FORC+: Extracting reversible as well as irreversible information from First Order Reversal Curves

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Outline

- FORC curves $M(H,H_R)$
- (Conventional) FORC distribution $\rho(H,H_R)$
  -- distribution of **ir**reversible hysterons
- (New) "FORC+" distribution = FORC dist. (irreversible) PLUS dist. of **reversible** "anhysterons"

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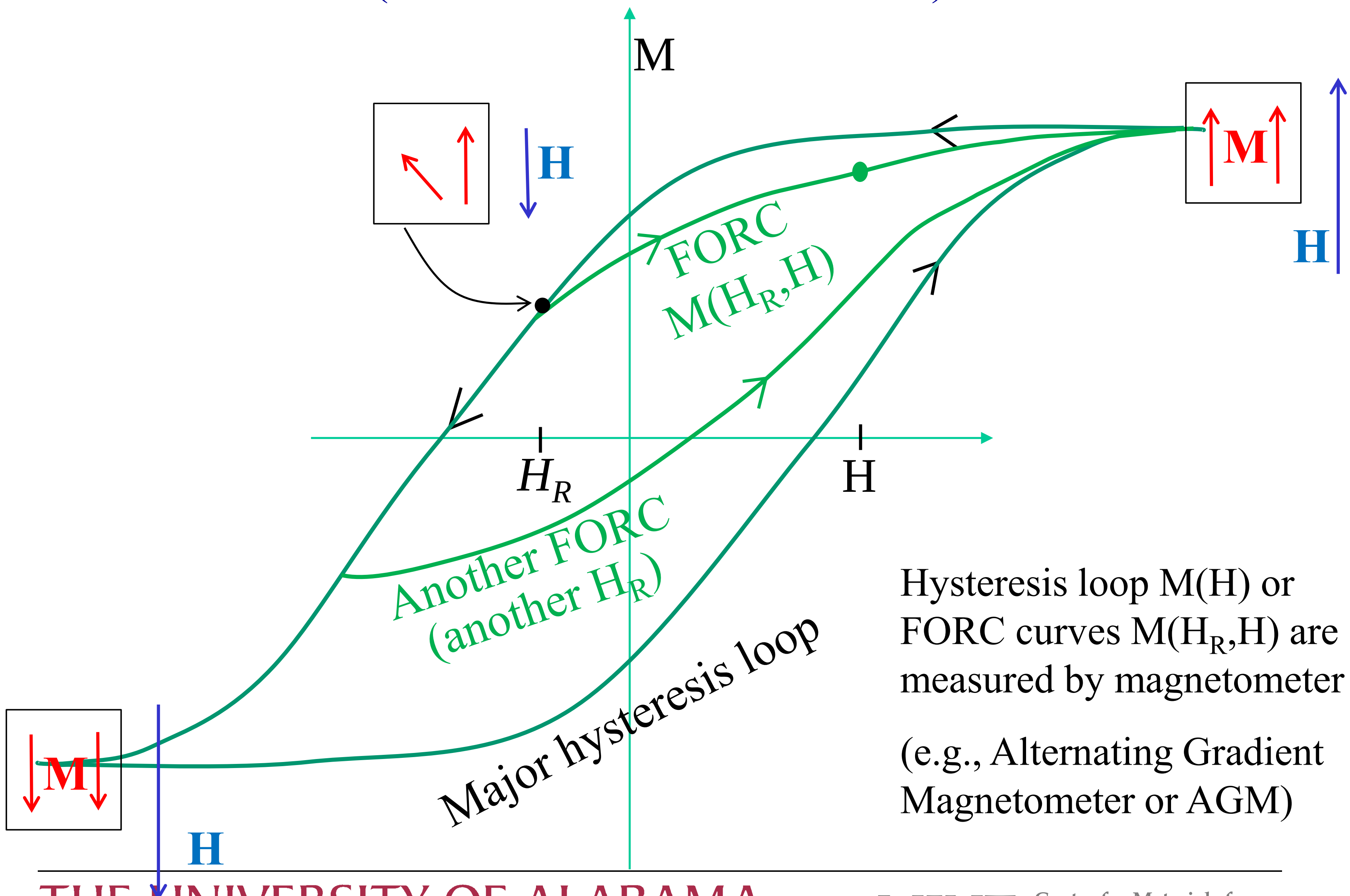
Basic FORC

(First Order Reversal Curves)

