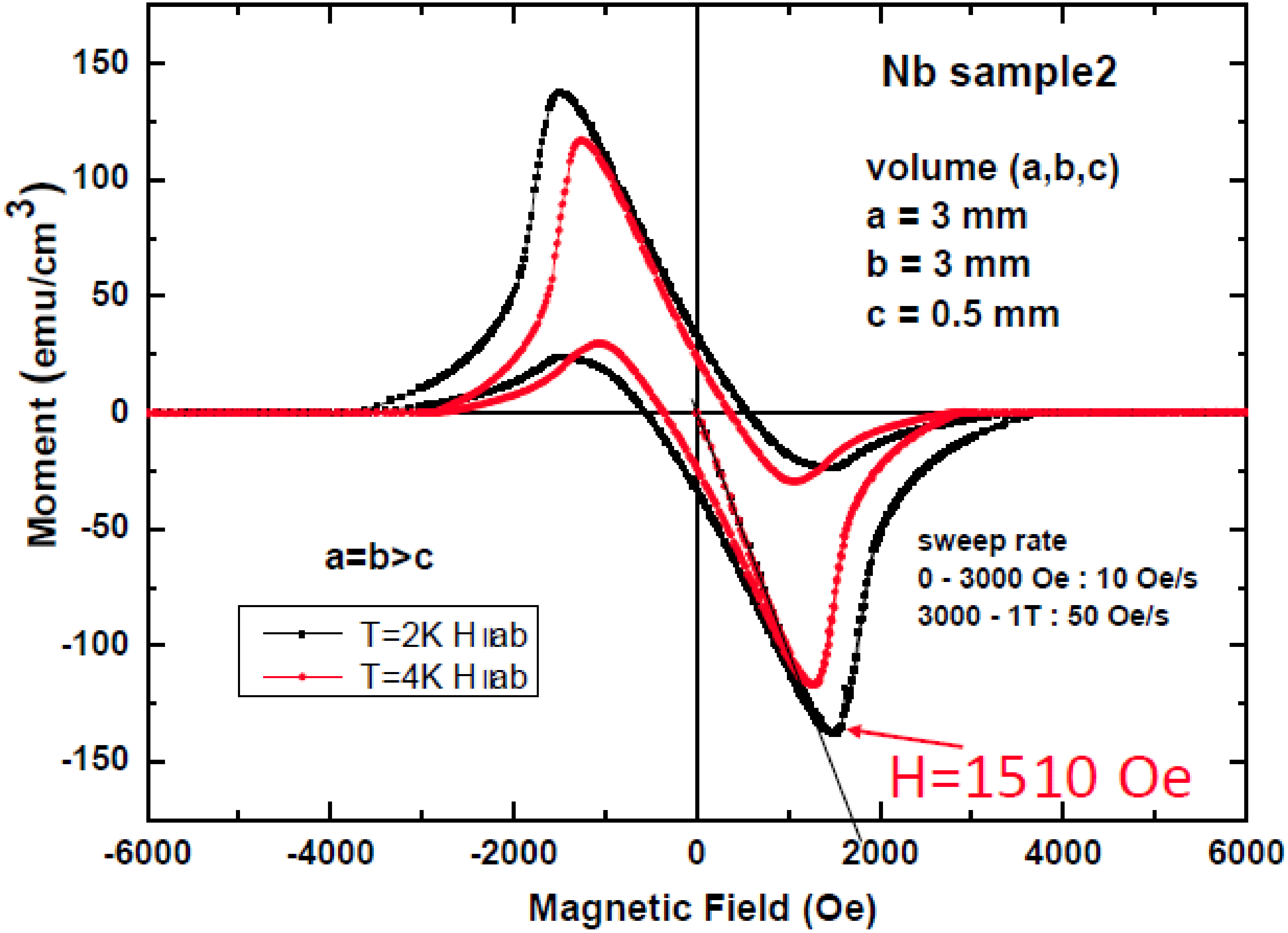
Magnetization of Nb **sample2**

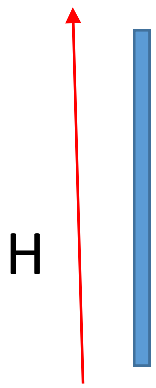


Message

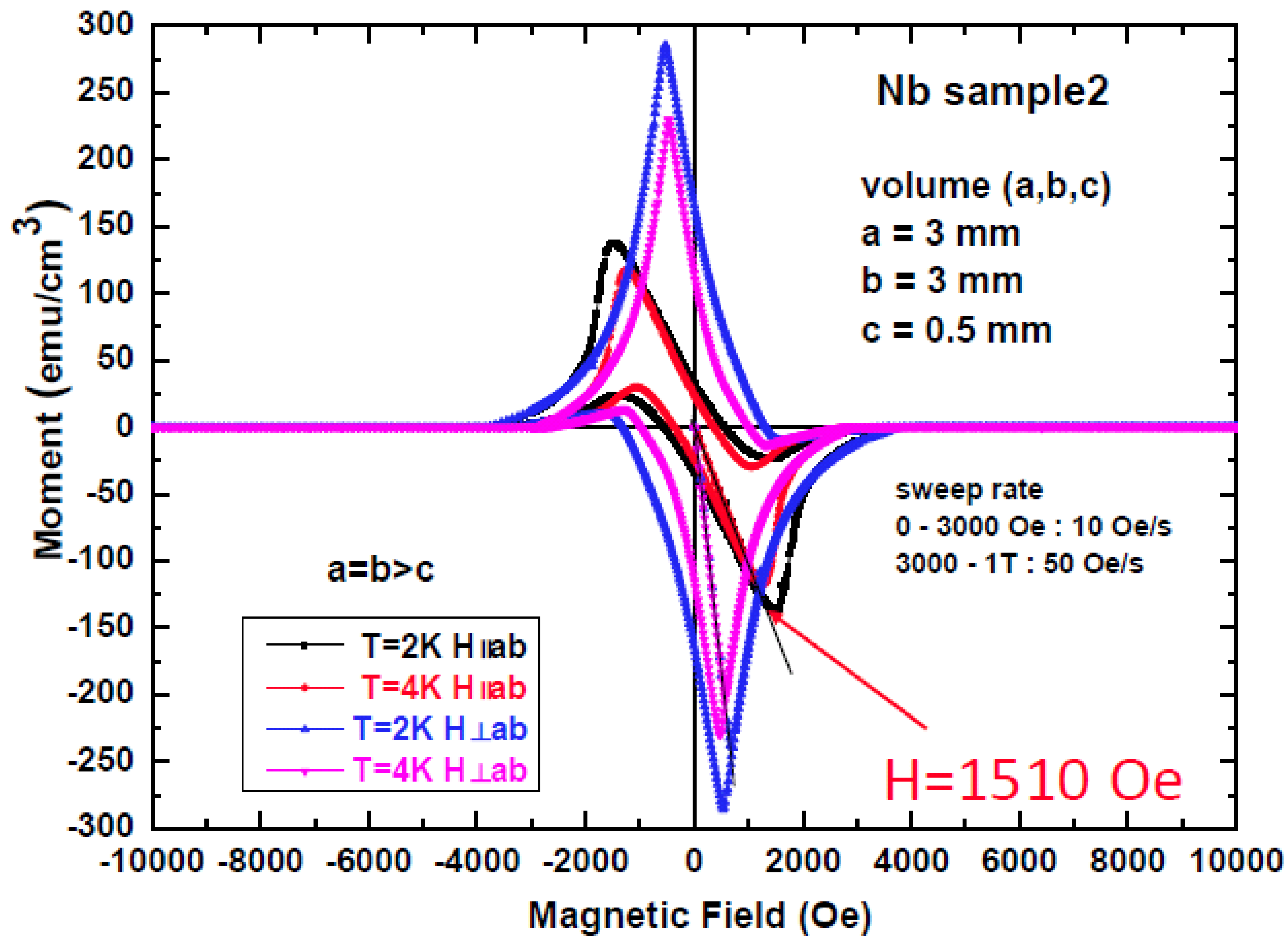
- Superconducting transition is very sharp
- Zero field cooling and field cooling M(T) curves are measured at H=10 Oe. The large negative $M(T)_{FC}$ indicates that the vortex bulk pinning is weak
- There is a demagnetization effect which gives the large difference between the M(T) curves with H||ab and H perp.to plate.