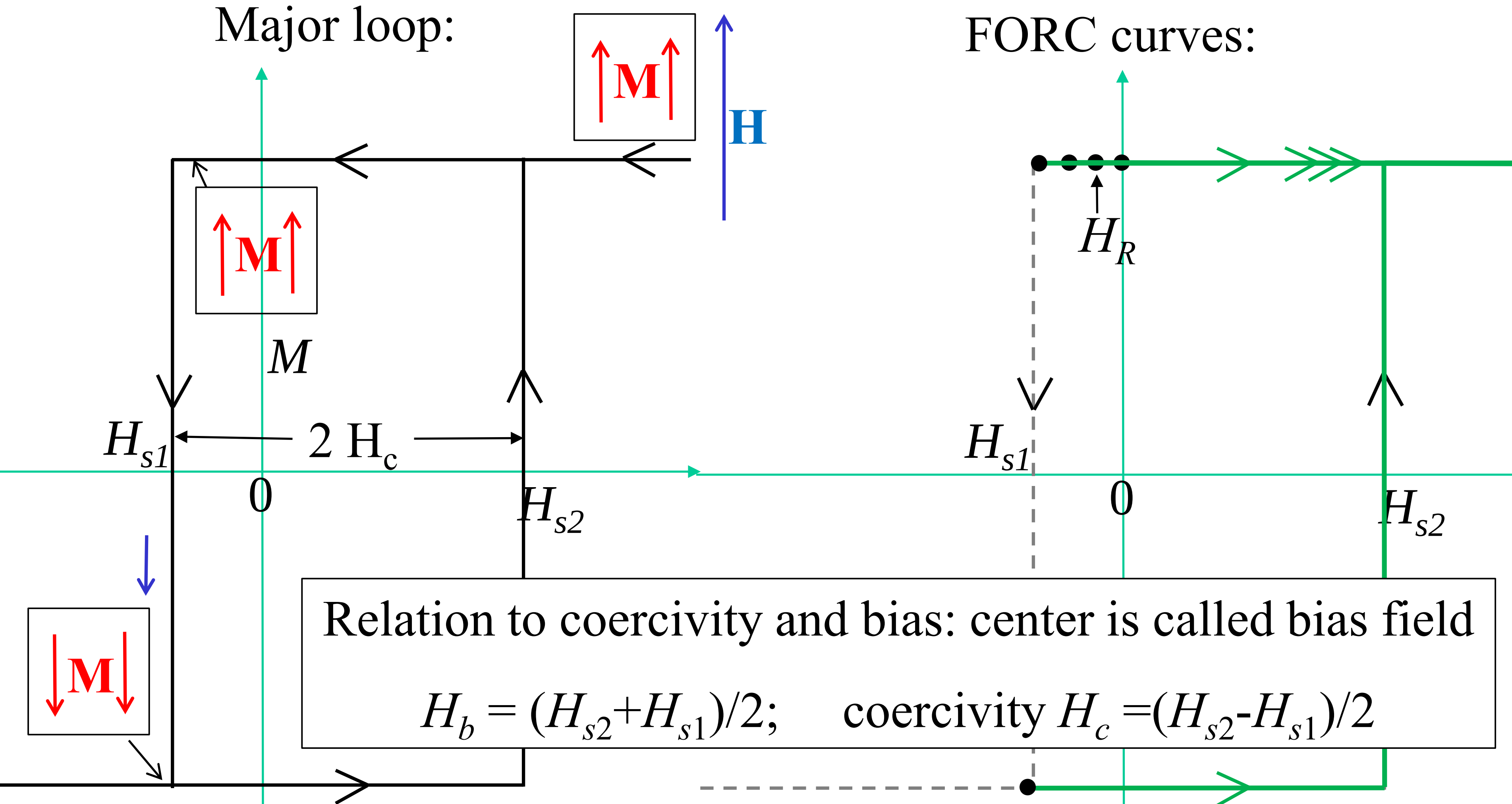


Hysteresis loop M(H) or FORC curves $M(H_R,H)$ are measured by magnetometer

(e.g., Alternating Gradient Magnetometer or AGM)

Simple FORC curves

Simple case: "Preisach hysteron" that switches at fields H_{s1} and H_{s2}.



Relation to coercivity and bias: center is called bias field

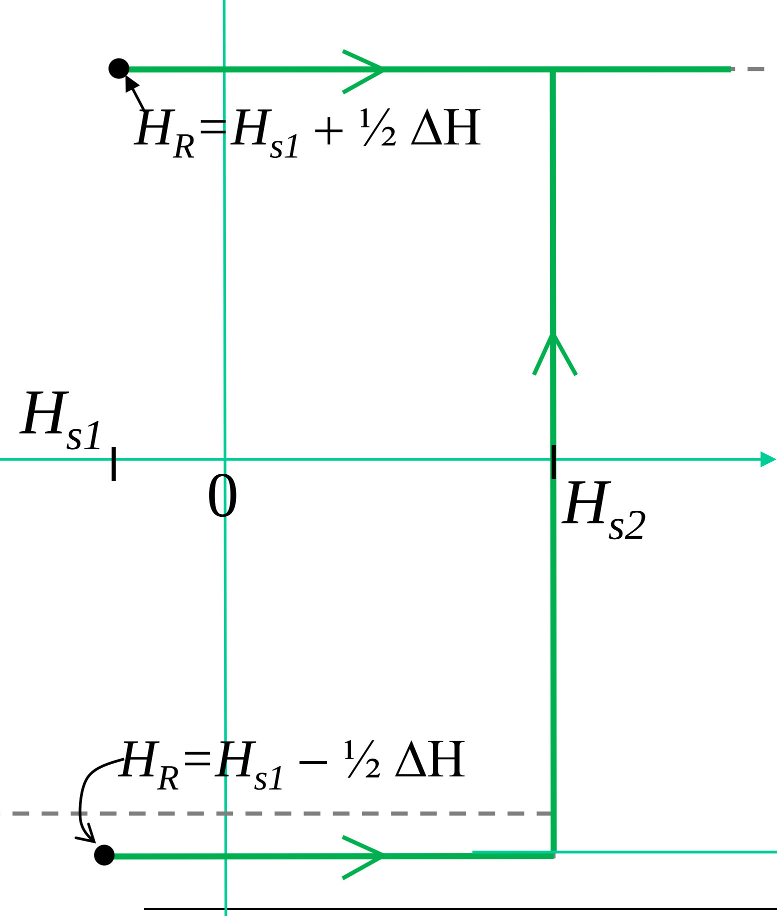
$$H_b = (H_{s2}+H_{s1})/2; \quad \text{coercivity } H_c = (H_{s2}-H_{s1})/2$$