Magnetization-hysteresis-loop(MHL) with H para.to and perp.to plate or ***pure Nb***





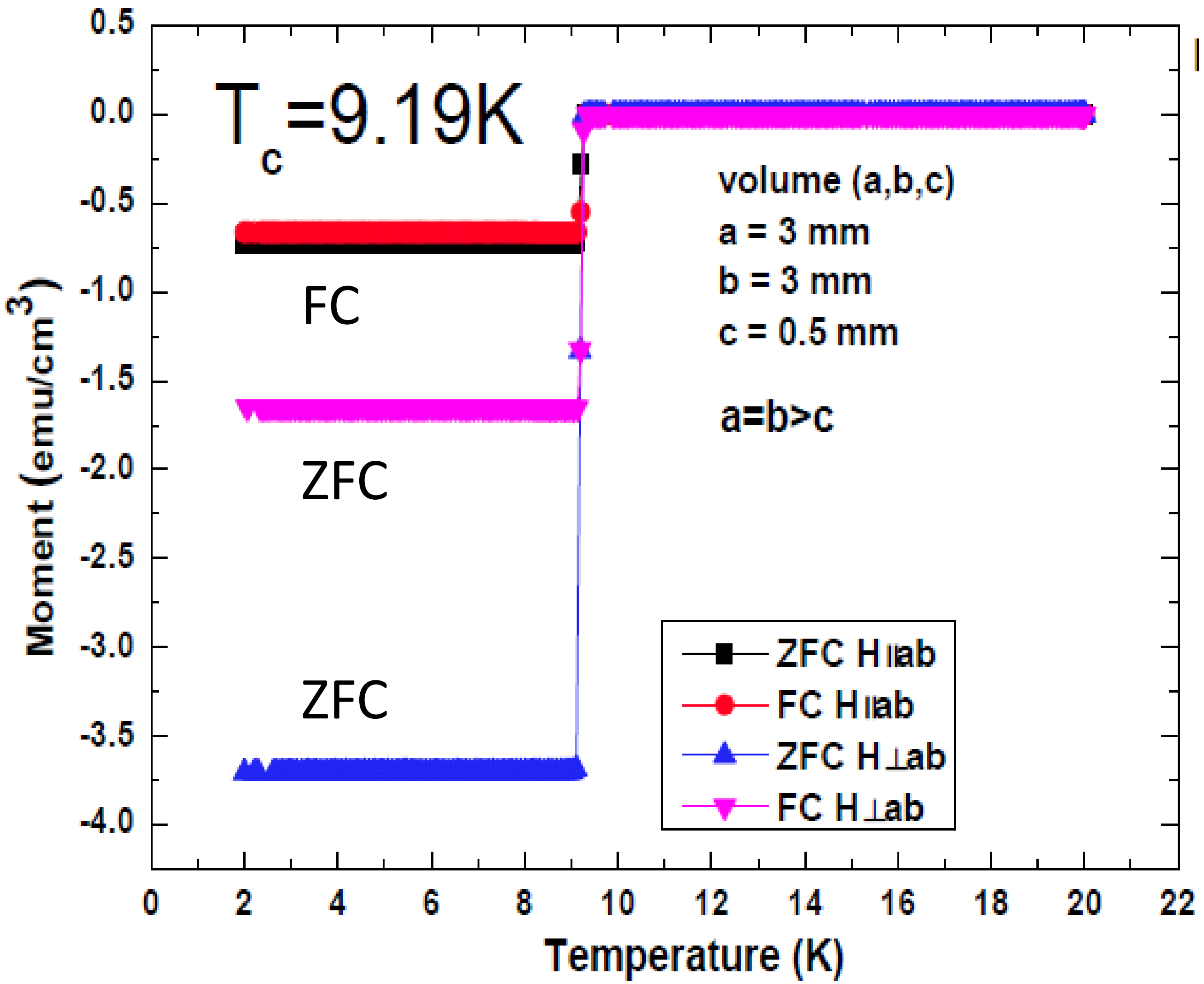
Magnetization-hysteresis-loop(MHL) with H para.to and perp.to plate or ***pure Nb***



Message:

- The first penetration field $H_p(2K)$=1510 Oe, $H_{c1}(0K)$=1700 Oe for Nb(?)
- Bulk pinning very weak
- MHL asymmetric (clear surface barrier or geometrical barrier)
- It seems the vortex entry is difficult, while exiting is easy. Thus the energy dissipations in the entry and exiting process are different.

N-doped Nb **sample1**



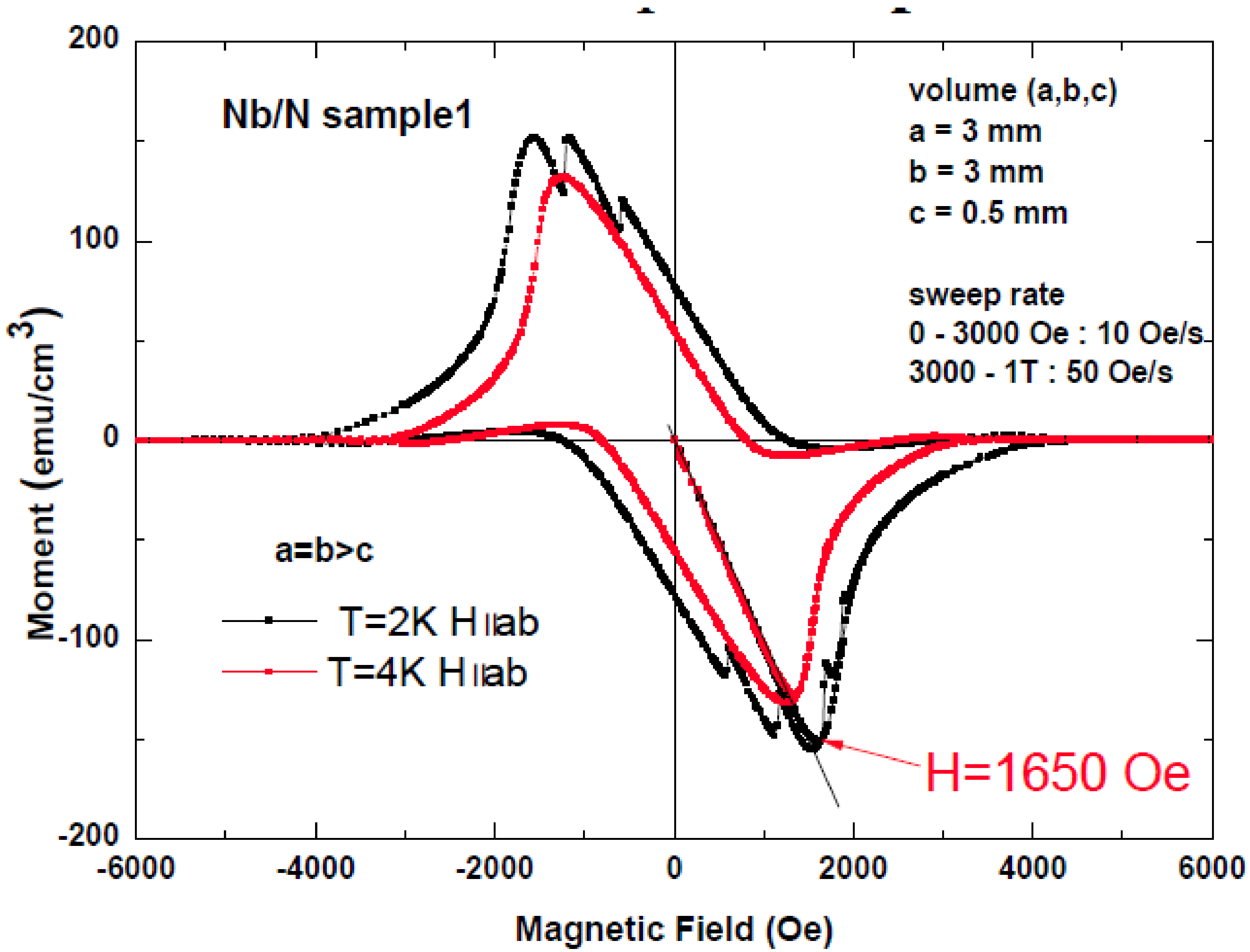
Doping N into Nb:

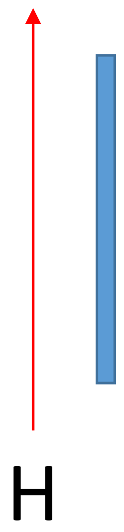
Heat up to 950°C, cool down to 800 ° C, then aneal in N_2 atmosphere (3-4 Pa). Evacuated N_2 at 800 ° C keep for 60 min. then cool down to RT.

Message

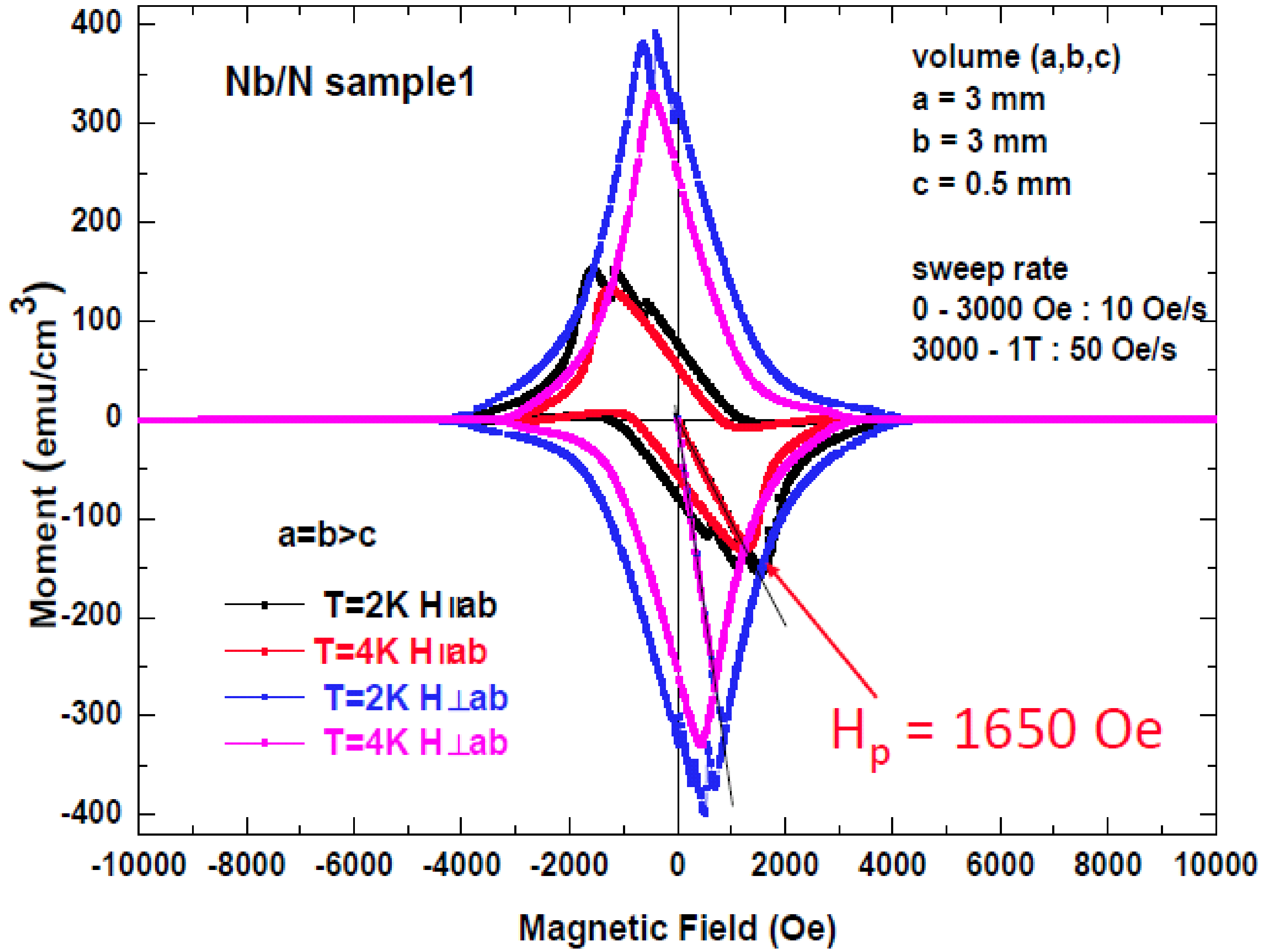
- Comparing with Nb (9.22K), T_c decreases slightly. SC transition is very sharp
- Zero field cooling and field cooling M(T) curves are measured at H=10 Oe. The large negative $M(T)_{FC}$ indicates that the vortex bulk pinning is weak
- There is a demagnetization effect which gives the large difference between the M(T) curves with H||ab and H perp. to the plates.