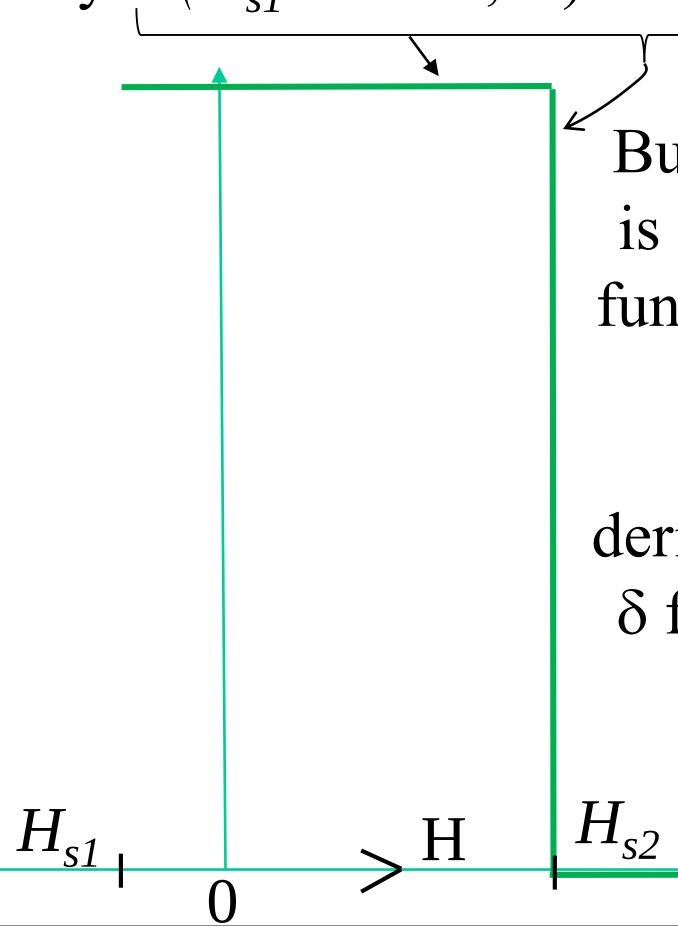
Note that FORC curve changes only when H_R passes H_{s1}.

Extracting information from FORC curves

Noted that FORC curve changes only when H_R passes H_{s1}.

So derivative $\frac{\partial}{\partial H_R} M(H_R, H) = 0$ except near H_{s1}, where it's a Dirac $\delta(H_R - H_{s1})$ times the discontinuity $M(H_{s1} + \frac{1}{2}\Delta H, H) - M(H_{s1} - \frac{1}{2}\Delta H, H)$





But discontinuity is ITSELF a step function (of H), so if we take ANOTHER derivative we get a δ function (of H)

Extracting information from FORC curves

Bottom line: The crossed partial derivative of $M(H_R,H)$

$$\rho(H_R,H) = -\tfrac{1}{2}\frac{\partial^2}{\partial H_R \partial H} M(H_R,H)$$

C. R. Pike, Phys.Rev. B 68, 104424 (2003).

C. R. Pike, C. A. Ross, R. T. Scalettar, and G. Zimanyi, Phys. Rev. B 71, 134407 (2005).

C.-I. Dobrota and A. Stancu, J. App. Phys. 113, 043928 (2013).

is nonzero only at $H_R = H_{s1}$, , $H = H_{s2}$ – it's proportional to

$\delta(H_R - H_{s1})\ \delta(H - H_{s2})$

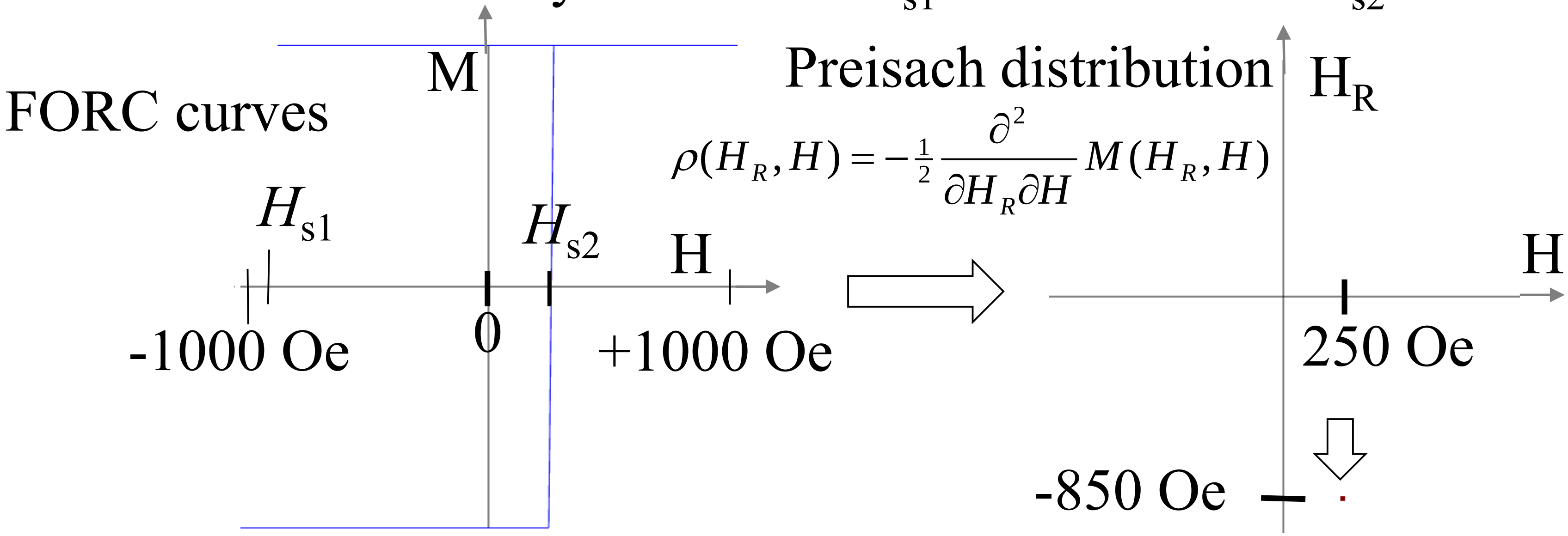
If our system has many hysterons with different H_{s1} and H_{s2} , we can interpret $\rho(H_R,H)$ as the amount (more precisely, total saturation moment) of hysterons with switching fields H_{s1}, H_{s2} equal to H_R, H.

This is called the Preisach distribution – it completely describes the irreversible part of our sample.

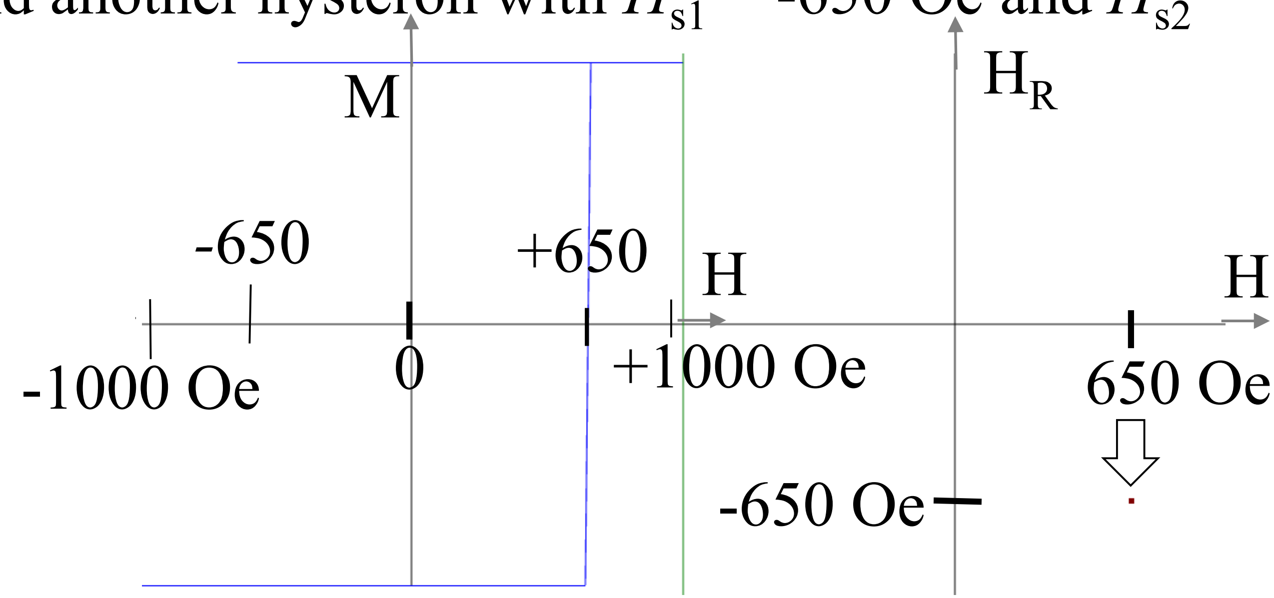
All of this has been worked out within the last 15 years or so, and has become a standard tool for determining the distribution of switching fields (or equivalently, bias field and coercivity.)

Simple Examples of FORC distributions

Consider a Preisach hysteron with H_{s1} = -850 Oe and H_{s2} = 250 Oe:

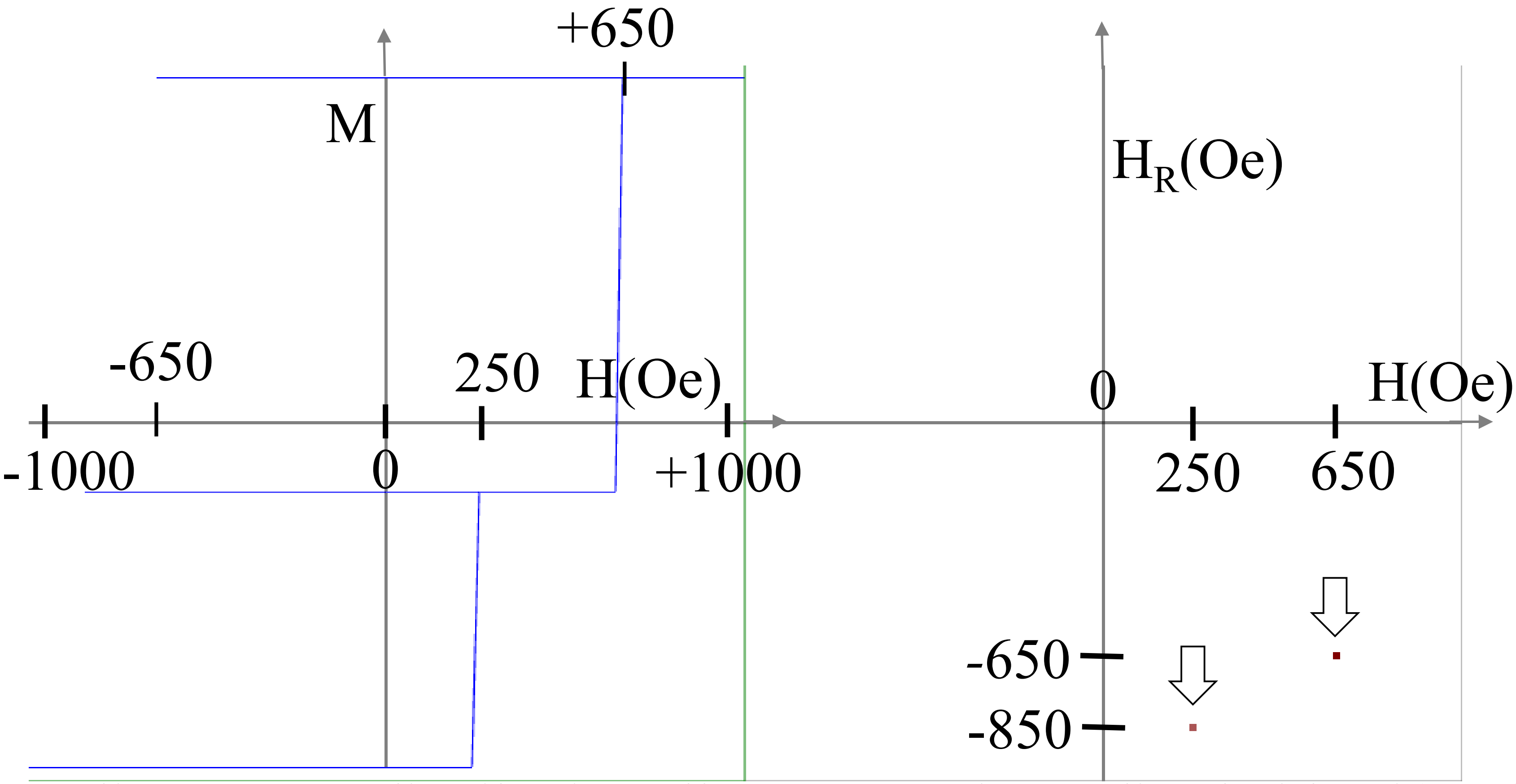


And another hysteron with H_{s1} = -650 Oe and H_{s2} = +650 Oe:



Combine two Preisach hysterons

Adding hysterons with H_{s1} , H_{s2} = -850 Oe , 250 Oe (weight 2) and -650, 650 (weight 3):

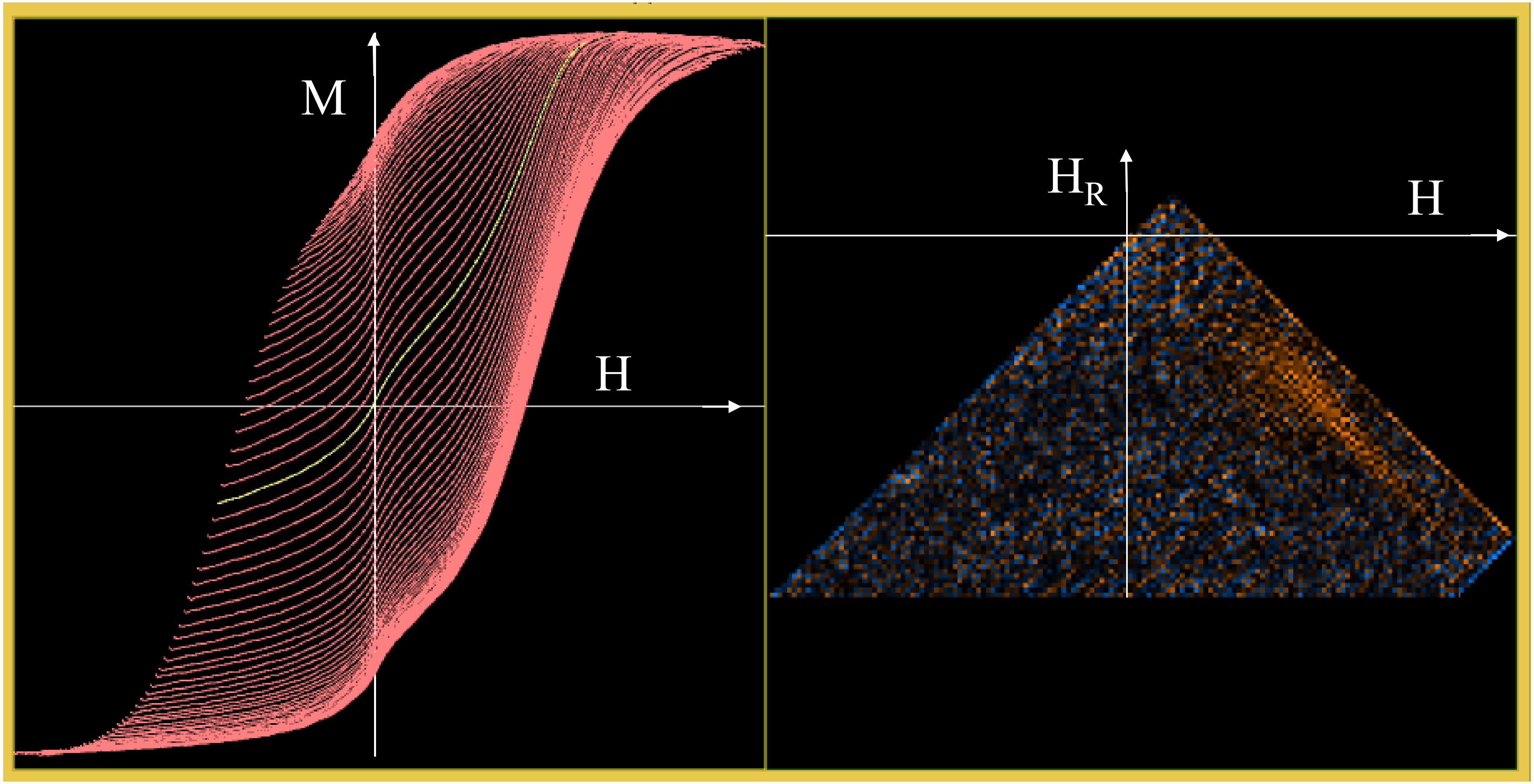


Bottom line: FORC distribution allows one to immediately identify what switching fields (or coercivity & bias field) are present, and how much.

Applying to a real sample

- FORC curves are usually produced by automated magnetometers (AGM, VSM).
- These can be set to measure FORC curves $M(H_R,H)$, where the magnetization M is measured approximately on a grid in the H_R,H plane.
- The magnetometer produces a file with a table of M, H_R, and H values
- There are many programs available for computing Preisach distributions. Most require a 3rd party visualization engine (e.g., MatLab, Mathematica, Igor Pro, …) and some pre-processing of the data file.
- Our "FORC+" is at http://visscher.ua.edu/FORC+
- Caveat: this is a very "beta" version – contact me if it doesn't work! Some details not implemented yet, e.g. axis labels.