Nb-Ndoped **sample1**





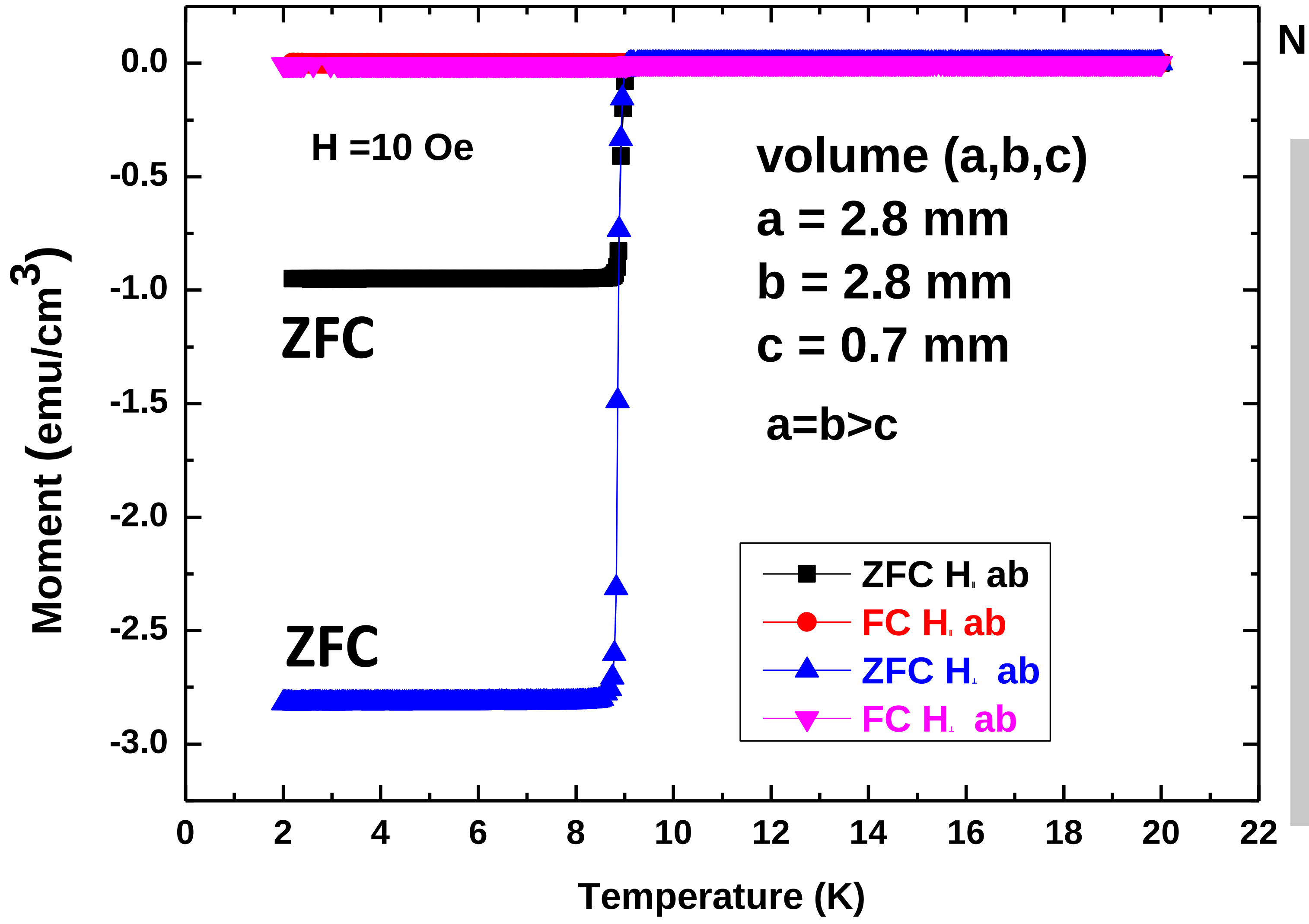
Nb-Ndoped **sample1**



Message:

- H_p(2K) = 1650 Oe, comparing with Nb (1510 Oe), it is increased.
- Bulk pinning becomes stronger, but still weak
- Slight avalanche effect at 2K, which may suggest that the thermal conductivity of N-Nb becomes worse.

M(T) curves in NbTi **sample3**

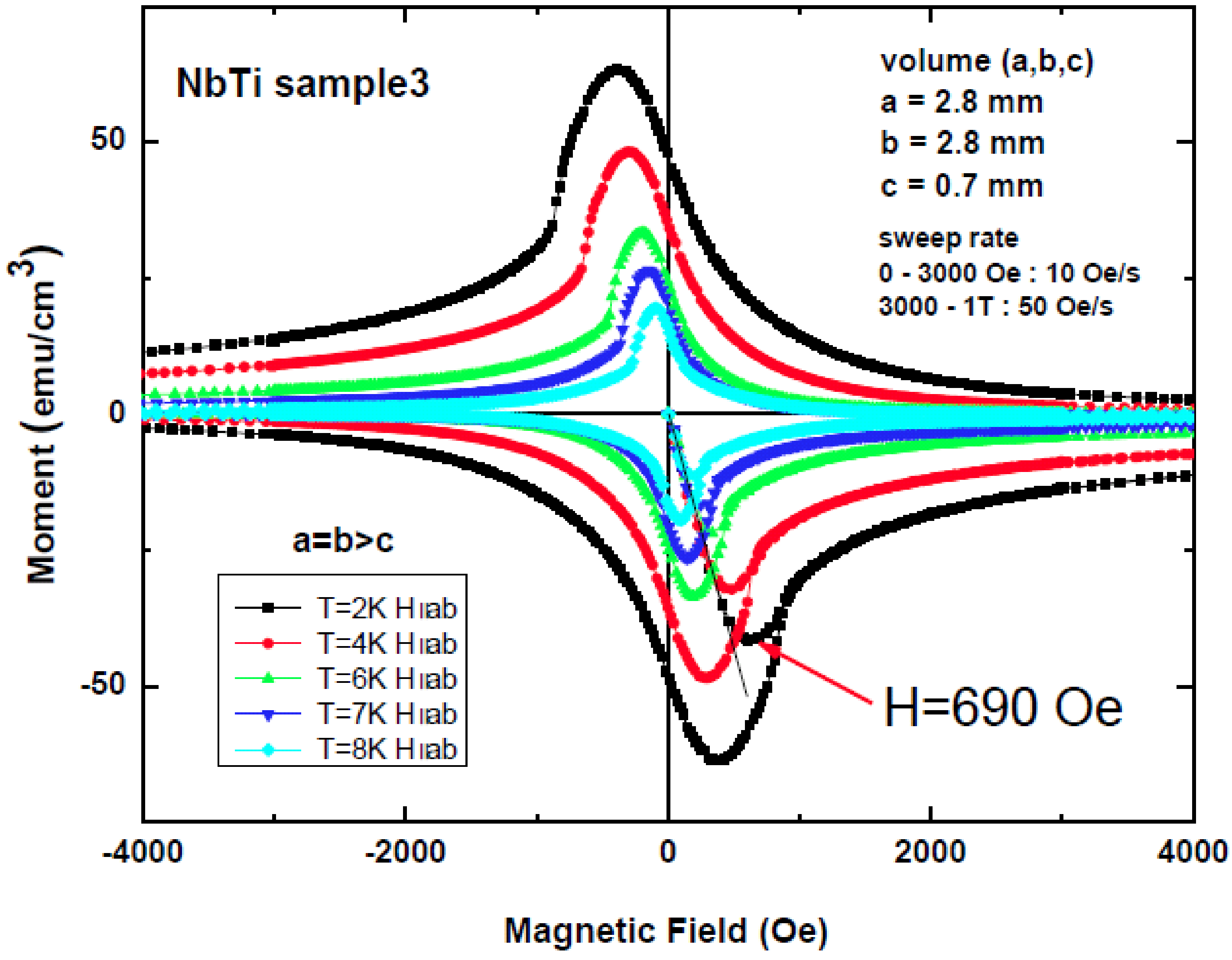


NbTi sample3

Message

- NbTi, T_c =9K. SC transition is very sharp
- Zero field cooling and field cooling M(T) curves are measured at H=10 Oe. The small $M(T)_{FC}$ indicates that the vortex bulk pinning is strong
- The demagnetization effect is clear.

MHL of NbTi **sample3**



Message

- H_p (2K) = 690 Oe (too weak)
- Bulk pinning is very strong
- E_{acc} may be higher if a NbTi cavity is used since the bulk pinning can last to high magnetic field. While the thermal conduction may be worse and the surface roughness may be larger compared with Nb.

Concluding remarks

M(T) and MHL curves have been measured for Nb, N-doped Nb and NbTi polished plates, we can reach the following conclusions:

- N-doped Nb has higher fully penetrating field, H_p=1650 Oe (2K) for N-doped Nb, 1510 Oe (2K) for Nb. Since the T_c of N-doped Nb is slightly lower, we believe the enhancement of H_p for N-doped Nb is not due to NbN, but induced by the N-doping effect.
- The MHLs of Nb and N-doped Nb are measured. The vortex entry is more difficult, and vortex exiting is easy, thus the energy dissipation of vortex entry and exiting are different.
- The NbTi has a much lower fully penetrating field H_p=690 Oe (2K), while it has stronger bulk pinning. The E_{acc} of NbTi could be higher if the surface can be well polished and thermal conduction is optimized.

Thank you for your attention!