FORC output from real data (Allen Owen)



What is missing from FORC distribution?

The FORC distribution $\rho(H_R,H)$ contains NO information about the reversible part of a system. If the system is reversible (no hysteresis), $\rho(H_R,H) = 0$ exactly!

The extraction of the FORC distribution is not invertible – you can't get the FORC curves back from the FORC distribution $\rho(H_R,H)$.

This is obvious from the fact that $\rho(H_R,H)$ is a 2nd derivative – if $M(H_R,H)$ is constant or linear, $\rho(H_R,H) = 0$. We can get dM/dH back by integration if we know a boundary condition – we will take this to be

$$\left[\frac{\partial}{\partial H} M(H_R,H)\right]_{H=H_R}$$

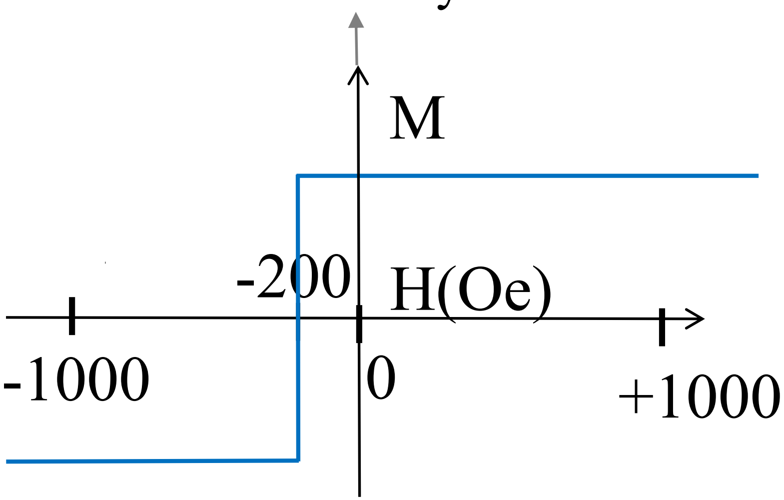
If we define a "reversible magnetization" $M_{rev}(H)$ (within an additive constant) from this by

$$\frac{\partial}{\partial H} M_{rev}(H) = \left[\frac{\partial}{\partial H} M(H_R,H)\right]_{H=H_R}$$

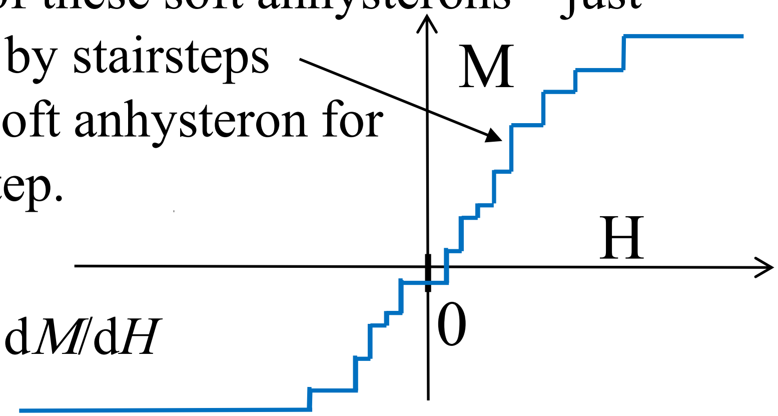
it turns out that the FORC distribution **plus** $M_{rev}(H)$ (plus the saturation magnetization, as a boundary condition at $H\to\infty$,) does uniquely determine the original FORC curves – it is a **complete** description of the system.

The “FORC+” distributions

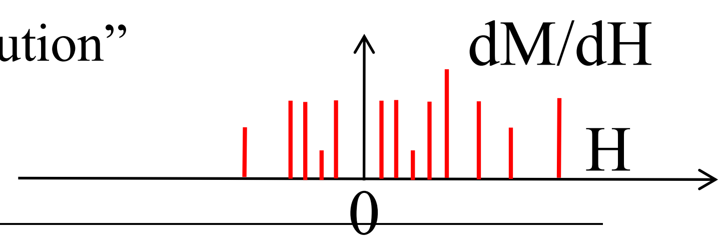
We’ve seen that the FORC distribution $\rho(H_R,H)$ contains information only on the irreversible part of our system, but we can get a complete description by adding a reversible magnetization $M_{rev}(H)$. We can think of this as coming from a distribution of elemental reversible objects (analogous to the irreversible Preisach hysterons) – in fact, if we take a Preisach hysteron whose up and down switching fields H_{s1} and H_{s2} are the same (zero coercivity), it is a reversible object we will call a “soft anhysteron”. As an example, take the switching field H_s to be -200 Oe:



Any function $M(H)$ can be expressed as a superposition of these soft anhysterons – just approximate it by stairsteps and include a soft anhysteron for each vertical step.



The derivative dM/dH is then a sum of δ functions, the “reversible switching field distribution” (a smooth function, in the limit of small steps).

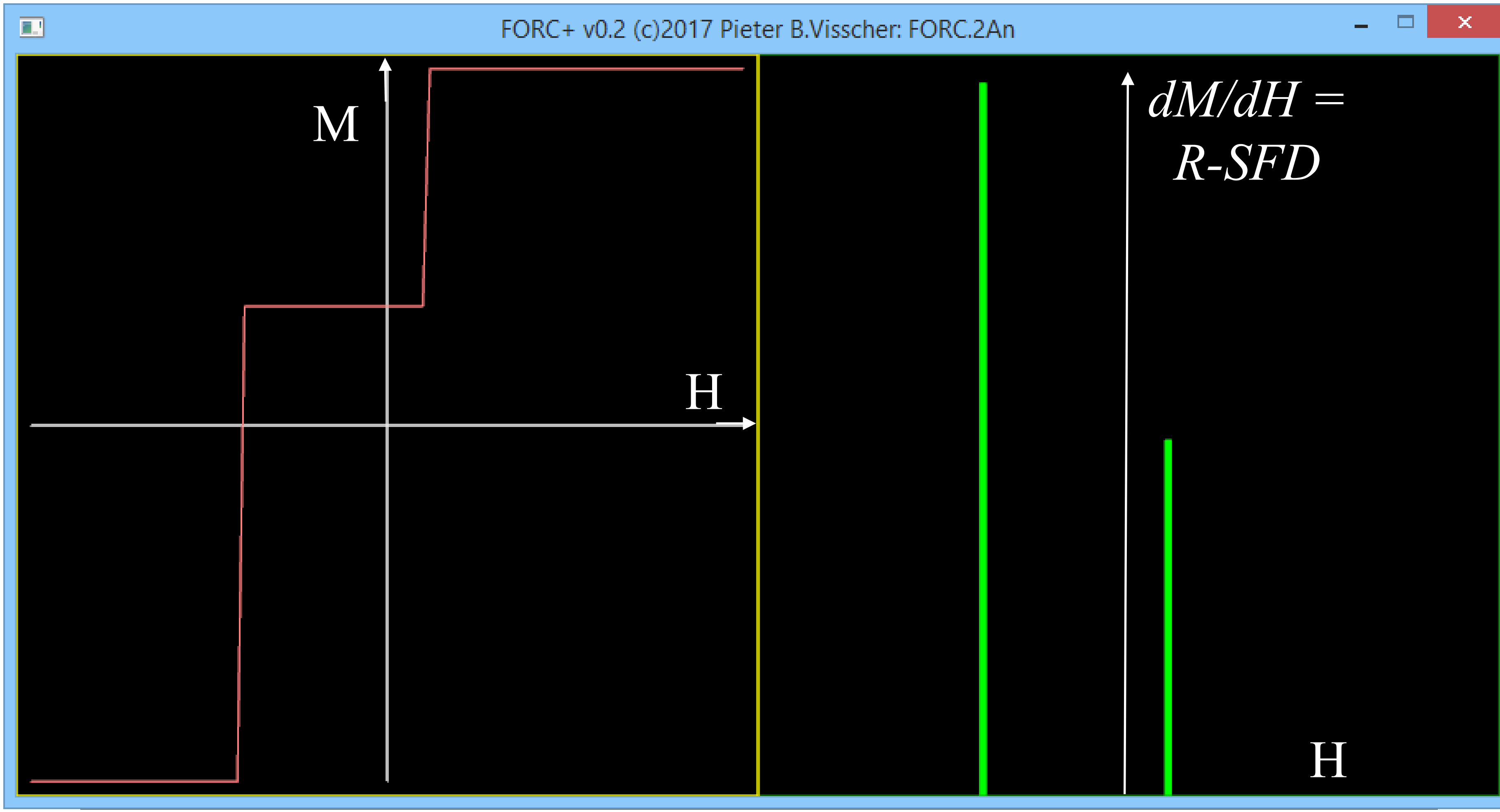


Extracting the anhysteron distribution (R-SFD) from the FORC curves

Reversible Switching Field Distribution

Example:

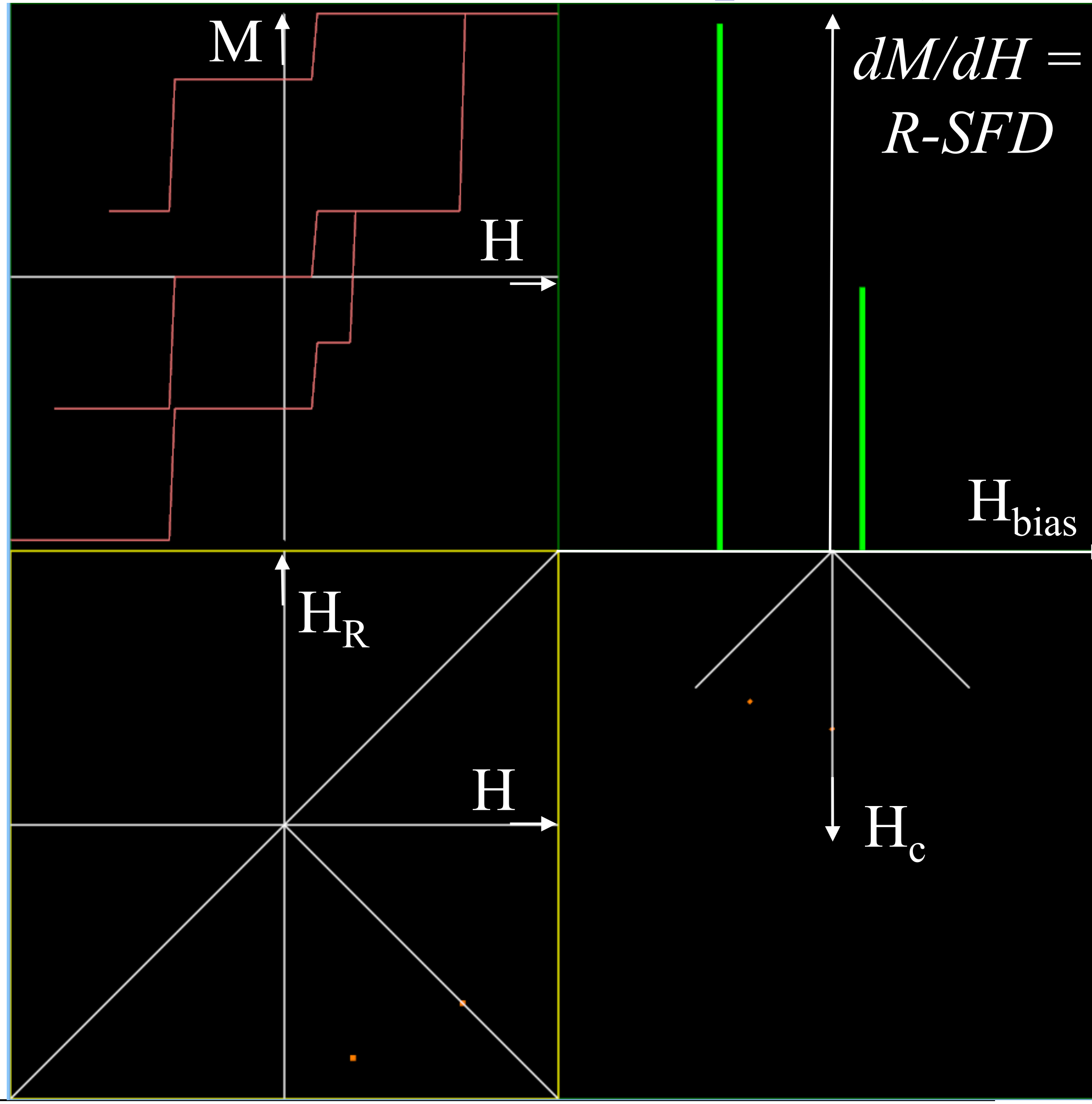
Two anhysterons, at switching fields -405 Oe (weight 2) and 105 Oe (weight 1).



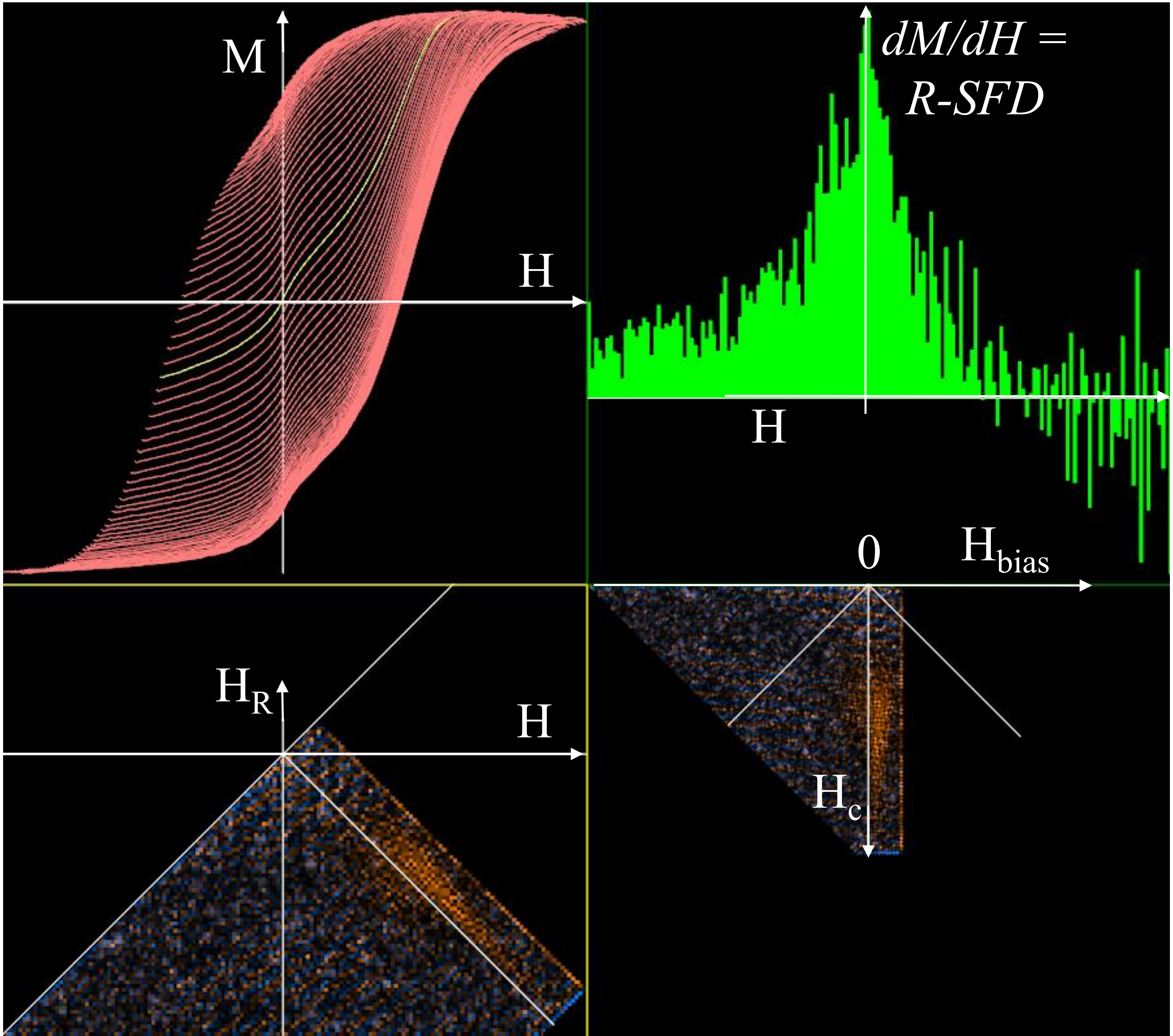
General systems
(with both reversible and irreversible pieces)

Include our two irreversible Preisach hysterons AND our two reversible anhysterons (with different weights):

This works for an arbitrary number of hysterons and anhysterons – each will appear as a δ-function in the Preisach distribution or in the R-SFD.



FORC+ output from real data (Allen Owen)



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